PHYSICAL REVIEW C **69**, 051303(R) (2004)

Test of calculations with single-particle density dependent pairing in ^{132}Te

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(Received 29 January 2004; published 25 May 2004)

New data, obtained from β^- decay of ^{132}Sb radioactive beam at HRIBF, has led to a significantly revised γ-decay scheme for ^{132}Te. The changes to the level scheme include a number of new, likely 2^+, states below 2.5 MeV, which allows a test of very recent quasiparticle random phase approximation calculations with a density-dependent pairing force, and the removal of a 3^- state at 2281 keV, which resolves an incompatibility with the shell model and leads to a simple interpretation of the low-lying negative parity states.

DOI: 10.1103/PhysRevC.69.051303 PACS number(s): 21.10.−k, 21.60.Cs, 27.60.+j

One of the main focus areas of current research with exotic nuclei concerns mass regions near doubly magic nuclei such as ^{132}Sn. Experiments to date in this region, especially Coulomb excitation studies, have revealed fascinating aspects of nuclear structure on the neutron-rich side of stability [1].

These studies have mapped level energies and $B(E2)$ values across the $N=82$ shell closure disclosing anomalies in the structure of Te isotopes with $N>82$ [2,3]. These experimental results have motivated new microscopic calculations in which the dependence of pairing on single-particle level density is explicitly taken into account [4]. Such calculations are important in their own right, but also as forerunners of an approach to exotic nuclei that is likely to have widespread use and enhanced significance as one advances towards more and more neutron-rich nuclei. To date, however, these calculations have not been tested for observables other than those by which they were originally motivated.

It is the purpose of this Rapid Communication to present new data on ^{132}Te, which has resulted in a very strongly revised level scheme compared to the published literature, and which, in particular, agrees excellently with the QRPA calculations of Refs. [4,5], thus supporting its underlying assumptions. The nucleus ^{132}Te was populated in β^- decay and studied through γ-ray coincidence spectroscopy at the Holifield Radioactive Ion Beam Facility (HRIBF). A radioactive nuclear beam of $\sim 10^7$ particles/s of ^{132}Sb at 396 MeV was embedded in a thick 14.3 mg/cm^2 Al+1.0 mg/cm^2 C foil target. The ^{132}Sb nuclei decay via two β^- channels, with half-lives of 2.8 minutes and 4.2 minutes from the 4^+ ground state and 8^- excited state, respectively, to ^{132}Te. The subsequent γ rays were detected with the CLARION array [6] consisting of 11 clover Ge detectors with a total photopeak efficiency of 2.3% for a 1.33 MeV γ-ray (at 22 cm from the target). The experiment was run for 2 days and a total of 2.5×10^7 γ-γ events were collected.

The new γ-γ coincidence data have led to a significantly revised γ-decay scheme for ^{132}Te. The new work has confirmed 20 of the transitions in the previous scheme and given 19 other transitions new placements. There are also 195 new transitions that have been added. Due to the higher statistics, the lowest resolvable intensity was reduced, by more than an order of magnitude, to $\sim$0.02% per decay from the previous $\sim$0.5%. A subsequent full length publication will present the complete experimental details and results. In this Rapid Communication we focus on the low-lying levels of ^{132}Te. Figure 1 shows the level scheme of ^{132}Te up to 2400 keV as deduced in this work. Newly placed γ rays and those with revised placements are specifically labelled. It is seen that, in fact, they comprise about half of the transitions connecting these levels.

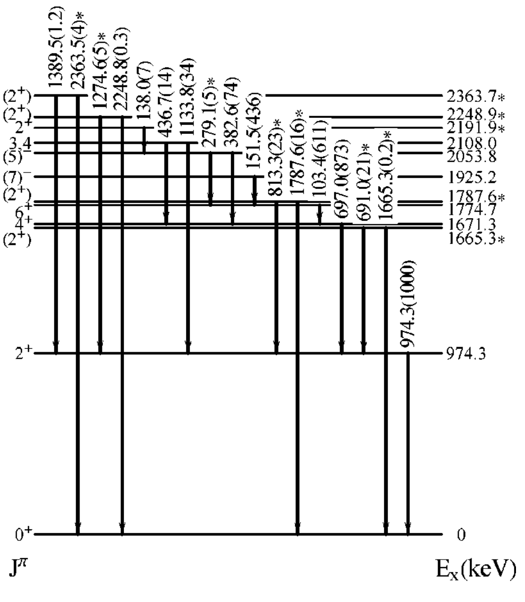

FIG. 1. Low-lying levels in ^{132}Te populated in ^{132}Sb β^- decay and their depopulating γ-ray transitions with energies in keV (uncertainties ±0.2 keV) and, in parentheses, their relative intensities. New levels and γ rays identified in the present work are marked with an asterisk.

