Nuclear shape and structure in neutron-rich $^{110, 111}$Tc

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Abstract

The structure of Tc nuclei is extended to more neutron-rich regions based on the measurements of prompt gamma rays from the spontaneous fission of ^{252}Cf at Gammasphere. The level scheme of N = 67 neutron-rich (Z = 43) ^{110}Tc is established for the first time and that of ^{111}Tc is expanded. The ground band of ^{111}Tc reaches the band-crossing region and the new observation of the weakly populated α = -1/2 member of the band provides important information of signature splitting. The systematics of band crossings in the isotopic and isotonic chains and a CSM calculation suggest that the band-crossing of the ground band of ^{111}Tc be due to alignment of a pair of $h_{11/2}$ neutrons. The best fit to signature splitting, branching ratios and excitations of the ground band of ^{111}Tc by RTRP model calculations result in a shape of $\varepsilon_2 = 0.32$ and $\gamma = -26^0$ for this nucleus. Its triaxiality is larger than that of $^{107,\ 109}$Tc, which indicates increasing triaxiality in Tc isotopes with increasing neutron number. The identification of the weakly populated ‘K+2 satellite’ band provides strong evidence for the large triaxiality of ^{111}Tc. In ^{110}Tc, the four lowest-lying levels observed are very similar to those in ^{108}Tc. At an excitation of 478.9 keV above the lowest state observed, ten states of a ΔI=1 band are observed. This band of ^{110}Tc is very analogous to the ΔI=1 bands in ^{106,108}Tc but it has greater and reversal signature splitting at higher spins.

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I. Introduction

The studies of shape coexistence and shape transitions in the neutron-rich A ~ 100 region have long been of major interest [1, 2]. In this region shape transitions from spherical to strongly deformed shapes are observed along the Z ~ 40 isotopic chains, and quadrupole deformations are found to decrease with increasing proton number between 38 and 42 [3-6]. Based on our systematic studies of neutron-rich odd-Z Y-Nb-Tc-Rh (Z =

39 – 41 – 43 – 45) isotopes, a shape transition was identified from an axially-symmetric shape with very large quadrupole deformations in ^{99,101}Y to large triaxial deformations in ^{107,109}Tc and ^{111,113}Rh isotopes [7, 8, 9].

It is of interest to explore further their structure along isotopic chains to the more neutron-rich region. For Rh (Z = 45) isotopes, N = 67 isotope ^{112}Rh and N = 68 isotope ^{113}Rh have been reached [7]. For Tc (Z = 43) isotopes, however, although the heavy N = 72 isotope ^{115}Tc was observed by using a projectile fragmentation technique [10], the high-spin structure of Tc isotopes was available only up to the N = 66 isotope ^{109}Tc [11, 8]. In the previous studies of lighter Tc isotopes, level schemes were established and a shift from a weak-coupling scheme towards a strong-coupling scheme from ^{97}Tc to ^{105}Tc was reported [12]. Afterwards the strong-coupling scheme and large signature splitting were extended to $^{107, 109}$Tc [8, 11]. This evolution of coupling schemes was interpreted as due to the location of the Fermi level changing with deformation as neutron number increases [10, 8]. The proton Fermi level, being close to $1/2^+$ and $3/2^+$ of the $\pi g_{9/2}$ subshell for $^{97, 99}$Tc with small deformations, approaches the $5/2^+$ of the same subshell for $^{103\text{-}109}$Tc with larger deformations. A quadrupole deformation $\varepsilon_2 = 0.32$ and triaxiality $\gamma = -22.5^0$ were deduced in ^{107}Tc [8].

In the present paper we report new experimental results on the N = 67 isotope ^{110}Tc and N = 68 isotope ^{111}Tc, which were achieved at almost the same time as we identified for the first time the level scheme of ^{138}Cs [13]. No low-lying yrast transitions had been reported in $^{110, 111}$Tc. The level scheme of ^{110}Tc is proposed for the first time. After we completed the work of both $^{110, 111}$Tc, a paper on ^{111}Tc was published by Urban et al. [14], where a less extended level scheme of ^{111}Tc was reported (see Section II for details).

Comparison and discussion are made in the present paper for the lowest levels and the ΔI = 1 yrast band of ^{110}Tc observed in the present work and those in $^{106, 108}$Tc [17]. The former shows an overall similarity to the latter [17] for low-lying levels and a sharp increase and reversal in the signature splitting compared to $^{106, 108}$Tc for higher spin levels, implying probably a significant increase in triaxiality in ^{110}Tc. Model calculations performed for ^{111}Tc are presented. The extension of the ground band and the observation of the band-crossing in this band of ^{111}Tc allow the study of systematics of band-crossing of Tc isotopes. The systematics of the band-crossing frequencies of the Tc isotopes and cranking shell model (CSM) calculations performed in the present work for ^{111}Tc suggest that this band-crossing be caused by alignment of a $h_{11/2}$ neutron pair. The observation of the weakly populated $\alpha = -1/2$ member of the ground band of ^{111}Tc provides important information of signature splitting in this nucleus. The rigid triaxial rotor plus particle model (RTRP) is employed to calculate the signature splitting, excitation energies and branching ratios of the ground band of ^{111}Tc. The best fits of RTRP calculation to the experiments for ^{111}Tc results in a shape of $\varepsilon_2 = 0.32$ and $\gamma = -26^0$, a larger triaxiality than those in the lighter Tc isotopes, indicating an increase of triaxiality in Tc with increasing neutron number.

II. Experimental Results

The populations and detections of the high-spin levels of $^{110, 111}$Tc were made by using spontaneous fission and measuring the prompt γ rays emitted in a multi-gamma detection array [15]. The $^{110, 111}$Tc were produced as complementary fission fragments of Cs isotopes. A ^{252}Cf source of 62 μCi, sandwiched between two 10 mg cm^{-2} Fe foils, was placed in an 8 cm polyethylene ball centered in Gammasphere, which consisted of 102 Compton-suppressed Ge detectors. Over 5.7×10^{11} triple and higher-fold events were accumulated. A Radware cube three-dimensional histogram was created [16]. A less compressed Radware cube was also used to clarify ambiguities caused by peaks overlapping, which was discussed in detail in [8].

As described in detail in our previous papers [e.g. 7], the identifications of the transitions of $^{110, 111}$Tc were based on cross-checking the coincident relationships with those of the complementary fission partner Cs isotopes, and with the relevant internal transitions as well. Careful background subtractions were always performed to eliminate possible accidental coincidences. Figure 1a and 1b show typical examples of double-gated, triple coincidence spectra for data analysis of ^{110}Tc and ^{111}Tc, respectively. In the spectra, transitions of ^{110}Tc (and ^{111}Tc) coincident with the gates are simultaneously seen with the strong transitions of the complementary fission partner Cs isotopes. Tables 1 and 2 summarize the transition energies and relative intensities determined in the present work for all the transitions identified in $^{110, 111}$Tc, respectively. Those reported in [14] for ^{111}Tc are also included in Table 2.

Table I Transition energies and relative intensities of the transitions in ^{110}Tc.

E_γ (keV)	Relative Intensities	Initial Level (keV)

53.5		53.5
88.1		240.5
98.9		152.4
104.5		256.9
126.3	100	605.2
128.8	2.4	2046.5
159.3	5.1	1430.4
178.3	57.8	783.5
178.9	25.5	962.3
222.0	89.6	478.9
238.4	32.1	478.9
304.5	19.9	783.5
309.0	11.6	1271.2
357.1	32.2	962.3
468.1	24.9	1430.4
487.3	3.3	1917.8
487.7	15.0	1271.2
616.1	14.5	2046.5
646.6	7.1	1917.8
(650.3)		2699.5
745.8	3.7	2792.3
781.7	1.9	2699.5
884.9	0.5	3677.3

Table II Transition energies and relative intensities of our measured transitions in ^{111}Tc and comparison energies (E_γ^*) from recent work of Urban et al. [14].

E_γ (keV)	Relative Intensities	E_γ^* (keV)	Initial Level (keV)
67.5		67.0	67.5
(124.0)			1830.7
126.5	14.3	126.5	610.1
132.0	100	131.6	199.5
132.6	3.6		1162.2
284.2	26.1	284.1	483.7
(293.6)			1182.0
313.1	4.2	312.2	888.4
375.8	13.6	375.8	575.3
410.6	47.7	410.6	610.1
416.3	12.9	415.5	483.7
419.5	7.0		1029.5

(507.8)			575.3
544.5	2.6		1706.8
545.8	6.9		1029.5
552.1	28.7	552.1	1162.2
606.7	3.2		1182.0
660.2	4.3		3214.5
668.5	19.2	668.4	1271.2
677.3	2.1		1706.8
723.6	9.5	723.4	2554.3
737.8	0.7		3952.3

Figures 2 and 3 show the level schemes of ^{110}Tc and ^{111}Tc proposed in the present work, respectively. The level scheme of ^{110}Tc represents the first observation of this nucleus. For ^{110}Tc, we have so far not been able to assign spins/parities to the levels observed. The levels observed in ^{110}Tc, Fig. 2, however, are quite similar to those in ^{106,108}Tc. The lowest energy levels in ^{110}Tc are rather similar to those in ^{108}Tc [17]. Then at 478.9 keV above the lowest state observed a $\Delta I = 1$ band with cascade and cross-over transitions begins that is very similar to those in ^{106,108}Tc as shown in Fig. 4 where the level energies of these high spin bands are compared. In Fig. 4, one also sees that there is a change in the signature splitting of this band in ^{110}Tc compared to ^{106,108}Tc. Assuming the same band-head spin of I for each of the three nuclei, one sees by the I + 4 level there is a sharp increase and reversal in the splitting with the I + 4 member somewhat closer to the I + 3 level in ^{108}Tc but the I + 4 level is much closer to the I + 5 level in ^{110}Tc. The splitting is also much greater in ^{110}Tc. The sharp increase in signature splitting in ^{110}Tc compared to ^{106,108}Tc may also be interpreted as a significant increase in triaxiality in ^{110}Tc.

The numbering for the bands identified in ^{111}Tc follows those for $^{105, 107, 109}$Tc in [8]. The level scheme of ^{111}Tc is considerably more extended than that reported in [14].

The α = +1/2 branch of the ground band (band 1) of ^{111}Tc reported in [14] reaches 2553.1 keV, ($25/2^+$) with no band-crossing observed; and for the α = -1/2 branch of band 1 only two levels at 67 and at 482.7 keV were reported [14]. It can be seen in Fig. 3 that the α = +1/2 branch of band 1 of ^{111}Tc identified in the present work reaches 3952.3 keV, ($33/2^+$) level and shows clearly a band-crossing. The α = -1/2 branch of band 1 reaches 1706.8 keV, ($19/2^+$) level, which provides important information about signature splitting of band 1. As can be seen in Fig. 3, band 6 observed in $^{105, 107, 109}$Tc [8] is also observed in ^{111}Tc.

