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EXPLORING FEW-VALENCE-PARTICLE NUCLEI AROUND MAGIC ^{132}Sn

P.J. DALY, C.T. ZHANG, P.K. BHATTACHARYYA, B. FORNAL,[a] R. BRODA,[a] Z.W. GRABOWSKI
Chemistry and Physics Depts., Purdue University, W. Lafayette, IN 47907, USA

I. AHMAD, T. LAURITSEN, L.R. MORSS
Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

W. URBAN,[b] W.R. PHILLIPS, J.L. DURELL, M.J. LEDDY, A.G. SMITH, B.J. VARLEY
Depts. of Physics and Astronomy, University of Manchester, M13 9PL Manchester, UK

N. SCHULZ, E. LUBKIEWICZ,[c] M. BENTALEB
Institut de Recherches Subatomique, Université Louis Pasteur, F67037 Strasbourg, France

J. BLOMQVIST
Dept. of Physics Frescati, Royal Institute of Technology, S-10405 Stockholm, Sweden

Excitations of nuclei close to magic ^{132}Sn have been investigated by analysis of fission product γ-ray data measured at Eurogam II using a ^{248}Cm source. Results for the N=82 isotones up to ^{136}Xe, for the one proton-one neutron nucleus ^{134}Sb, and for the N=84 isotones ^{134}Sn, ^{135}Sb, and ^{136}Te are summarized. The interpretation of the observed level spectra is mainly based on shell model calculations using empirical proton-proton interactions from ^{134}Te, neutron-neutron interactions from ^{134}Sn, and proton-neutron interactions estimated (with scaling as $A^{-1/3}$) from the well-known ^{210}Bi spectrum.

1 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 region of the chart. Our limited knowledge of the structure of ^{132}Sn and its neighbors derives mainly from β-decay studies of fission product radionuclides, supplemented

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[a] On leave from Inst. of Nuclear Physics, PL-31342 Cracow, Poland

[b] Present address: Inst. of Exp. Physics, Warsaw University, PL-00681 Warsaw, Poland

[c] On leave from Inst. of Physics, Jagellonian University, PL-30059 Cracow, Poland

^{248}Cm Fission

Xe	0.01 $\pi^4\nu^{-2}$	0.10 $\pi^4\nu^{-1}$	0.40 π^4 ✓	1.50 $\pi^4\nu^1$ ✓	3.10 $\pi^4\nu^2$
I	0.15 $\pi^3\nu^{-2}$	0.60 $\pi^3\nu^{-1}$	1.90 π^3 ✓	2.50 $\pi^3\nu^1$ ✓	3.80 $\pi^3\nu^2$
Te	0.80 $\pi^2\nu^{-2}$	2.10 $\pi^2\nu^{-1}$ ✓	2.90 π^2 ✓	3.20 $\pi^2\nu^1$ ✓	1.60 $\pi^2\nu^2$ ✓
Sb	1.20 $\pi^1\nu^{-2}$	2.70 $\pi^1\nu^{-1}$ ✓	2.70 $\pi^1\otimes C$ ✓	1.30 $\pi^1\nu^1$ ✓	0.50 $\pi^1\nu^2$ ✓
Sn.	1.60 ν^{-2}	1.10 $\nu^{-1}\otimes C$ ✓	0.90 Core Exci.	0.30 $\nu^1\otimes C$	0.05 ν^2 ✓
	80	81	82	83	84

# of Neutrons ⟶

Figure 1: The Z=50-54, N=80-84 square showing predicted % yields of fission products.

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 have identified prompt and delayed γ-ray cascades from individual product nuclei around ^{132}Sn, and have opened prospects for broad exploration of the yrast spectroscopy of the region.

2 Fission Yields and Isotopic Assignments

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 measured with a ^{248}Cm source at Eurogam II. Fig. 1 shows predicted yields for products of ^{248}Cm fission,[1] with checkmarks indicating the individual nuclei studied in the present work. First results for the three-proton N=82 nuclei ^{134}Te and ^{135}I, for the two-neutron nucleus ^{134}Sn, and for the N=83 nuclei ^{134}Sb, ^{135}Te, and ^{136}I have already been reported. [2,3,4] Cross-coincidences observed between γ-rays from complementary light and heavy fission fragments were vital for isotopic assignments of new γ-ray cascades. For example, a double gate on ^{109}Tc γ-rays showed in coincidence γ-ray cascades of ^{135}I, ^{136}I, and ^{137}I, the 4n, 3n, and 2n fission partners of ^{109}Tc; gating on ^{108}Tc γ-rays was seen to enhance the ^{137}I γ-rays (and to a lesser extent the ^{136}I γ-rays) relative to those of ^{135}I. Determining isotopic assignments from $\gamma\gamma$ cross coincidences requires considerable patience, but it is easy to recognize when correct assignments for both light and heavy partner fragments have been discovered, since all observations then fit consistently into a single pattern.

