Coupled Cluster Calculations of Ground and Excited States of Nuclei

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The standard and renormalized coupled cluster methods with singles, doubles, and noniterative triples and their generalizations to excited states, based on the equation of motion coupled cluster approach, are applied to the ⁴He and ¹⁶O nuclei. A comparison of coupled cluster results with the results of the exact diagonalization of the Hamiltonian in the same model space shows that the quantum chemistry inspired coupled cluster approximations provide an excellent description of ground and excited states of nuclei. The bulk of the correlation effects is obtained at the coupled cluster singles and doubles level. Triples, treated noniteratively, provide the virtually exact description.

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The description of finite nuclei requires an understanding of both ground- and excited-state properties based on a given nuclear Hamiltonian. While much progress has been made in employing the Green's function Monte Carlo calculation [1] and no-core shell-model [2] techniques, these methods have apparent limitations to light nuclei. Given that present nuclear structure research facilities and the proposed Rare Isotope Accelerator will continue to open significant territory into regions of medium-mass and heavier nuclei, it becomes imperative to investigate methods that will allow for a description of medium-mass systems. Coupled cluster theory is a particularly promising candidate for such an endeavor due to its enormous success in quantum chemistry [3-9].

Coupled cluster theory originated in nuclear physics [10,11] around 1960. Early studies in the 1970s [12] probed ground-state properties in limited spaces with free nucleon-nucleon interactions available at the time. The subject was revisited only recently by Guardiola et al. [13], for further theoretical development, and by Mihaila and Heisenberg [14], for coupled cluster calculations using realistic two- and three-nucleon bare interactions and expansions in the inverse particle-hole energy spacings. However, much of the impressive development in coupled cluster theory made in quantum chemistry in the last 15–20 years [5–9] still awaits applications to the nuclear many-body problem.

In this Letter, we apply quantum chemistry inspired coupled cluster methods [3-9,15,16] to finite nuclei. We show that the coupled cluster approach is numerically inexpensive and accurate by comparing our results for ⁴He with results from exact diagonalization in a model space consisting of four major oscillator shells. For the first time, we apply coupled cluster theory to excited states in nuclei, exploiting the equation of motion coupled cluster formalism [15,16]. We discuss several approximations within coupled cluster theory and also compute the ground state of the ¹⁶O nucleus within the same model space. We remind the reader that certain acronyms have become standard in quantum chemistry. For this reason, we use the same abbreviations in this Letter.

Coupled cluster theory is based on an exponential ansatz for the ground-state wave function $|\Psi_0\rangle =$ $\exp(T)|\Phi\rangle$. Here T is the cluster operator and $|\Phi\rangle$ is the reference determinant. In the CCSD ("coupled cluster with singles and doubles") method, we truncate the many-body expansion of the cluster operator T at twobody components. The truncated cluster operator $T^{(\text{CCSD})}$, used in the CCSD calculations, has the form [17] $T^{(\text{CCSD})} = T_1 + T_2$. Here $T_1 = \sum_{i,a} t_a^i a^a a_i$ and $T_2 = \frac{1}{4} \sum_{ij,ab} t_{ab}^{ij} a^a a^b a_j a_i$ are the singly and doubly excited clusters, with indices i, j, k (a, b, c) designating the single-particle states occupied (unoccupied) in the reference Slater determinant $|\Phi\rangle$ and $a^p(a_p)$ representing the creation (annihilation) operators. We determine the singly and doubly excited cluster amplitudes t_a^i and t_{ab}^{ij} , defining T_1 and T_2 , respectively, by solving the nonlinear system of algebraic equations, $\langle \Phi_i^a | \bar{H}^{(\text{CCSD})} | \Phi \rangle = 0$, $\langle \Phi_{ij}^{ab} | \bar{H}^{(\text{CCSD})} | \Phi \rangle = 0$, where $\bar{H}^{(\text{CCSD})} = \exp(-T^{(\text{CCSD})}) \times$ $H \exp(T^{(\text{CCSD})})$ is the similarity-transformed Hamiltonian and $|\Phi_i^a\rangle$ and $|\Phi_{ii}^{ab}\rangle$ are the singly and doubly excited Slater determinants, respectively. Once T_1 and T_2 amplitudes are determined, we calculate the ground-state CCSD energy $E_0^{(\text{CCSD})}$ as $\langle \Phi | \tilde{H}^{(\text{CCSD})} | \Phi \rangle$. For the excited states $|\Psi_K\rangle$ and energies $E_K^{(CCSD)}$ (K > 0), we apply the EOMCCSD ("equation of motion CCSD") approximation [15,16] (equivalent to the linear response and time-dependent CCSD methods [18]; cf. Refs. [5,6,16,19]), in which $|\Psi_K\rangle = R_K^{(\text{CCSD})} \times \exp(T^{(\text{CCSD})})|\Phi\rangle$. Here $R_K^{(\text{CCSD})} = R_0 + R_1 + R_2$ is a sum of the reference (R_0) , one-body (R_1) , and two-body (R_2) components obtained by diagonalizing $\bar{H}^{(\text{CCSD})}$ in the same space of singly and doubly excited determinants $|\Phi_i^a\rangle$ and $|\Phi_{ij}^{ab}\rangle$ as used in the ground-state CCSD calculations.

