Particle-hole excited states in ^{133}Te

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Excited states in neutron-rich ^{133}Te have been identified with the Gamma sphere array by measuring three- and higher-fold prompt coincidence events following spontaneous fission of ^{252}Cf. Four types of particle-hole bands built on the known 334.3 keV isomer in ^{133}Te are identified. The yrast and near yrast particle-hole states observed up to 6.2 MeV in ^{133}Te have characteristics quite similar to those in ^{134}Te. These states are interpreted as a result of coupling a neutron $\nu h_{11/2}$ hole to the ^{134}Te core. The group of states observed above 5.214 MeV is the result of a neutron particle-hole excitation of the double magic core nucleus ^{132}Sn, and is a candidate for a tilted rotor band. Shell-model calculations considering ^{132}Sn as a closed core have been performed and have provided guidance to the interpretation of the levels below 4.3 MeV. Very good agreement between theory and experiment is obtained for these states.

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Recently, the study of nuclei with one or two valence nucleons or holes near the double magic nucleus ^{132}Sn has been drawing much attention [1,2]. The properties of these nuclei are of special interest for a stringent test of the basic ingredients of shell-model calculations since they are direct sources of information about the *p*-*p* and *p*-*n* effective interactions in this region. The level scheme of ^{134}Te has been extended up to about 7.6 MeV [1]. All the observed levels arising from valence proton excitations are very well reproduced by shell-model calculations making use of a realistic effective interaction [3]. These calculations confirm the identification made in Ref. [1] where evidence is given that the yrast band with the spin sequence 0^+, 2^+, 4^+, and 6^+ results from the coupling of the two protons in $(g_{7/2})^2$ to the ^{132}Sn core, while one level at 2398 keV and three levels around 4014 keV are attributed to the one proton excitation from $g_{7/2}$ to $d_{5/2}$ and $h_{11/2}$, respectively. The group of levels from 4557 to 7565 keV in ^{134}Te are attributed to the $\pi(g_{7/2})^2\nu f_{7/2}(h_{11/2})^{-1}$ configuration. Regarding ^{135}I, which has an additional proton, ten new levels have been identified in Ref. [1] and their interpretation was based on comparison with the energy levels in ^{134}Te and on theoretical considerations. Calculations similar to those done in the case of ^{134}Te have also been carried out for ^{135}I [3] and the agreement with experiment is remarkably good. The nucleus ^{135}Te has two valence protons and one valence neutron. The first four levels observed in ^{135}Te [2] in the spontaneous fission of ^{248}Cm are assigned to the configuration $\pi(1g_{7/2})^2\nu 2f_{7/2}$ corresponding to the 0^+, 2^+, 4^+, and 6^+ $\pi(g_{7/2})^2$ states in ^{134}Te. The low-lying single-neutron states were observed in beta decay of ^{135}Sb [4]. But the interpretation of high-lying states (above 4 MeV) is more complicated because they originate from the excitation of one valence neutron across the $N=82$ shell gap.

The nucleus ^{133}Te is expected to have excited states originating from two protons in the $\pi g_{7/2}$ orbital above the $Z=50$ shell gap and one neutron hole in the $\nu h_{11/2}$ orbital below the $N=82$ shell gap. The level structure of ^{133}Te is very interesting to extend our understanding of the proton particle-neutron hole states in this region. From the β^- decay of ^{133}Sb [5] an $(11/2^-)$ isomer at 334.3 keV and 14 other states between the $(7/2^+,5/2^-)$ and $(5/2^+)$ levels at 1096 and 2755 keV, respectively, were known in ^{133}Te. Below the $(11/2^-)$ isomer the $d_{3/2}$ and $s_{1/2}$ neutron-hole states were observed [5]. Here we present new data on high spin levels in ^{133}Te from spontaneous fission work of ^{252}Cf including the identification of neutron particle-hole states which have never been observed. Also, we present results of a shell-model calculation within the $50-82$ shells. It is reported that the results from these calculations are in good agreement with the experimental data for the excitation energy levels up to 4.3 MeV.

