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Excited states in ^{139}Te and the properties of *r*-process nuclei with $Z\sim50$ and $N>86$

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Excited states in ^{139}Te were observed for the first time, using EUROGAM2 multidetector array to measure prompt-γ radiation following the spontaneous fission of ^{248}Cm. The systematic behavior of excitation energies in the $N=87$ isotones and the multipolarity measurements suggest spin $7/2^-$ for the ground state and $9/2^-$ for the 271.0 keV level in ^{139}Te. The 271.0 keV level most likely corresponds to the $\nu h_{9/2}$ single-particle excitation. A shape transition from spherical to prolate Te isotopes is observed at the neutron number $N=87$, in accord with the Hartree-Fock plus BCS, PES calculations. Predictions for excitations in the ^{137}Sn nucleus are made based on the extended systematics obtained for the $N=87$ isotones.

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The knowledge of the very neutron-rich ($N>82$) nuclei around the doubly magic ^{132}Sn is crucial for understanding the flow of the astrophysical *r* process [1]. Key experimental data required for calculations of the *r*-process path are the positions of single-particle orbits in the nuclear potential. In this region the positions of the $\nu h_{9/2}$ and $\pi h_{11/2}$ orbitals determine the Gamow-Teller, β^- decay rates and, consequently, nuclear half-lives, which decide about the direction of the *r*-process flow. One expects, that for the very neutron-rich tin isotopes, quenching of the $Z=50$ gap will appear. This would also influence the *r*-process path [2]. An indication of such quenching would be the observation of nuclear deformation in the very neutron-rich tin isotopes. Such deformation would help to explain discrepancies between the observed and calculated *r*-process abundances around mass $A=140$ [3].

To provide the relevant data, we studied the very neutron-rich tellurium isotopes, for which no excited levels had been reported previously. The properties of ^{137}Te and ^{138}Te have been published recently [4,5]. In the present work we report on the first observation of excited states in the ^{139}Te nucleus, located in between the *r*-process nuclei [1]. With 87 neutrons this nucleus is the most neutron-rich nuclide near the $Z=50$ closed shell, for which spectroscopic information has been obtained.

Levels in ^{139}Te were populated in the spontaneous fission of ^{248}Cm and multiple coincidences between prompt-γ rays following fission were measured with the EUROGAM2 array of Anti-Compton Spectrometers. More details about the experiment and data analysis techniques are given in Refs. [6–9].

Prior to this work nothing was known about levels in ^{139}Te. To identify γ transitions in ^{139}Te we gated on the known transitions in ruthenium isotopes [10], which are complementary fission fragments to Te isotopes. A cascade of γ rays of energies 271.0, 356.5, 436.4, 534.8, and 611.8 keV was found in prompt coincidence with transitions in $^{106-108}$Ru isotopes and was therefore assigned to a tellurium isotope. This is illustrated in Fig. 1, where coincidence spectra, double-gated on lines in Ru isotopes and the newly found

