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Directional Correlation and Intensity Studies of Electromagnetic Transitions in ^{181}Ta *

F. T. Avignone III and J. H. Trueblood

Department of Physics, University of South Carolina

and

Z. W. Grabowski

Department of Physics, Purdue University

ABSTRACT

Gamma-gamma directional correlations have been measured in ^{181}Ta using a 25 cc Ge(Li) detector and a 3" x 3" NaI(Tl) detector. Extra-nuclear perturbations were avoided by desolving the ^{181}Hf source in a solution of HF. The following correlation coefficients were measured: $A_2 = -0.295 \pm 0.005$, $A_4 = -0.069 \pm 0.008$ for the 133γ - 482γ cascade, $A_2 = +0.197 \pm 0.012$, $A_4 = -0.008 \pm 0.020$ for the 133γ - (346γ) - 136γ cascade and $A_2 = +0.110 \pm 0.010$, $A_4 = 0.022 \pm 0.014$ for the 133γ - 346γ cascade. The E2 internal conversion particle parameters for the 133 keV transition were determined by measuring the 133K - 482γ, the 133 LM - 482γ and the 133γ - 482γ correlations in the same solid source. The results are $b_2(133K) = 1.79 \pm 0.11$ and $b_2(133\ LM) = 1.18 \pm 0.10$ which are in good agreement with theory. The following internal conversion coefficients were also measured: $\alpha_K(136) = 1.46 \pm 0.15$, $\alpha_K(137) = 2.2 \pm 0.6$, $\alpha_K(482) = 0.0234 \pm 0.0015$ and $\alpha_K(615) = 1.32 \pm 0.20$. The directional correlation data imply E2/M1 multipole mixing ratios of $\delta(136) = 0.45 \pm 0.02$ and $\delta(482) = 5.8^{+0.3}_{-0.2}$ where δ is defined in terms of emission matrix elements. This value for δ(482) and a weighted average of the present and four previous values of $\alpha_K(482)$ were used to re-evaluate the internal conversion penetration parameter as $\lambda(482) = 175^{+7}_{-4}$.

DISCLAIMER

I. INTRODUCTION

The strongly deformed ^{181}Ta nucleus has been the subject of many investigations. A summary of the earlier level scheme studies is given by Muir and Boehm.[1] The presently accepted decay scheme is that given by Alexander et al.[2] The nuclear decay scheme of ^{181}Ta, involving levels populated by the beta decay of ^{181}Hf, is shown in Fig. 1.

The ^{181}Ta nucleus has several very interesting features. First, all of the excited states populated by the radioactive decays of ^{181}Hf and of ^{181}W, are consistent with the predictions of the unified model of the nucleus.[1,3] Second, the highly-retarded, multipole-mixed, 482 keV transition [H(M1) = 2.5 x 10^6; H(E2) = 35] exhibits strong penetration effects in its magnetic dipole internal conversion process.[4,5,6] Third, experimental evidence of parity impurities in the 482 keV level of ^{181}Ta has been found by observing circular polarization of the 482 keV gamma rays.[7,8,9]

The degree of circular polarization of the parity mixed 482 keV gamma ray is given by

$$P_\gamma = \frac{-2}{1+\delta^2} \frac{\langle E1 \rangle}{\langle M1 \rangle} , \qquad (I)$$

where $\langle E1 \rangle$ and $\langle M1 \rangle$ are the electric and magnetic dipole matrix elements respectively and δ is the E2/M1 multipole mixing ratio. Considering Eq. (I), it is evident that a meaningful interpretation of gamma-ray circular polarization data, depends critically on the accuracy of our knowledge of δ. Unfortunately the accurate determination of δ is rather difficult for two reasons. The unambiguous determination of δ with L-subshell conversion measurements is precluded by the presence of large penetration effects, while gamma-gamma directional correlation measurements are seriously complicated by extra-nuclear perturbations, arising from the large nuclear quadrupole moment and the long life-time ($\sim$ 11 ns) of the 482

keV level. In addition, the interference between the 133_γ - 482_γ and 137_γ - 482_γ cascades, necessitate the use of a high resolution Ge(Li) detector, in the directional correlation experiment in order to resolve the 133 and 137 keV gamma rays.

The discrepancy between two recently reported values for the E2/M1 mixing ratio of this transition i.e., $\delta = 5.0 \pm 0.2$ [8] and $7.2^{+1.8}_{-1.5}$, [10] can lead to uncertainties in the evaluation of the circular polarization P_γ of the order of 100%, i.e., $\Delta P_\gamma / |P_\gamma| \sim 1$. Here, $\bar{P}_\gamma$ is calculated with the average of the two central values of δ given in references (8) and (10), and ΔP_γ is computed with the extreme values. Similarly, the above uncertainty in δ leads to errors of greater than 40% in the penetration parameter λ extracted from internal conversion data.

The ^{181}Ta nucleus is also of interest in the search for anomalous internal conversion processes involving fast, pure E2 transitions. Previously, reported values of the internal conversion directional correlation particle parameters $b_2(E2)$, for the 122 keV transition in ^{152}Sm and for the 123 keV transition in ^{154}Gd, [11,12] deviate somewhat from theoretically predicted values. Measurements agreeing with theory have also been reported. [13,14,15] These measurements are not, however, consistent among themselves. The recent careful measurements of the $b_2(122K)$ particle parameter in ^{152}Sm by Blumberg et al. [21] confirmed the existence of a deviation of about 7%. Because both transitions with anomalous particle parameters are low energy transitions in strongly deformed nuclei, it is of interest to investigate similar cases in other deformed nuclei. The 133 keV E2 transition inthe highly deformed ^{181}Ta nucleus, is an excellent candidate. In addition, this transition has a hindrance factor of about

400 (indicating the effectiveness of the Nilsson asymptotic selection rules) which is an unusually high value for the E2 transition.

It might also be interesting to measure the E2/M1 multipole mixing ratio in the 136 keV transition using the γ-γ directional correlation technique. These mixing ratios are very sensitive tests of nuclear wave functions. The mixing ratio $|\delta(136)|$ has been measured by Alexander et al.[2] using internal conversion L-subshell ratios. They found the E2 admixture in this transition to be $(11 \pm 1)\%$.