The spin/parity assignments of the observed levels of ^{111}Tc are based on the level systematics observed in the Tc isotopic chains and by the observation of both cascade and linking transitions in the lower part of the bands. Shown in Fig. 5 are excitations of the levels of the ground $\pi g_{9/2}$ bands of $^{105, 107, 109, 111}$Tc. The smooth change of the level patterns with increasing neutron number supports the spin/parity assignments of the levels observed in ^{111}Tc (Fig. 3). It is reasonable to interpret the ground band of ^{111}Tc also as $\pi g_{9/2}$.

III. Discussion and calculations

The extending of ground band 1 of ^{111}Tc allows a study of the systematics of band-crossings in band 1 for the odd-A Tc isotopes. The kinematic moment of inertias of band 1 of $^{105, 107, 109, 110, 111}$Tc are given in Fig. 6a. As seen in the figure, a band crossing is observed in ^{111}Tc at a rotational frequency of ~ 0.35 MeV, with crossing frequency decreasing with increasing neutron number for the Tc isotopes; and for the odd-neutron neighbor ^{110}Tc, no band-crossing is observed in the frequency region. Figure 6b shows

J(1) of the ground bands in N = 68 isotones ^{111}Tc and ^{113}Rh [7]. As can be seen in the figure, band-crossing of the ground band of ^{111}Tc is observed at almost the same rotational frequency as that of ^{113}Rh, also with no band-crossing observed in the odd-neutron neighbor ^{112}Rh [7], where there is odd-neutron blocking. All the observations imply that the band-crossing of the ground band of ^{111}Tc can be interpreted to have the same origin as that of ^{113}Rh, that is, the breaking of a pair of $h_{11/2}$ neutrons [7].

Cranking shell model (CSM) calculations described by Bengtsson and Frauendorf [18 – 20] were performed in the present work for ^{111}Tc to give Total Routhian Surface (TRS) and Routhian. The TRS calculations gave deformation parameters of β_2 = 0.237, β_4 = -0.046, $\gamma = 60^0$ at ħω = 0.0 MeV. It can be seen in Fig. 7 that a minimum of TRS of ^{111}Tc is observed around deformation parameters β_2 = 0.295, β_4 = -0.004, $\gamma = -28.9^0$ at ħω = 0.2 MeV and β_2 = 0.262, β_4 = -.024, $\gamma = -38.7^0$ at ħω = 0.4 MeV, respectively. Inputting the β_2 and γ parameters obtained in the TRS calculations, the Routhian for ^{111}Tc is calculated by using CSM. An example of the Routhian calculations for ^{111}Tc is presented in Fig. 8 for quasi-protons (a) and for quasi-neutrons (b), respectively. One can see that the calculations for ^{111}Tc predict an alignment caused by two $h_{11/2}$ neutrons at a rotational frequency of ~ 0.36 MeV, which is in good agreement with the observation of the band-crossing of ^{111}Tc at ~ 0.35 MeV, supporting the interpretation of the band-crossing as alignment of a pair of $h_{11/2}$ neutrons.

Shown in Fig. 9 are the level systematics of the band 6 in $^{105, 107, 109, 111}$Tc observed in [8] and in the present work. Those of the Rh isotopes [7] are also given in the figure. A clear tendency is seen in the figure that with increasing neutron number the excitation energies of the bandhead of band 6 of the Tc isotopes is decreasing, even more rapidly than in the

Rh isotopes. Like the Rh and $^{105, 107, 109}$Tc cases, band 6 of ^{111}Tc, built on the excited $11/2^+$ state, de-excites to the $g_{9/2}$ ground band with predominant feeding to the $9/2^+$ level and very weak decay to the $7/2^+$ level. In view of the low excitation energy of the bandhead and the near vanishing of the E2 decay-out transition from the $(11/2^+)$ bandhead to the $7/2^+$ level of the ground band, the γ phonon interpretation for band 6 given in [14] and [21] is unlikely. Instead, as for $^{111, 113}$Rh [7] and $^{105, 107, 109}$Tc [8], we believe that the level energies and decay pattern of band 6 of ^{111}Tc provide strong evidence of triaxiality. The quenching of the $(11/2^+)_{2.} \rightarrow 7/2^+_1$ transition was explained by examining the wave functions [7]. The main core component in the wave functions of both the initial and final states is the first 2^+ core state; thus the E2 transition strength is mainly dictated by the diagonal E2 reduced matrix element, which vanishes for $\gamma = -30^0$. However, the main core component of the $9/2^+_1$ state is the 0^+ state of the core, resulting in a large B(E2, $11/2^+_{2.} \rightarrow 9/2^+_1$). Band 6 is thus considered to be in the collective family of the ground band, and the term 'K+2 satellite band' is suggested for it (see discussion in more detail in [8] and in the following paragraphs).

In our previous theoretical calculations dedicated to the investigation of the neutron-rich Y and Nb isotopes [9] and lighter odd-even Tc and Rh isotopes [7, 8] we employed the rigid tiaxial rotor plus particle model (RTRP) to calculate the energy levels and several E2 and M1 strengths of the ground bands and some yrare levels. The model described very well the basic properties of these nuclei, like signature splitting, excitation energies and branching ratios. In the present work, we describe the level structure of ^{111}Tc in the framework of the same model.

The model was introduced in detail in the paper by Larsson et al. [22], and calculations based on this model for several neutron-rich nuclei in the considered mass region can be found in [7, 8, 9]. In the RTRP model the odd particle occupying a deformed single-particle orbital is coupled to a rigid triaxial core. The nuclear field is described by a deformed modified oscillator potential characterized by the deformation parameters ε_2, ε_4 and γ, which are kept constant throughout the calculations (so-called rigid shape). In the present work, a value $\varepsilon_4 = 0$ was assumed. The asymmetry parameter γ was fitted from the splitting of the levels with opposite signature by using the signature-splitting function S(I) suggested by Zamfir et al. in [23],

where $$S(I) = \frac{E(I) - E(I-1)}{E(I) - E(I-2)} \cdot \frac{I(I+1) - (I-2)(I-1)}{I(I+1) - (I-1)I} - 1 \qquad (1)$$

We use the Lund convention for γ [24], for which the interval $0 \geq \gamma \geq -60^0$ describes the collective rotation, with $\gamma = 0$ corresponding to a prolate shape and $\gamma = -60^0$ corresponding to an oblate shape. The model uses the hydrodynamical irrotational flow formula for the ratios of the moments of inertia along the principal axes, which depend only on the deformation parameter γ. They can be normalized by using the effective value $E(2^+)$ of the core, which represents a scaling factor of the rotational energy. Pairing is included in the model by a standard BCS calculation. It is also possible to reduce the strength of the Coriolis force by an attenuation factor ξ [25]. Because of the triaxiality, the projection *K* of the total angular momentum *I* on the intrinsic axis 3 (quantization axis) is no longer equal to the projection Ω of the particle angular momentum *j* on the same axis. However, in triaxial nuclei, a rotational band can in principle be characterized by the *K* quantum number which has the dominant contribution to the total wave function.

In the case of ^{111}Tc the fitted parameters are $\varepsilon_2 = 0.32$, $\gamma = -26^0$, $E(2^+) = 0.25$ MeV and $\xi = 0.8$. The RTRP model reproduces very well the large splitting, S(I) experimentally found in ^{111}Tc as seen in Fig. 10. In [8], the model parameters found to best fit the shape of ^{107}Tc were $\varepsilon_2 = 0.32$ and $\gamma = -22.5^0$. In the present work RTRP calculations were also performed for ^{109}Tc, and the model parameters found to best fit the shape of ^{109}Tc were $\varepsilon_2 = 0.32$ and $\gamma = -25^0$. The RTRP calculations for $^{107,\,109,\,111}$Tc show that for neutron-rich nuclei with Z = 43 in A ~ 110 region, with increasing neutron number the quadrupole deformation remains practically unchanged while the asymmetry parameter γ becomes larger. The increase in triaxiality with increasing neutron number is in fact suggested by the increase in the signature splitting function when going from ^{105}Tc to ^{111}Tc, as seen in the plot of Fig. 11.

The model describes quite well also the excitation energies of the ground band and yrare band (see Fig. 12). The intrinsic wave functions for the states in both bands were found to be dominated by the $7/2^+[413]$ single-particle orbital. However, as in the case of ^{107}Tc [8], the model does not reproduce the experimental $5/2^+$ -- $7/2^+$ level ordering, with $5/2^+$ being the ground state. A Harris plot performed for the favored-signature band in ^{107}Tc showed that the $5/2^+$ state clearly deviates from the extrapolated plot, suggesting that the intrinsic structure of this state may be different from that of the rest of the band [8]. In our calculation, the $5/2^+$ level is dominated by a component with $K = 5/2$, while the higher-spin states were found to have a dominant $K = 7/2$ component. In the yrare band, however, the main contribution to the total wave function has $K = 11/2$. The different values of K in bands based on the same Nilsson state are caused by different orientations of the core angular momentum.

