Yrast spectroscopy of $N=82,83$ isotopes ^{136}Xe and ^{137}Xe from ^{248}Cm fission

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Prompt γ-ray cascades in neutron-rich nuclei around doubly magic ^{132}Sn have been studied at Eurogam II using a ^{248}Cm fission source. Here we report results for the four-valence-proton $N=82$ nucleus ^{136}Xe and for its $N=83$ neighbor ^{137}Xe. For both nuclei, the yrast level spectra have been considerably extended, and empirical nucleon-nucleon interactions have been used to assign probable shell model configurations. The ^{136}Xe level energies are compared with those calculated using different sets of proton-proton interaction matrix elements, both diagonal and nondiagonal, obtained by fitting experimental data for other $N=82$ isotones. [S0556-2813(99)00606-8]

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I. INTRODUCTION

There is special interest in the spectroscopy of the few-valence-particle nuclei around doubly magic ^{132}Sn, which can yield information about nucleon-nucleon interactions and effective charges in an important sector of the nuclidic chart. Our knowledge of the structure of ^{132}Sn and its neighbors derives mainly from β^- decay studies of short-lived fission product radionuclides, supplemented in a few cases by γ-ray decay data for yrast isomers. However, recent investigations using large γ-ray detector arrays to study fission fragments from actinide sources have identified prompt and delayed γ-ray cascades from individual product nuclei around ^{132}Sn, and have opened prospects for broad and detailed exploration of the yrast spectroscopy of the region.

We have been investigating the yrast excitations in the $Z=50$–54, $N=80$–84 range of nuclei by analyzing fission product γ-ray data acquired at Eurogam II using a ^{248}Cm source. First results for the two- and three-proton $N=82$ isotones ^{134}Te and ^{135}I [1], for the $N=83$ isotones ^{134}Sb, ^{135}Te, and ^{136}I [2], and for the two-neutron $N=84$ nucleus ^{134}Sn [3] have already been reported. For the $N=82$ nuclei, empirical two-body interactions from the experimental $\pi g_{7/2}^2$, $\pi g_{7/2}d_{5/2}$, and $\pi g_{7/2}h_{11/2}$ multiplets in ^{134}Te were used in shell model calculations to characterize the corresponding three-proton states in ^{135}I. Additionally, the highest-energy levels located in both ^{134}Te and ^{135}I were shown to be core-excited states involving $\nu f_{7/2}h_{11/2}^{-1}$ particle-hole excitations. In a separate theoretical development, calculations by Andreozzi *et al.* [4] using an effective interaction derived from the Bonn *A* free nucleon-nucleon interaction gave excellent agreement with the experimental energies of the two- and three-proton states in ^{134}Te and ^{135}I.

We have now extended these studies to the four-valence-proton $N=82$ nucleus ^{136}Xe and to its $N=83$ neighbor ^{137}Xe. The investigation of ^{136}Xe faced initial difficulties, since its predicted ^{248}Cm fission yield is only 0.4% [5], smaller than the ^{134}Te yield by a factor of 7; moreover, the yrast 6^+ state in ^{136}Xe has a 3 μs half-life, which ruled out the possibility of identifying higher-lying γ rays through prompt coincidences with known ^{136}Xe γ rays deexciting the isomer. However, close inspection of the $\gamma\gamma$ cross coincidences observed with known $^{106-109}$Mo γ rays led to firm identification of two moderately strong γ-ray cascades feeding the ^{136}Xe 3 μs isomer, thus locating new high-lying yrast states in this nucleus. It was easier to study the $N=83$ nucleus ^{137}Xe because its ^{248}Cm fission yield is higher (1.5%), and the only known yrast isomer in ^{137}Xe, with a half-life of ~ 8 ns, in no way hindered the detection by $\gamma\gamma$ coincidence measurements of γ-ray cascades feeding from above.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A. Experimental