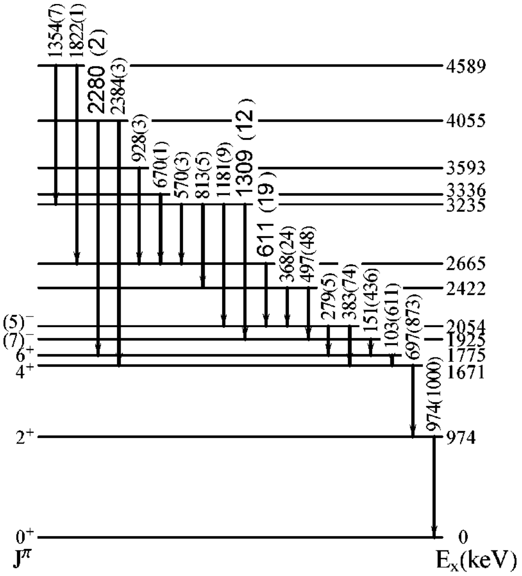

FIG. 2. Partial decay scheme of ^{132}Te showing the present placement of the three transitions (highlighted), 611 keV, 1309 keV, and 2281 keV, which previously were supposed to depopulate a 3^- level at 2281 keV. Included are only the levels and transitions relevant for the new placements. Each transition is labelled by its energy in keV and relative intensity.

A 3_1^- level was previously placed at 2281 keV [9]. The placement was based primarily on three transitions from this level to the 4_1^+, 2_1^+, and 0_1^+ states. The new coincidence data show that all three γ rays have the reported intensities but, in fact, must be placed elsewhere. Figure 2 is a partial decay scheme showing the present placement of the three transitions, 611 keV, 1309 keV, and 2281 keV. Two coincident spectra supporting these new placements are presented in Fig. 3. The new placements mean there are no transitions supporting a 3^- level at 2281 keV, and so it can be removed from the level scheme.

Five new levels were found below 2500 keV (marked with an asterisk in Fig. 1), two of them (at 1665 keV and 1788 keV) were listed in an unpublished β-decay work [7] but not in other experiments [9]. Based on their decay only to the 0^+ ground state and the 2^+ first excited state, tentative 2^+ assignments have been made to four of these new levels, namely those at 1665 keV, 1788 keV, 2249 keV, and 2364 keV. Under the assumption of $E1$, $M1$ or $E2$ radiation these levels could be $1^\pm$ or 2^+. However, below about 3 MeV, a $1^\pm$ level would be highly unlikely. For $^{132}_{52}\mathrm{Te}_{80}$, protons and neutrons are filling the single-particle levels of the 50–82 shell: in the beginning of the shell, $2d_{5/2}$ and $1g_{7/2}$, for protons, and at the end of the shell, $1d_{3/2}$ and $2s_{1/2}$ orbits, for neutrons. The negative parity orbit is $1h_{11/2}$ for both protons and neutrons. No two-particle configuration with $J=1^-$ can therefore be formed and a seniority 4, 1^- level would be quite high lying. A 2 quasiparticle 1^+ state can be formed with the configurations $|\pi\, 2d_{5/2}\, 1g_{7/2}\rangle$ or $|\nu\, 1d_{3/2}\, 2s_{1/2}\rangle$. However, for a short range residual interaction, the 1^+ level lies quite high at an unperturbed energy corresponding to the breaking of a pair plus the single-particle energy difference.

Therefore, based on these arguments we assign $J^\pi=(2^+)$ to the levels below 2500 keV that decay solely to the ground and first excited states. This gives five (2^+) states, at 974, 1665, 1788, 2249, and 2364 keV.

