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Realistic shell model study of nuclei around ^{132}Sn

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Abstract. We have performed shell model calculations for ^{134}Te, ^{130,134}Sn, and ^{132,134}Sb using a realistic effective interaction derived from the CD-Bonn nucleon-nucleon potential. The calculated results are compared with the available experimental data. The main aim of this study was to put to a comprehensive test our realistic effective interaction in the $A = 132$ region. A very good agreement is obtained for all the five nuclei considered.

PACS. 21.60.Cs Shell model – 21.30.Fe Forces in hadronic systems and effective interactions – 27.60.+j $90 \leq A \leq 149$

1 Introduction

In recent years, there has been significant progress in the experimental knowledge of neutron-rich nuclei with few particles or holes outside doubly magic ^{132}Sn [1]. These nuclei are of special interest since they provide direct information about effective charges, nucleon-nucleon effective interaction, and single-particle (SP) or single-hole (SH) energies in this mass region. To this end, the most appropriate systems are those having or lacking at most two nucleons with respect to ^{132}Sn (see fig. 1). For each of these nuclei, spectroscopic data are nowdays available, although still limited in number.

In this paper, we focus our attention on the five nuclei ^{134}Te, ^{130,134}Sn, and ^{132,134}Sb, which provide the opportunity of performing a complete study of the two-body matrix elements of the effective interaction in the $A = 132$ region. In fact, each of the three isobars ^{134}Te, ^{134}Sn, and ^{134}Sb yields direct information about the particle-particle (pp) matrix elements in the proton-proton, neutron-neutron, and proton-neutron channel, separately. The two nuclei ^{130}Sn and ^{132}Sb provide a test for the hole-hole (hh) and particle-hole (ph) matrix elements in the neutron-neutron and proton-neutron channel, respectively.

During the past few years, we have studied several nuclei around ^{132}Sn in terms of shell model employing realistic effective interactions derived from modern nucleon-nucleon (NN) potentials [2–6]. Here we present our results for the five nuclei mentioned above with the aim to give a scenario of the role of realistic effective interactions in this mass region.

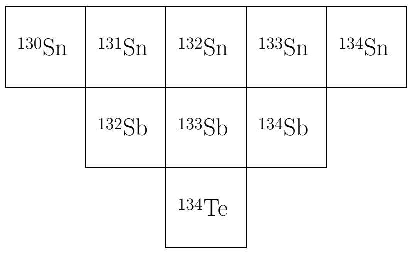

Fig. 1. Nuclei having at most two-valence particles or holes with respect ^{132}Sn.

In our calculations we have considered ^{132}Sn as a closed core and let the valence protons and neutron holes occupy the five levels of the 50-82 shell while the neutron particles fill the six levels of the 82-126 shell. The effective two-body matrix elements have been derived from the CD-Bonn NN potential [7]. The adopted SP and SH energies have been taken from the experimental spectra of the three odd nuclei of fig. 1, wherever available. Their values and a brief outline of the derivation of the realistic effective interaction $V_{\rm eff}$ is given in sect. 2, while our results are compared to the experimental data in sect. 3. Furthermore, based on the good agreement between theory and experiment obtained for all considered nuclei, we have found it challenging to make predictions which could stimulate experimental efforts to gain further information. Section 4 contains a summary of our conclusions.

2 Outline of calculations

As mentioned in the introduction, we have made use of a realistic effective interaction derived from the CD-Bonn

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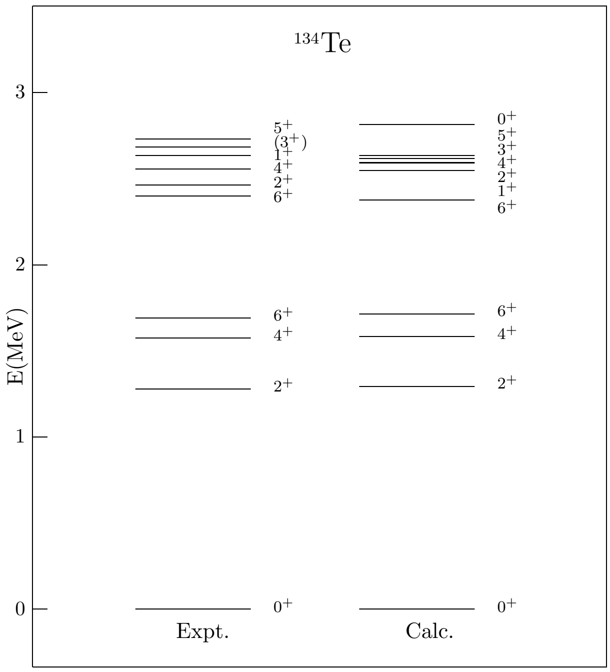

Fig. 2. Experimental and calculated spectra of ^{134}Te.

