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Authors

Tamura, T.
Rezanka, I.
Iwata, S.
et al.

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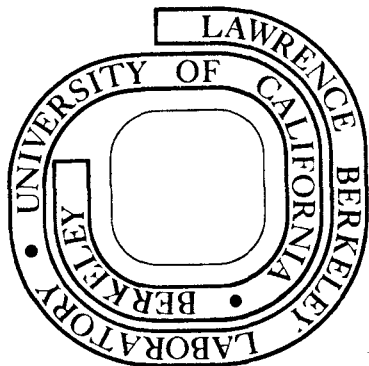
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LEVELS IN ^{165}Tm EXCITED BY DECAY OF 10 MIN ^{165}Yb
AND BY THE ^{158}Gd ($^{11}\text{B}, 4n\gamma$) REACTIONS*

T. Tamura[†], I. Rezanka and S. Iwata^{††}

Heavy Ion Accelerator Laboratory
Yale University
New Haven, Connecticut 06520

and

J. O. Rasmussen[‡] and J. Alonso[‡]

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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ABSTRACT

The levels of deformed nucleus ^{165}Tm were studied both by beta decay and by heavy ion in-beam gamma ray spectroscopy. In addition to confirming the four lowest bands $1/2 + [411]$, $7/2 + [404]$, $7/2 - [523]$, and $1/2 - [541]$, evidence is obtained for the $5/2 + [402]$ and $3/2 + [411]$ bands, and many other higher levels. Several higher members of the ground band are shifted in energy from earlier proposals. Comparison is made with theory both with regard to rotational spacing parameters and to band-head energies.

I. INTRODUCTION

The odd-mass thulium isotopes form a most interesting series from the standpoint of nuclear theory. Three Nilsson bands have been identified and traced¹⁻³ across the series from mass 165 through 171. These are the ground band $1/2 + [411]$ and excited bands $7/2 + [404]$ and $7/2 - [523]$. (Bands are designated by the usual Nilsson asymptotic quantum numbers $\Omega\pi[N, n_z, \Lambda]$.) The energy separations of these bands shift in ways not readily explainable in terms of simple deformation shifts in the Nilsson model. The ground band properties⁴ have been extensively studied, especially for stable ^{169}Tm , where Mössbauer scattering and Coulomb excitation are available tools.

We initiated two-fold studies of ^{165}Tm via radioactivity and heavy-ion in-beam gamma spectroscopy at the Yale Heavy Ion Accelerator Laboratory at a time when the information on this nucleus was limited. There had been a few decay scheme studies⁵⁻⁸ of the radioactivity of parent ^{165}Yb , made difficult by its inconveniently short half life of 10 minutes. We reported preliminary results of our studies earlier.⁹ Before completion of our work, the independent in-beam gamma studies of the Grenoble group of J. Gizon et al.¹⁰ were published, nicely establishing four rotational band sequences up to high spin. Our in-beam studies confirm their assignments except for some changes above the $7/2$ spin in the ground band, and our gamma angular distributions confirm multipolarity assignments. The complex radioactive decay populates many additional levels not observed by the in-beam work, thus providing a nice complementarity. After completion of our work a new independent study of the radioactive decay was reported by Adam et al.¹¹ This report shows only the decay to the lower levels,

in complete agreement with our work, but it supplements our work in that conversion electron and positron spectroscopy was performed, offering direct assignments of multipolarities and a needed redetermination of the positron end point. In Ref. 11 the ground state energy is about 2 keV lower than we propose. There is insufficient detail in Ref. 11 to resolve this discrepancy.

II. EXPERIMENTAL METHODS OF RADIOACTIVITY STUDY

The ^{165}Yb sources were produced by the $^{159}\text{Tb}(^{11}\text{B},5\text{n})$ reaction with ^{11}B ions accelerated in the Yale Heavy Ion Accelerator. The thickness of the metallic terbium target was $5 \sim 7 \text{ mg/cm}^2$ and the beam energy of ^{11}B ions was degraded from 116 MeV to 60 MeV with aluminum and terbium absorbers to enhance the $(^{11}\text{B},5\text{n})$ reaction over the 4n and 6n reactions.

Both in the gamma-ray singles and coincidence measurements, 40 cc Ge(Li) detectors in conjunction with pulse pile-up rejection amplifier chains were employed. The overall system energy resolution was 1.5 keV FWHM at 100 keV. A conventional fast-slow coincidence setup with 40 ns time resolution was used, the fast signals being used to trigger a time-to-height converter. The three signals for each coincidence event, namely, the energy of the first gamma-ray, the energy of the second one, and the time elapsed between the gammas, were digitized and recorded serially on a magnetic tape by a PDP 8/I computer system. The various coincidence relationships were unravelled by sorting through the tape after experiments.

Complementary to the $^{159}\text{Tb}(^{11}\text{B},5\text{n})$ reaction, the $^{169}\text{Tm}(p,5\text{n})$ reaction was utilized to observe the gamma-rays in the ^{165}Yb decay with an appreciable reduction of ^{164}Tm impurity. The 50 MeV proton beam was accelerated in the synchrocyclotron at the Institute for Nuclear Study, University of Tokyo.

For the energy and intensity calibrations, ^{177m}Lu and IAEA standard sources were employed in the Yale experiments, while ^{110m}Ag , ^{133}Ba , ^{152}Eu , ^{168}Tm and ^{170}Tm were used at I.N.S.

Following the experiments, the gamma-ray spectra were analyzed for peak positions, area and gamma-ray energies using the computer programs SAMPO¹² on the Yale Computer Center's 7040-7064 DCS system and BOB¹³ on the FACOM 230/60 system.

III. EXPERIMENTAL METHODS OF IN-BEAM GAMMA SPECTROSCOPY

The experimental techniques employed in this investigation are similar to those described previously.¹⁴ Usually three separate experiments are performed: excitation function measurements, gamma-gamma coincidences, and gamma angular distributions. For all of these experiments, an 8.6 mg/cm^2 metallic ^{158}Gd (97.6% enriched) target obtained from the Oak Ridge National Laboratory was irradiated with a ^{11}B beam from the Yale Heavy Ion Accelerator. For the excitation function measurements, ^{11}B beam energies of 47.5, 52, 60, 64.5, 70, and 88 MeV were used, the gamma ray spectra being observed at 55° with respect to the incident beam by a 40 cm^3 Ge(Li) detector.

For the gamma-gamma coincidence experiment, two 40 cm^3 Ge(Li) detectors were placed at 90° relative to the incident beam, each approximately 2 cm from the target, thus subtending a substantial solid angle, though open to spurious coincidences from Compton scattering events.

The angular distribution of gamma rays was measured by placing the target in a thin-walled (0.5 mm aluminum) cylindrical chamber 5 cm in diameter. The beam and any particles recoiling from the target was stopped by a 150 mg/cm^2 lead foil, curved to a radius of 0.5 cm, and placed 0.5 cm behind the target.

Gamma measurements were made at angles of 0° , 30° , 45° , 60° and 90° with respect to the beam, at a distance of 3.75 cm from the target. The target Gd K x-ray intensities were used for normalization of the spectra.

Calibrations of detectors and analyses of gamma-ray spectra were performed as described in Section II.

IV. RADIOACTIVITY RESULTS

By repeated bombardments and decay curve counting it was possible to assign nearly a hundred gamma lines to the decay of ^{165}Yb . Principal interfering activities are the decay of 30.1 hr ^{165}Tm itself and the activities in the adjacent mass chains 76 min ^{164}Yb and its daughter, 1.9 min ^{164}Tm , and 57.5 hr ^{166}Yb and its daughter, 7.7 hr ^{166}Tm , and 18 min ^{167}Yb and its daughter 9.6d ^{167}Tm . Figures 1a-c show the singles gamma-ray spectra of ^{165}Yb .

The first column of Table I lists the gamma rays assigned from singles spectra to decay of ^{165}Yb . (Table III is a supplementary gamma ray list of transitions inferred later from coincidence results or decay scheme considerations.) The energies are listed as determined and not readjusted in light of the proposed level scheme. The gamma energies listed on the proposed level schemes are those determined by exact subtraction of proposed level energies. Thus, a comparison of the energy consistency of the level scheme is readily

made. Where a dual assignment of a gamma ray has been made, asterisks are placed in the level scheme.

Column 2 lists the gamma ray intensities relative to the 80.1 keV gamma, taken as 100. Both energies and intensities were obtained from least squares fitting of the peaks by the Berkeley routine SAMPO¹² and by BOB.¹³

Column 3 lists assignments of initial and final states in the level scheme with the notation giving the spin, the K (angular momentum projection) value, and parity of the initial and final states, separated by the solidus. In cases where complete quantum number assignments could not be made, the energy of the level serves to specify the assignment. Multiple assignments of presumably unresolved lines are bracketed.

With the large number of gamma rays of ¹⁶⁵Yb it was crucial to have extensive coincidence measurements. Using the three-dimensional (gamma-gamma-time) event-by-event tape recording of coincidences on the Yale HIA computer and using many source preparations, it was possible to accumulate sufficient events to be statistically significant for all the stronger transitions. It is not practical here to present all the data, for even a tabular summary would be lengthy and possibly misleading in cases of low statistics. Three representative coincidence sorts are shown on Figs. 2a, 2b, and 2c. Contribution from the Compton pedestal backgrounds have been subtracted out by gating on flat portions of the spectra near the gate lines. Other coincidence results can be read from the level scheme diagram, where solid dots indicate the coincidence relationships.

