II. NUCLEAR STRUCTURE AND DYNAMICS

CONTENTS

INTRODUCTION

The present biennial (2011-2012) Report of activity of the theme "Nuclear Structure and Dynamics" appears to be much more extensive (and longer!) than all the previous ones. Not only the number of topics presented in the Report noticeably increases but the contributions themselves become longer and more detailed. Therefore it seems reasonable here, in the Introduction, to escape consideration of every contribution and instead to present the general picture of studies performed during the two years.

The investigations of nuclear theory community at BLTP can be conventionally divided into three parts: the theory of nuclear phenomena at low-energies (theory of nuclear structure and low-energy nuclear reactions), theory of few-body systems and theory of processes involving atomic nuclei at relativistic energies.

Almost half of all the contributions deals with the nuclear structure theory. Special attention is given to nuclei from the actinide region and beyond. The reason is evident: currently, the nuclei with $Z \gtrsim 95$ are the subjects of intensive experimental studies in view of still unanswered question about the magic shell numbers next to $Z = 82; N = 126$. Moreover, some specific features of the structure of actinide nuclei like octupole deformation, cluster manifestations, pseudospin symmetry etc attract attention of physicists. Many of these problems are discussed in the corresponding contributions (R.V. Jolos with collaborators, A. Bezbakh *et al.*, T. Shneidman *et al.*). Among other topics one can find a description of mixed-symmetry states in selected spherical nuclei (A. Severyukhin *et al.*), algebraic approach to structure of triaxial nuclei (H. Ganev), and a way to construct properly the fermionic many-body vacuum state (S. Mishev).

The high-lying nuclear modes, i.e. various giant resonances, are discussed in the contributions by A. Severyukhin *et al.*, E. Balbutsev *et al.*, and V. O. Nesterenko *et al.*

It is worthy to note a variety of theoretical tools which are exploited in the aforementioned studies. These are the phenomenological dinuclear system model, the well-known semi-microscopic Quasiparticle - Phonon Model, macro-microscopic approach based on the two-center shell model, the Two-Fluid Interacting Vector Boson Model, the supersymmetric quantum mechanics, the method of Wigner function moments, and the microscopic selfconsistent approach starting from the Skyrme-Hartree-Fock-QRPA and taking into account anharmonic terms, i.e. esssentially going beyond the QRPA. Let us stress, that some of the listed approaches were originally proposed and developed in BLTP.

The two contributions deal with the neutrino physics in its intimate connection with nuclear structure. In the contribution by F. Šimkovic *et al.* a new theoretical framework for the calculation of resonant neutrinoless double-electron capture (0νECEC) is proposed and new important theoretical findings with respect to the process are achieved. The investigations of $0\nu\beta\beta$ and 0νECEC decays performed by these authors were awarded the First JINR prize for the theoretical physics and the second prize for theoretical physics of the Institute for Theoretical and Experimental Physics (Moscow) in 2011. The other contribution (by A. A. Dzhioev *et al.*) treats the inelastic neutrino scattering off a hot nucleus — the process which seems to play an important role during some stage of star collapse.

Several contributions are devoted to the nuclear reaction theory. In most of them nucleus-nucleus collisions are considered within the aforementioned DNS model (A. Zubov *et al.*, Sh. Kalandarov *et al.*, A. Nasirov *et al.*. This model is developing successfully in BLTP for many years by the group of researchers. Being originally proposed to explain some

features of nucleus-nucleus collisions now the DNS model is applied to a more wide class of nuclear problems like cluster phenomena in heavy nuclei, theory of fission etc (see e.g. T. Shneidman *et al.*, A. Andreev *et al.*).
The contribution by V. Sargsyan *et al.* is devoted to a new approach based on quantum diffusion equations of motion for the collective coordinates of colliding nuclei. This approach is intended to analyze capture and fusion processes at near the Coulomb barrier and deep sub-barrier energies.
Along with heavy ion collisions the processes involving light exotic nuclei are considered as well. In particular, the recently published exciting data on the radius of the Borromean nucleus ^{22}C are analyzed by S. N. Ershov *et al.* and interaction of proton with ^{11}Li is described within the hybrid model of the microscopic optical potential developed by V. K. Lukyanov *et al.*. The latter model is successfully applied also to elastic pion-nucleus scattering (see the corresponding contribution by V. K. Lukyanov *et al.*).
Research subjects within the two other fields — the few-body theory and dynamics of relativistic processes with nuclei — appear to be rather scattered. Here we mainly enumerate them.
The few-body theory is represented by the three contributions. They include rigorous mathematical results concerning sharp-norm bounds for rotation angles of spectral subspaces of Hermitian operators under the action of self-adjoint and J-self-adjoint potentials (S. Albeverio and A. K. Motovilov), the new achievements in the theory of low-dimensional few-body systems (V. S. Melezhik *et al.*), results of application of the Dubna-Mainz-Taipei dynamical model for extraction of nucleon resonance properties from πN scattering data (D. Drechsel, S. S. Kamalov, *et al.*). It should be noted that the investigations in the field of the few-body physics at low dimensions which are partially presented in the contribution by V. S. Melezhik *et al.* were awarded by the Second JINR Prize for the theoretical physics in 2012.
The field of nuclear physics at relativistic energies is covered by the five contributions. In the extensive and detailed contribution V. D. Toneev presents recent applications of the so-called parton-hadron-string dynamics (PHSD) approach to the analysis of the evolution and role of retarded electromagnetic fields in a relativistic collision of heavy nuclei and to calculations of azimuthal anisotropies of the collective transverse flow of hadrons. A. S. Parvan explores the main thermodynamical properties of the first order phase transition of the relativistic mean-field hadronic model in the isobaric, the canonical and the grand canonical ensembles. Continuing the studies of short-range nuclear correlations (SRC) L. P. Kaptari calculates the single particle and two-body (np and pp) momentum distributions in selected very light nuclei to elucidate some universal features of SRC. A. I. Titov presents the well elaborated theory of electron-positron pair production in collision of high energy photons with a power laser pulse limited in space and time. In the contribution by S. G. Bondarenko *et al.* an improved version of relativistic complex separable kernel for the description of the neutron-proton interaction constructed within a covariant Bethe-Salpeter approach is presented.
The last (but not the least) contribution by R. G. Nazmitdinov is devoted to the non-nuclear subject — the interaction of light with nanoparticles. Members of the BLTP nuclear community quite often apply their skill, knowledge and strengths in other areas of theoretical physics. This is one of the examples. The other examples can be found in the section "Condensed Matter Theory and New Materials".
To complete this note let us add some formal data about activity of the BLTP nuclear

community in 2011-2012. Nuclear theorists have published 157 papers in peer reviewed journals and 54 contributions in the conference Proceedings (several papers are in the reference list of the theme "Condensed Matter Theory and New Materials"). The number of Proceeding contributions allows to estimate a number of talks given by our colleagues at various international conferences, schools and workshops over the world. Moreover, there were organized the Helmholtz International School on Nuclear Theory and Astrophysical Applications (July, 2011), International Conference on Nuclear Structure and Related Topics (July, 2012), XXI International Baldin Seminar "Relativistic Nuclear Physics & Quantum Chromodynamics" (September, 2012) and 5 Workshops covering different hot spots of comprehensive nuclear theory.

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SECOND ORDER PHASE TRANSITIONS FROM OCTUPOLE-NONDEFORMED TO OCTUPOLE-DEFORMED SHAPE IN THE ALTERNATING PARITY BANDS OF NUCLEI AROUND ^{240}Pu

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In recent years quantum phase transition phenomena in atomic nuclei came to the forefront of nuclear structure physics. Mainly, the phase transitions between spherical, axially deformed and γ-soft limits of nuclear structure have been analyzed. Shape-transitional nuclei always attracted attention. In most considered cases the focus was on the quadrupole deformation and the control parameters were the numbers of protons or neutrons. In the present paper [**?**] we present and analyze an example of the second order phase transition in nuclei related to the octupole deformation and the control parameter is the angular momentum. Our aim to show basing on the experimental data that an evolution of the reflection asymmetry in the alternating parity bands with increasing angular momentum gives a very clear example of a second order phase transition in nuclei.

In the consideration below we use a model which describes the collective octupole excitations of nuclei basing on the assumption that the most important degree of freedom is β_{30} which keeps axial symmetry. We thus assume a softness of β_{30} mode in contrast to the other octupole modes with $K \neq 0$. In the framework of this model, using the method suggested in [**?**] we have obtained an analytical expression for the collective potential as a function of β_{30}. The shape of this potential is completely determined by the experimental data on the parity splitting in the alternating parity band for all considered values of the angular momentum. It is shown that although for the low values of the angular momentum I the potential energy has a minimum at β_{30}=0, nevertheless, at some value of $I = I_{crit}$ the minimum at β_{30}=0 disappears and two minima at nonzero value of β_{30} develop. It is shown also that this is a second order phase transition from reflection-symmetric to reflection-asymmetric shape which is governed by the angular momentum. The important fact is that we determine the potential for several values of the angular momentum smaller and larger than the critical value of I. This give us a possibility to see an evolution of the potential along a sufficiently large interval of the values of the angular momentum which is the control parameter. Every step of this evolution is determined by data.

The Hamiltonian of the model used can be presented as

$$H_I = -\frac{\hbar^2}{2B}\frac{d^2}{d\beta_{30}^2} + V_I(\beta_{30}), \tag{1}$$

where the subscript I indicates that the shape of the potential depends on the angular momentum I.

We have started a consideration making the following ansatz for the positive parity wave function. Since this wave function has no nodes because it describes the lowest states for every I we have assumed that it can be presented by the sum of two Gaussians centered at $\beta_{30} = \pm\beta_m(I)$ whose width is determined by the parameter ω.

Following the procedure of the supersymmetric quantum mechanics we substitute the wave function into the Schrödinger equation and obtain the following relation for the potential $V_I(\beta_{30})$

$$V_I(\beta_{30}) = \frac{\hbar\omega}{2}\Big[-1 + s_3^2(I)\left(1 + \beta_{30}^2/\beta_m^2(I)\right) \\ -2s_3^2(I)\frac{\beta_{30}}{\beta_m(I)}\frac{\exp\left(s_3^2(I)\beta_{30}/\beta_m(I)\right) - \exp\left(-s_3^2(I)\beta_{30}/\beta_m(I)\right)}{\exp\left(s_3^2(I)\beta_{30}/\beta_m(I)\right) + \exp\left(-s_3^2(I)\beta_{30}/\beta_m(I)\right)}\Big] + E_I^*, \quad (2)$$

where for even I the quantity E_I^* is the experimental excitation energy of the lowest state with angular momentum I. For odd I this energy is determined by interpolation using the energies of the neighboring even-I states. As in the case of the wave function the shape of the potential (**??**) is determined completely by one parameter, namely, $s_3(I)$ only. In [**?**] it was shown basing on the results of calculations of the parity splitting $\Delta E(I)$ that the quantity $s_3(I)$can be parameterized by a linear function of the angular momentum

$$s_3(I) = c_0 + c_1 \cdot I, \quad (3)$$

where c_0 and c_1 are the fit parameters.
It is seen from the results of calculations for ^{240}Pu that at $I = 0$ the potential $V_I(\beta_{30})$ has a form of the harmonic oscillator with the minimum at $\beta_{30} = 0$. At I=24 it is a two-minima potential which describes a reflection-asymmetric shape of the nucleus. At I=12 we have a potential corresponding to transition from reflection-symmetric to reflection-asymmetric shape. Thus, with increasing angular momentum the shape phase transition takes place in the alternating parity band.
Let us consider this transition in details applying the Landau theory of phase transitions. In our case the role of the free energy in the Landau theory is played by the potential V_I taken at the minimum, β_{30} is an order parameter and I is a control parameter. The next step is a determination of the equilibrium value of the order parameter β_{30} which is the position of the minimum of the potential. This value of $(\beta_{30})_{min}$ is a function of the control parameter I. Then we investigate a behavior of the potential and its derivatives at the minimum of the potential.
The position of the minimum of the potential $V_I(\beta_{30})$, i.e. the equilibrium value of the order parameter β_{30} is determined by the condition

$$0 = \frac{dV_I(\beta_{30})}{d\beta_{30}}|_{\beta_{30}=(\beta_{30})_{min}} \quad (4)$$

This equation has two solutions. The first one is $(\beta_{30})_{min}$=0. The second one is given by the root of the following equation

$$1 - \frac{(\beta_{30})_{min}}{\beta_m(I)}\tanh\left(s_3^2(I)(\beta_{30})_{min}/\beta_m(I)\right) - \frac{s_3^2(I)}{\left(\cosh\left(s_3^2(I)(\beta_{30})_{min}/\beta_m(I)\right)\right)^2} = 0 \quad (5)$$

The minimum of V_I at $\beta_{30} = 0$ takes place only if $s_3(I) < \frac{1}{\sqrt{2}}$ when the second derivative of $V_I(\beta_{30})$ over β_{30} at $\beta_{30} = 0$ is positive. If $s_3(I) > \frac{1}{\sqrt{2}}$ then at $\beta_{30} = 0$ potential has

a maximum and the minimum is smoothly shifted to nonzero value of β_{30}. This value is determined by the numerical solution of the Eq. (**??**).
If $s_3(I)$ is larger but very close to $\frac{1}{\sqrt{2}}$ the root of the Eq. (**??**) is given approximately as

$$(\beta_{30})_{min} = \beta_m(I)\sqrt{\frac{3}{2s_3^6(I)}\left(s_3^2(I) - \frac{1}{2}\right)} \tag{6}$$

Let us find the value of the potential V_I at the minimum. If $s_3(I) < \frac{1}{\sqrt{2}}$ the minimum of the potential is located at β_{30}=0 and as it follows from (**??**)

$$V_I\left((\beta_{30})_{min}\right) \equiv V_I(min) = \frac{1}{2}\hbar\omega\left(-1 + s_3^2(I)\right) + E_I^*, \quad s_3(I) < \frac{1}{\sqrt{2}} \tag{7}$$

For $s_3(I) > \frac{1}{\sqrt{2}}$ but close to $\frac{1}{\sqrt{2}}$

$$V_I(min) \approx \frac{1}{2}\hbar\omega\left[-1 + s_3^2(I) - \frac{3}{s_3^4(I)}\left(s_3^2(I) - \frac{1}{2}\right)^2\right] + E_I^*, \quad s_3(I) > \frac{1}{\sqrt{2}} \tag{8}$$

In (**??**) the terms of the higher order in $\left(s_3^2(I) - \frac{1}{2}\right)^2$ are omitted. Comparing (**??**) and (**??**) we see that $V_I(min)$ is a continuous function of I at $s_3(I) = \frac{1}{\sqrt{2}}$. Taking the first order derivatives of the expressions (**??**) and (**??**) we see that both derivatives coincide at $s_3 = \frac{1}{\sqrt{2}}$. However, there is a discontinuity of the second order derivative over I at $s_3(I) = \frac{1}{\sqrt{2}}$. Thus, we have a second order phase transition.

Figure 1: Exact dependence of $(\beta_{30})_{min}$ on the angular momentum calculated for ^{240}Pu (solid line) and an approximate description of $(\beta_{30})_{min}$ by a square root function valid around $I = I_{crit}$ (dashed line).

The critical value of the angular momentum I_{crit} is determined according to Eq.(**??**) by the relation

$$c_0 + c_1 \cdot I_{crit} = \frac{1}{\sqrt{2}}. \tag{9}$$

We can rewrite the expression (**??**) in the following way

$$(\beta_{30})_{min} = \beta_m(I_{crit})\left(12\sqrt{2}c_1\left(I - I_{crit}\right)\right)^{1/2}. \tag{10}$$

The Eq.(**??**) holds in the vicinity of the critical point. We see that the critical exponent is equal to 1/2.
An exact dependence of $(\beta_{30})_{min}$ on the value of the angular momentum obtained numerically from Eq. (**??**) is shown in Fig. 1 for ^{240}Pu. An approximate dependence of

$(\beta_{30})_{min}$ described by the Eq. (**??**) is also shown in this figure for comparison. We see that the approximate expression holds in some interval of the values of I above I_{crit}. We see in Fig.1 that $(\beta_{30})_{min}$ is equal to zero for all values of the angular momentum below $I = I_{crit}$. However, at $I = I_{crit}$ there is a cusp in the dependence of $(\beta_{30})_{min}$ on I and $(\beta_{30})_{min}$ increases smoothly for higher values of I. Similar results are obtained for the other considered nuclei.

Thus, we have shown that the experimental data on the spectra of the ground state alternating parity bands of several actinides indicate a second order phase transition from reflection-symmetric to reflection-asymmetric shapes in these bands. The phase transition takes place at some value of the angular momentum which in our consideration plays the role of the control parameter.

[1] R. V. Jolos, P. von Brentano, J. Jolie, Phys. Rev. C **86** (2012) 024319.

[2] R. V. Jolos, P. von Brentano, Phys. Rev. C **84** (2011) 0243192.

PARITY SPLITTING AND E1/E2 BRANCHING IN THE ALTERNATING PARITY BAND OF ^{240}Pu

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The new beautiful data obtained at the ATLAS facility at ANL [**?**] for ^{240}Pu demonstrate a manifestation of the strong octupole correlations in the properties of nuclei in a way that had not been seen before. The low lying positive and negative parity rotational bands have been observed up to spin $I > 30$. The states of these bands almost merge at the high values of I thus forming a unified rotational band. The ratio of the transitional dipole to the transitional quadrupole moment has been extracted from the experimental data [**?**]. It was shown that this ratio increases with spin I.

We present below a quantitative interpretation of these data. We assume that the main role in description of the alternating parity bands is played by the octupole mode with K=0 (β_{30}) which preserves the axial symmetry. We present a method to calculate the parity splitting and the $E1$ transition probabilities up to very high angular momenta.

The collective Hamiltonian describing the octupole excitations can be written as

$$H_I^{(1)} = -\frac{\hbar^2}{2B}\frac{d^2}{d\beta_{30}^2} + V_I^{(1)}(\beta_{30}). \tag{1}$$

The numerical solutions of the Schrödinger equation with the Hamiltonian Eq. (**??**) with different two–center potentials have shown that the wave function of the state belonging to the ground state alternating parity band with even I can be approximated to a good accuracy by a sum of two Gaussians symmetric with respect to the $\beta_{30} \to -\beta_{30}$ transformation.

Having a parameterized wave function we can substitute it into the Schrödinger equation and obtain the potential $V_I^{(1)}(\beta_{30})$. This potential has the form

$$V_I^{(1)}(\beta_{30}) = \frac{\hbar^2}{2B}\frac{\left(\frac{d^2\Psi_I^{(1,+)}(\beta_{30})}{d\beta_{30}^2}\right)}{\Psi_I^{(1,+)}(\beta_{30})} + E_I^*, \tag{2}$$

where E_I^* is the excitation energy of the lowest state with spin I and positive parity.

The next problem which must be solved is to find the wave function of the negative parity states of the alternating parity band. To do this and to calculate the parity splitting it is convenient to follow the prescriptions of the supersymmetric quantum mechanics. At first, we determine the supersymmetric partner potential of the potential $V_I^{(1)}(\beta_{30})$ which we denote by $V_I^{(2)}(\beta_{30})$. It is presented as

$$V_I^{(2)}(\beta_{30}) = W_I^2(\beta_{30}) + \frac{\hbar}{\sqrt{2B}}\frac{dW_I(\beta_{30})}{d\beta_{30}} + E_I^*, \tag{3}$$

where

$$W_I(\beta_{30}) = -\frac{\hbar}{\sqrt{2B}}\frac{\left(\frac{d\Psi_I^{(1,+)}(\beta_{30})}{d\beta_{30}}\right)}{\Psi_I^{(1,+)}(\beta_{30})} \tag{4}$$

Table 1: The calculated and the experimental values of $\Delta E(I)$ for ^{240}Pu. The experimental data are taken from [**?**]. The following values of the parameters are used: $\hbar\omega$=0.585 MeV, c_0=0.04, c_1=0.055.

I	$\Delta E(I)$ in keV		I	$\Delta E(I)$ in keV		I	$\Delta E(I)$ in keV		I	$\Delta E(I)$ in keV	
	exp	cal		exp	cal		exp	cal		exp	cal
1	583	580	9	440	441	16	262	262	23	115	128
2	575	572	10	415	416	17	238	239	24	98	115
3	563	561	11	388	390	18	216	217	25	81	103
4	548	547	12	363	363	19	194	196	26	66	93
5	531	530	13	337	337	20	173	177	27	51	84
6	511	510	14	311	311	21	152	159	28	38	76
7	488	489	15	286	286	22	134	143	29	22	70
8	465	466							30	8	65

Both the potentials $V_I^{(1)}$ and $V_I^{(2)}$ were calculated using the parameters determined for description of the parity splitting in ^{240}Pu. They are shown in Figs. 1 and 2 for I=14 and I=20, respectively. We see that the supersymmetric partner potential $V_I^{(2)}$ is a one–center potential. This fact makes the solution of the Schrödinger equation with the potential $V_I^{(2)}$ simpler than a solution of the equation with the potential $V_I^{(1)}$ since in the case of the one–center potential the harmonic oscillator wave functions being used as a basis provide a good convergence. This is the main advantage connected to application of the supersymmetric quantum mechanics to this problem.

Figure 1: The supersymmetric partner potentials $V_I^{(1)} \equiv V1$ and $V_I^{(2)} \equiv V2$ as functions of $\beta_{30}/\beta_m(I) \equiv \beta_{30}/\beta_m$ calculated for I=14 with the parameters fixed for ^{240}Pu. The potential energy is counted from the excitation energy of the 14_1^+ state of ^{240}Pu.

Figure 2: The supersymmetric partner potentials $V_I^{(1)} \equiv V1$ and $V_I^{(2)} \equiv V2$ as functions of $\beta_{30}/\beta_m(I) \equiv \beta_{30}/\beta_m$ calculated for I=14 with the parameters fixed for ^{240}Pu. The potential energy is counted from the excitation energy of the 20_1^+ state of ^{240}Pu.

The results of the calculation of $\Delta E(I)$ for ^{240}Pu are presented in the Table 1 together with the experimental data from Ref. [**?**].
The calculated values of the ratio of the dipole and the quadrupole transitional moments are shown in Fig. 3.

Figure 3: Dependence of the calculated and experimental values of the ratio of the transitional dipole and the quadrupole moments Q(E1)/Q(E2) on the angular momentum obtained for ^{240}Pu. The ratio is given in the units fm/barn. The experimental data are taken from Fig.3 of [**?**]). The last three experimental points contains significant errors which are not indicated here.

Thus we suggest an interpretation of the recently obtained experimental data on the alternating parity band in ^{240}Pu basing on the assumption that the main role in formation of its

properties plays the octupole mode with K=0. The corresponding collective potential has at low spin I one minimum located at zero value of the octupole deformation. However, with increasing I the potential becomes more and more flat and finally at $I \geq 20$ a barrier appears which separates two minima symmetrically located at nonzero deformations. It corresponds to a transition from vibration to static deformation.

[1] X. Wang, R. V. F. Janssens, M. P. Carpenter *et al.*, Phys. Rev. Lett. **102** (2009) 122501.

[2] I. Wiedenhöver, R. V. F. Janssens, G. Hackman *et al.*, Phys. Rev. Lett. **83** (1999) 2143.

[3] R. V. Jolos, P. von Brentano, Phys. Rev. C **84** (2011) 0243192.

NUCLEAR STRUCTURE CALCULATIONS WITH A SEPARABLE APPROXIMATION FOR SKYRME INTERACTIONS

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The quasiparticle random phase approximation (QRPA) with the self-consistent mean-field derived by making use of the Skyrme force is one of the most successful modern ways to investigate the nuclear structure. In such a case calculations do not require to introduce new parameters since the residual interaction is derived from the same energy density functional as that determining the mean field. However, the complexity of calculations taking into account a coupling between simple and complex states increases rapidly with the size of the configuration space. The finite rank separable approximation (FRSA) for the residual interaction allows one to overcome this severe difficulty [1-3]. Various modes of the vibrational excitations in even-even nuclei are studied in the FRSA.

Figure 1: $B(E1)$ strength distributions in ^{130}Sn. (a) Experimental data; (b) QRPA results; (c) QRPA plus phonon-phonon coupling results.

We have studied the effects of the phonon-phonon coupling on the properties of the low-energy spectrum of 2^+ excitations and, in particular, on the $M1$ transitions between them in the mass range $A \approx 90$ [4,5]. With the same set of parameters the energies, the reduced probabilities $B(E2; 0^+_{gs} \to 2^+_i)$, $B(E2; 2^+_i \to 2^+_1)$ and $B(M1; 2^+_i \to 2^+_1)$ for the lowest 2^+_i $(i = 1 - 3)$ states in ^{90,92}Zr and ^{92,94}Mo were calculated. Our motivation was to find mixed-symmetry (MS) quadrupole states in ^{92}Zr and ^{94}Mo in comparison to the $N = 50$ isotones ^{90}Zr and ^{92}Mo. Our results indicate indeed the occurrence of MS states in the nuclei ^{92}Zr and ^{94}Mo that were predicted within the IBM-2 before. Our results with the Skyrme interaction are in reasonable agreement with experimental data. We like to stress that this is the first successful microscopic description of experimental $B(M1)$ values within selfconsistent approach based on the Skyrme interaction. It is important that the coupling between one- and two-phonon terms in the wave functions of excited states essentially affects theoretical results. The QRPA calculations tend to overestimate the 2^+_1 energies and the inclusion of the two-phonon configurations decreases them. Moreover, this coupling influences structures of the $2^+_{2,3}$ states. The structure of the low-lying 2^+ states calculated in our approach are close to those that were calculated within the quasiparticle-phonon model with a schematic interaction before.
Neutron excess effects on the properties of the low-energy 1^- excitations in the neutron-rich Sn isotopes with neutron number $N = 70 - 82$ were investigated in [6]. The centroid energy and summed strength decreases with the increase of the neutron number. The inclusion of the two-phonon configurations results in an increment of the widths of the pygmy and giant dipole resonances, as an example see Fig. 1.

Figure 2: Effects of tensor correlations on the GT strength distribution in $\sigma\tau_-$ channel of ^{130}Cd. Solid and dotted lines correspond to calculations with and without the tensor terms, respectively.

The Gamow-Teller (GT) and charge-exchange spin-dipole (SD) transition strength distributions from the parent nuclei ^{126,128,130}Cd in the T_+ and T_- channels were predicted by performing QRPA calculations with the FRSA. The major part of the GT distributions is concentrated in the peaks at E =14.9, 14.3, and 13.8 MeV in ^{126}Cd, ^{128}Cd, and ^{130}Cd, correspondingly. The largest contribution in the peaks comes from the configuration $\{\pi 1h\frac{9}{2}\nu 1h\frac{11}{2}\}$. It was found that the peak energies of the SD distributions in the Cd isotopes obey the energy hierarchy $E(2^-) < E(1^-) < E(0^-)$. For the T_- channel the fragmentation of the SD strengths increases with the angular momentum value J. The distributions are shifted to lower energies as one goes from ^{126}Cd to ^{130}Cd. As expected, the Pauli blocking effect leads to a small contribution to the SD sum rule in the T_+ channel. The effect of pairing on the spin-isospin modes is important in the isotopes ^{126,128}Cd and vanishes in ^{130}Cd due to closure of neutron shell ($N = 82$) and vanishing pairing correlations for neutrons. The strong difference in the neutron and proton chemical potentials plays the key role to explain this peculiarity [7,8]. Also, we observe that tensor component of the Skyrme interaction is important for predictions of the GT distributions [9]. The inclusion of the tensor correlations leads to a noticeable redistribution of the GT strength and an increase of the sum rule in both the T_- and T_+ channels. The tensor correlations push up 10% of the total GT strength to the higher energy region. A part of the main peak strength appears to be fragmented in the low-energy peaks and the main peak is moved downwards. In particular, for ^{130}Cd this shift is as large as 3.6 MeV (Fig. 2).

[1] Nguyen Van Giai, Ch. Stoyanov, V. V. Voronov, Phys. Rev. C **57** (1998) 1204.

[2] A. P. Severyukhin, V. V. Voronov, Nguyen Van Giai, Phys. Rev. C **77** (2008) 024322.

[3] A. P. Severyukhin, V. V. Voronov, Nguyen Van Giai, Eur. Phys. J. A **22** (2004) 397.

[4] A. P. Severyukhin, N. N. Arsenyev, V. V. Voronov, N. Pietralla, Nguyen Van Giai, J. Phys.: Conf. Ser. **321** (2011) 012050.

[5] A. P. Severyukhin, N. N. Arsenyev, N. Pietralla, Phys. Rev. C **86** (2012) 024311.

[6] N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov, Nguyen Van Giai, EPJ Web of Conferences **38** (2012) 17002.

[7] A. P. Severyukhin, V. V. Voronov, Nguyen Van Giai, J. Phys.: Conf. Ser. **267** (2011) 012025.

[8] A. P. Severyukhin, V. V. Voronov, Nguyen Van Giai, Prog. Theor. Phys. **128**, 489 (2012).

[9] A. P. Severyukhin, H. Sagawa, EPJ Web of Conferences **38** (2012) 06001.

STRUCTURE OF THE COLLECTIVE STATES IN NUCLEI WITH Z∼100 CONSIDERED IN THE QUASIPARTICLE-PHONON MODEL

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The structure of nuclei which are not investigated yet or whose investigations are just started is interesting because we don't exclude a manifestation of the features which have not been observed in the well investigated regions of the nuclide chart. In recent years an experimental programme has been started aimed to include nuclei with $Z \sim 100$ into the region of nuclei where detailed spectroscopic information about the low lying states is available. Especially interesting are the low lying collective nuclear excitations which tell us about a softness of a nucleus with respect to some collective modes. The low lying octupole states play an important role in the structure of the well deformed axially symmetric nuclei. Interesting examples of them can be found among the rare earth nuclei and the light actinides. As it was discussed in the literature the appearance of the low lying octupole excitations can be related to the alpha–clustering of nuclei involving α–particle moving relative to the rest part of a nucleus. If so, then the appearance of the collective octupole excitations in nuclei is correlated with the large α–decay probabilities. This is just the case for the light actinides. Superheavy nuclei with $Z \sim 100$ which are investigated in the present paper are also unstable with respect to α–decay. It means that α–cluster component may be presented in the wave function of the ground and the low-lying excited states. We have undertaken the investigations of the properties of the octupole states with different K. The results of our RPA type calculations performed in the framework of the Quasiparticle-Phonon Model are presented below [**?**]. The interaction constant was taken to be the same as for the light actinides in the previous calculations.

The collective octupole vibrational excitations with $K^\pi = 0^-, 1^-, 2^-$ have been observed in many well deformed nuclei and are well understood theoretically. For instance, at the beginning of the rare earth region the lowest ones are the excitations with $K^\pi = 0^-$. However, with increase of the mass number the excitations with $K^\pi = 1^-$ and then with $K^\pi = 2^-$ become the lowest one. The octupole excitations of nuclei located at the beginning of the actinide region are especially interesting. In these nuclei the excitations with $K^\pi = 0^-$ are characterized by the strong E1 transitions to the ground state band and have very low excitation energies. The results of calculations are presented in the Table 1. We see that for the majority of nuclei considered in this paper the lowest ones among the octupole excitations are the states with $K^\pi = 2^-$. These states are especially low in the isotopes of Cf and Rf. In the other considered nuclei the energies of the states with $K^\pi = 2^-$ are close to 1 MeV. Our calculations reproduce a minimum in the excitation energy of the 2^- state in the isotones with N=150 located at Z=98. The main components of the 2^- state are the neutron two–quasiparticle configuration $9/2^-[734] \otimes 5/2^+[622]$ with the weight 16% and the proton two–quasiparticle configuration $9/2^+[633] \otimes 5/2^-[521$ with the weight 62%. The fact that in ^{248}Cf the proton single-particle states $7/2^+[633]$ and $3/2^-[521]$ are located near the Fermi level explains the appearance of the minimum in the energy of the 2^- state at Z=98. This is confirmed by the results of the $^{249}\mathrm{Cf(d,t)}$ reaction [**?**]. The presence of these neutron quasiparticle orbits near the Fermi level in nuclei with N=150 is confirmed in [**?**].

Table 1: The calculated and the experimental values of the energies of the $K^\pi = 0^-, 1^-, 2^-$ states. The energies are given in keV.

Nucleus	$E(K^\pi = 2^-)$		$E(K^\pi = 1^-)$		$E(K^\pi = 0^-)$	
	exp	cal	exp	cal	exp	cal
$^{244}Cm_{148}$	–	864	–	1297	–	618
$^{252}Rf_{148}$	–	633	–	1368	–	1032
$^{246}Cm_{150}$	842	949	1079	1047	1250	1013
$^{248}Cf_{150}$	592	612	–	1073	–	1064
$^{250}Fm_{150}$	881	1061	–	1090	–	1061
$^{252}No_{150}$	930	998	–	1089	–	1232
$^{254}Rf_{150}$	–	746	–	1091	–	1355
$^{248}Cm_{152}$	–	1055	–	1157	1049	1244
$^{250}Cf_{152}$	872	724	1176	1184	1335	1288
$^{252}Fm_{152}$	–	1168	–	1200	–	1250
$^{254}No_{152}$	–	1124	–	1197	–	1424
$^{252}Cf_{154}$	831	689	–	1423	–	1412
$^{254}Fm_{154}$	–	1061	–	1435	–	1349

[1] R. V. Jolos, L. A. Malov, N. Yu. Shirikova, A. V. Sushkov, J. Phys. G: Nucl. Part. Phys. **38** (2011) 115103.

[2] A. P. Robinson, *et al.*, Phys. Rev. C **78** (2008) 034308.

[3] R. D. Herzberg, S. Moon, S. Eeckhaudt *et al.*, Eur. Phys. J. A **42** (2009) 333.

NEUTRON NUMBER DEPENDENCE OF THE ENERGIES OF γ-VIBRATIONAL STATES IN NUCLEI WITH Z$\sim$100 AND MANIFESTATION OF PSEUDOSPIN SYMMETRY

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It is well known that in nuclear theory the mean field concept plays the role of the basic approach for several more specific advanced theories. These theories can be build upon introducing the single particle mean field basis. Therefore it is very important for the whole field of nuclear structure to examine and use the consequences of the underlying mean field symmetries even if these symmetries are approximate.

The pseudospin symmetry is known as an approximate symmetry of the nuclear mean field. This symmetry is manifested in the nuclear excitation spectra by the presence of the quasi-degenerate doublets. At the same time, the existence of this symmetry is strongly related to the strength of the spin-orbit interaction term of the nuclear mean field.

Dynamical symmetry implies the existence of a characteristic multiplet structure. These multiplets are characterized by a magnitude of the multiplet splitting. The characteristic magnitude of the splitting of the pseudospin doublets in spherical nuclei is of the order of $0.1\hbar\omega_0$, where $\hbar\omega_0$ is the frequency of the harmonic oscillator approximating nuclear mean field. However, this splitting demonstrates a dependence on the ratio between the numbers of protons and neutrons in nucleus, and it is very small in some nuclei.

Single particle pseudospin doublets in the well deformed nuclei are characterized by a projection of the pseudo-orbital momentum on the axial symmetry axis. The splitting of these doublets are in several times smaller than in spherical nuclei. The calculations performed in [**?**] have shown that the goodness of the pseudospin symmetry improves if the nucleon binding energy decreases and the pseudo-orbital momentum decreases also. Therefore, weakly bound exotic nuclei are the most exciting one to search for the pseudospin symmetry manifestation.

It is well known from many calculations of the structure of the γ-vibrational states in the well deformed axially symmetric nuclei that the structure of a γ-phonon is mainly exhausted by a rather small number of the two-quasiparticle components. Due to this fact the energy of a γ-vibrational state can be strongly influenced by the presence of the low-energy two-quasiparticle state with $K^\pi = 2^+$. This happens if near the Fermi level are located two nearly lying single-particle states with the same parities and angular momentum projections on the axial symmetry axis whose sum or difference is equal to K=2. Such closely lying single-particle states can be the members of the pseudospin doublet. It is the aim of the present note to calculate the energies of the γ-vibrational states for the sequences of the isotopes of the elements with $Z \sim 100$ and investigate the influence of the appearance of the pseudospin doublets near the Fermi level on the energies of the γ-vibrational states. The γ-vibrational states can be considered as the most collective vibrational excitations in many well deformed axially symmetric nuclei. They have been observed in many nuclei and are well understood theoretically. However, the experimental information on these excitations in nuclei with $Z \sim$100 is rather scarce. The γ-vibrational excitations have been observed only in ^{246,248}Cm, ^{250,252}Cf and ^{254,256}Fm. We have undertaken calculations of the energies and the two-quasiparticle structure of the γ-vibrational states [**?**] for three values of the interaction constant of the quadrupole-

quadrupole forces in the particle-hole channel. The value of $\kappa_{22} = 0.0174\,\mathrm{fm}^2/\mathrm{MeV}$ was fixed previously in the calculations for U isotopes. As it is seen from Table 1 with this value of κ_{22} we obtain a good description of the known experimental data. The results for the other two values of κ_{22} are shown in order to get an idea of sensitivity of the energies of γ–phonons to variations of κ_{22}. The results given in Table 1 show that for all considered elements the energy of the γ-vibrational state takes the minimum in nuclei with the neutron number equals to N=156. To understand this fact we analyze the quasiparticle structure of the γ-phonon. It is seen from our results that if the number of neutrons approaches the value N=156 the contribution of the two-quasiparticle component 3/2[622] $\otimes$ 1/2[620] to the norm of the γ-vibrational one-phonon state becomes the largest one. It is seen from neutron single-particle scheme that at N=156 and $\beta_2 = 0.26$ the neutron Fermi level is located between the single particle states $3/2^+[622]$ and $1/2^+[620]$ and therefore the two–quasiparticle state consisting of these quasiparticles has the smallest energy compared to the other two-quasiparticle states. This energy is equal to 1.251 MeV. This explains why the energy of the γ-vibrational one-phonon state has a minimum when the number of neutrons is equal to N=156. The other important neutron two-quasiparticle component 7/2[613]$\otimes$3/2[622] has at N=156 the energy 1.343 MeV. However, our calculations have shown that the energy of this two-quasiparticle component has its minimum not at N=156 but at N=154. The energies of other neutron two-quasiparticle components are larger than 2 MeV for N=156.

To verify further the effect of the neutron two-quasiparticle component 3/2[622]$\otimes$1/2[620] on the neutron number dependence of the energies of the γ-vibrational states we shift up by hand the energy of the neutron single-particle state 3/2[622], i.e. decreases its binding, by 0.6 MeV and 1.2 MeV. As the result there appear two and three other neutron single-particle states, respectively, between the 1/2[620] and 3/2[622] neutron single-particle states at β_2=0.26. This shift of the single-particle state energy changes the neutron number dependence of the energy of the γ-vibrational state in such a way that the minimum at N=156 disappears and $E(2^+_\gamma)$ decreases continuously with increase in N from N=150 to N=160. The absolute value of $E(2^+_\gamma)$ increases due to this shift of the energy of the single-particle neutron state $3/2^+[622]$ for all considered isotopes. This fact indicates the strong neutron number dependence of the $E(2^+_\gamma)$ and its absolute value on a relative position of the neutron single-particle states 1/2[620] and 3/2[622].

