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HEAVY ION COULOMB EXCITATION OF DEFORMED NUCLEI

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F. S. Stephens, B. Elbek, and R. M. Diamond

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The Coulomb excitation program at the Berkeley HILAC has for the last few years been directed principally toward the determination of detailed level schemes of heavy deformed nuclei. Both odd-mass and even-even nuclei have been studied. As representives of the former nuclear type we report here the recently completed work on Tb^{159}, Ho^{165}, and Tm^{169} (ref. 1). Work on the even-even nuclei, Th^{232} and U^{238}, is still in progress; however, the principal features are well established and will also be reported.

1. Odd-Mass Nuclei

The Coulomb excitation of Tb^{159}, Ho^{165}, and Tm^{169} has been studied using as projectiles O^{16} ions produced at the HILAC. The beam energy was usually 60 MeV, but it could be varied from around 20 MeV to the maximum energy of 167 MeV by changing the tilt of the gradient in the post-stripper tank and adjusting the tank tuners to cause the beam to fall out of phase at the desired energy and coast the rest of the way down the tank. After leaving the accelerator, the beam passes through a deflecting magnet which bends it 22 deg through a quadrupole focusing magnet into a steel and concrete cave containing the gamma-ray and conversion-electron spectrometers. Beams of +6-charged O^{16} ions of about 1-μA average current can be obtained through a 2-by-2-mm collimator at the target position. Thin (~1 mg/cm^2) gold foils can be moved into the beam at the deflecting magnet and also near our target position in order to scatter the beam into silicon detectors to determine the beam energy and energy distribution. These detectors are calibrated against

the energy of the full energy beam (167 MeV).

Both gamma-ray and conversion electron spectra were taken. The singles gamma-ray spectra suffered from a large background produced partly from external sources, but mainly from the target. Surface impurities such as an oxide coating and possibly pump oil are the likely orgins. By means of the coincidence technique developed earlier in which only the gamma rays in coincidence with back-scattered O^{16} particles are recorded,[2] this background was reduced, and far superior spectra were obtained. For a more detailed investigation of the de-excitation transitions following Coulomb excitation, and one employing higher resolution than is possible through gamma-ray spectroscopy, we studied the internal conversion electron lines using a single wedge-gap spectrometer of the type developed by Kofoed-Hansen, Lindhard, and Nielsen.[3] A short description of our spectrometer has been given elsewhere.[4]

Examples of the gamma-ray spectra coincident with back-scattered O^{16} ions and of the electron spectra for the odd-mass rare earth isotopes are shown in figs. 1-6. From such primary data, one derives the energy and yield of each gamma-ray and conversion electron transition. The yields can be used to determine the excitation function of each transition, and thus the multipolarity of the excitation, and further to give the excitation transition moment--B(E2) in these cases. The energies and relative intensities of the transitions are used in conjunction with these yield data to deduce the level schemes shown in figs. 7-9. The detailed data can be found elsewhere, and therefore will not be reproduced here. Instead we will discuss the level schemes and their interpretation.

In constructing the level schemes we first establish the positions of the levels from the transition energies. Since there are usually two or three

transitions deexciting each level, this is a reasonably straightfoward and unambiguous procedure. These levels almost always fall into groups which are, in most cases obviously, rotational bands. To determine the K value and parity of the bands, we have analyzed (1) the moment of inertia implied by the gross spacing observed, (2) the detailed relative spacings of the levels, (3) the Coulomb-excitation multipolarity, transition moment, and relative population of the band members, and (4) the multipolarity and relative intensity of the deexciting transitions. For all bands below about 900 keV, the above criteria indicated reasonably definitely the K and parity values. For bands above about 900 keV, there were usually not sufficient data to make definite assignments. With the K and parity values established, the above criteria were again used to determine the nature of the bands (collective or single particle). The expected single particle states and their properties were taken from Nilsson's calculations,[5,6] and for this region the collective bands expected to lie lowest are the K_0-2 and K_0+2 gamma vibrational bands (where K_0 is the ground state K value). The principal conclusions from this type of analysis are summarized below.

Single particle states were seen in Tb^{159} at 348 and 971 keV, and probably in Tm^{169} at ~900 keV. These states are thought to be excited by E2 excitation from the ground state. The 361 keV single particle state in Ho^{165} is probably populated mainly by E1 decay from the 514 keV level, and hence may not represent a direct excitation from the ground state. In each case, assignment could be made to an expected Nilsson orbit and where such assignments are definite they are shown in figs. 7-9. The only further comment we will make is that the E2 strengths to these levels (0.3 to 1.0 single-particle unit) are rather large and most likely due to Coriolis admixtures of these states into their respective ground states. Such mixing, even though small, can introduce large E2- transition probabilities because of the very large collective quadrupole moments of nuclei

in this region.

The collective excitations, as expected, produced bands which seem to be related to the ground state by $K = K_0 \pm 2$. We call these "gamma-vibrational states" following the terminology of Bohr and Mottelson, although it must be recognized that the results of our measurements do not give any obvious means of distinguishing between different models which provide collective excitations with change of K by two units. Some of the systematic properties observed in these collective levels will be summarized in the following paragraphs.

The K_0-2 gamma vibrational band is almost certainly seen in Ho^{165} (514 keV band), very likely in Tb^{159} (580 keV band), and probably in Tm^{169} (570 keV band). The K_0+2 gamma band is probably seen in Ho^{165} (687 keV band) and possibly in the other two nuclei (~1280 and 1170 keV in Tb^{159} and Tm^{169}, respectively). In all three cases the K_0-2 band lies lower in energy; by 170 keV in Ho^{165}, and probably by 600 or 700 keV in the other cases. It is interesting to note that in Re^{187}, the only other odd-mass nucleus where gamma bands have been established reasonably well,[24] it is the K_0-2 bands alone that are seen. A reasonable implication is that these bands lie lower in energy than the K_0+2 bands. As far as we know there has been no theoretical treatment of the relative energies expected for such bands. While it seems quite reasonable to us that the K_0-2 band should lie lower, the magnitude of the splitting in Tb^{159} and Tm^{169} is surprising. Even if our tentative K_0+2 assignments are not correct in these cases, the failure of this band to show up at lower energies still implies a large splitting. The difference between these cases and that of Ho^{165}, which has a considerably smaller splitting, is not clear.

The E2-transition probabilities (for a vector-addition coefficient of unity) between these vibrational states and their respective ground states is

in all cases between one and two single-particle units. Furthermore in a given nucleus the E2 strengths to the K_0+2 and K_0-2 bands from the ground state are apparently nearly equal. The relative E2-transition probabilities for de-excitation of the bands in Ho^{165} (in Tb^{159} and Tm^{169} they de-excite principally by M1 radiation) followed the predictions of the vector-addition coefficients with a slight modification for mixing of the ground and vibrational states, as has been observed by O. B. Nielsen in even-even nuclei.[8] The evidence is fairly strong that this mixing correction is necessary. The relative E2-transition probabilities for Coulomb-exciting the members of these bands in all three nuclei seemed also to follow the modified vector-addition coefficients. However, these probabilities are subject to additional corrections because of the effects of multiple Coulomb excitation and intraband rotational de-excitations.

A surprising result was that when $|K_{vib}| = |K_{grd}| \pm 1$, as is the case for the K_0-2 bands of both Tb^{159} and Tm^{169}, the de-exciting transitions were predominantly M1 rather than E2. For these particular cases, M1 transitions are not K-forbidden. In fact, the appropriate vector-addition coefficients should be those for $|K_{vib}| \rightarrow |K_{grd}|$, and the data followed these within our limits of error. However, such transitions are not expected in a pure vibrational model. On this model we also would not have expected the relatively fast E1 transition(s) observed to occur in Ho^{165} between the K_0-2 gamma band (514 keV) and a nearby intrinsic (Nilsson) state (361 keV).

The occurence of such transitions does not argue against the collective nature of these states, which seems to us to be rather strongly suggested. Even a lack of K purity in these states is not indicated. The disagreement is with the detailed vibrational description, and particularly in the case of the E1 transitions, it is not clear to us that reasonable admixtures of nearby states can account for the observed transition moments. In this regard it would be interesting to see calculations based on the Davydov-Filippov model.[9] In this model such

transitions are not forbidden in general. On the other hand Davydov's calculation for $j = \Omega = 1/2$ is in very poor quantitative agreement with our data on Tm^{169} where $\Omega = 1/2$. It remains to be seen if relaxing the requirement $j = 1/2$, can bring this calculation into agreement with the experimental data.

We also Coulomb excited, via multiple E2 excitation, six to eight members of each ground state rotational band. Due to our use of thick targets, the intensity of population of each band member was not readily obtained. However, the energies of these levels were measured, and are included on the level schemes (figs. 7-9). From the rotational-energy formula,

$E_I = E_0 + A\, I(I + 1) + BI^2(I + 1)^2$, one can easily derive the equation

$(E_{I+1} - E_I)/2(I + 1) = A + (B/2)[2(I + 1)]^2$. Thus a plot of

$(E_{I+1} - E_I)/2(I + 1)$ vs $[2(I + 1)]^2$ should give a straight line for which the intercept is A, and the slope is B/2. Figs. 10 and 11 show the data for Ho^{165} and Tb^{159} plotted in this way. Whereas the Ho^{165} data are well fitted by a straight line, those for Tb^{159} are not at all consistent with a single line, but rather convincingly suggest two straight lines having very nearly a common intercept. This behavior is not completely unexpected. It has been predicted[10,11] that in a $K = 3/2$ band there will be a term in the above equation for E_I of the form $+C(-)^{I+1/2}(I - 1/2)(I + 1/2)(I + 3/2)$. This term comes from the Coriolis coupling of the $K = 3/2$ band to $K = 1/2$ bands, and is the direct result of the anomalous energy spacing of the $K = 1/2$ bands. This term will cause just the behavior noted in fig. 12; namely, two lines having a common intercept. The values of A, B and C required to fit the data are given on figs. 10 and 11. Our analysis of the C term in Tb^{159} suggests that it arises largely due to mixing of the ground state band with the band, 1/2 + [411], which we have tentatively identified at

971 keV in this nucleus. The ground state band of Tm^{169} also shows a C term of the above type, but somewhat larger than is found in Tb^{159}, as might be expected for a K = 1/2 band. The decoupling term in the rotational energy equation for K = 1/2 bands makes the presence of this C term less obvious than is the case for the K = 3/2 band in Tb^{159}.

