$\Delta(1232)$ isobar excitations and the ground state of nuclei

T. Frick, S. Kaiser, and H. Müther
Institut für Theoretische Physik, Universität Tübingen, D-72076 Tübingen, Germany

A. Polls
Departament d'Estructura i Constituents de la Matèria, Universitat de Barcelona, E-08028 Barcelona, Spain

D. R. Entem* and R. Machleidt
Department of Physics, University of Idaho, Moscow, Idaho 83844
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The influence of Δ isobar components on the ground-state properties of nuclear systems is investigated for nuclear matter as well as finite nuclei. Many-body wave functions, including isobar configurations and binding energies, are evaluated employing the framework of the coupled-cluster theory. It is demonstrated that the effect of isobar configurations depends in a rather sensitive way on the model used for the baryon-baryon interaction. As examples for realistic baryon-baryon interactions with explicit inclusion of isobar channels we use the local ($V28$) and nonlocal meson-exchange potentials (Bonn_{2000}) but also a model recently developed by the Salamanca group, which is based on a quark picture. The differences obtained for the nuclear observables are related to the treatment of the interaction, the π-exchange contributions in particular, at high momentum transfers.

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I. INTRODUCTION

The development of efficient computing facilities has enabled very sophisticated calculations for the solution of the nuclear many-body problem. Starting from realistic models for the nucleon-nucleon (NN) interaction, which give very accurate fits of the NN scattering data below the threshold for pion production [1–3], one can solve the few-nucleon problem up to $A=8$ nucleons in a way which yields essentially the exact solution [4]. Introducing an additional three-nucleon force [5,6] one can obtain results for the basic low-energy properties of these nuclei, which are in good agreement with the experimental data.

This demonstrates that the low-energy properties of nuclei are well described within the conventional model of nuclear physics, in which nuclei are considered as a system of nucleons, treated as inert particles interacting via two-body forces. All subnucleonic degrees of freedom, which may lead to modifications of the hadrons in the nuclear medium, and dynamical relativistic [7] effects are represented by a phenomenological three-nucleon force. On the other hand, however, one knows that nucleons cannot really be considered as elementary particles, and subnucleonic degrees of freedom, such as, e.g., the possibility to excite strongly interacting nucleons, could be very important. In particular the excitation of nucleons to the $\Delta(3,3)$ resonance may have some effect on the low-energy and bulk properties of nuclear systems. First investigations on the importance of isobar degrees of freedom were performed more than 20 years ago [8–11]. Those studies demonstrated that isobar configurations yield an important contribution to the medium-range attraction of the NN interaction. Conventional models of the NN interaction account for this mutual polarization of the interacting nucleons in a phenomenological way. For example, a part of the σ meson exchange in one-boson-exchange (OBE) models for the NN interaction can be related to such isobar terms [12].

In a conventional nuclear structure calculation this part of the NN interaction is identical in the nuclear medium as compared to the vacuum where the effective NN interaction has been adjusted to describe the NN scattering data. If, however, the isobar degrees of freedom are taken into account explicitly, one obtains a modification of the $N\Delta$ and $\Delta\Delta$ propagators in the medium. This implies that the effective NN interaction including such intermediate isobar states is different in nuclear matter as compared to the vacuum case. The corresponding part of the medium-range attraction is quenched. This feature has been investigated by various groups using the Brueckner-Hartree-Fock approximation [9–11] or within a lowest order variational calculation [13] and binding energies were obtained, which were much weaker than in corresponding calculations ignoring the explicit treatment of isobar excitations.

For nuclear matter at higher densities the explicit consideration of isobar configurations leads to an enhancement of the pion propagator which has been called a precursor phenomenon to a phase transition of pion condensation [14–16]. This leads to rather attractive contributions to the binding energy which originate from ring diagrams involving Δ-hole excitations [17]. Nuclear structure studies including isobar excitations have furthermore been performed for few-nucleon systems [18–20].

Most of these older studies have been performed using rather simple models for the baryon-baryon interaction. The transition potentials describing the $NN\rightarrow N\Delta$ and $NN\rightarrow\Delta\Delta$ were approximated in terms of local π-exchange potentials. During the last years new models for the baryon-

*On leave from the University of Salamanca, Spain.

