PHYSICAL REVIEW C VOLUME 52, NUMBER 6 DECEMBER 1995

Intruder bands in ^{114}Te: Smooth band termination

I. Thorslund,[1] D. B. Fossan,[1] D. R. LaFosse,[1] H. Schnare,[1] K. Hauschild,[2] I. M. Hibbert,[2] S. M. Mullins,[3] E. S. Paul,[4] I. Ragnarsson,[5] J. M. Sears,[1] P. Vaska,[1] and R. Wadsworth[2]

[1]*Department of Physics, State University of New York at Stony Brook, Stony Brook, New York 11794*

[2]*Department of Physics, University of York, Heslington, York YO1 5DD, United Kingdom*

[3]*Department of Physics and Astronomy, McMaster University, Hamilton, Ontario, Canada L8S 4M1*

[4]*Oliver Lodge Laboratory, University of Liverpool, P.O. Box 147, Liverpool L69 3BX, United Kingdom*

[5]*Department of Mathematical Physics, University of Lund, P.O. Box 118, S-22100 Lund, Sweden*

(Received 11 September 1995)

The nucleus ^{114}Te has been studied in heavy-ion γ-ray spectroscopy experiments performed with the early implementation of the GAMMASPHERE multidetector array. Three rotational intruder bands have been observed up to high spins. The yrast band, involving the $4p2h$ $(h_{11/2})^2(g_{7/2})^2(g_{9/2})^{-2}$ proton configuration, reaches $I=48\hbar$ at an excitation energy of 30.3 MeV, the highest observed spin connected by γ rays in this mass region. The band properties are interpreted in the framework of smooth band termination.

PACS number(s): 21.10.Re, 23.20.Lv, 27.60.+j

Several experiments have recently revealed exotic collective structures in nuclei near the $Z=50$ closed proton shell, with rotational intruder bands being observed up to unusually high frequencies in $Z=50$–53 nuclei [1–9]. These collective structures involve proton particle-hole excitations across the $Z=50$ shell gap via the $\pi g_{7/2}-\pi g_{9/2}$ level crossing at prolate deformations around $\beta_2\sim0.2$, which appears to stabilize deformed core configurations. At the higher frequencies, as additional particle alignment takes place with increasing spin, several of these intruder bands display the unique characteristic of gradually decreasing dynamic moments of inertia to unusually low values. This structure feature, so-called smooth band termination, has been interpreted by Ragnarsson *et al.* [10,11], who showed that, as the available valence nucleons outside of the $Z=N=50$ double shell closure align, the nuclear shape gradually traces a path through the triaxial γ plane from a collective prolate shape ($\gamma=0°$) to a noncollective oblate shape ($\gamma=+60°$) over many transitions. After the available valence particles for a specific configuration have aligned, the band sequence terminates at an angular momentum that exhausts the sum of the aligned single-particle spins. The purpose of the present experiment is to investigate these terminating intruder bands in the $Z=52$ ^{114}Te nucleus.

In order to search for this novel smooth band termination feature, the improved resolving power achieved for higher folds with the early implementation of the GAMMASPHERE multidetector array [12] at the Lawrence Berkeley Laboratory 88-inch cyclotron has been exploited. Both thin- and backed-target experiments were performed. The array consisted of three forward and three backward rings at angles θ = 17.3°, 31.7°, 37.4°, 142.6°, 148.3°, and 162.7° measured relative to the beam direction with five detector positions in each ring, and one ring with up to six detector positions at 90.0°. The target-detector distance was $\sim$25 cm. All detectors in the array were high purity Compton suppressed Ge detectors with an $\sim$80% relative efficiency. Events where three or more suppressed Ge detectors fired in prompt coincidence were stored on magnetic tape.