2. Even-Even Nuclei

The electron spectra from Th^{232} and U^{238} bombarded by ~80 MeV O^{16} ions are shown in figs. 12 and 13. These spectra are composites of many shorter runs, and the statistics and even to some extent the resolution vary from section to section. Although there are several groups of transition not get fully understood, most of the transitions observed have been fitted into the level schemes of Th^{232} and U^{238} shown in figs. 14 and 15. The basic features of these schemes have been known for some time; however, considerably greater detail is now available. As in the above discussion of the odd-mass nuclei, the data analysis will not be presented here, but will shortly be available elsewhere.

Three bands, all thought to be collective, are Coulomb excited in both U^{238} and Th^{232}. These are the even parity K = 0 (beta vibrational) and K = 2 (gamma vibrational) bands and an odd parity (octupole vibrational) band known to be K = 0 in U^{238}, but of uncertain K value in Th^{232}. We will first discuss the odd parity bands briefly and then the even parity ones at somewhat greater length.

In both Th^{232} and U^{238} the population of the odd parity band is primarily by E3 excitation. This has been shown both by studies of the excitation functions of these bands and also by the gamma ray intensities in coincidence with backward-scattered compared with forward-scattered projectile ions. The B(E3) values for these transitions are both between 10 and 20 times the single particle estimate. This fact, coupled with the knowledge that very similar bands occur systematically

in many even-even nuclei in this region, suggests rather strongly to us that these are collective states. The bands deexcite by E1 radiation; however, detailed information on these transitions is avilable only in the case of U^{238}. For this nucleus the relative transition intensities are such as to indicate the K = 0 assignment mentioned previously. Part of the work still in progress on these nuclei is an attempt to study the conversion lines of the high-energy E1 transitions in Th^{232}. In the absence of such detailed information no K assignment can be made in this case.

There is a wealth of data available on the even parity bands excited in Th^{232} and U^{238}.[12-14] No attempt can be made here to discuss these bands thoroughly, but some of the more prominant features will be mentioned. In each nucleus the total B(E2) to both bands is of order five single particle units. The bands lie very close together in both cases; the respective 2+ states being 11 keV apart in Th^{232} and 23 keV apart in U^{238}. The K = 2 band always lies higher in energy and receives 2/3 - 3/4 of the total population. A very prominant feature of both K = 0 bands is the electric monopole deexcitation to the ground state band. Of order 1/3 the population of each level decays via this mechanism. These very prominant electron lines have made it possible to identify 4 or 5 members of each K = 0 band; whereas, only the 2+ member of the K = 2 band is positively identified. This lack of other observed band members in the K = 2 band is also due partly to an unfavorable theoretical probability for exciting higher members in this band, and partly to the fact that the expected deexcitation lines of the 4+ member are masked by stronger lines. The moments of enertia in the K = 0 bands are 5 - 10% larger than in the respective ground state bands. All these features are in general accord with the known properties of these two types of states, both of which occur systematically in many even-even nuclei both in this region, and in other regions of the periodic table.

In the case of the relative E2 transition probabilities, however, one does not find agreement either with the theory or with previously known cases. The reason for this, we believe, is rather heavy mixing of the K = 0 and K = 2 bands. Reasonably direct evidence for this mixing is the high electron intensity for the $2+ \rightarrow 2+$ transition from the K = 2 band to the ground state band. There are insufficient photons in this energy region for this transition to be pure E2; it must either be largely M1 or have an appreciable E0 admixture. The former possibility is ruled out by angular correlation measurements made by Stelson and McGowan.[12] By far the most plausible explanation of and E0 component is admixture with the nearby K = 0 band. All the data on Th^{232} can be shown to be consistent with an analysis involving mixing of the K = 2 and ground bands, the K = 0 and ground bands, and the K = 0 and K = 2 bands. Mixing between the K = 2 band and the ground state band has been observed in many other cases by O. B. Nielsen,[8] and the amount of this mixing required for the present case is in good agreement with that found for other nuclei in this region. Mixing of the K = 0 and ground bands has not been observed previously due to the lack of experimental data on this type of band; but in Th^{232} it is several times larger than the K = 2-ground mixing and can largely account for the $I^2(I + 1)^2$ term in the analysis of the ground state rotational band energies. Mixing of the K = 0 and K = 2 bands is surprisingly heavy (20-25% in the amplititude) and almost undoubtedly occurs in this case due to the unusually small energy separation between the two bands. Unfortunately the number of parameters in this analysis almost equals the number of pieces of experimental data so that the result must, at the present time, be considered tentative. A similar analysis of U^{238} seems promising, but there are even fewer data.

In the present work heavy-ion Coulomb excitation has been found to be an excellent means of populating systematically and preferentially the collective modes of excitation of deformed nuclei. We feel the present work is sufficiently

detailed to indicate the wealth of data that will be obtained on these levels as beam intensities and instrumentation improve. Not only are there many other nuclei subject to this type of study, but also in every nucleus we have so far examined there are other weakly - populated bands and higher levels of known bands whose study was just outside the capabilities of the present work.

FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

Figure 1. Gamma-ray spectrum of Ho^{165} obtained in coincidence with back-scattered O^{16} ions.

Figure 2. Gammay-ray spectrum of Tb^{159} obtained in coincidence with back-scattered O^{16} ions.

Figure 3. Gamma-ray spectrum of Tm^{169} obtained in coincidence with back-scattered O^{16} ions.

Figure 4. Conversion-electron spectrum of Ho^{165}. The symbol ⧘ indicates the junction between different runs having slightly different back-grounds.

Figure 5. Conversion-electron spectrum of Tb^{159}.

Figure 6. Conversion-electron spectrum of Tm^{169}. The symbol ⧘ indicates the junction between different runs having slightly different back-grounds.

Figure 7. Level scheme of Ho^{165}.

Figure 8. Level scheme of Tb^{159}. The bands indicated by heavy lines were Coulomb-excited in the present study.

Figure 9. Level scheme of Tm^{169}. The bands indicated by heavy lines were Coulomb-excited in the present study.

Figure 10. Analysis of the energies of the ground-state rotational-band members for Ho^{165}.

FIGURE CAPTIONS (cont'd)

Figure 11. Analysis of the energies of the ground-state rotational-band members for Tb^{159}.

Figure 12. Electron spectrum of Th^{232} bombarded with ~70 MeV O^{16} ions. This spectrum is a composite of several shorter sections.

Figure 13. Electron spectrum of U^{238} bombarded with ~80 MeV O^{16} ions. This spectrum is a composite of several shorter sections.

Figure 14. Level scheme of Th^{232}.

Figure 15. Level scheme of ^{238}.