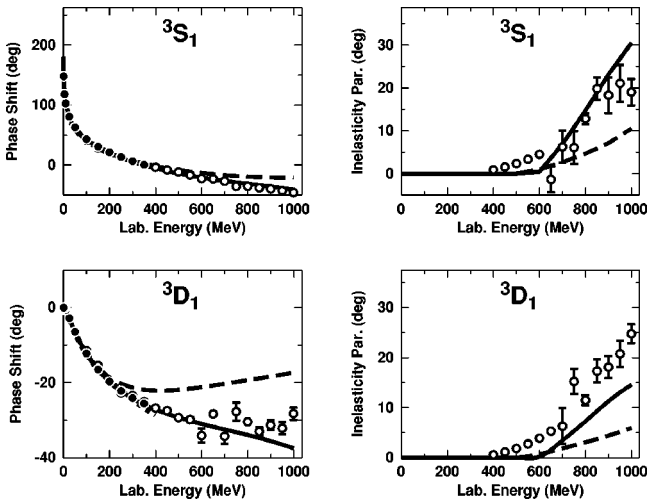

FIG. 1. Phase shifts and inelasticity parameters of neutron-proton (np) scattering in Arndt-Roper conventions (Ref. [29]) in $^3S_1$ and $^3D_1$ partial waves for laboratory energies below 1000 MeV. The solid curve is the prediction by the Bonn$_{2000}$ model (Ref. [26]) and the dashed curve represents the Salamanca model (Ref. [27]). The solid dots represent the Nijmegen multienergy np analysis (Ref. [30]) and the open circles are the GWU/VPI single-energy np analysis (Ref. [31]).

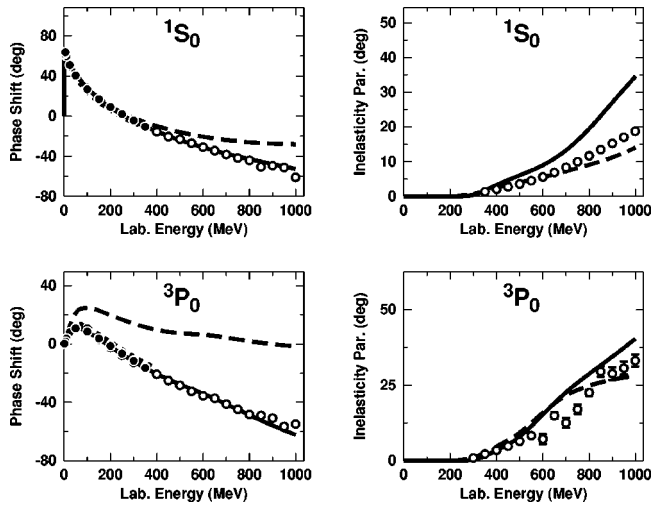

FIG. 2. Phase shifts and inelasticity parameters of neutron-proton (np) scattering in $^1S_0$ and $^3P_0$ partial waves. For further details, see Fig. 1.

baryon interaction have been developed. It has been demonstrated that a local approximation of the π-exchange term tends to overestimate these contributions considerably [21,22]. The effects of the nonlocalities in the π exchange on the properties of the deuteron have been studied in detail by Forest [23] who included unitary transformations, which essentially relate features of nonlocal and local potentials. Nonlocalities in the π exchange also have a non-negligible effect on the transition potentials leading to isobar excitations [24].

So it is one aim of the present investigation to update nuclear structure studies with explicit treatment of isobar excitations using modern models for the *NN* interaction. We are going to compare results for nuclear matter and finite nuclei, calculated for the Argonne $V28$ potential [25], a recent update of the nonlocal meson-exchange potential denoted as Bonn$_{2000}$ [26], and a model which has recently been developed by the Salamanca group [27]. This Salamanca interaction is derived in the framework of the chiral quark cluster (CQC) model. The problem of two interacting clusters (baryons) of quarks is solved by means of the resonating group method. The Pauli principle between the interacting quarks is an important source for the short-range repulsion of the *NN* interaction [28]. At large distances the π exchange between the quarks in the two clusters evolves to the π exchange between two baryons. At shorter distances, however, this nonlocal model for the baryon-baryon interaction might yield results that are quite different from a meson-exchange picture. This Salamanca potential does not give such a perfect fit to the *NN* scattering phase shifts as do the Bonn$_{2000}$ or the $V28$. For the $^1S_0$ and $^3S_1$-$^3D_1$ partial waves of the *NN* system, however, the agreement with the empirical data is rather good. This is visualized in Figs. 1 and 2, which exhibit phase shifts and inelasticity parameters for partial waves with isospins $T=0$ and $T=1$, respectively. Note that the Salamanca model does not include any spin-orbit force, which explains the predictions for the ^3P_J waves. An explicit evaluation of isobar components in the nuclear wave function is also motivated from recent experiments, which try to measure such isobar components [32].