The γ-ray measurements were performed at the Eurogam II array using a ^{248}Cm source which delivered $\sim 6 \times 10^4$ fissions/sec. The fission fragments were stopped inside the source within about 2 ps, with subsequent emission of almost all the deexcitation γ rays from nuclei at rest. Eurogam II at the time consisted of 52 large Ge detectors in anti-Compton shields, including 24 four-crystal clover detectors which could serve as Compton polarimeters. In addition, four Low Energy Photon Spectrometer (LEPS) detectors were used to measure x rays and low-energy γ rays. In total, about 2.5×10^9 threefold or higher-fold γ-ray coincidence events were recorded. These data were sorted into several $\gamma\gamma\gamma$ cubic arrays and into two-dimensional $\gamma\gamma$ matrices with both axes extending above 4 MeV.

A more complete account of the experimental details and of the data analysis has been given in earlier publications [1,6,7]. In particular, Urban *et al.* [6,7] have described how information about transition multipolarities could be extracted from analyses of double and triple γ-ray angular correlations and from directional-polarization correlations of γ rays. In the present work, these techniques were used to characterize a number of the strongest transitions in ^{137}Xe, but the ^{136}Xe γ rays of interest were all too weak.

B. Extending the ^{136}Xe level scheme

A 2.95 μs 6^+ isomer at 1892 keV in ^{136}Xe is well established from studies of the ^{136}I $I^{\pi}=(6^-)$ β decay [8], and of delayed γ rays following ^{252}Cf fission [9,10]. The isomer deexcites by a cascade of 197, 381, and 1313 keV $E2$ transitions to the ^{136}Xe ground state. A second 6^+ state at 2262 keV, also fed in the ^{136}I β decay, deexcites exclusively to the 3 μs isomer by a 370 keV $M1/E2$ transition. Up to now, no states with $I>6$ have been placed in the ^{136}Xe scheme.

In the present work, possible γ-ray cascades populating the long-lived ^{136}Xe 6^+ isomer following ^{248}Cm fission could not be identified from the available $\gamma\gamma\gamma$ coincidence data in any straightforward way. For example, a double gate on the 381 and 1313 keV γ rays deexciting the lowest 4^+ state in ^{136}Xe showed in coincidence [Fig. 1(a)] a few strong ^{136}Xe γ rays, all known transitions feeding the 4^+ state directly, as well as cross-coincident $^{106-109}$Mo γ rays from complementary fission fragments. In fact, the strongest peaks in Fig. 1(a) are the 193, 371, and 527 keV γ rays of ^{108}Mo, which is the fission partner of ^{136}Xe in the case of $4n$ emission. Double gating on the 371 and 527 keV γ rays showed in coincidence [Fig. 1(b)] known γ rays of ^{108}Mo, ^{136}Xe, ^{137}Xe, and ^{138}Xe, as well as other lines that could not immediately be assigned with confidence. Of these, the 370 keV γ ray in Fig. 1(b) was likely to be the ^{136}Xe $6_2^+\rightarrow 6_1^+$ transition previously mentioned, while the prominent 968 and 975 keV γ rays also appeared attractive candidates for placement in ^{136}Xe above the 3 μs isomer. The 370 and 968 keV γ rays were subsequently found to be in prompt coincidence, but not the 370 and 975 keV γ rays. Double gating on the 370 and 968 keV γ rays generated the coincidence spectrum of Fig. 1(c), where the relative intensities of the cross-coincidence ^{106,107,108,109}Mo γ rays are seen to be

