Contents

MASS TENSOR IN THE COLLECTIVE NUCLEAR HAMILTONIAN

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The Bohr Hamiltonian being applied to description of collective nuclear properties has usually a very simple form of the kinetic energy term which is determined by one constant mass coefficient for all three modes of excitation: rotation, β– and γ– vibrations. However, we found earlier that the assumption of a common mass coefficient for three bands contradicted, in the case of the well-deformed nuclei, the experimental data on energies and E2 transition probabilities. In [1], it was shown that significantly different mass coefficients for rotational and γ–vibrational motion are needed to explain experimental data on Grodzins products for the ground and the γ–bands. It was shown also in [2] that in order to resolve this contradiction it is necessary to consider the Bohr Hamiltonian not with a constant mass coefficient but with a mass tensor having also nonzero components with angular momentum L=2 and 4. In this case, in the limit of the well-deformed axially symmetric nucleus we obtain different mass coefficients for rotation (B_{rot}), γ–vibrations (B_γ) and β–vibrations (B_β).

There is also a contradiction between the phenomenological and the microscopic models which cannot be resolved if a unique constant mass coefficient is used in the Bohr Hamiltonian. In the phenomenological collective quadrupole model all dynamic variables, namely, the Euler angles and the β– and γ– shape variables are considered by definition as collective ones, i.e., describing a motion of many nucleons. At the same time, in RPA calculations performed for the well-deformed axially symmetric nuclei, a small number of components exhausts the structure of the γ– phonon . As a measure for the collectivity of the quadrupole state we consider the value of the corresponding E2 transition probability from the ground state to the vibrational state. In the case of the Bohr Hamiltonian with a constant mass coefficient, the rotational and vibrational degrees of freedom are not completely decoupled because the Grodzins products for different rotational bands are expressed in terms of the same mass coefficient. If, by varying some parameters of the Hamiltonian, we decrease the E2 transition probability for a transition from the ground state to the β– or γ– vibrational state, i.e., decrease the collectivity of the vibrational state in agreement with the RPA results, we automatically increase the energy of the vibrational state because the product of the energy and the corresponding B(E2) is inversely proportional to the mass coefficient B. However, if we do not want to change the result for the ground state band, we should keep B fixed. For instance, the moment of inertia is proportional to B.

At the same time in the RPA calculations performed for the well-deformed axially symmetric nuclei the description of the vibrational modes is completely decoupled from the description of the rotational motion, and the energies of the 2^+_γ and of the 0^+_β states cannot be higher than the energies of the lowest two-quasiparticle states with the corresponding value of K. Moreover, when the energy of the β– or γ– phonon is close to the two–quasiparticle energy a small change in the phonon energy produces a tremendous change in the B(E2) value.

We showed in [3] that this contradiction can be resolved if the Hamiltonian describing the collective quadrupole motion in even–even well-deformed nuclei has three different mass coefficients for the three excitation modes. In the case when B_β and B_γ are much

larger than B_{rot}, which is the case for the rare earth nuclei, we showed that the eigen solutions of the Schrödinger equation contained three different bands with fixed excitation energies and very weak E2 transitions between the bands. This was achieved by transforming Hamiltonian to new collective variables which differ from the previous ones by scaling factors. This property enabling one to vary B(E2) via B_β and B_γ gives also an intuitive feeling for the mass parameters. At this point, it becomes obvious that using only one mass coefficient is a significant approximation which is not realized in the experiment. It shows also that the Bohr Hamiltonian with three different mass coefficients applied to the well-deformed axially symmetric nuclei can describe a situation where β- and γ- bands are connected to the ground band by very weak E2 transitions but where, at the same time, the excitation energies are smaller than the pairing gap while E2 transitions inside the bands are strong.

The Bohr Hamiltonian with three different mass coefficients for different excitation modes was applied in [4] to describe the excitation spectra and the intra– and interband E2 transitions in the well-deformed nuclei. A good description of the properties was obtained. It was shown that without an introduction of the different mass coefficients for β- and γ- vibrational and rotational modes it was impossible to describe correctly the absolute values of the E2 reduced transition probabilities between the states of the β- and γ- vibrational bands and the states of the ground band.

The analysis of the mass tensor has been extended to the spherical and transitional nuclei. We showed basing on the experimental data that the mass tensor in the Bohr collective quadrupole Hamiltonian given in the laboratory frame and written in terms of Bohr's collective variables $\alpha_{2\mu}$ could not be reduced to one constant mass coefficient. The mass tensor contains not only scalar but also quadrupole and hexadecapole components and, therefore, is a function of the collective coordinates.

We have shown that the matrix elements of the mass tensor can be expressed as the nondiagonal energy weighted sum rules. We have suggested also the simplest form of the mass tensor which satisfies these relations. The parameters of this mass tensor are determined completely for many nuclei by the existing experimental data. The values of these parameters derived from the experimental data for the well-deformed axially symmetric nuclei are quite close to each other indicating the possibility to use an approximately universal mass tensor for the description of the well-deformed nuclei. There are not enough data to make a similar conclusion about a mass tensor for the spherical and the γ–unstable nuclei.

We have derived the expressions for the mass coefficients B_{rot}, B_γ and B_β for the Bohr Hamiltonian written in the intrinsic frame in terms of the excitation energies and the B(E2)'s for the low–lying collective states.

The relations derived show that the quadrupole and the hexadecapole components of the mass tensor can decrease the strength of the E2 transitions between the ground and the excited collective bands if they approach sufficiently large absolute values. This result is a generalization of the result obtained in [2] for the well-deformed nuclei.

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EFFECTS OF THE PARTICLE-PARTICLE CHANNEL ON PROPERTIES OF LOW-LYING VIBRATIONAL STATES

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Making use of the finite rank separable approach [1, 2] to the quasiparticle random phase approximation enables one to perform nuclear structure calculations in very large two-quasiparticle spaces. The approach is extended to take into account the residual particle-particle interaction [3]. The calculations are performed by using the Skyrme interaction in the particle-hole channel and the surface peaked density-dependent zero-range force in the particle-particle (p-p) channel. To illustrate our approach, we study the properties of the lowest quadrupole states in the even-even nuclei ^{128}Pd, ^{130}Cd, $^{124-134}$Sn, $^{128-136}$Te and ^{136}Xe. As one can see from Fig. 1, there is a decrease of the 2^+_1 energies due to the inclusion of the quadrupole p-p interaction. At the same time, the $B(E2)$-values do not change practically. It means that the collectivity of the 2^+_1 states is reduced. Using the same set of parameters we describe available experimental data and give predictions for the $N = 82$ isotones that are important for stellar nucleosynthesis.

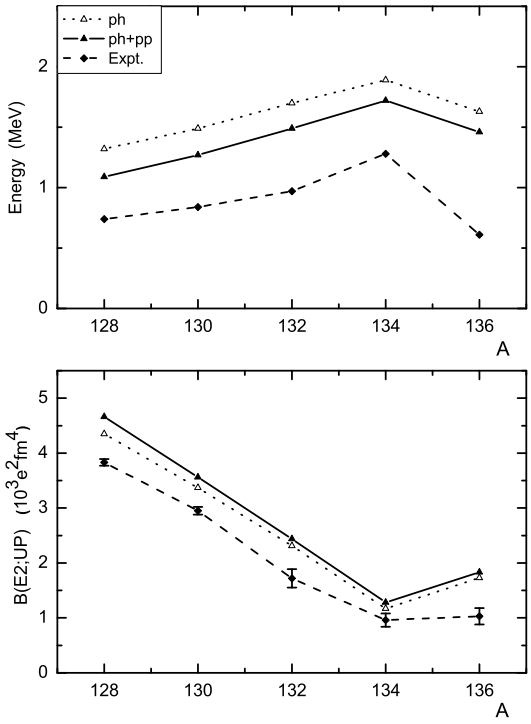

Figure 1: Energies and B(E2)-values for up-transitions to the first 2^+ states in $^{128-136}$Te.

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GRAND UNIFICATION, NEUTRINO MASSES AND NUCLEAR STRUCTURE

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After the nonzero mass of the neutrino has been recently confirmed by neutrino oscillation experiments the physics community worldwide is embarking on the next challenging problem, finding whether neutrinos are indeed Majorana particles (i.e., identical to its own antiparticle) as many particle models suggest or Dirac particles (i.e., is different from its antiparticle).

The total lepton number violating (LNV) neutrinoless double beta decay ($0\nu\beta\beta$-decay) is the most powerful tool to clarify if the neutrino is a Dirac or a Majorana particle. The $0\nu\beta\beta$-decay can occur through different processes but all of them require that the neutrino has nonzero mass and is a Majorana particle. The most proximate or discussed theoretical model is to mediate the $0\nu\beta\beta$-decay by the exchange of a light Majorana neutrinos. Experimental searches for the $0\nu\beta\beta$ decay, of ever increasing sensitivity, are being pursued worldwide. The observation of $0\nu\beta\beta$-decay will allow also to reveal the type of the neutrino mass spectrum, to determine the mass of the lightest neutrino and, possibly, Majorana CP phases. Interpreting existing $0\nu\beta\beta$ results as a measurement of the neutrino effective mass, and planning new experiments, depends crucially on the knowledge of the corresponding nuclear matrix elements (NMEs) that govern the decay rate.

The nuclear matrix elements for $0\nu\beta\beta$ decay must be evaluated using tools of nuclear structure theory. There are no observables that could be directly linked to the magnitude of $0\nu\beta\beta$ nuclear matrix elements. In Ref.[1], we performed a detailed anatomy of the $0\nu\beta\beta$-decay NMEs. We have showed that, within the quasiparticle random phase approximation (QRPA) and the renormalized QRPA (RQRPA) based on the Bonn-CD nucleon-nucleon interaction, the competition between the pairing and the neutron-proton particle-particle and particle-hole interactions causes contributions to the $0\nu\beta\beta$-decay matrix element to nearly vanish at internucleon distances of more than 2 or 3 fermis. As a result, the matrix element is more sensitive to short-range/high-momentum physics than one naively expects. We analyzed various ways of treating that physics and quantify the uncertainty it produces in the matrix elements, with three different treatments of short-range correlations.

In [2] it was shown that, within a given set of nuclei, the correlations among the $0\nu\beta\beta$-decay NME errors are as important as their size. This paper is the first attempt to quantify the covariance matrix of the NME, and to understand its effects in the comparison of current and prospective $0\nu\beta\beta$-decay results for two or more nuclei. The variances and covariances associated to the NMEs of the $0\nu\beta\beta$-decay have been estimated within the QRPA. It was found that breaking correlations between different nuclei is an important goal, which requires constraining (and improving) the theoretical model of each nucleus by means of many independent data. A covariance analysis like the one proposed in [2] may represent a useful tool, in order to correctly estimate current or prospective sensitivities to $0\nu\beta\beta$-decay decay and to Majorana neutrino parameters.

