Bogoliubov Laboratory of Theoretical Physics

Theory of Nuclear Systems

- 2014—2018 → 2019 – 2023

Theory of Nuclear Structure and Nuclear Reactions → **Theory of Nuclear Systems**

PAC for Nuclear Physics 17.01.2018

COMPLETING THEME: 2014-2018

Theory of Nuclear Structure and Nuclear Reactions
(Leaders: V.V. Voronov, A.I. Vdovin, N.V. Antonenko)
Projects:

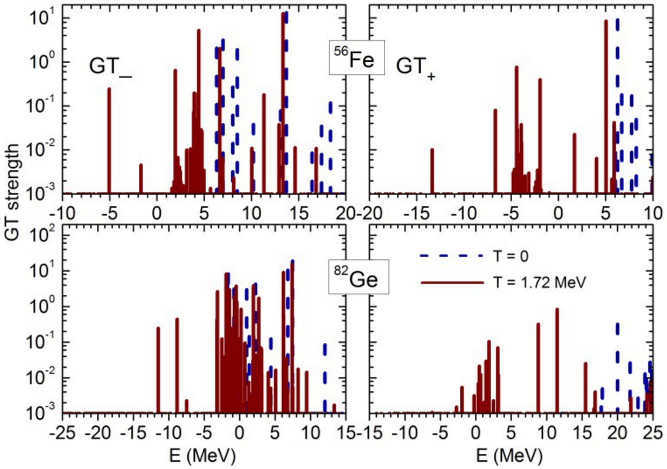
- Nuclear properties at the border of stability
  (Leaders: V.V. Voronov, A.A. Dzhioev, J. Kvasil)
- Low-energy dynamics and nuclear system properties
  (Leaders: S.N. Ershov, N.V. Antonenko, R.V. Jolos)
- Quantum few-body systems
  (Leaders: A.K. Motovilov, V.S. Melezhik)
- Processes with nuclei at relativistic energies and extreme states of matter
  (Leaders: V.V. Burov, M. Gaidarov)

COMPLETING THEME: 2014-2018

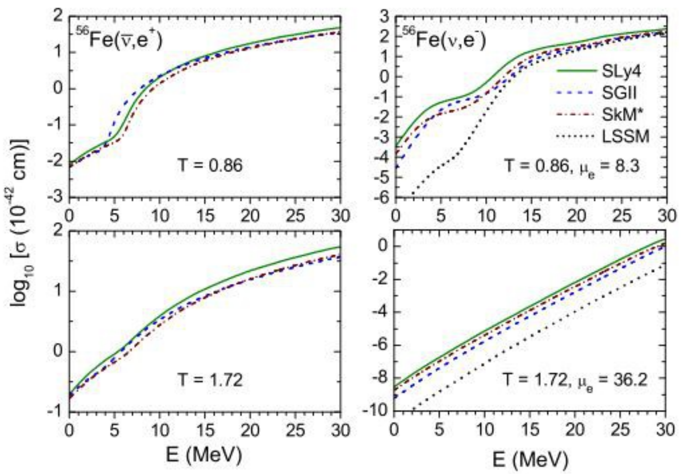
Statistics:

- Publications: $\sim$ 70–80 annually published papers in journals with high impact factors and $\sim$ 30 conference proceedings.
- Thesis Defences: 6 PhD and 1 Doctor of sciences (Habilitation)
- Conferences: NSRT2015, NSRT2018; XXII – XXIV Intern. Baldin Seminars (2014, 2016, 2018), Helmholtz Intern. School on Nuclear Theory and Astrophysical Applications (2014, 2017); $\gtrsim$ 8 Workshops
- JINR prizes: 1-st prize in theoretical physics (2015, 2016), 2-nd prize in theoretical physics (2014); 1-st prize in collaboration with experimentalists (2016)
- 2 patents
- 1 AvH fellowship
- 2 APS Outstanding referees

NEUTRINO PROCESSES WITH HOT NUCLEI IN SUPERNOVAE



The GT strength functions in ^{56}Fe and ^{82}Ge calculated at T=0 and T=1.72 MeV.



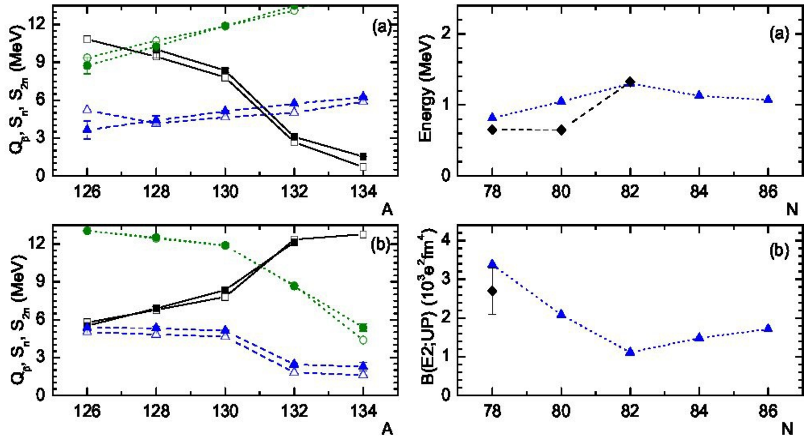
Finite temperature neutrino and antineutrino absorption cross sections on ^{56}Fe computed with different Skyrme forces.

The electron neutrino and antineutrino absorption cross sections on hot nuclei were studied in [1]. These reactions play a fundamental role in core-collapse supernova mechanism. The strength functions for charge-exchange Gamow-Teller transitions, which dominate low-energy neutrino-nucleus reactions, were obtained by applying the thermal quasiparticle RPA with Skyrme forces [2]. It was shown that temperature rise shifts the GT resonance peak to lower energies and unblocks negative-energy GT transitions. This effect does not depend on the Skyrme parametrization and it is observed in both iron-group and massive neutron-rich nuclei. The temperature-driven changes in the GT strength lead to a significant temperature dependence of the cross sections. The important point is that different Skyrme forces predict cross sections which do not differ significantly and this could indicate a robustness of the results against the variation of the Skyrme force parameters. The obtained cross sections are noticeable larger than those from shell-model calculations. The reason for this discrepancy is that shell-model calculations underestimate the contribution of low- and negative-energy GT transitions from thermally excited states.

[1] A.A. Dzhioev, A.I. Vdovin, Acta Phys. Polonica B**48** (2017) 667.

[2] A.A. Dzhioev, A.I. Vdovin, G. Martinez-Pinedo, J. Wambach, Ch. Stoyanov, Phys. Rev. C **94** (2016) 015805(13).

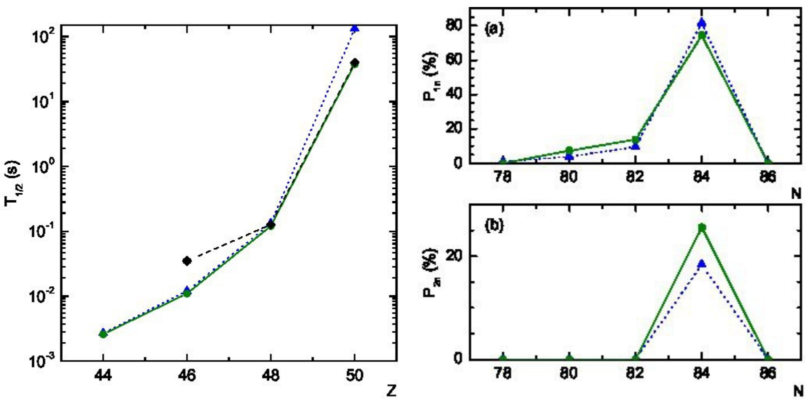
MULTI-NEUTRON EMISSION OF Cd ISOTOPES



Ground state (left panels) and 2_1^+state (right panels) properties in the neutron-rich Cd isotopes.

A combined effect of the tensor interaction and phonon-phonon coupling on the beta-decay half-lives and multi-neutron emission probabilities is analyzed within the microscopic model based on the Skyrme interaction. This study is relevant for analyses of radioactive ion-beam experiments and for modeling of the astrophysical r-process. It is shown that for neutron-rich Cd isotopes the Skyrme T43 interaction gives a reasonable agreement with experimental data for the characteristics of the ground states and collective quadrupole excitations.

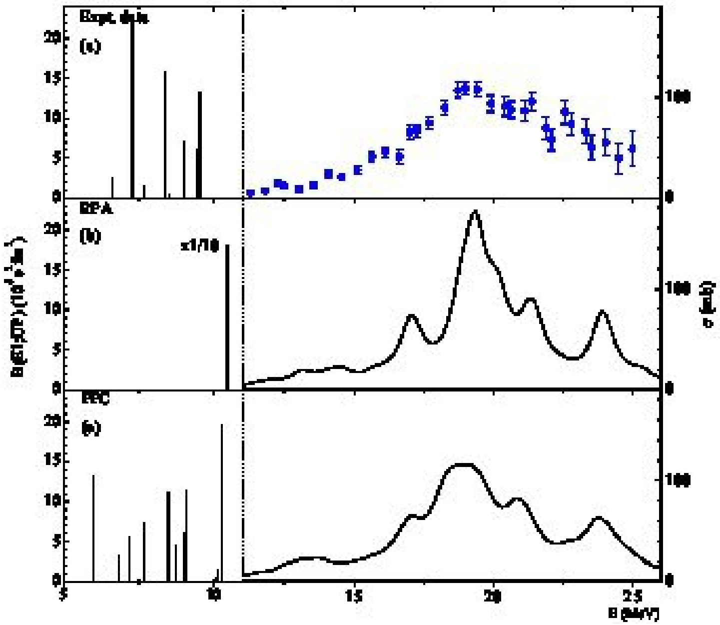
The β-decay rates of the even-even neutron-rich $^{126\text{-}134}$Cd isotopes near the N = 82 closed neutron shell are calculated with the T43 parametrization. A strong redistribution of the Gamow-Teller strength due to the phonon-phonon coupling accelerates the β-decay. Moreover, it is shown that the multi-neutron emission probability of the Cd isotopes is sensitive to all the above mentioned effects. In particular, the increase of the P_{2n}/P_{1n} ratio is predicted.



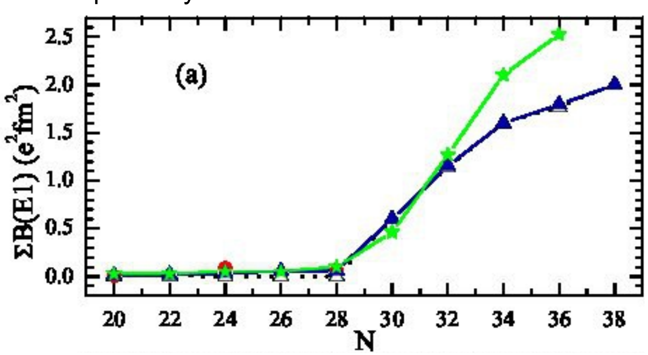
The phonon-phonon coupling effect on β-decay half lives (left panel) and on multi-neutron emission probability (right panels).

[1] A.P. Severyukhin, N.N. Arsenyev, I.N. Borzov, E.O. Sushenok , Phys. Rev. C95(2017) 034314(10).

INFLUENCE OF COMPLEX CONFIGURATIONS ON THE PROPERTIES OF THE PYGMY DIPOLE RESONANCE IN NEUTRON-RICH Ca ISOTOPES



E1 strength distribution for 48Ca. Panel (a) –experimental data ; panels (b) and (c) corresponds to the calculations within the RPA and taking into account the PPC respectively.



