First observation of excited states in ^{139}I

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This work reports on the first observation of excited levels in the ^{139}I nucleus. Levels in ^{139}I, populated in spontaneous fission of ^{248}Cm, were studied by means of prompt γ-ray spectroscopy, using the EUROGAM2 array. The level scheme of ^{139}I obtained in this work shows patterns characteristic of a spherical vibrator, which result from a weak interaction of the ^{138}Te core with the odd proton. No signs of octupole correlations were observed in ^{139}I. The new data allow, for the first time systematic predictions to be made of energies and spins of states in the ^{137}Sb nucleus, helping the future studies of the r-process nuclei at the $Z=50$ line.

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Our recent works on neutron-rich lanthanides have demonstrated that systematics of excitations energies in these nuclei, drawn along isotonic lines, show a high degree of regularity [1–3]. This feature allows reliable predictions of properties of some nuclei near the $Z=50$ closed shell, which are not accessible experimentally at present. An example is our recent prediction for excited states in the ^{135}Sn nucleus, based on the systematics for even-Z, $N=85$ isotones [4].

The structure of neutron-rich nuclei near the $Z=50$ closed shell is of interest because of theoretical suggestions [5], and some experimental hints [6], that beyond the doubly magic ^{132}Sn core, the $Z=50$ shell gap quickly disappears and nuclear deformation shows up already around $N=87$ [3]. Such observations are important for the calculation of the astrophysical r-process flow in this region. The appearance of nuclear deformation on the path of the r process can significantly influence its direction. It is predicted that from $N\approx 84$ up, the path of the r process in the ^{132}Sn region goes along the $Z=50$ line. It is a vital question as to where it departs from the $Z=50$ line. In our recent study [6] we found the half-life of the ^{135}Sn isotope $T_{1/2}=0.6(1)$ s, a value long enough for the r-process to continue to higher neutron number along the $Z=50$ line. The half-life of the next tin isotope, the even-even ^{136}Sn nucleus, is probably not much different and the r-process most likely continues to ^{137}Sn. A much shorter half-life is expected here due to the fact that this is an odd-A nucleus and because of the expectation that the $Z=50$ shell may disappear around $N=87$, where nuclear deformation is expected.

To verify these expectations, the measurement of halflives is required in this region. Of particular interest is the β-decay study of ^{137}Sn to ^{137}Sb. Such an experiment is rather difficult, since ^{137}Sn is the most neutron-rich tin isotope known. An important information, which could help here is the knowledge of the excitation scheme of the daughter nucleus ^{137}Sb. While at present this nucleus is also not accessible for spectroscopic studies, it is possible to learn about its excitations from systematics, as discussed above. This work, reporting on the first observation of excited levels in the ^{139}I nucleus, the isotone of ^{137}Sb, provides the data needed to build the systematics of excitation energies in the odd-Z, $N=86$ isotones.

To study the ^{139}I nucleus we measured high-fold coincidences between prompt γ rays following spontaneous fission of ^{248}Cm. The experiment was performed using the EUROGAM2 array of anti-Compton spectrometers at Strasbourg. For more details on the experiment and data analysis see Ref. [7].

Prior to this work nothing was known about excited levels in ^{139}I. To identify γ transitions in ^{139}I we gated on the known transitions in Tc isotopes [8], which are complementary fission fragments to iodine isotopes in fission of ^{248}Cm. Several new γ rays were found in prompt coincidence with transitions in $^{105-107}$Tc isotopes and have been, therefore, assigned to an iodine isotope. Figure 1 shows some of the coincidence spectra, double gated on lines in Tc isotopes and the newly found iodine lines. The 418–397 keV double gate, set on two newly observed γ lines, shows lines in $^{105-107}$Tc isotopes. In this spectrum one can also see new γ lines with energies 273.8, 464.5, 481.6, 652.7, and 728.8 keV, which belong to an iodine isotope. The 418–91 keV and 418–129 keV double-gated spectra show lines in ^{106}Tc, ^{105}Tc, and this iodine nucleus, respectively. The 273–652 keV double-gated spectrum shows lines from $^{105-107}$Tc and most of the lines from this iodine isotope. To find the mass of the iodine isotope, emitting the newly found γ rays, we used the technique of mass correlation proposed in Ref. [9]. The method is based on the smooth variation between the sum of the nucleons in a given (iodine) fragment, A(I) and the number of

