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First observation of excited states in ^{137}Te and the extent of octupole instability in the lanthanides

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Excited states in ^{137}Te, populated in spontaneous fission of ^{248}Cm, were studied by means of prompt-γ spectroscopy, using the EUROGAM2 multidetector array. This is the first observation of excited states in ^{137}Te. The yrast excitations of ^{137}Te are due to the three valence neutrons, occupying the $\nu f_{7/2}$ and $\nu h_{9/2}$ orbitals, similarly as observed in its heavier $N=85$ isotones. Systematic comparison of excited levels in the $N=85$ isotones shows inconsistencies in spin and parity assignments in ^{139}Xe and ^{141}Ba nuclei. The new data for ^{137}Te do not confirm earlier suggestions that octupole correlations increase in the $N=85$ isotones, close to the $Z=50$ closed shell.

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Studies of neutron-rich lanthanides have revealed a region of octupole instability around $N=88$ [1,2]. A key question concerns the extent of this region. In a previous study of the $N=85$ isotones [3], we have shown that the $N=85$ line marks the low-N border for the region of octupole instability in ^{145}Nd and ^{147}Sm. The structures of ^{145}Nd and ^{147}Sm, and that of ^{149}Gd studied earlier [4], were explained as due to excitations of three valence neutrons, occupying the $f_{7/2}$, $h_{9/2}$, and $i_{13/2}$ orbitals and quadrupole and octupole phonons coupled to them.

The development of large arrays of Anti-Compton Spectrometers (ACS), opened the way to γ-spectroscopic studies of medium-spin excitations in lighter $N=85$ isotones. Using the GAMMASPHERE ACS array, Zhu *et al.* [5] studied the ^{139}Xe and ^{141}Ba $N=85$ isotones and found that octupole correlations are stronger in these nuclei than in the heavier $N=85$ isotones. The excitation energy of the $13/2^+$ level, which is interpreted as an octupole phonon coupled to the $7/2^-$ ground states, is lower in energy in these nuclei than in the heavier isotones. Also, cascades of enhanced $E1$ transitions, characteristic of nuclei with octupole shapes, were reported. Figure 3 in Ref. [5] suggests that such enhanced correlations may also be observed in the ^{137}Te, $N=85$ isotone, and the $13/2^+$ excitation may be expected at an energy as low as 1 MeV. If this were so, it would indicate that the $N=85$ line does not mark the low-N border for the whole region of octupole instability in the lanthanides [3]. It would also suggest that octupole correlations in the Xe isotopes should not be markedly weaker than in the corresponding Ba nuclei [6]. It may be remarked that if the $13/2^+$ excitation is as low as 1 MeV, there is no increase of the 3^- phonon energy when approaching the $Z=50$ closed shell. If there is no such increase, the presence of the $Z=50$ shell closure at $N=85$ could be questioned.

To resolve some of these ambiguities we studied the ^{137}Te, $N=85$ isotone, where prior to this work no excited states were reported. ^{137}Te was populated in the spontaneous fission of ^{248}Cm and prompt γ rays studied using the EUROGAM2 ACS array. Details of the experiment and data analysis techniques have been described in a number of previous works (see, e.g., [7–10]).

In fission of $^{248}_{96}$Cm$_{152}$ Te isotopes are produced together with Ru isotopes. Prompt γ radiation from a given Te fragment may be in coincidence with that from several Ru fragments, reflecting the possibility of emitting from zero to several neutrons from the primary fission fragments. To find ^{137}Te we gated on known transitions in $^{106-110}$Ru nuclei [11]. Several new γ rays, with the strongest at energies 608.2 keV, 532.8 keV, and 336.4 keV, were found in prompt coincidence with transitions in $^{106-109}$Ru isotopes, and were therefore assigned to a tellurium isotope. To find which Te isotope, we used the technique of mass correlation proposed in Ref. [12]. The method is based on the observation that the average number of neutrons emitted from a pair of fission fragments in fission of ^{248}Cm is about 3. Therefore the mass of a given Te fragment, $A(\mathrm{Te})$ and the mean mass of complementary fragments, $\langle A(\mathrm{Ru})\rangle$, will show a smooth variation, which may be approximated by a straight-line dependence $A(\mathrm{Te})+\langle A(\mathrm{Ru})\rangle=245$. The mean mass of Ru fragments accompanying a particular Te isotope was determined from the relative intensities of the γ rays to the ground states of different Ru nuclei as observed in the coin-

