Eur. Phys. J. A **12**, 129–133 (2001)

THE EUROPEAN PHYSICAL JOURNAL A

Short Note

First measurements of yrast excitations in ^{137}I and the missing 12^+ isomer in ^{136}Te

A. Korgul[1], W. Urban[1,a], T. Rząca-Urban[1], M. Górska[2], J.L. Durell[3], M.J. Leddy[3], M.A. Jones[3], W.R. Phillips[3], A.G. Smith[3], B.J. Varley[3], M. Bentaleb[4], E. Lubkiewicz[4], N. Schulz[4], I. Ahmad[5], and L.R. Morss[5]

[1] Institute of Experimental Physics, Warsaw University, ul.Hoża 69, 00-681 Warszawa, Poland
[2] Instituut voor Kern- en Stralingsfysica, Katholieke Universiteit Leuven, B-3001 Heverlee, Belgium
[3] Schuster Laboratory, Department of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK
[4] Institut de Recherches Subatomiques UMR7500, CNRS-IN2P3 and Université Louis Pasteur, 67037 Strasbourg, France
[5] Argonne National Laboratory, Argonne, IL 60439, USA

Received: 6 June 2001 / Revised version: 23 September 2001
Communicated by D. Schwalm

Abstract. The ^{137}I nucleus, populated in the spontaneous fission of ^{248}Cm has been studied by means of prompt γ-ray spectroscopy using the EUROGAM2 array. Medium-spin yrast excitations in ^{137}I were observed for the first time. The experimental level scheme is compared to the shell model calculation with modified Kuo-Herling interaction. The theoretical predictions differ significantly from the experimental results, indicating that the excitation pattern in ^{137}I deviates significantly from the shell model scheme.

PACS. 23.20.Lv Gamma transitions and level energies – 21.60.Cs Shell model – 25.85.Ca Spontaneous fission – 27.60.+j $90 \leq A \leq 149$

The shell model provides a fundamental framework for describing the structure of doubly magic nuclei and their neighbours. For a complete decription the single-particle excitation energies and nucleon-nucleon effective interaction are indispensable. These quantities can be obtained from studies of nuclei surrounding the doubly magic cores, provided that they can be described within the shell model approximation.

To find how far from the doubly magic ^{132}Sn core extends the region where the shell model description still applies, we have investigated nuclei with a few valence particles outside this core. In our recent study of the ^{136}Te nucleus [1,2], which has two valence protons and two valence neutrons outside the core, we noticed deviations of the observed excitation pattern from the one predicted by the shell model calculation. The latter included modified Kuo-Herling interaction [3] and the empirical single-particle level energies (see further in the text for details). In particular, the expected isomeric level, corresponding to the $(\nu f^2_{7/2}\pi g^2_{7/2})_{12^+}$ yrast configuration, was not observed. Instead, we found a $I^\pi = 12^+$ level at 3187 keV, about 400 keV above the predicted position of the isomer. One explanation of this discrepancy is that the four valence particles polarize the ^{132}Sn core, leading to collective behaviour in ^{136}Te. This is observed in the heavier $N = 84$ isotone ^{138}Xe which has six valence particles. Another possibility is that the 3187 keV level is of non-yrast character, while the yrast $I^\pi = 12^+$ level is a long-lived isomer which had escaped detection.

In this context it is interesting to examine the ^{137}I, $N = 84$ isotone, located between ^{136}Te and ^{138}Xe. In this odd-Z nucleus one expects the density of levels at the yrast line ($\Delta I = 1$ cascades) to be higher than that observed in ^{136}Te ($\Delta I = 2$ cascades). Therefore, if there is an isomer in ^{137}I analogous to the hypothetical, long-lived isomer in ^{136}Te, it should have a better chance to decay and be detected.

The yrast excitation scheme of ^{137}I was not known before. In the present work we report for the first time such results for this nucleus. Excited levels in ^{137}I were populated in spontaneous fission of ^{248}Cm. Prompt γ-rays were measured using the EUROGAM2 array [4]. About 2×10^{10} $\gamma\gamma\gamma$ coincidence events were collected. More details on the experiment and the data analysis can be found in ref. [5].