We have not carried out new measurements of conversion electrons or positrons but would note here the essential results from earlier work published by Paris,⁷ by Tamura⁸ and by Adam et al.¹¹ In Ref. 7 the positron

end-point energy was determined as 1580 keV, and we use this value, which is near the average of all three determinations. Our subsequent analysis from the level scheme shows predominant decay to the 161.2 keV level. Hence, the total decay energy is the sum $Q_{\beta^+} = 1.74$ MeV and $Q_{EC} = 2.76$ MeV.

We defer review of the conversion coefficient data and multipolarity assignments to the discussion section, except for the microsecond isomeric transitions. In Refs. 7, 8, and 11 E1 multipolarity assignments were made to the 80.1 keV transition. However, in Refs. 7 and 8, where the numbered K and L conversion coefficients were given, they were about twice the Hager-Seltzer theoretical values¹⁵ for E1. Furthermore, the assumption of pure E1 multipolarity for the 80.1 keV transition would lead to serious difficulties in populating the 80.7 keV level. We believe that the conversion coefficients of the 80.1 keV transition are really higher than pure E1 and probably signify M2 admixture in the E1 transition. Taking Paris' value⁷ of 0.50 (E1) and 49 (M2) we get $\delta^2(M2/E1) = 0.008$. From the Moszkowski single-particle lifetime formula¹⁶ for the M2 transition we get a retardation factor of 40, a reasonable value. From the Moszkowski formula we recalculate the E1 retardation factor of 6×10^7 for the 80.1 keV and an E2 retardation factor of 4×10^2 for the 68.9 keV. It should be recognized that with E1 retardation so high for a K-allowed E1 transition, the penetration terms could give rise to anomalies¹⁷ in the E1 conversion coefficient hence to uncertainties in the above estimate of M2 admixture. However, Gopinathan, Jain, and Baba¹⁸ found no conversion anomaly in the analogous 63-keV transition in ¹⁶⁹Tm. Funke et al.¹⁹ found the K-conversion coefficient about 25% higher than theoretical for pure E1 in the analogous 113-keV transition in ¹⁶⁷Tm. Both these analogous cases involve less

retarded E1 transitions than in ^{165}Tm , so our assumption of M2 admixture seems reasonable. Whether the excess conversion electrons are due to M2 admixture or E1 penetration terms, does not affect the level scheme intensity balance; that is the experimentally high conversion coefficient of the 80.1 keV transition gives it a total transition intensity nearly equal to the 68.9 keV transition; hence, the cascade of these transitions does not require direct beta decay feed to the intermediate state.

V. IN-BEAM RESULTS

Table II summarizes the results of our $^{158}\text{Gd}(^{11}\text{B}, 4n\gamma)$ reaction studies. Column 1 lists the gamma ray energies with energy determinations having probable errors of about $\pm 0.05\%$. Columns 2 and 3 list for two bombarding energies, the gamma-ray intensities relative to the 147.2 keV line as 100. In general, the higher the spin of the parent level, the greater the rise in relative intensity of the gamma rays with respect to the beam direction. These coefficients are corrected for finite solid angle of the detectors. Substantial positive values of A_2/A_0 are indicators of stretched ($I \rightarrow I-2$) quadrupole character.

Figure 3 shows the angular distribution curves of fourteen gamma lines, taken at the optimum energy of 52 MeV.

Neither the singles nor coincidence spectra from in-beam work are presented here, as they confirm but do not essentially add to the published spectra of Gizon et al.¹⁰ from $^{165}\text{Ho}(\alpha, 4n\gamma) ^{165}\text{Tm}$. Our spectra all have lower statistics, a consequence of the 2% duty cycle of the Yale Heavy Ion Accelerator. Our spectra differ in replacement of the inelastic scattering gamma lines of the ^{165}Ho target by the lines of the ^{158}Gd target and in somewhat greater suppression of the radioactivity background. Our in-beam gamma measurements are gated

on only during the 2 ms beam puls, hence, are unusually free of interference from radioactivity build-up in the target.

VI. PROPOSED LEVEL SCHEME

Building on the framework of lower levels in the scheme of the Grenoble group,¹⁰ it is possible to take the radioactivity data to build-up an expanded decay scheme. Insofar as possible we have relied on our coincidence data, but they are seriously limited by the microsecond isomerism of the $7/2^+$ and $7/2^-$ bandheads. Hence, energy sum and difference information had to be relied on also. With the complexity of the decay we would concede that some of the transition placements and perhaps a level or two are accidental and incorrect. Dashed lines in the level scheme indicate uncertain features.

The proposed scheme of levels populated in radioactive decay of ^{165}Yb is presented in Fig. 4. The gamma energies given in the scheme are exactly the differences of the proposed energy values of levels. These exact differences are frequently not the same as the experimental transition energies from spectral least squares analysis as given in Tables I and II. Table III is a supplementary list of gamma rays of less certainty assigned to the radioactive decay. These gamma rays appear in the scheme as dashed lines, but they were not clearly resolvable in the singles spectrum and thus not listed in Table I.

To avoid undue confusion, the radioactive decay scheme of Fig. 4 excludes levels seen only by in-beam work and does not show transitions seen in-beam. The complete level scheme is given in Fig. 5, including levels populated by radioactivity and in-beam by either our group or the Grenoble group.¹⁰ The transition lines are indicated only for gammas observed by us in-beam and listed in Table II. Levels established by work of the Grenoble

group¹⁰ but for which our statistics were insufficient to find the confirming gamma rays are also shown. In no case are these unconfined levels inconsistent with our data. We have recalculated all level energies using our own best values where possible and working up to higher levels with best Grenoble group energies.

The level energies have not been given on Fig. 5 because of space limitations but are summarized by band in Table IV along with the values determined by the Grenoble group.¹⁰ Energies of levels not associated with bands can be read from Fig. 4 and are not repeated in Table IV.

VII. DISCUSSION

A. General

For nearly all but the uppermost levels, where we had insufficient statistics in-beam, our studies provide confirming evidence for the correctness of the Grenoble decay scheme.¹⁰ Only in the case of the weaker branch of transitions in the ground band do we propose differing assignments, downshifting alternate spin levels beginning at spin 9/2. This alteration results from our proposal of 203.3- and 232.5 keV lines to depopulate the 9/2+ level, instead of their 207.8 and 236.6, respectively. The assignment question was discussed at length by Drs. J. and A. Gizon, and J. O. Rasmussen, who re-examined Grenoble and Yale data together. Although it is almost impossible to decide between alternatives on the basis of in-beam data, the radioactivity data favor the new assignments for the 9/2+ state of the ground band. Consequently, the energies of the 13/2, 17/2, 21/2 and 25/2 levels are altered from Ref. 10.

The Grenoble level scheme with this minor alteration thus provided the invaluable framework from which to build with the complex gamma spectrum from

the radioactive decay. Several gamma lines were found to define new levels at 315.8, 420.1, and 552.2 keV. The decay patterns of the gamma rays clearly point to assignment as a $K = 5/2$ band, and the logical assignment by the Nilsson model is $5/2 + [402]$. Negative parity seems unlikely, as that would make the cross-band transitions into the ground band once-K-hindered E1 transitions, and these would not be expected to compete with allowed M1 transitions into the $7/2 - [523]$ band. There is also a weak transition to the $7/2 + [404]$ band-head, consistent with our assignment. Paris⁷ observed K and LI conversion lines of the 186 keV transition and tentatively assigned M1 multipolarity. In our scheme, the multipolarity is consistent with the $5/2+$ to $5/2+$ assignment.

Having assigned the new $5/2+$ band, we looked back at in-beam gamma data for evidence of its population. In the Yale data with boron ion reactions, only the 104.3 keV transition can be identified, but the Grenoble data¹⁰ with alpha particle reactions show relatively greater population of the $5/2+$ band. Following are the Grenoble group's unassigned gammas and intensities (an per cent of the 92.0 keV intensity in their Table I) associated with the new band: 104.6 keV(1.5%) and 303.9(19%). Other gamma transitions of the new band would be masked in their in-beam spectra.

It is somewhat surprising that Funke et al.¹⁹ do not find an analogous low-lying $5/2+$ band in their study of decay of ¹⁶⁷Yb, since the decay schemes are in so many ways closely analogous, a consequence of identical parent ground state assignments.