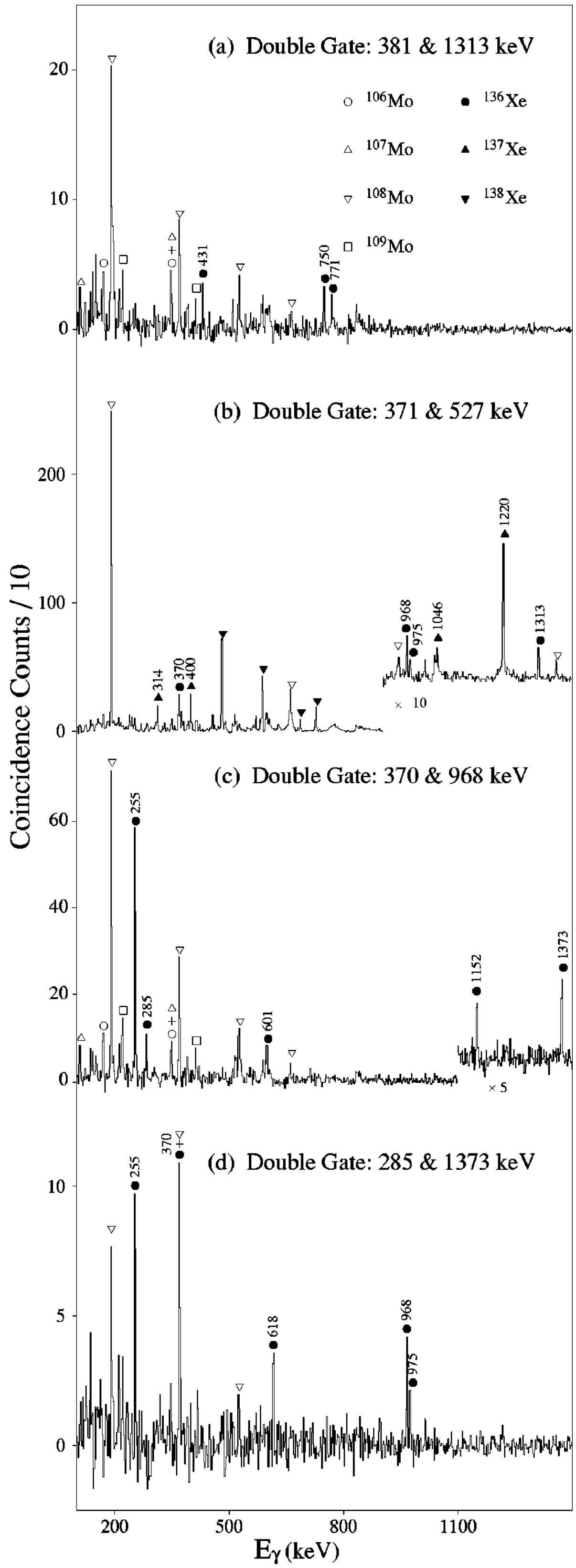

FIG. 1. Key $\gamma\gamma$ coincidence spectra for isotopic identification of ^{136}Xe transitions and construction of the ^{136}Xe level scheme.

TABLE I. Energies and relative intensities of ^{136}Xe γ rays above the 3 μs isomer observed following ^{248}Cm fission. Except for the weakest lines, the energy error is estimated to be about 0.3 keV and the intensity error to be less than 20%.

E_γ (keV)	Relative γ-ray intensity	Placement $E_i \rightarrow E_f$ (keV)
221.0	3	6173→5953
255.0	40	3484→3229
284.5	11	5143→4858
369.8	100	2262→1892
600.8	11	3830→3229
617.8	25	3484→2867
967.8	67	3229→2262
975.1	75	2867→1892
1094.3	5	5953→4858
1151.6	6	4381→3229
1373.2	14	4858→3484
1657.8	4	5143→3484

closely similar to those in Fig. 1(a), thus providing vital support for the assignments of the 370 and 968 keV γ ray pair to ^{136}Xe. Finally a double gate on 285 and 1373 keV γ rays, two high-lying transitions in ^{136}Xe, exhibits [Fig. 1(d)] the two main cascades feeding the 6^+ isomer, one consisting of the 255, 968, and 370 keV transitions, the other in parallel with the 618 and 975 keV transitions. The extended ^{136}Xe level scheme is displayed in Fig. 3, below, where tentative spin-parity assignments and dominant four-proton configurations are also indicated. These assignments are discussed below, and the relative intensities of ^{136}Xe transitions above the 3 μs isomer are shown in Table I.