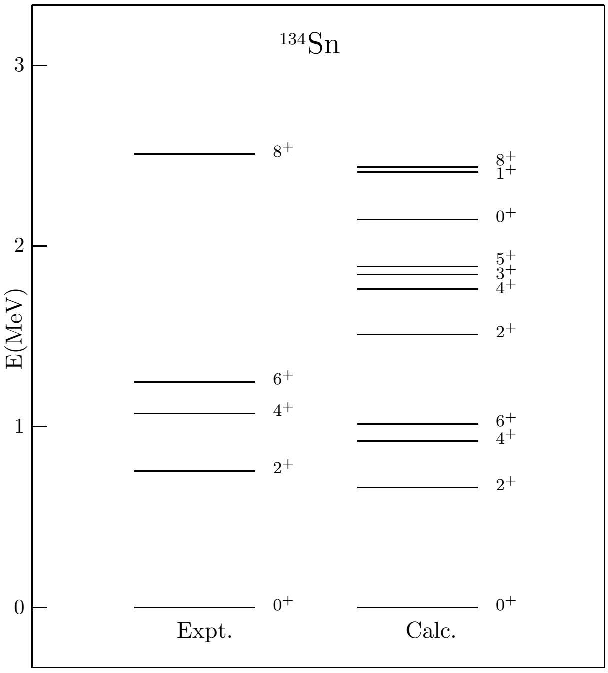

Fig. 3. Experimental and calculated spectra of ^{134}Sn.

NN potential. This potential, as all modern NN potentials, contains a strong repulsive core which prevents its direct use in nuclear-structure calculations. This difficulty is usually overcome by resorting to the well-known Brueckner G-matrix method. Here, we have made use of a new approach [8] which provides an advantageous alternative to the use of the above method. It consists in constructing a low-momentum NN potential, $V_{\text{low-}k}$, that preserves the physics of the original potential V_{NN} up to a certain cut-off momentum Λ. In particular, the scattering phase shifts and the deuteron binding energy calculated from V_{NN} are reproduced by $V_{\text{low-}k}$. The latter is a smooth potential that can be used directly as input for the calculation of shell model effective interactions. A detailed description of our derivation of $V_{\text{low-}k}$ can be found in [8], where a criterion for the choice of the cut-off parameter Λ is also given. We have used here the value $\Lambda = 2.1\,\text{fm}^{-1}$. Once the $V_{\text{low-}k}$ is obtained, the calculation of V_{eff} is carried out within the framework of a folded-diagram method, as described, for instance, in refs. [9] and [10] for matrix elements in the pp and hh formalism, while in [6] our procedure for the ph matrix elements can be found.

The SP energies for the proton and neutron levels of the 50-82 and 82-126 shells have been taken from the experimental spectra of ^{133}Sb [11] and ^{133}Sn [12], respectively. The only exceptions are the proton $\epsilon_{s_{1/2}}$ and the neutron $\epsilon_{i_{13/2}}$, which have been taken from refs. [2] and [5], since the corresponding SP levels have not been observed. Our adopted values for the single-proton energies are (in MeV): $\epsilon_{g_{7/2}} = 0.0$, $\epsilon_{d_{5/2}} = 0.962$, $\epsilon_{d_{3/2}} = 2.439$, $\epsilon_{h_{11/2}} = 2.793$, and $\epsilon_{s_{1/2}} = 2.800$, and for the single-neutron energies: $\epsilon_{f_{7/2}} = 0.0$, $\epsilon_{p_{3/2}} = 0.854$, $\epsilon_{h_{9/2}} = 1.561$, $\epsilon_{p_{1/2}} = 1.656$, $\epsilon_{f_{5/2}} = 2.055$, and $\epsilon_{i_{13/2}} = 2.694$. As regards the neutron SH energies, they have been taken from the experimental spectrum of ^{131}Sn [13,14] and their values are: $\epsilon^{-1}_{d_{3/2}} = 0.0$, $\epsilon^{-1}_{h_{11/2}} = 0.100$, $\epsilon^{-1}_{s_{1/2}} = 0.332$, $\epsilon^{-1}_{d_{5/2}} = 1.655$, and $\epsilon^{-1}_{f_{7/2}} = 2.434$.