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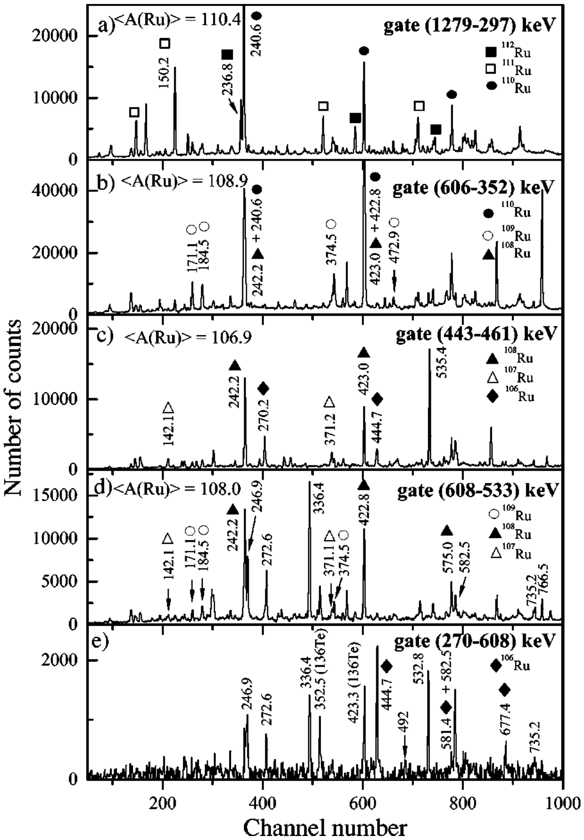

FIG. 1. Coincidence spectra gated on lines in Te and Ru isotopes. Transition energies are given in keV. Only the strongest three complementary fragments are labeled in (a)–(d), to simplify the picture.

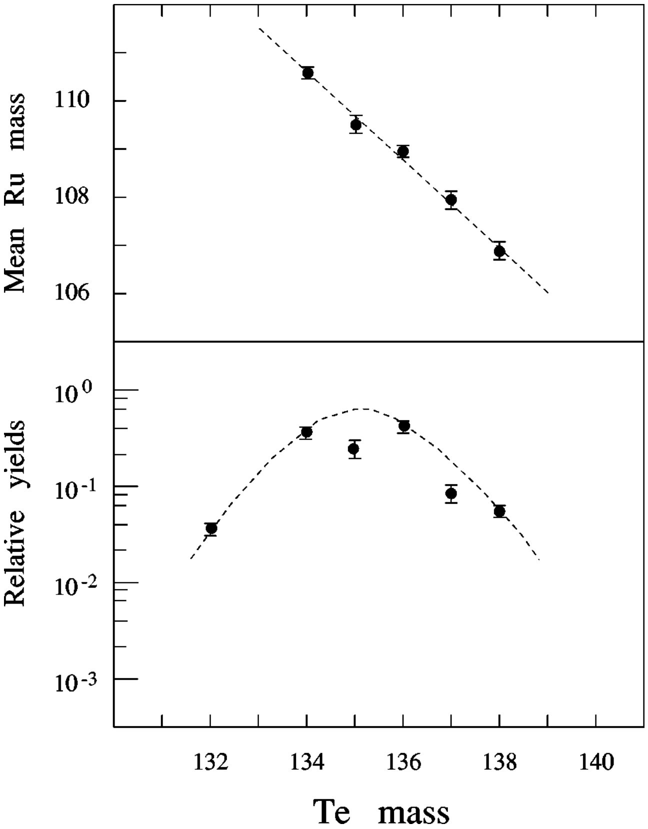

FIG. 2. Upper panel: correlation between masses of Te isotopes and mean mass of complementary Ru isotopes. Lower panel: population of Te isotopes in spontaneous fission of ^{248}Cm. See text for more explanations.