C. Extending the ^{137}Xe scheme

Many years ago, a study of delayed γ rays following ^{252}Cf fission [10] identified and assigned to the $N=83$ nucleus ^{137}Xe a cascade of 314, 400, and 1221 keV γ rays deexciting an isomer with $t_{1/2}\sim 8$ ns. The same γ rays had previously been reported in Ref. [9], where they were not assigned. The levels of ^{137}Xe populated in ^{137}I β decay include a 1220 keV level with $I^\pi = 11/2^-$ that deexcites to the $7/2^-$ ground state with emission of a 1220.1 keV γ ray [11,12]; this transition and the one observed in the 8 ns isomeric decay are probably identical. Indeed, a first inspection of the data from the present ^{248}Cm fission product measurements revealed intense 314.0, 400.2, and 1220.0 keV γ rays in mutual coincidence. This strong three-γ-ray cascade provided an excellent starting point for further investigation of the ^{137}Xe yrast level structure.

Some important γ-ray coincidence spectra for ^{137}Xe are displayed in Fig. 2. Detailed analyses of these and the rest of the $\gamma\gamma\gamma$ data established the ^{137}Xe level scheme shown in Fig. 3, which accommodates almost all the observed γ rays. Omitted from this simplified scheme are four near-yrast levels of ^{137}Xe at 1978, 2103, 3112, and 3252 keV, which are only weakly populated following ^{248}Cm fission. All the γ rays assigned here to ^{137}Xe are listed in Table II, where their placements are also indicated. For the stronger ^{137}Xe transitions, the angular correlation data provided useful multipolarity information, as summarized in Table III. Thus the 314 and 400 keV γ rays following the $\sim$8 ns isomer could be characterized as stretched quadrupoles, and the linear polarization results showed that they both have $E2$ character, establishing at $I^\pi = 19/2^-$ for the isomeric state. The polarization measurements indicated stretched $E2$ character also for the 312 keV transition, but they were inconclusive for the other transitions. Special mention is made of the strong 270 keV transition feeding the $19/2^-$ isomeric state which is interpreted as a $\Delta I = 0$ $M1/E2$ transition analogous to the strong 370 keV $6_2^+ \rightarrow 6_1^+$ $M1/E2$ transition in ^{136}Xe.