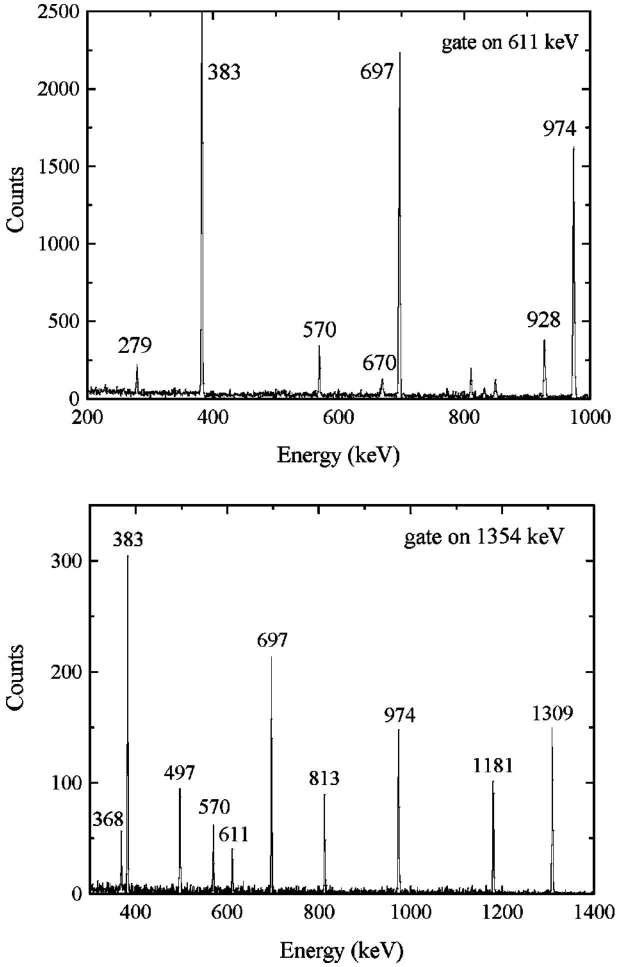

FIG. 3. Coincident spectra supporting the new placements of the 611 keV and 1309 keV transitions (see Fig. 2) which previously were supposed to depopulate a 3^- level at 2281 keV.

The (2^+) states identified in this work have significant consequences for our understanding of this region and for microscopic interpretation of data in new mass regions. Recently, an anomaly was found in $B(E2;0_1^+\rightarrow 2_1^+)$ values and 2_1^+ energies in the ^{132}Sn region [1]. Normally, these two quantities vary inversely to each other. In fact, this is reflected in the Grodzins rule [8] that, for a given region, $E(2_1^+)\times B(E2;0_1^+\rightarrow 2_1^+)\sim$constant. However, if one compares $^{132}\mathrm{Te}_{80}$ and $^{136}\mathrm{Te}_{84}$, both the 2_1^+ energy and the $B(E2)$ value are lower in ^{136}Te. In an effort to understand this anomaly, Terasaki *et al.* [4] noted that the density of neutron single-particle levels below and above $N=82$ were quite different, being denser below $N=82$. This would give a reduced neutron pairing gap above $N=82$ and, in turn, a lower 2_1^+ energy. Since the 2_1^+ state could then also be more neutron dominated, a lower $B(E2)$ value than for ^{132}Te would result.

In Ref. [4], QRPA calculations with the same Hamiltonian and interactions both below and above $N=82$ were carried out. These correctly reproduced both the $E(2_1^+)$ and the $B(E2;0_1^+\rightarrow 2_1^+)$ values in this region. However, the interpretation in Ref. [4] was developed *a posteriori* to account for

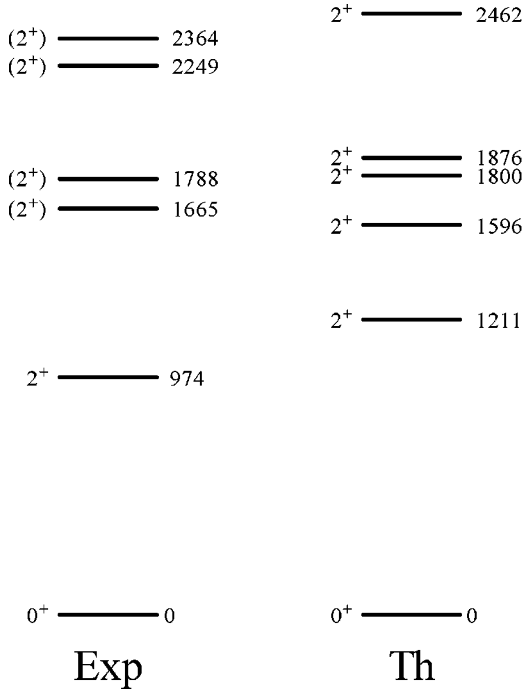

FIG. 4. Comparison of experimental and theoretical [5] 2^+ state energies in ^{132}Te.

the anomalous behavior already observed. It is therefore very valuable to have an independent test of these calculations.

The present set of 2^+ energies for ^{132}Te does precisely that. A comparison of these energies with those predicted in the calculations of Ref. [4] is shown in Fig. 4. Clearly, the agreement is quite good. The correct number of low-lying 2^+ levels is predicted and, except for one state, at approximately the observed energies.