This value disagrees with the value $\delta_{136} = 0.45 \pm 0.04$ measured by Debrunner et al.[16] This last value is in good agreement with the recent measurement by Wilson et al.[17] and it is also consistent with the reinterpreted results of the experiment by McGowan.[18]

The large discrepancy in δ-values measured from L-subshell ratios and from directional correlation of gamma rays could indicate presence of penetration effects in the conversion process of the 136 keV transition. These are, however, unlikely in this case due to the lack of appreciable retardation.[19] Furthermore, the value of the mixing ratio, $\delta_{136} = 0.360 \pm 0.015$, determined from angular distribution of gamma rays following Coulomb excitation[20] agree very well with the value measured in Ref. 2.

An independent measurement of $\delta(136)$ seems to be worthwhile in order to resolve these discrepancies.

II. EXPERIMENTAL PROCEDURE AND RESULTS

A. γ-γ Directional Correlation Experiments

An automatic gamma-gamma coincidence spectrometer was used for the directional correlation measurements. The spectrometer was provided with a 25 cm^3 true coaxial Ge(Li) detector and an integrally mounted 3 in. x

3 in. NaI(Tl) scintillation detector. A conventional coincidence system was utilized with a resolving time which was varied from 70 ns. to about 40 ns. in different experiments. For each measurement 2τ was adjusted so that the true to chance ratio was not less than 20.

The radio-active source of ^{181}Hf was obtained by irradiation of ^{180}Hf (enriched to 99%) with thermal neutrons. The source was prepared as a liquid by desolving HfO_2 in a solution of HF. Hydrofluoric acid solutions have been found to minimize, if not eliminate, the attenuations of the directional correlation due to extra-nuclear interactions.[16,18,22] The liquid source was placed in a teflon cylinder 0.15 cm. in diameter and 0.5 cm. high.

The coincidence rate was determined for the following angles between the symmetry axes of the detectors: 90°, 135°, 155°, 180°, 225°, 245°, and 260°. The coincidence rates were corrected for chance coincidences and, where necessary, for coincidences due to contributions from other cascades. The directional correlation coefficients A_{22} and A_{44} were calculated by fitting the experimental data to the directional correlation function of the form $W(\theta) = 1 + A_{22}P_2(\cos\theta) + A_{44}P_4(\cos\theta)$ in which $A_{KK} = A_K(1)A_K(2)$ and where (1) and (2) indicate dependence on the properties of the first and second gamma ray respectively.

The gamma-gamma directional correlations were measured for the following cascades: 133 - 482, 346 - 136, 133 - 346 and for the crossover cascade 133 - (346) - 136 in which the 346 keV gamma ray was unobserved. The results are summarized in Table I. Setting of the window in the Ge(Li) channel in all measurements involving 133γ is indicated in Fig. 2. The dashed area in Fig. 3 represents the energy region selected in the Ge(Li) channel for the 346γ - 136γ correlation measurement.

Table I

Cascade	$A_{22} \pm \Delta A_{22}$	$A_{44} \pm \Delta A_{44}$
133γ - 482γ	-0.295 ± 0.005	-0.069 ± 0.008
346γ - 136γ	0.168 ± 0.013	-0.013 ± 0.010
133γ - 346γ	0.110 ± 0.010	0.022 ± 0.014
133γ - (346γ) - 136γ	0.197 ± 0.012	-0.008 ± 0.020

B. e^--γ Directional Correlation Experiments

An automatic electron-gamma directional correlation apparatus was used in the e^--γ experiments. The electrons were energy selected and were detected using a high transmission, triangular field focusing, magnetic electron spectrometer developed by T. R. Gerholm.[18] The gamma rays were detected in a 2 in. x 2 in. NaTI(Tl) scintillation detector. Two independent experiments were performed. In one case, the γ-spectrum in coincidence with the 133K electron was observed at each angle. The coincidence spectra were stored in a multi-channel pulse height analyzer. In the second experiment, the gamma ray region of interest was selected using a single channel analyzer. The results of these experiments were in very close agreement as predicted.

Each experiment consisted of ten data groups. There were about 10^4 coincidences at each position for each data group, so that a total of approximately 2×10^5 coincidences at each detector position were recorded. Data were collected for angles of 105°, 135°, 180°, 225° and 255° between the symmetry axes of the spectrometer and scintillation detector. Accidental coincidence rates were measured periodically and were found consistently to be approximately 5 percent of the total count rate at 105°.

The spectrometer is completely iron encapsulated and stray magnetic fields are found to have a negligible effect on the R.C.A. 6810-A photomultiplier tube used in the γ-ray detector. The tube was shielded by two layers each of netic and co-netic, mu-metal shielding. A Cosmic Radiation Laboratories "Spectrostat", stabilized, high-voltage photomultiplier supply was used to eliminate gain shifts due to the various relative positions of the γ-ray counter and the iron casing. The gain stabilization was tested by observing the 482 keV gamma ray pulse height and the shape of the pulse height spectrum, when the detector was at the various positions. Time alignment was also checked under these conditions. Small error signals were noted when the γ-detector was near the iron casing of the spectrometer; however, no spectral or timing shifts were detected.

The low energy electron spectrum and that in coincidence with the 482 keV γ-ray are shown in Figs. 4 and 5 respectively. The correlation function, uncorrected for the detection geometry and quadrupole attenuation, was fit to the data by a least square fitting technique. The result is shown in Fig. 6.

The radio-active source was prepared by evaporating HfO_2 in a vacuum into a 1 mg/cm^2 aluminum backing. The active area was approximately 2 mm diameter. The experimental results are given in Table II. Corrections for the attenuation of the e^--γ directional correlations, due to the interaction of the quadrupole moment with electric field gradient in the solid source, were made by measuring the corresponding γ-γ correlation in the same source. The result of this experiment is also included in Table II.