Table III Comparison of theoretical and experimental branching ratios of the ground band of ^{111}Tc

Branching ratios	Theory	Expt.
$I(11/2^+ \rightarrow 9/2^+)/I(11/2^+ \rightarrow 7/2^+)$	1.74	2.02
$I(13/2^+ \rightarrow 11/2^+)/I(13/2^+ \rightarrow 9/2^+)$	0.2	0.3
$I(15/2^+ \rightarrow 13/2^+)/I(15/2^+ \rightarrow 11/2^+)$	0.85	1.0
$I(17/2^+ \rightarrow 15/2^+)/I(17/2^+ \rightarrow 13/2^+)$	0.07	0.125
$I(19/2^+ \rightarrow 17/2^+)/I(19/2^+ \rightarrow 15/2^+)$	0.55	1.24
$I(11/2^+_2 \rightarrow 9/2^+_1)/I(11/2^+_2 \rightarrow 7/2^+_1)$	10.8	>13.6

The comparison of theoretical and experimental branching ratios I_γ ($I \rightarrow I$-1) / I_γ ($I \rightarrow I$-2) for the transitions within the ground band and the ratio of the decays of the $11/2^+_2$ state $I(11/2^+_2 \rightarrow 9/2^+_1)/I(11/2^+_2 \rightarrow 7/2^+_1)$ are given in Table III. The agreement between experiment and theory is very good. The interesting feature observed in the lighter Tc isotopes, namely the predominant decay of the $11/2^+_2$ state to the $9/2^+$state of the ground band, is present also in ^{111}Tc. As a matter of fact, in ^{111}Tc the $11/2^+_2 \rightarrow 7/2^+$ transition is so weak that its relative intensity could not be extracted in the present experiment. As mentioned above, the preference for the decay of the $11/2^+_2$ to the $9/2^+_1$ state was explained by invoking the composition of the core wave functions of the states involved. In ^{111}Tc, for instance, the model predicts that the states $11/2^+_2$, $13/2^+_2$ and $15/2^+_2$ have a dominant K = 11/2 component and the dominant core angular momentum for the $11/2^+_2$ state is R = 2. The same core state has the maximum amplitude in the wave function describing the $7/2^+$ state of the ground band, which means that the $E2$ strength of the $11/2^+_2 \rightarrow 7/2^+$ transition is mainly determined by the diagonal matrix element of the quadrupole operator. For nuclei with γ = -30^0 this matrix element vanishes. For the 9/2$^+$ state the calculations reveal that the main contribution to the total wave function is determined by the R = 0 core state, resulting in a large matrix element of the quadrupole operator. This property is directly related to the triaxial deformation [26]. If we assume an upper limit of 0.01 relative intensity for the $11/2^+_2 \rightarrow 7/2^+_1$ transition then the lower limit for the intensity ratio $I(11/2^+_2 \rightarrow 9/2^+_1)$ / I(11/2+2 $\rightarrow$ $7/2^+_1$) is 13.6. Theoretically we obtained 10.8 for the same ratio, which describes rather well the enhancement of the $11/2^+_2 \rightarrow 9/2^+_1$ transition with respect to the$11/2^+_2 \rightarrow 7/2^+$ transition.

Finally, it is necessary to compare the shape parameters used in the CSM and RTRP calculations performed in the present work. The CSM calculations reproduced quite well the band-crossing of band 1 in ^{111}Tc, and the RTRP calculations gave best fits to the signature splitting, excitations and branching ratios of the band in the nucleus, respectively. Despite the differences in the absolute values of β_2 and γ parameters between CSM and RTRP calculations, the two calculations are in essential agreement, with very large β_2 for the ground band with slowly decreasing deformation with rotational frequency and triaxiality parameter γ that approaches -30^o with rotational frequency. We need to keep in mind that the RTRP calculations deal with one-quasiparticle states and are thus only valid within a rotational frequency region below the band-crossing. Since in our previous papers RTRP calculations were performed for the Tc and Rh isotopes [7, 8], we prefer to use the shape parameters for ^{111}Tc also obtained in RTRP calculations to study the shape evolutions in the isotopes.

In summary, an yrast level scheme of ^{110}Tc is established for the first time. Our extension of the level scheme of ^{111}Tc allows the study of band-crossing and signature splitting in the more neutron-rich Tc isotopes. The systematics of band-crossing frequencies of the $^{105-111}$Tc isotopes and N=68 Tc/Rh isotones and cranking shell model calculations suggest that the alignment of a pair of $h_{11/2}$ neutrons account for the band crossing of the ground band of ^{111}Tc. The very large signature splitting observed in ^{111}Tc (even larger than those observed in $^{105-109}$Tc) is accounted for by large triaxial deformations in the nucleus. A shape of ε_2 = 0.32 and γ = -26^0 is deduced with the best fits to signature splitting, branching ratios and excitations of the ground band of ^{111}Tc by the RTRP model calculations. This shows an increasing triaxiality with increasing neutron number for Tc isotopes. For ^{110}Tc, a ΔI = 1 band is observed that is overall similar to those in ^{106,108}Tc but shows larger signature splitting and a different sign of signature splitting with the I + 4 level much close to the I + 5 level and similarly for higher spins in ^{110}Tc, while the I + 4 level is closer to the I + 3 level in ^{106,108}Tc.

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Figure captions

Fig. 1a A double-gated triple-coincidence spectrum for ^{110}Tc data analysis. All transitions identified in ^{110}Tc coincident with the gates are simultaneously seen in the spectrum with those of the complementary fission partners, Cs isotopes.

Fig. 1b A double-gated triple-coincidence spectrum for ^{111}Tc data analysis. All transitions identified in ^{111}Tc coincident with the gates are simultaneously seen in the spectrum with those of the complementary fission partners, Cs isotopes.

Fig. 2 Level scheme of ^{110}Tc proposed for the first time in the present work, assuming band-head spin I, as for $^{106, 108}$Tc in [17].

Fig. 3 Level scheme of ^{111}Tc proposed in the present work. The α = +1/2 member of the ground band reaches the band-crossing region; and the weakly populated α = -1/2 member of the ground band is identified for the first time. A 'K+2 satellite band', band 6, similar to those in $^{105, 107, 109}$Tc [8] is also identified in ^{111}Tc. See text.

Fig. 4 Level systematics of the high spin bands in even-A ^{106,108,110}Tc. The ΔI=1 yrast band observed in ^{110}Tc is very analogous to those recently observed in ^{106,108}Tc [17], but it has greater and reversal signature splitting at higher spins.

Fig. 5 Systematics of the level patterns of the ground bands of odd-A $^{103-111}$Tc isotopes. The data are taken from the present work and [12, 8]. A smooth trend can be seen. See text.

Fig. 6a Kinematic moment of inertia $J^{(1)}$ of the ground bands of $^{105-111}$Tc. Also shown in the figure is that of ^{110}Tc. The crossing frequency is decreasing with increasing neutron number. However, no crossing is seen in ^{110}Tc in the frequency region. See text. Data are taken from the present work and [12, 8] (online in color)

Fig. 6b Kinematic moment of inertia $J^{(1)}$ of ground bands of the N = 68 isotones ^{111}Tc and ^{113}Rh. The $J^{(1)}$ of ^{112}Rh is also shown in the figure. Almost the same crossing frequency is observed in these isotones. However, no crossing is seen in ^{112}Rh in the frequency region. See text. The data of ^{112,113}Rh are taken from [7].(online in color)

Fig. 7 Polar coordinate plots of Total Routhian Surface (TRS) calculated at $\hbar\omega$ = 0.2 MeV and 0.4 MeV for ^{111}Tc, respectively.

Fig. 8 Calculated Routhian in ^{111}Tc for quasi-protons (a) and quasi-neutrons (b) plotted vs rotational frequency. The parity and signature (π, α) of the state are solid lines (+,+); dotted lines (+,-); dot-dashed lines (-,+); dashed lines (-,-).

Fig. 9 Level systematics of the band 6 of $^{105-111}$Tc. Those of the Rh isotopes are also shown. A rapid lowering of the low-lying bandhead of band 6 with increasing neutron number is observed for both Tc and Rh isotopes. See text. Data are taken from the present work and [7, 8, 12, 27].

Fig. 10 Comparison of theoretical and experimental signature splitting of the ground band of ^{111}Tc. Calculations were performed by using the RTRP model. A good agreement is obtained by using parameters $\varepsilon_2 = 0.32$, $\gamma = -26^0$, $E(2^+) = 0.25$ MeV and $\xi = 0.8$. See text.

Fig. 11 Experimental signature splittings of the ground bands of $^{105\text{-}111}$Tc ◊;: ^{105}Tc □; ^{107}Tc ●; ^{109}Tc ▲; ^{111}Tc. The signature splitting of ^{111}Tc is the largest among all the Tc isotopes, implying a larger triaxiality. Data are taken from the present work and [8]. See text. (online in color.)

Fig. 12 Comparison of theoretical and experimental excitation energies of the ground band (band 1) and band 6 of ^{111}Tc. Calculations were performed by using the RTRP. A good agreement is obtained by using the same parameters as in Fig. 10. See text.

