First identification of γ-ray transitions in ^{107}Te

B. Hadinia,[1,*] B. Cederwall,[1] K. Lagergren,[1,†] J. Blomqvist,[1] T. Bäck,[1] S. Eeckhaudt,[2] T. Grahn,[2] P. Greenlees,[2] A. Johnson,[1] D. T. Joss,[3] R. Julin,[2] S. Juutinen,[2] H. Kettunen,[2] M. Leino,[2] A.-P. Leppänen,[2] R. J. Liotta,[1] P. Nieminen,[2,‡] M. Nyman,[2] J. Pakarinen,[2] E. S. Paul,[4] P. Rahkila,[2] C. Scholey,[2] J. Uusitalo,[2] R. Wadsworth,[5] and D. R. Wiseman[4,‡]

[1]*Department of Physics, Royal Institute of Technology, SE-10691 Stockholm, Sweden*

[2]*Department of Physics, University of Jyväskylä, P.O. Box 35 (YFL), FIN-40014, University of Jyväskylä, Finland*

[3]*CCLRC, Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom*

[4]*Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom*

[5]*Department of Physics, University of York, York, United Kingdom*

(Received 10 August 2004; published 16 December 2004)

Gamma-ray transitions in ^{107}Te have been identified for the first time. The experiment, which utilized the recoil decay tagging technique, was performed at the accelerator laboratory of the University of Jyväskylä, Finland. Prompt gamma rays produced in ^{58}Ni(^{52}Cr,$3n$)^{107}Te* reactions were detected by the JUROGAM γ-ray spectrometer. The gamma rays belonging to ^{107}Te were selected based on the recoil identification provided by the RITU gas-filled recoil separator and the GREAT focal plane spectrometer. A first excited state at 90 keV, tentatively of $g_{7/2}$ character, is proposed.

DOI: 10.1103/PhysRevC.70.064314 PACS number(s): 23.20.Lv, 27.60.+j, 29.30.Kv

I. INTRODUCTION

The nucleus $^{100}_{50}$Sn$_{50}$ is predicted to be the heaviest particle-bound self-conjugate ($N=Z$) doubly magic nucleus and its properties have therefore been the subject of longstanding attention in nuclear structure physics. Experimental information on single-particle energies and residual interactions with respect to the ^{100}Sn core are of vital importance for testing nuclear models, e.g., relativistic mean field [1] and Hartree-Fock [2] predictions in this exotic domain. Neutrons and protons near the Fermi level here occupy identical orbitals, and neutron-proton correlations (e.g., the possibility of $T=0$ neutron-proton pairing) are therefore particularly important. An emergence of collective phenomena is also expected, enhanced by the interactions between neutrons and protons in similar orbits near the Fermi level. For the nucleus $^{107}_{52}$Te$_{55}$, the valence particles relative to the ^{100}Sn core are predicted to occupy the $2d_{5/2}$ and $1g_{7/2}$ subshells, and information on its excited states complements that obtained from, e.g., ^{103}Sn [3] and ^{105}Sn [4]. Recently, an astrophysical interest in studying this region of the nuclear chart has emerged due to its predicted role in stellar nucleosynthesis (see, e.g., [5] for a popular review). In particular, ^{107}Te has been predicted by Schatz *et al.* to constitute the end point of the astrophysical *rp*-process due to a closed Sn-Sb-Te cycle preventing heavier elements from forming [6].

In recent years, a rapid development of experimental sensitivity has spawned a large experimental effort on studies of the very neutron-deficient nuclei near the closed shell at $Z=50$. As the proton drip-line 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 the corresponding γ-ray spectra must therefore be extracted from a large γ-ray background arising from more abundantly populated channels using selective tagging techniques. The existence of an island of α radioactivity for the very neutron-deficient Te, I, Xe, and Cs isotopes is in this context very helpful. These characteristic α (or proton) decays can be used as a tag for identifying excited states in specific nuclei using the highly selective recoil decay tagging (RDT) technique [7,8]. This article presents the first γ-ray spectroscopic study of ^{107}Te.

