II. THEORY OF NUCLEI AND OTHER FINITE SYSTEMS

Nuclear physics focuses on the study of the structure and dynamics of complex systems of particles which build up hadrons and nuclei, and investigations carried out by nuclear physics community of the BLTP cover most of the modern topics. Main efforts in the field ”Theory of nuclei and other finite systems” in 2001-2002 went into the following subjects:

- Nuclear Structure under Extreme Conditions
- Dynamics and Manifestation of Structure in Nuclear and Mesoscopic Systems
- Few-Body Physics
- Relativistic Nuclear Dynamics

Many works were devoted to the theory of nuclear structure. A finite rank separable approximation for an effective interaction of the Skyrme type was extended to take into account the pairing effects. As an illustration of the method the finite rank p-h interaction derived from the Skyrme force SIII has been used to calculate the energies and transition probabilities for the quadrupole and octupole excitations in some O, Ar, Sn and Pb isotopes. Results of calculations are in reasonable agreement with experimental data (A.P. Severyukhin, V.V. Voronov). Properties of the nuclear scissors mode were studied within the method of Wigner function moments (E.B. Balbutsev). A thermal behavior of the giant dipole resonance spreading width at finite temperature in spherical nuclei was studied. It is found that this width is permanently increasing with temperature (A.I. Vdovin, A.N. Storozhenko).

New approaches to describe the low-energy nuclear reactions were developed. The dinuclear system phenomena in the nuclear structure and nuclear reactions were considered. It was found that hyperdeformed states could be seen as dinuclear resonance states in heavy ion reactions. The optimal conditions in heavy-ion and induced fission reactions for the population of long-lived cold dinuclear systems, which are related to the high- and low-spin hyperdeformed states or to nuclear molecular resonances, are determined (G.G. Adamian, N.V. Antonenko, S.P. Ivanova, R.V. Jolos, T.M. Shneidman). In collaboration with experimentalists from the Flerov Laboratory of Nuclear Reactions the implications of the fission modes in the γ-ray multiplicities from the fission fragments in the reaction $^{208}\mathrm{Pb}(^{18}\mathrm{O},\mathrm{f})$ were considered. It was shown experimentally that the mass distribution comprised four distinct fission modes (V.V. Pashkevich). A microscopic four-body DWIA theory for two-neutron halo breakup reactions were developed. The importance of including both elastic and inelastic fragmentation leading to low-lying halo excitations were demonstrated. The method was used to analyze recent GSI experimental data on ^{6}He fragmentation at 240 Mev/nucleon on ^{12}C and ^{208}Pb targets. In addition to a good simultaneous description of absolute cross sections and excitation spectra for both reactions, new insight into the interplay of reaction mechanisms and correlated continuum structure was obtained (S.N. Ershov). A new method of the nucleus-nucleus optical potential restoration at intermediate energies was developed. Applications of this method to the nucleus-nucleus potential were presented and, as a result, a set of surface-equivalent potentials was restored (V.K. Lukyanov).

Various problems were investigated within the project ”Few-Body Physics”. An example of collapsing solution to the Fadeev differential equations was presented (V.V. Pupyshev). The $^{4}\mathrm{He}_3$ bound states and the scattering of a ^{4}He atom off a ^{4}He dimer at ultra-low energies were investigated by using a hard-core version of the Faddeev differential equations. This method, unlike some competing methods, is exact and ideally suited for calculations in three-atomic systems where the two-body interactions usually have a strong repulsive component at small distances between atoms (E.A. Kolganova, A.K. Motovilov). The perturbation effect of a lattice spectral band by a nearby resonance was investigated. A rather general model Hamiltonian was considered. This Hamiltonian consists of a “nuclear” part, a “molecular” part with eigenvalues embedded in the continuous spectrum of the nuclear part, and a weak coupling term which turns these unperturbed eigenvalues into “molecular” resonances. The following property appears, in particular, as a general feature: if the “nuclear” channel itself has a narrow resonance with a position close to the “molecular” energy, then the width (the imaginary part) of the resulting “molecular” resonance is found to be inversely proportional to the “nuclear” width. In other words, a large increase in the decay rate of the “molecular” state, i.e., of the fusion probability, is observed in this case. Such a coincidence of nuclear and molecular energies is, of course, a rather rare phenomenon in nature (V.B. Belyaev, A.K. Motovilov). Within a meson-exchange dynamic model describing most of the existing pion electromagnetic production data up to the second resonance region, one is also able to obtain a good agreement with the π^0 photo- and electroproduction data near the threshold. The potentials used in the model are derived from an effective chiral Lagrangian (S.S. Kamalov).

Interesting results were obtained in the field of relativistic nuclear physics. The status of the OZI-rule with respect to the ϕNN and ϕNN^* coupling constants was discussed. To make an estimate of the nucleon and resonant channels the effective Lagrangian approach developed for the ω-meson photoproduction was used. It was pointed out that the combined examining of the ϕ and ω photoproduction at large angles allows one to analyze the status of the OZI-rule for ϕNN^* -interactions. A large (factor of 4) scale of this violation was found. The spin observables are very sensitive to the resonance excitation channel and can be used to study it in detail (A.I. Titov). The dispersion representation for the nucleon-nucleon T matrix in the Bethe-Salpeter approach was considered (S.G. Bondarenko, V.V. Burov). The role of the final state interaction in inclusive electro-disintegration and exclusive deuteron break-up reaction was investigated within different approaches. Recent data on the reaction $pD \to (pp)n$ with the fast, forwardly going pp-pair at zero-near excitation energies was analyzed within the Bethe-Salpeter formalism. It was demonstrated that relativistic corrections essentially improve the agreement of theoretical results with experimental data (L.P. Kaptari, S.S. Semikh). The collective directed flow of baryons from high-energy heavy-ion collisions based on a hydrodynamic approach with using the different equations of state (EoS) was studied. It was established that the directed flow excitation functions for baryons are sensitive to the EoS. Preliminary experimental results manifest no irregular behavior in excitation functions and, therefore, can be considered as an argument in favour of the quark-hadron mixed phase EoS and cross-over type of the deconfinement phase transition (V.D. Toneev).

The nuclear theory methods were applied in studying metallic clusters. A random-phase-approximation method with separable residual forces (SRPA) was proposed for description of multipole oscillations of valence electrons in deformed alkali metal clusters . Both the deformed mean field and residual interaction were derived self-consistently from the Kohn-Sham functional. SRPA drastically simplifies the computational effort which is urgent if not decisive for deformed systems. At the same time, SRPA provides high numerical accuracy. The method was applied to description of multipole (E1, E2, E3 and M1) plasmons in sodium clusters of a moderate size (V.O. Nesterenko, W Kleinig).

The most promising directions of our future studies are: the nuclear structure far from stability valley and clustering phenomena, reactions with heavy ions and the structure of superheavy elements, dynamics of resonance phenomena in few-body systems, relativistic nuclear dynamics and exotic properties of nuclear matter.

V.V. Voronov

NUCLEAR STRUCTURE CALCULATIONS WITH A SEPARABLE APPROXIMATION FOR SKYRME INTERACTIONS

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Among many microscopic nuclear models aiming at a description of the properties of nuclear excitations the most consistent model employs an effective interaction which can describe, throughout the periodic table, the ground states in the framework of the Hartree-Fock (HF) approximation and the excited states in the time-dependent HF, or random phase approximation (RPA). The Skyrme-type interactions [1] are very popular now. When the residual particle-hole (p-h) interaction is separable, the RPA problem can be easily solved no matter how many p-h configurations are involved. Starting from an effective interaction of Skyrme type, a finite rank separable approximation is proposed [2] for the residual particle-hole interaction to allow one to perform structure calculations in very large particle-hole spaces. Recently this approach was extended to take into account the pairing effects [3].

As an illustration of the method the finite rank p-h interaction derived from the Skyrme force SIII was used to calculate the energies and transition probabilities for the quadrupole and octupole excitations in some O, Ar, Sn and Pb isotopes. As one can see from the table, calculations are in reasonable agreement with experimental data.

Table 1: Energies and B(E2)-values for up-transitions to the first 2^+ states

Nucleus	Energy (MeV)		B(E2↑) (e^2fm^4)	
	Exp.	Theory	Exp.	Theory
^{18}O	1.98	4.75	45±2	14
^{20}O	1.67	4.17	28±2	20
^{36}Ar	1.97	1.91	300±30	310
^{38}Ar	2.17	2.51	130±10	110
^{40}Ar	1.46	2.17	330±40	290
^{112}Sn	1.26	1.49	2400±140	2600
^{114}Sn	1.30	1.51	2400±500	2100
^{206}Pb	0.80	0.96	1000±20	1700
^{208}Pb	4.09	5.36	3000±300	2000

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ON THE MIXING OF BOUND AND UNBOUND LEVELS

R.V. Jolos

The mixing of bound, or of bound and unbound levels is an interesting physical problem which becomes especially important in investigations of weakly bound halo nuclei. Consideration of a two-level mixing is useful for this problem. In particular, it generates a simple language in which the general phenomenon can be discussed. The previous analysis of the two-level mixing was carried out with non-Hermitian effective Hamiltonians with constant parameters. The result of this analysis is that the mixing of a resonance with nonvanishing width and of a state with zero width by an effective and energy independent Hamiltonian always leads to two resonances with nonvanishing widths. On the other hand, it is clear that a weak mixing between a resonance and a bound state will keep the bound state bound in contrast to the result for an energy independent Hamiltonian. The results of our investigations [1] show that the widths of the mixing levels have a characteristic energy behavior depending on a position of the discrete levels with respect to the channel threshold. When the interaction is sufficiently strong, the presence of nonvanishing widths does not change qualitatively the picture of mixing; however, it can influence numerical results.