Table II

Cascade	$G_{22}A_{22} \pm \Delta G_{22}A_{22}$
133K - 482γ	-0.138 $\pm$ 0.004
133LM - 482γ	-0.071 $\pm$ 0.005
133γ - 482γ	-0.077 $\pm$ 0.002

C. Relative Gamma-Ray Intensities

The relative intensities of the 133, 136 and 137 keV gamma rays were measured using a high resolution planar Ge(Li) photon spectrometer. The 136, 137 keV region of the spectrum is shown in Fig. 7. The two lines were not completely separated and were unfolded by use of a computer code which employs a steepest descent technique to fit known line shapes to the overlapping gamma ray lines. The 136 keV gamma ray line in the decay of ^{57}Co was used as a standard single line shape. The separated lines were then folded together again to insure that the observed composite line was reproduced. The errors in these relative intensities are due mainly to this stripping technique.

The relative intensities of the 482, 476 and 346 keV gamma rays were measured by observing the γ-rays in coincidence with the 133 keV gamma ray in a two Ge(Li) experiment. The coincidence requirement eliminated the interference from the 342 keV γ-ray in ^{175}Lu from the decay of the known ^{175}Hf contaminant. The 615 keV γ-ray intensity, relative to that of the 482 γ-ray, was measured in several singles counting experiments. These relative intensities were corrected for interference from the 619 keV transition by using the intensity ratio 619 K/615 K = 0.013 $\pm$ 0.006 given by Alexander et al.[2] and by assuming that the (3/2 + $\rightarrow$ 7/2 +) 619 keV

transition is pure E2. The correction is approximately 1%. The gamma ray intensities are compared to those of reference (2) and (24) in Table III.

Table III. Gamma Ray Intensities

γ Energy (keV)		Present Investigation	Boehm and Marmier	Alexander et al.
133	1000	444 ± 10	500	
136	127 ± 5	56 ± 2	71.4	608 ± 15
137	18 ± 3	8.0 ± 1.5	21.4	
346		210 ± 10[a]	164	206 ± 7.4
476		5 ± 1	21	1000
482		1000	1000	
615		2.30 ± .15	2.8	2.2 ± .2
619				

[a]The relative intensity 346/482 was measured in coincidence with the 133 keV γ-ray in order to eliminate interference from the 342 keV line in the ^{175}Lu contaminant.

D. Relative Conversion Electron Intensities and Conversion Coefficients

The (136K + 137K) conversion electron intensity was measured relative to the 133K line intensity in the magnetic spectrometer with its normal Hubert baffle system which was set to give an energy resolution of approximately 1 keV as shown in Fig. 4. The ratio (136K + 137K)/133K was taken from an average of several single counting experiments. The 137K/133K intensity ratio was measured by stepping the spectrometer current over the same range as in the previous experiment but counting only those electron pulses in coincidence with the 482 keV gamma ray. For this experiment the

γ-ray detector was set at $\theta = 126^{o}$ relative to the spectrometer axis so that $P_2(\cos\theta)$ vanishes and the angular correlation effect on the coincidence intensities can be neglected.

The relative intensities of the conversion electrons from the 482 keV and 615 keV transitions were measured by installing a 200 mm^2 Si(Li) detector with a special baffle system in the spectrometer. The baffles are designed to transmit electrons over an energy range of approximately 100 keV. The detector was maintained at near liquid nitrogen temperature and all of the energy resolution is due to the cooled Si(Li) detector. The spectrometer current can be accurately set so that a given line is maximally transmitted. It was shown, using calibration sources of ^{133}Ba, ^{137}Cs and ^{207}Bi, that the response of this system was linear for electron energies above about 100 keV. This system is very effective for observing internal conversion lines above 500 keV and has the advantage, over a bare Si(Li) detector, that it eliminates sum peaks and interference from gamma rays. The relative conversion electron intensities are given in Table IV. No attempt was made to measure the intensity of the conversion line of the 346 keV transition due to the admixture of electrons from the 342 keV line in the ^{175}Lu contaminant.

The 133, 136 and 137 keV conversion electron and gamma ray intensities were used with the theoretical $\alpha_K(E2)$ of the 133 keV transition, to determine the $\alpha_K(136)$ and $\alpha_K(137)$ as follows:

$$\alpha_K(x) = \frac{I_{e^-}(x)}{I_{e^-}(133)} \times \frac{I_\gamma(133)}{I_\gamma(x)} \alpha_K(133,E2) \ . \qquad \text{(II)}$$

The justification for the assumption that the 133 keV transition is pure E2 and has a normal E2 conversion process comes from the interpretation of our results for the 133K - 482γ directional correlation which are discussed in

Table IV. Internal Conversion Electron Intensities and Conversion Coefficients

Transition Line	Relative Electron Intensity	Conversion Coefficients
133 K	1000 [a]	--
136 K	452 ± 18 [a]	1.46 ± .15 (0)
137 K	80 ± 6 [a]	2.2 ± .6 (0)
482 K	1000	2.34 ± .15 (-2) [b]
482 L	216 ± 9	5.4 ± .28 (-3)
482 M+N	53 ± 3	1.24 ± .07 (-4)
615 K	11.9 ± .5	1.32 ± .20 (-1)
615 L	2.4 ± .1	2.2 ± .2 (-2)
615 M+N	.32 ± .06	3.6 ± .8 (-3)

[a] These intensities were measured by coincidence techniques and are normalized to the 133K line. The others were measured in single counting experiments and are normalized to the 482K line.

[b] Measured independently using a calibrated, single detector method described in reference (26).

the next section. The theoretical value of $\alpha_K(133,E2) = 0.497$, interpolated from the tables of Hager and Seltzer,[25] was used in Eq. (II).

The conversion coefficient $\alpha_K(482)$ was measured independently using a single detector method.[26] The value quoted here is the result of a continuation of the measurements discussed in reference (21). The relative electron and gamma ray intensities of the 482 keV and 615 keV transitions were then used with $\alpha_K(482) = 0.0234 \pm 0.0015$ in Eq. (II) to deduce the other conversion coefficients given in Table IV.