The measurements were carried out last year at the Lawrence Berkeley National Laboratory using a covered ^{252}Cf source inside the Gammasphere chamber. The data were taken in such a way as to increase the efficiency in the low-energy region, compared to the previous data, while keeping the efficiency in the high-energy region. A ^{252}Cf source of strength 62 μCi was sandwiched between two Fe foils of thickness 10 mg/cm^2 and was mounted in a 3 in. diameter plastic (CH) ball. It was placed at the center of the Gammasphere array which, for this experiment, consisted of 102 Compton suppressed Ge detectors. A total of 5.7×10^{11} triple- and higher-fold coincidence events were collected. The coincidence data were analyzed with the RADWARE software package [6]. The width of the coincidence time window was about 1 μs.

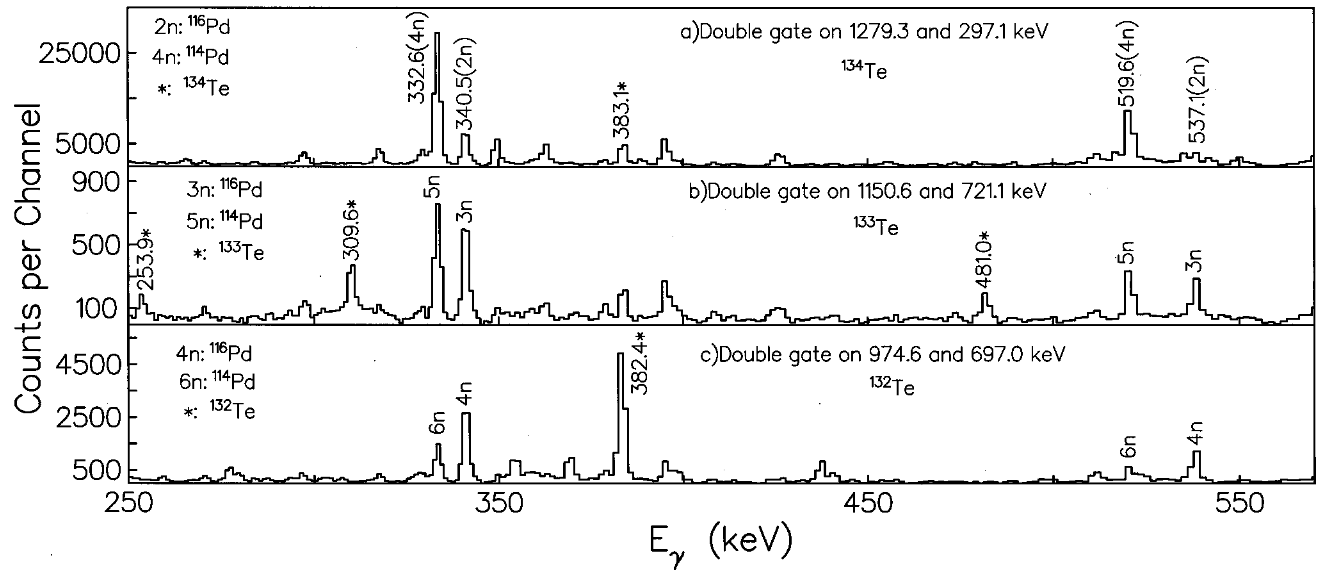

FIG. 1. Coincidence spectra with double gates set on (a) 1279.3 and 297.1 keV transitions in ^{134}Te, (b) 1150.6 and 721.1 keV transitions in ^{133}Te, and (c) 974.6 and 697.0 keV transitions in ^{132}Te.