The coupling of bound and unbound levels, and an effect of the width on this coupling becomes important in very weakly bound halo nuclei. A particularly interesting case is when single-particle energies of the levels occupied by the last valence particles lie in the continuum. Such a picture applies, for example, in the famous halo nucleus ^{11}Li. In the case of this halo nucleus the neighbor nucleus ^{10}Li is unbound. A natural mechanism to produce, despite this fact, a bound state in ^{11}Li is that the interaction among several unbound levels shifts one of them down so that it may become bound. This is possible because the energy gap between the last bound state and the first resonance state is fairly small. An example is the pairing interaction which scatters pairs of neutrons not only into bound single particle states, but also into the continuum. Previous authors have not discussed explicitly the effects of mixing on the width. In our analysis, the width is fully integrated in the discussion.

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THE NUCLEAR SCISSORS MODE IN A SOLVABLE MODEL

E.B. Balbutsev

The method of Wigner Function Moments (WFM) is applied to consider the issue of the physics behind the nuclear scissors mode. In spite of 25 years of research and many valuable contributions to this subject the subtleties of the scissors mode are still under debate [1]. To shed some light on the problem we study the coupled dynamics of the scissors mode and the isovector giant quadrupole resonance (IVGQR) in a model of the harmonic oscillator plus a separable quadrupole-quadrupole residual interaction. The physics becomes particularly transparent once the TDHF equations are written down in phase space and Wigner function moments are introduced [2]. This approach allows one to establish the optimum set of collective variables: quadrupole moment, angular momentum, pressure tensor, etc. These variables are, in the scheme of WFM formalism, absolutely unambiguous and, together with the analytic solution, they allow for a maximum of physical insight. First of all, the inevitable coupling of the scissors

mode with IVGQR becomes obvious already at the stage of formulation of the model. Furthermore, the Fermi surface deformation, whose decisive role in the physics of the scissors mode is difficult to predict employing naive phenomenological models, appears in our approach quite naturally. It is necessary also to notice that the equations of motion for collective variables are written in the laboratory coordinate system. It allows one to get rid of any troubles connected with spurious rotation, because the total angular momentum is conserved.
Analytical expressions for energies, B(M1)- and B(E2)-values, sum rules and flow-patterns of both modes are found [3,4] for arbitrary values of the deformation parameter δ. The eigenvalue equation yields two frequencies given by $\Omega_{\pm} = 2\omega\sqrt{1 \pm \sqrt{1-\frac{3}{4}\delta^2}}$. The low lying frequency corresponds to the one of the scissors mode proper, whereas the other is the so-called high lying scissors mode (IVGQR). Our analysis shows that the motion of both the modes is "scissors"-like in the sense that the long symmetry axes of proton and neutron distributions get tilted by a small angle during their oscillatory motion. Nevertheless, both modes are quite distinct: the low-lying mode has essentially a rotational flow pattern, whereas the high-lying mode has essentially irrotational character. Accordingly, the flow lines of the scissors mode are closed ellipses leading to a compression of the long axis, while the ones of the high lying mode are open hyperbolas leading to an elongation of the long axis. The analytical form of the results is very convenient to study the deformation dependence of the position of resonances and the transitions probabilities. In the small δ limit we mostly reproduce the results already obtained by other authors with different methods. However, for large δ we obtain predictions for superdeformed nuclei. This area is a practically new land still to be explored. The only investigation within a phenomenological model [5] is in sharp contradiction with our numbers. On the other hand, the only existing microscopic calculation [6] presents two sets of data, one of which agrees with the phenomenology [5], whereas the other is much closer to our predictions. The real disagreement in the last case is not very large and can be attributed to the difference in force parameters.
It is worth noticing that the dynamic equations derived for description of the scissors mode are general enough, and one may employ them for the description of the joint dynamics of the isoscalar and isovector giant monopole and quadrupole resonances plus the scissors mode in deformed rotating nuclei, the amplitudes of vibrations being not necessarily small. A large amplitude motion was already treated in the frame of this approach to describe the multiphonon giant quadrupole and monopole resonances [2]. One can think about two-phonon scissors - the first attempt to interpret some numerical results as the multiphonon scissors is already known [7].
One may also think of taking into account the spin degrees of freedom – only the number of dynamic equations must be doubled (spin projections up and down). Then, the theory becomes capable of describing spin-flip excitations. As a result, there appears a possibility of considering the orbital and spin components of the scissors mode simultaneously.
It would be especially interesting to study the behaviour of all modes in rotating superdeformed (SD) nuclei, because "the SD bands in nuclei around ^{152}Dy and ^{192}Hg are observed at high spins" [6]. The first interesting results of calculation interpreted as the rotational band built on the scissors excitation appeared in [7].

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THE TFD TREATMENT OF GIANT DIPOLE RESONANCE SPREADING WIDTH AT FINITE TEMPERATURE

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It is well proved experimentally that the width of a giant dipole resonance (GDR) strongly increases with temperature of a nucleus up to $T \sim 3$ MeV whereas the GDR energy centroid as well as the exhaustion of the energy weighted sum rule (EWSR) are quite stable against temperature. Different theoretical approaches [1-3] describe equally well the thermal behaviour of the energy centroid and EWSR, but provide quite different explanations for the thermal behavior of the GDR width.

We studied a thermal behaviour of the spreading part of the full GDR width in spherical nuclei within the approach based on the Quasiparticle-Phonon Model [4] extended to finite temperature using the Thermo Field Dynamics [5]. The thermal Hamiltonian $\mathscr{H}$ describing the system of interacting thermal quasiparticles β^+, $\tilde{\beta}^+$ and thermal phonons $Q^+_{\lambda\mu i}$, $\widetilde{Q}^+_{\lambda\mu i}$ was evaluated in [6]. It reads

$$\begin{aligned}
\mathscr{H} &= \sum_{\lambda\mu i} \omega_{\lambda i}\left(Q^+_{\lambda\mu i}Q_{\lambda\mu i} - \widetilde{Q}^+_{\lambda\mu i}\widetilde{Q}_{\lambda\mu i}\right) - \\
&- \frac{1}{2\sqrt{2}}\sum_{\lambda\mu i}\sum_{j_1 j_2}\frac{f^{(\lambda)}_{j_1 j_2}}{\sqrt{\mathscr{N}^{\lambda i}}}\Big\{((-)^{\lambda-\mu}Q^+_{\lambda\mu i} + Q_{\lambda-\mu i})B_\beta(j_1 j_2;\lambda-\mu) \\
&- ((-)^{\lambda-\mu}\widetilde{Q}^+_{\lambda\mu i} + \widetilde{Q}_{\lambda-\mu i})\widetilde{B}_\beta(j_1 j_2;\lambda-\mu) + h.c.\Big\}\ ,
\end{aligned}$$

where $\omega_{\lambda i}$ is the energy of the thermal phonon $|\lambda i\rangle$; $\mathscr{N}^{\lambda i}$ is a coefficient depending on a thermal phonon structure; $f^{(\lambda)}_{j_1 j_2}$ is a reduced single-particle matrix element of a multipole operator. The operator $B_\beta(j_1 j_2;\lambda\mu)$ is defined as follows:

$$\begin{aligned}
B_\beta(j_1 j_2;\lambda\mu) &= u^{(+)}_{j_1 j_2}\sqrt{1-n_{j_1}}\sqrt{n_{j_2}}\left(\left[\beta^+_{j_1}\tilde{\beta}_{j_2}\right]_{\lambda\mu} + (-)^{\lambda-\mu}\left[\beta_{j_1}\tilde{\beta}^+_{j_2}\right]_{\lambda-\mu}\right) \\
&- v^{(-)}_{j_1 j_2}\left(\sqrt{1-n_{j_1}}\sqrt{1-n_{j_2}}\left[\beta^+_{j_1}\beta_{j_2}\right]_{\lambda\mu} + \sqrt{n_{j_1}}\sqrt{n_{j_2}}\left[\tilde{\beta}_{j_1}\tilde{\beta}^+_{j_2}\right]_{\lambda\mu}\right),
\end{aligned}$$

where n_j is thermal Fermi-Dirac occupation numbers of the quasiparticle states. The energies of one-quasiparticle states are calculated within the thermal BCS approximation. The energies and structures of thermal phonons are calculated from the thermal RPA equations with separable multipole effective interactions.

Within this approach the fragmentation of the collective giant dipole vibrations at finite T is due to the coupling with "thermal two-phonon" configurations [6]. The coupling matrix element of thermal phonons is determined by their fermionic structure. In contrast with [1,2], only fermionic thermal occupation numbers appear in the theory.

