Recent measurements of the spherical and deformed isomers using the Lohengrin fission-fragment spectrometer

G.S. Simpson, J.C. Angélique, J. Genevey, J.A. Pinston, A. Covello, A. Gargano, U. Köster, R. Orlandi, A. Scherillo, W. Urban

RECENT MEASUREMENTS OF SPHERICAL AND DEFORMED ISOMERS USING THE LOHENGRIN FISSION–FRAGEMENT SPECTROMETER

G. S. SIMPSON, J. C. ANGELIQUE, J. GENEVEY and J. A. PINSTON

LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, F-38026 Grenoble Cedex, France

A. COVELLO and A. GARGANO

Dipartimento di Scienze Fisiche, Università degli Studi di Napoli Federico II and INFN, Complesso Universitario di Monte Sant'Angelo, Via Cintia, I-80126 Napoli, Italy

U. KÖSTER

Institut Laue-Langevin, B.P. 156, F-38042 Grenoble Cedex 9, France

R. ORLANDI

INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy

A. SCHERILLO

Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, United Kingdom

W. URBAN

Faculty of Physics, Warsaw University, ul.Hoża 69, PL-00-681 Warszawa, Poland

New experimental information has been obtained on the μs isomeric cascade in the very neutron-rich ^{136}Sb using γ-ray and conversion-electron spectroscopy at the Lohengrin fission-product spectrometer of the Institut Laue-Langevin, Grenoble. Two new transitions have been observed and their multipolarities determined, resolving the question of the origin of the isomerism. The new level scheme is in good agreement with predictions of a realistic shell-model calculation. Microsecond isomers in deformed neutron-rich fission fragments have also been studied in ^{107}Mo and ^{107}Tc with the Lohengrin spectrometer. These studies have been complemented by prompt γ-ray spectroscopy of these nuclei, plus the neighboring ^{105}Mo, following the spontaneous fission of a ^{248}Cm source inside EUROGAM2. Simple quasiparticle-rotor model calculations are able to reproduce the experimental level schemes and decay patterns.

1. ^{136}Sb

1.1. *Introduction*

Recent shell-model studies employing a two-body effective interaction derived from the CD-Bonn nucleon-nucleon (NN) potential, with no use of any adjustable parameter have been able to successfully reproduce the experimental level schemes of ^{134,135}Sb [1,2]. The Sb isotopes are most appropriate for testing the matrix elements of the proton-neutron interaction between valence nucleons in different major shells. These calculations show that there is no need to invoke shell-structure modifications to explain the presently available data on neutron-rich nuclei beyond ^{132}Sn. The nucleus ^{136}Sb, with an N/Z ratio of 1.67, is at present the most exotic open-shell nucleus beyond ^{132}Sn for which a spectroscopic study has been performed [3]. In this study it was concluded that the μs isomer observed most likely originates from the $I^{\pi} = 6^{-}$ state of the $\pi g_{7/2}\nu(f_{7/2})^3$ configuration. Only one γ-ray transition of 173 keV was observed in coincidence with ^{136}Sb ions, which alone was not enough to explain the origin of μs isomerism. In Ref. [3] an unseen low-energy $E2$ transition was postulated to be responsible for the μs lifetime. In the present work this nucleus has been studied with an experimental setup capable of detecting low-energy conversion electrons and γ rays.

1.2. *Experimental Method*

Delayed γ rays and conversion electrons from ^{136}Sb were observed using the Lohengrin mass spectrometer at the high-flux reactor of the Institut Laue-Langevin, Grenoble. Mass 136 nuclei were produced by thermal-neutron induced fission of a thin 7 $\times$ 0.5 cm^2, 1 mg ^{241}Pu target. The Lohengrin mass spectrometer was used to select nuclei recoiling from the target, according to their mass-to-ionic charge ratios (A/q). The flight time of the $A = 136$ nuclei through the spectrometer was around 2.3 μs. The energy of the fission fragments was detected in a $\Delta E1\Delta E2$ ionization chamber, filled with isobutane gas, allowing the identification of A/q. The pressure of the gas in the chamber was adjusted so that the fission products stopped in the last few μm of a 6 μm thick Mylar foil. A few mm behind the foil, two adjacent, rectangular, liquid-nitrogen cooled Si(Li) detectors were placed, to detect X rays and conversion electrons down to about 20 keV in energy. γ rays de-exciting isomeric states, and states below the isomer, were detected by two Clover Ge detectors. The total γ-ray detection efficiency was 14.6% and 3.5% for photons of 100 keV and 1 MeV, respectively. Any