II. EXPERIMENTAL DETAILS

The experiment was performed at the JYFL accelerator facility at the University of Jyväskylä, Finland. The ^{52}Cr ions, accelerated by the JYFL K130 cyclotron to an energy of 187 MeV, were used to bombard a target consisting of two stacked self-supporting foils of isotopically enriched (99.8%) ^{58}Ni. The targets were of thickness 580 μg/cm^2 and 640 μg/cm^2, respectively. The average beam intensity was 4.4 pnA during 5 days of irradiation time. The reaction channel of interest, ^{107}Te, was populated via the fusion-evaporation reaction ^{58}Ni(^{52}Cr,$3n$)^{107}Te*. Prompt γ-rays were detected at the target position by the JUROGAM γ-ray spectrometer consisting of 43 EUROGAM [9] type escape-suppressed high-purity germanium detectors. The germanium detectors were distributed over six angles relative to the beam direction with five detectors at 158°, ten at 134°, ten at 108°, five at 94°, five at 86°, and eight 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 using the gas-filled recoil separator RITU [10,11] and implanted into the two double-sided silicon strip detectors (DSSSDs) of the GREAT [12] focal plane

*Email address: hadinia@nuclear.kth.se

†Present address: Florida State University, Tallahassee, FL 32306.

‡Present address: Australian National University, Canberra ACT 0200, Australia.

spectrometer. The GREAT spectrometer is a composite detector system containing, in addition to the DSSSDs, a multiwire proportional avalanche counter (MWPAC), an array of 28 Si PIN photodiode detectors, and a segmented planar Ge detector. During this experiment, a Euroball clover detector was located at the focal plane and used in conjunction with GREAT. Each DSSSD has a total active area of 60×40 mm^2 and a strip pitch of 1 mm in both directions yielding in total 4800 independent pixels.

The signals from all detectors were recorded independently and provided with an absolute "time stamp" with an accuracy of 10 ns using the total data readout (TDR) [13] acquisition system. Spatial and temporal correlations of recoil implants and their subsequent α-decays were performed offline using the GRAIN [14] and TSCAN [15] software packages.

The RDT technique provides high confidence correlation in cases where the decay half-life and the recoil implantation rate are sufficiently low to prevent multiple hits in the pixel within a given correlation time. The 3.1 ms half-life [16] of ^{107}Te is short enough to allow clean correlations, even at high implant rates, and long enough to survive the 0.5 μs flight time through the separator. In the present experiment, the near-symmetric reaction proved challenging for the RITU separator and an overlap of the spatial distribution of the recoiling fusion products with that of the beam particles was difficult to eliminate. In order to minimize the number of beam ions deposited in the DSSSDs, a carbon charge reset foil (40 μg/cm^2) was placed immediately downstream of the target and the recoil distribution was centered close to the right-hand edge of the DSSSDs. Recoil discrimination was also possible at the focal plane using energy loss and time-of-flight measurements employing the GREAT MWPAC and implantation detector.

III. RESULTS

The ground state of ^{107}Te α decays with 70(30)% branching ratio [17] and has a 3.1 ms half-life [16]. The ^{107}Te ground state to ^{103}Sn ground state α-decay Q-value is 4.012 MeV [18], corresponding to an α-particle kinetic energy of 3.862 MeV. An additional weak (0.5%) α-decay branch to the first excited state in ^{103}Sn at 168 keV was observed recently by Seweryniak *et al.* [19]. The recoil-correlated α energy spectrum from the present experiment is shown in Fig. 1. The time difference between a recoil implant and its α decay is limited to 10 ms, corresponding to three half-lives of ^{107}Te. The nuclei in this mass region predominantly decay by β-emission and the only α-decaying nuclides produced with any significant cross sections in the present experiment are ^{107,108}Te, the isotope ^{108}Te having a much longer half-life of 2.1 s [17]. With a maximum correlation time of 10 ms, only one strong α peak, with an energy consistent with the decay of ^{107}Te, appears in the spectrum. In addition, one may discern a small peak at the energy of the weak decay branch to the first excited state in ^{103}Sn. With longer correlation times (up to seconds), the α peak corresponding to the decay of ^{108}Te was more prominent. A recoil-decay tagged γ-ray energy spectrum for ^{107}Te is shown in

