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First identification of excited states in ^{106}Te and evidence for isoscalar-enhanced vibrational collectivity

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Gamma-ray transitions in the extremely neutron-deficient nucleus ^{106}Te have been identified for the first time. The experiment utilized the ^{54}Fe(^{54}Fe,2n)^{106}Te* reaction, and the γ-ray transitions from excited states in ^{106}Te were selected by use of the recoil-decay-tagging technique. The production cross section was estimated at 25 nb, a new limit for in-beam γ-ray spectroscopy. A ground-state band tentatively extending up to $I^\pi = 10^+$ is proposed. The systematics of low-lying yrast states in the Te isotopes is discussed within the context of vibrational excitations and residual nucleon-nucleon interactions.

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Collective excitations, such as shape vibrations and rotations, are fundamental concepts for our understanding of nuclear structure. Although there is an abundance of rotational-like behavior over vast regions of the nuclear chart (the most striking examples being nuclei exhibiting superdeformed rotational bands), nuclear vibration is a more elusive phenomenon, and there are few cases of unambiguous experimental evidence for low-lying vibrational excitations. The tellurium isotopes may be among the best examples of near-harmonic quadrupole shape vibrations in nuclei. They provide a "laboratory" for studies of nuclear collectivity, in particular how collective excitations can develop as a result of the residual interactions between a small number of nucleons outside closed shells. Near the $N = Z$ line, nuclear collectivity may be enhanced by the interactions (in particular the $T = 0$ component) between neutrons and protons in similar orbits near the Fermi level. It is therefore of great interest to expand our experimental knowledge further toward the proton dripline and eventually the expected $N = 50$ shell closure. The nucleus $^{100}_{50}$Sn$_{50}$ is predicted to be the heaviest self-conjugate ($N = Z$) doubly magic nucleus that is particle bound, and its properties have been the subject of long-standing interest in nuclear structure physics. However, it is not until recently that the advancements in experimental techniques have begun to enable detailed structural studies of nuclei close to the presumed $N = Z = 50$ double-shell closure. Experimental information on single-particle energies and residual interactions with respect to the ^{100}Sn "core" are of vital importance for testing the nuclear shell model and other nuclear structure models such as relativistic mean-field models [1] and Hartree-Fock [2] predictions in this exotic domain. In the most neutron-deficient tellurium nuclides the valence neutrons and protons are predicted to occupy identical orbits in the $2d_{5/2}$ and $1g_{7/2}$ subshells, and neutron-proton correlations (possibly even $T = 0$ neutron-proton pairing) are therefore expected to be particularly important. In addition, light Te nuclei around $A = 110$ have been predicted to have pronounced octupole softness because of $\Delta l = \Delta j = 3$ residual interactions [3] and experimental evidence for octupole collectivity has also been observed in these nuclei [4]. In the nucleus ^{114}Xe a coherent neutron-proton contribution to octupole correlations has been proposed [5], and one may also note the prediction by Skalski of octupole stability in ^{112}Ba, ^{110}Xe, and a few surrounding nuclides [6], which still remains to be tested experimentally.

The nucleus ^{106}Te, which has two valence protons and four valence neutrons outside the ^{100}Sn core, lies at the lower mass limit of the tellurium isotopic chain. It is predicted to be unbound by approximately 0.2 MeV and unstable against two-proton decay [7]. An astrophysical interest in studying this region of the nuclear chart has also emerged because of its predicted role in stellar nucleosynthesis (see, e.g. [8] for a popular review). In particular, ^{106,107}Te has been predicted by Schatz *et al.* to constitute the end point of the astrophysical *rp* process because of (γ, α) reactions, leading to a closed Sn-Sb-Te cycle that prevents heavier elements from forming [9]. Experimental information on the low-lying energy spectra of the lightest Te isotopes are of importance for testing such model predictions.