In the following sections, our results for N=82, N=83, and N=84 isotones in the ^{132}Sn region will be presented, with emphasis on more recent findings. The N=81 results will be reported on another occasion.

3 N=82 Isotones

In Ref. 2, empirical two-body interactions from the experimental π^2 states in ^{134}Te were used in shell model calculations to interpret the level spectrum of the three-proton nucleus ^{135}I (Fig. 2). The highest levels located in both ^{134}Te and ^{135}I were shown to be core excited states involving $\nu f_{7/2}h^{-1}_{11/2}$ particle-hole excitations. In a separate theoretical development, Andreozzi et al.[5] obtained excellent agreement with the ^{134}Te and ^{135}I level energies using an effective interaction derived from the Bonn A free nucleon-nucleon interaction.

We have now extended our analyses 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 fission yield is small,[1] and the occurrence of a 6^+ yrast isomer with $t_{1/2} = 3\ \mu s$ ruled out the possibility of identifying directly from $\gamma\gamma$ coincidences the transitions feeding the isomer. However, careful inspection of cross-coincidence spectra observed with known γ-rays of complementary $^{106-109}$Mo fission products led to firm identification of several new ^{136}Xe γ-rays above the 3 μs isomeric state. Gating on these γ-rays then established the extended ^{136}Xe scheme shown in Fig. 2. To cite one key example, a double gate on 285 and 1373 keV γ-rays, both high-lying transitions in ^{136}Xe, selected the two main cascades feeding the 6^+ isomer, one consisting of 255, 968 and 370 keV transitions, the other in parallel of 618 and 975 keV transitions. Probable spin-parity assignments and dominant four-proton configurations are indicated in Fig. 2.

The simplest shell model calculations for the N=82 isotones adopt empirical two-body interactions from the ^{134}Te experimental spectrum. This approach, which takes account of diagonal matrix elements only and thereby neglects configuration mixing, provided valuable guidance in the interpretation of the observed ^{136}Xe levels. A few years ago, Wildenthal[6] performed comprehensive shell model calculations for all N=82 isotones then known, and used on iterative procedure to obtain a best fit set of 160 two-body matrix elements, both diagonal and off-diagonal. Since the results for ^{135}I and ^{136}Xe obtained in the present work, as well as those for ^{137}Cs reported by R. Broda et al.,[7] are significant additions to the N=82 data base, Blomqvist[8] has now updated the N=82 interaction parameters and has changed 54 of Wildenthal's matrix elements, mostly diagonal. These changes have significantly improved

