Microscopic Nuclear Structure Based upon a Chiral $NN$ Potential

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We report on shell-model calculations employing effective interactions derived from a new realistic nucleon-nucleon ($NN$) potential based on chiral effective field theory. We present results for $^{18}$O, $^{134}$Te, and $^{210}$Po. Our results are in excellent agreement with experiment indicating a remarkable predictive power of the chiral $NN$ potential for low-energy microscopic nuclear structure.

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One of the most fundamental challenges pervading theoretical nuclear physics for half a century is to understand the properties of nuclei in terms of the basic interactions between the constituents. After early progress \cite{1}, the field was plagued for decades by what is known as the off-shell uncertainty of the nuclear force. Related to this issue is the problem that it was not possible to derive the nuclear force from first principles.

Recently, the picture changed dramatically when the effective field theory (EFT) concept was recognized in nuclear physics \cite{2}. The fundamental theory of strong interaction, QCD, is nonperturbative in the low-energy regime characteristic for nuclear physics; and this fact was generally perceived as the great obstacle for a proper derivation of the nuclear force. EFT shows the way out of this dilemma. The key is to notice that different phenomena in nature are often characterized by different energy scales. Traditional nuclear physics typically deals with low energies below the so-called chiral symmetry breaking scale, $\Lambda\approx 1$ GeV, where the appropriate degrees of freedom are pions and nucleons (and not quarks and gluons) interacting via a force that is governed by the symmetries of QCD, particularly, (broken) chiral symmetry.

The derivation of the nuclear force from chiral EFT was initiated by Weinberg \cite{3} and pioneered by Ordóñez \cite{4} and van Kolck \cite{5,6}. Subsequently, many groups got involved in the subject \cite{7,8,9,10,11,12}. As a result, efficient methods for deriving the nuclear force from chiral Lagrangians emerged \cite{7,10} and the quantitative nature of the chiral $NN$ potential improved \cite{10}. Nevertheless, for a long time, even the ‘best’ chiral $NN$ potentials were too inaccurate to serve as reliable input for exact few-nucleon calculations or microscopic nuclear many-body theory. Recently, the situation has changed substantially with the appearance of the chiral $NN$ potential of Ref. \cite{13}, also known as the Idaho chiral potential. This potential reproduces the $NN$ data below 210 MeV with a $\chi^2$/datum = 0.98 \cite{14}, i. e., with the same accuracy as the high-precision $NN$ potentials constructed in the 1990’s \cite{15,16,17,18}.

The EFT approach inspires a new method \cite{19} to renormalize the bare $NN$ interaction. The idea is to derive a low-momentum $NN$ potential, $V_{\text{low}-k}$, that preserves the physics of the original $NN$ interaction up to a certain cut-off momentum $\Lambda$. The deuteron binding energy, low-energy scattering phase shifts, and low-momentum half-on shell T-matrix of the original $V_{NN}$ are reproduced by $V_{\text{low}-k}$ \cite{19}. This is achieved by integrating out high-momentum components of the original $V_{NN}$ by means of an iterative method \cite{20,21}. Such decimation is similar to a Renormalization Group (RG) transformation \cite{22}. The resulting $V_{\text{low}-k}$ is a smooth potential, which is suitable for being used in low-energy nuclear physics.

We have employed the chiral $NN$ potential to conduct shell-model calculations for various two valence-particles nuclei. More precisely, once we have derived the $V_{\text{low}-k}$, starting from the chiral Idaho-B $NN$ potential \cite{13}, we have employed it to calculate shell-model effective interactions using the $Q$-box plus folded diagram method \cite{23}. These are the first microscopic nuclear structure calculations, for a wide mass range, performed by using a new realistic $NN$ potential based on chiral effective field theory.

In order to illustrate how shell-model calculations based upon these new chiral effective interactions can describe the spectroscopic properties of nuclei near closed shells, we report here results we have obtained for $^{18}$O, $^{134}$Te, and $^{210}$Po, which are specimens of light-, medium-, and heavy-mass nuclei with two valence particles.

As customary, we use single-particle energies extracted from the experimental spectra of the corresponding single-particle valence nuclei. In Figs. 1-3 we compare the experimental \cite{24} and theoretical spectra for $^{18}$O, $^{134}$Te, and $^{210}$Po, respectively. More precisely, we consider the positive parity energy spectrum up to 4 MeV for $^{18}$O, while for $^{134}$Te and $^{210}$Po we report the whole...
experimental spectra up to 5 and 3.3 MeV, respectively.