III. DISCUSSION AND CONCLUSIONS

A. Mixing Ratios of the 482 and 136 keV Transitions

The γ-γ directional correlation coefficients, $A_{KK} = A_K(1)A_K(2)$, can be expressed in terms of the multipole mixing ratios $\delta(1)$ and $\delta(2)$ and F_K coefficients in the following well-known form:

$$A_K(1) = \frac{F_K(L_1L_1j_1j)+2(-)^{L_1+L_1'}\delta(1)F_K(L_1L_1'j_1j)+\delta(1)^2F_K(L_1'L_1'j_1j)}{1+\delta(1)^2} \qquad \text{(III)}$$

$$A_K(2) = \frac{F_K(L_2'L_2j_2j) + 2\delta(2)\,F_K(L_2L_2j_2j) + \delta(2)^2\,F_K(L_2'L_2'j_2j)}{1+\delta(2)^2}$$

where L_1 and L_2 are the multipolarities of the first and second radiation respectively, $L_1' = L_1 + 1$, $L_2' = L_2 + 1$ and j is the spin of the intermediate state in the cascade $j_1(L_1,L+1)j(L_2,L_2+1)j_2$.

In the case of the $133\gamma(346\gamma)136\gamma$ correlation, in which the 346 γ-ray was unobserved, the following general equation applies:

$$A_{KK} = A_K(1)U_{KK}(2)A_K(3)\ , \qquad \text{(IV)}$$

in which

$$U_{KK}(2) = \frac{(-1)^{L_2}\begin{Bmatrix} j & j & K \\ j' & j' & L_2 \end{Bmatrix} + \delta(2)(-)^{L_2'}\begin{Bmatrix} j & j & K \\ j' & j' & L_2' \end{Bmatrix}}{1 + \delta^2(2)} (-)^{j+j'} \sqrt{(2j+1)(2j'+1)} \quad \text{(V)}$$

for the γ-ray cascade $j_1(L_1,L_1')j(L_2,L_2')j'(L_3L_3')j_2$ and as before $L_2' = L_2+1$.

The multipole mixing ratios of the present work are defined, in terms of emission matrix elements according to the convention proposed by Krane and Steffen,[27]

$$\delta(1) \equiv \frac{\langle j \| L_1+1 \| j_1 \rangle}{\langle j \| L_1 \| j_1 \rangle}$$

and (VI)

$$\delta(2) \equiv \frac{\langle j_2 \| L_2+1 \| j \rangle}{\langle j_2 \| L_2 \| j \rangle}$$

When the coefficients, A_{22} and A_{44}, of the 133γ - 482γ cascade are analyzed with the foregoing conventions we find $\delta_{482} = 5.8^{+0.3}_{-0.2}$ which is to be compared to $\delta_{482} = 5.0 \pm 0.2$ and $\delta_{482} = 7.2^{+1.8}_{-1.5}$ given in references (8) and (10), respectively. There is a strong indication that the HfO_2 in HF solution gives unattenuated values for the correlation coefficients.[16,18,22]

The mixing ratio of the 136 keV transition can be determined in both 133γ - (346γ) - 136γ and 346γ - 136γ directional correlation measurements. Due to the fact that $A_K(133\gamma)U_K(346\gamma) = A_K(346\gamma)$ the results, in terms of A_{KK} values, should be identical. In the 133γ - (346γ) - 136γ measurement the background correlations were measured simultaneously using two separate channels with the window settings below the composed 133 keV photopeak. The result quoted in Table I is corrected for this contribution. The $\delta(136)$-value derived from this measurement is

$$\delta(136) = 0.45 \pm 0.02 .$$

This value is in very good agreement with the results of Refs. 16 and 17 but is in variance with the result for $\delta(136)$ obtained in Ref. 20.

In case of the 346γ - 136γ measurement there are background contributions from the 137γ - 346γ and the 137γ - 482γ cascades. The intensity of the first cascade in our window settings was evaluated from the 137γ/136γ intensity ratios. The contribution from the second cascade was determined from the relative intensities of the 482 keV and 346 keV peaks in the coincidence spectrum (Fig. 8). The correction applied depends, however, on the assumed spin value for the 619 keV level and the multipole mixture of the 137 keV gamma ray. The correlation coefficients quoted in Table I were corrected assuming that the spin I(619) = $3/2^+$ and that the 137 keV gamma transition is of a pure M1 character (see section II.C and Ref. 2). It is interesting to mention that the assumption I(619) = $5/2^+$ will give $A_{22} = 0.187 \pm 0.015$ and $A_{44} = -0.014 \pm 0.010$ for the corrected correlation coefficient of the 346γ - 136γ correlation. These values are in much better agreement with the 133γ - (346γ) - 136γ results. This argument for the $5/2^+$ spin-parity assignment to the 619 keV level is not, however, strong enough to be conclusive. Due to these ambiguities the 346γ - 136γ directional correlation measurement was not used for determination of the mixing ratio of the 136 keV transition.

The presently accepted decay scheme of ^{181}Ta predicts the spin sequence 1/2(E2)5/2(E2)9/2 for the 133γ - 346γ cascade. If both radiations are pure quadrupole in character then $A_{22} = F_2(22,1/2,5/2)\ F_2(22,9/2,5/2) = +0.102$ and $A_{44} = F_4(22,1/2,5/2)\ F_4(22,9/2,5/2) = +0.009$. The close agreement between these predictions and the measured values $A_{22} = 0.110 \pm 0.010$ and $A_{44} = 0.022 \pm 0.014$ of the present investigation support the presently accepted spin sequence for this cascade.

