Bogoliubov Laboratory of Theoretical Physics

THEORETICAL PHYSICS AT BLTP and some examples from the nuclear structure study

V. V. Voronov

9th APCTP-BLTP JINR Joint Workshop
Almaty, June 28-July 4, 2015


ЛАБОРАТОРИЯ
ТЕОРЕТИЧЕСКОЙ
ФИЗИКИ
ИМЕНИ
Н.Н.БОГОЛЮБОВА

Laboratory of Theoretical Physics, JINR

May 25, 1956

ПРИКАЗ

ПО ЛИЧНОМУ СОСТАВУ ОБ"ЕДИНЕННОГО ИНСТИТУТА

№ 5

"25" мая 1956 года.

До утверждения новой структуры Института возложить на академика БОГОЛЮБОВА Николая Николаевича /начальника сектора № 3 Теоретической лаборатории/ исполнение обязанностей директора Теоретической лаборатории Об"единенного Института.

ДИРЕКТОР

ОБ"ЕДИНЕННОГО ИНСТИТУТА ЯДЕРНЫХ ИССЛЕДОВАНИИ

Д.И. БЛОХИНЦЕВ

ПО ЛИЧНОМУ СОСТАВУ ОБ"ЕДИНЕННОГО ИНСТИТУТА

№ 6

"25" мая 1956 г.

ЗАЧИСЛИТЬ: 1. БОГОЛЮБОВА Николая Николаевича временно начальником сектора № 3 Теоретической лаборатории с окладом 6000 руб. в месяц, с 1 июня с.г.

2. ШИРКОВА Дмитрия Васильевича старшим научным сотрудником сектора № 3 Теоретической лаборатори с окладом 1500 руб. в месяц по совместительству, с 1 июня с.г.

3. МЕДВЕДЕВА Бориса Валентиновича старшим научным сотрудником сектора № 3 Теоретической лаборатории с окладом 1500 руб. в месяц по совместительству, с 1 июня с.г.

4. ПОЛИВАНОВА Михаила Константиновича научным сотрудником сектора № 3 Теоретической лаборатории с окладом 1000 руб. в месяц по совместительству, с 1 июня с.г.

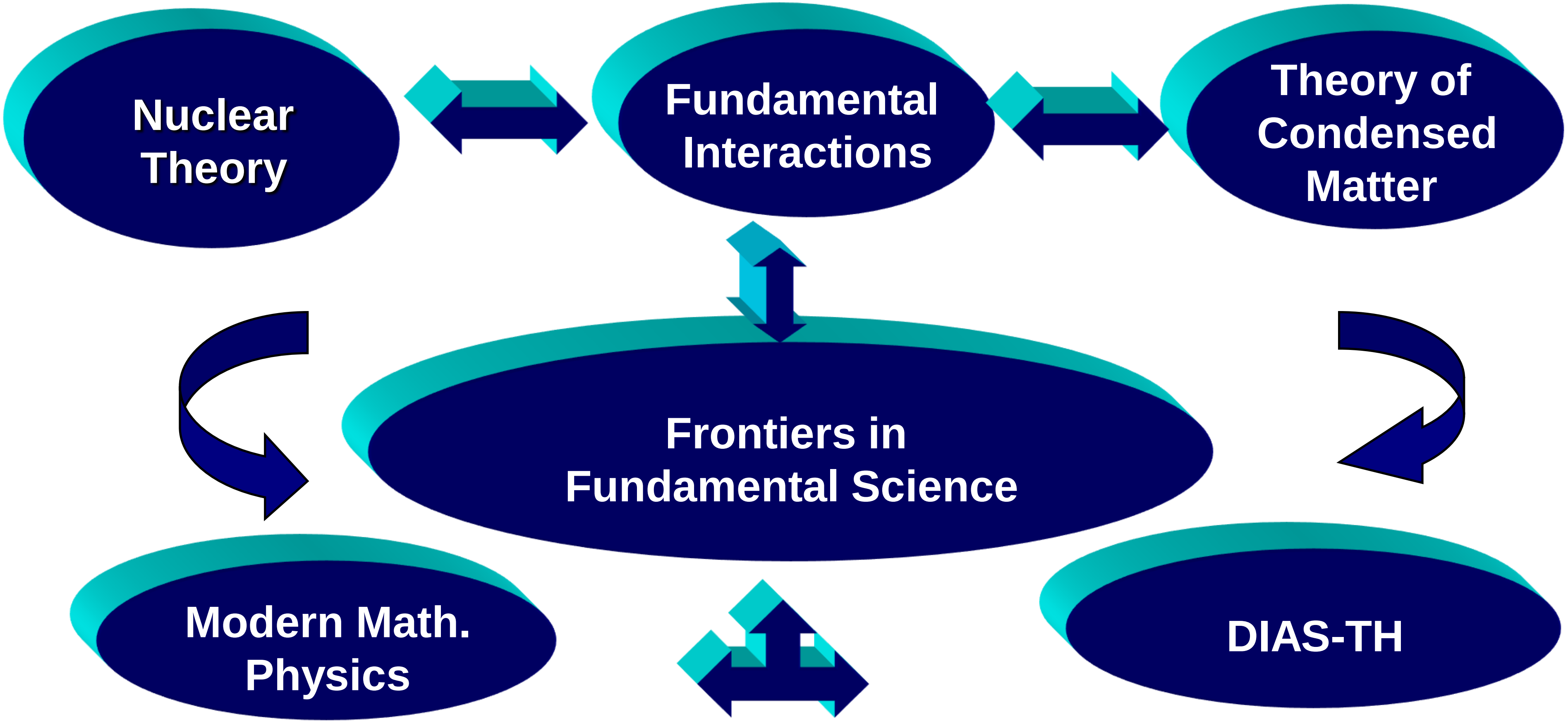
ДИРЕКТОР

Б"ЕДИНЕННОГО ИНСТИТУТА ЯДЕРНЫХ ИССЛЕДОВАНИИ

Д.И. БЛОХИНЦЕВ

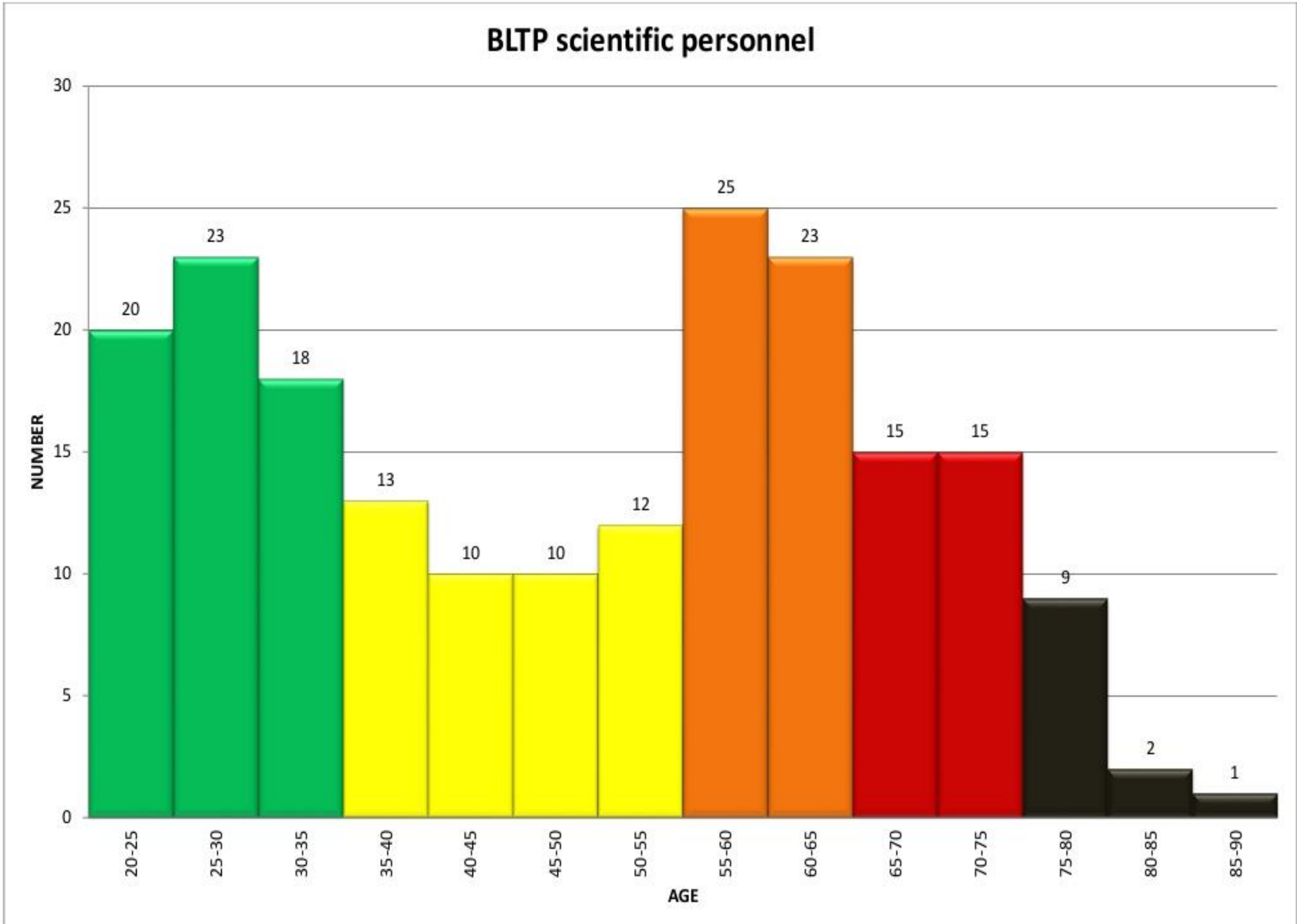
BLTP's Scientific Policy

Development of research in **Theoretical Physics**
on the basis of **Advanced Mathematics;**
Multidisciplinary research;
Support of the **JINR Experimental Programme;**
Strengthening of the **efficiency of scientific staff** through
the interplay of **Research and Education.**



Scientific Personnel

	D	C	O	Total
Fundamental Interactions	30	27	26	**83**
Nuclear Physics	25	23	20	**68**
Condensed Matter	16	22	10	**48**
Mathematical Physics	13	12	7	**32**
Total	**84**	**84**	**63**	**231**


BLTP scientific personnel
NUMBER
AGE
30
25
20
15
10
5
0
20
23
18
13
10
10
12
25
23
15
15
9
2
1
20-25
25-30
30-35
35-40
40-45
45-50
50-55
55-60
60-65
65-70
70-75
75-80
80-85
85-90

SCIENTIFIC PERSONNEL BY COUNTRY (BLTP)

Country	Total		Country	Total
Russia	165		Germany	6
Czech Republic	5		Poland	3
Mongolia	1		Bulgaria	7
Turkey	1		Korea	1
Belarus	2		India	3
Kazakhstan	9		Uzbekistan	3
Slovakia	7		Moldavia	1
Azerbaijan	2		Mexico	1
Ukraine	3		Romania	3
Tajikistan	1		Japan	1
Vietnam	1		Argentina	1
Armenia	4			
Total - 231 (165 scientists from Russia and 66 from other countries)				

2014-2018: Themes and projects

Theory of Theory of Fundamental Interactions

Projects:
- Standard Model and Its Extension,
- QCD Parton Distributions for Modern and Future Colliders,
- Physics of Heavy and Exotic Hadrons,
- Mixed Phase in Heavy-Ion Collisions.