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Experimental studies of nuclei with extreme proton-to-neutron ratios are highly challenging. For neutron-deficient nuclei, fusion-evaporation reactions are a favorable production method. Such reactions have cross sections that decrease rapidly with decreasing neutron number. Studies of highly neutron-deficient tellurium isotopes illustrate this effect: The production cross section for ^{108}Te was reported to be about 0.2% of the total fusion-evaporation cross section [4], corresponding to a cross section of the order of 1 mb. For ^{107}Te [10], the most neutron-deficient tellurium isotope for which information on excited states was available prior to the present study, the production cross section was approximately 1 μb. In the present investigation of ^{106}Te, the production cross section is estimated to be 25 nb. Hence the production cross section is found to drop by orders of magnitude per neutron for these extremely neutron-deficient tellurium isotopes. As the proton dripline is approached, the barriers inhibiting the emission of α particles and protons decrease. This leads in typical experiments to a population of a multitude of different reaction channels. The nuclei of interest are often the most weakly populated, and their γ-ray spectra must be extracted by use of highly selective techniques from a large background arising from a multitude of more abundantly populated reaction channels. The lightest Te isotopes belong to the "island" of α radioactivity that also includes very neutron-deficient I, Xe, and Cs isotopes. The characteristic α (or proton) decays can be used as a signature ("tag") for identifying excited states in specific nuclei by use of the highly selective recoil-decay-tagging (RDT) technique [11,12]. This article presents the first γ-ray spectroscopic study of ^{106}Te, at the very limits of what is achievable with current detector systems for nuclear spectroscopy. It represents an experimental landmark for nuclear structure physics; at an estimated 25 nb the production cross section for ^{106}Te is the lowest ever reported for in-beam γ-ray spectroscopy.

The experiment was performed at the JYFL accelerator facility at the University of Jyväskylä, Finland. The ^{54}Fe ions, accelerated by the JYFL K130 cyclotron to an energy of 182 MeV, were used to bombard a target consisting of a 1.1-mg/cm^2 self-supporting foil of isotopically enriched (99.9%) ^{54}Fe. The average beam intensity was around 10 pnA during 5 days of irradiation. Prompt γ rays were detected at the target position by the jurogam γ-ray spectrometer consisting of 43 eurogam [13] type escape-suppressed high-purity germanium detectors. The germanium detectors were distributed over six angles relative to the beam direction with 5 detectors at 158°, 10 at 134°, 10 at 108°, 5 at 94°, 5 at 86°, and 8 at 72°. In this configuration, JUROGAM had a total photopeak efficiency of about 4.2% at 1.3 MeV.

The fusion-evaporation products were separated in-flight from the beam particles by the gas-filled recoil separator Recoil Ion Transport Unit (RITU) [14,15] and implanted into the two double-sided silicon strip detectors (DSSDs) of the Gamma Recoil Electron Alpha Tagging (GREAT) [16] focal-plane spectrometer. The GREAT spectrometer is a composite detector system containing, in addition to the DSSDs, a multiwire proportional avalanche counter (MWPAC), an array of 28 Si p-i-n photodiode detectors, a segmented planar Ge detector, and a large Ge clover detector. Each DSSD has a total active area of 60 mm × 40 mm and a strip pitch of 1 mm in both directions, yielding in total 4800 independent pixels.

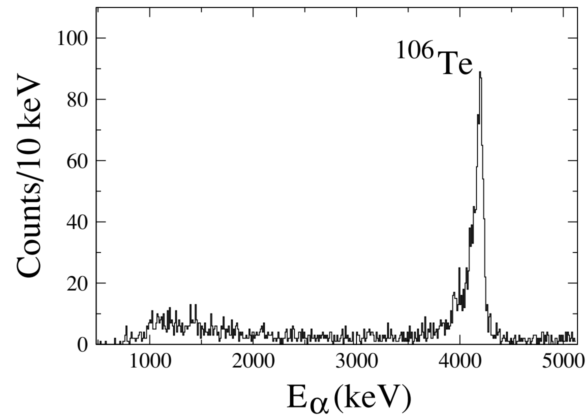

FIG. 1. Recoil-correlated α-decay energy spectrum for ^{106}Te.