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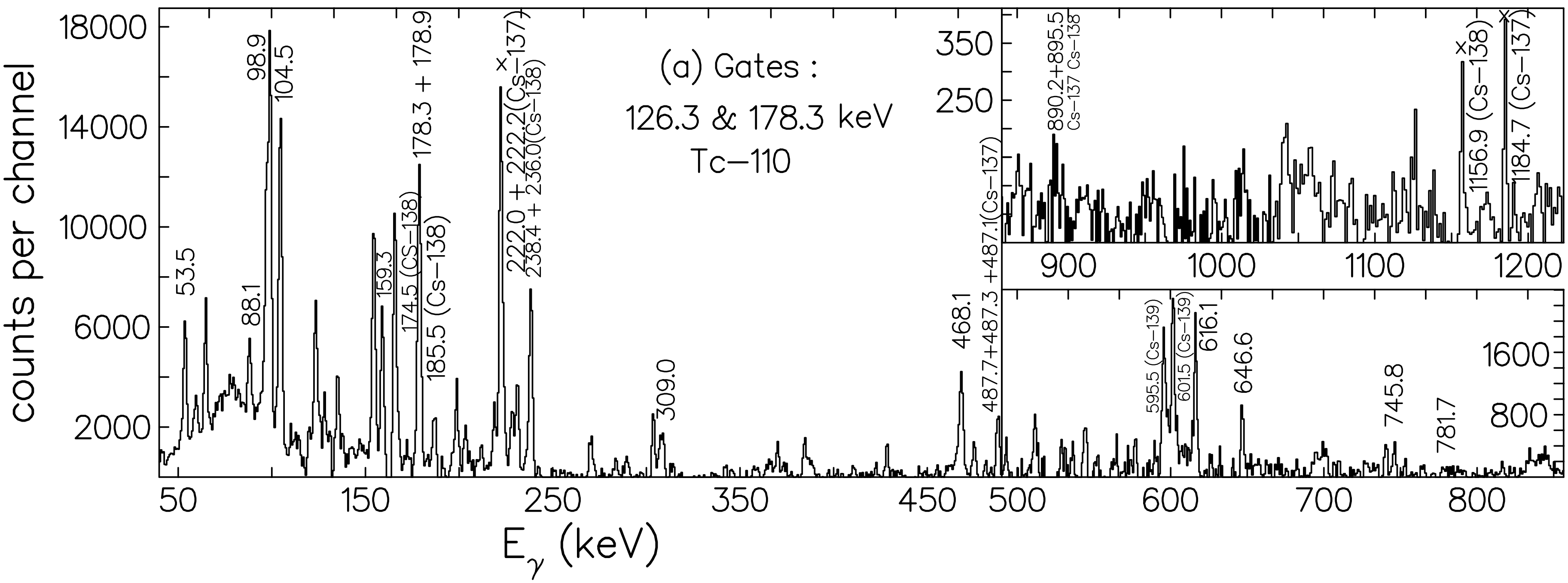
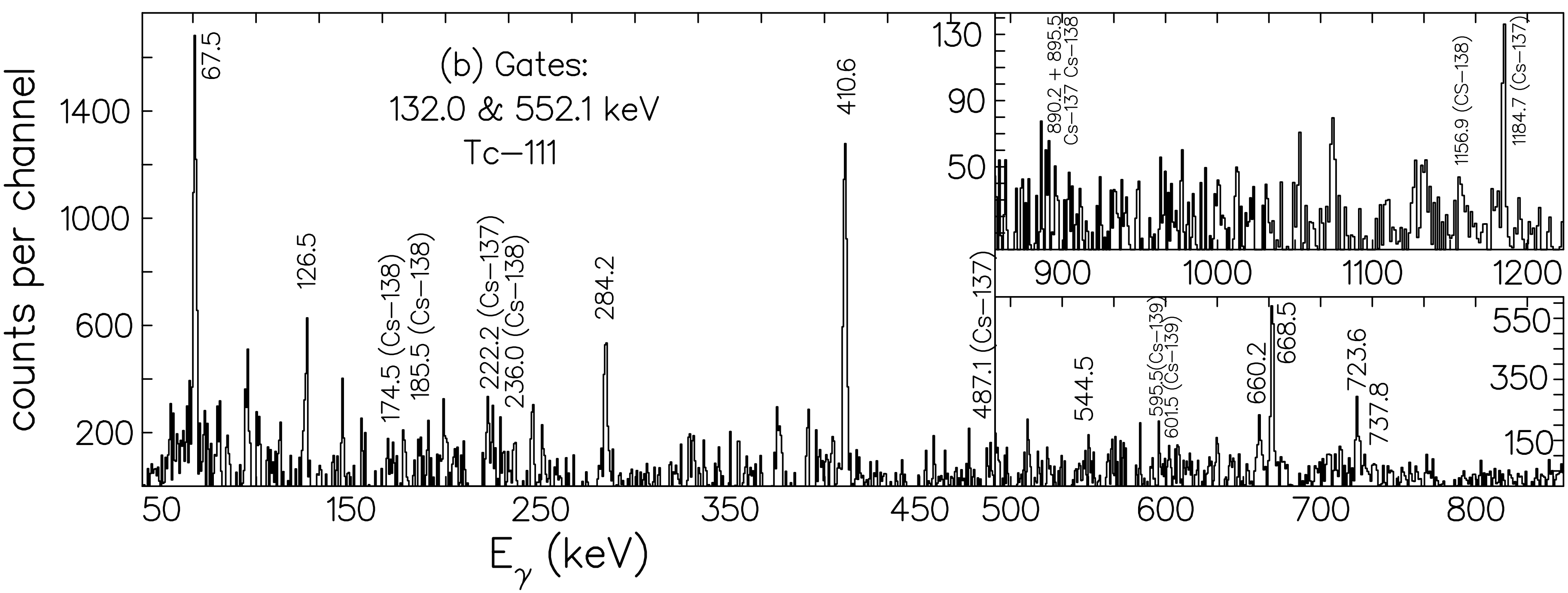
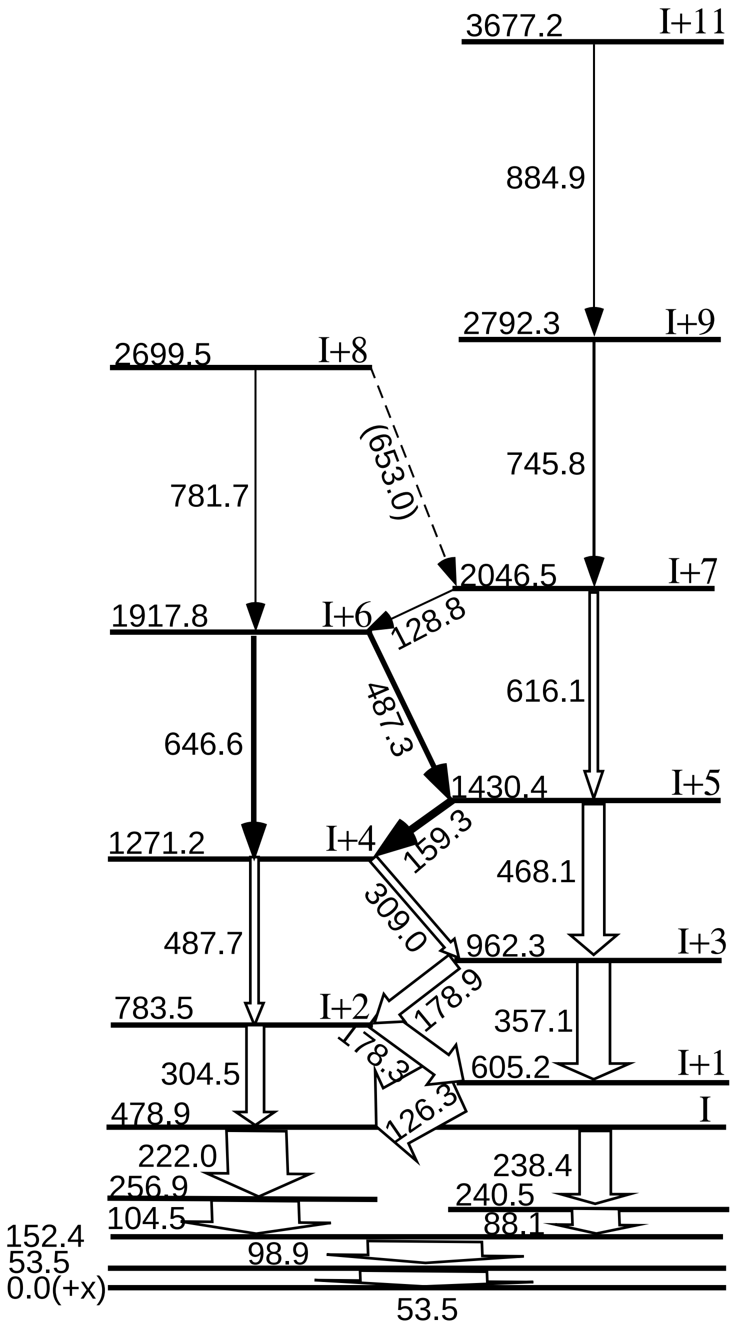


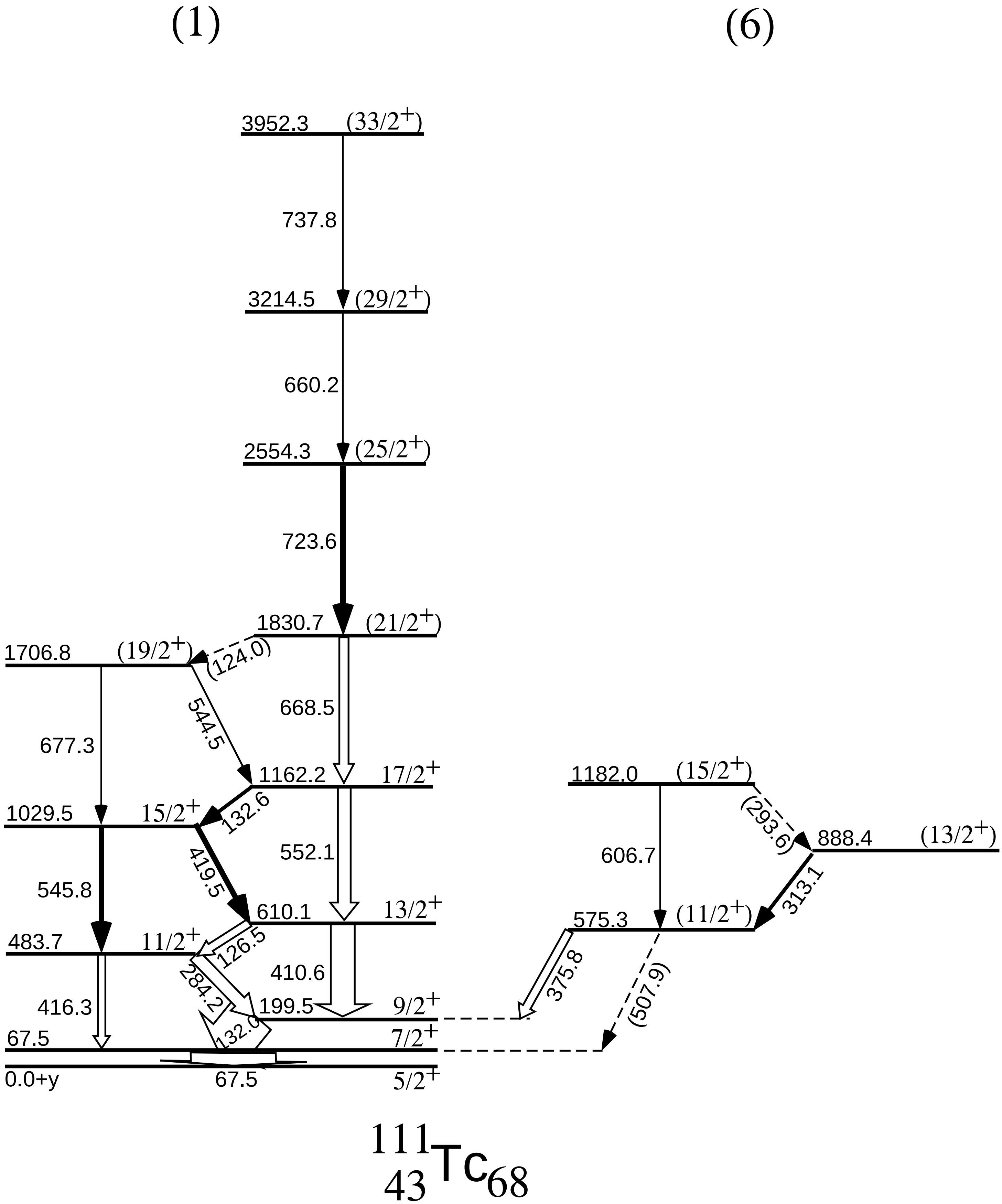
(a) Gates :
126.3 & 178.3 keV
Tc−110
counts per channel
E_γ (keV)
53.5
88.1
98.9
104.5
159.3
174.5 (CS−138)
178.3 + 178.9
185.5 (Cs−138)
222.0 + 222.2(Cs−137)
238.4 + 236.0(Cs−138)
309.0
468.1
487.7+487.3 +487.1(Cs−137)
595.5 (Cs−139)
601.5 (Cs−139)
616.1
646.6
745.8
781.7
890.2+895.5
Cs−137 Cs−138
1156.9 (Cs−138)
1184.7 (Cs−137)