Nuclear Theory

Projects:
- Nuclear Structure far from Stability Valley
- Nucleus-Nucleus Collisions and Nuclear Properties
- Exotic Few-Body Systems,
- Nuclear Structure and Dynamics at the Relativistic
- Energies.

Theory of Condensed Matter

Projects:
- Physical properties of complex materials and nanostructures
- Mathematical problems of many-particle systems

Modern Mathematical Physics:

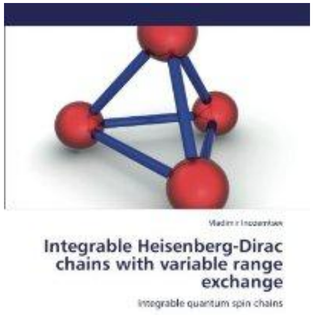
Projects:
- Quantum groups and integrable systems
- Supersymmetry
- Quantum gravity, cosmology and strings

Education Project
“Dubna International School of Theoretical Physics (DIAS-TH)”

Bogoliubov Laboratory of Theoretical Physics

Publications, 2014

Journals & Conf. Proc ~ **490**



Conferences and Schools

Total - **16 (~ 1000 participants)**

DIAS-TH and Helmholtz Schools - **4**

> 20 countries were represented

Educational Activity

More than **40 lecture courses** at JINR UC, DIAS-TH, Moscow U., Dubna U., MPTI, etc.

Awards, Grants and Fellowships

Outstanding APS Referee Award – V.S. Melezhik

Panarmenian Award by World Armenian Congress "Best scientific work" - V. Sargsyan

The Grant of RF President for Young Scientists – A.Bednyakov, A. Pikelner

Fellowship for Young International Scientists of CAS – T. Schneidman

Fellowship FAIR Russia Research Center Young Scientist – I.Egorova

Dozens of grants: RFBR, RFBR-CNSF, RFBR-DFG, RFBR-CNRS, etc.

Dubna International Advanced School of Theoretical Physics (DIAS-TH)

Training courses for students, graduates, and young scientists in the JINR Member States and other countries.

Looking for and supporting gifted young theorists in the JINR Member States.

Organization of schools of different scales in Dubna and coordination with similar schools.

Cooperation with the JINR University Center in training students and postgraduates as well as in organizing schools for students.

Publication of lectures with the use of modern electronic equipment.

Joint Institute for Nuclear Research

Bogoliubov Laboratory of Theoretical Physics

BLTP

Dubna International Advanced School of Theoretical Physics

2014

February 2 – 8
XII Winter School on Theoretical Physics

April 1 – 30
XVIII Research Workshop
Nucleation Theory and Applications

July 21 – August 1
Helmholtz International Summer School
Nuclear Theory and Astrophysical Application

August 25 – September 6
Helmholtz International Summer School
Lattice QCD, Hadron Structure
and Hadronic Matter

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http://theor.jinr.ru/~diastp/diasth/

AGREEMENTS

- **BLTP – ICTP** (since ’88)
- **BLTP – Germany** (since ’91)

  Heisenberg-Landau Program
- **BLTP – INFN** (since XII ’95)

  6 month visits to Italy
- **BLTP – CERN-TH** (since XII ’95)

  3 month visits to CERN
- **BLTP – Poland** (since XII ’98)

  Bogoliubov-Infeld Program
- **BLTP – Czech Republic** (since XII ’99)

  Blokhintsev-Votruba Program
- **BLTP – Romania** (since XII ’03)

  Titeica-Markov Program
- **BLTP – APCTP, Pohang** (since ’07)
- **BLTP – Bulgaria** (since ’09)

  Soloviev-Khristov Program
- **BLTP – ITP CAS, China** (since VII ’10)
- **BLTP – IOP VAST, Vietnam** (since VIII ’11)
- **BLTP – Physical Inst., NAS, Armenia** (since ’09)

Smorodinsky - Ter-Martirosyan Program

Meetings in BLTP 2015

April 1 - 30
XIXth Research Workshop
Nucleation Theory and Applications

April 6 - 8
Seminar dedicated to the memory of E.A. Kuraev
Selected problems in quantum field theory

June 15 - 19
Brasil - JINR Forum
Frontiers in Nuclear, Elementary Particle and Condensed Matter Physics

June 23 - 27, Prague, Czech Republic
XXIII International Colloquium
Integrable Systems and Quantum Symmetries

June 27 - July 4, Almaty, Kazakhstan
The 9th APCTP-BLTP JINR Joint Workshop
Modern problems in nuclear and elementary particle physics

June 29 - July 11
Helmholtz - DIAS International Summer School
Dense Matter

July 6 - 11
The 15th International Conference
Strangeness in Quark Matter (SQM-2015)

July 6 - 11, Tsakhkadzor, Armenia
The IVth International School
Symmetry in Integrable Systems & Nuclear Physics

July 13 - 18, Yerevan, Armenia
The 9th International Conference
Quantum Theory and Symmetries (QTS-9)

July 14 - 18
The International Conference
Nuclear Structure and Related Topics (NSRT15)

July 20 - 30
Helmholtz - DIAS International Summer School
Theory challenges for LHC physics
and Workshop
Calculations for Modern and Future Colliders

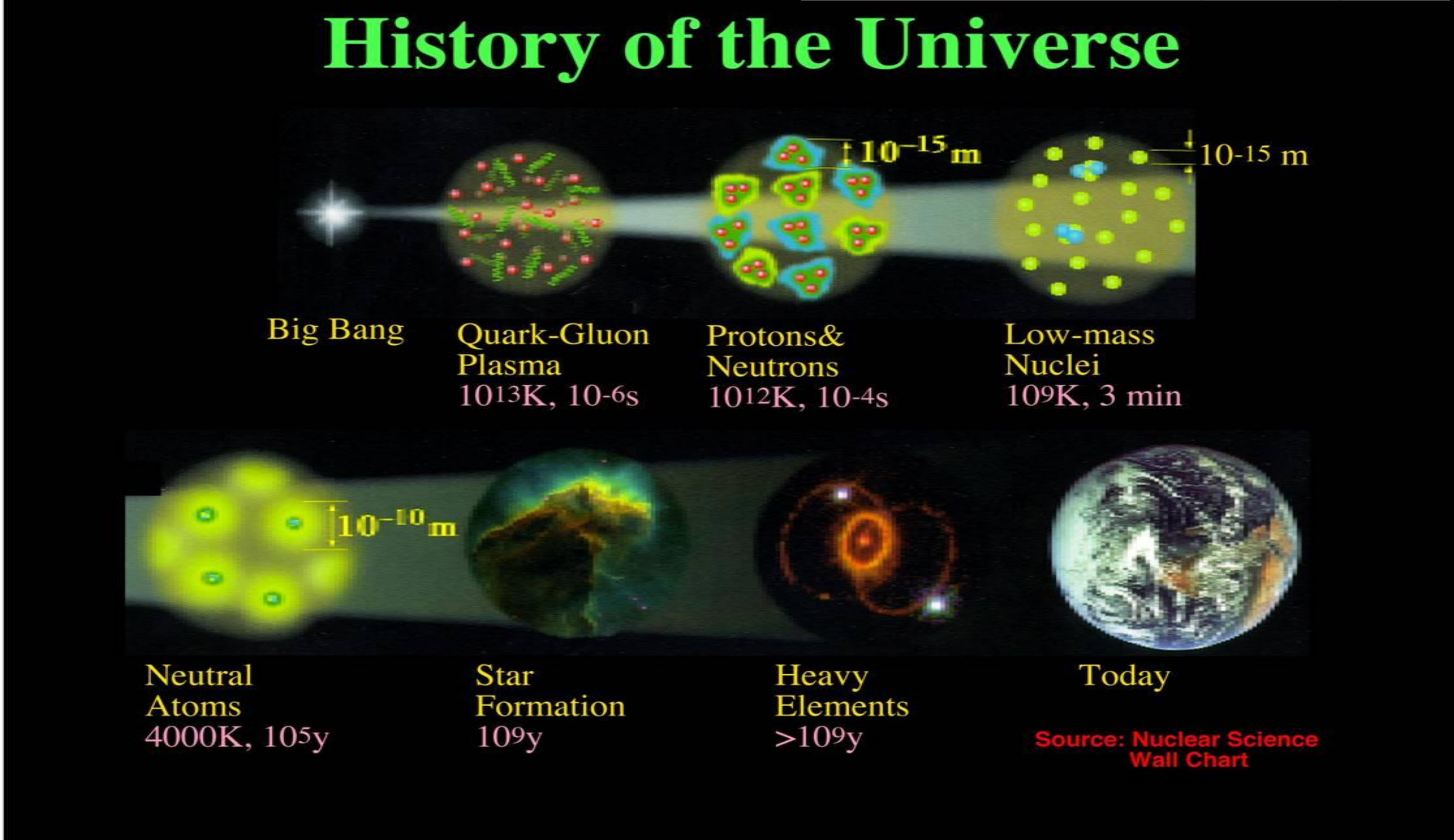
August 3 - 8
International Workshop
Supersymmetries and Quantum Symmetries (SQS'2015)

August 27 - September 4, Horny Smokovec, Slovakia
VI International Pontecorvo
Neutrino Physics School

