Five-valence-proton $N=82$ isotone ^{137}Cs

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Yrast excitations in the $N=82$ isotone ^{137}Cs have been identified for the first time in thick-target γ-ray coincidence measurements for the system ^{232}Th+^{136}Xe using the Gammasphere array. The ^{137}Cs nuclei were produced in deep inelastic one-proton-transfer reactions. By-products of the main investigation were two well-developed rotational bands which were identified in heavy reaction partner products complementary to ^{137}Cs and are tentatively assigned to the little studied nucleus ^{231}Ac. There was no difficulty in placing the 11 observed ^{137}Cs transitions in a yrast level scheme extending to an $I^{\pi}=(31/2^{-})$ level at 5494 keV. Interpretation was also straightforward, since the experimental level energies are in close agreement with results of shell model calculations performed earlier using empirical single particle energies and interaction matrix elements derived from experimental data for other $N=82$ isotones. [S0556-2813(99)00706-2]

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I. INTRODUCTION

The study of yrast excitations through a series of nuclei with a closed major shell for either protons or neutrons provides an attractive testing ground for developments of the nuclear shell model. In accessible regions of the nuclidic chart the best examples are the $Z=50$ tin isotopes and the $N=82$ isotones, for which the proton/neutron shell closure remains stable while the active particles of the opposite isospin are distributed in the multiorbit space between magic numbers 50 and 82. In shell model terms, these particles occupying the $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, $2s_{1/2}$, and $0h_{11/2}$ orbits determine fully the active degrees of freedom to be taken into account in calculations. Along these lines, a few years ago Wildenthal [1] performed comprehensive and generally successful calculations for all the $N=82$ isotones then known.

On the experimental side, our knowledge of $N=82$ yrast states extends from $Z=50$ ^{132}Sn to $Z=72$ ^{154}Hf. At the proton-rich end, the isotones ^{153}Lu and ^{154}Hf were studied in a highly focused recoil mass separator experiment which took advantage of the occurrence of long-lived yrast isomers in these products [2]. Further progress to isotones above $Z=72$ will be difficult because they cannot be reached by any favorable reaction involving stable projectile and target nuclei. On the other hand, advances were recently made at the neutron-rich end close to doubly magic ^{132}Sn, where the level structures of the two- and three-valence-proton nuclei ^{134}Te and ^{135}I have been considerably extended in β-decay [3] and fission product γ-ray studies [4]. As described in the preceding paper [5], analysis of ^{248}Cm fission product γ-ray data has now also extended the yrast level spectrum of the four-proton nucleus ^{136}Xe.

Next in line of the $N=82$ isotones is ^{137}Cs, with five protons outside the ^{132}Sn core. Although ^{137}Cs is a well-known long-lived radioisotope, commonly used as a γ-ray calibration source and widely recognized as a dangerous radioactive pollutant, the yrast levels of the ^{137}Cs nucleus were until now completely unknown. In fact, ^{137}Cs is not accessible in any standard reaction populating high-spin states, and its production yield from spontaneous fission sources is small. In the present work we used ^{232}Th+^{136}Xe collisions at energies just above the Coulomb barrier to populate ^{137}Cs yrast states by deep inelastic reactions involving transfer of one proton from the target to the ^{136}Xe projectile. In the following sections we describe how the ^{137}Cs transitions were identified and placed in a level scheme and how the results obtained compare with shell model calculations for this five-valence-proton nucleus.

Aside from the main topic of this paper, we also report on two rotational bands, each with nine observed transitions, which we tentatively assign to the little studied nucleus ^{231}Ac, the one-proton-transfer complementary partner of ^{137}Cs in the reaction system studied.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The main goal of the ^{136}Xe+^{232}Th experiment at Gammasphere was the study of high-spin states in Rn and Ra isotopes populated in multinucleon transfer reactions. This part of the investigation was successfully completed by identification of several alternating parity high-spin bands in isotopes close to the $N=134$ neutron number which elucidated octupole structures expected in the region [6]. It was anticipated that the same data set might also provide new spectroscopic information on nuclei located around the ^{136}Xe projectile, with particular interest in those that are hard to reach by other means. One prime objective of this kind was the investigation of the ^{137}Cs nucleus discussed here.