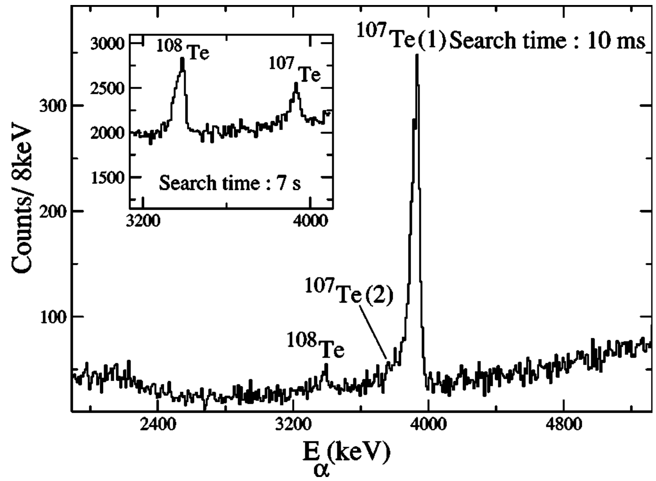

FIG. 1. Energy spectrum for α-decays occurring within 10 ms of a recoil implantation in the same pixel of the DSSSD. The α line attributed to the ground-state decay of ^{107}Te (^{107}Te(1)) dominates with a weaker decay branch (^{107}Te(2)) assigned to the same nucleus and an α line corresponding to the longer-lived decay of ^{108}Te. The inset shows a spectrum sorted with a correlation time limit of 7 s. The large background of this spectrum is due to the long correlation time (note the offset in the ordinate axis).

Fig. 2. Also here the time difference between a recoil implant and its α decay was limited to 10 ms and in addition a gate on the 3.862 MeV α energy was set to select the ^{107}Te channel. In Table I, we have listed the energies and relative intensities of the γ-rays associated with ^{107}Te.

The only γ-ray transition for which internal conversion might be expected to contribute significantly to the total transition probability is the 90 keV transition. Assuming it has M1 character (see below), the internal conversion coefficient would be around 0.98, which indicates that about 50% of the intensity is converted. Due to the lack of sufficient statistics

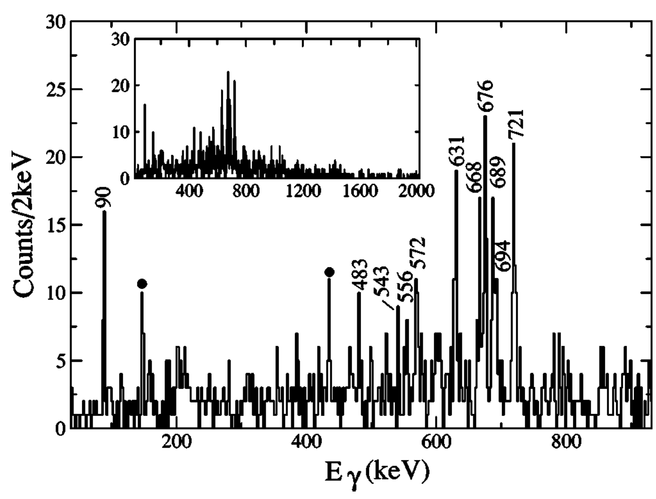

FIG. 2. Recoil decay tagged γ-ray spectrum from the decay of excited states in ^{107}Te. The spectrum has been produced using a search time limit of 10 ms between a recoil implant and a subsequent α decay in the 3.862 MeV energy gate. Contamination lines arising from the strongest reaction channel, ^{58}Ni(^{52}Cr, 3p)^{107}In [21], are indicated by filled circles.

TABLE I. Gamma rays assigned to ^{107}Te. Gamma-ray intensities (statistical uncertainties are given within parentheses) are adjusted for detector efficiencies and normalized to the intensity of the strongest transition in the spectrum (90 keV).

Energy (keV)	Relative intensity (%)
90.3(4)	100(23)
482.7(7)	19(14)
542.6(8)	19(14)
556.2(8)	19(14)
571.8(5)	38(19)
631.3(5)	71(23)
668.1(6)	52(19)
676.4(4)	90(23)
688.6(7)	62(23)
693.9(9)	38(19)
721.0(4)	90(23)