Summed dipole strength below 10 MeV calculated in the QRPA (open triangles) and PPC (filled triangles).

Starting from the quasiparticle RPA based on the Skyrme interaction SLy5, the effect of phonon-phonon coupling (PPC) on the low-energy electric dipole response in $^{40-48}$Ca was studied [1,2]. It is shown that the inclusion of two-phonon configurations brings a considerable redistribution of the low-lying strength and leads to a reasonable agreement with experimental data. In particular, it was found that within the RPA there is no states below 10 MeV, whereas the PPC results in the formation of the pigmy dipole resonance in this energy region.

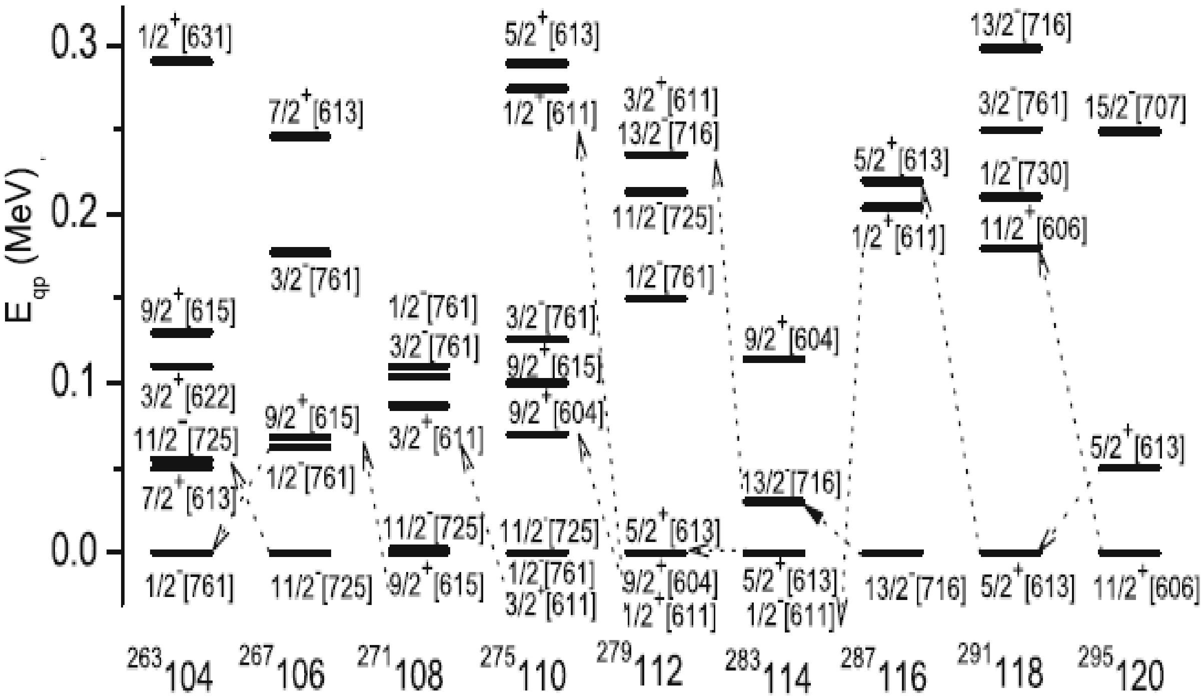
A strong increase (by a factor of 9!) of the summed E1 strength below 10 MeV is observed with increasing neutron number from ^{48}Ca until ^{50}Ca. The analysis showed that this jump is due to the interference between proton and neutron two-quasiparticle contributions to the wave-function.

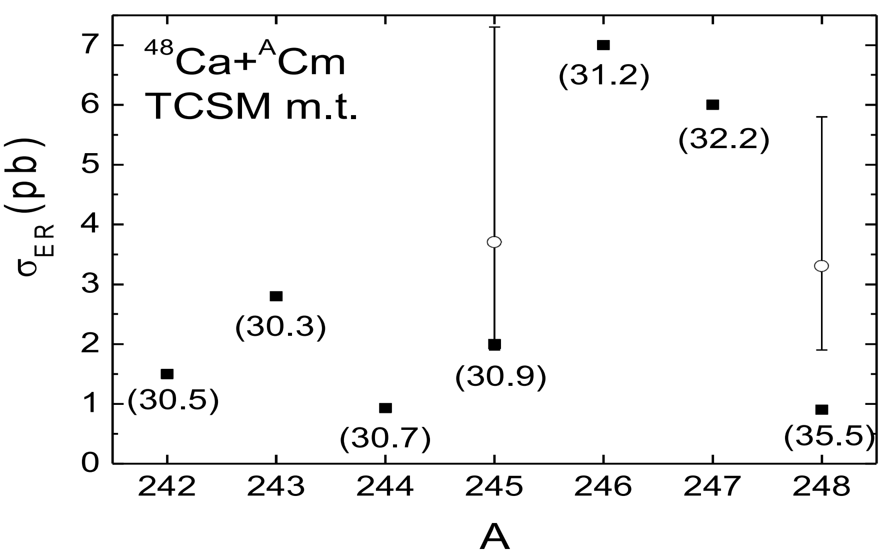
[1] N.N. Arsenyev, A.P. Severyukhin, V.V. Voronov, Nguyen Van Giai, Phys. Rev. C **95** (2017) 054312(10).
[2] N.N. Arsenyev, A.P. Severyukhin, V.V. Voronov, Nguyen Van Giai, Acta Phys. Polonica B **48** (2017) 513

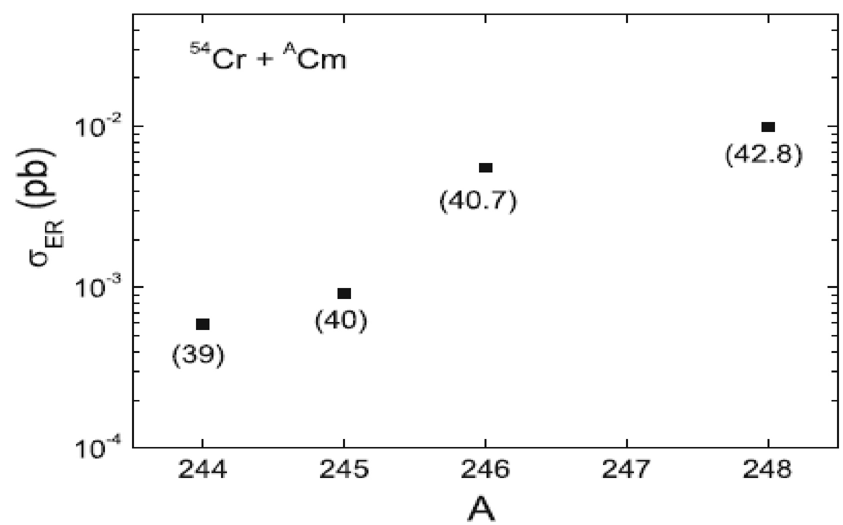
Impact of nuclear structure on production and identification of superheavy nuclei

G.G.Adamian, N.V.Antonenko, A.N.Bezbakh, R.V.Jolos, V.G.Kartavenko, L.A.Malov, V.O.Nesterenko, N.Yu.Shirikova, A.V.Sushkov

PRC 92 (2015) 014329
EPJA 51 (2015) 21
Chinese Phys. C 41 (2017) 074105



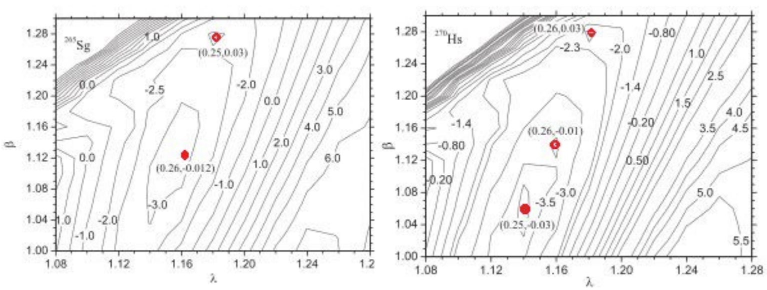




Examination of production and properties of $^{268–271}$Hs

Reaction	E^*_{CN} (MeV)	xn	$\sigma^{xn}_{ER}(th.)$ (pb)	$\sigma^{xn}_{ER}(\exp)$ (pb)	Hs isotope
$^{22}Ne + ^{249}Cf$	35.2	3n	1.5		^{268}Hs
	46	4n	3.4		^{267}Hs
$^{26}Mg + ^{248}Cm$	33.4	3n	1.5	~2.5 [6]	^{271}Hs
	44.8	4n	10	~3 [6]	^{270}Hs
	50.8	5n	6	~7 [6]	^{269}Hs
$^{30}Si + ^{244}Pu$	33.4	3n	0.7		^{271}Hs
	46	4n	5.1		^{270}Hs
	51.4	5n	4.4		^{269}Hs
$^{36}S + ^{238}U$	34.6	3n	0.5	<2.9 [35]	^{271}Hs
	43.6	4n	4	$0.8^{+2.6}_{-0.7}$ [35]	^{270}Hs
	49.6	5n	1.1	<1.5 [35]	^{269}Hs
$^{48}Ca + ^{226}Ra$	32.8	3n	7.2		^{271}Hs
	38.8	4n	7	16^{+13}_{-7} [36]	^{270}Hs

The evaporation residue cross sections for reactions leading to Hs isotopes .



The calculated potential energy surfaces for ^{265}Sg and ^{270}Hs as functions of λ and β. The red circles correspond to the ground state potential minimum.

The evaporation residue cross sections for the production of Hs isotopes is estimated with the dinuclear system (DNS) model. The reactions resulting in larger yields of Hs isotopes are indicated. The calculated residue cross sections are in a good agreement with existing experimental data. This verifies the description of fusion at the bombarding energies near the Coulomb barrier taking into consideration the orientation effect.

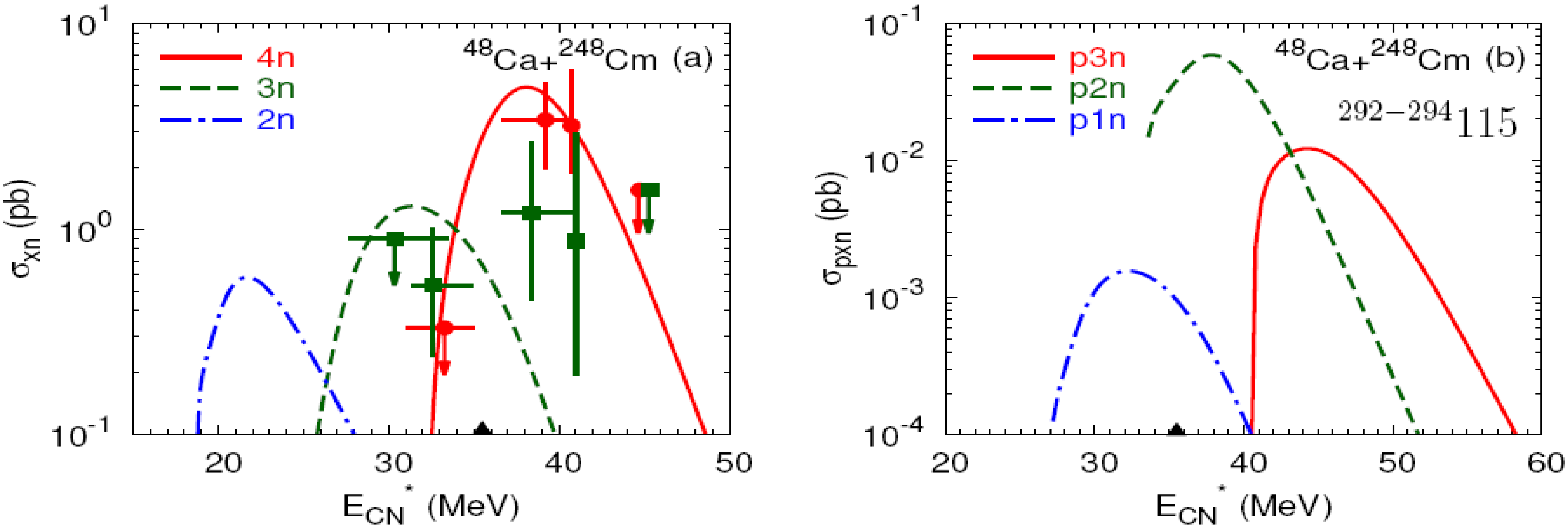
The properties of several nuclei from the α-decay chains containing the isotopes $^{268-271}$Hs were investigated. The calculated energies of α decays are in satisfactory agreement with the available experimental data.