Since the partners of the Te isotopes are Pd isotopes, the γ transitions belonging to ^{133}Te are identified in the following way: With double gates set on the known transitions in the Pd isotopes, first we confirmed a new transition of energy 1150.6 keV as belonging to one of the Te isotopes. By double gating on this 1150.6 keV transition and other known Pd transitions we identified several new transitions, the strongest at 125.5 keV, 193.5, and 721.1 keV, etc. The mass assignment of these transitions has been determined by the yield of partner Pd isotopes. In Figs. 1(a) and 1(c) are shown the coincidence spectra with the double gates set on the 1279.3 and 297.1 keV transitions in ^{134}Te and on the 974.6 and 697.0 keV transitions in ^{132}Te, respectively. In these two coincidence spectra, the 332.6 and 519.6 keV transitions in ^{114}Pd and the 340.5 and 537.1 keV transitions in ^{116}Pd are marked with the number of evaporated neutrons. In the coincidence spectrum, Fig. 1(b), with the double gate set on the new 1150.6 and 721.1 keV transitions, the γ transitions belonging to the partner ^{114,116}Pd isotopes are shown. From the comparison of these three spectra [Figs. 1(a)–1(c)], it is clearly seen that the 1150.6 and 721.1 keV transitions belong to the 5n and 3n channels that correspond to the ^{114,116}Pd-^{133}Te splits, respectively. Therefore, the 1150.6 and 721.1 keV transitions are assigned to ^{133}Te. In Fig. 2, 13 of 21 new transitions identified in the present work are marked. From the comparison of the relative intensities and coincidence relationships of the observed γ transitions, the level scheme of ^{133}Te is established as shown in Fig. 3.

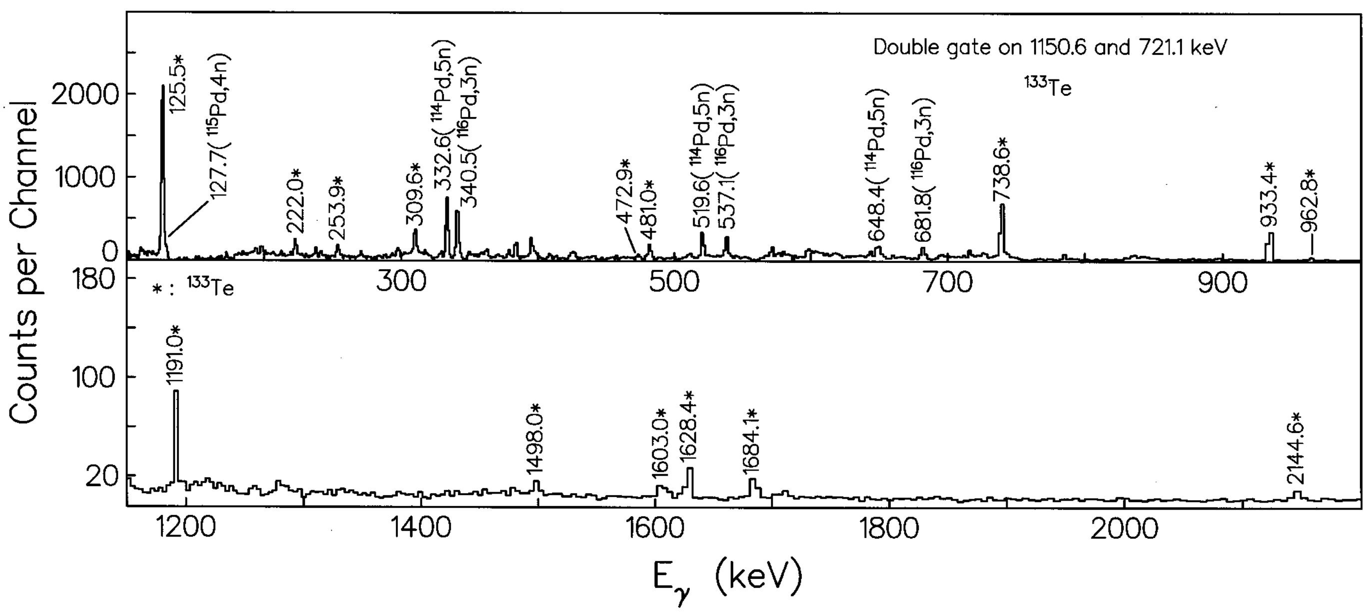

FIG. 2. Coincidence spectra with double gates set on 1150.6 and 721.1 keV transitions in ^{133}Te.

