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Identification of the γ transitions in Tc and Cs products of ^{252}Cf fission and possible 7/2$^+$ [413] bands in $^{105-109}$Tc isotopes

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Several γ transitions in $^{105-109}$Tc nuclei were identified for the first time from spontaneous fission studies with a ^{252}Cf source and the Gammasphere. New level schemes are proposed and related to the underlying nuclear structure. Positive parity bands with a large signature splitting observed in ^{105,107,109}Tc are evidently derived from $g_{9/2}$ orbitals and are similar to analogous bands in ^{103}Rh, ^{103}Ag, and ^{99}Y. New γ transitions have also been identified in $^{139-143}$Cs and used to construct level schemes for these isotopes. Correlated-pair fission yields extracted from the data show an appreciable field for the zero neutron ^{109}Tc/^{143}Cs pair. [S0556-2813(98)05205-4]

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I. INTRODUCTION

The analysis of prompt γ-ray spectra of nuclei produced in the spontaneous fission (SF) of actinide nuclei is currently the preferred approach to the study of the level structure of neutron-rich nuclei in the fission product mass range and is generating a growing body of nuclear structure data on this interesting but hard to access region. The odd-A nuclei with $Z=39$ and 41 have rotational bands built on the 5/2$^+$ [422] and 5/2$^-$ [303] proton configurations [1]. In ^{99}Y and ^{101}Y with $Z=39$, the ground states were assigned the 5/2$^+$ [422] quasiparticle configuration [1] similar to the ground state bands in ^{101}Nb and ^{103}Nb with $Z=41$. In these two Nb nuclei side bands with the configurations 3/2$^-$ [301] and 5/2$^-$ [303] have also been identified, but in the spontaneous fission of ^{248}Cm only the 5/2$^-$ [303] side band in ^{103}Nb was observed [1]. This was confirmed in our work with the ^{252}Cf source. In the present work, we report our new data concerning the structure of $^{105-109}$Tc nuclei with $Z=43$. The bands in Tc isotopes with $Z=43$ have not been studied, because the bands in Cs nuclei, the fission partners of Tc isotopes, were not known. Recently the yrast bands in ^{141,143,145}Cs nuclei were reported [2]. Therefore, on the basis of these γ transitions in Cs nuclei and of some low-energy transitions in Tc nuclei known from β-decay work [3], we can identify γ transitions in Tc nuclei and elucidate their level schemes. Also, the known multipolarities of the 85.4 keV ($E1$) and 64.1 keV ($M1$) γ transitions in ^{105}Tc, and of the 65.7 keV ($M1+E2$) and 71.7 keV ($E1$) γ transitions in ^{107}Tc as well as the known spins and parities of low-lying levels in ^{105}Tc can be utilized for tentative spin and parity assignments to the new levels. Positive parity bands identified in ^{105}Tc, ^{107}Tc, and ^{109}Tc show remarkable similarities and are interpreted as rotational bands with the probable 7/2$^+$ [413] configuration. Level schemes have also been constructed for the odd-odd ^{106}Tc and ^{108}Tc nuclei, as well as for the fission partner nuclei $^{139-143}$Cs.

II. EXPERIMENTAL TECHNIQUES

A ^{252}Cf source of strength 25μCi was sandwiched between two Ni foils of thickness 11.3 mg/cm^2 and then sandwiched between 13.7 mg/cm^2 thick Al foils and placed at the center of the Gammasphere. This experiment was carried out with 72 Compton-suppressed Ge detectors. The γ-ray spectra obtained in this type of experiments are very complex, since in fission one produces more than 100 nuclei with varying yields. In a single SF event predominantly two fragments (a heavy and a light fragment) are produced along

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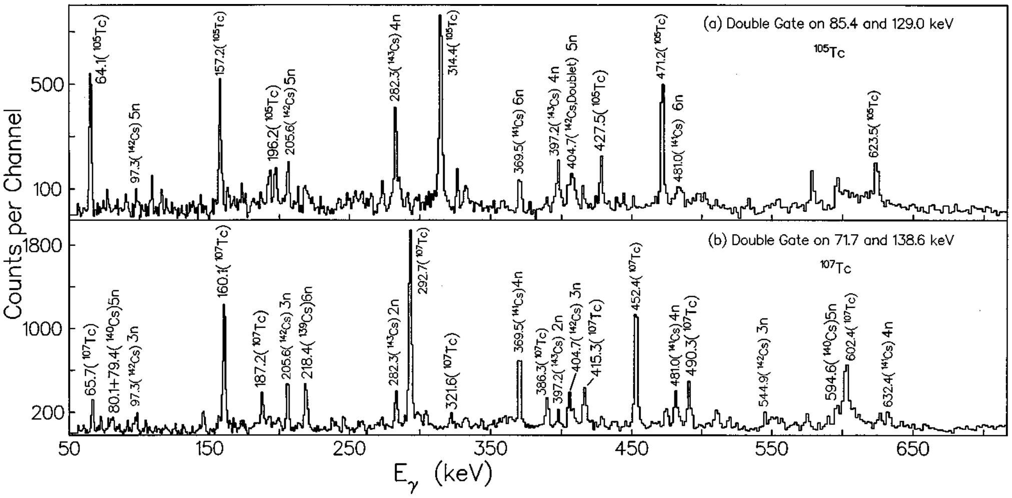

FIG. 1. (a) Partial coincidence spectrum setting double gate on 85.4 and 129.0 keV transitions in ^{105}Tc. (b) Partial coincidence spectrum setting double gate on 71.7 and 138.6 keV transitions in ^{107}Tc.