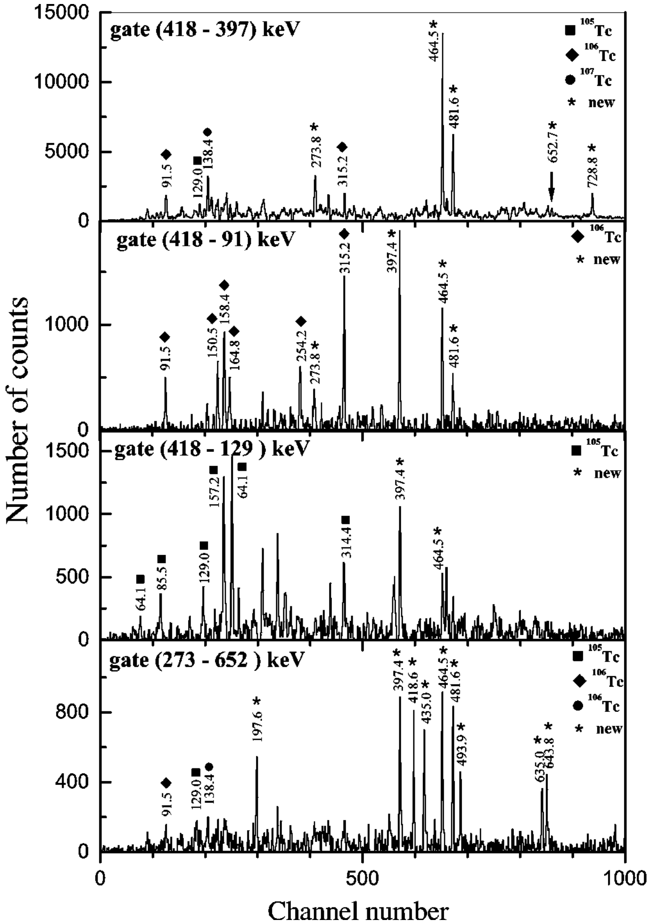

FIG. 1. Double-gated spectra of prompt γ rays from Tc and I isotopes, produced in spontaneous fission of ^{248}Cm.

nucleons corresponding to the mean mass of the accompanying complementary (technetium) fragments, $\langle A(\mathrm{Tc})\rangle$. On average, about three neutrons are emitted in the spontaneous fission of ^{248}Cm and, to a reasonable approximation, the sum of $A(\mathrm{I})$ and $\langle A(\mathrm{Tc})\rangle$ should equal 245.

Figure 2 shows $\langle A(\mathrm{Tc})\rangle$ values obtained in this work as a

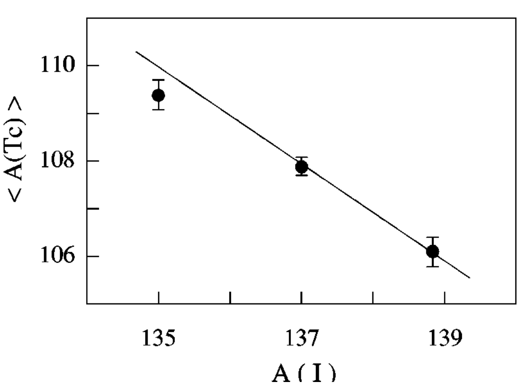

FIG. 2. Correlation between masses of iodine isotopes and mean masses of complementary Tc nuclei, as produced in spontaneous fission of ^{248}Cm. The solid line represents the linear mass calibration $A(I)+\langle A(\mathrm{Tc})\rangle=245$. Data points for ^{135}I and ^{137}I are taken from Ref. [10].