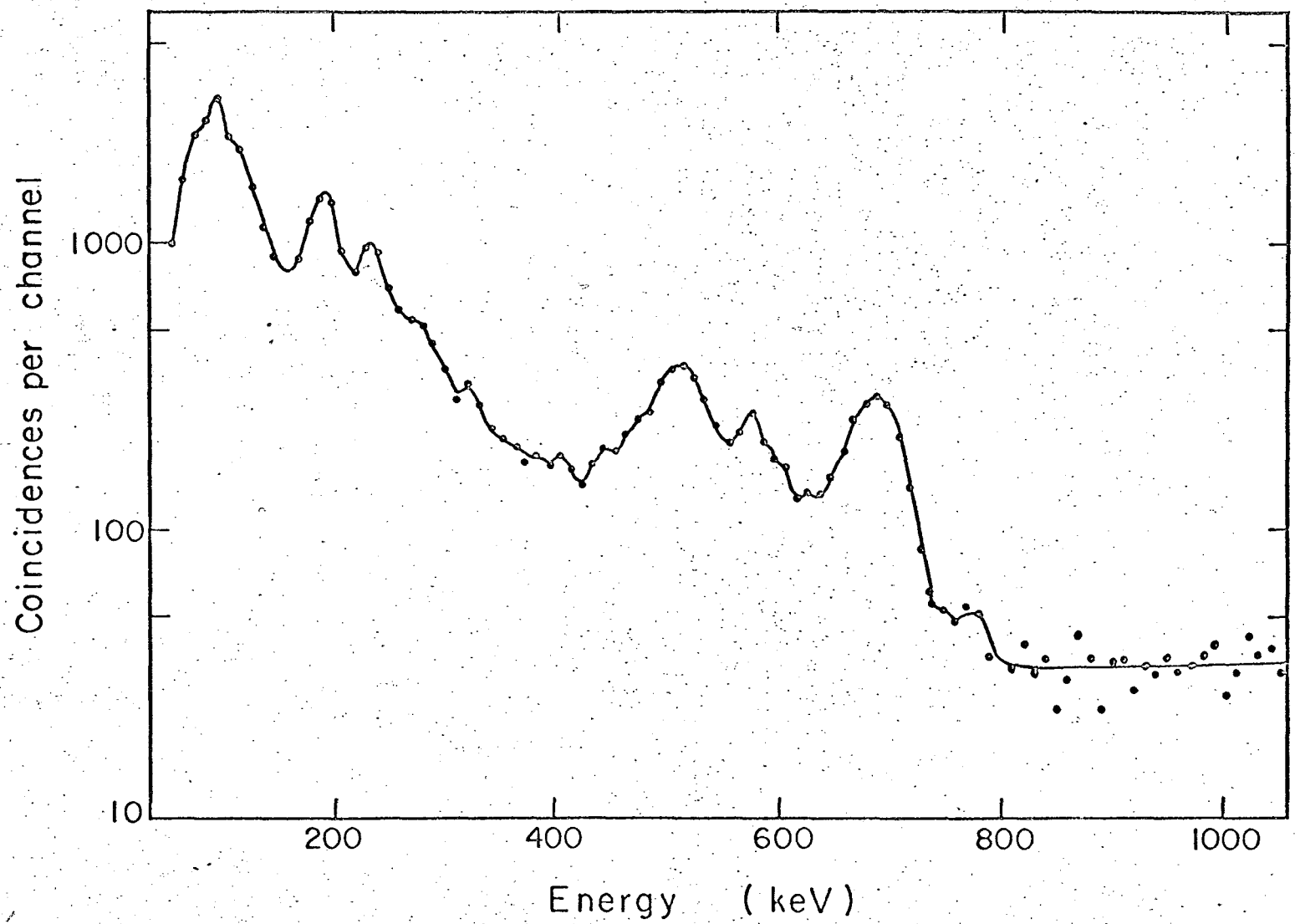

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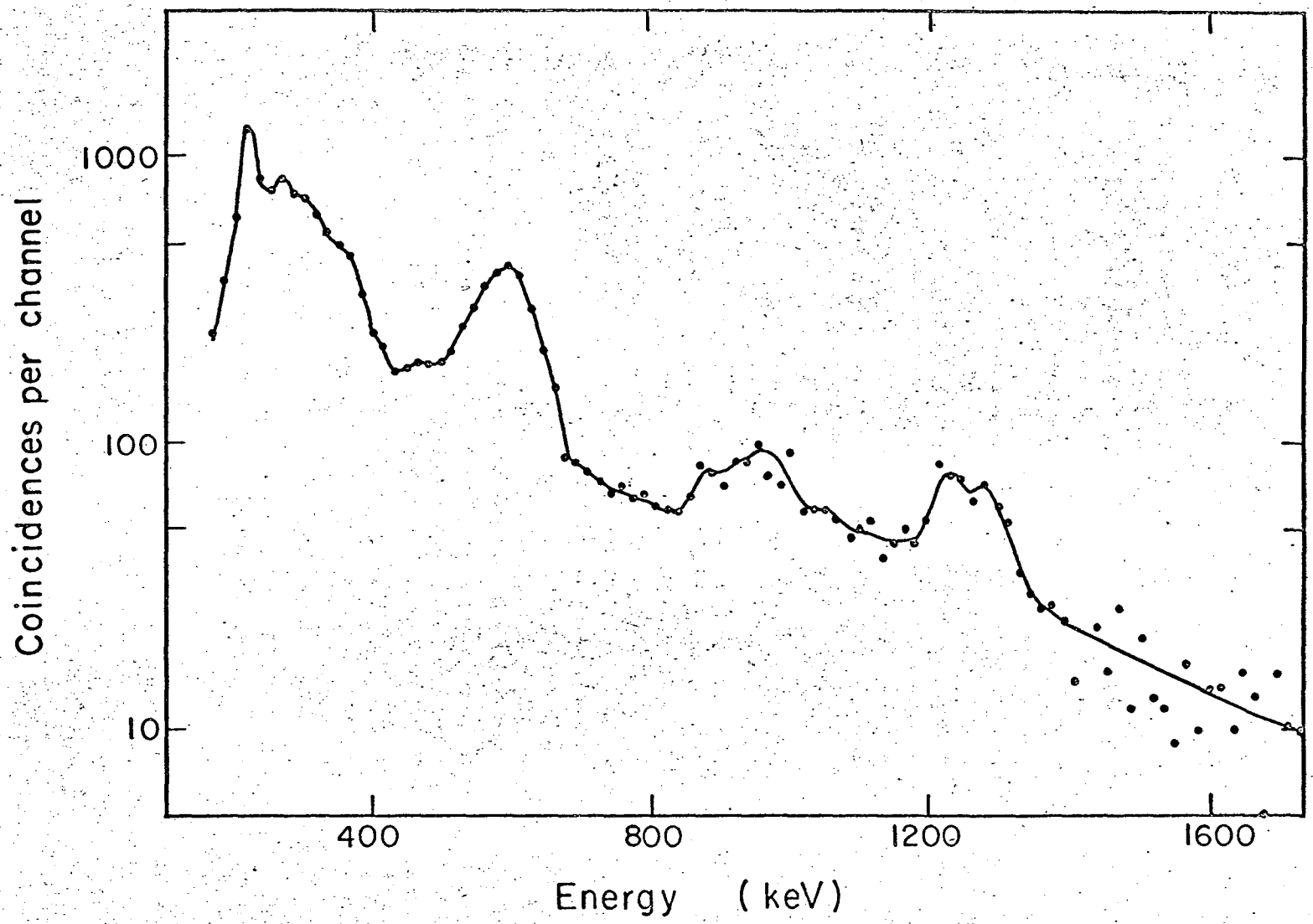
Fig 1