The CCSD and EOMCCSD methods are expected to describe the bulk of the correlation effects with inexpensive computational steps that scale as $n_o^2 n_u^4$, where $n_o(n_u)$ is the number of occupied (unoccupied) single-particle orbitals. While the inclusion of triply excited clusters T_3 in the cluster operator T and three-body component R_3 in the excitation operator R_K (or, using the language of quantum chemistry, "triples") increases the accuracy of the method, the resulting full CCSDT ("T" stands for triples) [20] and EOMCCSDT [21] methods scale as $n_o^3 n_u^5$ and are rather expensive. For this reason, we estimate the effects of T_3 and R_3 on ground- and excited-state energies by adding the *a posteriori* corrections due to triples to the CCSD/EOMCCSD energies, which require only the $n_o^3 n_u^4$ noniterative steps. These corrections can be derived using the method of moments of coupled cluster equations [8,9,22-24] and the perturbative analysis of the CCSDT/EOMCCSDT equations. The resulting groundand excited-state triples corrections, δ_0 and δ_K (K > 0), respectively, are calculated with the CR-CCSD(T)["completely renormalized CCSD(T)"] approach [8,9,22,23] in which

$$\delta_{K} = \frac{1}{36} \sum_{ijk,abc} \langle \tilde{\Psi}_{K} | \Phi_{ijk}^{abc} \rangle \mathcal{M}_{abc}^{ijk}(K) / \Delta_{K}.$$
(1)

Here $|\Phi_{ijk}^{abc}\rangle$ are the triply excited determinants and $\mathcal{M}_{abc}^{ijk}(K)$ are the generalized moments of the CCSD (K = 0) and EOMCCSD (K > 0) equations [22–24], $\mathcal{M}_{abc}^{ijk}(K) = \langle \Phi_{ijk}^{abc} | \bar{H}^{(\text{CCSD})} S_K^{(\text{CCSD})} | \Phi \rangle$, where $S_0^{(\text{CCSD})} = 1$ and $S_K^{(\text{CCSD})} = R_K^{(\text{CCSD})}$ for K > 0. They can be calculated using the CCSD and EOMCCSD cluster and excitation operators $T^{(\text{CCSD})}$ and $R_K^{(\text{CCSD})}$, respectively. The Δ_K denominators are defined as

$$\Delta_K = \langle \tilde{\Psi}_K | S_K^{(\text{CCSD})} \exp(T^{(\text{CCSD})}) | \Phi \rangle.$$
 (2)

The states $|\tilde{\Psi}_{K}\rangle$ in Eqs. (1) and (2) represent perturbative estimates of the CCSDT and EOMCCSDT wave functions. We have $|\tilde{\Psi}_{0}\rangle = \bar{P} \exp(T^{(\text{CCSD})} + \tilde{T}_{3})|\Phi\rangle$ and $|\tilde{\Psi}_{K}\rangle = \bar{P}(R_{K}^{(\text{CCSD})} + \tilde{R}_{3})\exp(T^{(\text{CCSD})})|\Phi\rangle$ for K > 0, where \bar{P} is a projection operator on the subspace spanned by the reference $|\Phi\rangle$ and singly, doubly, and triply excited determinants. The most complete forms of \tilde{T}_{3} and \tilde{R}_{3} defining the CR-CCSD(T), c approximation are [8,23]