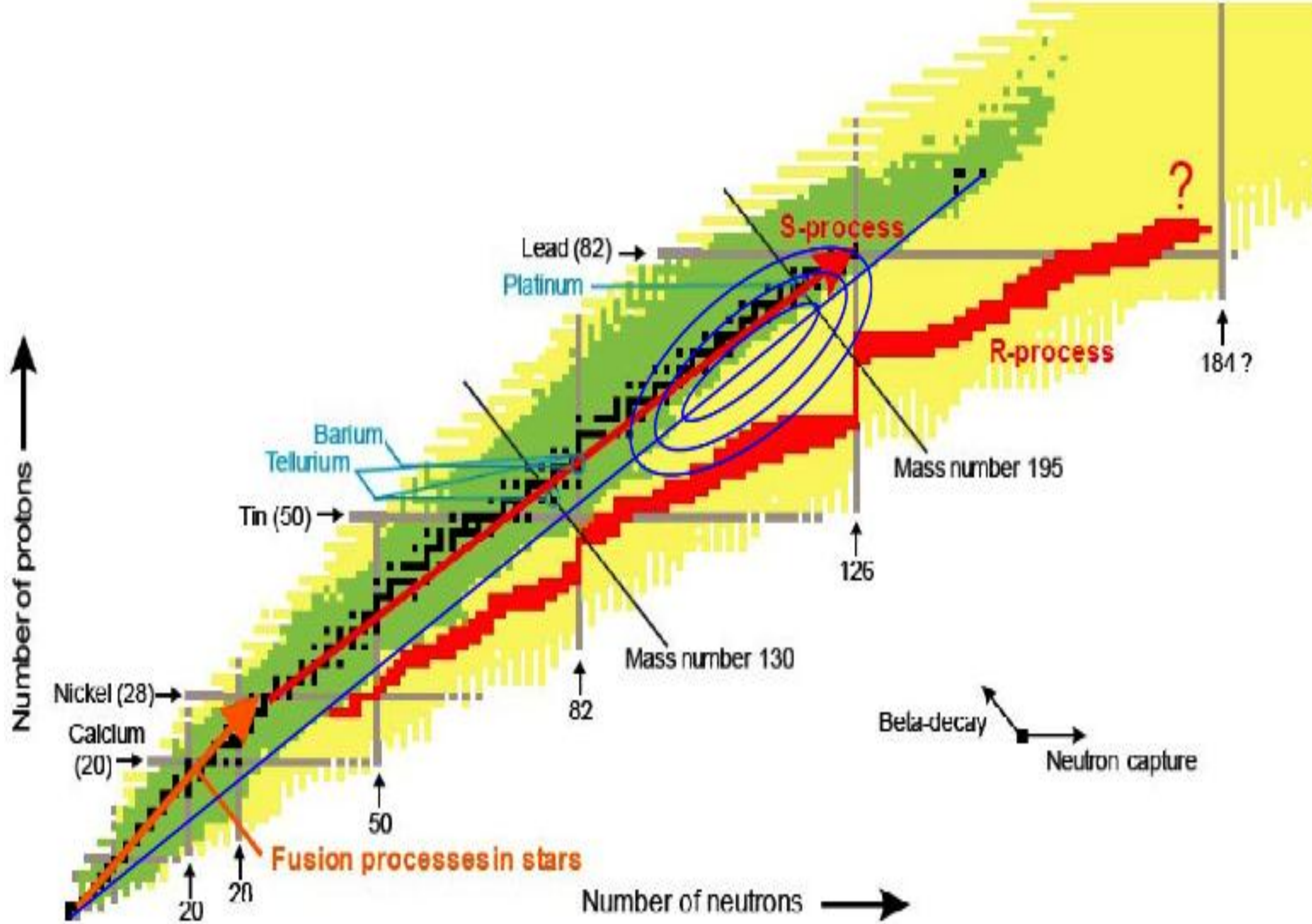
September 8 - 12
XVIth International Workshop
High Energy Spin Physics (DSPIN-15)

September 21-25
4th South Africa - JINR Symposium
Few to Many Body Systems: Models and Methods and Applications

"The most incomprehensible thing about our universe, is that it can be comprehended" (A. Einstein)



- The big bang theory states that the universe began as a gigantic explosion
- This idea has entered popular culture


S-process
?
Lead (82)
Platinum
R-process
184 ?
Barium
Tellurium
Mass number 195
Tin (50)
126
Mass number 130
Nickel (28)
82
Beta-decay
Calcium
(20)
Neutron capture
50
Fusion processes in stars
20
20
Number of neutrons
Number of protons

- s-process path in the (N, Z) diagram (Fig. 5.3):
  - ⇝ leaves out some n-rich isotopes: define them as **pure r-process** nuclei
  - ⇝ leaves out some p-rich isotopes: define them as **pure p-process** nuclei
  - ⇝ define **pure s-process** nuclei such that
    - a) they lie on the s-process path
    - b) they can not form from β^--decays of nuclei far from the valley of stability

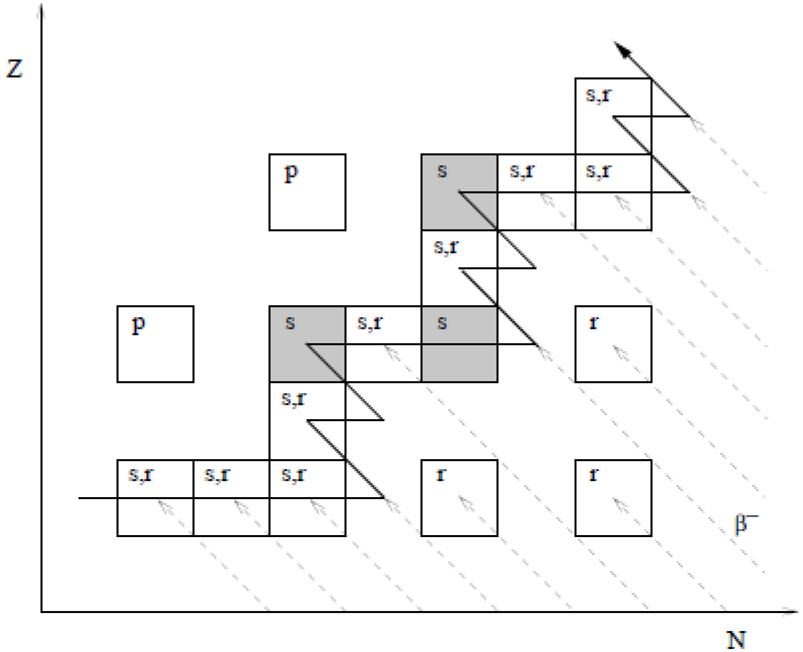


Figure 5.3: Schematic section of the nuclide chart, showing the *s*-process path as the thick solid line. Dashed lines show the β-decay paths of neutron-rich nuclei produced by the *r*-process. Shaded boxes show nuclei that are shielded from the *r*-process.

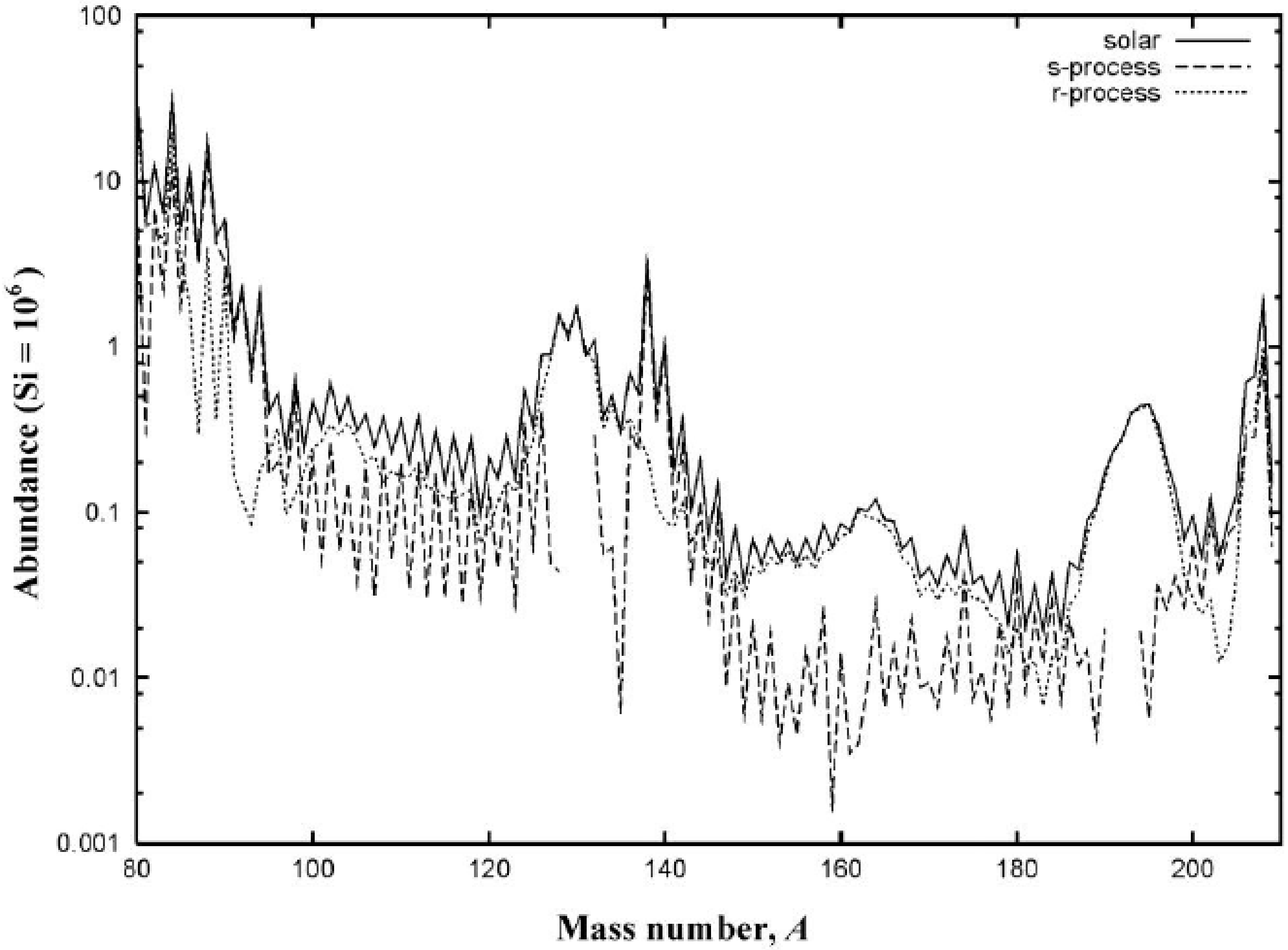


FIGURE 12. Contribution of s- and r-process to the solar abundances of the isobars for heavy elements (p-isotopes cannot be seen in this figure because of their very small abundances). Solar system abundances are measured (Anders and Grevesse 1989), s- and r-abundances are calculated. The peaks in the solar abundances around mass numbers A = 88, 138, 208 are formed in the s-process, whereas the broader companion peaks shifted to slightly lower mass number are r-process peaks.

Microscopic approaches to many-body, finite nuclear systems

- Theoretical models based on effective interactions between nucleons:
- - Nuclear shell model
- - Mean field approaches (and beyond)
- - molecular dynamics

- * going away from stability regions, we need a theoretical framework which can be predictive and able to handle new situations (continuum, pairing correlations in continuum).
- * the Hartree-Fock-Bogoliubov + Quasiparticle Random Phase Approximation can be used from unstable nuclei to neutron star crust.

Hohenberg-Kohn theorem

We consider a realistic manybody system with the kinetic energy T and two-body interaction $V(r_i,r_k)$ in an external field $U(r)$. In this case the expectation value of the exact energy

$$E_{HK}[\rho(\mathbf{r})] = \langle \hat{T} + \hat{V} \rangle$$

is given by a universal functional $E_{HK}[\rho]$, which does only depend on the local density $\rho(r)$, and not on the external potential $U(r)$.