MU-27564

Fig 2

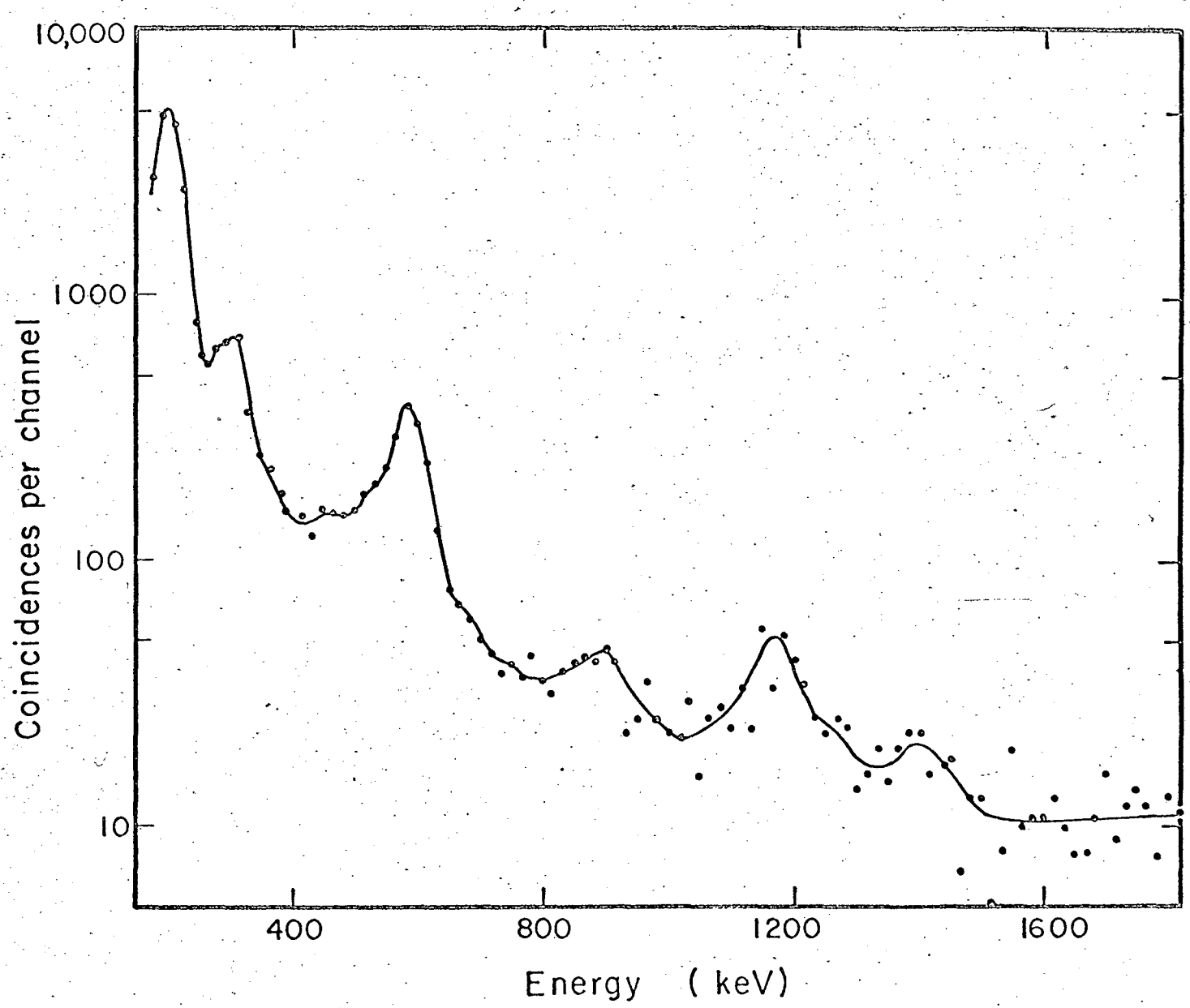


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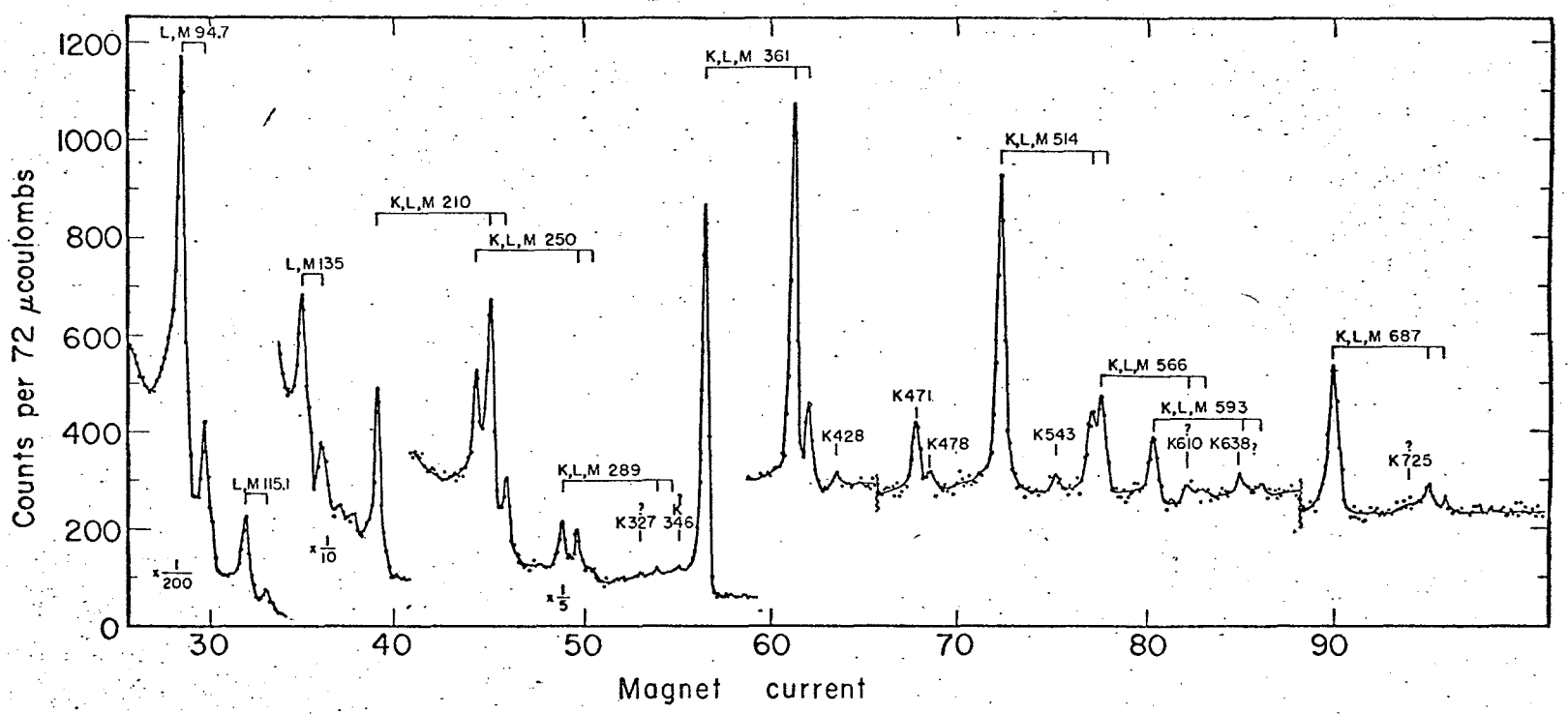
Fig 3


Counts per 72 μcoulombs
Magnet current
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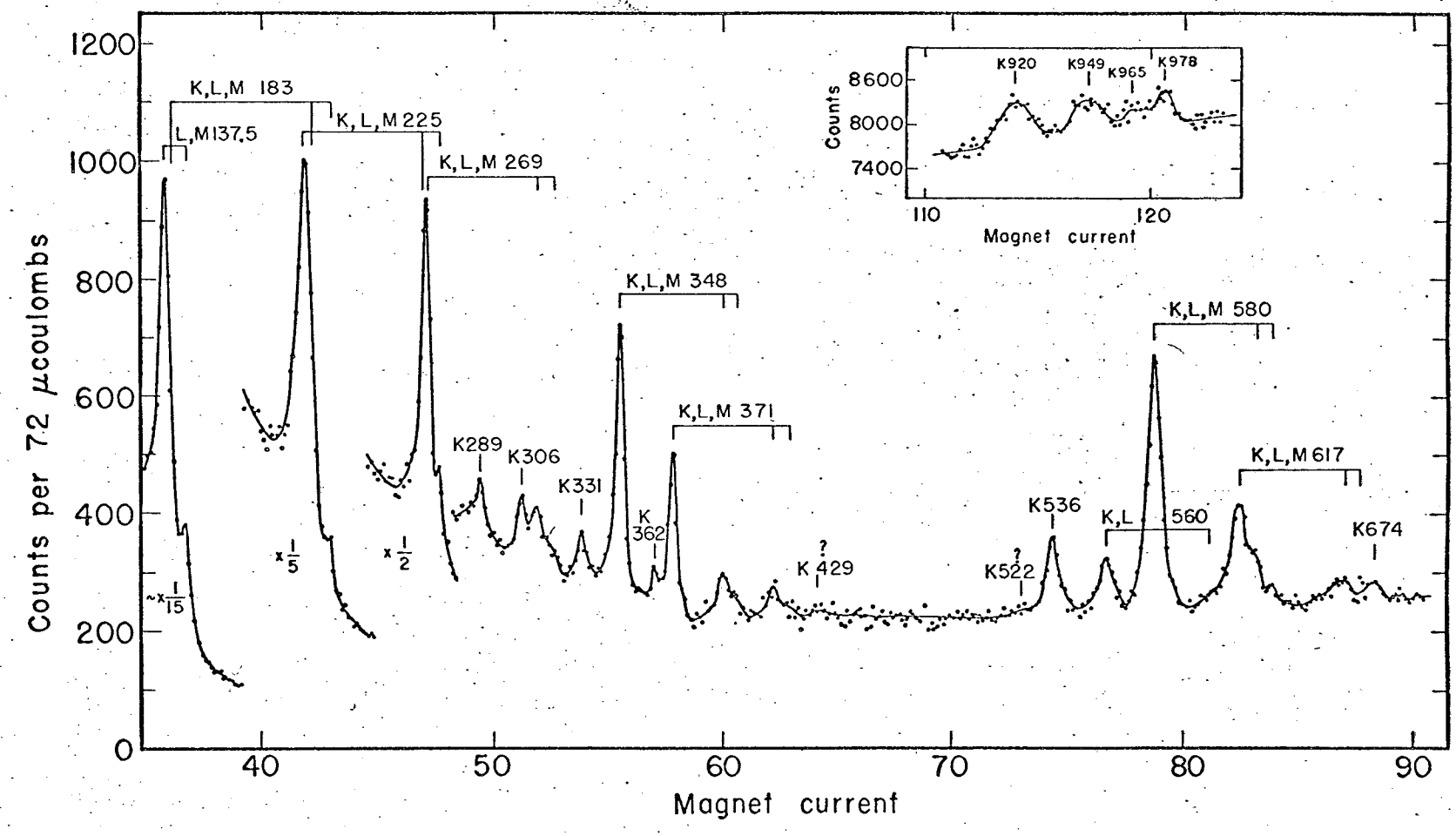
L,M 115.1
L,M 135
K,L,M 210
K,L,M 250
K,L,M 289
K327
K346
K,L,M 361
K428
K471
K478
K,L,M 514
K543
K,L,M 566
K,L,M 593
K610
K638
K,L,M 687
K725
x 1/200
x 1/10
x 1/5
0
200
400
600
800
1000
1200
30
40
50
60
70
80
90

