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UCRL-PROC-201751

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Janaury 15, 2004

The Sixth International Conference on Radioactive Nuclear
Beams (RNB6)
Argonne, IL
September 22-26, 2003

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No-core shell-model calculations in light nuclei with three-nucleon forces

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The *ab initio* No-Core Shell Model (NCSM) has recently been expanded to include nucleon-nucleon (NN) and three-nucleon (3N) interactions at the three-body cluster level. Here it is used to predict binding energies and spectra of *p*-shell nuclei based on realistic NN and 3N interactions. It is shown that 3N force (3NF) properties can be studied in these nuclear systems. First results show that interactions based on chiral perturbation theory lead to a realistic description of ⁶Li.

1. Introduction

One of the most demanding goals of nuclear physics is still the understanding of the underlying interaction. In recent years several advances have been made. Firstly, it was possible to develop a series of interaction models, which describe the rich set of NN data perfectly [1–3]. In few-nucleon systems, predictions, e.g. binding energies, of all these models can differ from the experiment, which is seen as a first signature of 3NF's. *Ad hoc* combinations of NN and 3NF's are able to provide the correct binding energies for the 3N and 4N system [4,5], but fail for *p*-shell nuclei and some 3N scattering observables. On the other hand, the application of chiral perturbation theory made the development of consistent NN and 3NF models possible [6,7]. It remains to be shown, whether this effective-field-theory (EFT) approach describes the *p*-shell nuclei correctly.

The current contribution presents a first step in this direction. Recent results for the *p*-shell nuclei using the NCSM approach are based not only on realistic NN, but also on 3N interactions [8]. Thereby, one is not restricted to local or simplified interactions. More details on the formalism of this approach to nuclear structure can be found in Vary's contribution to these proceedings [9].

*Supported in part by NSF grant PHY-0070858.

†This work was partly performed under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

‡Supported in part by USDOE grant No. DE-FC02-01ER41187 and DE-FG03-00ER41132

§Supported in part by USDOE grant No. DE-FG-02-87ER-40371.

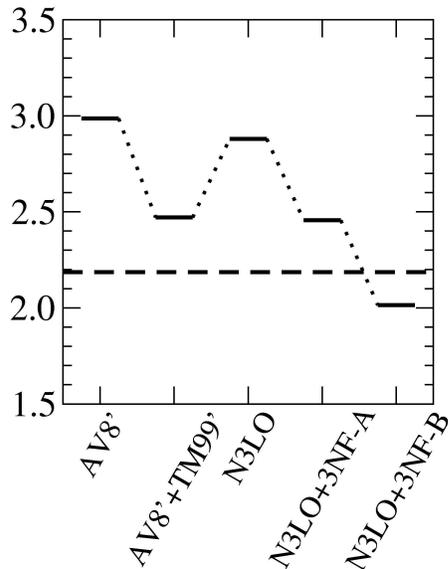


Figure 1. The excitation energy of the 3^+ state of ${}^6\text{Li}$ for various NN and 3N interactions. The dashed line marks the experimental value.

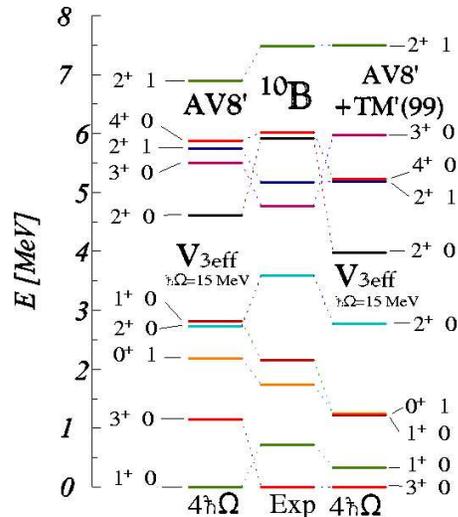


Figure 2. Comparison of ${}^{10}\text{B}$ excitation spectra for AV8' and AV8' and TM99'.

2. Results

It was found earlier using the Greens Function Monte Carlo (GFMC) technique that, *e.g.*, the ${}^6\text{Li}$ binding energy and excitation energy are not correctly described by the AV18 NN and Urbana IX 3N interaction, though they predict the ${}^3\text{H}$ and ${}^4\text{He}$ binding energies almost correctly (see *e.g.* [5]). This and other failures in more complex p -shell nuclei motivated the extension of the Argonne-Urbana interaction model, leading to the series of Illinois 3N interactions [5], which resolve this problem. However, the proposed structure is expected to be of less importance in the EFT approach, and we argue here that the necessity of extending the 3NF as done in [5] is not confirmed by other realizations of the 2π exchange 3NF.