The experiment was performed at Lawrence Berkeley NL using the Gammasphere spectrometer and an 833 MeV ^{136}Xe beam from the 88-In. Cyclotron. A thick 36 mg/cm^2 ^{232}Th target was placed in the center of the detector array, which consisted at the time of 73 large-volume (75% efficient) Compton-suppressed Ge detectors and the BGO ball. During 49 h of beam on target a total of 1.1×10^{10} unpacked triple Ge coincidences, triggered by firing of at least two BGO elements, were collected on Exabyte tapes. The beam was pulsed with 200 ns repetition time, which provided clean separation of prompt and isomeric events, and simplified identification of the many products of deep inelastic reactions. The subsequent analysis provided no evidence for isomers in ^{137}Cs with half-lives greater than 5 ns. Consequently the construction of the ^{137}Cs level scheme was based entirely on the prompt γ-ray coincidence data, which were extremely complex. The success of the analysis relied on the high resolving power that could be achieved by setting double gates during sorting of the triple γ-ray coincidence events.

A. Overview of the ^{232}Th+^{136}Xe γ-ray data

In the thick ^{232}Th target the reaction products were stopped within a few picoseconds, most of the γ rays were emitted from nuclei at rest, and no Doppler corrections were necessary. Nonetheless, the γ-ray spectra recorded were extremely complicated, with sizable contributions from a wide variety of excited reaction products. By far the strongest component of the total γ-ray projection was a complex spectrum of lines arising from Coulomb excitation of the ^{232}Th target. Background from these dominant ^{232}Th γ rays tended to obscure low-energy portions of single-gated coincidence spectra, but the interference could be reduced to negligible levels by setting double γ-ray gates.

Various reactions in the front layer of the target, where the beam energy still exceeded the 721 MeV Coulomb barrier, yielded product nuclei widely distributed over the nuclidic chart. Quasielastic transfer products close to ^{232}Th or ^{136}Xe were produced with rather large cross sections, but since the associated γ-ray multiplicity was generally low, they did not contribute significantly to the triple coincidence γ-ray events. Deep inelastic collisions led to much broader product distributions around target and projectile that were heavily skewed towards mass symmetry [7]. The high-spin population of ^{137}Cs, which is the object of the present study, may be included in this category. In fact, long series of $^{126-135}$Te, $^{128-138}$Xe, $^{134-144}$Ba, and $^{140-146}$Ce isotopes were produced by such multinucleon transfer processes, often followed by evaporation of a few neutrons. It appears that most of the heavy targetlike fragments coming from the same reactions underwent fission; for example, almost no trace of ^{234}U γ rays could be detected in coincidence with the clearly observed yrast transitions of its $2p$ transfer partner ^{134}Te. On the other hand, the heavy deep inelastic products below ^{232}Th evidently survived fission, since they were observed in good yields stretching down to the ^{208}Pb region; these included the light Rn and Ra isotopes discussed in Ref. [6]. The fission of heavy binary reaction fragments gave many products extending down to Ga and Ge isotopes and overlapping to some extent with the multinucleon transfer products. Finally, fusion reactions of the ^{136}Xe beam with unavoidable trace impurities of oxygen and carbon in the target gave rise to high-multiplicity γ-ray cascades in fusion-evaporation products, such as neutron-deficient Sm, Pm, and Nd nuclei.