Besides the ground-state minima, the additional shallow minima were found on the potential energy surface of nuclei $^{268-271}$Hs, $^{264-267}$Sg. Because these minima correspond to the deformation parameters close to those for the ground state, one can say that they are the shape isomers at the normal deformation. If these minima are quite close in the energy to the ground state, the α decays can populate them in the daughter nucleus.

[1] G.G. Adamian, N.V. Antonenko, L. A. Malov, and H. Lenske ,
Phys. Rev. C **96** (2017) 044310(12).

PRODUCTION OF NEW SUPERHEAVY ISOTOPES IN CHARGED PARTICLE EVAPORATION CHANNELS

J.Hong, G.Adamian, N.Antonenko, EPJA 52, 305 (2016), PLB 764, 42 (2017)



New isotopes of heaviest nuclei with Z=112 - 117 can be synthesized in ^{48}Ca-induced actinide-based fusion reactions with emission of charged particles.

Evaporation of proton or alpha-particle from the CN in these reactions leads to the formation of nucleus with smaller *Z* but with a larger neutron excess:

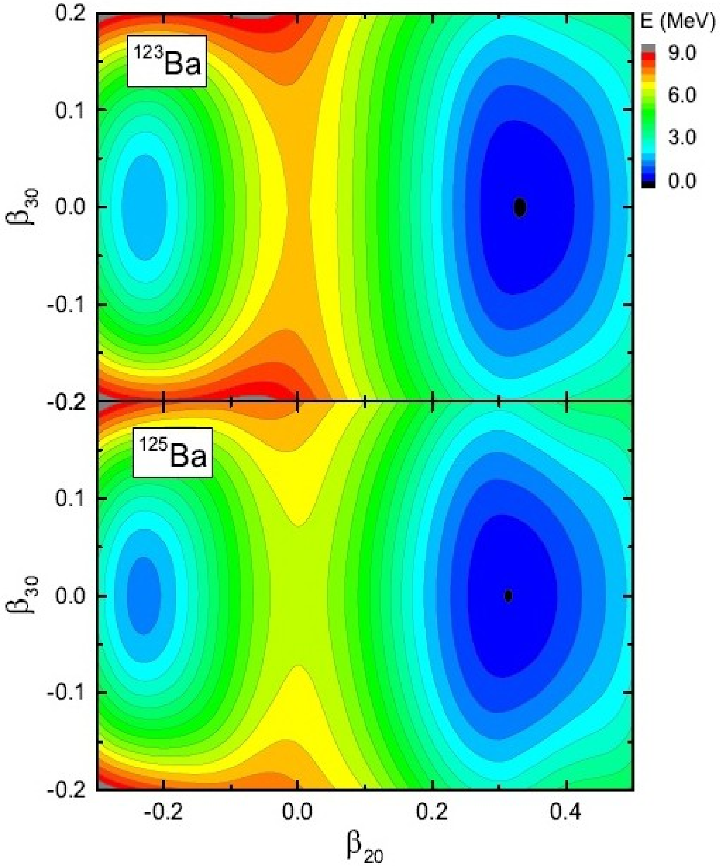
^{48}Ca+^{248}Cm $\longrightarrow$ $^{(293)}$115+*p2n*, ^{48}Ca+^{243}Am$\longrightarrow$ $^{(288)}$115+*3n*

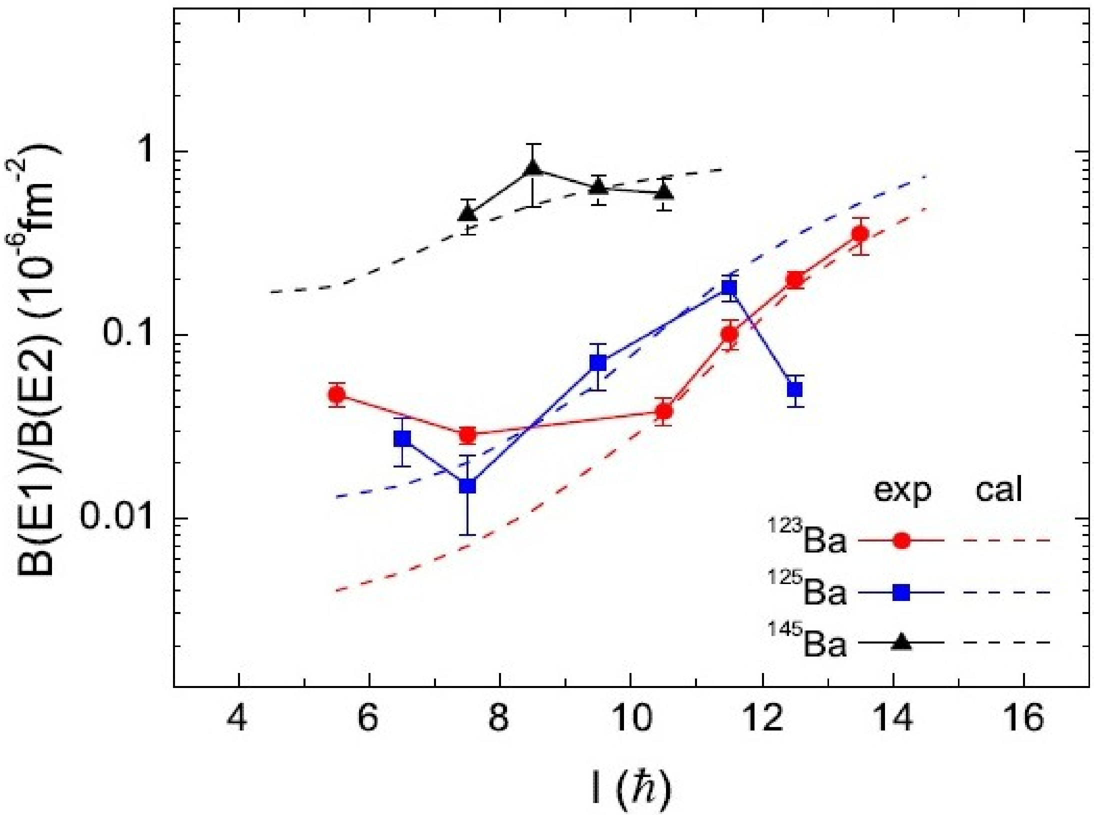
In the SHN formed, an electron capture can occur by adding one more neutron to daughter nucleus.

Cluster Approach to Reflection Asymmetric Deformation of Nuclei

G.G. Adamian, N.V. Antonenko, R.V. Jolos, T.M. Shneidman

The collective motion of nucleus in mass asymmetry coordinate leads to the admixture of the asymmetric cluster configurations to the intrinsic nuclear wave function and creates deformation of even- and odd multipolarities.