B. Particle Parameters of the 133 keV Transition

The present experimental values of the internal conversion directional correlation particle parameters are given by

$$b_2(133K) = \frac{G_{22}A_{22}(133K\text{-}482\gamma)}{G_{22}A_{22}(133\gamma\text{-}482\gamma)} = \frac{-0.138 \pm 0.004}{-0.077 \pm 0.002} = 1.79 \pm 0.11$$

and

$$B_2(133LM) = \frac{G_{22}A_{22}(133LM\text{-}482\gamma)}{G_{22}A_{22}(133\ \text{-}482\gamma)} = \frac{-0.091 \pm 0.005}{-0.077 \pm 0.002} = 1.18 \pm 0.10$$

These values are in good agreement with the theoretically calculated values for a normal E2 transition, $b_2^{Th}(133K) = 1.82$ and $b_2^{Th}(133LM) = 1.21$.[29] The very good agreement between the ratio of the e^--γ results

$$\frac{G_{22}A_{22}(133K\text{-}482\gamma)}{G_{22}A_{22}(133LM\text{-}482\gamma)} = 1.52 \pm 0.12 ,$$

as compared to the theoretical ratio $b_2(133K)/b_2(133LM) = 1.50$, suggests that no attenuation due to electron scattering in the source was present.

We conclude that the internal conversion process for the 133 keV transition in ^{181}Ta shows no anomalous behavior.

C. Conversion Coefficients of the 136, 137 and 615 keV Transitions

The present value $\alpha_K(136) = 1.46 \pm 0.15$ is in good agreement with the measurement by Ashery et al.[20] and the K/L ratio as reported in Ref. 28. All these values agree with theory under the assumption that the 136 keV transition is predominantly (83%) M1 as obtained from our γ-γ directional correlation measurement.

The experimental result $\alpha_K(137) = 2.2 \pm 0.6$ is to be compared to the theoretical values $\alpha_K(M1,137) = 1.52$ and $\alpha_K(E2) = 0.462$ which supports the predominantly M1 multipolarity assignment to this transition.

The result $\alpha_K(615) = 0.132 \pm 0.020$ is in fair agreement with the theoretical value $\alpha_K(M3) = 0.167$ which is consistent with presently accepted spin assignment of $1/2^+$ to the 615 keV level (see also section III.A.).

D. Penetration Parameter of the 482 keV Transition

Our measured value of $\alpha_K(482)$ is in good agreement with the four values reported in the review by Hamilton et al.[30] A weighted average of the five values gives $[\alpha_K(482)]_{av} = 0.0240 \pm 0.0007$. The dependence of the internal conversion coefficient on λ and δ is given by[31]

$$\alpha_K(\lambda,\delta) = \frac{\beta(M1)(1+B_1\lambda+B_2\lambda^2)+\delta^2\ \alpha(E2)}{1+\delta^2}$$

where $\beta(M1)$ and $\alpha(E2)$ are the usual conversion coefficients given in reference (29), B_1 and B_2 are penetration coefficients tabulated in reference (31) and λ is the penetration parameter in the approximation used in reference (31). Using the present value of the multipole mixing ratio $\delta(482) = 5.8^{+0.3}_{-0.2}$ and the average value of the conversion coefficient $\alpha_K(482)$ in Eq. (VII), we find $\lambda(482) = 175^{+7}_{-4}$. This result is in agreement with the value $\lambda = 210 \pm 30$ given by Gerholm et al.[5] and $\lambda = 175 \pm 25$ given by Seltzer and Hager.[6] The exact agreement with the λ-value of reference (6) is accidental since a different $\delta(482)$-value was used in that calculation.

It should be pointed out that when the theoretical conversion coefficients and penetration parameters of Hager and Seltzer[25,31] are used, no anomalous behavior of the E2 contribution of this transition is evidenced as reported earlier by one of the authors (F.T.A.)[32] and, in fact, all the preliminary data reported in reference (32) is consistent with a normal E2 component of the 482 keV transition.

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FIGURE CAPTIONS

Fig. 1. Decay scheme of ^{181}Hf as given in Ref. 2.

Fig. 2. Singles and coincidences Ge(Li)-spectrum in the 133 keV energy region. For the coincidence spectrum the 482 keV photopeak was selected in the NaI(Tl) detector. The window setting for all the directional correlation measurements involving 133 keV transition is indicated in the figure.

Fig. 3. Singles and coincidences Ge(Li)-spectrum in the 133 keV energy region. For the coincidence spectrum the 346 keV photopeak was selected in the NaI(Tl) detector. The dashed area represents the window setting in the 346γ - 136γ directional correlation experiment.