To identify new transitions in ^{137}I, we gated on the known transitions from the ^{109}Tc complementary fragment. In a spectrum double gated on the 69.1 keV and 137.6 keV gamma-rays from ^{109}Tc [6], apart from the

[a] e-mail: urban@fuw.edu.pl

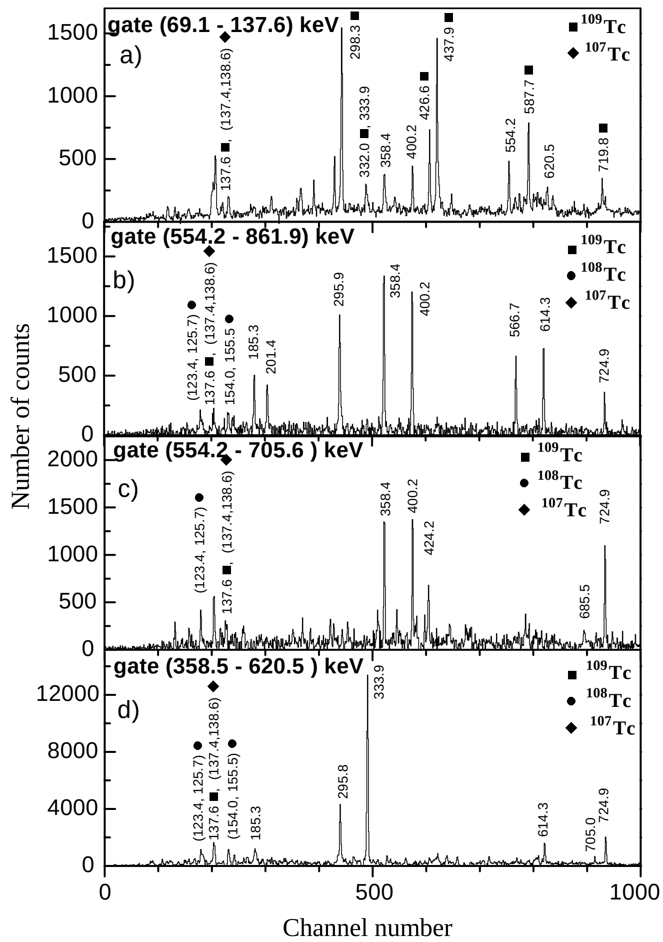

Fig. 1. γ-γ coincidence spectra double gated on lines in ^{137}I and ^{107,109}Tc isotopes. Transition energies are given in keV.

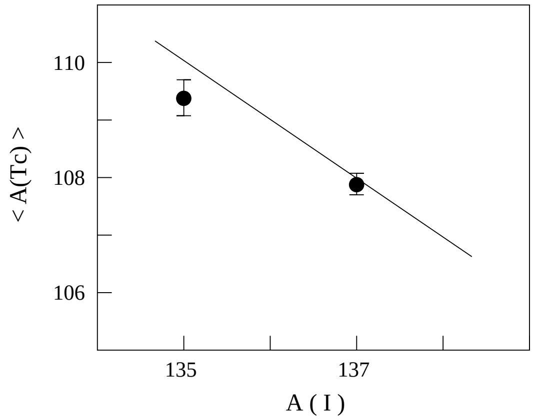

Fig. 2. Correlation between masses of I isotopes and the mean mass of complementary Tc isotopes, as produced in the spontaneous fission of ^{248}Cm. The solid line represents the linear mass calibration $A(\mathrm{I}) + \langle A(\mathrm{Tc})\rangle = 245$ (see ref. [7]).