The isobar components in the nuclear wave function and the resulting ground-state properties will be evaluated in an extension of the coupled-cluster method [33]. This extension is presented in Sec. II where we will also compare predictions of the coupled-cluster method with the Brueckner-Hartree-Fock approximation. Results for the binding energy and isobar probabilities obtained for nuclear matter and finite nuclei will be presented in Sec. III. Special attention will be paid to the difference between the various interaction models.

II. COUPLED-CLUSTER APPROACH WITH ISOBAR EXCITATIONS

In the coupled-cluster approach [33] one starts assuming an appropriate Slater determinant Φ as a reference state for the system under consideration. In the examples considered below this reference state will be a Slater determinant defined in terms of appropriate oscillator single-particle wave functions for the case of ^{16}O, while for the case of infinite nuclear matter Φ stands for the antisymmetrized wave function built in terms of plane waves with momenta less than the Fermi momentum k_F. The exact eigenstate Ψ is then written as

$$\Psi = e^S \Phi, \tag{1}$$

with S being an operator of the form

$$S = \sum_{n=1}^{A} S_n, \tag{2}$$

where S_n is an n-particle operator and in order to be complete one has to consider operators up to $n=A$ with A the number of baryons in the system. The operator S_n describes the formation of an n-particle n-hole excitation relative to the reference state Φ. For the case of $n=2$ it can be written

$$S_2=\frac{1}{4}\sum_{\nu_1,\nu_2,\rho_1,\rho_2}\langle\rho_1\rho_2|S_2|\nu_1\nu_2\rangle a^\dagger_{\rho_1}a^\dagger_{\rho_2}a_{\nu_2}a_{\nu_1}. \quad (3)$$

In this equation $a^\dagger_{\rho_i}$ stand for fermion creation operators in states which are unoccupied in Φ, while a_{ν_i} represent annihilation operators for the nucleon single-particle states which are occupied in the Slater determinant Φ. Note that the $a^\dagger_{\rho_i}$ may also represent the creation of Δ isobar states. Therefore the S_2 amplitudes describe two-particle two-hole excitations relative to Φ but also $N\Delta$ and $\Delta\Delta$ excitations.

One can now use the Schrödinger equation in the form

$$e^{-S}He^S\Phi=E\Phi, \quad (4)$$

and project this equation on the reference state Φ and n-particle n-hole states relative to Φ which we will identify by $\Phi_{\rho_1\cdots\rho_n\nu_1\cdots\nu_n}$. This leads to an expression for the energy,

$$E=\langle\Phi|e^{-S}He^S|\Phi\rangle=\langle\Phi|H(1+S_1+\tfrac{1}{2}S_1^2+S_2)|\Phi\rangle, \quad (5)$$

and to a set of coupled equations for the amplitudes of linked n-particle n-hole excitations S_n. This set of equations is truncated by assuming that amplitudes S_n with n larger than a given value m can be ignored. As an example we consider the $m=2$ approximation, i.e., we ignore the effects of linked three-particle three-hole excitations and higher, and in order to simplify the notation, we furthermore assume that we have chosen the reference state such that S_1 vanishes (note that this is true in particular for infinite nuclear matter because of the translational symmetry). In this case we can write the correlated two-body state as

$$\chi_2|\nu_1\nu_2\rangle_A=(1+S_2)|\nu_1\nu_2\rangle_A,$$

where a subscript A is used to identify antisymmetrized two-body states. With these simplifications, the equation for the amplitudes S_2 can be reduced to

$$\langle\rho_1\rho_2|(T_1+T_2)S_2|\nu_1\nu_2\rangle_A-\sum_\nu\{\langle\rho_1\rho_2|S_2|\nu\nu_2\rangle_A\langle\nu|h|\nu_1\rangle + \langle\rho_1\rho_2|S_2|\nu_1\nu\rangle_A\langle\nu|h|\nu_2\rangle\}+\langle\rho_1\rho_2|V\chi_2|\nu_1\nu_2\rangle_A + \underbrace{\frac{1}{2}\sum_{\nu\nu'}\langle\rho_1\rho_2|S_2|\nu\nu'\rangle_A\langle\nu\nu'|V\chi_2|\nu_1\nu_2\rangle_A}_{(*)}=0. \quad (6)$$