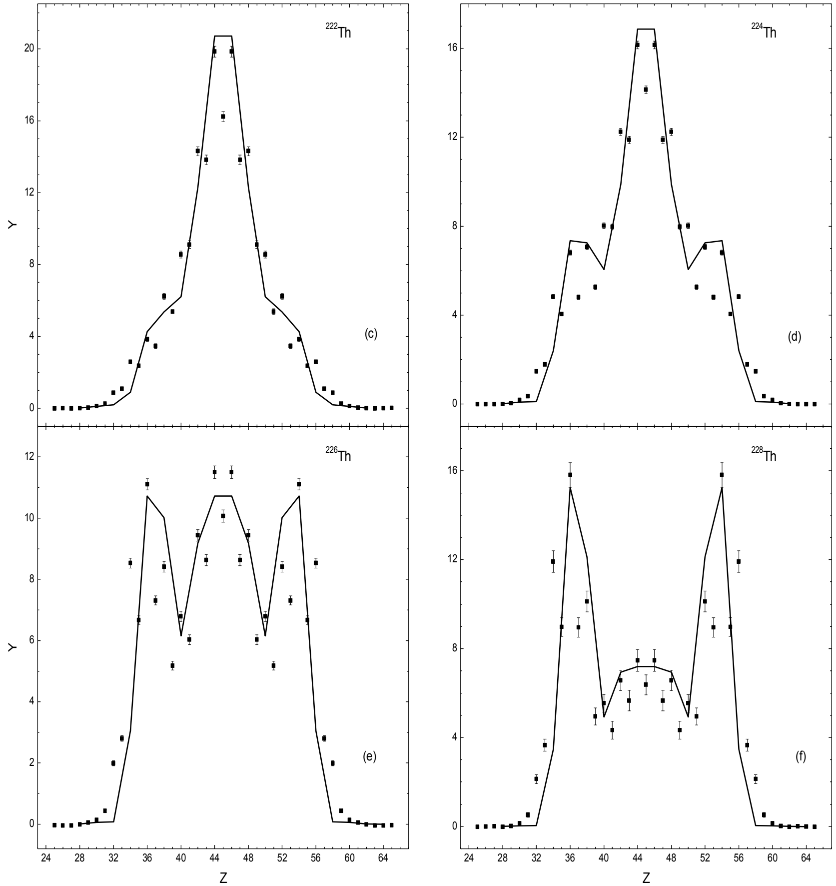




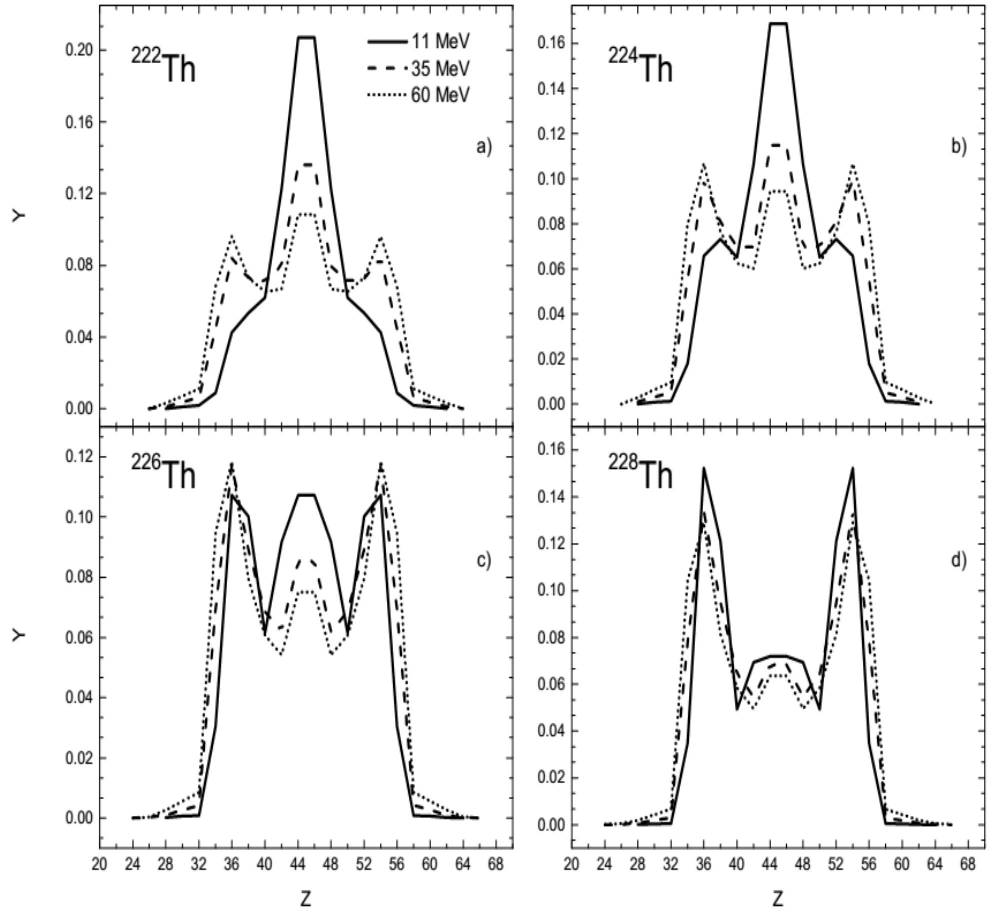
Publications: PRC **92** (2015) 034302; Phys. of At. Nucl. **79** (2016) 963; PRC **94** (2016) 021301(R)

Cluster Approach to Nuclear Fission

H. Paska, A.V. Andreev, G.G. Adamian, N.V. Antonenko, R.V. Jolos, A.K. Nasirov



Calculated and experimental charge distributions of the same isotopes at 11 MeV excitation energy.



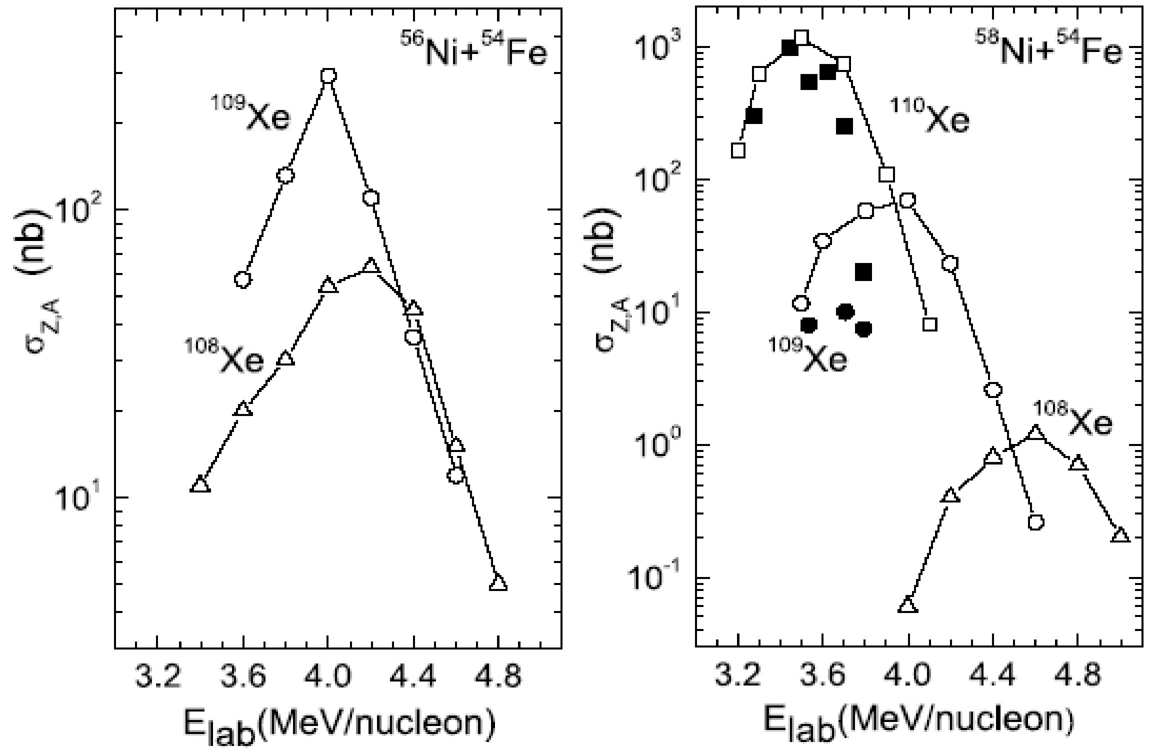
Predicted charge distributions for electromagnetic-induced fission of Th isotopes at higher energies.

Phys.Lett.B **760** (2016) 800; PRC **93** (2016) 054602; PRC **94** (2016) 054614

Expected production of new exotic α emitters ^{108}Xe and ^{112}Ba in complete fusion reactions

Sh. A. Kalandarov et al. PRC 93 , 054607 (2016)

The excitation functions were calculated for the production of neutron-deficient isotopes $^{108–110}$Xe and $^{112–114}$Ba in the fusion-evaporation reactions.



Calculated excitation functions (open symbols connected by lines) for the production of isotopes $^{108–110}$Xe in the reactions ^{58,56}Ni+^{54}Fe are compared to the available experimental data (solid symbols)

S. N. Ershov et al. Phys. Rev. C90, 064610 (2014)

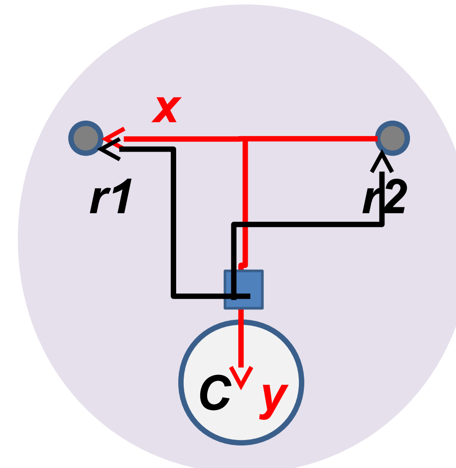
" Binding energy constraint on matter radius and soft dipole excitations of ^{22}C "

^{22}C is now the heaviest observed Borromean nucleus

the nuclear three-body cluster model *^{20}C(core)+2n*

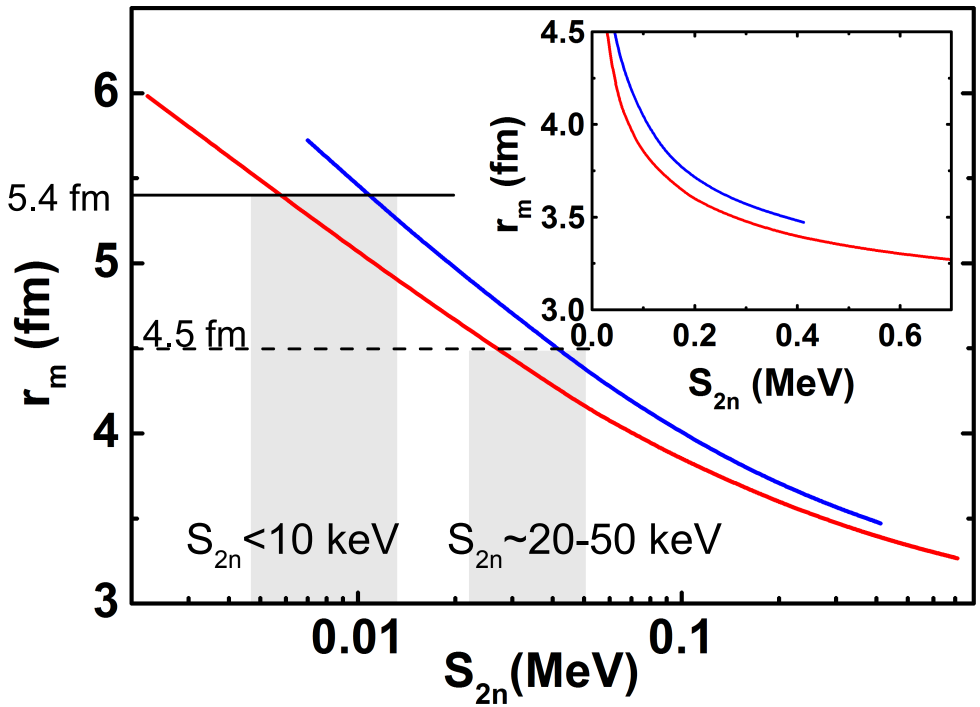
$$\Psi_{JM}(\vec{r}_1,\ldots,\vec{r}_A) \simeq \phi_C(\vec{r}_1,\ldots,\vec{r}_{A_C})\ \Phi_{JM}(\vec{x},\vec{y})$$

$$(T + V(\vec{r}_{12}) + V(\vec{r}_{1C}) + V(\vec{r}_{2C}) - E)\ \Phi_{JM}(\vec{x},\vec{y}) = 0$$



$$\{\vec{x},\vec{y}\} \Rightarrow \{\rho, \Omega_5\}$$

$$\rho^2 = \mu_x \vec{x}^2 + \mu_y \vec{y}^2$$
$$\alpha = \arctan(x/y)$$
$$\Omega_5 = \{\alpha, \hat{x}, \hat{y}\}$$