With the predominance of the beta decay to the $7/2 - [523]$ band head with log ft of 4.83 we retain the parent ¹⁶⁵Yb assignment of $5/2 - [523]$ as made by Paris.⁷ As discussed earlier, the total ground-to-ground electron

capture decay energy is $Q_{ec} = 2.76$ MeV. With the same ground state assignment for $^{165}_{70}\text{Yb}_{95}$ as for its neighbor $^{167}_{70}\text{Yb}_{97}$ the two decay schemes are very similar. The decay scheme of the latter nucleus has been presented in detail by the Rossendorf group.²⁰

With a Yb parent spin as low as 5/2 we expected that the radioactivity offered a hope of populating hitherto unobserved 1/2, 3/2, or 7/2 members of the 1/2- [541] band. Dzhelepov et al.⁴ in their Table 1.1a list six cases in which this Nilsson proton band occurs with at least three band members known. In three cases the 1/2- member lies within 5 keV of the 5/2-, twice above it and once below. In other cases it is 25 keV below, 30 keV above and 76 keV above. The 3/2- member ranges in the five known cases from 130 keV to 234 keV above the 5/2-. The one known 7/2- member (in ^{177}Lu) is 354 keV above the 5/2- and 272 keV above the 9/2-. The characteristic decay of a 3/2- level in our case should be decay by E1 gammas to the ground and/or first excited states, since it is known that the interband E1 transitions of these bands are competitive with interband M1 and E2. The 7/2- level might decay by E1's to the 5/2+ and/or 7/2+ members of the ground band or by intraband transitions to 3/2-, 5/2-, or 9/2- members below it. Possible trial level assignments were tested by least squares band fitting with a rotational band energy routine and the formula

$$E = E_0 + AI(I+1) + BI^2(I+1)^2 + CI^3(I+1)^3 = (-)^{I+K} \frac{(I+K)}{(I-K)} [A_{2K} + B_{2K} I(I+1)] \quad (1)$$

The only possibility consistent with our data is the assignment shown in our level schemes and Table IV, namely, the 3/2- level at 275.0 keV and the 7/2- at 451.1 keV. Admittedly, the evidence for these assignments is rather weak, and critical re-examination would be desirable in any future studies. Our decoupling parameter $\underline{a} = \left(\frac{A_1}{A} \right) = + 2.94$ is close to that of

+2.91±0.15 in nearby ^{161}Ho , although the decoupling parameter is generally higher in the four known Lu cases, ranging between +3.8 and +4.6.

We are handicapped in making spin and parity assignments to the many weakly populated "other levels" above the assigned bands; for there are neither conversion coefficients nor angular distributions for a guide. Furthermore, given the short half life and weak population, such data will be difficult to obtain. Paris⁷ and Tamura⁸ were able to obtain conversion electron spectra only for the lower energy transitions, though Adam et al.¹¹ were able to augment the multipolarity assignments. Our decay scheme is consistent with the multipolarity assignments of Refs. 7, 8, and 11, although we propose attributing M2 admixture to the 80.1 keV E1. By our level scheme the 118.1 keV transition could have E2 admixture, but it is expected to be mainly M1 by analogy with ^{167}Tm and ^{169}Tm , where the analogous transitions are reportedly 0.8% E2 and 2% E2, respectively. The log ft values of the higher levels are in a range consistent with beta decay spin changes of 0, ±1 either with or without parity change. Hence, we may only say for levels that receive direct beta decay that the spin is 3/2, 5/2, or 7/2. Log ft values for the less populated lower levels may often be just lower limits, as unassigned feeder gamma rays might account for some population. It is unreasonable that beta feeding be seen to the 9/2- levels, since that would be second forbidden. It is possible to have a 9/2+ assignment if the log ft value is near 8, typical of Gamow-Teller unique first forbidden.

We have noted three levels (491.2, 609.5, and 725.8) as a "low K" band because these levels decay to the $K = 1/2+$ and $K = 1/2-$ bands, predominantly to the former. If we are to choose a sequence of spin values for the "low K"

band, consistent with transition multipolarities no higher than quadrupole, the sequence $3/2$, $5/2$, $7/2$ shown on the level scheme is most likely. At this point it is appropriate to look to theoretically predicted band-head energies for guidance. Soloviev and Fedotov have recently made extensive calculations of band energies and wave functions for odd-mass rare-earth nuclei.²¹ These sophisticated calculations with nucleon wave functions in a deformed Woods-Saxon potential include quasi-particle-phonon mixing, with quadrupole and octupole phonons, as well as explicit consideration of three quasi-particle states. In our Table V we compare our present experimental values with their theoretical results. Soloviev and Fedotov predict a $3/2+$ state at 660 keV in ^{165}Tm . In their Table 12 for ^{167}Tm , the $3/2+$ state is predicted at 670 keV, with an experimental value of 471 keV listed. In their Table 13 for ^{171}Tm , the $3/2+$ state is predicted at 680 keV and experimentally known at 676 keV.

Diamond, Elbek, and Stephens²² first Coulomb-excited in ^{169}Tm a $3/2+$ band with levels at 570, 633 and 718 keV. They also observed levels near 900 keV and near 1170 keV. Subsequent Coulomb excitation studies have confirmed these results. Aleksandrov, Balalaev, Dzhelepov and Ter-Nersesyants²³ more precisely measured the $3/2+$ [411] band in ^{169}Tm with first four level energies of 571, 633, 718, and 825 keV, very weakly populated in decay of ^{169}Yb . They proposed a regular ascending spin sequence $3/2$, $5/2$, $7/2$, $9/2$.

The systematic Coulomb excitation of bands differing in K by two units from the ground band K stimulated theoretical calculations of gamma vibrational phonon character in odd- A nuclei. Theoretical studies of both Bes and Cho²⁴ and Soloviev and Vogel²⁵ show a fair amount of mixing of $3/2+$ [411] one quasi-particle band and the band composed of gamma phonon plus $1/2+$ [411] quasi proton.

In ¹⁶⁹Tm Bes and Cho predicted the 3/2+ band head at 718 keV and 5/2+ at 1211. Soloviev and Vogel predict 3/2+ band heads at 620 and 1200 (compared to experimental 570 and ~1170) and 5/2+ band at 900, 950, and 1350.

In view of the experimental and theoretical evidence on the systematic occurrence of the 3/2+ [411] band in odd-A thulium isotopes, we make this assignment to our "low K" band. Our assignment of spins is somewhat speculative. At first we thought to include the level, at 592.2 keV in the band, giving anomalous spacing, but we decided to exclude it on the basis of its higher log ft and the preferability of a regularly spaced band.

The 3/2+ and 5/2+ bands predicted around 1100 keV have predominant parentage of ground band plus gamma vibrational phonon. Thus, we might expect enhanced E2 decay from these bands to the ground band. The following levels in our scheme have energies and show decay patterns that might suggest their association with these predicted bands: 1100.5, 1129.1, 1251. There is no good basis to make more definite assignments.

The 1250.9 and 1325.8 levels stand out in that they receive more beta feed than their neighbors and they decay mainly into the 7/2- [523] band. We suggest these levels may be, respectively, the 5/2- and 7/2- members of the 5/2- [532] band predicted at 1400 keV.

Finally, there is the rather amazing level at 1582 keV that decays to nearly all lower levels with spins 5/2, 7/2, or 9/2, regardless of K or parity. That behavior would suggest a mixed-K character. The spin assignment of 7/2 is favored by the decay pattern and by the fact that the log ft value to the level is relatively low but with no comparably populated level higher. We favor a negative parity assignment, since the allowed beta decay classification

better permits a rather mixed character for the state. Soloviev and Fedotov do not predict a second $7/2^-$ band in their table, but they have not gone above 1470 keV for the general calculations, and they have not considered quadrupole phonons of $K = 0$ (beta or pairing vibrations). It is known²⁶ that neighboring ^{161}Er has its first excited 0^+ state at 1245 keV and a 1^- , $K = 0$ state at 1386 keV. It may well be that our 1582 keV level mainly is composed of these phonon states, coupled respective, to the $7/2^- [523]$ and $7/2^+ [404]$ quasi-proton components.

Referring to Table V, can we make any more assignments of higher levels with the aid of the theory? We have searched for the $9/2^-$ band predicted around 550 keV but see no evidence for it. Beta decay to this band would be second forbidden so it could only be seen if fed by gamma transitions from higher levels. From the same considerations we would not expect to see the predicted $11/2^-$ state.

Before leaving the comparison with Soloviev-Fedotov theory, we would note the large disagreement in the position of the $1/2^- [541]$ band shifts energy rapidly as neutron number is changed in Lu isotopes. Since the $1/2^-$ orbital comes from a higher oscillator shell, its relative energy is quite sensitive to deformation and to spin-orbit splitting. Thus, slight modifications of the deformed well parameters could bring the $1/2^- [541]$ orbital down, so the disagreement with theory is not serious. It may be, however, that the orbital energy shifts among the Tm isotopes are not explainable in the framework of an average potential model and that Hartree-Bogoliubov theory will be needed to explain the shifts.

B. Rotational Energy Parameters

We have applied the usual power series expansion Eq. (1) to fit the rotational band energies by least squares, and one of these fits is presented in Table IV for each band. The fits of Table IV were made to the Grenoble energies,¹⁰ except for the $K = 1/2+$ and $K = 1/2-$ bands, where substantial shifts or new levels are proposed in our work. The fits presented use the full six parameter expansion, fitting on levels up to the underlined value. It is readily seen that the predictions diverge from experiment at the next level above the last fitted level. Thus, the series expansions are not very satisfactory for any of the bands at highest spin values. It is necessary to be cautious in cross-comparing rotational expansion coefficients with those determined by least squares in other nuclei, since the parameters depend both on how many terms were taken in the expansion and how many levels were fit. Table VI gives the parameter values for the particular fits given in Table IV. These points of caution are well brought out in the discussion and more sophisticated analyses by Hjorth and Ryde²⁷ and by Hjorth, Ryde, and Skanberg.²⁸ The signs and magnitudes of these parameters are in accord with data on these same bands in other nuclei. It would take too much space here to make a detailed cross-comparison with other nuclei or with theory. In an earlier publication²⁹ we discussed the significance of some of the parameters in light of theoretical work of Hamamoto and Udagawa.³⁰ The same remarks apply here as to differences between parameters of the $7/2-$ and $7/2+$ bands.