for a γ-γ-coincidence analysis, it was not possible to construct a firm level scheme for ^{107}Te. However, considering the energy and intensity relationships between the strongest observed γ-rays, we tentatively propose that the 721 keV line deexcites a $(9/2^+)$ state to the $(5/2^+)$ ground state, whereas the 631 keV line deexcites the same state to a first excited $(7/2^+)$ state at 90 keV. The 90 keV transition, which is the most intense of the observed γ-rays, would then connect this $(7/2^+)$ state with the $(5/2^+)$ ground state. This scenario is supported by the observation of Schardt *et al.* of two α-decay lines at 3480(30) keV and 3580(30) keV associated with the decay of ^{111}Xe [20]. Schardt *et al.* reported that these α decays were time correlated with the characteristic ^{107}Te α decay, although it was not clear whether these decays proceeded from two isomeric states in ^{111}Xe to ^{107}Te or from one state in ^{111}Xe to two final states in ^{107}Te. In light of the present work, it seems reasonable to interpret these two α-decay lines as fine structure in the decay of the ^{111}Xe ground state, the lower-energy branch populating the first excited 90 keV state in ^{107}Te tentatively inferred from the present data. The difference in the α-decay energies measured by Schardt *et al.* then corresponds to an excitation energy of 100 ± 60 keV, which is in agreement with the 90 keV energy proposed here for the first excited state in ^{107}Te.

IV. DISCUSSION

The ground states of the previously studied lightest odd-A Te isotopes, ^{109}Te and ^{111}Te, have been tentatively assigned to have spin-parity $5/2^+$ [22,23]. These states were interpreted as being built on a $d_{5/2}$ configuration whereas the first excited states are tentatively assigned to be $I^\pi = 7/2^+$, and are predicted to be predominantly of $g_{7/2}$ parentage (see [22,23] and refs. therein). These spin assignments are based on systematics and IBFM calculations [24] as well as on the experimentally deduced multipolarities of γ-rays connecting

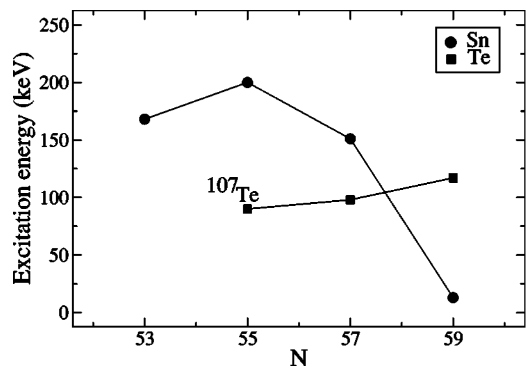

FIG. 3. Energy systematics for the first excited $7/2^+$ states in the very neutron deficient Sn (circles) and Te (triangles) isotopes. The data are from the present work and Refs. [3,4,22,24,25,29].

these states with the $\nu h_{11/2}$ isomeric state in ^{111}Te [25]. The energy systematics of the first excited states in the lightest odd-neutron Sn and Te isotopes are shown in Fig. 3. The energy of the first excited $7/2^+$ state in the light odd-N Te isotopes decreases from an excitation energy of 117 keV in ^{111}Te [25] to 98 keV in ^{109}Te [24,26,27]. This trend continues with our placement of the first excited state in ^{107}Te at 90 keV. It is interesting to note that the opposite trend is observed for the odd-N light Sn isotopes [28]. For the Sn isotopes, the tendency of increasing $7/2^+$ excitation energy as a function of decreasing neutron number is, however, broken for ^{103}Sn with the observation of the first excited $(7/2^+)$ state at 168 keV [3]. This behavior can be explained within the framework of standard shell model calculations. Considering the quite different energy systematics of the $g_{7/2}$ states in the isotopic chains of the light Te and Sn nuclei, the effect points to a strong influence from neutron-proton (np) residual interactions. The excitation energy of the $g_{7/2}$ state as a function of neutron number may be expected to be quite sensitive to not only the overall np interaction strength but also to the detailed properties of the np interaction. This issue deserves further attention, both from a theoretical and from an experimental perspective. From the experimental point of view, more information on the very neutron-deficient Sn and Te isotopes is clearly needed.

As mentioned in the Introduction, Schatz *et al.* have suggested that the isotope ^{107}Te forms the end point of the astrophysical *rp*-process [6]. Their results are based on extensive reaction network calculations [30] for various hydrogen burning scenarios on the surface of accreting neutron stars. The available experimental data on excited states in the nuclei of interest for these calculations are quite limited and nuclear level densities were modeled schematically using a Fermi gas approach. The experimental identification of low-lying excited states in ^{107}Te and neighboring nuclei should provide valuable input for further studies of the *rp*-process path. In particular, our proposed placement of the first excited state in ^{107}Te at a mere 90 keV above the ground state should be relevant to further studies of the ^{107}Te$(\gamma,\alpha)^{103}$Sn reaction rate.