with several neutrons. The partner nuclei are usually produced in excited states, and the γ rays emitted by the two partners during the deexcitation process will be in coincidence with each other. The analysis is complicated by the fact that a nucleus of interest will have several partner isotopes that have the same atomic number but different neutron numbers, because the number of neutrons emitted in a SF event can vary between 0 and 10. Triple and higher fold coincidences must be used for unambiguous peak identification and assignment. The data were recorded in an event by event mode. Cubes of triple coincidence events (with the three γ-ray energies as axes) were then constructed and analyzed using the RADWARE software [4]. The width of the coincidence time window was about 1 μs, but narrower time gates could be implemented in software at the cube generation stage. Most of the data analyzes presented below were performed on a cube with a 100 ns wide time requirement. New transitions were identified and assigned in the present work by setting several double gates on the known γ transitions in $^{141-143}$Cs and ^{105,107,109}Tc. Newly assigned transitions were then used as gates to identify additional transitions in these and in other Tc and Cs isotopes. For example, in ^{105}Tc three γ transitions of energies 85.4, 64.1, and 129.0 keV are known from the β decay of ^{105}Mo [5,6]. By double gating on these γ rays, we observed several new transitions and assigned them to ^{105}Tc. Similarly, in ^{107}Tc, two γ transitions of energies 65.7 and 71.7 keV are already known from the β decay of ^{107}Mo [7,8]. Gating on these γ rays, we could identify additional γ transitions which are now assigned to ^{107}Tc. Some transitions in ^{109}Tc have been recently identified by Bhattacharya *et al.* [9] in the SF of ^{248}Cm. By double gating on these transitions, we have added transitions attributed to this nuclide. Additional transitions observed in coincidence with Cs partner γ rays were assigned to the

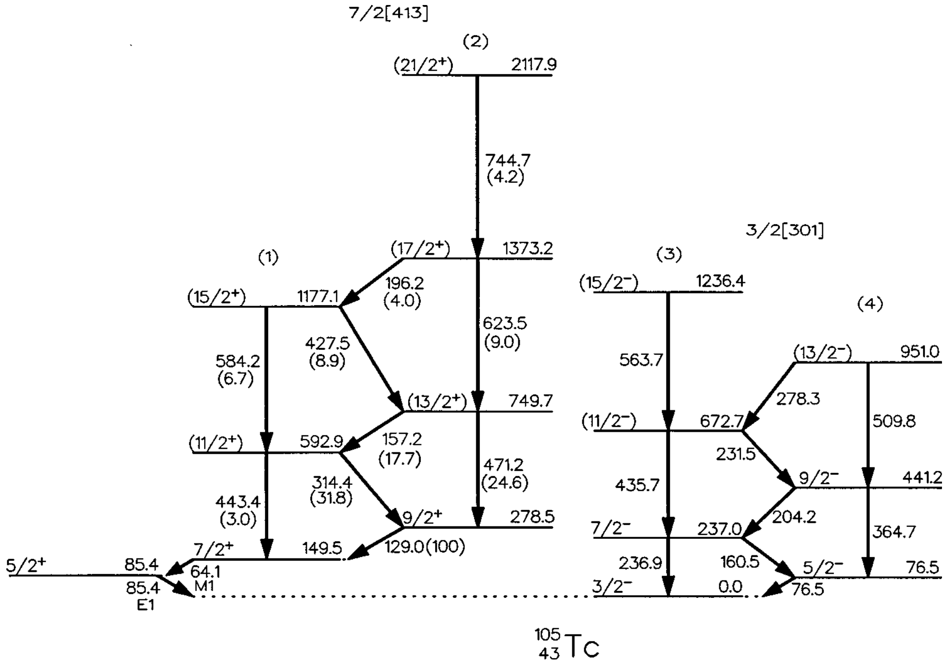

FIG. 2. Level scheme of ^{105}Tc.

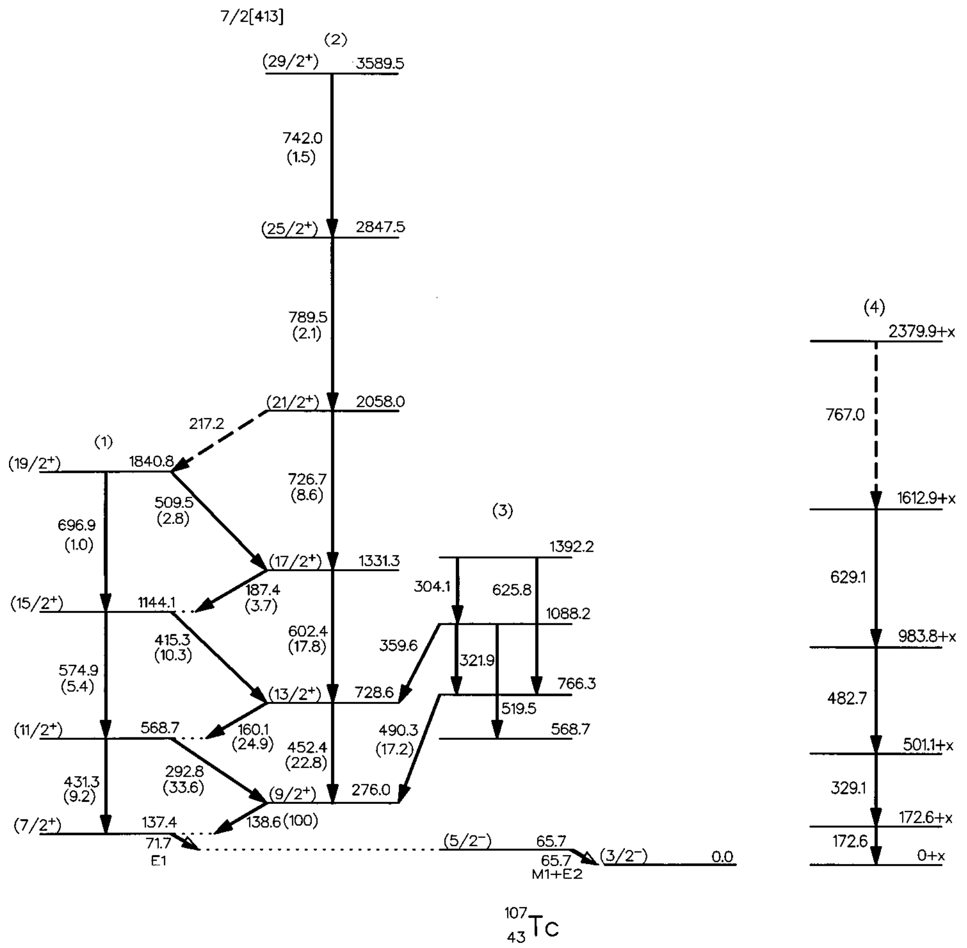

FIG. 3. Level scheme of ^{107}Tc.

odd-odd isotopes ^{106}Tc and ^{108}Tc. Gating on the newly assigned Tc γ rays, we were able to observe transitions in ^{141,143}Cs that were not reported in Ref. [2], as well as to identify numerous previously unreported γ rays in ^{139,140,142}Cs.