B. Identification of yrast γ-ray cascades in ^{137}Cs

The five-valence-proton nucleus ^{137}Cs has an $I^{\pi}=7/2^+$ ground state of $g_{7/2}$ character. One expects in the 1.1–2.0 MeV range a pattern of $11/2^+$, $15/2^+$, and $17/2^+$ yrast excitations, involving $g_{7/2}$ and $d_{5/2}$ proton orbits, rather similar to those already located [4] in the three-proton-nucleus ^{135}I. What we know about excited states in ^{137}Cs comes mainly from studies of 3.8 min ^{137}Xe $(\nu f_{7/2})$ β^- decay. The known ^{137}Cs levels include one at 1185 keV, which is only indirectly fed in the ^{137}Xe β decay and that deexcites exclusively by a 1184.7 keV γ ray to the ^{137}Cs ground state [8]. This level is almost certainly the counterpart of the 1134 keV $I^{\pi}=11/2^+$ yrast level in ^{135}I, which is similarly indirectly fed following ^{135}Te $\nu f_{7/2}$ β^- decay and which also deexcites directly to the ground state.

In the present work, an intense 1184.6 keV γ ray was indeed observed, with strong 487 and 222 keV transitions in coincidence, which fitted well the energies predicted for the $17/2^+\rightarrow15/2^+\rightarrow11/2^+\rightarrow7/2^+$ yrast cascade in ^{137}Cs (see below). Later inspections of low-energy portions of the coincidence spectra showed Ac x rays in coincidence with these γ rays. Those observations clinched the isotopic assignment of the 222, 487, and 1185 keV three-γ-ray cascade to ^{137}Cs. Further analysis of the coincidence data identified other weaker transitions in the same nucleus, as will be discussed in a later section.

The upper part of Fig. 1, showing the x-ray region of the $\gamma\gamma$ coincidence projection, demonstrates how the target x-ray lines and the 113 keV ^{232}Th $4^+\rightarrow2^+$ transition dominate. In the lower spectrum, double gated on 1185 and 487 keV transitions, the energies and relative intensities of the four labeled components correspond to K x rays of actinium, which is complementary to Cs in reactions involving one-

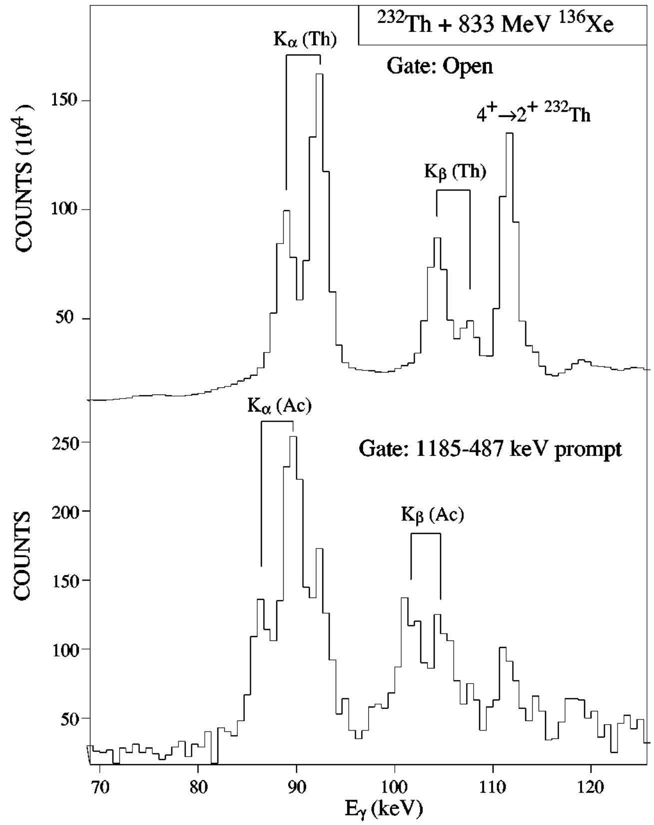

FIG. 1. The low-energy region of the prompt γ-ray coincidence projection in the ^{232}Th+^{136}Xe reaction (upper), and the same region with a double gate on 1185 and 487 keV γ rays (lower). The dominance of Ac γ rays in the lower spectrum confirms the assignment of the gating transitions to a Cs isotope.