The theoretical results presented in the next section have been obtained by using the OXBASH shell model code [15].

3 Results and comparison with experiment

Let us start by showing our results for nuclei with two identical-valence particles or holes, *i.e.* ^{134}Te, ^{134}Sn, and ^{130}Sn. The calculated spectra of these three nuclei are compared with the experimental ones in figs. 2-4.

As regards the two-proton nucleus ^{134}Te, all the calculated and experimental [16,17] levels up to about 3 MeV are reported. We see that a one-to-one correspondence can be established between the levels of the two spectra, the only exception being the second calculated 0^+ state at 2.81 MeV with no experimental counterpart. The existence of this state is, however, strongly supported by the information available for the two heavier $N = 82$ isotones. In fact, in ^{136}Xe and ^{138}Ba a 0^+ state has been observed at 2.58 and 2.34 MeV, respectively. The calculated states shown in fig. 2 are all the 10 states arising from the $g^2_{7/2}$ and $g_{7/2}d_{5/2}$ configurations, in addition to the second 0^+ state which is dominated by the $d^2_{5/2}$ configuration. The excitation energies of all calculated states are in a very good agreement with the experimental values, the discrepancies being smaller than 50 keV for most of them.

For ^{134}Sn, with two neutrons outside the $N = 82$ shell, rather little experimental information is presently available [18,19]. As we can see in fig. 3, a much richer spectrum

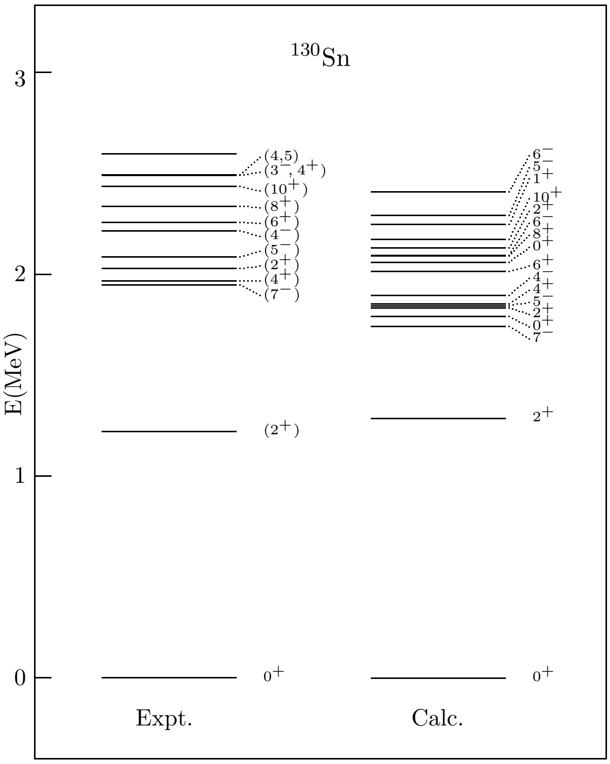

Fig. 4. Experimental and calculated spectra of ^{130}Sn.

is, however, predicted by the theory. For the first four observed states, a correspondence can be established with the lowest calculated ones with the same angular momentum and parity, which we find to pertain to the $f_{7/2}^2$ multiplet. The other observed level can be safely associated with the calculated 8^+ state at 2.44 MeV, which is the highest-spin member of the $f_{7/2}h_{9/2}$ multiplet. Between 1.5 and 2.4 MeV we predict the existence of six more states. In particular, we find four seniority-2 and one seniority-0 states coming from the $f_{7/2}p_{3/2}$ and $p_{3/2}^2$ configurations, in addition to the lowest-spin member (1^+) of the $f_{7/2}h_{9/2}$ multiplet. The agreement between experimental and calculated excitation energies is quite satisfactory, the largest discrepancy being about 200 keV for the 6^+ state.