In the first set of experiments, the reaction ^{54}Fe(^{63}Cu,$3p$)^{114}Te was used at a beam energy of 245 MeV, with a stacked target of two self-supporting 0.50 mg/cm^2 thick ^{54}Fe foils, and a backed target consisting of 0.50 mg/cm^2 ^{54}Fe on 15 mg/cm^2 Au. A total of 32 Ge detectors were used with 29 detectors in the forward-backward direction and 3 detectors at 90°. A total of $\sim1\times10^9$ unfolded triple events were collected in the thin-target experiment, while the backed-target experiment yielded $\sim1\times10^8$ such events. Approximately 33% of the total number of events came from the ^{114}Te channel and 25% from the ^{113}Te ($3pn$) channel.

A second set of experiments populated ^{114}Te via the ^{64}Ni(^{56}Fe,$\alpha2n$)^{114}Te reaction at a beam energy of 236 MeV. These experiments were directed at the study of ^{115,116}Te via the $2p3n$ and $2p2n$ channels, respectively, although the $\alpha2n$ channel to ^{114}Te was also populated with considerable strength. A stacked target of two self-supporting 0.50 mg/cm^2 thick ^{64}Ni foils and a backed target consisting of 1.00 mg/cm^2 ^{64}Ni on 60 mg/cm^2 Au were used in these experiments. Three more Ge detectors had been added to the 90° ring for these experiments, resulting in a total of 35 Ge detectors. A total of $\sim2\times10^9$ unfolded triple events were collected in the thin-target experiment, while the backed-target experiment yielded $\sim2\times10^8$ such events. Approximately 14% of the total number of events came from the ^{114}Te channel.

Data from a thin-target experiment performed at the Centre de Researches Nucléaires, Strasbourg, using the EUROGAM II spectrometer [12] (54 high purity Ge detectors) and the reaction ^{90}Zr(^{31}P,$\alpha p2n$)^{114}Te at 150 MeV, have been used to verify the level scheme of ^{114}Te presented in this paper. This experiment was aimed at the study of ^{117}I ($2p2n$ channel) [13], but a substantial part of the approximately 8.5×10^8 five- or higher-fold suppressed coincidence events came from the ^{114}Te channel. The amount of angular momentum brought into the reaction was not sufficient to populate the highest spin states in ^{114}Te observed in the GAMMASPHERE experiments; however, the high statistics in combination with the clean data provided an opportunity