The ground state is determined by minimizing $E_{HK}[\rho]$ with respect to ρ

Kohn-Sham theorem

For the same system the expectation value of the exact energy is also given by a functional

$$E_{KS}[\rho(\mathbf{r}), \tau(\mathbf{r})] = \langle \hat{T} + \hat{V} \rangle$$

is given by a universal functional $E_{KS}\rho]$, which does depend on $\rho(r)$ and on the kinetic energy density

$$\tau(\mathbf{r}) = \nabla_r \nabla_{r'} \langle a^+(\mathbf{r}) a(\mathbf{r}') \rangle \Big|_{\mathbf{r}=\mathbf{r}'}$$

Density functional theory

$$E = \langle \Psi | \hat{H} | \Psi \rangle = \langle \Phi | \hat{H}_{eff} | \Phi \rangle = E[\hat{\rho}]$$

$|\Phi\rangle$ **Slater determinant** $\Leftrightarrow$ $\hat{\rho}$ **density matrix**

$$|\Phi\rangle = \mathbf{A}(\varphi_1(\mathbf{r}_1)\cdots\varphi_A(\mathbf{r}_A)) \qquad \hat{\rho}(\mathbf{r},\mathbf{r}') = \sum_{i=1}^{A} |\varphi_i(\mathbf{r})\rangle\langle\varphi_i(\mathbf{r}')|$$

Mean field:

$$\hat{h} = \frac{\delta E}{\delta \hat{\rho}}$$

Eigenfunctions:

$$\hat{h}|\varphi_i\rangle = \varepsilon_i |\varphi_i\rangle$$

Interaction:

$$\hat{V} = \frac{\delta^2 E}{\delta \hat{\rho} \delta \hat{\rho}}$$

LOW-ENERGY DIPOLE STATES IN NEUTRON-RICH $N = 80, 82, 84$ ISOTONES

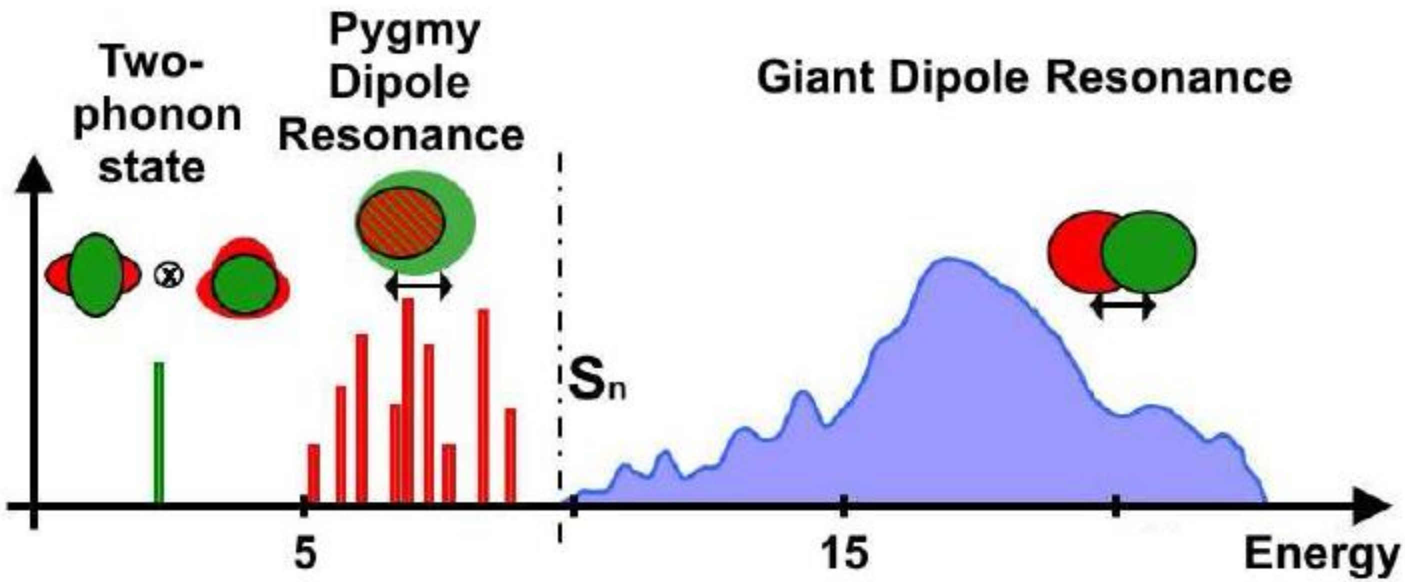
In collaboration with

N.N. Arsenyev, BLTP JINR, Dubna

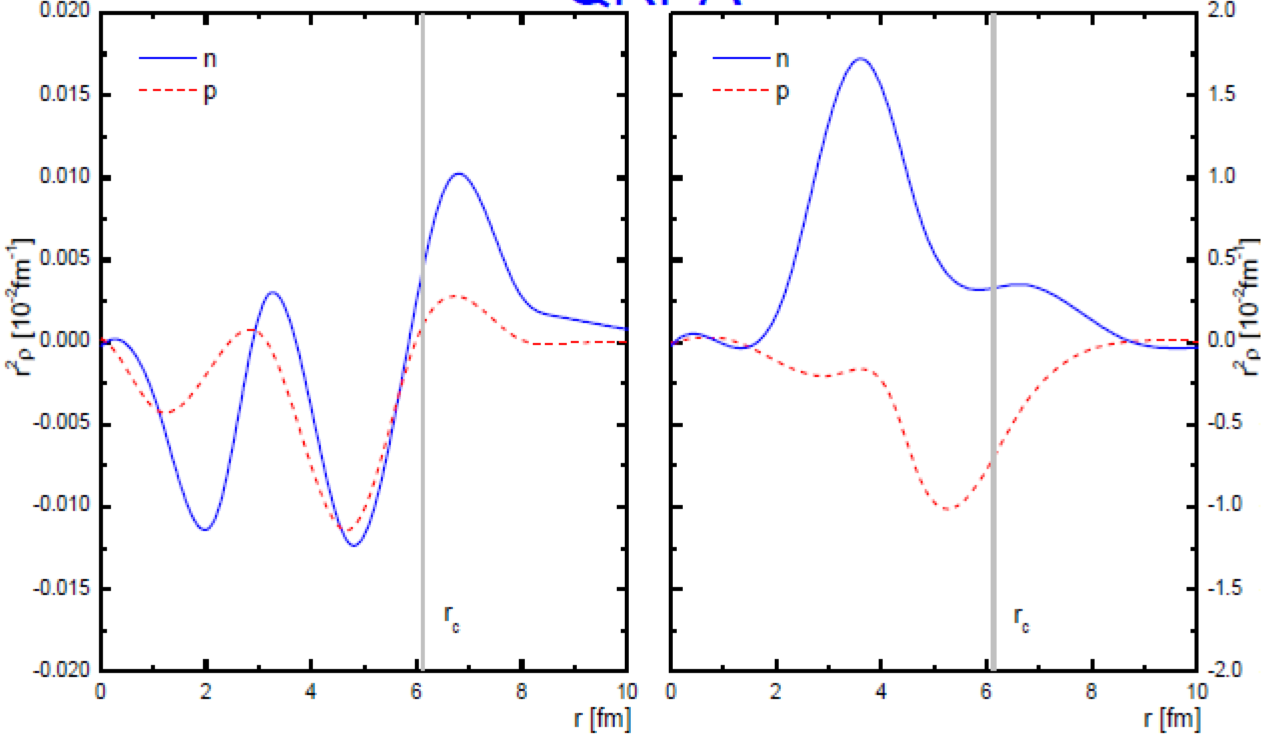
A.P. Severyukhin, BLTP JINR, Dubna

Nguyen Van Giai, IPN , Orsay

*E*1 strength in (spherical) atomic nuclei



QRPA


0.020
0.015
0.010
0.005
0.000
-0.005
-0.010
-0.015
-0.020
$r^2\rho$ [10^{-2}fm^{-1}]
n
p
r_c
0
2
4
6
8
10
r [fm]
n
p
r_c
0
2
4
6
8
10
r [fm]
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
$r^2\rho$ [10^{-2}fm^{-1}]

Relevance of the PDR

1. The PDR might play an important role in nuclear astrophysics. For example, the occurrence of the PDR could have a pronounced effect on neutron-capture rates in the r-process nucleosynthesis, and consequently on the calculated elemental abundance distribution.

– *S. Goriely*, Phys. Lett. **B436**, 10 (1998).

2. The study of the pygmy $E1$ strength is expected to provide information on the symmetry energy term of the nuclear equation of state. This information is very relevant for the modeling of neutron stars.

– *C. J. Horowitz and J. Piekarewicz*, Phys. Rev. Lett. **86**, 5647 (2001).

3. New type of nuclear excitation: these resonances are the low-energy tail of the GDR, or if they represent a different type of excitation, or if they are generated by single-particle excitations related to the specific shell structure of nuclei with neutron excess.

– *N. Paar et al.*, Rep. Prog. Phys. **70**, 691 (2007).

Realization of QRPA

We employ the effective Skyrme interaction in the particle-hole channel

$$V(\vec{r}_1,\vec{r}_2) = t_0\left(1+x_0\hat{P}_\sigma\right)\delta(\vec{r}_1-\vec{r}_2) + \frac{t_1}{2}\left(1+x_1\hat{P}_\sigma\right)\left[\delta(\vec{r}_1-\vec{r}_2)\vec{k}^2 + \vec{k}'^2\delta(\vec{r}_1-\vec{r}_2)\right]$$
$$+ t_2\left(1+x_2\hat{P}_\sigma\right)\vec{k}'\cdot\delta(\vec{r}_1-\vec{r}_2)\vec{k} + \frac{t_3}{6}\left(1+x_3\hat{P}_\sigma\right)\delta(\vec{r}_1-\vec{r}_2)\rho^\alpha\left(\frac{\vec{r}_1+\vec{r}_2}{2}\right)$$
$$+ iW_0\left(\vec{\sigma}_1+\vec{\sigma}_2\right)\cdot\left[\vec{k}'\times\delta(\vec{r}_1-\vec{r}_2)\vec{k}\right].$$

D. Vautherin and D. M. Brink, Phys. Rev. **C5**, 626 (1972).

The Hamiltonian includes the surface peaked density-dependent zero-range force in the particle-particle channel.

$$V_{pair}(\vec{r}_1,\vec{r}_2) = V_0\left(1-\frac{\rho(r_1)}{\rho_c}\right)\delta(\vec{r}_1-\vec{r}_2),$$

where $\rho(r_1)$ is the particle density in coordinate space, ρ_c is equal to the nuclear saturation density. The strength V_0 is a parameter fixed to reproduce the odd-even mass difference of nuclei in the studied region.