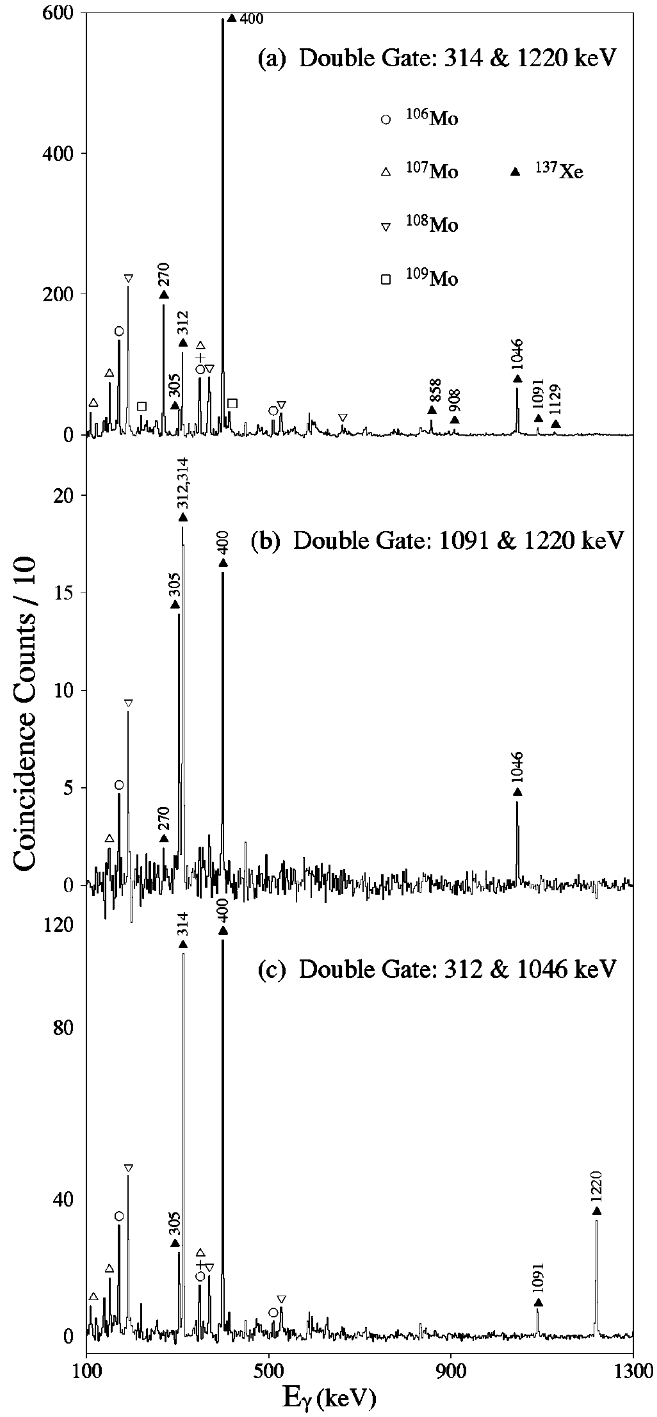

FIG. 2. Key $\gamma\gamma$ coincidence spectra for ^{137}Xe.

The spin-parity assignments proposed for the ^{137}Xe levels in Fig. 3 are consistent with all the experimental results.

