1.3 Nuclear Theory

Nuclear physics focuses on the study of the structure and dynamics of complex systems of particles which build up hadrons and nuclei. Investigations carried out by nuclear physics community of the BLTP cover most of the modern problems in nuclear physics. Main efforts in the field "Nuclear Theory" in 2003-2004 were devoted to the following subjects:

- Theory of Nuclear Excitations
- Dynamics and Manifestation of Structure in Nuclear and Mesoscopic Systems
- Few-Body Physics
- Relativistic Nuclear Dynamics

Many works were concentrated on the theory of nuclear structure. A finite rank separable approximation for an effective interaction of Skyrme type was extended to take into account the phonon-phonon coupling effects. The influence of such a coupling on energies and transition probabilities of the low-lying vibrational states in the neutron-rich Sn isotopes is studied. The results of calculations are in agreement with experimental data (A.P. Severyukhin, V.V. Voronov). The properties of the low-lying dipole states in chains of different isotopes were investigated within the Q-phonon approach (R.V. Jolos, N.Yu. Shirikova, V.V. Voronov). A nature of an unexpected a large number of low-lying 0^+ levels in the deformed ^{158}Gd was established within the quasiparticle-phonon model (A.V. Sushkov, N.Yu. Shirikova). The gross shell structure at high spins in heavy nuclei was considered. It was shown that the ground-state shell energies, nuclear deformations and deviations from rigid-body moments of inertia are all due to the same periodic orbits (V.V. Pashkevich). The symmetry-conserving extended Holstein-Primakoff mapping for bosonic and fermionic systems was combined with the thermo field dynamics to construct a consistent thermal boson expansion for the $SU(2)$ Lipkin model (A.A. Dzhioev, A.I. Vdovin, A.N. Storozhenko).

The dinuclear system model was applied to treat the isotopic trends of production cross sections for superheavy nuclei in the cold and hot fusion-evaporation reactions. The optimal excitation energies and the combinations of colliding nuclei were suggested for future experiments (G.G. Adamian, N.V. Antonenko, S.P. Ivanova, R.V. Jolos, Yu.V. Palchikov, T.M. Shneidman). Inelastic scattering of ^{11}Li on proton target at collision energy of 68 MeV/u was analysed in the framework of the microscopic four-body distorted-wave model. The calculations of inelastic scattering showed accumulation of dipole and monopole excitations of ^{11}Li near the three-body threshold and described well the observed peak in the experimental energy spectrum of ^{11}Li (S.N. Ershov). A model for the nucleus-nucleus optical potential restoration at intermediate energies was developed (V.K. Lukyanov).

Various problems were investigated within the project "Few-Body Physics". A procedure of extrapolating the triplet phases of the proton- proton scattering to low energies was suggested(V.V. Pupyshev). The three-atomic He systems were studied within the hard-core Fadeev approach. The ^{3}He–^{4}He$_2$ scattering length and phase shifts were also calculated (E.A. Kolganova, A.K. Motovilov). A time-dependent grid method for treating

different few-body dynamics without a usual partial-wave analysis was developed. Calculations of the stripping and excitation/deexcitation in the collisions $(\mathrm{He}^+)_{nl} + p$ and $(\mu\mathrm{He}^+)_{nl} + d$ with n in the final states up to 10 from the initial $n \leq 3$ were performed. Specifically, the direct calculation of the μ-stripping and $\mu\mathrm{He}^+$ excitation/deexcitation including an important effect of the finiteness of the muon mass ($m_\mu/M_{He} \neq 0$) was realized for the first time (V.S. Melezhik). A new approach to treat three charge particles in the continuum was used to study several three-body reactions of astrophysical interest. In particular, the $p + p + e \to d + \nu$ reaction of *pp*-cycle at conditions in the center of Sun ($T = 1.5$ keV) was discussed (V.B. Belyaev). The meson-exchange πN model was extended in the S_{11} channel up to 2 GeV by explicitly introducing a set of S_{11} resonances into the model. The results are then fed into the pion photoproduction model to analyze the existing ${}_pE_{0+}$ multipole. Calculations indicate the existence of the third and fourth S_{11} resonance with the masses 1846 ± 47 and 2113 ± 70 MeV (S.S. Kamalov).

Interesting results were obtained in the field of relativistic nuclear physics. Global effects of strangeness production in hot and dense nuclear matter within a collective thermodynamic approach were explored. Thermodynamic properties of excited systems were analyzed with various phenomenological models for the equation of state (EoS) which differ by the order of the deconfinement phase transition: a first order transition (the two–phase bag model), a crossover–type transition (the statistical mixed–phase model) and no phase transition (pure hadronic models). The consequences of strangeness separation (strangeness distillation effect) and softening of the (EoS) were discussed (V.D. Toneev). The contribution of the final-state interaction to the differential cross-section of deuteron photodisintegration at laboratory photon energies below 50 MeV was analyzed in the framework of the Bethe–Salpeter formalism with a phenomenological rank-one separable interaction. It was found that the relativistic effects slightly increased the magnitude of the final-state interaction (S.G. Bondarenko, V.V. Burov). Within an effective meson-nucleon theory, the Okubo-Zweig-Iisuka rule was analyzed in processes of vector meson production in near-threshold elementary nucleon-nucleon collisions $pp \to ppV$, $pn \to pnV$ and $pn \to dV$ ($V = \omega, \phi$). It was shown that a set of effective parameters could be established to explain fairly well the available experimental data on angular distributions and the energy dependence of the total cross sections without explicit implementation of the Okubo-Zweig-Iisuka rule violation. Isospin effects were considered in detail and compared with experimental data whenever available (L.P. Kaptari, S.S. Semikh).

The nuclear theory methods were applied to study metallic clusters. Within the time-dependent local-density approximation the origin and main features of the electron infrared quadrupole modes (IRQM) in sodium clusters were described. The connection of some IRQM with the scissors M1 mode was demonstrated (V.O. Nesterenko, W. Kleinig).

The most promising directions of our future studies are: the nuclear structure far from stability valley, 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

EFFECT OF PHONON-PHONON COUPLING ON THE LOW-LYING STATES IN Sn ISOTOPES

A.P. Severyukhin, V.V. Voronov and Nguyen Van Giai[1]

[1]Institut de Physique Nucléaire, F-91406 Orsay Cedex, France

Starting with an effective Skyrme interaction we present a method to take into account the coupling between one- and two-phonon terms in the wave functions of excited states. The approach is the development of a finite rank separable approximation for the quasiparticle RPA calculations proposed in our previous works [1,2]. The influence of the phonon-phonon coupling on energies and transition probabilities for the low-lying quadrupole and octupole states in the neutron-rich Sn isotopes is studied. The results of our calculations [3] for the quadrupole states in $^{124-134}$Sn are shown in Fig. 1.

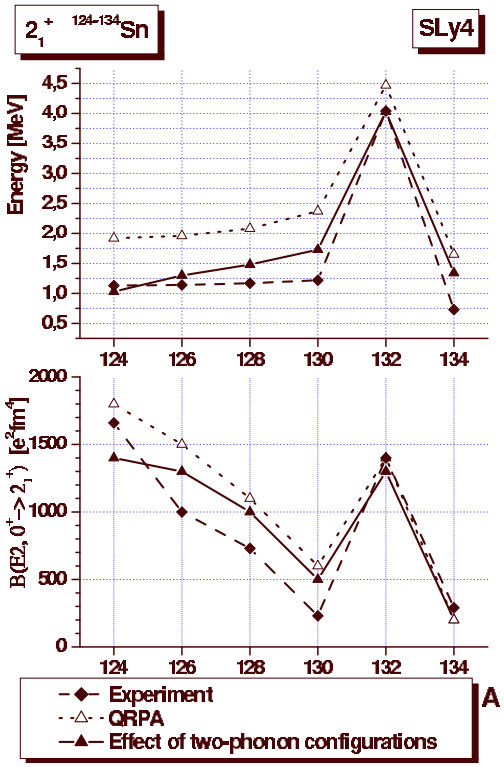

Figure 1: Energies and transition probabilities for Sn isotopes

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Q – PHONON DESCRIPTION OF LOW-LYING 1^- TWO–PHONON STATES IN SPHERICAL NUCLEI

R.V. Jolos, N.Yu. Shirikova[1], V.V. Voronov

[1]Laboratory of Information Technologies, JINR, Dubna

The properties of 1^-_1 two–phonon states and the characteristics of E1 transition probabilities between low–lying collective states in spherical nuclei were analyzed within the Q–phonon approach to the description of collective states [1]. Several relations between observables were obtained. Microscopic calculations of the E1 $0^+_1 \to 1^-_1$ transition matrix elements were performed on the basis of RPA. A satisfactory description of the experimental data was obtained. The results of the calculations of the electric dipole transition matrix elements are presented in Table 1.

Table 1: The experimental (exp) and calculated electric dipole transition matrix elements for Cd, Sn and Ba isotopes obtained including all contributions (total) and without a contribution of the two–quasiparticle admixture to the 1^-_1 state (T=0) (in units $e \cdot fm$).