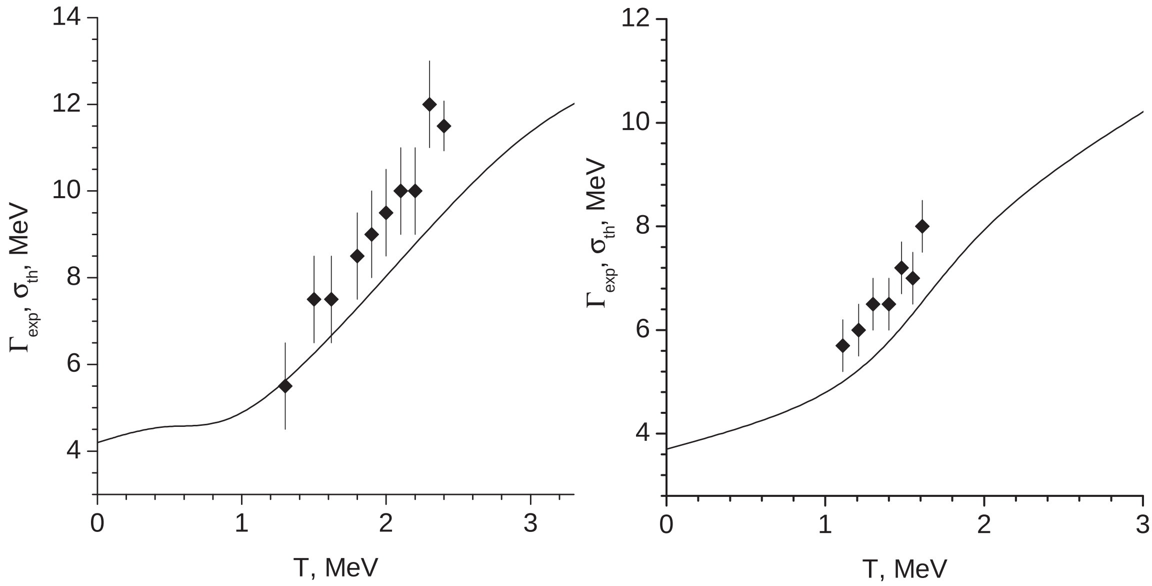

Figure 1: Temperature dependence of the experimental GDR width Γ_{exp} and the dispersion σ_{th} of the theoretical E1 strength function in ^{120}Sn (left panel) and ^{208}Pb (right panel). Dimonds – revised experimental data from [8].

Since a shape of the theoretical E1 strength function deviates quite strongly from that of the Lorentz curve we cannot compare directly the experimental width Γ_{exp} with the theoretical GDR half-width. As a measure of the GDR spreading we use the dispersion σ of the theoretical E1 strength function [7]. The temperature dependence of σ in compound nuclei ^{120}Sn and ^{208}Pb is displayed in Fig.1 together with the experimental data revised in [8].
One can see the dispersion $\sigma(T)$ permanently increasing with temperature. The main reason of this behavior is the coupling of the thermal GDR phonons with very low-lying particle-particle (hole-hole) thermal phonons [7]. These phonons appear only at $T \neq 0$, they are noncollective ones.
These results agree qualitatively with those obtained in [2,3], but contradict the conclusions of [1].

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FISSION MODES IN LIGHT RADIUM AND THORIUM ISOTOPES

V.V. Pashkevich

In collaboration with experimentalists [1] the implications of the fission modes in the γ -ray multiplicities from the fission fragments in the reaction $^{208}\mathrm{Pb}(^{18}\mathrm{O,f})$ were considered. This paper is a continuation of the previous studies of the properties of the fission modes in light thorium isotopes [2]. In [2], the analysis of the mass distribution of the compound system formed in the reaction $^{208}\mathrm{Pb}(^{18}\mathrm{O,f})$ was performed. It was shown experimentally that the mass distribution comprised four distinct fission modes.
It is shown in [1], the phenomenon of multimodal fission also manifests itself in the γ-ray multiplicities from the fission fragments. The calculated shapes of the fission fragments help to explain the observed multiplicities in the symmetric and asymmetric fission and confirm the interpretation of each of the fission modes as going along its own fission valley.
It is concluded that the concept of the valley structure of the potential energy surface is a universal tool for explanation of properties of both a fissioning nucleus and fission fragments [1].
The symmetric and asymmetric fission modes and the corresponding nuclear shapes of light Ra isotopes and of ^{232}Th were considered in [3]. It was shown that the fission of ^{216}Ra was expected to be predominantly symmetric, in accordance with recent experimental findings.
In [4], the two-stage approach to the description of fusion-fission reaction was suggested. At each stage (fusion or fission) the three-dimensional Langevin equation for the variables describing the shape of a nuclear system is solved. In this way, it turned out possible to describe simultaneously for the reaction ^{18}O+^{208}Pb both fusion and fission cross sections, the energy and the mass distribution of fission fragments, the probability of the evaporation residue formation, the dependence of prefission neutron multiplicities on the fragment mass number.

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FRAGMENTATION IN THE REGION OF NUCLEAR SURFACE

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Recent progress in modern experimental techniques gives new experimental data confirming that the following collective modes: heavy cluster radioactivity, bimodal fission, and cold fission, could belong to the general phenomena of cold nuclear fragmentation. Cold fragmentation leads to the large density redistribution and indicates the formation of a binary or possibly multi-center quasistationary nuclear systems, which lives $\sim 10^{-21}$sec without reaching statistical equilibrium. Fragmentation on the surface and between nuclear surfaces, especially the neck region, is the object of special interest. Nuclear scission can be described by random neck rupture which could be traced back to a series of instabilities. Nuclear density falls considerably down in the region of nuclear surface. This fact is very important due to the possibility of clustering and other fluctuations of the nuclear density leading to instability in the surface region.

Dynamics of shapes of complicated systems inevitably leads to a mathematical problem to describe global geometric quantities such as the surface and the enclosed volume in different dimensions (polymer, cell membranes, 3D droplets etc.). The important feature of nonlinear dynamics is that after scale transformations the same dimensionless nonlinear differential equations are valid which can be used in the very different micro and macro systems. We suggested the general formalism to describe the nonlinear evolution of the nuclear surface without the usual additional assumptions of the shape of a nuclear system [1]. Uniformly charged incompressible nuclear fluid bounded by a closed axisymmetric surface $\Gamma(\vec{r},t) \equiv \sigma - P(z,t) = 0, \quad \vec{r} = (\sigma, \phi, z)$ was considered. A nonlinear integro-differential equation for the contour $P(z,t)$ was derived. The direct correspondence between $P(z,t)$ and a local curvature was shown, which gave a possibility of using methods of differential geometry to analyze evolution of axisymmetric nuclear surface.

In the framework of nonlinear quantum hydrodynamics we formulated a new approach to describe evolution of a localized density fluctuation in the region of nuclear surface [2]. The general quantum scheme to analyze large amplitude vibrational and vortical modes and their coupling was given.

The problem of dynamic instability and clustering (stable fragment formation) in a breakup of excited nuclear systems were considered from the point of view of the soliton concept [3]. It was shown that the volume (spinodal) instability could be associated with nonlinear terms, and the surface (Rayleigh-Taylor type) instability, with the dispersion terms in the evolution equations. Both the instabilities may compensate each other and lead to stable solutions (solitons).

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DINUCLEAR SYSTEM PHENOMENA IN NUCLEAR STRUCTURE AND NUCLEAR REACTIONS

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The dinuclear system (DNS) model of fusion considers fusion as diffusion of the DNS in the mass asymmetry defined by $\eta = (A_1 - A_2)/(A_1 + A_2)$ (A_1 and A_2 are the mass numbers of DNS nuclei). The potential barrier in η supplies a hindrance for fusion. The experimental evaporation residue cross sections in cold (^{208}Pb- and ^{209}Bi-based) and hot (actinide-based) fusion reactions leading to the production of heavy and superheavy nuclei (Z=104-116) are well reproduced [1]. The diffusion in charge (mass) asymmetry and in relative distance (the DNS decay) coordinates contributes to the yields of quasifission products [1]. In hot fusion reactions the main contribution to symmetric and near symmetric fragmentations comes from the quasifission process.

The survival probabilities of superheavy nuclei were analyzed [2] using various damping parameters, and fission and neutron separation characteristics predicted in different theoretical models. For $Z \geq 112$, there is quite a large difference in the survival probabilities calculated with different theoretical predictions of the properties of these superheavies.

The angular momenta of fission fragments were calculated under the assumption that the bending angular vibrations of DNS are responsible for the generation of angular momenta of the fragments [3].

Hyperdeformed (HD) states can be seen as dinuclear resonance states in heavy ion reactions [4]. The optimal conditions in heavy-ion and induced fission reactions for the population of long-lived cold DNS, which are related to the high- and low-spin HD states or to nuclear molecular resonances, were determined. To identify the populated high-spin HD states, the γ-transitions between these states should be measured in coincidence with the decay of the nucleus into cluster fragments.

The octupole-deformed reflection-asymmetric shapes near the ground state are thought to arise from the DNS configurations consisting of an alpha-particle and the rest nucleus. The alternating parity bands in actinides were calculated [5] and found to be in good agreement with experimental data.

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INELASTIC EXCITATIONS AND MOMENTUM DISTRIBUTIONS IN KINEMATICALLY COMPLETE BREAKUP REACTIONS OF TWO-NEUTRON HALO NUCLEI

S.N. Ershov

The characteristics of halo phenomena in light Borromean nuclei are present in properties of both bound and continuum states near the three-body breakup threshold. The nuclear reaction mechanism intertwines bound and excited states and reveals the peculiarities of halo structure via transitions to low-lying halo excited states which subsequently decay into fragments. These events can be studied by a hierarchy of observables in kinematically complete experiments. In the quantitative theoretical analysis of such experiments, the final state interactions between all halo fragments have to be taken into account.