It is important to stress that, except for the 2_1^+ level at 974 keV, none of these 2^+ levels were known to Terasaki *et al.* [4] prior to their calculations and therefore the present level scheme, extensively revised relative to earlier publications, provides a sensitive and yet robust test of an approach that takes account of the dependence of pairing on single-particle level densities.

Another interesting feature of the level scheme concerns the lowest negative parity states. Previous literature evaluations [9] give the set 7^- (1925 keV), 5^- (2053 keV), and 3^- (2281 keV). Negative parity levels available at low energies must involve the $1h_{11/2}$ orbit (both for neutrons and protons) and, for neutrons, either the $2d_{3/2}$ or $3s_{1/2}$ orbits, or, for protons, the $2d_{5/2}$ and $1g_{7/2}$ orbits, are relevant. For a short range attractive interaction (δ-force-like), the level sequences for these four possible configurations are given in Table I [10]. The previously existing level scheme, therefore, presented a significant puzzle. Only the proton excitations include a 3^- level. For the $|1h_{11/2}2d_{5/2}J\rangle$ configuration, it should be lower than the 7^- and 5^- levels, not higher. For the $|1h_{11/2}1g_{7/2}J\rangle$ configuration there should be a 9^- below the 7^- and 5^-. No simple configuration gives the previous assigned level sequence. However, with the removal of the 3^- level and no evidence for a low-lying 9^- level, these low-lying negative parity states can now be naturally explained as having a large amplitude for the neutron configuration $|\nu 1h_{11/2}2d_{3/2}J=4,5,6,7\rangle$ for which the sequence, in order of increasing energy, should be 7^-, 5^-, and nearly degenerate 6^- and 4^- levels. The 6^- level at 2422 keV is likely part of this multiplet. These assignments thus fit the new level scheme quite well.

TABLE I. Negative parity multiplets and expected level ordering.

Configuration	J values	Multiplet levels in expected order of increasing energy[a]
Protons		
$1h_{11/2}2d_{5/2}$	3–8	3, 5, 7, (4, 6, 8)
$1h_{11/2}1g_{7/2}$	2–9	9, 7, 5, 3, (2, 4, 6, 8)
Neutrons		
$1h_{11/2}3s_{1/2}$	5, 6	5, 6
$1h_{11/2}2d_{3/2}$	4–7	7, 5, (4, 6)

[a] Assuming a short range, attractive residual interaction. Levels expected to be nearly degenerate are grouped with parentheses.

Shell model calculations [11] indicate that the 4_1^+ and 6_1^+ states are dominated by seniority two components of the form $|\nu(j^2)J=0;\pi(g^2_{7/2})J=4^+,6^+\rangle$. Therefore, the 6^+ state is largely a proton excitation. Hence the $E1$ decay $7^-\rightarrow 6^+$ should be extremely hindered $[\nu 1h_{11/2}2d_{3/2}\rightarrow \pi(g^2_{7/2})]$. Experimentally, the $B(E1;7^-\rightarrow 6^+)$ is $\sim 10^{-9}$ W [9] which is indeed consistent with the neutron assignment for the 7^- level.

To recapitulate, in this study, a large number of changes were made to the existing ^{132}Te level scheme. Many new transitions were placed, and new levels proposed. A number of previous placements were found to be inconsistent with the high quality coincidence data presented here. Several previously proposed levels were shown not to exist. Some of these changes also appear in the work of Ref. [7].

Important alterations to the level scheme are a number of new, likely 2^+, states below 2500 keV. Of these, only the first excited state at 974 keV had been previously published. Our results allow a test of very recent quasiparticle random phase approximation calculations [4] with a density dependent pairing force that accounts for the anomalous violation of the Grodzins rule above $N=82$ in the Te isotopes. Another important result is the removal of a 3^- state at 2281 keV. This fact in turn removes an incompatibility of the low-lying negative parity states with possible shell model configurations and leads to a simple interpretation of their structure.

Work supported by U.S. DOE Grant Nos. DE-FG02-91ER-40609, DE-FG02-91ER-40608. Research at the Oak Ridge National Laboratory is supported by the U.S. Department of Energy under Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC. We are especially grateful to Witek Nazarewicz and to J. Terasaki for discussions of the calculations in Ref. [4] and to J. Terasaki for providing detailed predictions [5] from those calculations that are not included in Ref. [4]. We thank B. Walters for informing us of Ref. [7] and P. Regan and E. Henry for useful discussions.

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