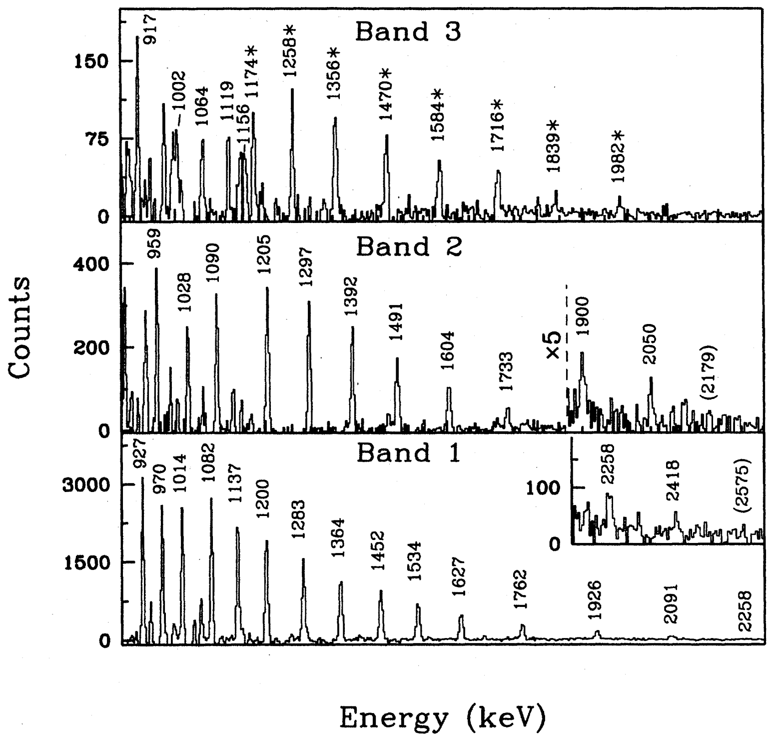

FIG. 1. Summed double-gated coincidence spectra from the GAMMASPHERE data displaying the three intruder bands in ^{114}Te. Energy labels are given in keV. All intraband transitions have been used for gating. For bands 1 and 2, all labeled peaks correspond to intraband transitions. For band 3, peaks corresponding to intraband transitions are labeled with an asterisk (*). The other labeled five peaks are linked to the feed-out of this band and have not been used for gating. The intense peak at 917 keV is partially due to contaminations from transitions in ^{113}Sb and ^{113}Te. The peaks at 1002 keV (^{113}Te), 1119 keV (^{113}Te, ^{111}Sb), and 1064 keV (^{112}Te) are also partially contaminated by γ rays from the nuclei in brackets.

to investigate weak parts of the level scheme extracted from the GAMMASPHERE data, and in particular to confirm the connecting transitions for the three bands to the lower part of the level scheme.

The recorded events for the various experiments were unfolded off-line into doubles and triples and sorted into E_{γ_1}-E_{γ_2} coincidence matrices and E_{γ_1}-E_{γ_2}-E_{γ_3} coincidence cubes, respectively. In addition, triple and quadruple coincident events were sorted into single- and double-gated matrices, respectively, in order to enhance the relative fraction of ^{114}Te events in the sorted data. Analyses of the data in the matrices and in the cubes were performed by using the ESCL8R and LEVIT8R software [14]. Backed-target data from the second set of experiments, with 6 Ge detectors at 90°, were also used for DCO ratio analysis [15]. Energies of γ rays detected in these 6 detectors at 90°, were sorted into a matrix versus energies of γ rays detected in any of the 29 detectors in the forward-backward rings. Gates were put on strong stretched $E2$ transitions on both axes of the matrix, and the intensity ratio between these two gates for a specific transition gave information on its multipolarity.

Three rotational bands have been identified up to high spins in the present set of experiments, and connecting transitions to the lower part of the ^{114}Te level scheme have been found for all three bands. It was possible to resolve the γ rays deexciting the higher spin levels of these three bands only by summing up double-gated spectra created from all combinations of intraband transitions in each band using data from the thin-target cubes. The summed coincidence spectra for the three bands are shown in Fig. 1. The gradual increase in the γ-ray energy spacings in going up the band to higher transition energies is clearly observed for band 1, and is also present for the two other bands.

Figure 2 shows the extended level scheme of ^{114}Te resulting from this work. The placement of the γ rays is based on intensity and coincidence relations, and the assigned level spins are extracted from the DCO ratios in combination with results from systematic decay properties. The three rotational intruder bands showing smooth band terminating properties have been observed up to high spins and frequencies. Band 1 was observed up to $I^\pi=48^+$ with 18 stretched $E2$ transitions plus one tentative transition, band 2 reached $I^\pi=(40^-)$ plus one tentative transition, and band 3 was observed up to $I=(40)$. A spin of $48\hbar$ is the highest nuclear spin observed in this mass region. The irregular lower portion of the level scheme has previously been studied in Refs. [16–18].

The focus of the present experimental study of ^{114}Te is directed at the intruder bands and their terminating properties. The low-spin structure of neutron deficient Te isotopes, which involves two valence protons outside the $Z=50$ closed shell, has been addressed elsewhere in the literature [6,16,18,19]; data from the present experiment do not disagree with this interpretation, and thus this low-spin structure will not be discussed further.