γ rays detected in the Ge or Si detectors up to 20 μs after the arrival of an ion were recorded by the the data acquisition system. Measurements of delayed γ rays and conversion electrons from ^{136}Sb were an experimental challenge as the ionization chamber was unable to resolve the different isobars in the $A = 136$ mass chain. Another μs isomer exists in this mass chain, the 2.95 μs 6^+ state ^{136}Xe [4], whose fission yield is a factor 25 higher than that of ^{136}Sb. The previously measured short lifetime of the isomer (565(50) ns) [3], meant also that much of the intensity of the isomeric state decayed during the 2.3 μs flight time through the spectrometer. Hence, delayed γ-ray and conversion-electron spectra were dominated by transitions from the ^{136}Xe isomer.

1.3. *Results*

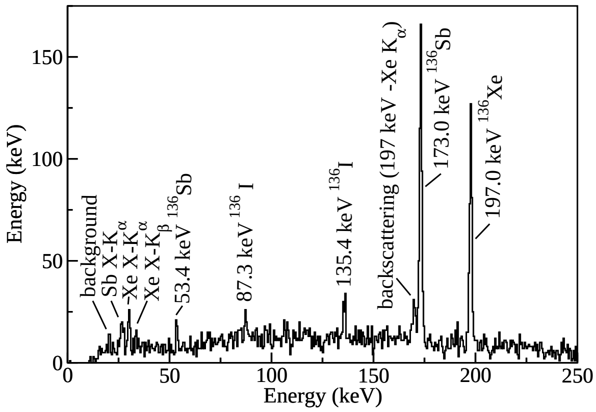

Fig. 1. γ rays observed in the Ge detectors in coincidence with Sb K_α X rays measured in the Si detectors. Background transitions are present from the strongly produced isomer in ^{136}Xe [4] and from ^{136}I, produced by β decay

In addition to the previously reported delayed 173 keV γ ray from ^{136}Sb [3], two new delayed transitions of 53.4(3) keV and 51.4(5) keV have been observed. The 53.4 keV γ ray was observed in coincidence with Sb K_α X-rays and $A = 136$ ions, as shown in Fig. 1. By gating on the 173.0 keV γ-ray transition, observed in the Ge detectors, and $A = 136$ ions it was possible to observe coincident conversion electrons at 47.1 keV (corrected for the energy loss in the Mylar foil), as shown in Fig. 2. These electrons correspond to the L+M groups, of the two new transitions. Correcting for the weighted mean L binding energy for Sb and the energy loss in the Mylar foil gives a transition energy of 51.4(5) keV. By examining the γ ray and conversion-electron intensity ratios it was possible to assign M1 and E2 multipolarities to the 53.4 and 51.4 keV transitions respectively. More details on the assignments of these multipolarities are given in Ref. [5]. The halflife of the isomeric state was measured to be 480(100) ns, as shown in Fig. 3, in agreement with 565(50)ns measured in Ref. [3].

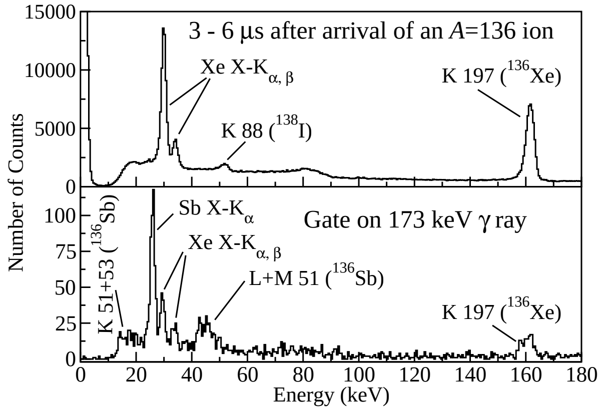

Fig. 2. Conversion electrons and X-rays observed in the Si detectors, in the upper spectrum 3 to 6 μs after the arrival of an $A = 136$ ion and in the lower spectrum in coincidence with the 173.0 keV γ ray in the Ge detectors, 0 to 1.5 μs after the arrival of an $A = 136$ ion. A conversion-electron line of 47.1 keV is observed and is identified as the $L + M$ lines of a 51.4 keV transition from ^{136}Sb.

1.4. *Discussion*

A shell-model calculation has been performed with the same realistic interaction used for ^{134}Sb and ^{135}Sb [1,2] and is described in the proceedings of A. Covello at this conference and in [5]. The proposed experimental level scheme of ^{136}Sb is shown in Fig. 4, where it is compared with the calculated results. In this figure the first four calculated states are reported and each of them has a counterpart in the experimental spectrum. The 51.4 keV $E2$ is almost certainly the $6^- \rightarrow 4^-$ isomeric transition, from lifetime arguements. The order of the 173 keV and 51.4 keV transitions has been assigned by comparison with the calculation. Note that the ground state spin was already identified as 1^- in Ref. [6].