III. RESULTS

A. ^{105}Tc nucleus

The partial coincidence spectrum obtained by double gating on the known [3,5,6] 85.4- and 129.0 keV γ rays in ^{105}Tc is shown in Fig. 1(a). The transitions belonging to partner Cs nuclei and to ^{105}Tc are marked. The $^{141-143}$Cs isotopes are the partners of ^{105}Tc with 6, 5, and 4 neutrons emitted, respectively. One can easily see that the 282.3 keV transition in ^{143}Cs, which corresponds to the 4n channel, is the strongest partner transition. In general, we expect either the 3n or the 4n channel to have the highest yield in ^{252}Cf spontaneous fission [10]. As indicated in Fig. 1(a), six new transitions of energies 157.2, 196.2, 314.4, 427.5, 471.2, and 623.5 keV were assigned to ^{105}Tc on the basis of this coincidence spectrum. The assignments were confirmed by the

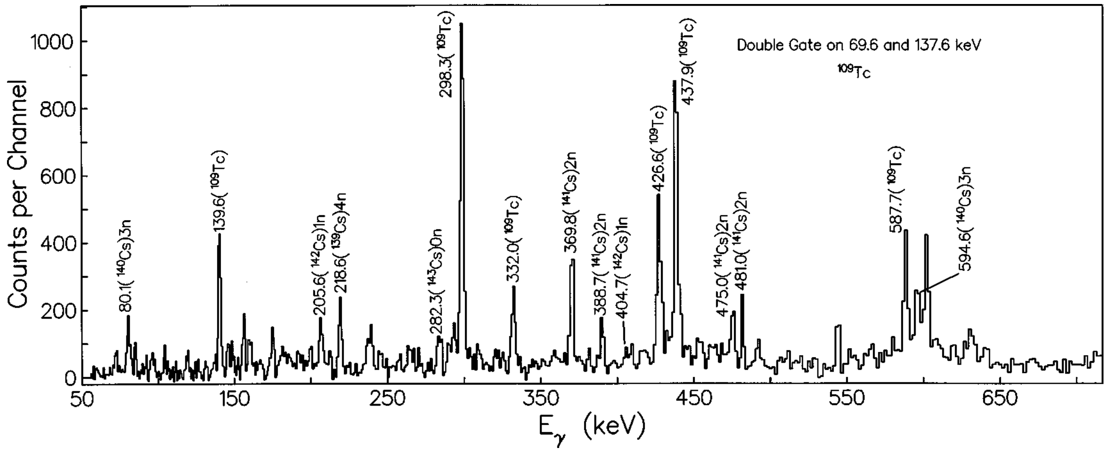

FIG. 4. Partial coincidence spectrum setting double gate on 69.6 and 137.6 keV transitions in ^{109}Tc.

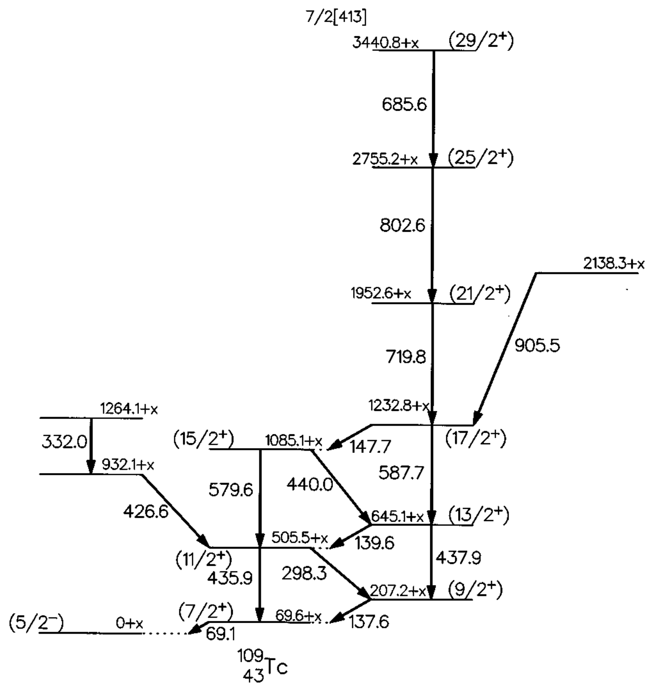

FIG. 5. Level scheme of ^{109}Tc.

observation of the same transitions in spectra gated on other combinations of the 85.4, 64.1, 129.0 keV γ-ray cascade [3,5,6]. Several double gates were then set on these new transitions to build the partial level scheme denoted as bands 1 and 2 in Fig. 2. In all the gates we also observed the correct transitions in Cs partner nuclei. Five additional low-lying γ-transitions in ^{105}Tc, with energies of 76.5, 160.5, 204.2, 236.9, and 364.7 keV were observed in the β decay of ^{105}Mo [5,6]. By double gating on these γ rays, we observed five new transitions of energies 231.5, 278.3, 435.7, 509.8, and 563.7 keV. We attribute them to ^{105}Tc and the bands built with these transitions are shown as bands 3 and 4 in Fig. 2 and are tentatively assigned the proton $3/2^-$ [301] configuration. No interband transitions connecting bands 1,2 with bands 3,4 could be identified.