We have gone one step further in the rotational band analysis by applying the two-band-Coriolis mixing expressions of Eqs. (1) and (2) in Ref. 31. Table VII shows results of two-band least squares fits to the $7/2 + [404]$ and $5/2 + [402]$ bands. In this treatment, as presented in detail in Ref. 31,

analytical energy expressions are derived for Coriolis mixing of two bands with zeroth order energies given by power series expansions in $I(I+1)$. For Table VII we have allowed the full six-parameter variation to fit the lowest ten levels of the $7/2+$ band and the lowest three levels of the $5/2+$ band. The parameters found by the search are as follows:

$$\alpha = \hbar^2/2J = 14.76 \text{ keV}$$

$$\beta \text{ (softness parameter)} = 9.05 \times 10^{-4}$$

$$\alpha_{2K} \text{ (generalized decoupling parameter)} = -3.26 \times 10^{-4} \text{ keV}$$

$$\langle j+ \rangle \text{ (intrinsic Coriolis matrix element)} = 0.626$$

$$\text{Band-Head Difference (zeroth order)} = 246.4 \text{ keV}$$

$$\text{Band-Head Sum (zeroth order)} = 311.8 \text{ keV}$$

The rather small value of Coriolis matrix element is reasonable, since the operator is not allowed by asymptotic quantum number selection rules between the two bands. The rather small decoupling parameter reflects the fact that the $5/2 + [402]$ band has small Coriolis coupling to $K = 1/2$ bands and perhaps partially cancelling contributions from the coupling.

With all the work that has gone into the nuclear properties of ^{165}Tm we do not regard the story as completed. Despite the awkwardly short half life of 10.5 min, new conversion electron data must be obtained to facilitate multipolarity and spin assignments. Gamma-gamma angular correlation work would be helpful though difficult to obtain. The gamma spectra and coincidence studies ought to be repeated at highest resolution with isotopically separated sources. Proton stripping studies on erbium targets into ^{165}Tm and neighboring Tm isotopes would be most welcome.

The bands here identified (lowest $1/2+$, $3/2+$, $5/2+$, and $7/2+$) should facilitate Coriolis band-mixing studies of the low-j orbital family. Generally such studies have been confined to high-j orbitals.

We hope that the work presented here can be a stimulus to further experimental and theoretical work in this region.

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FOOTNOTES AND REFERENCES

- * Work performed under the auspices of the U. S. Atomic Energy Commission.
- † Present address: Division of Physics, Tokai Establishment, Japan Atomic Energy Research Institute, Tokai-mura Ibaraki-Ken, Japan.
- †† Present address: Research Reactor Institute, Kyoto University Kumatori-cho, Sennan-gun, Osaka, Japan.
- ‡ Yale Heavy Ion Accelerator Staff members during experimental work.
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Table I. Gamma Rays in ^{165}Yb Decay Studies

E γ	I γ	Assignment		Remarks
		Initial	Final State	
		IK π or E(keV)		
30.8 \pm 0.1	W	(7/2 7/2-	/ 5/2 1/2+)	Not shown on decay scheme.
68.9 \pm 0.1	17	7/2 7/2+	/ 3/2 1/2+	
80.1 \pm 0.1	100	7/2 7/2-	/ 7/2 7/2+	
91.7 \pm 0.1	1.2	9/2 7/2-	/ 7/2 7/2-	^{164}Tm fraction subtracted.
104.3 \pm 0.1	0.40	7/2 5/2+	/ 5/2 5/2+	
118.1 \pm 0.1	4.8	5/2 1/2+	/ 3/2 1/2+	
129.9 \pm 0.1	1.1	{ 5/2 1/2+	/ 1/2 1/2+	
		{ 9/2 7/2+	/ 7/2 7/2+	
132.2 \pm 0.1	0.20	9/2 5/2+	/ 7/2 5/2+	
134.6 \pm 0.1	0.18	9/2 1/2-	/ 7/2 1/2+	
147.3 \pm 0.1	1.8	7/2 1/2+	/ 3/2 1/2+	
156.5 \pm 0.1	0.29	5/2 5/2+	/ 7/2 1/2+	
158.2 \pm 0.1	0.13			
170.3 \pm 0.1	1.1	5/2 1/2-	/ 3/2 1/2+	
185.8 \pm 0.3	0.64	5/2 5/2+	/ 5/2 1/2+	
203.3 \pm 0.1	0.55	9/2 1/2+	/ 7/2 1/2+	
208.0 \pm 1.	Masked	(11/2 7/2-	/ 7/2 7/2-)	Mainly ^{164}Tm
232.5 \pm 0.2	0.37	9/2 1/2+	/ 5/2 1/2+	
235.1 \pm 0.2	0.13	5/2 5/2+	/ 7/2 7/2+	
255.1 \pm 0.2		{ 11/2 1/2+	/ 7/2 1/2+	
		{ (1582.0 / 1326.5)		
261.0 \pm 0.2	0.13	7/2 5/2+	/ 7/2 1/2+	
264.0 \pm 0.5	VW	(3/2 1/2-	/ 3/2 3/2+)	
275.5 \pm 0.2	0.30	3/2 1/2-	/ 1/2 1/2+	
282.5 \pm 0.5	W			
290.3 \pm 0.5	0.10	7/2 5/2+	/ 5/2 1/2+	
292.2 \pm 0.5	0.04			
304.0 \pm 0.1	1.60	5/2 5/2+	/ 3/2 1/2+	

(continued)

Table I. Continued

E γ	I γ	<u>Assignment</u>		<u>Remarks</u>
		Initial/Final State		
		IK π or E(keV)		
312.0 \pm 1.0	0.15			
320.8 \pm 1.0	0.36	7/2 1/2-	/ 5/2 1/2-	
332.3 \pm 0.5	W	491.2	/ 7/2 1/2+	
361.5 \pm 0.3	0.34	491.2	/ 5/2 1/2+	
363.3 \pm 0.5	0.14	725.1	/ 9/2 1/2+	
391.0 \pm 0.2	0.53			
404.3 \pm 0.2	0.26	1014.2	/ 609.5	
415.9 \pm 0.2	0.27			
422.2 \pm 0.3	0.05			
427.0 \pm 0.5	0.06			
433.1 \pm 0.1	0.31	592.2	/ 7/2 1/2+	
462.2 \pm 0.2	0.12	592.2	/ 5/2 1/2+	
479.6 \pm 0.2	0.50	491.2	/ 3/2 1/2+	
		609.5	/ 5/2 1/2+	
491.5		491.2	/ 1/2 1/2+	
544.4 \pm 0.3	0.07			
566.7 \pm 0.5	0.16	725.8	/ 7/2 1/2+	
578.4 \pm 0.5	0.10			
589.3 \pm 0.7	W	1315.0	/ 725.1	
597.8 \pm 0.5	0.04	609.5	/ 3/2 1/2+	
605.8 \pm 0.2	0.05			
636.5 \pm 0.3	0.33	1188.8	/ 9/2 5/2+	
655.8 \pm 0.3	0.58	950.0	/ 5/2 1/2-	
675.1 \pm 0.1	0.13			
728.9 \pm 0.5	0.07			
736.8 \pm 0.5	0.09			
743.0 \pm 0.5	0.03			
772.0 \pm 0.5	0.09			
784.3 \pm 0.5	0.52	1100.5	/ 5/2 5/2+	

(continued)

Table I. Continued

E γ	I γ	Assignment	Remarks
		Initial/Final State IK π or E(keV)	
825.8 \pm 0.5	0.35	1037.8 / 9/2 7/2+	
830.3 \pm 0.5	0.29	1013.1 / 5/2 1/2-	
838.8 \pm 0.5	0.11		
853.5 \pm 1.0	0.06		
854.9 \pm 1.0	0.05	1014.2 / 7/2 1/2+	
878.6 \pm 1.0	0.39	{ 1370.4 / 491.2 1037.8 / 7/2 7/2-	
920.0 \pm 1.0	0.04		
935.0 \pm 0.3	0.69	1251.0 / 5/2 5/2+	
938.0 \pm 0.5	0.21		
944.0 \pm 1.0	0.06		
948.0 \pm 1.0	0.05		
956.5 \pm 0.2	1.71	{ 1037.8 / 7/2 7/2+ 1326.5 / 11/2 7/2-	
963 \pm 1.0	0.05		
972.7 \pm 0.5	0.07		
976.8 \pm 1.0	0.04		
989 \pm 1.0	0.09		
999.2 \pm 0.1	1.10	{ 1315.0 / 5/2 5/2+ 1129.1 / 5/2 1/2+	
1002.5 \pm 0.5	0.04		
1009.5 \pm 1.0	0.06		
1012.6 \pm 0.5	0.10		
1015.6 \pm 0.2	0.17		
1029.9 \pm 0.1	1.22	{ 1582.0 / 9/2 5/2+ 1188.8 / 7/2 1/2+	
1073.3 \pm 0.1	1.44	1326.5 / 9/2 7/2-	
1090.1 \pm 0.1	1.00	{ 1251.0 / 7/2 7/2- 1100.5 / 3/2 1/2+	