The single-particle neutron states $3/2^+[622]$ and $1/2^+[620]$ are the members of the pseudospin doublet with the quantum numbers $[\tilde{N}\tilde{n_3}\tilde{\Lambda}]$=[521]. The correspondence between the pseudospin quantum numbers and the Nilsson asymptotic quantum numbers $[Nn_z\Lambda_{1,2}]$ is the following: $\tilde{N} = N - 1, \tilde{n_3} = n_3, \tilde{\Lambda} = \frac{1}{2}(\Lambda_1 + \Lambda_2)$. Our discussion above showed that the difference between the single-particle energies of these states influences on the neutron number dependence and the absolute energy value of the γ-vibrational state. Small splitting of the 1/2[620] and 3/2[622] single-particle state means that the pseudospin symmetry is approximately preserved. Thus, the experimental observation (or nonobservation) of the minimum of the energy of the γ-vibrational one-phonon state when the number of neutrons is equal to N=156 is important for studying manifestation of the pseudospin symmetry in very heavy exotic nuclei. The value of $E(2^+_\gamma)$ at N=156 gives an information on the splitting of the pseudospin doublet $[\tilde{N}\tilde{n_3}\tilde{\Lambda}]$=[521].

To get the feeling of the effect of the mixing of the one-phonon and the two-phonon states we have performed the calculations for the Cf isotopes with and without the mixing. The results of the calculations showed that the mixing decreases the energies of the $E(2^+_\gamma)$

Table 1: The experimental and the calculated energies of the $K^\pi = 2^+$ γ-vibrational states. The energies are given in keV. The quadrupole interaction constant κ_{22} is given in fm^2/MeV. This dimension of the interaction constant is determined by the use of the radial derivative of the Woods-Saxon potential as a formfactor of the multipole–multipole interaction.

Nucleus	$E(2^+_\gamma)_{\rm exp}$	$E(2^+_\gamma)_{\rm calc}$		
		κ_{22}=0.0174	κ_{22}=0.0165	κ_{22}=0.0150
^{246}Cm	1124	1225	1432	1680
^{248}Cm	1049	997	1229	1492
^{248}Cf	–	1289	1478	1708
^{250}Cf	1032	1079	1282	1517
^{252}Cf	805	781	987	1207
^{254}Cf	–	553	758	957
^{256}Cf	–	612	834	1058
^{250}Fm	–	1181	1354	1543
^{252}Fm	–	1021	1225	1462
^{254}Fm	694	735	933	1148
^{256}Fm	682	510	713	909
^{258}Fm	–	586	812	1042
^{252}No	–	1261	1461	1703
^{254}No	–	1065	1274	1520
^{256}No	–	809	1018	1251
^{258}No	–	531	725	914
^{260}No	–	602	826	1052
^{254}Rf	–	1291	1478	1626
^{256}Rf	–	1077	1277	1497
^{258}Rf	–	833	1049	1286
^{260}Rf	–	539	731	917
^{262}Rf	–	606	832	1057

states approximately by 50 keV. However, the mixing does not influence on the neutron number dependence of the $E(2^+_\gamma)$ and keeps the minimum at N=156. Approximately 98% of the state vectors norm corresponding to the γ-vibrational states obtained in the calculations including the mixing effect are provided with the one-phonon component.

[1] J. Meng, K. Sugawara–Tanabe, S. Yamaji, P. Ring, and A. Arima, Phys. Rev. C **58** (1998) R628.

[2] R. V. Jolos, N. Yu. Shirikova, A. V. Sushkov, Phys. Rev. C **86** (2012) 044320.

STRUCTURE OF THE PHONON VACUUM STATE

S. Mishev

The action of the long-range residual force on the expectation value of observables in the nuclear ground states of even-even nuclei is evaluated by finding optimal values for the coefficients of the canonical transformation which connects the phonon vacuum state with the (quasi-)particle vacuum state. The problem of approximating the correlated ground state of a many-body quantum system has been receiving considerable attention since the early days of nuclear structure physics [**?**] and degenerate electron gas theory [**?**] and still represents a formidable challenge. This is an arduous task within the "beyond the mean-field" theories because of the action of the residual interaction which brings particle-hole admixtures into the ground states.

A general form of the phonon vacuum was proposed by Sorensen [**?**] and later Goswami and Pal [**?**] estimated explicitly the correlation coefficients of the 2p-2h admixtures into the BCS wave function [**?**] relating them to the forward and backward phonon amplitudes. The relation they obtained turned out to be also valid for higher order correlations [**?**] in the the random phase approximation (RPA) [**?**]. Being a small amplitude limit of the time-dependent Hartree-Fock approximation, however, RPA is known to be able to account only for small correlation effects. Since in open-shell nuclei the backward phonon amplitudes are by no means small, RPA is becoming questionable in describing the low-energy states of such nuclei. During the years numerous successful improvements over the standard RPA have been invented and applied to both even-even and odd-even nuclei, as for example those in Refs. [**?**, **?**, **?**, **?**, **?**]. The variational character of some of these extensions is preserved and in some of them it is violated, leading to overbinding of the ground state.

In our latest development [**?**] we keep using the explicit form of the fermionic many-body vacuum [**?**] but depart from varying the excited-state wave function. On the contrary we use the correlation coefficients as parameters which we fix by optimizing the ground-state trial wave function using a variational procedure insuring a converging succession of approximations to the exact solution. This approach also benefits from the findings in Ref. [**?**] where it was shown that this class of wave functions is a vacuum for a generalized phonon operator, adding to the standard one specific two-body operators correcting for the Pauli principle which improve the convergence substantially. In this way the phonon vacuum state absorbs additional correlations effects than the ones obtained using the equations-of-motion method [**?**] for the standard phonon operator. Applying our idea to the uncomplicated Lipkin-Meshkov-Glick model [**?**], we showed the superiority of the presented approach over the RPA and its extended version, based on comparison with the exact solution for the binding energy.

[1] M. Baranger, Phys. Rev. **120** (1960) 957.

[2] K. Sawada, Phys. Rev. **106** (1957) 372.

[3] R.A. Sorensen, Nucl. Phys. **25** (1961) 674.

[4] A. Goswami, M.K. Pal, Nucl. Phys. **44** (1963) 294.

[5] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108** (1957) 1175.

[6] E.A. Sanderson, Phys Lett. **19**(2) (1965) 141.

[7] K. Hara, Progr. Theor. Phys. **32** (1964) 88.

[8] R. V. Jolos, W. Rybarska, Z. Phys. A **296** (1980) 73.

[9] P. Schuck, S. Ethofer, Nucl. Phys. A **212**(2) (1973) 269; J. Dukelsky, P. Schuck, Nucl. Phys. A **512**(3) (1990) 466.

[10] D. Karadjov, V. V. Voronov, and F. Catara, Phys. Lett. B **306** (1993) 197.

[11] S. Mishev and V. V. Voronov, Phys. Rev. C **82** (2010) 064312.

[12] S. Mishev, http://arxiv.org/abs/1211.4730

[13] M. Jemai and P. Schuck, Phys. At. Nucl. **74**(8) (2011) 1139.

[14] D. Rowe, Nuclear collective motion. London: Menthuen, 1970.

[15] H. Lipkin, N. Meshkov, A. Glick, Nucl. Phys. **62** (1965) 188.

NUCLEAR SHAPES AND TRIAXIALITY WITHIN THE FRAMEWORK OF THE TWO-FLUID INTERACTING VECTOR BOSON MODEL

H. G. Ganev

Atomic nuclei exhibit the feature of collective motion induced by the dynamics of all the constituent nucleons, resulting in a variety of geometrical shapes that reflect deformations of the nuclear surface. Shapes of most non-spherical nuclei are characterized by axially symmetric quadrupole deformations-prolate or oblate ellipsoids. Theoretically, collective motion in nuclei connected with the change of their shape can be investigated either within the framework of the geometrical models or the algebraic models based on the concept of dynamical symmetry. In the algebraic models the shapes (phases) are related with all possible breakings of the dynamical symmetry algebra into its subalgebras.
There are many approaches which allow the association of a certain geometry to any abstract algebra, but the most convenient is the method of coherent states. By means of the latter, the phase structure (Figure **??**) of the two-fluid Interacting Vector Boson Model (IVBM) is investigated [**?**] and the following basic phase shapes, connected to a specific geometric configurations of the ground state, are determined: spherical (vibrational), $U_p(3)\otimes U_n(3)$, γ-unstable, $O(6)$, and axially deformed shape, $SU(3)\otimes U_T(2)$. The ground-state quantum phase transitions between different phase shapes, corresponding to the different dynamical symmetries and mixed symmetry case, are also investigated [**?**].

Figure 1: (Color online) Phase diagram of IVBM. The corners of the triangle correspond to exact dynamical symmetries.

It turns out that there exists one more phase, the triaxial one, in the phase diagram of IVBM. The possibility of static triaxial shapes for the ground state of nuclei is a long-standing problem in nuclear structure physics despite the fact that very few candidates have been found experimentally. In the geometrical approach the triaxial nuclear properties are usually interpreted in terms of either the γ-unstable rotor model of Wilets and Jean or the rigid triaxial rotor model of Davydov. In this respect, the possibility for the appearing of triaxial shapes in the IVBM is studied [**?**]. For this purpose, a new dynamical symmetry limit of the two-fluid IVBM, defined through the $SU^*(3)$ algebra, is introduced. The latter closely resembles many properties of the $SU^*(3)$ limit of IBM-2, which have been shown by many authors geometrically to correspond to the rigid triaxial model. The influence of different types of perturbations on the $SU^*(3)$ energy surface, in particular the addition of a Majorana interaction and an $O(6)$ term to the model Hamiltonian, is studied. The effect of these perturbations results in the formation of a stable triaxial minimum [**?**] in the energy surface of the IVBM Hamiltonian under consideration.

Figure 2: (Color online) Excitation energies for GSB and γ band in ^{192}Os and ^{190}Os, respectively.

The new dynamical symmetry limit of the IVBM, defined through the chain $Sp(12,R) \supset U(3,3) \supset U_p(3)\otimes\overline{U_n(3)} \supset U^*(3) \supset O(3)$, is further applied for the description of nuclear

Figure 3: (Color online) Calculated and experimental staggering $S(L)$ of the γ band in ^{192}Os and ^{190}Os, respectively. The predictions of the sextic and Mathieu approach (SMA) and the IBM-1 with a term quadratic in $(Q \otimes Q \otimes Q)_0$ (IBM-1) are also shown.

collective spectra exhibiting axially asymmetric features [**?**]. The effect of the Majorana perturbation on structure of the γ band is studied in detail as well. It is shown that by taking into account the full symplectic structures in the considered dynamical symmetry of the IVBM, the proper description of the low-lying energy spectra and the γ band energy staggering in the full range from γ-unstable to γ-rigid nuclei can be achieved [**?**]. The theoretical predictions are compared with the experimental data for some even-even nuclei assumed to be axially asymmetric (Figs. **??** and **??**).
The standard approach to obtain the geometrical properties of the system is to express the collective variables in the intrinsic (body-fixed) frame of reference. Then the ground-state energy surface is obtained by calculating the expectation value of the boson Hamiltonian under consideration with respect to the corresponding coherent states. In the case of IVBM, the (scaled) energy surfaces $\varepsilon(\rho, \theta)$ depend on two coherent state parameters ρ and θ, determining the "shape" of the nucleus [**?**, **?**]. The latter are related to the standard collective model "shape" parameters β and γ. The ground state energy surfaces in ^{192}Os and ^{190}Os are plotted in the form of contour plots in Fig. **??**. From the figure one sees a nearly γ-flat potential with a very shallow triaxial minimum for the ground state in ^{192}Os, while for ^{190}Os a typical for the $O(6)$ limit θ-unstable (or in IBM terms a γ-flat) potential is observed. Thus the obtained results for the potential energy surface for ^{192}Os suggest a more complex and intermediate situation between γ-rigid and γ-unstable structures.

Figure 4: (Color online) A contour plot of the scaled energy surface $\varepsilon(\rho, \theta)$ obtained for the model Hamiltonian in two isotopes ^{192}Os and ^{190}Os, respectively. Only the region $\rho > 0$ is depicted.

It is known that the comparison of the experimental data with the calculated transition probabilities is a more sensitive test for each model under consideration. In this respect, the electromagnetic properties of the IVBM with respect to the reduction chain incorporating the triaxial shapes are investigated [**?**]. The tensor properties of the algebra generators are determined in respect to the reduction chain $Sp(12, R) \supset U(3, 3) \supset U_p(3) \otimes \overline{U_n(3)} \supset U^*(3) \supset O(3)$. The symplectic basis according to the considered chain is thus constructed and the action of the $Sp(12, R)$ generators as transition operators between the basis states is illustrated. The matrix elements of the $U(3, 3)$ ladder operators in the so obtained symmetry-adapted basis are given. The $U(3, 3)$ limit of the model is further tested [**?**] on the more complicated and complex problem of reproducing the $B(E2)$ transition probabilities between the collective states of the ground band in ^{104}Ru, ^{192}Os, ^{192}Pt, and ^{194}Pt isotopes, considered by many authors to be axially asymmetric. The theoretical predictions are compared with the experimental data and some other collective models which accommodate the γ-rigid or γ-soft structures (Fig. **??**).

[1] H. G. Ganev, Phys. Rev. C **83** (2011) 034307.

Figure 5: (Color online) Comparison of theoretical and experimental values for the $B(E2)$ transition probabilities between the collective states of the ground state band in ^{104}Ru, ^{192}Os, and ^{194}Pt. The theoretical results of some other collective models which accommodate the γ-rigid or γ-soft structures are also shown.

[2] H. G. Ganev, Phys. Rev. C **84** (2011) 054318.

[3] H. G. Ganev, in the Proceedings of the XXXI Intern. Workshop on Nuclear Theory, ed. A. Georgieva and N. Minkov, (Heron Press, Sofia, 2012), p. 195.

[4] H. G. Ganev, Phys. Rev. C **86** (2012) 054311.

Figure 1: Calculated energies of low-lying two-quasiproton (black signs) and two-quasineutron (red signs) states in the indicated nuclei of the α–decay chain of $^{298}120$. The resulting K values are indicated. The presented Q_α are for the ground-state–to–ground-state α–decays.

Figure 2: The same as in Fig. **??**, but for the nuclei of the α–decay chain of $^{296}120$.

ROLE OF PROTON SHELL CLOSURE ON PRODUCTION AND IDENTIFICATION OF NEW SUPERHEAVY NUCLEI

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Studying the structure of superheavy nuclei, it is important to find ways for their synthesis and identification, which is a priority in the development of modern nuclear physics. In recent years, experiments on the synthesis of superheavy nuclei with $Z = 112 - 118$ with ^{48}Ca beams and various actinide targets were successfully carried out at FLNR (JINR), GSI (Darmstadt) and LBNL (Berkeley). The found experimental trend of nuclear properties (Q_α-values and half-lives) and cross sections of production of superheavy nuclei reveals increasing stability of nuclei approaching the spherical closed neutron shell $N = 184$, and also indicates a relatively small effect of the proton shell at $Z = 114$ predicted with the microscopic-macroscopic models. This experimental observation seems to be in accordance with predictions of relativistic and nonrelativistic mean field models where the island of stability corresponds to $Z = 120 - 126$ and $N = 184$. If there is a strong shell effect at $Z = 120 - 126$, then there is a hope to synthesize new superheavy elements with $Z \geq 120$ by using the present experimental set up and actinide-based reactions with neutron-rich stable projectiles heavier than ^{48}Ca.

In our works the microscopic-macroscopic approach was proposed based on a modified two-center shell model. To get the best description of the spins and parities of the ground states of the known heavy and superheavy nuclei, as well as two-quasiparticle states in the nuclei of the rare-earth region, there were introduced new two-center Hamiltonian parameters that depend on the isospin $(N - Z)$.

In Figs. **??** and **??** the energies of two-quasiparticle states are presented for the nuclei of α–decay chains of $^{296,298}120$ [**?**]. While for nuclei with $Z \leq 118$ the first two-quasiproton states have energies smaller than 1.2 MeV, in $^{296,298}120$ the energies of the first two-quasiproton states are at about 1.9 MeV. This indicates a larger gap in the proton single-particle spectrum. So, the shell effects become stronger beyond $Z = 114$. The α–decay chain starting from $^{298}120$ likely terminates at ^{282}Cn by spontaneous fission. The α–decay chain starting from $^{296}120$ probably terminates at $^{284}114$ by spontaneous fission. Indeed, $^{284}114$ is predicted to decay by spontaneous fission in 0.012 s whereas α decay is expected to have a longer half-life of 0.045 s.

The two-quasiparticle isomeric states are predicted in our calculations. The states $8^-_\nu\{15/2^-[707] \otimes 1/2^+[600]\}$ and $11^-_\nu\{15/2^-[707] \otimes 7/2^+[604]\}$ in $^{298}120$, the state

Figure 3: (Color online) Calculated α–decay energies (symbols connected by lines) are compared with available experimental data (symbols) for even-Z (b) and odd-Z (a) nuclei with $107 \leq Z \leq 126$. The calculated values of Q_α are for the ground-state-to-ground-state α decay.

$13^-_\nu\{11/2^+[606]\otimes 15/2^-[707]\}$ in $^{294}118$, and the state $8^+_\pi\{7/2^-[503]\otimes 9/2^-[505]\}$ in $^{290}116$ (Fig.**??**) can be treated as isomers in the region of the heaviest nuclei. If they survive long enough (> 0.05 s) with respect to γ decay, one can expect α decays from these states which will be distinguished from the ground-state-to-ground-state α decays by other T_α and energies. The spontaneous fission from these isomeric states seems to be delayed with respect to the spontaneous fission from the ground state. The lowest two-quasiparticle isomeric states in $^{296}120$, $^{292}118$, $^{288}116$, and $^{284}114$ are $13^-_\nu\{11/2^+[606] \otimes 15/2^-[707]\}$, $8^+_\nu\{5/2^+[602]\otimes 11/2^+[6076]\}$, $8^-_\pi\{7/2^-[503]\otimes 9/2^-[505]\}$, and $7^-_\nu\{1/2^+[611]\otimes 13/2^-[716]\}$, respectively (Fig. **??**).

In Ref. [**?**] the calculated one-quasineutron spectra of nuclei of the α-decay chains of $^{287}114$, $^{293}116$ and energies of low-lying two-quasiparticle states in the indicated nuclei of the α-decay chains of $^{286,288}114$ are shown. In Ref. [**?**] the calculated one-quasineutron spectra of nuclei of the α-decay chains of ^{291,293} 117.

The calculated mass excesses $M_{\rm th}$, neutron separation energies S_n, shell corrections E_{sh}, and Q_α–values are listed in Ref. [**?**] for nuclei with $105 \leq Z \leq 126$. We treat only the isotopes of superheavy nuclei which can be reached in complete fusion reactions with available projectiles and targets. As seen in Fig. **??**, the calculated Q_α are in a good, within 0.3 MeV, agreement with the available experimental Q^{exp}_α. The shell at $N = 162$ is pronounced in our calculations as in works of other scientific groups. The shell effects at $Z = 114$ and $N = 172 - 176$ provide rather weak dependence of Q_α on N. The strong role of the shell at $N = 184$ is reflected in the well pronounced minimum of Q_α.

With our predictions of nuclear properties in Ref. [**?**], we calculated the evaporation residue cross sections in the reactions ^{48}Ca, ^{50}Ti,^{54}Cr,^{58}Fe,^{64}Ni+^{238}U,^{244}Pu, ^{248}Cm,^{249}Cf (Fig. **??**). In comparison to our previous calculations with the mass predictions of Ref. [**?**], in Fig. **??** the values of σ_{ER} decreases slower with increasing Z. The stronger shell effect revealed here for nuclei with $Z > 118$ result larger survival probabilities and larger values of σ_{ER}. In the reactions ^{48}Ca+^{238}U,^{248}Cm,^{249}Cf the experimental values of σ^{3n}_{ER} are 0.5–2.5 pb, about 3 pb, and 0.5 pb, respectively. Thus, the difference between the calculated and experimental σ_{ER} are within the experimental and theoretical uncertainties. A good description of existing data allows us to be reliable in the predictions for the reactions with projectiles heavier than ^{48}Ca.

With ^{50}Ti beam the values of σ_{ER} for the nuclei with $Z = 114 - 118$ are expected to be 5–10 times smaller than those resulted by ^{48}Ca beam. The main reason for this is the decrease of P_{CN} with mass asymmetry in the entrance channel of reaction. For the production of nuclei with $Z = 122 - 126$, ^{64}Ni beam would lead to larger cross sections, 1-8 fb.

The evaporation residue cross-sections in the maxima of excitation functions and corresponding optimal excitation energies calculated with the mass predictions of Ref. [**?**] are presented in Fig. **??** for the reactions ^{50}Ti,^{54}Cr,^{58}Fe,^{64}Ni+ ^{238}U,^{244}Pu,^{248}Cm,^{249}Cf. The

Figure 4: The evaporation residue cross sections in the maxima of excitation functions versus charge number Z for the reactions ^{48}Ca,^{50}Ti,^{54}Cr,^{58}Fe,^{64}Ni+^{238}U,^{244}Pu,^{248}Cm,^{249}Cf. The predicted properties of superheavy nuclei are from the Table in Ref. [**?**]. The excitation energies of compound nuclei are given in brackets.

Figure 5: The same as in Fig. **??**, but with using the predicted properties of superheavy nuclei from Ref. [**?**].

values of σ_{ER} decrease by about two-three orders of magnitude with increasing the charge number of the target from 92 to 98. The reactions with lighter targets are more favorable for larger σ_{ER}. The main reason of the fall-off of σ_{ER} with Z of the compound nucleus is the strong decrease of the fusion probability P_{CN}. The quasifission channel becomes much stronger than the complete fusion with increasing $Z_1 \times Z_2$. Only the projectiles ^{50}Ti and ^{54}Cr results in the production cross- section of $Z = 114$, 116, and 118 on the level of present experimental possibilities.

Using our predictions of nuclear properties, we calculated the isotopic trends of the evaporation residue cross section for the reactions ^{50}Ti+^{A}Cf and ^{54}Cr+^{A}Cm (Fig. **??**) [**?**]. At zero excitation energy, the predicted values of fission barriers used in the calculations are in the energy interval 8.1–10.1 MeV. Note that for the reactions ^{48}Ca+^{238}U, ^{244}Pu, ^{248}Cm, ^{249}Cf the calculated and experimental values of evaporation residue cross sections are quite close. A good description of existing data allows us to be confident in the predictions for the reactions with heavier projectiles. In the ^{50}Ti+^{249}Cf (Q=-194.75 MeV) reaction the nucleus ^{295}120 is predicted to be produced in a $3n$ evaporation channel with a cross section of 23 fb. In the ^{54}Cr+^{248}Cm (Q=-205.59 MeV) reaction the compound nucleus would have 3 neutrons more than in the ^{50}Ti+^{249}Cf reaction. Therefore, the decrease of P_{CN} is partly negated by the increase of W_{sur}, and the nucleus ^{298}120 is predicted to be produced with a cross section of 10 fb ($4n$ evaporation channel). The isotopic dependence of σ_{ER} is rather weak in the treated interval of mass numbers A. Indeed, the values of σ_{ER} are almost the same in the cases of ^{246}Cm (Q=-208.07 MeV) and ^{248}Cm as target. There is a certain interval of mass numbers of target nuclei where the product $P_{CN}W_{sur}$ changes rather weakly.

The calculations performed with the modified TCSM reveal quite strong shell effects at $Z = 120 - 126$ and $N = 184$. So, our microscopic-macroscopic treatment qualitatively leads to the results close to those in the self-consistent mean-field treatments. If our prediction of the structure of heaviest nuclei is correct, than one can expect the production of evaporation residues $Z = 120$ in the reactions ^{50}Ti+^{249}Cf and ^{54}Cr+^{248}Cm with the cross sections 23 and 10 fb, respectively. The $Z = 120$ nuclei with $N = 175 - 179$ are

a) b)

Figure 6: Evaporation residue cross sections in the maxima of excitation functions of the reactions (a) ^{50}Ti+^{A}Cf and (b) ^{54}Cr+^{A}Cm versus A. The excitation energies of compound nuclei are given in brackets. Ground-state mass excesses $M_{\rm th}$=211.8, 213.05, 213.76, 215.15, and 216.05 MeV for the nuclei ^{298}120, ^{299}120, ^{300}120, ^{301}120, and ^{302}120, respectively, were used in the calculations.

expected to have Q_α about 12.1 – 11.2 MeV and lifetimes 1.7 ms – 0.16 s in accordance with our predictions. These Q_α are in fair agreement with Ref. [**?**] and about 2 MeV smaller than in Refs. [**?**, **?**]. The experimental measurement of Q_α for at least one isotope of $Z = 120$ nucleus would help us to set proper shell model for the SHE with $Z > 118$. Note that the definition of maxima of the excitation functions provides a good test for the predictions of the models as well.

[1] A.N. Kuzmina, G.G. Adamian, N.V. Antonenko, Eur. Phys. J. A **47** (2011).

[2] A.N. Kuzmina, G.G. Adamian, N.V. Antonenko, Phys. Rev. C **85**, 027308 (2012).

[3] A.N. Kuzmina, G.G. Adamian, N.V. Antonenko, Phys. Rev. C **85**, 017302 (2012).

[4] A.N. Kuzmina, G.G. Adamian, N.V. Antonenko and W. Scheid, Phys. Rev. C. **85**, 014319 (2012).

[5] P. Möller, J.R. Nix, W.D. Myers, and W.J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).

[6] S. Liran, A. Marinov, and N. Zeldes, Phys. Rev. C **62**, 047301 (2000); **63**, 017302 (2000); **66**, 024303 (2002); arXiv:nuclth/0102055 (2001).

[7] I. Muntian, Z. Patyk, and A. Sobiczewski, Acta. Phys. Pol. B **32**, 691 (2001); **34**, 2141 (2003); I. Muntian, S. Hofmann, Z. Patyk, and A. Sobiczewski, Acta. Phys. Pol. B **34**, 2073 (2003); Phys. At. Nucl. **66**, 1015 (2003); A. Parkhomenko, I. Muntian, Z. Patyk, and A. Sobiczewski, Acta. Phys. Pol. B **34**, 2153 (2003); A. Parkhomenko and A. Sobiczewski, Acta. Phys. Pol. B **36**, 3095 (2005).

Figure 1: Calculated and experimental level scheme of ^{220}Th. Experimental energies, spin and parity assignments are taken from [**?**].

MANIFESTATION OF CLUSTER DEGREES OF FREEDOM IN THE STRUCTURE OF HEAVY NUCLEI

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In the even–even isotopes of actinides and also in the heavy Ba and Ce isotopes the low–lying negative parity states are observed together with the usually presented collective positive parity states combined into rotational or quasirotational ground state bands. Formation of the positive parity rotational or quasirotational bands is connected in general to the quadrupole collective motion, while the lowering of the negative parity states is a signature of a presence of the reflection asymmetric collective mode. In the cluster model developed in [**?**] the reflection asymmetric deformation of nuclei in $A \sim 220$ and $A \sim 150$ mass regions was shown to be a consequence of the significant contribution of alpha-cluster configuration to the intrinsic nuclear wave function.

Previously, we considered the mass–asymmetry as the only intrinsic collective coordinate describing dinuclear system (DNS). However, nuclei demonstrate also another sign of reflection asymmetry, namely, the low–lying (started below 1 MeV) negative parity rotational bands with $K \neq 0$ which can be related to the non axially symmetric reflection asymmetric collective mode. The natural way to obtain such an excitation in the framework of the cluster model based on the DNS concept is to consider the intrinsic excitations of the fragments of the DNS together with a relative angular motion of the fragments.

The DNS model was successfully applied for the description of low energy excitation spectra of different isotopes of Ra, Th, U, Pu, and No [**?**]. As an example, here we present the description of multiple negative parity bands in ^{220}Th [**?**, **?**]. The calculated energy spectra of the ground state band and the two lowest negative parity bands in ^{220}Th are presented in Fig. **??** together with the available experimental data. The resulting energy spectrum consists of the ground state band and several negative parity bands which exhibit nearly equidistant behaviour.

The angular momentum dependence of the parity splitting is described Fig. **??**. The possibility for the negative values of the parity splitting is related in the present model to the interplay between the quadrupole vibrations of the heavy fragment and the rotational motion of the light fragment.

Figure 2: Calculated (lines) and experimental (solid squares connected by lines) values of parity splitting. Experimental values are taken from [**?**].

We describe the observed staggering behaviour of the $B(E1)/B(E2)$–ratios as a function of the angular momentum Fig. **??**. The $B(E1)$ transitions from the state of the negative

parity to the state of the positive parity are hindered. In this case, in contrast to the transitions from the positive to the negative parity state, the $E1$ transition operator relates only a part of the components of the wave functions of the bands. The results of calculations are in overall agreement with the experimental data.

Figure 3: Angular momentum dependence of the ration of the reduced transition probabilities $B(E2, I \to (I-2))/B(E2, 2^+ \to 0^+)$ for the quadrupole transitions between the subsequent levels in the ground state band and the first negative parity band.

The main idea behind the calculations performed is that the reflection asymmetric deformation of heavy nuclei can be explained as a consequence of the significant contribution of alpha-cluster dinuclear configuration to the intrinsic nuclear wave function. To prove the strong physical relationship between the reflection asymmetric deformation and alpha-clusterization it is very natural to investigate the alpha-decay properties of the heavy nuclei in the frame of our model. The model of alpha–radioactivity of even–even nuclei, based on DNS concept, is presented in [**?**]. The decay process was described as the evolution of the system in the collective coordinates of charge (mass) asymmetry and in the relative distance between the center of mass of the clusters. Calculation the penetrabilities of the barrier of the nucleus-nucleus potential we took into consideration the possibility of decays to configurations involving different orientations of clusters.
The alpha–decay half–lives and fine structures in alpha–decay of the even-even $^{224-238}$U isotopes were described. The predictions were made for possible fine structure in the alpha-decay of isotopes ^{224,226}U. The calculated half-lives of the even-even isotopes of $^{184-208}$Po and $^{194-210}$Rn with respect to alpha-decay were found to follow the Geiger-Nuttall law, when all daughter nuclei are almost spherical. We revealed that the dinuclear system model reproduces most available data except the lightest isotopes ^{186,188}Po. So, a better understanding of the alpha decay of these isotopes have to await further experimental data.
Note that our model allows to extract the deformations of daughter nuclei from the description of the experimental alpha-decay half-lives. Our calculations demonstrated that the even-even isotopes $^{182-204}$Pb and $^{194-206}$Po are almost spherical in the ground state. For the ^{192}Po (^{190}Po) ground state, the large quadrupole deformation parameter β =0.24 (β =0.17) or $\beta = -0.35$ ($\beta = -0.24$) was deduced. The strong difference in the ground-state deformations of daughter nuclei can be the reason of the deviation of the alpha decays from the Geiger-Nuttall law.
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[1] T.M. Shneidman, G.G. Adamian, N.V. Antonenko, R.V. Jolos, W. Scheid, Phys. Lett. B **526** (2002) 322.

[2] T.M. Shneidman, G.G. Adamian, N.V. Antonenko, R.V. Jolos, W. Scheid, in the Proceedings of the 29th Intern. Workshop on Nuclear Theory, p. 145 (Heron Press, Sofia, 2010).

[3] T.M. Shneidman, G.G. Adamian, N.V. Antonenko, R.V. Jolos, W. Scheid, Eur. Phys. J. A **42** (2011) 481.

[4] T.M. Shneidman, G.G. Adamian, N.V. Antonenko, R.V. Jolos, W. Scheid, Acta Phys. Polonica A **47** (2011) 34.

[5] W. Reviol *et al.*, Phys. Rev. C **74** (2006) 044305.

[6] S.N. Kuklin, T.M. Shneidman, G.G. Adamian, and N.V. Antonenko, Eur. Phys. J. A **48** (2012) 112.

NEW TYPE OF NUCLEAR COLLECTIVE MOTION — SPIN SCISSORS

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The generalization of the Wigner Function Moments (WFM) method by including spin dynamics allowed one to reveal a variety of new types of nuclear collective motion involving spin degrees of freedom [**?**]. The most remarkable result was the discovery of the new type of the nuclear collective motion - rotational oscillations of "spin-up" nucleons with respect of "spin-down" nucleons (spin scissors).
The basis of the WFM method is the Time Dependent Hartree-Fock equation. Being written in coordinate space with all spin indices it reads [**?**, **?**]:

$$i\hbar\dot{\hat{\rho}}_{\mathbf{r}s,\mathbf{r}''s''} = \sum_{s'}\int d^3r'(\hat{h}_{\mathbf{r}s,\mathbf{r}'s'}\hat{\rho}_{\mathbf{r}'s',\mathbf{r}''s''} - \hat{\rho}_{\mathbf{r}s,\mathbf{r}'s'}\hat{h}_{\mathbf{r}'s',\mathbf{r}''s''}). \tag{1}$$

With the help of the Wigner transformation [**?**] $f^{ss'}(\mathbf{r},\mathbf{p}) = \int d^3q e^{-i\mathbf{pq}/\hbar}\hat{\rho}_{\mathbf{r}_1 s,\mathbf{r}_2 s'}$, where $\mathbf{q} = \mathbf{r}_1 - \mathbf{r}_2$ and $\mathbf{r} = \frac{1}{2}(\mathbf{r}_1 + \mathbf{r}_2)$, the equation for the density matrix (**??**) is transformed into equation for Wigner function $f(\mathbf{r},\mathbf{p})$. Integrating the last equation over phase space with the weights $W = \{r\otimes p\}_{\lambda\mu}$, $\{r\otimes r\}_{\lambda\mu}$, $\{p\otimes p\}_{\lambda\mu}$, and 1 one gets the dynamic equations for the following collective variables:

$$L^{\tau\varsigma}_{\lambda\mu}(t) = \int\frac{d^3rd^3p}{(2\pi\hbar)^3}\{r\otimes p\}_{\lambda\mu}f^{\tau\varsigma}(\mathbf{r},\mathbf{p},t), \quad R^{\tau\varsigma}_{\lambda\mu}(t) = \int\frac{d^3rd^3p}{(2\pi\hbar)^3}\{r\otimes r\}_{\lambda\mu}f^{\tau\varsigma}(\mathbf{r},\mathbf{p},t),$$
$$P^{\tau\varsigma}_{\lambda\mu}(t) = \int\frac{d^3rd^3p}{(2\pi\hbar)^3}\{p\otimes p\}_{\lambda\mu}f^{\tau\varsigma}(\mathbf{r},\mathbf{p},t), \quad F^{\tau\varsigma}(t) = \int\frac{d^3rd^3p}{(2\pi\hbar)^3}f^{\tau\varsigma}(\mathbf{r},\mathbf{p},t),$$

where $\{r\otimes p\}_{\lambda\mu} = \sum_{\alpha,\beta} C^{\lambda\mu}_{1\alpha,1\beta}r_\alpha p_\beta$ with r_{-1}, r_0, r_1 being cyclic coordinates [**?**], $C^{\lambda\mu}_{1\alpha,1\beta}$ is a Clebsch-Gordan coefficient, τ is an isospin index, $\varsigma = +,-,\uparrow\downarrow,\downarrow\uparrow$ and $f^{\pm} = f^{\uparrow\uparrow} \pm f^{\downarrow\downarrow}$. The conventional notation $\uparrow$ for $s = \frac{1}{2}$ and $\downarrow$ for $s = -\frac{1}{2}$ are used.
We are interested in the scissors mode with quantum number $K^\pi = 1^+$. Therefore, we only need the part of dynamic equations with $\mu = 1$.
The microscopic Hamiltonian of the model is given by

$$H = \sum_{i=1}^{A}\left[\frac{\hat{\mathbf{p}}_i^2}{2m} + \frac{1}{2}m\omega^2\mathbf{r}_i^2 - \eta\hat{\mathbf{l}}_i\hat{\mathbf{S}}_i\right] + H_{qq} + H_{ss}, \tag{2}$$

where H_{qq} is the well known quadrupole-quadrupole residual interaction and

$$H_{ss} = \sum_{\mu=-1}^{1}(-1)^\mu\left\{\bar{\chi}\sum_i^Z\sum_j^N\hat{S}^i_{-\mu}\hat{S}^j_\mu + \frac{1}{2}\chi\left[\sum_{i\neq j}^Z\hat{S}^i_{-\mu}\hat{S}^j_\mu + \sum_{i\neq j}^N\hat{S}^i_{-\mu}\hat{S}^j_\mu\right]\right\}\delta(\mathbf{r}_i - \mathbf{r}_j) \tag{3}$$

is the spin-spin residual interaction; N and Z are the numbers of neutrons and protons and $\hat{S}_\mu$ are spin matrices [**?**].

The results of calculations are given in Tables 1 and 2. The values of constants are taken from the paper [**?**], where the notation $\chi_s = K_s/A$, $\bar{\chi}_s = q\chi_s$ was introduced.

Table 1. Isovector energies and excitation probabilities calculated for ^{164}Er with the spin-orbit constant $\eta = 0.36$ MeV and three sets of spin-spin interaction constants: I – $K_s = 0$ MeV; II – $K_s = 92$ MeV, $q = -0.8$; III – $K_s = 200$ MeV, $q = -0.5$. Quantum numbers (including indices $\varsigma = +, -, \uparrow\downarrow, \downarrow\uparrow$) of variables responsible for the generation of the present level are shown in first column.

$(\lambda,\mu)^{\varsigma}$	$E_{\rm iv}$, MeV			$B(M1),\ \mu_N^2$			$B(E2),\ B_W$		
	I	II	III	I	II	III	I	II	III
$(1,1)^-$	1.61	2.02	2.34	3.54	5.44	7.91	0.12	0.36	0.82
$(1,1)^+$	2.18	2.45	2.76	5.33	4.48	2.98	1.02	1.23	1.26
$(0,0)^{\downarrow\uparrow}$	12.80	16.81	20.02	0.01	0.01	0.04	0.04	0.13	0.52
$(2,1)^-$	14.50	18.52	21.90	0.01	0.02	0.34	0.03	0.13	4.29
$(2,2)^{\uparrow\downarrow}$	16.18	20.61	24.56	0.02	0.23	0.03	0.18	3.09	0.44
$(2,0)^{\downarrow\uparrow}$	16.20	22.65	27.67	0	0.03	0	0	0.39	0.02
$(2,1)^+$	20.59	21.49	22.42	2.78	2.19	1.77	35.45	30.47	27.43

Three low lying levels correspond to the excitation of new types of modes. The isovector level marked by $(1,1)^-$ describes rotational oscillations of nucleons with the spin projection "up" with respect of nucleons with the spin projection "down", i.e. one can talk of a nuclear spin scissors mode. Having in mind that this excitation is an isovector one, we can see that the resulting motion looks rather complex – proton spin scissors counter-rotates with respect to the neutron spin scissors. Thus the experimentally observed group of 1^+ peaks in the interval 2–4 MeV, associated usually with the nuclear scissors mode, in reality consists of the excitations of the "spin" scissors mode together with the conventional [**?**] scissors mode (the level $(1,1)^+$). The isoscalar level $(1,1)^-$ describes the real spin scissors: all spin up nucleons (protons together with neutrons) oscillate rotationally out of phase with all spin down nucleons.

Table 2. The same as in Table 1, but for isoscalar excitations.

$(\lambda,\mu)^{\varsigma}$	$E_{\rm is}$, MeV			$B(M1),\ \mu_N^2$			$B(E2),\ B_W$		
	I	II	III	I	II	III	I	II	III
$(1,1)^-$	1.73	2.04	2.40	0	0	0	0.65	0.39	1.12
$(1,1)^+$	0.39	0.37	0.37	0.24	0.24	0.24	117.90	118.27	117.19
$(0,0)^{\downarrow\uparrow}$	12.83	15.59	18.72	0	0	0	0.31	0.15	0.66
$(2,1)^-$	14.51	17.40	20.65	0	0	0	0.06	0.03	0.12
$(2,2)^{\uparrow\downarrow}$	16.20	19.43	23.09	0	0	0	0.07	0.04	0
$(2,0)^{\downarrow\uparrow}$	16.22	20.09	24.80	0	0	0	0.02	0.01	0.20
$(2,1)^+$	10.28	11.92	13.60	0	0	0	57.78	50.87	66.50

One more new low lying mode (isoscalar $(1,1)^+$) is generated by relative motion of the orbital angular momentum and spin of the nucleus (they can change their absolute values and directions keeping the total angular momentum unchanged).