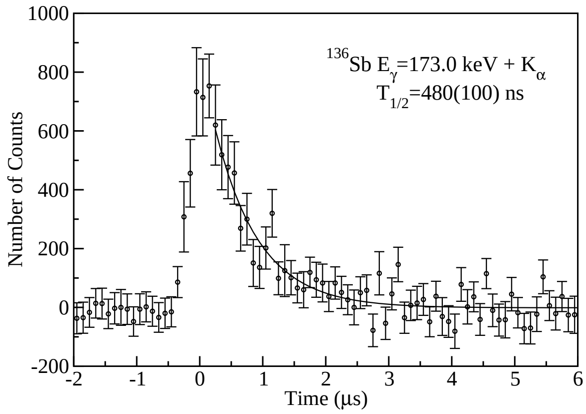

Fig. 3. Summed time spectrum of gates on the 173.0 keV γ-ray transition detected in the Clover Ge detectors and the Sb K_α X-rays in the Si detectors.

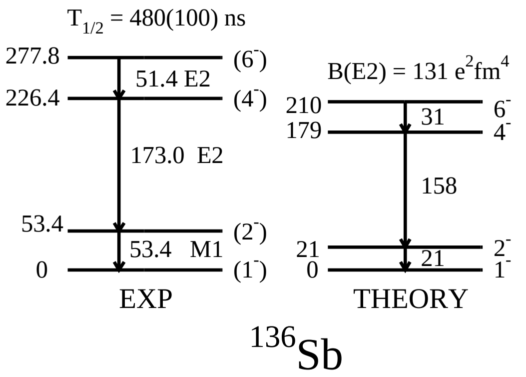

Fig. 4. Proposed decay scheme of the ^{136}Sb isomer.

The four observed levels in ^{136}Sb are all identified with states which are dominated by the configuration $\pi g_{7/2}\nu(f_{7/2})^3$. It is worth mentioning that the percentages of configurations other than the dominant one in the considered states of ^{136}Sb are rather large, ranging from 24% to 32%.

An important piece of information is provided by the measured halflife of the 6^- state, from which a $B(E2; 6^- \rightarrow 4^-)$ value of 170(40) e^2 fm^4 = 4.2 W.u. is extracted. Using effective proton and neutron charges of 1.55e and 0.70e, respectively, we obtain the value 131 e^2 fm^4, which compares very well with experiment. It is worth mentioning that these values of the effective charges have been consistently used in previous calculations for nuclei in the ^{132}Sn region [7].

1.5. *Summary*

Delayed γ rays and conversion electrons have been measured in the very neutron-rich nucleus ^{136}Sb, which represents a further step in the far-from-stability region beyond N=82. The multipolarities of these transitions have been determined and a level scheme constructed by comparison with the results of a realistic shell-model calculation. The predicted energies and $B(E2; 6^- \rightarrow 4^-)$ are in very good agreement with measured values. This shows that a consistent shell-model description can be given of the presently known nuclei in this region.

2. ^{105,107}Mo, ^{107}Tc

2.1. *Introduction*

The rapid shape change of the low lying states in the Sr and Zr nuclei, from spherical to deformed, when the neutron number increases from 58 to 60 neutrons is well known. In the nearby even-even $^{104-108}$Mo a new situation occurs. These nuclei are strongly deformed [8–10] but, at the same time, the levels of the $K^\pi = 2^+$, γ-band descrease in energy with increasing neutron number, suggesting that the triaxial degree of freedom plays an important role in these isotopes. However, the nature of this triaxiality is not well understood. Calculations by Skalski *et al.* [11] predict ground state triaxial minima, with γ = 19-21° for these nuclei. In constrast Smith *et al.* suggest that the triaxiality is dynamic in nature [8], with $\gamma \sim 0°$ at low spins and a rotation-induced change occurring around $J \sim 10 - 12\hbar$, the latter being supported by the experimental observation of a decrease in the quadrupole moment. To better understand the nature of this non-axial deformation it is also important to study the structure of the odd Mo nuclei. The nuclei ^{105}Mo and ^{107}Mo have been revisited experimentally in the present work and the structure of these nuclei was analyzed in the framework of the particle-rotor coupling model. Similarly the influence of an odd-proton on the even-even core was examined by studying ^{107}Tc.