MUB-909

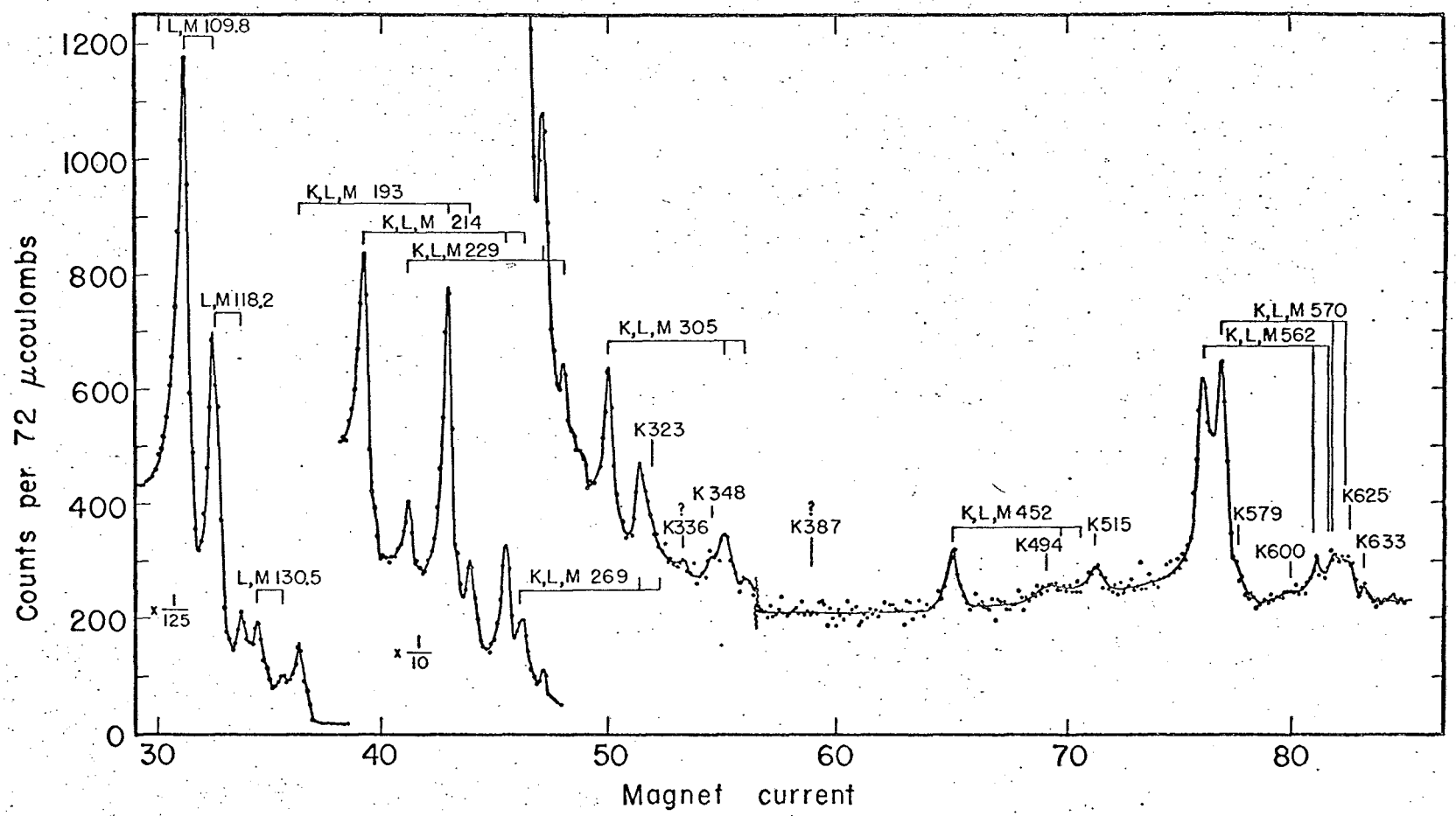
Fig 4



Counts per 7.2 μcoulombs
Magnet current
K,L,M 183
L,M137.5
K,L,M 225
K,L,M 269
K289
K306
K331
K,L,M 348
K 362
K,L,M 371
K 429
K522
K536
K,L 560
K,L,M 580
K,L,M 617
K674
~x 1/15
x 1/5
x 1/2
Counts
Magnet current
K920
K949
K965
K978

Fig 5

MUB-907


L,M 109.8
L,M 118.2
L,M 130.5
K,L,M 193
K,L,M 214
K,L,M 229
K,L,M 269
K,L,M 305
K323
K 348
?
K336
?
K387
K,L,M 452
K494
K515
K,L,M 570
K,L,M 562
K579
K600
K625
K633
x 1/125
x 1/10
Counts per 72 μcoulombs
Magnet current
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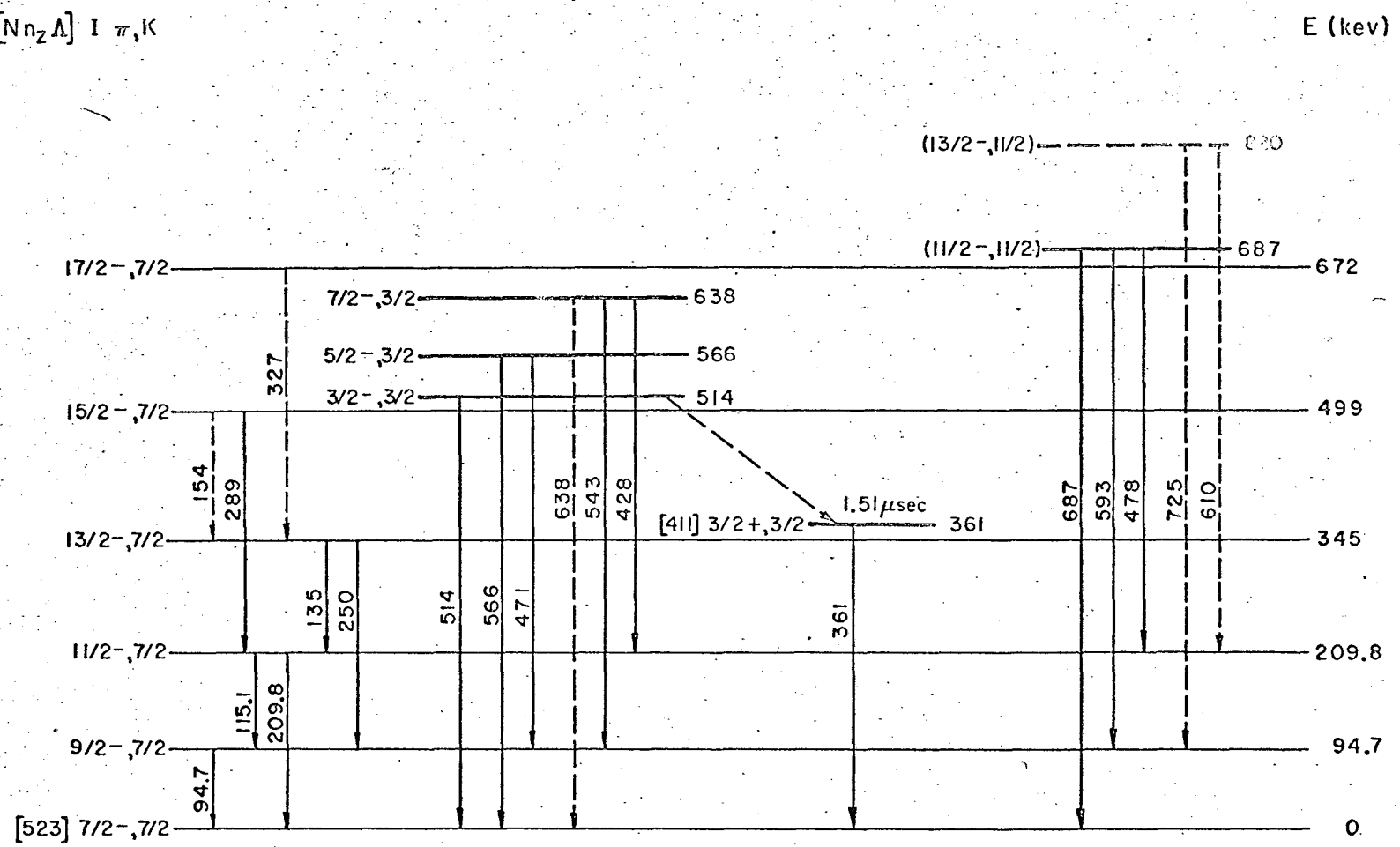
200
400
600
800
1000
1200
30
40
50
60
70
80