Note that the term identified with (*) includes a summation over intermediate hole states. If we ignore this term and assume furthermore that the single-particle Hamiltonian of nuclear matter is diagonal in the plane wave states, $\langle\alpha|h|\beta\rangle=\epsilon_\alpha\delta_{\alpha\beta}$, we can rewrite Eq. (6) into

$$V\chi_2|\nu_1\nu_2\rangle_A=V|\nu_1\nu_2\rangle_A+V\underbrace{\frac{Q_P}{\epsilon_{\nu_1}+\epsilon_{\nu_2}}}_{=\omega}-T_1-T_2V\chi_2|\nu_1\nu_2\rangle_A = V|\nu_1\nu_2\rangle_A+VS_2|\nu_1\nu_2\rangle_A. \quad (7)$$

In this equation we have introduced the starting energy ω and the Pauli operator Q_P, which restricts the sum over intermediate states to those of the form $|\rho_1\rho_2\rangle$; i.e., to nucleon single-particle states ρ_i which are unoccupied in the reference state Φ or to isobar excitations. If we identify $V\chi_2$ with the Brueckner G matrix, Eq. (7) takes the form of the Bethe-Goldstone equation,

$$G(\omega)=V+V\frac{Q_P}{\omega-H_0}G(\omega), \quad (8)$$

with H_0 the operator of the kinetic energy, i.e., assuming the conventional choice for the spectrum of the particle states [22,34,35].

In order to visualize the relevance of the hole-hole term (*) in Eq. (6) we have performed calculations for nuclear matter with and without this term, using two different models for the NN interaction, which do not include isobar degrees of freedom, explicitly. One of these examples is the Argonne $V14$ potential [25], which is defined in terms of 14 operators, each of them multiplied with a local potential. The second example is the charge dependent Bonn potential [1], a meson-exchange interaction, which is evaluated in momentum space and contains nonlocal contributions.

The results of the energy of nuclear matter as a function of the Fermi momentum k_F, calculated in the Brueckner-Hartree-Fock (BHF) approximation, are displayed by the dashed lines in Fig. 3. The differences originating from the two interaction models have been discussed, e.g., in Ref. [21]: A local interaction ($V14$) tends to be stiffer than an NN interaction based on the nonlocal meson-exchange model (CDBonn), fitting the same NN scattering data. Since the two-body correlations in nuclear matter are quenched as compared to the case of NN scattering in the vacuum, a stiffer interaction tends to predict less binding energy than a softer one. As a consequence, the BHF energy calculated for the $V14$ interaction is much less attractive than for CDBonn.

If one also includes the hole-hole ladder terms in solving Eq. (6), one obtains the corresponding solid lines in Fig. 3. The comparison shows that the effect of these hole-hole ladders on the calculated energy of nuclear matter is rather weak in this range of densities. The hole-hole ladders yield an effect which is weakly repulsive. The effect is a little bit larger for the $V14$ interaction as compared to the softer CDBonn. All these results indicate that the coupled-cluster approach, restricted to the S_m amplitudes with $m\leqslant 2$, yields results very similar to the BHF approximation, employing the conventional choice for the intermediate particle spectrum.

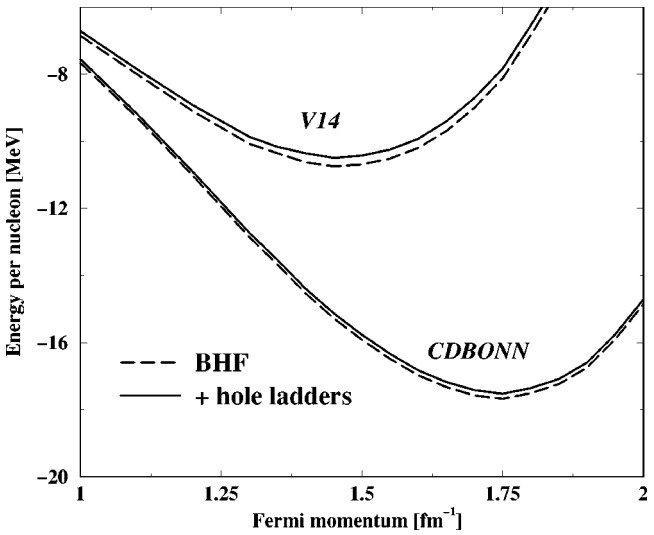

FIG. 3. Binding energy of nuclear matter as a function of the Fermi momentum. Results are given for the Argonne $V14$ and the CDBonn interaction, using the BHF approximation (dashed lines) and with inclusion of hole-hole ladder terms (solid lines).