Two high lying excitations of the new nature are found. They are marked by $(2,1)^-$ and following the paper [**?**] can be called spin-vector giant quadrupole resonances. The isovector one corresponds to the following motion: the proton system oscillates out of

phase with the neutron system, whereas inside of each system spin up nucleons oscillate out of phase with spin down nucleons. The respective isoscalar resonance describes out of phase oscillations of all spin up nucleons (protons together with neutrons) with respect of all spin down nucleons.
Six high lying modes can be interpreted as spin-flip giant monopole (marked by $(0,0)^{\downarrow\uparrow}$) and quadrupole (marked by $(2,0)^{\downarrow\uparrow}$ and $(2,2)^{\uparrow\downarrow}$) resonances. The excitations marked by $(2,1)^{+}$ are the well known isovector and isoscalar GQR.
Comparing the results of calculations without (column I) and with (columns II, III) spin-spin interaction one can see that spin-spin interaction does not change the qualitative picture of excitations. It pushes all levels up proportionally to its strength (20-30% in the case II and 40-60% in the case III) without changing their order. It is necessary to note also that in the isoscalar case the low lying mode marked by $(1,1)^{+}$ is practically insensitive to the spin-spin interaction. The most interesting result in isovector case concerns B(M1) values of both scissors – the spin-spin interaction strongly redistributes M1 strength in the favour of the spin scissors. We tentatively want to link this fact to the recent experimental finding in isotopes of Th and Pa [**?**], where for the two low lying magnetic states a stronger B(M1) transition for the lower state with respect to the higher one was found. A tentative explanation in terms of a slight triaxial deformation failed. However, our theory can naturally predict such a scenario with a non vanishing spin-spin force. It would indeed be very exciting, if the results of [**?**] had already discovered the isovector spin scissors mode. However, much deeper experimental and theoretical results must be obtained before a firm conclusion on this point is possible.

[1] E. B. Balbutsev, I.V. Molodtsova, P. Schuck, Nucl. Phys. A **872** (2011) 42.

[2] P. Ring and P. Schuck, *The Nuclear Many-Body Problem* (Springer, Berlin, 1980).

[3] D. A. Varshalovitch, A. N. Moskalev and V. K. Khersonski, *Quantum Theory of Angular Momentum* (World Scientific, Singapore, 1988).

[4] P. Sarriguren, E. Moya de Guerra, R. Nojarov, Phys. Rev. C **54** (1996) 690;
P. Sarriguren, E. Moya de Guerra, R. Nojarov, Z. Phys. A **357** (1997) 143.

[5] K. Heyde, P. von Neuman-Cosel and A. Richter, Rev. Mod. Phys. **82** (2010) 2365.

[6] F. Osterfeld, Rev. Mod. Phys. **64** (1992) 491.

[7] M. Guttormsen, L. A. Bernstein, A. Bürger, *et al.*, Phys. Rev. Lett. **109** (2012) 162503.

TOROIDAL, COMPRESSION AND VORTICAL STRENGTHS

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The toroidal and compression modes represent a subject of keen interest for many years, see e.g. the review [**?**]. The toroidal mode (TM) is known to be determined by the second order correction to the leading long-wave part of the transition $E\lambda$ operator [**?**, **?**]. The compression mode (CM) [**?**], being different from TM by construction, is related, nevertheless, to TM and also represents the second-order correction [**?**, **?**]. Despite the long studies, the vorticity of TM and CM and is still disputed [**?**]. Besides a possible interplay of E1 TM and pygmy mode becomes actual [**?**, **?**, **?**]. These problems were recently investigated both analytically and numerically [**?**, **?**, **?**]. The calculations were performed within the fully self-consistent separable Skyrme random-phase-approximation (SRPA) approach [**?**].
The multipole TM and CM operators read [**?**]:

$$\begin{aligned}
\hat{M}_{tor}(E\lambda\mu) &= -\frac{i}{2c}\sqrt{\frac{\lambda}{2\lambda+1}}\int d^3r\,\hat{\vec{j}}_{nuc}(\vec{r})\cdot r^{\lambda+1}\left[\vec{Y}_{\lambda\lambda-1\mu}(\hat{\vec{r}})+\sqrt{\frac{\lambda}{\lambda+1}}\frac{2}{2\lambda+3}\vec{Y}_{\lambda\lambda+1\mu}(\hat{\vec{r}})\right] \\
&= -\frac{1}{2c}\sqrt{\frac{\lambda}{\lambda+1}}\,\frac{1}{2\lambda+3}\int d^3r\,r^{\lambda+2}\vec{Y}_{\lambda\lambda\mu}(\hat{\vec{r}})\cdot\left(\vec{\nabla}\times\hat{\vec{j}}_{nuc}(\vec{r})\right)\,, \qquad (1) \\
\hat{M}_{com}(E\lambda\mu) &= \frac{i}{2c}\sqrt{\frac{\lambda}{2\lambda+1}}\int d^3r\,\hat{\vec{j}}_{nuc}(\vec{r})\cdot r^{\lambda+1}\left[\vec{Y}_{\lambda\lambda-1\mu}(\hat{\vec{r}})-\sqrt{\frac{\lambda+1}{\lambda}}\,\frac{2}{2\lambda+3}\vec{Y}_{\lambda\lambda+1\mu}(\hat{\vec{r}})\right] \\
&= -\frac{i}{2c}\,\frac{1}{2\lambda+3}\int d^3r\,r^{\lambda+2}Y_{\lambda\mu}(\hat{\vec{r}})\left(\vec{\nabla}\cdot\hat{\vec{j}}_{nuc}(\vec{r})\right)\,, \qquad (2)
\end{aligned}$$

where the current-dependent CM operator (**??**) is straightforwardly transformed, $\hat{M}_{com}(E\lambda\mu)=-k\hat{M}'_{com}(E\lambda\mu)$, to the familiar density-dependent counterpart [**?**]

$$\hat{M}'_{com}(E\lambda\mu)=\frac{1}{2(2\lambda+3)}\int d^3r\hat{\rho}(\vec{r})r^{\lambda+2}Y_{\lambda\mu}(\hat{\vec{r}}). \qquad (3)$$

Here $\hat{\rho}$ and $\hat{\vec{j}}_{nuc}=\hat{\vec{j}}_c+\hat{\vec{j}}_m$ are density and current density operators (where the current includes the convection and magnetization parts); $\vec{Y}_{\lambda\lambda'\mu}$ and $Y_{\lambda\mu}$ are vector and scalar spherical harmonics; k is the wave number. Following (**??**)-(**??**), the TM and CM deliver the information on the current curl $\vec{\nabla}\times\hat{\vec{j}}_{nuc}(\vec{r})$ and divergence $\vec{\nabla}\cdot\hat{\vec{j}}_{nuc}(\vec{r})$, respectively.
In hydrodynamics, the vorticity is defined by the curl of the velocity field. Then TM is vortical and CM is irrotational [**?**]. However, nuclear models deal with the nuclear current rather than the velocity, which leads to alternative definitions of the vorticity. In [**?**], the nuclear current component $j^{(fi)}_{\lambda,\,\lambda+1}(r)$, arising in the multipole decomposition of the current transition density $<f|\hat{\vec{j}}_{\rm nuc}(\vec{r})|i>$, is treated as unconstrained by the continuity equation

Figure 1: Isoscalar (T=0) vortical, toroidal, and compression E1 strengths in ^{208}Pb, calculated within SRPA with the force SLy6 [**?**].

and thus suitable as a measure of the vorticity. We have derived the relevant vortical operator and its relation to the CM and TM operators [**?**]:

$$\hat{M}_{vor}(E\lambda\mu) = \hat{M}_{tor}(E\lambda\mu) + \hat{M}_{com}(E\lambda\mu) \ . \tag{4}$$

This relation may be very useful for the analysis of TM and CM vorticity.
In the dipole case, the vortical, toroidal and compression strengths are exhibited in Fig. 1 for ^{208}Pb [**?**]. It is seen that the vorticity is mainly concentrated at 6-19 MeV. What is most remarkable, the vorticity and TM are strictly peaked at 6-10 MeV, i.e. just in the location of the pygmy mode (PM). The similar result was obtained for Sn isotopes [**?**]. Further analysis of the transition densities and velocity distributions within full Skyrme RPA has shown that the dominant flow in PM region is indeed the toroidal isoscalar mode [**?**].

[1] N. Paar, D. Vretenar, E. Khan, and G. Colo, Rep. Prog. Phys. **70** (2007) 691.

[2] V. M. Dubovik and A. A. Cheshkov, Sov. J. Part. Nucl. **5** (1975) 318.

[3] J. Kvasil, V.O. Nesterenko, W. Kleinig, P.-G. Reinhard, and P.Vesely, Phys. Rev. C**84** (2011) 034303.

[4] M.N. Harakeh, *et al.*, Phys. Rev. Lett. **38** (1977) 676; S.F. Semenko, Sov. J. Nucl. Phys. **34** (1981) 356.

[5] N. Ryezayeva, *et al.*, Phys. Rev. Lett. **89** (2002) 272502.

[6] J. Kvasil, V.O. Nesterenko, A. Repko, W. Kleinig, P.-G. Reinhard, and N. Lo Iudice, arXiv:1211.2978[nucl-th], to be published in Phys. Scripta.

[7] A. Repko, P.-G. Reinhard, V.O. Nesterenko, and J. Kvasil, arXiv:1212.2088[nucl-th]; to be published in Phys. Rev. C.

[8] V.O. Nesterenko, J. Kvasil, and P.-G. Reinhard, Phys. Rev. C **66** (2002) 044307; V.O. Nesterenko, W. Kleinig, J. Kvasil, P.-G. Reinhard, and P. Vesely, Phys. Rev. C **74** (2006) 054306.

[9] D.G. Raventhall, J. Wambach, Nucl. Phys. A **475** (1987) 468.

RESONANT NEUTRINOLESS DOUBLE-ELECTRON CAPTURE

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The physics community faces a challenging problem, finding whether neutrinos are indeed Majorana particles (i.e. identical to its own antiparticle) as many particle models suggest or Dirac particles (i.e. is different from its antiparticle). The best sensitivity on small Majorana neutrino masses can be reached in the investigation of neutrinoless double-beta decay ($0\nu\beta\beta$-decay) [**?**],

$$(A, Z) \to (A, Z + 2) + e^- + e^- \tag{1}$$

and the resonant neutrinoless double-electron capture (0νECEC) [**?**, **?**],

$$e_b^- + e_b^- + (A, Z) \to (A, Z - 2)^{**}. \tag{2}$$

The two asterisks denote the possibility of leaving the system in an excited nuclear and/or atomic state. The energy excess given by the Q-value of the initial atom is carried away by emission of x rays (or Auger electrons) as the daughter atom has two electron holes and by emission of a single or few photons due to de-excitation of final nucleus.
A significant progress has been achieved in theoretical description of the resonant 0νECEC in [**?**]. A new theoretical framework for the calculation of resonant 0νECEC transitions, namely the oscillation of stable and quasi-stationary atoms due to weak interaction with violation of the total lepton number and parity, was proposed in [**?**]. The 0νECEC transition rate near the resonance is of Breit-Wigner form,

$$\Gamma_{ab}^{0\nu\mathrm{ECEC}}(J^\pi) = \frac{|V_{ab}(J^\pi)|^2}{\Delta^2 + \frac{1}{4}\Gamma_{ab}^2}\Gamma_{ab}, \tag{3}$$

where J^π denotes angular momentum and parity of final nucleus. The degeneracy parameter can be expressed as $\Delta = Q - B_{ab} - E_\gamma$. Q stands for a difference between the initial and final atomic masses in ground states and E_γ is an excitation energy of the daughter nucleus. $B_{ab} = E_a + E_b + E_C$ is the energy of two electron holes, whose quantum numbers (n, j, l) are denoted by indices a and b and E_C is the interaction energy of the two holes. The width of the excited final atom with the electron holes is given by

$$\Gamma_{ab} = \Gamma_a + \Gamma_b + \Gamma^*. \tag{4}$$

Here, $\Gamma_{a,b}$ is one-hole atomic width and Γ^* is the de-excitation width of daughter nucleus, which can be neglected. Numerical values of Γ_{ab} are about up to few tens eV.
For light neutrino mass mechanism and favorable cases of a capture of $s_{1/2}$ and $p_{1/2}$ electrons the explicit form of lepton number violating amplitude associated with nuclear

transitions $0^+ \to J^\pi = 0^{\pm 1}, 1^{\pm 1}$ is given in [**?**]. By factorizing the electron shell structure and nuclear matrix element one get

$$V_{ab}(J^\pi) = \frac{1}{4\pi}\, m_{\beta\beta} G_\beta^2 \frac{g_A^2}{R} < F_{ab} > M^{0\nu ECEC}(J^\pi). \tag{5}$$

Here, $m_{\beta\beta}$ is the effective mass of Majorana neutrinos, $< F_{ab} >$ is a combination of averaged upper and lower bispinor components of the atomic electron wave functions and $M^{0\nu ECEC}(J^\pi)$ is the nuclear matrix element (NME). We note that by neglecting the lower bispinor components $M^{0\nu ECEC}(0^+)$ takes the form of the $0\nu\beta\beta$-decay NME for ground state to ground state transition after replacing isospin operators τ^- by τ^+.
New important theoretical findings with respect of the 0νECEC were achieved in [**?**]. They are as follows:
i) Effects associated with the relativistic structure of the electron shells reduce the 0νECEC half-lives by almost one order of magnitude.
ii) The capture of electrons from the $np_{1/2}$ states is only moderately suppressed in comparison with the capture from the $ns_{1/2}$ states unlike in the non-relativistic theory.
iii) For light neutrino mass mechanism selection rules appear to require that nuclear transitions with a change in the nuclear spin $J \geq 2$ are strongly suppressed.
iv) New transitions due to the violation of parity in the 0νECEC process were proposed. For example, nuclear transitions $0^+ \to 0^\pm, 1^\pm$ are compatible with a mixed capture of s- and p-wave electrons.
v) The interaction energy of the two holes E_C has to be taken into account by evaluating a mass degeneracy of initial and final atoms.
vi) Based on the most recent atomic and nuclear data and by assuming $M^{0\nu ECEC}(J^\pi) =$ 6 the 0νECEC half-lives were evaluated and the complete list of the most perspective isotopes for further experimental study was provided. Some isotopes such as ^{156}Dy have several closely-lying resonance levels. A more accurate measurement of Q-value of ^{156}Dy by Heidelberg group confirmed the existence of multiple-resonance phenomenon for this isotope [**?**].
vii) In the unitary limit some 0νECEC half-lives were predicted to be significantly below the $0\nu\beta\beta$-decay half-lives for the same value of $\langle m_\nu \rangle$. A probability of finding resonant transition with low 0νECEC half-life was evaluated.
viii) The process of the resonant neutrinoless double electron production (0νEPEP), i.e. neutrinoless double beta decay to two bound electrons, namely

$$(A, Z) \to (A, Z+2)^{**} + e_b^- + e_b^-, \tag{6}$$

was proposed and analyzed. This process was found to be unlikely as it requires that a Q-value is extremely fine tuned to a nuclear excitation. The two electrons must be placed into any of the upper most non-occupied electron shells of the final atom leaving only restricted possibility to match to a resonance condition.
The probability of the 0νECEC is increased by many orders of magnitude provided the resonance condition is satisfied within a few tens of electron-volts. For a long time there was no way to identify promising isotopes for experimental search of 0νECEC, because of poor experimental accuracy of measurement of Q-values of the order of 1 - 10 keV for medium heavy nuclei. Progress in precision measurement of atomic masses with Penning traps [**?**, **?**] has revived the interest in the old idea on the resonance 0νECEC.

The accuracy of Q-values at around 100 eV was achieved. The estimates of the 0νECEC half-lives were recently improved by more accurate measurements of Q-values for ^{74}Se, ^{96}Ru, ^{106}Cd, ^{102}Pd, ^{112}Sn, ^{120}Te, ^{136}Ce, ^{144}Sm, ^{152}Gd, ^{156}Dy, ^{162}Er, ^{164}Er, ^{168}Yb and ^{180}W. It allowed to exclude some of isotopes from the list of the most promising candidates (e.g., ^{112}Sn, ^{164}Er, ^{180}WW) for searching the 0νECEC.

Among the promising isotopes, ^{152}Gd has likely resonance transitions to the 0^+ ground states of the final nucleus as it follows from improved measurement of Q-value for this transition with accuracy of about 100 eV [**?**]. A detailed calculation of the 0νECEC of ^{152}Gd was performed in [**?**, **?**, **?**]. The atomic electron wave functions were treated in the relativistic Dirac-Hartree-Fock approximation. The NME for ground state to ground state transition $^{152}\text{Gd} \rightarrow {}^{152}\text{Sm}$ was calculated within the proton-neutron deformed QRPA with a realistic residual interaction [**?**, **?**]. For the favored capture of electrons from K and L shells in the case of ^{152}Gd the 0νECEC half-life is in the range 4.7×10^{28} - 4.8×10^{29} years by assuming $|m_{\beta\beta}| = 50$ meV. This transition is still rather far from the resonant level. Currently, the 0νECEC half-life of ^{152}Gd is 2-3 orders of magnitude longer than the half-life of $0\nu\beta\beta$ decay of ^{76}Ge corresponding to the same value of $|m_{\beta\beta}|$ and is the smallest known half-life among known 0νECEC.

Observing the $0\nu\beta\beta$-decay and/or 0νECEC would tell us that the total lepton number is not a conserved quantity and that neutrinos are massive Majorana fermions. There is an increased experimental activity in the field of the resonant 0νECEC [**?**, **?**]. The resonant 0νECEC has some important advantages with respect to experimental signatures and background conditions. The de-excitation of the final excited nucleus proceeds in most cases through a cascade of easy to detect rays. A two- or even higher-fold coincidence setup can cut down any background rate right from the beginning, thereby requiring significantly less active or passive shielding. A clear detection of these γ rays would already signal the resonant 0νECEC without any doubt, as there are no background processes feeding those particular nuclear levels. It is worth noting that lepton number conserving ECEC with emission of two neutrinos, is strongly suppressed due to almost vanishing phase space [**?**]. The ground state to ground state resonant 0νECEC transitions can be detected by monitoring the x rays or Auger electrons emitted from excited electron shell of the atom. This can be achieved, e.g., by calorimetric measurements. Recently, the most stringent limit on the resonant 0νECEC were established for ^{74}Se [**?**] and ^{106}Cd [**?**]. The TGV experiment situated in Modane established limit on the 0νECEC half-life of 1.1×10^{20} years [**?**]. Subject of interest was the 0νECEC resonant decay mode of ^{106}Cd (KL-capture) to the excited 2741 keV state of ^{106}Pd. For a long time the spin value of this final state was unknown and it was assumed to be $J^\pi = (1,2)^+$. However, a new value for the spin of the 2741 keV level in ^{106}Pd is $J = 4^+$ and this transition is disfavored again due to selection rule.

[1] J.D. Vergados, H. Ejiri, F. Šimkovic, Rept. Prog. Phys. **75** (2012) 106301.

[2] F. Šimkovic, M.I. Krivoruchenko, Phys. Part. Nucl. Lett. **6** (2009) 298-303;
M.I. Krivoruchenko, F. Šimkovic, D. Frekers, A. Faessler, Nucl. Phys. A **859** (2011) 140.

[3] S. Eliseev, C. Roux, K. Blaum, M. Block, C. Droese, F. Herfurth, H.-J. Kluge, M. I. Krivoruchenko, Yu. N. Novikov, E. Minaya Ramirez, L. Schweikhard, V. M. Shabaev,

F. Šimkovic, I.I. Tupitsyn, K. Zuber, and N. A. Zubova, Phys. Rev. Lett. **106** (2011) 052504.

[4] S. Eliseev, C. Roux, K. Blaum, M. Block, C. Droese, F. Herfurth, M. Kretzschmar, M. I. Krivoruchenko, E. Minaya Ramirez, Yu. N. Novikov, L. Schweikhard, V. M. Shabaev, F. Šimkovic, I. I. Tupitsyn, K. Zuber, and N. A. Zubova, Phys. Rev. Lett. **107** (2011) 152501.

[5] F. Šimkovic, M.I. Krivoruchenko, A. Faessler, Prog. Part. Nucl. Phys. **66** (2011) 446.

[6] Dong-Liang Fang, K. Blaum, S. Eliseev, Amand Faessler, M.I. Krivoruchenko, V. Rodin, F. Šimkovic, Phys. Rev. C **85** (2012) 035503.

[7] Amand Faessler, V.A. Rodin, F. Šimkovic, J. Phys. G **39** (2012) 124006.

[8] D. Frekers, P. Puppe, J.H. Thies, P.P. Povinec, F. Šimkovic, J. Staniček, I. Sýkora, Nucl. Phys. A **860** (2011) 1.

[9] N.I. Rukhadze, A.M. Bakalyarov, Ch. Briançon, V.B. Brudanin, P. Čermák, V.G. Egorov, A.A. Klimenko, A. Kovalík, V.I. Lebedev, F. Mamedov, Yu.A. Shitov, F. Šimkovic, I. Štekl, V.V. Timkin, S.V. Zhukov, Nucl. Phys. A **852** (2011) 197.

NEUTRINO-NUCLEUS INELASTIC SCATTERING IN HOT AND DENSE STELLAR ENVIRONMENT

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Since most of the supernova explosion energy is radiated in neutrinos, neutrino interaction with stellar matter plays important role in supernova understanding and simulations. During many years considering the energy loss by neutrinos it was assumed that neutrinos lose energy by neutral-current scattering off electrons and by their charge-current reactions on free protons and neutrons (and some nuclei) as well as by charge-current ν_e and $\bar{\nu_e}$ scattering off electrons. However, at the end of 80ies W. C. Haxton pointed out in [**?**] that inelastic neutrino-nucleus scattering (INNS) mediated by the neutral-current can be of importance comparable with the other processes of neutrino down-scattering. One of the reason is the nuclear GT_0-resonance with $J^\pi = 1^+$ and excitation energy $E_{\mathrm{res}} \simeq 10$ MeV which is intensively excited by low-energy neutrinos. The matter is that the GT_0 resonance is strongly coupled with the ground state of a nucleus by the operator $\sigma\tau_0$ which is just the operator of neutrino-nucleus interaction at low neutrino energies.

Later, it was realized that since the INNS occurs in hot stellar environment ($T \geq 0.8$ MeV) some changes of the INNS cross section can be expected due to thermal population of nuclear excited states. The effect was firstly analyzed in [**?**] and then in [**?**] on the basis of large-scale shell-model (LSSM) calculations. In Refs. [**?**, **?**], it was revealed that the INNS cross section noticeably increases at $T \neq 0$ and neutrino energies $E_\nu \lesssim 10$ MeV. However, the full scale shell model calculations are not feasible yet and the Brink hypothesis was used partially in [**?**, **?**] when calculating the transitions between nuclear excited states. Moreover, for the same reason the contributions of the first-forbidden transitions with $J^\pi = 0^-, 1^-, 2^-$ were calculated in the random phase approximation.

In treating the thermal effects on the cross section of INNS we applied the other approach. It is based on the thermal quasiparticle random phase approximation formulated in the context of the thermo field dynamics (TFD) [**?**] which enables a transparent treatment of excitation and de-excitation processes in a hot many-body system like a nucleus (for more details see [**?**, **?**]). This thermodynamically consistent approach was successfully used in studies of the electron capture on hot iron and germanium nuclei under stellar conditions [**?**]. In contrast to the large-scale shell-model studies [**?**, **?**] we do not apply the Brink hypothesis when treating transitions between thermally excited nuclear states and calculate the first-forbidden transitions within the same approach.

Considering neutrino-nucleus inelastic scattering in stellar environments we assumed that a nucleus is in a thermal equilibrium state or, in TFD terms, in the thermal (phonon) vacuum state. An inelastic collision of a hot nucleus with neutrino leads to transition from the thermal vacuum to thermal one-phonon states. In this context the two types of transitions are distinguished: the first one corresponds to the process when neutrino loses a part of its energy giving it to a nucleus (so called down-transitions), the other type is the up-transitions when the nucleus de-excites giving up a part of its energy to outgoing neutrino. In the framework of our approach the down-transitions involve the thermal one-phonon states whereas the up-transitions are the transitions from thermal vacuum to

thermal tilde one-phonon state which energies are lower than the energy of the thermal vacuum.
Calculating the INNS cross section $\sigma_{\nu A}$ we took into account the contributions of the allowed 1^+ transitions and first-forbidden transitions 0^-, 1^-, and 2^-. For the all multipole contributions the calculations were performed with Walecka-Donely [**?**, **?**] formalism, which describes in a unified way electromagnetic and weak semi-leptonic processes in a nucleus by taking advantage of the multipole decomposition of the relevant hadronic current density operator.
Numerical calculations were performed for the ^{54}Fe nucleus [**?**]. Single-particle wave functions and energies were calculated in the spherically symmetric Woods-Saxon potential. The constants of pairing interaction were determined to reproduce experimental pairing energies in the BCS approximation. All these parameters are the same as in our previous calculations of electron capture rates on the same nuclide at $T \neq 0$ [**?**]. The coupling constants of schematic spin-dependent isoscalar and isovector residual interactions were fitted to experimental data basing on the results of Refs. [**?**, **?**].

Figure 1: The neutrino-nucleus inelastic cross sections as the sum of allowed and first-forbidden contributions for ^{54}Fe at different temperatures T. The dashed line shows the cross section of inelastic neutrino-electron scattering as a function of neutrino energy.

In Fig. **??**, the INNS cross sections (a sum of $1^+, 0^-, 1^-$, and 2^- contributions) are shown as the function of neutrino energy E_ν at different temperatures T. At low E_ν the cross sections are almost completely dominated by the GT_0 transitions. The part of the cross sections arising from the first-forbidden transitions becomes increasingly important at larger E_ν. For $E_\nu = 30$ MeV up to 20% of the cross section is due to first-forbidden transitions. For $E_\nu = 40$ MeV allowed and forbidden transitions contribute about equally, while at $E_\nu = 50$ MeV the contribution of the first-forbidden transitions is nearly twice as large as that of 1^+ transitions.
In the LSSM calculations [**?**] the temperature-related enhancement of $\sigma(E_\nu)$ was only due to the neutrino up-scattering. In our approach both the up-scattering and down-scattering parts of $\sigma(E_\nu)$ are temperature dependent. We display the down- and up- parts of INNS cross section separately as the functions of E_ν for different values of T in Fig. **??**.
A weak T-dependence of σ_d is seen at neutrino energies $E_\nu < 12$ MeV, and then, at higher energies, σ_d practically does not depend on T. Moreover, the down-scattering cross section sharply increases at low neutrino energies and then its growth becomes smoother. Instead, σ_u appears to be sensitive to T but its dependence on E_ν is obviously smoother than that of σ_d (at least at $E_\nu < 15$ MeV). The absolute values of σ_d and σ_u are of the same order only at quite low neutrino energies $E_\nu \lesssim 4 - 10$ MeV.
Thus, our calculations have revealed the same thermal effects as were found in [**?**, **?**]: The temperature increase leads to a considerable enhance of the INNS cross section for neutrino energies lower than the energy of GT_0 resonance, and this enhancement is mainly due to neutrino up-scattering at finite temperature. Moreover, the calculated cross sections for ^{54}Fe are very close to that given in [**?**].

[1] W. C. Haxton, Phys. Rev. Lett. **60** (1988) 1999.

[2] G. M. Fuller and B. S. Meyer, Astrophys. J. **376** (1991) 678.

[3] J. M. Sampaio *et al.*, Phys. Lett. B **529** (2002) 19.

Figure 2: The down-scattering $\sigma_d(E_\nu)$ (a) and the up-scattering $\sigma_d(E_\nu)$ (b) parts of the INNS cross section for ^{54}Fe at different T.

[4] A. Juodagalvis *et al.*, Nucl. Phys. A **747** (2005) 87.

[5] Y. Takahashi and H. Umezawa, Collective Phenomena, **2** (1975) 55.

[6] A. A. Dzhioev and A. I. Vdovin, Int. J. Mod. Phys. E **18** (2009) 1535.

[7] A. I. Vdovin, A. A. Dzhioev, Phys. Part. Nucl. **41** (2010) 1127.

[8] Alan A. Dzhioev, A. I. Vdovin, V. Yu. Ponomarev, J. Wambach, K. Langanke, and G. Martínez-Pinedo, Phys. Rev. C **81** (2010) 015804.

[9] J.D. Walecka, in *Muon Physics*, vol. 2, ed. by V.W. Hughes and C.S. Wu (Academic Press, New York, 1975), p. 113.

[10] T.W. Donnelly and R.D. Peccei, Phys. Rep. **50** (1979) 1.

[11] Alan A. Dzhioev, A. I. Vdovin, V. Yu. Ponomarev, J. Wambach, Phys. At. Nucl. **74** (2011) 1162.

[12] Dao Tien Khoa *et al.*, Preprint JINR, E4-86-198, JINR, Dubna (1986).

[13] V. Yu. Ponomarev *et al.*, J. Phys. G: Nucl. Part. Phys. **13** (1987) 1523.

POPULATION OF GROUND-STATE AND SUPERDEFORMED ROTATIONAL BANDS IN FUSION-EVAPORATION REACTIONS

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1. Population of ground-state rotational bands of superheavy nuclei produced in complete fusion reaction

Experimental and theoretical study of rotational bands of superheavies is especially hopeful, as the limits of stability of these nuclei in spin and excitation energy are governed by the fission barrier, which is mostly defined by shell component. The investigation of high-spin spectra also provides information about angular momentum dependence of the shell effects. Using the statistical and quantum diffusion approaches, we studied the pop-

Figure 1: Relative transition intensities in the yrast rotational band of ^{254}No, produced in the reaction ^{208}Pb(^{48}Ca, $2n$)^{254}No at the beam energy 215 MeV. The experimental data from Ref. [**?**] are presented by squares. The calculated points are connected by lines. Solid, dashed, dashed-dot and curves correspond to D=600, 800, 1000, and 1200, respectively.

ulation of rotational bands in superheavy nuclei produced in fusion-evaporation reactions ^{206,208}Pb(^{48}Ca, $2n$)^{252,254}No and ^{204}Hg(^{48}Ca, $2n$)^{250}Fm. The Fermi-gas model was applied for calculating the level densities. For the description of the capture process, we used the quantum diffusion approach based on the formalism of reduced density matrix. The interval D=600–1000 for the damping parameter was found for the description of the damping of the shell effects with the angular momentum and used in the calculations of the relative transition intensities in the ground state rotational bands and the entry spin distributions of the evaporation residues and the evaporation residue cross sections for all considered reactions. The calculated results are in a good agreement with the experimental data. Angular momentum dependence of these observables mainly comes from the partial capture and survival probabilities. The results were published in Ref. [**?**].

2. Population and properties of superdeformed bands in $A \sim 150$ region

The known superdeformed (SD) states of several isotopes of Dy, Gd and Tb are produced in different evaporation channels of fusion evaporation reactions. In this region of nuclear chart it possible to observe the rotational γ-transitions from very high ($\sim 60\hbar$) to lower ($\sim 20\hbar$) spins and, in some cases, to determine the energy of the lowest state in SD band. Such experimental basis allows one to describe theoretically not only the structure of SD states, but also the mechanism of their population.

According to the cluster interpretation, the strongly deformed nuclear state can be treated as the cold rotating dinuclear systems (DNS). The relative distance between the centers of two touching clusters corresponds to the minimum of the pocket of nucleus-nucleus

interaction potential. The pocket of nucleus-nucleus potential at given angular momentum contains the quasibound states with the energies below the potential barrier and with quite large half-lives. The lowest quasibound state is identical to the superdeformed (hyperdeformed) state in the case of asymmetric (symmetric) DNS configuration.

Figure 2: Measured [**?**] (circles), [**?**] (squares) and calculated (line) intensities of the SD band in ^{152}Dy produced in the reaction ^{108}Pd(^{48}Ca,4n).

Using the cluster and statistical approaches, we studied the population of SD band of ^{152}Dy, produced in different evaporation channels of fusion-evaporation reactions. The calculated characteristics (moments of inertia, quadrupole moments, relative intensities of $E2$-transitions between the rotational states) of superdeformed band of ^{152}Dy are close to the experimental values.
The agreement of the results of our calculations [**?**] with the experimental data proves the validity of cluster interpretation of strongly deformed nuclear states and supports the predictions concerning the possible formation of hyperdeformed states in the entrance channel of heavy ion reactions [**?**, **?**], based on the same theoretical approach.

[1] P. Reiter *et al.*, Phys. Rev. Lett. **82** (1999) 509; **84** (2000) 3542.

[2] A.S. Zubov, V.V. Sargsyan, G.G. Adamian, and N.V. Antonenko Phys. Rev. C **84** (2011) 044320.

[3] P.J Twin *et al.*, Phys. Rev. Lett. **57** (1986) 811.

[4] T. Lauritsen *et al.*, Phys. Rev. C **75** (2007) 064309.

[5] A.S. Zubov, V.V. Sargsyan, G.G. Adamian, and N.V. Antonenko, in the Proceedings of 10th Intern. Conference on Clustering Aspects of Nuclear Structure and Dynamics (Debrecen, Hungary, 2012), J. Phys.: Conf. Ser., (2013) to be published.

[6] A.S. Zubov, V.V. Sargsyan, G.G. Adamian, N.V. Antonenko, and W. Scheid, Phys. Rev. C **81** (2010) 024607.

[7] A.S. Zubov, V.V. Sargsyan, G.G. Adamian, N.V. Antonenko, and W. Scheid, Phys. Rev. C **82** (2010) 034610.

EMISSION OF HEAVY CLUSTERS IN NUCLEAR REACTIONS AT LOW COLLISION ENERGIES

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Recent experimental investigations revealed the possibility of producing new neutron deficient isotopes of nuclei via the emission of heavy clusters [**?**]. Those investigations were performed with the aim of producing neutron deficient nuclei in the vicinity of the doubly magic nucleus of ^{100}Sn, which are not formed in actual practice in channels of light particle evaporation. Predominantly, one considers channels involving the emission of carbon (^{12}C) and oxygen (^{16}O) nuclei, since it is precisely these clusters that have maximum yields among all heavy clusters. Since neutron deficient compound nuclei originate from complete fusion reactions, the emission of charged particles became more probable because of a high neutron separation energy.
In Ref. [**?**], we developed the theoretical model for calculating the cross sections of final reaction products in the framework of dinuclear system concept [**?**]. Cluster emission is treated under the assumption that light clusters are produced by collective motion of the nuclear system in the charge asymmetry coordinate, with further thermal escape over the Coulomb barrier. The advantage of the model is that the emission of light particles and heavy clusters are treated on the same basis and the model automatically takes into account the contribution from quasifission process to the cross sections for heavy fragments. In Refs. [**?**, **?**] we have studied the role of the angular momentum, the asymmetry of the entrance channel, the N/Z ratio and the excitation energy of the excited nuclear system in the formation of final reaction products. It was found that the shape of charge distributions of final reaction products are completely different in asymmetric and symmetric reactions and odd-even staggering effect is much smaller for the neutron-rich systems than for the neutron-deficient ones [**?**, **?**].

Figure 1: Calculated (solid lines) and measured [**?**] (symbols) charge distributions of products of the ^{78}Kr+^{40}Ca (lower panel) and ^{82}Kr+^{40}Ca (upper panel) reactions at E_{lab} = 5.5 MeV/nucleon. In order to demonstrate the sensitivity of the calculations to variations in J_{max}, the charge distributions at $J_{max} = 65$ in the ^{78}Kr+^{40}Ca reaction and at $J_{max} = 67$ in the ^{82}Kr+^{40}Ca reaction are also shown here (dotted lines).

The predictions of our model (see Fig. 1) for the cross sections σ_Z describing the formation of final reaction products of the ^{78}Kr + ^{40}Ca (lower panel) and ^{82}Kr + ^{40}Ca (upper panel) reactions at $E_{lab} = 5.5$ MeV/nucleon were confirmed in experiments performed at GANIL (France) [**?**]. A global shape of Z distribution featuring strong even-odd effects for $5 < Z < 10$ nuclei and a maximum at $Z \sim 28$ is reproduced fairly well for both reactions. The calculated product yields in the vicinity of the symmetric configuration are close to their experimental counterparts, but in the range of $Z = 18 - 24$, our model underestimates the cross sections by a factor of two to three. The reason behind this discrepancy may be that the presence of contributions from products of deep inelastic transfers is possible in the experimental cross sections for $J > J_{max}$. Even-odd effects are

present in cross sections for light fragments and become weaker as the N/Z ratio grows. The fact that the amplitudes of the calculated even-odd oscillations are substantially greater than their experimental counterparts stems from underestimating cross sections for odd Z nuclei such as N and F. The yields of the even nuclei of C and O agree well with experimental data. Since the pairing energy (excitation energy) of the light nucleus in DNS decreases (increases) as the mass number grows, even-odd effects decrease for large values of Z. Sequential light particle evaporation from primary decay product washes out even-odd effects for $Z > 10$ decay products. These primary fragments have an excitation energy between 10 and 30 MeV and a spin between 2 and 8. Comparing the calculated cross sections at $J_{max} = 65$ and 73 ($J_{max} = 67$ and 75) for the ^{78}Kr + ^{40}Ca (^{82}Kr + ^{40}Ca) reactions (Fig. 1), we arrive at the conclusion that the contributions of high partial waves to the yields of $Z < 10$ fragments are negligible. Indeed, with increasing angular momentum, the probability of finding the system in symmetric DNS configurations increases strongly and the symmetric splitting of the system becomes a main decay channel of the excited nuclear system.

Figure 2: Calculated (open squares) and measured (closed squares) isotopic distributions of Rn, Fr, and Ra nuclei formed via the emission of heavy clusters in the ^{36}S + $^{\rm nat}$Pt reaction at $E_{lab} = 5.96$ MeV/nucleon (right panels) and the ^{48}Ca +$^{\rm nat}$W reaction at $E_{lab} = 5.41$ MeV/nucleon (left panels).

In Ref. [**?**], on the basis of DNS model, we developed a new method for calculating cross sections of the formation of evaporation residues in nuclear reactions of complete fusion of massive nuclei. The possibility of calculating the cross section for the formation of specific evaporation residues, for example, neutron deficient heavy nuclei, with allowance for both channels of light particle evaporation and channels of heavy cluster emission is an advantage of this new method. We have showed for the first time, that at specific excitation energies of the compound nucleus, the cluster emission channel is dominant in the formation of $Z \leq Z_{CN} - 6$ evaporation residues from an excited compound nucleus of Pu ($Z_{CN} = 94$) [**?**]. In Fig. 2, the calculated isotopic distributions of $Z = 86$-88 residual nuclei formed through cluster emission channels in the ^{36}S + $^{\rm nat}$Pt $\rightarrow^{228,230,231,232,234}$Pu* and ^{48}Ca +$^{\rm nat}$W $\rightarrow^{228,230,231,232,234}$Pu* reactions are contrasted against respective distributions measured at the SHIP setup in GSI (Germany). The calculated and measured cross sections for the formation of Rn, Fr, and Ra residual nuclei in cluster-emission channels are in satisfactory agreement. For the radium residual nucleus, the measured isotopic distributions are qualitatively reproduced by our model for both reactions. The calculated cross sections are five times larger in the S + Pt than in the Ca + W reaction, since the cross sections for compound nucleus formation in these reactions are 51.2 and 10.9 mb, respectively. The main formation channels of these residual nuclei with $Z = 86$-88 are the emission of heavy clusters ^{12,14}C and ^{16,18}O with a few nucleons. It should be noted that, in our calculations, the contributions from different isotopes of the compound nucleus to cluster emission channels were evaluated with allowance for the isotopic composition of the natural materials of Pt and W targets. The more neutron deficient isotopes of Pt and W targets have larger contributions to the cross sections of residual nuclei which are formed through the cluster emission channels.
Good agreement between our theoretical predictions and experimental data confirms that collective degrees of freedom, such as the mass and charge asymmetries, play an important

role in reaction mechanism of complete fusion and quasifission processes. The approach that we developed makes it possible to find optimum experimental conditions (projectile-target combination and bombarding energy) to study processes involving the emission of heavy clusters.