N.Arseny

We work in the quasiparticle representation defined by the canonical Bogoliubov transformation:

$$a_{jm}^{+} = u_j \alpha_{jm}^{+} + (-1)^{j-m} v_j \alpha_{j-m},$$

where jm denote the quantum numbers $nljm$.

N. N. Bogoliubov, Sov. Phys. JETP **7**, 41 (1958).

The starting point of the method is the HF-BCS calculations of the ground state, where spherical symmetry is assumed for the ground states. The continuous part of the single-particle spectrum is discretized by diagonalizing the HF Hamiltonian on a harmonic oscillator basis.

J. P. Blaizot and D. Gogny, Nucl. Phys. **A284**, 429 (1977).

The residual interaction in the particle-hole channel V_{res}^{ph} and in the particle-particle channel V_{res}^{pp} can be obtained as the second derivative of the energy density functional $\mathcal{H}$ with respect to the particle density ρ and the pair density $\tilde{\rho}$, respectively.

$$V_{res}^{\mathrm{ph}} \sim \frac{\delta^2 \mathcal{H}}{\delta \rho_1 \delta \rho_2} \quad V_{res}^{\mathrm{pp}} \sim \frac{\delta^2 \mathcal{H}}{\delta \tilde{\rho}_1 \delta \tilde{\rho}_2}.$$

We simplify V_{res}^{ph} by approximating it by its Landau-Migdal form. Moreover we keep only Landau parameters F_0, F_0', G_0, G_0'. Thus, we can write the residual interaction in the following form:

$$V_{res}^{\mathrm{ph}}(\vec{r}_1, \vec{r}_2) = N_0{}^{-1}\Big[F_0(r_1) + G_0(r_1)\sigma_1 \cdot \sigma_2$$
$$+ (F_0'(r_1) + G_0'(r_1)\sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2)\Big]\delta(\vec{r}_1 - \vec{r}_2),$$

where τ_i is the isospin operator, and $N_0 = 2k_F m^*/\pi^2\hbar^2$ with k_F and m^* standing for the Fermi momentum and nucleon effective mass.
The corresponding Landau parameters can be expressed via the Skyrme force parameters.

N.Arsenyev

BLTP

N. V. Giai and H. Sagawa, Phys. Lett. **B106**, 379 (1981).

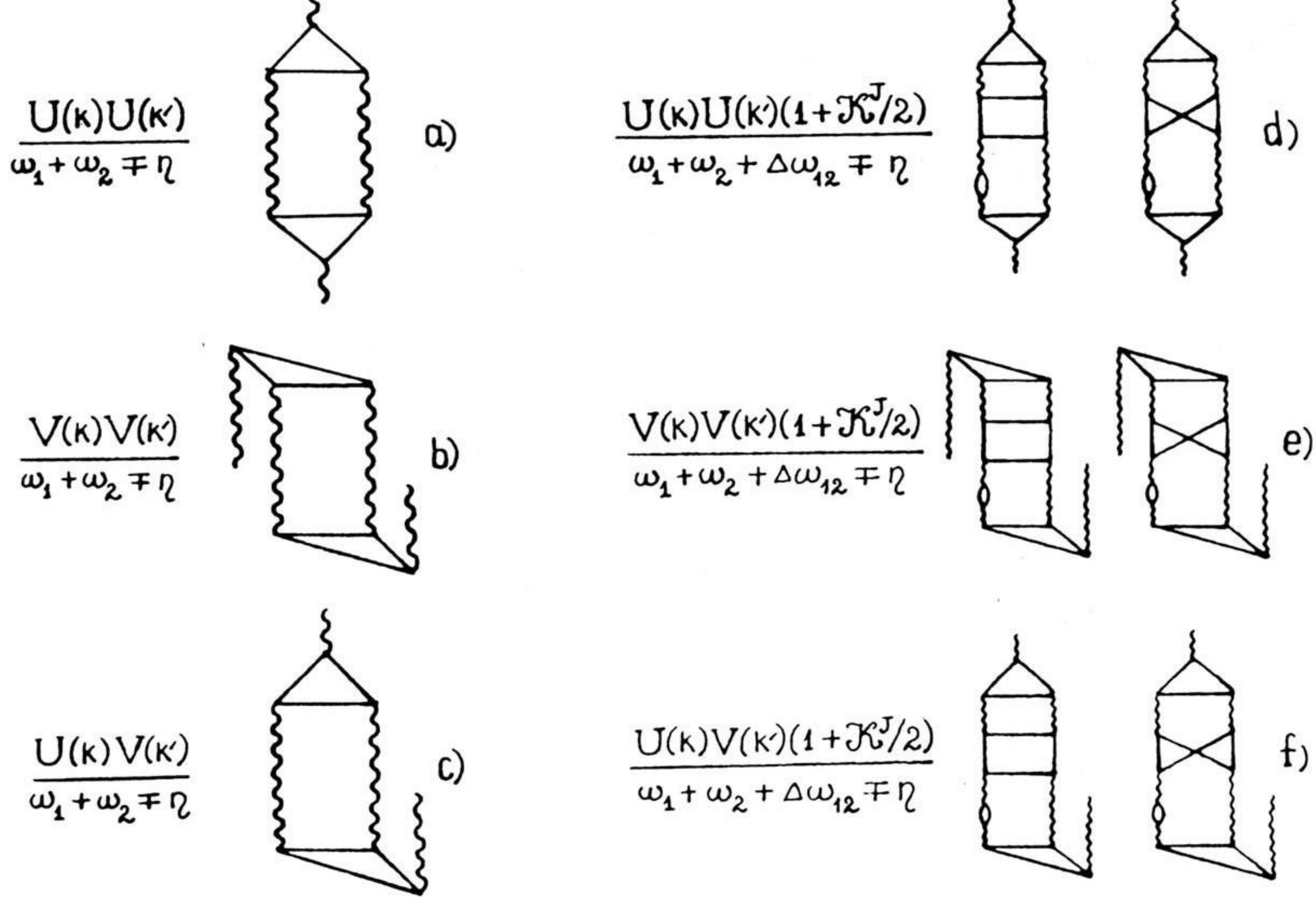
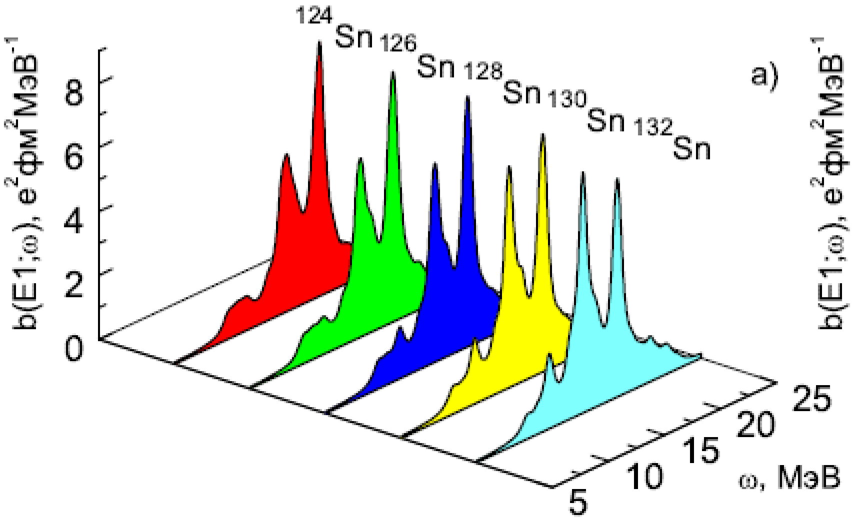
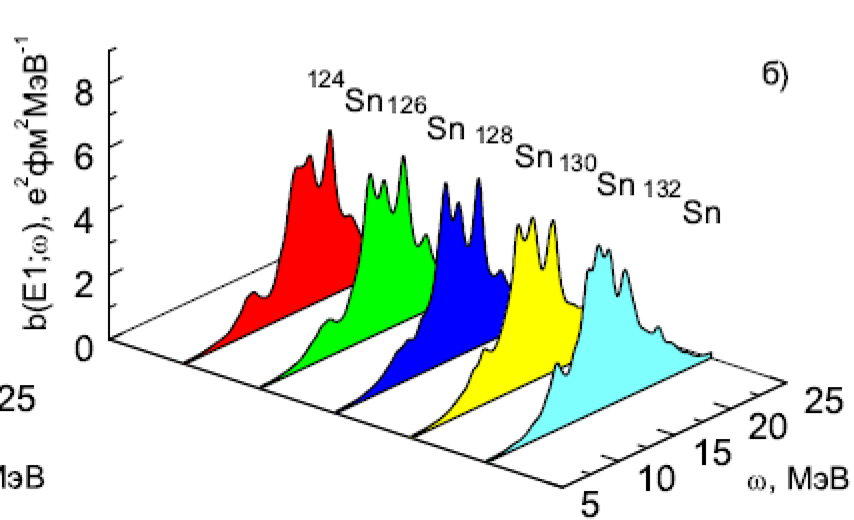


Fig.3. Correspondence between the diagrams included in the QPM with the matrix elements $M_{kk'}(12)$ a,b,c) if the corrections of the Pauli principle are neglected. d,e,f) if the corrections of the Pauli principle are taken into account.