A microscopic four-body DWIA theory for two-neutron halo breakup reactions have been developed [1]. The importance of including both elastic and inelastic fragmentation leading to low-lying halo excitations have been demonstrated. Within this approach the Coulomb and nuclear dissociations are included in a consistent way which also accounts for Coulomb-nuclear interference. The method of hyperspherical harmonics is used for a consistent description of genuine features of the halo bound state and final state interactions between all halo fragments. The method was used to analyze recent GSI experimental data [2,3] on ^{6}He fragmentation at 240 Mev/nucleon on ^{12}C and ^{208}Pb targets. In addition to a good simultaneous description of absolute cross sections and excitation spectra for both reactions, new insight into the interplay of reaction mechanisms and correlated continuum structure was obtained. It was shown that in breakup of Borromean nuclei a fragment momentum distribution has a symmetrical shape for transverse while it may be asymmetrical for the longitudinal distribution. A number of other energy and angular correlations between halo fragments were calculated within the same dynamic picture. The important role found for inelastic fragmentation, i.e., inclusion of target excitations, and Coulomb-nuclear interference is consistent with experimental data.

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NEW METHOD OF NUCLEUS-NUCLEUS OPTICAL POTENTIAL RESTORATION AT INTERMEDIATE ENERGIES

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The method is developed to determine the parameters of the symmetrized Woods-Saxon (SWS) nucleus-nucleus optical potential with the shape of the symmetrized Fermi (SF) function

$$U_{opt} = (V_0 + iW_0)\frac{\sinh(R/a)}{\cosh(R/a)+\cosh(r/a)} \simeq (V_0 + iW_0)\frac{1}{1+\exp[(r-R)/a]}.$$

To this aim, the Glauber-Sitenko multiscattering theory [1,2] and its generalization to the nucleus-nucleus scattering [3] are used to present the microscopic eikonal phase in the form

$$\chi_m(b) = \bar{\sigma}_{NN}\int d^2s\,\rho_p^\circ(|\vec{b}-\vec{s}|)\,\rho_t(s).$$

Here σ_{NN} is the nucleon-nucleon total cross section which depends on the nucleon kinetic energy E/A_p, whereas ρ_p° and $\rho_t(s)$ are the profile functions for the point nucleon density and the nuclear density distributions of the projectile and target nuclei, respectively. The expressions for profile functions themselves were obtained in analytic forms in [4] for the realistic density distributions having the shape of the SF-function. These densities are known from independent experiments and, therefore, $\chi_m(b)$ has no free parameters. On the other hand, for the same phase one can get the analytic expression when scattering occurs in the phenomenological SWS potential [4,5]

$$\chi_p(b) = -\frac{kR}{E}(V_0 + iW_0)\frac{\sinh(R/a)}{\cosh(R/a)+\cosh(r/a)}P(b/R, R/a),$$

where P is the smooth function of b [4], which may be taken approximately as a constant $P(1, R/a)$ at $b \simeq R$. Note that using the analytic phase $\chi_p(b)$ for the optical SWS potential, one can successfully describe both the total reaction cross sections [5] and differential elastic cross sections [6]. However, in the phenomenological consideration, its parameters are traditionally obtained by comparing cross-sections with the experimental data and, therefore, they have no meaning other than the fitted parameters. Contrastingly, we propose to fit the phase χ_p as a whole to the microscopic phase χ_m, and then the obtained quantities V_0, W_0, R, a gain certain physical meaning based on the knowledge of the structure of colliding nuclei and the mechanism of their interaction. In this procedure, we take into consideration that in nucleus-nucleus scattering the peripheral region of collision gives the main contribution to cross sections. Therefore, first of all one should take care of fitting the phase $\chi_p(b)$ in the region of the exponential fall of the microscopic phase $\chi_m(b)$. Applications of this inversion method to the nucleus-nucleus potential are presented in [7,8] (see, e.g., the figure) and, as a result, a set of surface-equivalent potentials is restored.

The important feature of this method is that it produces potentials with the same realistic form of the exponential asymptotics. All the inversion potentials (dashed curves) as well as that

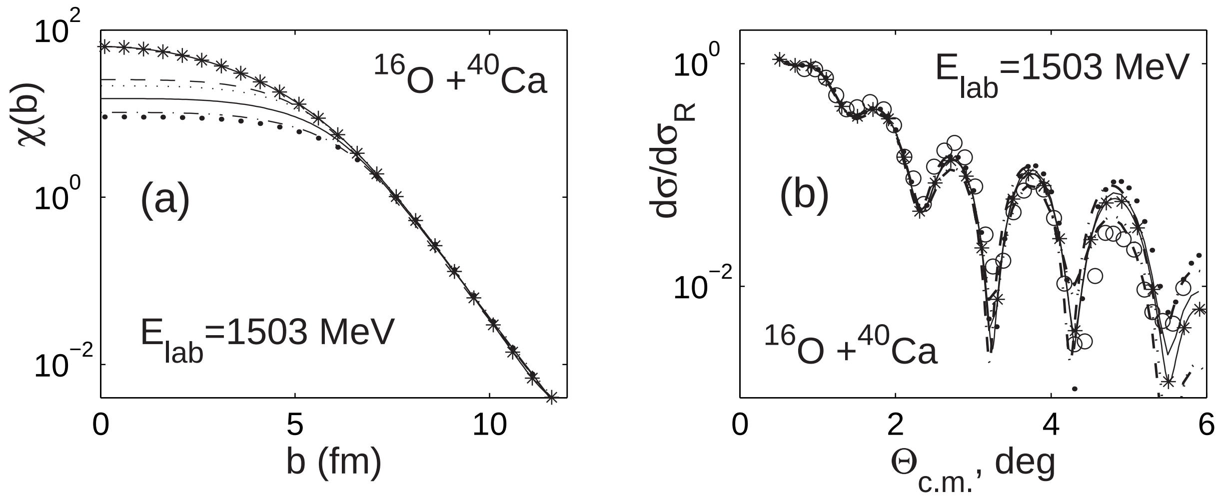

Figure 1: (**a**). Imaginary parts of the optical potentials restored from the calculated microscopic phase, and (**b**), the corresponding differential elastic cross sections compared with the experimental data [9].

obtained in [9] by a direct fit to the experimental data (solid curve), explain successfully the experimental data [9]. They have different shapes in the internal region, and the problem of this ambiguity is a goal of further investigations.

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AN EXAMPLE OF COLLAPSING SOLUTION TO THE FADDEEV DIFFERENTIAL EQUATIONS

V.V. Pupyshev

To present an example of collapsing solution to the Faddeev differential equations we consider the system of three identical bosons p_1, p_2, p_3 with the zero total angular momentum, negative total energy E and the S-wave inverse square interactions $V_{ij} = c/r_{ij}^2$, where c is real constant and r_{ij} is the distance between the bosons p_i and p_j, $i \neq j = 1,2,3$. For this system the Faddeev differential equations [1] written in the hyperspherical coordinates (r, φ) are reduced [2,3] to two eigenvalue problems connected by an unknown constant p^2 of separation of the arguments $r \in [0,\infty)$ and $\varphi \in [0,\pi/2]$.

The first problem is the Bessel problem for unknown eigenvalue E and eigenfunction $f_p(z)$ of the argument $z \equiv kr$, where $k \equiv \sqrt{E}$,

$$\left(z^2\partial_z^2 + z\partial_z + z^2 - p^2\right) f_p(z) = 0, \lim_{z\to 0} \sqrt{z}\, f_p(z) \to 0,\ \sqrt{z} f_p(z) \in \mathscr{L}^2_{[0,\infty)}. \tag{1}$$

The other problem is the integro-differential equation

$$\left(-\partial_\varphi^2 + \frac{c}{\cos^2\varphi}\right) g(\varphi) + \frac{c}{\cos^2\varphi}\, s \int_{C_-(\varphi)}^{C_+(\varphi)} d\varphi'\, g(\varphi') = p^2 g(\varphi), \tag{2}$$
$$C_-(\varphi) \equiv |\varphi - \pi/3|, \quad C_+(\varphi) \equiv \pi/2 - |\pi/6 - \varphi|, \quad s \equiv 4/\sqrt{3}.$$

for searched eigenvalue p^2 and eigenfunction g obeying the conditions

$$g(\varphi) = 0, \quad \varphi = 0, \pi/2; \quad g \in \mathscr{C}^2_{(0,\pi/2)}. \tag{3}$$

The problem (1) has a square integrable solution only if $E < 0$ and $p^2 < 0$, i.e., if $k = i\sqrt{|E|}$ and $p = i|p|$. This solution is the Hankel function $f_p = H_p^{(1)}(z)$ which rapidly oscillates as $|z| =\to 0$ and exponentially decreases as $|z| \to \infty$

$$\begin{aligned} f_p(z) &\sim \sin\left[\,|p|\ln(|z|/2) - \arg\Gamma(1+i|p|)\right], \quad |z| = |k|r \to 0; \\ f_p(z) &\sim |z|^{-1/2}\exp\left(-|z| + |p|\pi/2\right), \qquad |z| =\to \infty. \end{aligned} \tag{4}$$

Therefore, $|f_p| \ll 1$ for all $r \gg |E|^{-1/2}$. Hence, if $E \to -\infty$ then f_p is located in the infinitesimal neighborhood of the point $r = 0$.