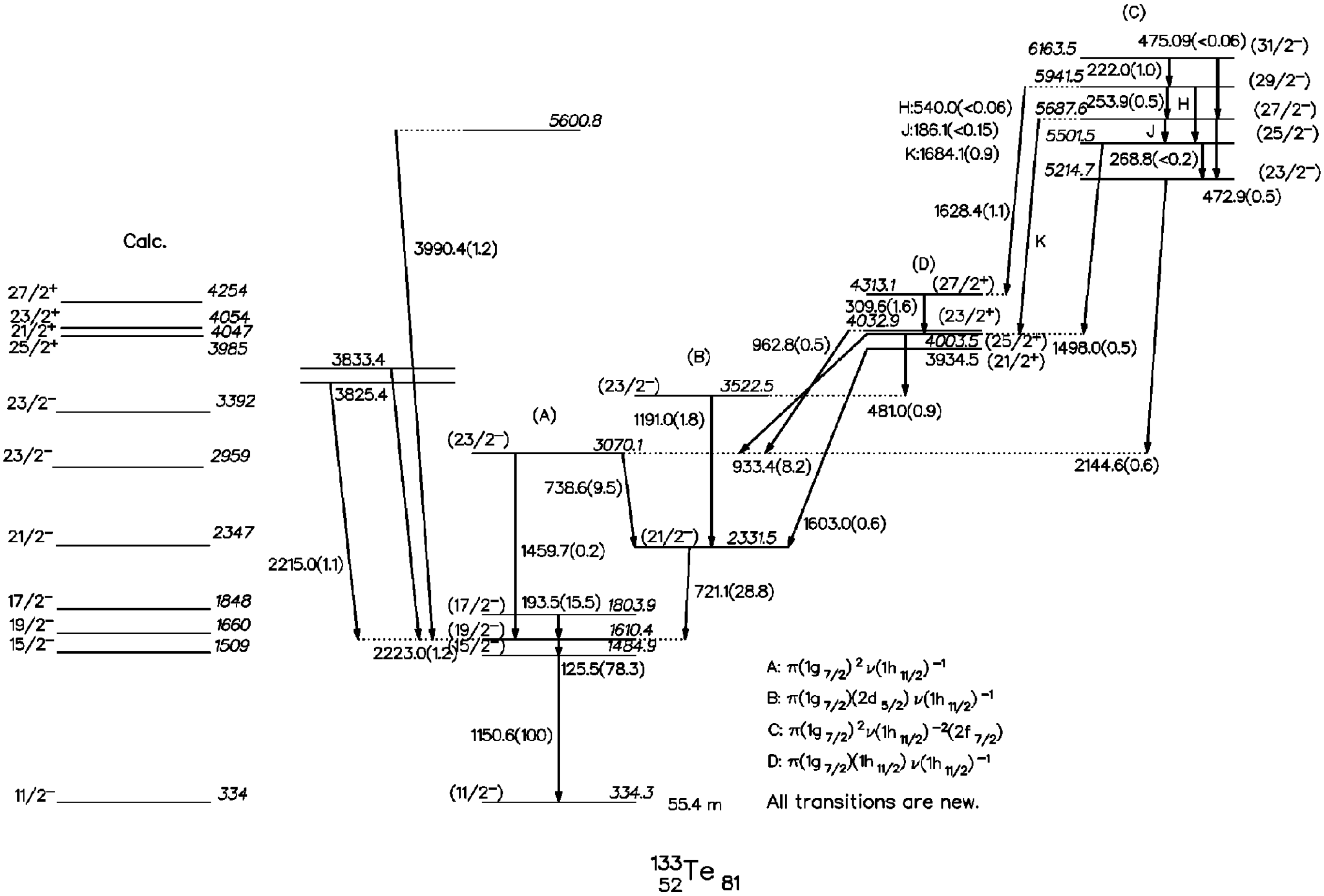

FIG. 3. Experimental and calculated level scheme of ^{133}Te.