It was recognized that the GUT's and R-parity violating SUSY models offer a plethora of the $0\nu\beta\beta$-decay mechanisms triggered by exchange of neutrinos, neutralinos, gluinos, leptoquarks etc. In Ref.[3], we analyzed the $0\nu\beta\beta$-decay of several nuclei induced by

the LNV effective operators originating from the R-parity breaking SUSY trilinear interactions involving squark and neutrino exchange. We focused on the hadronization prescription of the quark-level operators and analyzed both the conventional two-nucleon mode and the pion-mode of hadronization. We have shown that the pion-mode absolutely dominates over the two-nucleon mode. Previously, we demonstrated that the pion-mode dominates over the two-nucleon mode in the case of the short-range R-parity breaking SUSY mechanism. Thus, with the result of the present paper we conclude that all the mechanisms based on the trilinear R-parity violating SUSY interactions dominantly contribute to $0\nu\beta\beta$-decay via the pion-mode of hadronization.

A new possibility for study of lepton number non-conservation has been proposed in [4], namely oscillations plus deexcitations of neutral atoms. This phenomenon is a consequence of a mixing of two neutral atoms, which lepton numbers differ by two units, due to lepton number violating weak interactions. One of the neutral atoms is stable, the other one represents a quasistationary state subjected to electromagnetic deexcitation. The system of neutral atoms exhibits oscillations similar to the system of neutral kaons and neutron-antineutron oscillations in the nuclear medium. A phenomenological analysis of this process lead to a resonant enhancement of the neutrinoless double electron capture, that has a Breit-Wigner form. It was manifested that it is reasonable to hope that a search for oscillation plus deexcitation of atoms, which are sufficiently long lived to conduct a practical experiment, may uncover processes with lepton number violation. For that purpose systems of two atoms with the smallest mass difference have to be found.

We presented the relativistic calculation of the β-decay of tritium in a hadron model [5]. The elementary particle treatment (EPT) of the transition $^3H \rightarrow {}^3He + e^- + e^-$ was performed in analogy with the description of the β-decay of neutron. The effects of higher order terms of hadron current and nuclear recoil were taken into account in this formalism. The relativistic Kurie function was derived and presented in a simple form suitable for the determination of neutrino masses from the shape of the endpoint spectrum. A connection with the commonly used Kurie function was established.

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GAMOW-TELLER TRANSITIONS IN HOT NUCLEI AND ASTROPHYSICAL APPLICATIONS

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There are many interesting problems in astrophysics which require e^--capture and β^--decay rates as input parameters. These rates are used in numerical simulations of the gravitational collapse of the core of a massive star, a supernova explosion, the formation of heavy elements above iron, etc [1]. In a hot and dense stellar medium these reactions are dominated by the Gamow-Teller (GT) transitions and, therefore, the determination of their rates requires to reproduce the GT strength distributions.

Since the stellar medium can reach temperatures larger than a few hundred keV, nuclear excited states are thermally populated in accordance with the Boltzmann distribution. Consequently, in order to calculate the decay and capture rates, it is necessary to know the GT strength distributions built on the ground as well as on excited states. We studied the GT transitions in hot nuclei within the approach based on two main ingredients, the thermo field dynamics [2] and the quasiparticle-phonon model [3].

The thermal pnQRPA equations describing the GT strength distribution at finite temperature in spherical nuclei were derived [4, 5]. It was found that thermal effects led to appearing of a new kind of the GT transitions which were absent at zero temperature. They are the transitions from thermally excited nuclear states. Moreover, it was proved that within the employed approach the Ikeda sum rule was valid at $T \neq 0$.

Figure 1 displays the GT_- and GT_+ strength distributions in ^{54}Fe at different temperatures. Since the ground state of ^{54}Fe is stable against β^--decay, at $T = 0$ the whole $\mathrm{GT}_\mp$ strength is at $E > 0$. With increasing temperature a small amount of the

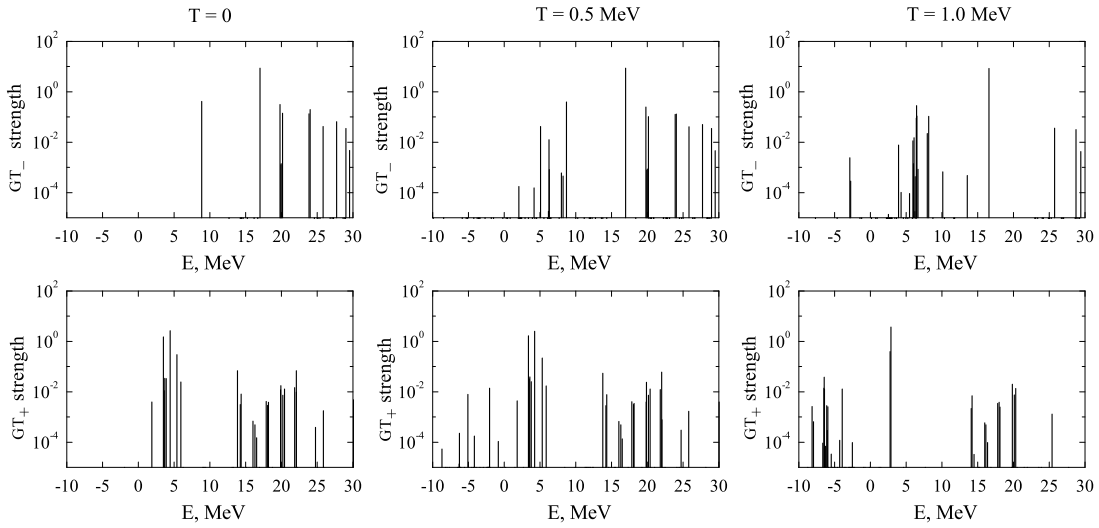

Figure 1: GT_- (upper part) and GT_+ (lower part) strength distributions for ^{54}Fe at different temperatures T. E – energy transferred to the parent nuclei.

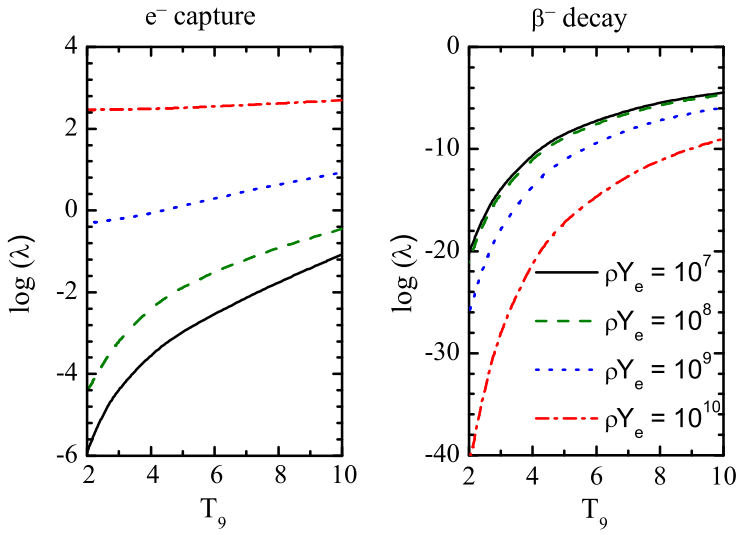

Figure 2: e^--capture and β^--decay rates for ^{54}Fe as a function of temperature for selected values of density ρY_e (in mol/cm^3). Temperature T_9 is in units of 10^9 K

GT$_\mp$ strength is shifted to negative energies. This part of the GT$_-$ (GT$_+$) strength corresponds to the $n \to p$ ($p \to m$) transitions from thermally excited states of ^{54}Fe to low-lying states of the daughter nucleus ^{54}Co (^{54}Mn) and is responsible for the β^-- (β^+-) decay of the hot ^{54}Fe.

The calculated GT$_\mp$ strength distributions were used to calculate the e^--capture and β^--decay rates for ^{54}Fe. The results are displayed in Fig. 2. The e^--capture rate increases with T and the density ρY_e of the degenerate electron gas surrounding the nuclei. The reason of this behavior is an increase in a number of electrons with energies close to or higher than the energy of the GT$_+$ resonance. Decrease of the GT$_+$ strength centroid when T increases also contributes to the increment of the e^--capture rate. The β^--decay rate is affected by T and ρY_e in opposite way. Growth of the density suppresses the β^--decay rate due to diminishing of phase space available for escaping electrons. At the same time, increase in T weakens the Pauli blocking and consequently enlarges a contribution of the GT$_-$ transitions from excited states of ^{54}Fe.

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DEVELOPMENT OF THE WFM METHOD AND THE NUCLEAR SCISSORS MODE

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Recent achievements in the development of the method of Wigner Function Moments (WFM) were reviewed in paper [1]. More complete analysis of the theory was produced in [2], where the detailed comparison of the WFM with the Random Phase Approximation (RPA) and the Green Function (GF) methods was performed to understand the place of the WFM among various methods describing the collective motion. This comparison was exemplified by the Harmonic Oscillator plus Quadrupole–Quadrupole (HO+QQ) force model. It turns out that the WFM and GF methods are very close to one another. Contrary to RPA, both work in phase space and incorporate semiclassical aspects, with no need to introduce a single particle basis. Finally, both the methods yield identical sets of dynamical equations for the moments. For the harmonic oscillator with multipole–multipole residual interaction of arbitrary rank (multipolarity) the equations of both the methods can be derived without any approximations – the interaction of the multipolarity n generates a set of dynamic equations for tensors (moments) of the rank n. However, in the case of realistic forces the GF method loses its simplicity, whereas the WFM method continues to be a convenient and powerful tool for description of collective motions, as it was demonstrated in [3] by employing Skyrme forces.

The exact relation between the RPA and WFM variables and the respective dynamic equations was found. The analytical equivalence between the WFM and RPA methods was established by introducing the dynamic equations for transition matrix elements. They can be derived either from the RPA equations for the amplitudes X_{ph}, Y_{ph} or from the WFM dynamic equations for the moments. This proves the identity of eigenvalues in both the methods under the condition that a complete basis is used in both the cases. However, both the methods behave differently when the dimension of the space is reduced. Actually, the WFM is designed to use only rather a few moments of low rank. The restricted number of eigenvalues approximates the collective states in an optimal way, representing their strengths and centroid positions, as this was shown in [3]. On the contrary, in the RPA one needs in general rather large space to correctly account for the collectivity of, e.g., giant resonances. At the same time, a certain fine structure of the resonances is also obtained. Both the methods are thus complementary. An interesting situation is observed for currents. In the RPA the current lines can even in the simple HO+QQ model be calculated only numerically (and only approximately because of the basis truncation) whereas by the WFM and GF methods they are found analytically.

All these investigations were performed without pair correlations. However, it is well known [4] that pairing is very important for a correct description of the scissors mode. A first attempt to include pairing into the WFM method was made in [5]. The equations of motion for angular momentum, quadrupole moment and other relevant collective variables were derived on the basis of the time dependent Hartree-Fock-Bogoliubov equations. Analytical expressions for energy centroids and transition probabilities were found for the HO+QQ model. Deformation dependence of energies and $B(M1)$ values of the scissors mode was correctly reproduced. The inclusion of pairing gave the drastic improvement

in the description of its qualitative and quantitative characteristics. However, a variation of the gap while a nucleus vibrates was neglected in [5], resulting in the violation of the continuity equation and in the appearance of instability in the isoscalar channel. This problem was solved in [6] by taking into account the exact relation between the pairing field and the abnormal density, which allowed one to reproduce the continuity equation without any approximations. Naturally, the aforementioned instability disappeared. The Gauss force was used to calculate the pairing field. The obtained results are demonstrated in the figure, where the calculated scissors mode energies E_{sc} and transition probabilities $B(M1)$ are compared with experimental data [7] for most of the nuclei where this mode is observed.

