PHYSICAL REVIEW C VOLUME 56, NUMBER 1 JULY 1997

Structure of neutron-rich nuclei around ^{132}Sn

F. Andreozzi,[1] L. Coraggio,[1] A. Covello,[1] A. Gargano,[1] T. T. S. Kuo,[2] and A. Porrino[1]
[1]*Dipartimento di Scienze Fisiche, Università di Napoli Federico II and Istituto Nazionale di Fisica Nucleare, Mostra d'Oltremare, Pad. 20, 80125 Napoli, Italy*
[2]*Department of Physics, SUNY, Stony Brook, New York 11794*

(Received 31 January 1997)

Recent studies have provided new experimental information on neutron-rich nuclei around doubly magic ^{132}Sn. We have performed shell-model calculations for the two- and three-proton $N=82$ isotones ^{134}Te and ^{135}I using a realistic effective interaction derived from the Bonn A nucleon-nucleon potential. The results are in remarkably good agreement with the experimental data evidencing the reliability of our realistic effective interaction. [S0556-2813(97)50407-9]

PACS number(s): 21.60.Cs, 21.10.Dr, 21.30.Fe, 27.60.+j

The $N=82$ region has long come in focus for shell-model studies of nuclear structure. The ^{132}Sn nucleus shows, in fact, strong shell closures for both protons and neutrons. In addition, a long string of nuclei is built by adding protons to the doubly closed core.

From the experimental point of view, the naturally stable nuclei in this region have been extensively investigated and a large amount of experimental data is available for them. On the other hand, the neutron-rich nuclei, with few valence protons, lie well away from the valley of stability and until now experimental information, especially for ^{134}Te and ^{135}I, was very scanty. The properties of these nuclei are of special interest for a stringent test of the basic ingredients of a shell-model calculation, as they represent a direct source of knowledge of the effective proton-proton interaction in this region. Recently, use of large multidetector γ-ray arrays with high analyzing power has made accessible the study of these nuclei. In particular two recent studies [1,2] have led to new experimental data for ^{134}Te and ^{135}I.

In Ref. [1] the level scheme of ^{134}Te has been extended up to about 4.6 MeV excitation energy. All the states arising from the $\pi g_{7/2}^2$ and $\pi g_{7/2} d_{5/2}$ configurations, except the 3^+, have been observed below 3 MeV, while five negative-parity states, belonging to the $\pi g_{7/2} h_{11/2}$ configuration, have been identified between 4.0 and 4.6 MeV. The experiment of Ref. [2] has also revealed seven positive-parity levels lying between 4.56 and 7.56 MeV, which have been interpreted as excitations of the ^{132}Sn core.

Regarding ^{135}I, five new states, three of them with negative parity, have been identified [2] below 3.8 MeV. However, no information about transition multipolarities was obtained and spin-parity assignments were based in part on theoretical considerations. As in the case of ^{134}Te, the observed levels above 4.2 MeV have been interpreted as neutron particle-hole states.

In this paper, we present the results of a shell-model study of ^{134}Te and ^{135}I, in which we assume that ^{132}Sn is a closed core and let the valence protons occupy the five single-particle (s.p.) orbits $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, and $0h_{11/2}$. As regards the energy spacings between the five s.p. levels, we take three of them from the experimental spectrum of ^{133}Sb [3]. In fact, the $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, and $h_{11/2}$ states can be associated with the ground state and the 0.962, 2.708, and 2.793 MeV excited levels, respectively. As for the $s_{1/2}$ state, its position has been determined by reproducing the experimental energy of the $\frac{1}{2}^+$ state at 2.150 MeV in ^{137}Cs, which is predominantly of s.p. nature, as indicated by the experimental one-proton spectroscopic factor [4]. This yields the value $\epsilon_{s_{1/2}}=2.8$ MeV, which comes close to that obtained from the empirical analysis of Ref. [5] (2.99 MeV).