Nucleus	$\lvert\langle 1^-_1 \parallel \mathcal{M}(E1) \parallel 0^+_1\rangle\rvert_{\text{total}}$	$\lvert\langle 1^-_1 \parallel \mathcal{M}(E1) \parallel 0^+_1\rangle\rvert_{\text{T=0}}$	$\lvert\langle 1^-_1 \parallel \mathcal{M}(E1) \parallel 0^+_1\rangle\rvert_{\text{exp}}$
^{108}Cd	0.140	0.018	0.050
^{110}Cd	0.119	0.024	0.048
^{112}Cd	0.115	0.026	0.041
^{114}Cd	0.114	0.031	0.044
^{116}Cd	0.109	0.036	0.034
^{116}Sn	0.170	0.066	0.081
^{118}Sn	0.173	0.073	0.085
^{120}Sn	0.169	0.076	0.087
^{122}Sn	0.156	0.073	0.085
^{124}Sn	0.134	0.063	0.078
^{134}Ba	0.086	0.019	0.048
^{136}Ba	0.113	0.040	0.071
^{138}Ba	0.160	0.082	0.114
^{140}Ba	0.152	0.074	–
^{142}Ba	0.153	0.078	–
^{144}Ba	0.158	0.079	–

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INTERACTING BOSON MODEL STUDY OF THE SPIN EVOLUTION OF YRAST $E2$ TRANSITION PROBABILITIES IN ^{162}Yb

J. Dobeš[1], R.V. Jolos

[1]Nuclear Physics Institute, Řež, Czech Republic

Over the last years a series of experiments has been performed to obtain information on $E2$ transition probabilities between the states of the ground state band of even-even nuclei. In some cases, including the ^{162}Yb nucleus, the results were unexpected.
It is commonly assumed that the ratio of $E2$ reduced transition probabilities connecting the states of the ground state band takes the values between the rotational and vibrational limits. The ^{162}Yb nucleus represents a notable exception. This nucleus is situated in the transitional region between the vibrational and rotational limits. Its spectrum is very well described by the $X(5)$ critical point symmetry. However, available experimental data for ^{162}Yb indicate that $B(E2)$ ratios for the ground state band transitions increase with spin at even slower rate than in the rotational limit and are in strong contradiction to the $X(5)$ prediction.
It was shown in [1] that in the interacting boson model (IBM) it is possible to describe simultaneously the transition-like low-lying level scheme with the rotational-like yrast $B(E2)$ values. For some values of the parameters of the general IBM Hamiltonian the values of the $B(E2)$ ratio can fall down below the rotational limit. It happens because a deformation-like behavior can be reproduced not only in the $SU(3)$ limit of IBM but also with the IBM Hamiltonian parameters producing a deformed minimum in the potential energy at the values of deformation significantly smaller than that in the $SU(3)$ limit. In this case the values of the $B(E2)$ ratio fall down below the rotational limit.

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MICROSCOPIC STRUCTURE OF LOW-LYING 0^+ STATES IN THE DEFORMED ^{158}Gd

A.V. Sushkov, N.Yu. Shirikova[1] and N. Lo Iudice[2]

[1]Laboratory of Information Technologies, JINR, Dubna
[2]Università di Napoli "Federico II" and INFN, I-80126 Napoli, Italy

The identification of a large number of low-lying 0^+ levels in the deformed ^{158}Gd via a high resolution (p,t) experiment [1] has aroused renewed interest in 0^+ states. Similar (p,t) measurements, carried out with the same apparatus, detected an equally large number of 0^+ levels in a few deformed actinides and in ^{168}Er, confirming the expectation that the abundance of low-lying 0^+ states is a common feature of several deformed nuclei.
The experiment immediately stimulated theoretical studies. The first one was carried out within the interacting boson model (IBM) and the geometrical collective model (GCM) [2]. A projected shell model (PSM) calculation attempted to explain the nature of the observed states in terms of quasiparticle excitations [3].
We performed a microscopic calculation within the quasiparticle-phonon model (QPM) [4-6]. This consists in generating microscopic phonons in RPA and then diagonalizing a

Hamiltonian composed of a sum of separable two-body potentials with different multipolarity in a basis of multiphonon states. Since both collective and noncollective RPA phonons are included in the multiphonon basis, the approach offers a less unbiased criterion for determining the nature of these 0^+ states.
A thorough investigation of the properties of the 0^+ states in ^{158}Gd was performed by computing spectra, $E2$ as well as normalized $E0$ transition strengths, and spectroscopic factors of the two-nucleon transfer (p,t) and (t,p) reactions [7].
An appreciable fraction of the QPM 0^+ states was found to have large two-phonon components, mostly built out of collective octupole phonons, in agreement with the previous IBM predictions [2]. The small $E2$ and $E0$ strengths obtained confirm the lack of quadrupole collectivity predicted by the PSM [3] for all the 0^+ states. Most of the low-lying 0^+ states are linear combinations of several, huge in some cases, two-quasiparticle $q\bar{q}$ components. Not all these states, however, display pairing collectivity. The quasiparticle components, in fact, act coherently only in the first excited 0^+_1. As a result, only this state is predicted to be strongly populated in (p,t) two-nucleon transfer reactions. The same 0^+_1 state is predicted to be strongly populated also in (t,p) reactions. The latter result strongly suggests that the 0^+ states of ^{158}Gd are not pairing isomeric states.

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GROSS SHELL STRUCTURE AT HIGH SPIN IN HEAVY NUCLEI

M.A. Deleplanque[1], S. Frauendorf [2], V.V. Pashkevich, S.Y. Chu[1], A. Unzhakova[3]

[1]Lawrence Berkeley National Laboratory, Berkeley, California, USA
[2] Physics Department, University of Notre Dame, Notre Dame, Indiana, USA
[3]Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia

Average yrast moments of inertia at high spins, where the pairing correlations are expected to be largely absent, were found to deviate from the rigid-body values. This indicates that shell effects contribute to the moment of inertia, as it was pointed out by Pashkevich and Frauendorf [1] long ago. The deviations from the rigid-body moment of inertia imply that the flow pattern must substantially deviate from the current of a rigidly rotating mass distribution, i.e. there are strong net currents **in the body fixed frame.** The deviations of the moments of inertia from $\mathcal{J}_{rig}$ were investigated [2] in a systematic way and gave a qualitative interpretation in the frame of the semiclassical Periodic Orbit Theory [3],

which relates the shell structure to classical periodic orbits in the nuclear potential. This approach becomes a very instructive tool for interpretation if one is interested in the gross structure which is determined by only a few shortest orbits. One takes a fresh look at the angular momentum generation in nuclei through this perspective. The gross dependence of moments of inertia and shell energies on the neutron number in terms of both the semiclassical periodic orbit theory and the level bunching in the calculated single-partical spectra in the rotating Woods-Saxon potential (the shell effects) was interpreted. It was shown that the ground-state shell energies, nuclear deformations and deviations from rigid-body moments of inertia were all due to the same periodic orbits.

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SYMMETRY CONSERVATION AND EXTENDED HOLSTEIN-PRIMAKOFF MAPPING FOR BOSONIC AND FERMIONIC SYSTEMS

A. Dzhioev, J. Wambach[1,2], A. Vdovin, A. Storozhenko, Z. Aouissat[1]

[1]Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany

[2]Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany

For the last decades the perturbative boson expansion (PBE) theory played an effective role in the development of approximate solutions in nuclear theory [1]. However, this technique appears to be a powerful tool for building symmetry-conserving and nonperturbative approaches in quantum field theories (QFT) as well. For example, in Ref. [2] it was demonstrated that the Holstein-Primakoff mapping (HPM) for boson pairs could be used to systematically classify the dynamics, according to the $1/N$ expansion, rendering a promising and efficient alternative to the well-known functional methods.

However, PBE in general, and HPM in particular, rely on bosonization of pairs of particles and, therefore, single particle images are absent after mapping. For the linear sigma model the lack of ideal single-boson states was an obstacle for defining unambiguously the two-point function for the Goldstone mode [2]. For fermionic systems the absence of single-fermion degrees of freedom after mapping means that all thermal densities of states appear to be of bosonic type although the original system is purely fermionic one. Therefore, amendments are needed for HPM in order to reconcile it with the requirement of the statistics.

To solve the problems outlined above for fermionic systems the extended Holstein-Primakoff boson-fermion mapping (EHPM) proposed by Marshalek in [3] was used. This type of mapping is of crucial importance to correctly imbed the quantum statistics in the expansion. In Refs. [4,5], the boson-fermion EHPM was combined with the thermo field dynamics (TFD) [6] to construct a consistent thermal boson expansion for the $SU(2)$ Lipkin model consisting of N fermions distributed over two levels with degeneracy N.

Thermalization of the Lipkin system was simulated by applying the thermal Bogoliubov transformation to the ideal fermions and their tilde counterparts leaving the auxiliary bosons $B, \widetilde{B}$ unaltered, i.e., "cold". In spite of this, in the leading order the energy of the collective mode was found to obey the *thermal* RPA equation. Then diagonalizing the thermal Hamiltonian up to the next-to-leading order in $1/\sqrt{N}$ expansion a temperature dependence of single-particle and collective modes as well as their coupling was computed for the normal and deformed phase [5] of the model.
For a system of bosons the new version of EHPM, which accommodates single-boson and boson-pair mappings was introduced in [7]

$$\begin{aligned}(\vec{a}\vec{a})_I &= \mathcal{G}_N(n,m)A\ , \quad (\vec{a}^+\vec{a}) = 2n+m, \quad (\vec{a}^+\vec{a}^+)_I = (\vec{a}\vec{a})_I^+ \\ (a_i)_I &= \mathcal{G}_N(n,m)\Gamma_N(m)\alpha_i + 2\alpha_i^+ A\Gamma_N(m)\ , \quad (a_i^+)_I = (a_i)_I^+\ ,\end{aligned}$$

where N is an integer, $n = A^+A$, $m = \sum_i \alpha_i^+\alpha_i$, and $\mathcal{G}_N$, Γ_N are given by

$$\mathcal{G}_N = \sqrt{2N + 4(n+m)}, \qquad \Gamma_N(m) = \left[\frac{m+N-2}{2(2m+N)(2m+N-2)}\right]^{1/2}\ .$$