The signals from all detectors were recorded independently and provided with an absolute "time stamp" with an accuracy of 10 ns by use of the total data readout (TDR) [17] acquisition system. Spatial and temporal correlations of recoil implants and their subsequent α decays were performed on-line and off-line by use of the GRAIN [18] and TSCAN [19] software packages, respectively.

The half-life of ^{106}Te has previously been measured to be 70^{+20}_{-10} μs [20,21]. This is short enough to allow clean correlations with the RDT technique, even at high implantation rates, and long enough to survive the ~0.5-μs flight time through the recoil separator. In the present experiment the symmetric reaction proved challenging for the RITU separator. A carbon charge reset foil of 40 μg/cm^2 mass thickness was placed immediately downstream of the target to minimize the overlap of the spatial distribution of the recoiling fusion products with that of the beam particles. Furthermore, the magnetic-field intensity of the RITU dipole magnet was adjusted in order to center the recoil distribution in the right-hand DSSD so that a majority of the beamlike particles did not impinge on the detectors. In addition, active beam/recoil discrimination was possible at the focal plane by use of energy-loss and time-of-flight measurements from the GREAT MWPAC and implantation detector. Since ^{106}Te was the only α emitter populated with significant intensity in the reaction, the α-energy spectrum from the DSSD detectors was essentially background free.

The ground state of ^{106}Te has previously been reported to α decay with 100% branching ratio and with $Q_\alpha \simeq 4.29$ MeV [20–22] (corresponding to an α-particle kinetic energy of 4.13 MeV). Figure 1 shows the correlated α-energy spectrum that was obtained with a correlation time of 180 μs between the implanted recoil and its subsequent α decay. The half-life of the α decay from the present data is measured to be 69± 5 μs, which is in agreement with previous measurements. No evidence for the predicted two-proton decay mode was found, although it cannot be excluded since such "exotic" events might be hidden among the continuous distribution of α-decay events for which the α particle has escaped out of the GREAT focal plane DSSD. Furthermore, the two-proton

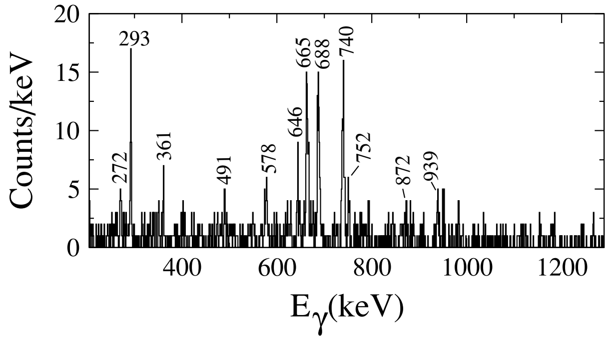

FIG. 2. γ-ray energy spectrum tagged by the α decay of ^{106}Te.

decay mode is expected to have a much longer partial half-life and could hardly compete effectively with the α decay.

Figure 2 shows the prompt γ-ray energy spectrum detected in delayed coincidence with the recoil-correlated α decays registered at the focal plane. The γ rays assigned to ^{106}Te and their corresponding intensities are listed in Table I.