(continued)

Table I. Continued

E γ	I γ	Assignment	Remarks
		Initial/Final State IK π or E(keV)	
1100.6 \pm 1.0	0.1	{ 1100.5 / 1/2 1/2+ 1283.4 / 5/2 1/2-	
1117.2 \pm 0.2	0.36	1129.1 / 3/2 1/2+	
1121.6 \pm 0.2	0.24	1251.0 / 5/2 1/2+	
1126.0 \pm 0.2	0.16	{ 1308.7 / 5/2 1/2- 1283.4 / 7/2 1/2+	
1145.6 \pm 0.5	0.013		
1149.5 \pm 0.5	0.013	{ 1308.7 / 7/2 7/2- 1308.7 / 7/2 1/2+	
1154.3 \pm 0.3	0.68		
1161.5 \pm 0.5	0.19	1582.0 / 7/2 5/2+	
1165.2 \pm 0.2	0.37	1326.5 / 7/2 7/2-	
1188.1 \pm 0.2	0.22	1370.4 / 5/2 1/2-	
1192.8 \pm 0.2	0.12	1352.6 / 7/2 7/2-	
1202.5 \pm 0.2	0.23	{ 1283.4 / 7/2 7/2+ 1565.0 / 9/2 1/2+	
1209.3 \pm 0.3	0.11		
1212.0 \pm 0.3	0.11	1370.4 / 7/2 1/2+	
1219.5 \pm 0.5	0.83	1582.0 / 9/2 1/2+	
1239.2 \pm 0.5	0.44	1251.0 / 3/2 1/2+	
1248.8 \pm 0.2	0.07	1565.0 / 5/2 5/2+	
1253.2 \pm 1.0	0.01		
1265.6 \pm 0.3	0.30	{ 1424.8 / 7/2 1/2+ 1582.0 / 5/2 5/2+	
1269.3 \pm 0.3	0.23		
1289.1 \pm 0.2	0.27	1582.0 / 9/2 1/2-	
1296 \pm 1.0	0.48	1424.8 / 5/2 1/2+	Doublet with ^{164}Tm

(continued)

Table I. Continued

E _γ	I _γ	<u>Assignment</u>		<u>Remarks</u>
		Initial/Final State IKπ or E(keV)		
1306 ± 1.0	0.04			
1309 ± 1.0	0.07			
1312.4 ± 0.3	0.17			
1329.0 ± 0.1	0.49	1582.0 / 9/2	7/2-	
1341.5 ± 0.5	0.04			
1353.5 ± 0.5	0.03			
1367.2 ± 0.2	0.15			
1370.8 ± 0.2	0.23	1582.0 / 9/2	7/2+	
1390.2 ± 0.3	0.13			
1399.5 ± 1.0				
1402.8 ± 0.5	0.10			
1405.5 ± 0.5	0.07	1565.0 / 7/2	1/2+	
1421.0 ± 0.1	0.45	{ 1582.0 / 7/2	7/2-	
		{ 1582.0 / 7/2	1/2+	
1426.6 ± 0.3	0.22			
1435.0 ± 0.3	0.14	1565.0 / 5/2	1/2+	
1451.9 ± 0.2	0.33	1582.0 / 5/2	1/2+	
1501.0 ± 0.2	0.85	1582.0 / 7/2	7/2+	
1530.7 ± 0.5	0.091			

Table II. Gamma-Rays Assigned to $^{158}\text{Gd}(^{11}\text{B}, 4n\gamma)$ Reaction

E_γ^a (keV)	$I_\gamma^{b,c}$ (52MeV)	I_γ (60MeV)	A_2/A_0^d	A_4/A_0^d	Assignments $2I_i 2k_i \pi / 2I_f 2K_f \pi$
68.7 ^g	34	39			7 7+ / 3 1+
84.5	16	22			U
92.0	43	48			9 7- / 7 7-
104	9.6	weak			7 5+ / 5 5+
111.9	10	14	0.33 ± 0.37	0.06 ± 0.16	9 1- / 5 1-
116.6	64	90	-0.33 ± 0.22	0.16 ± 0.23	11 7- / 9 7-
118.1	34	36	0.13 ± 0.37	-0.38 ± 0.46	5 1+ / 3 1+
120.6	17	21	-0.20 ± 0.28	0.05 ± 0.30	11 1+ / 9 1-
130.0 ^e	54	53	0.26 ± 0.10	0.17 ± 0.10	{ 5 1+ / 1 1+ 9 7+ / 7 7+
134.4	98	118	-0.18 ± 0.11	0.07 ± 0.10	9 1- / 7 1+
142.0	69	112	0.18 ± 0.14	0.01 ± 0.15	13 7- / 11 7-
147.2	100	100	0.28 ± 0.06	0.01 ± 0.01	7 1+ / 3 1+
152	weak	weak			U
155.5	22	28	0.54 ± 0.23		11 7+ / 9 7+
164.4	66	102	0.02 ± 0.08	-0.05 ± 0.9	15 7- / 13 7-
170.4	22	42	-0.21 ± 0.13	-0.05 ± 0.15	5 1- / 3 1+
178.8	20	40			13 7+ / 11 7+
183	20	40			U
191.1	84	104	0.13 ± 0.12	0.02 ± 0.12	17 7- / 15 7-
202.6	10	43			15 7+ / 13 7+
203.4 } 204.1 }	160	239	0.24 ± 0.08	-0.08 ± 0.08	{ 9 1+ / 13 7+ 13 1- / 9 1-
207.1	81	87	0.09 ± 0.09	-0.07 ± 0.14	19 7- / 17 7-
212.4	15	40			U
218.5	12	40			U
221.6	12	40			17 7+ / 15 7+
232.9	44	39	0.22 ± 0.14	-0.26 ± 0.5	9 1+ / 5 1+
236.6	44	59	0.12 ± 0.17	-0.23 ± 0.2	21 7- / 19 7-
241.2	25	45			23 7- / 21 7-

(continued)

Table II. Continued

E_γ^a (keV)	$I_\gamma^{b,c}$ (52MeV)	I_γ (60MeV)	A_2/A_0^d	A_4/A_0^d	Assignments $2I_i, 2K_i, \pi 2I_f, 2K_f, \pi$
245.3	14	46			U
255.0	77	89	0.32 ± 0.06	-0.13 ± 0.08	11 1+ / 7 1+
259.1	22	18			13 7- / 9 7-
270.1	10	10			27 7- / 25 7-
277.2	42	45			{ 25 7- / 23 7- (13 1+ / 11 1+)
285.9	33	46			11 7+ / 7 7+
298.5	98	136	0.31 ± 0.03	0.01 ± 0.09	17 1- / 13 1-
306.6	38	46	0.32 ± 0.08	0.11 ± 0.18	15 7- / 11 7-
322					U
327.2	26	20	0.38 ± 0.23	0.25 ± 0.25	13 1+ / 9 1+
334.7	46	60	0.19 ± 0.10	0.06 ± 0.10	{ 17 1+ / 15 1+ 13 7+ / 9 7+
340.3	23	16			U
347	weak	10			U
355.0	92	132	0.26 ± 0.10	0.16 ± 0.27	{ 15 1+ / 11 1+ 17 7- / 13 7-
363.9	17	15			U
380.5	43	48	0.36 ± 0.20	-0.17 ± 0.20	15 7+ / 11 7+
385	weak				U
389.7	71	126	0.29 ± 0.15	-0.01 ± 0.15	21 1- / 17 1-
397.3	50	67	0.33 ± 0.20	-0.17 ± 0.20	19 7- / 15 7-
403.1	9.3	8.8			U
412.8	21	10			17 1+ / 13 1+
418.5	10	10			U
422.3	36	60			17 7+ / 13 7+
443.0	30	41	0.25 ± 0.20	-0.02 ± 0.19	21 7- / 17 7-
447.8	11	21			19 1+ / 15 1+
460.3	10	15			19 7+ / 15 7+

(continued)

Table II. Continued

472	18	weak			U
475	68	104			25 1- / 21 1-
479	50	58			23 7- / 19 7-
482	17	weak			U
500	27	38	0.36 ± 0.16	0.18 ± 0.15	21 7+ / 17 7+
562	20	35			25 7+ / 21 7+

^aThe accuracy of the energy values is within ± 0.3 keV for strong discrete lines and 0.5-1.0 keV for weaker lines.

^bThe intensity is given relative to the 147.2 keV γ -ray for 52 MeV and 60 MeV incident beam energy.

^cThe accuracy of the relative intensity of γ -rays is $\pm 10\%$ for strong well resolved lines, 20% for the rest of lines.

^dThe errors in A_2/A_0 , A_4/A_0 coefficients are only statistical ones, i.e. due

to uncertainty in area determination and to the deviation from the interpolating polynomial, whichever is larger for any particular point.

^eFrom the $\gamma\gamma$ -coincidence and γ -ray single measurements in ^{165}Yb decay, the intensity of 130 keV in the $5/2\ 1/2^+ \rightarrow 1/2\ 1/2^+$ transition was estimated to be 10 in the units used for both 52 and 60 MeV incident beam. And therefore, a large part of this peak intensity should be considered to be due to $9/2\ 7/2^+ \rightarrow 7/2\ 7/2^+$ transition.