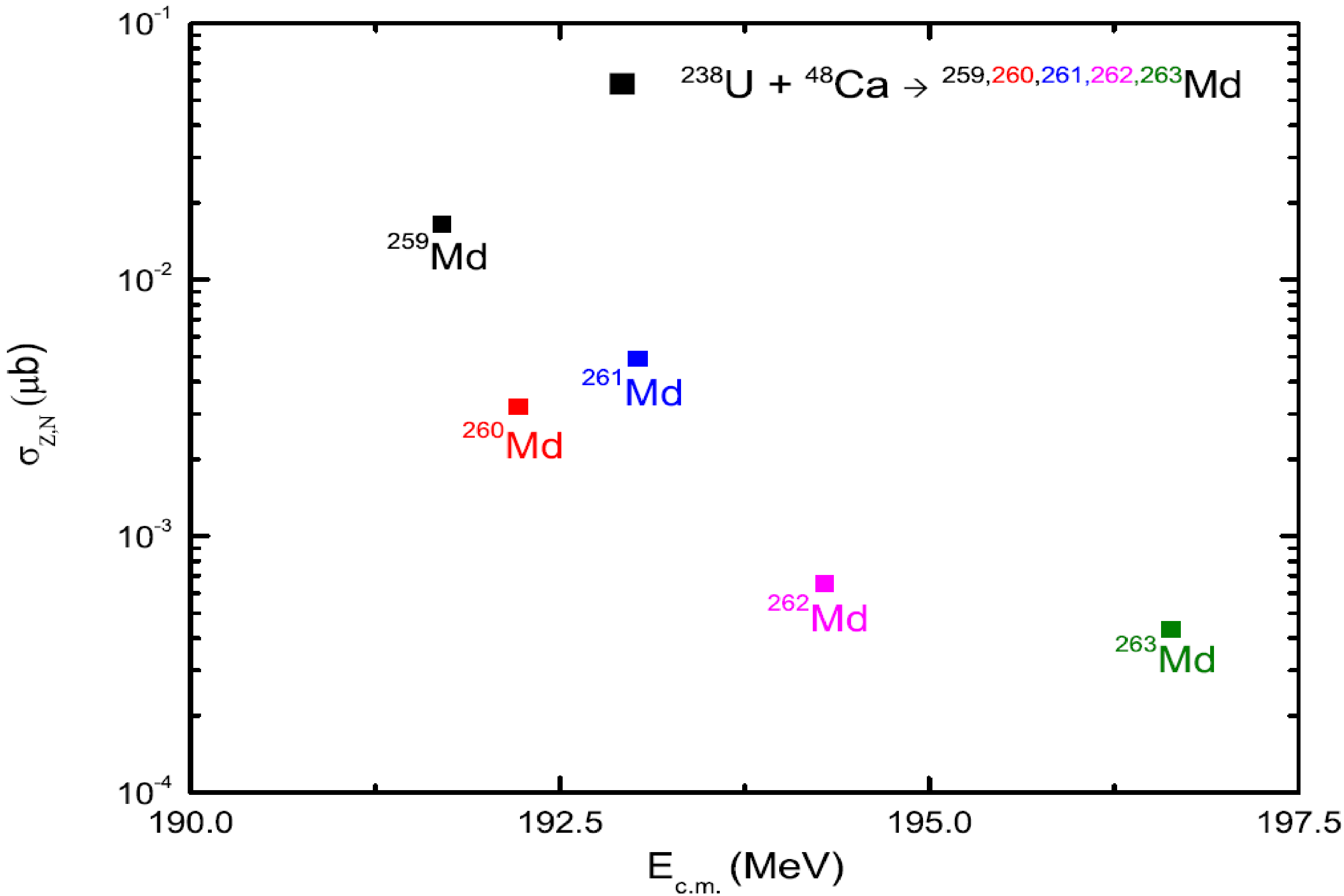


K. Tanaka et al, PRL 104, 062701 (2010)

$$\langle r^2 \rangle^{\frac{1}{2}} = 5.4 \pm 0.9\ \text{fm}$$

Red and blue lines present the calculated matter radius versus S_{2n} at two available sets of parameters. The uncertainties of S_{2n} at r_m=5.4 and 5.4-0.9 fm are marked.

Possibilities of production of neutron-rich Md isotopes in multi-nucleon transfer reactions



EPJA **52**, 363 (2016)

Quantum diffusion approach

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

Model

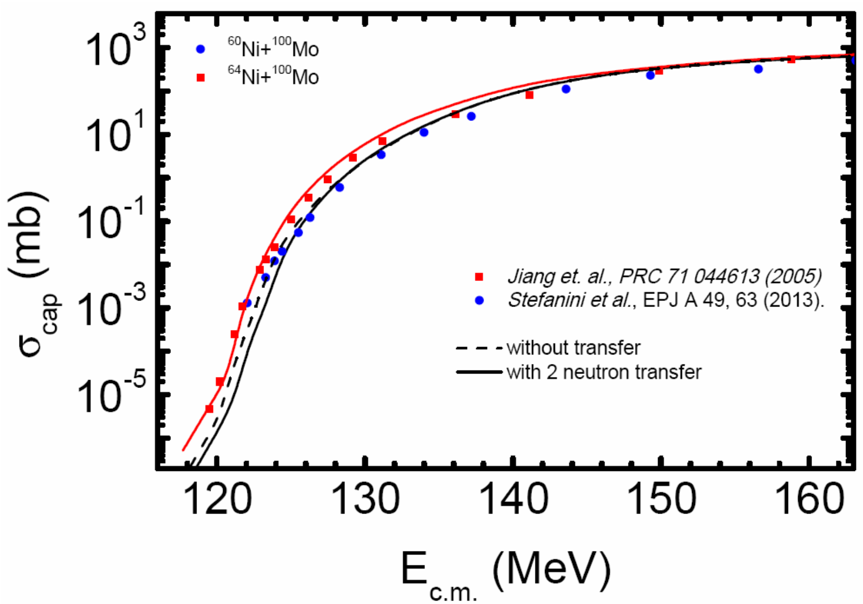
1. Capture (fusion) can be treated in term of a single collective variable
2. Collective motion is effectively coupled with internal excitations.

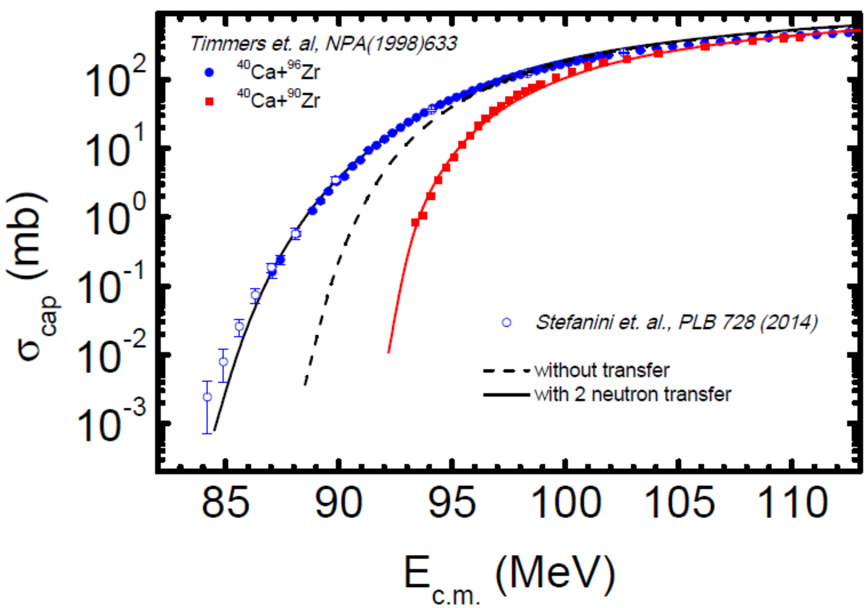
This approach takes into account non-Markovian, fluctuation and dissipation effects in the collisions of heavy ions which model the coupling with various channels.

Role of neutron transfer

Sargsyan et.al., PRC **91,** 014613 (2015)

The change of the magnitude of the capture cross section after the neutron transfer occurs because of the change of the deformations of nuclei!

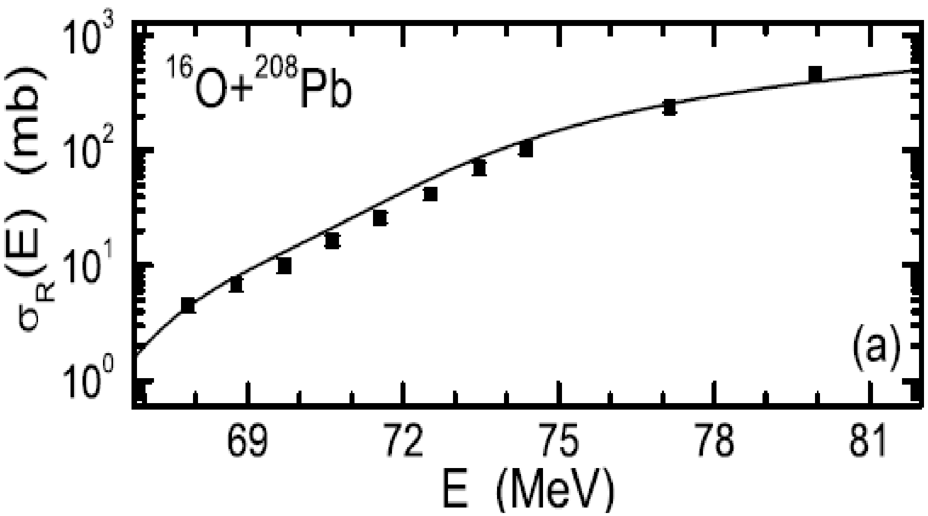


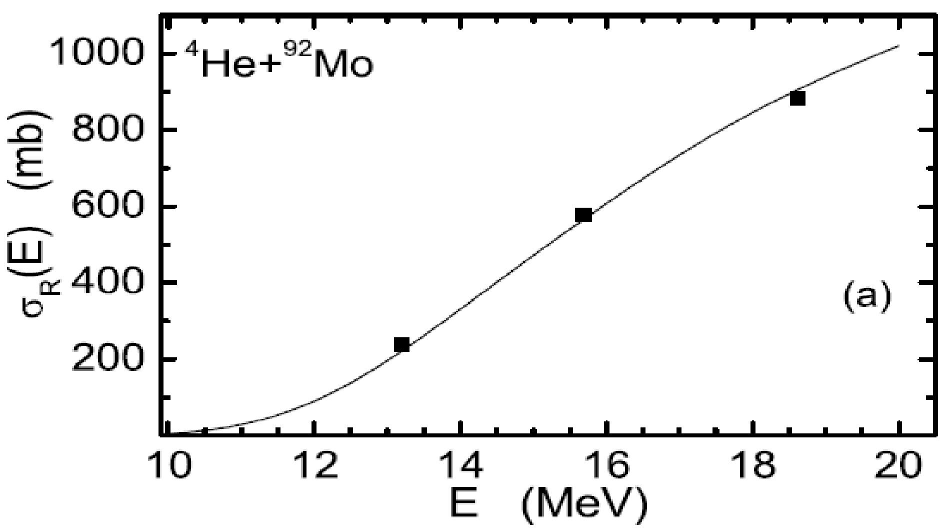


Deriving capture and reaction cross sections from observed quasi-elastic and elastic backscattering

V.V. Sargsyan, G.G. Adamian, N.V. Antonenko,
A. Diaz-Torres, P.R.S. Gomes, H. Lenske

Phys. Rev. C 90, 064601 (2014); 92, 054620 (2015)





$$\sigma_R(E) = \frac{\pi R_b^2}{E}\int_0^E d\epsilon\, P_R^{ex}(\epsilon,0)\left[1 - \frac{4(E-\epsilon)}{\mu\omega_b^2 R_b^2}\right]$$

$$P_R^{ex}(E,0) = 1 - P_{el}^{ex}(E,0)$$

New methods are proposed to determine the total and partial reaction and [capture (complete fusion)] cross sections from the experimental elastic [quasi-elastic] backscattering excitation function P_{el}^{ex}

The extracted total reaction cross sections (lines) are compared with the results of direct measurements.