B. ^{107}Tc nucleus

Two low-lying transitions of energies 65.7 and 71.7 keV have been observed in the β decay of ^{107}Mo [3,7,8]. When we gated on these two energies, we observed a strong transition at 138.6 keV. The coincidence spectrum obtained by gating on the 71.7 and 138.6 keV transitions is shown in Fig. 1(b). The transitions assigned to ^{107}Tc and to its partner Cs isotopes are marked in the figure. In this case, ^{141}Cs is the partner of ^{107}Tc with four neutrons evaporated. As expected, the 369.5 keV transition in ^{141}Cs is the strongest relative to other Cs isotopes. By double gating successively with one of these three transitions and other transitions observed in the spectrum, we could assign several new transitions to ^{107}Tc and to construct the partial decay scheme denoted as bands 1, 2, and 3 in Fig. 3. In a similar manner, starting with a spectrum gated on the strong 369.7- and 481.1 keV transitions in ^{141}Cs [2], we identify a cascade of 172.6, 329.1, 482.7, 629.1, and 767.0 keV coincident γ rays. In a spectrum gated on the 172.6 and 329.1 keV transitions the value of $I_\gamma(282.3)/I_\gamma(369.5)$ [the intensity ratio of the 282.3 keV (^{143}Cs) and 369.7 keV (^{141}Cs) peaks] is 0.43(4), identical to the value of the same ratio in a spectrum gated on the 71.7 and 138.6 keV transitions assigned to ^{107}Tc. This means that the 172.6, 329.1 keV, etc., cascade belongs to ^{107}Tc. It is designated as band 4 in Fig. 3. Since no transitions connecting this band to the previously identified bands or to the ground state were observed, the absolute energy scale of this band is uncertain.

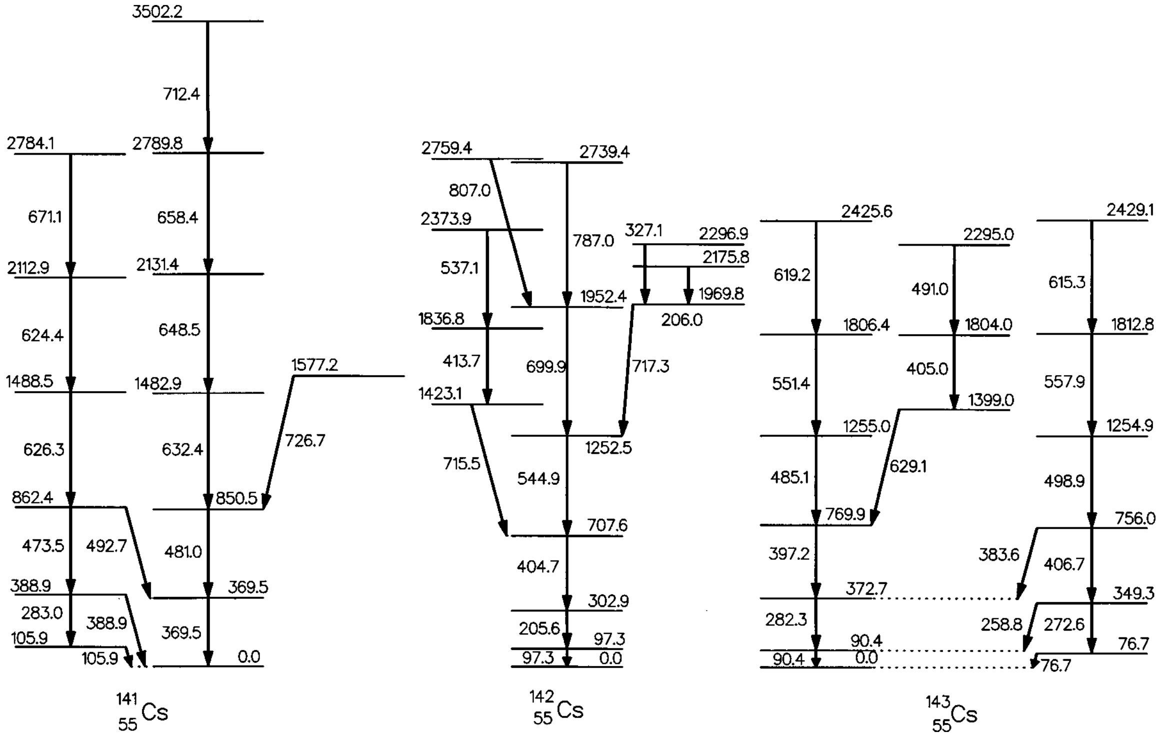

FIG. 6. Level schemes of $^{141-143}$Cs.

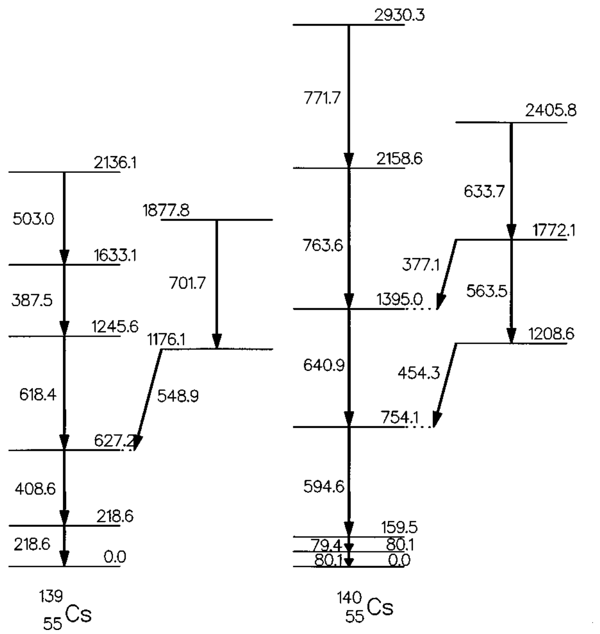

FIG. 7. Level schemes of ^{139,140}Cs.

C. ^{109}Tc nucleus

^{109}Tc has been the subject of two conflicting reports [12,13], where in Ref. [12] transitions of 125.3 and 123.5 keV were assigned to ^{109}Tc and in Ref. [13] the 125.5 keV transition was assigned to ^{108}Tc from β-decay work. Recently, γ rays of 137, 437 keV, and a number of additional transitions in ^{109}Tc were identified by Bhattacharyya *et al.* [9] in the spontaneous fission of ^{248}Cm. No level scheme was presented. Setting double gates on these transitions, we were able to confirm their assignments, to add several new γ rays and to construct a partial level scheme, quite similar to those of ^{105}Tc and ^{107}Tc. A partial coincidence spectrum double gated on the 69.6 and 137.6 keV transitions of ^{109}Tc is shown in Fig. 4, and the proposed level scheme in Fig. 5. The position of our observed ground state with respect to the true ground state is still uncertain, as indicated by the energy scale of the level scheme. No evidence for additional bands, similar to those observed in ^{105,107}Tc, could be found.