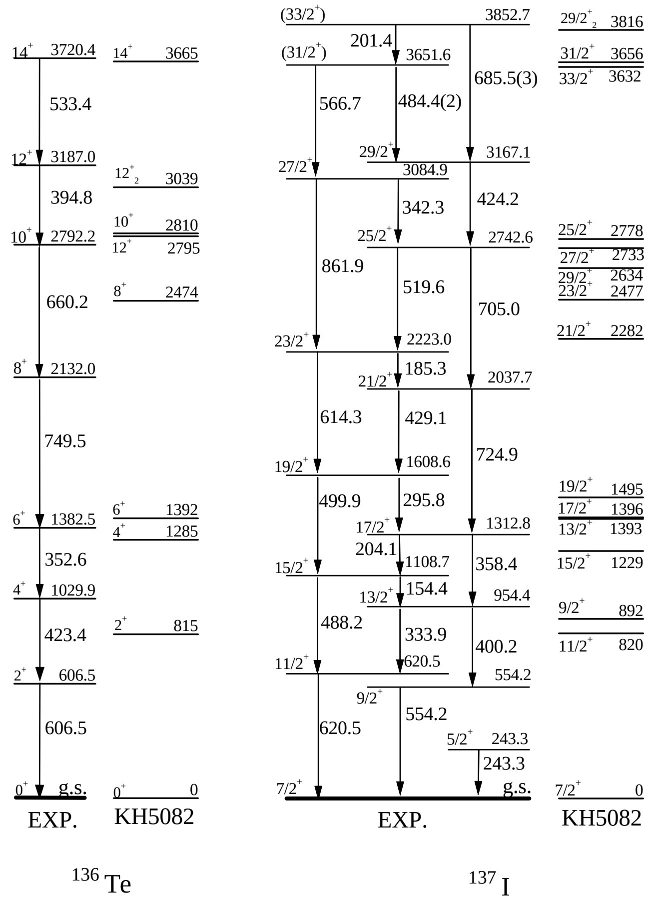

Fig. 3. Partial level scheme of ^{137}I as obtained in this work. The 243.3 keV level and transition are drawn after ref. [10]. On the left-hand side of the picture the partial level scheme of ^{136}Te taken from [2] is shown. For both nuclei, the KH5082 [3] shell model predictions are included (see text for more details).

known gamma-rays from the decay of ^{109}Tc [6], we observed new transitions with energies 358.4, 400.2, 554.2 and 620.5 keV, as shown in fig. 1a. By gating on these new transitions further new transitions in iodine isotopes were found. Figures 1b, 1c and 1d show the relevant, double-gated spectra.

In order to find the origin of the new gamma-rays, we applied the mass correlation technique, proposed in [7] and described in more detail in ref. [8]. The results of these correlations for I-Tc pairs of fission fragments (including the known ^{135}I isotope [9]) are shown in fig. 2. They indicate that the new transitions belong to the ^{137}I nucleus.

Our identification is consistent with beta-decay work [10], where the authors assigned a transition of 554 keV energy to the ^{137}I nucleus, although it was not placed in the level scheme. We have not observed any other of the levels reported in beta-decay [10], most likely due to their non-yrast character and low population in fission.

The partial level scheme of ^{137}I, as obtained in the present work, is shown on the right-hand side of fig. 3 together with shell model predictions. On the left-hand side, experimental and calculated schemes for ^{136}Te [2] are included, to help the discussion later in the text. The properties of γ transitions in ^{137}I are given in table 1.

Table 1. Intensities and values of linear polarization P for transitions in ^{137}I, measured in this work.

Energy (keV)	Intensity (relative)	$P(E_\gamma)$	Correlating E_γ (keV)	Multi-polarity
154.4(1)	–			
185.3(1)	3.6(1)			
201.4(1)	0.9(1)			
204.1(1)	–			
295.8(1)	9.4(1)			
333.9(1)	17(1)	−0.3(1)	620.5	$M1+E2$
342.3(1)	0.15(3)			
358.4(1)	44(1)	+0.15(5)	400.2	$E2$
400.2(1)	64(2)	+0.16(6)	358.4	$E2$
429.1(1)	0.4(1)			
424.2(1)	1.5(1)			
484.4(1)	–			
488.2(1)	4.6(7)	+0.3(2)	620.5	$E2$
499.9(1)	1.3(4)			
519.6(1)	0.7(1)			
554.2(1)	100(1)	+0.08(3)	400.2	$M1+E2$
566.7(1)	2.2(1)			
614.3(1)	7(1)			
620.5(1)	37(2)			$E2$
685.5(3)	0.30(5)			
705.0(1)	2.3(1)			
724.9(1)	11(1)	+0.2(1)	358.4	$E2$
861.9(1)	1.8(1)			