The nuclear structure of the collective bands observed in the $^{114}_{52}$Te nucleus can be classified in terms of the number of proton particle-hole excitations across the $Z=50$ closed shell, which relates to the amount of deformation. The intruder bands, which were observed in the Sn [1,2] and Sb [4,5] isotopes to be yrast over a large spin range, involved $2p$-$2h$ proton excitations. The deformed $2p2h$ $\pi(g_{7/2})^2(g_{9/2})^{-2}$ configuration, when coupled with the valence neutrons outside of the $N=50$ closed shell, was the basis of the terminating bands in the even Sn isotopes. Related terminating bands in the Sb isotopes involved the $\pi h_{11/2}\otimes 2p2h$ configuration, namely, a $3p2h$ proton struc-

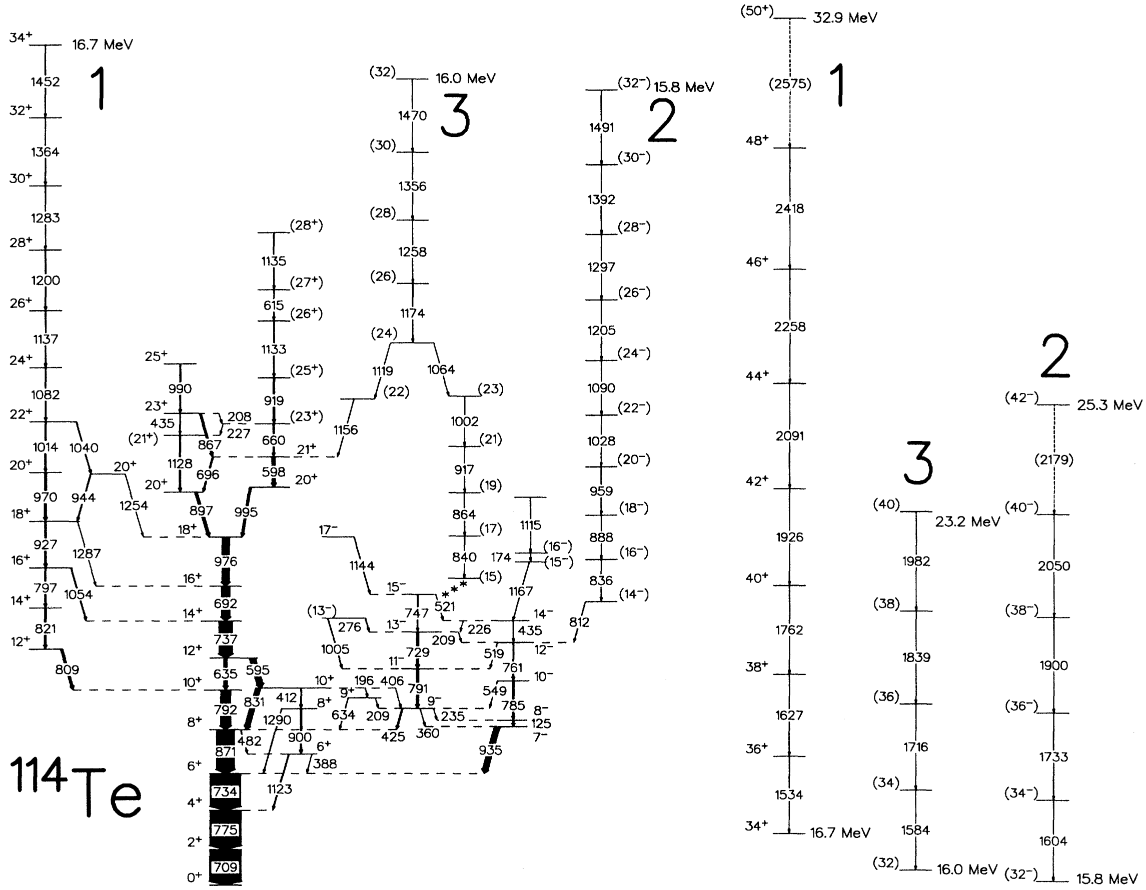

FIG. 2. Level scheme of ^{114}Te deduced from this work. Transition energies are given in keV and their relative intensities are indicated by the widths of the arrows. The left part displays the lower portion of the level scheme including the connecting transitions for the three intruder bands. The right part shows the extension of these bands up to the highest observed spins. The three asterisks in the left part indicates that band 3 also feeds into the negative-parity section of the level scheme.

ture. It is thus anticipated that the $(h_{11/2})^2 \otimes 2p2h$ proton configuration $(4p2h)$ would produce terminating bands in ^{114}Te, with the 12 valence neutrons distributed over the $\nu(g_{7/2}, d_{5/2})$ and $\nu h_{11/2}$ orbitals.