Thus, instead of the original bosons a_i $(i = 1, ...N)$ one has ideal bosons α_i which can obey the symmetry requirement and the new boson A which corresponds to a two-boson mode and plays an auxiliary role.
In [4,8], this version of EHPM was applied to the quantum anharmonic $O(N+1)$ oscillator model with broken symmetry which imitates essential features of the linear sigma model in QFT. The termalization of the system was undertaken also by applying the TFD formalism (TFD) [7]. The thermal Hamiltonian of the system was obtained as usual by considering the tilde conjugate (t.c) of all operators such as A, α_i and others. Then the thermal quasiparticle representation was obtained by the thermal Bogoliubov rotation of only the ideal bosons α_i^+, $\widetilde{\alpha}_i^+$. Again the auxiliary bosons A and $\tilde{A}$ need not be transformed. In the leading order of $1/N$ expansion the existence of N uncoupled modes that are nothing else but the thermal Hartree pions in QFT were found. As was mentioned above, without the single-boson mapping these pions are missing from the spectrum of the theory. Besides the pions there exist other excitations which correspond at the RPA level to the mixed sigma-boson and two pion states.
At zero temperature, using Hartree pions and RPA bosons as a basis and applying a quantum analog of the classical Birkhoff-Gustafson method the Hamiltonian of the anharmonic $O(N+1)$ oscillator was diagonalized up to the order $1/N$ [8]. It was proved that in the next-to-leading order pions conserve the Goldstone character. In other word, their frequency obeys the Ward identity and vanishes in exact symmetry limit as it should be in accordance with the Goldstone theorem. This result is the evidence of symmetry conservation in EHPM. Also, it was found that EHPM removes a number of ambiguities while computing anharmonicities in the next-to-leading order which are very much relevant to the $\pi\pi$ scattering problem. For matrix elements of the pion-pion interaction the equivalence of the results obtained by a diagrammatic technique and the EHPM application was shown .

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PAIRING MODEL AT FINITE TEMPERATURE: SELF-CONSISTENT RPA APPROACH

A.N. Storozhenko, P. Schuck[1], A.I. Vdovin

[1]Institut de Physique Nucléaire, F-91406 Orsay Cedex, France

There are different ways to construct a theory which can treat adequately two-body correlations. One of the greatest promising approaches providing such a consideration is the self-consistent RPA (SCRPA) theory [1] which grew out of the works by Ken-ji Hara and D. Rowe [2] who firstly suggested a way for the RPA generalization. In the last few years the self-consistent RPA was successfully applied to various non-trivial models where two-body correlations are of importance [3].

Extensions of SCRPA to finite temperatures were studied as well. In Refs. [4], besides a general formulation of the new thermal approximation within the framework of the thermofield dynamics, applications of the thermal SCRPA (TSCRPA) to simple model systems with particle-hole correlations were considered. Advantages of TSCRPA over THF and TRPA were found.

Recently [3], SCRPA was applied to many-particle systems where a particle-particle interaction plays an essential role. In particular, the many level paring model (also known as the picket fence model (PFM)), whose exact solution was found in [5] and which was initially developed to describe deformed superfluid nuclei, was considered. In this context, SCRPA can be viewed as a self-consistent mean field theory for pair fluctuations.

The success of SCRPA in the latter case motivated us to study in the framework of this approximation the thermodynamic properties of the BCS Hamiltonian using PFM as an example [6]. Our studies were based on the Matsubara one- and two- particle Green functions, which allows us to calculate correlation and excitation energies, a specific heat, level densities, etc. The studies were restricted to values of the coupling constant G which are below or slightly above the critical value, i.e. the system in question is in the normal phase or not very deep in the superfluid one.

The PF model consists of an equidistant multilevel pairing Hamiltonian with each level twofold degenerate. The numerical calculations were performed for the system with $N = 10$ particles distributed among $\Omega = 10$ levels. We compare the SCRPA results with the

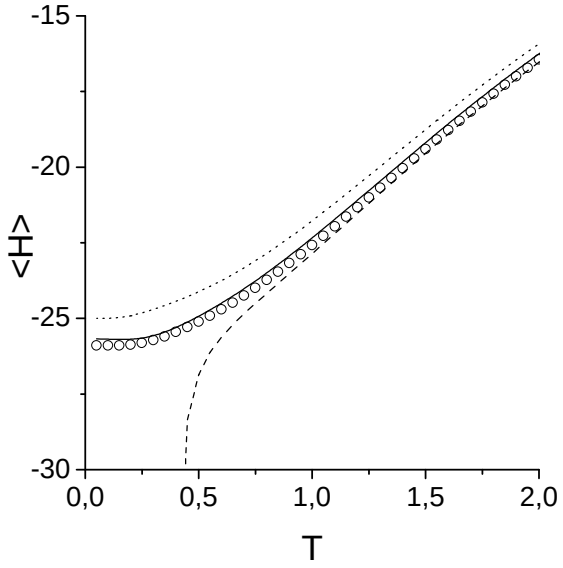

Figure 1: The average energy $\langle H \rangle$ as a function of the temperature for the coupling constant $G = 0.4$. The exact results – open circles; the TMFA results – dotted line; the TRPA results – dashed line and the TSCRPA results – solid line.

exact ones for the grand canonical ensemble as well as with the results of the standard thermal RPA (TRPA) and thermal mean field approximation (TMFA).
In Fig. 1, the average energy $\langle H \rangle$ as a function of T is displayed for the interaction constant $G = 0.4$ (at $T = 0$ this value of G is larger than the critical value $G_{cr} \simeq 0.33$). With increasing T the mean field rearrangement occurs and the system goes from the superfluid phase to the normal one at $T_{cr} \simeq 0.38$. Note that within the TRPA the lowest excitation energy ω_1 vanishes when $T \to T_{cr}$, whereas within the TSCRPA ω_1 stays finite. As one can see in Fig. 1, TSCRPA gives more precise results as compared to the other approximations. It is remarkable that the TSCRPA results are accurate down to practical zero temperature, in spite of the fact that within the standard BCS theory one enters the superfluid regime. The quality of our results for the other calculated quantities also turns out to be very good. It can be considered as a general advantage of our approach that all these quantities are directly accessible in the whole range of temperatures and coupling constants. Most of the time the agreement with the exact solution is within the couple of per cent level.
A particularly interesting feature of our investigation is the fact that we managed to calculate the single particle Green function consistently within TSCRPA. This enabled us to give, for the first time, the evolution of the single particle level density with temperature. An interesting aspect of our calculation is that with decreasing temperature the density of single particle states around the Fermi level decreases even above the critical temperature as defined by the BCS theory.

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CLUSTER MANIFESTATION IN HEAVY NUCLEI AND IN FUSION REACTIONS

G.G. Adamian[1], N.V. Antonenko, S.P. Ivanova[2], R.V. Jolos, Yu.V. Palchikov, W. Scheid[3], T.M. Shneidman

[1] Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna, Russia

and

Institute of Nuclear Physics, Tashkent, Uzbekistan

[2]University Center, JINR, Dubna, Russia

[3]Institut für Theoretische Physik der Justus–Liebig–Universität, Giessen, Germany

In the cold and hot fusion-evaporation reactions the isotopic trends of production cross section for the superheavy nuclei were treated within the dinuclear system model [1]. The optimal excitation energies and the combinations of colliding nuclei were suggested for future experiments. It was found that the use of projectiles with larger number of neutrons is not lways expected to increase the production cross section of the elements with Z=110, 112 and 114 in cold fusion. It was shown that in ^{48}Ca-induced hot fusion-evaporation reactions most neutron-rich actinide targets available for the experiment lead to smaller cross sections. The production of superheavies in hot fusion reactions on targets with a less neutron number would be important for additional confirmation of superheavy nuclei synthesized in hot fusion reactions because the alpha-decay chains end at the region of known nuclei. The actinide-based hot fusion reactions with stable projectiles heavier than ^{48}Ca were analyzed.

The structure of alternative parity collective bands in actinides and rare-earth nuclei was described in a cluster model [2]. The model is based on the assumption that cluster type shapes are produced by the motion of the nuclear system in the mass asymmetry coordinate. The calculated parity splittings and the electric multipole transitions are in good agreement with the experimental data.

In Ref. [3], it was shown for the first time that the collective states generated by the cluster motion describe both superdeformed and those normal deformed states into which superdeformed states decay. The yrast superdeformed band termination phenomenon in the mass region $A \approx$190 was explained by the crossing of the superdeformed rotational band and the nearest neighbouring excited collective normal-deformed cluster band.

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INFLUENCE OF THE ENTRANCE CHANNEL DYNAMICS ON THE EVAPORATION RESIDUE FORMATION

G. Fazio[1], G. Giardina[1], A. Lamberto[1], A.I. Muminov[2], A.K. Nasirov[2,3], F. Hanappe[4], L. Stuttg'e[5]

[1]INFN, Sezione di Catania, and Dipartimento di Fisica dell'Universit'a di Messina, Messina, Italy

[2]Institute of Nuclear Physics, Tashkent, Uzbekistan

[3]Bogoliubov Laboratory of Theoretical Physics, JINR, Dubna, Russia

[4]Universit'e Libre de Bruxelles, Bruxelles, Belgium

[5]Institut de Recherches Subatomiques, Strasbourg, France

The dynamical effects of the entrance channel on the competition between quasifission and fusion processes, and on the evaporation residue formation were investigated. We obtained results on the fusion angular momentum distribution for the ^{16}O + ^{204}Pb and ^{96}Zr + ^{124}Sn reactions leading to compound nucleus of the same mass and charge numbers, ^{220}Th*.