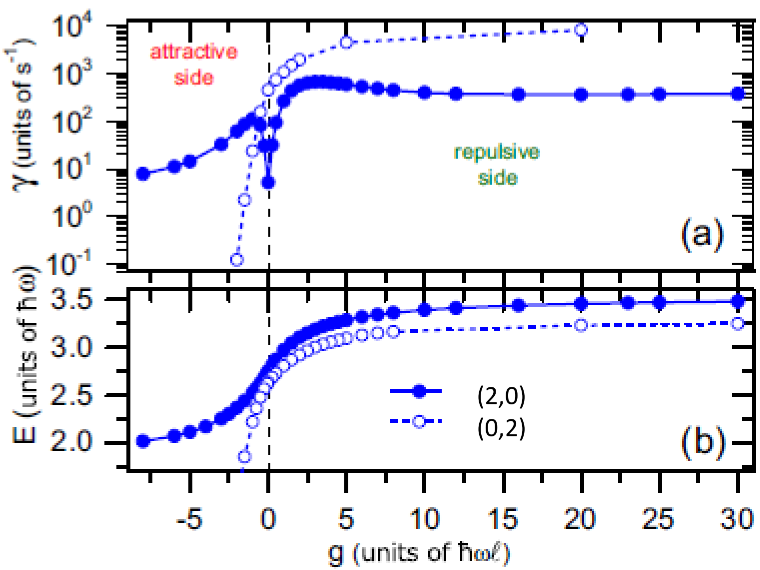
Tunneling of two bosonic atoms from a one-dimensional anharmonic trap

I. Ishmukhamedov, V. Melezhik, Phys. Rev. A95, 062701 (2017)

tunneling rate of atoms confined in 1D trap $\gamma = -\frac{1}{P(t)}\frac{dP(t)}{dt}$

$$P(t) = \int_{-x_m}^{x_m}\int_{-x_m}^{x_m} dx_1 dx_2 |\psi(x_1,x_2,t)|^2 \sim \exp\{-\gamma t\}$$

calculated as a function of the coupling constant g
from the ground (n = N = 0) and first excited states
with respect to relative (2,0) and CM (0,2) atomic motion

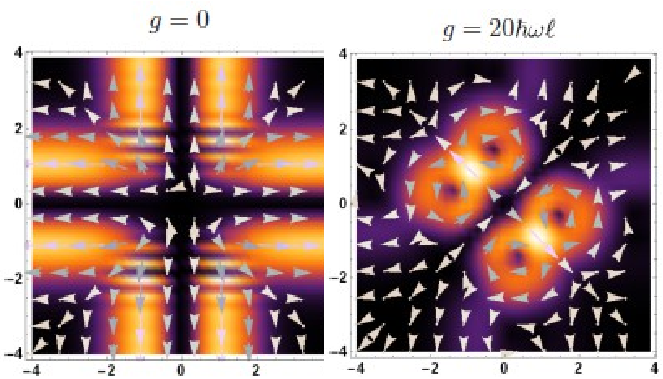


$$H = -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_1^2} - \frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_2^2} + V(x_1) + V(x_2) + V_{\rm int}(x_1 - x_2)$$

$$V_{int}(x_1 - x_2) = g\delta(x_1 - x_2)$$

$$V(x_i) = \hbar\omega\left[\frac{1}{2}\left(\frac{x_i}{l}\right)^2 + \alpha\left(\frac{x_i}{l}\right)^4 + \frac{4\alpha^2}{5}\left(\frac{x_i}{l}\right)^6\right] \qquad l = \sqrt{\frac{\hbar}{m\omega}}$$

γ is experimentally measurable parameter of quantum system giving information about interaction (g) and population dynamics



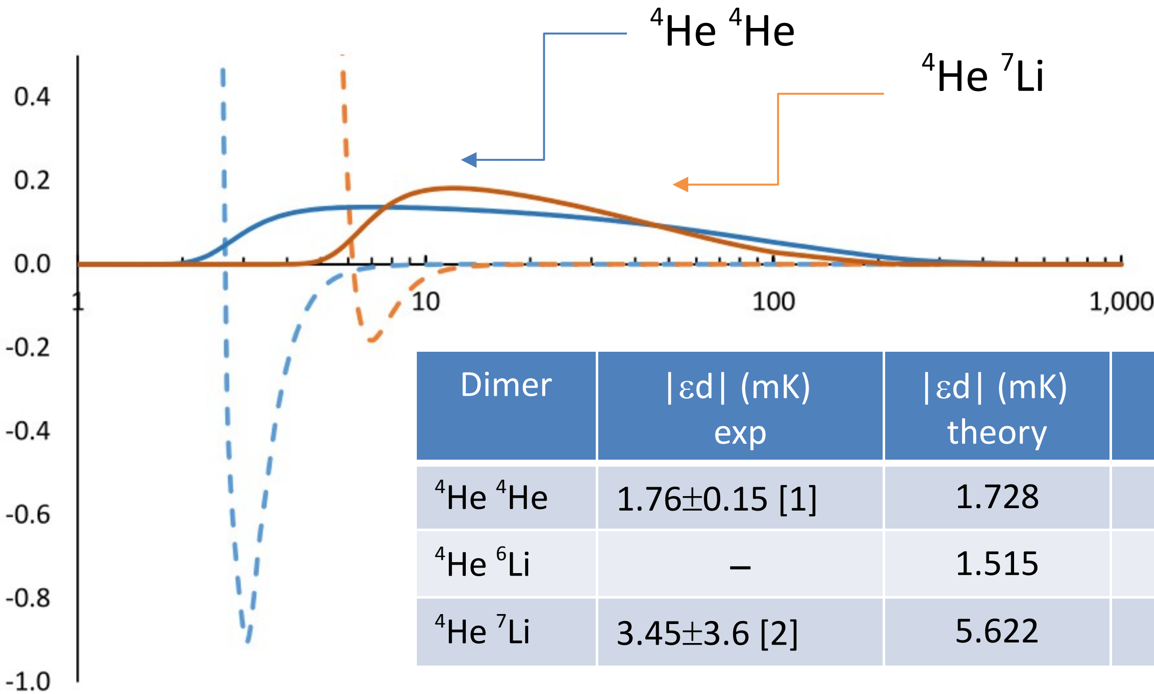
Distribution of a modulus of the flux $|\mathbf{j}(x_1,x_2,t)|$

confined ultracold atomic systems – fast growing field,
promising application to different important problems:
quantum simulation with fully controlled systems

I.M.Georgescu et al. Quantum simulations, Rev.Mod.Phys. 86 (2014) 153
J.I. Cirac and P.Zoller, Goals and opportunities in quantum simulation, Nature Phys. 8 (2012) 264
M.Dalmonte and S.Montangero, Lattice gauge theories simulations, arXiv:1602.03776

Asymmetric Three-Body Atomic Clusters

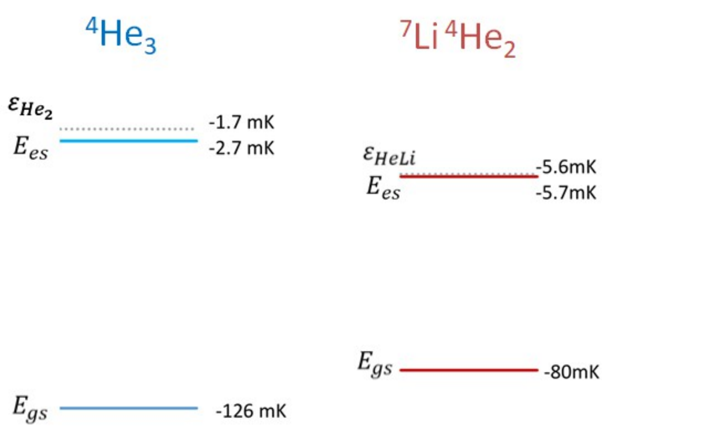
E.A.Kolganova *Few-Body Systems,* **58** (2017) 57; *PEPAN* **48** (2017)892; *J.Phys.:Conf.Ser.* **915** (2017) 012003



Dimer	|εd| (mK) exp	|εd| (mK) theory	asc (Å) theory
^{4}He ^{4}He	1.76±0.15 [1]	1.728	87.5
^{4}He ^{6}Li	–	1.515	89.4
^{4}He ^{7}Li	3.45±3.6 [2]	5.622	48.8

[1] S.Zeller *et.al.*, PNAS **113** (2016) 14651; arXiv:1601.03247

[2] N.Tariq *et.al.*, PRL **110**, 153201 (2013).



$^4He + {}^4He_2 \to {}^4He + {}^4He_2$ $\quad$ $^4He + {}^7Li^4He \to {}^4He + {}^7Li^4He$

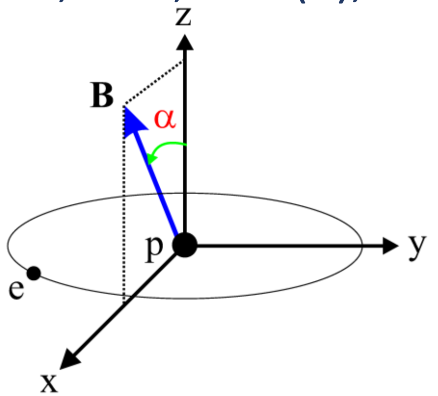
Scattering length $\sim +116$Å $\quad$ ~ -267Å

The Efimov effect in heteronuclear cold atomic systems is studied. The binding energies of $^6Li\,^4He_2$ and $^7Li\,^4He_2$ systems and for the first time the scattering length for the collision of ^{4}He atom with $^4He^7Li$ dimer are calculated. It is shown that the excited in both systems are of the Efimov-type. The large value of the scattering length is also support this conclusion. The results were obtained using the hard-core version of the Faddeev differential equations and realistic interactions.

Anisotropic Features of Two-Dimensional (2D) Hydrogen Atom in Magnetic Field

E. A. Koval, O. A. Koval, JETP, **125** (1), 35–42 (2017)

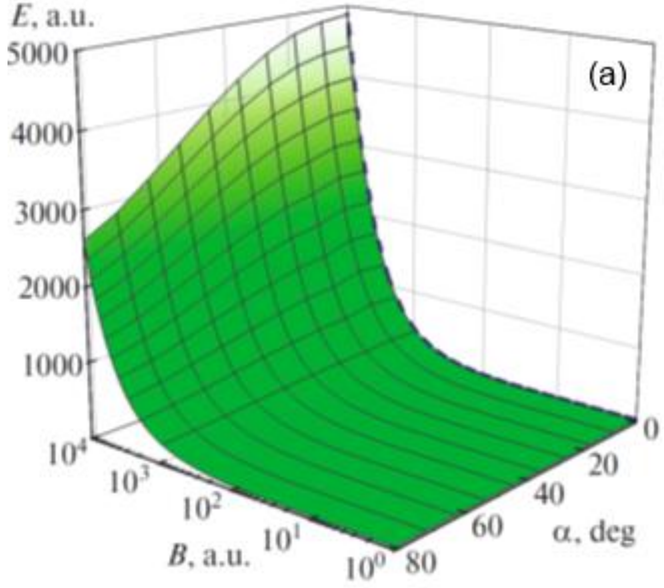
- The results of the numerical research of anisotropic characteristics of a 2D hydrogen atom and a 2D exciton induced by a magnetic field are presented.
- The nonlinear dependence of the ground state energy (GSE) of the 2D Hydrogen atom and 2D exciton in $GaAs/Al_{0.33}Ga_{0.67}As$ on angle α between the magnetic field vector and the normal to the electron motion plane has been found in a wide range of the magnetic field. The effect of a significant reduction of the GSE (up to 1.9-fold) is observed with increasing the angle α up to 90°. The agreement with experimental data has been demonstrated.
- The variation of the method of discrete variable and seven-point finite-difference approximation are used, while the eigenvalue problem is solved by the inverse iteration method with shift.