[1] M. La Commara *et al.*, Nucl. Phys. A **669** (2000) 43.

[2] Sh.A. Kalandarov, G.G. Adamian, N.V. Antonenko, and W. Scheid, Phys. Rev. C **82** (2010) 044603.

[3] V.V. Volkov, Izv. AN SSSR, ser. fiz. **50** (1986) 1879; G.G. Adamian, A.K. Nasirov, N.V. Antonenko, and R.V. Jolos, Phys. Part. Nucl. **25** (1994) 583; G.G. Adamian, N.V. Antonenko, and W. Scheid, Nucl. Phys. A **618** (1997) 176.

[4] Sh. A. Kalandarov, G.G. Adamian, N.V. Antonenko, and W. Scheid, Phys. Rev. C **83** (2011) 054611.

[5] Sh. A. Kalandarov, G.G. Adamian, N.V. Antonenko, and W. Scheid, J. -P. Wieleczko, Phys. Rev. C **84** (2011) 064601.

[6] G. Ademard, *et al.*, Phys. Rev. C **83** (2011) 054619.

[7] Sh.A. Kalandarov, *et al.*, Phys. Rev. C **84** (2011) 054607.

NEW QUANTUM DIFFUSION APPROACH FOR FUSION AND CAPTURE PROCESSES

V. V. Sargsyan, G. G. Adamian, and N. V. Antonenko

A new approach, based on quantum diffusion equations of motion for the collective coordinates of colliding nuclei, is developed for the investigation of capture and fusion processes at near the Coulomb barrier and deep sub-barrier energies [1–3].In our model the collisions of nuclei are treated in terms of a single collective variable: the relative distance between the colliding nuclei. Our approach takes into consideration the fluctuation and dissipation effects in collisions of heavy ions which model the coupling with various channels. Also, the proposed formalism gives one possibility to take into consideration many quantum-mechanical and non-Markovian effects accompanying the passage through the potential barrier, which seems to be very important especially at deep sub-barrier energies.

For the verification of our approach we compare the calculated capture cross sections with experimental data for the spherical nuclei [**?**]. The choose of the target and projectile nuclei was dictated by neglect of other reaction channels such as neutron transfer or nuclear deformations effects. For the reactions ^{16}O+^{208}Pb and ^{48}Ca+^{208}Pb the calculated results reproduce the experimental data with a good agreement in large energy scale from about 15 MeV below the barrier and up to 30 MeV above the barrier.

However, the nuclear deformation and neutron-transfer process have been identified as playing a major role in the magnitude of the sub-barrier capture and fusion cross sections. If the target nucleus is prolate in the ground state, the Coulomb field on its tips is lower than on its sides, that then increases the capture or fusion probability at energies below the barrier corresponding to the spherical nuclei. In our model the nuclear deformation effects are taken into consideration through the dependence of the nucleus-nucleus potential on the deformations and orientations of colliding nuclei [3–8].

To separate the effects of deformation and neutron transfer, firstly we consider the reactions with deformed nuclei in which Q-value for the neutron transfer are small, i.e. the neutron transfers can be disregarded.

In Fig. 1 the calculated capture cross sections for the reactions ^{16}O,^{48}Ca+^{144,154}Sm are in a good agreement with the available experimental data showing that the quadrupole deformations of the interacting nuclei are the main reasons for the enhancement of the capture cross section at sub-barrier energies. Usually, the experimentally observed enhancement of sub-barrier fusion explained by the nucleon transfer and neck formation effects. However, we demonstrate that a good agreement with the experimental data at sub-barrier energies could be reached taking only the quadrupole deformations [**?**] of interacting nuclei into consideration. We should mention, that for the sub-barrier energies the results of calculations are very sensitive to the quadrupole deformation parameters β_2 of the interacting nuclei. Since there are uncertainties in the definition of the values of β_2 in the light- and the medium-mass nuclei, one can extract the quadrupole deformation parameters of these nuclei from the comparison of the calculated capture cross sections with the experimental data.

The role of neutron transfer reactions is less clear. In literature, it is usually discussed a correlation between the overall transfer strength and fusion enhancement. The importance of neutron transfer with positive Q-values on nuclear fusion (capture) originates from the fact that neutrons are insensitive to the Coulomb barrier and therefore they can start

Figure 1: The calculated capture cross sections versus $E_{\rm c.m.}$ for the indicated reactions ^{16}O,^{48}Ca + ^{154}Sm (solid lines), and ^{16}O + ^{144}Sm (dashed line). The experimental data are marked by symbols.

Figure 2: The same as in Fig. 1, but for the indicated reactions ^{40}Ca,^{32}S + ^{96}Zr (solid lines). The calculated capture cross sections without taking into consideration the neutron transfer process are shown by dotted lines. The experimental data are marked by symbols.

being transferred at larger separations before the projectile is captured by target-nucleus. Therefore, it is generally thought that the sub-barrier fusion cross section will increase because of the neutron transfer. The enhancements in fusion yields may be due to the transfer of a neutron pair with a positive Q-value.

However, the two-neutron transfer channel with large positive Q-value weakly influences the fusion (capture) cross section in the some reaction at sub-barrier energies. So, from the present data an unambiguous signature of the role of neutron transfer channel could not be inferred.

In our approach we assume that the sub-barrier capture mainly depends on the two-neutron transfer with the positive and relatively large Q-value. Our assumption is that, before the projectile is captured by target-nucleus (before the crossing of the Coulomb barrier) which is the slow process, the two-neutron transfer occurs at larger separations that can lead to the population of the first 2^+ state in the recipient nucleus [**?**, **?**].

Since after two-neutron transfer the mass numbers, the deformation parameters of interacting nuclei, and, respectively, the height and shape of the Coulomb barrier are changed, one can expect the enhancement or suppression of the capture. For example, after the neutron transfer in the reaction ^{40}Ca($\beta_2 = 0$) + ^{96}Zr($\beta_2 = 0.08$)$\rightarrow$^{42}Ca ($\beta_2 = 0.247$) + ^{94}Zr ($\beta_2 = 0.09$) the deformation of the nuclei increases and the mass asymmetry of the system decreases and thus the value of the Coulomb barrier decreases and the capture cross section becomes larger (Fig. 2(a)). One can see a good agreement between the calculated results and the experimental data.

One can find the reactions with large positive two-neutron transfer Q-values where the transfer weakly influences or even suppresses the capture process. This happens if after transfer the deformations of nuclei almost do not change or even decrease. For instance, in the reaction ^{32}S($\beta_2 = 0.312$) + ^{96}Zr($\beta_2 = 0.08$)$\rightarrow$^{34}S($\beta_2 = 0.252$) + ^{94}Zr($\beta_2 = 0.09$) one can expect weak dependence of the capture cross section on the neutron transfer (Fig. 2(b)).

The choice of the projectile-target combination is crucial in the understanding of pair tunneling phenomena in the capture process. In the capture reactions with $Q_{1n} < 0$ and $Q_{2n} > 0$, the two-step sequential transfer is almost closed before capture. So, by properly choosing the reaction combination, one can reduce the role successive transfer plays in the process. For the systems studied one can make unambiguous statements regarding the neutron transfer process with a positive Q_{2n} value when the interacting nuclei are double magic or semimagic nuclei. In this case one can disregard the strong nuclear deformation effects before the neutron transfer. In Fig. 3 the calculated capture cross sections for the reactions ^{40}Ca + ^{48}Ca ($Q_{1n} = -1.6$ MeV, $Q_{2n} = 2.6$ MeV), ^{40}Ca + ^{116}Sn ($Q_{1n} = -1.2$ MeV, $Q_{2n} = 2.8$ MeV), and ^{40}Ca + ^{124}Sn ($Q_{1n} = -0.1$ MeV, $Q_{2n} = 5.4$ MeV) are in a good agreement with the available experimental data.

In these reactions $1n$-neutron transfer process are closed ($Q_{1n} < 0$) and Q_{2n}-values for

the $2n$-transfer processes are positive. Thus, the $2n$-neutron transfer has to be taken into account for good description of the experimental data. The influence of the $2n$-neutron transfer on the capture cross section occurs due to the change of the isotopic composition and the deformations of the reaction partners. The $2n$-transfer indirectly influence the quadrupole deformation of the nuclei. When after the neutron transfer (just before the crossing of the Coulomb barrier) in the reactions ^{40}Ca($\beta_2 = 0$) + ^{48}Ca($\beta_2 = 0$)$\rightarrow$^{42}Ca ($\beta_2 = 0.247$) + ^{46}Ca($\beta_2 = 0$), ^{40}Ca($\beta_2 = 0$) + ^{116}Sn($\beta_2 = 0.112$)$\rightarrow$^{42}Ca($\beta_2 = 0.247$) + ^{114}Sn($\beta_2 = 0.121$), and ^{40}Ca($\beta_2 = 0$) + ^{124}Sn($\beta_2 = 0.095$)$\rightarrow$^{42}Ca ($\beta_2 = 0.247$) + ^{122}Sn($\beta_2 = 0.104$) the deformations of nuclei increase, the values of the corresponding Coulomb barriers decrease. As a result, the neutron transfer enhances the capture process in these reactions at the sub-barrier energies. The enhancement becomes stronger with decreasing bombarding energy (Fig. 3).

Figure 3: The same as in Fig. 1, but the indicated reactions ^{40}Ca+^{48}Ca,^{116,124}Sn (solid lines). The calculated capture cross sections without taking into consideration the neutron transfer process are shown by dotted lines. The experimental data are marked by symbols.

Figure 4: The dependence of the extracted breakup probability P_{BU} vs $E_{c.m.} - V_b$ for the indicated reactions with ^{9}Be-projectiles in %.

Since $Q_{1n} < 0$ in these reactions, the enhancement arises not from the coherent successive transfer of two single nucleons, but from the direct transfer of one spatially correlated pair (the simultaneous transfer of two nucleons). Neutron pair transfer indicates that stable nucleus at low densities around nuclear surface may exhibit features of the strong coupling pairing, characterized by the small size of the Cooper pair comparable with average internucleon distance. This may suggest a possible enhancement of the pair correlation in the surface of nuclei ^{48}Ca and ^{116,124}Sn. Our results show that the capture (fusion) cross section of the reactions under consideration can be described by assuming the preformed dineutron-like clusters in the ground state of these nuclei. Note that the spatial two-neutron correlation and the strong surface enhancement of the neutron pairing in the cases of a slab and a semi-infinite nuclear matter are well known and it is well established that nuclear superfluidity is mainly a surface effect.

Using the quantum diffusion approach, we try to reveal a systematic behavior of the complete fusion suppression as a function of the target charge Z_T and colliding energy $E_{\rm c.m.}$ and by comparing the calculated capture cross sections in the absence of breakup with the experimental complete fusion cross sections [**?**]. Note that the effects of deformation and neutron transfer on the complete fusion suppression are taken into consideration as well.

The difference between the capture cross section and the complete fusion cross section can be ascribed to the breakup effect. Comparing σ_c^{th} and σ_{fus}^{exp}, one can estimate the breakup probability $P_{\rm BU} = 1 - \sigma_{fus}^{exp}/\sigma_c^{th}$. If at some energy $\sigma_{fus}^{exp} > \sigma_c^{th}$, the values of σ_c^{th} was normalized so to have $P_{\rm BU} \geq 0$ at any energy.

As seen in Fig. 4, at energies above the Coulomb barriers the values of $P_{\rm BU}$ vary from 10 to 60%. In the reactions ^{9}Be+^{144}Sm,^{208}Pb,^{209}Bi the value of $P_{\rm BU}$ increases with charge number of the target at $E_{\rm c.m.} - V_b > 3$ MeV. However, the reactions ^{9}Be+^{89}Y,^{124}Sn are out of this systematics. In the reactions ^{9}Be+^{89}Y,^{144}Sm,^{208}Pb,^{209}Bi the value of $P_{\rm BU}$ has a minimum at $E_{\rm c.m.} - V_b \approx 0$ and a maximum at $E_{\rm c.m.} - V_b \approx -(1-3)$ MeV, in the ^{9}Be+^{124}Sn

reaction the value of $P_{\rm BU}$ steady decreases with energy. The possible explanation of it is that there are probably some problems with the data analysis. Note that our conclusions coincide with others, where the universal fusion function formalism was applied for the analysis of experimental data.

It could be also that at energies near the Coulomb barrier the characteristic time of the breakup is larger than the characteristic time of the capture process and influences the complete fusion.

In conclusion, the quantum diffusion approach [1–5,7,8] was applied to study the capture process in the reactions with deformed and spherical nuclei at sub-barrier energies. The available experimental data at energies above and below the Coulomb barrier are well described. As shown, the experimentally observed sub-barrier fusion enhancement is mainly related to the quadrupole deformation of the colliding nuclei and neutron transfer with the positive Q-value. The change of the magnitude of the capture cross section after the neutron transfer occurs due to the change of the deformations of nuclei. When after the neutron transfer the deformations of nuclei do not change or decrease, the neutron transfer weakly influences or suppresses the capture process. It would be interesting to study such type of reactions.

As shown within the quantum diffusion [1–5,7,8] approach due to a change of the regime of interaction (the external turning point leaves the region of the nuclear forces and friction) at deep sub-barrier energies, the curve related to the capture cross section as a function of bombarding energy has smaller slope. Although there are some experimental indications of this effect the error-bars are still large and more efforts are required to verify the change of slope in the capture excitation function.

The importance of quasifission near the entrance channel was noticed for the reactions with medium-mass nuclei at extreme sub-barrier energies [**?**]. The quasifission can explain the difference between the capture and fusion cross sections [**?**]. One can try to check experimentally these predictions.

Analyzing the extracted breakup probabilities, we showed that there are no systematic trends of breakup in the reactions studied [**?**]. Moreover, for some system with larger (smaller) Z_T we found the contribution of breakup to be smaller (larger). Almost for all reactions considered we obtained a satisfactory agreement between calculated capture cross section and experimental fusion data, if the calculated capture cross section or the experimental fusion data are renormalized by some average factor which does not depend on the bombarding energy. As shown, one no needs to measure directly the breakup process in different systems, especially light ones, to understand the role of the breakup in the capture (complete fusion) process. Employing the experimental quasielastic backscattering data with weakly and toughly bound isotopes of light nucleus and analytical formula suggested by us [**?**], the dependence of breakup probability on $E_{\rm c.m.}$ can be extracted for the systems suggested. Analyzing the extracted breakup probabilities, one can indirectly study the trends of breakup in the different reactions at energies near and below Coulomb barrier.

[1] V.V. Sargsyan, *et al.*, Eur. Phys. J. A **45** (2010) 125.

[2] V.V. Sargsyan, *et al.*, Eur. Phys. J. A **47** (2011) 38.

[3] V.V. Sargsyan, *et al.*, Phys. Rev. C **84** (2011) 064614.

[4] V.V. Sargsyan, *et al.*, Phys. Rev. C **85** (2012) 037602.

[5] V.V. Sargsyan, *et al.*, Phys. Rev. C **85** (2012) 017603.

[6] V.V. Sargsyan, *et al.*, Phys. Rev. C **86** (2012) 034614.

[7] V.V. Sargsyan, *et al.*, Phys. Rev. C **86** (2012) 014602.

[8] V.V. Sargsyan, *et al.*, Phys. Rev. C **85** (2012) 024616.

[9] S. Raman, *et al.*, At. Data Nucl. Data Tables **78** (2001) 1.

[10] V.V. Sargsyan, *et al.*, Phys. Rev. C **86** (2012) 054610.

[11] V.V. Sargsyan, *et al.*, Eur. Phys. J. A **48** (2012) 188.

EFFECTS OF THE ENTRANCE CHANNEL AND FISSION BARRIER IN SYNTHESIS OF SUPERHEAVY ELEMENTS

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The cross section of the evaporation residue (ER) formation being a superheavy element $Z > 112$ is very small: some picobarns, or even the part of picobarn. To find favorable reactions (projectile and target pair) and the optimal beam energy range leading to larger cross sections of synthesis of superheavy elements, we should establish conditions leading to increase as much as possible the events of ER formation.

1. Advantage of hot fusion reactions with massive nuclei

The advantage of hot fusion reactions in comparison with cold fusion reactions is due to the relatively small hindrance in the compound nucleus (CN) formation. The hot fusion of colliding nuclei takes place in reactions with large charge asymmetry in the entrance channel (a projectile is ^{48}Ca, ^{50}Ti or lighter one), consequently, the intrinsic fusion barrier $B^*_{\rm fus}$ of the corresponding dinuclear system (DNS) is smaller in comparison with the one for cold fusion reactions [**?**, **?**]. As a result fusion probabilities calculated for the set of cold fusion reactions are much smaller than ones for the hot fusion reactions (see Table **??**). The large excitation energy of CN is an inevitable circumstance in the hot fusion reactions connected with the capture dynamics (formation of the DNS) and the reaction energy balance. As a result the ER formation in hot fusion reactions has a small cross section due to the small survival probability of CN against fission ($W_{\rm surv} \approx 10^{-8}$). Nevertheless, the superheavy elements $Z \geq 114$ were synthesized in hot reactions only.

Table 1: Comparison of the fusion probabilities ($P_{\rm CN}$) for the cold (left side) and hot (right side) fusion reactions calculated in the dinuclear system model [1–3].

Cold fusion reactions	$Z_{\rm CN}$	$P_{\rm CN} \cdot 10^{-8}$	Hot fusion reactions	$Z_{\rm CN}$	$P_{\rm CN} \cdot 10^{-2}$
^{64}Ni+^{208}Pb*	110	14.0	^{48}Ca+^{243}Am†	115	5.02
^{64}Ni+^{209}Bi*	111	7.0	^{48}Ca+^{248}Cm†	116	1.13
^{70}Zn+^{208}Pb*	112	0.25	^{48}Ca+^{249}Bk‡	117	2.06
^{70}Zn+^{209}Bi*	113	0.052	^{50}Ti+^{249}Cf‡	120	0.112
^{76}Ge+^{208}Pb*	114	0.012	^{54}Cr+^{248}Cm‡	120	0.0231

*The estimations made from the results of Ref. [**?**].
†The estimations made from the results of Ref. [**?**].
‡The estimation of our work [**?**].

Table 2: Comparison of the predicted maximum values of the evaporation residues cross section ($\sigma_{\rm ER}$) in the ^{54}Cr+^{248}Cm and ^{50}Ti+^{249}Cf reactions obtained in Refs.[**?**, **?**, **?**] with our results for the 3 and 4 neutrons emission channels as a function of the collision energy in the center-of-mass system $E_{\rm c.m.}$. The presented data about maximum values from Refs.[**?**, **?**, **?**] were extracted from the figures of the ER excitation functions.

^{50}Ti+^{249}Cf				^{54}Cr+^{248}Cm				Reference
$E_{\rm c.m.}$	$\sigma_{\rm ER}^{(3n)}$	$E_{\rm c.m.}$	$\sigma_{\rm ER}^{(4n)}$	$E_{\rm c.m.}$	$\sigma_{\rm ER}^{(3n)}$	$E_{\rm c.m.}$	$\sigma_{\rm ER}^{(4n)}$	
MeV	fb	MeV	fb	MeV	fb	MeV	fb	
227.5	760.0	239.0	28.0	241.5	76.0	252.0	12.0	[**?**]†
225.0	100.0	231.5	2.5	237.2	55.0	241.0	13.0	[**?**]*
231.5	60.0	232.5	40.0	-	-	-	-	[**?**]*
236.0	40.0	241.0	46.0	246.7	14.0	249.6	28.0	[**?**]*
236.0	1.5	-	-	248.2	0.2	-	-	[**?**]*

†The corresponding authors used data from the mass table [**?**].
*The corresponding authors used data from the mass table [**?**].

In Table **??**, the predictions of the maximum values of the evaporation residue excitation functions for the 3n- and 4n-channel by different models (see [6–9]) are presented. The results presented in Refs. [**?**, **?**, **?**] were obtained with the theoretical binding energies from the mass table by P. Möller *et al.* [**?**], while the authors of Ref. [**?**] have used the mass data calculated by I. Muntian *et al.* [**?**].

2. Investigation on the ^{48}Ca+$^{249-250}$Cf reactions synthesizing isotopes of the superheavy element 118 by different masses and barriers of compound nuclei

In Fig. **??** we display [**?**] the ER cross sections for the ^{48}Ca+^{249}Cf reaction after emission of 2, 3, 4, and 5 neutrons from the ^{297}118 CN as a function of the $E^*_{\rm CN}$ excitation energy. The calculated ER cross sections were obtained by using the mass and fission barrier values given in Refs. [**?**, **?**] of the Warsaw group. In this figure we present the data obtained in the ^{48}Ca+^{249}Cf experiment reported in Ref. [**?**] regarding the synthesis of the ^{294}118 superheavy nucleus obtained after 3 neutron emission from the ^{297}118 CN, at two projectile energies corresponding to the CN excitation energies of $E^* = 29.2$ and 34.4 MeV. The calculated values of the ER cross sections at $E^*_{\rm CN}$=29.2 and 34.4 MeV are close to the experimental data barely within the error bars. For this reason we decided to continue analysis with the aim to clarify the cause of difference between our results and experimental data (see forward Fig. **??**).
In Fig. **??** we compare theoretical ER cross sections for the ^{48}Ca+^{250}Cf reaction leading to the ^{298}118 CN which were calculated with the masses of Ref. [**?**] and the fission barriers of Ref. [**?**] given by Möller *et. al* (thin lines) and by using the masses [**?**] and fission barriers of the Warsaw group [**?**] (thick lines). The experimental data for the ^{48}Ca+^{249}Cf reaction obtained in Ref. [**?**] are shown in Fig. **??** by full squares. As the figure shows, the excitation function of the 3n evaporation channel is in good agreement with the second experimental point only, but in general the excitation functions of evaporation residue

Figure 1: Comparison of the evaporation residue excitation functions after emission of 2 (dashed line), 3 (full line), 4 (dash-dotted line), and 5 (dash-double dotted line) neutrons from the ^{297}118 CN in the ^{48}Ca+^{249}Cf reaction. Thick lines present results calculated by using the masses and fission barrier values of Refs. [**?**, **?**] while thin lines are results of calculation by using those values of Refs. [**?**, **?**]. The experimental data (full squares) of the ^{294}118 ER formation cross section obtained from Ref. [**?**].

Figure 2: The similar comparison but for the emission neutrons from ^{298}118 CN which is formed in the ^{48}Ca+^{250}Cf reaction.

nuclei are higher than the results obtained with the masses from [**?**] and fission barriers of the Warsaw group [**?**].

In the experimental identification of the ER nucleus by the α-decay chain assures only the ^{294}118 formation but the predecessor de-excitation cascade–3 neutrons emission from the ^{297}118 CN or 4 neutrons emission from the ^{298}118 CN can not be distinguished. The problem is that the presence of the ^{250}Cf isotope in the used target in addition to the ^{249}Cf isotope is inevitable and, therefore, it is necessary to take into account the ^{294}118 contributions caused by the both ^{48}Ca+^{249}Cf and ^{48}Ca+^{250}Cf reactions.

In Fig. **??** we show the excitation functions of the 3n evaporation channel in the reaction with the ^{249}Cf isotope and 4n evaporation channel in the reaction with ^{250}Cf isotope, as well as the experimental data from Ref. [**?**]. In this figure we add the weighed two excitation functions of the same evaporation residue nucleus ^{294}118 reached by both ^{48}Ca+^{249,250}Cf reactions after 3 and 4 neutron emission, respectively (see Figs. **??** and **??**), represented by the dotted line in Fig. **??**. As one can see, this averaged excitation function of the ^{294}118 formation is in complete agreement with the data of Ref. [**?**].

Figure 3: Contributions of the ^{294}118 evaporation residue nucleus synthesized by the ^{48}Ca+^{249}Cf (full line) and ^{48}Ca+^{250}Cf (dash-dotted line) reactions. The dotted line represents the weighed average sum of the two mentioned contributions.

3. Conclusions

In the framework of the combined DNS and advanced statistical models, the ER excitation functions have been calculated for the ^{48}Ca+^{249}Bk reaction and the results are compared with the experimental data given in Ref. [**?**]. The ER cross section of the 4n-channel is well described while the 3n-channel is described in a satisfactory way, in both cases of the used Möller and Nix [**?**] and Muntian *et al.* [**?**] mass tables.

The capture, complete fusion and evaporation residue excitation functions of the ^{50}Ti+ ^{252}Cf and ^{54}Cr+^{248}Cm reactions, which could lead to the synthesis of the superheavy element $Z = 120$, have been calculated. The comparison of the results show that at low $E_{\rm c.m.}$ energies the capture cross sections of the ^{54}Cr+^{248}Cm reaction are larger than the ones of the ^{50}Ti+^{249}Cf reaction, while these cross sections become comparable at higher energies corresponding to the 3n- and 4n-channel formations. The fusion cross section for the ^{50}Ti+^{249}Cf reaction is significantly larger than that for the ^{54}Cr+^{248}Cm

reaction, though the former system has a smaller number of neutrons than the latter one. The stronger hindrance to complete fusion in the case of the ^{54}Cr+^{248}Cm reaction is connected with the larger intrinsic fusion barrier $B^*_{\rm fus}$ and smaller quasifission barrier $B_{\rm qf}$ than in the case of the ^{50}Ti+^{249}Cf reaction. In any case, it appears in the present study–when the Möller-Nix mass table is used–the maximum values of the excitation function corresponding to the 3n-channel of the evaporation residue formation for the ^{50}Ti+^{249}Cf and ^{54}Cr+^{248}Cm reactions are not higher than 0.1 and 0.07 pb, respectively, while the maximum yield of residue for the 4n-channel (0.01 pb) for the reaction induced by ^{54}Cr is higher than the one (0.004 pb) found for the reaction induced by ^{50}Ti.
By comparing the results of our analysis regarding the study of the ^{48}Ca+^{249,250}Cf reactions with the data obtained in the experiment of Ref. [**?**] regarding the observation of the ^{294}118 evaporation residue nucleus, we conclude that the better description of the experimental results is that the observed ^{294}118 synthesis events [**?**] registered at two different beam energies are contributed by the the 3n-channel in the ^{48}Ca+^{249}Cf reaction and 4n-channel in the ^{48}Ca+^{250}Cf reaction, due to the inevitable presence of the ^{250}Cf isotope in the ^{249}Cf enriched target. Moreover, the comparison of results obtained for the ER nuclei in the investigation of the ^{48}Ca+^{252}Cf reaction suggest to use one target only constituted of all the Cf isotopes of more long lifetimes. It is more convenient the procedure for its preparation, and in one experiment only it is possible to observe and study a wide set of ER nuclei formed by 2n, 3n, 4n, and 5n emission channels, only changing the ^{48}Ca beam energy in the about $E_{\rm lab} = 235 - 260$ MeV range.

[1] G. Giardina, *et al.*, Eur. Phys. J. A **8** (200) 205.

[2] A. K. Nasirov,*et al.*, Phys.Rev. C **79** (2009) 024606.

[3] A.K. Nasirov, *et al.*, Nucl. Phys. A **759** (2005) 342.

[4] G. Fazio, *et al.*, Eur. Phys. J. A **19** (2004) 89.

[5] A.K. Nasirov, *et al.*, Phys. Rev. C **84** (2011) 044612.

[6] K. Siwek-Wilczyńska, T. Cap, J. Wilzcyński, Int. J. Mod. Phys. E**19** (2010) 500.

[7] Z. H. Liu and Jing-Dong Bao, Phys. Rev. C **80** (2009) 054608.

[8] Valery Zagrebaev and Walter Greiner, Phys. Rev. C **78** (2008) 034610.

[9] G.G. Adamian N.V. Antonenko, and W. Scheid, Eur. Phys. J. A **41** (2009) 235.

[10] P. Möller and J.R. Nix, J. Phys. G: Nucl. Part. Phys. **20** (1994) 1681.

[11] I. Muntian, Z. Patyk, and A. Sobiczewski, Phys. At. Nucl. **66** (2003) 1015.

[12] G. Mandaglio, G. Giardina, A. K. Nasirov and A. Sobiczewski, Phys. Rev. C **86** (2012) 064607.

[13] M. Kowal and A. Sobiczewski, Int. J. Mod. Phys. E **18** (2009) 914.

[14] Yu. Ts. Oganessian *et al.*, Phys. Rev. C **74** (2006) 044602.

[15] P. Möller, *et al.*, Phys. Rev C **79** (2009) 064304.

[16] Yu. Ts. Oganessian, *et al.*, Phys. Rev. Lett. **104** (2010) 142502.

MASS DISTRIBUTIONS FOR INDUCED FISSION OF DIFFERENT MERCURY ISOTOPES

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The asymmetric shape of the mass distribution is well known for low-energy fission of most actinide isotopes, it was theoretically explained by taking into account the shell structure of the fragments. Based on the most of experimental data, one could conclude that the asymmetric shape of mass distribution in low-energy fission changes to symmetric one with decreasing mass number of the fissioning nucleus. It was unexpected that in the recent experiment [**?**] on β-delayed fission of ^{180}Tl the shape of the mass distribution was found to be clearly asymmetric. In the present study we describe this interesting result within the improved scission-point model [**?**].

The fissioning nucleus at the scission point is modeled by the two nearly touching coaxial spheroids — fragments of a dinuclear system with the masses (charges) A_L (Z_L) and A_H (Z_H), the distance between the centers of the fragments is R and the parameters of deformation of the fragments β_L and β_H defined as the ratios of the major and minor semi-axes.

Figure 1: Calculated (solid line) mass distribution of fission fragments in comparison with the experimental data [**?**] (points) for induced fission of ^{198}Hg in the reaction ^{197}Au(p,f) at $E_p = 22.4$ MeV (a) and in the reaction ^{194}Pt(α,f) at $E_\alpha = 50.4$ MeV (b).

The potential energy of the system U is the sum of the liquid drop energies of each fragment, the energy of interaction of the fragments, the rotational energy, the energy of zero-point vibrations, and the shell correction terms of each fragment. The shell corrections are calculated with the Strutinsky method and two-center shell model [**?**], the damping of the shell corrections with excitation energy and angular momentum is introduced in our model. The interaction energy consists of the Coulomb interaction of two uniformly charged spheroids and nuclear interaction in the form of a double folding of nuclear densities and density-dependent Skyrme-type nucleon-nucleon forces [**?**]. For β-delayed and induced fission, we use zero and non-zero angular momenta l, respectively (see below). We related the energy $U^{zpv} = E_i^{2^+} \coth[E_i^{2^+}/T(l)]$ of zero-point vibrations with the energies $E_i^{2^+}$ of the first 2^+ excited states of the fragments from Ref. [**?**]. For calculation of the potential energy we take the value of interfragment distance $R = R_m$ corresponding to the calculated minimum of the interaction potential which is at the distance between the tips of the spheroids of about 0.5–1 fm.

The excitation energy $E^*(l)$ of the nuclear system at scission is calculated as a difference between the potential energy of the compound nucleus (fissioning nucleus) and the potential energy of dinuclear system at the scission point plus the initial excitation energy of the compound nucleus. The temperature is calculated as $T(l) = \sqrt{E^*(l)/a}$, where $a = A/12$ is the level density parameter in the Fermi-gas model. The yield of a particular scission configuration with given mass and charge numbers and deformation parameters of the fragments is proportional to the exponential Boltzmann-factor:

$$Y(A_i, Z_i, \beta_i, l) \sim \exp\left\{-\frac{U(A_i, Z_i, \beta_i, l)}{T(l)}\right\}. \quad (1)$$

To obtain the relative mass distribution as a function of the mass number of one of the fragments, one should integrate the yields of different binary systems over their parameters.

Figure 2: Calculated mass distribution of fission fragments for β-delayed fission of ^{180}Tl (fissioning nucleus is ^{180}Hg).

We performed the calculations of mass distributions for isotopes of Hg with the mass numbers $A = 180$, 184, 188, 192, 196, and 198. We calculated the mass distribution for the reactions ^{197}Au(p,f) at the energy of the proton of 22.4 MeV and ^{194}Pt(α,f) at the energy of the alpha-particle of 50.4 MeV [the fissioning compound nucleus is ^{198}Hg with $E^*_{CN}(l = 0) = 29.4$ MeV and $E^*_{CN}(l = 0) = 49.0$ MeV, respectively]. Figure **??** shows a comparison of our calculations with the experimental data [**?**]. The calculated and experimental distributions have a similar shape with a dip at the top for the reaction ^{197}Au(p,f), the maxima almost coincide, but the calculated distribution is slightly narrower than the experimental one. For the reaction ^{194}Pt(α,f) this dip almost disappears due to larger excitation energy that is in agreement with the experimental data.
For β-delayed fission of ^{180}Tl [**?**], the excitation energy $E^*_{CN}(l = 0)$ of the fissioning nucleus ^{180}Hg does not exceed 10.44 MeV. The mass distribution of fission fragments is presented in Fig. **??**. We obtained clearly asymmetric mass distribution with the average masses of the light and heavy fragments about 80 and 100, respectively, that is in agreement with the experimental data. The calculated $\overline{TKE} = 136$ MeV is also in good agreement with the experiment.

Figure 3: Calculated mass distributions of fission fragments for induced fission of ^{180,184,188,192,196}Hg with the impact energies of 10 MeV (solid lines, $E^*_{CN}(l = 0)$=44.2, 43.9, 49.7, 62.4, 56.0 MeV for ^{180,184,188,192,196}Hg, respectively) and 30 MeV (dashed lines, $E^*_{CN}(l = 0)$=64.2, 63.9, 69.7, 82.4, 76.0 MeV for ^{180,184,188,192,196}Hg, respectively) above the corresponding Coulomb barriers for the spherical nuclei.

Figure **??** shows a change in the shape of the mass distribution from asymmetric to more symmetric with increasing mass number A of the fissioning nucleus ^{A}Hg. While the mass distribution is well asymmetric for ^{180}Hg and ^{184}Hg, for ^{188}Hg the asymmetry is less pronounced, and for ^{192}Hg and ^{196}Hg the mass distribution looks more symmetric but with a dip on the top similar to that observed experimentally in the fission of ^{198}Hg [**?**] (Fig. **??**). To study the fission properties of all considered isotopes ^{180}Hg, ^{184}Hg, ^{188}Hg, ^{192}Hg, and ^{196}Hg (Fig. **??**), we propose the induced fission reactions at bombarding energies 10 MeV and 30 MeV above the corresponding Coulomb barriers V_b for the spherical nuclei: ^{36}Ar+^{144}Sm$\rightarrow^{180}$Hg (V_b=126.2 MeV, l_{max}=44 and 61); ^{40}Ar+^{144}Sm$\rightarrow^{184}$Hg (V_b=124.55 MeV, l_{max}=46 and 71); ^{40}Ar+^{148}Sm$\rightarrow^{188}$Hg (V_b=123.9 MeV, l_{max}=46 and 66); ^{32}S+^{160}Gd$\rightarrow^{192}$Hg (V_b=114.4 MeV, l_{max}=42 and 63); ^{36}S+^{160}Gd$\rightarrow^{196}$Hg (V_b=112.8 MeV, l_{max}=45 and 70).
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[1] A.N. Andreyev, *et al.*, Phys. Rev. Lett. **105** (2010) 252502.

[2] A.V. Andreev, G.G. Adamian, and N.V. Antonenko, Phys. Rev. C. **86** (2012) 044315.

[3] J. Maruhn and W. Greiner, Z. Physik **251** (1972) 431.

[4] G.G. Adamian, *et al.*, Int. J. Mod. Phys. E **5** (1996) 191.

[5] S. Raman *et al.*, At. Data Nucl. Data Tables **78** (2001) 1.

[6] M.G. Itkis, *et al.*, Sov. J. Nucl. Phys. **52** (1990) 601; **53** (1991) 757.

NEW METHOD FOR SOLUTION OF COUPLED RADIAL SCHRÖDINGER EQUATIONS: APPLICATION TO THE BORROMEAN TWO-NEUTRON HALO NUCLEUS ^{22}C

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1. Introduction

The Schrödinger equation of quantum mechanical systems is often converted into systems of coupled radial equations, with applications in nuclear physics, quantum chemistry etc. A variety of solution methods has been developed. A widespread approach consists of two steps. First, sets of linear independent solutions are calculated and then, exploiting the linearity of the coupled equations, a suitable combination of different sets with the required boundary conditions is found. A major problem in numerical solution of the coupled equations is the difficulty of maintaining the linear independence of the solution vectors. Troubles come from existence of radial regions where some components of the wave function are classically forbidden and others not. The components with negative radial kinetic energy will in general have an exponentially growing and an exponentially decreasing part. If the integration is continued through a classically forbidden region, the exponentially growing components of the wave function increase faster in the most strongly closed channels and soon start to dominate the entire wave function matrix. The small components become insignificant on the scale of the relative accuracy of the calculation. Eventually different solutions become linearly dependent and, thus, useless for finding linear combinations with required boundary conditions. In the classically allowed region, an uneven growth of the components does not occur, since the components are mainly oscillating. But all problems involve an integration through at least one classically forbidden region, and an instability from growth of nearly dependent solutions causes a serious numerical inaccuracy. This difficulty arises from the natural properties of solutions rather then from any particular method for their construction.
Recently, we developed [**?**] a novel method for solution of coupled radial Schrödinger equations, consisting of two steps. First, the full radial interval is split into finite intervals, and then the radial equations are rearranged on each interval in a way that is tailored to avoid numerical instabilities associated with components of a wave function in their classically forbidden regions. Finally, global solutions are constructed from local ones. Now [**?**] the same idea on rearrangement of coupled equations is applied to the *variable phase method* for solutions of Schrödinger equations. The modified method is, however, simpler and numerically more effective than that previously developed in [**?**]. Applications of the modified variable phase method to nuclear structure calculations within the hyperspherical harmonics approach, are given [**?**] for loosely bound halo nuclei ^{22}C.

2. Theory

The system of N coupled radial Schrödinger equations may be written as

$$\left(\frac{d^2}{dr^2} + \frac{2mE}{\hbar^2} - \frac{\mathcal{L}_i(\mathcal{L}_i+1)}{r^2}\right)\psi_{in}(r) = \sum_{j=1}^{N} V_{ij}(r)\,\psi_{jn}(r) \qquad (1)$$

where E is a total energy and $\mathcal{L}_i$ is the orbital angular momentum in channel i. The first index of $\psi_{in}(r)$ denotes the ith component of a wave function ($i = 1, \ldots, N$) while the second index n marks different linear independent solutions. The $N \times N$ matrix of coupling potentials $V_{ij}(r)$ is assumed symmetric, i. e. $V_{ij}(r) = V_{ji}(r)$. Note that the potentials include the factor $2m/\hbar^2$ and have the dimension fm^{-2}. Only solutions that satisfy definite boundary conditions imposed at the origin and at the infinity, have physical meaning.

The general method to solve the boundary value problem for coupled equations (**??**) is to construct a set of linear independent solutions and then find a linear combination of these solutions which satisfies the required asymptotic behaviour. To find a set of solutions we will apply the *variable phase method* that requires the knowledge of solutions for some simplified system. To this end two linear independent solutions $f_i(x)$ and $g_i(x)$ of the free Schrödinger equation are selected

$$\left(\frac{d^2}{dx^2} \pm 1 - \frac{\mathcal{L}_i(\mathcal{L}_i+1)}{x^2}\right)\begin{pmatrix} f_i(x) \\ g_i(x)\end{pmatrix} = 0 \tag{2}$$

where $x = kr$. The different signs before 1 in (**??**) correspond to positive or negative energy E. Free solutions are normalized by demanding the Wronskian $W(f_i, g_i) = f_i(x)\, g_i'(x)$ - $f_i'(x)\, g_i(x)$ = -1. Functions $f_i(k\,r)$ and, $g_i(k\,r)$ have the regular and irregular behaviour at the origin, respectively.