2.2. *Experimental Method and Results*

The nuclei ^{105,107}Mo and ^{107}Tc were studied by γ-ray spectroscopy following the spontaneous fission of ^{248}Cm using the EUROGAM2 array. Previously, four different configurations were proposed in ^{105}Mo however only one well-developed band was observed which fed the ground state [10]. In the present work four well developed bands were observed in ^{105}Mo.

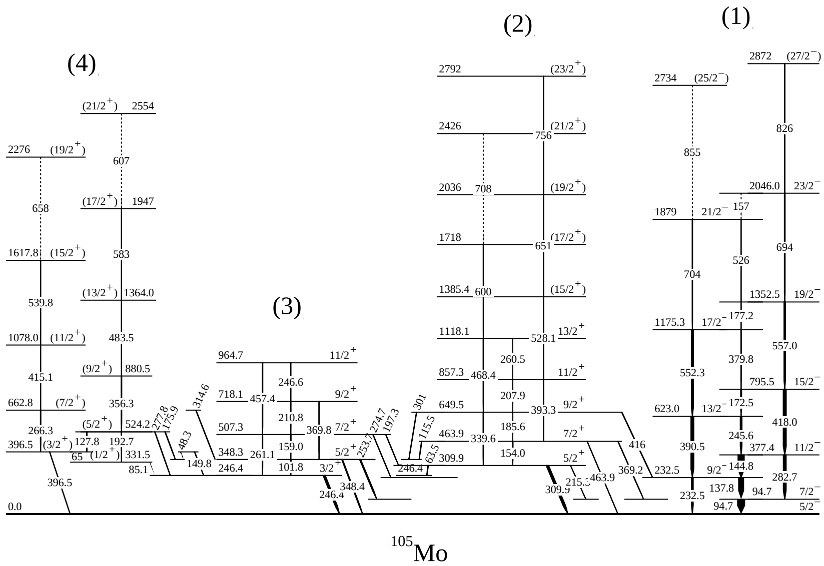

Fig. 5. Partial level scheme of ^{105}Mo as obtained in this work.

Three well developed bands were previously reported in ^{107}Mo from γ-ray measurements of the spontaneous fission of ^{248}Cm [12]. To complete the level scheme, the Lohengrin mass spectrometer has been used to search for delayed γ-rays and conversion electrons in this nucleus using the setup described in Section 1.2. A new isomer with a 420 ns half life was observed in ^{107}Mo. It was tentatively assigned to be a $1/2^+$ state deexciting by a 65.4 keV $E2$ transition to the $5/2^+$ ground state. A 30 keV, E1, 3.85 μs transition from the $3/2^+$ level of the $1/2^+[431]$ intruder band to the ground state was observed in ^{107}Tc.

2.3. *Discussion*

The excited states of the bands in ^{105,107}Mo and ^{107}Tc and their γ-ray decay patterns were calculated using the code ASYRMO. In the present calculation, values $\kappa = 0.068$ and $\mu = 0.35$ were taken for the strength parameters of the **ls** and $\mathbf{l^2}$ terms, for both N=4 and N=5 neutron shells. The other parameters entering in the level calculations are pairing introduced via a standard BCS calculation, the deformation parameters ϵ_2 and γ of the single-particle potential in the intrinsic system and the inertia parameter a of the bands. Agreement with theory can be improved by introducing an *ad hoc* "Coriolis attenuation" parameter, ξ. An effective value of $\xi = 0.7$ is common in these calculations. Finally, the number of variable parameters was minimized by imposing that all bands of the same nucleus have the same parameter values.

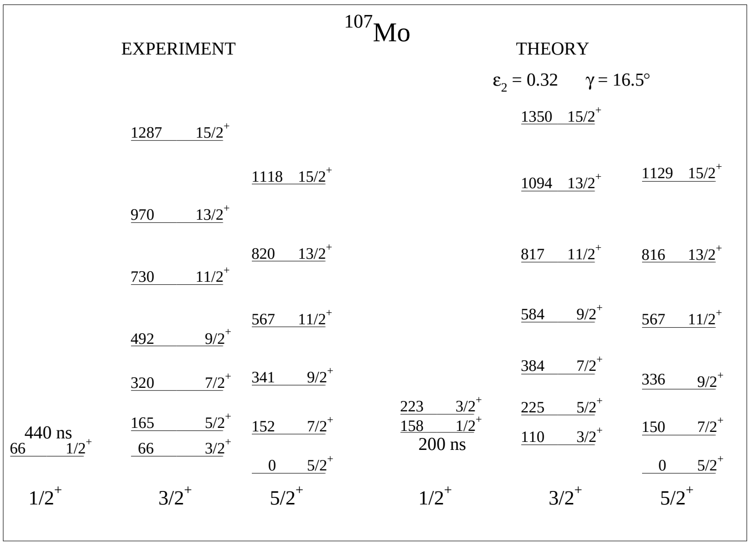

Fig. 6. Comparison of experimental and calculated positive-parity bands in ^{107}Mo.