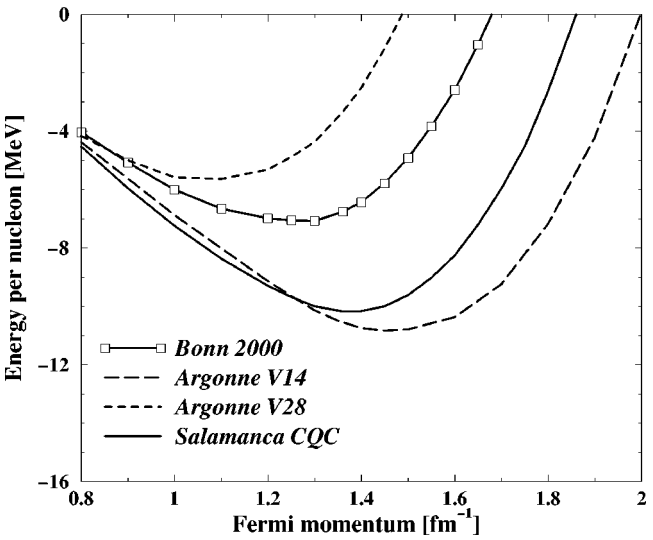

FIG. 4. Binding energy of nuclear matter as a function of the Fermi momentum. The contributions from hole-hole ladders, which are negligibly small (see Fig. 1), have been ignored in the results displayed here. Results are given for the various interaction models with explicit consideration of isobar excitations. For a comparison, the result obtained for the conventional Argonne $V14$ interaction is also included.

However, it is not the aim of the present work to perform nuclear structure studies within the conventional approach. More sophisticated calculations including up to three-hole line terms in the Brueckner expansion scheme for nuclear matter [35] or coupled-cluster calculations for finite nuclei including S_3 terms have been performed [36,37].

The central aim of this work is to account for the isobar excitations using the coupled-cluster approach restricted to $m \leqslant 2$. For that purpose we consider the baryon-baryon interaction models $V28$ [25], Bonn_{2000} [26], and the chiral quark cluster (CQC) model developed in Salamanca [27], which all include the scattering to $N\Delta$ and $\Delta\Delta$ states. While $V28$ and Bonn_{2000} yield rather accurate fits of the NN phase shifts in all partial waves, the CQC model leads to such a good fit only for the channels with isospins $T=0, J=1$ and $T=1, J=0$ channels. Therefore we have replaced the CQC model by the Bonn_{2000} interaction model in all other channels.

For the case of nuclear matter Eq. (6) has been solved as an integral equation employing the usual angle-average approximation for the Pauli operator [38]. The hole-hole ladder term can be introduced as an additional nonlinear term, for which self-consistency is obtained in an iterative procedure.

In the case of finite nuclei we have solved the coupled-cluster equation by considering an expansion of the correlated two-body wave function in a basis of relative wave function defined in a box of a given radius. This basis provides an independent control of the maximal distance and momentum relevant for the correlated waves. The method, restricted to nucleon-nucleon correlations only, has been described in Ref. [39]. The extension to include isobar configurations is straightforward [24].

As a result of the calculation we not only obtain the energy of the system (5) but one can also calculate the one-body density matrix

$$\rho_{\alpha\beta} = \frac{\langle \Psi | a_\alpha^\dagger a_\beta | \Psi \rangle}{\langle \Psi | \Psi \rangle}, \tag{9}$$

using the techniques described in Ref. [40]. This one-body density allows for the evaluation of the radius of finite nuclei and also yields the probability that Δ is excited.