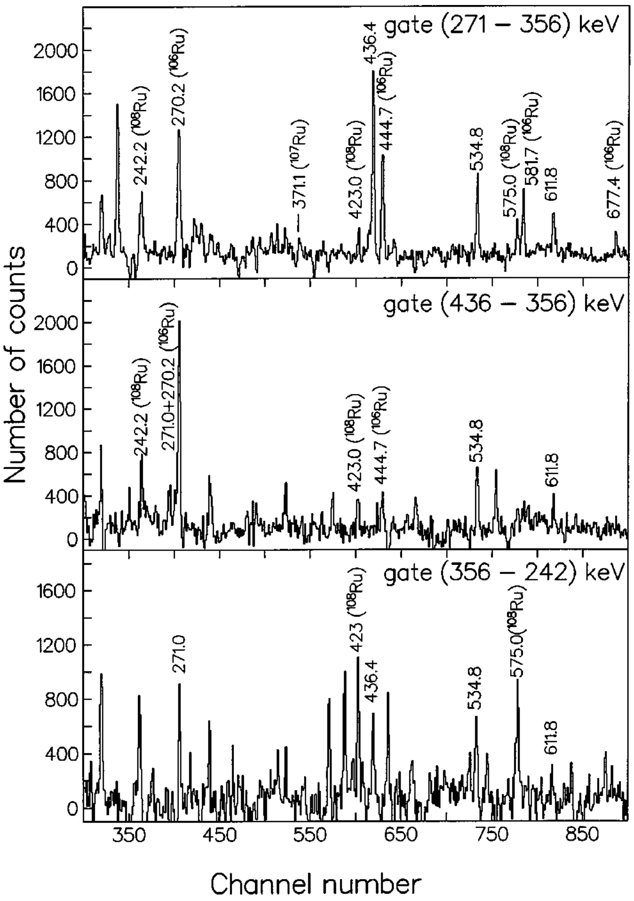

FIG. 1. Coincidence spectra double-gated on lines in ^{139}Te and ^{106,108}Ru isotopes. Transition energies are given in keV.

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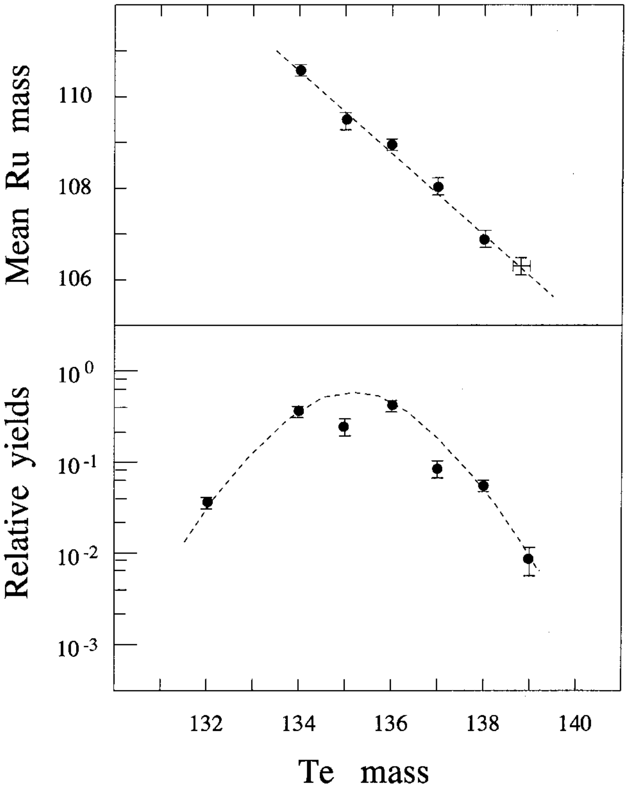

FIG. 2. Upper panel: correlation between masses of Te isotopes and mean mass of complementary Ru isotopes. Lower panel: population of Te isotopes in spontaneous fission of ^{248}Cm. See text for more explanations.

tellurium lines, are shown.

To find the mass of this Te isotope we used the technique of mass correlation proposed in Ref. [11]. The method is based on the smooth variation between the sum of the nucleons in a given Te fragment $A(\mathrm{Te})$ and the number of nucleons corresponding to the mean mass $\langle A(\mathrm{Ru})\rangle$, of the accompanying complementary fragments. On average, about three neutrons are emitted in the spontaneous fission of ^{248}Cm and, to a reasonable approximation, the sum of $A(\mathrm{Te})$ and $\langle A(\mathrm{Ru})\rangle$ should equal the nucleon number of ^{248}Cm less 3. This determines the linear mass calibration $A(\mathrm{Te})+\langle A(\mathrm{Ru})\rangle=245$. This method was used for Te-Ru fission partners in our recent study of ^{137}Te isotope [4].