D. Cs nuclides

Hotchkis *et al.* [1] have assigned both the 205.6, 404.7 keV and the 282.3, 397.2 keV cascades to ^{143}Cs. Comparison of the relative intensities of these transitions in Figs. 1(a) and 1(b) clearly indicates that 205.6 and 282.3 keV transitions belong to different Cs isotopes. Since the 282.3 keV transition is in coincidence with a 90.4 keV γ ray observed in β decay of ^{143}Xe [3], we attribute the 282.3 keV transition and coincident Cs γ rays to ^{143}Cs. This assignment, as well as our level scheme for ^{143}Cs are in agreement with the results of Rzaca-Urban *et al.* [2]. As shown in Fig. 6, the level scheme includes an additional side band not reported in Ref. [2]. On the basis of the relative yields of partner Tc isotopes and noting that the strong 205.6 and 404.7 keV transitions are not included in the spectra of ^{141,143}Cs of Ref. [2], we conclude that these and related coincident transitions belong to ^{142}Cs and not to ^{143}Cs [1]. The partial yrast level scheme we propose for ^{142}Cs is shown in Fig. 6. As is common in many other odd-odd isotopes, there is little or no overlap between this scheme and the level scheme derived from β decay of ^{142}Xe [3]. For ^{141}Cs we were able to extend the level scheme of Ref. [2] by adding a level at 3502.2 keV

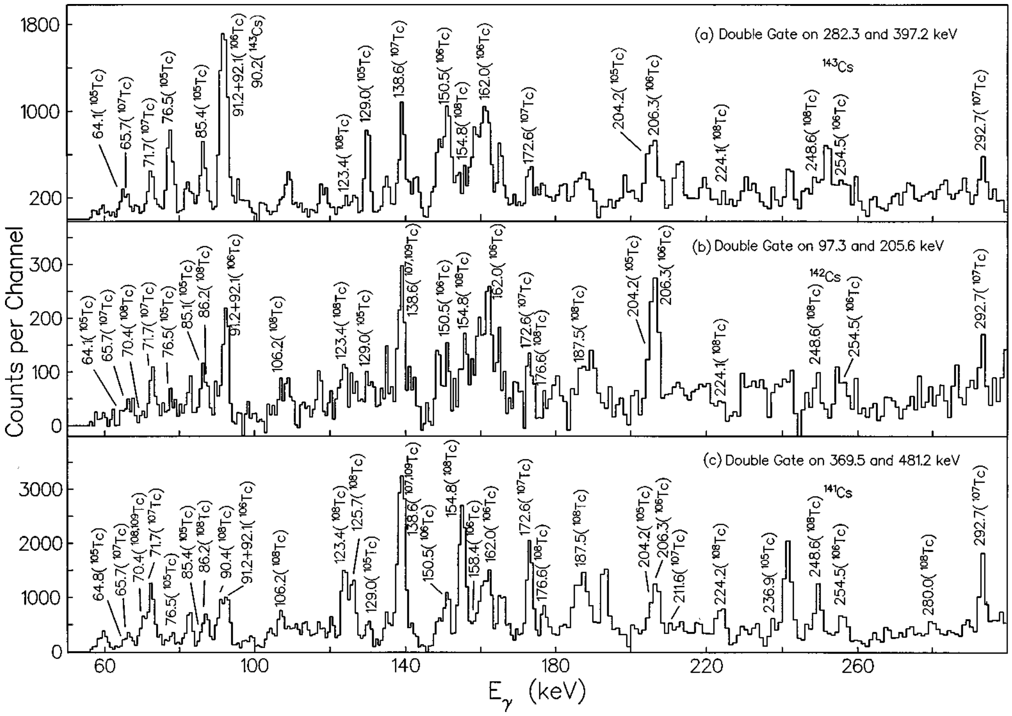

FIG. 8. (a) Partial coincidence spectrum setting double gate on 282.3 and 397.2 keV transitions in ^{143}Cs. (b) Partial coincidence spectrum setting double gate on 97.3 and 205.6 keV transitions in ^{142}Cs. (c) Partial coincidence spectrum setting double gate on 369.5 and 481.2 keV transitions in ^{141}Cs.

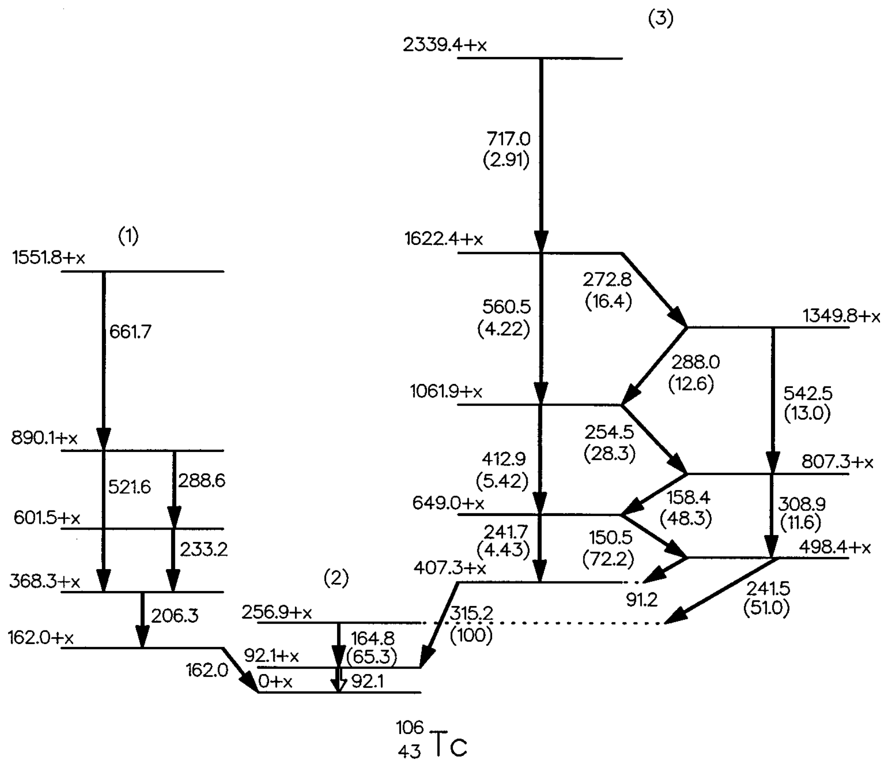

FIG. 9. Level scheme of ^{106}Tc.