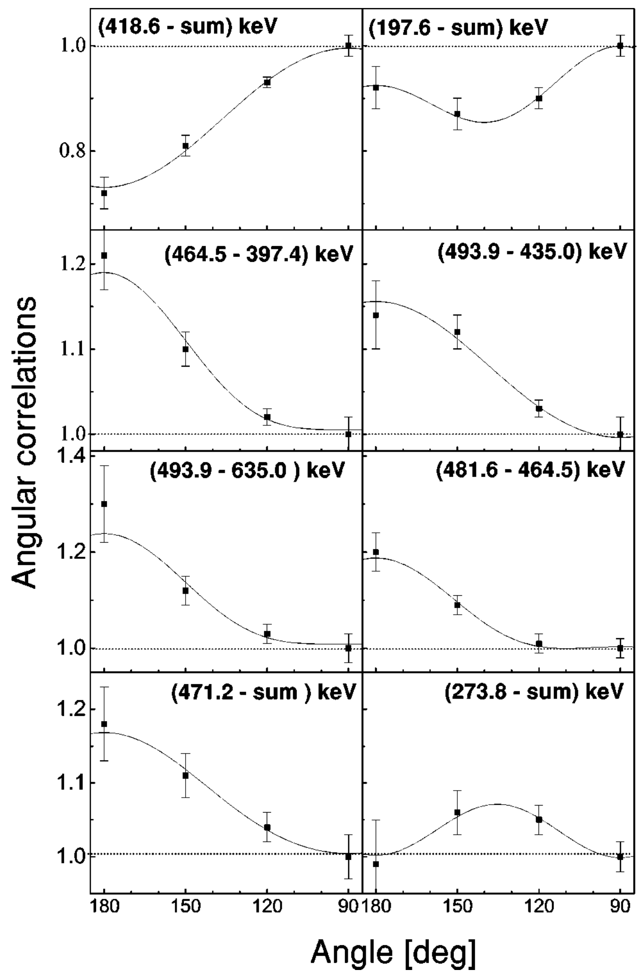

FIG. 3. Examples of γ-γ angular correlations for transitions in ^{139}I as obtained in this work.

function of $A(\mathrm{I})$. The solid line represents the $A(\mathrm{I})+\langle A(\mathrm{Tc})\rangle=245$ linear dependence. The relative intensities of the γ rays to the ground states of different Tc nuclei, as observed in the coincidence spectrum obtained by gating on the transitions in the newly found cascade, provided the mean mass of the complementary Tc fragments of $\langle A(\mathrm{Tc})\rangle=106.1(3)$. This value placed on the calibration line determines the corresponding iodine mass of 138.8(3), which uniquely points to the mass $A=139$ for the searched iodine isotope.

Multipolarities of transitions in ^{139}I were determined from angular correlations and directional-polarization measurements performed with EUROGAM2 [7,11]. Examples of γ-γ angular correlations for transitions in ^{139}I, as obtained in this work are shown in Fig. 3.

Because of the low transition intensities, some correlations were generated by adding gates, as indicated in Fig. 3 by "sum." This denotes the summed effect of γ-γ angular correlations of two or more consecutive quadrupole transitions in a cascade with the studied transition. For instance, the effect for the 197.6 keV transition is a sum of angular correlations of this transition with the 435.0, 493.9, and 653.5 keV transitions, all of which are found to be quadrupole in character as can be seen from other correlations shown in Fig. 3.

TABLE I. Properties of levels and depopulating γ transitions in the ^{139}I nucleus.