From Figs. 1-3 we see that the experimental spectra are very well reproduced by the calculated ones, the discrepancy in the excitation energies being less than 100 keV for most of the states. As a matter of fact the rms deviation $\sigma$ turn out to be 140, 111, and 86 keV for $^{18}$O, $^{134}$Te, and $^{210}$Po, respectively.

In Table I, we show the observed [26, 27] and calculated ground-state binding energies relative to the closest doubly closed core for the three nuclei under consideration. For the absolute scaling of the sets of single-particle energies, the mass excess values for nuclei with one particle with respect to $^{16}$O, $^{132}$Sn, and $^{208}$Pb have been taken from Ref. [28].

For $^{134}$Te and $^{210}$Po, we assume that the contribution of the Coulomb interaction between the valence protons is equal to the matrix element of the Coulomb force between the states \( (g_{\pi})_{\gamma=0+} \) and \( (h_{\pi})_{\gamma=0+} \), respectively. From Table I we see that our predictions are in very good agreement with experiment.

In summary, we have performed shell-model calculations in which $V_{low-k}$ vertices derived from a chiral NN potential (Idaho B) are used as input instead of $G$ matrix vertices. The calculated spectra as well as the binding energies for the three nuclei $^{18}$O, $^{134}$Te, and $^{210}$Po are in excellent agreement with the experimental data. We wish to point out that the degree of accuracy is comparable to that obtained in our previous studies using effective interactions derived from modern realistic NN potentials rooted in the meson theory of nuclear forces, in particular the CD-Bonn potential [28]. We may conclude that our present calculations, which are the first where a realistic chiral NN potential has been used, show that this potential is a valid input for a microscopic description of nuclear structure properties.

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[25] We define $\sigma = \left\{ \frac{1}{N_d} \sum_{i} \left[ E_{\exp}(i) - E_{\text{calc}}(i) \right]^2 \right\}^{1/2}$, where $N_d$ is the number of data.
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TABLE I: Experimental and calculated ground-state binding energies (MeV). See text for comments.

| Nucleus | Expt.       | Calc.  |
|---------|-------------|--------|
| $^{18}\text{O}$ | $12.19 \pm 0.00$ | $12.19$ |
| $^{134}\text{Te}$ | $20.56 \pm 0.03$ | $20.64$ |
| $^{210}\text{Po}$ | $8.78 \pm 0.00$ | $8.78$ |

FIG. 1: Experimental and calculated spectrum of $^{18}\text{O}$.
FIG. 2: Experimental and calculated spectrum of $^{134}\text{Te}$.
FIG. 3: Experimental and calculated spectrum of $^{210}\text{Po}$. 
$^{18}\text{O}$

| Energy (MeV) | Expt. | Calc. |
|--------------|-------|-------|
| 0            | 0$^+$ | 0$^+$ |
| 1            |       |       |
| 2            | 2$^+$ |       |
| 3            | 0$^+$ | 2$^+$ |
| 4            | 2$^+$ | 0$^+$ | 4$^+$ |
\[ \begin{align*}
\text{E(MeV)} & \quad 0^+ & \quad 1 & \quad 2 & \quad 3 & \quad 4 \\
\text{Expt.} & \quad 2^+ & \quad 6^+ & \quad 4^+ & \quad 2^+ & \quad 0^+ \\
\text{Calc.} & \quad 0^+ & \quad 6^+ & \quad 4^+ & \quad 2^+ \\
\text{134 Te} & \quad 8^- & \quad 6^+ & \quad 5^- & \quad 5^+ & \quad 8^- \\
& \quad 5^- & \quad 5^- & \quad 5^- & \quad 5^- & \quad 5^- \\
& \quad 9^- & \quad 9^- & \quad 9^- & \quad 9^- & \quad 9^- \\
& \quad 2^+ & \quad 2^+ & \quad 2^+ & \quad 2^+ & \quad 2^+ \\
& \quad 6^+ & \quad 6^+ & \quad 6^+ & \quad 6^+ & \quad 6^+ \\
& \quad 4^+ & \quad 4^+ & \quad 4^+ & \quad 4^+ & \quad 4^+ \\
& \quad 2^+ & \quad 2^+ & \quad 2^+ & \quad 2^+ & \quad 2^+ \\
\end{align*} \]