In other words, f_p collapses and describes the physical state in which all three bosons collapse, i.e., "fall" at their center of mass $r = 0$.

Let $s = 0$ in eq. (2). At any c and p^2 this homogeneous equation has a fundamental system of bounded and real solutions g^+ and g^- which can be represented in terms of the Gauss series ${}_2F_1$ converging for all $\varphi \in [0,\pi/2]$

$$\begin{aligned} g^\pm(\varphi) &= \mathrm{Re}\left\{(\cos\varphi)^{1/2\pm\nu}\ {}_2F_1\left(\alpha^\pm, \beta^\pm, 1\pm\nu; \cos^2\varphi\right)\right\}, \\ \alpha^\pm &\equiv (1/2 \pm \nu + p)/2, \quad \beta^\pm \equiv \alpha^\pm - p, \quad \nu \equiv (c + 1/4)^{1/2}. \end{aligned} \tag{5}$$

At any $c \geq 0$ and $p^2 < 0$ the problem (2)-(3) with $s = 0$ is unsolvable, while at any $c < 0$ and $p^2 < 0$ there is a unique real solution $g \equiv \tilde{g}$,

$$\tilde{g}(\varphi) = g^-(0)g^+(\varphi) - g^+(0)g^-(\varphi),\ g^\pm(0) = \sqrt{\pi}\mathrm{Re}\left\{\Gamma(1\pm\nu)/\left[\Gamma(\alpha^\pm)\Gamma(\beta^\pm)\right]\right\}.$$

This solution has the asymptotics $\tilde{g}(\varphi) \sim \exp\{(\varphi-\pi/2)|p|\}$ as $\varphi \to 0$ and the asymptotics as $\varphi \to \pi/2$ depending on sign$(c+1/4)$ and $\delta \equiv$ atan $[g^+(0)/g^-(0)]$:

$$\begin{aligned} \tilde{g}(\varphi) &\sim (\cos\varphi)^{1/2+\nu}\left[1-\mathrm{tg}\,\delta\,(\cos\varphi)^{-2\nu}\right], \quad -1 \le 4c < 0, \\ \tilde{g}(\varphi) &\sim (\cos\varphi)^{1/2}\cos\left[|\nu|\ln(\cos\varphi)+\delta\right], \quad 4c < -1. \end{aligned} \tag{6}$$

Therefore, $\tilde{g} \to 0$ for all $\varphi \gg 1/|p|$ when $p^2 \to -\infty$, and $\tilde{g}$ rapidly oscillates when $c < -1/4$ and $\varphi \to \pi/2$. Hence, in this limit $\tilde{g}$ is located near the point $\varphi = \pi/2$ and describes the physical state in which two bosons collapse.
Now let $s \neq 0$, $R(\varphi)$ be the integral term of (2) and $W(\varphi)$ be the Wronskian of functions (5). Then a general solution of the problem (2)-(3) always contains its particular solution t and reads as $g = a\tilde{g} + t$, $\forall a = \mathrm{Re}\, a$,

$$t(\varphi) = g^-(\varphi)\int^{\varphi} d\varphi' g^+(\varphi')R(\varphi')/W(\varphi') - g^+(\varphi)\int^{\varphi} d\varphi' R(\varphi')/W(\varphi'). \tag{7}$$

The limits $C_\pm(\varphi)$ of the integral $R(\varphi)$ tend to $\pi/3 \pm 0$ if $\varphi \to 0$ and to $\pi/6 \pm 0$ if $\varphi \to \pi/2$. Therefore, replacing $g(\varphi')$ by its Taylor series with the center $\pi/3$ or $\pi/6$, one can prove that the asymptotics of (7) differs from the asymptotics (6)

$$t(\varphi) \sim \varphi^3\, 2cs\, g(\pi/3), \quad \varphi \to 0; \quad t(\varphi) \sim (\varphi-\pi/2)\, 2s\, g(\pi/6), \quad \varphi \to \pi/2.$$

Hence, at $p^2 < 0$ the problem (2)-(3) may have two quite different solutions: $g = a\tilde{g} + t$ and $g = t$. The solution $g = a\tilde{g} + t$ with the collapsing term $a\tilde{g}$ exists at any $c < 0$. The condition $c < -0.267\ldots$ for existence of the solution $g = t$ was obtained in [3] by using the high accuracy spline algorithm [4].

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BINDING ENERGIES AND SCATTERING OBSERVABLES IN THE $^4He_3$ ATOMIC SYSTEM

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The $^4He_3$ bound states and the scattering of a ^4He atom off a ^4He dimer at ultra-low energies are investigated by using a hard-core version of the Faddeev differential equations. Our method, unlike some competing methods, is exact and ideally suited for calculations in three-atomic systems where the two-body interactions usually have a strong repulsive component at small distances between atoms. In the present investigation [1,2] we employed various realistic ^4He–^4He interactions, among them the LM2M2 potential by Aziz and Slaman and the more recent

TTY potential by Tang, Toennies and Yiu. Our results for the ground-state energy of the ^{4}He trimer compare favorably with alternative results in the literature. It was found that most of the contribution to the ground-state energy stems from the $l = 0$ and $l = 2$ partial components, the latter being slightly larger than 30 %, and is approximately the same for all potentials used. The contribution from the $l = 4$ partial wave is of the order of 3-4 %. Furthermore, we successfully located the excited state of the trimer, interpreted as an Efimov state. In addition to binding energy calculations, we applied the formalism to calculate scattering lengths and low-energy phase shifts of the ^{4}He atom scattered off the ^{4}He dimer for $L = 0$.

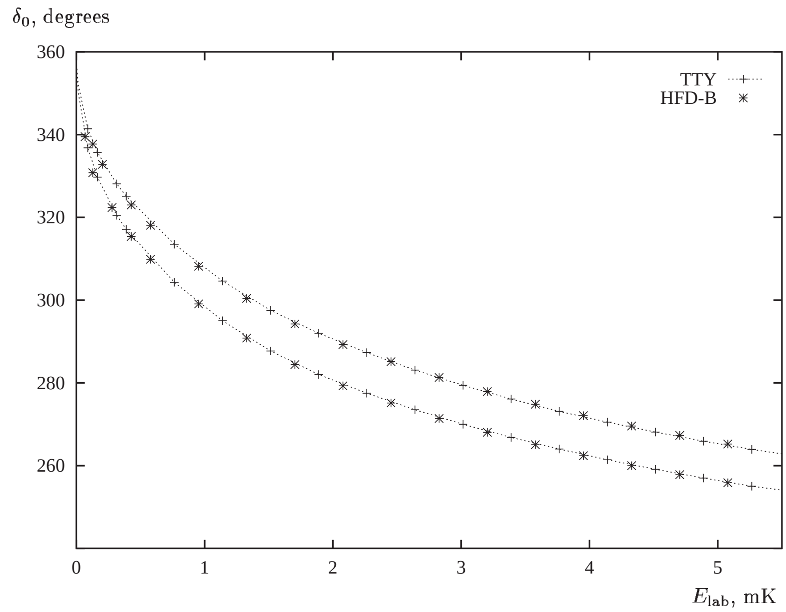

Figure 1: S-wave helium-atom helium-dimer scattering phase shifts δ_0 for the HFD-B and TTY ^{4}He–^{4}He potentials as functions of the energy $E_{\rm lab}$ in the laboratory system. The lower curve corresponds to $l_{\rm max} = 0$ while for the upper one to $l_{\rm max} = 2$.

For scattering, we consider incident energies below as well as above the breakup threshold, *i.e.*, for the $(2+1 \longrightarrow 2+1)$ and the $(2+1 \longrightarrow 1+1+1)$ processes. It is found that when transforming to the laboratory system the phase shifts obtained with the He–He HFD- B, LM2M2, and TTY potentials are practically the same (see Fig. 1), especially those obtained with the LM2M2 and TTY. The difference between the phase shifts calculated with inclusion of the partial waves for $l \le l_{\rm max} = 2$ and the shifts calculated with the inclusion of the partial waves for $l \le l_{\rm max} = 4$ is of the order of $\sim$0.5 %.

In general, the presence of the highly repulsive core in the He–He inter-atomic potentials, together with the Efimov properties of the excited state of the trimer, makes calculations of the He_3 system tedious and numerically unstable. This is not the case in our formalism where the hard core is taken into account from the very beginning in a mathematically rigorous way. Our formalism paves the way to study various ultra-cold three-atomic systems, and to calculate important quantities such as cross-sections, recombination rates, *etc.*

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PERTURBATION OF A LATTICE SPECTRAL BAND BY A NEARBY RESONANCE

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Molecules are usually treated as purely Coulombic systems, while the strong interaction between their nuclear constituents is assumed to play a negligible role. However, at least in principle, any Coulombic molecular level lying above the lower threshold of the nuclear subsystem, is embedded in the continuous spectrum of the nuclear sub-Hamiltonian. The coupling between the molecular and nuclear channels, hence, turns this level into a resonance. Of course, due to the wide Coulombic barrier between the nuclei and the short-range character of the nuclear interaction, this coupling, and thus the width of the resonance, which determines the fusion probability of the nuclear constituents of the molecule, is in general extremely small.