In the variable phase method the regular and irregular solutions of the free Schrödinger equation take centrifugal barriers explicitly into account. As a result, centrifugal barriers drop out from the final system of the first order differential equations, and their influence appears only via free solutions that can however differ in magnitude by many orders. Thus, the system of coupled equations contains terms that are very different in absolute values and numerical instabilities may develop when the solution accuracy falls short. The modification of the variable phase method suggested in [**?**] tries to remedy this. The modification consists of a rearrangement of equations into a set which includes only logarithmic derivatives of free solutions. Since variations of the magnitude of logarithmic derivatives are essentially smaller, compared to the absolute value variation of free solutions, conditions for developing numerical instabilities are strongly suppressed. Thus, instead of the original set of equations (**??**), the following system obtained in [**?**] within the variable phase method has to be solved

$$U_{in}'(r) = k\,\delta_{in} + k\left(\frac{g_i'(k\,r)}{g_i(k\,r)} + \frac{g_n'(k\,r)}{g_n(k\,r)}\right) U_{in}(r) - \sum_{j,m=1}^{N} U_{ij}(r)\,\frac{1}{k} V_{jm}(r)\, U_{mn}(r)) \tag{3}$$

$$\alpha_{in}'(r) = -k\,\frac{g_i'(k\,r)}{g_i(k\,r)}\,\alpha_{in}(r) + \frac{1}{k}\sum_{j,m=1}^{N} V_{ij}(r)\, U_{jm}(r)\,\alpha_{mn}(r) \tag{4}$$

The wave function $\psi_{in}(r)$ and its derivative $\psi_{in}'(r)$ are related to the matrices (denoted by bold letters) $\boldsymbol{U}(r)$ and $\boldsymbol{\alpha}(r)$ in the following way

$$\psi_{in}(r) = \sum_{j=1}^{N} U_{ij}(r)\,\alpha_{jn}(r) \tag{5}$$

$$\psi_{in}'(r) = k\left(\alpha_{in}(r) + \frac{g_i'(k\,r)}{g_i(k\,r)}\sum_{j=1}^{N} U_{ij}(r)\,\alpha_{jn}(r)\right) \tag{6}$$

The boundary conditions for the functions $U_{ij}(r)$ and $\alpha_{jn}(r)$ are given in [**?**]. The coupled equations (**??**)-(**??**) do not contain centrifugal barriers, their influence on dynamics has been taken into account analytically via the logarithmic derivatives of free solutions (**??**). Such a rearrangement minimizes the difference of absolute values for free solutions and leads to significantly weaker demands for numerical accuracy enhancing the stability of numerical integrations.

3. Applications

As an example of current interest we consider the heaviest known Borromean two-neutron halo nucleus ^{22}C. Note again that the experimental value of the two-neutron separation energy S_{2n} is not yet known. Within the (^{20}C + n + n) three-body cluster model we have explored the sensitivity of the ^{22}C geometry to the two-neutron separation energy using the hyperspherical harmonic method.

Within a cluster three-body (^{20}C + n + n) model the bound state properties of ^{22}C are defined by the intercluster potentials. The main problem in selecting binary potentials between the constituents, is the absence of experimental information about the neutron-core system, beyond the fact that a bound state of ^{21}C does not exist. Within the shell-model picture this implies that the $1s_{1/2}$ orbit is unbound. In the single available realistic three-body calculation of the ^{22}C nuclear structure [**?**], deep potentials that also support extra orbits including $0s_{1/2}$, were used and these forbidden states were projected out in the process of wave function calculations. These calculations were done within the stochastic variational method, well suited for solving three-body problems. The authors got (using different n - ^{20}C interactions) S_{2n} = 0.388 - 0.573 MeV and correspondingly a ^{22}C r.m.s. matter radius r_m = 3.74 - 3.58 fm (using a 2.98 fm [**?**] r.m.s. radius of the ^{20}C core). There are several important findings in this paper: Non-central forces give negligible contributions to the results, the $(s_{1/2})^2$ configuration is predominant, many other components add only small admixtures, the ground state of ^{22}C consists almost entirely of configurations with total spin of halo neutrons $S = 0$ (weight more then 98%), emphasizing the halo structure of this nucleus. This underpins our model assumptions.

Since our aim is to explore principal relationships between binding energies and matter radii of ^{22}C, we have used [**?**] a simpler approach and apply shallow potentials that do not support bound states. Using the findings of [**?**], we neglected non-central forces and wave function components with total spin $S = 1$. We used a central neutron-core potential of the Woods-Saxon shape, with diffuseness a = 0.6 fm and radius R = 3.5 fm, the same geometry as in [**?**]. The potential depth was varied from the deepest possible (that does not support neutron-core binding) to more shallow. The neutron-neutron potential had a Gaussian shape (depth V = -31 MeV and radius R = 1.8 fm) and reproduced the basic properties of the n-n interaction. All combinations of orbital angular momenta (l_x, l_y) possible for the given hypermoment K were included and only even values of K are allowed for positive parity states. We checked that calculations with hypermoment up to K_{max} = 14 were close to convergence, independent of the potential depth. Thus calculations of the bound state will correspond to bases with K_{max} = 14. More details about these calculations and obtained results can be found in [**?**].

Figure **??** shows the calculated dependence [**?**] of the ^{22}C matter radius on the value of the two-neutron separation energy. The experimental value 2.98 fm extracted from reaction cross sections was used as the ^{20}C core matter radius. The lower curve corresponds

Figure 2: Calculated ^{22}C dipole strength function distributions for separation energy S_n = 50 keV, 100 keV, 200 keV and 400 keV (upper to lower curve). The insert compares dipole strength distributions for S_n = 10 keV (upper line) and 50 keV (lower line).

Figure 4: The dependence of the ^{22}C r.m.s. matter radius on the two-neutron separation energy (logarithmic scale). The lower and upper curves correspond to calculations with the radius of the neutron-core potential equal to 3.5 fm and 4.5 fm, respectively. The horizontal solid and dashed lines are the mean value and lower boundary of the experimental matter radius [?], respectively. Bars show theoretical estimations of the S_n energy at which the experimental mean value and lower boundary of the matter radius can be obtained. The insert shows the same curves, but for a linear energy scale.

to calculations with the geometry mentioned above. We obtained matter radii slightly smaller than the ones reported in [?] at corresponding energies. One of the reasons for this may be that at the ground state energy, the width of deep potentials assumed in [?] is essentially larger than for our shallow potentials.

To check the sensitivity of the ^{22}C r.m.s radius to the potential geometry we also performed [?] calculations (the upper curve in Fig. **??**) with a neutron-core potential having a 1 fm increased radius of 4.5 fm. As expected a broader potential leads to larger radii at the same binding energy. The upper curve starts from ground state energies of about 400 keV. Continuation of this curve to larger binding energies requires larger depths of the core-neutron potential and leads to appearance of two-body bound states. As mentioned above, such potentials were excluded from the consideration.

Concerning the general behaviour of the ^{22}C matter radius with binding energy, we notice that this dependence is close to linear at larger separation energies, becoming strongly nonlinear at smaller energies and diverging in the vicinity of the breakup threshold. Figure **??** shows curves versus a logarithmic scale of energy and compares calculations with the values of the ^{22}C matter radius tentatively extracted [?] from experimental cross sections. Bars show that even the lower experimental value of this radius would require quite small binding energy of a few tens of keV, diminishing to a very tiny binding for the suggested ^{22}C experimental radius.

Characteristics of nuclear halos are revealed not only in the specific structure of the ground state (loosely bound, abnormal spatial extension with extreme clusterization) but also in low-energy excitations above the breakup threshold where a concentration of transition strength is observed. The most spectacular is the appearance of a soft dipole excitation mode that dominates the electromagnetic dissociation cross section. In stable nuclei all dipole excitations are usually concentrated in the giant dipole resonance that corresponds to high-frequency collective proton-neutron vibrations. In neutron halo nuclei all charges are concentrated in the core, thus the charge and matter c.m. do not coincide and low-frequency dipole oscillations of the halo neutrons against the core may easily be excited. Figure **??** shows the ^{22}C dipole strength functions [?] for bound ground states (with different two-neutron separation energies from 400 keV to 50 keV. The peak of the dipole strength function moves closer to the breakup threshold with decreasing separation energy and simultaneously rapidly grows in absolute value. This remarkable enhancement clearly reflects the strong dependence of the soft dipole modes on the looseness of the halo systems and, respectively, on the difference between the charge and matter r.m.s. radii that increases with weakening of the binding.

4. Conclusion

The internal dynamics described by the Schrödinger equation may be very versatile and complicated due to coupling potentials, but also carries general features due to universality of the kinetic energy operator. The numerical integration of coupled equations in radial regions where the motion in some channels is classically forbidden may lead to development of numerical instabilities in the solution vectors and loss of the linear independence

for different sets of solutions. The modified variable phase method [**?**] rearranges the coupled equations to a form which contains free solutions only as logarithmic derivatives, i. e. a combination which minimizes variations of absolute values. As a result, the new system is less prone to develop numerical instabilities.
The modified method was applied to the calculations of nuclear structure of two-neutron halo nuclei. We have shown how the separation energy S_{2n} of the Borromean halo nucleus ^{22}C influences the spatial extension and also other observables that are directly connected to the large size of the ground state. For that purposes we applied the cluster three-body hyperspherical harmonic model that gives the most simple and physically transparent description of the two-neutron halo structure. To simulate the absence of a bound ^{21}C we used a shallow ^{20}C-neutron potential that does not allow the ^{21}C to bind, and fixed its strength to the required binding energy of the ^{22}C.
These simulations show that to reach the experimentally suggested lower boundary of the extracted matter radius, the separation energy S_{2n} of two neutrons in the ^{22}C should be of the order of tens of keV, while to reach the mean value the binding must be much weaker. Our solution method works well down to very small separation energies. The strength and position of soft dipole excitations are very sensitive to the separation energy, thus to the system's spatial extension.

[1] S. N. Ershov, J. S. Vaagen, M. V. Zhukov, Phys. At. Nucl. **74** (2011) 1151.

[2] S. N. Ershov, J. S. Vaagen, M. V. Zhukov, Phys. Rev. C **84** (2011) 064308.

[3] S. N. Ershov, J. S. Vaagen, M. V. Zhukov, Phys. Rev. C **86** (2012) 034331.

[4] W. Horiuchi and Y. Suzuki, Phys. Rev. C **74** (2006) 034311.

[5] K. Tanaka *et al.*, Phys. Rev. Lett. **104** (2010) 062701.

MICROSCOPIC ANALYSIS OF ^{11}Li+p ELASTIC SCATTERING AND BREAKUP PROCESSES

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In the first part of the note, the results are presented of calculations [**?**] of elastic scattering cross section for ^{11}Li+p at three incident energies performed within the hybrid model of the microscopic optical potential (OP) [**?**], which has been applied successfully before [**?**, **?**, **?**] for ^{6,8}He+p and ^{6}He+^{12}C elastic scattering. The real part of OP is calculated by a single-folding procedure [**?**] using the large-scale shell model (LSSM) density of ^{11}Li [**?**], while the imaginary part is derived basing on the high-energy approximation (HEA) theory. Besides, in the second part of the work we estimate the reaction mechanism such as the ^{11}Li breakup cross section with a help of the model of ^{11}Li consisting of the di-neutron and ^{9}Li core clusters, and then we also calculate the fragment momentum distributions from the ^{11}Li+p breakup reaction.
The optical potential used in our calculations has the form

$$U_{opt}(r) = N_R V^F + iN_I W^H + 2\lambda_\pi^2 \left\{ \frac{N_R^{SO}}{r}\frac{dV_0^F}{dr} + i\frac{N_I^{SO}}{r}\frac{dW_0^H}{dr} \right\} (\mathbf{l}.\mathbf{s}). \quad (1)$$

The real part V^F is constructed as a single folding of the ^{11}Li density $\rho(r)$ and of the effective NN potential, and involves the direct and exchange parts [**?**]. The imaginary part W^H was derived [**?**] by comparison of the eikonal phase with the corresponding HEA phase of the Glauber theory to get

$$W^H = -\frac{\hbar v}{(2\pi)^2}\bar{\sigma}_{NN}\int_0^\infty dqq^2 j_0(qr)\rho(q)f_{NN}(q), \quad (2)$$

where $\bar{\sigma}_{NN}$ is the isospin averaged NN total cross section, and f_{NN} is the form factor of the NN amplitude of scattering. The calculated potentials are shown in Fig. 1. The effect of the spin-orbit (SO) interaction is shown in Fig. 2 and occurs to be negligibly small. We fit the depths of OPs in the form of V^F and $W = V^F$ or W^H by introducing the re-normalization parameters that were obtained for case $W = V^F$ at three energies 62, 68.4 and 75 MeV equal to N_R=0.871, 0.625, 0.679, N_I=0.953, 0.186, 0.370, respectively. Here, to overcome the familiar problem of ambiguity of the obtained sets of parameters we selected the one which corresponds to the known behavior of the volume integrals J_V and J_W of OPs as functions of energy.
Then, to present results of estimations of the total breakup cross sections of ^{11}Li we consider this nucleus consisting of two clusters, the ^{9}Li core and the correlated pair of neutrons $h = 2n$ (as it was done for ^{6}He=2n+^{4}He in [**?**]). To this end the s-state wave function $\phi_{00}(\mathbf{s}) = (1/\sqrt{4\pi})\phi_0(s)$ of the relative motion of clusters in ^{11}Li was obtained for the respective energy 0.27 MeV of separation of 2n-cluster from ^{11}Li. After that, the "breakup" V^F and W^H potentials of p+^{11}Li were estimated, in its turn, as folding of the

Figure 1: Microscopic OPs for ^{11}Li+p scattering calculated using the LSSM density of ^{11}Li at E = 62 (solid), 68.4 (dashed) and 75 MeV/nucleon (dotted lines).

Figure 2: The ^{11}Li+p elastic scattering cross section at E = 62, 68.4, and 75 MeV/nucleon. Solid line: without SO term; dashed line: with SO term.

Figure 3: Elastic scattering cross section of ^{11}Li+p at E = 62 MeV/nucleon using ^{9}Li+2n model.

Figure 4: Cross section of stripping in ^{11}Li+p reaction at E = 62 MeV/nucleon.

folded OPs of p+h and p+^{9}Li, too. The corresponding elastic scattering cross sections calculated with the help of these "breakup" potentials are shown in Fig.3 for $W^{(b)} = V^F$ and $W^{(b)} = W^H$, where the corresponding parameters are N_R=1.407, 1.381 and N_I=1.195, 1.306, and the total cross sections for absorbtion σ_{abs}^{tot}=79, 78.6 mb, breakup σ_{bu}^{tot}=431.8, 405.3 mb and reaction σ_R^{tot}=501.8, 483.9 mb.
In the case of the stripping reaction when the h - cluster leaves the elastic channel, the cross section takes the form:

$$\left(\frac{d\sigma}{dk_L}\right)_{str} = \frac{1}{2\pi^2}\int_0^\infty b_h db_h d\varphi_h \left[1 - |S_h(b_h)|^2\right] \times \int \rho d\rho d\varphi_\rho |S_c(b_c)|^2 \left[\int_0^\infty dz \cos(k_L z)\phi_0\left(\sqrt{\rho^2+z^2}\right)\right]^2 \quad (3)$$

As is seen from Fig. 4 the width of the peak of this cross section in reaction of ^{11}Li with the proton target is about 100 MeV/c, which is twice larger than those obtained in the experiments for reactions with nuclei ^{9}Be, ^{93}Nb and ^{181}Ta. The problem of this kind of disagreements remains open and depends, *e.g.* on suggestions on a number of notes in the cluster wave functions as well as on dimensions and forms of clusters themselves involved in the model.
As a whole one can summarize the obtained results as follows:

- The ^{11}Li+p microscopic OP and elastic scattering cross sections were calculated and successfully compared to the available experimental data at three energies.
- The SO-term was included in the OP, but didn't contribute significantly.
- The problem of selection of the N's weight parameters of potentials from available sets of them was solved using information on behavior of the volume integrals.
- The other folding approach was considered where ^{11}Li consists of two clusters. This model predicts the breakup cross section σ_{bu}^{tot} that exceeds 80% from σ_R^{tot}.
- The width of the momentum distributions of ^{9}Li fragments from breakup reactions of ^{11}Li with protons was predicted larger than those known from experiments on nuclear targets. S, we emphasize the necessity of experiments on stripping reactions of ^{11}Li on protons at $E < 100$ MeV/nucleon.

[1] V. K. Lukyanov, *et al.*, Phys. At. Nucl., **75** (2012) 1407.

[2] V. K. Lukyanov, *et al.*, Phys. At. Nucl. **69** (2006) 240.

[3] V. K. Lukyanov, *et al.*, Eur. Phys. J. A **33** (2007) 389.

[4] V. K. Lukyanov, *et al.*, Phys. Rev. C **80**, 024609 (2009).

[5] V. K. Lukyanov, *et al.*, Phys. Rev. C **82** (2010) 024604.

[6] D. T. Khoa and G. R. Satchler, Nucl. Phys. A **668** (2000) 3.

[7] S. Karataglidis, *et al.*, Phys. Rev. C **61** (2000) 024319.

[8] V. K. Lukyanov, *et al.*, Int. J. Mod. Phys. E **20** (2011) 2039.

A NEW SUBSPACE PERTURBATION BOUND: THE APRIORI TAN Θ THEOREM

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One of fundamental problems in the perturbation theory of self-adjoint operators is to study the variation of the spectral subspace corresponding to a subset of the spectrum that is subject to a perturbation (in general the perturbation is not assumed to be small). Classical trigonometric estimates in the subspace perturbation problem have been established by Davis and Kahan [1]. For further results on subspace variation bounds for self-adjoint operators we refer to the review parts of the articles [2, 3]

In the recent paper [4] we consider a self-adjoint operator A on a separable Hilbert space $\mathfrak{H}$ under the assumption that its spectrum, $\mathrm{spec}(A)$, consists of two disjoint components σ_0 and σ_1 such that the set σ_0 lies in a finite gap of the set σ_1. In other words, we suppose that

$$\mathrm{spec}(A) = \sigma_0 \cup \sigma_1, \quad \sigma_0 \cap \sigma_1 = \emptyset, \quad \text{and} \quad \sigma_0 \subset \Delta, \tag{1}$$

where Δ denotes the finite gap of σ_1. (We recall that by a finite gap of a closed set $\sigma \subset \mathbb{R}$ one understands an open bounded interval on $\mathbb{R}$ that does not intersect this set but both of its ends belong to σ.) The perturbations V are assumed to be bounded and off-diagonal with respect to the partition $\mathrm{spec}(A) = \sigma_0 \cup \sigma_1$, that is, V should anticommute with the difference $\mathsf{E}_A(\sigma_0) - \mathsf{E}_A(\sigma_1)$ of the spectral projections $\mathsf{E}_A(\sigma_0)$ and $\mathsf{E}_A(\sigma_1)$ of A associated with the sets σ_0 and σ_1, respectively. Notice that A may be viewed as an unperturbed Hamiltonian and V as a potential.

For the spectral disposition (**??**), it has been proven in [5] that the gaps between σ_0 and σ_1 remain open if the off-diagonal self-adjoint perturbation V satisfies the (sharp) condition

$$\|V\| < \sqrt{2}\, d, \tag{2}$$

where $d = \mathrm{dist}(\sigma_0, \sigma_1)$ is the distance between the sets σ_0 and σ_1. Under this condition the spectrum of the perturbed operator $L = A + V$ consists of two isolated components $\omega_0 \subset \Delta$ and $\omega_1 \subset \mathbb{R} \setminus \Delta$.

The goal of [4] consists in finalizing a sharp norm estimate on the variation of the spectral subspace $\mathrm{Ran}\, \mathsf{E}_A(\sigma_0)$ that was conjectured and partly proven in [**?**]. The main result of [4] is as follows.

Theorem 1. *Given a self-adjoint operator A on a separable Hilbert space $\mathfrak{H}$, assume that its spectrum consists of two disjoint components σ_0 and σ_1 satisfying condition* (**??**). *Let V be a bounded self-adjoint operator on $\mathfrak{H}$ off-diagonal with respect to the partition* $\mathrm{spec}(A) = \sigma_0 \cup \sigma_1$ *and set $L = A + V$,* $\mathrm{Dom}(L) = \mathrm{Dom}(A)$. *Assume in addition that V satisfies the bound* (**??**) *and let $\omega_0 = \mathrm{spec}(L) \cap \Delta$. Then the difference of the spectral projections $\mathsf{E}_A(\sigma_0)$ and $\mathsf{E}_L(\omega_0)$ of A and L associated with the respective spectral sets σ_0 and ω_0 satisfies the norm estimate*

$$\|\mathsf{E}_A(\sigma_0) - \mathsf{E}_L(\omega_0)\| \le \sin\left(\arctan\frac{\|V\|}{d}\right) \quad \left(< \sqrt{\frac{2}{3}}\right). \tag{3}$$

For $\|V\| \le d$ the bound (**??**) was established in [2]. Having proved Theorem 1 we close the gap in the subspace perturbation problem for dispositions (**??**) which remained for $\|V\|/d \in (1, \sqrt{2})$. Thus we completely settle the issue.
The estimate (**??**) may be equivalently written in the form

$$\tan \|\Theta\| \le \frac{\|V\|}{d} \tag{4}$$

where Θ denotes the operator angle between the unperturbed and perturbed spectral subspaces $\operatorname{Ran} \mathsf{E}_A(\sigma_0)$ and $\operatorname{Ran} \mathsf{E}_L(\omega_0)$, respectively. For the concept of operator angle and related material we refer to [6] and references therein. Here we only remark that $\|\mathsf{E}_A(\sigma_0) - \mathsf{E}_L(\omega_0)\| = \sin \|\Theta\|$. The bound (**??**) implies that under conditions (**??**) and (**??**) the norm of the operator angle Θ can never exceed the value of $\arctan \sqrt{2}$ ($\approx 54^\circ 44'$).

Figure 1: The sharp estimating function $M(D, d, v)$ plotted in terms of the dimensionless variables $x = \dfrac{D - 2d}{D}$ and $y = \dfrac{4v^2}{D^2}$, $0 \le x < 1$, $0 \le y < 2(1 - x)$.

In fact, by using a result from [2], we have proven in [4] a more detailed optimal bound

$$\tan \|\Theta\| \le M(|\Delta|, d, \|V\|) \quad \left(\le \frac{\|V\|}{d} \right), \tag{5}$$

where the estimating function $M(D, d, v)$ is defined for $d > 0,\ D \ge 2d,\ 0 \le v < \sqrt{dD}$ (see [4, Theorem 4.1] for the explicit expressions of M). The estimate (**??**) is valid under the sharp gap-nonclosing condition $\|V\| < \sqrt{d|\Delta|}$ involving the length $|\Delta|$ of the gap Δ (see [**?**] for the proof of this condition). The optimal estimating function $M(D, d, v)$ is plotted in Fig. 1. The a priori $\tan \Theta$ estimate (**??**) is a consequence of the bound (**??**).

[1] C. Davis and W. M. Kahan, SIAM J. Numer. Anal. **7** (1970) 1.

[2] A. K. Motovilov and A. V. Selin, Integral Equ. Oper. Theory **56** (2006) 511.

[3] S. Albeverio and A. K. Motovilov, Compl. Anal. Oper. Theory, DOI: 10.1007/s11785-012-0245-7.

[4] S. Albeverio and A. K. Motovilov, Integral Equ. Oper. Theory **73** (2012) 413.

[5] V. Kostrykin, K. A. Makarov, and A. K. Motovilov, Integral Equ. Oper. Theory **51** (2005) 121.

[6] V. Kostrykin, K. A. Makarov, and A. K. Motovilov, Contemp. Math. (AMS) **327** (2003) 181.

SHIFTS AND WIDTHS OF FESHBACH RESONANCES IN ATOMIC WAVEGUIDES

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Impressive progress of the physics of ultracold quantum gases have opened new pathways for the study of low-dimensional few-body systems (see, for example [1]) as well as strongly correlated many-body systems [2]. Specifically, it was shown that the confining geometry of atomic traps can drastically change the scattering properties of ultracold atoms and induce resonances in the collisions (confinement-induced resonances (CIRs)) [3].
A necessary ingredient for the appearance of the CIR in a confining trap is the existence of Feshbach resonances in free-space [1-5]. So far single-channel potential models with zero-energy bound states were used for simulating the magnetic Feshbach resonances in the 3D free-space [3,6,7]. However, the single-channel interatomic interaction approach permits to explore only the main attribute of the Feshbach resonances in the 3D free-space, namely the appearance of a singularity in the s-wave scattering length $a \to \pm\infty$ when the molecular bound state with energy E_c crosses the atom-atom scattering threshold at energy $E = 0$ in the entrance channel. Other important parameters of the Feshbach resonance, such as the rotational and spin structure of the molecular bound state in the closed channel, background scattering length a_{bg} as well as the width Δ of the resonance characterizing the coupling Γ of the molecular state with the entrance channel [1], were ignored. The main goal of our work in 2012 [8] was to exit from the frame of the single-channel theoretical approaches developed earlier for the CIRs and take into account the effects of different rotational structure of the Feshbach resonance, the resonance width and the background scattering. We have developed and analyzed a theoretical model [8]

Figure 1: The transmission coefficient T(B) as a function of the strength of the magnetic field for several trap frequencies $\omega_\perp$. Here the s-wave scattering length $a(B)$ as a function of B is also given (solid curve).

which yields the shifts and widths of Feshbach resonances in an atomic waveguide. It is based on our multichannel approach for CIRs and atomic transitions in the waveguides in the multimode regime [6]. We replace in this scheme the single-channel scalar interatomic interaction by the four-channel tensorial potential modeling resonances of broad, narrow and overlapping character according to the two-channel parametrization of A.D.Lange *et al.* [9]. As an input the experimentally known parameters of Feshbach resonances in the absence of the waveguide, namely the resonant energies $E_{c,i}$ (or the corresponding values of the field strengths $B_{c,i}$ of the external magnetic field), the widths of the resonances $\Delta_i(\Gamma_i)$, spin characteristics and the background scattering length a_{bg}, were used. We have calculated the shifts and widths of s-, d- and g-wave magnetic Feshbach resonances of Cs atoms emerging in harmonic waveguides as CIRs and resonant enhancement of transmission T(B) at zeros $a(B) = 0$ of the free-space scattering length. The results are illustrated by the curves T(B) calculated near the d-wave resonance for different $\omega_\perp$ (Fig. 1) corresponding to the transverse frequencies of the optical trap being used in the experiment

Figure 2: The dependence of the s-wave scattering length $a(B)$ on the width $a_\perp$ of the waveguide at the points B_{min} of the minimum of the transmission coefficient $\mathrm{T}(a(B), a_\perp)$ (see Fig. 1). The dots, pluses and cycles correspond to the calculated points near the s-,d- and g-wave magnetic Feshbach resonances, respectively. The solid line corresponds to the formula $a = a_\perp/C$ (where C=1.4603) from [3].

[5]. It is shown that the position of B_{min} of the transmission coefficient T(B) minimum is dependent on the trap width $a_\perp = \sqrt{\hbar/(\mu\omega_\perp)}$ and the corresponding scattering length $a(B_{min})$ at the point B_{min} is accurately described by the formulas $a(B_{min}) = a_\perp/C$ obtained by Olshanii [3] for the position of the CIR in s-wave case. Our analysis has shown that this law is fulfilled for Feshbach resonances of different tensorial structure (see Fig. 2). We have also found the linear dependence of the width of the resonance at the point $a(B) = 0$ on the longitudinal atomic momentum and quadratic dependence on the trap width: $\Gamma_i^* \sim \Delta_i k_{||} a_\perp^2/a_{bg}$, an effect which could potentially be used experimentally. Our model opens novel possibilities for quantitative studies of the ultracold atomic processes in waveguides beyond the framework of s-wave resonant scattering.

[1] C. Chin, R. Grimm, P.S. Julienne, and E. Tiesinga, Rev. Mod. Phys. **82** (2010) 1225.

[2] I. Bloch, J. Dalibard, and W. Zwerger, Rev. Mod. Phys. **80** (2008) 885.

[3] M. Olshanii, Phys. Rev. Lett. **81** (1998) 938.

[4] G. Lamporesi, J. Catani, G. Barontini *et al.* Phys. Rev. Lett. **104** (2010) 153202.

[5] E. Haller, M.J. Mark, R. Hart, J.G. Danzl, L. Reichsöllner, V. Melezhik, P. Schmelcher, and H.C. Nägerl, Phys. Rev. Lett. **104** (2010) 153203.

[6] S. Saeidian, V.S. Melezhik, and P. Schmelcher, Phys. Rev. A **77** (2008) 042721.

[7] V.S. Melezhik and P. Schmelcher, Phys. Rev. A **84** (2011) 042712.

[8] S. Saeidian, V.S. Melezhik, and P. Schmelcher, Phys. Rev. A **86** (2012) 062713.

[9] A.D. Lange, K. Pilch, A. Prantner, F. Ferlaino *et al.* Phys. Rev. A **79** (2009) 013622.

BARYON STRUCTURE IN DUBNA-MAINZ-TAIPEI AND MAID MODELS

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One of the most important tasks in the study of baryon structure is to extract their properties like, mass, width, and helicity amplitudes etc. from πN scattering and pion electromagnetic (EM) production. There are several approaches to extract properties of nucleon resonances (N^*) from πN data, like speed plot, regularization method, dispersion relation, and meson-exchange model [**?**].

In this contribution, we present results only for P_{11} resonances obtained from analyzing data of πN scattering and pion EM production with Dubna-Mainz-Taipei (DMT) and MAID models which we have constructed in [2-4]. More complete results can be found in [2-7].

Figure 1: Re $t_{\pi N}(P_{11})$ (upper panel) and Im $t_{\pi N}(P_{11})$ (lower panel) parts of πN scattering amplitudes. The solid, dashed, and dash-dotted curves correspond to the predictions of full DMT model, without the 2nd and 3rd resonances and with the removal only 2nd resonance, respectively. The data are from [**?**].

The model parameters, including bare resonance masses, coupling constants, and cut-off parameters for each resonance are fitted to πN phase shifts and inelasticity parameters in all channels up to F waves and for the total CM energies W less than 2 GeV. The results for the P_{11} channel is shown in Fig. 1. The indication for need of three resonances in order to reach a reasonable description of the data within DMT model seems stronger than what was found by the EBAC group [**?**].

With the inclusion of the three P_{11} resonances determined from πN data we also are able to obtain a description of the multipoles ${}_pM_{1-}(1/2)$ (for the proton) and ${}_nM_{1-}(1/2)$ (for the neutron) for the pion EM production in the range of photon *lab.* energy E_γ between 150-1650 MeV as shown in Fig. 2 (black curves), except in the neighborhood of $E_\gamma \sim 1050$ MeV where a peak and a bump are seen in the imaginary and real parts of ${}_pM_{1-}(1/2)$ multipole, respectively. If a narrow P_{11} resonance of mass 1700 MeV and total width of 47 MeV is included within MAID2007 [**?**], then the peak and bump mentioned above can be very nicely described, as shown in Fig. 2 (red curves).

In summary, we find that, with the use of the DMT dynamical model for analyzing the πN scattering data, three P_{11} resonances with masses of 1418, 1803, and 2247 MeV are needed, all with rather broad widths. By analyzing pion EM production data, we further find that, within MAID2007 model the inclusion of a narrow P_{11} resonance at $W = 1700$ MeV with total width $\Gamma = 47$ MeV can greatly improve the agreement with ${}_pM_{1-}(1/2)$ data in the vicinity of photon *lab.* energy $E_\gamma \sim 1050$ MeV.

[1] L. Tiator, S. S. Kamalov, S. Ceci, G. Y. Chen, D. Drechsel, A. Svarc and S. N. Yang, Phys. Rev. C **82** (2010) 055203.

Figure 2: Imaginary (upper panel) and real (lower panel) parts of ${}_pM_{1-}(1/2)$ multipole in pion EM production on the proton. Black and red curves denote results of MAID2007 [**?**] and MAID2007 with an addition of a narrow P_{11} resonance of mass 1700 MeV and total width of 47 MeV, for ${}_pM_{1-}(1/2)$ multipole, respectively. The data are from [**?**].

[2] G. Y. Chen, S. S. Kamalov, S. N. Yang, D. Drechsel and L. Tiator, Phys. Rev. C **76** (2007) 035206.

[3] S. S. Kamalov and S. N. Yang, Phys. Rev. Lett. **83** (1999) 4494.

[4] D. Drechsel, S. S. Kamalov, and L. Tiator, Eur. Phys. J. A **34** (2007) 69.

[5] L. Tiator, D. Drechsel, S. S. Kamalov and M. Vanderhaeghen, Eur. Phys. J. ST **198** (2011) 141.

[6] S. N. Yang, S. S. Kamalov and L. Tiator, AIP Conf. Proc. **1432** (2012) 293.

[7] R. L. Workman, M. W. Paris, W. J. Briscoe, L. Tiator, S. Schumann, M. Ostrick and S. S. Kamalov, Eur. Phys. J. A **47** (2011) 143.

[8] R. A. Arndt, *et al.*, Phys. Rev. C **74** (2006) 045205.

[9] H. Kamano, *et al.*, Phys. Rev. C **81** (2010) 065201.

CALCULATIONS OF THE PION-NUCLEUS ELASTIC SCATTERING USING THE MICROSCOPIC OPTICAL POTENTIAL AND THE IN-MEDIUM πN SCATTERING AMPLITUDE

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In this paper, the $\pi^{\pm}$-meson scattering on nuclei is studied using the microscopic optical potential (OP). It was derived in [**?**] basing on the eikonal phase of the Glauber multiple scattering theory in its optical limit and has the following form:

$$U_{opt}(r) \,=\, -\frac{(\hbar c)\beta_c}{(2\pi)^2}\,\sigma\,[i+\alpha]\cdot\int_0^\infty j_0(qr)\,\rho(q)\,f(q)\,q^2dq, \qquad f(q) \,=\, e^{-\beta q^2/2}. \quad (1)$$

Here $\rho(r)$ is the nucleon density distribution normalized to the atomic number A. The parameters $\sigma,\ \alpha,\ \beta$ are composed from those obtained in the phase shift analysis of the data on the pion scattering on free protons and neutrons and then averaged by using the isospin symmetry relations $(\pi^{\pm}n) = (\pi^{\mp}p)$. Such the "free" parameters are presented in Refs. [**?**] and [**?**] in the region of (3,3)-resonance at energies T_{lab} from 90 to 280 MeV. Later on, analyzing in [**?**] the data on the pion scattering on nuclei ^{28}Si,^{58}Ni,^{208}Pb at 291 MeV [**?**], we extrapolated the reported magnitudes of $\sigma,\ \alpha,\ \beta$ from lower energies to the energy of 291 MeV. They are done in the last column of Table 1. As to the density distributions of the bare nucleons $\rho(r)$ they were taken from [**?**, **?**, **?**]. Then the microscopic OP (**??**) was inserted into the relativistic wave equation that was solved numerically to get the corresponding cross sections. The calculated differential cross sections we adjusted to the experimental data [**?**] and the fitting procedure was started from the free parameters $\sigma,\ \alpha$ while the slope parameter was left to be the free one β=0.434 fm^2. The middle-squared deviations χ^2 were estimated suggesting the 10% error of the cross section in every experimental point i. The obtained "in-medium" parameters and corresponding χ^2 per one point are done in Table 1.

Table 1: The adjusted parameters of amplitudes of the pion scattering on nucleons in nuclei.

	^{28}Si		^{58}Ni		^{208}Pb		πN
	π^+	π^-	π^+	π^-	π^+	π^-	free
σ, fm^2	5.55	4.81	5.43	4.09	4.04	4.23	4.76
α	-0.64	-0.88	-0.68	-1.02	-0.56	-0.92	-0.95
β, fm^2	0.434		0.434		0.434		0.434
χ^2	2.30	3.56	1.73	4.25	3.94	6.95	
χ^2_0	23.5	5.46	17.7	9.92	676.4	28.1	

Figure 1: The numbers on lines in the σ, α planes show the respective χ^2/point values obtained in the fitting procedure to experimental differential cross sections of the pion scattering on ^{28}Si, ^{58}Ni, ^{208}Pb at T_{lab}=291 MeV.

As an illustration, Fig.1 shows dynamics of the fitting procedure when χ^2 values come to their minima in three processes π^++^{28}Si,^{208}Pb and π^-+ ^{58}Ni. In Fig.2, solid curves show the best fit cross sections in comparison to experimental data. The dashed curves are calculations using the free amplitudes with parameters given in the last column of Table 1, and the respective χ^2_0 values are done in the last line. Analyzing the obtained results one can conclude that, the microscopic OP (**??**) and the developed scheme of calculations reproduce the general features of cross sections fairly well. However one can see that the usage of free πN amplitudes does not allow one to get successful correspondence to the experimental cross sections. Good agreement is achieved if one fits the σ and

Figure 2: Comparisons of the calculated $\pi^{\pm}$-mesons scattering cross sections to experimental data. Dashed curves are for parameters of free πN amplitudes, solid lines are for the fitted in-medium parameters.

α parameters to the data, which demonstrate the typical in-medium effect on the πN scattering amplitude in nuclei. This effect is seen more evidently if one compares the free and in-medium parameters averaged over all six cases of the $\pi^{\pm}$ scattering on three considered target nuclei. Table 1 shows the averaged in-medium $\pi^{\pm}$ scattering cross sections $\bar{\sigma}$ = 4.69 fm^2, that coincides fairly well with the free πN scattering cross section σ = 4.76 fm^2 in limits of accuracy of analysis of the data. At the same time, the average deflection parameter $\bar{\alpha}$ = -0.78 occurs in about 20% larger than the respective free α = -0.95. As to the cross section parameters σ, one can note that at 291 MeV the πN system takes place in a boundary of existence of the (3,3)-resonance region. At this energy, two factors influence on mechanism of the process. One of them is the "swelling" of nucleons in nuclei [**?**], that tends to increase cross sections, while the other factor is the suppression of interaction of pions with the bounded nucleons in nuclei because of the Pauli blocking effect (see, e.g., [**?**]). With increasing the energy this latter effect becomes weaker, that is seen, e.g., from analysis of the pion scattering o n the ^{12}C nucleus [**?**] at comparably larger energy 672 MeV. In this case, the first factor plays the decisive role and therefore the corresponding total πN cross section occurs in about 10% larger than that for a free nucleon.
In conclusion, one can note that analysis in [**?**] was also made by adjusting only two parameters σ and α while β was taken to be equal as for the scattering on free protons. By the way one should note that the slope β is also connected to the radius of interaction. Therefore the actual task is retained to fit the all three parameters σ, α, β simultaneously and also to move the investigations in the 33-resonance region of energies with the aim to study the role of different factors in the mechanism of scattering of pions on nuclei.

[1] V.K. Lukyanov, E.V. Zemlyanaya, K.V. Lukyanov, Phys. At. Nucl. **69** (2006) 240.

[2] M.P. Locher, O. Steinmann, N. Straumann, Nucl. Phys. B **27** (1971) 598.

[3] N. Bano, I. Ahmad, J. Phys. G: Nucl. Phys. **5** (1979) 39.

[4] V.K. Lukyanov, E.V. Zemlyanaya, K.V. Lukyanov, *et al.*, PoS (Baldin ISHEPP XXI) 020 (2012); Bull. RAS, Physics, **77** (2013) 467.

[5] D.F. Geesaman, C. Olmer, B. Zeidman, *et al.*, Phys. Rev. C **23** (1981) 2635.