Fig 6

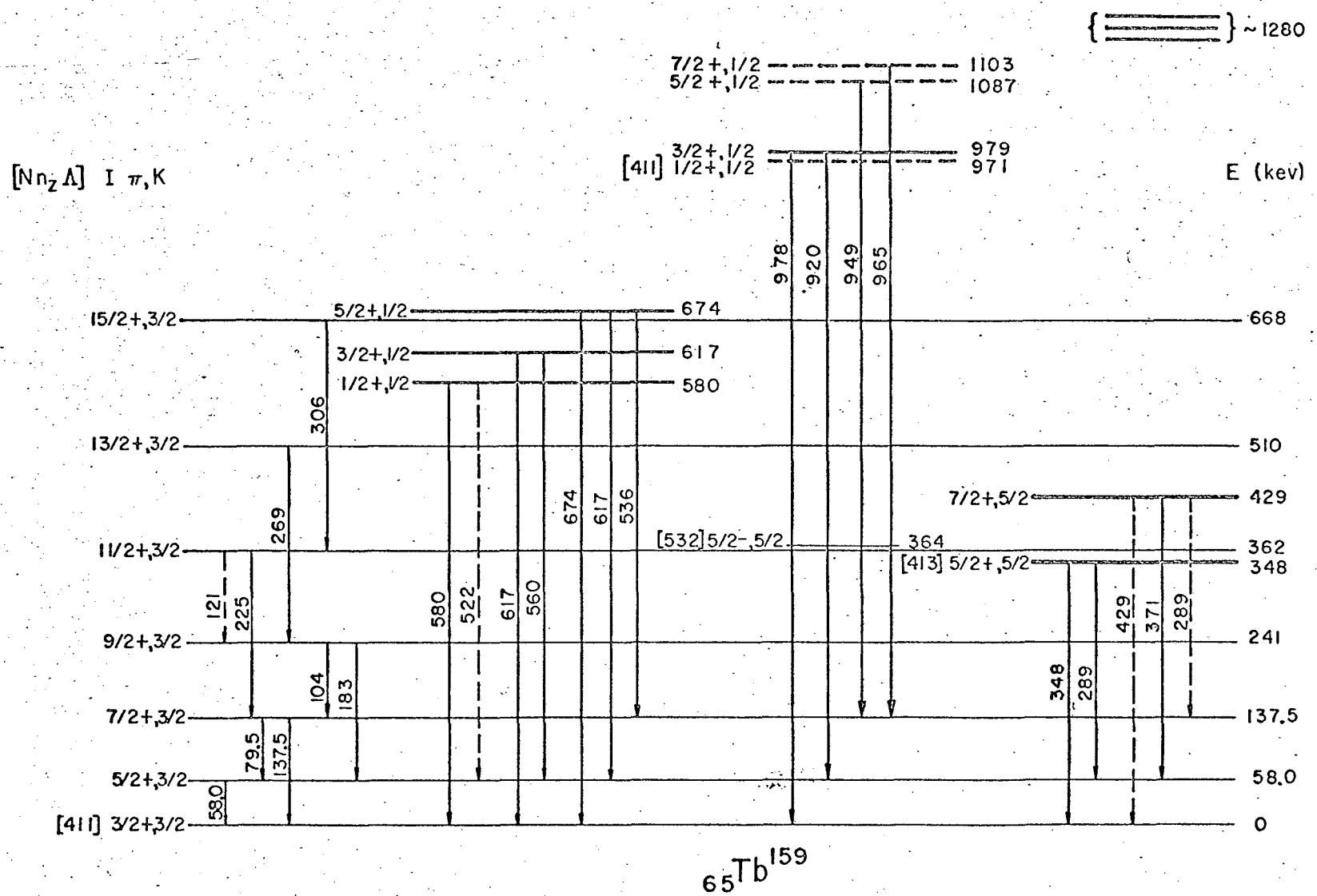
MUB-908



$_{67}Ho^{165}$

MU-25477

Fig 7


[Nn_z Λ] I π,K
E (kev)
~1280
7/2+,1/2 1103
5/2+,1/2 1087
3/2+,1/2 979
[411] 1/2+,1/2 971
15/2+,3/2 668
5/2+,1/2 674
3/2+,1/2 617
1/2+,1/2 580
13/2+,3/2 510
7/2+,5/2 429
11/2+,3/2 362
[532] 5/2-,5/2 364
[413] 5/2+,5/2 348
9/2+,3/2 241
7/2+,3/2 137.5
5/2+,3/2 58.0
[411] 3/2+,3/2 0
978
920
949
965
306
269
121
225
104
183
79.5
137.5
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65Tb159
MU-25479