$$\tilde{T}_{3} = \frac{1}{36} \sum_{ijk,abc} [\mathcal{M}_{abc}^{ijk}(0)/D_{ijk}^{abc}(0)] a^{a} a^{b} a^{c} a_{k} a_{j} a_{i}, \quad (3)$$

$$\tilde{R}_{3} = \frac{1}{36} \sum_{ijk,abc} \left[\mathcal{M}_{abc}^{ijk}(K) / D_{ijk}^{abc}(K) \right] a^{a} a^{b} a^{c} a_{k} a_{j} a_{i}, \quad (4)$$

where $D_{ijk}^{abc}(K) = E_K^{(\text{CCSD})} - \langle \Phi_{ijk}^{abc} | \bar{H}^{(\text{CCSD})} | \Phi_{ijk}^{abc} \rangle$. In the case of the ground-state calculations, we also consider simplified variants of the CR-CCSD(*T*) theory, termed 132501-2

CR-CCSD(T), a and CR-CCSD(T), b. In the case of CR-CCSD(T), b, the perturbative denominator $D_{ijk}^{abc}(0)$ is replaced by $-\langle \Phi_{ijk}^{abc} | \bar{H}_1^{(\text{CCSD})} | \Phi_{ijk}^{abc} \rangle$, where $\bar{H}_1^{(\text{CCSD})}$ is the one-body part of $\overline{H}^{(\text{CCSD})}$. For CR-CCSD(T), a we replace $D_{iik}^{abc}(0)$ by the standard many-body perturbation theory (MBPT) triples denominator ($\epsilon_i + \epsilon_j + \epsilon_k - \epsilon_k$ $\epsilon_a - \epsilon_b - \epsilon_c$), where ϵ_i and ϵ_a are the diagonal elements of the Fock matrix. Very accurate results for the excitation energies $E_K - E_0$ of many-electron systems are obtained if we use the complete CR-CCSD(T), c theory to calculate the energies of excited states and the CR-CCSD(T), b approximation for the ground-state energy [23]. For the ground states, it may sometimes be worthwhile to replace the Δ_0 denominator, Eq. (2), which renormalizes the triples correction δ_0 , by 1, since Δ_0 equals 1 plus terms of the second MBPT order or higher [22]. We indicate this by using acronyms, such as CR-CCSD(T), $c/\Delta_0 = 1$ [as opposed to CR-CCSD(T), c, where Δ_0 is included].

We use the Idaho-A nucleon-nucleon potential [25], which was produced using techniques of chiral effective field theory [26,27]. Modern two-nucleon interactions, such as Idaho-A, include short-range repulsive cores that require calculations in extremely large model spaces to reach converged results [14]. In order to remove the hard-core part of the interaction from the problem and thereby allow for realistic calculations in manageable model spaces, we renormalize the interactions through a G-matrix procedure for use in the 0s-0p-0d1s-0f1p oscillator basis. Our Hamiltonian is thus given by H = t + t $G(\tilde{\omega})$, where $\tilde{\omega}$ is the G-matrix starting energy. We use a simple procedure described in Ref. [28] to alleviate the starting-energy dependence of the G matrix in orbitals below the Fermi surface. We also modify the Hamiltonian by adding to it the center-of-mass Hamiltonian times a Lagrange multiplier $\beta_{c.m.}$. Thus, our Hamiltonian becomes $H' = H + \beta_{c.m.} H_{c.m.}$. We choose $\beta_{c.m.}$ such that the ground-state expectation value of $H_{c.m.} = 0.0$ MeV. Details may be found in Ref. [29].

We performed coupled cluster calculations for two closed-shell nuclei, ⁴He and ¹⁶O. We choose the oscillator strength $\hbar\omega$ to variationally minimize the CCSD energy. Shell-model diagonalization provided an exact answer in the ⁴He case. Comparing the exact ground- and excitedstate energies resulting from the diagonalization of the Hamiltonian in the small model space with the coupled cluster energies obtained in the same model space, we can assess the usefulness of various coupled cluster approximations in calculations for atomic nuclei. In particular, we can learn about the possible role of triply excited clusters in an accurate description of ground and excited states without confusing the inaccuracies resulting from the inadequate treatment of the many-body problem by a given coupled cluster approximation with other sources of error.