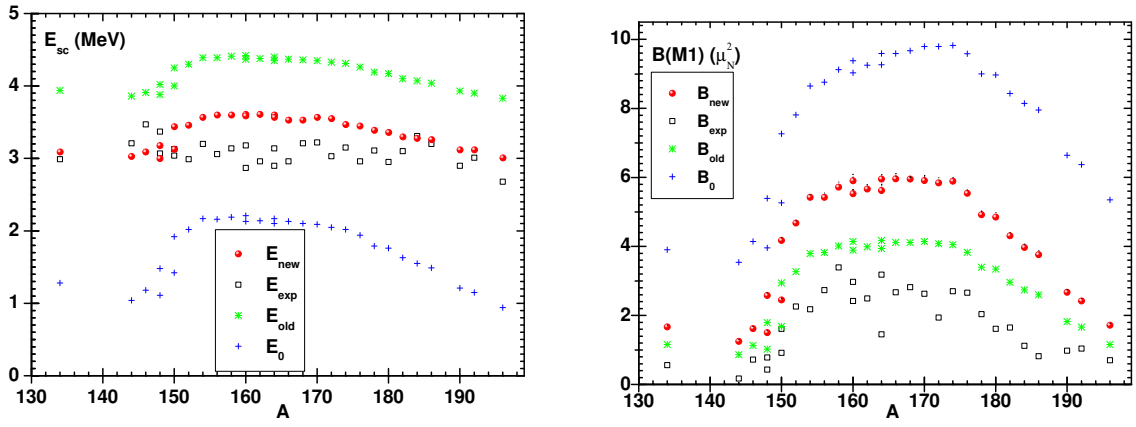

Figure 1: Energies and transition probabilities of the scissors mode as a function of atomic number. E_{new}, B_{new}: new theory [6], E_{old}, B_{old}: old theory [5], E_0, B_0: theory without pairing.

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SKYRME-RPA INVESTIGATION OF GIANT RESONANCES IN RARE-EARTH, ACTINIDE AND SUPERHEAVY NUCLEI

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Multipole giant resonances (GR) were investigated in the framework of the time-dependent density functional theory with Skyrme forces. As a relevant theoretical tool, the novel separable RPA (SRPA) method [1, 2] was used. The method is fully self-consistent and does not need additional parameters. It takes care of the full residual interaction including both time-even and time-odd coupling terms, Coulomb contribution and pairing particle-particle channel. Due to self-consistent factorization of the residual interaction, SRPA drastically reduces the computational effort while keeping accuracy of full RPA methods. This feature becomes crucial for systematic studies of collective dynamics in heavy nuclei, especially deformed ones.

The study covered spherical and axially deformed nuclei in rare-earth, actinide and superheavy regions. The isovector (T=1) E1, E2 and E3 and isoscalar (T=0) E0, E2 and E3 GR were explored. The main attention was paid to E1(T=1) GR. A representative set of Skyrme forces (SkT6, SkO, SkM*, SIII, SGII, SLy4, SLy6, SkI3) was used. We pursued the systematic exploration of GR properties with the aim to relate them with basic characteristics of nuclear matter (effective masses, incompressibility, etc) and implement further upgrade of Skyrme forces.

The effect of time-odd densities on GR properties was examined for a particular case of the current density $\vec{j}(\vec{r})$ [2-7]. Time-odd densities are known to restore Galilean invariance of the Skyrme functional, violated by the effective-mass and spin-orbital terms, and so represent an essential part of this functional. The current $\vec{j}(\vec{r})$ is one of the most important time-odd densities as it is related to the effective masses. SRPA calculations have shown that impact of $\vec{j}(\vec{r})$ on the GR is strong and fully determined by isoscalar and isovector parameters B_0 and B_1 of the Skyrme forces, responsible for the effective masses. In other words, the impact is fully determined by the Skyrme force and GR isospin. These results allowed to classify the Skyrme forces into 3 groups, depending on the magnitude and sign of B_1 [3]. The GR multipolarity, nuclear deformation, and neutron number of the isotope were found to be irrelevant for the impact. The later means that influence of $\vec{j}(\vec{r})$ on GR properties is similar for stable and exotic nuclei. It worth noting that such similarity takes place for many other effects of Skyrme forces. So it seems to be reasonable to explore these effects in stable nuclei (where there are experimental data) and then safely apply them to exotic areas.

As a next step, it was shown that inclusion of $\vec{j}(\vec{r})$ leads to much closer results of different Skyrme forces for the E0(T=0) GR and so for incompressibility of finite nuclei extracted from this GR [7]. Altogether, our systematic explorations for various GR have demonstrated that the current density $\vec{j}(\vec{r})$ is indeed important for description of electric GR with Skyrme forces. Further analysis of this fundamental density can be helpful for upgrade and unification of Skyrme forces.

The calculations with different Skyrme parametrizations have shown that SLy6 force is most appropriate for description of E1(T=1) GR. Hence this force was used for systematic exploration of E1(T=1) GR in heavy and superheavy deformed nuclei. Within SRPA, a wide sample of 18 rare-earth nuclei, 4 actinides and three chains of superheavy elements (Z=102, 114 and 120) was analyzed [8]. Very nice agreement with available photoabsorption experimental data (energies and widths) in the rare-earth and actinide regions was demonstrated. The E1(T=1) GR in superheavy nuclei was shown to be similar to its counterpart in stable nuclei. In both stable and superheavy nuclei, the main mechanisms of forming the resonance width were analyzed. The dominant contribution of the Landau fragmentation was established. The deformation splitting was shown to contribute about one third to the width, and about 1 MeV of further broadening was associated to mechanisms beyond the mean-field description (escape, coupling with complex configurations). The trend of the resonance peak energies was shown to follow mainly the estimates from collective models, with a bias to the volume mode for the rare-earths isotopes and a mix of volume and surface modes for actinides and superheavy elements.

Further, the low-energy E1 strength in ^{92,94,96,98,100}Mo was investigated at 4-12 MeV, i.e., near and below the particle thresholds [9]. Being rather weak, this strength is nevertheless of keen interest to tackle some problems of nucleosynthesis. In this connection, it is important to understand mechanisms of formation of this strength, in particular its dependence on deformation. We investigated this problem with Skyrme forces SkT6, SkM*, SLy6, and SkI3. It was found that influence of the deformation on the low-energy E1 strength strictly depends on a particular energy interval. While approaching the E1(T=1) GR, $E > 12$ MeV, one gets a definite increment of the strength with the deformation. However, at $E < 12$ MeV, i.e., at energy relevant for understanding of stellar photodisintegration rates, the influence of nuclear deformation on E1 strength is very weak and is mainly determined by the tail of E1(T=1) GR. The negligible deformation effect is naturally explained by mutual compensation of the contributions of the $\mu = 0$ and $\mu = 1$ GR branches.

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SYMMETRY BREAKING PHENOMENA IN ROTATING NUCLEI

R. G. Nazmitdinov

Symmetry breaking phenomena in finite systems elucidate the nature of correlations between particles localized in restricted space. The discovery and observation of such phenomena provide a basis for important fundamental issues, including the microscopic origin of quantum phase transitions and spontaneous symmetry breaking (SSB) in finite systems.

A convenient starting point to treat Fermion systems is, in many cases, a mean field description. 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 underlying many-body quantum Hamiltonian (the SSB effect). A natural question arises: does a broken mean field solution correspond to a real physical state ? Obviously, quantum fluctuations, beyond the mean field approach, are quite important for finite systems. The RPA being an efficient tool to study these quantum fluctuations (vibrational and rotational excitations) provides also a consistent way to treat broken symmetries. Moreover, it separates collective excitations associated with each broken symmetry as a spurious RPA mode and fixes the corresponding inertial parameter (cf. Ref.[1]).

Backbending is a paradigm of structural changes in a nucleus under rotation. It may be considered as a quantum phase transition as a function of nonthermal control parameter which is a rotational frequency. There is a general persuasion that this phenomenon is a result of the rotational alignment of angular momenta of a nucleon pair occupying a high-j intruder orbital near the Fermi surface. Recently, we have found that in ^{156}Dy the backbending can be explained as a result of disappearance of gamma-vibrational excitations in the rotating frame [2]. As a result, the nuclear mean field spontaneously breaks the axial symmetry and gives rise to nonaxially deformed shape in the rotating frame.

A transparent physical idea that instability of a nuclear potential with respect to a given deformation implies a softening of the corresponding vibrational mode enables us to shed light on these results. Let us consider an axially deformed system defined by the Hamiltonian $\tilde{H}$ in the laboratory frame, which rotates about a symmetry axis z with a rotational frequency Ω. The angular momentum is a good quantum number and, consequently, $[\hat{J}_z, O^\dagger_K] = KO^\dagger_K$. Here, the phonon $O^\dagger_K$ describes the vibrational state with K being the value of the angular momentum carried by the phonons $O^\dagger_K$ along the symmetry z axis. Thus, one obtains

$$[H_\Omega, O^\dagger_K] = [\tilde{H} - \Omega\hat{J}_z, O^\dagger_K] = (\tilde{\omega}_K - K\Omega)O^\dagger_K \equiv \omega_K O^\dagger_K, \quad (1)$$

where $\tilde{\omega}_K$ is the phonon energy of the mode K in the laboratory frame at $\Omega = 0$. This equation implies that at the rotational frequency $\Omega_{cr} = \tilde{\omega}_K/K$ one of the RPA frequencies ω_K vanishes in the rotating frame. At this point of bifurcation, we could expect the SSB effect of the rotating mean field due to the appearance of the Goldstone boson related to the multipole-multipole forces with quantum number K. For an axial quadrupole-deformed system, one obtains the breaking of the axial symmetry, since the lowest critical frequency corresponds to γ-vibrations with $K = 2$ [3].

We established the connection between the backbending and the quantum shape-phase transition of the *first order* in ^{156}Dy caused by the instability of γ- vibrations in the

rotating frame. We extended the classical Landau theory for the description of continuos shape-phase transitions that occur at the backbending. Applying this theory to the description of the backbending in ^{162}Yb, caused by the alignment of the two-quasiparticle configuration, we have found that the shape-phase transitions carry all features of the *second order* phase transition [2].

We recall that the quest for manifestations of nonaxial deformation is one of the driving forces in high spin physics nowadays. The analysis of low-lying excited states near the yrast line could shed light on existence of the nonaxiality. For nonaxial shapes one expects the appearance of specific low-lying vibrational state that may be associated with a classical wobbling motion. We have found that a phase transition in ^{156}Dy produces relatively high-lying vibrational states associated with a wobbling mode [4]. In contrast, a soft shape-phase transition from the axially deformed to nonaxial shapes in ^{162}Yb provides the low-lying wobbling excitations.