However, as was pointed out in [1], the situation is rather different if the nuclear subsystem of a molecule has a sufficiently narrow near-threshold resonance. Examples of such nuclear systems may be read off from the data presented in [2]. Among them are even customary systems like $p\,p\,^{16}$O and $p\,^{17}$O, i. e., the nuclear constituents of the water molecule H_2O or the hydroxyl ion OH^- with O being the isotope ^{17}O. The best example of such phenomena is the muon catalyzed fusion of deuteron and triton in the $dt\mu$ molecule, where the near-threshold nuclear resonance ^{5}He$(3/2^+)$ is known to play a decisive role.

Being motivated by the above special cases, we deal in [3] with a rather general model Hamiltonian. This Hamiltonian consists of a “nuclear” part, a “molecular” part with eigenvalues embedded in the continuous spectrum of the nuclear part, and a weak coupling term which turns these unperturbed eigenvalues into “molecular” resonances. The following property pointed out in [1] appears, in particular, as a general feature: if the “nuclear” channel itself has a narrow resonance with a position close to the “molecular” energy, then the width (the imaginary part) of the resulting “molecular” resonance is found to be inversely proportional to the “nuclear” width. In other words, a large increase in the decay rate of the “molecular” state, i. e., of the fusion probability, is observed in this case. Such a coincidence of nuclear and molecular energies is, of course, a rather rare phenomenon in nature.

A further goal of the paper [3] is to show that the decay rate may be considerably enhanced when arranging molecular clusters of this type within a crystalline structure. The reason is that in such a configuration the original discrete molecular energy turns into a band, i. e., into a whole interval of the continuous spectrum. That is, even if the position of the “nuclear” resonance differs from the original “molecular” level, it can get into this band. This allows for a fine tuning by exciting the crystalline structure to energies as close as possible to the energy of the “nuclear” resonance. We show that the lattice states, which correspond to such an initial choice of their quasimomentum distribution, decay exponentially with a rate which is again inversely proportional to the width of the “nuclear” resonance.

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ANALYSIS OF PION PHOTO- AND ELECTROPRODUCTION USING DYNAMIC MODEL AND DISPERSION RELATIONS

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We show that within a meson-exchange dynamic model [1] describing most of the existing pion electromagnetic production data up to the second resonance region one is also able to obtain good agreement with the π^0 photo- and electroproduction data near the threshold [2] (see Fig.1, dash-dotted curves). The potentials used in the model are derived from an effective chiral Lagrangian. The only sizable discrepancy between our results and the data is in the P-wave amplitude $P_3 = 2M_{1+} + M_{1-}$, where our prediction underestimate the data by about 20%. In the case of π^0 production, the effects of final state interaction in the threshold region are nearly saturated by single charge exchange rescattering. This indicates that in Chiral Perturbation Theory it might be sufficient to carry out the calculation just up to one-loop diagrams for threshold neutral pion production.

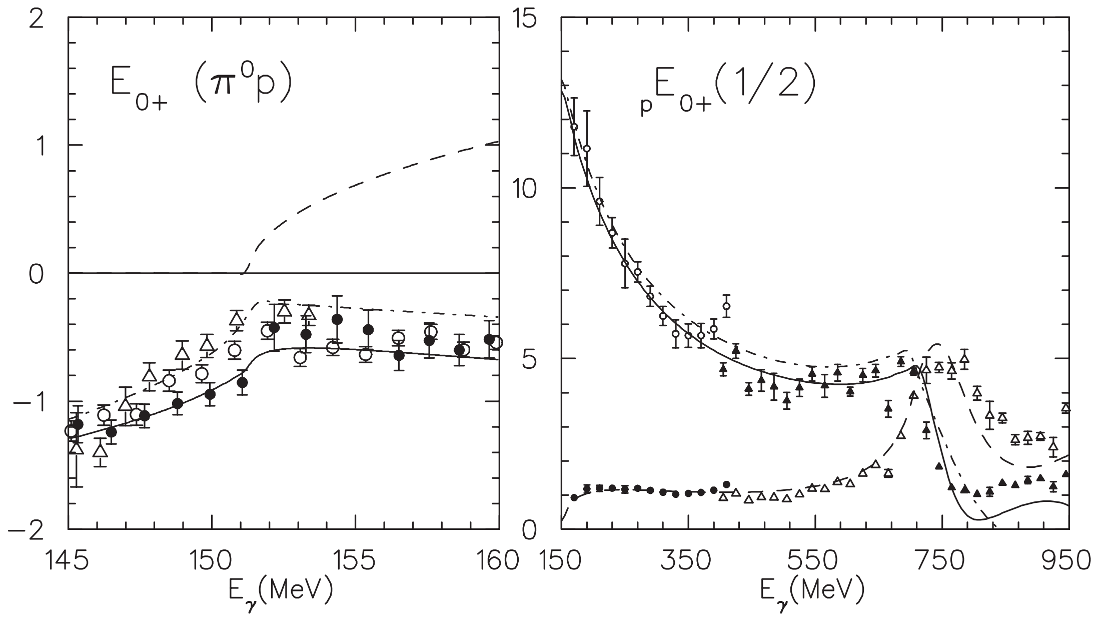

Figure 1: E_{0+} multipoles (in units $10^{-3}/m_\pi$) for pion photoproduction on the proton. Dash-dotted and solid curves are the results for the real parts obtained using dynamic model [2] and dispersion relations [4], respectively. Dashed curve is the imaginary part of the E_{0+} multipole which was used as an input in the dispersion relations. Data points from [5] (△), [6] (●), and [7] (○) are in the left figure; and from [8,9], in the right figure.

We developed dispersion relations to analyze pion photo- and electroproduction on the nucleon. The goal is to arrive at a consistent description of pion photo- and electroproduction that satisfies fundamental principles like unitarity, analyticity, and gauge invariance. For this purpose the fixed-t dispersion relations with the imaginary parts predicted by the Unitary Isobar Model [3] was used as an input. In Fig. 1 (solid curves) we illustrate how powerful this method could be [4]. Here we show the results for the real part of the S-wave neutral pion photoproduction amplitude at the threshold obtained using dispersion relations with the imaginary parts predicted by the Unitary Isobar Model.

We extended the corresponding formalism which will allow us to analyze all currently available experimental data for pion photo- and electroproduction in the first, second, and third resonance regions. Within the developed framework we expect to get new knowledge about the properties of the $\Delta(1232)$ and other baryon resonances, in particular the Q^2 dependence of $E2/M1$ from pion electroproduction for investigation of the transition from nonperturbative QCD to perturbative QCD. Such a study is in direct support of the ongoing and future experimental efforts relating to N* physics at Jefferson Lab, MAMI (Mainz), ELSA (Bonn) and other facilities. For higher resonances we expect to get reliable results for the transverse helicity amplitudes $A_{1/2}(Q^2)$ and $A_{3/2}(Q^2)$, and make comparison with the predictions of different quark models, in particular with the Genova hypercentral quark model [10] and eventually to implement the quark model predictions for resonance excitation into our reaction models.

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NON-DIFFRACTIVE PROCESSES AND STATUS OF OZI-RULE IN ω AND ϕ - MESON PHOTOPRODUCTION

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The status of the OZI-rule with respect to the ϕNN and ϕNN^* coupling constants is one of the most exciting problem of hadron physics. The finite strange content in a nucleon leads to increasing of these strengths in comparison with expectation based on the standard OZI-rule. There are several indications of essential violation of the OZI-rule in the interaction of the ϕ-mesons with baryons which come from: analysis of magnetic and electroweak [1] moments of baryons, measurements of the π-nucleon term, ϕ-meson production in the proton annihilation at rest and deep-inelastic electroweak lepton-nucleon scattering (see [2] for references and compilation of the data). The combined analysis of ω and ϕ-meson photoproduction processes at large momentum transfers seems to be promising for studying this subject, because they are dominated by the s and u channels of the nucleon and resonant amplitudes and depend on the strength of ωNN, ωNN^*, ϕNN and ϕNN^*-interactions.

To make an estimate of the nucleon and resonant channels, we use the effective Lagrangian approach developed for the ω-meson photoproduction and discussed in our recent paper [3]. We consider all isospin $I = 1/2$ nucleon resonances with empirically known helicity amplitudes of $\gamma N \to N^*$ transitions with spin (J) and parity (P) $J^P = \frac{1}{2}^{\pm}, \frac{3}{2}^{\pm}, \frac{5}{2}^{\pm}, \frac{7}{2}^{\pm}$. We define the ωNN^* coupling constant $f_{\omega NN^*}$ by using the vector dominance model.

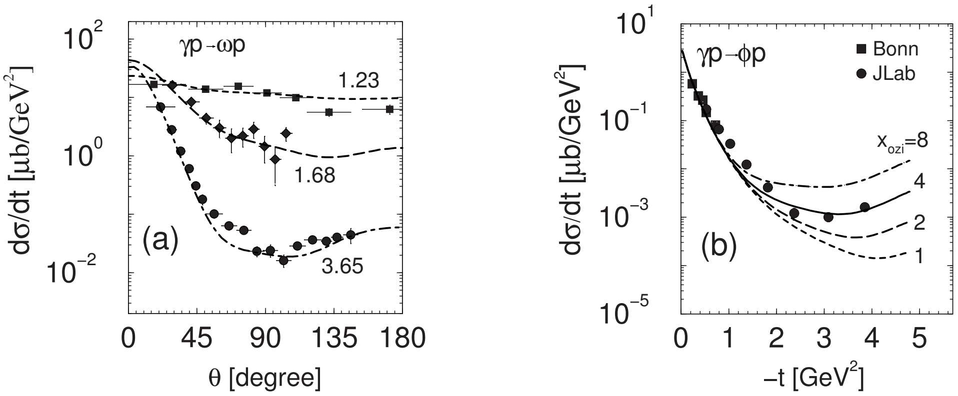

Figure 1: (a): The differential cross section as a function of the ω production angle at $E_\gamma =$ 1.23, 1.45, 1.68 GeV and 3.65 GeV. Data are taken from [4,5]. (b): The differential cross section of $\gamma p \to \phi p$ reaction as a function of t at $E_\gamma = 3.6$ GeV for different values of the OZI-rule evading parameter $x_{\rm OZI}$. Data are taken from [6,7].