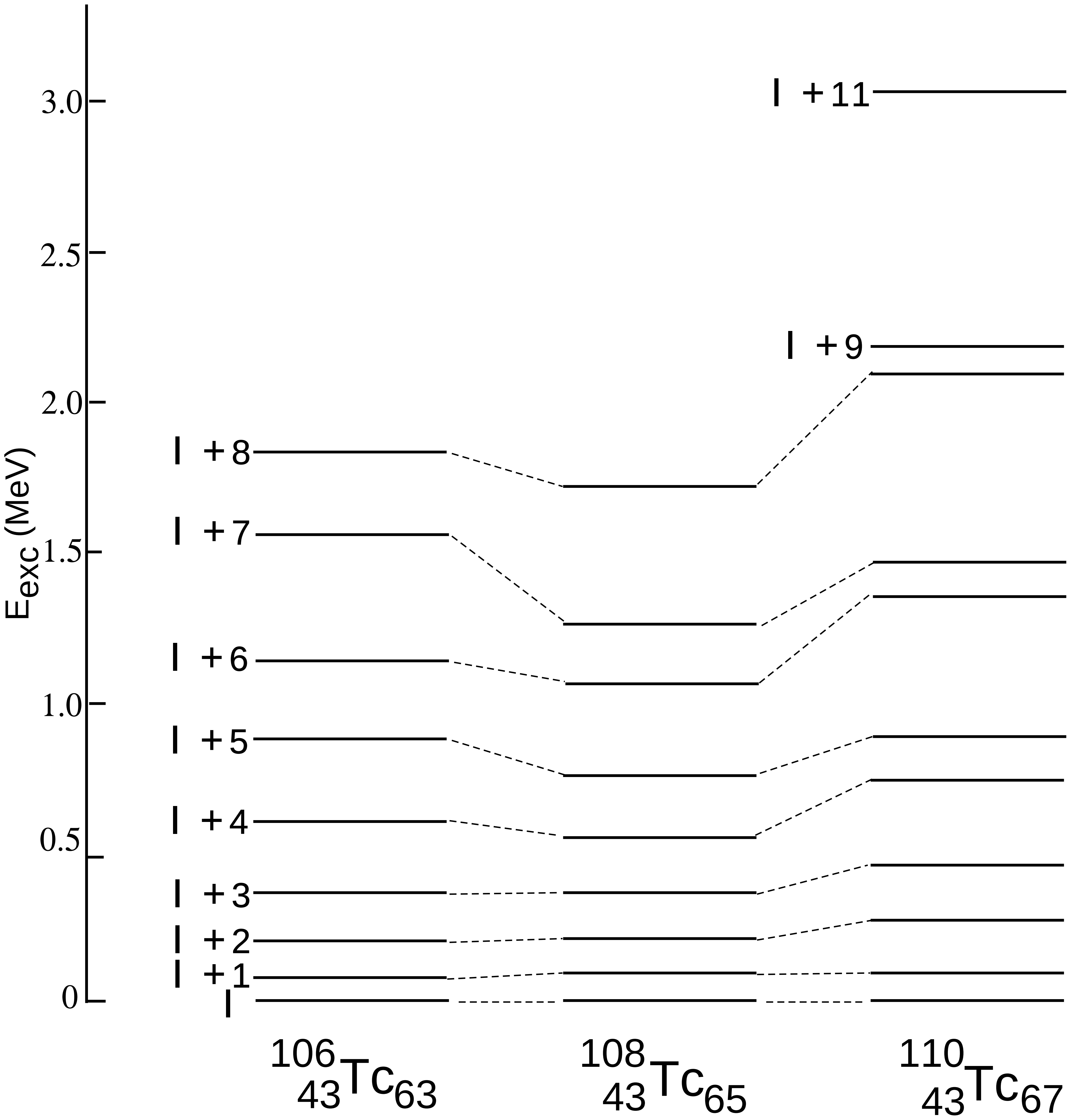


(b) Gates:
132.0 & 552.1 keV
Tc−111
counts per channel
E_γ (keV)
67.5
126.5
174.5 (Cs−138)
185.5 (Cs−138)
222.2 (Cs−137)
236.0 (Cs−138)
284.2
410.6
487.1 (Cs−137)
544.5
595.5(Cs−139)
601.5 (Cs−139)
660.2
668.5
723.6
737.8
890.2 + 895.5
Cs−137 Cs−138
1156.9 (CS−138)
1184.7 (Cs−137)

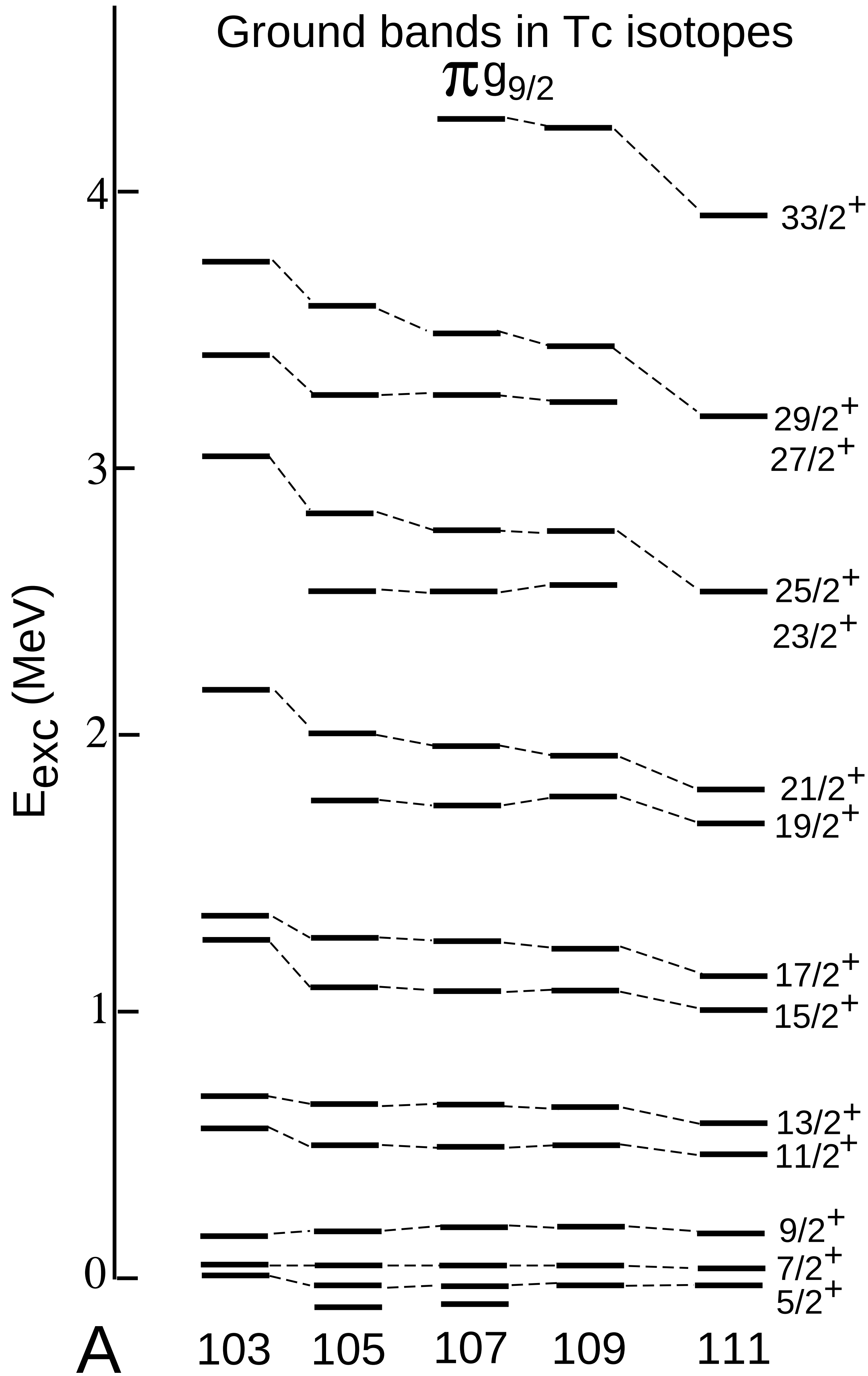

3677.2
I+11
884.9
2792.3
I+9
2699.5
I+8
(653.0)
781.7
745.8
2046.5
I+7
1917.8
I+6
128.8
487.3
646.6
616.1
1430.4
I+5
1271.2
I+4
159.3
468.1
309.0
487.7
962.3
I+3
783.5
I+2
178.9
357.1
178.3
304.5
605.2
I+1
126.3
478.9
I
222.0
238.4
256.9
240.5
104.5
88.1
152.4
98.9
53.5
0.0(+x)
53.5