One of the interesting questions in physics of fast rotating nuclei is the violation of the parity symmetry in the intrinsic rotating frame. It is associated with breaking of the reflection symmetry for the pear shaped nuclei. Recently, using the cranked Skyrme mean field approach, we have found that a spontaneous symmetry breaking phenomenon occurs in ^{162}Yb at large rotational frequencies (see Fig.1 in Ref.[5]). The HF solution with broken reflection symmetry (with nonzero $\langle Q_{30}\rangle$, $\langle Q_{31}\rangle$ momenta and a small admixture of $\langle Q_{32}\rangle$ one) becomes favorable at $\hbar\Omega > 0.4$MeV, in contrast to the solution with reflection symmetry. In ^{164}Yb, both solutions are very close in energy, while the pure quadrupole one determines the properties of yrast states at fast rotation.

Guided by the idea on the instability of the vibrational mode, we have analyzed the formation of the octupole deformed shape at fast rotation in the cranked Nilsson model that incorporates a random phase approximation (CRPA) [5]. From our calculations (see Fig.4 in Ref.[5]) one observes that the first negative signature and parity RPA (octupole) solution tends to zero in ^{162}Yb. The collectivity of the lowest negative parity RPA solutions of both signatures increases noticeably with the rotational frequency. Several two-quasiparticle components originated from $h_{11/2}$ and $g_{7/2}$ subshells for protons and $i_{13/2}$ and $h_{9/2}$ subshells for neutrons contribute to the collectivity of the lowest negative parity one-phonon states. The maximal weight of two-quasiparticle components is $\sim 65\%$. All these features reveal the nature of a shape transition at $\hbar\Omega \sim 0.45$MeV. The onset of the static octupole deformations becomes feasible, since the instability point found in the CRPA approach coincides with the result of the Skyrme mean field calculations. These results suggest that the octupole deformations are due to the octupole phonon condensation at fast rotation. In contrast, in ^{164}Yb the octupole correlations manifest themselves as low-lying octupole vibrations of the quadrupole deformed rotating nucleus, in agreement with the Skyrme results.

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BREAKUP REACTIONS OF TWO-NEUTRON HALO NUCLEI

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The specific features of the halo structure in light Borromean nuclei are manifested in the properties of both bound states and states of the continuum near the breakup threshold. By investigating nuclear reactions in which the ground and excited low-lying states of the continuum are strongly connected by reaction mechanisms, we obtain information on the properties and specific features of the structure of halo nuclei. In kinematically complete experiments, the hierarchical chain of observables which provide the possibility of reconstruction of excitation spectra and many different correlations of fragments becomes available. For quantitative theoretical analysis of these experiments, the final state interaction of all fragments of the halo nucleus should be taken into account. At low excitation energies, the relative velocities of motion of fragments are low; therefore, none of the interactions of fragments can be neglected. As a result, frequently used spectator models which do not completely take into account the final state interaction cannot reproduce adequately dynamics and cannot describe the mechanism of the reaction resulting in low-lying excitations of the nucleus.

For certain physical conditions, the reaction mechanism is simplified, which enables the development of realistic models for description of nucleus-nucleus collisions. At intermediate energies in direct reactions, one-step processes dominate, and it is possible to use the distorted wave approximation. This approximation contains the microscopic three-body structure of the continuum and the ground state as the basic part. Therefore, we can study, at least in principle, the internal structure of halo nuclei via different correlations for the motion of fragments. The three-body breakup is a much richer and more complex process than the breakup into two fragments. For a fixed energy of the continuum, the relative motion of three fragments has the continuous distribution as a function of kinetic energies. At low excitation energies the basic specific features of the structure of Borromean nuclei are contained in several elementary modes characterized by several orbital angular momenta. The objective of the spectroscopy of the continuum is the determination of the dominating excitation modes (multipolarities) and their quantum numbers (elementary modes). To meet this objective, kinematically complete experiments and a theoretical understanding of the nuclear structure and reaction dynamics are necessary. The first steps in this direction have already been made.

The microscopic four-body approach in the distorted wave framework is presented in [1]. The approach was used for description of breakup reactions of two–neutron halo nuclei in collisions with electrons, nucleons, and complex nuclei. In the framework of this approach, Coulomb and nuclear dissociation was taken into account in a consistent way, including the possibility of Coulomb-nuclear interference. The importance of accurate account of recoil effects in the reaction dynamics at breakup of light nuclei is demonstrated. The method of hyperspherical harmonics is used for a consistent description of specific features of the halo structure of the ground state and the fragment motion in the continuum.

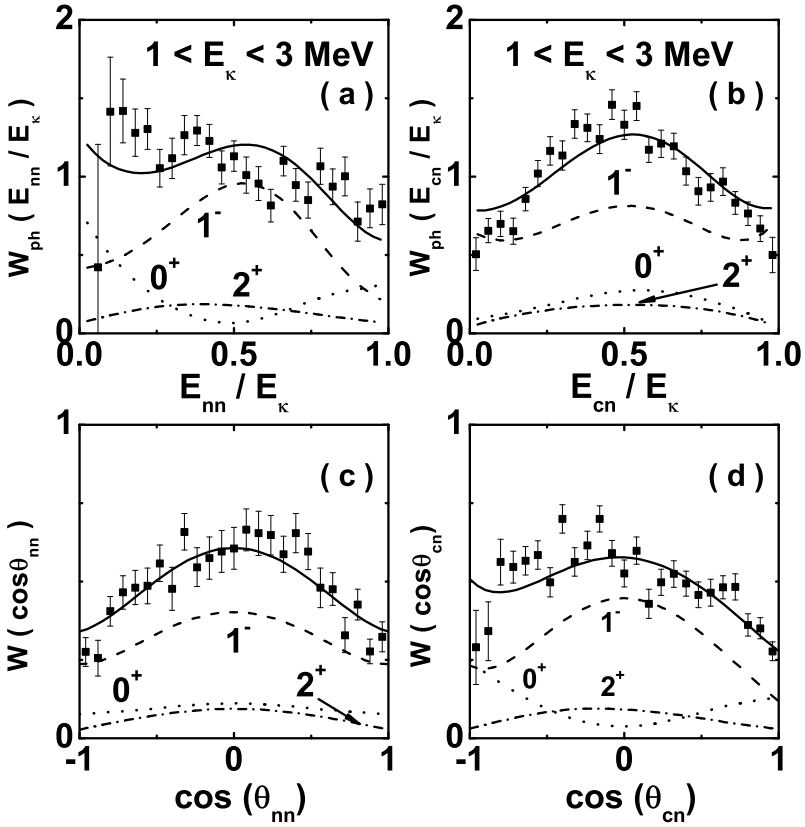

Figure 1: Energy and angular fragment correlations in the ^{6}He + ^{208}Pb breakup reaction at 240 MeV/nucleon for excitation energies $1 < E_\kappa < 3$ MeV

The developed four-body theory in the distorted wave framework can be applied to extract the most valuable information on the correlations characteristic of two-neutron halo nuclei. Simultaneous analysis of the set of observable characteristics in the framework of one theory was used for reducing uncertainties in model assumptions related with the reaction dynamics. Figure 1 shows the comparison of theoretical calculations of different fragment correlations which take into account excitations with different multipolarity (dipole, quadrupole, and monopole) and GSI experimental data for the ^{6}He breakup on ^{208}Pb at 240 MeV/nucleon. The developed approach provides the possibility to achieve a good description of experimental correlations in the excitation energy interval $1 < E_\kappa < 3$ MeV. It is shown that correlations in breakup reactions are a valuable tool for investigation of the true nature of the continuum of halo nuclei.

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PRODUCTION OF NEUTRON-RICH AND NEUTRON-DEFFICIENT NUCLEI

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Projectile fragmentation at intermediate energies is a well-established method for the production of rare isotopes. In addition to the fragmentation reactions the multinucleon transfer reactions are actively discussed to produce exotic nuclei. These binary reactions have been known for producing exotic nuclei for many years. In the transfer reactions the excitation energies of the fragments are smaller than in the fragmentation reactions. In order to estimate the role of multinucleon transfer in the production of exotic nuclei, we assumed that the reactions at intermediate energies remain binary at high angular momenta like at low energies. The dynamics of the binary deep inelastic process is considered as the diffusive multinucleon transfer between the interacting nuclei in the peripheral collisions when the excitation energy of the produced exotic isotope is lower than the threshold for the neutron emission. The calculated results indicate that the Q_{gg} values and the narrow interval of the entrance channel angular momenta influence the production cross sections.

The calculated results [1] are in good agreement with most of the available experimental data. From the point of view of the reaction mechanism, it is surprising and interesting to find that the binary deep inelastic transfer process still accounts for the most part of the production cross section of exotic isotopes in the intermediate energy region. Therefore, transfer reactions provide a very efficient tool for the production of nuclei far from stability. It is crucial for planning future experiments with the stable or secondary beams that within the multinucleon transfer model the yields of the exotic nuclei near the neutron drip line are accurately predicted. Since the predicted production cross sections for new exotic isotopes ^{47}P, ^{51,53,55,57}Cl, ^{52,54}Ar, ^{56,58,60}Ca, ^{59,61,63}Sc, and ^{62,64,66}Ti are larger than 0.1 pb, they can be synthesized and detected at present experimental possibilities. The production cross sections and excitation functions for different neutron-deficient isotopes of U, Np, Pu, Am, Cm, and Cf were analyzed in the framework of the dinuclear system model [3]. In these nuclei the evaporation of charged particles compete with neutron emission and has properly been taken into account. In order to check our predictions, we calculated with the same approach the evaporation residues in several reactions for which the experimental data are available. Our results are in good agreement with them.

For the synthesis of neutron-deficient nuclei $^{223-227}$Pu one can use the xn evaporation channel in the reactions ^{24}Mg+^{204,206,208}Pb and ^{26}Mg+^{204,206}Pb which lead to the cross sections of (0.1–50) nb. In the αxn evaporation channel of the reactions ^{40}Ca+^{190,192}Os one can expect cross sections of 3–20 pb. The nuclei $^{218-222}$Pu can be produced in the xn evaporation channels of the reactions ^{40,44}Ca+^{184}W and ^{32}S+^{192}Pt with 2 pb$< \sigma_{ER}^{xn} <$ 8 nb.

The reactions ^{28}Si+^{192}Pt, ^{23}Na+^{204}Pb, and ^{27}Al+^{204,206}Pb are suitable for producing $^{214-216}$U,$^{223-225}$Np, and $^{228-230}$Am, respectively, with cross sections larger than 1 nb. The neutron-deficient nuclei $^{228-231}$Cm ($^{234-238}$Cf) can be produced in the xn evaporation

channels of the reactions ^{28,30}Si+^{204}Pb (^{34}S+^{204,206}Pb) with cross sections of (0.5-20) nb [(0.1-20) nb].

Our suggestion is to use the asymmetric reactions with Na, Mg, Al, Si, and S and the reactions with Ca to extend the region of neutron-deficient isotopes of U, Np, Pu, Am, Cm, and Cf with cross sections above the 1 nb level. In the neutron-deficient nuclei one can study the role of $N = 126$ closure by looking for the half-life times with respect to the α-decay.