III. RESULTS AND DISCUSSION

The energy per nucleon calculated for homogenous nuclear matter at various densities is displayed in Fig. 4. The results obtained for the three different interactions treating isobar excitations explicitly (Argonne $V28$, Bonn_{2000}, and Salamanca CQC) are compared to those obtained within the conventional framework using the Argonne $V14$ interaction model. All results have been obtained in the coupled-cluster or exponential S approach restricting the excitation operator to S_m with $m \leqslant 2$. All calculations including isobar configurations yield results for the binding energy, which are less attractive than the result obtained for the conventional calculation.

The reason for this loss of binding energy has been presented already a long time ago (see, e.g., Ref. [10]) and we just want to repeat it using the language of perturbation theory. The contribution of isobar configurations to the effective interaction of two nucleons can be written in lowest perturbation theory as

$$\Delta V = V_{N\Delta}^\dagger \frac{Q}{\omega - H_{N\Delta}} V_{N\Delta} + V_{\Delta\Delta}^\dagger \frac{1}{\omega - H_{\Delta\Delta}} V_{\Delta\Delta}, \tag{10}$$

where $V_{N\Delta}$ and $V_{\Delta\Delta}$ represent the transition potentials for the $NN \to N\Delta$ and $NN \to \Delta\Delta$ transitions, respectively. The energy of the interacting nucleons is denoted by ω, and $H_{N\Delta}$ ($H_{\Delta\Delta}$) describes the Hamiltonian for the intermediate $N\Delta$ ($\Delta\Delta$) states. These contributions are responsible for a sizable

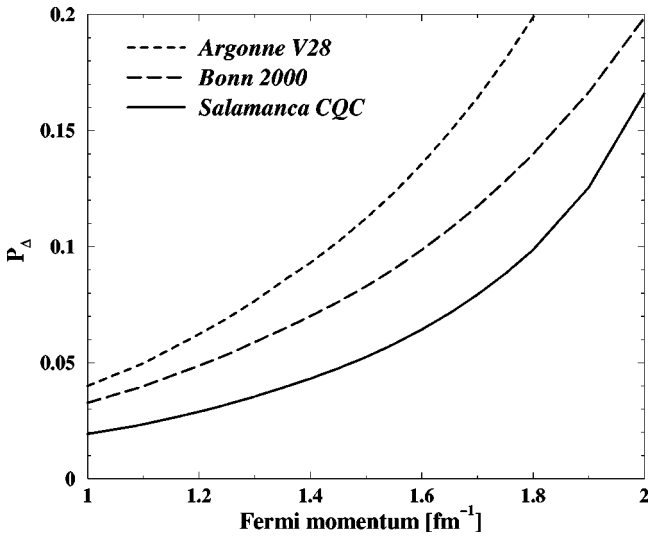

FIG. 5. Δ probability per nucleon in nuclear matter as a function of the Fermi momentum. Results are presented for the various interaction models discussed in text.

part of the medium-range attraction of the *NN* interaction. Therefore a realistic interaction model like the Argonne *V*14, which does not allow for isobar configurations, contains attractive components which simulate the effects of isobar excitations in fitting the *NN* scattering phase shifts. The effects of the attractive isobar terms displayed in Eq. (10) are reduced in the nuclear medium, since the interacting nucleons are bound (ω becomes negative) and because a part of the $N\Delta$ configurations is unavailable due to the Pauli blocking. This quenching of the attractive isobar terms is observed only if the isobar effects are treated explicitly, and it is not contained in the conventional models that simulate the isobar effects in the effective *NN* interaction in a pure phenomenological way.

These arguments explain the loss of attraction due to the explicit inclusion of isobar excitations. Since the reduction of the isobar terms increases with density, this can also explain why the repulsion increases with increasing density, a feature which tends to shift the saturation point to lower densities.

The calculated binding energy is smallest for the Argonne *V*28 interaction model and slightly larger for the Bonn_{2000} and the Salamanca CQC models. To some extent this could be explained by the observation that local interaction models, like Argonne *V*28, tend to predict weaker binding than do nonlocal interactions, which fit the same *NN* phase shifts [21]. This feature, however, may also be interpreted as an indication that the predicted isobar effects are larger for Argonne *V*28 than for the other two models under consideration. This interpretation is supported by the calculated probabilities of isobar excitations in nuclear matter, displayed in Fig. 5.