^fThis peak consists of two γ -rays 204.1 keV of $13/2\ 1/2^- \rightarrow 9/2\ 1/2^-$ and 203.4 keV of $9/2\ 1/2^+ \rightarrow 7/2\ 1/2^+$. From the γ -single in ^{165}Yb decay the intensity of 203.4 keV γ -ray was estimated to be 80 for both 52 and 60 MeV incident beam.

^gBecause of the energy fit, part of the intensity of this peak may be possibly placed as $9/2, 1/2^+ \rightarrow 9/2, 1/2^-$ transition.

Table III. Supplementary Gamma

List for ^{165}Dy Decay		
E γ (keV)	Assignment	Remarks
29.2	$7/2\ 1/2\ +\ /\ 5/2\ 1/2+$	Needed for intensity balance. Presumably too highly converted to observe photon.
40.5	$9/2\ 1/2\ -\ /\ 9/2\ 7/2-$	Seen by Grenoble group ¹⁰ in beam.
93.3	$9/2\ 1/2\ -\ /\ 5/2\ 1/2-$	Seen in-beam, both studies.
116.6	$11/2\ 7/2\ -\ /\ 9/2\ 7/2-$	Coinc. only. Singles masked.
120.4	$11/2\ 1/2\ +\ /\ 9/2\ 1/2-$	Seen in beam. ¹⁰
176.1	$7/2\ 1/2\ -\ /\ 3/2\ 1/2-$	Line possible but obscured by ^{167}Yb activity.
189.8	552 / $9/2\ 1/2+$	Coinc. only. No singles.
269.4	$7/2\ 1/2\ -\ /\ 5/2\ 1/2-$	Tentative coincidence evidence; no singles.
431.0	592.2 / $7/2\ 7/2-$	Unresolved, broadening of 433.1 line.
563.1	1014.2 / $7/2\ 1/2-$	Possible, but ^{165}Tm decay masks.
595.2	725.1 / $5/2\ 1/2+$	Tentative coincidenc; possible unresolved singles component.
894.9	1315.0 / $7/2\ 5/2+$	Part of unresolved triplet also involving another isotope.
895.7	1188.8 / $9/2\ 1/2-$	
996.5	1308.7 / $5/2\ 5/2+$	Coinc. only. No singles.
1222.7	1352.6 / $5/2\ 1/2+$	Coinc. only. Singles masked.

Table IV. Level Energies in ^{165}Tm

Spin	<u>1/2+ [411] Band</u>		<u>E_{calc} (keV)</u>
	<u>E_{exp} (keV)</u>		<u>6 Parameter Power Series^c</u>
	This Work	Grenoble ¹⁰	
1/2	0	0	-0.17
3/2	11.8	11.9	12.11
5/2	129.9	130.2	129.80
7/2	159.1	159.2	159.54
9/2	362.4	367.0 ^b	362.92
11/2	414.1	414.2	413.62
13/2	689.7	703.4 ^b	689.87
15/2	769.2	769.5	769.70
17/2	1103.7	1128.2 ^b	<u>1104.13</u>
19/2	1216.8	1216.9	1229.40
21/2		1630.1 ^b	1609.58
23/2	1746.1 ^a	1746.2	1809.57
25/2		2184.7 ^b	2230.78
27/2		2333	2553.79
29/2			
<u>7/2+ [404] Band</u>			
7/2	80.9	81.1	81.09
9/2	211.3	211.3	211.29
11/2	366.9	366.9	366.88
13/2	546.1	546.1	546.28
15/2	747.4	747.2	747.04
17/2	968.4	969.0	968.97
19/2	1207.7	1207.0	1207.07
21/2	1468.5	1467.6	1467.60
23/2	1737.0 ^a	1736.3	<u>1736.29</u>
25/2	2030.3 ^a	2029.4	2038.16
27/2		2335.1	2334.17
29/2		2660	2690.83

(continued)

Table IV. continued

Spin	E_{exp} (keV)		E_{calc} (keV)
	This Work	Grenoble ¹⁰	6 Parameter Power Series ^c
<u>7/2- [523] Band</u>			
7/2	161.2	161.4	159.51
9/2	253.2	253.4	254.49
11/2	369.8	370.2	371.99
13/2	511.8	512.7	513.19
15/2	676.2	676.9	676.61
17/2	867.3	868.0	866.59
19/2	1073.5	1074.5	1073.25
21/2	1310.3	1311.0	1312.01
23/2	1552.5	1552.5	1553.34
25/2	1829.4	1830.2	1829.98
27/2	2099.5	2099.2	<u>2099.03</u>
29/2		2411.4	2365.18
31/2		2698.2	2690.94
<u>1/2- [541] Band</u>			
1/2			156.55
3/2	275.0		276.11
5/2	182.2	182.2	180.99
7/2	451.1		450.44
9/2	293.7	293.9	294.30
11/2			690.77
13/2	497.8	498.4	499.37
15/2			986.74
17/2	796.3	796.9	797.06
19/2			1325.78
21/2	1186.0 ^a	1186.6	1185.79
23/2			1692.59
25/2	1661.0 ^a	1661.3	1660.91
27/2			2068.46
29/2	2212.9 ^a	2213.2	<u>2213.98</u>
31/2			2430.43
33/2		2832.5	2831.86

Table IV. continued

Spin	<u>5/2+ [402] Band</u>		E _{calc} (keV) 6 Parameter Power Series ^c
	E _{exp} (keV) This Work	Grenoble ¹⁰	
5/2	315.8		
7/2	420.1		
9/2	552.2		
<u>"Low K Band"</u>			
(3/2+ [411])			
3/2	491.2		
5/2	609.5		
7/2	725.1		

^aOne or more transition energies from Grenoble work¹⁰ used to calculate level energy.

^bThese differing energies result from our different gamma ray assignments from the original Grenoble paper.¹⁰

^cSix parameter energy expansion least squares fit up through underlined level.

Table V. Experimental Band-Head Energies of ^{165}Tm
and ^{167}Tm Compared with Theory

K π	^{167}Tm Energy (keV)		^{165}Tm	Main Components from Theory ²¹
	(Ref. 19)	This Experiment		
1/2+		0	0	411 ↓ 96%
7/2-	293	161	300	523 ↑ 94%
9/2-			550	514 ↑ 94%
7/2+	180	81	630	404 ↓ 96%
3/2+	471	(491)	660	411 ↑ 84%
5/2+		316	990	411 ↓ + Q ₁ (22) 49% 402 ↑ 42%
3/2-			1010	523 ↑ + Q ₁ (22) 96%
11/2-			1060	523 ↑ + Q ₁ (22) 100%
3/2+		(1100-1251)	1100	411 ↓ + Q ₁ (22) 94%
5/2+	(1581)		1100	411 ↓ + Q ₁ (22) 46% 402 ↑ 44%
7/2+		(1230)	1250	411 ↑ + Q ₁ (22) 98%
1/2+			1320	411 ↑ + Q ₁ (22) 100%
1/2-	172	182 ^a	1340	541 ↓ 89%
5/2-	(1527)	(1251)	1400	532 ↑ 75%
3/2+			1470	404 ↓ + Q ₁ (22) 86%
17/2+			1960	p523 ↑ n642 ↑ n523 ↓

^aEnergy is for 5/2- spin member of band in ^{165}Tm , since 1/2- spin is unknown, but presumably near.

Table VI. Parameters of the Energy Formula of Bands in ^{165}Tm

	$\frac{1}{2}[411]$	$\frac{1}{2}[541]$	$\frac{7}{2}[523]$	$\frac{7}{2}[404]$
Parameters				
A (keV)	14.02	10.19	10.20	15.17
B (eV)	-14.69	-3.94	9.78	-18.19
C (eV $\times 10^{-3}$)	55	-3.25	-35.7	30.04
A_{2k}	-9.98 keV	30.03 keV	603 μeV	164 μeV
B_{2k}	42.3 eV	-127.9 eV	-3.0 μeV	-.35 μeV

Table VII. Two-Band Coriolis Mixing Fit and Predictions for 7/2+ and 5/2+ Bands

Spin	$E_{\text{(calc)}}$	ΔE (calc-exp)
7/2	82.52	1.62
9/2	211.25	-.05
11/2	365.80	-1.10
13/2	544.90	-1.21
15/2	746.08	-1.31
17/2	969.27	0.87
19/2	1208.68	0.98
21/2	1469.54	1.04
23/2	1736.80	-0.20
25/2	<u>2029.67</u>	-0.63
27/2	2312.80	
29/2	2627.52	
31/2	2936.26	
5/2	316.02	0.22
7/2	419.70	-0.40
9/2	<u>552.37</u>	0.17
11/2	707.81	
13/2	896.48	
15/2	1090.91	

FIGURE CAPTIONS

Figs. 1a-c. Singles gamma ray spectrum of radioactive decay of 10 m. ^{165}Yb .

Shown is the sum of spectra from three separate irradiations. Each of the three was observed over the time interval 5 to 25 min after the end of 10 min bombardments of Tb targets with ^{11}B ions; (a), (b), and (c) are the corresponding spectra for the low, medium and high energy parts for the sources produced by the $^{169}\text{Tm}(\text{p},5\text{n})$ reaction.