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THEORETICAL ANALYSIS OF THE ^{6}He + p DIFFERENTIAL AND OF THE ^{6}He+^{28}Si REACTION CROSS SECTIONS USING THE MICROSCOPIC OPTICAL POTENTIAL

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The microscopic optical potential (OP), introduced in [1], was calculated and applied in [2-4] to study the ^{6}He + p differential elastic scattering and the ^{6}He+^{28}Si total reaction cross sections. The aim was to explain the existing experimental data (including the data from FLNR JINR) so that to test the three current models of the ^{6}He exotic structure and, besides, to search the mechanism of the considered processes, namely, the in-medium effect on NN-forces, the role of spin-orbital terms and the nonlinearity of the OP's. We take OP in the form

$$U_{opt} = N_R V^F + iN_I W^H, \tag{1}$$

where the fitted parameters are N_R, N_I which renormalize the "strengths" of the calculated real V^F and imaginary W^H parts of OP (1). The real part of OP is the standard folding potential $V^F = V^D + V^{EX}$ [5] which includes the direct and exchange terms. Both of them are integrals whose integrands are proportional to the density distribution functions $\rho(r)$ of the nuclei-participants. Also, the important role in the integrand is played by the effective potentials v_{NN} of the NN-interaction in the nuclear matter. The necessary formulas and the procedure of the numerical calculations of V^F are given in [6]. As an example, the direct part of OP is as follows:

$$V^D(r) = \frac{1}{2\pi^2}\int_0^\infty \rho_1(q)\rho_2(q)v_{NN}(\rho,q)j_0(qr)q^2dq, \tag{2}$$

where $\rho(q)$ and $v_{NN}(q)$ are the form factors of the unfolded nuclear densities and of the NN-potential. The imaginary part W^F was obtained in [1] within the optical limit of the Glauber high-energy approximation. It has the form

$$W^H = -\frac{\hbar v}{(2\pi)^2}\sigma_{NN}\int_0^\infty \rho_1(q)\rho_2(q)f_{NN}j_0(qr)q^2dq. \tag{3}$$

Here σ_{NN} is the NN total cross section known from independent experiments. (In the case of the ^{6}He + p scattering, the only ^{6}He form factor ρ_1 takes place in Eqs.(2) and (3)).

Using these OP the ^{6}He + p differential cross sections were calculated and thus the three model density distributions were tested, namely, the large-scale shell model (LSSM) suggested in [7], the form of ρ applied by Tanihata in [8], the cluster-orbital shell model (COSMA) introduced in [9]. In examples in Fig. 1, the case of 41.6 Mev/N is shown

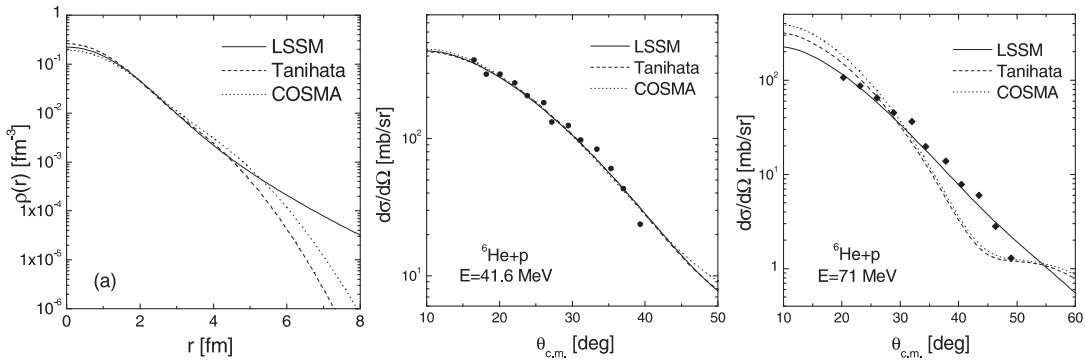

Figure 1: The ^{6}He density distributions obtained in the models LSSM [7], Tanihata [8], COSMA [9], and the respectively calculated differential elastic cross sections.

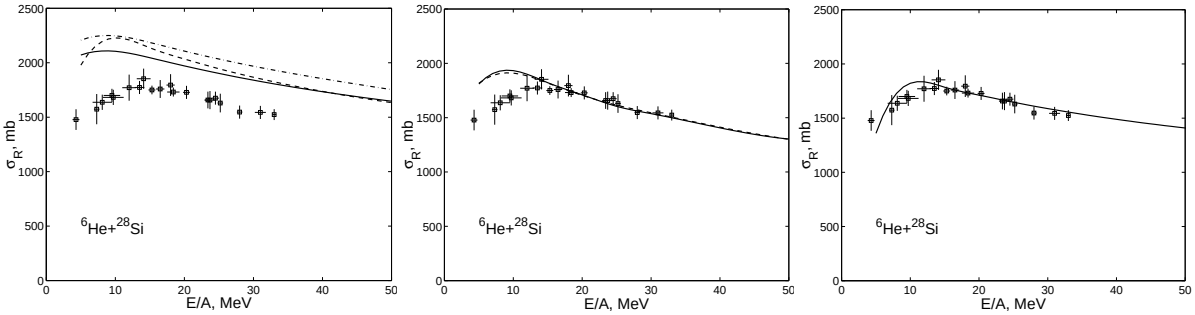

Figure 2: The total reaction cross sections. Theoretical σ_R's in the left block correspond to three model densities of ^{6}He. The middle block is the fit with OP (1), and the right block is the fit when the surface terms are included in OP. Solid curves are for the LSSM density.

when N_R=1 and N_I=1 are taken for all densities, and at E=71 MeV/N the corresponding $\{N\}$ are the following one for LSSM (0.6;1.0), Tanihata (1.0, 0.5) and COSMA (0.8, 1.0). Besides, the total reaction cross sections were calculated in [4]. In Fig. 2, the left-hand side figure shows calculations for the three models of ρ when $N_R = N_I = 1$. The middle section of Fig. 2 is the best fit result N_R=1, N_I=0.4 when one uses OP (1). The data at E<15 MeV/N can be explained only if one adds to OP (1) the surface terms "$-N_s$r(dU/dr)", responsible for accounting for the collective nuclear effects. This result is shown in the right section of Fig. 2.

Conclusions:

(A) The LSSM model is preferable between three models of ^{6}He;

(B) The good agreement with the data is obtained at E>40 MeV/N;

(C) At lower energies (the FLNR data), one should decrease the strength of W^H by about one order to get the shallow potential or to account for the channels with collective effects and removing of nucleons.

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MULTI-CHANNEL ATOMIC SCATTERING AND CONFINEMENT-INDUCED RESONANCES IN WAVEGUIDES

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During the last years, the field of ultracold few-body confined systems has progressed remarkably. By employing optical dipole traps [1] and atom chips [2] it is possible to fabricate mesoscopic structures in which the atoms are freezed to occupy a single or a few lowest quantum states of a confining potential such that in one or more dimensions the characteristic length possesses the order of the atomic deBroglie wavelength. Free-space scattering theory is no longer valid in such systems and a new theory is needed. This stimulated the development of quantum scattering theory in low dimensions. However, up to our work [3] the existing theoretical estimates were practically all limited by the single-mode regime: the atomic scattering in the ground state of the transverse confining waveguide. The only one estimate for the multi-mode regime was done by Olshanii et al.[4] in the s-wave pseudopotential approximation and the zero-energy limit.

The problem of atomic pair collisions under the action of a harmonic trap in the multi-mode regime when the energy of the atoms E exceeds the level spacing of the transverse trapping potential $\hbar\omega$ is much more intricate than the single-mode regime $\hbar\omega \leq E \leq 3\hbar\omega$ due to several open transverse channels. It demands the development of a multi-channel scattering theory accounting for the possible transitions between the levels of the confining potential. In our work [3] we have developed a general grid method for multi-channel scattering of atoms in a waveguide with harmonic confinement. With our approach we have analyzed transverse excitations/deexcitations $n\hbar\omega \leftrightarrow n'\hbar\omega$ in the course of the collisional process including all important partial waves and their couplings due to the broken spherical symmetry. In Fig. 1, we present a result of calculation of the scattering amplitude in case of the multi-mode regime up to four open transverse channels as a function of $\varepsilon = E/(2\omega) - 1/2 \leq 4$. Figure 1 shows considerable deviation of our

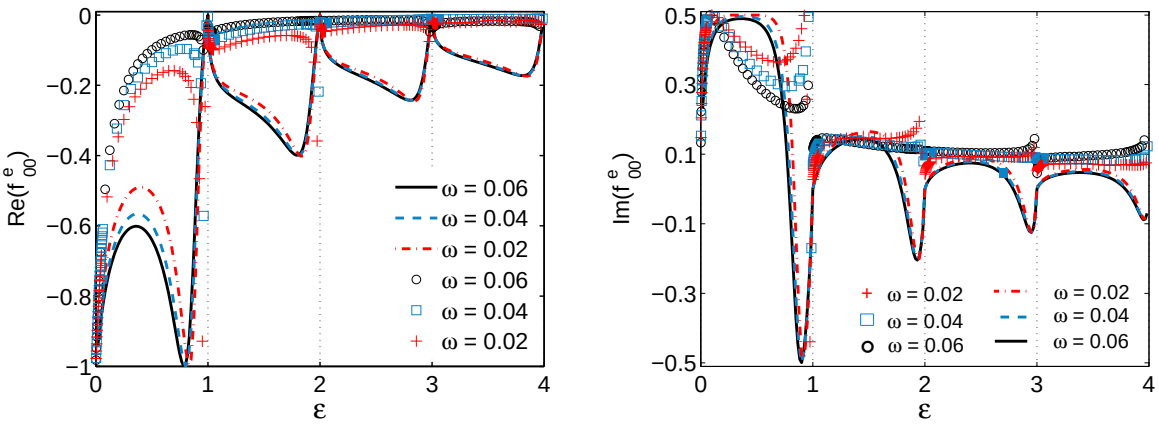

Figure 1: The scattering amplitude f^e_{00} as a function of the dimensionless energy ε for several values of ω. The solid lines show the analytical results [4]

results from the analytical ones [4] which are valid only in the zero energy limit $\varepsilon \to 0$.