We report our results for the ground-state energy of ⁴He in Table I. Here we use an oscillator strength of

TABLE I. The ground-state energies of ⁴He calculated using the oscillator (Osc) and Hartree-Fock (HF) basis states. Units are MeV. The reference energies $\langle \Phi | H' | \Phi \rangle$ are -7.211 (Osc) and -10.520 (HF) MeV.

Method	Osc	HF
CCSD	-21.978	-21.385
$\operatorname{CR-CCSD}(T), a$	-22.841	-22.395
$\operatorname{CR-CCSD}(T), a/\Delta_0 = 1$	-23.524	-22.711
$\operatorname{CR-CCSD}(T), b$	-22.396	-22.179
$\operatorname{CR-CCSD}(T), b/\Delta_0 = 1$	-22.730	-22.428
$\operatorname{CR-CCSD}(T), c$	-22.630	-22.450
$\operatorname{CR-CCSD}(T), c/\Delta_0 = 1$	-23.149	-22.783
CISD	-20.175	-20.801
CISDT	-22.235	_
Exact	-23.484	-23.484

 $\hbar\omega = 10$ MeV, and $\beta_{c.m.} = 0.5$. The exact diagonalization shows that there is almost no center-of-mass contamination since $\langle \beta_{c.m.} H_{c.m.} \rangle \approx 0.7$ MeV. We used two types of reference determinants $|\Phi\rangle$: one constructed from the lowest-energy oscillator states and the unrestricted Hartree-Fock determinant. The two best methods in the oscillator basis are CR-CCSD(T), $a/\Delta_0 = 1$ and CR-CCSD(T), $c/\Delta_0 = 1$. They yield results within 40 and 300 keV of the full configuration interaction (CI) diagonalization problem, respectively. The CR-CCSD(T), a-c approaches are slightly less accurate than their $\Delta_0 =$ 1 analogs, but they have an advantage of providing upper bounds to the energy [the $\Delta_0 = 1$ methods may overshoot the exact results; cf. the CR-CCSD(T), $a/\Delta_0 = 1$ energy in Table I]. In general, the CR-CCSD(T) results are considerably more accurate than the results of the CCSD calculations, in which T_3 is ignored, although the CCSD approach describes the bulk of the correlation effects, reducing the large 16.273 MeV error obtained by calculating $\langle \Phi | H | \Phi \rangle$ with the oscillator reference $| \Phi \rangle$ to 1.5 MeV. We also compared the CCSD approach with the results of truncated shell-model calculations (CISD), in which the Hamiltonian is diagonalized in the space of singly and doubly excited determinants. The costs of the CISD and CCSD calculations are almost identical (both are $n_o^2 n_u^4$ procedures), and yet the error in the CISD energy obtained in the oscillator basis is twice as large as the error obtained with CCSD. The noniterative triples corrections defining the CR-CCSD(T) approaches reduce these errors to as little as 40 keV, which is a lot better than the 1.3 MeV error in the CISDT calculations, where the Hamiltonian is diagonalized in the much larger space of all singly, doubly, and triply excited determinants. This demonstrates the advantages of coupled cluster methods over the diagonalization techniques. Similar observations apply to the Hartree-Fock basis, although the coupled cluster results obtained with this basis are not as good as those obtained with the oscillator basis. Our Hartree-Fock basis results from a symmetry-breaking unrestricted calculation. Thus, a significant part of the coupled cluster effort

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must be spent to restore the symmetry. This is reminiscent of the molecular applications of coupled cluster theory, where the symmetry adapted restricted Hartree-Fock basis is often superior to the unrestricted and symmetrybreaking Hartree-Fock references. While the oscillator basis is superior in closed-shell nuclei, the CR-CCSD(T) results from the Hartree-Fock basis are not unreasonable, allowing us to contemplate using this basis in calculations for open-shell nuclei. (This would parallel the Hartree-Fock-based coupled cluster calculations for open-shell electronic states in chemistry.)