The γ rays assigned to ^{106}Te were ordered based on their relative intensities. Despite the large experimental uncertainties of the intensity values, it is likely that the first two transitions of the ground-state band correspond to the 665- and 688-keV γ rays. We tentatively place them in order of increasing energy and decreasing intensity. The next transition is assumed to be the 293-keV γ ray since the 740-keV transition is a self-coincident doublet and the observed intensity is most likely divided in similar proportions on two identical γ-ray transitions in the yrast cascade. Lack of sufficient statistics prevented a full γ–γ coincidence study. However, there is evidence (albeit with very poor statistics) that the 665-, 688-, 293-, 740-, and 740-keV γ rays form a mutually coincident decay sequence. An attempt was made to extract information on the γ-ray multipolarities by means of an angular-distribution analysis. Although lack of statistics precluded firm assignments for individual γ rays, it was found that the results for summing the four strongest transitions show that they collectively behave like a stretched quadrupole transition. The tentatively proposed ground-state band of ^{106}Te is placed into the context of the systematics of low-lying yrast states in even-even tellurium isotopes in Fig. 3.

TABLE I. γ rays assigned to ^{106}Te. Statistical uncertainties are given in parentheses. The γ-ray intensities are adjusted for detection efficiency and normalized to the intensity of the strongest transition in the spectrum (665 keV).

Energy (keV)	Relative intensity (%)
271.6(6)[a]	21(8)
293.0(3)	62(11)
361.5(7)	17(5)
491.1(9)	12(5)
578.2(6)	27(6)
645.6(6)	31(8)
664.8(3)	100(12)
688.4(3)	97(12)
740.4(4)[b]	97(12)
752.2(9)	24(7)
872.0(12)	19(6)
939.3(10)	30(8)

[a]There is a possibility that the 272-keV γ ray is at least partly contaminated by a strong γ-ray transition at this energy in the strongest populated reaction channel, ^{105}In [23].
[b]The 740-keV γ ray is a self-coincident doublet transition.

The first excited 2^+ and 4^+ states in the chain of even-even tellurium isotopes reveal remarkably regular, vibrationallike patterns that extend from the very neutron-rich nuclides around the $N = 82$ shell closure toward the most neutron-deficient nuclides, approaching $N = 50$. The exception is the closed-neutron-shell ($N = 82$) nucleus $^{134}_{52}$Te$_{82}$, which, as expected, reveals a senioritylike yrast spectrum. Interestingly, the level spacings between the tentative 2^+ and 4^+ states in ^{106}Te are closer to the harmonic-vibrator limit than are those of the nearest heavier isotopes.

To elucidate the vibrationallike features in the chain of Te isotopes, the energy ratios, E_4^+/E_2^+ and E_6^+/E_2^+ are plotted versus neutron number N in Fig. 4. The harmonic limits for $E_4^+/E_2^+ = 2$ and $E_6^+/E_2^+ = 3$ are indicated by dotted lines. It might be pointed out here that, while such energy ratios serve as excellent indicators of collective vibrational behavior, other complementary experimental observables such as $B(E2)$ values and the observation non-yrast members of the vibrational multiplets are required for more conclusive evidence.

Starting at the top of the $N = 50$–82 neutron shell, it is not surprising that the vibrational collectivity appears to increase as N decreases toward midshell ($N = 66$). In fact, around $N = 66$ the E_4^+/E_2^+ and E_6^+/E_2^+ energy ratios almost perfectly correspond to those of a harmonic quantum vibrator. The absolute excitation energies of the 2^+ and 4^+ states are also consistent with this trend of increasing collectivity as they decrease continuously with decreasing neutron number toward midshell. Initially, as the neutron number is decreased further below midshell this trend is reflected, i.e., in increasing 2^+ and 4^+ energies. However, below $N = 62$ a different pattern appears, reminiscent of *increasing* collectivity as the neutron number is further decreased.

For the 6^+–4^+ energy difference there is a clear sign of increased influence from normal seniority coupling as the $N = 82$ shell is approached. Before to the present study, this effect was absent in the available data approaching the bottom of the neutron shell. It is first at $N = 54$, with our tentative placement of the 293-keV γ ray, that the typical signs of single-particle structure appear in the low-lying spectrum of the tellurium isotopes. Hence, a striking feature of the energy ratio plot of Fig. 4 is the clear asymmetry with respect to the neutron midshell. As the neutron number is further decreased, away from midshell, the energy ratios initially depart from the harmonic limits but then return toward the harmonic values (with the exception of the tentative E_6^+/E_2^+ energy ratio for ^{106}Te) as $N \to Z$. This intriguing trend cannot readily be understood in terms of available theoretical calculations. For example, the experimental data gathered in recent years, including the present work, reveal the opposite trend compared with calculations within the framework of the interacting boson model [40].