In our study we make use of a realistic effective interaction derived from the Bonn A free nucleon-nucleon potential. Our effective interaction was obtained using a G-matrix folded-diagram formalism, including renormalizations from both core polarization and folded diagrams. For the $N=82$ isotones we have chosen the Pauli exclusion operator Q_2 in the G-matrix equation,

$$G(\omega)=V+VQ_2\frac{1}{\omega-Q_2TQ_2}Q_2G(\omega), \tag{1}$$

as specified by (n_1,n_2,n_3) = (11, 28, 45) [6]. Here V represents the NN potential, T denotes the two-nucleon kinetic energy, and ω is the so-called starting energy. We employ a matrix inversion method to calculate the above G matrix in an essentially exact way [6]. The effective interaction $V_{\rm eff}$, which is energy independent, can be schematically written in operator form as

$$V_{\rm eff}=\hat{Q}-\hat{Q}'\int\hat{Q}+\hat{Q}'\int\hat{Q}\int\hat{Q}-\hat{Q}'\int\hat{Q}\int\hat{Q}\int\hat{Q}\cdots, \tag{2}$$

where $\hat{Q}$ and $\hat{Q}'$ represent the $\hat{Q}$ box, composed of irreducible valence-linked diagrams, and the integral sign represents a generalized folding operation. We take the $\hat{Q}$ box to be composed of G-matrix diagrams through second order in G; they are just the seven first- and second-order diagrams considered by Shurpin *et al.* [7]. Since the valence-proton and -neutron orbits outside the ^{132}Sn core are different, in the present calculation we use an isospin uncoupled representation, where protons and neutrons are treated separately. The shell-model oscillator parameter used by us is $\hbar\omega=7.72$ MeV. A detailed description of our derivation including more references can be found in Ref. [8].

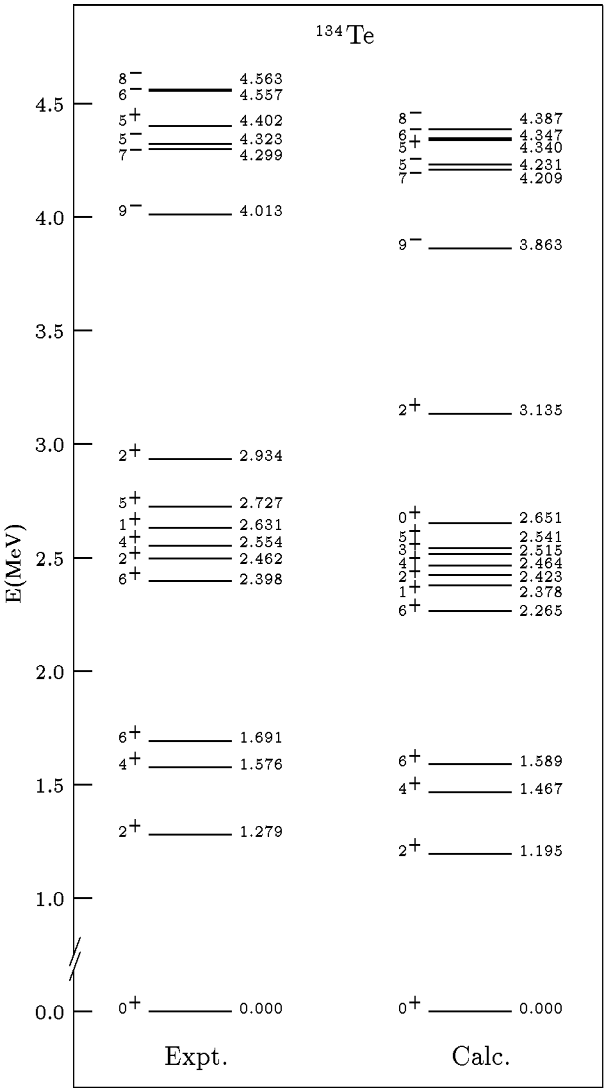

FIG. 1. Experimental and calculated spectrum of ^{134}Te.

To our knowledge, these are the first realistic shell-model calculations for $N=82$ nuclei. To date, the most complete shell-model calculations are those of Ref. [5] which were carried out in the same model space employing a semirealistic interaction (a bare reaction matrix of the Reid soft core potential plus phenomenological corrections). In an earlier work [9], use was made of the modified surface delta interaction in a restricted model space. The new experimental results [1,2] offer a unique opportunity to test directly the matrix elements of our calculated realistic effective interaction.