proton transfer from ^{232}Th target to ^{136}Xe projectile. Gates were also set on known yrast transitions in the ^{137}Ba, ^{138}Ba, and ^{139}Ba isotopes; as expected these showed x rays of Ra complementary fragments in coincidence. We compared approximate yields for yrast 6^+ and $15/2^+$ states of various $N=82$ isotones produced by transfer of protons between ^{232}Th and ^{136}Xe. In arbitrary units, the relative populations were estimated to be ^{134}Te$(6+)$, 0.22 units; ^{135}I$(15/2+)$, 1.0 units; ^{137}Cs$(15/2^+)$, 2.3 units; and ^{138}Ba(6^+), 0.72 units for the $-2p$, $-1p$, $+1p$, and $+2p$ transfers, respectively. The large yield for ^{137}Cs fits well with general trends and expectations.

C. Gamma rays assigned to ^{231}Ac

Further inspection of the coincidence spectrum double gated on the 487 and 1185 keV ^{137}Cs γ rays showed many other transitions besides the Ac x rays of Fig. 1 appearing in the energy range below 500 keV. These transitions could be arranged in two sequences resembling known rotational bands in actinide nuclei. The coincidence relationships within the new bands were checked in detail before they were tentatively assigned to ^{231}Ac, a largely unknown nucleus but one that must be produced as the main reaction partner complementary to ^{137}Cs. The transitions are grouped into two bands in the following way:

Band *A*: (106), 163.3, 216.8, 264.8, 307.0, 343.8, 374, 405, 426 keV.

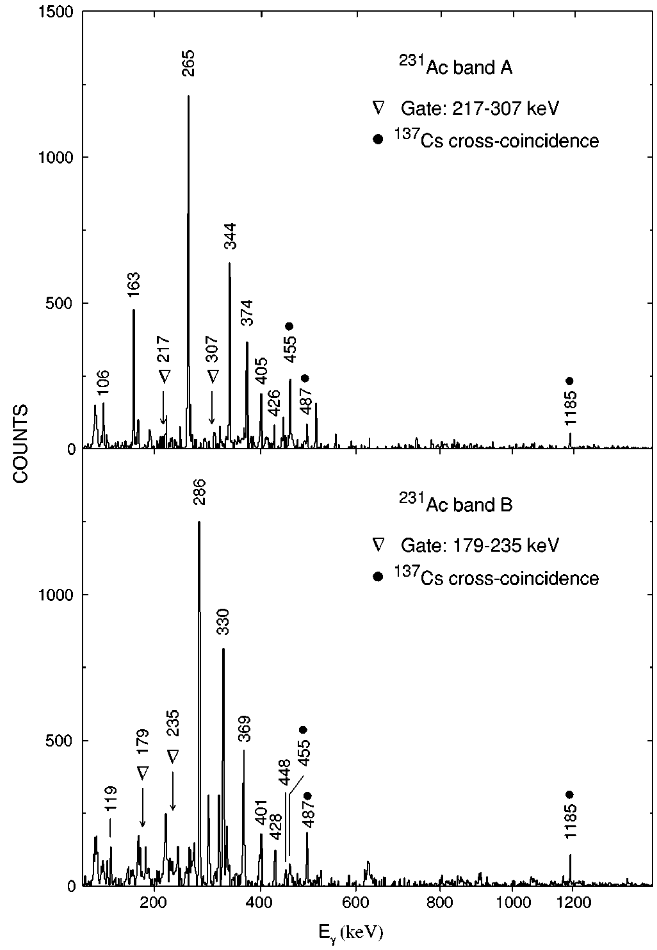

FIG. 2. Gamma-ray coincidence spectra with double gating on prominent pairs of transitions within band *A* (upper) and band *B* (lower), both tentatively assigned to ^{231}Ac.

Band *B*: 119.3, 178.6, 234.8, 285.8, 330.4, 368.8, 401.2, (428), (448) keV.