For the ground state, spin-parity $7/2^+$ was adopted from systematics [11]. Spins and parities of excited levels in ^{137}I, presented in fig. 3, were determined using γ-γ angular correlations and directional-polarization correlations measured with EUROGAM2 and analysed as described in [12,13]. Examples of angular correlations are shown in fig. 4, where the Legendre polynomial expansion $W(\theta) = A_{00} + A_{22}P_2\,(\cos(\theta)) + A_{44}P_4(\cos(\theta))$ was fitted to the experimental data points. The A_{22}/A_{00} and A_{44}/A_{00} coefficients resulting from the fit are shown in the corresponding panels of fig. 4. Theoretical values for γ-γ correlations for stretched transitions, are $A_{22} = 0.10$ and $A_{44} = 0.01$ for a quadrupole-quadrupole cascade; $A_{22} = -0.07$ and $A_{44} = 0$ for a quadrupole-dipole cascade; and $A_{22} = 0.05$ and $A_{44} = 0$ for a dipole-dipole cascade [12] ($A_{00} = 1$). The measured data are consistent with $\Delta I = 2$ spin change for the 620.5, 488.2, 614.3, 861.9, 400.2, 358.4, 724.9, 705.0 and 424.2 keV transitions and $\Delta I = 1$ spin change for the 554.2, 333.9, 295.8 and 185.3 keV transitions. No half-lives longer than 10 ns were observed for any of the quadrupole transitions in ^{137}I. Therefore, we conclude that they are of an $E2$ character rather than $M2$. Consequently, parities of levels linked by these transitions are the same. In particular, positive parities were assigned to the 620.5 keV and 1108.7 keV levels, because of the positive parity of the ground state. Spin assignments shown in fig. 3 were made assuming that spin values increase with increasing excitation energy. This assumption is based on many observations that the fission process populates predominantly yrast levels.

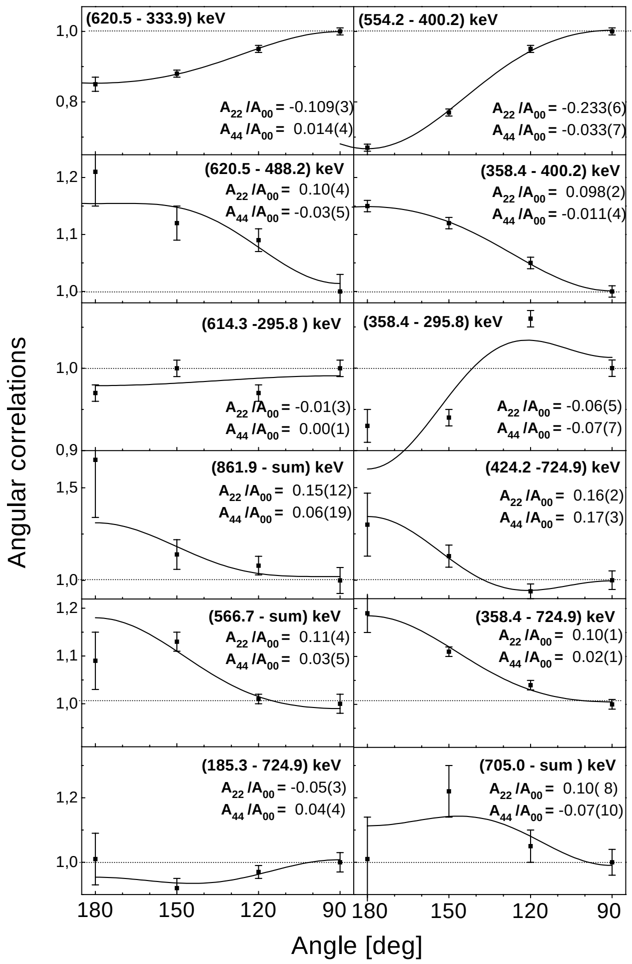

Fig. 4. Examples of γ-γ angular correlations for transitions in ^{137}I. Solid lines represent fits of the Legendre polynomial expansions to the data. Coefficients of the fits are shown in the panels.

Additional information about parities was obtained from directional-polarization correlations. The results obtained in this work for γ transitions in ^{137}I are listed in table 1. The polarization data confirm an electric character of the 358.4, 400.2, 488.2, 620.5 and 724.9 keV quadrupole transitions. For the 333.9 keV, $\Delta I = 1$ transition, the negative value of polarization indicates its $M1+E2$ character and therefore positive parity for the 954.4 keV level. Considering the $E2$ character of the 400.2, 358.4 and 724.9 keV transitions, we assigned positive parity to the 554.2, 1312.8 and 2037.7 keV levels.