in the main band and the band head of a second side band (analogous to the one in ^{143}Cs) at 1577.2 keV. The modified level scheme is also shown in Fig. 6. Figure 7 shows the new partial yrast level schemes we were able to construct for ^{140}Cs and ^{139}Cs. The lowest-lying levels at 80.1 and 218.6 keV, respectively, were also observed in the β-decay of the respective xenon isotopes [3], confirming the mass assignments obtained from Tc yield ratios. The well developed side band seen in both ^{141}Cs and ^{143}Cs [2] could not be observed in ^{139}Cs. This may be related to the systematics of the $3/2^+$ [422] orbital in this region (see Fig. 2 in Ref. [2]). Further work is required to elucidate the spin-parity assignments and the underlying nuclear structure of these Cs nuclei.

E. ^{106,108}Tc nuclei

Low spin levels and γ-transitions in ^{106}Tc and ^{108}Tc have been observed in beta decay of ^{106,108}Mo [11]. However, the transitions reported for ^{106}Tc [11] are not observed in our fission studies. We observe only the 106.2 and 86.2 keV transitions in ^{108}Tc. The partial coincidence spectra obtained by setting double gates on the 282.3 and 397.2 keV transi-

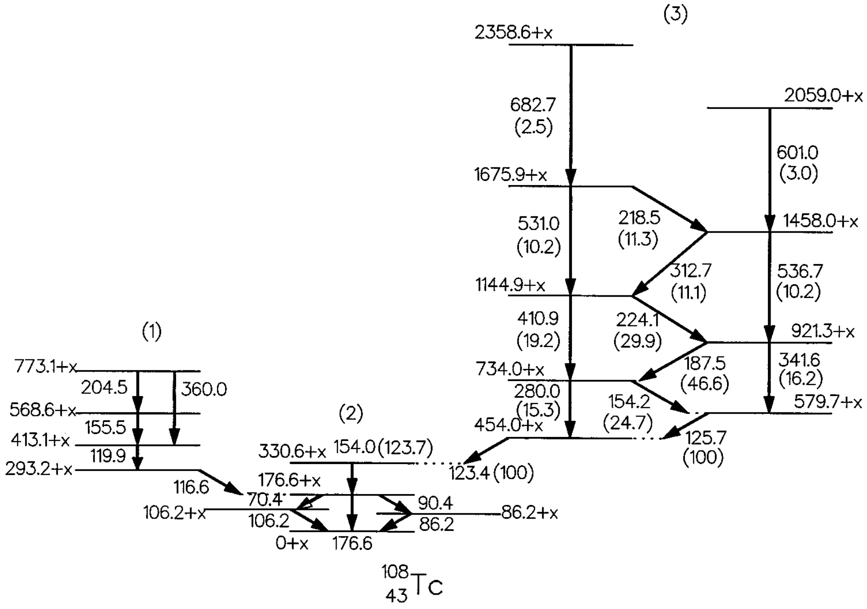

FIG. 10. Level scheme of ^{108}Tc.

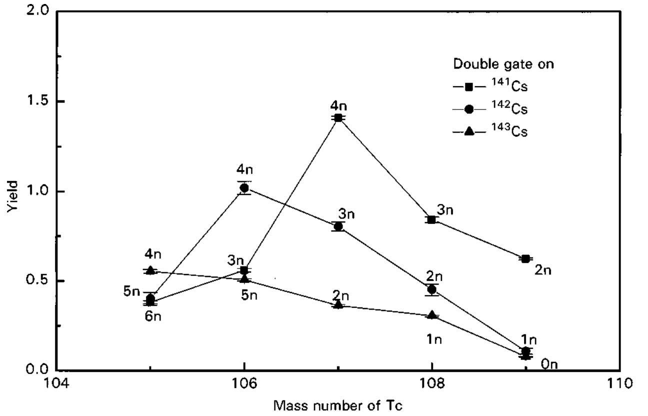

FIG. 11. Yield functions of correlated Tc-Cs partner pairs.

tions of ^{141}Cs, on the 97.3 and 205.6 keV transitions of ^{142}Cs and on the 369.5 and 481.2 keV transitions of ^{143}Cs are shown in Figs. 8(a), 8(b), and 8(c). In these spectra we observed several new transitions that were not assigned to ^{105,107,109}Tc or to ^{141,142,143}Cs isotopes. They must belong to other Tc isotopes. The new transitions can be divided by their coincidence relationships into two groups: one, consisting primarily of 91.2, 92.1, 150.5, 158.4, 254.5, and 315.2 keV transitions; and a second, comprising of 123.4, 125.7, 154.2, 176.6 keV and several weaker transitions. From these coincidence relationships, and many other coincidence spectra, level schemes were constructed as shown in Figs. 9 and 10 with mass numbers of 106 and 108 assigned. The remaining task now is to substantiate this mass number assignment. Assuming that the level schemes are correct (and more or less complete), the correlated pair yield functions for the Tc isotopes, normalized to Wahl's fission yield tables [14] can be calculated. These are shown in Fig. 11. As expected, the yield systematics definitely confirm our identification of ^{106,108}Tc. The relatively high yield of the ''cold fission'' ($0n$) ^{109}Tc-^{143}Cs channel is quite noteworthy. The identification of ^{108}Tc is further confirmed by the observation of the 86.2 and 106.2 keV γ rays also seen in β decay of ^{108}Mo [11]. A partial coincidence spectrum double gated on the 123.4 and 125.7 keV transitions in ^{108}Tc is shown in Fig. 12. Thirteen transitions in ^{108}Tc can readily be seen. In a similar spectrum taken with a 28 ns (instead of 100 ns) time window, the relative intensity of the 176.6 keV peak (as well as that of the 70.4, 86.2, 90.4, and 106.2 keV gamma rays which depopulate the same level) is reduced, indicating a relatively long half life for the 176.6 keV level in ^{108}Tc. From the measured ratio of 2.0 ± 0.2 between the intensity of the 176.6 keV gamma ray in a wide open 1 μs time window and that in a 28 ns window, taken with several ^{141}Cs and ^{108}Tc double gates, we derive a value of 28 ± 4 ns for this half life which is consistent with an $E2$ multipolarity for the 176.6 keV transition. No other levels with half lives longer than ≈ 20 ns could be found in our Tc data.