cidence spectrum obtained by gating on the $2_1 \rightarrow 0_1$ γ ray in this Te isotope. Figures 1(a)–(c) show spectra of gamma rays in coincidence with strong transitions in ^{134}Te, ^{136}Te, and the newly identified ^{138}Te [13], respectively. Relative intensities of the ground-state transitions of different Ru, labeled in the spectra, were used to determine mean masses of Ru isotopes, $\langle A(\mathrm{Ru}) \rangle$, shown in the figures.

Figure 1(d) shows a spectrum obtained by gating on the two strongest candidate lines in ^{137}Te. The mean mass of complementary Ru fragments is here $\langle A(\mathrm{Ru}) \rangle = 108.0(2)$. This value correlates well with a tellurium mass $A(\mathrm{Te}) = 137$, as shown in the upper pannel of Fig. 2. The dashed line represents a straight-line fit to the points for ^{134}Te, ^{136}Te, and ^{138}Te isotopes.

This identification is further supported by the population yields of the newly observed gamma cascades, as illustrated in the lower panel of Fig. 2, where the observed γ-coincidence yields corresponding to Te isotopes, produced in spontaneous fission of ^{248}Cm, are shown. The dashed line represents the Gaussian function which describes the population of even-even Te isotopes. The odd-even effect in the population of the odd-*A* nuclei compared with that of the even is apparent, although the effect may be exaggerated in Fig. 2 because of the nonobservation of some weak cascades feeding odd-*A* ground states. With this in mind, we conclude that the new point assigned to ^{137}Te follows consistently the population pattern of the tellurium isotopes, supporting further the isotope identification.

In Fig. 1(d) several new transitions in ^{137}Te are identified. Gating on these transitions allowed the construction of the partial level scheme in ^{137}Te shown in Fig. 3. A spectrum double gated on the 608.2 keV in ^{137}Te and 270.2 keV transition in ^{106}Ru, shown in Fig. 1(e), indicates that apart from the transitions displayed in the scheme, there is no other significant gamma decay to the 608.2 keV level (^{106}Ru was used for gating rather than ^{108}Ru, because it produces simpler spectrum).

Spin and parity assignments to the excited levels in ^{137}Te were determined using angular correlations and directional-polarization correlations [9,15], assuming the $7/2^-$ assignment for the ground state [14]. Double-γ angular correlations for pairs of strong, consecutive transitions in ^{137}Te are shown in Fig. 4 together with coefficients of Legendre polynomial expansions fitted to the data. Theoretical values for γ-γ correlations for stretched transitions are $A_{22} = 0.10$ and $A_{44} = 0.01$ for a quadrupole-quadrupole cascade, $A_{22} = -0.07$ for a quadrupole-dipole cascade, and $A_{22} = 0.05$ for a dipole-dipole cascade.

The data shown in Fig. 4 indicate a stretched quadrupole character for the 608.2 keV, 532.8 keV, 582.5 keV, and 518.6 keV transitions and stretched dipole character for the 336.4 keV, 246.0 keV, and 272.6 keV transitions. In the 608.2 keV gate, the directional-polarization value for the