The calculations are able to correctly reproduce the four bands of the experimental level schemes only when deformations of $\epsilon_2 = 0.32$ and $\gamma \sim 17°$ are used throughout. More details of the results of the calculation can be found in Ref. [13]. These values were compared to the deformations extracted for the neighboring even-even Mo nuclei, using the the Davydov and Filippov theory, and found to be very similar at low spins, suggesting that all these nuclei have similar core deformations. The isomeric state in ^{107}Tc and level scheme of ^{105}Tc have also been well reproduced using similar values in the calculations [14], showing that the odd proton does not greatly effect the deformation of the core.

2.4. *Summary*

New information on prompt γ-ray has been collected on ^{105,107}Mo, comprising of four well-developed bands in ^{105}Mo. New isomeric states have been reported for ^{107}Mo and ^{107}Tc. These data have been successfully interpreted using simple quasiparticle-rotor model calculations, where deformations of $\epsilon_2 = 0.32$ and $\gamma \sim 17°$ were found to correctly reproduce the experimental level schemes..

References

1. L. Coraggio, A. Covello, A. Gargano and N. Itaco, *Phys. Rev. C* **72**, p. 057302 (2005).
2. L. Coraggio, A. Covello, A. Gargano and N. Itaco, *Phys. Rev. C* **73**, p. 031302R (2006).
3. M. N. Mineva, M. Hellström *et al.*, *Eur. Phys. J. A* **11**, 9 (2001).
4. A. A. Sonzogni, *Nuclear Data Sheets* **95**, p. 837 (2002).
5. G. S. Simpson, J. C. Angelique, J. Genevey, J. A. Pinston, A. Covello, A. Gargano, U. Köster, R. Orlandi and A. Scherillo, *Physical Review C (Nuclear Physics)* **76**, p. 041303 (2007).
6. P. Hoff, J. P. Omtvedt, B. Fogelberg, H. Mach and M. Hellström, *Phys. Rev. C* **56**, 2865(Nov 1997).
7. A. Covello, L. Coraggio, A. Gargano and N. Itaco, *Prog. Part. Nucl. Phys.* **59**, p. 401 (2007).
8. A. G. Smith, J. L. Durell, W. R. Phillips, M. A. Jones, M. Leddy, W. Urban, B. J. Varley, I. Ahmad, L. R. Morss, M. Bentaleb, A. Guessous, E. Lubkiewicz, N. Schulz and R. Wyss, *Phys. Rev. Lett.* **77**, 1711(Aug 1996).
9. A. Guessous, N. Schulz, M. Bentaleb, E. Lubkiewicz, J. L. Durell, C. J. Pearson, W. R. Phillips, J. A. Shannon, W. Urban, B. J. Varley, I. Ahmad, C. J. Lister, L. R. Morss, K. L. Nash, C. W. Williams and S. Khazrouni, *Phys. Rev. C* **53**, 1191(Mar 1996).
10. H. Hua, C. Y. Wu, D. Cline, A. B. Hayes, R. Teng, R. M. Clark, P. Fallon, A. Goergen, A. O. Macchiavelli and K. Vetter, *Phys. Rev. C* **69**, p. 014317(Jan 2004).
11. J. Skalski, S. Mizutory and W. Nazarewicz, *Nucl. Phys. A.* **617**, p. 282 (1997).
12. W. Urban, T. Rzaca-Urban, J. A. Pinston, J. L. Durell, W. R. Phillips, A. G. Smith, B. J. Varley, I. Ahmad and N. Schulz, *Physical Review C (Nuclear Physics)* **72**, p. 027302 (2005).
13. J. A. Pinston, W. Urban, C. Droste, T. Rzaca-Urban, J. Genevey, G. Simpson, J. L. Durell, A. G. Smith, B. J. Varley and I. Ahmad, *Physical Review C (Nuclear Physics)* **74**, p. 064304 (2006).
14. G. Simpson, J. Genevey, J. A. Pinston, U. Köster, R. Orlandi, A. Scherillo and I. A. Tsekhanovich, *Physical Review C (Nuclear Physics)* **75**, p. 027301 (2007).