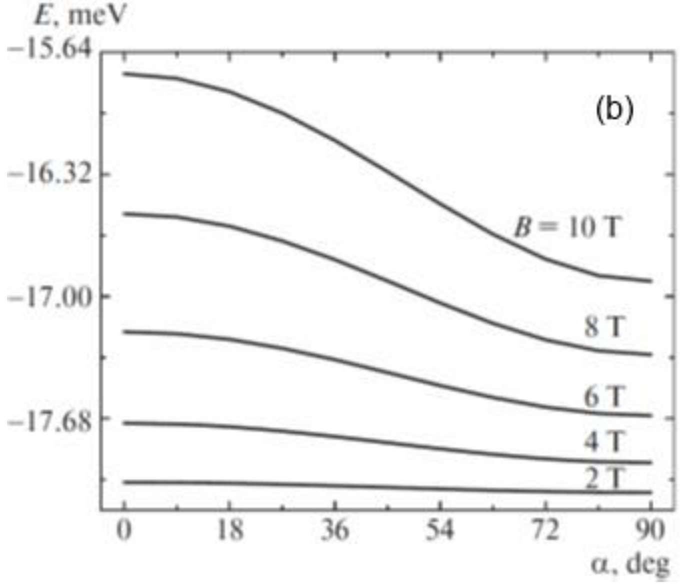


Scheme of a 2D Hydrogen atom in the tilted magnetic field

B, a.u.	E, a.u. [1]	E, a.u. [2]	E, a.u.
0.1	−1.999530	−1.999531	−1.999531
0.25	−1.997078	−1.997079	−1.997079
107/250	−1.991490	−1.991490	−1.991491
1	−1.955159	−1.955159	−1.955159

Values of GSE for α=0°, calculated in our work, agree with the values obtained by other authors



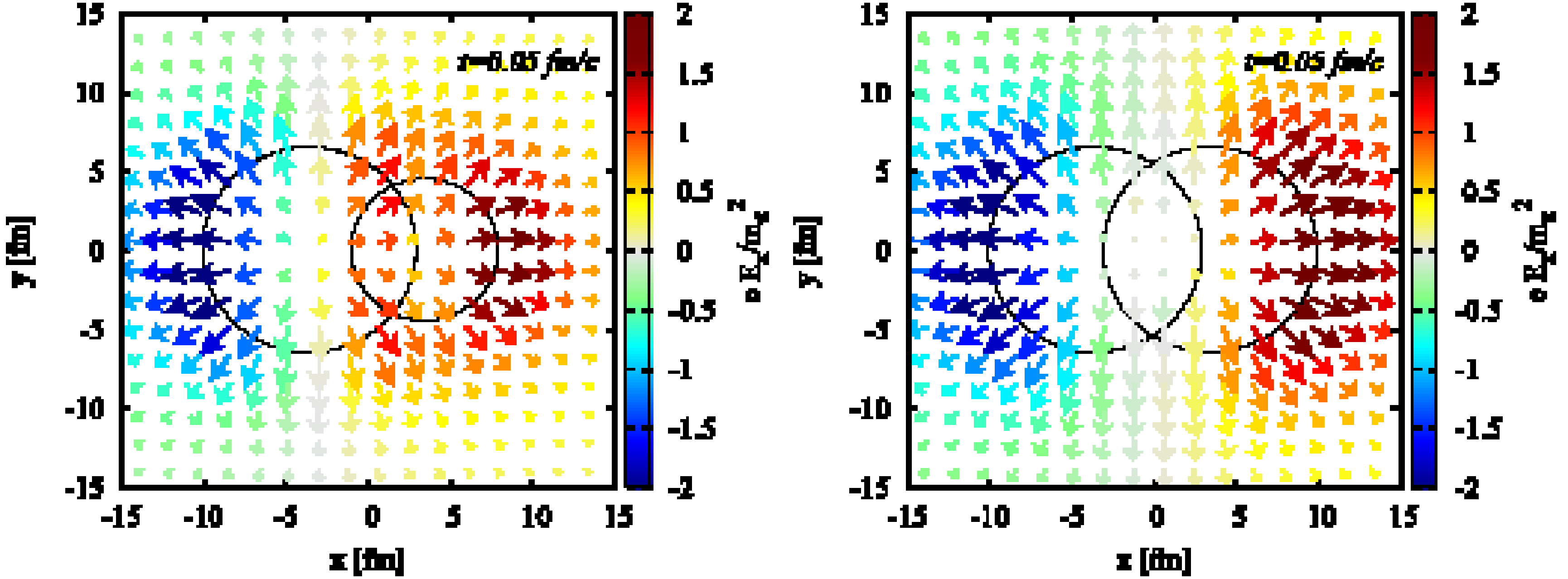


Dependences of the ground state energy of the 2D hydrogen atom (a) and of the 2D exciton (b) on the magnetic field and on the angle α

[1] A. Soylu et.al., Int. J. Mod. Phys. E **15**, 1263 (2006); [2] A. V. Turbiner et.al., Ann. Phys. (N.Y.) **340**, 37 (2014)

Electric field in asymmetric collisions

Cu-Au $\sqrt{s_{NN}}$ =200 GeV **Au-Au**



Due to the difference in the number of protons of the colliding nuclei an electric field directed from the heavy to the light nucleus emerges in the nuclear overlapping region

V. Voronyuk, V. D. Toneev, S. A. Voloshin, W. Cassing, Phys. Rev. C **90**, 064903 (2014)

V.P.Konchakovski, W.Cassing, V.D.Toneev, J. Phys. G 42, 055106 (2015)

L. Kaptari, S. Dorkin

Solving the Dyson-Schwinger-Bethe-Salpeter eqs. at finite T; Transverse momentum distributions and nuclear effects

A. Del Dotto, L.P. Kaptari, E. Pace, G. Salme, S. Scopetta, PRC, 96, 6, 065203, 2017

A. Del Dotto, L. Kaptari, E. Pace, G. Salme, S. Scopetta, Few Body Systems 58, 1, 2017

E. Pace, A. Del Dotto, L. Kaptari, G.Salmé, S. Scopetta, Few Body Systems, 57, 7, 601, 2016

S.M. Dorkin, L.P. Kaptari, B. Kämpfer, PRC 91, 055201-201-13, 2016

S. M. Dorkin, M. Viebach, L. P. Kaptari, B. Kaempfer, J. Modern Physics, 7, 2071, 2016

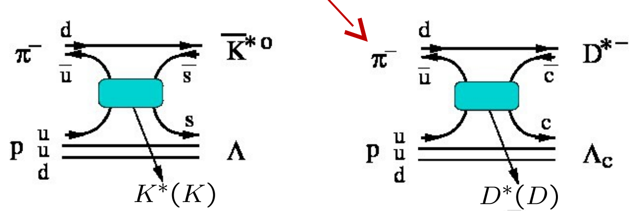
S.M. Dorkin, L.P. Kaptari, B. Kaempfer, *" Solving the Dyson-Schwinger equation at zero and finite temperatures"* , Modern Problems in Nuclear ans Elementary Particle Physics, APCTP-BLTP NRC KI SbSU, Petergoff, Russia 2017

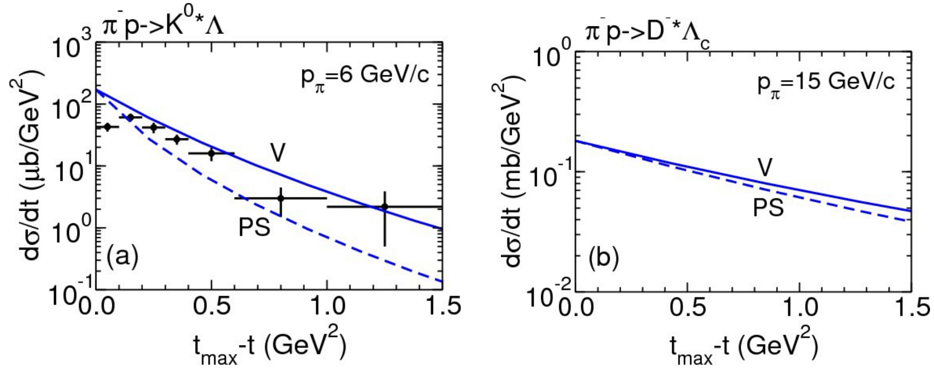
A.I.Titov, S-H Oh, and Yongseok Oh PRC 95, 055206-1-10, 2017

Angular distribution of the pseudoscalar mesons in decay of K* and D* mesons produced in pion-proton interaction as a tool for open charm production

Reaction

$$\pi^- + p \to V + Y \to P + \pi + Y \quad \text{with } V = K^* \text{ or } D^*, \text{ and } Y = \Lambda \text{ or } \Lambda_c$$

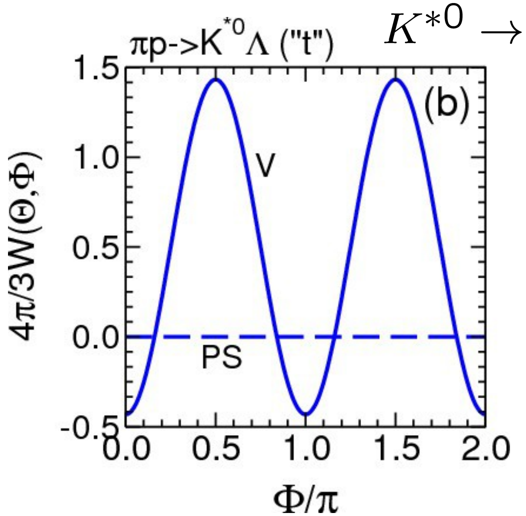




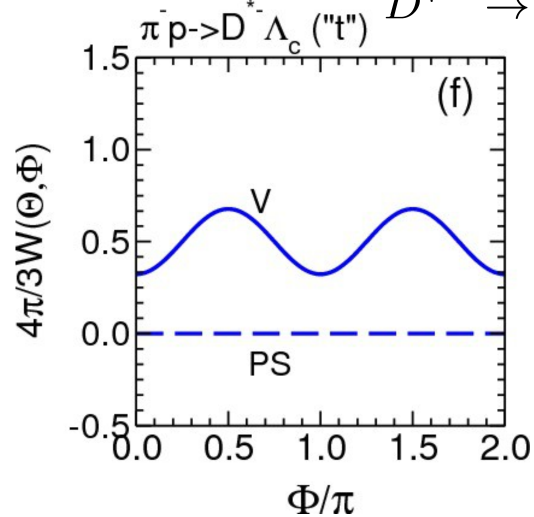
Unpolarized cross sections are not sensitive to the production mechanism

Azimuthal angle distributions are very sensitive to the production mechanism

$K^{*0} \to K^+\pi^-$



$D^{*-} \to D^-\pi^0$

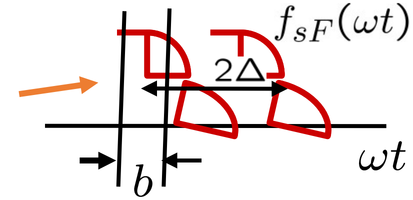


A.I. Titov et al, Phys. Rev. D 93 (2016) 045010

In reaction: $\gamma + Laser \rightarrow e^{+} + e^{-}$

For the first time it has been found that the short pulses "generates" high momentum components which produce a great amplifier effect for the multi-photon, sub-threshold events. Enhancement may reach many orders of magnitude depending on field intensity and the beam shape