The experimental [1,10] and theoretical spectra of ^{134}Te are compared in Fig. 1, where all the calculated and experimental levels up to 3.2 MeV excitation energy are reported. We see that while the theory reproduces all the observed levels, it also predicts the existence of a 3^+ and a 0^+ state at 2.51 and 2.65 MeV, respectively. This prediction is strongly supported by the experimental information available for the two heavier even isotones. In fact, in ^{136}Xe a 0^+ state has been observed at 2.56 MeV, while in ^{138}Ba both a 0^+ and a 3^+ state have been located at 2.34 and 2.45 MeV, respectively. Above 3.2 MeV excitation energy the comparison between theory and experiment is made only for those observed levels which have received a spin-parity assignment. We do not include the new levels observed in [2] since, as already mentioned, all of them should be interpreted as neutron particle-hole states. This interpretation is confirmed by our calculations. In fact, the only two states, having $J^\pi=8^+$ and 10^+, which can be constructed in our model space are both predicted to lie at about 7.1 MeV, while the two experimental states with these spin-parity assignments have been located at 4.557 and 5.622 MeV, respectively [2]. We see that the calculated spectrum reproduces very well the experimental one, the discrepancies between theory and experiment being smaller than 100 keV for the excitation energies of several states. A measure of the quality of the results is given by the rms deviation σ [11], whose value is 145 keV. It should be noted that all the calculated states lie below the experimental ones, the only exception being the 2_3^+ state. The experimental level at 2.934 MeV excitation energy was, however, only tentatively identified as a 2^+ state [12] and is not reported in [1]. It turns out that a downshift of 100 keV of the calculated ground state brings σ down to 100 keV and to only 60 keV if we exclude the 2_3^+ state.

As regards the structure of the states, we find that the three groups of states reported in Fig. 1 (the first one up to 1.7 MeV, the second between 2.2 and 3.2 MeV, and the third above 3.8 MeV) are dominated by the $g_{7/2}^2$, $g_{7/2}d_{5/2}$, and $g_{7/2}h_{11/2}$ configurations, respectively. Of course, this is not true for the 0_2^+, 2_3^+, and 5_2^+ states. In fact, the dominant configuration is $d_{5/2}^2$ for the two former states and $g_{7/2}d_{3/2}$ for the latter. Our results substantiate the interpretation given in [2] of the nature of the levels in ^{134}Te. It should be mentioned, however, that our wave functions are not really pure, as assumed in [2], the contribution coming from other configurations being particularly significant for the ground state, for which the percentage of configurations other than $g_{7/2}^2$ is 17%.

In Fig. 2 we compare the calculated spectrum of ^{135}I with the experimental one [2,13] up to 4.0 MeV excitation energy. As in the case of ^{134}Te, we exclude the experimental levels above 4.2 MeV, which originate from core excitations. We should note that the spectra of Fig. 2 include all experimental and calculated levels up to 1.5 MeV. The experimental level at 1.184 MeV has been observed in a ^{135}Te β^--decay study [14] and the most likely spin-parity assignment is $\frac{9}{2}^+$. Our results strongly favor this assignment. Above 1.5 MeV several other levels without assigned spin and parity are reported in [13]; we compare our calculated states only with those observed in [2]. From Fig. 2 we see that the excitation energies are remarkably well reproduced for all the reported states, the σ value being 77 keV. We have associated the experimental level at 1.010 MeV with the theoretical $\frac{3}{2}^+$ at 0.931 MeV.

From the structure of our wave functions, it turns out that the states up to 1.5 MeV excitation energy, but the first $\frac{5}{2}^+$ state, can be identified as the members of the $g_{7/2}^3$ multiplet. These states are, however less pure than those of ^{134}Te. The percentage of other components is about 4% for all the states, except the ground state and the $(\frac{5}{2}^+)_2$ state, for which this value becomes 18% and 11%, respectively. The $(\frac{5}{2}^+)_1$ state is of $v=1$ nature and is dominated by the $g_{7/2}^2d_{5/2}$ con-