Many of these γ rays are seen in Fig. 2, which displays coincidence spectra with double gates set on prominent pairs of transitions in each band. The 1185 and 487 keV ^{137}Cs γ rays seen in both spectra of Fig. 2 provide an argument for placing both bands in the ^{231}Ac isotope; in other reactions of this type involving one-proton transfer, the direct complementary fragment without any neutron evaporation was generally observed in greatest yield [7].

The $I^\pi=1/2^+$ ground state and $3/2^+$ 38 keV first excited state assigned to ^{231}Ac in earlier work [9] suggest an appealing interpretation of bands *A* and *B* as the two signature branches of a $K=1/2$ rotational band in ^{231}Ac, resembling the extended $K=1/2$ bands already established in ^{239}Pu and other odd-*A* actinides. However, there is a puzzle, since the 455 keV γ ray (taken to be the known $5/2^+\rightarrow 7/2^+$ ^{137}Cs transition of this energy) appears with very different intensities in the two spectra of Fig. 2. While the 455 keV γ ray is much stronger than the 1185 and 487 keV γ rays in cross coincidence with band *A*, the situation is opposite in the coincidences with band *B*. It is difficult to reconcile these observations with an interpretation of the two sequences as signature branches of a single $K=1/2$ rotational band. Our conclusion is that the assignment of band *A* to the ^{231}Ac

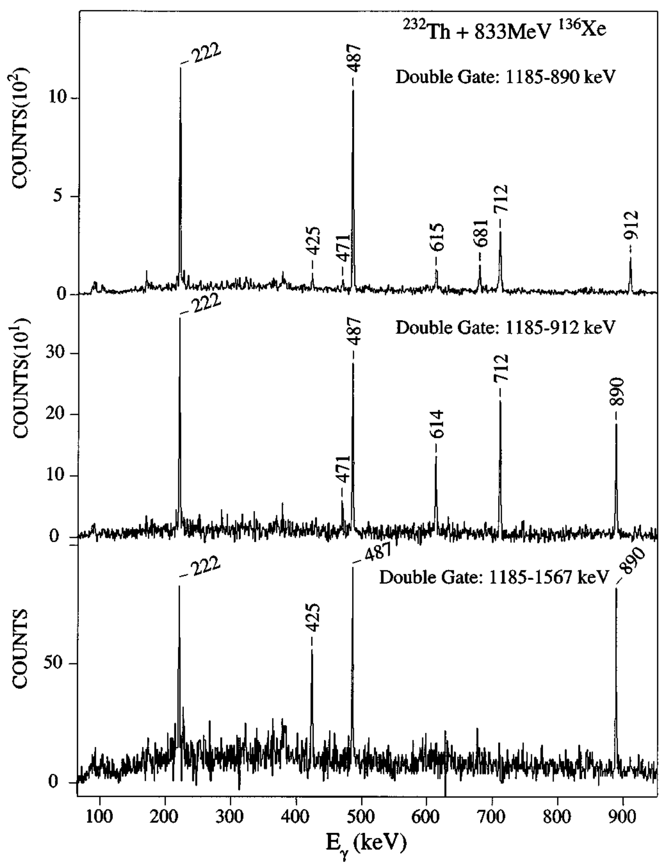

FIG. 3. Key γ-ray coincidence spectra for ^{137}Cs γ rays.