V. SUMMARY

Gamma-ray transitions in the very neutron-deficient nuclide ^{107}Te have been identified for the first time. A first excited state at 90 keV is proposed and assigned to be of mainly $g_{7/2}$ parentage. This low excitation energy of the first excited state may have implications for the reaction rates in the closed Sn-Sb-Te cycle, recently predicted to form the end point of the astrophysical *rp*-process. It is noted that the excitation energy of the tentative $7/2^+$ states in the isotopic chains of the very neutron-deficient Sn and Te nuclei exhibit opposite trends as a function of neutron number. This points to the importance of np correlations in the structures of these $N \approx Z$ nuclei.

ACKNOWLEDGMENTS

The authors would like to thank Geirr Sletten and Jette Sørensen at NBI, Denmark for preparing the targets. This work was supported by the Swedish Research Council, the Academy of Finland under the Finnish Center of Excellence Programme 2000–2005 (Project No. 44875, Nuclear and Condensed Matter Physics Programme at JYFL), the UK Engineering and Physical Sciences Research Council, and the European Union Fifth Framework Programme "Improving Human Potential–Access to Research Infrastructure" (Contract No. HPRI-CT-1999-00044).

[1] K. Rutz *et al.*, Nucl. Phys. **A634**, 67 (1998).
[2] B. A. Brown, Phys. Rev. C **58**, 220 (1998).
[3] C. Fahlander *et al.*, Phys. Rev. C **63**, 021307 (2001).
[4] A. Gadea *et al.*, Phys. Rev. C **55**, R1 (1997).
[5] R. Irion, Science **297**, 2199 (2002).
[6] H. Schatz *et al.*, Phys. Rev. Lett. **86**, 3471 (2001).
[7] E. S. Paul *et al.*, Phys. Rev. C **51**, 78 (1995).
[8] R. S. Simon *et al.*, Z. Phys. A **325**, 197 (1986).
[9] C. W. Beausang *et al.*, Nucl. Instrum. Methods Phys. Res. A **313**, 37 (1992).
[10] M. Leino *et al.*, Nucl. Instrum. Methods Phys. Res. B **99**, 653 (1995).
[11] M. Leino, Nucl. Instrum. Methods Phys. Res. B **126**, 320 (1997).
[12] R. D. Page *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 634 (2003).
[13] I. H. Lazarus *et al.*, IEEE Trans. Nucl. Sci. **48**, 567 (2001).
[14] P. Rahkila (unpublished).
[15] H. Jin, http://www-highspin.phys.utk.edu/hjin
[16] R. D. Page *et al.*, Phys. Rev. C **49**, 3312 (1994).
[17] D. Schardt *et al.*, Nucl. Phys. **A326**, 65 (1979).
[18] F. Heine *et al.*, Z. Phys. A **340**, 225 (1991).
[19] D. Seweryniak *et al.*, Phys. Rev. C **66**, 051307 (2002).
[20] D. Schardt *et al.*, Nucl. Phys. **A368**, 153 (1981).
[21] S. K. Tandel *et al.*, Phys. Rev. C **58**, 3738 (1998).
[22] J. Blachot, Nucl. Data Sheets **86**, 505 (1999).
[23] J. Blachot, Nucl. Data Sheets **100**, 179 (2003).
[24] Zs. Dombrádi *et al.*, Phys. Rev. C **51**, 2394 (1995).
[25] K. Starosta *et al.*, Phys. Rev. C **61**, 034308 (2000).
[26] G. de. Angelis *et al.*, Phys. Lett. B **C437**, 236 (1998).
[27] A. J. Boston *et al.*, Phys. Rev. C **61**, 064305 (2000).
[28] J. Blomqvist, N. Sandulescu, and R. J. Liotta, Nucl. Phys. **A582**, 257 (1995).
[29] J. Blachot, Nucl. Data Sheets **89**, 213 (2000).
[30] Th. Rauscher and F.-K. Thielemann, At. Data Nucl. Data Tables **75**, 1 (2000).