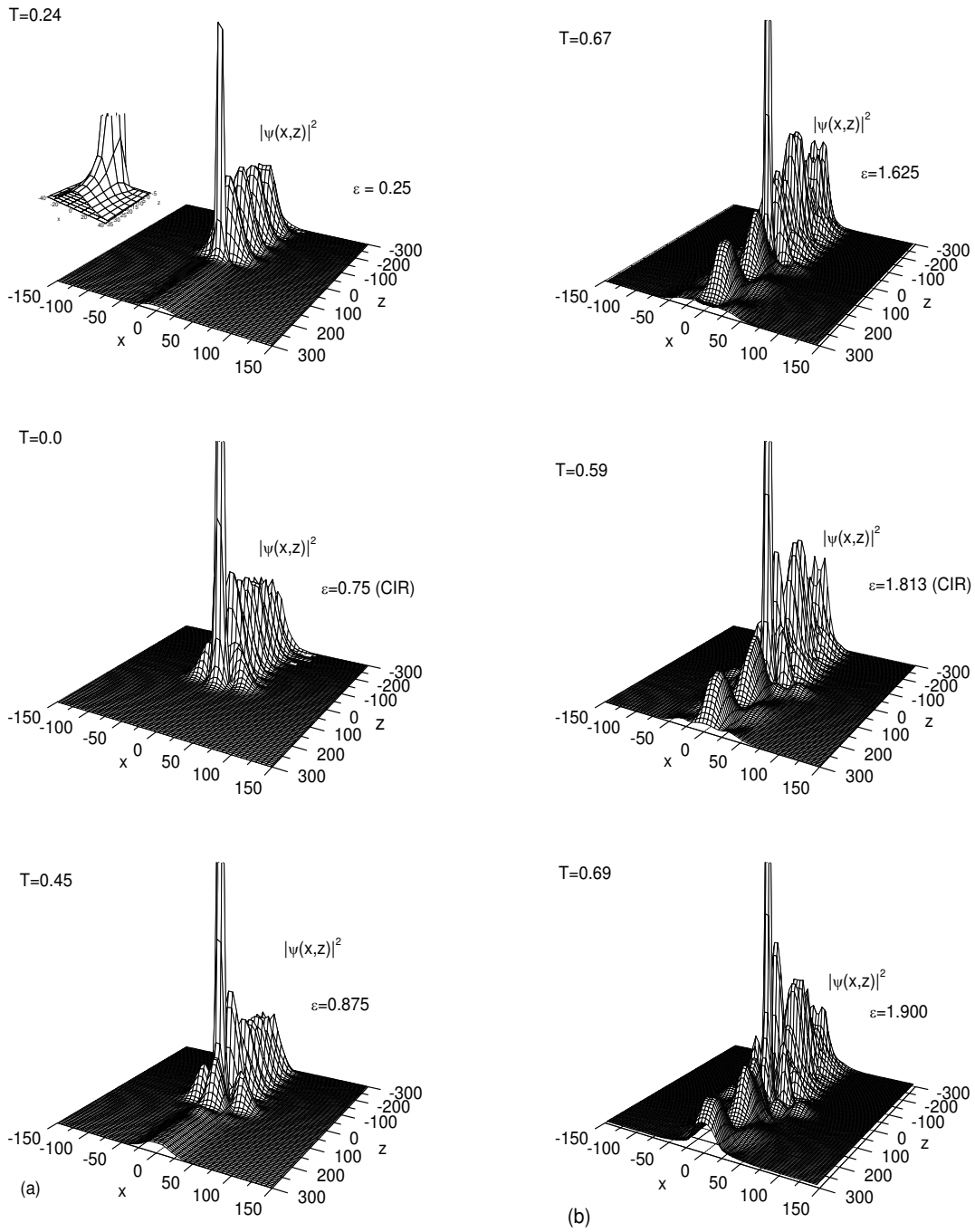

Figure 2: The probability density $|\psi(x,z)|^2$ for bosonic collisions as a function of x and z for two cases of the single-mode regime (a) and two-mode regime (b) with different values of ε. The confinement potential $1/2\mu\omega^2\rho^2$ is acting along the x-axis, atoms move in the z-direction. The corresponding transmission values are also indicated. All subfigures are for $\omega = 0.002$.

In the zero-energy limit and single mode regime we reproduce the well-known confinement-induced resonances (CIRs) [5-8] for bosonic, fermionic and heteronuclear collisions. We also performed a nontrivial extension of the CIRs theory (developed before our work [3] only for the single-mode regime and zero-energy limit) to multi-mode regimes for nonzero collision energies. Figure 2 exhibits calculated probability densities for one and two open transverse channels. The appearance of additional nodes in x-direction indicates virtual transitions to closed channels at the points of the CIRs.

We have also revealed in the multi-channel regimes the dual CIR leading to a complete quantum suppression of atomic scattering which was predicted and analyzed in the single-mode regime in our papers [9, 10]. Possible applications include cold and ultracold atom-atom collisions in atomic waveguides and electron-impurity scattering in quantum wires.

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EXPANSIONS OF REGULAR SOLUTIONS OF SCHRÖDINGER AND FADDEEV EQUATIONS IN THE LINEAR THREE-PARTICLE CONFIGURATION LIMIT

V. V. Pupyshev

We begin with the basic definitions. Let $\mathbf{x}$ and $\mathbf{y}$ be the three-dimensional reduced Jacobi vectors [1] in the six-dimensional coordinate space $\mathcal{R}^6$ of a system $\{p_1, p_2, p_3\}$ of three particles p_1, p_2, and p_3. By definition, the vector $\mathbf{x}$ connects the particles p_2 and p_3, while the vector $\mathbf{y}$ is directed from the particle p_1 to the center of mass of the pair $\{p_2, p_3\}$.

For this pair, the configuration in which all particles lie on the same straight line (axis) $\mathcal{L}$ and the particles p_2 and p_3 are separated from the particle p_1 and from each other, $\mathcal{L} : \{x > 0, y = 0\}$, is called the linear three-particle configuration (the axial degeneration). A small neighborhood $\mathcal{F}$ of the straight line $\mathcal{L}$ is defined as a domain, where the two particles p_2 and p_3 are separated from each other ($x > 0$) and the particle p_1 is close ($y \ll 1$) to the center of mass of these two particles lying on the straight line $\mathcal{L}$.

Let all pairwise interactions V_k, $k = 1, 2, 3$, be the sum of the Coulomb potentials V_k^c and the potentials $\bar{V}_k$ be represented as a series in integer powers of their arguments. For example,

$$V_1(x) = q_1/x + \bar{V}_1(x)\,, \quad \bar{V}_1(x) = \sum_{n=0}^{\infty} x^n\, \bar{V}_{1n}\,, \quad q_1, \bar{V}_{1n} = \text{const}\,. \tag{1}$$

As a rule, the explicit form of the general regular solution Ψ to the Schrödinger equation for the system $\{p_1, p_2, p_3\}$ is unknown. Therefore, any conclusions about its behavior (construction) in physically interesting domains of the space $\mathcal{R}^6$ can be drawn only from asymptotic expansions. Deriving and analyzing asymptotic expansions of the general regular solution Ψ seem important and interesting from the theoretical standpoint. If such expansions are known, then the expansion of regular particular solution can be easily found, for example, the three-particle wave function Ψ^ε, which in contrast to Ψ has a complete set ε of conserved quantum numbers. Deriving the expansion for Ψ^ε reduces to projecting the expansion obtained for Ψ on the basis consisting of the eigenfunctions of all operators commuting with the total Hamiltonian H. Moreover, replacing the function Ψ^ε in the Faddeev equations [1]

$$(H_0 - E)\,\Psi_k^\varepsilon = -V_k\,\Psi^\varepsilon\,, \quad \Psi^\varepsilon = \Psi_1^\varepsilon + \Psi_2^\varepsilon + \Psi_3^\varepsilon\,, \tag{2}$$

with the obtained expansion is the key point in deriving the corresponding expansion of the Faddeev components Ψ_k^ε.

The asymptotic expansions of the wave function Ψ^ε are required for calculating its approximations $\tilde{\Psi}^\varepsilon$ with a high accuracy and hence subsequently defining all observed variables reliably. The point is that taking all the singularities of the behavior of the sought solution (Ψ^ε in our case) of the differential equation into account improves the point-wise convergence of any numerical method [2]. In the Riesz approach [2], in variation-difference and projection-difference schemes [2], and in the spline-collocation method [2], the problem of point-wise approximation in $\mathcal{F}$ can be solved by subjecting the partial

derivatives of the sought function $\tilde{\Psi}^{\varepsilon}$ or its projections on the three-body angular bases to the same linear boundary conditions (constraints) on the straight line $\mathcal{L}$ that are satisfied by the partial derivatives of the exact solution $\tilde{\Psi}^{\varepsilon}$ of the Schrödinger equation or by the corresponding projections of that solution. An example of such a constraint is given by the relation

$$\sum_{n=0}^{n'<\infty} A_n(\mathbf{x}, \hat{y})\, \partial_y^n \Psi^{\varepsilon}(\mathbf{x}, \mathbf{y}) = 0\,, \quad (x, y) \in \mathcal{L}\,, \tag{3}$$

where A_n are known functions or linear combinations of known functions and the operators of partial derivatives with respect to the arguments x and y . The use of constraints of form (3) in the spline approximation of the Faddeev components is a simple and promising method for improving the point-wise convergence of the computed solution of the Faddeev equations to the exact solution in the domain $\mathcal{F}$. Knowing explicit expansions of wave functions and of their Faddeev components in this domain is especially useful in quantum mechanical analysis and for calculations of the properties of two rather wide classes of real three-particle systems with a precise accuracy. The first class, known for a long time in atomic physics [3], includes the three-particle systems consisting of an ion and two slow electrons; this kind of systems is formed by a single ionization of an atom or ion by an electron. Such systems have a nearly linear configuration, which was first proved in [3]. The second class is well known in quantum chemistry [4]. This is the class of linear three-atom molecules formed by all three-atom *sp*-hybridized molecules, for example, the CO2 , HCN, and BeCl molecules.

It follows from the reasons listed above that deriving and analyzing the asymptotic expansions (in the linear three-particle configuration limit) of the regular solutions of the Schrödinger and Faddeev equations are interesting and important from both theoretical and practical standpoints.

However, for such solutions in this limit, not only asymptotic but even simple formal expansions in the form of infinite series in integer powers of the distance y from one of the particles to the center of mass of the other two particles and in the sought functions of the other three-particle coordinates were unknown up to our work [5].

In this work, the six-dimensional Schrödinger and Faddeev equations for a three-body system with two-body central potentials of a more general form (1) than the Coulomb ones are studied. The regular general and particular physical solutions Ψ, $\{\Psi_1, \Psi_2, \Psi_3\}$ and Ψ^{ε}, $\{\Psi_1^{\varepsilon}, \Psi_2^{\varepsilon}, \Psi_3^{\varepsilon}\}$ of these equations are represented as infinite series in integer powers of the distance y between one particle and the center of mass of two other particles and the sought functions of other three-particle coordinates. In the angular basis, formed by the spherical and bispherical harmonics or the symmetrized Wigner D-functions, the construction of these functions is reduced to solving simple algebraic recurrence equations. For the projections of the physical solutions Ψ^{ε} and $\{\Psi_1^{\varepsilon}, \Psi_2^{\varepsilon}, \Psi_3^{\varepsilon}\}$ to the Schrödinger and Faddeev equations onto angular basic functions the boundary conditions in the limit of the linear three-body configuration are derived.

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RELATIVISTIC MULTIRANK INTERACTION KERNELS OF THE NEUTRON-PROTON SYSTEM

S. G. Bondarenko, V. V. Burov, E. P. Rogochaya

The simplest way to investigate the np interaction is to describe properties of their elastic scattering and the corresponding bound state - deuteron. One of the most consistent approaches is based on the solution of the Bethe-Salpeter (BS) equation [1]. In this case, we have to deal with a nontrivial integral equation. The exact solution of the BS equation is based on the use of the separable ansatz for the interaction kernel in the BS equation [2]. Then we can transform an integral equation to a system of linear equations. Parameters of the kernel are fitted by the description of phase shifts for respective partial states and low-energy parameters. First separable parametrizations were worked out within nonrelativistic models. However, relativistically generalized form factors have second- and higher order poles on a real axis in the relative energy complex plane. So, at high energies, one would have to deal with several thresholds corresponding to the production of one, two and more mesons of different types. This is clearly not feasible. A more practical approach is to employ phenomenological covariant separable kernels which do not exhibit the meson-production thresholds and can even be constructed in a singularity-free fashion with the form factors chosen in the present paper and our Wick-rotation prescription. The parametrization like that was proposed in [3].