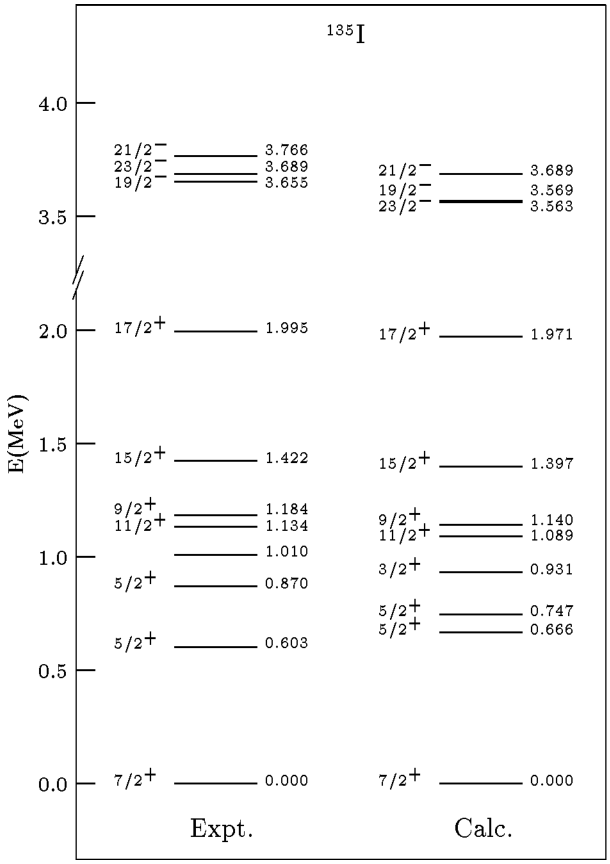

FIG. 2. Experimental and calculated spectrum of ^{135}I.

figuration. As regards the $\frac{17}{2}^+$ state, as well as the three negative-parity states, our wave functions are dominated by the two configurations $g_{7/2}^2 d_{5/2}$ and $g_{7/2}^2 h_{11/2}$, respectively.

We have also calculated the ground-state binding energies (relative to ^{132}Sn) for ^{134}Te and ^{135}I. The mass excess value for ^{133}Sb needed for absolute scaling of the s.p. levels was taken from [15]. As for the Coulomb energy, we have taken that of a homogeneous charged sphere with $r_0 = 1.2$ fm. We find $E_b(^{134}\mathrm{Te}) = 20.563$ MeV and $E_b(^{135}\mathrm{I}) = 29.440$ MeV, to be compared with the experimental values 20.357 ± 0.045 MeV [15] and 29.034 ± 0.037 MeV [16], respectively. Keeping in mind how simple is the model used for the evaluation of the Coulomb corrections, the agreement between theory and experiment may be considered quite satisfactory. A more reliable way of estimating the Coulomb energy is provided by the work of Ref. [17]. Making use of Eq. (3) of this paper, one obtains an expression for the binding energy of an $N = 82$ isotone depending on two parameters, V_c and b. Typical values [17] of these parameters extracted from experimental Coulomb displacement energies for the mass region $A = 41-56$ are 0.3 and 0.1 MeV, respectively. Since no such analysis is available for the $N = 82$ isotones, we make use of the two above values of V_c and b to calculate the binding energies for ^{134}Te and ^{135}I. We obtain $E_b(^{134}\mathrm{Te}) = 20.383$ and $E_b(^{135}\mathrm{I}) = 29.098$ MeV, in excellent agreement with the experimental values.

At this point we should mention that the authors of Ref. [2] claim to have discovered a serious inconsistency in the accepted masses of $N = 82$ isotones near ^{132}Sn. In this regard, we note that in the calculation of the mass ''window'' W of [2] two approximations are made which cast doubts on the above conclusion. On the one hand, the value of W obtained directly from the relevant $N = 82$ masses (see [2]) does not take into account the Coulomb corrections. On the other hand, the value of W from spectroscopy is obtained by making the assumption that the $J^\pi = \frac{15}{2}^+$ state in ^{135}I is a pure $g_{7/2}^3$ configuration. From our calculation it turns out that the percentage of this component is 96%.

TABLE I. Calculated and experimental $B(E\lambda)$ values (in W.u.) for ^{134}Te. The experimental data are from [1].

$J_i^\pi \to J_f^\pi$	λ	$B(E\lambda)_{\mathrm{expt}}$	$B(E\lambda)_{\mathrm{calc}}$
$4_1^+ \to 2_1^+$	2	4.3 ± 0.3	4.3
$6_1^+ \to 4_1^+$	2	2.05 ± 0.03	2.0
$9_1^- \to 6_1^-$	3	3.8 ± 0.2	1.0
$9_1^- \to 6_2^-$	3	8.0 ± 1.3	8.7