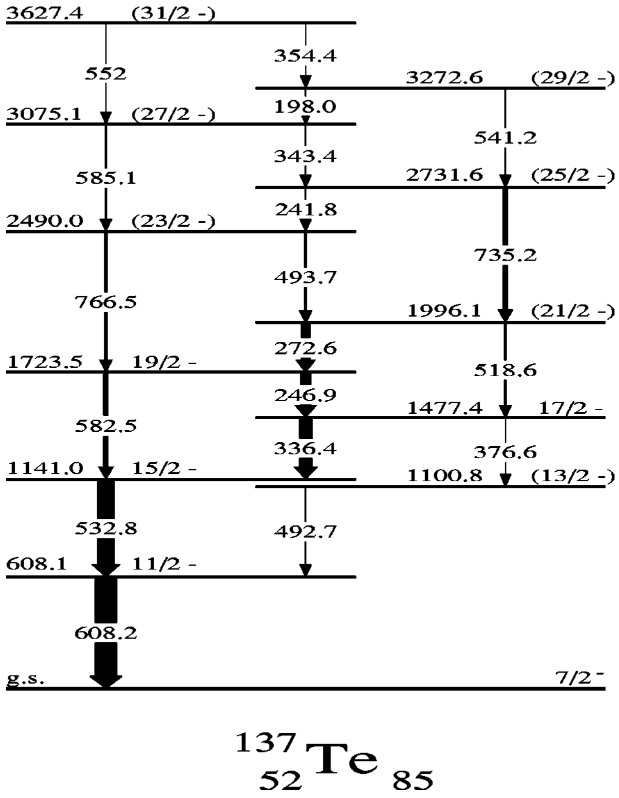

FIG. 3. Level scheme of ^{137}Te as obtained in this work.

532.8 keV transition is $P(532.8)=+0.22(7)$ while in the 532.8 keV gate it is $P(608.2)=+0.19(6)$ for the 608.2 keV transition and $P(336.4)=-0.15(7)$ for the 336.4 keV transition. These results are consistent with a stretched $E2$ multipolarity for the 608.2 keV and 532.8 keV transitions and a stretched $M1$ multipolarity for the 336.4 keV transition. Tentative spin assignments shown in brackets are based on the observed γ-ray branchings, on the assumption that fission populates yrast and near-yrast levels and on the assumption that magnetic quadrupole ($M2$) transitions may be excluded due to the nonobservation of any isomers longer than 10 ns in ^{137}Te.

With three neutrons outside the $N=82$ closed shell, the $N=85$ isotones show an excitation pattern characteristic of spherical nuclei, i.e., single-particle excitations and vibrationlike excitations coupled to them. The low energy levels have all three neutrons in the $f_{7/2}$ orbital. Excited states at higher energy can be obtained by promoting one of the neutrons into the $h_{9/2}$ or $i_{13/2}$ orbital.

The decay scheme of ^{137}Te is remarkably similar to decay schemes of the heavier $N=85$ isotones. This suggests that the structure of yrast levels is similar in all these nuclei allowing a systematic comparison of ^{137}Te with other $N=85$ nuclides, for which detailed studies have already been performed [4,3].

In Fig. 5 the yrast excitations observed in the ^{137}Te nucleus are compared with analogous excitations in the heavier $N=85$ isotones. Filled and open circles represent negative and positive parity excitations in the $N=85$ isotones, respectively, while filled and open squares represent 2^+ and 3^- excitations in their $N=84$ core nuclei, respectively. Lines drawn in Fig. 5 are to guide the eye. Data for the $N=85$ nuclei are from this work and Refs. [3–5], while data for the $N=84$ core nuclei are taken from Refs. [16–21]