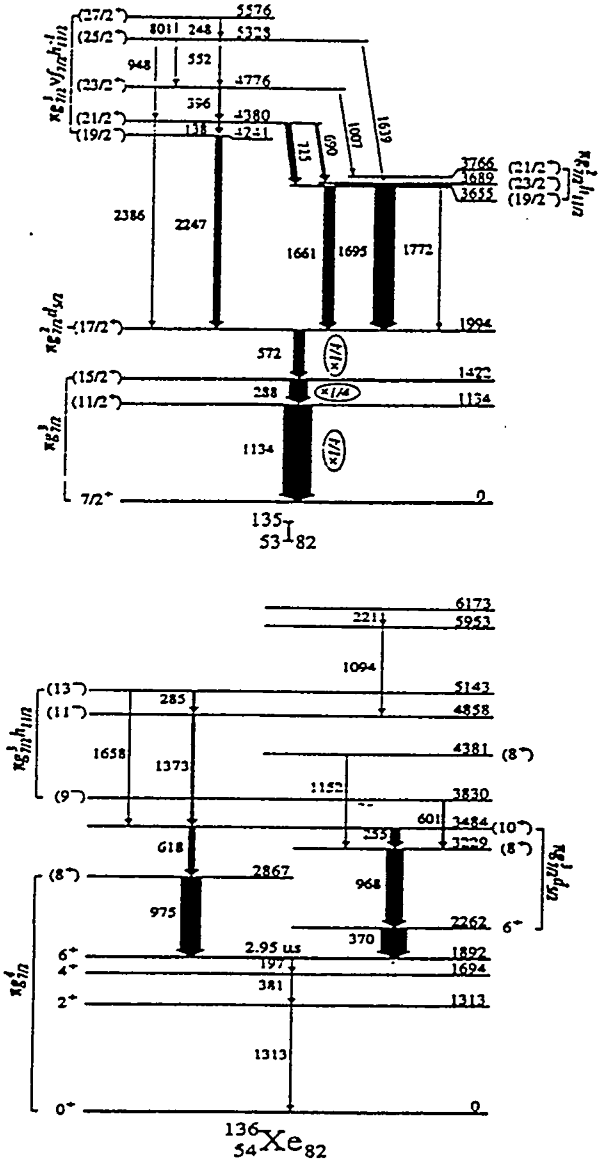

Figure 2: Yrast level schemes for the three- and four-proton nuclei ^{135}I and ^{136}Xe. The dominant configurations assigned are indicated.

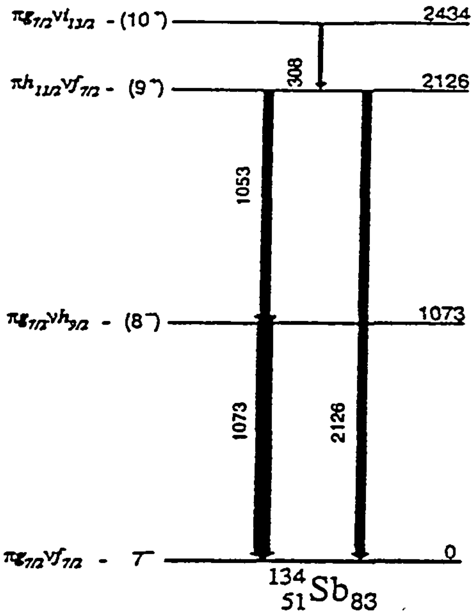

Figure 3: Yrast level scheme for ^{134}Sb. Dominant configurations are indicated.

the overall agreement between theory and experimental energies for the N=82 isotone series.

4 N=83 Isotones

We turn attention to the largely unexplored N=83 nuclei near ^{132}Sn, which should provide key information about empirical proton-neutron interactions in the region. First results have been reported in a short paper,[4] which gave rudimentary yrast level schemes for the isotones ^{134}Sb, ^{135}Te, and ^{136}I. Interpretation of these schemes was heavily based on results of shell model calculations using known single particle energies, proton-proton interactions from ^{134}Te, and proton-neutron interactions estimated from the well known ^{210}Bi spectrum.

We focus here on the important proton-neutron nucleus $^{134}_{51}Sb_{83}$ for which no yrast transitions were known previously. Through detailed examination of cross coincidence relationships with ^{110,111,112}Rh γ-rays, transitions of 308, 1053, 1073, and 2126 keV were identified and assigned to ^{134}Sb. They are accommodated in a simple level scheme (Fig. 3), built on the $(\pi g_{7/2}\nu f_{7/2})7^-$

^{134}Sb state known from β-decay.[9] The excited states are interpreted as $(\pi g_{7/2}\nu h_{9/2})8^-$, $(\pi h_{11/2}\nu f_{7/2})9^+$, and $(\pi g_{7/2}\nu i_{13/2})10^+$ excitations. In the corresponding ^{210}Bi nucleus, the counterpart excitations $(\pi h_{9/2}\nu g_{9/2})9^-$, $(\pi h_{9/2}\nu i_{11/2})10^-$, $(\pi i_{13/2}\nu g_{9/2})11^+$, and $(\pi h_{9/2}\nu j_{15/2})12^+$ are all known, and they furnish proton-neutron interactions that can be used, with appropriate $A^{-1/3}$ scaling, to calculate the excitation energies in ^{134}Sb. This procedure gives good agreement (within 50 keV) for the ^{134}Sb levels up to the 2126 keV level, supporting the proposed configuration assignments. The $(\pi g_{7/2}\nu i_{13/2})10^+$ energy cannot be calculated because the $\nu i_{13/2}$ single particle energy around ^{132}Sn is not known up to now. However, one may reverse the procedure by assuming that the 2434 keV level in ^{134}Sb is correctly interpreted as this specific 10^+ state, and then use its excitation energy to estimate the $\nu i_{13/2}$ s.p. energy. The result thus obtained is:

$$E_{s.p.}(\nu i_{13/2}) \;=\; 2.7\ MeV$$

which is in reasonable agreement with the value ~3.0 MeV calculated many years ago[10] using a Woods-Saxon potential.