easily from the QPM formula in the transition, when one of

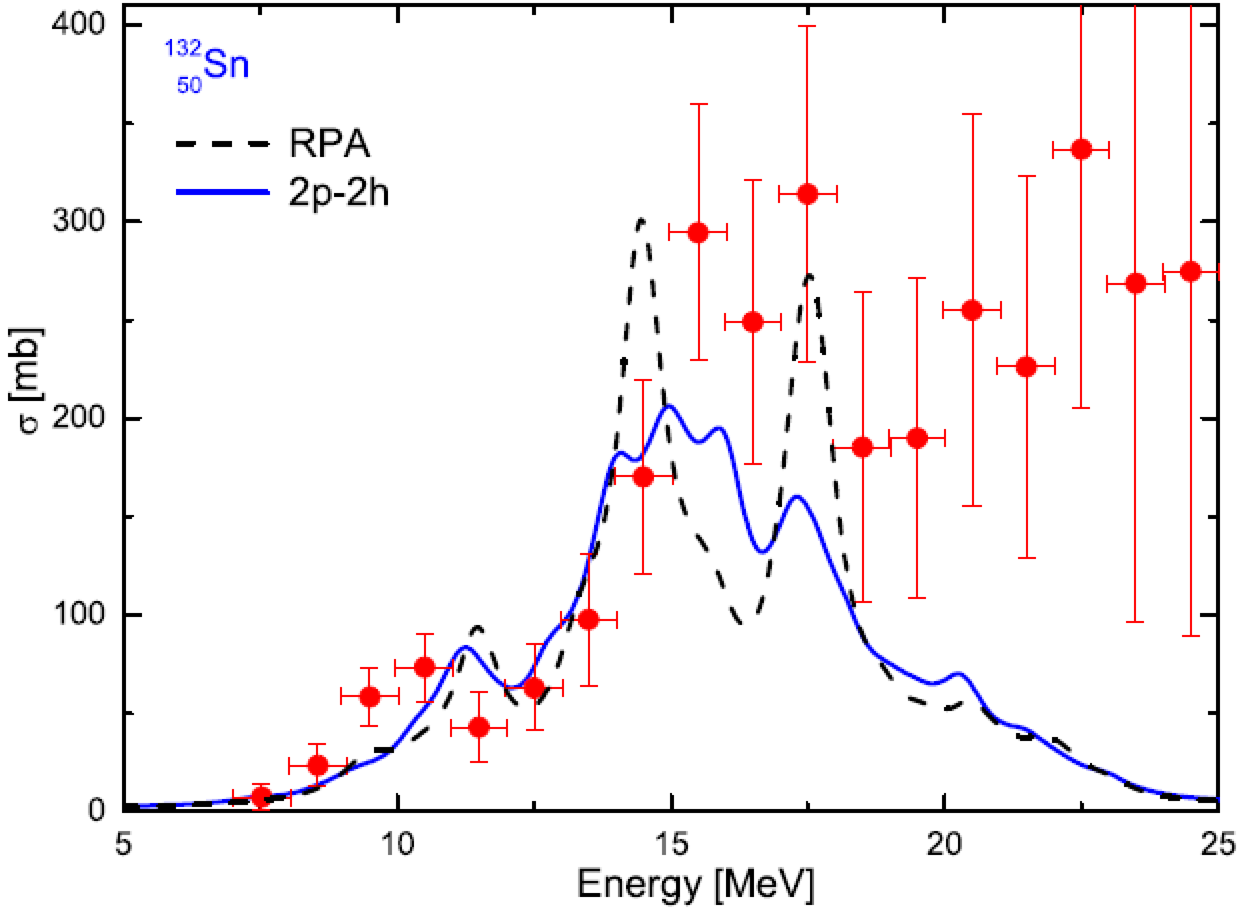


b(E1;ω), e²фм²МэВ⁻¹
0
2
4
6
8
¹²⁴Sn ¹²⁶Sn ¹²⁸Sn ¹³⁰Sn ¹³²Sn
а)
5
10
15
20
25
ω, МэВ



b(E1;ω), e²фм²МэВ⁻¹
0
2
4
6
8
¹²⁴Sn ¹²⁶Sn ¹²⁸Sn ¹³⁰Sn ¹³²Sn
б)
5
10
15
20
25
ω, МэВ

Photo-absorption cross section for ^{132}Sn

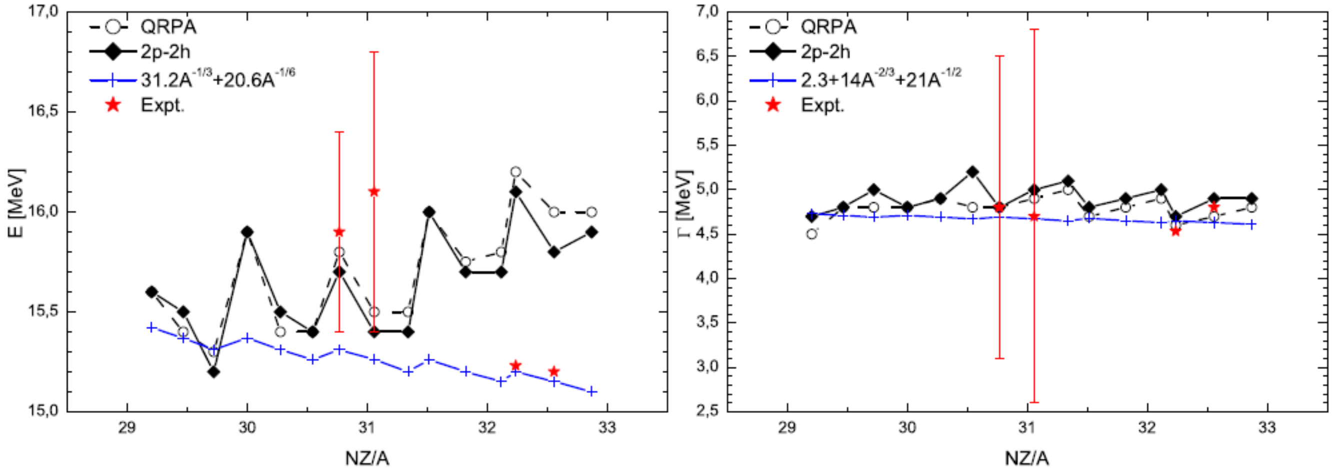


N. N. Arsenyev, A. P. Severyukhin, V. V. Voronov, N. V. Giai, Acta Phys. Pol. **B46**, 517 (2015).

P. Adrich et al., Phys. Rev. Lett. **95**, 132501 (2005).

N.Arsenyev

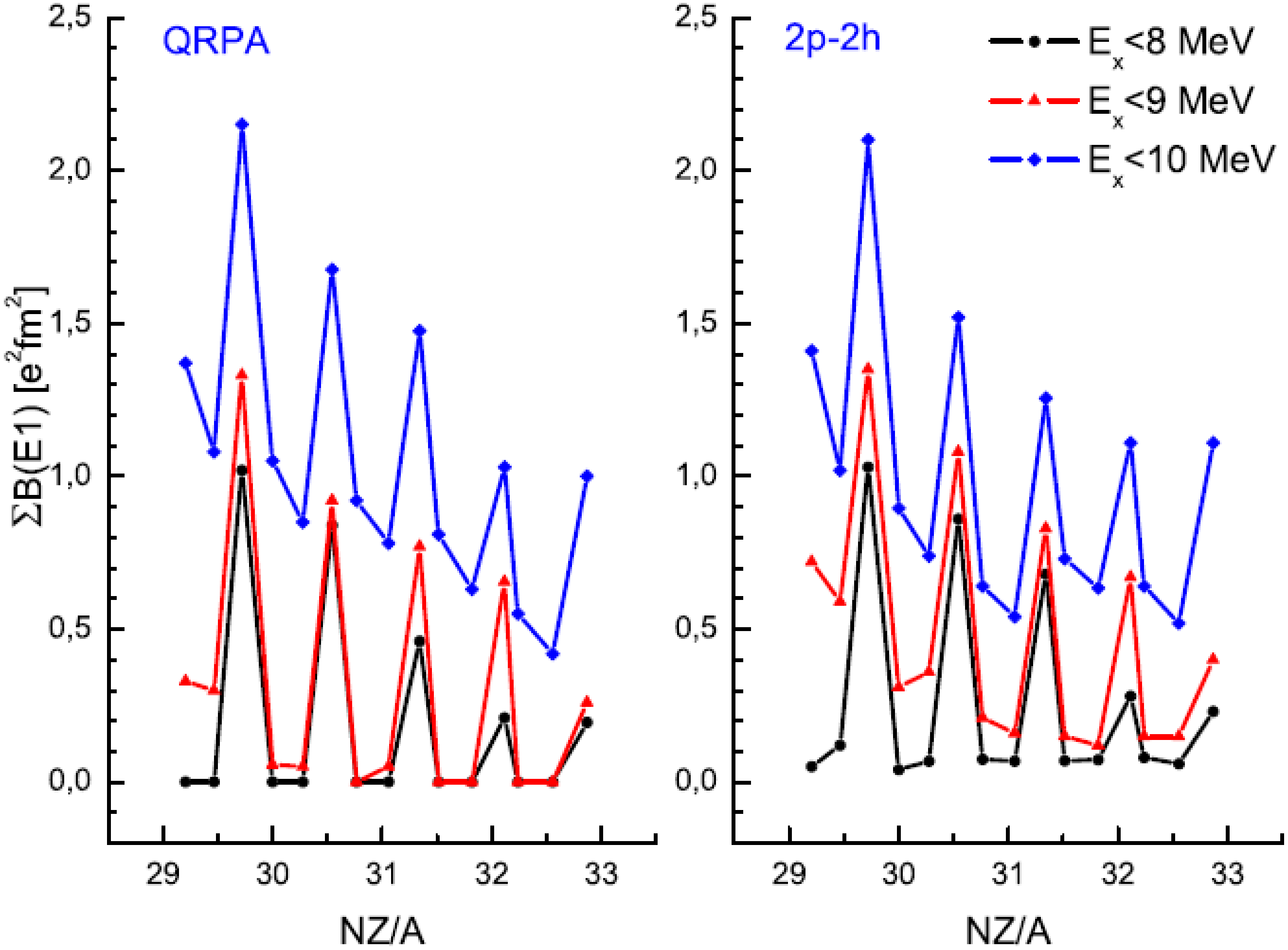
Integral characteristics of the GDR



B. L. Berman and S. C. Fultz, Rev. Mod. Phys. **47**, 713 (1975).

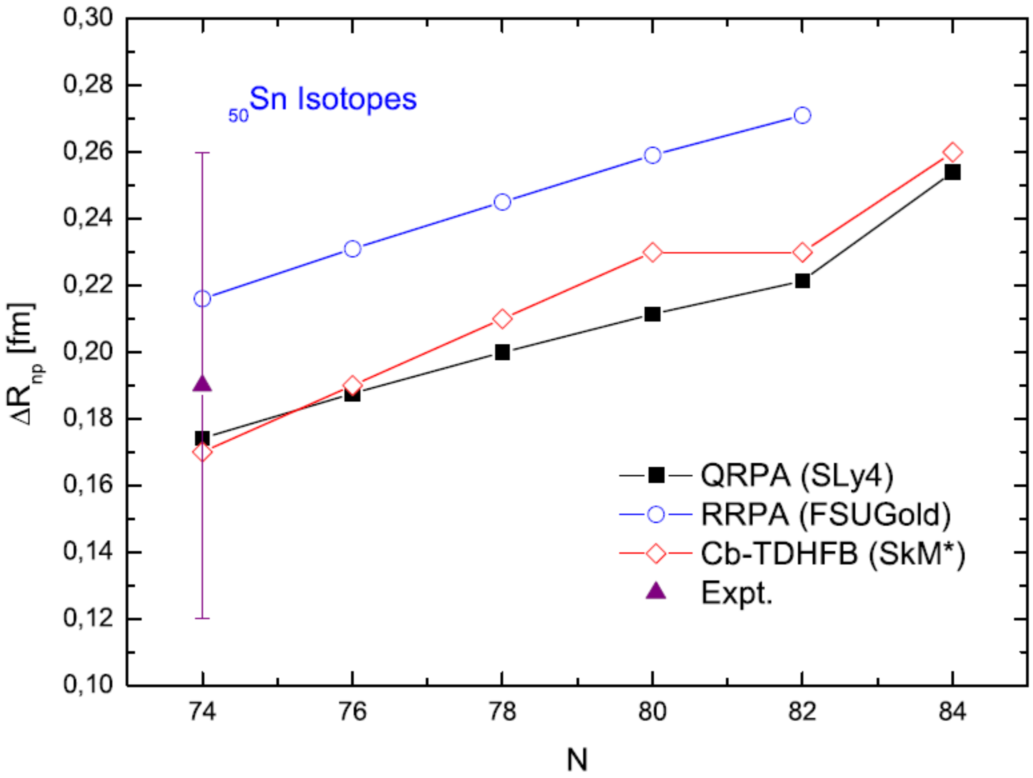
N. Auerbach and A. Yeverechyahu, Ann. Phys. **95**, 35 (1975).