Spin and parity assignments to the 3651.6 keV and 3852.7 keV levels are based on the observed branching ratios and the assumption of their yrast character.

An additional comment is needed about the polarization value of the 554.2 keV transition. The positive value of polarization for this $\Delta I = 1$ transition might suggest its $E1$ character. However, high negative anisotropy of the angular correlation with the 400.2 keV quadrupole transition, twice that observed for the 333.9 keV, $\Delta I = 1$ transition, suggests a rather large admixture of a quadrupole component in the 554.2 keV line. The mixing ratio, δ, can be deduced from the observed $A_2^{\rm exp}$ coefficient. The experimental $A_2^{\rm exp}$ value relates to the maximum value $A_2^{\rm max}(\delta)$, which is a function of δ [14], via the $A_2^{\rm exp} = \alpha_2 A_2^{\rm max}(\delta)$ expression, where α_2 is a coefficient describing the population of magnetic substates of the level depopulated by the studied transition [14]. The α_2 coefficient is independent of δ but depends on the spin, I_0, of the decaying level. It can be determined by applying the above relation to stretched $E2$ transitions, which are unmixed. Such an analysis, performed for a number of $E2$ transitions provides an $\alpha_2(I)$-dependence, giving the required $\alpha_2(I_0)$ value. In our case, we obtained $\alpha_2(9/2) = 0.22(2)$, which gives $A_2^{\rm max} = 1.1(1)$ for the 554.2 keV line. Comparing this value to the $A_2^{\rm max}(\delta)$-dependence tabulated in ref. [14], one obtains two solutions for δ: $\delta = 0.5(1)$ and $\delta = 1.7(3)$. The experimental $A_4^{\rm exp} = -0.03(1)$ for the 554.2 keV transition is in favour of the $\delta = 0.5(1)$ solution. The δ coefficient can also be deduced from a combined analysis of angular and directional-polarization correlations. Using the experimental $A_2^{\rm exp}$ and $A_4^{\rm exp}$ values one can calculate linear polarization as a function of δ for a mixed dipole + quadrupole transition from the formula

$$P(\delta) = \pm[3A_2^{\rm exp}H_2(\delta) + 1.25A_4^{\rm exp}]/[2 - A_2^{\rm exp} + 0.75A_4^{\rm exp}],$$

where "+" applies to $M1 + E2$ and "−" to $E1 + M2$ mixed transitions and $H_2(\delta)$ is a coefficient tabulated in ref. [15]. This $P(\delta)$-dependence, compared to the experimental value of polarization for the 554.2 keV transition, $P^{\rm exp} = +0.08(3)$, gives two solutions: $\delta = 1.7(3)$ and $\delta = -2.5(5)$. Considering the results obtained in both ways, one can conclude that the mixing ratio for the 554.2 keV is rather large, with a value in the region $0.5 \le \delta \le 1.7$.

A similar analysis performed for the 333.9 keV transition, taking into account $A_2^{\rm exp}$, $A_4^{\rm exp}$ and $P^{\rm exp}$ values, gives a small mixing ratio for this transition of $\delta = 0.08(3)$.

In the ^{137}I nucleus we observe twice the number of levels seen in ^{136}Te. This is due to the presence in ^{137}I of the low-lying $5/2^+$ level at 243 keV [10], which most likely originates from the $\pi(g^3_{7/2})_{5/2^+}$ coupling, with possible admixtures of the $\pi d_{5/2}$ excitation. Excitations in the ^{136}Te core, coupled to both the $7/2^+$ ground state and the low-lying $5/2^+$ level, produce the observed scheme of ^{137}I.

To interpret the excitations in ^{137}I, we performed shell model calculations using OXBASH code [16]. The results are shown in fig. 3 next to the experimental level scheme. The shell model calculation were performed involving proton $\pi(g_{7/2}, d_{5/2}, h_{11/2})$ and neutron $\nu(h_{9/2}, f_{7/2}, f_{5/2}, i_{13/2})$ orbitals outside the ^{132}Sn core. The occupation of all the orbitals, except the $\pi g_{7/2}$, was restricted to two particles. The single-particle energies were taken from experiment and are listed in table 2. The residual interactions used, denoted KH5082 [3], were obtained from Kuo-Herling matrix elements, determined for ^{208}Pb region [17], after two modifications. First, according to the expected mass dependence of the residual interactions all two-body matrix elements were scaled by a factor of $(132/208)^{1/3}$. Second, six neutron-neutron $J = 0$ interactions, which are too attractive, were reduced by a factor of 0.6.