We used the EOMCCSD method and its CR-CCSD(T)extension to compute excited states. To our knowledge, this is the first time that nuclear excited states are computed using coupled cluster methods. The results for ⁴He are given in Table II. The low-lying J = 1 state has a considerable center-of-mass contamination (as indicated in the last column of Table II). The J = 0 (almost no center-of-mass contamination) and J = 2 (significant contamination) states calculated using EOMCCSD and CR-CCSD(T) are in excellent agreement with the results from the exact diagonalization. For these two states, the EOMCCSD approach provides the relatively small, 0.3-0.4 MeV, errors, which are further reduced by the CR-CCSD(T) triples corrections to <0.1 MeV. Based on the experience with the equation of motion coupled cluster methods in chemistry [5,8,15,21,23,24], the EOMCCSD approach works for the lowest-energy excited states of ⁴He since these states are dominated by singleparticle excitations. Again, a comparison of the EOMCCSD and CISD results shows that coupled cluster theory offers much higher accuracies compared to truncated diagonalization of similar numerical effort. This suggests that excitations in ⁴He and other nuclei can be computed with coupled cluster theory. Our results in Table II are indicative of the accuracies we may expect from such calculations.

We also applied the CCSD and CR-CCSD(*T*) methods to ¹⁶O, using an oscillator strength of $\hbar \omega = 14$ MeV and $\beta_{c.m.} = 1.0$. Table III shows the total ground-state energy values obtained with the CCSD and CR-CCSD(*T*) approaches. As in the ⁴He case, coupled cluster methods recover the bulk of the correlation effects, producing the results of the CISDTQ, or better, quality. CISDTQ stands for the expensive shell-model diagonalization in a huge space spanned by the reference and all singly, doubly,

TABLE II. The excitation energies of ⁴He calculated using the oscillator basis states (in MeV). The last column indicates the energy expectation for the center of mass mode.

State	EOMCCSD	$\operatorname{CR-CCSD}(T)^a$	CISD	Exact	$\langle \beta_{\rm c.m.} H_{\rm c.m.} \rangle$
J = 1	11.791	12.044	17.515	11.465	8.2
J = 0	21.203	21.489	24.969	21.569	0.8
J = 2	22.435	22.650	24.966	22.697	14.3

^aThe difference of the CR-CCSC(T), c energy of the excited state and the CR-CCSD(T), b energy of the ground state.

TABLE III. The ground-state energy of ¹⁶O calculated using various coupled cluster methods and oscillator basis states. The reference energy $\langle \Phi | H' | \Phi \rangle$ is -109.452 MeV.

Method	Energy
CCSD	-139.310
$\operatorname{CR-CCSD}(T), a$	-139.465
$\operatorname{CR-CCSD}(T), a/\Delta_0 = 1$	-139.621
$\operatorname{CR-CCSD}(T), b$	-139.375
$\operatorname{CR-CCSD}(T), b/\Delta_0 = 1$	-139.440
$\operatorname{CR-CCSD}(T), c$	-139.391
$\operatorname{CR-CCSD}(T), c/\Delta_0 = 1$	-139.467
CISD	-131.887
CISDT	-135.489
CISDTQ	-138.387

triply, and quadruply excited determinants (the most expensive steps of CISDTQ scale as $n_o^4 n_u^6$). To understand this result, we note that the CCSD T_1 and T_2 amplitudes are similar in order of magnitude. (For an oscillator basis, both T_1 and T_2 contribute to the first-order MBPT wave function.) Thus, the T_1T_2 disconnected triples are large, much larger than the T_3 connected triples, and the difference between the CISDT (CI singles, doubles, and triples) and CISD energies is mostly due to T_1T_2 . The small T_3 effects, as estimated by CR-CCSD(T), are consistent with the CI diagonalization calculations. If the T_3 corrections were large, we would observe a significant lowering of the CCSD energy, far below the CISDTQ result. The CISDTQ diagonalization is not size extensive, while the CCSD and $\text{CR-CCSD}(T)/\Delta_0 = 1$ methods maintain this property. Moreover, the CCSD and CR-CCSD(T) methods bring the non-negligible higher-than-quadruple excitations, such as $T_1^3 T_2$, $T_1 T_2^2$, and T_2^3 , which are not present in CISDTQ. It is, therefore, quite likely that the CR-CCSD(T) results are very close to the results of the exact diagonalization, which cannot be performed.

In summary, we used the quantum chemistry inspired coupled cluster approximations to calculate the ground and excited states of the ⁴He and ¹⁶O nuclei. By comparing coupled cluster results with the exact results obtained by diagonalizing the Hamiltonian in the same model space, we demonstrated that relatively inexpensive coupled cluster approximations recover the bulk of the nucleon correlation effects in ground- and excited-state nuclei. These results are a strong motivation to further develop coupled cluster methods for the nuclear manybody problem, so that accurate *ab initio* calculations for small- and medium-size nuclei become as routine as the molecular electronic structure calculations.