Summed $B(E1)$ values for the low-energy dipole states



N.Arsenyev

The neutron skin thickness: $\Delta R_{np} = \sqrt{\langle r^2 \rangle_n} - \sqrt{\langle r^2 \rangle_p}$



A. Krasznahorkay et al., Phys. Rev. Lett. **82**, 3216 (1999).

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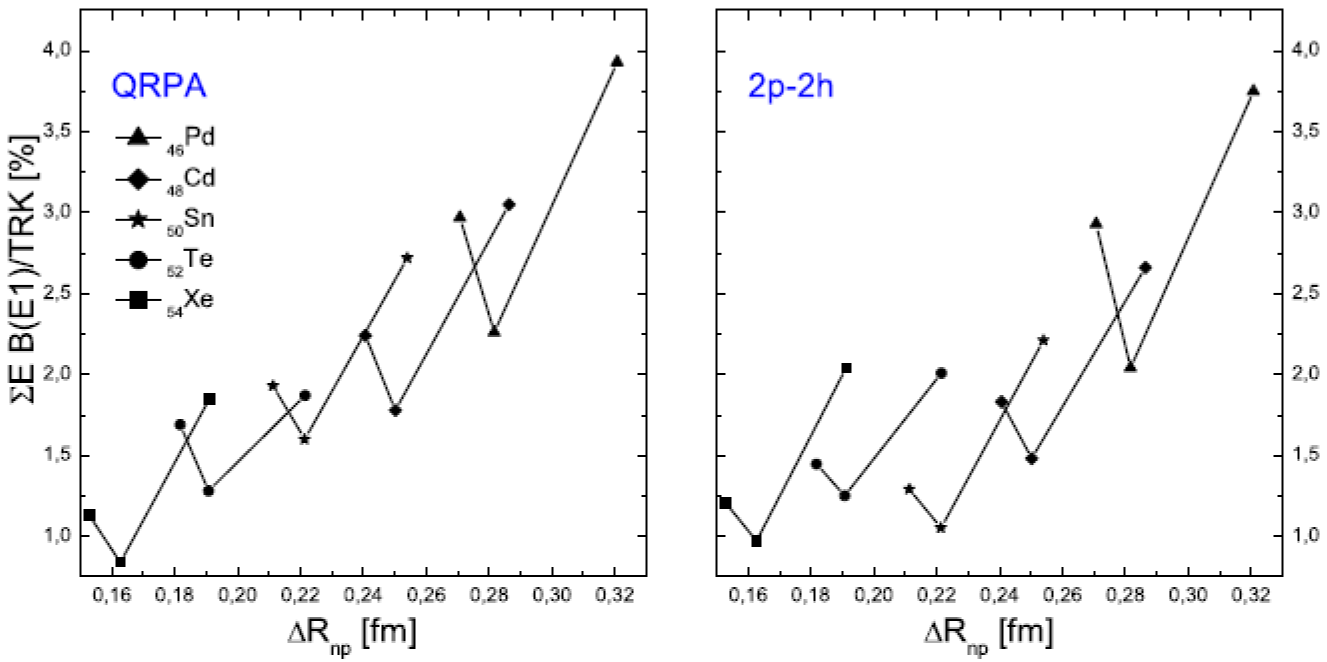
The PDR fractions as functions of the neutron skin ΔR_{np}



$TRK = 432 \div 486$ e^{2}fm^{2}MeV.

PDR fraction/ΔR_{np} shows a universal rate (about 0.2÷0.4 fm^{-1}).

N.Arsenyev

Conclusion

Neutron excess effects on the PDR excitation energy and transition strength have been investigated for the even-even nuclei $^{126-130}$Pd, $^{128-132}$Cd, $^{130-134}$Sn, $^{132-136}$Te, and $^{134-138}$Xe. We have found the impact of the neutron shell closure on the PDR strength. The strong enhancement of the PDR strengths are studied by taking into account with the $2p-2h$ configurations. Correlations between the PDR strength and the neutron skin thickness are observed.

N.Arsenyev

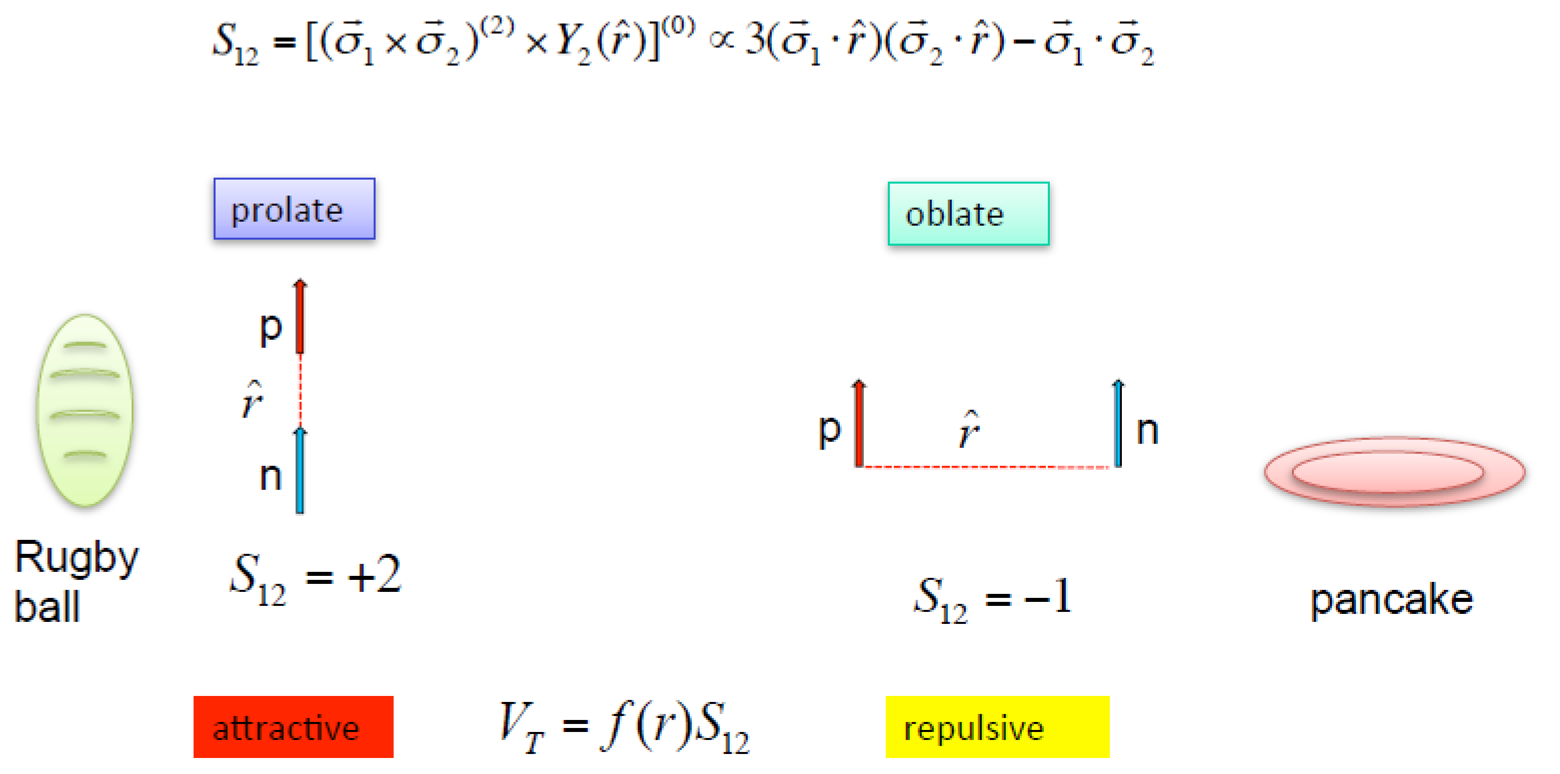


Figure 1: Schematic picture of the expectation values of the tensor operator S_{12} whe are either aligned with (prolate configuration) or perpendicular to (oblate configuration) t distance vector $\vec{r}$. The function $f(r)$ is negative, favouring a prolate shape for the deuteron