The validity of the model for the ω-meson photoproduction is illustrated by Fig. 1(a), where we show the differential cross section of the $\gamma p \to \omega p$ reaction for the full model which also includes diffractive channels important at small momentum transfers, together with the available experimental data. The contribution of the resonance excitations dominates at backward angles and it brings agreement with the data at large momentum transfers.

For the ϕ-meson photoproduction we assume the same N^* excitation mechanisms by substitution $f_{\omega NN^*} \to f_{\phi NN^*}$ with using the "minimal" parametrizations

$$f_{\phi NN^*} = -\tan \Delta\theta_V \, x_{\rm OZI} \, f_{\omega NN^*},$$

where $\Delta\theta_V$ is the deviation of the $\phi - \omega$ mixing angle from the ideal mixing ($\Delta\theta_V \simeq 3.7^0$ and $x_{\rm OZI}$ is the OZI-rule evading parameter. Fig. 1(b) shows the differential cross section at $E_\gamma = 3.6$ GeV as a function of t at different values of $x_{\rm OZI}$, together with the experimental data [7]. The calculation brings agreement with data at $x_{\rm OZI} \simeq 4$. Our analysis shows that

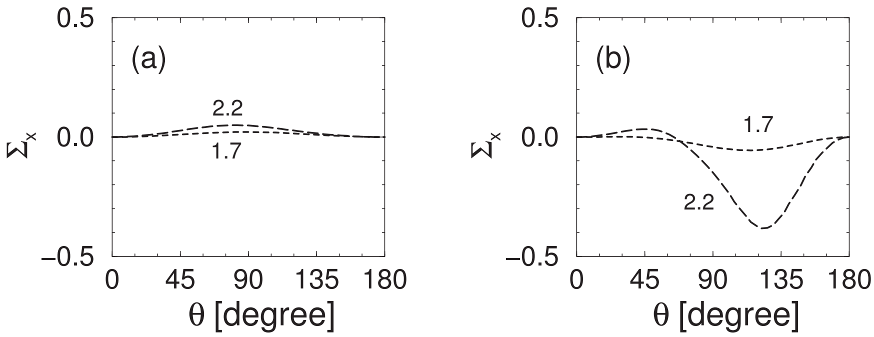

Figure 2: The beam asymmetry for the $\gamma p \to \phi p$ reaction at $E_\gamma = 1.7$ and 2.2 GeV. (a): Result for the Pomeron exchange channel. (b): Result for the full model.

the spin observables in ϕ-meson photoproduction are very sensitive not only to the value of $x_{\rm OZI}$, but to details of the resonance properties. As an example, in Fig. 2 we show the beam asymmetry Σ_x [3] calculated without (a) and with the resonant channel at $E_\gamma = 2.2$ GeV. The shape and sign of Σ_x are defined completely by the resonant dynamics.
Finally, we note that the combined examining of the ϕ and ω photoproduction at large angles allows one to analyze the status of the OZI-rule for ϕNN^* -interactions. We found a large (factor of 4) scale of this violation which agrees with other independent indications of this effect. The spin observables are very sensitive to the resonance excitation channel and can be used to study it in detail.

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DIRECTED FLOW OF BARYONS FROM HIGH-ENERGY HEAVY-ION COLLISIONS

V.D. Toneev

Collective flows of various types (radial, directed, elliptic, ...) observed experimentally in heavy-ion collisions reveal a space–momentum correlated motion of strongly interacting nuclear matter. This collective motion is essentially caused by the pressure gradients arising during the time evolution in the collision, and hence opens a promising way for obtaining information on the equation of state (EoS) and, in particular, on a possible phase transition. Since a phase transition slows down the time evolution of the system due to *softening* of the EoS, a remarkable loss of correlation between the observed particle momenta and the reaction plane and hence a reduction of the directed flow is expected around some critical incident energy.

The results of such analysis [1] based on hydrodynamic approach with using different EoS's are summarized in Fig. 1, where the excitation functions for the mean baryonic directed flow, defined as

$$\frac{\langle P_x \rangle}{N} = \frac{\int dp_x dp_y dy \; p_x \; \left(E\frac{d^3N}{dp^3} \right)}{\int dp_x dp_y dy \; \left(E\frac{d^3N}{dp^3} \right)} \quad ,$$

are given. Here p_x is the projection of the transverse momentum of a nucleon on the reaction plane and the integration is carried out in the c.m. system over the rapidity region $[0, y_{cm}]$. The comparison of two dashed curves shows that within one-fluid (1F) hydrodynamics the excitation function for the directed flow indeed exhibits a deep minimum near $E_{lab} \approx 6$ A·GeV, when the first-order deconfinement phase transition is taken into account, as was predicted earlier by Rischke et al. [2]. This loss of memory on the initial reaction plane is a consequence of the deep minimum in the pressure-to-energy density ratio (the softest point of EoS) specific of the bag–model EoS with the first-order phase transition. The statistical mixed phase model (MPM), which assumes that unbound quarks and gluons may coexist with hadrons forming a mixed homogeneous quark/gluon–hadron phase, predicts a cross-over type of the deconfinement phase transition [3] to be consistent with available QCD lattice data. In this model the softest point minimum is rather shallow and completely washed out at the baryon density $n_B \gtrsim 0.5 n_0$. As is seen from two solid curves in Fig. 1 presented for two values of the impact parameter b, the directed flow excitation functions in the MPM turn out now to be smooth functions in the whole energy range studied. One should note that the last results are obtained in the two-fluid (2F) relativistic hydrodynamics which properly takes into account the finite stopping power of colliding nuclei. Both EoS and nuclear dynamics have an influence on the excitation functions of the baryon directed flow. This is illustrated by squares with statistical error bars in Fig. 1, which represent the calculation results for the bag-model EoS within three-fluid hydrodynamics [4]. In this treatment the third fluid describes self-interacting baryon-free matter and, as regards baryon characteristics, the approach is completely equivalent to our two-fluid description. As is seen, the minimum of the directed flow excitation function, predicted by the one-fluid hydrodynamics with the bag-model EoS, survives in the three-fluid regime but its depth decreases and its position is shifted towards higher energy, $E_{lab} \approx 20$ A·GeV.

So, the directed flow excitation functions for baryons are sensitive to the EoS, though this sensitivity is significantly masked by nonequilibrium dynamics of nuclear collisions. Preliminary

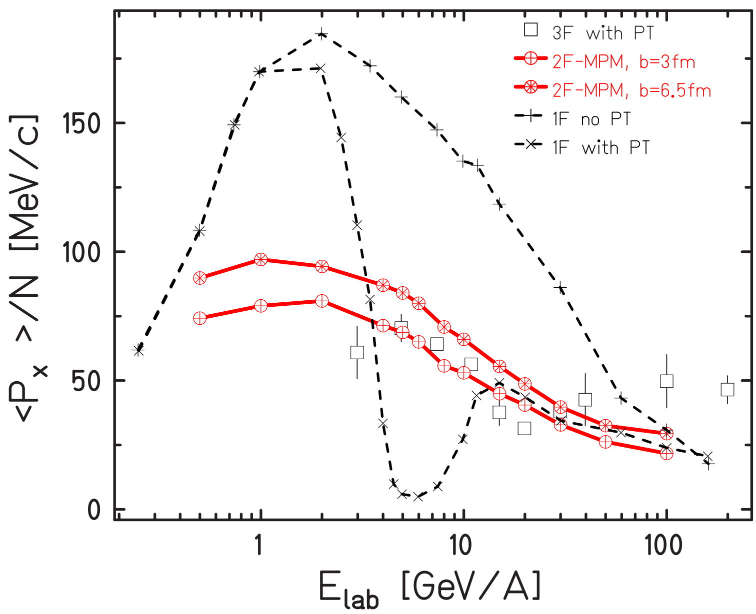

Figure 1: Beam energy dependence of the mean directed flow for baryons from $Au+Au$ collisions. The curves are calculated for one-, two- and three-fluid (1F, 2F and 3F) hydrodynamics and different EoS's with and without phase transition (PT). See the text for details.

experimental results [5] in this energy range manifest no irregular behavior in excitation functions and, therefore, can be considered as an argument in favour of the quark-hadron mixed phase EoS and cross-over type of the deconfinement phase transition.