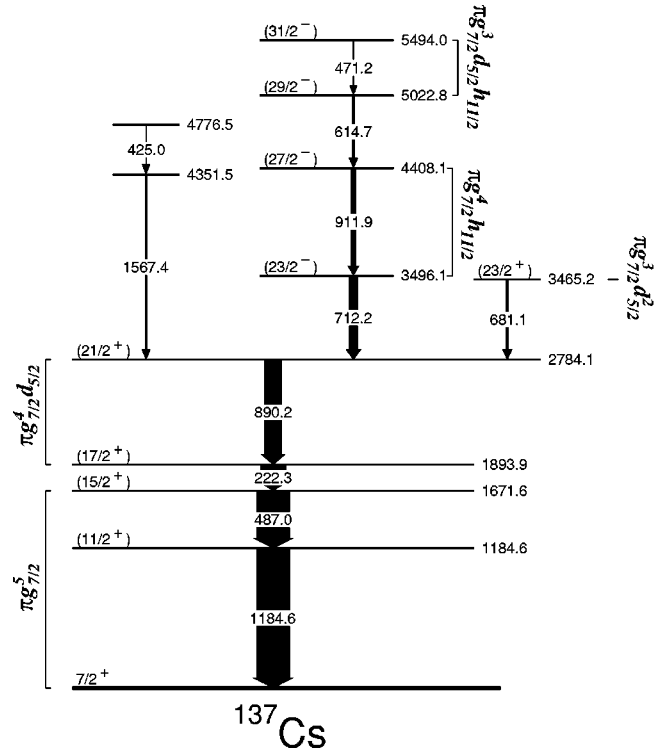

FIG. 4. The ^{137}Cs yrast level scheme with spin-parity assignments based on results of shell model calculations. The main five-proton configurations are indicated.

nucleus is very probably correct, but it is less certain that the band *B* transitions belong also to the same nucleus.

D. Construction of the ^{137}Cs yrast level scheme

The high quality of the γ-ray triple coincidence data enabled us to obtain clean, background-free, coincidence spectra, which led straightforwardly to the construction of the ^{137}Cs level scheme. Illustrative examples of these spectra are shown in Fig. 3, and the level scheme is displayed in Fig. 4.

In all, eight additional γ rays coincident with the 1185-487-222 keV cascade were identified in the ^{137}Cs nucleus. A list of γ-ray energies and intensities derived from quantitative analyses of all the coincidence spectra is given in Table I. As shown in Fig. 4, most of the ^{137}Cs transitions are accommodated within the main yrast sequence, extending up to the highest-energy level at 5494 keV. The transition ordering is settled unambiguously by the γ-ray intensities of Table I. Of the remaining three transitions, the 1567-425 keV cascade and the 681 keV γ ray feed separately and directly into the 2784 keV level; no connections from the parent levels to other states could be detected. Spin-parity assignments indicated in Fig. 4 are based entirely on the striking level-to-level correspondence found between the experimental scheme and a theoretical ^{137}Cs level spectrum that was calculated earlier using shell model methods [10]. This correspondence is discussed further in the following section.

III. DISCUSSION

The main features of the ^{137}Cs yrast level scheme may be understood in a qualitative way by considering simple yrast configurations involving the coupling of the five valence protons. Only the $g_{7/2}$, $d_{5/2}$, and $h_{11/2}$ proton orbitals need to be included. The ^{137}Cs $7/2^+$ ground state, in which two 0^+ proton pairs are coupled to the odd $g_{7/2}$ proton, is fed by the strong yrast γ-ray cascade connecting three levels below 2 MeV. As in ^{135}I, these are seniority three states $11/2^+$, $15/2^+$ of mainly $\pi g_{7/2}^5$ character and $(\pi g_{7/2}^4 d_{5/2})17/2^+$. Whereas, in ^{135}I, $17/2^+$ is the maximum spin achievable with three protons in $g_{7/2}$ and $d_{5/2}$, in ^{137}Cs an extra pair of

TABLE I. Energies and relative intensities of the 11 γ rays assigned to ^{137}Cs. The intensities are normalized to the 487 keV γ-ray intensity observed in coincidence with the 1185 keV ground state transition.

E_γ (keV)	I_γ
222.3(1)	77(4)
425.0(2)	3.1(3)
471.2(3)	2.5(3)
487.0(1)	100
614.7(2)	6.7(4)
681.1(2)	8.3(5)
712.2(1)	25(2)
890.2(1)	52(3)
911.9(1)	14(1)
1184.6(1)	(>100)
1567.4(3)	5.5(1)

valence protons is available to help form higher-spin yrast states. These are the $v=5$ $(\pi g_{7/2}^4 d_{5/2})21/2^+$ and $(\pi g_{7/2}^3 d_{5/2}^2)23/2^+$ configurations, matched to the experimental levels at 2784 and 3465 keV. Next come the negative parity excitations involving one $h_{11/2}$ proton. The $v=3$ $(\pi g_{7/2}^4 h_{11/2})23/2^-$ state at 3496 keV has a counterpart at similar energy in ^{135}I, but all five valence protons are active in the higher-lying $27/2^-$, $29/2^-$, and $31/2^-$ excitations. The shell model configurations that are likely to be dominant are indicated in Fig. 4.