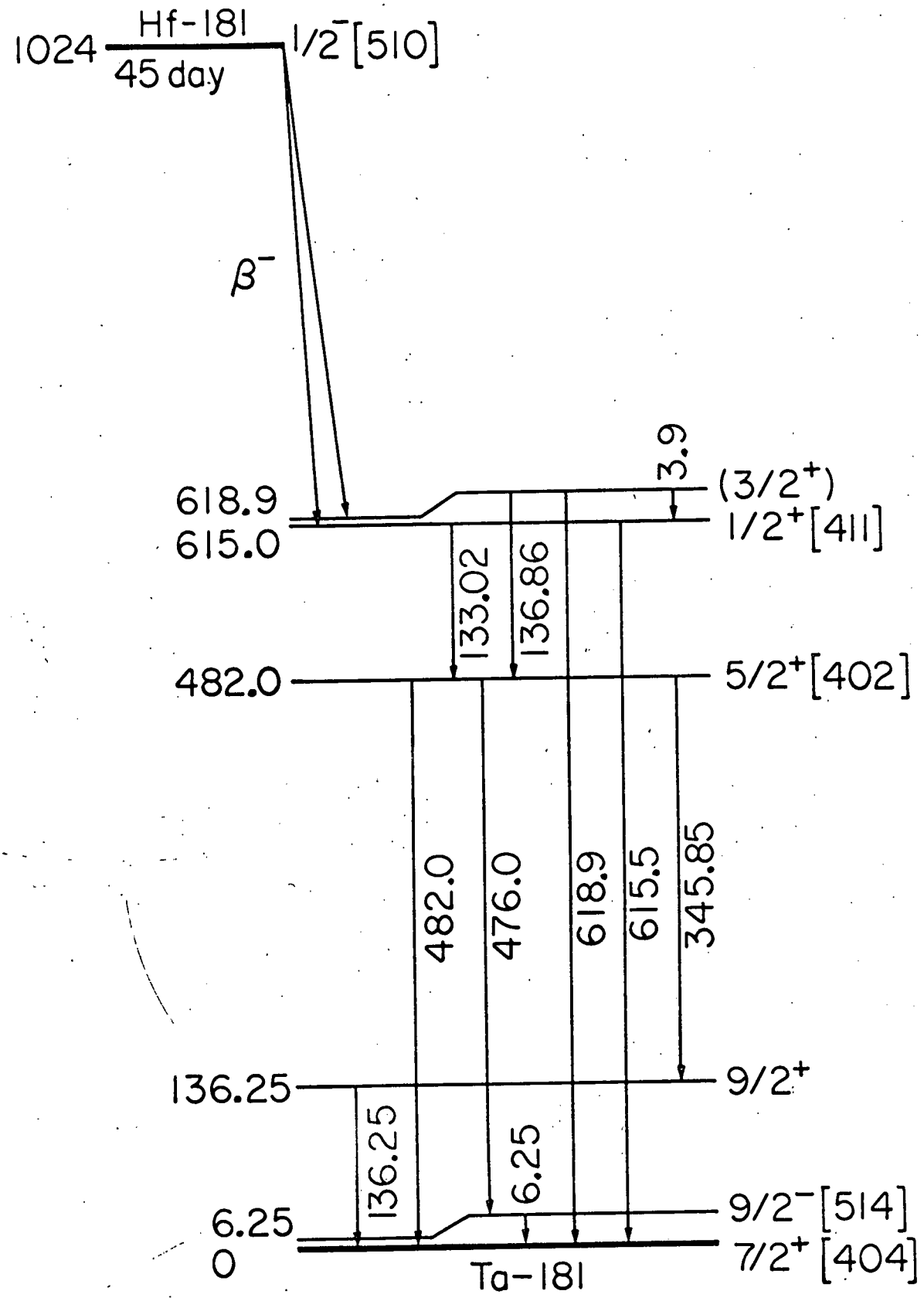
Fig. 4. γ-ray spectrum in coincidence with the 136-keV transition selected in the Ge(Li) counter window setting as indicated in Fig. 3) recorded with NaI(Tl) detector.