In fig. 4, all the experimental [16] and calculated levels up to about 2.5 MeV are reported for ^{130}Sn, which has two-neutron holes in the 50-82 shell. It should be mentioned that above this excitation energy there is a pronounced gap (about 700 keV), both in the experimental and theoretical spectrum. This is essentially due to the structure of the SH spectrum, as is evidenced by the fact that the calculated states below 2.5 MeV have angular momenta and parities which are just those arising from the six $(s_{1/2},d_{3/2},h_{11/2})^{-2}$ configurations. Each of the nine lowest-lying excited states in the observed spectrum, but the second 2^+ state, can be identified with a level predicted by the theory. Concerning the 2^+ state at 2.03 MeV, it can be associated to either the second or the third calculated 2^+ state, which are at 1.83 and 2.13 MeV, respectively. For the three observed highest-lying levels with no firm or without spin-parity assignment, we cannot propose any safe identification with our calculated states. Note that we predict six more states in addition to the above-mentioned ones. As regards the quantitative agreement for the eight identified levels, we find in this case slightly larger discrepancies as compared to ^{134}Te and ^{134}Sn. In fact, for 5 out of the 8 levels the differences between calculated and experimental energies are from 200 to 300 keV.

We come now to discuss the two odd-odd nuclei ^{132}Sb and ^{134}Sb, which are the most appropriate systems to study the proton-neutron interaction. Let us start with ^{132}Sb with one-proton valence particle and one-neutron valence hole with respect to ^{132}Sn. Several calculated multiplets of this nucleus are reported in fig. 5 and compared with the existing experimental data [20,21]. The energies in fig. 5(a) are relative to the 4^+ state while in fig. 5(b) they are relative to the 8^- state. The spacing between these two levels is, in fact, unknown. There are indications that the 8^- state is located about 200 keV above the 4^+ state [22], in agreement with our calculations which predict an excitation energy for the 8^+ of 226 keV. Note that in the $\pi h_{11/2}\ \nu h_{11/2}^{-1}$ multiplet we have not included the 0^+, 1^+, and 2^+ states, since no positive-parity state with one of these angular momenta was found to be dominated by this component. As regards the comparison between theory and experiment, we see that the calculated energies are in good agreement with the observed ones. In fact, the discrepancies are all in the order of few tens of keV, the only exceptions being the 1^+ and 9^- states of the $\pi d_{5/2}\ \nu d_{3/2}^{-1}$ and $\pi g_{7/2}\ \nu h_{11/2}^{-1}$ multiplets, which come about 300 and 200 keV above their experimental counterparts, respectively. It is evident from fig. 5 that a main feature of all these multiplets (obviously leaving aside the doublet $\pi g_{7/2}\ \nu s_{1/2}^{-1}$) is that the states with minimum and maximum J have the highest excitation energy, while the state with next-to-the-highest J is the lowest one. This pattern is in agreement with the experimental one for the $\pi g_{7/2}\ \nu d_{3/2}^{-1}$ multiplet and the few experimental data available for the other multiplets also go in the same direction. It should be mentioned that in ref. [6] we have also studied the $\pi g_{7/2}\ \nu h_{11/2}^{-1}$ multiplet of ^{130}Sb, for which more experimental data are available. The behavior of this multiplet, which is also very well reproduced by our calculations, completely supports our predictions for ^{132}Sb.

Finally, in fig. 6 we report the calculated multiplet $\pi g_{7/2}\ \nu f_{7/2}$ of ^{134}Sb, with one-proton and one-neutron valence particle outside the ^{132}Sn core. Some preliminary experimental results for the lowest excited states with $J^\pi = 1^-, 2^-, 3^-$, and 4^- are also shown [23]. The agreement between theory and experiment is good, the most significant discrepancy being the position of the 1^- level which we predict to lie about 200 keV above the observed one.

4 Summary

In this paper, we have presented results of a shell model study of the five nuclei ^{134}Te, ^{130,134}Sn, and ^{132,134}Sb, where use has been made of effective interactions derived