Theoretical calculations have been performed to investigate and identify the configurations involved in the ^{114}Te intruder bands as well as to understand the band termination properties. A Nilsson-Strutinski cranking model [20], involving modified oscillator basis wave functions along with specific techniques (see Refs. [10,11]) for identifying the $N=4$ $\pi g_{9/2}$ holes, has been employed. The calculations minimize the energy with respect to the deformation parameters $(\epsilon_2, \epsilon_4, \gamma)$, which are treated self-consistently. Since pairing correlations have been neglected, the theory does not address the alignment features at low frequencies. An important property of nuclei in this region is that intruder bands identified with specific configurations can be theoretically followed over a large spin range up to the maximum spin allowed by the configuration at band termination. Theoretical calculations for the band member energies as a function of spin for favored deformed configurations based on $1p$-$1h$ and $2p$-$2h$ proton excitations across the $Z=50$ gap are displayed in Fig. 3 together with the observed bands in ^{114}Te.

The favored theoretical yrast band at high spin involves the expected $4p2h$ proton configuration $\pi(h_{11/2})^2(g_{7/2})^2(g_{9/2})^{-2}$ coupled to the $\nu(g_{7/2}, d_{5/2})^8(h_{11/2})^4$ neutron configuration, as shown in Fig. 3. The maximum spin of this configuration, assuming alignment of all involved particles/holes consistent with the Pauli principle, is $I^\pi = 52^+$. As can be seen in the figure, the correspondence between the shape of the experimental curve for band 1 and this theoretical curve is reasonably good at high spin with the observed band reaching to within $4\hbar$ of the predicted termination spin, not including the tentative transition. It is worth noting that the terminating transition for other intruder bands in this region has been observed to be significantly reduced in intensity [4].

A characteristic feature of smooth band termination is a decreasing dynamic moment of inertia $\mathcal{J}^{(2)}$ for increasing spin. This decrease appears to be caused by the high energy cost to align the high-$\Omega g_{9/2}$ holes and by the midshell position of the $g_{7/2} d_{5/2}$ neutrons [11]. For the ^{109}Sb terminating bands [4], the $\mathcal{J}^{(2)}$ drops to a third of the rigid-body value near termination. The experimental $\mathcal{J}^{(2)}$ for band 1 is shown in Fig. 4 together with the theoretical result for this configuration. As can be seen from the figure, the agreement between theory and experiment is good, consistent with the smooth band termination interpretation. The rigid-body value for a deformation of $\beta_2 = 0.2$ has been marked in the figure,