Figure 2 shows $\langle A(\mathrm{Ru})\rangle$ values obtained in Ref. [4] as a function of $A(\mathrm{Te})$. The dashed line represents a linear fit to the points for $A(\mathrm{Te})$ equal to 134, 136, and 138. Data for ^{135}Te and ^{137}Te [4], which are also included in the figure, show that odd-A isotopes follow the same smooth trend. We used the obtained linear fit for mass calibration at $A(\mathrm{Te})=139$. The relative intensities of the γ rays to the ground states of different Ru nuclei, as observed in the coincidence spectrum obtained by gating on the transitions in the newly found cascade, provide the mean mass of the complementary Ru fragments of $\langle A(\mathrm{Ru})\rangle=106.3(2)$. This value placed on the calibration line determines the new Te mass to be 138.8(2), which uniquely points to the mass $A=139$ for the newly identified tellurium isotope.

This identification is further supported by the yield of ^{139}Te deduced from the observed γ rays in the cascade. This is illustrated in the lower panel of Fig. 2 which shows the observed yields of the different Te isotopes produced in the experiment. The dashed line represents a Gaussian function describing the population of the even-even isotopes. The population of the odd-A nuclei falls sometimes below the curve describing the even-even yields, which may be due to the odd-even effect and the non-observation of some weak cascades feeding the ground state. In Fig. 2 this effect is observed clearly for ^{135}Te and to a lesser extent for ^{137}Te isotopes. Within the experimental error, the whole expected yield of ^{139}Te is found in the newly observed γ cascade.

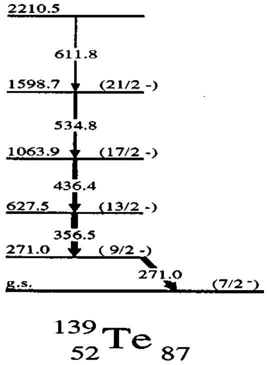

FIG. 3. The partial level scheme of ^{139}Te, as obtained in the present work.

The γ transitions in ^{139}Te were arranged into a partial decay scheme as shown in Fig. 3. The order of transitions in the cascade was decided based on the observed γ-ray intensities, proportional to the arrow thicknesses in Fig. 3.

Our measurement allows spin assignments to the excited levels to be made using γ-γ angular correlations, as described in Refs. [8,9]. 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. Double-γ angular correlations for transitions in ^{139}Te are shown in Fig. 4, together with coefficients of Legendre polynomial expansions fitted to the data. Because of the low transition intensities, some correlations were generated by adding gates, as indicated in Fig. 4. The 356.5 keV transition was correlated with the sum of gates on the 436.4 and 534.8 keV transitions, while the 271.0

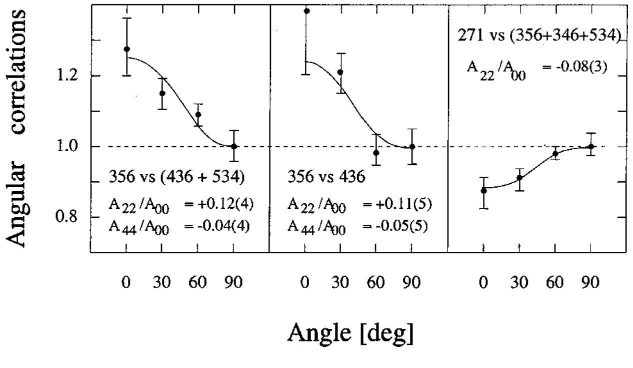

FIG. 4. γ-γ angular correlations for transitions in ^{139}Te, as obtained in the present work.

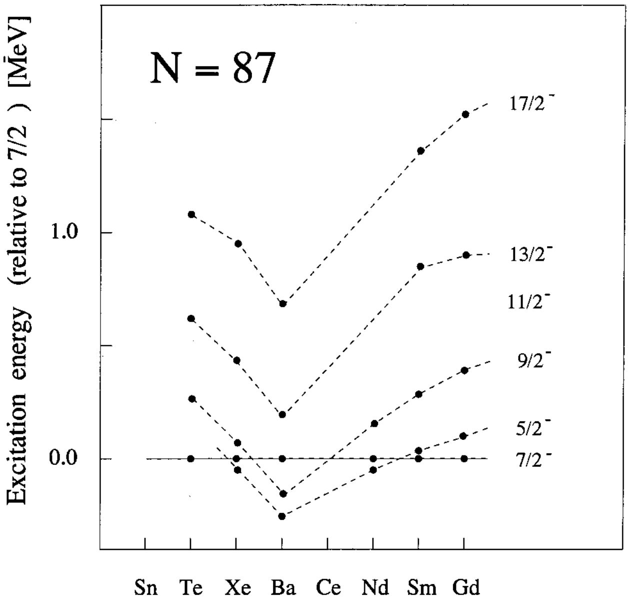

FIG. 5. Systematics of yrast excitations in the $N=87$ lanthanides, drawn relative to the yrast $7/2^-$ levels.