The use of these results in calculations of the evaporation residue formation after a step by step emission of neutrons and charge particles leads to the different evaporation residue cross sections. Good agreement of our theoretical results with the experimental data for ^{16}O + ^{204}Pb and ^{96}Zr + ^{124}Sn reactions allowed us to find the effect of the entrance channel on the different excitation functions of the evaporation residues.

First, due to a mass difference, charge asymmetry and peculiarity of the shell structure of initial nuclei the competition between fusion and quasifission for these reactions appeared to be different. This leads to a different angular momentum distribution of compound nucleus at the same excitation energy.

Second, the cooling of the formed compound nucleus was found different along the compound nucleus deexcitation cascade due to the dependence of the branching ratio of particle emission and fission channels on the angular momentum. The conclusion is that the role of the mass asymmetry in the entrance channel evident in both the formation of the excited compound nucleus as its cooling by deexcitation cascade in competition with fission.

This result seems to be very useful for planning experiments on the synthesis of superheavy elements.

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BREAKUP REACTIONS OF HALO NUCLEI

S.N. Ershov

Two-neutron halos have by now been found in many light dripline nuclei, in the cardinal cases ^{6}He, ^{11}Li, but also in ^{14}Be, ^{17}B, and carbon and oxygen isotopes. In Borromean halo nuclei the three-body continuum is most intriguing. For example, in the case of ^{6}He, a concentration of transition strengths is experimentally observed at 1-3 MeV above the $\alpha + n + n$ threshold in addition to the well known 2^+ resonance, and the nature of this strength is still being clarified. A similar situation pertains to the case of ^{11}Li, where a peak is experimentally observed at $\sim$1 MeV above the $^9\mathrm{Li} + n + n$ threshold. These strength concentrations may contain ordinary resonances or a new kind of collective motion, a soft dipole mode of excitation corresponding to oscillations of the core against the halo neutrons.

The intrinsic properties of the continuum of Borromean nuclei could in principle be revealed in $3 \rightarrow 3$ scattering. To perform this type of experiment is however practically impossible. Thus one has to resort to binary reactions, where the continuum is usually explored via responses which are induced by transitions from the ground state to the continuum. A reliable way to study the continuum properties is to explore nuclear reactions under conditions where one-step transitions dominate. This is, however, still a rather comprehensive task, because of the intertwining of the ground state and continuum structures, influenced by reaction mechanisms.

In Ref. [1], a reaction model was presented which allows calculations of a variety of observables in fragmentation processes leading to the low-energy excitations of two-neutron halo nuclei. Some calculations of halo breakup in collisions with different probes were given.

Inelastic scattering of ^{11}Li on proton target at collision energy of 68 MeV/u, was analysed in the framework of the microscopic four-body distorted-wave model [2]. The ground state and the three-body continuum excitations of ^{11}Li were calculated in the three-body $^9\mathrm{Li} + n + n$ cluster model using the method of hyperspherical harmonics. Effective density-dependent nucleon-nucleon forces were used for the interaction of the proton target with the core nucleons, while free t-matrix forces were used for interaction with the halo neutrons. The parameters of the effective forces were checked by calculating the single folding optical potentials which were applied to describe experimental data on the elastic scattering of both ^{9}Li and ^{11}Li on proton. The theory describes well the available elastic scattering data and correctly reproduces the experimentally observed difference in cross sections for ^{11}Li and ^{9}Li. This difference is explained by a motion of the ^{9}Li core within ^{11}Li. Thus, there are no new parameters when the theory is applied to inelastic scattering of ^{11}Li.

The calculations of inelastic scattering showed accumulation of dipole and monopole excitations of ^{11}Li near the three-body threshold and described well the observed peak in the experimental energy spectrum of ^{11}Li. Also, the theory reproduces well the corresponding experimental angular distribution and confirms a dominance of the dipole excitation. To reveal clearly the monopole excitation, experimental data at small angles are needed.

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MODEL FOR RESTORATION OF HEAVY-ION POTENTIALS AT INTERMEDIATE ENERGIES

K.M. Hanna[1], K.V. Lukyanov[2], V.K. Lukyanov,
B. Słowiński[3,4], E.V. Zemlyanaya[2]

[1]Mathematical and Theoretical Physics Department, NRC, Atomic Energy Authority, Cairo, Egypt

[2]Laboratory of Information Technologies, JINR, Dubna, Russia

[3]Faculty of Physics, Warsaw University of Technology, Warsaw, Poland

[4]Institute of Atomic Energy, Otwock-Swierk, Poland

Contrary to the usual phenomenological optical potentials we suggest that the following forms be constructed:

$$U_{opt}^{A,B,C} \;\Rightarrow\; N_r^A\, V^H \,+\, iN_{im}^A\, W^H; \quad N_r^B\, V^{DF} \,+\, iN_{im}^B\, W^H; \quad N_r^C\, V^{DF} \,+\, iN_{im}^C\, V^{DF},$$

which are based on the microscopically calculated patterns for the real V^H and imaginary W^H parts of the potential obtained in [1], which reproduce the high-energy amplitude of scattering [2]. Another used template V^{DF} is calculated within the standard double-folding (DF) model with the exchange term included [3]. They are as follows:

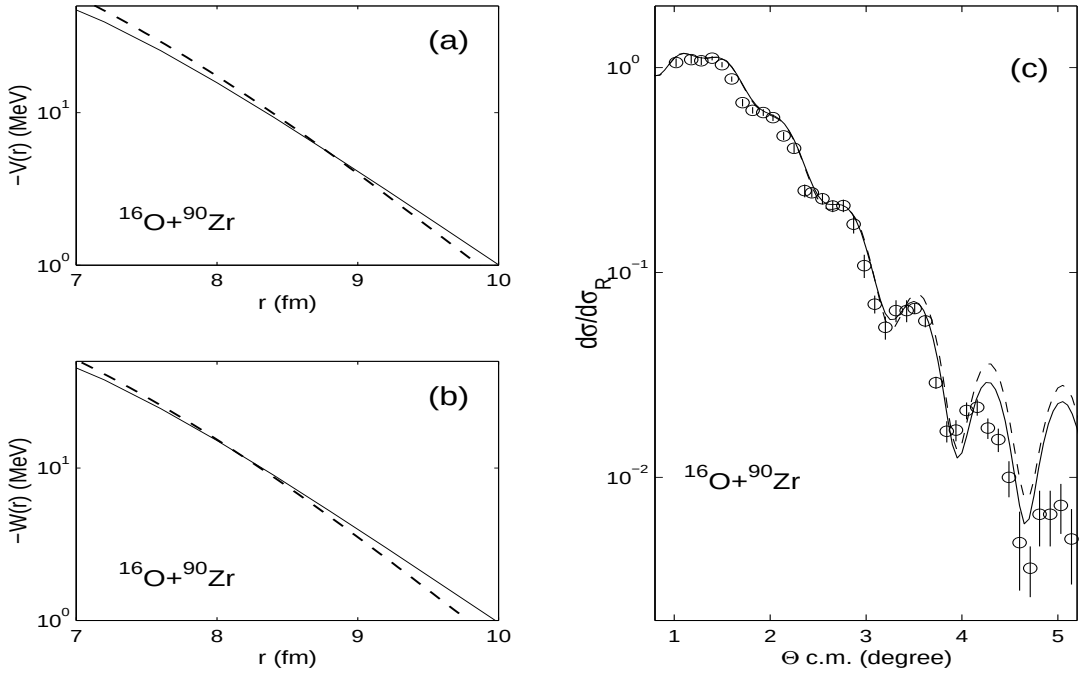
$$U_{opt}^H(r) \,=\, V^H + iW^H = -\frac{2E}{k(2\pi)^2}\bar{\sigma}_{NN}(\bar{\alpha}_{NN}+i)\int dq\; q^2 j_0(qr)\tilde{\rho^\circ}_p(q)\tilde{\rho^\circ}_t(q)\tilde{f}_N(q),$$

$$V^{DF}(r) = \int d^3r_p d^3r_t\, \rho_p^\circ(\mathbf{r}_p)\, \rho_t^\circ(\mathbf{r}_t)\, v_{NN}^D(\mathbf{r}_{pt}=\mathbf{r}+\mathbf{r}_t-\mathbf{r}_p) \,+$$

$$+ \int d^3r_p d^3r_t\, \rho_p^\circ(\mathbf{r}_p, \mathbf{r}_p+\mathbf{r}_{pt})\, \rho_t^\circ(\mathbf{r}_t, \mathbf{r}_t-\mathbf{r}_{pt}) v_{NN}^{EX}(\mathbf{r}_{pt})\, \exp\left[\frac{i\mathbf{K}(r)\mathbf{r}_{pt}}{M}\right].$$

Here $\tilde{\rho^\circ}_{p(t)}(q)$ are form factors of the point densities $\rho_{p(t)}^\circ(r)$ of the projectile and target nuclei, $\tilde{f}_N(q)$ is expressed through the form factor of the NN-scattering amplitude, $\bar{\sigma}_{NN}$ is the total cross section while $\bar{\alpha}_{NN}$ is the ratio of the real-to-imaginary part of the forward NN-scattering amplitude. The "bar" means averaging over isotopic spins of colliding nuclei. Also, $K(r)$ is the local relative momentum motion of nuclei, $Mm = A_pA_tm/(A_p+A_t)$ is the reduced mass, and v_{NN}, the effective NN-potential given in [3]. Thus, we do not introduce free parameters except the N_r and N_{im} fitted factors, the weights of contributions of the microscopic real and imaginary heavy-ion potentials of scattering. Doing so, we calculated within the high-energy approximation (HEA) (see, e.g. [4]) the differential cross-sections for scattering of the ^{16,17}O heavy-ions on different target-nuclei at about hundred MeV/nucleon [1,5,6] and compare them with the experimental data from [7]. As an example, the figure shows that the potential $U_{opt}^A = 1.13V^H + iW^H$ (dashed lines in (a),(b)) behaves in a peripheral region in agreement with the phenomenological 4-parameter WS-potential [7] and results in the corresponding cross-section (dashed curve in (c)) closed to that calculated for the WS-potential.