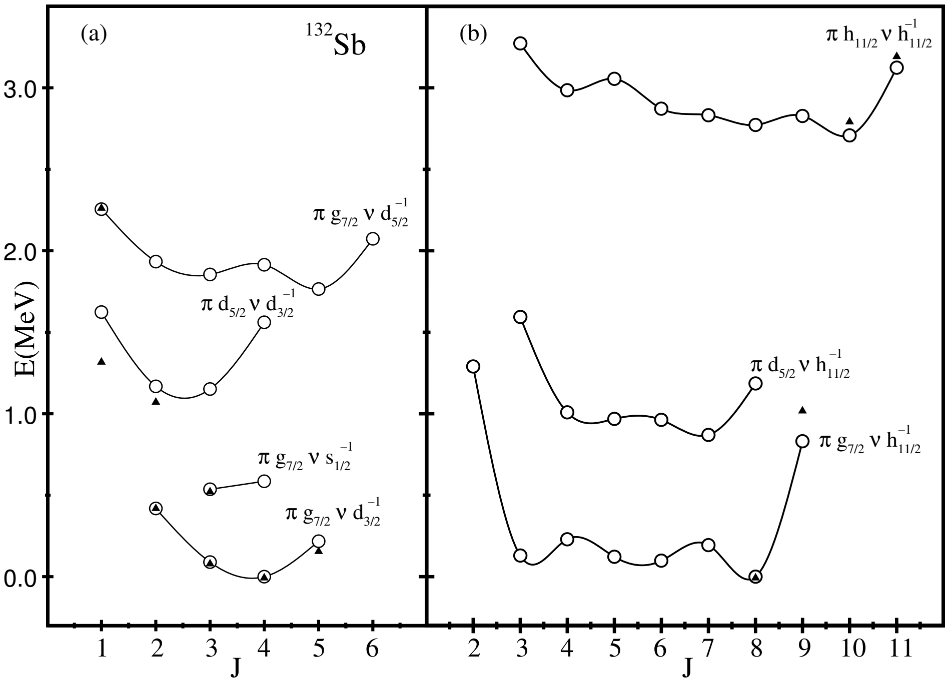

Fig. 5. Proton particle-neutron hole multiplets in ^{132}Sb. The theoretical results are represented by open circles while the experimental data by solid triangles. The lines are drawn to connect the points. See text for comments.

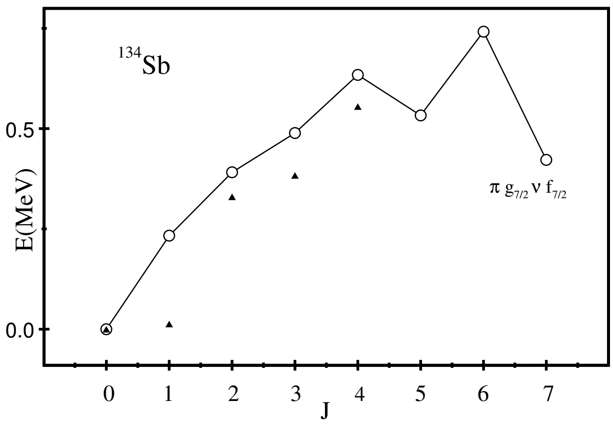

Fig. 6. Same as fig. 5, but for $\pi g_{7/2}\nu f_{7/2}$ multiplet in ^{134}Sb.

from the CD-Bonn NN potential. To this end, a low-momentum potential $V_{\text{low-}k}$ was constructed by integrating out the high-momentum part of the original V_{NN} potential containing a strong repulsive core. This $V_{\text{low-}k}$ potential, having a smooth behavior, has been used directly to calculate the model-space effective interaction within the framework of a folded-diagram formalism. The matrix elements of V_{eff}, needed in the description of the three isobars with $A = 134$, have been derived in the *pp* formalism, while those concerning ^{130}Sn and ^{132}Sb in the *hh* and *ph* formalism, respectively.

We have shown that all the experimental data available for these nuclei are well reproduced by the theory, thus evidencing the reliability of our realistic effective interactions in the proton-proton, neutron-neutron, and proton-neutron channels. Note that our study regards neutron particles as well as neutron holes with respect to the $N = 82$ closed core. However, the data, aside those on ^{134}Te, are still rather scanty and we have have found it interesting to make some predictions which may provide a guidance in the interpretation of the results of future experiments.

In this connection, of great interest are the proton-neutron multiplets, which we have discussed for ^{132}Sb and ^{134}Sb. It is a finding of our calculations that the *ph* multiplets (^{132}Sb) are all very similar in shape and their behavior is quite different from the *pp* case (^{134}Sb). This result is supported by the experimental data (only one multiplet in ^{132}Sb, however, is completely known) and is consistent with the behavior of the *ph* and *pp* multiplets observed in the heavier nuclei ^{208}Bi and ^{210}Bi.

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