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- S. C. Pieper, K. Varga, and R. B. Wiringa, Phys. Rev. C 66, 044310 (2002).
 - [2] P. Navratil, J. P. Vary, and B. R. Barrett, Phys. Rev. Lett. 84, 5728 (2000).
 - [3] J. Čížek, J. Chem. Phys. 45, 4256 (1966).
 - [4] J. Čížek, Adv. Chem. Phys. 14, 35 (1969).
 - [5] R. J. Bartlett, in *Modern Electronic Structure Theory*, edited by D. R. Yarkony (World Scientific, Singapore, 1995), Vol. 1, pp. 1047–1131.
 - [6] J. Paldus and X. Li, Adv. Chem. Phys. 110, 1 (1999).
 - [7] T. D. Crawford and H. F. Schaefer III, Rev. Comput. Chem. 14, 33 (2000).
 - [8] P. Piecuch, K. Kowalski, I.S.O. Pimienta, and M.J. McGuire, Int. Rev. Phys. Chem. 21, 527 (2002).
 - [9] P. Piecuch, K. Kowalski, P.-D. Fan, and I. S. O. Pimienta, in *Progress in Theoretical Chemistry and Physics*, edited by J. Maruani, R. Lefebvre, and E. Brändas (Kluwer, Dordrecht, 2003), Vol. 12, pp. 119–206.
 - [10] F. Coester, Nucl. Phys. 7, 421 (1958).
 - [11] F. Coester and H. Kümmel, Nucl. Phys. 17, 477 (1960).
 - [12] H. Kümmel, K. H. Luhrmann, and J. G. Zabolitzky, Phys. Rep. 36, 1 (1978), and references therein.
 - [13] R. Guardiola et al., Nucl. Phys. A609, 218 (1996).
 - [14] J. H. Heisenberg and B. Mihaila, Phys. Rev. C 59, 1440 (1999); B. Mihaila and J. H. Heisenberg, Phys. Rev. C 61, 054309 (2000).
 - [15] J. F. Stanton and R. J. Bartlett, J. Chem. Phys. 98, 7029 (1993).
 - [16] P. Piecuch and R. J. Bartlett, Adv. Quantum Chem. 34, 295 (1999).
 - [17] G. D. Purvis and R. J. Bartlett, J. Chem. Phys. 76, 1910 (1982).
 - [18] H. Monkhorst, Int. J. Quantum Chem. Quantum Chem. Suppl. 11, 421 (1977); K. Emrich, Nucl. Phys. A351, 379 (1981); E. Dalgaard and H. Monkhorst, Phys. Rev. A 28, 1217 (1983); M. Takahashi and J. Paldus, J. Chem. Phys. 85, 1486 (1986).
 - [19] R.F. Bishop, in *Microscopic Quantum Many-Body Theories and Their Applications*, Lecture Notes in Physics Vol. 510, edited by J. Navarro and A. Polls (Springer, Berlin, 1998), pp. 1–70.
 - [20] J. Noga and R. J. Bartlett, J. Chem. Phys. 86, 7041 (1987);
 89, 3401(E) (1988); G. E. Scuseria and H. F. Schaefer III, Chem. Phys. Lett. 152, 382 (1988).
 - [21] K. Kowalski and P. Piecuch, J. Chem. Phys. 115, 643 (2001).
 - [22] K. Kowalski and P. Piecuch, J. Chem. Phys. 113, 18 (2000).
 - [23] K. Kowalski and P. Piecuch, J. Chem. Phys. 120, 1715 (2004).
 - [24] K. Kowalski and P. Piecuch, J. Chem. Phys. 115, 2966 (2001).
 - [25] D. R. Entem and R. Machleidt, Phys. Lett. B 524, 93 (2002).
 - [26] S. Weinberg, Phys. Lett. B 251, 288 (1990).
 - [27] U. van Kolck, Prog. Part. Nucl. Phys. 43, 337 (1999).
 - [28] K. Gad and H. Müther, Phys. Rev. C 66, 044301 (2002).
 - [29] D. J. Dean and M. Hjorth-Jensen, e-print nucl-th/ 0308088 [Phys. Rev. C (to be published)].