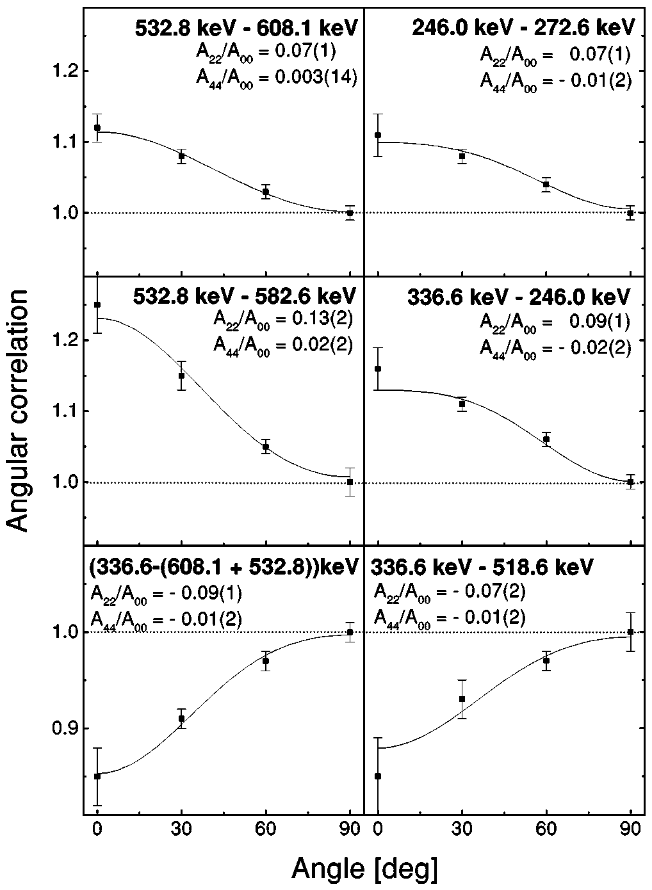

FIG. 4. γ-γ angular correlations for transitions in ^{137}Te, as measured in this work.

The three lowest states, shown in Fig. 5, are interpreted as arising from the $\nu(f_{7/2}{}^3)_j$ configuration [4]. Near the closed shells at $Z=64$ and $Z=50$ the $\nu(f_{7/2}{}^3)_{7/2^-}$ coupling tends to be the lowest in energy. The systematics shown in Fig. 5 support the $I^\pi=7/2^-$ assignment to the ground state in ^{137}Te, though no candidates for the the $I^\pi=3/2^-$ and $I^\pi=5/2^-$ levels were found so far in this nucleus.

The $I^\pi=11/2^-$ and $15/2^-$ yrast levels are higher-spin members of the $\nu(f_{7/2}{}^3)_j$ multiplet [4]. In Fig. 5 they are compared to the 2^+ excitations in the corresponding $N=84$ cores. The points for the $N=85$ isotones follow closely the $N=84$ data. Thus the $I^\pi=11/2^-$ and $15/2^-$ yrast levels can be alternatively seen as a result of a weak coupling of the odd neutron in the $\nu(f_{7/2})$ orbital to the $N=84$, core excitations.

With one neutron promoted to the $h_{9/2}$ orbital the $\nu[h_{9/2}(f_{7/2}{}^2)]_{9/2^-,13/2^-,17/2^-,21/2^-}$ multiplet is formed. This multiplet is observed, although sometimes only partly, in all the $N=85$ isotones studied. In ^{137}Te the $\nu[h_{9/2}(f_{7/2}{}^2)]_{9/2^-}$ member has not been identified although higher-spin members are seen. In ^{139}Xe and ^{141}Ba, in contrast, the $9/2^-$ level is present while higher-spin members of the multiplet are absent. Instead, positive-parity $13/2^+$, $17/2^+$, and $21/2^+$ lev-

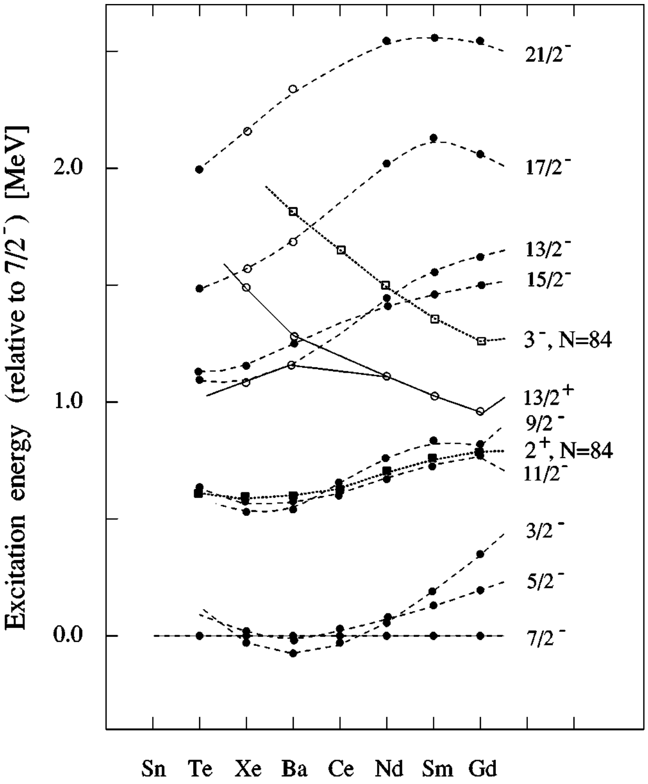

FIG. 5. Systematics of yrast excitations in the $N=85$ lanthanides. See text for a discussion.