One particular N=83 product that we searched for in vain was the single-valence-neutron nucleus ^{133}Sn. No trace of the known[11] 1561 keV $(\pi h_{9/2} \rightarrow \nu f_{7/2})$ γ-ray could be detected, even though yrast γ-ray cascades in neighboring ^{132}Sn and ^{134}Sn (see below) were seen rather clearly. The low ^{133}Sn neutron separation energy of about 2.6 MeV is probably an important factor.

5 N=84 Isotones

In the ^{248}Cm fission data, known ^{128}Sn, ^{130}Sn, and ^{132}Sn γ-rays appeared in coincidence with several Pd isotopes, but gates on ^{112}Pd transitions also showed new 347 and 725 keV γ-rays. Double gating on these two γ-rays revealed a 174 keV transition in coincidence, and convincing evidence was obtained for assigning this three γ-ray cascade, which de-excites an 80(15) ns isomer, to the two-neutron nucleus ^{134}Sn.[3] The ^{134}Sn levels located are naturally interpreted as the complete $\nu f_{7/2}^2$ spectrum up to the maximally aligned 6^+ isomeric state at 1246 keV (Fig. 4). The B(E2; $6^+ \rightarrow 4^+$, ^{134}Sn) is determined to be 36(7) $e^2 fm^4$ or 0.88(17) W.u., corresponding to the E2 effective charge of 1.01(10) e. This result is similar to the value 0.88(5)e reported[12] for $\nu g_{9/2}$ in ^{210}Pb, which also has two valence neutrons outside a doubly magic core.

Recently, we searched for and found some γ-rays in the N=84 nucleus ^{135}Sb, with one proton more than ^{134}Sn. When gates were set on ^{111}Rh transitions, known γ-rays of ^{133}Sb and ^{134}Sb, the 4n and 3n fission partners, appeared in coincidence as well as new 224.9, 410.9 and 706.5 keV γ-rays (in order of increasing intensity), which we here assign to the 2n partner ^{135}Sb.