Within the relativistic field theory, the elastic NN scattering can be described by the scattering T matrix which satisfies the inhomogeneous BS equation. Supposing the separable (rank N) ansatz for the kernel of the NN interaction

$$V_{l'l}(p'_0,|\mathbf{p}'|;p_0,|\mathbf{p}|;s)=\sum_{i,j=1}^{N}\lambda_{ij}(s)g_i^{[l']}(p'_0,|\mathbf{p}'|)g_j^{[l]}(p_0,|\mathbf{p}|), \tag{1}$$

where the form factors $g_j^{[l]}$ represent the model functions, we can obtain the solution of the BS equation in a similar separable form for the T matrix:

$$T_{l'l}(p'_0,|\mathbf{p}'|;p_0,|\mathbf{p}|;s)=\sum_{i,j=1}^{N}\tau_{ij}(s)g_i^{[l']}(p'_0,|\mathbf{p}'|)g_j^{[l]}(p_0,|\mathbf{p}|), \tag{2}$$

where

$$\tau_{ij}(s)=1/(\lambda_{ij}^{-1}(s)+h_{ij}(s)), \tag{3}$$

$$h_{ij}(s)=-\frac{i}{4\pi^3}\sum_l\int dk_0\int \mathbf{k}^2 d|\mathbf{k}|\frac{g_i^{[l]}(k_0,|\mathbf{k}|)g_j^{[l]}(k_0,|\mathbf{k}|)}{(\sqrt{s}/2-E_{\mathbf{k}}+i\epsilon)^2-k_0^2}, \tag{4}$$

$\lambda_{ij}(s)$ is a matrix of model parameters. The square of the total momenta $s=(p_1+p_2)^2$ and the relative momentum $p=(p_1-p_2)/2$ $[p'=(p'_1-p'_2)/2]$ are defined via the nucleon momenta $p_1,\ p_2$, $E_{\mathbf{k}}=\sqrt{\mathbf{k}^2+m^2}$, m is the mass of the nucleon; $l=l'=J$ for spin-singlet and uncoupled spin-triplet states and $l,l'=J\pm1$ for coupled spin-triplet states.

The form factors $g_i^{[l]}$ used in the separable representation of the interaction kernel (1) are obtained by a relativistic generalization of the initially nonrelativistic Yamaguchi-type functions depending on the three-dimensional squared momentum $|\boldsymbol{p}|$. There are two methods to derive covariant relativistic generalizations of nonrelativistic form factors.

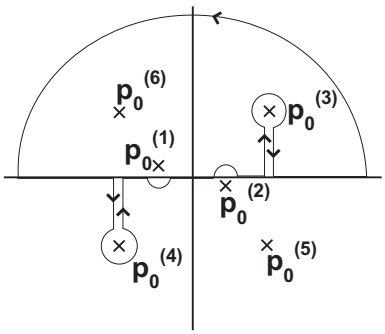

Figure 1: Contour for integration over p_0.

1. One of the common methods is to replace three-momentum squared by four-momentum squared:

$$\mathbf{p}^2 \to -p^2 = -p_0^2 + \mathbf{p}^2. \tag{5}$$

This formal procedure converts three-dimensional functions to covariant four-dimensional ones. In application to the nonrelativistic Yamaguchi-type function

$$g(|\mathbf{p}|) = \frac{1}{\mathbf{p}^2 + \beta^2}. \tag{6}$$

using the substitution (5) we obtain the covariant function in the form:

$$g_p(p, P) = \frac{1}{-p^2 + \beta^2} \xrightarrow{\text{c.m.}} \frac{1}{-p_0^2 + \mathbf{p}^2 + \beta^2 + i\epsilon}. \tag{7}$$

2. The other method is based on the introduction of the formal four-vector Q via the relative p and total P four-momenta of the two-body system by the following relation:

$$Q = p - \frac{P \cdot p}{s} P, \tag{8}$$

with the total momentum squared $s = P^2$. For (6) we obtain the function:

$$g_Q(p, P) = \frac{1}{-Q^2 + \beta^2} \xrightarrow{\text{c.m.}} \frac{1}{\mathbf{p}^2 + \beta^2}. \tag{9}$$

The functions with Q can be obtained from them by the change $p^2 \to Q^2$. The presented functions (7), (9) have rather different properties in the relative energy p_0 complex plane in c.m. The function g_p has two poles on the real axis for p_0 at $\pm\sqrt{\mathbf{p}^2 + \beta^2} \mp i\epsilon$ while the function g_Q has no poles on it.

The integral (4) with form factors of type (7) over p_0 is worthy of a special discussion. All poles $p_0^{(1,2)} = \pm\sqrt{s}/2 \mp E_{\mathbf{p}} \pm i\epsilon, p_0^{(3,4)} = \pm\sqrt{\mathbf{p}^2 + \beta^2 + i\alpha^2}, p_0^{(5,6)} = \pm\sqrt{\mathbf{p}^2 + \beta^2 - i\alpha^2}$, and the contour of integration are pictured in Fig. 1. The idea how to choose the contour appeared owing to [4, 5]. It consists in that the contour must envelope the poles from form factors which will be inside the standard contour after the $\alpha \to 0$ limit. "Standard"

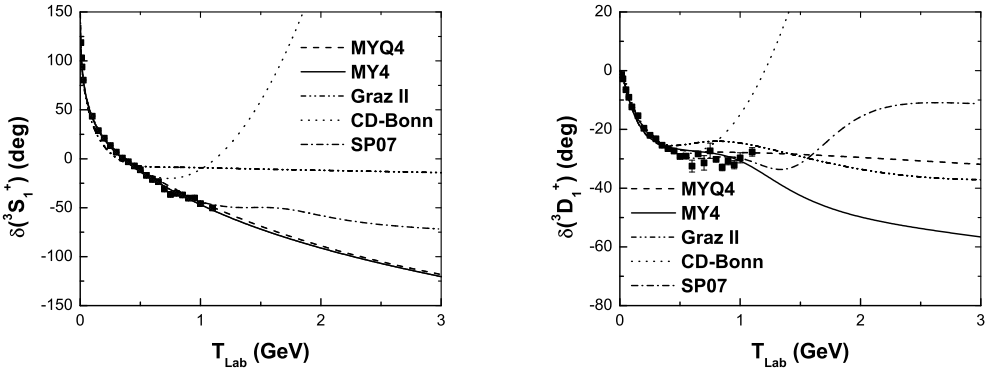

Figure 2: Phase shifts for the ${}^3S_1^+$ and ${}^DS_1^+$ waves. For comparison the results of three alternative descriptions [9], [10] and [11] are presented.

means the one used in the quantum field theory calculations with a propagator which has poles only on the real axis in the p_0 complex plane; one of them is rounded from below and the other, from above. So the path of integration is defined by an appropriate contour for the propagator. The calculation over the presented path leads to the pure real contribution from the form factor poles and, therefore, to the unitary T matrix. We also obtain a correct transition to ordinary form factors of type $g \sim 1/(p_0^2 - \mathbf{p}^2 - \beta^2)^2$ in the $\alpha \to 0$ limit.

Using the multi-rank kernels (two-rank for P waves, three-rank for the ${}^1S_0^+$ partial state, and four-rank for the coupled ${}^3S_1^+$-${}^3D_1^+$ channel) we have constructed an adequate description of all existent experimental data for phase shifts taken from SAID program (http://gwdac.phys.gwu.edu) and low-energy parameters taken from [6] with capable accuracy. Form factors and parameters of the kernels are presented in [7, 8]. The only exclusion is the mixing parameter ε which cannot be described in our model. However, as in [9], we do not think this circumstance to be an obstacle in using our parametrization for calculations of the observables in reactions with the deuteron within the Bethe-Salpeter approach. As an example, in Fig. 2 the results of our calculations for phase shifts of ${}^3S_1^+$-${}^3D_1^+$ partial state are presented.

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η AND η' PRODUCTION IN NUCLEON-NUCLEON COLLISIONS

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The pseudo-scalar mesons η and η' represent a subject of considerable interest for some time (cf. [1] for reports). Investigations of various aspects of η and η' mesons are tightly related with several theoretical challenges and can augment the experimental information on different phenomenological model parameters. For instance, the "anomalously" large mass of the η' meson, as a member of the SU(3) nonet, can be directly connected with the $U(1)$ axial anomaly in QCD. Yet, a combined phenomenological analysis of η and η' production in $N+N$ reactions together with the $U_A(1)$ anomaly provides additional information on the gluon-nucleon coupling, which can be used to describe, e.g., the so-called "spin crisis". Also, the knowledge of the nucleon-nucleon-η' coupling constant $g_{NN\eta'}$ allows to better understand the origin of the OZI rule violation in $N+N$ reactions.

Another aspect of η and η' production in elementary hadron reactions is that both mesons have non-negligible Dalitz decay channels into $e^+e^-\gamma$. As such, they constitute further sources of di-electrons. It is, in particular, the η which is a significant source of e^+e^- pairs, competing at invariant masses of 150 - 400 MeV with Δ Dalitz decays and bremsstrahlung, as the analysis [2] of HADES data [3] shows. One of the primary aims of the HADES experiments [3] is to seek for signal of chiral symmetry restoration in compressed nuclear matter. For such an endeavor one needs a good control of the background processes, including the η' Dalitz decay, in particular at higher beam energies, as becoming accessible at SIS100 within the FAIR project [4]. The η' Dalitz decays depend on the pseudo-scalar transition form factor which encodes hadronic information accessible in first-principle QCD calculations or QCD sum rules. The Dalitz decay process of a pseudo-scalar meson ps can be presented as $ps \to \gamma + \gamma^* \to \gamma + e^- + e^+$. Obviously, the probability of emitting a virtual photon is governed by the dynamical electromagnetic structure of the "dressed" transition vertex $ps \to \gamma\gamma^*$ which is encoded in the transition form factors.