$^{110}_{43}Tc_{67}$

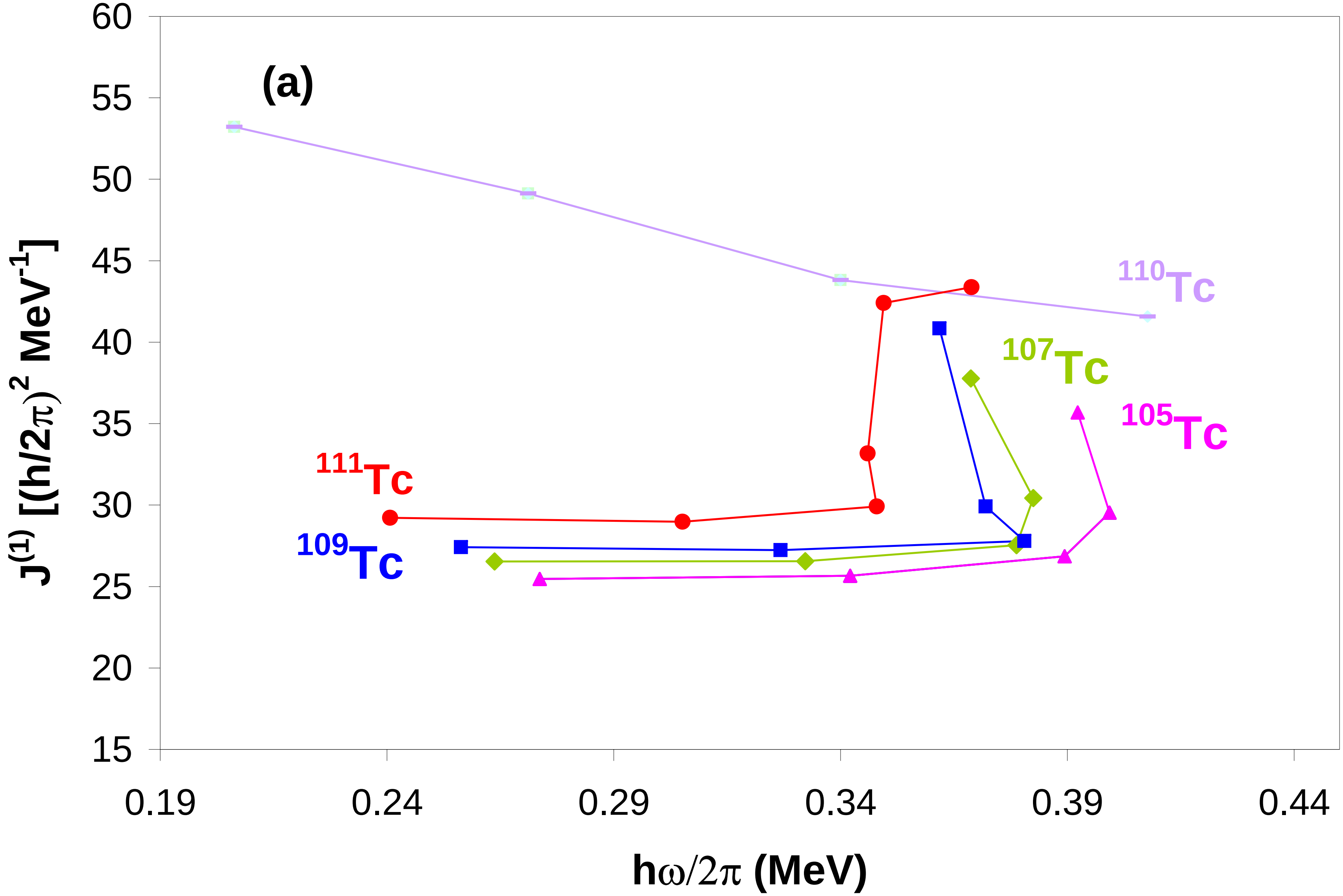

(1)
(6)
3952.3
(33/2+)
737.8
3214.5
(29/2+)
660.2
2554.3
(25/2+)
723.6
1830.7
(21/2+)
1706.8
(19/2+)
(124.0)
668.5
677.3
544.5
1162.2
17/2+
1182.0
(15/2+)
1029.5
15/2+
132.6
(293.6)
888.4
(13/2+)
552.1
606.7
545.8
419.5
313.1
610.1
13/2+
575.3
(11/2+)
483.7
11/2+
126.5
410.6
416.3
284.2
375.8
(507.9)
199.5
9/2+
67.5
132.0
7/2+
0.0+y
67.5
5/2+
$^{111}_{43}Tc_{68}$



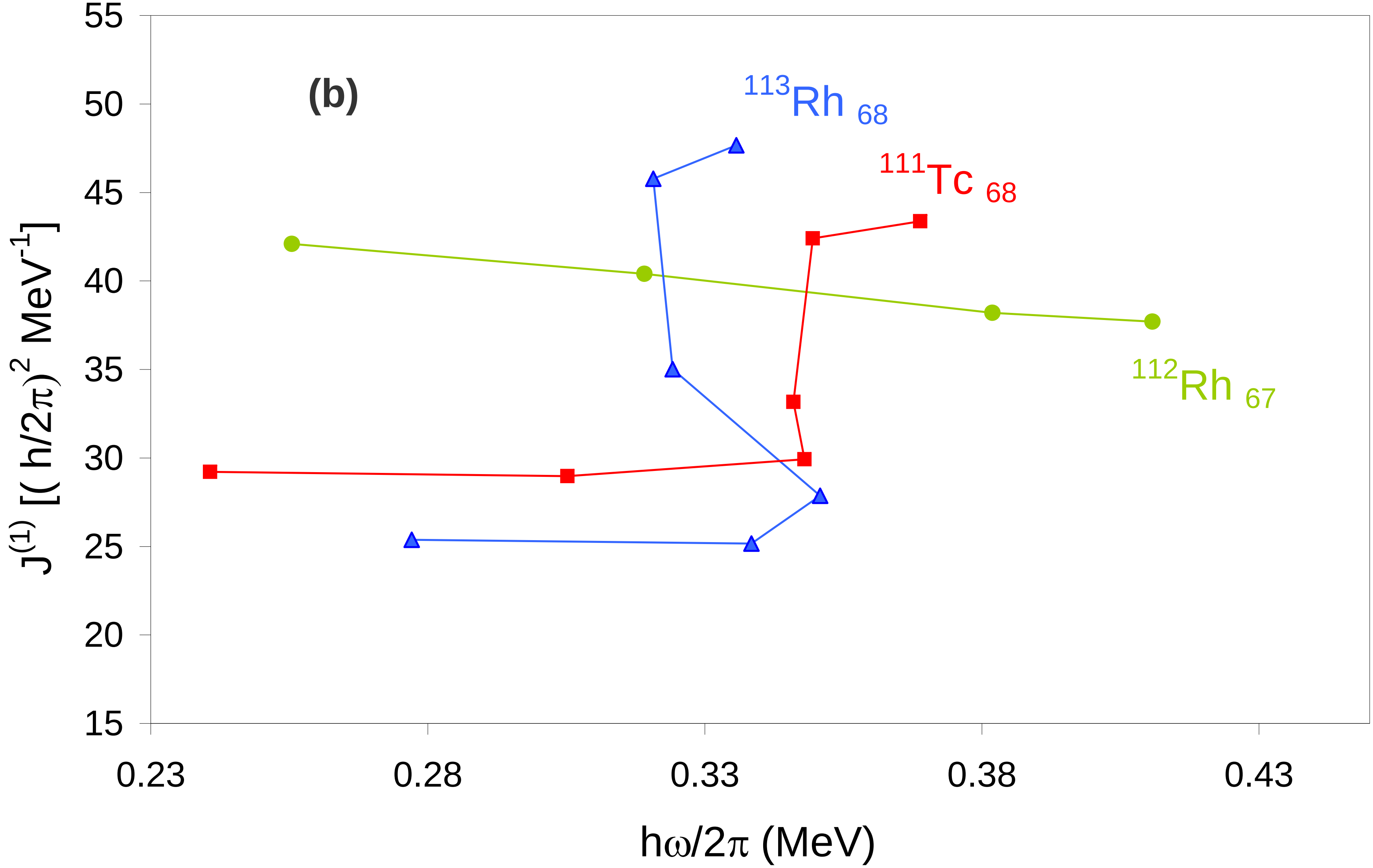
3.0
2.5
2.0
1.5
1.0
0.5
0
E exc (MeV)
I + 11
I + 9
I + 8
I + 7
I + 6
I + 5
I + 4
I + 3
I + 2
I + 1
I
$^{106}_{43}Tc_{63}$
$^{108}_{43}Tc_{65}$
$^{110}_{43}Tc_{67}$



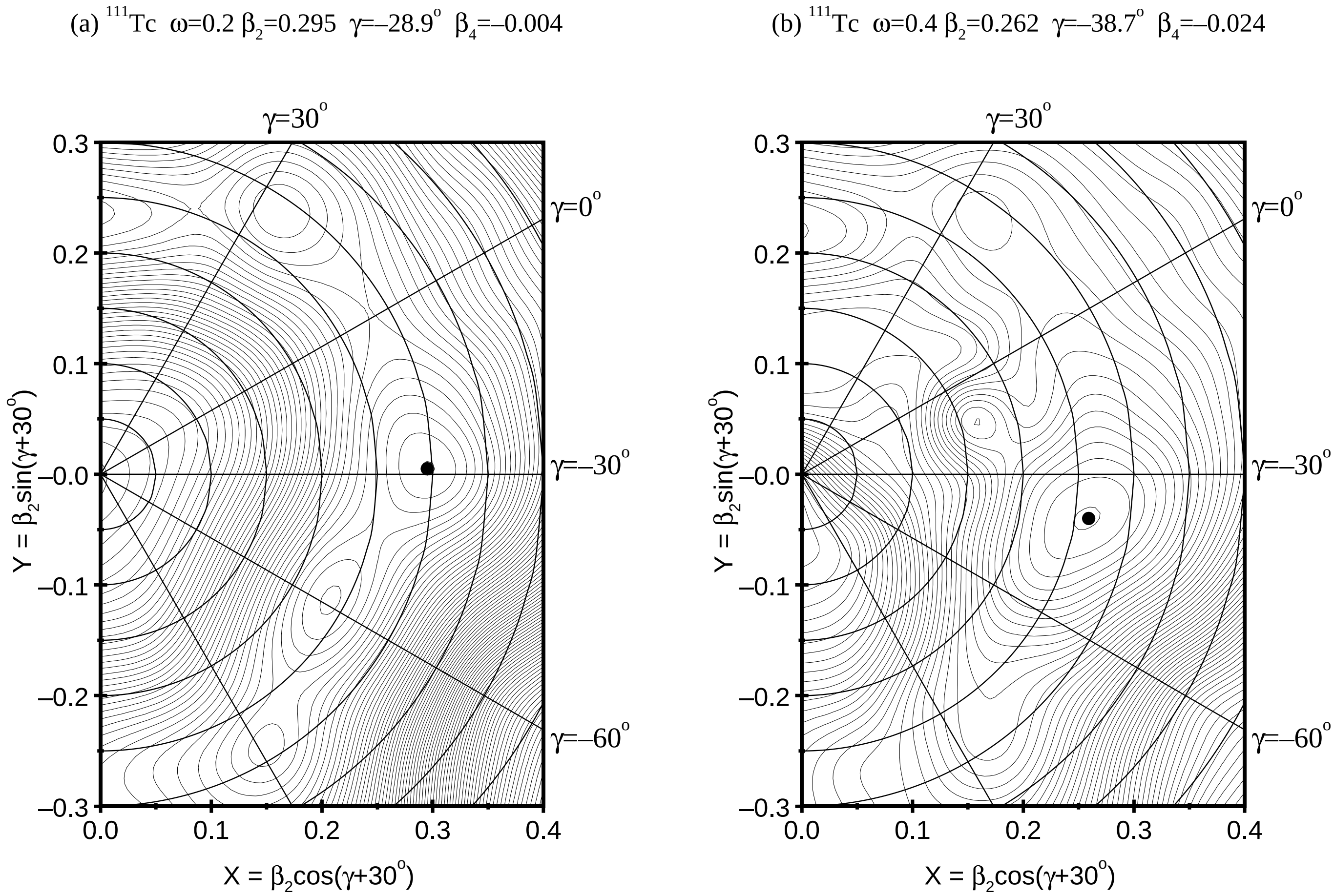
Ground bands in Tc isotopes
πg9/2
Eexc (MeV)
4
3
2
1
0
33/2+
29/2+
27/2+
25/2+
23/2+
21/2+
19/2+
17/2+
15/2+
13/2+
11/2+
9/2+
7/2+
5/2+
A
103
105
107
109
111