Our main conclusion is that the presented idea proves to utilize the microscopic models as patterns for a further fit with experimental data. Moreover, at high energy interactions, one can be confident to claim that the results of the calculations carried out by using the microscopic potentials show that in the outer region of interactions a true prediction and behavior of these potentials can be gained in the very sensitive domain of the heavy-ion scattering.



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EXTRAPOLATION OF TRIPLET PHASES OF PROTON-PROTON SCATTERING TO LOW ENERGIES

V. V. Pupyshev

Since a direct experimental investigation of the triplet NN scattering in the range of energies below several megaelectronvolts is impossible at the present state of technology, a theoretical study of the role of electromagnetic corrections to the nuclear NN interaction in this energy domain remains an interesting and topical problem.
In [1], we have shown that to correctly extrapolate the triplet phases of *pp* scattering to a range of energies below several MeV, one should take into account, together with the Coulomb and nuclear interactions, the interactions of the magnetic moment of a proton with the Coulomb field and the magnetic moment of another proton.
The main results of our analysis of triplet phases of the *pp* scattering are the following. The interactions between the magnetic moment of a proton and the Coulomb field and the magnetic moment of another proton have a substantial effect on the behavior of the triplet phases at energies below several MeV. Owing to these interactions, in the limit of zero collision energy, all triplet phases should be proportional to the cube of the collision momentum, and the ${}^3P_0$ phase and the ${}^3P_2 - {}^3F_2$ phase should change their signs at energies of $E \approx 120$ keV and $E \approx 4$ MeV, respectively. All the features of the energy dependence pointed out above are *the theoretically predicted facts* and are described to good accuracy by the simple proposed extrapolation formula, which is independent of the choice of a model of nuclear interaction among all phase-equivalent interactions. To calculate with high accuracy, the coefficients and higher order terms in the low-energy representations of the Coulomb-nuclear phases and the mixing parameters, we suggest that the derived energy-independent equations be applied.

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THREE-ATOMIC HELIUM SYSTEMS WITHIN THE HARD-CORE FADDEEV APPROACH

E.A. Kolganova, A.K. Motovilov, W. Sandhas[1]

[1] Physikalisches Institut der Universität Bonn, Bonn, Germany

The system of three ^{4}He atoms is of great interest for various problems as, e.g., the formation of liquid helium drops, superfluidity or Bose-Einstein condensation. In addition, it represents an almost ideal quantum-mechanical three-body problem, free of any complications due to spin, isospin or long-range Coulomb forces. Moreover, the Borromean phenomenon shows up most clearly in this system: an extremely small ^{4}He dimer energy of about 1 mK is accompanied by a two orders of magnitude bigger trimer energy, and even an excited state of Efimov nature is found.
Experimentally, the ^{4}He trimer was observed by Schöllkopf and Toennies [1]. Hyperspherical, variational, and Faddeev-type techniques were successfully employed to treat this system theoretically. In order to overcome technical complications due to the strong repulsive part in the atomic interaction, a hard-core version of the Faddeev differential equations was developed by S. P. Merkuriev and A. K. Motovilov (see [2] and references

therein). High accuracy was achieved along this line providing us with a $^4He_3$ ground-state energy of $E_t^{(0)} = 125.8\,\mathrm{mK}$ or $125.9\,\mathrm{mK}$ for the Tang-Toennies-Yiu (TTY) or the LM2M2 Aziz and Slaman potentials, respectively [3]. This agrees almost perfectly, or at least fairly well, with almost all alternative approaches. The same holds true for the energy $E_t^{(1)} = 2.28\,\mathrm{mK}$ we obtained for the excited (Efimov-type) state. Scattering phase shifts for the ^{4}He atom – ^{4}He dimer collisions were calculated for the first time in [4] and then updated in [3]. A certain discrepancy in the scattering length results has recently been overcome [5] with more powerful computer facilities available.
This rather a clear situation suggests that the asymmetric ^{3}He–^{4}He–^{4}He system be studied within the same framework. Here, besides the very loosely bound ^{4}He dimer we have two ^{3}He–^{4}He subsystems which are unbound as a consequence of a smaller ^{3}He mass ($m_{^3\mathrm{He}}/m_{^4\mathrm{He}} = 0.753517$). Nonetheless, a ^{3}He^{4}He$_2$ bound state exists of an energy one order of magnitude bigger than the ^{4}He dimer energy. We found $13.78\,\mathrm{mK}$ for TTY and $13.84\,\mathrm{mK}$ for LM2M2, again in fairly good agreement with alternative calculations. Thus, this case represents another interesting example of the Borromean phenomenon. The ^{3}He –^{4}He$_2$ scattering length and phase shifts were also calculated [6].

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COULOMB BREAKUP OF HALO NUCLEI AND ATOMIC IONES IN TIME-DEPENDENT APPROACH

V.S. Melezhik

We develop a time-dependent grid method for treating different few-body dynamics without a usual partial-wave analysis [1,2]. The approach has a special advantage for the breakup processes: the absence of the problem of matching the boundary conditions for the few-body wave function in the breakup channel. The developed scheme allows a full quantum three-dimensional treatment of a valence particle of the projectile in the breakup on a charged target. It permits an accurate quantum description for the extended wave function of the valence particle of the projectile and also includes the Coulomb or nuclear distortions in the breakup channel. The only remaining simplification is the use of the classical approximation for the relative projectile-target trajectory. However, the computational scheme includes the coupling between the projectile and relative projectile-target variables and conserves the total energy and momentum of the system. At that, the coupled system of the Shrödinger equation for the projectile and the classical Hamiltonian

equations for the relative projectile-target trajectory is integrated simultaneously (see [2,6] and refs. therein).
The efficiency of the method for analysis of a broad class of the breakup processes was found in the recent investigations:
1. The approach has provided a non-perturbative analysis of the breakup for nuclei with a neutron or a proton halo on heavy targets including Coulomb and nuclear distortions in the final state [3,4]. The role of the nuclear interaction between the target and the projectile was analyzed. We also investigated the influence of the forbidden states in the potential describing a valence particle of the projectile on the breakup processes with a supersymmetric transformation reducing the initial potential to the phase-equivalent one [5]. Note that in this approach we overcame the essential simplifications of the previous time-dependent computations: the use of a multipole expansion for the Coulomb projectile-target interaction and of a perturbation approximation in the calculation of the breakup cross sections. The calculated breakup cross sections of weakly-bound nuclei ^{11}B and ^{15}C on ^{208}Pb at energies around 70 MeV/nucleon are in fair agreement with the RIKEN experimental data [3,4]. A possible Coulomb breakup determination of the astrophysical S factor for the $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$ radiative capture reaction to the ^{17}F ground state was analyzed with the developed computational scheme [3].
2. We succeeded [6] in calculating the stripping and excitation/deexcitation in the collisions $(\mathrm{He}^+)_{nl}+p$ and $(\mu\mathrm{He}^+)_{nl}+d$ with n in the final states up to 10 from the initial $n \leq 3$. Specifically, the direct calculation of the μ-stripping and $\mu\mathrm{He}^+$ excitation/deexcitation including an important effect of the finiteness of the muon mass ($m_\mu/M_{He} \neq 0$) was realized for the first time.

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THREE CHARGED PARTICLES IN THE CONTINUUM. ASTROPHYSICAL EXAMPLES.

V.B. Belyaev, S.B. Levin[1,2], S.L. Yakovlev[2]

[1]Department of Physics, Stockholm University, Stockholm, Sweden
[2]Institute for Physics, St.-Petersburg State University, St.-Petersburg, Russia

Three-particle systems with Coulomb interaction play a very important role in many areas such as atomic physics, plasma physics, and astrophysics. However, due to the long range character of Coulomb interaction, treatment of these systems, especially in the continuum, is very difficult as compared to the systems with short range interactions. A new approach to overcome particular difficulties related to Coulomb interactions has been

suggested recently in [1]. The main idea of [1] consists in application of the Coulomb-Fourier transform to the initial three-body Coulomb Hamiltonian. This allows one to exclude one of the three Coulomb interactions and then to develop approximate schemes to handle the problem. A scheme of such a kind was suggested in [2] to treat specific Coulomb systems where two of the particles had masses larger than the mass of the third particle. This method has two essential differences from the popular Born-Oppenheimer approach. First, it allows one to obtain expansion of the total three-body wave function in powers of the small parameter $(m/2M)^{1/2}$ where m and M are the masses of the light and heavy particles, respectively. Second, it allows one to obtain a three-body wave function in the continuum, which is a very difficult task for the Born-Oppenheimer method as well as for some other methods. The representation obtained for the three-body Coulomb wave function was used to study several three-body reactions of astrophysical interest. In particular, the $p+p+e \to d+\nu$ reaction of *pp*-cycle under conditions in the center of the Sun ($T = 1.5$ keV) was discussed. The initial wave function for this process was expanded in series with respect to the powers of the small ratio of masses. Due to symmetry reasons, in this case the expansion parameter appears to be equal to $m/2M$, with m and M being the masses of electron and proton, respectively. Since $m/M \sim 1/2000$, it is reasonable to use the zero term of the expansion as a good approximation for the wave function. This term is equal to the product of the *pp* Coulomb wave function and Coulomb wave function for an electron moving in a Coulomb field with charge two.