[6] V.K. Lukyanov, E.V. Zemlyanaya, B. Słowiǹski, Phys. At. Nucl. **67** (2004) 1282.

[7] M. El-Azab, G.R. Satchler, Nucl. Phys. A **438** (1985) 525.

[8] J.D. Patterson, R.J. Peterson, Nucl. Phys. A **717** (2003) 235.

[9] G.E. Brown, *et al.*, Phys. Rev. Lett. **60** (1988) 2723.

[10] E. Oset, H. Toki, W. Weise, Phys. Rep. C **83** (1982) 281.

[11] M. Mizoguchi, H. Toki, Nucl. Phys. A **513** (1990) 685.

CREATION OF A STRONG ELECTROMAGNETIC FIELD IN RELATIVISTIC HEAVY-ION COLLISIONS

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The study of properties of QCD matter in the presence of strong uniform magnetic fields has attracted much attention during recent years due to several remarkable observations. They include such a universal phenomenon as the magnetic catalysis in which the magnetic field acts as a strong catalyst of dynamical flavor symmetry breaking which might lead to the generation of a dynamical fermion mass. Furthermore, in dense QCD matter in the presence of an external magnetic field and/or topological defects, a spontaneous creation of axial currents may happen. Moreover, at finite baryon density, due to a response of the QCD ground state to a strong magnetic field, a metastable object, the π^0 domain wall (or "Goldstone current state" in quark matter), could appear which energetically may be more favorable than nuclear matter at the same density. The presence of a magnetic field also favors the formation of spatially inhomogeneous spiral-like quark condensate configurations at low temperatures and non-zero chemical potentials. The influence of a constant magnetic field on possible color-superconducting phases (the color Meissner effect) has also actively been discussed. More specifically, the quark-hadron and chiral symmetry restoration transitions might be dramatically modified in the presence of a strong magnetic field.

In the last few years, particular attention was paid to the chiral magnetic effect (CME) closely related to a possible local $\mathcal{P}$ and $\mathcal{CP}$ symmetry violation in strong interactions. This effect originates from the existence of nontrivial topological configurations of gauge fields and their interplay with the chiral anomaly which results in an asymmetry between left- and right-handed quarks. In the presence of a strong magnetic field as created by colliding nuclei such a chiral asymmetry induces an electric charge current along the direction of a magnetic field thereby separating particles of opposite charges with respect to the reaction plane. It is remarkable that the proposed CME observable, i.e. the electric charge asymmetry of produced particles with respect to the reaction plane, has been recently measured by the STAR Collaboration. Qualitatively the experimental results agree with the magnitude and gross features of the theoretical predictions for local $\mathcal{P}-$odd violation in heavy-ion collisions. The observed signal can not be described by the background models and alternative mechanisms resulting in a similar charge separation effect are not fully excluded. This issue is under intensive debate now [**?**].

The hadron string dynamics (HSD) model is generalized to include the creation and evolution of retarded electromagnetic fields as well as the influence of the magnetic and electric fields on the quasiparticle propagation [**?**]. One should note that the electromagnetic field generated by moving nuclei may be considered as an external field: the value of the electromagnetic field at a given point is determined by the global charge distribution of colliding nuclei and thus, in good approximation, independent of the local strong interaction dynamics. However, the presence of the electromagnetic field can affect the interactions among particles, which simultaneously carry electric and (possibly) color charges.

For particles of a charge e the system of the Boltzmann-like kinetic equations is reduced to a familiar form:

$$\left\{\frac{\partial}{\partial t}+\left(\frac{\mathbf{p}}{p_0}+\nabla_{\mathbf{p}}\,U\right)\nabla_{\mathbf{r}}\;+(-\nabla_{\mathbf{r}}\,U+e\mathbf{E}+e\mathbf{v}\times\mathbf{B})\,\nabla_{\mathbf{p}}\right\}f=C_{coll}(f,f_1,...f_N)\quad(1)$$

where C_{coll} is the collisional term and the strength of the magnetic $\mathbf{B}$ and electric $\mathbf{E}$ fields is related with the electromagnetic potential $(\Phi, \mathbf{A})$

$$\mathbf{B} = \nabla \times \mathbf{A} \ , \qquad \mathbf{E} = -\nabla\Phi - \frac{\partial \mathbf{A}}{\partial t} \ . \tag{2}$$

More accurately, the HSD transport model is based on Kadanoff-Baym equations for Green's function accounting for the first order gradient expansion of the Wigner transformed Kadanoff-Baym equation. The hadronic mean field in Eq. (**??**) is $U \sim Re(\Sigma^{ret})/2p_0$ where Σ^{ret} denotes the retarded selfenergy.
Transport equations for a strongly interacting particle with the electric charge e Eq. (**??**) are supplemented by the electromagnetic field equations

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \ , \qquad \nabla \cdot \mathbf{B} = 0 \ . \tag{3}$$

The general solution of the wave equations (**??**) with the charge distribution $\rho(\mathbf{r}, t) = en$ and electric current $\mathbf{j}(\mathbf{r}, t) = e\mathbf{v}$ are

$$\Phi(\mathbf{r}, t) = \frac{1}{4\pi} \int \frac{\rho(\mathbf{r}', t') \ \delta(t - t' - |\mathbf{r} - \mathbf{r}'|/c)}{|\mathbf{r} - \mathbf{r}'|} \ d^3r'dt' \tag{4}$$

for the electromagnetic scalar potential $\Phi(\mathbf{r}, t)$ and

$$\mathbf{A}(\mathbf{r}, t) = \frac{1}{4\pi} \int \frac{\mathbf{j}(\mathbf{r}', t') \ \delta(t - t' - |\mathbf{r} - \mathbf{r}'|/c)}{|\mathbf{r} - \mathbf{r}'|} \ d^3r'dt' \tag{5}$$

for the vector potential. For a moving point-like charge one gets

$$\rho(\mathbf{r}, t) = e \ \delta(\mathbf{r} - \mathbf{r}(t)), \quad \mathbf{j}(\mathbf{r}, t) = e \ \mathbf{v}(t) \ \delta(\mathbf{r} - \mathbf{r}(t)). \tag{6}$$

Eqs. (**??**) and (**??**) lead to the retarded Liénard-Wiechert potentials acting at the point $\mathbf{R} = \mathbf{r} - \mathbf{r}'$ at the moment t. The electromagnetic potentials $\Phi(\mathbf{r}, t)$ and $\mathbf{A}(\mathbf{r}, t)$ are generated by every moving charged particle and describe generally the elastic Coulomb scattering as well as inelastic bremsstrahlung processes. Using the definition (**??**) we get

$$\mathbf{E}(\mathbf{r}, t) = \frac{e}{4\pi} \left[\frac{\mathbf{n}}{\kappa R^2} + \frac{-\mathbf{b}/c - [(\mathbf{n} \cdot \mathbf{v})\mathbf{n} - \mathbf{v}]/R}{\kappa^2 cR} \right]_{ret} - \frac{e}{4\pi} \left[\frac{(-\mathbf{v}(t')/c + \mathbf{n}(t'))(v^2/c - \mathbf{n} \cdot \mathbf{v} - R/c(\mathbf{n} \cdot \mathbf{b}))}{\kappa^3 cR^2} \right]_{ret} , \tag{7}$$

$$\mathbf{B}(\mathbf{r}, t) = \frac{e}{4\pi} \left[\frac{\mathbf{v} \times \mathbf{n}}{\kappa R^2} + (\frac{\mathbf{b}(t') \times \mathbf{n}(t') + \mathbf{v}(t') \times [(\mathbf{n} \cdot \mathbf{v})\mathbf{n} - \mathbf{v}]/R}{\kappa^2 cR}) \right]_{ret} - \frac{e}{4\pi} \left[\frac{(\mathbf{v}(t') \times \mathbf{n}(t'))(v^2/c - \mathbf{n} \cdot \mathbf{v} - R/c(\mathbf{n} \cdot \mathbf{b}))}{\kappa^3 cR^2} \right]_{ret} \tag{8}$$

with the acceleration $\mathbf{b} = d/dt'\mathbf{v}$ (to be neglected below) and the unit vector $\mathbf{n} = \mathbf{R}/R$. The set of transport equations (**??**) is solved in the quasiparticle approximation by using the Monte-Carlo parallel ensemble method. To find the electromagnetic field, a space grid

is used. The quasiparticle propagation in the electromagnetic field is taken into account in accordance with Eq. (**??**) as

$$\frac{d\mathbf{p}}{dt} = e\mathbf{E} + \frac{e}{c}\mathbf{v} \times \mathbf{B} \ . \tag{9}$$

The change of the electromagnetic energy is $(e/c)(\mathbf{v} \cdot \mathbf{E})$ *i.e.* the magnetic field does not change the quasiparticle energy. To avoid singularities and self-interaction effects, particles within a given Lorentz-contracted cell are excluded from the field calculation.

Figure 1: Time dependence of the spatial distribution of the magnetic field B_y at times t created in Au+Au ($\sqrt{s}$=200 GeV) collisions with the impact parameter b =10 fm. The location of spectator protons is shown by dots in the $(x-z)$-plane. The level $B_y = 0$ and the projection of its location on the $(x-z)$ plane are shown by the solid lines.

The time-space structure of the fields was analyzed in detail [**?**]. For illustration, the time evolution of $eB_y(x, y = 0, z)$ for Au+Au collisions for the colliding energy $\sqrt{s_{NN}}$ =200 GeV at the impact parameter b =10 fm is shown in Fig. **??**. If the impact parameter direction is taken as the x axis, then the magnetic field will be directed along the y-axis perpendicularly to the reaction plane $(z-x)$. The geometry of the colliding system at the moment considered is demonstrated by points in the $(z-x)$ plain where every point corresponds to a spectator nucleon. It is seen that the largest values of $eB_y \sim 5m_\pi^2$ are reached in the beginning of a collision for a very short time corresponding to the maximal overlap of the colliding ions. Note that this is an extremely high magnetic field, since $m_\pi^2 \approx 10^{18}$gauss.
It is shown that the created magnetic field is highly inhomogeneous but in the central region of the overlapping nuclei it changes relatively weakly in the transverse direction. We find that at any time the location of the maximum in the eB_y distribution correlates with that of the energy density of the created particles.
The background electric field, being orthogonal to the magnetic one, is directed along the x axis. The evolution of the eE_x field for peripheral (b =10 fm) collisions of Au+Au at the top RHIC energy is presented in Fig. **??**. Similar to the case of the magnetic field, the $eE_x(x, y = 0, z)$ distribution is also inhomogeneous and closely correlates with geometry while the field strength looks "hedgehog" shaped. When the two nuclei collide, the electric fields in the overlap region significantly compensate each other, and the electric field $\mathbf{E}$ in the target and projectile spectator parts have opposite directions.

Figure 2: Evolution of the x- and y-components of the electric field at incoming and maximal overlap in Au+Au ($\sqrt{s}$= 200 GeV) collisions at the impact parameter b =10 fm. The $eE_x = const$ levels and spectator points are shown in the projection on the $(x-z)$ plane.

Furthermore, the field characteristics are presented in [**?**] as a function of the collision energy and the centrality of the collisions. To explore the effect of the back-reaction of the fields on hadronic observables, a comparison of HSD results with and without fields is exemplified. Unexpectedly, our actual calculations showed no noticeable influence of

the electromagnetic fields – created in heavy-ion collisions – on the effect of the electric charge separation with respect to the reaction plane to be a signal of a possible local strong parity violation.
The recent STAR data within the RHIC beam-energy-scan (BES) program allows us to study the CME in a large energy range. In terms of the HSD approach with retarded electromagnetic field, we investigate the charged pions correlation function in the azimuthal angle ψ that is expected to be sensitive to a signal of local strong parity violation

$$\langle \cos(\psi_\alpha + \psi_\beta - 2\Psi_{RP}) \rangle, \tag{10}$$

where Ψ_{RP} is the azimuthal angle of the reaction plane.
The main results [**?**] are presented in Fig. **??**.

Figure 3: Angular correlations of oppositely and same charged pions in azimuthal angles for Au + Au collisions at $\sqrt{s_{NN}}$ =7.7, 11.5, 39 and 200 GeV as a function of centrality. The full symbols are preliminary STAR data [**?**] and published STAR data for $\sqrt{s_{NN}}$ = 200 GeV [**?**]. The dashed lines connect for orientation the experimental points as in the experimental works.

The HSD model reasonably reproduces STAR data for $\sqrt{s_{NN}}$ =7.7 GeV and 11.5 GeV while there are some deviations between theory and experiment at $\sqrt{s_{NN}}$ =39 GeV. For reference, the results for $\sqrt{s_{NN}}$ = 200 GeV are given as well which are in disagreement with experiment. The retarded electromagnetic field is too small. It was found that the reason of that is not a shortness of the interaction time, when the electromagnetic field is maximal, but the compensation of the mutual action of transverse electric and magnetic components, as was demonstrated.
We conclude that the recent RHIC BES data at $\sqrt{s_{NN}}$ =7.7 and 11.5 GeV can be understood on the hadronic level without involving the idea of a strong parity violation; however, the HSD model fails to reproduce data for $\sqrt{s_{NN}}$ ∼40 GeV and above which suggests that at these energies one has to take into account explicit partonic (quark-qluon) degrees-of-freedom for a proper treatment of the dynamics as well as a coupling of the partons to fluctuating color fields.
In the next paper [**?**] we checked the importance of partonic degrees of freedom. We generalized the parton-hadron-string dynamics (PHSD) model to include retarded electromagnetic field. In contrast with the HSD model, quark and gluon quasiparticles are included here. The agreement with CME experiments at moderate energies survives but it is impossible to say that the agreement at $\sqrt{s_{NN}} > 30$ GeV becomes better. For the early time of interaction, we consider fluctuations in the position of charged spectators resulting in electromagnetic field fluctuations as well as in the position of participant baryons defining the event plane. For partonic and hadronic phases in intermediate stages of the interaction we study also the possible formation of excited matter in electric charge dipole and quadrupole form as generated by fluctuations. The role of the transverse momentum and local charge conservation laws in the observed azimuthal asymmetry is investigated, too. All these above-mentioned effects are incorporated in our analysis [**?**] based on event-by-event PHSD calculations but do not essentially influence on observable. We conclude that color degrees of freedom should be taken into consideration explicitly.

A large azimuthal anisotropic flow at the relativistic-heavy-ion-collider provides a conclusive evidence for the creation of dense partonic matter in ultra-relativistic nucleus-nucleus collisions. The mentioned above BES program covers the energy interval from $\sqrt{s_{NN}} =$ 200 GeV, where partonic degrees-of-freedom play a decisive role, down to the AGS energy of $\sqrt{s_{NN}} \approx 5$ GeV, where most experimental data may be described successfully in terms of hadronic degrees-of-freedom, only. The obtained results presented in Fig. **??** allow to follow the creation of the partonic matter with the energy increase. As is seen in the left

Figure 4: The average elliptic flow v_2 of charged particles (left panel) at midrapidity for minimum bias collisions at $\sqrt{s_{NN}} = 9.2$, 19.6, 62.4 and 200 GeV (given by stars) is taken from the data compilation of Ref. [**?**]). Evolution of the parton fraction of the total energy density at midrapidity is presented in right panel for different collision energies.

panel, hadronic HSD and UrQMD models correctly describe the elliptic flow v_2 at the moderate AGS energies while the quark AMPT and AMPT-SM models agree with experiment at the top RHIC energy. However, neither of these models besides PHSD [**?**, **?**] is able to describe the v_2 growth in the considered energy range. An explanation for this increase of v_2 is provided in Fig. **??** (right panel). Here we show the partonic fraction of the energy density with respect to the total energy where the energy densities are calculated at mid-rapidity. The parton fraction goes up substantially with increasing the bombarding energy while the duration of the partonic phase is roughly the same. The repulsive mean-field for partons in the PHSD model leads to an increase of the flow v_2 with respect to HSD predictions. Thus, the observed rise of the azimuthal anisotropy can be considered as a signal of the partonic matter formation.
As noted above [**?**], the influence of the created electromagnetic fields on the elliptic flow is practically negligible.

[1] V.D. Toneev and V. Voronyuk, Phys. At. Nucl. **75** (2012) 607; V. D. Toneev and V. Voronyuk, Acta Phys. Polonica Suppl. B **5** (2012) 887.

[2] V. Voronyuk, V.D. Toneev, W. Cassing, E.L. Bratkovskaya, V.P. Konchakovski, and S.A. Voloshin, Phys. Rev. C **83** (2011) 054911.

[3] D. Gangadharan (for the STAR Collaboration), J. Phys. G: Nucl. Part. Phys. **38** (2011) 124166.

[4] STAR Collaboration, B.I. Abelev, *et al.*, Phys. Rev. C **81** (2010) 054908.

[5] V.D. Toneev, V. Voronyuk, E.L. Bratkovskaya, W. Cassing, V.P. Konchakovski and S.A. Voloshin, Phys. Rev. C **85** (2012) 034910.

[6] V.D. Toneev, V.P. Konchakovski, V. Voronyuk, E.L. Bratkovskaya and W. Cassing, Phys. Rev. C **86** (2012) 064907.

[7] M. Nasim, L. Kumar, P.K. Netrakanti and B. Mohanty, Phys. Rev. C **82** (2010) 054908.

[8] V.P. Konchakovski, E.L. Bratkovskaya, W. Cassing, V.D. Toneev, and V. Voronyuk, Phys. Rev. C **85** (2012) 011902.

[9] V.P. Konchakovski, E.L. Bratkovskaya, W. Cassing, V.D. Toneev, S.A. Voloshin, and V. Voronyuk, Phys. Rev. C **85** (2012) 044922.

PHASE TRANSITIONS IN HEAVY ION COLLISIONS

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The study of the phase transitions in the nuclear matter under extreme conditions is important for the theoretical analysis of heavy ion collision experiments at the intermediate and high energies [**?**, **?**] and for understanding of many critical issues in astrophysics [**?**]. The first order phase transition in almost all classification schemes has the Ehrenfest definition, which is one associated with a finite discontinuity in one or more of the first derivatives of the appropriate thermodynamic potential with respect to its variables of state [**?**, **?**]. The concrete type of the first order phase transition is related to an appropriate potential [**?**]. For example, for the liquid-gas phase transition the Gibbs free energy G is relevant and there are discontinuities in its first derivatives, the entropy and the volume, across the temperature-pressure coexistence curve [**?**].

In the paper [**?**], the main thermodynamical properties of the first order phase transition of the relativistic mean-field (RMF) hadronic model [**?**, **?**] were explored in the isobaric, the canonical and the grand canonical ensembles on the basis of the method of the thermodynamical potentials and their first derivatives. It was proved that the first order phase transition of the RMF model is the liquid-gas type one associated with the Gibbs free energy G. The thermodynamical potential G is the piecewise smooth function and its first order partial derivatives with respect to variables of state are the piecewise continuous functions. We have found that the energy in the caloric curve is discontinuous in the isobaric and the grand canonical ensembles at fixed values of the pressure and the chemical potential, respectively, and it is continuous, i.e. it has no plateau, in the canonical and microcanonical ensembles at fixed values of baryon density, while the baryon density in the isotherms is discontinuous in the isobaric and the canonical ensembles at fixed values of the temperature. Thus, the general criterion for the nuclear liquid-gas phase transition in the canonical ensemble was identified.

The relativistic mean-field hadronic model [**?**, **?**, **?**] is defined by the effective Lagrangian of the system of the low-lying baryons interacting through the exchange of the scalar meson σ and the intermediate abelian $U(1)$ gauge boson, i.e. vector meson ω, which is given by [**?**]

$$\mathcal{L} = \frac{\imath}{2}\left[\overline{\psi}\gamma^{\mu}D_{\mu}\psi - (D^{*}_{\mu}\overline{\psi})\gamma^{\mu}\psi\right] - m\overline{\psi}\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{v}^{2}A_{\mu}A^{\mu} + \frac{1}{2}(\partial_{\mu}\phi\partial^{\mu}\phi - m_{s}^{2}\phi^{2}) + g_{s}\phi\overline{\psi}\psi, \quad (1)$$

where $\psi = \begin{pmatrix} \psi^{1} \\ \psi^{2} \end{pmatrix}$ is the isodoublet of the group SU(2), ψ^{1} and ψ^{2} are the spinor fields for protons and neutrons with common mass m, γ^{μ} is the Dirac gamma matrix, A^{μ} is the real isoscalar vector Proca field for the ω meson with mass m_{v}, ϕ is the real isoscalar scalar field for σ meson with mass m_{s} and g_{v}, g_{s} are the coupling constants, respectively. In the mean-field approximation [**?**], we have $\phi = \phi_{0}$ and $A_{\mu} = \delta^{0}_{\mu}A_{0}$, where $\partial_{\mu}A_{0} = 0$

and $\partial_\mu \phi_0 = 0$. In the grand canonical ensemble the thermodynamic quantities are [**?**]

$$\Omega = -T \ln Z = -\lambda_{(-)} - T \sum_{\vec{p}\sigma} \left[\ln(1 + e^{-\frac{\varepsilon_{(+)} - \mu}{T}}) + \ln(1 + e^{-\frac{\varepsilon_{(-)} + \mu}{T}}) \right], \tag{2}$$

$$\rho - \frac{1}{V} \sum_{\vec{p}\sigma} [\langle n_{\vec{p}\sigma} \rangle - \langle \bar{n}_{\vec{p}\sigma} \rangle] = 0, \tag{3}$$

$$\rho_s - \frac{1}{V} \sum_{\vec{p}\sigma} \frac{m^*}{E^*} [\langle n_{\vec{p}\sigma} \rangle + \langle \bar{n}_{\vec{p}\sigma} \rangle] = 0, \tag{4}$$

with the mean occupation numbers given by the Fermi-Dirac distribution functions

$$\langle n_{\vec{p}\sigma} \rangle = \frac{1}{e^{\frac{\varepsilon_{(+)} - \mu}{T}} + 1}, \qquad \langle \bar{n}_{\vec{p}\sigma} \rangle = \frac{1}{e^{\frac{\varepsilon_{(-)} + \mu}{T}} + 1} \tag{5}$$

where $\lambda_{(\mp)} = \frac{1}{2}(a_v \rho^2 \mp a_s \rho_s^2) V$, $\varepsilon_{(\pm)} = E^* \pm a_v \rho$, $m^* = m - a_s \rho_s$, $\rho \equiv A_0 g_v / a_v$, $\rho_s \equiv \phi_0 g_s / a_s$, $a_v \equiv g_v^2 / m_v^2 \equiv C_v^2 / m^2$, $a_s \equiv g_s^2 / m_s^2 \equiv C_s^2 / m^2$, with C_v and C_s being dimensionless parameters of the model [**?**]. Equations (**??**)–(**??**) constitute a closed system of equations.

Figure 1: (Color online) Grand canonical ensemble (T, μ). The specific thermodynamical potential p (the pressure), the entropy density S/V, the baryon density ρ, the density of free energy F/V, the energy density $\langle H \rangle / V$ and the effective nucleon mass m^* as functions of the chemical potential μ at fixed temperature T for the RMF approach. The curves $1, 2, 3, 4$ are obtained at $T = 7, 15$ MeV, $T = T_c$ and $T = 22$ MeV, respectively. The solid lines $1, 2$ are the results with the Maxwell construction. The symbol is the critical point and the dashed line is the phase diagram.

The phase transition that appears in the nuclear matter in the RMF model in the grand canonical ensemble is accompanied by discontinuities in the first order derivatives of the thermodynamic potential Ω and therefore is a first order phase transition in the Ehrenfest classification [**?**]. The graphical representation of this phase transition can be seen in Fig. **??**, which represents the behavior of the pressure p, the entropy density s, the baryon density ρ, the density of free energy f, the energy density ε and the effective nucleon mass m^*, as functions of the chemical potential μ at fixed temperature T. For $T \geq T_c$, the thermodynamical variables $p(\mu)$, $\rho(\mu)$, $s(\mu)$, $\varepsilon(\mu)$, $f(\mu)$ and $m^*(\mu)$ are continuous, one-valued, monotonic and differentiable functions of μ (the line $3, 4$ in all panels of Fig. **??**). For $T < T_c$, the specific grand potential $p(\mu)$, with the Maxwell construction, is a piecewise smooth function. The point of phase transition, denoted by μ^*, is a point of discontinuity of the first derivative of p (the solid lines $1, 2$ in Fig. **??**). For $T < T_c$, with the Maxwell construction, p is continuous and single-valued for all μ, and has a cusp, but its first order partial derivatives with respect to variables of state, namely $\rho(\mu)$ and $s(\mu)$, are discontinuous at $\mu = \mu^*$. The jump of the entropy density at $\mu = \mu^*$ is related to the latent heat–$\lambda = T \delta s$. Moreover, p, ρ and s, are strictly increasing functions of μ.
We have found that for the nuclear liquid-gas phase transition of the RMF model the energy in the caloric curve is discontinuous in the isobaric and the grand canonical ensembles at fixed values of the pressure and the chemical potential, respectively, and it is continuous, i.e. it has no plateau, in the canonical and the microcanonical ensembles at fixed values of the baryon density (see Fig. **??**). However, the baryon density in the equation of

Figure 2: (Color online) The temperature T as function of the excitation energy per nucleon E^* (the caloric curve) for the RMF model in the different statistical ensembles at three points of phase transition (lines $1, 2, 3$): (a) the isobaric ensemble at fixed pressure p, (b) the canonical and microcanonical ensembles at fixed baryon density ρ and (c) the grand canonical ensemble at fixed chemical potential μ. (d) The isotherms in the canonical and isobaric ensembles at fixed temperature T (solid lines) in the same points of phase transition. Symbol is the critical point and the dotted line is the phase diagram.

state (the isotherm) is discontinuous in the isobaric and the canonical ensembles at fixed values of the temperature. For one of the variants of the statistical multifragmentation model the similar results were obtained in [**?**]. Thus, the general criterion for the nuclear liquid-gas phase transition, i.e. the first order phase transition associated with the Gibbs free energy G, in the canonical ensemble requires that the baryon density in the isotherms should be discontinuous at fixed values of the temperature and the energy in the caloric curves should be continuous, i.e. it should not have plateau, at fixed values of the baryon density (the baryon charge and the volume).

[1] K. Yagi, T. Hatsuda, Y. Miake, *Quark-gluon plasma. From big bang to little bang* (Cambridge University Press, 2005).

[2] J.P. Bondorf, A.S. Botvina, A.S. Iljinov, I.N. Mishustin, K. Sneppen, Phys. Rep. **257** (1995) 133.

[3] A.W. Steiner, M. Prakash, J.M. Lattimer, P.J. Ellis, Phys. Rep. **411** (2005) 325.

[4] P. Ehrenfest, Commun. Kamerlingh Omnes Lab. Univ. Leiden Suppl. **75b** (1933).

[5] P. Papon, J. Leblond, P.H.E. Meijer, *The physics of phase transitions* (Springer-Verlag, Berlin, 2006).

[6] J.M. Yeomans, *Statistical mechanics of phase transitions* (Clarendon Press, Oxford, 1992).

[7] A.S. Parvan, Nucl. Phys. A **887** (2012) 1.

[8] J.D. Walecka, Ann. Phys. **83** (1974) 491;
F.E. Serr, J.D. Walecka, Phys. Lett. B **79** (1978) 10.

[9] B.D. Serot, J.D. Walecka, Adv. Nucl. Phys. **16** (1986) 1; Int. J. Mod. Phys. E **6** (1997) 515.

[10] C.E. Aguiar, R. Donangelo, S.R. Souza, Phys. Rev. C **73** (2006) 024613.

UNIVERSALITY OF NUCLEON-NUCLEON SHORT-RANGE CORRELATIONS: NUCLEON MOMENTUM DISTRIBUTIONS AND THEIR SPIN-ISOSPIN DEPENDENCE

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Since the pioneering calculations of the single particle momentum distributions $n_A(k)$ [**?**, **?**] it has been commonly accepted that at large values of k the nuclear distribution can be associated to the deuteron momentum distribution $n_D(k)$. Namely, most calculations involving $n_A(k)$ presumed that at $k \gtrsim 250 - 350\,\mathrm{MeV/c}$ the nuclear wave function factorizes into a product of wave functions of deuteron-like NN pairs and $(A-2)$ remnants, which automatically results in the relation $n_A(k) = C_A n_D(k)$, where the constant C_A is almost A-independent. Nowadays we are able to check such a conjecture by performing exact calculations [**?**] using the status-of-the-art few-body wave functions corresponding to most recent NN potentials. In Fig. **??** we present results of our calculations of the neutron (left panel) and proton (right panel) momentum distributions in ^{3}He compared with the deuteron distribution.

Figure 1: The neutron and proton momentum distributions in ^{3}He vs. momentum k in comparison with the deuteron momentum distribution $n_D(k)$. Calculations have been performed [**?**] with the ^{3}He and D wave functions obtained with the AV18 potential.

At first glance it seems that at large values of the momentum $k \gtrsim 500\,\mathrm{MeV/c}$ such a dependence indeed holds. However, in the linear scale it can be clearly seen that for all considered nuclei the ratio $n_A(k)/n_D(k)$ is not a constant and increases with increasing k, see Fig. **??**. In order to clarify the physical meaning of such a behaviour we have analyzed the two body momentum distribution for pn and pp pairs and their S (spin) and T (isospin) dependencies as functions of the relative, k_{rel}, and total, K_{CM}, momentum of the pair. It is expected that at low values of $K_{CM} \sim 0$ the momentum distribution is entirely governed by the lowest configurations of the NN pair, which, for the pn pairs, are exactly the deuteron-like configuration (ST)=(10). For the pp and/or nn pairs the main configuration is the $^1S_0$ state, which evidently differs from the deuteron configuration. In Fig. **??** we present results of calculations of the ratio of partial (ST) components of the two-particle momentum distribution n_A/n_D at $K_{CM} = 0$ for ^{3,4}He as a function of the relative momentum k_{rel}. It is seen that this ratio for the deuteron-like components (ST)=(10) indeed manifests a constant behaviour, while for the (ST)=(01) states the ratio slightly increases. This tendency is more apparent at moderate and high values of K_{CM}, see Ref. [**?**]. From these results it becomes evident that, since the single-particle momentum distribution $n_A(k)$ is obtained from the two-body momentum distribution by integrating over one of the momenta of the nucleon in the pair, the center of mass motion of the pair can affect the simple picture, according to which the high momentum behaviour of $n_A(k)$ is solely governed by deuteron-like configurations. Clearly, other (ST) states contribute to the total distribution. This has an important consequence in determining the probability of the two nucleon short range correlations (SRC) in nuclei. According to the SRC model,

Figure 2: The ratio $n_A(k)/n_D(k)$ for light, ^{3,4}He, and heavy ^{16}O and ^{40}Ca nuclei.

at high values of p the nucleus can be treated as a deuteron-like pair and a (A-2) core, both at rest. Within such a picture the total internal momentum is carried out exclusively by the pair having momenta of nucleons large enough and with opposite directions. This is considered as the main feature of the SRC and, consequently in experimental searching for SRC one propose to knock out two nucleons in the so-called "back-to-back" direction. This would be a clear signal of existence of SRC in nuclei. However, as was demonstrated in Ref. [**?**] values of K_{CM} different from zero also contribute to the total momentum distribution and that other (ST)-configurations, different from the deuteron ones, can modify this simple SRC picture, resulting in different experimental predictions. In Fig. **??** there are presented results of our calculations of the contribution of partial (ST) states into the total momentum distribution for nuclei with A=3,4,16 and 40. From the above results one can conclude that (i) at large values of $k \sim 2\,\mathrm{fm}^{-1}$, due to the effects of SRC, the momentum distributions exhibit a k dependence which is very similar in different nuclei; (ii) calculations of the contribution of the states (ST)=(10), (00), (01) and (11) demonstrate that all of them, except (00), have comparable effects. The contribution of the isosinglet state T=0 is almost entirely exhausted by the (10) state, whereas both states (01) and (11) contribute to the isotriplet state (11); (iii) in the region of SRC, $k \gtrsim 2\,\mathrm{fm}^{-1}$, the ratio $n_A(k)/n_D(k)$ does not stay constant but increases with increasing p, which is interpreted as the contribution of the c.m. motion of a pair differing from the "back-to-back" nucleons configuration; (iv) our spin-isospin dependent approach allowed us to calculate also: (1) the relative momentum distribution of a proton-neutron pair moving with small c.m. momentum and its integral in the range $1.5 < k < \infty$, a quantity which is assumed to represents the probability of two nucleon SRC in a nucleus, finding similar values ($\simeq 0.04$) in a wide range of A, $2 \leq \mathrm{A} \leq 40$; (2) the total number of SRC pairs in (10) state, interpreting its A-dependence in terms of the A-dependence of the c.m. momentum distribution; (3) the per-nucleon probability of two-nucleon SRC in nuclei, a quantity which is under active experimental investigation.

Figure 3: The momentum distributions of the pn pairs in ^{3}He and ^{4}He vs. momentum k in comparison with the deuteron momentum distribution $n_D(k)$.

Figure 4: The neutron and proton momentum distributions in ^{3}He vs. momentum k in comparison with the deuteron momentum distribution $n_D(k)$. Calculations have been done in [**?**] with the ^{3}He and D wave functions obtained with the AV18 potential.

[1] J. G. Zabolitzky and W. Ey, Phys. Lett. B **76** (1978) 527.

[2] R. Schiavilla, V.R. Pandharipande, R.B. Wiringa, Nucl. Phys. A **449** (1986) 219.

[3] M. Alvioli, C. Ciofi degli Atti, L.P. Kaptari, C.B. Mezzetti, S. Scopetta, Phys. Rev. C **85** (2012) 021001(R).

[4] M. Alvioli, C. Ciofi degli Atti, L.P. Kaptari, C.B. Mezzetti, H. Morita, e-Print: arXiv:1211.0134 [nucl-th].

ENHANCED SUBTHRESHOLD $\mathbf{e^+e^-}$ PRODUCTION IN SHORT LASER PULSES

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It is expected that the electron-positron pairs can be produced in collision of high energy photons with a power laser pulse limited in space and time. But the question is whether the production probability depends on the pulse duration or not. This problem is essentially important for sub-threshold pair production where the energy of photon-photon interaction is below the threshold of the reaction and incoming photon must interact with a few photons of the laser pulse simultaneously. Rapidly evolving laser technology can provide the laser power up to 10^{24} – 10^{25} W/cm^2 in near future which is sufficient for the different purposes in basic (particle and nuclear physics, non-linear electrodynamics in strong fields etc.) and applied research, moreover, the next generation of optical laser beams are expected to be essentially short (femtosecond duration) with only a few oscillation of the e.m. field in the pulse. This requires elaboration some methods to evaluate the cross sections of the elementary $\gamma\gamma$, $e\gamma$, and so on processes in a strong and short electromagnetic fields. For definiteness we will consider most important and interesting effect production of e^+e^- pairs in interaction of the probe photon with intense laser pulse. The previous analysis given by Ritus group is limited by the consideration of the external e.m. field as an infinite plane wave, or infinite pulse approximation (IPA). It was found that the probabilities of the e^+e^- pair emission depend on the reduced strength of the e.m. field A^μ, $\xi^2 = -e^2\langle A^2\rangle/M_e^2 \equiv e^2a^2/M_e^2$, where M_e is the electron mass (we use $c = \hbar = 1$, $e^2/4\pi = \alpha = 1/137$). Furthermore, the dimensionless variable $\zeta = s_{\rm thr}/s$ is introduced, where s is the square of the total energy in the center of mass system (c.m.s.) of the Breit-Wheeler process $\gamma'+\gamma \to e^+ + e^-$ and $s_{\rm thr} = 4M_e^2$ is its threshold value. The case of $\zeta > 1$ corresponds essentially to multi-photon processes.

In [**?**] we have elaborated a new theoretical approach for calculation of probability of e^+e^- pair production with a short intensive laser pulse. We denote it as a finite pulse approximation (FPA). We found that due to the modulation of the pulse envelope function, the power spectrum contains high momentum components which enhance the probability of pair production in the subthreshold region even for moderately strong laser intensities.

We consider the e.m. four-potential $A \sim (0, \mathbf{A})$ depending solely on the invariant phase $\phi = k \cdot x$,

$$\mathbf{A}(\phi) = f(\phi)(\mathbf{a}_1 \cos\phi + \mathbf{a}_2 \sin\phi) \ , \tag{1}$$

where $|\mathbf{a}_1| = |\mathbf{a}_2| = a$, $\mathbf{a}_1\mathbf{a}_2 = 0$ for circular polarization. We employ here the envelope function $f(\phi) = 1/\cosh(\phi/\Delta)$, where $\Delta = \pi\,\tau/\tau_0 = \pi N$, and N characterizes the number of cycles in a pulse; $\tau_0 = 2\pi/\omega$ is the time of one cycle for the laser frequency ω. Thus, τ is the time scale of the pulse duration. Utilizing the e.m. potential (**??**) in the Volkov solutions leads to two significant modifications of the transition amplitude. Besides physical asymptotic momenta and masses, the finite time τ requires Fourier integrals in the integrand of invariant amplitudes, and the discrete harmonics become continuous. Thus,

the S matrix element of the process $\gamma' \to e^+(\gamma) + e^-(\gamma)$, where $e^\pm(\gamma)$ refers to Volkov states in the field (**??**), is expressed as

$$S = \int_\zeta^\infty dl\, M(l)(2\pi)^4\delta^4(k' + lk - p - p') \ , \tag{2}$$

where k, k', p, p' correspond to momenta of laser field photon, incoming "probe" photon, outgoing positron and electron, respectively. Our method allows to evaluate the transition matrices $M(l)$ and the corresponding cross sections and probabilities in a closed analytical form. Thus for example, the probability of e^+e^- production in sub-threshold region with $\zeta = 1 + \delta s_l/s > 1$, where $\delta s_l = s_{\rm thr} - s$ is the "lack of energy", is expressed through the probability in above threshold region as

$$W^{\rm FPI} = \mathcal{I}_1 W^{\rm IPA}(n=1) + \mathcal{I}_2 W^{\rm IPA}(n=2) + \ ..., \tag{3}$$

where $W^{\rm IPA}(n=1)$ is the probability of e^+e^- pair production in above thresold region given in case of the infinite pulse. The term $W^{\rm IPA}(n=2)$ is the probability of e^+e^- production in interaction of the probe photon with two photons in the laser field. Both have the same functional dependence on ξ and other kinematical variables as in IPA. The factor $\mathcal{I}_1$ reads

$$\mathcal{I}_1(\Delta, \delta s_l/s) \simeq {\rm e}^{-\pi\Delta\delta s_l/s}/(1 + {\rm e}^{-\pi\Delta\delta s_l/s}) \ ,$$

For $\delta s_l/s \lesssim 1 - 0.65/N$ one gets for the factor $\mathcal{I}_2$

$$\mathcal{I}_2 = (1/\pi^2)\int_{\pi\Delta(\zeta-2)}^{\pi\Delta} x^2\exp(-x)(1-\exp(-x))^{-2}dx \simeq 2/3.$$

Figure 1: The total cross section of e^+e^- pair production as a function of the total energy in c.m.s., $\sqrt{s}$, for the finite pulse with $\Delta = \pi N$. The dashed and thick solid curves correspond to $N = 2$ and 5, respectively. The thin solid curve "inf." is for IPA. The thin dashed curve "B-W" corresponds to Breit-Wheeler $\gamma + \gamma \to e^+e^-$ process. Left and right panels are for $\xi = 0.01$ and 0.1, respectively.