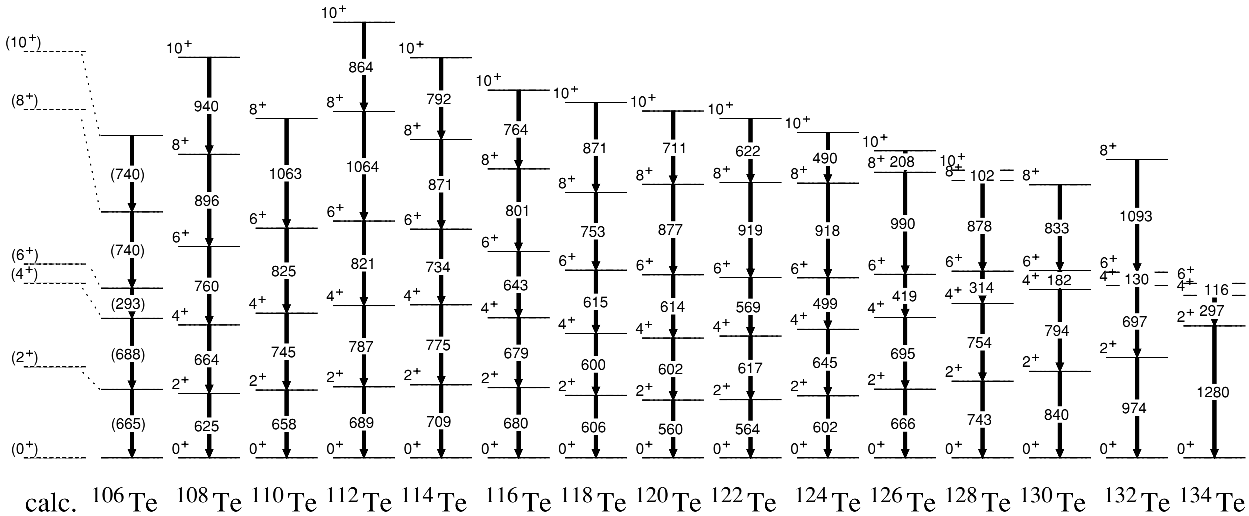

FIG. 3. Low-lying yrast state energies for even-even tellurium isotopes. The data for ^{106}Te are based on the present work, and it should be noted that the ordering of the γ-ray transitions is tentative (see text for details). The data for heavier Te isotopes are taken from [24–39]. The dashed levels are a shell-model calculation for ^{106}Te.

In an attempt to address this issue, total routhian surface (TRS) calculations [41] and shell-model calculations were performed. Near closed shells, the emergence of collective phenomena is believed to be due to the residual interactions between only a few valence nucleons and detailed theoretical calculations are therefore manageable. One key question is how a spherical nucleus can be made susceptible to shape vibrations by the interactions between only a handful of valence nucleons. The result of the TRS calculation for ^{106}Te is shown in Fig. 5. The TRS plot reveals a shallow minimum at a weakly deformed prolate shape (with $\beta_2 \approx 0.12$). There is also a pronounced softness in the triaxial γ degree of freedom as well as in β_2 (for smaller β_2 values toward spherical shape). The TRS calculations are thus consistent with a near-spherical shape that is susceptible to surface vibrations of the quadrupole type (i.e., β or γ vibrations). To address explicitly the single-particle structure of ^{106}Te, shell-model calculations have been performed. The calculations were restricted to the $2d_{5/2}$ and $1g_{7/2}$ subshells for both neutrons and protons. This is a reasonable truncation of the shell-model basis for low-lying states. The resulting level structure predicted for ^{106}Te is shown in Fig. 3. Up to the tentative 6^+ state the general features of the proposed level scheme are reproduced, even though the 6^+–4^+ level spacing is somewhat smaller in the calculation. The results indicate a rather abrupt transition in the structure between the yrast 4^+ and 6^+ states that appears in the highly neutron-deficient even-N tellurium isotopes as