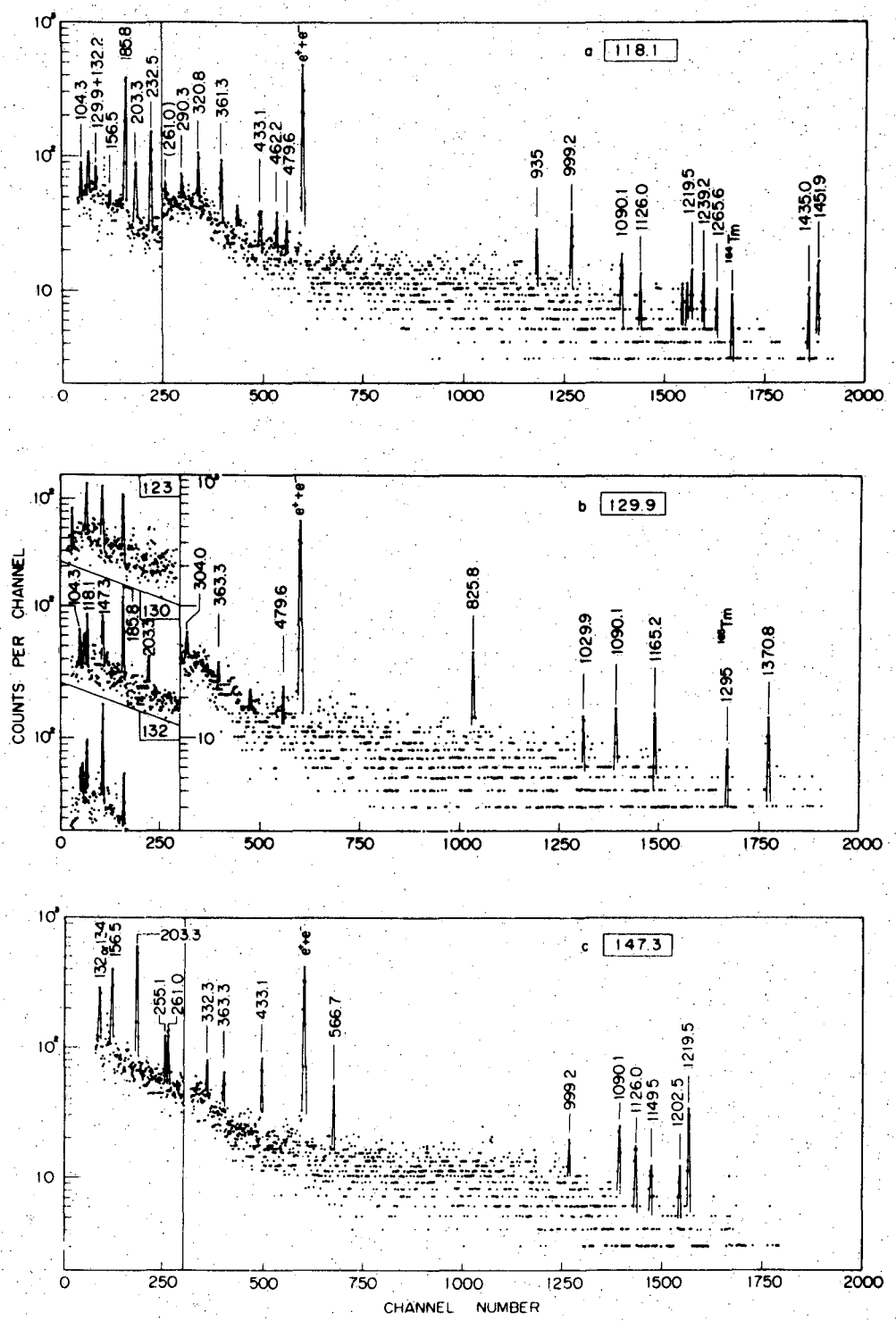
The figure labels the ^{165}Yb lines by energy (keV) only and the peaks of contaminants by energy and isotopic label. Decay curves were followed to establish isotopic assignment of the lines.

Figs. 2a-c. Representative sorts of the three-dimensional (γ - γ -t) coincidence data from the decay of ^{165}Yb . The gate energies are indicated in the square boxes near the upper right of each spectrum and inset. Spurious contributions from Compton events have been subtracted out by gating on a nearby flat portion of the spectrum in each case.

Fig. 3. Gamma angular distributions with respect to the beam direction for the $^{158}\text{Gd}(\text{}^{11}\text{B},4\text{n}\gamma)$ at 52 MeV bombarding energy. The solid curves represent least squares best fits with even Legendre functions of orders 0, 2, and 4. Note that all the transitions in the two bands, except for the 334 keV, are uniquely assigned to stretched E2 cross-over transitions, consistent with the strong positive anisotropy. The 334-keV transition is believed to be an unresolved doublet of a stretched E2 cross-over in the $7/2 + [404]$ band and a cascade in the $1/2 + [411]$. Of the other transitions, the lower three are assigned as stretched E1 transitions between the $1/2+$ and $1/2-$ bands, and the negative anisotropies are consistent with this assignment. The 190-keV transition is assigned as a cascade M1-E2 transition in the $7/2-[523]$ band, and the near isotropy is consistent with such assignment.

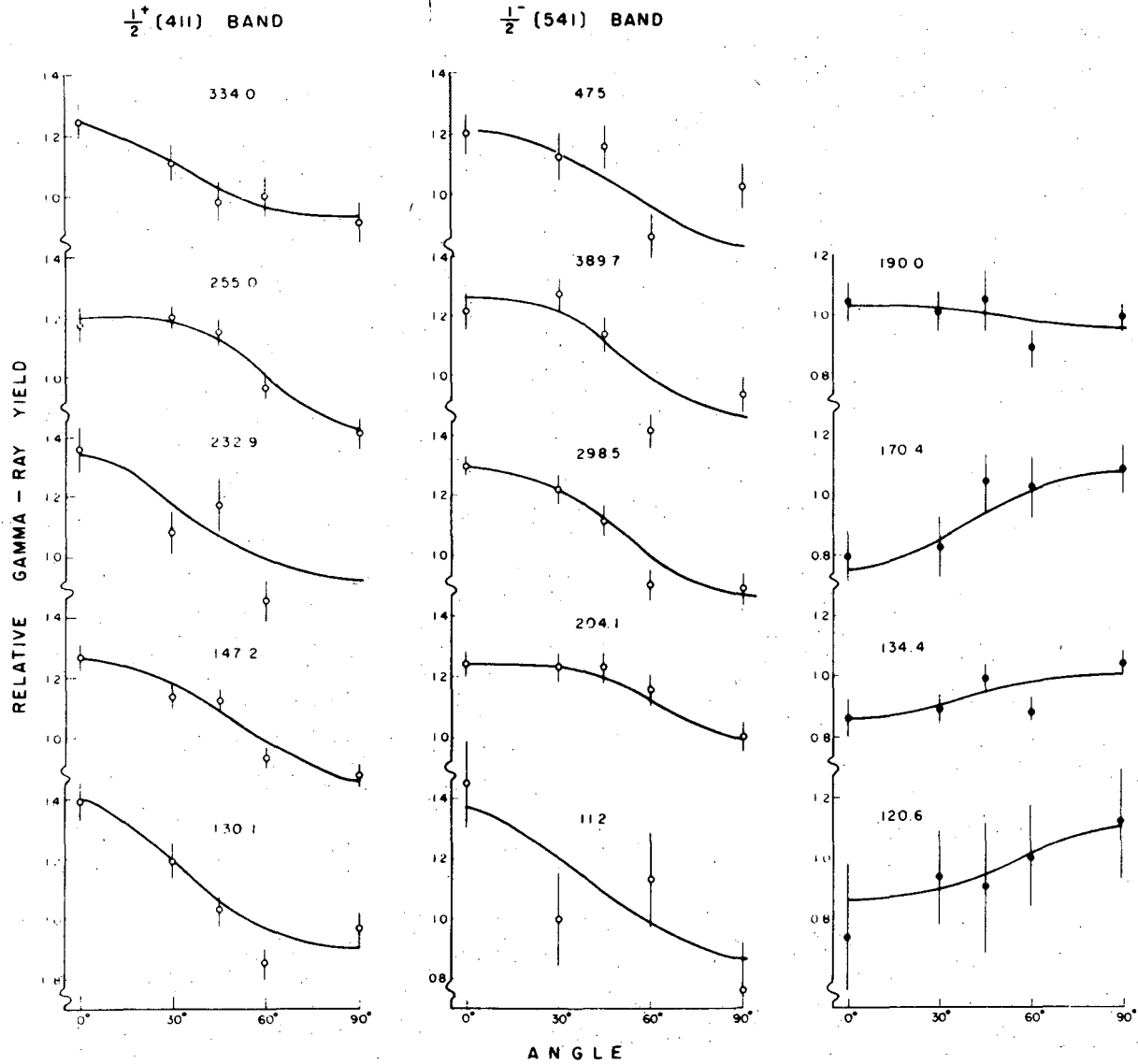
Fig. 4. Proposed radioactive decay scheme of ^{165}Yb . Only those transitions and levels involved in the radioactive decay are shown. Dashed levels and transitions are placed with less certainty than others. All energies are in keV, and Nilsson quantum number assignments are the usual $K\pi[Nn_z\Lambda]$. The level energies are best values derived from experimental transition energies, but the gamma transition energies shown above each line are exact differences of the level energies and not the experimental values. Thus, the transition energies of the decay scheme may not always correspond exactly to the experimental energies of Table I; the energy differences afford a ready test on consistency of the scheme. Multiply assigned transitions are indicated by asterisks. A solid dot at the upper (lower) end of a transition line means that transition has been measured to be in coincidence with some higher (lower) transition. Open circles indicate less certain coincidence observations.