E_{exc} (keV)	I^{π}	E_{γ} (keV)	I_{γ} (rel.)	A_2/A_0	A_4/A_0	Pol.
0.0	$7/2^+$					
209.5	$(5/2^+)$	209.5	6(2)			
418.6	$9/2^+$	209[a]	4(2)			
		418.6	80(4)	−0.19(2)	−0.004(2)	−0.2(1)
435.0	$11/2^+$	435.0	100(5)	0.09(1)	−0.02(1)	0.3(1)
816.0	$13/2^+$	381.0	7(1)	−0.13(3)	−0.05(4)	
		397.4	64(3)	0.12(1)	−0.03(2)	0.12(3)
928.9	$15/2^+$	493.9	65(3)	0.10(1)	0.01(2)	0.2(1)
1280.5	$17/2^+$	351.5	9(1)			
		464.5	42(2)	0.10(2)	0.04(2)	0.08(3)
1564.4	$19/2^+$	635.5	33(2)	0.11(2)	0.00(2)	0.15(8)
1762.0	$21/2^+$	197.6	20(2)	−0.10(1)	0.10(1)	
		481.6	25(2)	0.10(1)	0.05(2)	0.2(1)
2035.6	$23/2^+$	273.8	18(2)	0.03(1)	−0.06(2)	
		471.2	6(1)	0.10(2)	0.01(2)	
2221.2		940.7	2(1)			
2316.0		751.6	7(2)			
2392.2		827.8	3(1)			
2490.8	$25/2^+$	728.8	12(2)	0.08(2)	0.02(4)	
2688.3	$(27/2^+)$	652.7	5(1)			
3332.1		643.8	2(1)			

[a]Denotes tentative placement.

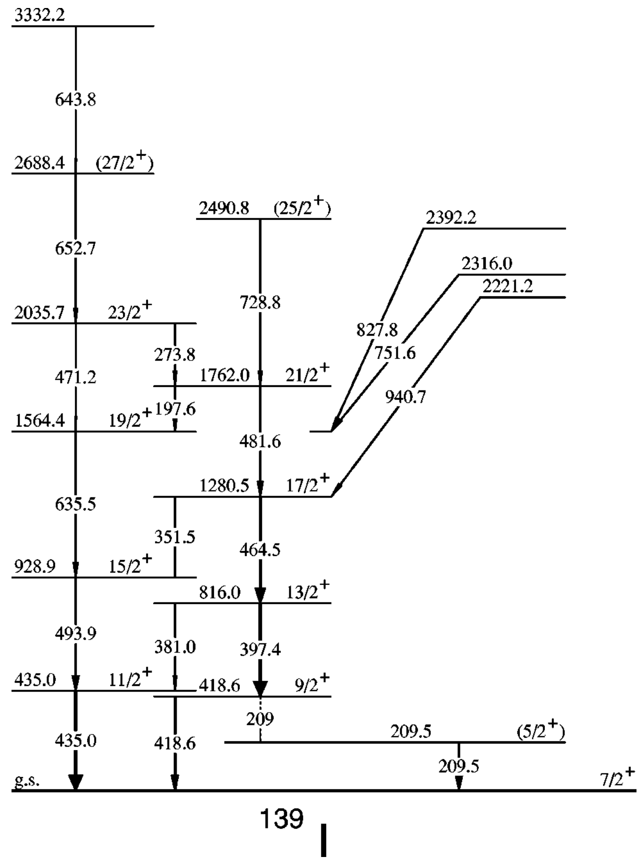

FIG. 4. Partial level scheme of ^{139}I as obtained in the present work.

Theoretical values for γ-γ correlations for stretched transitions are $A_{22}=0.10$ and $A_{44}=0.01$ for a quadrupole-quadrupole cascade and $A_{22}=-0.07$ for a quadrupole-dipole cascade [11]. Angular correlations obtained in this work are consistent with stretched quadrupole character for the 397.4, 435.0, 464.5, 471.2, 481.6, 493.9, 635.5, and 728.8 keV transitions while the 197.6, 273.8, and 418.6 keV transitions correspond to spin change $\Delta I=1$.