The prediction for the isobar probabilities derived from the various interaction models differs in a very significant way. At the empirical saturation density, which corresponds to a Fermi momentum $k_F = 1.36$ fm^{-1}, the difference is larger than a factor of 2 (see also Table I). Despite these differences in the prediction of the total Δ probability, there

TABLE I. Δ probability per nucleon in nuclear matter at saturation density derived from various interaction models. The total probability originates from the excitation of $N\Delta[P(N\Delta)]$ and $\Delta\Delta$ configurations. Also shown are predictions if only the coupling to the Δ configuration from *NN* channels $^1S_0$ and $^3S_1$ is considered. All entries are in percent.

	V_{28}	Bonn_{2000}	CQC
P_Δ (total)	8.67	6.55	4.00
$P(N\Delta)$	4.03	2.79	1.87
$P(\Delta\Delta)$	4.64	3.76	2.13
$P_\Delta(^1S_0)$	2.77	2.43	1.24
$P_\Delta(^3S_1)$	1.80	2.00	0.64

are some common features in the predictions of these models with quite different origins. If one tries to analyze which partial waves provide the most important contributions, one observes that all interaction models predict a larger contribution from the excitation of $\Delta\Delta$ configurations, which can occur in interacting pairs of baryons with $T=0$ and $T=1$, than from the excitation of $N\Delta$ excitations, which occur in $T=1$ partial waves only.

All interaction models predict large contributions from those partial waves, in which the interacting nucleons are in a state with relative angular momentum $l=0$. However, for a complete calculation one cannot ignore the contributions from the higher partial waves (see also Table I).

The features we have discussed so far for the case of infinite nuclear matter are also observed in the results obtained for the finite nucleus ^{16}O, which are displayed in Table II. The calculated binding energy per nucleon is smallest for the Argonne *V*28, about 0.7 MeV, and 2.4 MeV per nucleon larger for the Bonn_{2000} and Salamanca models, respectively. The increase in the calculated binding energy is correlated with a smaller prediction for the Δ probability P_Δ. Also for ^{16}O we observe a difference by almost a factor of 2 between P_Δ derived from the *V*28 and Salamanca CQC models. The probabilities P_Δ calculated for ^{16}O are similar in magnitude to those evaluated for nuclear matter at small densities (k_F around 1 fm^{-1}). Therefore a nuclear matter

TABLE II. Energy per nucleon (E/A), radius (r), single-particle energies for the nucleons, and Δ probability per nucleon for ^{16}O. The total probability originates from the excitation of $N\Delta[P(N\Delta)]$ and $\Delta\Delta$ configurations. Results are presented for the various interaction models discussed in text.

	V_{28}	Bonn_{2000}	CQC
E/A[MeV]	−2.73	−3.49	−5.15
r[fm]	2.81	2.65	2.53
$\varepsilon_{s1/2}$ [MeV]	−34.65	−37.88	−44.25
$\varepsilon_{p3/2}$ [MeV]	−16.49	−18.54	−22.03
$\varepsilon_{p1/2}$ [MeV]	−13.56	−14.82	−17.67
P_Δ [%]	3.87	3.71	1.97
P_Δ ($N\Delta$) [%]	1.75	1.43	0.88
P_Δ ($\Delta\Delta$) [%]	2.12	2.28	1.08

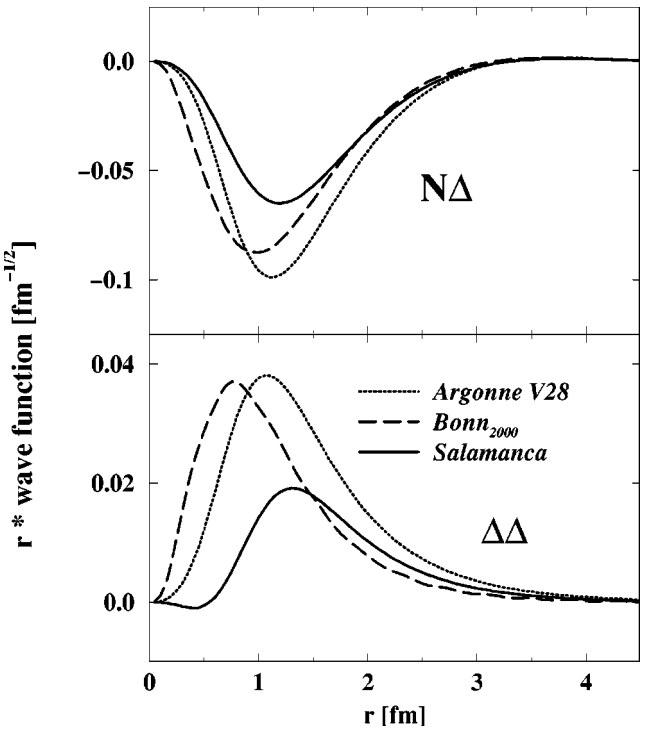

FIG. 6. $N\Delta$ (upper part) and $\Delta\Delta$ correlation functions originating from two nucleons in the $0s_{1/2}$ shell of ^{16}O as a function of the relative distance r.