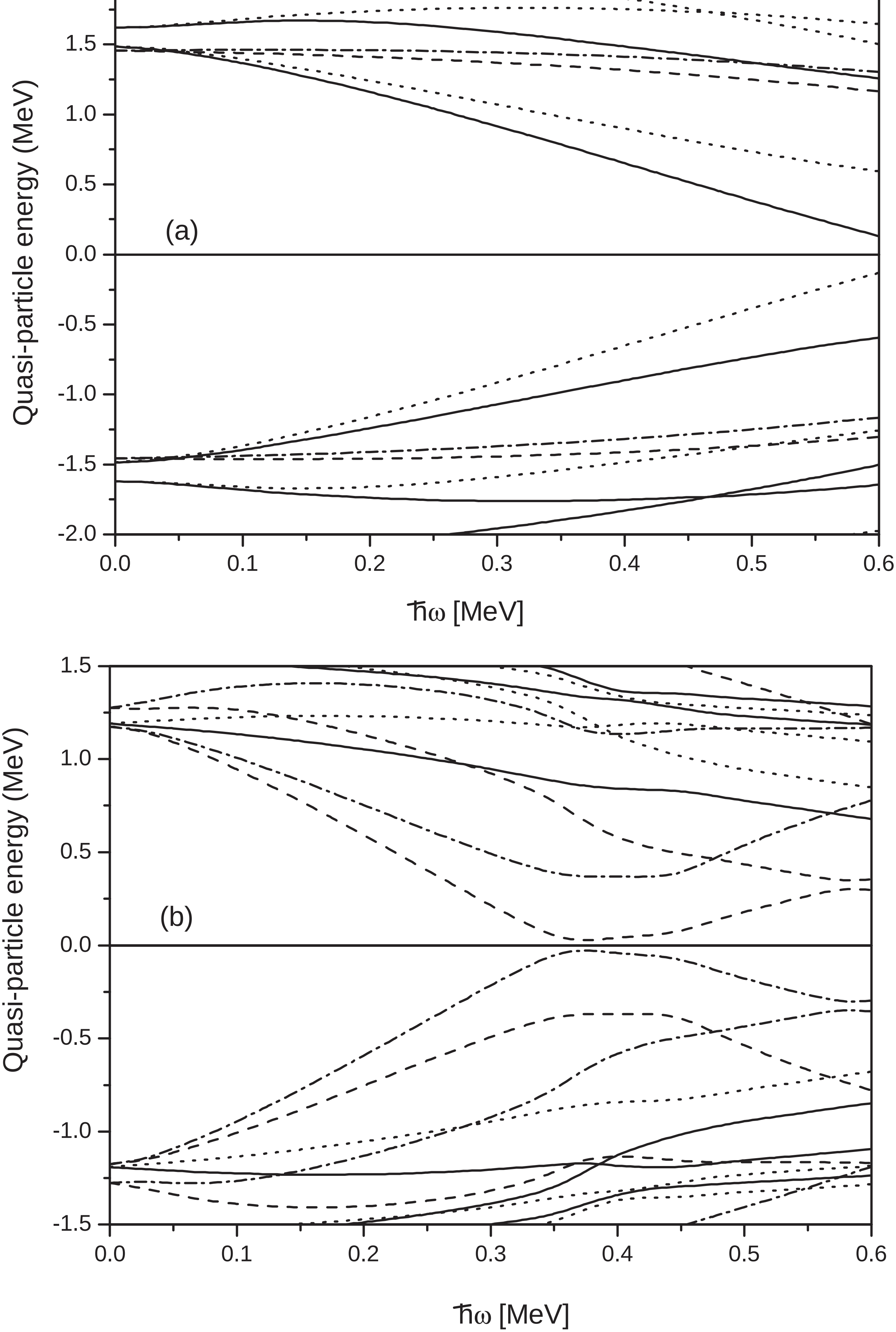


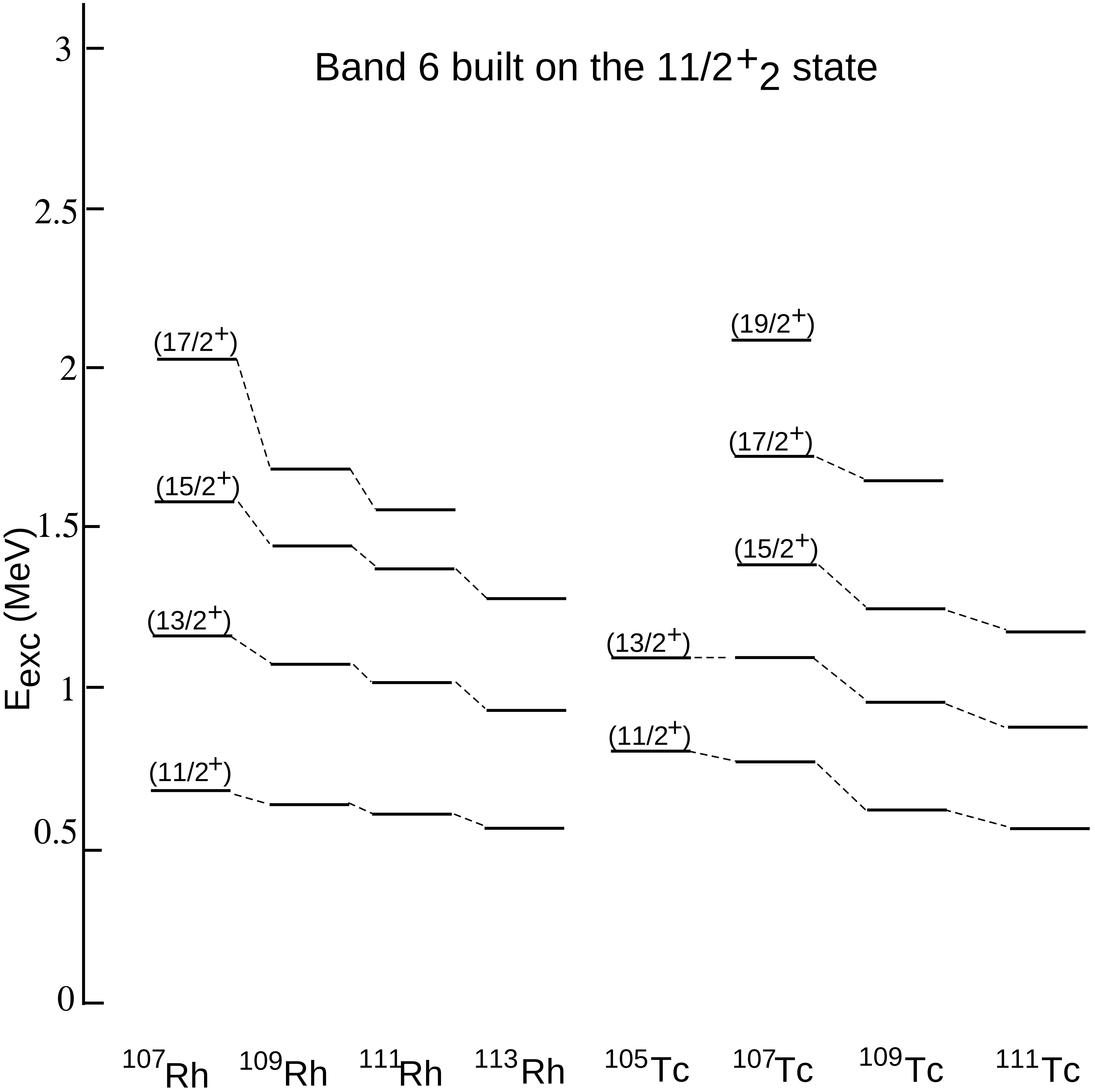
(a)
110Tc
107Tc
105Tc
111Tc
109Tc
J(1) [(h/2π)2 MeV-1]
hω/2π (MeV)
60
55
50
45
40
35
30
25
20
15
0.19
0.24
0.29
0.34
0.39
0.44

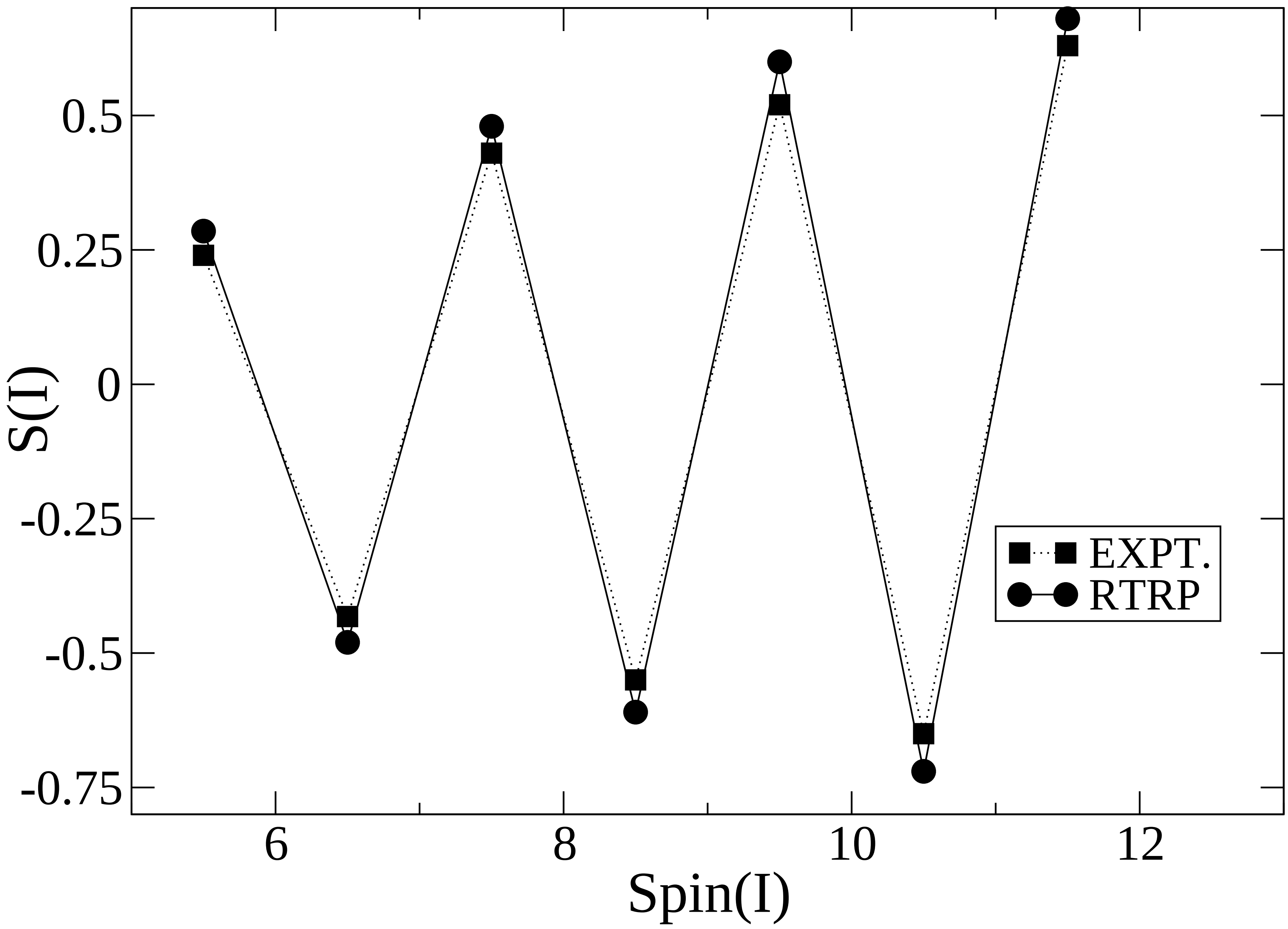


(b)
$^{113}Rh_{68}$
$^{111}Tc_{68}$
$^{112}Rh_{67}$
55
50
45
40
35
30
25
20
15
0.23
0.28
0.33
0.38
0.43
$J^{(1)}$ [(h/2π)^2 MeV^{-1}]
hω/2π (MeV)