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RELATIVISTIC EFFECTS IN PROTON-INDUCED DEUTERON BREAK-UP AT INTERMEDIATE ENERGIES

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The role of the Final State Interaction (FSI) in inclusive electro-disintegration and exclusive deuteron break-up reaction has been investigated within different approaches. A detailed comparison between an improved Glauber method and Schrödinger approach is presented for the electro-disintegration processes. It is shown that both methods become inadequate at large values of Q^2 where the virtuality of the hit nucleon after photon absorption is very high. The concept of Finite Formation Time (FFT) required by the hit nucleon to reach its asymptotic form is introduced by a Feynman diagram approach and by explicitly taking into account the dependence of the ejectile on its virtuality. Numerical calculations (see Fig. 1) show that the effects of FFT almost completely cancel the contribution from the rescattering processes. In the cumulative region the color transparency become fairly visible [1-4].

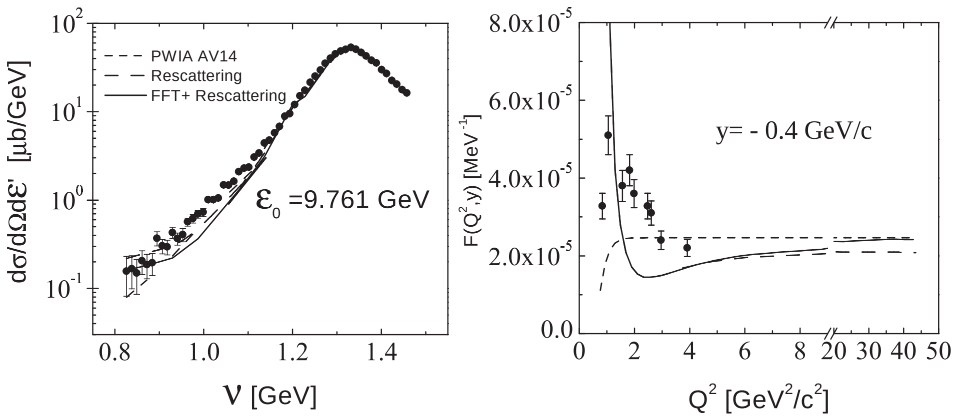

Figure 1: The cross section (left) and scaling function (right) for the quasielastic $D(e,e')X$ reaction computed within the impulse approximation (short-dashed lines), with FSI effects by Glauber approximation (dashed lines) and with FFT effects taken into account (solid lines).

The exclusive charge exchange reaction $pD \to n(pp)$ at intermediate and high energies is studied within the Bethe-Salpeter (BS) formalism [5,6]. The final state interaction in the detected pp pair at nearly zero excitation energy is described by the $^1S_0$ component of the BS amplitude. The results of numerical calculations of polarization observables and differential cross-section persuade that, as in the nonrelativistic case, this reaction (i) can be utilized as a “relativistic deuteron polarimeter” and (ii) delivers further information about the elementary nucleon-nucleon charge-exchange amplitude.

Recent data on the reaction $pD \to (pp)n$ with the fast, forwardly going pp-pair at zero-near excitation energies is analyzed within a BS formalism [7]. It is demonstrated that the minimum in the cross section predicted by nonrelativistic models is completely masked by relativistic effects properly taken into account, e.g., Lorentz boost and the negative-energy P components in the $^1S_0$ Bethe-Salpeter amplitude of the pair. Relativistic corrections essentially improve the agreement of theoretical results with experimental data, see Fig. 2.

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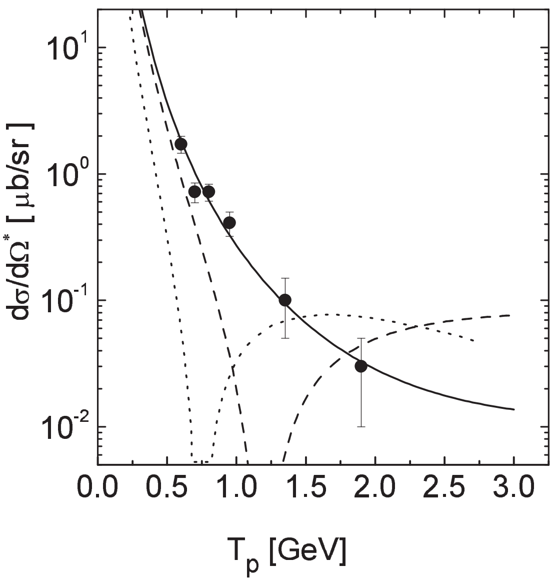

Figure 2: Differential cross section in the center of mass system integrated over the excitation energy E_x as a function of the kinetic energy T_p of the incident proton.

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ELECTRIC AND MAGNETIC ORBITAL PLASMONS IN DEFORMED METAL CLUSTERS

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A random-phase-approximation method with *separable* residual forces (SRPA) was proposed for description of multipole oscillations of valence electrons in *deformed* alkali metal clusters [1]. Both the deformed mean field and residual interaction were derived self-consistently from the Kohn-Sham functional (similar approach was recently proposed for description of nuclear collective excitations with the Skyrme functional [2,3]). The SRPA drastically simplifies the computational effort which is urgent if not decisive for deformed systems. At the same time, SRPA provides high numerical accuracy. The method was applied to description of multipole (E1, E2, E3 and M1) plasmons in sodium clusters of a moderate size [1,4,5].

Recent experimental data [6] on the E1 plasmon in axial sodium clusters were analyzed within jellium SRPA [1,4]. The calculations show that, while in light clusters plasmon properties (gross structure and width) are mainly determined by deformation splitting, in medium clusters with $N > 50$ the Landau fragmentation becomes decisive. Moreover, shape isomers come into play with contributions to the plasmon spectrum comparable to the ground state one. As a result, commonly used methods of the experimental analysis of cluster deformation become doubtful and a correct treatment of a cluster shape should be based on microscopic calculations.

The magnetic orbital low-energy (0.3-1.0 eV) M1 scissors mode (SM) in deformed clusters [7] was studied in jellium approximation [5]. This mode is a general dynamic feature of any *deformed* two-component finite quantum system. It was already observed or predicted in atomic nuclei, quantum dots, diluted gases of Bose and Fermi atoms. In clusters, the SM determines Van-Vleck paramagnetism and leads to a strong anisotropy of magnetic susceptibility (dia-para anisotropy in Na_{27}^{+}) [5].

The SM built on spin-saturated ground and spin-polarized isomeric states was analyzed taking into account triaxiality of the system and detailed ionic structure [8]. The coupling with dipole and spin-dipole modes was studied in detail. It was shown that triaxiality and ionic structure considerably complicate the scissors response, mainly at the expense of stronger fragmentation of the strength. Nevertheless, even in these complicated cases the scissors mode is mainly determined by the global deformation. It is remarkable that the detailed ionic structure destroys the local spherical symmetry and causes a finite M1 response even in clusters with zero global deformation.

Perspectives of physics of atomic clusters in general (including nanotechnologies) [9] and of the search of the SM in particular [5] were outlined. In the latter case, photoabsorption and inelastic electron scattering were analyzed in detail [5]. It was shown that the most promising are clusters of the controlled size and shape, supported on dielectric surfaces. The optimal cluster size is $10^3 - 10^4$ atoms. In the case of photoabsorption, the s-polarized (p-polarized) light under the angle $\sim 0^\circ$ $(\sim 90^\circ)$ should be used.

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PECULIARITIES OF ELECTROMAGNETIC FIELDS IN VACUUM AND MEDIUM

G.N. Afanasiev

Electromagnetic fields of the simplest time-dependent sources (current loop, electric dipole, toroidal solenoid, etc.) are applied to the analysis of the Lorentz and Feld-Tai lemmas (or reciprocity-like theorems) having numerous applications in electrodynamics, optics, radio-physics, electronics, etc. It is demonstrated that these lemmas are valid for more general time-dependencies of the electromagnetic field sources than it was suggested up to now. It is shown also that the validity of reciprocity-like theorems is intimately related to the equality of electromagnetic action and reaction: both of them are fulfilled or violated under the same conditions. Conditions are stated under which reciprocity-like theorems can be violated. The concrete example of their violation is presented [1].

The charge motion in medium in a finite space interval is considered. We analyze alternative attempts to interpret the radiation described by the Tamm formula as an interference of two instantaneous accelerations arising at the beginning and termination of motion. Exact solution of the Tamm problem in the time representation shows that in some time interval, only the bremsstrahlung shock wave associated with the beginning of motion and the Cherenkov shock wave exist, and there is no bremsstrahlung shock wave associated with the end of motion. This proves that in the time representation the Cherenkov radiation is not necessarily related to the interference of initial and final bremsstrahlung shock waves. In the spectral representation, we consider the motion consisting of accelerated, decelerated, and uniform parts. Analytic formulae are obtained describing electromagnetic fields and radiation intensities corresponding to this motion. Approximating the instantaneous acceleration in the original Tamm problem by the acceleration in a finite path and then tending its length to zero, we prove that the radiation intensity produced on the accelerated part of the charge trajectory also tends to zero (despite the infinite value of acceleration in this limit). This means that in the original Tamm problem the instantaneous acceleration and deceleration do not contribute to the radiation intensity (as it is usually believed). It seems that only the combined consideration of the Tamm problem in the time and spectral representations shows that the above-mentioned alternative interpretation of the Cherenkov radiation fails [2].

We study also the properties of the synchrotron radiation in vacuum. The behaviour of time averaged radial, azimuthal, and polar components of the radiated energy flux is investigated for different velocities of a moving charge and at different distances from a charge orbit (both outside and inside it). Analytic formulae are found for the instantaneous position of the radiation intensity maxima and minima at the fixed moment of the laboratory time. They generalize the famous Schwinger formula for arbitrary velocities and distances [3].

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