Four types of particle-hole bands (bands A, B, C, and D) are here proposed for ^{133}Te. The band head of band A in ^{133}Te (Fig. 3) is taken as the $11/2^-$ isomeric state at 334.3 keV but not the $3/2^+$ ground state. The spins, parities, and dominant configurations of bands A, B, and D in ^{133}Te are assigned by the theoretical predictions of the shell-model calculations as shown in Fig. 3. In these calculations we have assumed ^{132}Sn to be closed core and let the valence protons and neutrons occupy the five single-particle (sp) orbits of the 50–82 shells. As a two-body interaction between the valence nucleons we have employed a realistic effective interaction derived from the Bonn-A free nucleon-nucleon potential [7]. This effective interaction has already produced quite satisfactory results for the light $N=82$ isotones as well as for ^{132}Sb [8]. As regards the single-proton and -neutron energies, we have taken them from the experimental spectra of ^{133}Sb and ^{131}Sn, respectively. The latter, however, have been slightly modified to accurately reproduce the $1/2^+$ and $11/2^-$ neutron-hole states in ^{133}Te.

The configurations assigned to the bands A, B, C, and D are confirmed by comparing the ^{133}Te band head energies to those in ^{134}Te and ^{135}I. In Fig. 4, the band head energies of the four bands in ^{134}Te and ^{135}I are drawn for energy comparison. One proton excited states from the $1g_{7/2}$ orbital to the $2d_{5/2}$ orbital are identified at 2.3, 2.4, and 2.0 MeV for ^{133}Te, ^{134}Te, and ^{135}I, respectively. The one proton excited states from the $g_{7/2}$ orbital to $h_{11/2}$ orbital are identified at 3.9, 4.0, and 3.7 MeV for ^{133}Te, ^{134}Te, and ^{135}I, respectively. The states corresponding to the $\nu f_{7/2}(h_{11/2})^{-1}$ particle-hole first excited state at 4041 keV of the doubly magic core nucleus, ^{132}Sn, are reported at 4.6 MeV in ^{134}Te and at 4.2 MeV in ^{135}I [1]. The appearance of the neutron particle-hole excited states around 4–5 MeV has been suggested by shell-model calculations employing empirical nucleon-nucleon interactions [1]. On this basis, the band C beginning at 5.2 MeV in ^{133}Te is interpreted as the particle-hole excitation from the core. It is impressive that the particle-hole excitation energy of 5.2 MeV in ^{133}Te is the highest ever observed. The spins of band C are assigned on the basis that $E1$ transitions dominate between the negative paritive bands (bands B and C) and the positive paritive band (band D), such as those in the cases of ^{134}Te and ^{135}I [1]. Angular correlation and polarization measurements are needed to determine the proper spin, parity, and multipolarity assignments.

The highest band C in ^{133}Te may be a candidate for a ‘‘tilted rotor’’ band [9] within some range of spins. This may also be the case for the highest band at 4023 keV in ^{135}Te [2,9]. Near the lower end of the bands the angular momentum of holes couple nearly at right angles to the angular momentum vector of the particles beyond the closed shells. As one goes up the band, the angle between the vectors becomes smaller as they approach an alignment. Such bands