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S_{11} RESONANCES IN π AND η CHANNELS

S.S. Kamalov, G.-Y. Chen[1], S.N. Yang[1], D. Drechsel[2], L. Tiator[2]

[1] Department of Physics, National Taiwan University, 10764 Taipei, Taiwan

[2]Institut für Kernphysik, Universität Mainz, 55099 Mainz, Germany

At present, the resonance properties are extracted mainly from πN scattering, 2π and η production and pion photoproduction using different approaches. The first coupled channel analysis that combines pion and eta data was carried out in [1] within the isobar model. Later, more sophisticated models were developed which account for background contributions. Most of them are based on the solution of coupled-channel equations by using the K-matrix approximation, i.e., by ignoring off-shell intermediate scattering states. On the other hand, in the analysis of pion scattering and pion photoproduction within dynamical models [2–4], the off-shell dynamics (i.e., the dynamics at a short distance) is taken into account. Within this framework we have recently developed a meson-exchange (MEX) model for pion-nucleon scattering [5] which gives good agreement with the data up to 400 MeV pion lab energy. In addition, we also constructed a dynamical model for pion electromagnetic production [6,7] which describes well the π^0 photo- and electro-production data near the threshold [8] and most of the existing data up to the second resonance region.

Recently, we extended our meson-exchange πN model in the S_{11} channel up to 2 GeV by explicitly introducing a set of S_{11} resonances into the model [9]. The results are then fed

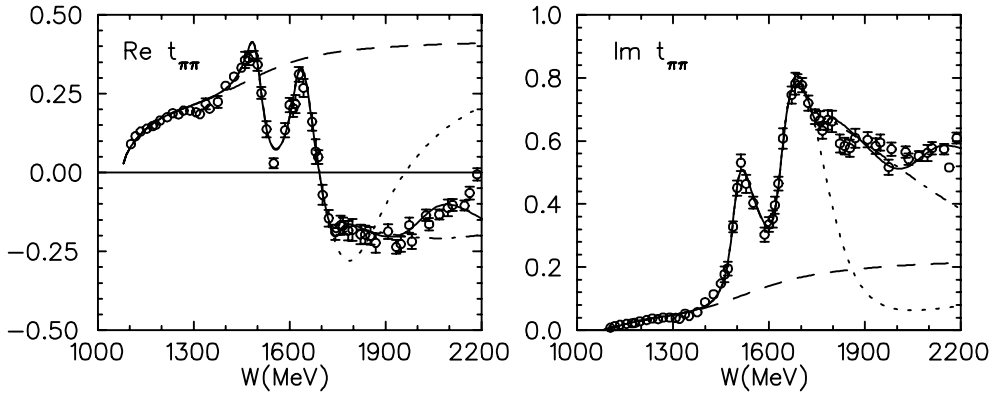

Figure 1: Real and imaginary parts of the S_{11} pion scattering amplitude. Dashed curves: nonresonant background contribution $\tilde{t}^B_{\pi\pi}$. Dotted, dash-dotted, and solid curves: total $t_{\pi\pi}$ amplitude obtained after the best fit with two, three, and four S_{11} resonances, respectively. Data points: results of the single energy analysis from [10].

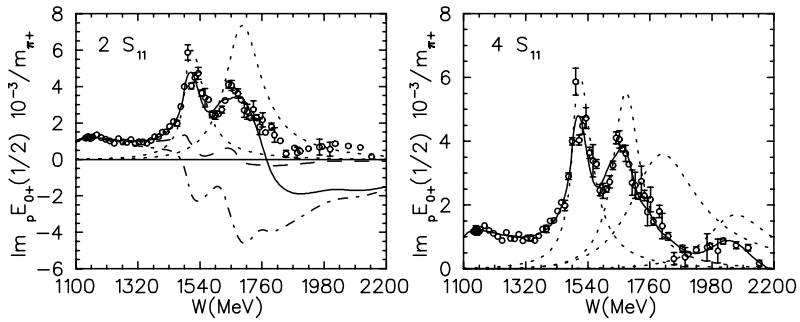

Figure 2: Imaginary parts of the ${}_pE^{1/2}_{0+}$ multipoles. Dashed and dash-dotted curves in the left panel: background contributions obtained using the K-matrix approximation and DMT model, respectively. Solid curve is the result obtained with two S_{11} resonances. Solid curves in the right panel: total multipole with four S_{11} resonances. The individual contributions from each resonance (with bare electromagnetic vertex) are shown by the dotted curves. Data points: results of the single energy multipole analysis from [11].

into the pion photoproduction model to analyze the existing ${}_pE_{0+}$ multipole. The results for both reactions are presented in Figs. 1 and 2.

The results indicate the existence of the third and fourth S_{11} resonance with the masses 1846±47 and 2113±70 MeV. In the case of pion photoproduction, we obtained background contributions to the imaginary part of the S-wave multipole which differ considerably from the result based on the K-matrix approximation. Within the dynamical model these background contributions become large and negative in the region of the $S_{11}(1535)$ resonance. Due to this fact much larger resonance contributions are required in order to explain the results of the recent multipole analysis. For the first $S_{11}(1535)$ resonance, as a value of the electromagnetic helicity amplitude we obtained $A_{1/2} = 72 \pm 2 \times 10^{-3}\text{GeV}^{-1/2}$.

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STRANGENESS PRODUCTION IN EXPANSION DYNAMICS

V.D. Toneev

The quest for the deconfinement transition, the phase transition from a confined hadronic phase to a deconfined quark–gluon phase, remains a major challenge in strong interaction physics. Enhanced production of strangeness relative to that from proton–proton and proton–nucleus collisions was one of the conjecture signals of the quark–gluon plasma formation in heavy ion collisions. In Ref. [1], global effects of strangeness production in hot and dense nuclear matter within a collective thermodynamic approach were explored. Thermodynamical properties of excited systems were analyzed with various phenomenological models for the equation of state (EoS), which differ by the order of the deconfinement phase transition: the first order transition (the two–phase bag model), a crossover–type transition (the statistical mixed–phase model) and no phase transition (pure hadronic models). The consequences of strangeness separation (strangeness distillation effect) and softening of the (EoS) were discussed. We expect that these peculiarities of the deconfinement phase transition may manifest themselves in observables through expansion dynamics [1].

As an illustration, Fig. 1 shows the influence of the EoS and the order of the phase transition on strangeness excitation function calculated in a longitudinally expanding fireball model [1]. Calculated curves are rather smooth. However, it is remarkable that an oversimplified statistical model of the early stage [4] predicted a peak-like structure in these excitation functions near the bombarding energy $E_{lab} \approx 30\ A \cdot \mathrm{GeV}$ as the onset of the first order deconfinement phase transition. As seen from the figure, low-energy SPS measurements at $E_{lab} = 80$ and $40\ A \cdot \mathrm{GeV}$ stimulated by this theoretical work exhibit some trend of growing yield of strange hadrons with the energy decrease. Recent preliminary measurements at $E_{lab} = 30$ and $20\ A \cdot \mathrm{GeV}$ gave $\langle K^+ \rangle / \langle \pi^+ \rangle = 0.215 \pm 0.009$

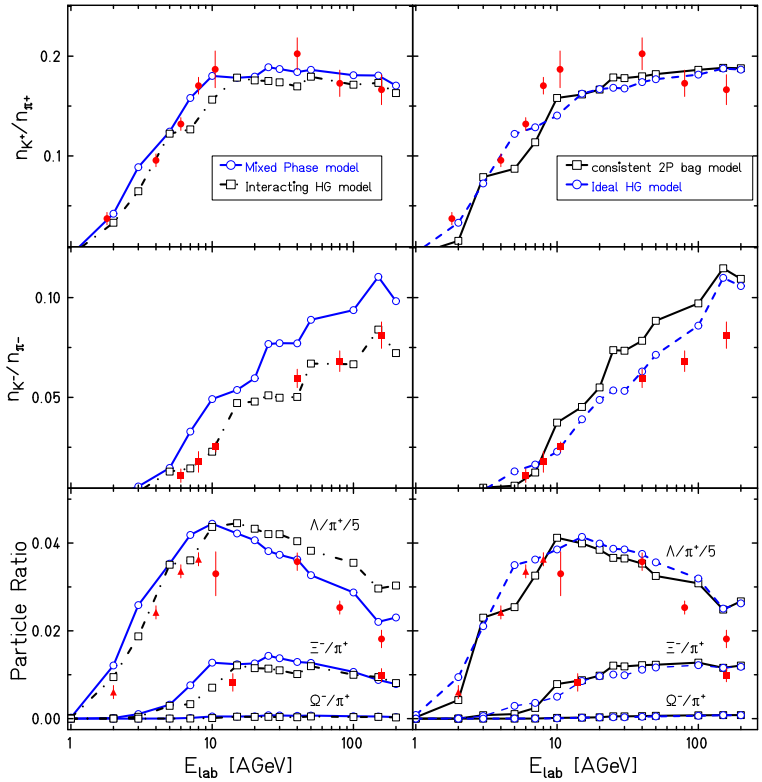

Figure 1: The ratios of 4π–integrated strange particle yields per pion yields for central Au–Au collision as a function of beam–energy. The compilation of experimental data is taken from [2,3]. The calculated excitation functions are given for different EoS with the canonical suppression factor.

and 0.207 ± 0.008, respectively [5], i.e., a peaked maximum was really observed at the expected bombarding energy.