calculation of isobar effects seems to provide a reasonable first estimate for the case of finite nuclei, if one uses a local density approximation. For a more detailed information, like the relative importance of different partial waves, an explicit calculation of the finite systems is required.

The differences in the calculated energies and Δ probabilities obtained in these different interaction models originate of course mainly from the different transition potentials $V_{N\Delta}$ and $V_{\Delta\Delta}$ [see also Eq. (10)]. Some of these differences, like the treatment of the π-exchange contribution or the short-range behavior in the local $V28$ approximation as compared to the nonlocal calculation in the other models, have been discussed already in Ref. [24]. These differences are also the main origin for the different predictions obtained in the present calculation. As a typical example we show the amplitudes

$$\langle N\Delta\,{}^5D_0|S_2|0s_{1/2}0s_{1/2}\rangle_{J=0,T=1}, \tag{11}$$

calculated for ^{16}O as a function of the relative distance r of the $N\Delta$ pair in the upper part of Fig. 6. The lower part contains the corresponding correlation function for the $\Delta\Delta$ configuration. Inspecting the differences obtained from the three interaction models, one can see that the $V28$ interaction leads to a larger amplitude at larger distances r than do the other two. This can be related to the fact that $V28$ uses a local π-exchange contribution in the transition potential, which does not account for retardation effects which are due to the $N\Delta$ mass difference. The different behavior in the correlation functions S_2 at small distances r must be related to the different kinds of models. While the short-range behavior in the $V28$ and Bonn$_{2000}$ models are controlled by local and nonlocal form factors, respectively, it is the coupled channel calculation within the chiral quark model that provides the short-range behavior in the Salamanca model.

IV. CONCLUSIONS

In the present investigation we try to compare the predictions for the bulk properties of nuclei derived from three different baryon-baryon interaction models, which account for isobar configurations explicitly. The main differences can be related to the models for transition potentials describing $NN\rightarrow N\Delta$ and $NN\rightarrow\Delta\Delta$ transitions. The quark model of the Salamanca CQC approach predicts weaker transition amplitudes at short range than do the more phenomenological cutoffs in the Bonn$_{2000}$ and Argonne $V28$ interactions. The long-range components of these amplitudes are dominated by the π exchange, which is weaker in the nonlocal models (Salamanca and Bonn$_{2000}$) than in the local interaction model ($V28$). These differences in the interactions are responsible for the differences in the predicted Δ probabilities in ^{16}O, which vary between 1.97% derived for the Salamanca model and 3.87% for Argonne $V28$. The results are in fair agreement with the estimates derived from experiment in Ref. [32], which reports Δ probabilities ranging between 1.5% and 3.1% for light nuclei. Comparing these data one must keep in mind that the Δ probability is not an observable, which can be deduced from experiment in a model-independent way. Therefore one should be satisfied with such a qualitative agreement between theory and experiment.

A large probability for isobar excitations is related to weak binding energy. Similar results are obtained for infinite nuclear matter. The isobar effects discussed here would correspond to the inclusion of a repulsive three-nucleon force in conventional nuclear structure calculations. Comparing the calculated binding energies with empirical values, one must keep in mind that the coupled-cluster approximation (including terms up to S_2) essentially corresponds to the Brueckner-Hartree-Fock approximation with a conventional choice of the intermediate particle spectrum. More binding energy is obtained from including three-body terms or using the so-called continuous choice spectrum. This is known from corresponding calculations using nucleon degrees of freedom only [35]. The explicit treatment of isobar configurations, however, would give rise to additional three-body terms, which are not yet taken into account. The effects become very large at higher densities if one considers old local models for the isobar excitations [16,17]. The isobar effects may provide reasonable corrections if the modern interaction models are considered.

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