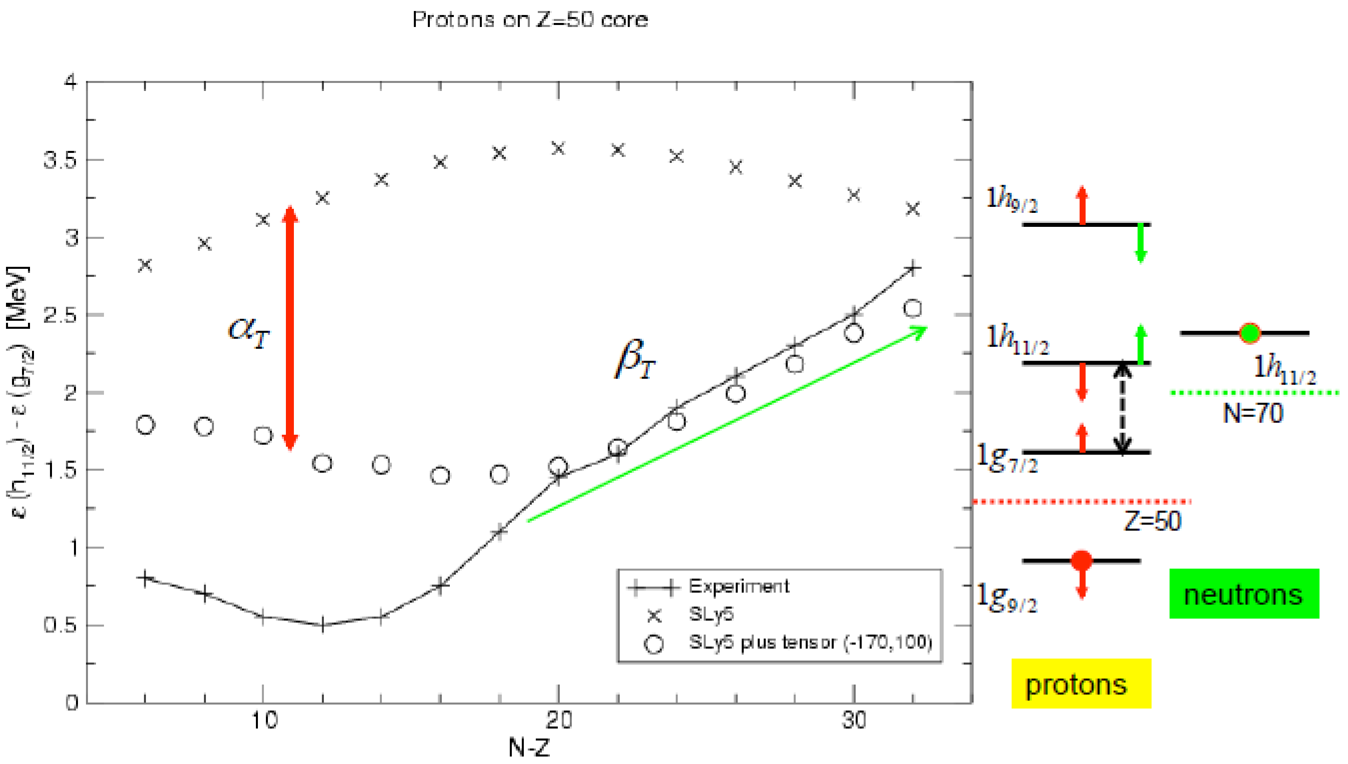
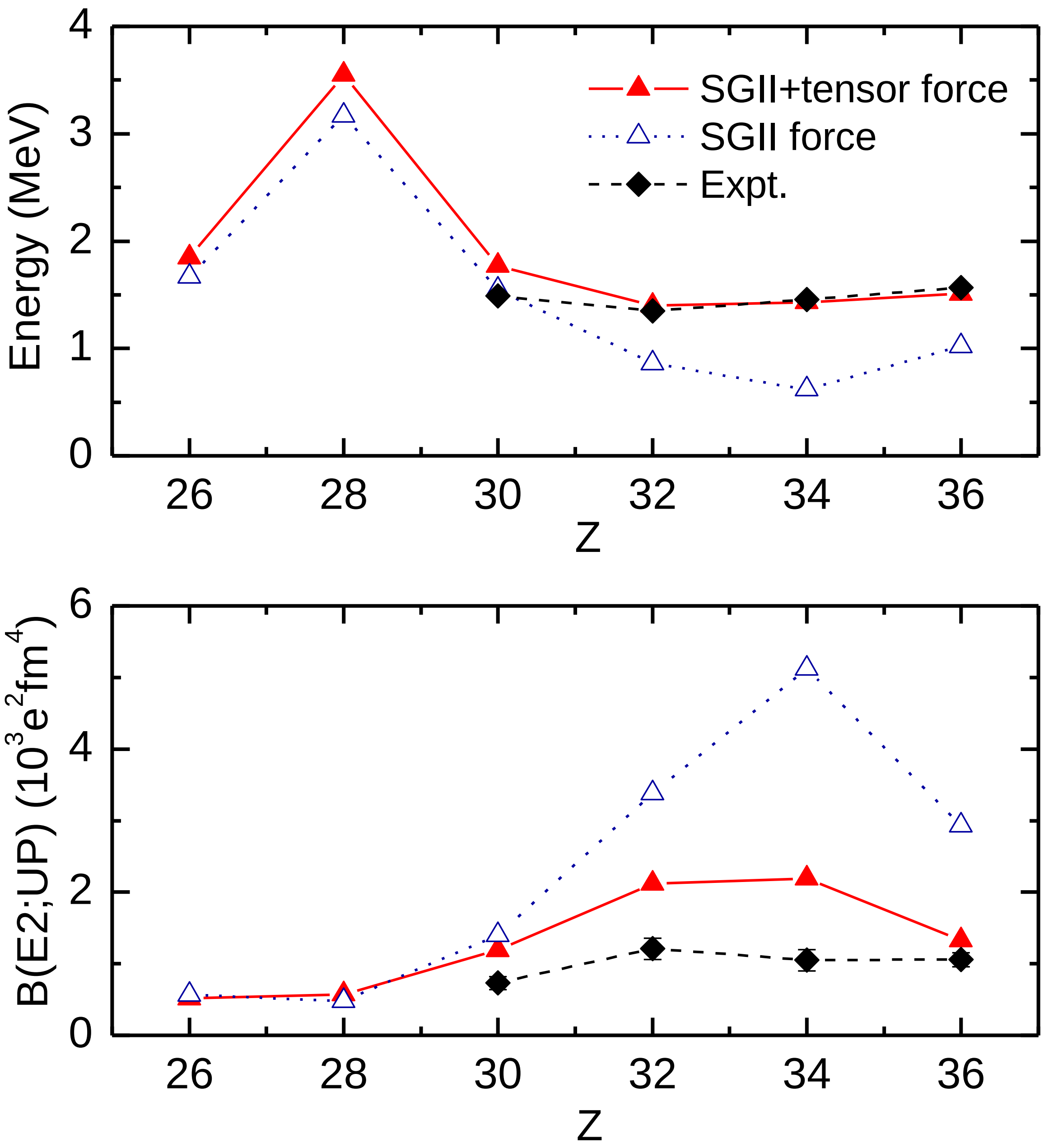
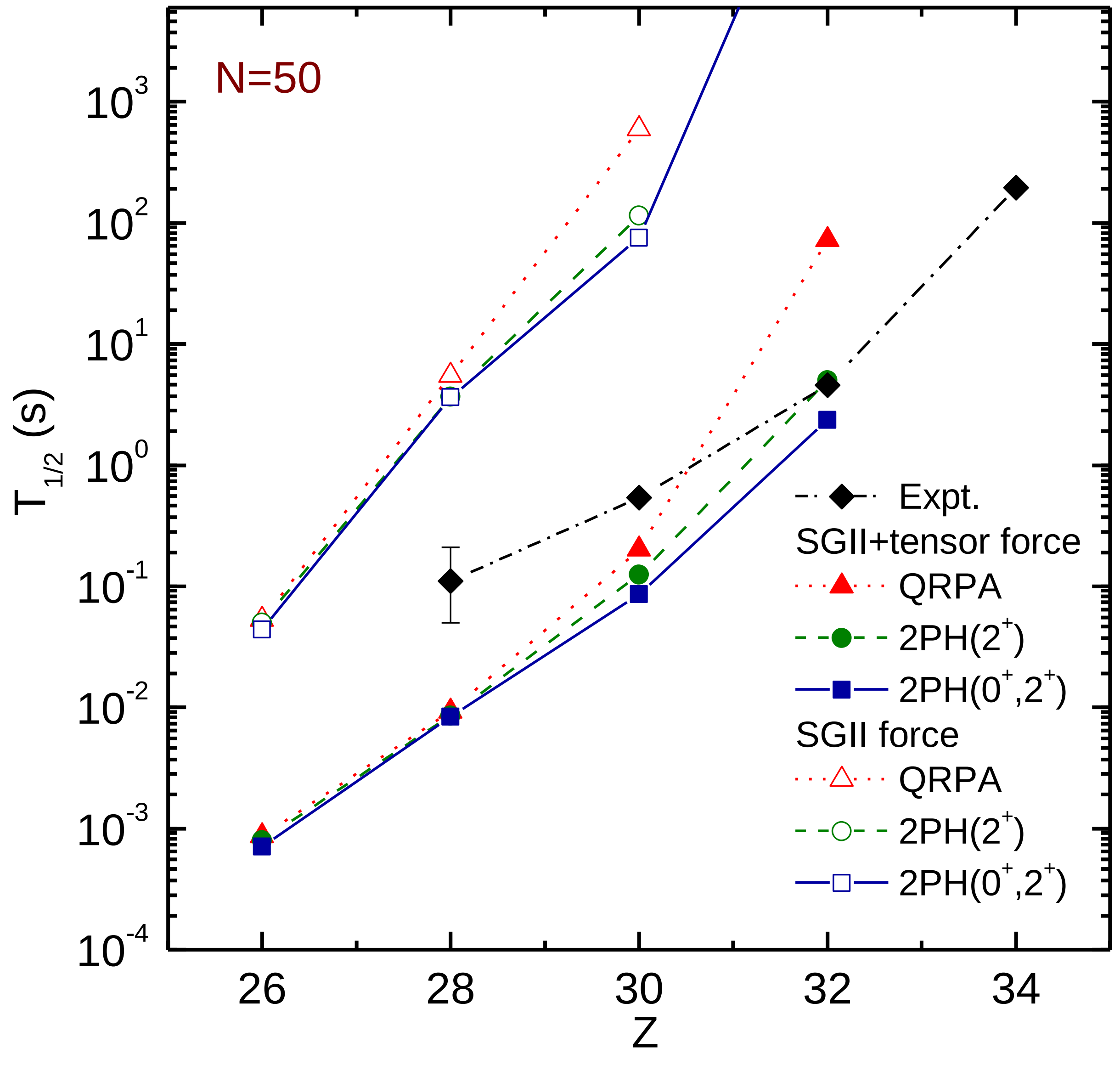


Figure 6: Energy difference between the single-particle $1g_{7/2}$ and $1h_{11/2}$ proton states along the Z=50 isotopes. The calculations are performed with and without tensor terms in the spin-orbit potential (19), on top of the SLy5 [73] parameter set. The experimental data are taken from Ref. [74]. See the text for details.



A.P.S., V.V.Voronov, I. N. Borzov, N. N. Arsenyev, Nguyen Van Giai, JINR preprint E4-2013-133.



N=50
$T_{1/2}$ (s)
Z
Expt.
SGII+tensor force
QRPA
2PH(2+)
2PH(0+,2+)
SGII force
QRPA
2PH(2+)
2PH(0+,2+)

SUMMARY

Many properties of the nuclear collective excitations in stable and unstable nuclei can be described within a microscopic approach based on the density functional method.

Nuclear structure studies are very important for the nuclear physics and nuclear astrophysical applications.

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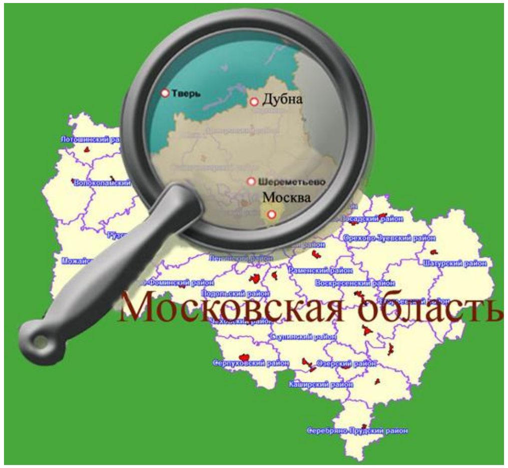

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Welcome!

Thank you for your attention!