Fig 8

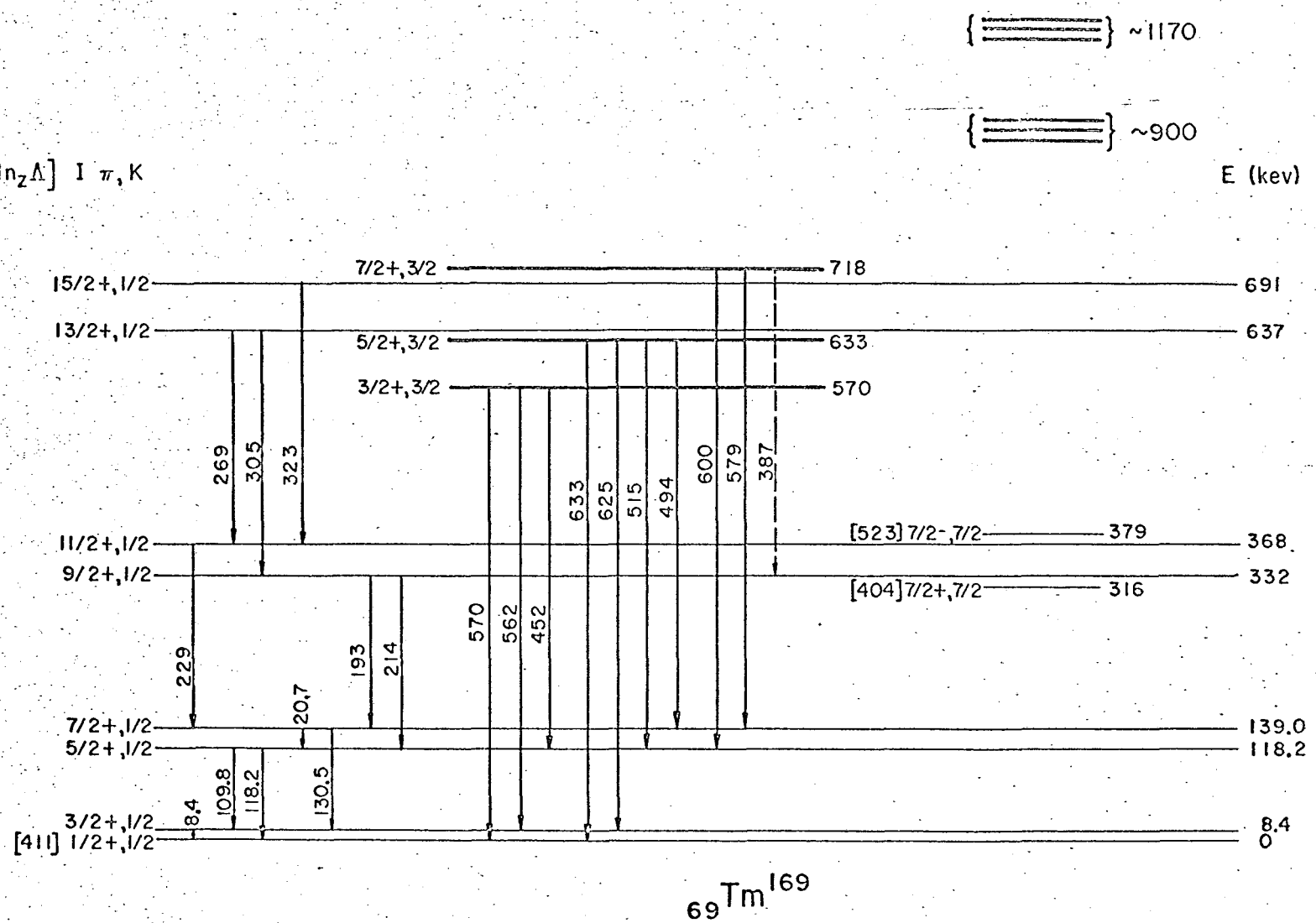

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Fig 9

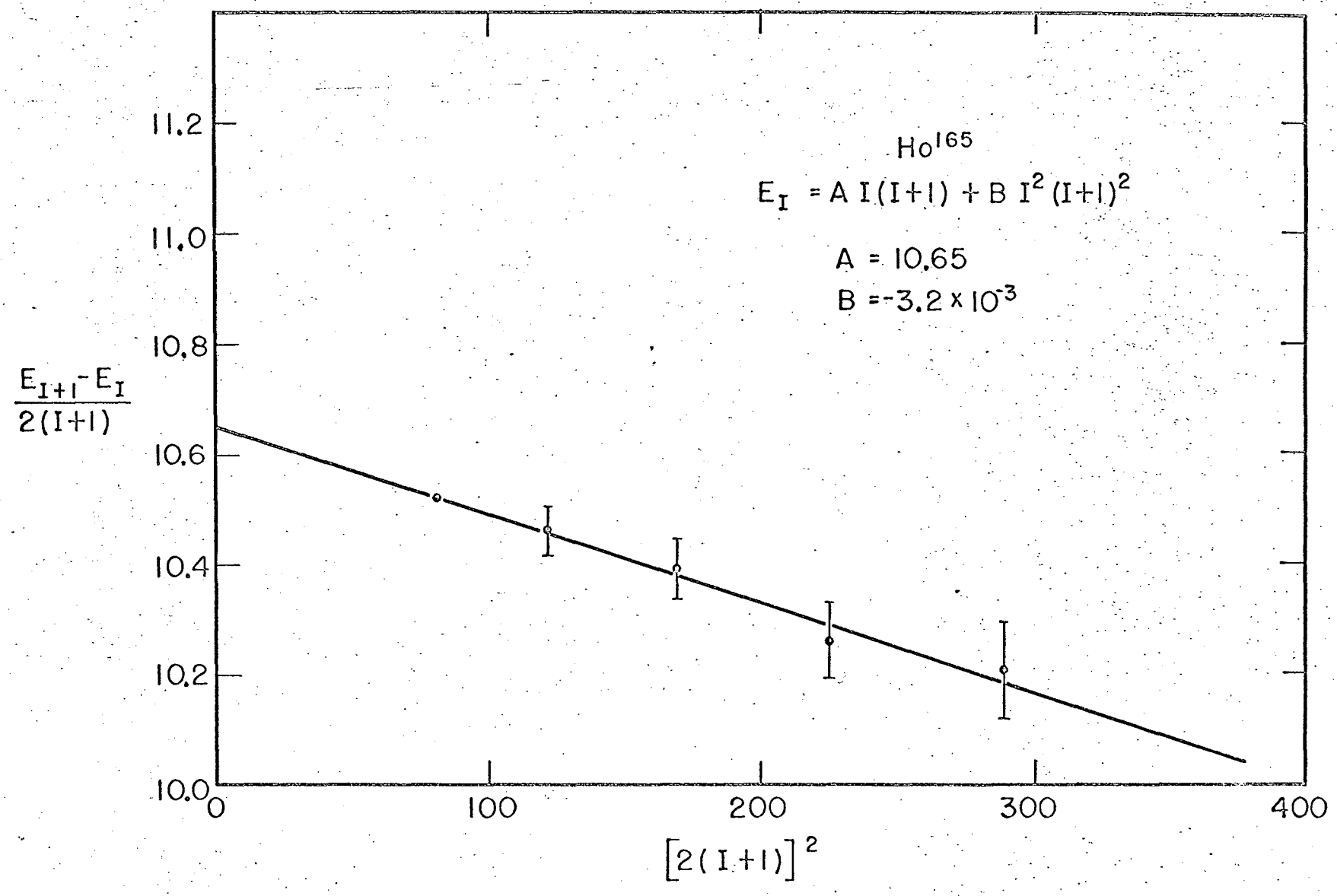


Fig 10

MU-25482

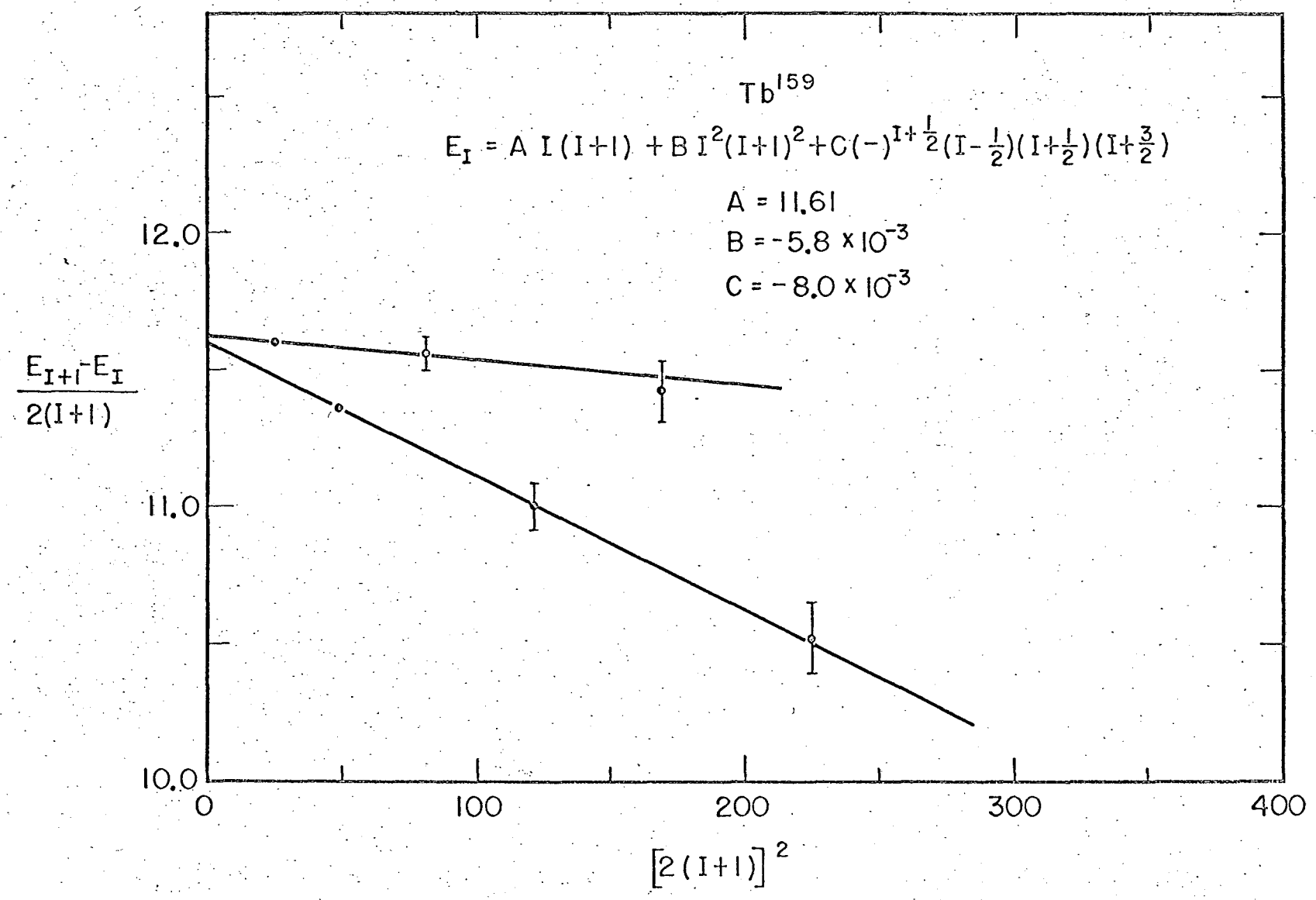
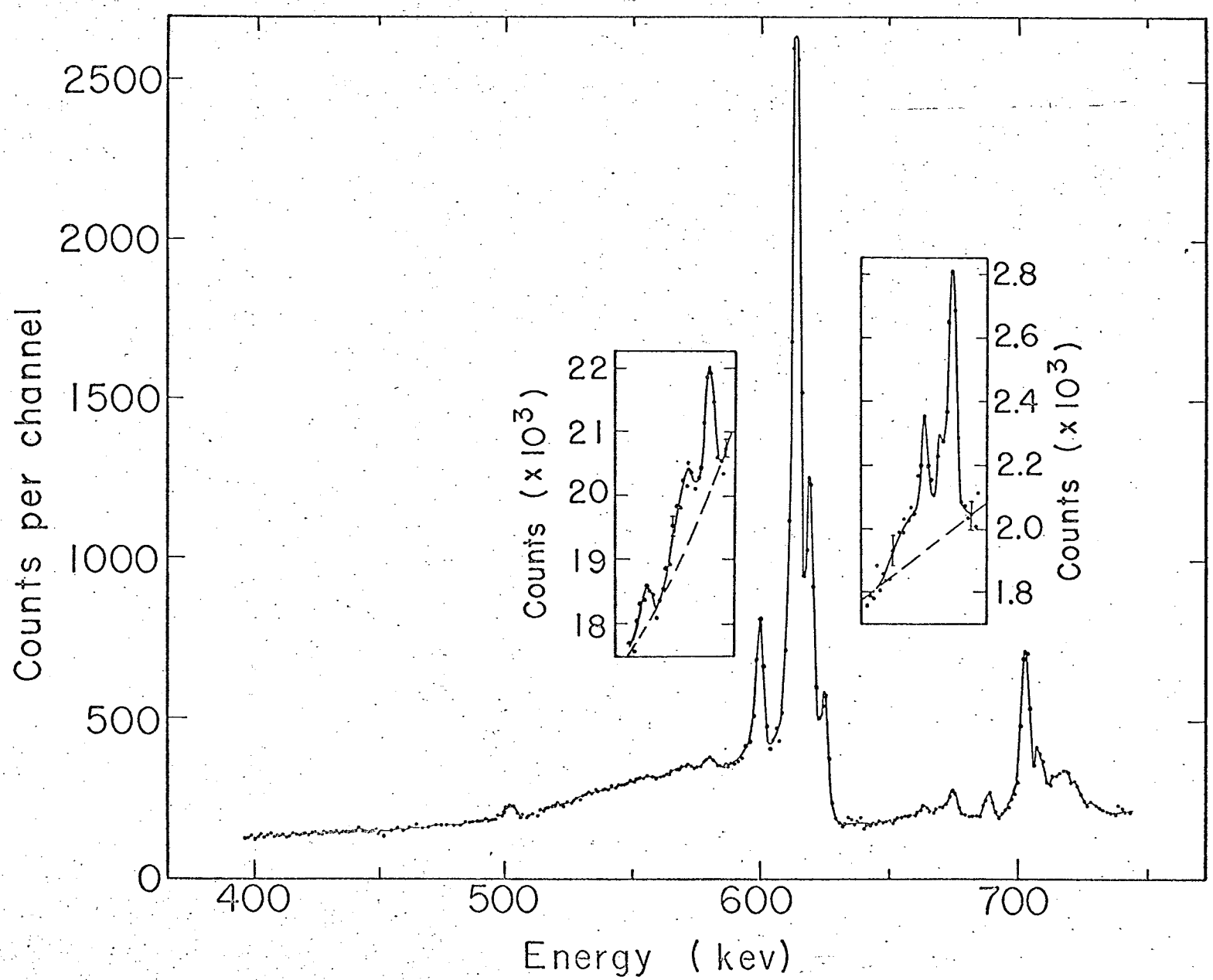