keV transition was correlated with the sum of gates on the 356.5, 436.4, and 534.8 keV transitions. The data shown in Fig. 4 are consistent with a stretched quadrupole character for the 356.5, 436.4, and 534.8 keV transitions and a stretched dipole character for the 271.0 keV transition. Spins and parities in ^{139}Te, shown in Fig. 3, were proposed based on the measured angular correlations, assuming spin $7/2^-$ for the ground state.

Nothing is known in the literature about the ground state of ^{139}Te. The systematic trend of yrast excitations in the $N=87$ isotones, drawn relative to the yrast $7/2^-$ levels and shown in Fig. 5 suggests, however, possible spin and parity for this state. The data for Ba-Gd isotopes were taken from Refs. [12–15] and for ^{141}Xe from Ref. [16], where spins and parities were determined experimentally as $5/2^-$, $7/2^-$, $9/2^-$, and $13/2^-$ for the ground state, 35.6, 112.2, and 370.1 keV levels, respectively. For ^{145}Ce, where the $7/2^-$ level is not identified, no data is presented. The trends observed in Fig. 5 suggest that the ground state of ^{139}Te has spin and parity $I^{\pi}=7/2^-$. An alternative, $5/2^-$ assignment is less likely because the 271.0 keV, first excited state fits very well the systematics for the $9/2^-$ levels in the $N=87$ isotones and the 271.0 keV transition is of a stretched dipole character. Higher excitations in ^{139}Te also follow the pattern. The 627.5, 1063.9, and 1598.7 keV levels fit the systematics if they are assigned spins $13/2^-$, $17/2^-$, and $21/2^-$, respectively, in accord with the stretched quadrupole character of γ transitions, depopulating these levels.

The decay scheme of ^{139}Te is remarkably similar to decay schemes of heavier $N=87$ isotones. This suggests that the yrast excitations are similar in all these nuclei and allows a comparison of ^{139}Te with other $N=87$ isotones, for which detailed studies have been performed [14,15].

With five neutrons outside the $N=82$ closed shell, the $N=87$ isotones show an excitation pattern characteristic of transitional nuclei, i.e., single-particle excitations with both vibration- and rotationlike excitations coupled to them. An extensive discussion of shape coexistence in the $N=87$ isotones has been presented in Refs. [14,15], where ^{149}Sm, ^{151}Gd, and ^{153}Dy were discussed in detail. The excitations in the $N=87$ isotopes were classified as the $\nu f^N_{7/2}$ cluster vibration, $\nu h_{9/2}$ deformed, $\nu i_{13/2}$ deformed, $\nu i_{13/2}+\nu f^N_{7/2}\otimes 3^-$ octupole-coupled, and $\nu h^{-1}{}_{11/2}$ intruder-hole states. The last three types are nonyrast structures and are less likely to be observed in ^{139}Te populated in fission.