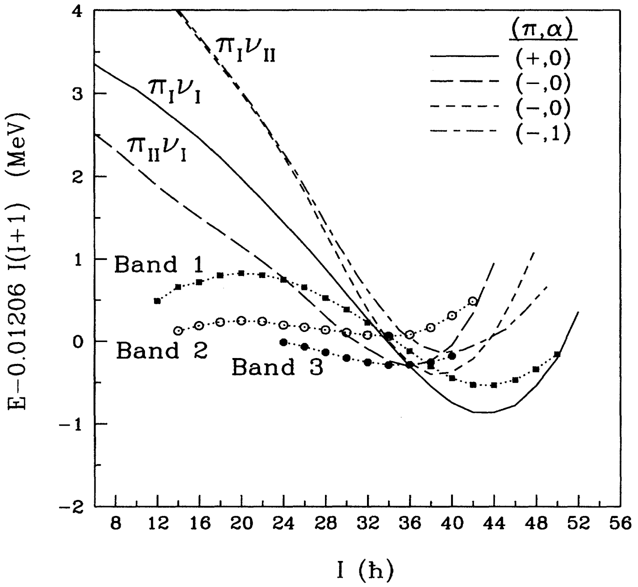

FIG. 3. Comparison between theory and experiment for the three intruder bands in ^{114}Te. The same smooth liquid-drop reference $(\hbar^2/2\mathscr{J}_{\rm rig})I(I+1)$ has been subtracted in each case [11]. The labeling of the theoretical curves corresponds to the following configurations: $\pi_I=\pi(h_{11/2})^2(g_{7/2})^2(g_{9/2})^{-2}$, $\pi_{II}=\pi(h_{11/2})^1(g_{7/2})^2(g_{9/2})^{-1}$, $\nu_I=\nu(g_{7/2},d_{5/2})^8(h_{11/2})^4$, and $\nu_{II}=\nu(g_{7/2}d_{5/2})^9(h_{11/2})^3$. Only the $\alpha=0$ signature partner is shown for the $\pi_{II}\nu_I$ configuration due to the small energy difference between the two signatures. The two tentative transitions in bands 1 and 2 are included in the figure.

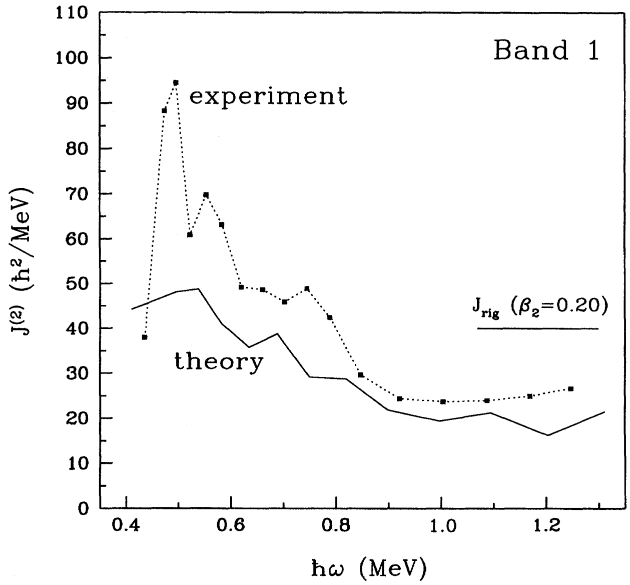

FIG. 4. Theoretical and experimental dynamic moments of inertia $\mathscr{J}^{(2)}$ for band 1 in ^{114}Te, plotted as a function of rotational frequency. The discontinuities in the theoretical $\mathscr{J}^{(2)}$ are numerical in nature and have no physical significance.

showing that the decrease for ^{114}Te is not as large as for ^{109}Sb.

The theoretical calculations predict other intruder bands related to near-yrast negative-parity configurations, which are also shown in Fig. 3. One of these bands involves the same $4p2h$ proton configuration but with the neutrons rearranged in the $\nu(g_{7/2}d_{5/2})^9(h_{11/2})^3$ configuration giving maximum spins of 48 and 49 for the two signatures. The other involves a $1p$-$1h$ excitation across the $Z=50$ shell gap giving a $3p1h$ proton configuration $\pi h_{11/2}(g_{7/2})^2(g_{9/2})^{-1}$ coupled to the previous $\nu(g_{7/2},d_{5/2})^8(h_{11/2})^4$ neutron configuration, which has maximum spins of 43 and 44 for the two signatures.

Experimentally, bands 2 and 3, which were observed up to spins of (40^-) and (40), respectively, also show the characteristic decrease in $\mathscr{J}^{(2)}$ with increasing spin for terminating bands. Although the parities of these two bands are not defined, the negative-parity configurations shown in Fig. 3 are those which best describe the experimental data. With only fair agreement, however, definite conclusions cannot be drawn about the configurations of these two bands.

In summary, three rotational intruder bands have been observed up to high spins in ^{114}Te. The three bands show characteristic features associated with the so-called smooth band termination, with dynamic moments of inertia gradually decreasing with spin. The configuration of the positive-parity band (band 1) has been established, and is observed up to within $4\hbar$ of the predicted terminating spin.

This work was supported by the NSF (U.S.A.) and the EPSRC (U.K.). K.H. acknowledges support from the University of York.

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