One can expect a significant enhancement of pair production for the short pulse because the probability of single photon events ($n = 1$) is much greater than the probability of the two-photon events ($n = 2$): $W^{\rm IPA}(n=1)/W^{\rm IPA}(n=2) \sim \xi^{-2} \gg 1$. When the length of the pulse (Δ) increases the contribution of the first term in Eq. (**??**) decreases exponentially due to $\mathcal{I}_1$, and the prediction of FPA approaches to the IPA one.
Fig. 1 illustrates our prediction for the cross sections of e^+e^- production as a function of $\sqrt{s}$ in the subthreshold region for finite pulses with $\Delta = \pi N$. One can see that in the subthreshold region, $\sqrt{s} = 0.85$ – 1.02 MeV, the cross section for short pulses is significantly greater than in IPA and the difference may reach one or two orders of magnitude for $\xi = 0.1$ and $\xi = 0.01$, respectively. Such a non-trivial dependence of the cross section (production probability) on the pulse duration must be taken into account in the evaluation of e^+e^- pair production in cascade processes produced by the high-power laser fields.

[1] A. I. Titov, H. Takabe, B. Kämpfer and, A. Hosaka, Phys. Rev. Lett. **108** (2012) 240406.

RELATIVISTIC COMPLEX NEUTRON-PROTON SEPARABLE POTENTIAL

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Using the Bethe-Salpeter (BS) [**?**] equation to describe the NN interaction is one of the most consistent approaches. In this formalism, one has to deal with a system of nontrivial integral equations for both the NN scattered states and the bound state – the deuteron. To solve a system of integral equations, it is convenient to use a separable ansatz [**?**] for the interaction kernel in the BS equation. This report is based on our papers [**?**] where multirank separable potentials MYN (Modified Yamaguchi of rank N) were proposed to describe the scattered neutron-proton (np) system with total angular momentum $J = 0, 1$ and the bound state – the deuteron. There, various methods of relativistic generalization of initially non-relativistic separable functions parameterizing the interaction kernel were considered. The elaborated potentials allow us to describe the experimental data for the phase shifts up to the laboratory kinetic energy $T_{\rm Lab}\sim 3\,{\rm GeV}$, static properties of the deuteron, and the exclusive electron-deuteron breakup in the plane-wave approximation [**?**, **?**]. However, it is well known that an influence of inelastic channels

Figure 1: Phase shifts and inelasticity parameter for the ${}^1P_1^+$ partial-wave state. The results of calculations with the potentials - real-valued MY2 [**?**] (red solid line), complex MYI2 (red dashed line), and the SP07 solution [**?**] (green dashed-dotted line) are compared.

Figure 2: Phase shifts and inelasticity parameter for the ${}^3P_0^+$ partial-wave state. The notations are the same as in Fig. **??**.

related with non-nucleon degrees of freedom (mesons, Δ isobars, nucleon excitations, six-quark admixtures, etc.) becomes significant with increasing energy of a nucleon-nucleon system. An inelasticity parameter which is responsible for a proper flux behavior is introduced to treat them in the elastic NN scattering. The calculation is performed for all available experimental data for the phase shifts and the inelasticity parameters taken from the SAID program [**?**]. Thus, at the given real part of the separable potential adding the imaginary part parameters make it possible to describe the inelasticity with a minimal change of the phase shift description.

Figure 3: Phase shifts and inelasticity parameter for the ${}^3P_1^+$ partial-wave state. The notations are the same as in Fig. **??**.

Figure 4: Phase shifts and inelasticity parameter for the ${}^1S_0^+$ partial-wave state. The results of calculations with the potentials - real-valued MY3 [**?**] (red solid line), complex MYI3 (red dashed line), and the SP07 solution [**?**] (green dashed-dotted line) are compared.

In Figs. **??**-**??**, we see that the calculations for our complex potential MYIN (Modified Yamaguchi Imaginary of rank N) and the solution SP07 give an excellent description of

the phase shifts and of the inelasticity parameter for all available experimental data (up to $T_{\rm Lab}\sim 3\,{\rm GeV}$) for the ${}^1P_1^+$, ${}^3P_0^+$, ${}^3P_1^+$, ${}^1S_0^+$ partial-wave state.
The proposed complex potentials allow us to describe an inelasticity appearing in the elastic *np* scattering with increasing energy of the nucleons. They have been constructed by introduction of an imaginary part (minimal extension) into the real-valued potentials elaborated earlier [**?**]. The imaginary part parameters have been found from the description of the experimental data for the phase shifts and the inelasticity parameters for the laboratory energy up to 3 GeV.

[1] E.E. Salpeter, H.A. Bethe, Phys. Rev.**84** (1951) 1232.

[2] S.G. Bondarenko, V.V. Burov, A.V. Molochkov, G.I. Smirnov, H. Toki, Prog. Part. Nucl. Phys.**48** (2002) 449.

[3] S.G. Bondarenko, V.V. Burov, W.-Y. Pauchy Hwang, E.P. Rogochaya, Nucl. Phys. A **832** (2010) 233; Nucl. Phys. A **848** (2010) 75.

[4] S.G. Bondarenko, V.V. Burov, E.P. Rogochaya, Few Body Syst. **49** (2011) 121; Phys. Lett. B **705**, 264 (2011); JETP Lett. **94**, 3 (2012); Nucl. Phys. Proc. Suppl. **219-220** (2011) 126.

[5] R.A. Arndt, W.J. Briscoe, I.I. Strakovsky, R.L. Workman, Phys. Rev. C **76** (2007) 025209.

[6] http://gwdac.phys.gwu.edu

SOME FEATURES OF LIGHT+NANOSYSTEM DYNAMICS

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The advent of nanotechnology gives impetus to the field of plasmonics which enables one to operate with light at the nanoscale, well below the scale accessible for the classical techniques. Indeed, nowadays there is an enormous experimental and theoretical activity focussed on the study of properties localized surface plasmon resonances (SPR) in metal nanoparticles. We recall that, in general, SPR are produced by collective oscillations of valence electrons in a solid stimulated by incident light. This interest is due to enhanced light absorption, spectral tuning of SPR by controlling the size, shape, composition of metal nanoparticles and surrounding medium [**?**, **?**]. Nanoplasmonics offers to employ various remarkable optical properties of nanoparticles for design of novel devices based on the interaction between photons and nanosystems. Among many of them are, for example, such as solar cells and narrow band-pass optical filters.

Narrow optical band-pass filters are widely used in the systems with optical processing of information, color displays development and optical computers. Existing optical band-pass filters are based on the interference of optical modes from multiple thin dielectric layers which are manufactured by different types of expensive layer deposition techniques. The cost of such optical filters can be greatly reduced if one would apply simple non-vacuum technology for their fabrication. Among well-known narrow band-pass optical filters are those that are based on the Christiansen effect [**?**]. This effect is due to scattering by small particles in a transparent medium at a wavelength for which the refractive index of the particle material and that of the medium are equal. These filters transmit unscattered light at this wavelength and incoherently scatter light of other wavelengths. A change of the transmission behavior of this dispersion filter can be achieved by variation of the composed materials and external conditions.

To give a better insight into the role of nanoplasmonics for such devices let us consider a nanoparticle composed of a dielectric core and a homogeneous metallic nanoshell. On the one hand, Mie scattering theory [**?**] predicts that by varying the ratio of the shell thickness with the respect to the overall diameter of the particle it is possible to obtain the invisibility of the nanoparticle at a specific wavelength [**?**, **?**, **?**]. In this case a scattering cancellation is based on the negative local polarizability of a metallic nanoshell with respect to the positive dielectric core polarizability. On the other hand, for a small nanoparticle a plasmon resonance leads to a large absorption cross section at the plasmon resonance frequency [**?**, **?**]. In addition, the interaction of the plasmons on the inner and outer surfaces of the shell gives rise to two hybridized plasmon modes which energies can be also varied with the variation of the inner to outer shell radius ratio [**?**]. The combination of the *invisibility* and a *strong absorption* are two important ingredients which we propose to use to create a narrow optical window with the enhanced transparency [**?**]. This property can be used to design a narrow optical band-pass filters by means of nanoparticles which consist of a dielectric core (a quantum dot) surrounded by a metallic shell. The components can be adjusted such that there is a remarkable transparency at the desired wavelength range, while a strong absorption takes place outside of this region. We show that the validity of our conclusions is based on the Fano resonance mechanism in strongly coupled systems, which gives rise to *a plasmon-induced transparency* of complex nanoparticles [**?**].

It is a fundamental feature of quantum theory that the dynamics of an isolated system will follow a unitary evolution, and thus be fully reversible. In practice, most quantum systems are influenced by uncontrolled and inevitable interactions with an often incoherent environment, and this influence will typically destroy this deterministic evolution and result in the rapid vanishing of any quantum coherence within the open system. The vast majority of theoretical work has been carried out throughout the last half century devoted to open quantum systems. As a result, Markovian approaches have been successfully employed to study various phenomena in open systems, when the past memory of the system is neglected [**?**]. The advent in ultra-fast laser-pulse technology [**?**], quantum information processing [**?**], synthesis of new super-heavy elements in cold and hot-fusion reactions [**?**] are requiring a resolution of quantum dynamics, when a system is far from equilibrium. It is also non clear how the memory effects affect solar energy conversion to chemical energy or electricity in biological systems [**?**]. All mentioned problems require the development of non-Markovian approaches to describe transport phenomena in mesoscopic systems.
From this point of view, the photosynthetic reaction center (RC) of bacteria provides an interesting system for studying a high-efficiency electron transfer in an organized molecular complex. The RC is a special pigment-protein complex, that functions as a photochemical trap (the analogue of a quantum dot). In such systems, after excitation the electron transfer is so fast that there can exist unrelaxed vibrational modes in the considered system in the primary stage of electron transfer.
Creation of electrons or excitons by the incident light (photons) in a system (with initially statistically independent unrelaxed vibrational modes) leads to an initial condition term (IT) in the generalized master-equation approach, due to interaction of an electron (an exciton) with vibrational modes (phonons) (see [**?**]). The contribution of this term in the time convolution generalized master-equation approach is studied in the second order of the perturbation theory in path-integral formalism [**?**]. The developed approach, applied for the analysis of dynamics in the RC, exhibits the key role of the ITs at the primary stage of electron transfer. It was shown that the memory effects associated with the ITs depend mainly on the amount of energy stored in the initially unrelaxed phonon modes and also on the lifetime of the electron in the system. If the electron lifetime is much longer than the phonon relaxation time, the ITs do not affect the quantum yields of electron transfer via possible pathways. In systems, where this condition is not fulfilled, the ITs can cause the electron transfer via channels which are closed in the case without the ITs. These features may found applications at the design of new generation of solar cells based on quantum dots.

[1] J.A. Schuller, *et al.*, Nat. Mat. **9** (2010) 193.

[2] V. Klimov, *Nanoplasmonics* (Pan Stanford Publishing, Singapore, 2011).

[3] C. Christiansen, Ann. Phys. Chem. **23** (1884) 298; *ibid* **24** (1885) 439; R.A. Smith, F.E. Jones, and R.P. Chasmar, *The Detection and Measurement of Infra-Red Radiation* (Oxford University Press, London, 1968) 2nd ed..

[4] J.D. Jackson, *Classical Electrodynamics* (Wiley, New York, 1999) 3rd ed..

[5] M. Kerker, J. Opt. Soc. Am. **65** (1975) 376; H. Chew and M. Kerker, *ibid* **66** (1976) 445.

[6] C.F. Bohren and D.R. Huffman, *Absorption and Scattering of Light by Small Particles* (Wiley, New York, 1998).

[7] A. Alú and N. Engheta, Phys. Rev. E **72** (2005) 016623.

[8] E. Prodan, C. Radloff, H.J. Halas, and P. Nordlander, *Science* **302** (2003) 419 (2003).

[9] Y.B. Martynov, R.G. Nazmitdinov, I.A. Tanachev, and P.P. Gladyshev, JETP Lett. **95** (2012) 122 [Pis'ma v ZhETF **95** (2012) 138 (2012)].

[10] Y.B. Martynov, R.G. Nazmitdinov, P.P. Gladyshev, and I.A. Tanachev, J. Phys.: Conf. Ser. **393** (2012) 012007.

[11] U. Weiss, *Quantum Dissipative Systems* (World Scientific, Singapore, 2008).

[12] J. Shah, *Ultrafast Spectroscopy of Semiconductors and Semiconductor Nanostructures* (Springer, New York, 1999).

[13] S.M. Barnett, *Quantum Information* (Oxford University Press, New York, 2009).

[14] Yu. Ts. Oganessian, J. Phys. G: Nucl. Part. Phys. **34** (2007) R165; V.V. Sargsyan, Z. Kanokov, G.G. Adamian, N.V. Antonenko, and W. Scheid, Phys. Rev. C **80** (2009) 034606.

[15] D. DeVault, *Quantum Mechanical Tunneling in Biological Systems* (Cambridge University Press, Cambridge, 1995).

[16] M. Pudlak, K.N. Pichugin, R.G. Nazmitdinov, and R. Pincak, Phys. Rev. E **84** (2011) 051912.

MONOGRAPHS

1. V. D. Toneev, in "The CBM physics book: Compressed baryonic matter in laboratory experiments, Chapter III: Collision dynamics", Eds. B. Friman, C. Hohne, J. Knoll, S. Leupold, J. Randrup, R. Rapp,, P. Senger; Conveners: J. Knoll, J. Randrup, Ch. Fuchs, *Lect. Notes Phys.* **814**, *531–680 (2011).*

JOURNAL PUBLICATIONS

1. Kh. U. Abraamyan,...V. D. Toneev, et al., "The MPD detector at the NICA heavy-ion collider at JINR", *Nucl. Instrum. Meth. A* **628** *(2011) 99–102.*

2. Kh. U. Abraamyan, M. I. Baznat, A. V. Friesen, K. K. Gudima,... A. N. Sissakian, A. S. Sorin, and V. D. Toneev, "Resonance structure in the $\gamma\gamma$ invariant mass spectrum in pC, dC, and dCu interactions", *Phys. At. Nucl.* **75** *(2012) 657–660.*

3. G. G. Adamian, N. V. Antonenko, V. V. Sargsyan, W. Scheid, "Production of neutron-rich isotopes in transfer-type reactions", *Int. J. Mod. Phys. E* **20** *(2011) 999–1002.*

4. G. G. Adamian, N. V. Antonenko, W. Scheid, "Isotopic dependence of the production cross sections of superheavy nuclei", *Romanian J. Phys.* **57** *(2012) 9–17.*

5. G. G. Adamian, N. V. Antonenko, V. V. Sargsyan, A. S. Zubov, W. Scheid, "Formation of hyperdeformed states from dinuclear system", *Int. J. Mod. Phys. E* **20** *(2011) 919–922.*

6. G. G. Adamian, N. V. Antonenko, S. N. Kuklin, B. N. Lu, L. A. Malov, and S. G. Zhou, "Behavior of one-quasiparticle levels in odd isotonic chains of heavy nuclei", *Phys. Rev. C* **84** *(2011) 024324 (9 pages).*

7. G. Ademard, J. P. Wieleczko,... Sh. A. Kalandarov,...R. Roy, G. G. Adamian, N. V. Antonenko, "Decay of excited nuclei produced in ^{78,82}Kr+^{40}Ca reactions at 5.5 MeV/nucleon", *Phys. Rev. C* **83** *(2011) 054619 (14 pages).*

8. S. Albeverio, A. K. Motovilov, "Operator integrals with respect to a spectral measure and solutions to some operator equations", *Trudy Moskov. Matem. Obshch.* ***72****:1 (2011) 63–103.*

9. S. Albeverio, A. K. Motovilov, and C. Tretter, "Bounds on the spectrum and reducing subspaces of a J-self-adjoint operator", *Indiana University Math. J.* ***59****:5 (2010) 1737–1776* http://www.iumj.indiana.edu/IUMJ/FULLTEXT/2010/59/4225.

10. S. Albeverio and A. K. Motovilov, "The a priori $\tan\theta$ theorem for spectral subspaces", *Integral Equations and Operator Theory* ***73*** *(2012) 413–430.*

11. M. Alvioli, C. Ciofi degli Atti, L. P. Kaptari, C. B. Mezzetti, H. Morita, and S. Scopetta, "Universality of nucleon-nucleon short-range correlations: Two-nucleon momentum distributions in few-body systems", *Phys. Rev. C* **85** *(2012) 021001(R) (5 pages).*

12. A. V. Andreev, G. G. Adamian, and N. V. Antonenko, "Mass distributions for induced fission of different Hg isotopes", *Phys. Rev. C* **86** *(2012) 044315 (2012).*

13. D.-V. Anghel, A. S. Parvan, A. S. Khvorostukhin, "Fractional exclusion statistics applied to relativistic nuclear matter", *Physica A* **391** *(2012) 2313–2321.*

14. A. N. Antonov, ... , S. N. Ershov, ... , A. Heinz, "The electron-ion scattering experiment ELISe at the International Facility for Antiproton and Ion Research (FAIR) - A conceptual design study", *Nucl. Instr. Meth. Phys. Res. A* **637** *(2011) 60–76.*

15. A. B. Arbuzov, B. M. Barbashov, R. G. Nazmitdinov, V. N. Pervushin, A. Borowiec, K. N. Pichugin, A. F. Zakharov, "Universe as a representation of affine and conformal symmetries", *Part. Nucl. Lett.* **8** *(2011) 318–342.*

16. N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov and Nguyen Van Giai, "Structure of low-lying quadrupole states in ^{134}Xe", *Bull. RAS. Physics* **75** *(2011) 1602–1605.*

17. E. B. Balbutsev, L. A. Malov, and P. Schuck, "Spatial dependence of pairing in deformed nuclei", *Phys. At. Nucl.* **74** *(2011) 1651–1654.*

18. E. B. Balbutsev, I. V. Molodtsova, P. Schuck, "Spin scissors mode and the fine structure of $M1$ states in nuclei", *Nucl. Phys. A* **872** *(2011) 42–68.*

19. D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, L. Rumyantsev, A. Sapronov, and W. von Schlippe, "SANC Integrator in the progress: QCD and EW contributions", *JETP Lett.* **96** *(2012) 285–289.*

20. D. Bardin, S. Bondarenko, P. Christova, L. Kalinovskaya, V. Kolesnikov, V. von Schlippe, and K. Yordanova, "Standard SANC modules for NLO QCD radiative corrections to single top-quark production", *Phys. Part. Nucl. Lett.* **9** *(2012) 472–483.*

21. V. B. Belyaev, "Can water burn?", *Kommersant–Nauka No. 7 (7), 03.10.2011* http://www.kommersant.ru/doc/1781270/print

22. V. B. Belyaev, A. A. Naumkin, "Approximate treatment of 3-body Coulomb systems. Discrete spectrum", *Few-Body Syst.* **50** *(2011) 403–405.*

23. V. B. Belyaev, I. I. Shlyk, "Few-body meson-nuclear clusters", *Vestnik S.- Peterburgskogo un-ta. Series 4: Physics and Chemistry* **3** *(2011) 110–114*

24. S. M. Bilenky, F. Šimkovic, "A possible probe of neutrinoless double-beta decay nuclear matrix elements", *Phys. Part. Nucl. Lett. 9 (2012) 220–227.*

25. S. G. Bondarenko, V. V. Burov, E. P. Rogochaya, "Covariant relativistic separable kernel approach for electrodisintegration of the deuteron at high momentum transfer", *Few Body Syst.* **49** *(2011) 121–128.*

26. S. G. Bondarenko, V. V. Burov, E. P. Rogochaya, "Relativistic complex separable potential of the neutron-proton system", *Phys. Lett. B* **705** *(2011) 264–268.*

27. S. Bondarenko, V. Burov, E. Rogochaya, "Relativistic complex separable potential for describing the neutron-proton system in $3^S_1 - 3^D_1$ partial-wave state", *Nucl. Phys. B (Proc. Suppl.)* **219-220** *(2011) 126–129.*

28. S. G. Bondarenko, V. V. Burov and E. P. Rogochaya, "Final state interaction effects in electrodisintegration of the deuteron within the Bethe-Salpeter approach", *JETP Lett.* **94** *(2011) 738–743.*

29. C. Ciofi degli Atti, L. P. Kaptari, H. Morita, S. Scopetta, "Short range correlations and wave function factorization in light and finite nuclei", *Few-Body Syst.* **50** *(2011) 243–246.*

30. C. Ciofi degli Atti, L. P. Kaptari, "Semi-inclusive deep-inelastic scattering off few-nucleon systems: Tagging the EMC effect and hadronization mechanisms with detection of slow recoiling nuclei", *Phys. Rev. C* **83** *(2011) 044602 (8 pages).*

31. C. Ciofi Degli Atti, L. P. Kaptari, Ch. B. Mezzetti, "Tagging EMC effects and hadronization mechanisms by semi-inclusive deep inelastic scattering off nuclei", *Fizika B* **20** *(2011) 161–172.*

32. J. Darai, J. Cseh, N. V. Antonenko, G. Royer, A. Algora, P. O. Hess, R. V. Jolos, and W. Scheid, "Clusterization in the shape isomers of the ^{56}Ni nucleus", *Phys. Rev. C* **84** *(2011) 024302 (11 pages).*

33. S. M. Dorkin, L. P. Kaptari, C. Ciofi degli Atti, B. Kämpfer, "Solving the Bethe-Salpeter equation in Euclidean space", *Few Body Syst.* **49** *(2011) 233–246.*

34. S. M. Dorkin, T. Hilger, L. P. Kaptari, B. Kämpfer, "Heavy pseudoscalar mesons in a Schwinger-Dyson-Bethe-Salpeter approach", *Few Body Syst.* **49** *(2011) 247–254.*

35. R. Dvornický, K. Muto, F. Šimkovic, A. Faessler "The absolute mass of neutrinos and the first unique forbidden β-decay of ^{187}Re", *Phys. Rev. C* **83** *(2011) 045502 (4 pages).*

36. A. A. Dzhioev, A. I. Vdovin, V. Yu.Ponomarev, and J. Wambach, "Thermal effects on neutrino-nucleus inelastic scattering in stellar environments", *Phys. At. Nucl.* **74** *(2011) 1162–1170.*

37. I. A. Egorova, R. J. Charity, L. V. Grigorenko, Z. Chajecki,... M. Youngs, and M. V. Zhukov, "Democratic decay of ^{6}Be exposed by correlations", *Phys. Rev. Lett.* **109** *(2012) 202502 (5 pages).*

38. S. N. Ershov, J. S. Vaagen, and M. V. Zhukov, "Novel method for solution of coupled radial Schrödinger equations", *Phys. At. Nucl.* **74** *(2011) 1151–1161.*

39. S. N. Ershov, J. S. Vaagen, M. V. Zhukov, "Modified variable phase method for the solution of coupled radial Schrödinger equations", *Phys. Rev. C* **84** *(2011) 064308 (8 pages).*

40. S. N. Ershov, J. S. Vaagen, M. V. Zhukov, "Binding energy constraint on matter radius and soft dipole excitations of ^{22}C", *Phys. Rev. C* **86** *(2012) 034331 (8 pages).*

41. Amand Faessler, V.A. Rodin, F. Šimkovic, "Nuclear matrix elements for neutrinoless double-beta decay and double-electron capture", *J. Phys. G: Nucl. Part. Phys.* **39** *(2012) 124006 (20 pages).*

42. Dong-Liang Fang, K. Blaum, S. Eliseev, Amand Faessler, M. I. Krivoruchenko, V. Rodin, and F. Šimkovic, "Evaluation of the resonance enhancement effect in neutrinoless double-electron capture in ^{152}Gd, ^{164}Er, and ^{180}W atoms", *Phys. Rev. C* **85** *(2012) 035503 (6 pages).*

43. Dong-Liang Fang, K. Blaum, S. Eliseev, Amand Faessler, M. I. Krivoruchenko, V. Rodin, and F. Šimkovic, "Evaluation of the resonance enhancement effect in neutrinoless double-electron capture in ^{152}Gd, ^{164}Er, and ^{180}W atoms", *Phys. Rev. C* **85** *(2012) 035503 (6 pages).*

44. D. Fink, J. Barea, D. Beck, K. Blaum, Ch. Böhm,... L. Schweikhard, F. Šimkovic, J. Stanja, and K. Zuber, "Q value and half-lives for the double-β-decay nuclide ^{110}Pd", *Phys. Rev. Lett.* **108** *(2012) 062502 (5 pages).*

45. A. S. Fomichev, I. G. Mukha,... I. Egorova, M. S. Golovkov... G. M. Ter-Akopian, R. Wolski, M. V. Zhukov, "Lifetime of ^{26}S and a limit for its 2p decay energy", *Int. J. Mod. Phys. E* **20** *(2011) 1491–1508.*

46. A. S. Fomichev, V. Chudobaa, I. A. Egorova, S. N. Ershov, M. S. Golovkova,... G. M. Ter-Akopian, R. Wolski, M. V. Zhukov, "Isovector soft dipole mode in ^{6}Be", *Phys. Lett. B* **708** *(2012) 6–13.*

47. A. V. Friesen, Yu. L. Kalinovsky, V. D. Toneev, "Decay of a scalar σ-meson near the critical end-point in the PNJL model", *Phys. Part. Nucl., Lett.* **9** *(2012) 1–6.*

48. A. V. Friesen, Yu. L. Kalinovsky, V. D. Toneev, "Effects of model parameters in thermodynamics of the PNJL model", *Int. J. Mod. Phys. A* **27** *(2012) 1250013 (15 pages).*

49. H. G. Ganev, "Triaxial shapes in the interacting vector boson model", *Phys. Rev. C* **84** *(2011) 054318 (10 pages).*

50. H. G. Ganev, "Transition probabilities in the U(3,3) limit of the symplectic interacting vector boson model", *Phys. Rev. C* **86** *(2012) 054311 (11 pages).*

51. P. Giannakeas, V. S. Melezhik, P. Schmelcher, "Resonant d-wave scattering in harmonic waveguides", *Phys. Rev. A* ***84*** *(2011) 023618 (6 pages).*

52. P. Giannakeas, V. S. Melezhik, and P. Schmelcher, "Analytical treatment of bosonic d-wave scattering in isotropic harmonic waveguides", *Phys. Rev. A* ***85*** *(2012) 042703 (6 pages).*

53. W. D. Heiss, R. G. Nazmitdinov, "Spectral singularities and zero energy bound states", *Eur. Phys. J. D* **63** *(2011) 369–373.*

54. R. V. Jolos, "Extension of the random-phase approximation for γ-soft nuclei", *Phys. At. Nucl.* **74** *(2011) 1147–1150.*

55. R. V. Jolos, and P. von Brentano, "Parity splitting and $E1/E2$ branching in the alternating parity band of ^{240}Pu from two-center octupole wave functions using supersymmetric quantum mechanics", *Phys. Rev. C* **84** *(2011) 024312 (7 pages).*

56. R. V. Jolos and P. von Brentano, "Particle-core coupling model approach to structure of the low-lying states of ^{11}B and the effect of the Pauli blocking", *Romanian J. Phys.* **57** *(2012) 288–295.*

57. R. V. Jolos and P. von Brentano, "Intrinsic frame inverse mass tensor as a function of β and γ in the Bohr Hamiltonian", *Phys. At. Nucl.* **75** *(2012) 411–419.*

58. R. V. Jolos, P. von Brentano, and J. Jolie, "Second order phase transitions from octupole-nondeformed to octupole-deformed shape in the alternating parity bands of nuclei around ^{240}Pu based on data", *Phys. Rev. C* **86** *(2012) 024319 (8 pages).*

59. R. V. Jolos, L. A. Malov, N. Yu. Shirikova, and A. V. Sushkov, "Structure of some low lying two-quasiparticle and collective states in nuclei with $Z \sim 100$ considered in the quasiparticle phonon model", *J. Phys. G: Nucl. Part. Phys.* **38** *(2011) 115103 (11 pages).*

60. R. V. Jolos, N. Pietralla, N. Yu. Shirikova, and V. V. Voronov, "Schematic microscopic approach to the description of $M1$ transitions between mixed-symmetry and fully symmetric collective states in γ-soft nuclei based on RPA-IBM boson mapping", *Phys. Rev. C* **84** *(2011) 014315 (10 pages).*

61. R. V. Jolos, N. Yi. Shirikova, and A. V. Sushkov, "Neutron number dependence of the energies of the γ -vibrational states in nuclei with $Z \sim$100 and the manifestation of pseudospin symmetry", *Phys. Rev. C* **86** *(2012) 044320 (7 pages).*

62. Sh. A. Kalandarov, G. G. Adamian, N. V. Antonenko, and W. Scheid, "Role of angular momentum in the production of complex fragments in fusion and quasifission reactions", *Phys. Rev. C* **83** *(2011) 054611 (8 pages).*

63. Sh. A. Kalandarov, G. G. Adamian, N. V. Antonenko, W. Scheid, J. P. Wieleczko, "Angular momentum dependence of cluster emission from highly excited nuclei", *Acta Phys. Polonica B* **42** *(2011) 487–491.*

64. S. A. Kalandarov, Z. Kanokov, G. G. Adamian, N. V. Antonenko, W. Scheid, "Non-Markovian dynamics of an open quantum system with nonstationary coupling", *Phys. Rev. E* **83** *(2011) 041104 (11 pages).*

65. Sh. A. Kalandarov, G. G. Adamian, N. V. Antonenko, W. Scheid, S. Heinz, V. Comas, S. Hofmann, J. Khuyagbaatar, D. Ackermann, J. Heredia, F. P. Heßberger, B. Kindler, B. Lommel, R. Mann, "Emission of clusters with $Z > 2$ from excited actinide nuclei", *Phys. Rev. C* **84** *(2011) 054607 (11 pages).*

66. Sh. A. Kalandarov, G. G. Adamian, N. V. Antonenko, W. Scheid, J. P. Wieleczko, "Role of the entrance channel in the production of complex fragments in fusion-fission and quasifission reactions in the framework of the dinuclear system model", *Phys. Rev. C* **84** *(2011) 064601 (11 pages).*

67. Sh. A. Kalandarov, G. G. Adamian, and N. V. Antonenko, "Emission of heavy clusters in nuclear reactions at low collision energies", *Phys. Part. Nucl.* **43** *(2012) 825–866.*

68. A. S. Khvorostukhin, V. D. Toneev, and D. N. Voskresensky, "Shear and bulk viscosities for pure glue matter", *Phys. Rev. C* **83** *(2011) 035204 (8 pages).*

69. A. S. Khvorostukhin, V. D. Toneev, D. N. Voskresensky, "Viscosity of hadron matter within relativistic mean-field-based model with scaled hadron masses and couplings", *Phys. At. Nucl.* **74** *(2011) 650–658.*

70. A. S. Khvorostukhin, V. D. Toneev, D. N. Voskresensky, "Relaxation time ansatz and shear and bulk viscosities of gluon matter", *Phys. Rev. C* **84** *(2011) 035202 (9 pages).*

71. E. A. Kolganova, A. K. Motovilov, W. Sandhas, "The ^{4}He trimer as an Efimov system", *Few-Body Syst.* **51** *(2011) 249–257.*

72. E. A. Kolganova, V. Roudnev, and M. Cavagnero, "Helium trimer calculations with a public quantum three-body code", *Phys. At. Nucl.* **75** *(2012) 1240–1244.*

73. V. P. Konchakovski, E. L. Bratkovskaya, W. Cassing, V. D Toneev, V. Voronyuk, "Rise of azimuthal anisotropies as a signature of the quark-gluon plasma in relativistic heavy-ion collisions", *Phys. Rev. C* **85** *(2012) 011902(R) (4 pages).*

74. V. P. Konchakovski, E. L. Bratkovskaya, W. Cassing, V. D. Toneev, S. A. Voloshin, and V. Voronyuk, "Azimuthal anisotropies for Au + Au collisions in the parton-hadron transient energy range", *Phys. Rev. C* **85** *(2012) 044922 (13 pages).*

75. V. N. Kondratyev, "Magic ultramagnetized nuclei in explosive nucleosynthesis", *Phys. Atom. Nucl.* ***78*** *(2012) 1368–1372.*

76. A. Korgul, K.P. Rykaczewski, J.A. Winger, S.V. Ilyushkin, C.J. Gross, J.C. Batchelder, C. Bingham, I.N. Borzov,... K. Sieja, and E.F. Zganjar, "Beta-gamma and beta-delayed neutron-gamma decay of neutron-rich copper isotopes", *Phys. Rev. C* **86** *(2012) 024307 (9 pages).*

77. S. N. Kuklin, T. M. Shneidman, G. G. Adamian, and N. V. Antonenko, "Alpha-decay fine structures of U isotopes and systematics for isotopic chains of Po and Rn", *Eur. Phys. J. A (2012) 48: 112 (11 pages); DOI 10.1140/epja/i2012-12112-8.*

78. V. A. Kuz'min, T. V. Tetereva, "Influence of monopole pairing on the energies of single-nucleon states in the problem of superconducting pairing correlations", *Phys. At. Nucl.* **75** *(2012) 805–810.*

79. A. N. Kuzmina, G. G. Adamian, N. V. Antonenko, "Impact of nuclear structure on production and identification of new superheavy nuclei", *Eur. Phys. J. A* **47***: 145 (2011); DOI 10.1140/epja/i2011-11145-9.*

80. A. N. Kuzmina, G. G. Adamian, and N. V. Antonenko, "Structures of nuclei in α-decay chains of ^{291,293}117", *Phys. Rev. C* **85** *(2012) 017302 (4 pages).*

81. A. N. Kuzmina, G. G. Adamian, N. V. Antonenko, and W. Scheid, "Influence of proton shell closure on production and identification of new superheavy nuclei", *Phys. Rev. C* **85** *(2012) 014319 (11 pages).*

82. A. N. Kuzmina, G. G. Adamian, and N. V. Antonenko, "Role of quasiparticle structure in α decays of the heaviest nuclei", *Phys. Rev. C* **85** *(2012) 027308 (5 pages).*

83. R. A. Kuzyakin, V. V. Sargsyan, G. G. Adamian, and N. V. Antonenko, "Peculiarities of parabolic-barrier penetrability and thermal decay rate with the quantum diffusion approach", *Phys. Rev. A* **83** *(2011) 062117 (8 pages).*

84. R. A. Kuzyakin, V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, "Probability of passing through a parabolic barrier and thermal decay rate: Case of linear coupling both in momentum and in coordinate", *Phys. Rev. A* **84** *(2011) 032117.*

85. R. A. Kuzyakin, V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, E. E. Saperstein, S. V. Tolokonnikov, "Isotopic trends of capture cross section and mean-square angular momentum of the captured system", *Phys. Rev. C* **85** *(2012) 034612 (12 pages).*

86. R. A. Kuzyakin, V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, "Quantum diffusion description of the subbarrier-capture process in heavy-ion reactions", *Phys. At. Nucl.* **75** *(2012) 439–448.*

87. J. Kvasil, V. O. Nesterenko, W. Kleinig, D. Božhík, and P.-G. Reinhard, "Skyrme-Hartree-Fock description of the dipole strength in neutron-rich tin isotopes", *Int. J. Mod. Phys. E* **20** *(2011) 281–291.*

88. J. Kvasil, V. O. Nesterenko, W. Kleinig, P.-G. Reinhard, and P. Vesely, "General treatment of vortical, toroidal, and compression modes", *Phys. Rev. C* **84** *(2011) 034303 (14 pages).*

89. J. Kvasil, A. Repko, V. O. Nesterenko, W. Kleinig, and P.-G. Reinhard, "E1 strength in light nuclei: Skyrme RPA analysis", *Int. J. Mod. Phys. E* **21** *(2012) 1250041 (9 pages).*

90. V. L. Litnevsky, G. I. Kosenko, F. A. Ivanyuk, and V. V. Pashkevich, "Allowance for the shell structure of colliding nuclei in the fusion-fission process", *Phys. At. Nucl.* **74** *(2011) 1001–1009.*

91. V. L. Litnevsky, G. I. Kosenko, F. A. Ivanyuk, and V. V. Pashkevich, "Allowance for the shell structure of the $^{100}_{42}$Mo and $^{110}_{46}$Pd nuclei in the synthesis of $^{200}_{84}$Po, $^{210}_{88}$Ra, and $^{220}_{92}$U", *Phys. At. Nucl.* **75** *(2012) 37–44.*

92. V. L. Litnevsky, V. V. Pashkevich, G. I. Kosenko, F. A. Ivanyuk, "Influence of the shell structure of colliding nuclei in fusion-fission reactions", *Phys. Rev. C* **85** *(2012) 034602 (9 pages).*

93. V. L. Litnevsky, G. I. Kosenko, F. A. Ivanyuk, V. V. Pashkevich, "Allowance for the orientation of colliding ions in describing the synthesis of heavy nuclei", *Phys. At. Nucl.* **75** *(2012) 1500–1512.*

94. N. Lo Iudice, V. Yu. Ponomarev, Ch. Stoyanov, A. V. Sushkov, and V. V. Voronov, "Low-energy nuclear spectroscopy in a microscopic multiphonon approach", *J. Phys G: Nucl. Part. Phys.* **39** *(2012) 043101 (37 pages).*

95. V. K. Lukyanov, E. V. Zemlyanaya, K. V. Lukyanov, D. N. Kadrev, A. N. Antonov, M. K. Gaidarov, "Theoretical analysis of ^{6}He+^{12}C scattering by means of the model of microscopic Optical Potential", *Bull. RAS. Physics* **75** *(2011) 495–499.*

96. V. K. Lukyanov, D. N. Kadrev, E. V. Zemlyanaya, L. N. Antonov, K. V. Lukyanov, M. K. Gaidarov, and K. Spasova, "Microscopic analysis of the elastic scattering of ^{11}Li neutron-rich nuclei on protons", *Phys. At. Nucl.* **75** *(2012) 1407–1412.*

97. M. Madurga, R. Surman, I. N. Borzov, K. P. Rykaczewski,... M. Wolinska-Cichocka, E. F. Zganjar, "New half-lives of neutron-rich Zn and Ga isotopes measured with electromagnetic separation", *Phys. Rev. Lett.* **109** *(2012) 112501 (5 pages).*

98. G. Mandaglio, G. Giardina, A. K. Nasirov, and A. Sobiczewski, "Investigation of the ^{48}Ca+$^{249-252}$Cf reactions synthesizing isotopes of the superheavy element 118", *Phys. Rev. C* **86** *(2012) 064607 (9 pages).*

99. Y. B. Martynov, R. G. Nazmitdinov, I. A. Tanachev, P. P. Gladyshev, "Effects of plasmonic resonances and transparency of nanoshells for optical filtering", *JETP Lett.* **95** *(2012) 138–142.*

100. V. S. Melezhik, "Multi-channel computations in low-dimensional few-body physics", *Lecture Notes Comp. Sci.* **7125** *(2012) 94–107.*

101. V. S. Melezhik, P. Schmelcher, "Multichannel effects near confinement-induced resonances in harmonic waveguides", *Phys. Rev. A* ***84*** *(2011) 042712 (7 pages).*

102. S. Mishev, V. V. Voronov, "Ground-state correlations and structure of the low-lying states in odd-even spherical and transitional nuclei", *Romanian J. Phys.* **57** *(2012) 380–398.*

103. A. K. Nasirov, G. Fazio, G. Giardina, G. Mandaglio, M. Manganaro, A. I. Muminov, "Appearance of nuclear shell effects and initial charge (mass) asymmetry in formation of products in heavy ion collisions", *Int. J. Mod. Phys. E* **20** *(2011) 406–414.*

104. A. K. Nasirov, G. Mandaglio, G. Giardina, A. Sobiczewski, A. I. Muminov, "Effects of the entrance channel and fission barrier in the synthesis of superheavy element $Z = 120$", *Phys. Rev. C* **84** *(2011) 044612 (8 pages).*

105. A. K. Nasirov, R. B. Tahkhodzhaev, and O. O. Abdurazakov, "True ternary fission of ^{236}U: A sequential mechanism?", *Bull. RAS. Physics* **76** *(2012) 467–471.*

106. T. Nousch, D. Seipt, B. Kämpfer, A.I. Titov, "Pair production in short laser pulses near threshold", *Phys. Lett. B* **715** *(2012) 246–250.*

107. A. S. Parvan, T. S. Biró, "'Equilibrium statistical mechanics for incomplete nonextensive statistics", *Phys. Lett. A* **375** *(2011) 372–378.*