Physical scenario of our model follows quite closely that of [4], but it was elaborated in more details. In particular, strangeness formed at the initial stage may be changed in subsequent hydrodynamic evolution of the system. As is seen from Fig. 1, the behavior of the strangeness excitation functions is rather smooth and does not reproduce the recent results of the NA49 Collaboration on anomalous enhancement [5] mentioned above. But the most striking result is that bulk properties of strangeness production in A–A collisions depend only weakly on the particular form of the EoS: hydrodynamics with the assumption of a shock–like particles freeze–out in heavy-ion collisions practically washes out particularities of the EoS used.

In this respect, a new scenario based on the strangeness distillation idea was proposed [6], where this anomalous strangeness enhancement is considered as a sign of passing the evolving system near the critical end-point rather than a latent heat jump emerging from the onset of the first order deconfinement phase transition. As was shown by lattice QCD, on the phase diagram there exists a critical end-point, where the crossover proceeds to the first order phase transition. If at the freeze-out there is no chemical equilibrium between different components of the mixed phase, then the strangeness distillation effect at the critical end-point may result in such a peaked behavior in strangeness excitation

functions [6]. This effect should be the most sizeable for the $\langle K^+\rangle/\langle\pi^+\rangle$ ratio. It is of interest that dynamical trajectories on the phase diagram pass near the critical end-point just for $E_{lab} \approx 30\ A \cdot \mathrm{GeV}$.

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PARITY VIOLATION IN DEUTERON PHOTO-DISINTEGRATION

M. Fujiwara[1], A.I. Titov

[1]Japan Atomic Energy Research Institute, Tokai, Ibaraki, Japan

For more than forty years the parity non-conservation (PNC) in nuclear processes has attracted attention as a unique tool for studying the strangeness conserving ($\Delta S = 0$) weak nucleon-nucleon interaction defined by a nontrivial interplay of the weak quark-quark interaction and the QCD-dynamics of composite hadrons at short distances. Most of the present theoretical studies of parity nonconservation in nuclear processes are based on the finite-range π-, ω-, and ρ-meson exchange potential of Desplanques, Donoghue, and Holstein (DDH) [1]. Using the symmetry consideration and the constituent quark model, DDH found the "reasonable range" and the "best values" of the PNC meson-nucleon coupling constants.

Analysis of the available data from nuclear PNC-experiments suggests that the isoscalar PNC nuclear forces dominated by the ρ- and ω-meson exchange are comparable with the DDH "best values", whereas the isovector interaction dominated by the π-meson exchange is weak by a factor of 3. For example, the measurement of the circular polarization of the photons emitted from ^{18}F results in the constraint of $0 \leq h_\pi \leq 1.8\,(\times 10^{-7})$ [2], where h_π is the pion PNC-coupling constant. This constraint is in disagreement with the recent analysis of the ^{133}Cs anapole moment [3], where for adequate description of the data on the anapole moment, one needs to use h_π which is a factor of about 2 greater than the DDH "best value" $h_\pi^{\mathrm{best}} \simeq 4.6 \cdot 10^{-7}$. These experiments call for the new measurements and theoretical studies to resolve subsisting inconsistencies.

With the advent of the high-intensity polarized photon beams, investigation of PNC-effects in the $\gamma D \to np$ reaction becomes very important. In fact, the study of the PNC-asymmetries as a function of the photon energy (contrary to the radiative np-capture,

where the photon energy is fixed: $E_\gamma \simeq 2.23$ MeV) allows us to obtain additional information which might reduce the ambiguity induced by uncertainties of the nuclear matrix elements and the parity-conserving NN-forces at short distances.

In our paper [4], we discussed two PNC-asymmetries. One is the asymmetry A_{RL} in deuteron disintegration in the reaction between the circularly polarized photon and an unpolarized deuteron. The second one is the deuteron spin asymmetry A_D in the reaction between an unpolarized photon and a polarized deuteron (polarized along-opposite to the beam direction). It depends on the isovector PNC-interaction and, therefore, may be used for examining h_π.

The results of our calculation of the asymmetry A_{RL} as a function of ΔE_γ is shown in Fig. 1 on the left panel. We show the result for the two potentials ("Paris" and "Hamada-Johnston" (HJ)). For illustration, we also show the prediction of Ref. [5] for the modified zero range approximation model. One can see that the behaviour of the asymmetry A_{RL} is similar qualitatively to quite different models. The coherent interference of the $\Delta I = 0, 2$, $\Delta S = 1$ transition terms leads to a sharp decrease of A_{RL} down to zero at $\Delta E_\gamma \simeq 1.3$ MeV (in case of the Paris potential) and changes a sign from positive to negative. The destructive interference of the $\Delta I = 1$, $\Delta S = 0$-transitions reduces considerably the contribution of the pion-exchange amplitude which brings problems with determination of h_π.

Fig. 1 (right panel) shows the A_D-asymmetry as a function of ΔE_γ for two potentials. The main differences between A_D and A_{RL} are in quite a different interference in both $\Delta I = 0$, $\Delta S = 1$ and $\Delta I = 1$, $\Delta S = 0$-transitions, which changes the shape of asymmetry and allows one to determine PNC π-meson exchange coupling constant at higher energies.

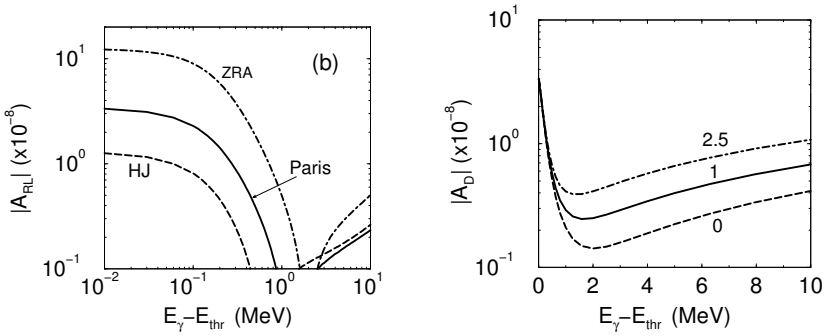

Figure 1: Asymmetries A_{RL} and A_D of the deuteron disintegration in the reaction $\gamma D \to pn$ with circular polarized photon and unpolarized deuteron as a function of the energy excess $E_\gamma - E_{\rm thr}$ at the left and right panels, respectively.

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FINAL-STATE INTERACTION CONTRIBUTION TO THE DEUTERON PHOTODISINTEGRATION IN THE BETHE-SALPETER FORMALISM

S.G. Bondarenko, V.V. Burov, K.Yu. Kazakov[1], D.V. Shulga[1]

[1]LTNP, Far Eastern National University, Vladivostok, Russia

The contribution of the final-state interaction to the differential cross-section of deuteron photodisintegration at laboratory photon energies below 50 MeV was analyzed in the framework of the Bethe–Salpeter formalism with a phenomenological rank-one separable interaction [1]. The approximations made are the neglect of two-body exchange currents, negative-energy components of the bound-state vertex function and the scattering T matrix. It was found that the gross effect of the final-state interaction with $J \leq 1$ comes from the net negative contribution of the spin-triplet final states and spin-singlet ${}^1S_0^+$-state. The relativistic results were compared with the nonrelativistic ones in every partial-wave channel. It was found that the relativistic effects slightly increase the magnitude of the final-state interaction (Fig. 1).

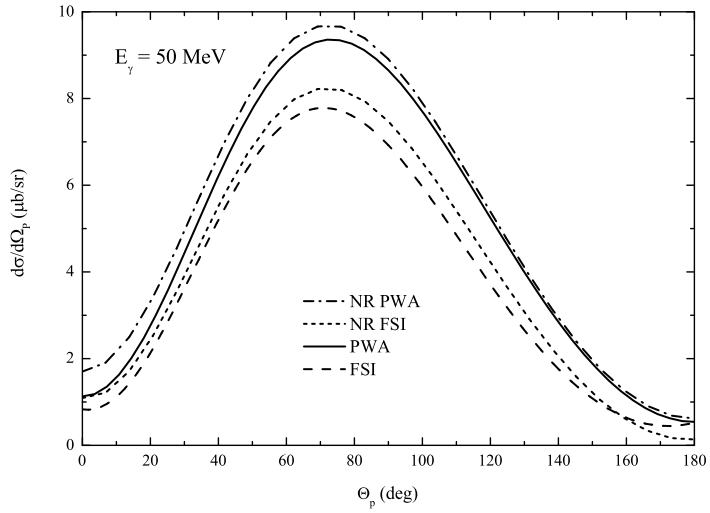

Figure 1: C.m. differential cross section at lab. photon energy $E_\gamma = 50$ MeV. The relativistic calculations (PWA - plane wave approximation, FSI - final state interaction is included) in comparison with nonrelativistic ones (NR PWA, NR FSI).

The extended Siegert theorem was applied to construct the conserved EM current of the nuclear system with the presence of two-body currents in addition to the one-body current.

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FINAL STATE INTERACTION EFFECTS IN REACTIONS OF LEPTON AND PROTON SCATTERING FROM LIGHT NUCLEI

L.P. Kaptari

The exclusive processes ^{2}H$(e,e'p)n$, ^{3}He$(e,e'p)^2$H and ^{3}He$(e,e'p)(pn)$ were analyzed by using realistic few-body wave functions and treating the final state interaction (FSI) within a Generalized Eikonal Approximation (GEA), based upon the direct calculation of the Feynman diagrams describing the rescattering of the struck nucleon with the nucleons of the $A-1$ system. The approach allows one to take into account the effects of the nuclear excitation of the $A-1$ system on the rescattering of the struck nucleon. Using realistic three-body wave functions corresponding to the $AV18$ interaction, the results of our calculations were compared with available experimental data. It was found that at some kinematic conditions FSI effects were small corrections, whereas under other kinematics conditions they were very large and absolutely necessary to provide a satisfactory agreement between theoretical calculations and experimental data [1].