Table 2. The single-particle energies in the ^{132}Sn region used in the present shell model calculation.

Neutron level	Energy (MeV)	Reference
$\nu h_{9/2}$	−0.884	[18]
$\nu f_{7/2}$	−2.445	[19]
$\nu f_{5/2}$	−0.440	[18]
$\nu i_{13/2}$	+0.250	[20]
Proton level	**Energy (MeV)**	**Reference**
$\pi g_{7/2}$	−9.663	[21]
$\pi d_{5/2}$	−8.663	[22]
$\pi h_{11/2}$	−6.833	[22]

Two maximum-aligned configurations,

$$[\nu(f^2_{7/2})_{6^+}\pi(g^2_{7/2})_{0^+}]_{6^+}$$

and

$$[\nu(f_{7/2}h_{9/2})_{8^+}\pi(g^2_{7/2})_{6^+}]_{14^+}$$

in ^{136}Te and the respective

$$[\nu(f^2_{7/2})_{6^+}\pi(g^3_{7/2})_{7/2^+}]_{19/2^+},$$

$$[\nu(f_{7/2}h_{9/2})_{8^+}\pi(g^3_{7/2})_{15/2^+}]_{31/2^+}$$

and

$$[\nu(f_{7/2}h_{9/2})_{8^+}\pi(g^2_{7/2})_{6^+}d_{5/2}]_{33/2^+}$$

configurations in ^{137}I are well reproduced. The observation of the $31/2^+$ and $33/2^+$ doublet, in good agreement with OXBASH calculations, confirms the presence of both $\pi(g^3_{7/2})_j$ and $\pi(g^2_{7/2}d_{5/2})_j$ couplings in the yrast spectrum of ^{137}I.

Calculations of mixing ratios, δ, for the $9/2^+ \to 7/2^+$ (554 keV) and $13/2^+ \to 11/2^+$ (334 keV) transitions performed using the KH5082 interactions, give satisfactory results of $\delta = 1.0$ and $\delta = 0.06$, respectively. Similar calculations, performed for the pure $g^3_{7/2}f^2_{7/2}$ configuration, give $\delta = 0.14$ for the 554 keV transition and $\delta = 0.03$ for the 334 keV transition. In the calculation the values of effective charges of $e_\pi = 1.72$, $e_\nu = 1.0$, and the bare proton and neutron g-factors were used. This comparison illustrates the importance of small admixtures to the wave functions of low-spin states, which are well reproduced in the KH5082 interaction.

Levels in ^{137}I are spaced more evenly than in ^{136}Te which suggests that the addition of one proton to ^{136}Te induces a change towards a collective motion. Such motion is clearly observed in the ^{138}Xe isotone [2], having two protons more than ^{136}Te. One may therefore expect that, despite some successes, the shell model description of ^{137}I may be limited. In ^{136}Te a particularly dramatic difference between shell model expectations and experiment is observed for the 12^+ level. The calculated energy for the $[\nu(f^2_{7/2})_{6^+}\pi(g^2_{7/2})_{6^+}]_{12^+}$ configuration is significantly lower than the observed 12^+ level. According to the calculations, the 12^+_1 level in ^{136}Te should be a spin gap isomer. The decay of this state has then several competing modes: i) an $E4$ transtion with a *lower* limit for partial half-life of 5 s for $12^+ \rightarrow 8^+ \leq 660$ keV and the 1 W.u. reduced transition strength, which was deduced from the shell model calculation with the same effective $E4$ charge as used for $E2$ transitions; ii) the β-decay with half-life of about 15 s, provided similar decay energy as for the ground-state decay; iii) α-decay to the ground state of ^{132}Sn, analogues with the $t_{1/2} = 45.1$ s α-decay of the 18^+ isomer of ^{212}Po. However, the $E4$, γ- and α-decay modes prefer *longer* half-lives, the "faster" beta-decay following fission process is well studied [23] and no high-spin state was observed.