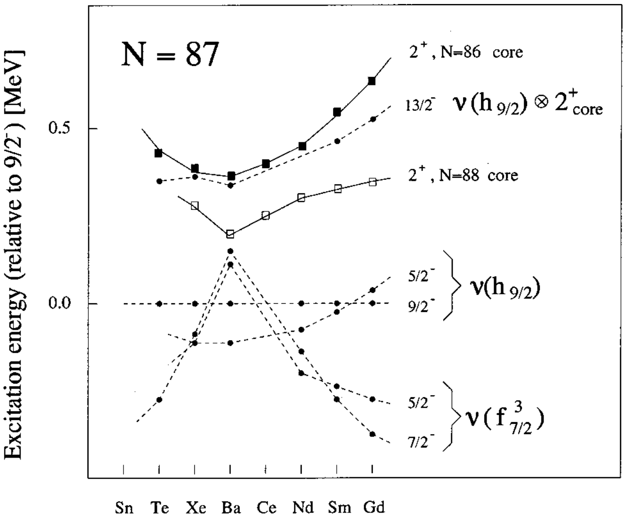

FIG. 6. Systematics of low-spin excitations in the $N=87$ lanthanides, drawn relative to the yrast, $9/2^-$ levels.

The $f^N_{7/2}$ cluster states result from coupling of three nucleons in an orbit with spin j, producing a doublet of states with spins j and $(j-1)$. A characteristic pair of $5/2^-$ and $7/2^-$ excitations, observed systematically in the $N=87$ isotones, was interpreted as the $[\nu f^3_{7/2}(i^2_{13/2})_{0^+}]_{5/2^-,7/2^-}$ configuration, corresponding to a nondeformed shape [14,15]. The ground state of ^{139}Te, most likely corresponds to the $[\nu f^3_{7/2}(i^2_{13/2})_{0^+}]_{7/2^-}$ configuration. The $[\nu f^3_{7/2}(i^2_{13/2})_{0^+}]_{5/2^-}$ level is not seen in the present work, probably due to its nonyrast character.

In the heavier $N=87$ isotones, the yrast $9/2^-$ level, with a rotational band on top of it, corresponds to a deformed configuration with $\beta_2\approx 0.2$. A similar band is now observed in ^{139}Te on top of the $9/2^-$, 271.0 keV level. As suggested in Refs. [14,15], the yrast $9/2^-$ level corresponds to the $[\nu f^2_{7/2} i^2_{13/2} h_{9/2}]_{9/2^-}$ configuration, in which the odd neutron occupies the $\nu h_{9/2}$ orbit. Unlike the $f^N_{7/2}$ cluster, this configuration does not form the $(j-1)$ but rather a $(j-2)$ coupling [14]. A $5/2^-$ excitation, which appears close in energy to the the $9/2^-$, yrast level in the $N=87$ isotones, was interpreted as due such $(j-2)$ coupling [15]. Thus, in the $N=87$ isotones there are two $5/2^-$ excitations associated with the $7/2^-$ and $9/2^-$ levels, respectively. This is illustrated in Fig. 6, where the relevant $N=87$ excitations are shown relative to the yrast $9/2^-$ level. The data shown in Fig. 6 were taken from Refs. [12–16]. The 2^+ levels in the $N=86$ and $N=88$ cores are also shown in Fig. 6 as filled and open squares, respectively. The $13/2^-$ excitations follow closely the 2^+ excitations in the $N=86$ core nuclei, supporting the

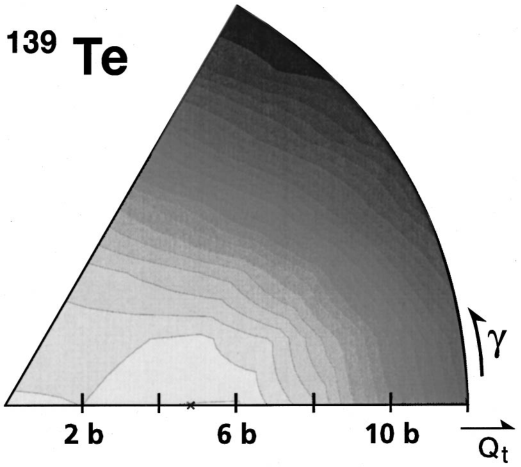

FIG. 7. Potential energy surface in the (Q_t,γ) plane for ^{139}Te, calculated via Hartree-Fock plus BCS code. The distance between contour lines is 500 keV. The minimum in the potential is marked by an asterisk.

proposed nature of these excitations as the $\nu h_{9/2}\otimes 2^+_{\mathrm{core}}$ configuration. Figure 6 suggests that the excitation pattern in ^{139}Te is similar to that in ^{149}Sm, with the $\nu h_{9/2}\otimes 2^+_{\mathrm{core}}$ excitation well separated from the $\nu(f^3_{7/2})$ cluster. Therefore one expects that the two structures do not mix strongly and the $9/2^-$ level in ^{139}Te corresponds to a rather pure $\nu h_{9/2}$ configuration, as observed in ^{149}Sm [14].