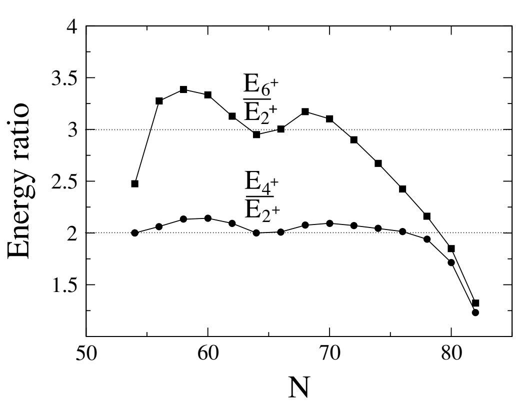

FIG. 4. E_4^+/E_2^+ and E_6^+/E_2^+ plotted versus N for even-even tellurium isotopes in the mass region $106 \leqslant A \leqslant 134$. The data are taken from the present work and [24–39].

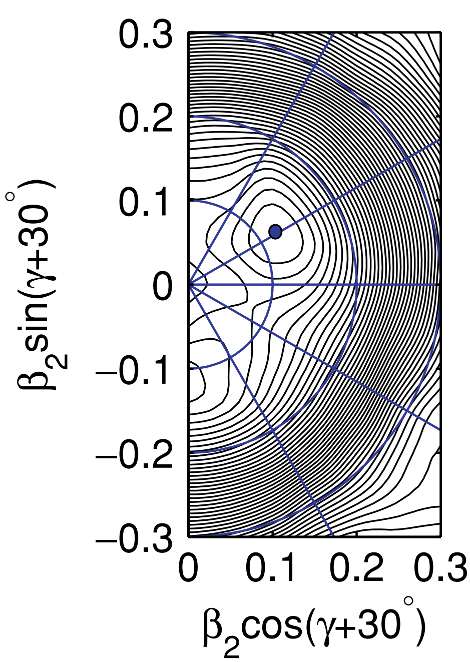

FIG. 5. (Color online) TRS calculation for ^{106}Te at $\hbar\omega = 0.16$ MeV. The energy spacing between contour lines is 200 keV. The minimum point is located at a prolate shape with $\beta \approx 0.12$.

the neutron number is decreased below $N = 56$. This is quite different from the gradual depression of the 6^+ level energies observed close to the top of the neutron shell. This effect could emanate from a shift in the balance between single-particle (seniority) coupling and collective vibrational behavior that is due to residual neutron-proton interactions. We somewhat speculatively suggest that the systematic behavior of the low-lying yrast states in the tellurium isotopic chain implies enhanced vibrational collectivity that is due to the influence of isoscalar neutron-proton residual interactions that become favorable as N approaches Z.

In summary, γ-ray transitions in the very neutron-deficient nuclide ^{106}Te have been identified for the first time. The estimated cross section for the ^{54}Fe(^{54}Fe,2n)^{106}Te* production reaction is 25 nb, setting a new limit for in-beam γ-ray spectroscopy. A cascade of γ-ray transitions that initially resembles a near-harmonic collective vibrational structure is proposed based on the available experimental information. The systematics of low-lying yrast states in the light even-even tellurium isotopes reveal a pattern that significantly deviates from the expected increased influence from single-particle seniority coupling as the $N = 50$ shell closure is approached. These findings may constitute new evidence for the importance of isoscalar neutron-proton interactions for the development of nuclear collectivity.

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