As can be seen, similar situation is observed in ^{137}I. Here again, the $29/2^+$ level, corresponding to the $[\nu(f^2_{7/2})_{6^+}\pi(g^2_{7/2})_{6^+}d_{5/2}]_{29/2^+}$ configuration, analogous to the expected 12^+ isomer in ^{136}Te, is calculated well below the observed $29/2^+$ level and should form a long-lived isomer. Higher level density in ^{137}I makes a difference, however, and the expected half-life of the isomer is shorter than 5 s, calculated assuming reduced $M3$ strength of 1 W.u. for the 138 keV predicted transition. This excludes α- and most probably the β-decay competition for this hypotetical isomer, although the reduced strength for an $M3$ transition is difficult to predict and thus it is not possible to put a sharp border between the competing modes. A γ cascade, depopulating such an isomer, which should receive an abundant population in fission, ought to be observed in our measurement. Moreover, the feeding of significant intensity from the higher-spin states to such isomer should be present. Since none of it is seen, we conclude that this isomer is not present in ^{137}I. This suggests that, except for some simple, maximum-aligned configurations, the yrast excitations in ^{137}I may have significant admixtures of collectivity and supports our suggestion [2] that the same happens for the 12^+ level in ^{136}Te.

In summary, yrast excited levels in the ^{137}I nucleus were observed for the first time. Most of the levels were assigned spins and parities on the basis of angular correlations and linear polarization measurements. Shell model, OXBASH calculations predict in ^{137}I a $29/2^+$ isomeric level with a half-life significantly shorter than that predicted for the analogous, hypothetical isomer in ^{136}Te. The non-observation of the isomer in ^{137}I in our data indicates that it is not present in this nucleus and that there are limitations to the use of a simple shell model description here.

This work was supported by the Bilateral Scientific Technological Cooperation between Flanders and Poland (KBN) and by the US Department of Energy under contract No. W-31-109-ENG-38. The authors are indebted for the use of ^{248}Cm to the Office of Basic Energy Sciences, US Department of Energy, through the transplutonium elements production facilities at the Oak Ridge National Laboratory. One of the authors (A.K.) acknowledges the scholarship from the Foundation for Polish Science.

References

1. A. Nowak et al., Eur. Phys. J. A **3**, 111 (1998).
2. A. Korgul et al., Eur. Phys. J. A **7**, 167 (2000).
3. W.-T. Chou, E.K. Warburton Phys. Rev. C **45**, 1720 (1992).
4. P.J. Nolan et al., Annu. Rev. Nucl. Part. Sci. **44**, 561 (1994).
5. W. Urban et al., Z. Phys. A **358**, 145 (1997).
6. J.K. Hwang et al., Phys. Rev. C **57**, 2250 (1998).
7. M.A.C. Hotchkis et al., Nucl. Phys. A **530**, 111 (1991).
8. W. Urban et al., Phys. Rev. C **61**, 41301(R) (2000).
9. C.T. Zhang et al., Phys. Rev. Lett. **77**, 3743 (2000).
10. M. Samri et al., Z. Phys. A **321**, 255 (1985).
11. J.J. Tuli, Nucl. Data Sheets **72**, 355 (1994).
12. M.A. Jones et al., Rev. Sci. Instrum. **69**, 4120 (1998).
13. W. Urban et al., Nucl. Instrum. Methods A **365**, 596 (1995).
14. E.D. Mateosian, A.W. Sunyar, Nucl. Data Tables **13**, 391 (1974).
15. T. Aoki et al., At. Data Nucl. Data Tables **23**, 369 (1979).
16. B.A. Brown, A. Etchegoyen, W.D.H. Rae, code OXBASH (1984) unpublished.
17. E.K. Warburton, B.A. Brown, Phys. Rev. C **43**, 602 (1991).
18. P. Hoff et al., Phys. Rev. Lett. **77**, 1020 (1996).
19. K.A. Mezilev et al., Phys. Scripta T **56**, 272 (1995).
20. W. Urban et al., Eur. Phys. J. A **5**, 239 (1999).
21. B. Fogelberg et al., Phys. Rev. Lett. **82**, 1823 (1999).
22. J. Blomqvist et al., Z. Phys. A **312**, 27 (1983).
23. R.B. Firestone, *Table of Radioactive Isotopes*, 8th edition (1998).