IV. DISCUSSION

The level scheme of ^{105}Tc is shown in Fig. 2. The ground state spins of ^{105}Tc and ^{103}Tc are already known as $3/2^-$ and $5/2^+$, respectively [3]. The lowest $5/2^+$, $7/2^+$, $9/2^+$, $3/2^-$, $5/2^-$, $7/2^-$, and $9/2^-$ levels in ^{105}Tc are also known [6]. The spin and parity assignments of these levels are based on the $M1$ character of the 64.1 keV transition [6] and the $E1$ character of the 85.4 keV transition [6]. From the intensity balance of the 157.2 and 314.4 keV transitions in a spectrum double-gated on the 129.0 and 623.5 keV transitions and shown in Fig. 13(b), we have extracted a value of 0.096(32) for the total internal conversion coefficient of the 157.2 keV transition in ^{105}Tc. Similarly, we derive a value of 0.095(10) for the total internal conversion coefficient of the 160.1 keV transition in ^{107}Tc from the intensity balance of the 292.8 and 160.1 keV transitions in a spectrum gated on the 138.6 and 602.4 keV transitions and shown in Fig. 13(a). The theoretical total internal conversion coefficients are $\alpha(E1) = 0.0357$, $\alpha(E2) = 0.246$, $\alpha(M1) = 0.0819$, $\alpha(M2) = 0.579$ for the 157.2 keV transition of ^{105}Tc and $\alpha(E1) = 0.0339$, $\alpha(E2) = 0.231$, $\alpha(M1) = 0.0779$, $\alpha(M2) = 0.543$, for the 160.1 keV transition of ^{107}Tc. The measured α's establish the $M1(+E2)$ character of these two γ transitions.

The most probable configuration of the $3/2^-$ ground state of ^{105}Tc is $3/2^-$ [301], since this orbital is near the Fermi surface for $Z = 43$ at a prolate deformation of ≈ 0.25. We therefore assign the rotational band denoted as bands (3) and (4) in Fig. 2 to this configuration. The positive parity band of ^{105}Tc may have the $5/2^+$ [422] or $7/2^+$ [413] configuration, based on the $\pi g_{9/2}$ orbital. As shown in Fig. 2, this positive parity band shows appreciable signature splitting characteristic of bands built on the $7/2^+$ [413] orbital [3]. In Fig. 14 we plot the energy difference $(E_I\text{-}E_{I-1})/2I$ versus $(2I)^2$,

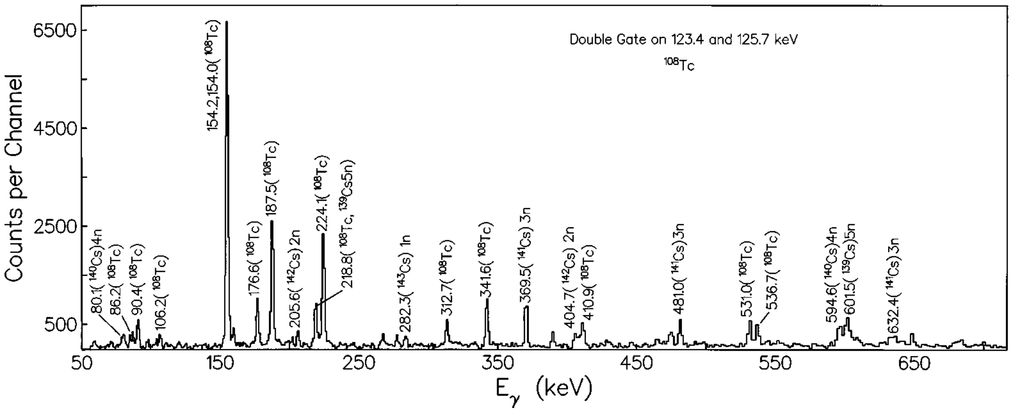

FIG. 12. Partial coincidence spectrum setting double gate on 123.4 and 125.7 keV transitions in ^{108}Tc.

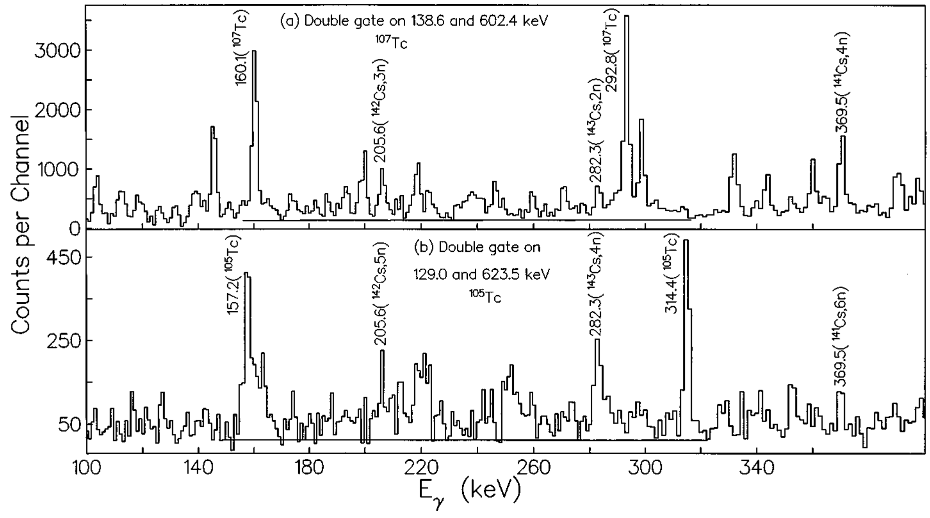

FIG. 13. (a) Partial coincidence spectrum setting double gate on 138.6 and 602.4 keV transitions in ^{107}Tc. (b) Partial coincidence spectrum setting double gate on 129.0 and 623.5 keV transitions in ^{105}Tc.