The weakly populated and unassigned ^{137}Cs levels at 4352 and 4777 keV almost certainly involve particle-hole neutron excitations of the ^{132}Sn core. States of this kind with configurations $\pi g_{7/2}^3 \nu f_{7/2} h_{11/2}^{-1}$ have been identified in ^{135}I, with firm support from calculations [4]. The energies and decay properties of the 4352 and 4777 keV levels in ^{137}Cs suggest I^π values of $21/2^+$ and $23/2^+$, respectively, but these probable assignments are omitted from Fig. 4, because they are not quite as certain as those for the five-valence-proton yrast states.

Before the present results for ^{137}Cs were known, a shell model calculation for this nucleus had been performed using the known proton single particle energies and the updated set of diagonal and nondiagonal nucleon-nucleon interaction matrix elements specified in Ref. [10] and referred to in the preceding paper [5]. The calculated ^{137}Cs energies are compared with experiment in Table II, where the agreement for all levels can be seen to be quite excellent. The root mean square deviation between experimental and calculated energies is less than 23 keV. This indicates that the accuracy of the truncated shell model applied to singly closed shell nuclei is intrinsically high. The main limitation comes from the accuracy with which a few crucial matrix elements of the effective two-body interaction are known. When these are constrained by experimental data, in particular from the key nucleus with two valence nucleons, the predictive power of the shell model is clearly manifested.

TABLE II. Comparison of the experimental yrast level energies for ^{137}Cs with those calculated using the proton single particle energies and the best fit set of nucleon-nucleon interaction matrix elements adopted in Ref. [10]. Deviations between experimental and calculated energies are shown in the right hand column.

Level I^π	Expt. (keV)	Calc. (keV)	Expt.-Calc. (keV)
$7/2^+$	0	−15	+15
$(11/2^+)$	1185	1223	−38
$(15/2^+)$	1672	1642	+30
$(17/2^+)$	1894	1879	+15
$(21/2^+)$	2784	2827	−43
$(23/2^+)$	3465	3462	+3
$(23/2^-)$	3496	3503	−7
$(27/2^-)$	4408	4424	−16
$(29/2^-)$	5023	5007	+16
$(31/2^-)$	5494	5492	+2

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[1] B. H. Wildenthal, in *Understanding the Variety of Nuclear Excitations*, edited by A. Covello (World Scientific, Singapore, 1991).
[2] J. H. McNeill *et al.*, Phys. Rev. Lett. **63**, 860 (1989).
[3] J. P. Omtvedt *et al.*, Phys. Rev. Lett. **75**, 3090 (1995).
[4] C. T. Zhang *et al.*, Phys. Rev. Lett. **77**, 3743 (1996).
[5] P. J. Daly *et al.*, Phys. Rev. C **59**, 3066 (1999), the preceding paper.
[6] J. F. C. Cocks *et al.*, Phys. Rev. Lett. **78**, 2920 (1997).
[7] T. Pawlat *et al.*, Nucl. Phys. **A574**, 23 (1994).
[8] *Table of Isotopes*, 8th ed., edited by R. B. Firestone *et al.* (Wiley Interscience, New York, 1996), and references therein.
[9] R. C. Thompson *et al.*, Phys. Rev. C **15**, 2019 (1977).
[10] J. Blomqvist, in Proceedings of the XXXIII Zakopane School of Physics, 1998, edited by R. Broda, B. Fornal, and W. Meczynski [Acta Phys. Pol. B (to be published)].