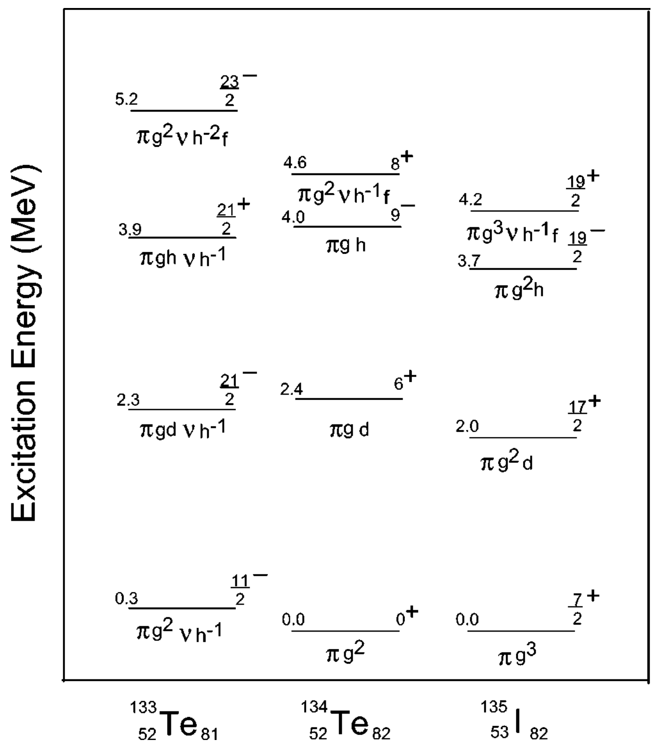

FIG. 4. Band head energies of the bands A, B, C, and D (see text) in ^{133}Te, ^{134}Te, and ^{135}I.

are characterized by strong $M1$ cascade transitions with weak $E2$ crossover transitions. One can also visualize these bands with the Nilsson deformed orbital representation. We would expect on geometrical grounds that fission fragments would prefer populating some kind of prolate bands as intermediates on the path to ground states. The high-energy band in ^{135}Te is very regular. Fornal *et al.* [2] assigned it as the promotion of a $1h_{11/2}$ neutron across the 82 shell gap to pair up with the $2f_{7/2}$ neutron. If we have a prolate deformed potential, the two protons would be in the 1/2[431] orbital and the neutrons would have a pair in the 1/2[541] and a hole in the 11/2[505]. At high spins the Coriolis force would introduce a considerable mixing of the projection (omega) 1/2 orbitals with the higher 3/2 and 5/2 ones. However, the ^{135}Te band could have regular spacing and strong $M1s$. Independent studies of ^{135}Te give the relative intensities and energy values to an additional significant figure [9]. The crossing transitions are much stronger than the crossover transitions in every case as expected by the tilted axis cranking model "shear bands" [10]. The similar particle-hole structure is assigned in ^{133}Te, except that it has only one neutron in the 1/2[541] and a pair of holes in the 11/2[505]. Such a band will be quite irregular from the outset, having a projection 1/2 orbital with an odd nucleon for band C in ^{133}Te. We have estimated the upper limits for the intensities of the very weak $E2$ transitions and calculated lower limits for the $B(M1)/B(E2)$ ratios which are quite large to support our assignment. The lower limits for the $B(M1;31/2^- \rightarrow 29/2^-)/B(E2;31/2^- \rightarrow 27/2^-)$ and $B(M1;29/2^- \rightarrow 27/2^-)/B(E2;29/2^- \rightarrow 25/2^-)$ are 25.8 and $16.2\mu^2\,10^{-4}\,\mathrm{fm}^{-4}$, respectively. Indeed all four shell-model configurations for bands A, B, C, and D in ^{133}Te as shown in Fig. 3 can have a combination of particles and holes which can be interpreted in terms of the tilted axis cranking model [9,10]. While this manuscript was under consideration, the results on ^{133}Te were published in [11]. Our results agree with those published and we found several new levels that were not reported. Our theoretical calculations agree much better with our experimental results.

In summary, the yrast and near yrast particle-hole states are observed up to 6.2 MeV in ^{133}Te. All of the new γ transitions in ^{133}Te were identified in the spontaneous fission work of ^{252}Cf. The particle-hole states in ^{133}Te show characteristics similar to those in ^{134}Te. The low-lying $11/2^-, 15/2^-, 19/2^-$, and $17/2^-$ levels in ^{133}Te are assigned mainly as the $\pi(g_{7/2})^2\nu(h_{11/2})^{-1}$ states. States related to the neutron $f_{7/2}(h_{11/2})^{-1}$ particle-hole excitation of the doubly magic nucleus ^{132}Sn are proposed at 5.2147 MeV in ^{133}Te which is the highest energy observed for such a structure. Shell-model calculations yield results for bands A, B, and D in ^{133}Te in good agreement with the experimental data for the excitation energy levels up to 4.3 MeV.

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