where I is the level spin, for some bands built on the $7/2^+$ [413] configuration and on the $5/2^+$ [422] configuration [3], as well as those for the positive parity bands in ^{105,107,109}Tc identified in this paper. The signature splittings in the three Tc isotopes are almost identical and although smaller than those found in ^{103}Rh and ^{103}Ag [3], clearly establish the $7/2^+$ [413] configuration of these bands, and a $7/2^+$ spin-parity assignment to their band heads. The spin-parity assignments of the other members of the bands follow from this interpretation. However, considerable Coriolis mixing of the $7/2^+$ [413] and $5/2^+$ [422] orbitals is quite likely and may explain differences in signature splittings.

The level scheme of ^{107}Tc is shown in Fig. 3. To assign spins and parities to the low-lying levels we start with the $M1(+E2)$ character [8] of the 65.7 keV transition and the $E1$ character [8] of the 71.7 keV transition. This determines the negative parity of both the ground state and the 65.7 keV level and supports our tentative spin-parity assignment of $3/2^-$ and $5/2^-$, respectively, to these levels, in analogy with ^{105}Tc. The ground state negative parity band interpreted as a $3/2^-$ [301] band was not oserved in ^{107}Tc. Instead, there is the unconnected band with undetermined band head energy denoted as band (4) in Fig. 3. There is not enough information to assign spins and parities to this band and to determine its nature. Similarly, we are unable to further characterize the side band labeled (3) in the figure.

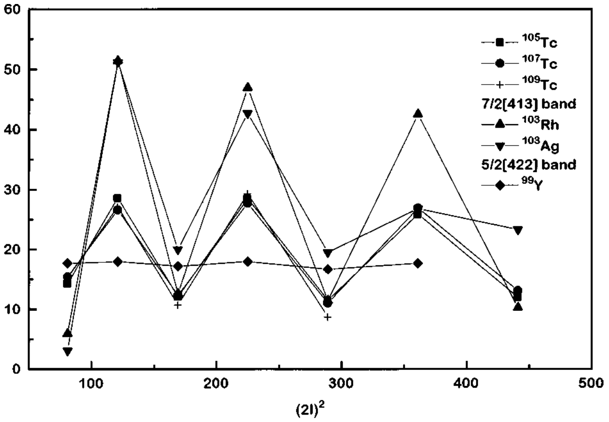

FIG. 14. Energy difference $(E_I$-$E_{I-1})/2I$ of the positive parity bands in Tc, Rh, Ag, and Y.

In ^{109}Tc there is no β-decay information to help with the identification of the ground state and of other low-lying levels and no ground state band was observed. We are therefore left with a residual uncertainty x in the energy scale. Only the $7/2^+$ [413] is seen (assigned on the basis of analogy with ^{105,107}Tc) with an indication of a side band feeding the $11/2^+$ level (see Fig. 5).

We were not able to assign spins and parities to levels in ^{106,108}Tc $(Z=43,\ N=63,65)$. In Ref. [11] evidence is presented for a 2^+ assignment to the ground state of both isotopes. On the other hand, according to Ref. [3] the neighboring nuclei ^{104}Nb $(Z=41,\ N=63)$ and ^{108,110}Rh $(Z=45,\ N=63,65)$ have a 1^+ ground state with a low lying 5^+ (or, possibly 4^+ or 6^+) isomer. Since we do not observe any of the low spin, low-lying levels and transitions in ^{106}Tc identified from the beta decay of ^{106}Mo [11], it is probable that our lowest state in ^{106}Tc is actually the $(4^+,\ 5^+$, or $6^+)$ isomer commonly found in this region [3]. This uncertainty in the true position of the ground state is denoted in Fig. 9 by adding x to the energy scale. In ^{108}Tc, our observation of the 86.2 and 106.2 keV levels in prompt SF decay may indicate that there is no long-lived (beta decaying) isomer in this nucleus. At higher spins, ^{106}Tc and ^{108}Tc exhibit similar band structures with moderate signature splitting, analogous to the positive parity bands of ^{105,107,109}Tc.

V. CONCLUSION

In summary in ^{105}Tc rotational bands with the $7/2^+$ [413] and $3/2^-$ [301] proton configurations are identified to high spins. The $7/2^+$ [413] band is more strongly populated (up to spin $21/2^+$) than the $3/2^-$ [301] band. The nuclei ^{103}Tc, ^{101,103,105}Nb, and ^{99,101}Y with $N=60$, 62 or 64 all have a ground state spin of $5/2^+$. ^{105}Tc has a ground state spin of $3/2^-$. It is difficult to understand the change of the ground state spin from $5/2^+$ to $3/2^-$ in the $Z=43$ nuclei (Tc) with the increase of N from 60 to 62 but it may indicate a change in deformation. The 7/2$^+$ [413] assignments in ^{107,109}Tc are made in analogy to ^{105}Tc. The 5/2$^+$ level in ^{105}Tc may have shifted up in ^{107}Tc and not be populated. Also, on the basis of the coincidence relations and yield function between the fission partner nuclei, Tc and Cs, twenty two γ transitions of ^{106}Tc and twenty five γ transitions of ^{108}Tc are identified for the first time predicted. In ^{106}Tc and ^{108}Tc bands with similar $E2$ transition energies are observed. Because of the prevalence of γ softness or triaxiality in this region [15], we have been alert to side bands or other features possibly related to triaxial deformation. The unassigned band starting at 766.3 keV in ^{107}Tc [band (3) in Fig. 3] is interesting in this regard, but more work to determine multipolarities and mixing ratios is needed. The correlated-pair fission yields, and especially the $0n$ ‘‘cold fission’’ ^{109}Tc/^{143}Cs case, are noteworthy and merit a more detailed study.

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