In Table I we compare the experimental reduced transition probabilities in ^{134}Te with the calculated ones. We have used an effective proton charge $e_p^{\mathrm{eff}} = 1.55e$. This is consistent with the values adopted by other authors [4,18]. The theoretical $B(E2)$ values are in very good agreement with experiment. As regards the $E3$ transitions, we find that the $B(E3; 9_1^- \to 6_2^+)$ is well reproduced, while the $B(E3; 9_1^- \to 6_1^+)$ is underestimated by a factor of about 4. A possible reason for this discrepancy lies in the fact that only a small amount of configuration mixing is present in the calculated 6^+ states. In fact, the decay to the 6_2^+ state is dominated by the single-proton transition $(h_{11/2} g_{7/2})_{9^-} \to (g_{7/2} d_{5/2})_{6^+}$, while that to the 6_1^+ state by the transition $(h_{11/2} g_{7/2})_{9^-} \to (g_{7/2}^2)_{6^+}$, which is retarded owing to spin flip. The theoretical $B(E3; 9_1^- \to 6_1^+)$ value could be brought in agreement with experiment by an amount of configuration mixing of about 15%, which would, of course, reduce the $B(E3; 9_1^- \to 6_2^+)$ value. It should be noted, however, that the latter would still be within the error bar.

The magnetic moment of the 6_1^+ state in ^{134}Te has been measured to be 5.08 ± 0.15 n.m. [10]. We have calculated it by using the g_s^{free} factor and an effective g_l factor $g_l^{\mathrm{eff}} = 1.3 g_l^{\mathrm{free}}$. We obtain $\mu(6_1^+) = 5.01$ n.m. The above values of the gyromagnetic factors have been determined from an analysis of the measured magnetic moments in the three isotones ^{134}Te, ^{136}Xe, and ^{137}Cs and lead to an excellent agreement between theory and experiment also for the two latter nuclei [19].

In summary, we have shown that our effective interaction derived from the Bonn A nucleon-nucleon potential leads to a very good description of the two $N = 82$ nuclei ^{134}Te and ^{135}I. It should be stressed that no adjustable parameter appears in our calculations.

Based on these findings, we are currently studying the heavier $N = 82$ isotones using the same realistic effective interaction. This should permit to gain further insight into the role of modern realistic interactions in the shell-model approach to the nuclear many-body problem.

This work was supported in part by the Italian Ministero dell'Università e della Ricerca Scientifica e Tecnologica (MURST) and by the U.S. DOE Grant No. DE-FG02-88ER40388.

[1] J. P. Omtvedt *et al.*, Phys. Rev. Lett. **75**, 3090 (1995).
[2] C. T. Zhang *et al.*, Phys. Rev. Lett. **77**, 3743 (1996).
[3] Yu. V. Sergeenkov and V. M. Sigalov, Nucl. Data Sheets **49**, 39 (1986).
[4] B. H. Wildenthal, E. Newman, and R. L. Auble, Phys. Rev. C **3**, 1199 (1971).
[5] W. J. Baldridge, Phys. Rev. C **18**, 530 (1978).
[6] E. M. Krenciglowa, C. L. Kung, T. T. S. Kuo, and E. Osnes, Ann. Phys. (N.Y.) **101**, 154 (1976).
[7] J. Shurpin, D. Strottman, and T. T. S. Kuo, Nucl. Phys. **A408**, 310 (1983).
[8] A. Covello, F. Andreozzi, L. Coraggio, A. Gargano , T. T. S. Kuo, and A. Porrino, Prog. Part. Nucl. Phys. **38** (1997) (in press).
[9] B. H. Wildenthal and D. Larson, Phys. Lett. B **37**, 266 (1971).
[10] Yu. V. Sergeenkov, Nucl. Data Sheets **71**, 557 (1994).
[11] We define $\sigma=\{(1/N_d)\Sigma_i[E_{\rm expt}(i)-E_{\rm calc}(i)]_2\}^{1/2}$, where N_d is the number of data.
[12] B. Fogelberg, B. Ekström, L. Sihver, and G. Rudstam, Phys. Rev. C **41**, R1890 (1990).
[13] Yu. V. Sergeenkov, Nucl. Data Sheets **52**, 205 (1987).
[14] M. Samri, G. J. Costa, G. Klotz, D. Magnac, R. Seltz, and J. P. Zirnheld, Z. Phys. A **321**, 255 (1985).
[15] K. A. Mezilev, Yu. N. Novikov, A. V. Popov, B. Fogelberg, and L. Spanier, Phys. Scr. **T56**, 272 (1995).
[16] G. Audi and A. H. Wapstra, Nucl. Phys. **A565**, 1 (1993).
[17] B. J. Cole, J. Phys. G **11**, 351 (1985).
[18] K. Heyde, J. Sau, E. A. Henry, and R. A. Meyer, Phys. Rev. C **25**, 3193 (1982).
[19] F. Andreozzi, L. Coraggio, A. Covello, A. Gargano, T. T. S. Kuo, and A. Porrino (to be published).