108. A. S. Parvan, "Caloric curve for nuclear liquid-gas phase transition in relativistic mean-field hadronic model", *Nucl. Phys. A* **887** *(2012) 1–21.*

109. V. N. Pervushin, A. B. Arbuzov, B. M. Barbashov, R. G. Nazmitdinov, A. Borowiec, K. N. Pichugin, A. F.Zakharov, "Conformal and affine Hamiltonian dynamics of general relativity", *General Relativ. & Gravit.* **44** *(2012) 2745–2783.*

110. V. N. Pervushin, A. B. Arbuzov, B. M. Barbashov, R. G. Nazmitdinov, A. Borowiec, K. N. Pichugin, A. F. Zakharov, "The general relativity with conformal units", *Fiz. Elem. Chast. At. Yadra* **43** *(2012) 1319–1331.*

111. M. Pudlak, K. N. Pichugin, R. G. Nazmitdinov, R. Pincak, "Quantum non-equilibrium approach for fast electron transport in open systems: Photosynthetic reaction centers", *Phys. Rev. E* **84** *(2011) 051912 (6 pages).*

112. S. Saeidian, V. S. Melezhik, and P. Schmelcher, "Shifts and widths of Feshbach resonances in atomic waveguides", *Phys. Rev. A* ***86*** *(2012) 062713 (9 pages).*

113. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, and H. Q. Zhang, "Sub-barrier capture with quantum diffusion approach: Actinide-based reactions", *Eur. J. Phys. A* **47***: 38 (2011) DOI 10.1140/epja/i2011-11038-y.*

114. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, and H. Q. Zhang, "Erratum to: Sub-barrier capture with quantum diffusion approach: Actinide-based reactions", *Eur. J. Phys. A* **47***: 39 (2011) DOI 10.1140/epja/i2011-11039-x*

115. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, H.Q. Zhang, "Effects of nuclear deformation and neutron transfer in capture processes, and fusion hindrance at deep sub-barrier energies", *Phys. Rev. C* **84** *(2011) 064614 (12 pages).*

116. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, C. J. Lin, and H. Q. Zhang, "Oblate-prolate deformation effect in capture reactions at sub-barrier energies", *Phys. Rev. C* **85** *(2012) 017603 (4 pages).*

117. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, and H. Q. Zhang, "Role of neutron transfer in capture processes at sub-barrier energies", *Phys. Rev. C* **85** *(2012) 024616 (5 pages).*

118. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, and H. Q. Zhang, "Erratum: Role of neutron transfer in capture processes at sub-barrier energies [Phys. Rev. C 85, 024616 (2012)]", *Phys. Rev. C* **85** *(2012) 069903(E) (1 page).*

119. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, C. J. Lin, and H. Q. Zhang, "Deformation effect in the sub-barrier capture process", *Phys. Rev. C* **85** *(2012) 037602 (4 pages).*

120. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, and H. Q. Zhang, "Influence of neutron transfer in reactions with weakly and strongly bound nuclei on the sub-barrier capture process", *Phys. Rev. C* **86** *(2012) 014602 (10 pages).*

121. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, and H. Q. Zhang, "Astrophysical S factor, logarithmic slope of the excitation function, and barrier distribution", *Phys. Rev. C* **86** *(2012) 034614 (6 pages).*

122. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, and H.Q.Zhang, "Search of systematic behavior of breakup probability in reactions with weakly bound projectiles at energies around Coulomb barrier", *Phys. Rev. C* **86** *(2012) 054610 (9 pages).*

123. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, and H.Q.Zhang, "Quasifission at extreme sub-barrier energies", *Eur. J. Phys. A* **48***: 188 (2012) (4 pages) DOI 10.1140/epja/i2012-12188-0.*

124. A. P. Severyukhin, N. N. Arsenyev, V. V. Voronov, N. Pietralla, and Nguyen Van Giai, "Description of proton-neutron mixed-symmetry states with Skyrme interaction", *Phys. At. Nucl.* **74** *(2011) 1171–1175.*

125. Alexey P. Severyukhin, Victor V. Voronov, and Nguyen Van Giai, "Charge-exchange excitations with Skyrme interactions in a separable approximation", *Progress Theor. Phys.* **128** *(2012) 489–506.*

126. A. P. Severyukhin, N. N. Arsenyev, and N. Pietralla, "Proton-neutron symmetry in ^{92}Zr, ^{94}Mo with Skyrme interactions in a separable approximation", *Phys. Rev. C* **86** *(2012) 024311 (8 pages).*

127. V. M. Shilov, "Sub-barrier fusion of spherical nuclei of intermediate nuclear numbers", *Phys. At. Nucl.* **75** *(2012) 485–490.*

128. T. M. Shneidman, G. G. Adamian, N. V. Antonenko, R. V. Jolos, W. Scheid, "Multiple reflection asymmetric type band structures in ^{220}Th and dinuclear model", *Eur. J. Phys. A* **47***: 34 (2011) DOI 10.1140/epja/i2011-11034-3.*

129. T. M. Shneidman, G. G. Adamian, N. V. Antonenko, R. V. Jolos, W. Scheid, "Multiple reflection asymmetric type band structures in ^{220}Th and dinuclear model", *Acta Phys. Polonica B* **42** *(2011) 481–486.*

130. S. I. Sidorchuk, A. A. Bezbakh, V. Chudoba, I. A. Egorova, A. S. Fomichev, et al., "Structure of ^{10}He low-lying states uncovered by correlations", *Phys. Rev. Lett.* **108** *(2012) 202502 (5 pages).*

131. S. A. Sofianos, R. M. Adam, V. B. Belyaev, "α-cluster-model description of nuclei", *Phys. Rev. C* **84** *(2011) 064304 (6 pages).*

132. E. A. Solov'ev, "Classical approach in atomic physics", *Eur. Phys. J. D* **65** *(2011) 331–351.*

133. Evgeni A. Solov'ev, "On the foundations of quantum physics", *Phys. Essays* **25** *(2012) 27–33.*

134. M. K. Suleymanov, R. G. Nazmitdinov, E. I. Shahaliev, O. B. Abdinov, A. Ajaz, A. Zaman, K. H. Khan, and Z. Wazir, "Applying a new method for analyzing experimental data on nuclear reactions at high energies", *Bull. RAS. Physics* **76** *(2012) 1089–1092.*

135. A. I. Svirikhin, A. V. Andreev, V. N. Dushin,... E. A. Sokol, and A. V. Yeremin, "The emission of prompt neutrons from the spontaneous fission of ^{252}No and ^{244}Fm", *Eur. Phys. J. A* **48***: 121 (2012) (6 pages); DOI 10.1140/epja/i2012-12121-7.*

136. R. B. Tashkhodjaev, A. K. Nasirov, W. Scheid, "Collinear cluster tripartition as sequential binary fission in the ^{235}U(n_{th}, f) reaction", *Eur. Phys. J. A* **47***: 136 (2011) DOI 10.1140/epja/i2011-11136-x.*

137. G. M. Ter-Akopian, A.A. Bezbakh, R. Wolski,...I. A. Egorova,... A. S. Fomichev, V. Chudoba, "Research program for the radioactive beams of the ACCULINNA-2 separator", *Bull. RAS: Physics* **76** *(2012) 1172–1176.*

138. L. Tiator, D. Drechsel, S. S. Kamalov, M. Vanderhaeghen, "Electromagnetic excitation of nucleon resonances", *Eur. Phys. J. ST* ***198*** *(2011) 141–170.*

139. A. I. Titov, B. Kämpfer, H. Takabe, A. Hosaka, "Neutrino pair emission off electrons in a strong electromagnetic wave field," *Phys. Rev. D* **83** *(2011) 053008 (13 pages).*

140. A. I. Titov, H. Takabe, B. Kämpfer, A. Hosaka, "Enhanced subthreshold e^+e^- production in short laser pulses", *Phys. Rev. Lett.* **108** *(2012) 240406 (5 pages).*

141. V. D. Toneev, V. Voronyuk, "Beam-energy and system-size dependence of the CME", *Phys. Part. Nucl. Letters* **8** *(2011) 938–943.*

142. V. D. Toneev, V. Voronyuk, "The chiral magnetic effect: Beam-energy and system-size dependence", *Phys. At. Nucl.* **75** *(2012) 607–612.*

143. V. D. Toneev, V. Voronyuk, E. L. Bratkovskaya, W. Cassing, V. P. Konchakovski, S. A. Voloshin, "Theoretical analysis of a possible observation of the chiral magnetic effect in Au + Au collisions within the RHIC beam energy scan program", *Phys. Rev. C* **85** *(2012) 034910 (6 pages).*

144. V. D. Toneev, V. P. Konchakovski, V. Voronyuk, E. L. Bratkovskaya, W. Cassing, "Event-by-event background in estimates of the chiral magnetic effect", *Phys. Rev. C* **86** *(2012) 064907 (19 pages).*

145. J. D. Vergados, H. Ejiri, and F. Šimkovic, "Theory of neutrinoless double-beta decay", *Rep. Prog. Phys.* **75** *(2012) 106301 (52 pages).*

146. V. Voronyuk, V. D. Toneev, W. Cassing, E. L. Bratkovskaya, V. P. Konchakovski, S. A. Voloshin, "Electromagnetic field evolution in relativistic heavy-ion collisions", *Phys. Rev. C* **83** *(2011) 054911 (16 pages).*

147. R. L. Workman, M. W. Paris, W. J. Briscoe, L. Tiator, S. Schumann, M. Ostrick, S. S. Kamalov, "Model dependence of single-energy fits to pion photoproduction data", *Eur. Phys. J. A* **47** *(2011) 143–155.*

148. A. S. Zubov, V. V. Sargsyan, G. G. Adamian, and N. V. Antonenko, "Population of ground-state rotational bands of superheavy nuclei produced in complete fusion reactions", *Phys. Rev. C* **84** *(2011) 044320 (10 pages).*

ARTICLES ACCEPTED FOR PUBLICATIONS

1. S. Albeverio and A. K. Motovilov, "Sharpening the norm bound in the subspace perturbation theory", *Complex Analysis and Operator Theory*, Online First; DOI: http://dx.doi.org/10.1007/s11785-012-0245-7

2. N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov, "Description of properties of quadrupole states in ^{94}Mo with Skyrme interaction", *Bull. RAS. Physics, accepted.*

3. J. L. Birman, R. G. Nazmitdinov, V. I. Yukalov, "Effects of symmetry breaking in finite quantum systems", *Phys. Rep., accepted.*

4. S. I. Fedotov, O. I. Kartavtsev, "Transformations of the three-body pseudo-vector ($L^P = 1^+$) hyper-spherical harmonics", *Phys. Rev. A, accepted*

5. R. V. Jolos, N. Yu. Shirikova, A. V. Sushkov, "Relation between the mass coefficients for rotational and gamma-vibrational states in the well deformed nuclei", *Phys. Atom. Nucl., in print.*

6. A. N. Kuzmina, G. G. Adamian, N. V. Antonenko, "The effect of quasiparticle structure on alpha decay of superheavy nuclei", *Bull. RAS. Physics, accepted.*

7. J. Kvasil, V. O. Nesterenko, A. Repko, W. Kleinig, P.-G. Reinhard, and N. Lo Iudice, "Toroidal, compression, and vortical dipole strengths in ^{124}Sn", *Physica Scripta, accepted*; arXiv: 1211.2978, 2012.

8. V. K. Lukyanov, E. V. Zemlyanaya, K. V. Lukyanov, E. I. Zhabitskaya, M. V. Zhabitsky, "Modeling the pion-nucleus microscopic optical potential at the (3,3)-resonance energy and in-medium effect on the pion-nucleon amplitude", *Yad. Fiz., accepted*; JINR Preprint, P4-2012-105 , JINR, Dubna, 2012.

9. V. K. Lukyanov, E. V. Zemlyanaya, K. V. Lukyanov, A. Y. Ellithi, I.A.M. Abdel-Magead, B. Slowinski, "Calculations of the pion-nucleus elastic scattering differential cross sections using the microscopic optical potential", *Izv. RAN., ser. fiz., accepted*

10. C. Mazzocchi, K.P. Rykaczewski, A. Korgul, R. Grzywacz,... M. Wolinska-Cichocka, and I. N. Borzov, "New half-life measurements of the most neutron rich arsenic and germanium isotopes", *Phys. Rev. C (R), accepted.*

11. V. V. Pupyshev, "Modeling of the proton-proton reaction in the electron gas", *Vestnik MSTU "Stankin", accepted.*

12. V. V. Pupyshev, "Proton-hydrogen atom scattering in effective two-body model", *Phys. At. Nucl., accepted*; JINR Preprint P4-2011-123, Dubna, JINR, 2011.

13. V. V. Pupyshev, "Proton-hydrogen reaction in effective two-body model", *Phys. At. Nucl., accepted*; JINR Preprint P4-2011-129, Dubna, JINR, 2011.

14. J. S. Vaagen, S. N. Ershov and M. V. Zhukov, "New method for solution of coupled radial Schrödinger equations: application to the Borromean two-neutron halo nucleus ^{22}C", *Phys. At. Nucl., accepted*.

15. A. S. Zubov, V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, "Production of superdeformed states in A $\sim$ 150 region", *Phys. Rev. C, accepted*.

PREPRINTS AND DATA BASES

1. E. B. Balbutsev, I. V. Molodtsova, P. Schuck, "A new type of nuclear collective motion - the spin scissors mode", arXiv: 1301.2513, 2013.

2. V. B. Belyaev, M. B. Miller, "Quantum amplification on molecular-nuclear transitions", arXiv: 1104.2709, 2011.

3. V. B. Belyaev, P. Ricci, F. Šimkovic, E. Truhlík, "The consequence of total lepton number violation in strongly magnetized white dwarfs", arXiv: 1212.3155, 2012.

4. Alan A. Dzhioev, A. I. Vdovin, "Thermal QRPA equations with finite rank separable approximation for residual forces based on the Skyrme type interactions", arXiv: 1112.6152, 2011.

5. Amand Faessler, Vadim Rodin, Fedor Šimkovic, "Nuclear matrix elements for neutrinoless double-beta decay and double-electron capture", arXiv: 1206.0464, 2012.

6. A. S. Fomichev, A. A. Bezbakh, I. A. Egorova, V. Chudoba, A. V. Daniel, M. S. Golovkov, V. A. Gorshkov, L. V. Grigorenko, S. A. Krupko, Yu. Ts. Oganessian, Yu. L. Parfenova, S. I. Sidorchuk, R. S. Slepnev, S. V. Stepantsov, P. G. Sharov, G. M. Ter-Akopian, S. N. Ershov, V. K. Lukyanov, B. V. Danilin, A. A. Korsheninnikov, . . Kuzmin, V. Z. Goldberg, I. G. Mukha, M. Pfutzner, H. Simon, O. B. Tarasov, N. K. Timofeyuk, A. A. Yukhimchuk, and M. V.Zhukov, "Long-range plans for research with radioactive ion beams at JINR", JINR Communication, 7-2012-73, JINR, Dubna, 2012.

7. B. F. Irgaziev, V. B. Belyaev, and J.-U. Nabi, "Three-body calculation of the rate of reaction $p + p + e \to d + \nu_e$ in the Sun", arXiv: 1212.3882, 2012.

8. O. I. Kartavtsev and A. V. Malykh, "Recent advances in description of few two-component fermions", arXiv: 1211.5557, 2012.

9. V. P. Konchakovski, V. D. Toneev, W. Cassing, E. L. Bratkovskaya, S. A. Voloshin, and V. Voronyuk, "Collective properties of nucleus-nucleus collisions from AGS to LHC energies", arXiv: 1207.3272v2, 2012.

10. A. Meroni, S. T. Petcov, F. Šimkovic, "Multiple CP non-conserving mechanisms of $0\nu\beta\beta$-decay and nuclei with largely different nuclear matrix elements", arXiv: 1212.1331, 2012.

11. S. Mishev, "Structure of the phonon vacuum state", arXiv: 1211.4730, 2012.

12. A. K. Motovilov, "Comment on 'The tan θ theorem with relaxed conditions', by Y. Nakatsukasa", arXiv:1204.4441, 2012.

13. A. S. Parvan, "Critique of multinomial coefficients method for evaluating Tsallis and Rényi entropies", arXiv: 0911.0383v3, 2012.

14. A. S. Parvan, "Special relativity with an arbitrary invariant limiting velocity of a particle", arXiv: 1202.3319v2, 2012.

15. A. S. Parvan, "Nuclear first order phase transition associated with Helmholtz free energy of canonical ensemble", arXiv: 1206.6753v1, 2012.

16. V. V. Pupyshev, "Scattering of a slow quantum particle by a central short-range potential ", JINR Preprint P4-2012-101, Dubna, JINR, 2012.

17. V. V. Pupyshev, "Scattering of a slow quantum particle by an axially symmetrical short-range potential", JINR Preprint P4-2012-119, Dubna, JINR, 2012.

18. A. Repko, P.-G. Reinhard, V.O. Nesterenko, and J. Kvasil, "On the toroidal nature of the low-energy $E1$ mode", arXiv: 1212.2088, 2012.

19. A. P. Severyukhin, V. V. Voronov, Nguyen Van Giai, "Spin-isospin excitations in nuclei and a separable approximation for Skyrme interactions", JINR Preprint, E4-2011-107, JINR, Dubna, 2011.

20. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, and H.Q.Zhang, "Threshold energy for sub-barrier fusion hindrance phenomenon", arXiv: 1211.2312v2, 2012.

21. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, and H.Q.Zhang, "Sub-barrier capture reactions with ^{16,18}O beams", arXiv: 1211.4330, 2012.

22. F. Šimkovic, S. M. Bilenky, Amand Faessler, Th. Gutsche, "On the possibility of a measurement of the CP Majorana phase in the $0\nu\beta\beta$-decay", arXiv: 1210.1306, 2012.

23. E. A. Solov'ev, "Physics and Metaphysics", arXiv: 1212.1299, 2012.

CONFERENCE CONTRIBUTIONS

1. G. G. Adamian, N. V. Antonenko, V. V. Sargsyan, W. Scheid, A. S. Zubov, "Production of exotic nuclei in quasifission-type reactions", *in the Proceedings of Intern. Symposium on Quasifission Process in Heavy Ion Reactions (Messina, Italy, November 8-9, 2010); J. Phys.: Conf. Ser.* **282** *(2011) 012002 (16 pages).*

2. G. G. Adamian, N. V. Antonenko, W. Scheid, "Mechanism of heavy ion fusion to superheavy nuclei", *in the Proceedings of XXXIV Symposium on Nuclear Physics (Cocoyoc, Morelos, Mexico, January 4-7, 2011); J. Phys.: Conf. Ser.* **322** *(2011) 012009 (9 pages).*

3. G. Ademard, J. P. Wieleczko,... Sh. A. Kalandarov,...R. Roy, G. G. Adamian, N. V. Antonenko, "Decay of excited nuclei produced in ^{78,82}Kr+^{40}Ca reactions at 5.5 MeV/nucleon", *in the Proceedings of the 5th Intern. Conference FUSION11 (Saint-Malo, France, May 2-6, 2011) Ch. Schmitt, A. Navin, M. Rejmund, D. Lacroix and H. Goutte (Eds.), EPJ Web Conf.* **17** *(2011) 10005 (4 pages).*

4. N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov, "Properties of the low-lying states in ^{94}Mo", *in the Proceedings of the Scientific session MEPHI-2011 (Moscow, Russia, February 1-5, 2011), MEPHI, Moscow, 2011, V. 2, p. 169.*

5. N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov, "Properties of the low-lying states in ^{94}Mo", *in the Proceedings of XV$^{\underline{th}}$ scientific conference of young scientists and specialists JINR (Dubna, Russia, February 14–19, 2011), JINR, Dubna, 2011, pp. 22–25.*

6. N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov, and Nguyen Van Giai, "Effects of phonon-phonon coupling on properties of pygmy resonance in $^{124-132}$Sn", *in the Proceedings of Intern. Conference on Nuclear Structure and Related Topics (Dubna, Russia, July 3–7, 2012); EPJ Web of Conf.* **38** *(2012) 17002.*

7. E. B. Balbutsev, I. V. Molodtsova, "Fine structure of the Nuclear Scissors Mode (new type of collective motion)", *in the Proceedings of the XIX Intern. School on Nuclear Physics, Neutron Physics and Applications (Varna, Bulgaria, September 19-25, 2011), J. Phys.: Conf. Ser.* **366** *(2012) 012002.*

8. D. Boer, M. Diehl, R. Milner, R. Venugopalan, W. Vogelsang, ...L. P. Kaptari, et al., "Gluons and the quark sea at high energies: distributions, polarization, tomography", *a report on the joint BNL/INT/Jlab program on the science case for an Electron-Ion Collider (INT, Seattle, USA, September 13 to November 19, 2010)* arXiv: 1108.1713 [nucl-th]; preprints: INT-PUB-11-034, BNL-96164-2011, JLAB-THY-11-1373.

9. S. G. Bondarenko, V. V. Burov, E. P. Rogochaya, "Relativistic separable interaction kernel of the neutron-proton system with inelasticities", *in "Relativistic Nuclear Physics and Quantum Chromodynamics": the Proceedings of the XX Intern. Baldin Seminar on High Energy Physics Problems (Dubna, Russia, October 4-9, 2010) v. 1, 112-117, Dubna, JINR, 2011, pp. 112–117.*

10. S. G. Bondarenko, V. V. Burov and E. P. Rogochaya, "Final state interaction effects in exclusive electrodisintegration of the deuteron", *in the Proceedings of the XXI Intern. Baldin Seminar on High Energy Physics Problems (Dubna, Russia, September 10-15, 2012); PoS(Baldin ISHEPP XXI)026*; http://pos.sissa.it.

11. I. N. Borzov, "Evolution of single-particle structure and beta-decay near ^{78}Ni", *in the Proceedings of Intern. Conference on Nuclear Structure and Related Topics (Dubna, Russia, July 3–7, 2012); EPJ Web of Conf.* **38** *(2012) 12002.*

12. E. L. Bratkovskaya, V. P. Konchakovski, O. V. Voronyuk, V.D. Toneev, O. Linnyk, and W. Cassing, "The QGP phase in relativistic heavy-ion collisions", *to appear in the Proceedings of the Intern. Symposium on 'Exciting Physics' (Makutsi-Range, South Africa, November 13-20, 2011)*; arXiv: 1202.4891, 2012.

13. J. Cseh, J. Darai, A. Algora, N. Antonenko, G. Adamian, "Super and hyperdeformed states, and reactions to populate them", *in the Proceedings of the 5th Intern. Conference FUSION11 (Saint-Malo, France, May 2-6, 2011) Ch. Schmitt, A. Navin, M. Rejmund, D. Lacroix and H. Goutte (Eds.), EPJ Web Conf.* **17** *(2011) 16001 (4 pages).*

14. J. Darai, J. Cseh, G. G. Adamian, N. V. Antonenko, A. Georgieva, "Dipole and quadrupole collectivity in atomic nuclei", *in the Proceedings of the XIX Intern. School on Nuclear Physics, Neutron Physics and Applications (Varna, Bulgaria, September 19-25, 2011), J. Phys.: Conf. Ser.* **366** *(2012) 012009.*

15. J. Darai, J. Cseh, G. Adamian and N. Antonenko, "Extreme quadrupole deformation and clusterization", *in the Proceedings of Intern. Conference on Nuclear Structure and Related Topics (Dubna, Russia, July 3–7, 2012) S. Ershov, T. Shneydman, A. Vdovin, and A. Zubov (Eds.); EPJ Web Conf.* **38** *(2012) 16001.*

16. R. Dvornicky, F. Šimkovic, "Second unique forbidden beta decay of ^{115}In and neutrino mass", *in the Proceedings of the Workshop on Calculation of Double Beta Decay Matrix Elements, (Prague, Czech Republic, June 13-16, 2011), AIP Conf. Proc.* **1417** *(2011) 33–36.*

17. K. G. Dvoyan, V. V. Evoyan, E. M. Kazaryan, R. G. Nazmitdinov, H. A. Sarkisyan, "Magneto-absorption in ellipsoidal quantum dot", *in the Proceedings of the Intern. Conference on Laser Physics 2011 (Ashtarak, Armenia, October 11-14, 2011) A. Papoyan (Ed.); Int. J. Mod. Phys. CS* **15** *(2012) 40–47.*

18. A.S. Fomichev, A.A. Bezbakh, V. Chudoba, I.A. Egorova, S.N. Ershov,...A.A. Kirdyashkin, I.P. Maksimkin, and O.P. Vikhlyantsev, "Recent results related to excited states of ^{6}Be and ^{10}He", *in the Proceedings of Intern. Conference on Nuclear Structure and Related Topics (Dubna, Russia, July 3–7, 2012) S. Ershov, T. Shneydman, A. Vdovin, and A. Zubov (Eds.); EPJ Web Conf.* **38** *(2012) 15002.*

19. H. G. Ganev, "Triaxiality in the IVBM", *in the Proceedings of the XXXI Intern. Workshop on Nuclear Theory (Rila Mountains, Bulgaria, June 24-30, 2012), A. Georgieva and N. Minkov (eds.), Heron Press, Sofia, 2012, pp. 204–214..*

20. G. Giardina, A. K. Nasirov, G. Mandaglio, F. Curciarello, V. De Leo, G. Fazio, M. Manganaro, M. Romaniuk, C. Saccá, "Investigation on the quasifission process by theoretical analysis of experimental data of fissionlike reaction products", *in the Proceedings of Intern. Symposium on Quasifission Process in Heavy Ion Reactions (Messina, Italy, November 8-9, 2010); J. Phys.: Conf. Ser.* **282** *(2011) 012006 (20 pages).*

21. D. N. Kadrev, V. K. Lukyanov, A. N. Antonov, E. V. Zemlyanaya, K. V. Lukyanov, M. K. Gaidarov, K. Spasova, "Microscopic analysis of ^{11}Li elastic scattering from protons", *in the Proceedings of the 30th Intern. Workshop on Nuclear Theory, (Rila Mountains, Bulgaria, June 26 – July 02, 2011): "Nuclear Theory", v. 30, eds. A. Georgieva, N. Minkov, Heron Press, Sofia, 2011, pp.126–137.*

22. Sh. A. Kalandarov, G. G. Adamian, N. V. Antonenko, J. P. Wieleczko, "Production of doubly magic nucleus ^{100}Sn in ^{72,74,76}Kr + ^{40}Ca, ^{72,74,76}Kr + ^{40}Ar and ^{72,74,76}Kr + ^{32}S reactions at 4–6 MeV/nucleon", *in the Proceedings of the 5th Intern. Conference FUSION11 (Saint-Malo, France, May 2-6, 2011) Ch. Schmitt, A. Navin, M. Rejmund, D. Lacroix and H. Goutte (Eds.), EPJ Web Conf.* **17** *(2011) 10004 (4 pages).*

23. Sh. A. Kalandarov, G. G. Adamian, and N. V. Antonenko, "Description of light charged particle multiplicities in the framework of dinuclear system model", *in the Proceedings of Intern. Conference on Nuclear Structure and Related Topics (Dubna, Russia, July 3–7, 2012) S. Ershov, T. Shneydman, A. Vdovin, and A. Zubov (Eds.); EPJ Web Conf.* **38** *(2012) 09002.*

24. V. N. Kondratyev, "Creation and transmutation of magnetized nuclei at explosively dense matter", *in the Proceedings of Intern. Conference on Nuclear Structure and Related Topics (Dubna, Russia, July 3-7, 2012); EPJ Web Conf.* ***38*** *(2012) 17008.*

25. A. A. Korobitsin, E. A. Kolganova, "Dimer and trimer of helium at ultralow energies", *in the Proceedings of the XV Conference of young scientists and specialists JINR (Dubna, Russia, February 14-19, 2011), JINR, Dubna, 2011, pp. 34–35.*

26. A. N. Kuzmina, G. G. Adamian, N. V. Antonenko, "Influence of proton shell closure on production of new superheavy nuclei", *in the Proceedings of Intern. Conference on Nuclear Structure and Related Topics (Dubna, Russia, July 3–7, 2012) S. Ershov, T. Shneydman, A. Vdovin, and A. Zubov (Eds.); EPJ Web Conf.* **38** *(2012) 17004.*

27. J. Kvasil, V. O. Nesterenko, P. Vesely, W. Kleinig, and P.-G. Reinhard, "Description of giant resonances with Skyrme forces", *in the Proceedings of 10th Intern. Spring Seminar on Nuclear Physics: New Quests in Nuclear Structure (Vietri Sul Mare, Italy, May 21-25, 2010); J. Phys.: Conf. Ser.* **267** *(2011) 012055 (6 pages).*

28. V. K. Lukyanov, D. N. Kadrev, E. V. Zemlyanaya, A. N. Antonov, K. V. Lukyanov. M. K. Gaidarov, "Analysis of ^{6}He+^{12}C elastic scattering and breakup reactions using a microscopic optical potential model", *in the Proceedings of the XIX Intern. School on Nuclear Physics, Neutron Physics and Applications (Varna, Bulgaria, September 2011); J. Phys. Conf. Ser.* **366** *(2012) 012032 (5 pages).*

29. V. K. Lukyanov, E. V. Zemlyanaya, K. V. Lukyanov, A. Y. Ellithi, I. A. M. Abdel-Magead, B. Słowiǹski, "Calculations of the pion-nucleus elastic scattering differential cross sections using the microscopic optical potential", *in the Proceedings of the XXI Intern. Baldin Seminar on High Energy Physics Problems (Dubna, Russia, September 10-15, 2012); PoS(Baldin ISHEPP XXI)020*; http://pos.sissa.it.

30. V. K. Lukyanov, E. V. Zemlyanaya, E. I. Zhabitskaya, K. V. Lukyanov, M. V. Zhabitsky, "Study of in-medium effect on the pion-nucleon amplitude from analysis of pion-nucleus data within the microscopic optical potential", *in the Proceedings of the XXI Intern. Baldin Seminar on High Energy Physics Problems (Dubna, Russia, September 10-15, 2012); PoS(Baldin ISHEPP XXI)021*; http://pos.sissa.it.

31. V. K. Lukyanov, D. N. Kadrev, E. V. Zemlyanaya, K. Spasova, A. N. Antonov, K. V. Lukyanov, M. K. Gaidarov, "Analysis of the ^{11}Li breakup on a proton target", *Proceedings of the 31th Intern. Workshop on Nuclear Theory, (Rila Mountains, Bulgaria, June 24–30, 2012): "Nuclear Theory", v. 31, eds. A. Georgieva, N. Minkov, Heron Press, Sofia, Bulgaria, 2012, pp.225-233.*

32. L. Majling, O. Majlingová, V. A. Kuz'min, and T.V. Tetereva, "Hyperfragments from light 1p-shell nuclei", *in the Proceedings of Intern. Conference on Nuclear*

Structure and Related Topics (Dubna, Russia, July 3–7, 2012); EPJ Web of Conf. **38** *(2012) 14005.*

33. G. Mandaglio, A. K. Nasirov, F. Curciarello, V. De Leo, M. Romaniuk, G. Fazio and G. Giardina' "Processes in massive nuclei reactions and the way to complete fusion of reactants. What perspectives for the synthesis of heavier superheavy elements ?", *in the Proceedings of Intern. Conference on Nuclear Structure and Related Topics (Dubna, Russia, July 3–7, 2012) S. Ershov, T. Shneydman, A. Vdovin, and A. Zubov (Eds.); EPJ Web Conf.* **38** *(2012) 01001.*

34. G. Mandaglio, A. K. Nasirov, F. Curciarello, V. De Leo, M. Romaniuk, G. Fazio, G. Giardina, "What perspectives for the synthesis of heavier superheavy nuclei? Results and comparison with models", *to appear in the Proceedings of the 11th Intern. Conference on Nucleus-Nucleus Collisions (NN2012) (San Antonio, Texas, USA, May 27 – June 1, 2012), J. Phys. Conf. Ser.*; arXiv: 1208.5363v2, 2012.

35. Vladimir S. Melezhik, "Nondirect product discrete variable representation in multidimensional quantum problems", *in the Proceedings of the Intern. Conference on Numerical Analysis and Applied Mathematics (Kos, Greece, September 19–25, 2012); AIP Conf. Proceedings* **1479** *(2012) 1200–1203.*

36. Avazbek Nasirov, Giorgio Giardina, Giuseppe Mandaglio, Marina Manganaro, Werner Scheid, "Dynamics of dinuclear system formation and its decay in heavy ion collisions", *in the Proceedings of Intern. Symposium on Quasifission Process in Heavy Ion Reactions (Messina, Italy, November 8-9, 2010); J. Phys.: Conf. Ser.* **282** *(2011) 012010 (20 pages).*

37. N. I. Rukhadze, A. M. Bakalyarov, Ch. Briançon, V. B. Brudanin,...F. Šimkovic,... S. V. Zhukov, "Experiment TGV-2. Search for double beta decay of ^{106}Cd", *in the Proceedings of 12th Intern. Conference on Topics in Astroparticle and Underground Physics (TAUP 2011) (Münich, Germany, September 5–9, 2011), J. Phys. Conf. Ser.* **375** *(2012) 042020.*

38. V. V. Sargsyan, R. A. Kuzyakin, G. G. Adamian, N. V. Antonenko, W. Scheid, H.Q. Zhang, "Sub-barrier capture with quantum diffusion approach", *in the Proceedings of the 5th Intern. Conference FUSION11 (Saint-Malo, France, May 2-6, 2011) Ch. Schmitt, A. Navin, M. Rejmund, D. Lacroix and H. Goutte (Eds.), EPJ Web Conf.* **17** *(2011) 04003 (6 pages).*

39. V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, W. Scheid, and H. Q. Zhang, "Role of neutron transfer and deformation effect in capture process at sub-barrier energies", *in the Proceedings of Intern. Conference on Nuclear Structure and Related Topics (Dubna, Russia, July 3–7, 2012) S. Ershov, T. Shneydman, A. Vdovin, and A. Zubov (Eds.); EPJ Web Conf.* **38** *(2012) 09005.*

40. A. P. Severyukhin, V. V. Voronov, and Nguyen Van Giai, "A separable approximation for Skyrme interactions and charge-exchange excitations", *in the Proceedings of 10th Intern. Spring Seminar on Nuclear Physics: New Quests in Nuclear Structure (Vietri Sul Mare, Italy, May 21-25, 2010); J. Phys.: Conf. Ser.* **267** *(2011) 012025 (6 pages).*

41. A. P. Severyukhin, N. N. Arsenyev, V. V. Voronov, N. Pietralla, Nguyen Van Giai, "Proton-neutron mixed-symmetry states and a separable approximation for Skyrme interactions", *in the Proceedings of the Intern. EFES-IN2P3 Conference "Many-body correlations from dilute to dense nuclear systems" (MBC 2011) (Paris, France, 15-18 February 2011); J. Phys.: Conf. Ser.,* **321** *(2011) 012050 (4 pages).*

42. A.P. Severyukhin and H. Sagawa, "Gamow-Teller resonances and a separable approximation for Skyrme tensor interactions", *in the Proceedings of Intern. Conference on Nuclear Structure and Related Topics (Dubna, Russia, July 3–7, 2012); EPJ Web of Conf.* **38** *(2012) 06001.*

43. T. M. Shneidman, A. V. Andreev, M. Sin, C. Massimi, G. Vannini, A. Ventura, "Advanced fission models in nuclear data calculations", *in the Proceedings of the XIX Intern. School on Nuclear Physics, Neutron Physics and Applications (Varna, Bulgaria, September 19-25, 2011), J. Phys.: Conf. Ser.* **366** *(2012) 012046.*

44. T .M. Shneidman, A. V. Andreev, M. T. Pigni, C. Massimi, G. Vannini, and A. Ventura, "Collective spectra along the fission barrier", *in the Proceedings of Intern. Conference on Nuclear Structure and Related Topics (Dubna, Russia, July 3–7, 2012) S. Ershov, T. Shneydman, A. Vdovin, and A. Zubov (Eds.); EPJ Web Conf.* **38** *(2012) 07001.*

45. F. Šimkovic, "Massive Majorana neutrinos in nuclear pro- cesses", *in the Proceedings of 19th Intern. School on Nuclear Physics, Neutron Physics and Applications (VARNA2011) (Varna, Bulgaria, September 19-25, 2011), J. Phys. Conf. Ser.* **366** *(2012) 012041.*

46. A.I. Titov, B. Kämpfer, H. Takabe, A. Hosaka, "Neutrino pair emission in a strong electromagnetic wave field", *in the Proceedings of the Intern. Conference on the Structure of Baryons (BARYONS' 10) (Osaka, Japan, December 7-11, 2010); AIP Conf. Proc.* **1388** *(2011) 225–228.*

47. J. S. Vaagen, S. N. Ershov, and M.V. Zhukov, "Lessons from 25 years on the driplines: still a catwalk ?", *in the Proceedings of the Symposium in Advance in Nuclear Physics in Our Time (Goa, India, November 28 - December 2, 2010) D. Bandyopadhyay (Ed.), World Scientific, Singapore, 132–141 (2012).*

48. Shin Nan Yang, S. S. Kamalov, L. Tiator, "P_{11} resonances with Dubna-Mainz-Taipei dynamical model for πN scattering and pion electromagnetic production", *in the Proceedings of the 8th Intern. Workshop on the Physics of Excited Nucleons: NSTAR 2011 (Newport News, VA, USA, May 17-20, 2011); AIP Conf. Proceedings* ***1432*** *(2012) 293– 296.*

49. E. V. Zemlyanaya, V. K. Lukyanov, K. V. Lukyanov, E. I. Zhabitskaya, M. V. Zhabitsky, "Pion-nucleus microscopic optical potential at intermediate energies and in-medium effect on the elementary πN scattering amplitude", *in the Proceedings of the 31th Intern. Workshop on Nuclear Theory, (Rila Mountains, Bulgaria, June 24–30, 2012): "Nuclear Theory", v. 31, eds. A. Georgieva, N. Minkov, Heron Press, Sofia, 2012, pp.175–184;[arXiv: 1210.1069, 2012]*

50. H. Q. Zhang, C. L. Zhang, and C. J. Lin, A. K. Nasirov, G. Mandaglio, M. Manganaro, and G. Giardina, "Fusion-fission and quasifission competition in the $^{32}S + ^{184}W$ reaction", *in the Proceedings of Intern. Symposium on Quasifission Process in Heavy Ion Reactions (Messina, Italy, November 8-9, 2010); J. Phys.: Conf. Ser.* **282** *(2011) 012013 (13 pages).*

51. H. Q. Zhang, C. L. Zhang, C. J. Lin, Z. H. Liu, F. Yang, A. K. Nasirov, G. Mandaglio, M. Manganaro, G. Giardina, "Quasifission and fusion-fission competition in $^{32}S + ^{184}W$ reaction", *in the Proceedings of the 5th Intern. Conference FUSION11 (Saint-Malo, France, May 2-6, 2011) Ch. Schmitt, A. Navin, M. Rejmund, D. Lacroix and H. Goutte (Eds.), EPJ Web Conf.* **17** *(2011) 04002 (4 pages).*

52. A. S. Zubov, V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, "Population of rotational bands in superheavy nuclei", *in the Proceedings of the 3rd Intern. Workshop on Compound-Nuclear Reactions and Related Topics, (Prague, Czech Republic, September 19-23, 2011), EPJ Web Conf.* **21** *(2012) 06002 (14 pages) DOI: 10.1051/epjconf/20122106002.*

53. A. S. Zubov, V. V. Sargsyan, G. G. Adamian, N. V. Antonenko, "Population and properties of superdeformed bands in A$\sim$150 region", *to be published in the Proceedings of 10th Intern. Conference on Clustering Aspects of Nuclear Structure and Dynamics (Debrecen, Hungary, September 24-28, 2012), J. Phys. Conf. Ser. (2013).*