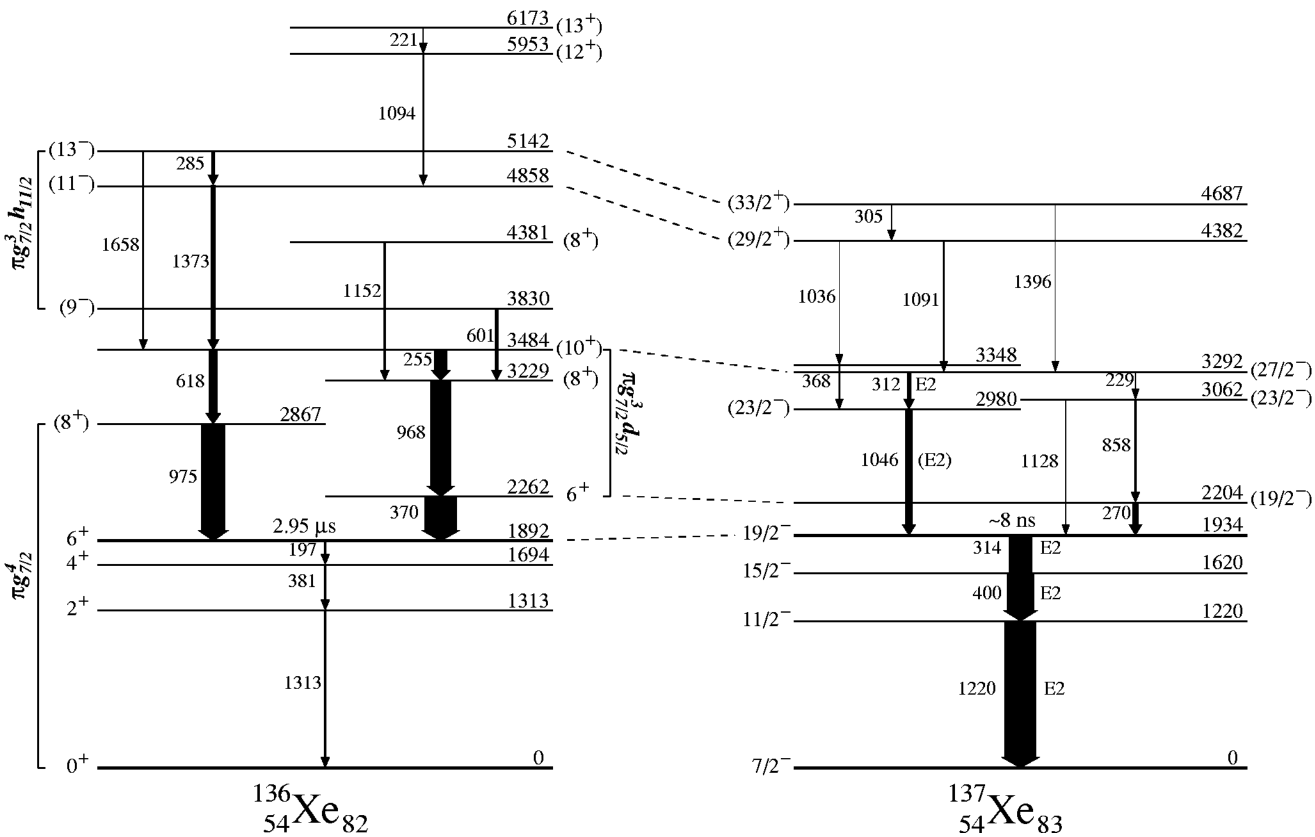

FIG. 3. The ^{136}Xe and ^{137}Xe level schemes with dominant shell model configurations indicated.

TABLE II. Energies and relative intensities of ^{137}Xe γ rays observed following ^{248}Cm fission. Except for the weakest lines, the energy error is estimated to be about 0.3 keV and the intensity error to be less than 20%.

E_γ (keV)	Relative γ ray intensity	Placement $E_i \rightarrow E_f$ (keV)
101.1	<1	2204→2103
124.9	~ 1	2103→1978
139.5	~ 1	3252→3112
190.2	~ 1	3252→3062
229.4	~ 1	3292→3062
269.7	19	2204→1934
304.8	3	4687→4382
311.6	12	3292→2980
314.0	63	1934→1620
358.2	8	1978→1620
367.7	3	3348→2980
400.2	87	1620→1220
483.3	6	2103→1620
857.9	5	3062→2204
907.4	2	3112→2204
1035.6	1	4382→3348
1045.8	21	2980→1934
1090.8	3	4382→3292
1128.3	2	3062→1934
1220.0	100	1220→0
1396.0	1	4687→3292

Broad correspondence between the ^{136}Xe and ^{137}Xe yrast excitations is evident, with most prominent features of the ^{137}Xe level structure attributable to the coupling with an additional $f_{7/2}$ valence neutron.

III. DISCUSSION

One of the main objectives in studying the spectroscopy of few-valence-particle nuclei around ^{132}Sn is to characterize the nucleon-nucleon interactions in this region. To perform shell model calculations for the $N=82$ isotones, the simplest method is to adopt two-body interactions from the experi-

TABLE III. Angular correlation results and multipolarity assignments for ^{137}Xe transitions. In all cases, the gating γ ray is the 1220 keV stretched $E2$ transition.

	$W(\theta)$				
E_γ (keV)	0°	30°	60°	90°	Assignment
400	1.14(2)	1.09(1)	1.01(1)	1.00(1)	$\Delta I=2$, $E2$
314	1.19(2)	1.11(1)	1.03(1)	1.00(1)	$\Delta I=2$, $E2$
1046	1.20(3)	1.08(1)	1.03(1)	1.00(1)	$\Delta I=2$
270	1.24(2)	1.17(1)	1.07(1)	1.00(1)	$\Delta I=0$, see text
1128	1.35(31)	1.11(7)	1.01(5)	1.00(7)	($\Delta I=2$)
312	1.18(2)	1.12(1)	1.05(1)	1.00(1)	$\Delta I=2$, $E2$
368	0.86(5)	0.92(2)	0.95(2)	1.00(2)	$\Delta I=1$
1091	0.89(10)	0.91(4)	0.97(2)	1.00(4)	$\Delta I=1$
1396	1.3(5)	1.43(12)	1.16(10)	1.00(15)	($\Delta I=2$)

TABLE IV. The experimental level energies in ^{136}Xe are compared with theoretical energies calculated using diagonal matrix elements from ^{134}Te (DIAG), and using the best fit parameter sets of Wildenthal (WILD) and Blomqvist (BLOM) discussed in the text.