The effects of the final state interaction in semi-exclusive deep-inelastic scattering of electrons off the deuteron were analyzed in [2,3] paying particular attention to the two extreme kinematic regions: i) the one where FSI effects are minimized, so that the quark distribution of bound nucleons could be investigated; ii) the one where the re-interaction of the produced hadrons with the spectator nucleon is maximized, which would allow one to study the mechanism of hadronization of highly virtual quarks. The analysis was based upon the hadronization model in which the formation of the final hadron occurred after the space-time propagation of the created nucleon debris with a sequence of soft and hard production processes. These latter processes, which generally cannot be treated within perturbative QCD, were described by a model approach, where both the color string model and the gluon perturbative bremsstrahlung mechanism were taken into account. The results of our calculations show that when the recoiling spectator nucleon is detected in the backward hemisphere with low momentum, the effects of the FSI are negligible, whereas at large transverse momenta of the spectator FSI effects are rather large and appreciably depend upon the hadronization mechanism. Preliminary results of calculations within our model show encouraging good agreement with recent preliminary data from Jlab.

Within an effective meson-nucleon theory, the Okubo-Zweig-Iisuka rule was analyzed in processes of vector meson production in near-threshold elementary nucleon-nucleon collisions $pp \to ppV$, $pn \to pnV$ and $pn \to dV$ ($V = \omega, \phi$). It was shown that a set of effective parameters could be established to explain fairly well the available experimental data on angular distributions and the energy dependence of the total cross sections without explicit implementation of the Okubo-Zweig-Iisuka rule violation. Isospin effects were considered in detail and compared with experimental data whenever available [4,5,6].

We developed an advanced method of solving homogeneous and inhomogeneous Bethe-Salpeter (BS) equations by using the expansion over the complete set of 4-dimensional spherical harmonics. We solved the Bethe-Salpeter equations for bound and scattering states of scalar and spinor particles for the case of one meson exchange kernels. Phase shifts calculated for the scalar model are in agreement with the previously published results. Possible manifestations of separability for one meson exchange interaction kernels were discussed. The obtained solution of the BS equation in the continuum is an important ingredient in covariant computations of FSI effects in reactions of deuteron electro-

disintegration (JLAB, SACLAY, NIKHEF ...) and break-up (COSY, Dubna...) at high energies and high momentum transfers [7].

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INFRARED ELECTRON MODES IN LIGHT DEFORMED ATOMIC CLUSTER: APPLICATION OF TWO-PHOTON PROCESSES

V.O. Nesterenko, P.-G. Reinhard[1]

[1]Institut für Theoretische Physik, Universität Erlangen, Erlangen, Germany

Single-electron spectra of light atomic clusters are sensitive to diverse cluster features (ionic structure, shape isomers, temperature effects, etc.) and so can deliver important information about these features. Besides, the electron spectra serve as a robust test for the theory. For these reasons, investigation of single-electron spectra is now an increasingly important part of cluster physics (see, e.g., [1]).

Photo-electron data, a single experimental source, give information only about occupied (hole) levels [1]. To cover the particle levels as well, we proposed to study electron infrared quadrupole modes (IRQM) in light deformed clusters by means of two-photon processes [2]. In light clusters with a low spectral density, IRQM are unambiguously related to specific electron-hole excitations, thus giving access to the single-electron spectra near the Fermi surface. Most of IRQM's are determined by cluster deformation and so can serve as a sensitive probe of the deformation effects in the mean field. In our study in terms of the time-dependent local-density approximation [3], we described the origin and main features of IRQM's in sodium clusters. Besides, the connection of some IRQM's with the scissors M1 mode [4] was demonstrated.

The familiar two-photon processes like Raman scattering stimulated emission pumping and stimulated adiabatic Raman passage (STIRAP), are widely used in atomic and molecular spectroscopy to populate nondipole modes and it would be very promising to use these techniques for investigation of IRQM in atomic clusters. At a glance, some cluster properties (broad level structures, short lifetimes, nonradiative decay channels, ...) make questionable a straightforward implementation of two-photon methods. However, we showed that these methods could be applied to clusters and provide valuable information on cluster spectra [2]. The two-photon process is assumed as a sequence of two E1

transitions (absorption and emission) running through the intermediate dipole state, e.g. the dipole plasmon. A short life-time of the plasmon is not the obstacle for such processes as STIRAP, since in this case the intermediate state is not populated. A proper duration of laser pulses and ratio between Rabi and interlevel frequencies are crucial to fulfill the effective adiabatic coherent transfer.

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SPONTANEOUS SYMMETRY BREAKING EFFECTS IN FINITE FERMI SYSTEMS

R.G. Nazmitdinov

A convenient starting point to treat Fermi systems is, in many cases, a mean field description like the Hartree-Fock (HF) or Hartree-Fock-Bogoliubov (HFB) approach. The self-consistency between the mean field and the single-particle orbitals and total energy minimization are the basic conditions at this level. It may happen that the self-consistent solution breaks one of the symmetries of the exact Hamiltonian, a well-known phenomenon called *spontaneous symmetry breaking*. Obviously, for finite systems quantum fluctuations, beyond the mean field approach, are quite important. The random phase approximation (RPA) being an efficient tool to study these quantum fluctuations (vibrational and rotational excitations) provides also a consistent way to restore broken symmetries. Moreover, it separates collective excitations associated with each broken symmetry as a spurious RPA mode and fixes the corresponding inertial parameter.

Recent progress in nanostructure technology allows us to thoroughly investigate a quantum motion of confined electrons in semiconductors. Small quantum dots (QDs) provided us with a good scenario to assess the above properties of RPA by numerical and analytical calculations, since the interaction between electrons was known and the confinement potential was well approximated by the harmonic oscillator. For large enough values of the interaction-confinement ratio R_W the HF mean field breaks circular symmetry for two-dimensional QDs; the electrons being localized in specific geometric distributions. Quite important, RPA provides a physical interpretation of this broken-symmetry phenomenon: mean-field solutions lacking one symmetry of the Hamiltonian represent, according to RPA, true *internal* deformations of the system having an associated collective motion at vanishing energy (the spurious RPA mode). For considered cases we obtained the spurious RPA mode related to the global rotation, with its associated moment of inertia (see Refs. [1,2]). The corresponding rotational spectra may be associated with the rotation of a Wigner molecule. A systematics with R_W for the 2-electron dot was presented, while for 6- and 12-electron dots the calculations were performed with the R_W value suggested by experiments.

Applying similar ideas to rapidly rotating nuclei we found that in ^{156}Dy and ^{158}Er the backbending occurs when the positive signature *gamma*-vibrational excitations vanish in the rotating frame (the appearance of the nuclear Goldstone boson in the system) [3]. As a result, a nuclear mean field spontaneously breaks the axial symmetry and gives rise to the true non-axially deformed shape in the rotating (intrinsic) frame. We discovered that this transition leads to a strong enchantment of the scissor-like M1 excitations which should be seen experimentally [4].

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TOPICS ON THE CHERENKOV RADIATION

G.N. Afanasiev

The so-called Tamm problem plays the fundamental role in studying the Vavilov-Cherenkov radiation. In it, a charge being initially at rest at some spatial point of the medium, accelerates instantaneously up to reaching the velocity v with which it moves in a finite space interval. Then it decelerates instantaneously down to reaching the permanent state of rest. Tamm found the approximate analytic solution of this problem. The angular radiation intensity found by him had a very narrow peak at the Cherenkov angle θ_c. We succeeded in solving the problem both exactly (numerically) and approximately (analytically) [1,2]. Both these radiation intensities agree perfectly with each other and disagree sharply with the radiation intensity found by Tamm. The radiation intensities found by us had a plateau with sharp maxima at the ends of this plateau. We associated the plateau and the intensity bursts at its ends with the two kinds of shock waves: the ones originating at the start and end of the charge motion and the Cherenkov shock wave associated with its overcoming the medium light velocity barrier. These considerations were applied to experiments performed by Zrelov more than 40 years ago.

There was an intensive discussion in the physical literature whether the Cherenkov radiation is due to the interference of the shock waves arising at the start and end of the charge motion. To answer this question we considered an absolutely continuous motion of the charge in a finite space interval [3]. Despite the absence of the velocity and acceleration discontinuities, there was a pronounced maximum at the Cherenkov angle. The radiation intensity dropped very sharply for angles greater than θ_c and decreased rather smoothly for $\theta < \theta_c$. This behaviour of the radiation intensity was associated with the existence of the shock waves arising from the charge passing the light velocity barrier.

Transition radiation arises when a charge intersects a boundary between two media. For the plane boundary, approximate solutions were given by Frank and Ginzburg. We succeeded in finding the exact solution for the spherical boundary [4]. It shows that the usual belief that the charge passage through the dielectric layer can be described in terms of the Tamm problem is not always valid.

The existence of the two-photon Cherenkov radiation was predicted by Tamm and Frank. A thorough analysis of the kinematic relations for this process performed in [5] points out the existence of angles at which the radiation intensity is maximal. This may be useful for the setup of experiments searching for the two-photon Cherenkov effect.
These topics on the Cherenkov radiation and related scientific fields were summarized in [6].

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