Cross sections of interest are

$$d^5\sigma^{tot}_{NN\to NNps} = \frac{1}{8(2\pi)^5\sqrt{\lambda(s,m^2,m^2)}}\sum_{spins}|T_{NN\to NNps}|^2 ds_{1'2'} dR_2^{N_1N_2\to s_{ps}s_{1'2'}} dR_2^{s_{1'2'}\to N_1'N_2'}$$

for the production of $ps \equiv \eta, \eta'$ and

$$\frac{d\sigma}{ds_{ps}ds_{\gamma^*}} = \frac{d\Gamma_{ps\to\gamma e^+e^-}}{ds_{\gamma^*}}\,\frac{1}{4\pi\sqrt{s_{ps}}}\,\frac{1}{\left(\sqrt{s_{ps}}-m_{ps}\right)^2+\frac{1}{4}\Gamma^2_{ps}}\,d^5\sigma^{tot}_{NN\to NNps} \tag{1}$$

for the Dalitz decay. The decay rate $\frac{d\Gamma_{ps\to\gamma e^+e^-}}{ds_{\gamma^*}}$ is directly related to the transition form factor $F_{ps\gamma\gamma^*}(s_{\gamma^*})$ [5, 6]. We employ here a one-boson exchange model, where the η and η' production is described by a series of Feynman diagrams for the invariant amplitude $T_{NN\to NNps}$ which include the nucleon current diagrams and nucleon resonances. The corresponding interaction Lagrangians and the choice of the effective parameters (coupling strengths, form factors and their cut-offs) can be found in Refs. [5, 7].

Numerical evaluation of the given formalism results in the total cross sections exhibited in Fig. 1. Available data (cf. [5, 7] for quotations) are fairly nicely reproduced in the $p+p$

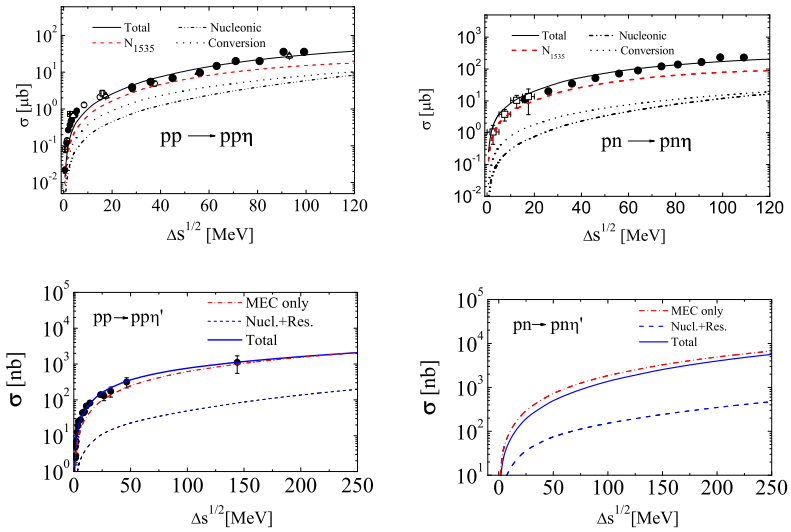

Figure 1: Total cross sections for η (top) and η' (bottom) production as a function of the energy excess in $p+p$ (left) and $n+p$ reactions (right).

channel (a concern could be the region of excess energy $\Delta s^{1/2} \sim 10$ MeV for η). Since no new parameters enter, the channel $n+p$ represents a prediction, in agreement with data in the case of η; no data are available for η'.

The cross sections $d\sigma/ds_{\gamma*}^{1/2}$ resulting from the integration of (1) over s_{ps} are exhibited in Fig. 2. There is a tiny difference when neglecting the internal strong interaction structure of η ("QED form factor") or when using the VMD form factor, see the left panel. The situation changes drastically for η'. Here the account of the internal structure becomes important, see the right panel. Precision data would even allow for a test of the VMD hypothesis. As has been shown in [5, 7], the form factors can be deduced from the given cross section $d\sigma/ds_{\gamma*}^{1/2}$.

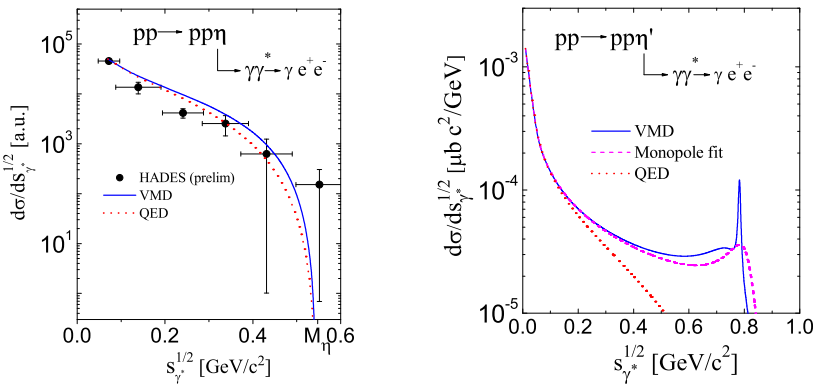

Figure 2: Differential cross sections for η (left, HADES data from [8], for $T_p = 2.2$ GeV) and η' (right, for $T_p = 2.5$ GeV) which give access to the form factors.

In summary, we report on calculations of the reaction $NN \to NNps$ with $ps = \eta, \eta'$ and subsequent Dalitz decay $ps \to \gamma e^+ e^-$ within a one-boson exchange model. We point out that isolating η and η' contributions, e.g., in $p+p$ collisions, allows for an experimental

determination of the transition form factors $F_{ps\gamma\gamma*}$.

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OPEN CHARM PRODUCTION IN $p\bar{p}$ REACTIONS AT FAIR ENERGY REGION

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Open charm production will be one of the major topics of the hadron and heavy-ion programme at FAIR. On the one hand, charm spectroscopy will be addressed by the PANDA collaboration, while the CBM collaboration will exploit charmed particles as probes of the nuclear medium at maximum compression. For both large-scale experiments at FAIR one needs to know the properties of charmed baryons and mesons as well as their production processes in elementary pp and $\bar{p}p$ reactions. For this purpose the opportunities at FAIR are promising, as for instance, the PAX collaboration envisages the use of a polarized antiproton beam. This offers a chance to study in depth the mechanism of open charm production at moderate energies from the threshold to $\sqrt{s} \lesssim 15$ GeV. In this energy range the phenomenology of charm production is not well established. In our study we select one important problem of this wide field, namely, the analysis of exclusive binary reactions $\bar{p}p \to \bar{Y}_c Y_c$, $\bar{p}p \to D\bar{D}$, $\bar{p}p \to D\bar{D}^*$ etc., in peripheral collisions in the mentioned energy range.

Our consideration is based on the topological decomposition of the planar quark and diquark diagrams, which allows one to estimate consistently meson and baryon exchange trajectories and energy scale parameters as well. The spin dependence is determined by the effective interaction of the lowest exchanged resonance. Unknown parameters are fixed by an independent analysis of open strangeness production in $\bar{p}p \to \bar{Y}Y$ and $\bar{p}p \to \bar{K}K$ reactions and of SU(4) symmetry [1].

As an example, in Fig. 1(a) we show the differential cross section of the reaction $\bar{p}p \to \bar{\Lambda}\Lambda$ and $\bar{p}p \to \bar{\Lambda}\Sigma^0$ as a function of the momentum transfer $t = (p_p - p_Y)^2$ at the initial momentum $p_L = 6$ GeV/c together with the available experimental data. The

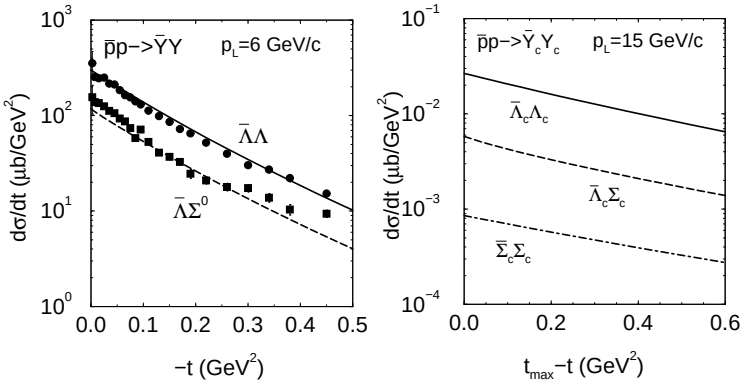

Figure 1: (a) The differential cross section of the reactions $\bar{p}p \to \bar{\Lambda}$ (solid curve) and $\bar{p}p \to \bar{\Lambda}\Sigma^0$ (dashed curve) as a function of the momentum transfer t at $p_L = 6$ GeV. (b) The differential cross sections of the reactions $\bar{p}p \to \bar{\Lambda}_c\Lambda_c$ (solid curve), $\bar{p}p \to \bar{\Lambda}_c\Sigma_c$ (dashed curve), and $\bar{p}p \to \bar{\Sigma}_c\Sigma_c$ (dot-dashed curve) as a function of $t_{\max} - t$ at $p_L = 15$ GeV/c.

predicted differential cross sections of the charm hyperon production as a function of $t_{\max} - t$ at fixed $p_L = 15$ GeV/c are exhibited in Fig. 1(b). Here we use the notation

$\Lambda_c \equiv \Lambda_c^+$ and $\Sigma_c \equiv \Sigma_c^+$. In this case, the main contribution to the cross sections comes from the strange/charmed vector meson exchanged trajectories.

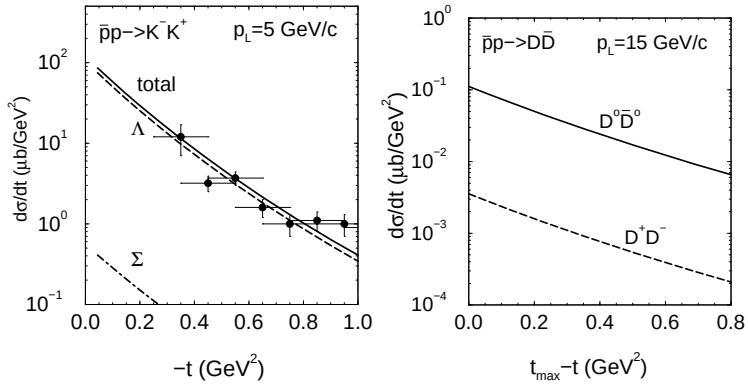

Figure 2: (a) The differential cross section of the $\bar{p}p \to K^-K^+$ reaction as a function of momentum transfer t at $p_L = 5$ GeV. The contributions from Λ and Σ exchanges are shown by dashed and dot dashed curves, respectively. (b) The differential cross sections of the reactions $\bar{p}p \to \bar{D}^0D^0$ (solid curve) and $\bar{p}p \to D^-D^+$ (dashed curve), as a function of $t_{\max-\mathrm{t}}$ at $p_L = 15$ GeV/c.

In Fig. 2, we show an example of strange/charmed meson production in $p\bar{p}$ interaction. Now the dominant contribution comes from the hyperon exchange trajectories. The differential cross section of the $\bar{p}p \to \bar{K}^-K^+$ reaction as a function of the momentum transfer $t = (p_p - p_{K^+})^2$ at initial momentum $p_L = 5$ GeV/c together with available experimental data is presented in Fig. 2(a). Our prediction for the differential cross sections of $D\bar{D}$ pair production is presented in Fig. 2(b). The figure illustrates the dependence of the differential cross section on $t_{\max} - t$ at fixed $p_L = 15$ GeV/c. We found that the cross sections decrease rapidly with energy as $s^{-6.18}$; therefore, the region with small excess energy is more suitable for studying these reactions.

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1. B. N. Zakhariev, V. M. Chabanov, "Submissive Quantum Mechanics: New Status of the Theory in Inverse Problem Approach", Nova Sci. Publ. New York, 1-265, 2007

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