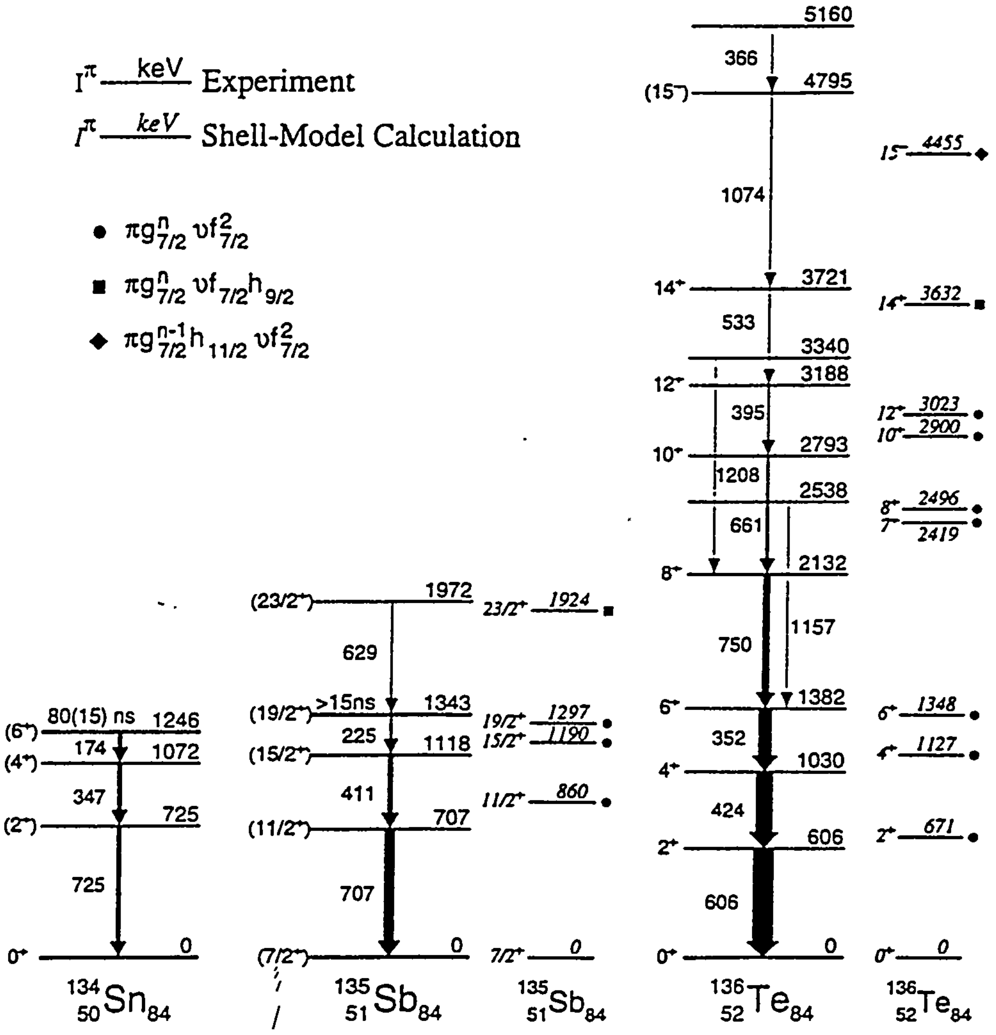

Figure 4: Yrast level schemes of the N=84 isotones ^{134}Sn, ^{135}Sb, and ^{136}Te. Results of shell model calculations for ^{135}Sb and ^{136}Te are also displayed.

Double gating on these new γ-rays showed coincidences with ^{109,110,111}Rh, the γ-rays of the 2n fission partner ^{111}Rh being clearly the strongest; the result is similar to the cross coincidence intensity pattern observed in the case of ^{134}Sn. A fourth ^{135}Sb γ-ray of 629.1 keV also appeared in coincidence. The $t_{\gamma\gamma}$ time distributions indicated that the 225, 411, and 707 keV γ-ray cascade de-excites an isomeric state with $t_{1/2} \sim 20$ ns at 1343 keV in ^{135}Sb, while the 629 keV transition feeds the isomer (Fig. 4).

The 1.7 s ($7/2^+$) ground state in ^{135}Sb was known from β-decay. One may expect low-lying $\pi g_{7/2} \nu f_{7/2}^2$ states in ^{135}Sb, and the 707, 1118 and 1343 keV levels located here are interpreted as the $I^\pi = 11/2^+$, $15/2^+$, and $19/2^+$ members of this multiplet. The 1972 keV level is likely to be the $(\pi g_{7/2} \nu f_{7/2} h_{9/2}) 23/2^+$ state, with one neutron promoted from $\nu f_{7/2}$ to $\nu h_{9/2}$. The results of shell model calculations, shown in Fig. 4, support these assignments. The approximate half-life value for the 1343 keV isomer is consistent with the proposed interpretation, but more accurate lifetime measurements will allow a more useful comparison of B(E2)s for the $\nu f_{7/2}^2 6^+ \rightarrow 4^+$ in ^{134}Sn and the related $19/2^+ \rightarrow 15/2^+$ transition in ^{135}Sb.

The next N=84 isotone ^{136}Te had previously been studied by fission fragment γ-ray spectroscopy, and a cascade of five γ-rays up to an $I^\pi=(10^+)$ level at 2.79 MeV had been found.[13] We built on the earlier findings, and established the extended ^{136}Te scheme shown in Fig. 4. The $\gamma\gamma$ spectra for ^{136}Te were particularly good, and the main cascade of nine transitions up to 5160 keV seems quite firm. Angular correlation results are consistent with stretched E2 character for the six transitions up to 3188 keV, with statistics being insufficient for the highest transitions. There is good general correspondence between the experimental and calculated level spectra (Fig. 4). The outstanding problem is that the observed 10^+-12^+ spacing of 395 keV is much greater than the calculated 123 keV, and it is not obvious how to doctor the calculation in order to improve the agreement. Work continues on this problem, which recalls the much studied situation [14] in the counterpart nucleus ^{212}Po, where a related high-spin yrast isomer is forced to de-excite by α-decay.

6 Conclusion

Neutron-rich fission product nuclei around doubly magic ^{132}Sn are now accessible for detailed study by prompt γ-ray measurements using multidetector arrays. In the present work a start has been made on investigating the yrast spectroscopy of the N=81, 82, 83 and 84 few-valence-particle nuclei in the region. Most of the results are interpreted in the light of shell model calculations using empirical nucleon-nucleon interactions, but much remains to be done. Transition multipolarity determinations and short half-life measurements would be particularly useful experimental contributions.

Acknowledgments

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