For some strong transitions we could determine linear polarization from directional-polarization correlations [11]. These data indicate that the observed quadrupole transitions are of an electric character while the 418.6 keV transition is of an $M1+E2$ character.

The K-conversion coefficient of the 197.6 keV transition was determined using triple coincidences measured by the Ge and LEPS detectors of EUROGAM2. A spectrum double gated on the 273.8 keV line and the sum of 435.0, 493.0, and 635.5 keV lines, observed in Ge detectors, and projected onto the LEPS axis shows the 197.6 γ ray and the corresponding X_K line. The α_K conversion coefficient found from this spectrum is $\alpha_K=0.20(5)$, indicating an $M1+E2$ character of the 197.6 keV transition (theoretical α_K values are 0.03, 0.10, and 0.11 for $E1$, $M1$, and $E2$ transitions, respectively).

Properties of the newly found γ transitions in ^{139}I are summarized in Table I. In Fig. 4 we display a partial excitation scheme of the ^{139}I nucleus, as obtained in the present work. The order of transitions in cascades is based on the observed coincidence relations and γ-ray intensities.

Spins and parities of excited levels in ^{139}I, shown in Fig. 4, were proposed based on the measured angular correlations, assuming spin $7/2^+$ for the ground state, as deduced from the systematic trend of the lowest yrast excitations in the odd-Z, $N=86$ isotones. The available data, displayed in Fig. 5, show the systematics of the two lowest $5/2^+$ excitations [12], drawn relative to the $7/2^+$ level. The systematics suggests that the first $5/2^+$ excitation in I, Cs, La, and Pr isotones probably originates from the $\pi(g_{7/2})^n$ configuration (the corresponding $5/2^+$ excitation in ^{143}La is still not known but the present systematics suggests its excitation energy of about 80 keV). With the proton number approaching $Z=64$, the $\pi d_{5/2}$ orbital starts to be occupied and the $5/2^+$ ground state in ^{149}Eu is most likely of this nature. The systematics in Fig. 5 suggest that $5/2^+_2$ levels in ^{143}La and ^{145}Pr also correspond to the $\pi d_{5/2}$ configuration. The $5/2^+_2$ in ^{149}Eu could therefore belong to the $\pi(g_{7/2})^n$ multiplet. If this picture holds then there should be a low-lying $5/2^+$ level in ^{147}Pm corresponding to the $\pi d_{5/2}$ configuration. The data shown in Fig. 5, strongly suggest that the ground state of ^{139}I has spin and parity $I^{\pi}=7/2^+$ and the first excited state at 209.5 keV most likely has spin-parity $I^{\pi}=5/2^+$. Unfortunately, the 209.0 keV transition, deexciting the 418.6 keV level, belongs to a doublet and can be placed only tentatively.

The above conclusions are supported by another systematic, shown in Fig. 6, where we display a correlation between the excitation energies of $11/2^+$ levels in the odd-Z lan-