Fig. 5. Complete summary schematic of all levels observed in ^{165}Tm by radioactivity and in-beam gamma spectroscopy. Spins are labeled by the integer that is twice the spin value. The only transition lines indicated are for transitions observed in our in-beam work. The higher levels seen by the Grenoble group¹⁰ with their spectra of better statistics are also included on the diagram. As in Fig. 4 the energies are differences of adopted level energy values, not experimental energies themselves. Asterisks indicate unresolved doublet assignments. The three slanted-line transitions not terminating on a level line go between the $1/2^+$ and $1/2^-$ bands. There was not space to enter exact level energies, but they may be read from Fig. 4 or from Table IV.



XBL 736-800

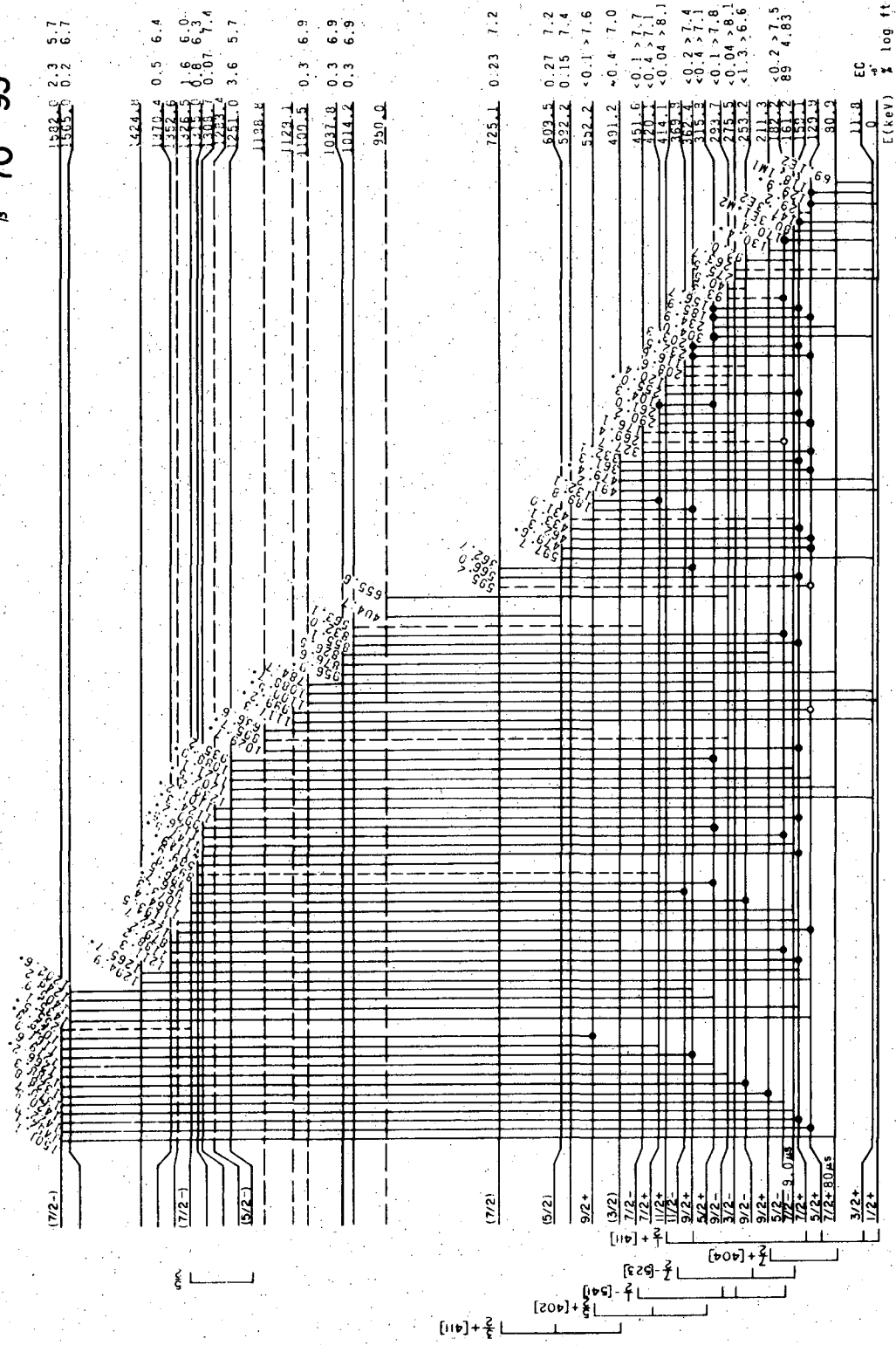
Figs. 2a-c



XBL 735-667

Fig. 3

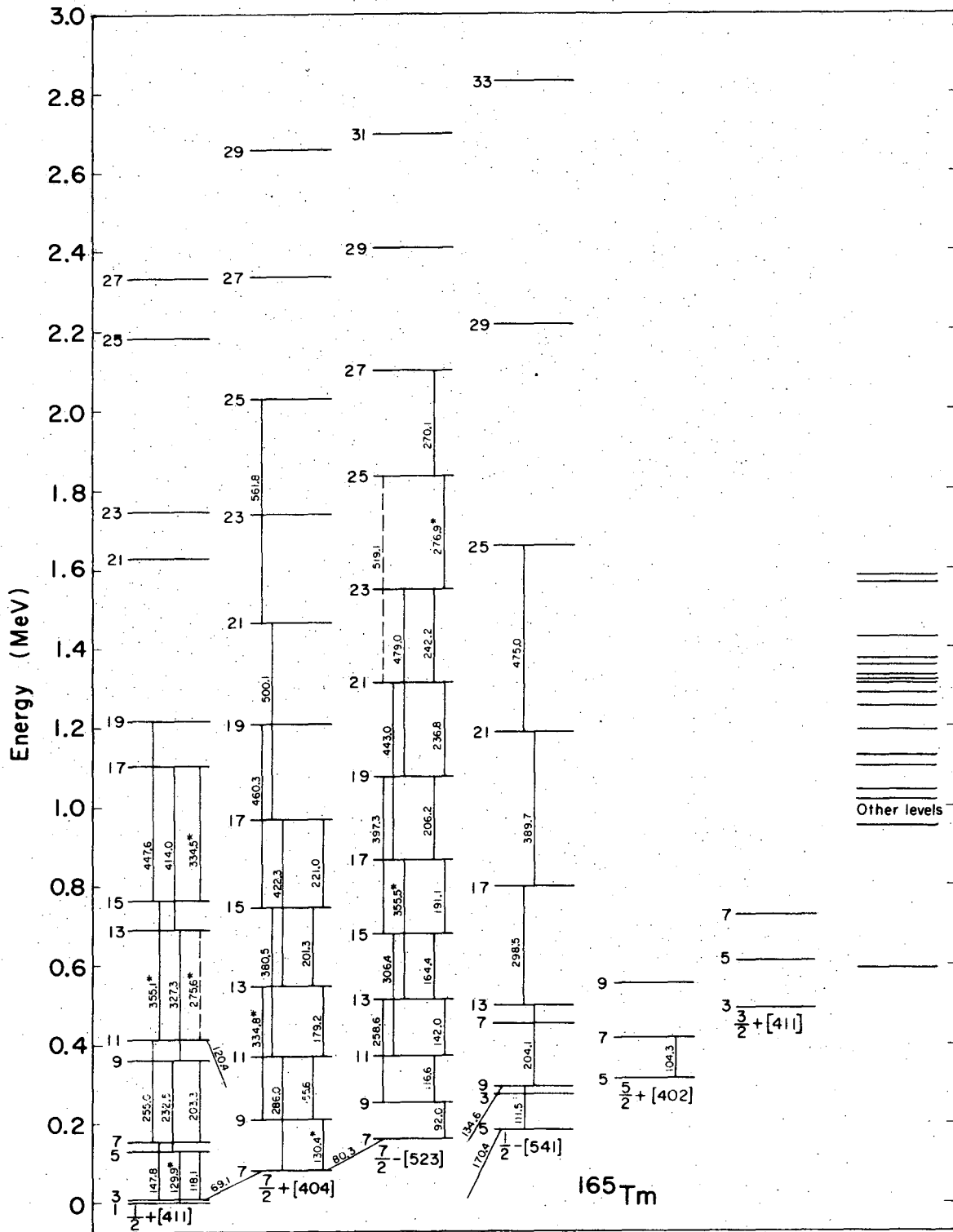
$\frac{3}{2}$ - [523] $\frac{5}{2}$ -
EC $^{165}\text{Yb}95$
 β^+



$^{165}\text{Tm}96$

XBL734-2805

Fig. 4



XBL 734-2649

Fig. 5

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TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720