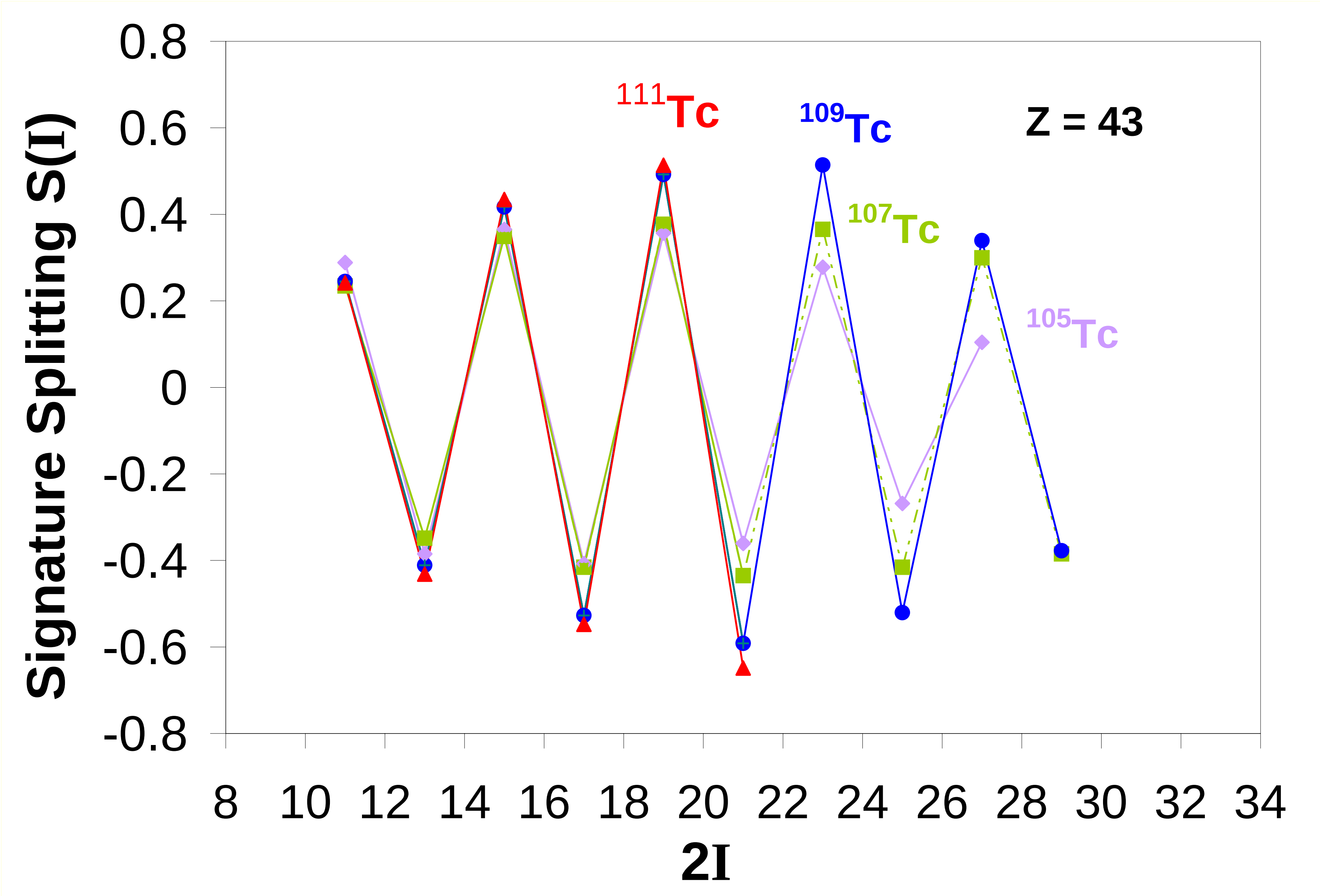

(a) ^{111}Tc ω=0.2 β_2=0.295 γ=–28.9^o β_4=–0.004
(b) ^{111}Tc ω=0.4 β_2=0.262 γ=–38.7^o β_4=–0.024
γ=30^o
γ=0^o
γ=–30^o
γ=–60^o
Y = $\beta_2$sin(γ+30^o)
X = $\beta_2$cos(γ+30^o)
0.3
0.2
0.1
–0.0
–0.1
–0.2
–0.3
0.0
0.1
0.2
0.3
0.4


Quasi-particle energy (MeV)
ħω [MeV]
(a)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Quasi-particle energy (MeV)
ħω [MeV]
(b)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6

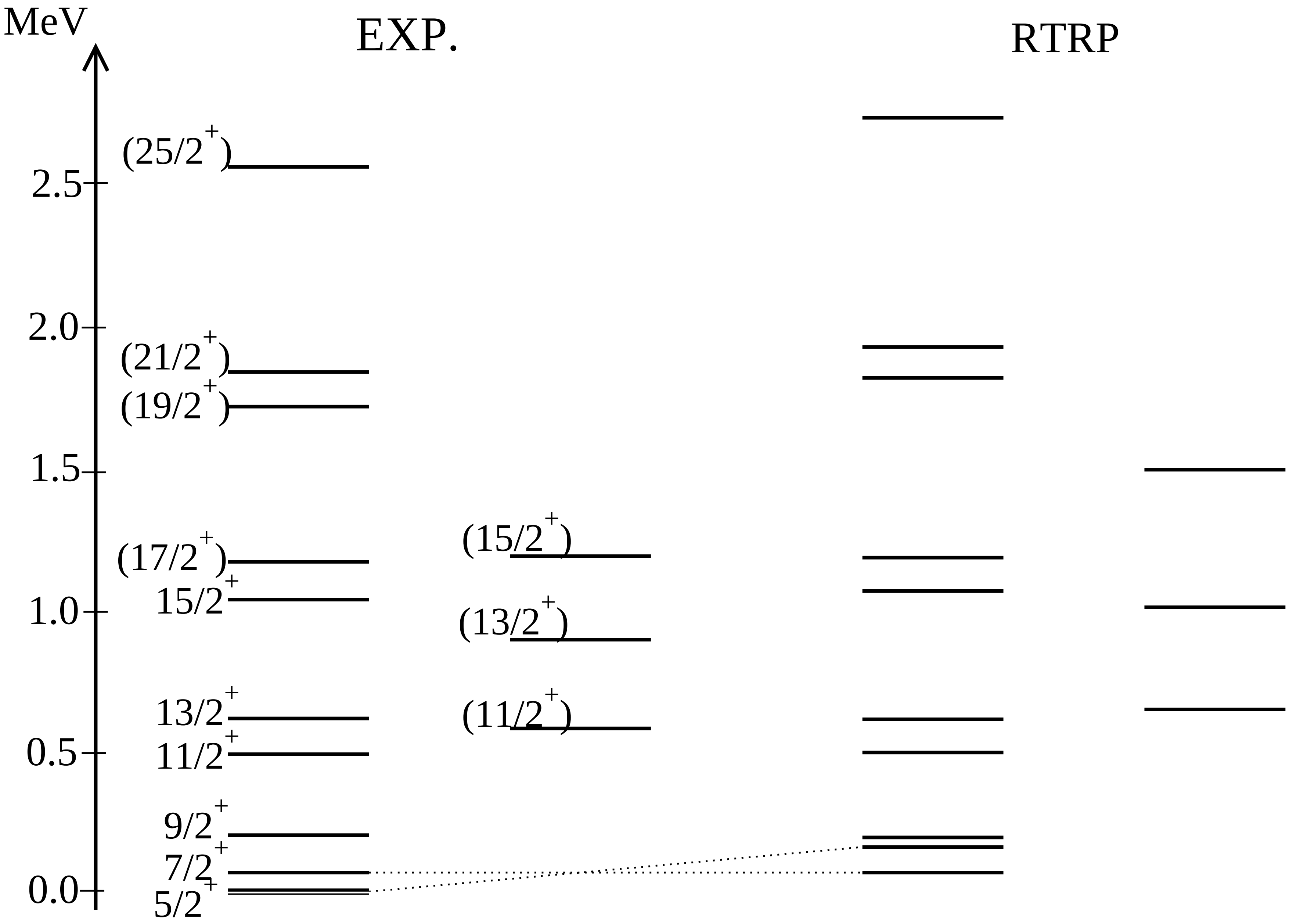

Band 6 built on the $11/2^+_2$ state
E_{exc} (MeV)
3
2.5
2
1.5
1
0.5
0
(17/2+)
(15/2+)
(13/2+)
(11/2+)
(19/2+)
(17/2+)
(15/2+)
(13/2+)
(11/2+)
107Rh
109Rh
111Rh
113Rh
105Tc
107Tc
109Tc
111Tc



0.5
0.25
0
-0.25
-0.5
-0.75
S(I)
6
8
10
12
Spin(I)
EXPT.
RTRP



Signature Splitting S(I)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
8
10
12
14
16
18
20
22
24
26
28
30
32
34
2I
111Tc
109Tc
107Tc
105Tc
Z = 43


MeV
EXP.
RTRP
2.5
2.0
1.5
1.0
0.5
0.0
(25/2+)
(21/2+)
(19/2+)
(17/2+)
15/2+
13/2+
11/2+
9/2+
7/2+
5/2+
(15/2+)
(13/2+)
(11/2+)