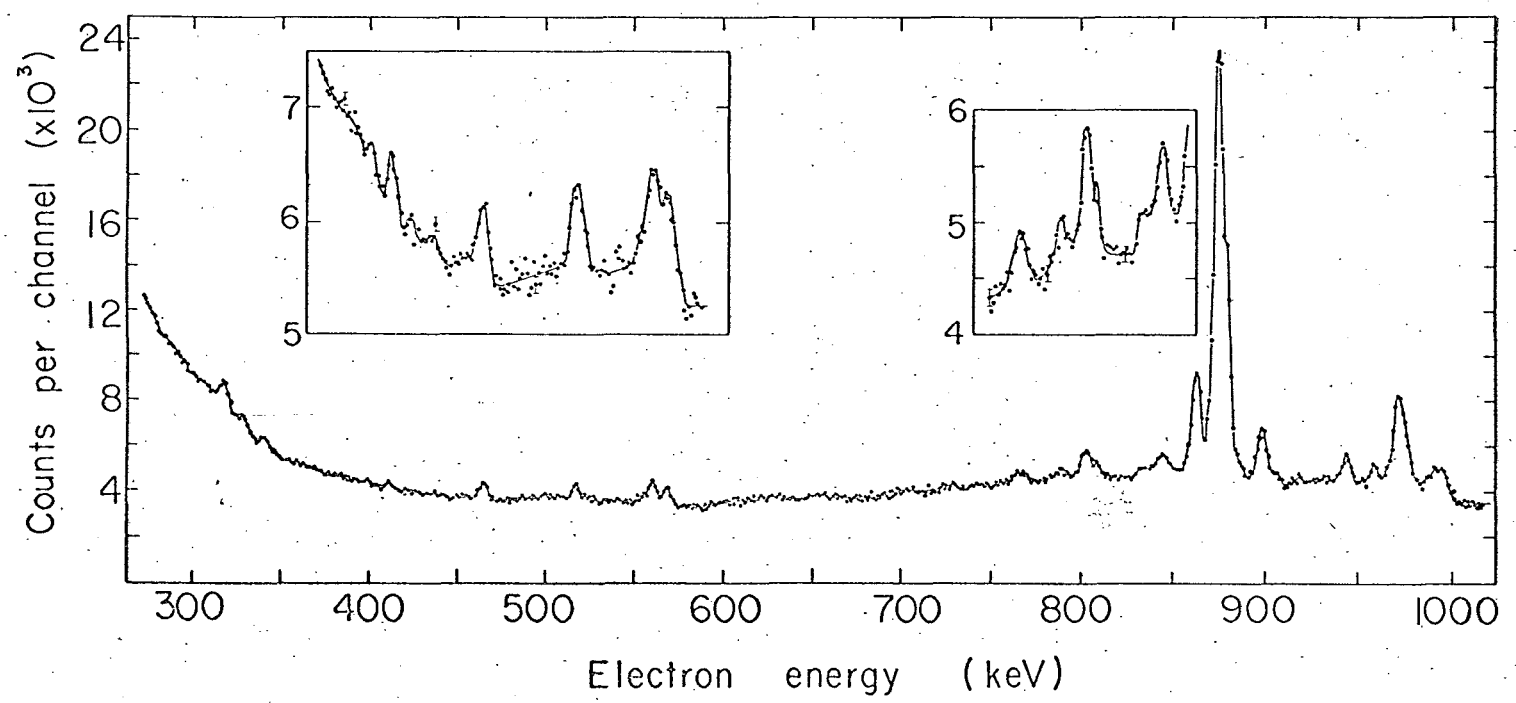
Fig 11

MU-25481



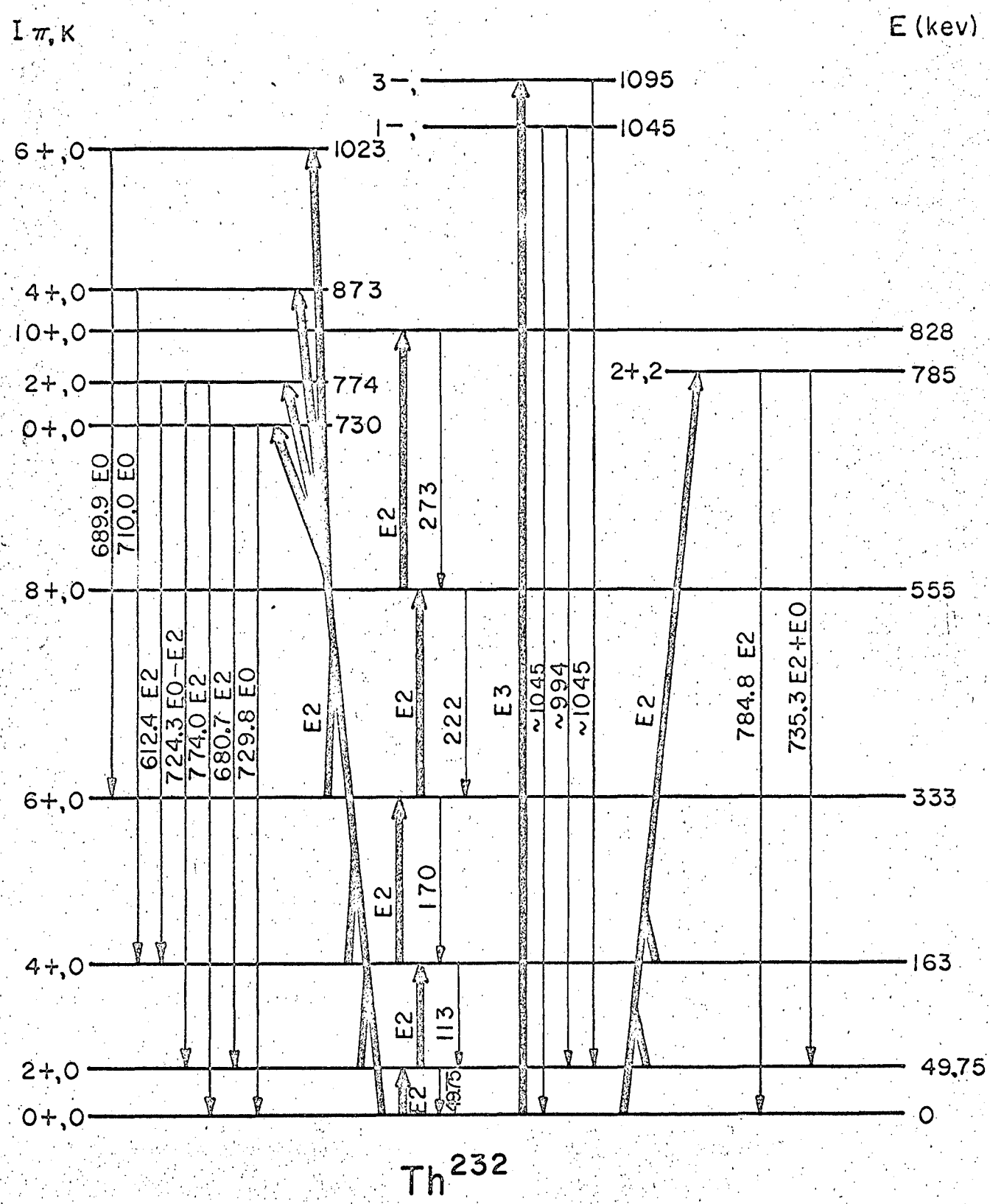
MU-24811

Fig 12



MUB-1686

Fig 13



MU-25483

Fig 14

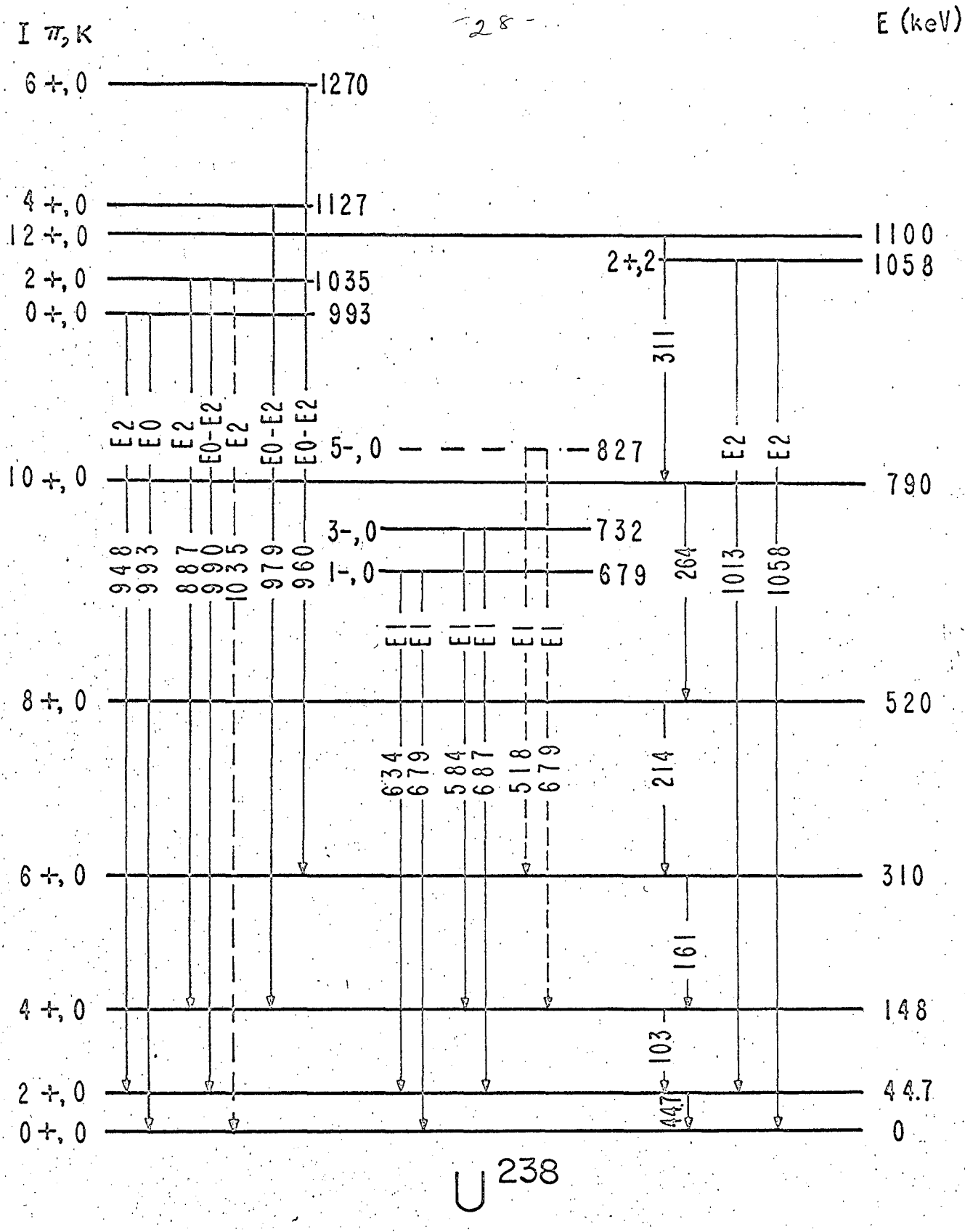


Fig 15

MU-29982