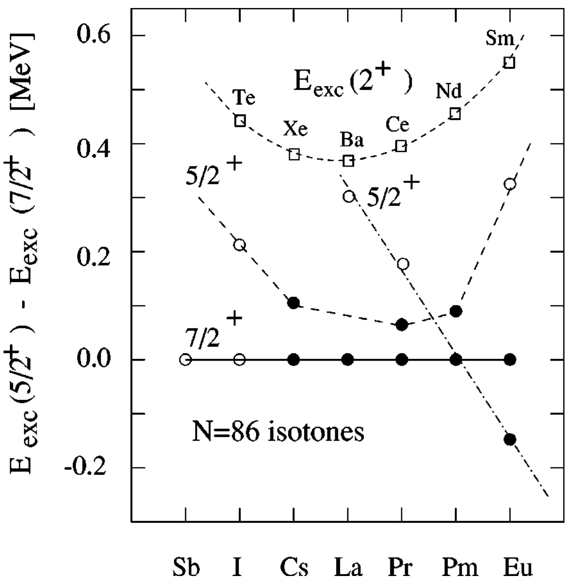

FIG. 5. Excitation energies of $5/2^+$ levels in odd-Z, $N=86$ isotones, calculated relative to $7/2^+$ levels. Open circles represent the new points for ^{139}I and tentative assignments in other nuclei. Excitation energies of 2^+ levels in the $N=86$ even-even core nuclei are drawn to help the discussion in the text. Solid and dashed lines connect data points.

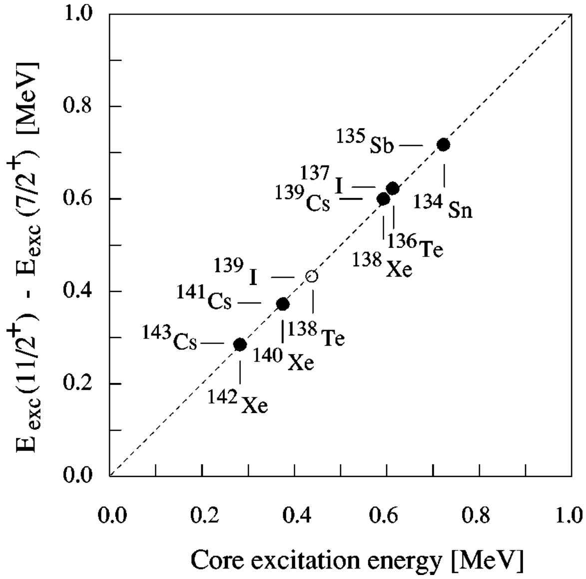

FIG. 6. Excitation energies of $11/2^+$ levels in odd-Z lanthanides calculated relative to $7/2^+$ levels and shown as a function of the 2_1^+ energy in the corresponding core with $Z-1$ protons. The open circle represents the new data point obtained in this work for ^{139}I. Filled points are taken from Ref. [13]. The dashed line is drawn to help compare the energies in the odd-Z nuclei and their cores.

thanides, calculated relative to the $7/2^+$ levels and energies of 2^+ excitations in the corresponding even-even core nuclei, having one proton less. As can be seen the correlation is nearly perfect. The new data point obtained in this work for ^{139}I is represented by the open circle. It fits the systematics very well and thus supports the assumption that the 435.0 keV transition in ^{139}I deexcites the $11/2^+$ level to the $7/2^+$ ground state.

The level scheme of ^{139}I obtained in this work shows patterns characteristic of a spherical vibrator. It is similar to that of ^{137}I but more collective, as suggested by lower transition energies. No octupole excitations are observed in ^{139}I.

Systematics in Figs. 5 and 6 give first indications about low-lying levels in ^{137}Sb. The ground state, most likely has spin and parity $I^{\pi}=7/2^+$, as follows from Fig. 5. The systematics of 2^+ excitations in even-even, $N=86$ isotones, shown in Fig. 5, suggest that the energy of the, yet unknown, 2^+ excitation in ^{136}Sn is about 600 keV. Assuming that the correlation shown in Fig. 6 applies also to ^{137}Sb (as it does for ^{135}Sb), one estimates the excitation energy of the $11/2^+$ level in ^{137}Sb to be about 600 keV. Figure 5 suggests that there may be a $5/2^+$ excited state at about 350 keV. A $5/2^+$ level at 281.7 keV was recently observed in ^{135}Sb [6]. It is an interesting question of what might be its origin. The $\pi d_{5/2}$ single particle excitation should imply a significant lowering of this orbital. It is observed at 962 keV in ^{133}Sb, an energy closer to the position of the second $5/2^+$ excitation, extrapolated in Fig. 5 to ^{137}Sb.

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