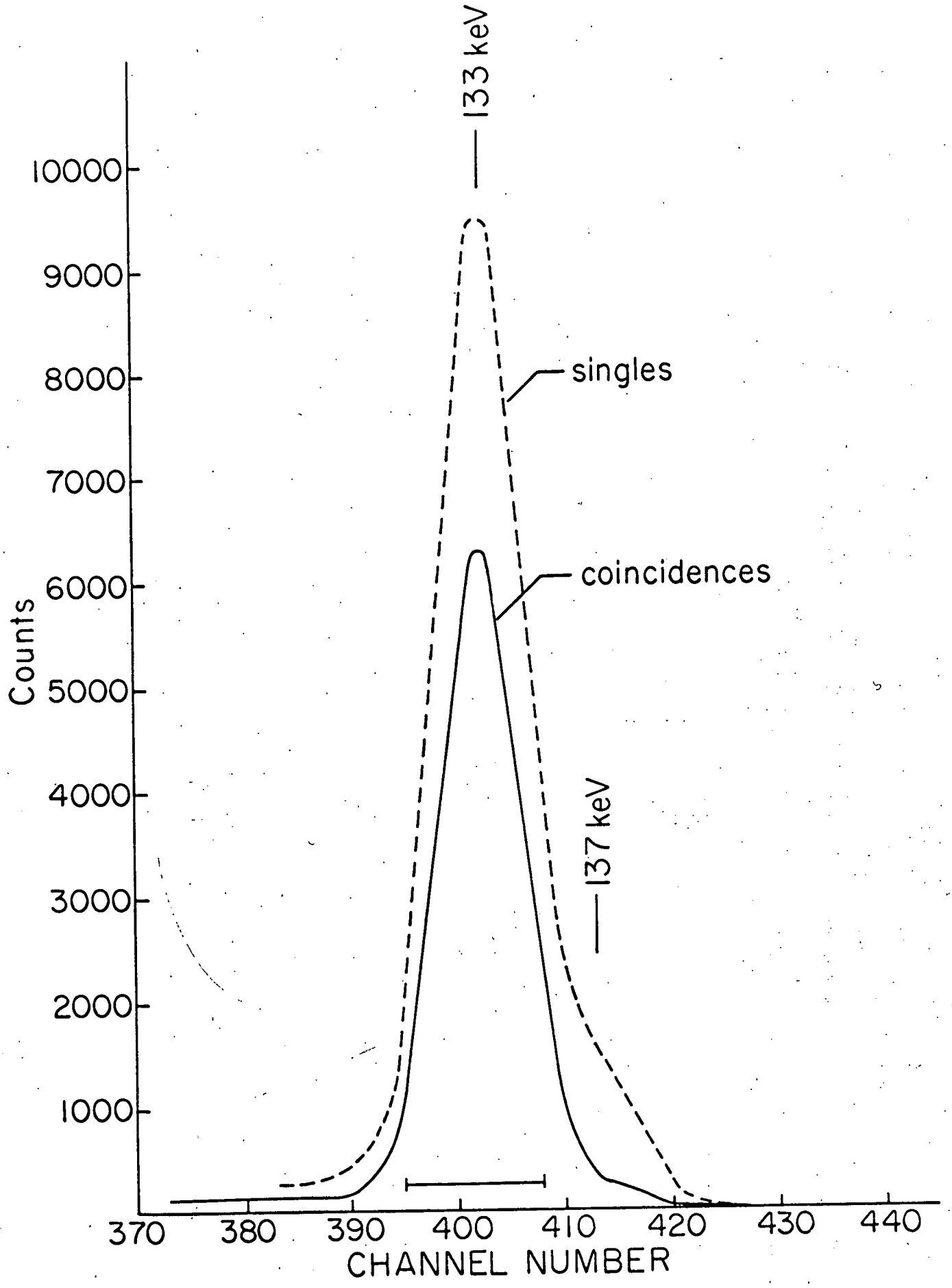
Fig. 5. Low energy electron spectrum

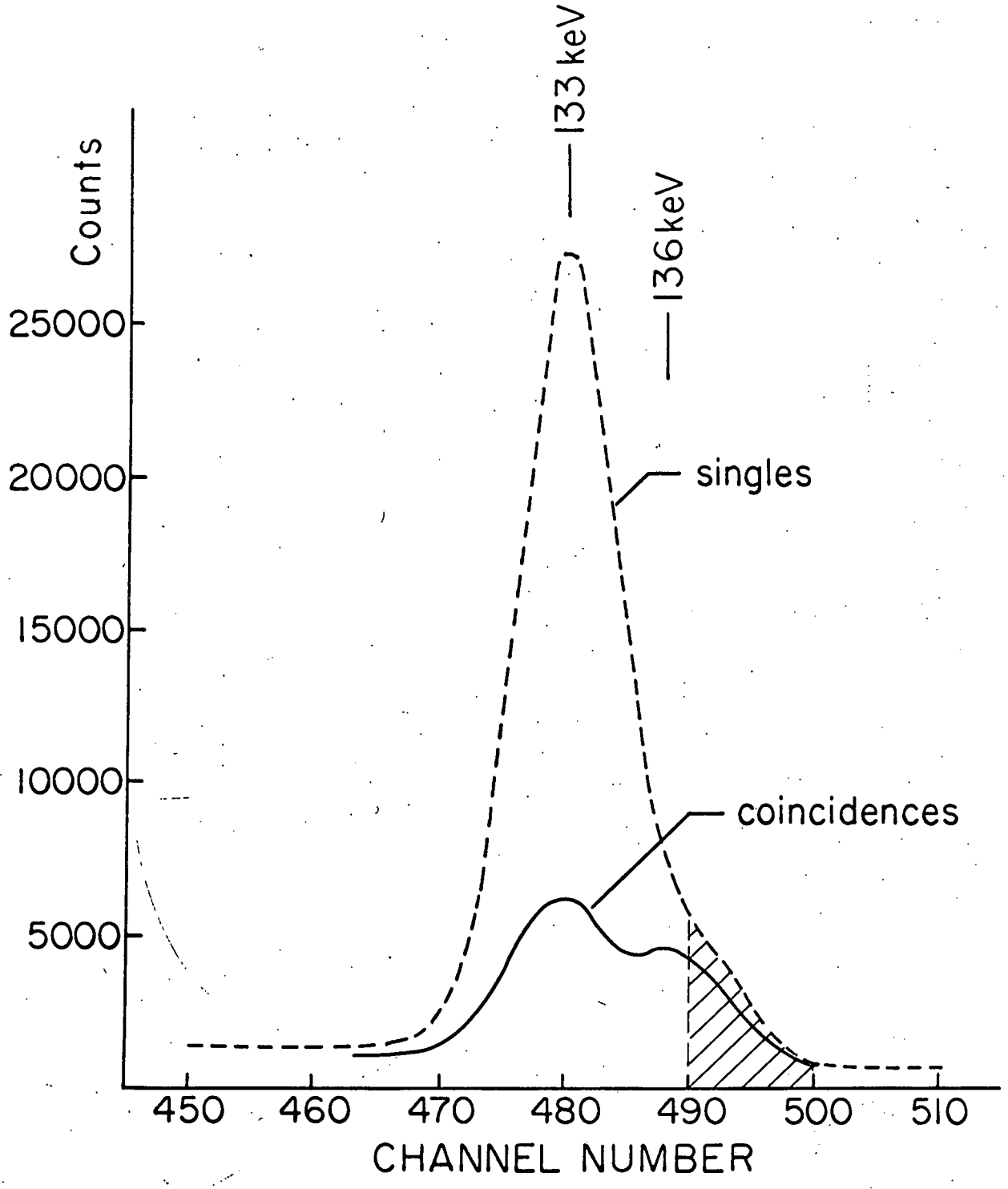
Fig. 6. Low energy electron spectrum in coincidence with 482 keV photopeak selected in NaI(Tl) detector.