The $N=88$, 2^+ core excitations are significantly lower in energy than the corresponding $N=86$, 2^+ core excitations. This reflects the fact that the $N=88$ isotones are more deformed than those at $N=86$. The heavy Te isotope are expected to exhibit a shape transition from spherical to prolate nuclei, which is predicted to occur between ^{136}Te and ^{140}Te, as discussed in our recent study of ^{138}Te [5]. Hartree-Fock plus BCS calculations for ^{139}Te, performed in the same way as those in Ref. [5], show a rather β-soft potential energy surface (PES) with an absolute minimum situated at $\beta=0.11$, as illustrated in Fig. 7. In the case of ^{138}Te, the vibrational character of the collective motion had been established following the $E(6^+)/E(2^+)=3.3$ and $E(4^+)/E(2^+)=2.0$ ratios [5]. In the ^{139}Te nucleus the $E(21/2^-)/E(13/2^-)$, and $E(17/2^-)/E(13/2^-)$, where the excitations are measured with respect to the $9/2^-$ level, are 3.7 and 2.2, respectively. The increase of the observed ratios from ^{138}Te to ^{139}Te agrees with the decrease of the β softness observed in the PES display and indicates, that the expected shape transition in Te isotopes takes place at the neutron number $N=87$.

The clear systematic trends seen in Fig. 6 provide a reliable prediction for the $Z=50$ closed shell nucleus ^{137}Sn, located at a crucial point of the *r*-process path. The expected excitation pattern of ^{137}Sn is similar to that observed in ^{151}Gd at $Z=64$ closed subshell. The ground state most likely has spin and parity $7/2^-$ and the $9/2^-$ level, corresponding to the $\nu h_{9/2}$ configuration is predicted at about 350 keV above the ground state.

One expects that the 2^+ excitations in $^{136}\mathrm{Sn}_{86}$ and $^{138}\mathrm{Sn}_{88}$ isotopes will have similar energies if the $Z=50$ shell closure is still well developed at these neutron numbers. What is shown in Fig. 6 suggests that in tin isotopes the $Z=50$ shell closure is still well developed at the neutron number $N=86$ but the deformation may set already at $N=88$, as observed in the tellurium isotopes.

In summary, excited levels in the ^{139}Te nucleus were observed for the first time. The ground state and the first excited 271.0 keV state were assigned spins and parities of $7/2^-$ and $9/2^-$, respectively. The structure of the yrast excitations in ^{139}Te is similar to that observed in the heavier $N=87$ isotones, with the ground state and the 271.0 keV level corresponding to the $[\nu f^3_{7/2}(i^2_{13/2})_{0^+}]_{7/2^-}$ and $[\nu h_{9/2}\nu(f^2_{7/2})_{0^+}(i^2_{13/2})_{0^+}]_{9/2^-}$ configurations, respectively. The properties of the ^{139}Te nucleus indicate, that at the neutron number $N=87$ a shape transitions between spherical and prolate nuclei takes place in Te isotopes, confirming the PES, Hartree-Fock, plus BCS calculations. Systematic trends in the excitation energies of the $N=87$ nuclei, extended now by the ^{139}Te data, allow a reliable prediction of the excitation energy of the $\nu h_{9/2}$ configuration in the ^{137}Sn nucleus, which is expected at about 350 keV above the $(\nu f^N_{7/2})_{7/2^-}$ ground state. Further studies are needed to complete the energy systematics for the $N=87$ isotones, which can be used for extensive tests of nuclear models in this region. The identification of the $5/2^-$ excitation in ^{139}Te is especially important, as are experimental determinations of spins and parities of low-energy excitations in the ^{145}Ce nucleus.

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