I^{π}	Expt. (keV)	DIAG (keV)	WILD (keV)	BLOM (keV)
0^+	0	0	0	15
2^+	1313	1279	1314	1372
4^+	1694	1577	1714	1717
6^+	1892	1691	1846	1858
6^+	2262	2097	2260	2236
8^+	2867	2666	2931	2862
8^+	3229	3200	3230	3242
10^+	3484	3499	3582	3484
(9^-)	3830	3666	3738	3840
(11^-)	4858	4783	4844	4923
(13^-)	5142	5047	5157	5138

mental level spectrum of the two-proton nucleus ^{134}Te. This approach, which takes account of diagonal matrix elements only, and thereby neglects configuration mixing, provided valuable guidance in the initial interpretation of the observed ^{136}Xe levels, which were thus assigned the dominant four-proton configurations indicated in Fig. 3. The experimental ^{136}Xe level energies may be compared in Table IV with the values calculated using diagonal matrix elements taken from the ^{134}Te spectrum. The agreement is seen to be only fair, but this is in line with expectations of appreciable mixing between such configurations as $\pi g_{7/2}^4$, $\pi g_{7/2}^3 d_{5/2}$, and $\pi g_{7/2}^2 d_{5/2}^2$. Lawson [13] and others have already noted that the yrast $6^+ \rightarrow 4^+$ transition in ^{136}Xe is unusually slow [$B(E2) < 0.02$ Weisskopf units (W.u.)], a clear indication that the $\pi g_{7/2}$ subshell is very close to being half-filled in these states.

A few years ago, Wildenthal [14] carried out a detailed analysis of the level spectra of $N=82$ isotones ranging from $^{133}_{51}$Sb to $^{154}_{72}$Hf. In a model space consisting of the $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$ proton orbits, he performed, with some truncation, comprehensive shell model calculations, and used an iterative procedure to extract a best-fit set of five single particle energies and 160 two-body matrix elements, both diagonal and off diagonal. These parameters were found to be consistent with the extensive body of spectroscopic observables then available for the $N=82$ isotones [14]. When the ^{136}Xe level energies were here recalculated using the Wildenthal parameter set, much better overall agreement with experiment was obtained (Table IV).

Since our results for ^{135}I and ^{136}Xe are significant additions to the data set, and all the required proton single particle energies are now known from experiment, Blomqvist has recently updated the $N=82$ interaction parametrization and has changed 54 of Wildenthal's matrix elements, mostly diagonal ones. Details will be presented elsewhere [15]. As shown in Table IV, these changes improve the agreement between theory and experiment for ^{136}Xe, if only to a small extent. The following paper [16] presents first results for the five valence proton nucleus ^{137}Cs, which were still unknown when the input parameters for the $N=82$ shell model calculations were modified. The new ^{137}Cs data are thus particularly suitable for testing the updated set of nucleon-nucleon interaction matrix elements presented in Ref. [15].

The highest levels located at 5953 and 6173 keV in ^{136}Xe are probably core-excited $\pi g_{7/2}^4 \nu f_{7/2} h_{11/2}^{-1}$ states corresponding to the yrast 12^+ and 13^+ states at $\sim$6 MeV in ^{134}Te. Moreover, the lower ^{136}Xe level at 4381 keV may be the 8^+ core excitation built on the ground state, analogous to the known 8^+ states in ^{132}Sn and ^{134}Te at 4848 and 4557 keV, respectively. The 8^+ energy systematics supports this interpretation.

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