els were reported in ^{139}Xe and ^{141}Ba [5] (open circles in Fig. 5), which, however, follow closely systematics for the $\nu[h_{9/2}(f_{7/2}{}^2)]_{9/2^-,13/2^-,17/2^-,21/2^-}$ multiplet, as can be seen in Fig. 5.

Finally, when a neutron is promoted to the $i_{13/2}$ orbital, the $\nu[i_{13/2}(f_{7/2}{}^2)]_{13/2^+,17/2^+,21/2^+,25/2^+}$ multiplet of states is formed. In this multiplet only the $I^\pi=25/2^+$ member can have a pure $\nu[i_{13/2}(f_{7/2}{}^2)]$ configuration [4]. Other members of the multiplet may have admixtures of collective octupole excitations. The authors of Ref. [5] have proposed that in ^{139}Xe and ^{141}Ba two bands of the same simplex are present, based on two $I^\pi=13/2^+$ levels, one of which has a single-particle $\nu i_{13/2}$ nature and the other, lower in energy, is due to an octupole phonon coupled to the $\nu(f_{7/2}{}^3)_{7/2^-}$ configuration. This is illustrated in Fig. 5, where the systematics for $I^\pi=13/2^+$ levels splits into two branches below proton number $Z=60$ (cf. Fig. 3 in Ref. [5]). Due to its predicted yrast character, the lower $I^\pi=13/2^+$ level should be clearly seen in ^{137}Te at an excitation energy of about 1 MeV. We could not see such a level in ^{137}Te. Instead, a strongly populated $I^\pi=13/2^-$ was identified at 1100.8 keV and, as mentioned above, lower-energy $I^\pi=13/2^+$ levels in ^{139}Xe and ^{141}Ba follow closely the systematics for the $I^\pi=13/2^-$ levels, which includes the newly found $13/2^-$ level in ^{137}Te.

The trend in the energies of the higher-lying $I^\pi=13/2^+$ levels in five $N=85$ isotones is similar to that of the 3^- excitation in the $N=84$ core nuclei. This observation suggests an octupole character for the higher-energy $I^\pi=13/2^+$ excitation. It also indicates that octupole correlations decrease when approaching the $Z=50$ closed shell, as previously concluded in Ref. [6]. The higher energy $I^\pi=13/2^+$ level is not observed in ^{137}Te, probably because of its non-yrast character, as suggested by the systematics.

In summary, excited levels in ^{137}Te have been observed for the first time. The structure of yrast excitations in ^{137}Te is similar to that observed in heavier $N=85$ isotones and can be interpreted as due to three valence neutrons in the $\nu(f_{7/2}{}^3)_j$ or $\nu[h_{9/2}(f_{7/2}{}^2)]_j$ configurations and core vibrations coupled to them. The present data do not support earlier suggestions that in the $N=85$ isotones octupole correlations increase when approaching the $Z=50$ shell. On the contrary, the data indicate that octupole correlations decrease rather than increase. The systematic behavior of excitations in the $N=85$ isotones, which are now enriched with the ^{137}Te data, strongly suggests reinvestigation of spin and parity assignments in the ^{139}Xe and ^{141}Ba nuclei. Further studies of low-spin excitations in ^{137}Te, especially the identification of the $3/2^-$ and $5/2^-$ members of the $\nu(f_{7/2}{}^3)_j$ configuration, the $9/2^-$ member of the $\nu[h_{9/2}(f_{7/2}{}^2)]_j$ configuration, and the yrast $13/2^+$ level, are of a great interest.

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