For this task, the spectra of the light nuclei are well suited. As shown in Vary's contribution [9], the NCSM results for the spectra can be predicted more accurately than the binding energies. Figure 1 shows our results for the excitation energy of the 3^+ state in ${}^6\text{Li}$. Looking at the predictions for the AV8' NN interaction [10] with and without the 2π exchange Tucson-Melbourne (TM99') 3NF[11]. To assure the correct ${}^3\text{H}$ binding energy, we adjusted the form factor cut-off in TM99' correspondingly. One observes that the TM99' 3NF reduces the splitting by 500 keV leaving only 300 keV overprediction. This is considerably smaller than the 800 keV predicted by AV18+Urbana using GFMC[5]. We consider the small 300 keV deviation as an indication that the spin-orbit strength of TM99' is almost sufficient. This feature of TM99' becomes even more pronounced for ${}^{10}\text{B}$. As seen in Fig. 2, calculations using only NN forces predict the wrong ordering of

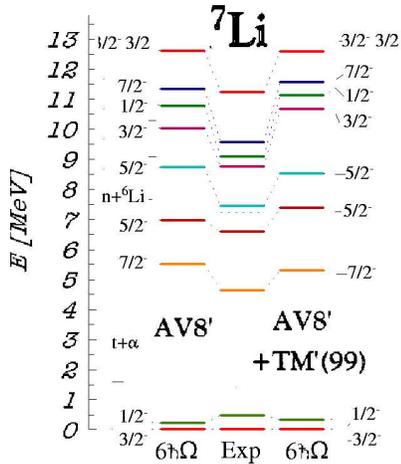


Figure 3. Comparison of ${}^7\text{Li}$ excitation spectra for AV8' and AV8' and TM99'.

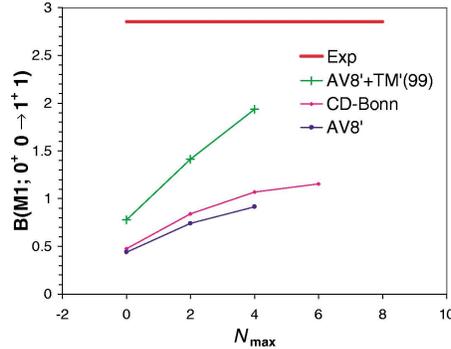


Figure 4. M1 transition matrix element for Gamow-Teller transitions from the 0^+0 to the 1^+1 states in ${}^{12}\text{C}$.

ground state and first excited state. The Urbana IX 3NF does not change this incorrect prediction [12]. On the other hand, we find that the contribution of TM99' is large enough to cure this insufficiency, which clearly shows that both forces differ and that these differences can be seen in the spectra of p -shell nuclei.

Another important aspect, which cannot be investigated by nucleon-deuteron scattering, is the isospin dependence of the 3NF. The spectra of the light nuclei reveal interesting differences of the Urbana IX and TM99' predictions. It is known that the Urbana IX interaction increases the binding energy difference of the $\frac{3}{2}^-$ states of ${}^7\text{He}$ and ${}^7\text{Li}$ by 1.6 MeV [5], though the experimental difference is almost correctly predicted by AV18 only. As can be seen in Fig. 3, we find almost no difference between the the $J^\pi T = \frac{3}{2}^+ \frac{1}{2}$ and $\frac{3}{2}^+ \frac{3}{2}$ level splittings of ${}^7\text{Li}$ using our AV8' calculations with or without TM99'. This indicates that also the isospin dependence of the TM99' and Urbana 3NF's are different and that p -shell nuclei are sensitive to these differences.

Chiral EFT predicts consistent NN and 3NF's. This has been exploited recently [7] and determines the 2π exchange part of the 3NF once the NN force is given. Additionally, in leading order, a 1π exchange and a pure contact part of the 3NF are found. The strengths of both parts can be determined from 3N and 4N observables. We augment the chiral Idaho N3LO interaction [13] by the chiral 3NF and fix these strengths using the 3N and 4N binding energies. The results for the ${}^6\text{Li}$ excitation energy are also shown in Fig. 1. Two sets of the parameters can be found, which describe the 3N and 4N binding energies equally well. They are labeled by 3NF-A and 3NF-B in the figure, and our calculations show that their predictions for the ${}^6\text{Li}$ excitation energy differ. It is seen that both predictions are of similar quality. We are currently investigating both 3NF's in more complex systems, which will hopefully allow us to rule out one set of parameters and come to a unique, chiral NN and 3N interaction model.

Finally, we would like to discuss the sensitivity of matrix elements to 3NF's. Such

sensitivity has been found for the B(M1) matrix element of the Gamow-Teller transition from the ^{12}C ground to the $J^\pi T = 1^+1$ state in [14]. The calculation was performed without renormalization of the bare transition operator, which leads to a large model space dependence of this result. As can be seen in Fig. 4, we seem to obtain convergence for the most advanced calculations with the model space size $N = 6$ (see [9] for an explanation of N), utilizing only the NN force. Without 3NF's, we underpredict the experimental value by almost a factor of 3. Including the TM99' 3NF, we cannot reach convergence, but observe an considerable increase of the matrix element. The TM99' interaction gives important contributions to the spin-orbit strength, which may bring experiment and theory into agreement for this observable.

3. Summary

In summary we presented results of recent NCSM calculations for light nuclei based on realistic NN and 3N interactions. We showed that the Urbana and TM99' interaction models predict different spectra, though both are based on a 2π exchange model. For the new chiral NN and 3NF's, we presented first results for ^6Li . Two sets of parameters of the 3NF lead to different excitation energies, though both sets give accurate 3N and 4N binding energies. Both excitation energies are in reasonable agreement with experiment. Therefore we are currently extending these calculations to more complex systems to pin down the parameters realized in nature. It will also be interesting to see whether the EFT inspired interactions have a reasonable spin and isospin dependence. Finally, we reported results for ^{12}C that show that also matrix elements can be sensitive to the 3NF's. Therefore the 3NF's are an important ingredient in nuclear structure calculations.

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