Two parameter pulse shape function:"summarized Fermi (sF)"***shape***



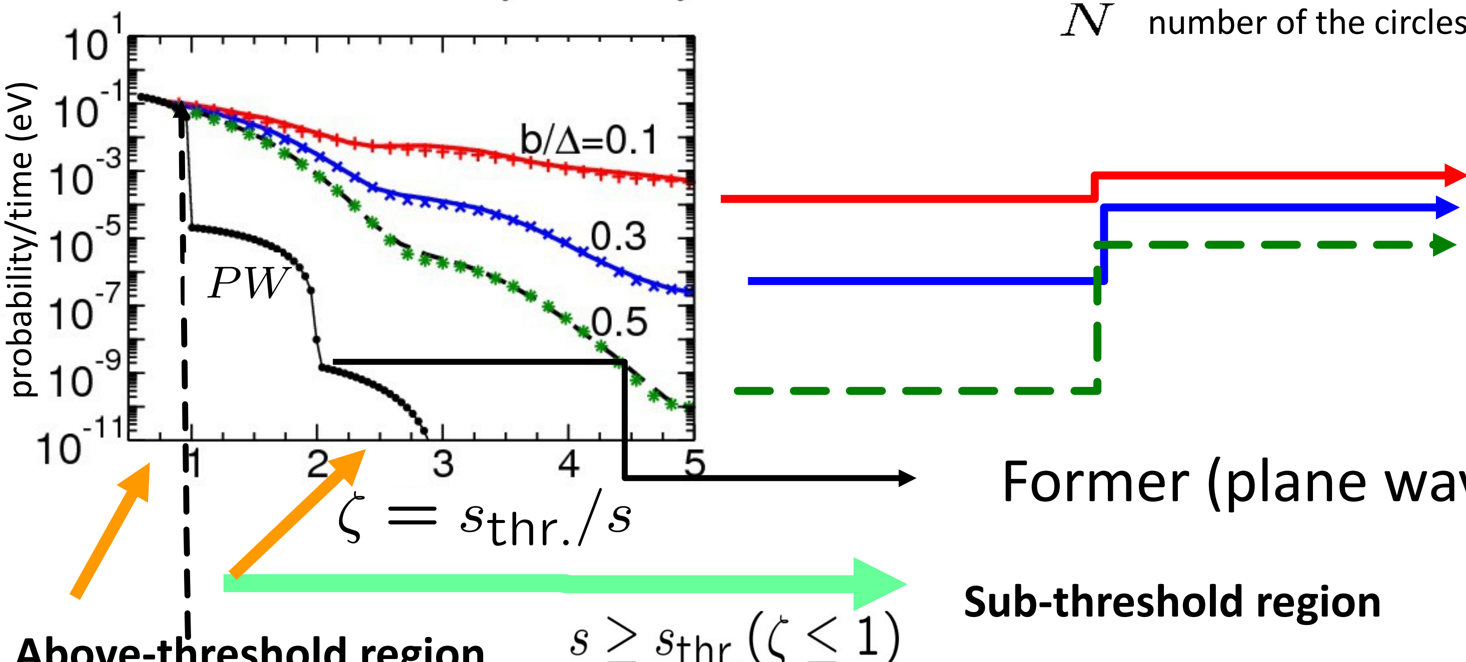
Lukyanov et al.,'70~'80

$$f_{\mathrm{sF}}(\omega t) = \frac{\cosh\frac{\Delta}{b} + 1}{\cosh\frac{\Delta}{b} + \cosh\frac{\omega t}{b}}$$

$\Delta = \pi N$

Δ length of the pulse

N number of the circles in the pulse



Our (new) result

Former (plane wave) prediction

Sub-threshold region $s < s_{\mathrm{thr.}} (\zeta > 1)$

Above-threshold region

A.S. Parvan, "*Ultrarelativistic transverse momentum distribution of the Tsallis statistics*", **Eur. Phys. J. A 53 (2017) 53**

The analytical expressions for the ultrarelativistic transverse momentum distributions of the Tsallis and the Tsallis-2 statistics were obtained. We found that the transverse momentum distribution of the Tsallis-factorized statistics, which is now largely used to describe the experimental transverse momentum spectra of hadrons measured in *pp* collisions at LHC and RHIC energies, in the ultrarelativistic case is not equivalent to the transverse momentum distributions of the Tsallis and the Tsallis-2 statistics. However, we revealed that this distribution exactly coincides with the transverse momentum distribution of the Tsallis-2 statistics in the zeroth term approximation and is transformed to the transverse momentum distribution of the Tsallis statistics in the zeroth term approximation by changing the parameter q to $1/q$. We demonstrated analytically on the basis of the ultrarelativistic ideal gas that the Tsallis-factorized statistics is not equivalent to the Tsallis and the Tsallis-2 statistics.

A.S. Parvan, O.V. Teryaev, and J. Cleymans, "*Systematic comparison of Tsallis statistics for charged pions produced in pp collisions*", **Eur. Phys. J. A 53 (2017) 102**

The energy dependence of Tsallis statistics parameters is presented for charged pions produced at beam energies ranging between 6.3 GeV and 7TeV. It is found that deviations from Boltzmann statistics are monotonically growing with beam energy. The energy dependence of the parameters T and q of the negatively charged pions in the energy range $6.3 < \sqrt{s} < 7000$ GeV reveals that the deviation of the transverse momentum distribution from the exponential becomes more and more pronounced as the beam energy is increased. The parameter q increases with beam energy while the temperature T slowly decreases.

Other Publications (2017):

- A.S. Parvan, "*Finite size effects in the thermodynamics of a free neutral scalar field*", Physica A, 2017 (accepted for publication).
- A.S. Parvan, "*Transverse momentum distributions of hadrons in the Tsallis-1 and Tsallis-2 statistics*", EPJ Web of Conf. 138 (2017) 03008.
- J. Cleymans, M.D. Azmi, A.S. Parvan, and O.V. Teryaev, "*The Parameters of The Tsallis Distribution at the LHC*", EPJ Web of Conf. 137 (2017) 11004.

Concept of the Theme «Theory of Nuclear Systems»

Development of theoretical methods ⟺ Applications for experiments

Multidisciplinar nature

Our future theoretical studies will be closely coordinated with programs of operated and commissioning facilities which exploit various high-intensity beams of stable and/or radioactive ions at JINR (SHE-factory, ACCULINA-2) and in the world (FAIR, ISOL facilities HIE-ISOLDE, SPES, SPIRAL2, FRIB). The studies of heavy-ion collisions at high energies will be related to the NICA project at JINR.

NEW THEME: 2019-2023

Theory of Nuclear Systems
(Leaders: N.V. Antonenko, S.N. Ershov, A.A. Dzhioev)
Projects:

- Microscopic models for exotic nuclei and nuclear astrophysics
  (рук. V.V. Voronov, A.A. Dzhioev, J. Kvasil)
- Low-energy dynamics and nuclear system properties
  (Leaders: S.N. Ershov, N.V. Antonenko, R.V. Jolos)
- Quantum few-body systems
  (Leaders: A.K. Motovilov, V.S. Melezhik)
- Nucleus-nucleus collisions at relativistic energies and extreme states of matter
  (Leaders: V.V. Burov, M. Gaidarov, S.G. Bondarenko)

Staff: 35 senior, leading, and principal researchers + 15 junior researchers and PhD students
Costs: 3.5 M$/year, personal costs $\sim$ 48%

It is not fully clear how magic numbers evolve as a function of the neutron-to-proton ratio. Comparison of the theoretical results with available experimental energies of first excited states would be a good test of the nuclear-shell-model inputs.

The developed self-consistent EDF methods will be applied to the area of beta-decay (especially in the context of astrophysical r-process) and others weak-interaction responses of nuclei and nuclear matter in various astrophysical scenarios (supernova explosions, associated nucleosynthesis and neutrino production).

Low-energy dipole excitations presumably playing a prominent role in stellar nucleosynthesis have to be investigated. This study can be related to the future experiments at ELI-NP.

The systematic study of the properties of heavy nuclei within the suggested shell models would shed light on the positions of shell closures. The vast majority of level assignments are derived from alpha-decay spectroscopy. So, the microscopic study of alpha-decays of heavy nuclei is required. The alpha-decays from the isomeric states have to be analyzed. The fission of nuclei from the isomeric states is going to be considered as well. The analysis of the data obtained at FLNR will be performed.

Investigating collisions with weakly bound nuclei, one can apply the Faddeev formalism, the continuum coupled-channels methods, few-body reaction formalisms. The transfer reaction formalism can be improved by incorporating non-local interactions and pair or cluster transfers. Several developments would be desirable: improvements in effective nucleus-nucleus potentials by using the microscopic inputs, accurate treatment of breakup reactions with calculation of spectroscopic factors for each decaying configuration, improvement of energy-density functional to make it suitable for description the nucleus-nucleus interaction.

• Fusion of nuclei involves the collision of two quantum many-body systems that form a hot compound nuclear system following dissipation of their relative kinetic energy. The challenge for theory is to incorporate dissipation into the models and retain the essence of quantum many-body nature of the colliding nuclei. The fusion model should consider the evolution from dinuclear system configuration to a compound nucleus and describe contributions of each reaction channel. The methods of the theory of open quantum systems will be used.

Exploring formation of superheavies in fusion and transfer reactions. The dinuclear system model suggested at BLTP can be improved by incorporating microscopically calculated transport coefficients and nucleus-nucleus potential. The mass and TKE distributions of quasifission products will be studied and compared with those for fission products. The challenge is to find out the firm criteria to discriminate fission and quasifission.

New isotopes of heavy nuclei, which are not reachable in complete fusion reactions, can be produced in transfer reactions. These possibilities must be investigated and the available experimental yields have to be described. The study of production of new isotopes of superheavies in charge particle evaporation channels must be continued to find out the most suitable reactions for future experiments.

• The increased disparity between number of neutrons and protons in radioactive nuclei leads to enhancement of clustering phenomena in nuclear structure, weak binding energy and possibility of exotic decay modes. Studies of near-threshold effects demand a unified description of nuclear structure and reactions. A development of few-body cluster models which allow us transparently understand peculiarities in nuclear structure at extremes of the neutron-proton map would be in a priority.
We are planning to develop the fully quantum model for a halo-nucleus breakup, investigate the Coulomb breakup of proton halo in light nuclei taking into account the effect of external field. Few-body systems provide us important observables for testing and constraining nuclear forces.

• Study of universal laws in behavior of three-particle systems at ultralow energies and numerical calculations of characteristics of ultra-cold three-atom systems in Efimov or pre-Efimov situations are of current interest. To develop theoretical tools, we will study the generalized invariant sub-spaces of a multi-channel Hamiltonian corresponding to the Feshbach resonances and establish the links between these resonances and complex scaling of the associated operator Riccati equations.

To establish the interplay between the atomic and nuclear physics, we will study the ionization/excitation of atoms and nuclei in a strong laser field by applying the Faddeev reduction of wave function in the non-stationary Schrödinger equation. The dynamic-adiabatic theory and theory of hidden intersections of potential energy curves will be applied to calculate inelastic transitions in atomic collisions. The numerical approaches will be developed based on finite element method and parametric basis functions. The approaches will be applied to the analysis of bound and metastable states, scattering processes in few-particle systems.

• Exploring the heavy-ion collisions at NICA energies we plan to simulate a vorticity and investigate its properties. It is clear that gluon field drives the system towards isotropy much faster than initially thought and that viscous fluid dynamics can accommodate the residual anisotropy. The dense gluon fields in a nucleus may be related to forward particle production. Moreover, expansion of the developed approach to ultra-relativistic energies achievable at RHIC and LHC is desirable. A connection with the P-odd correlations of quarks and mesons, and possibly with a chiral magnetic effect will be elucidated.

• In view of development of the European ELI research center which involves JINR-member countries, the investigations of non-linear quantum processes in very strong polarized electromagnetic fields are of interest. The particle production as a result of interaction of photons with ELI laser pulses will be studied.

• It is planned to explore three-nucleon systems within the relativistic extension of the Bethe-Salpeter-Faddeev formalism. The binding energies, electromagnetic form-factors and polarization observables will be calculated.