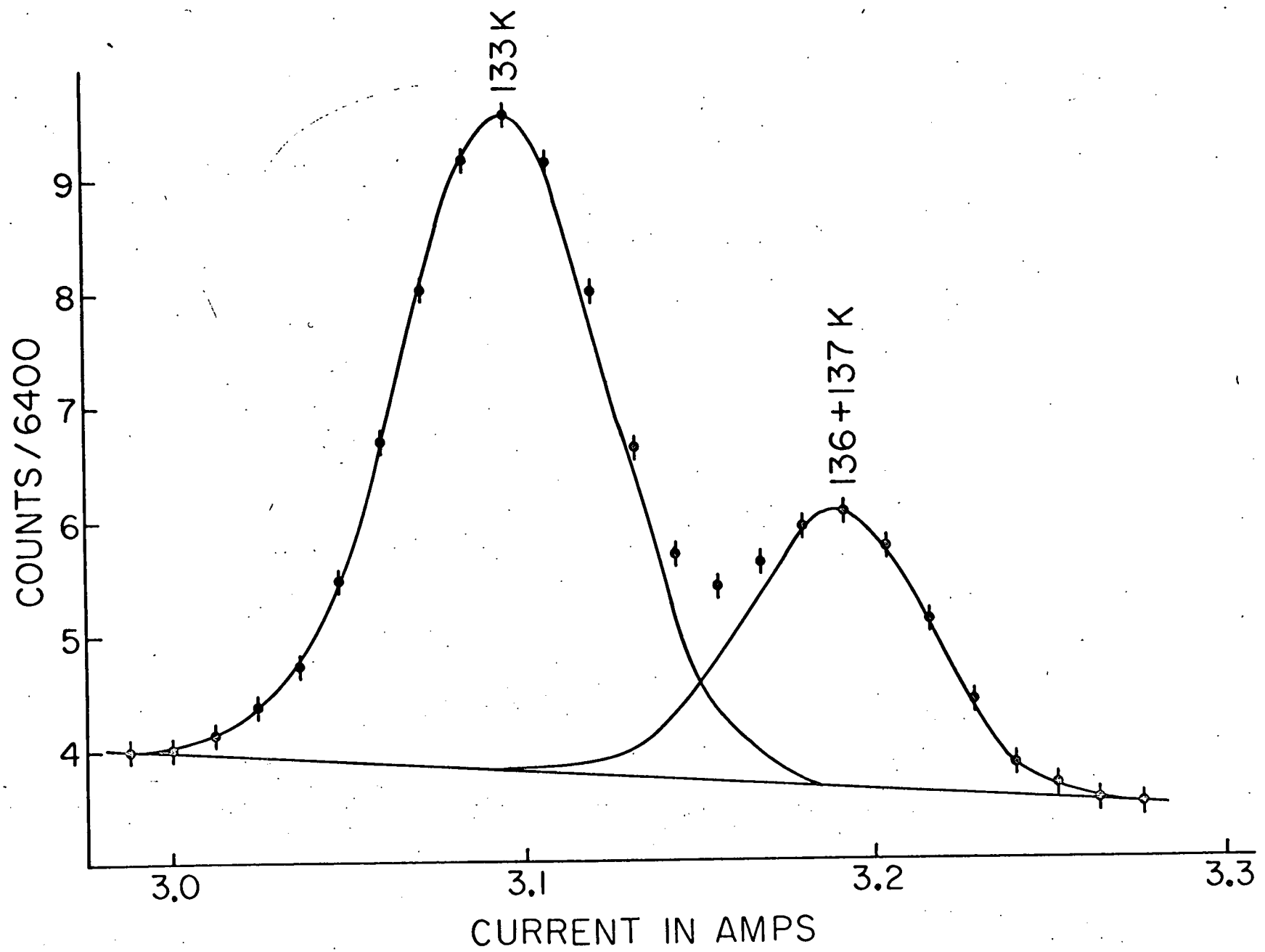
Fig. 7. Least squares fit of the experimental data for the 133K - 482γ cascade to the directional correlation function.

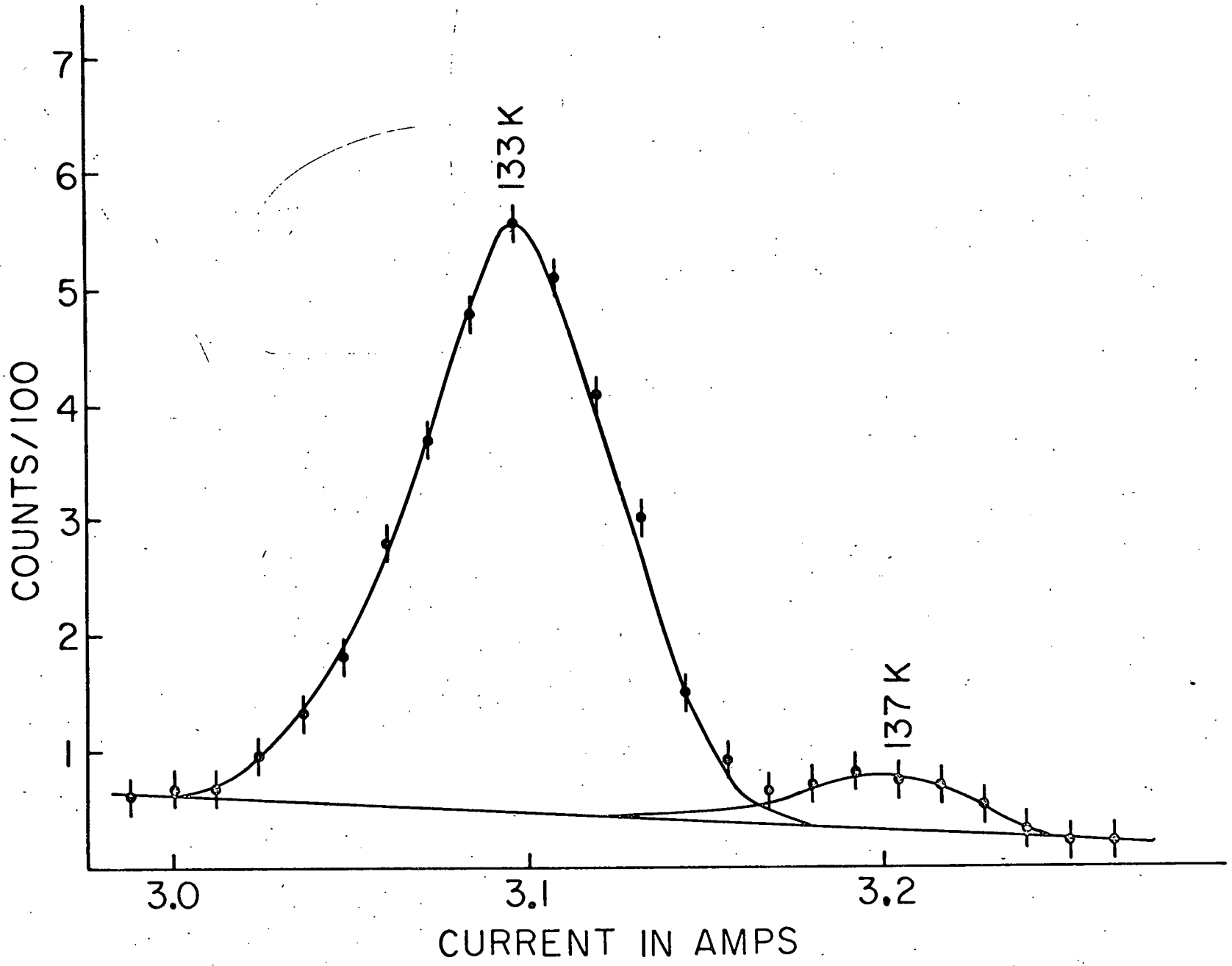
Fig. 8. High-resolution Ge(Li) gamma spectrum in the 136 keV energy region.

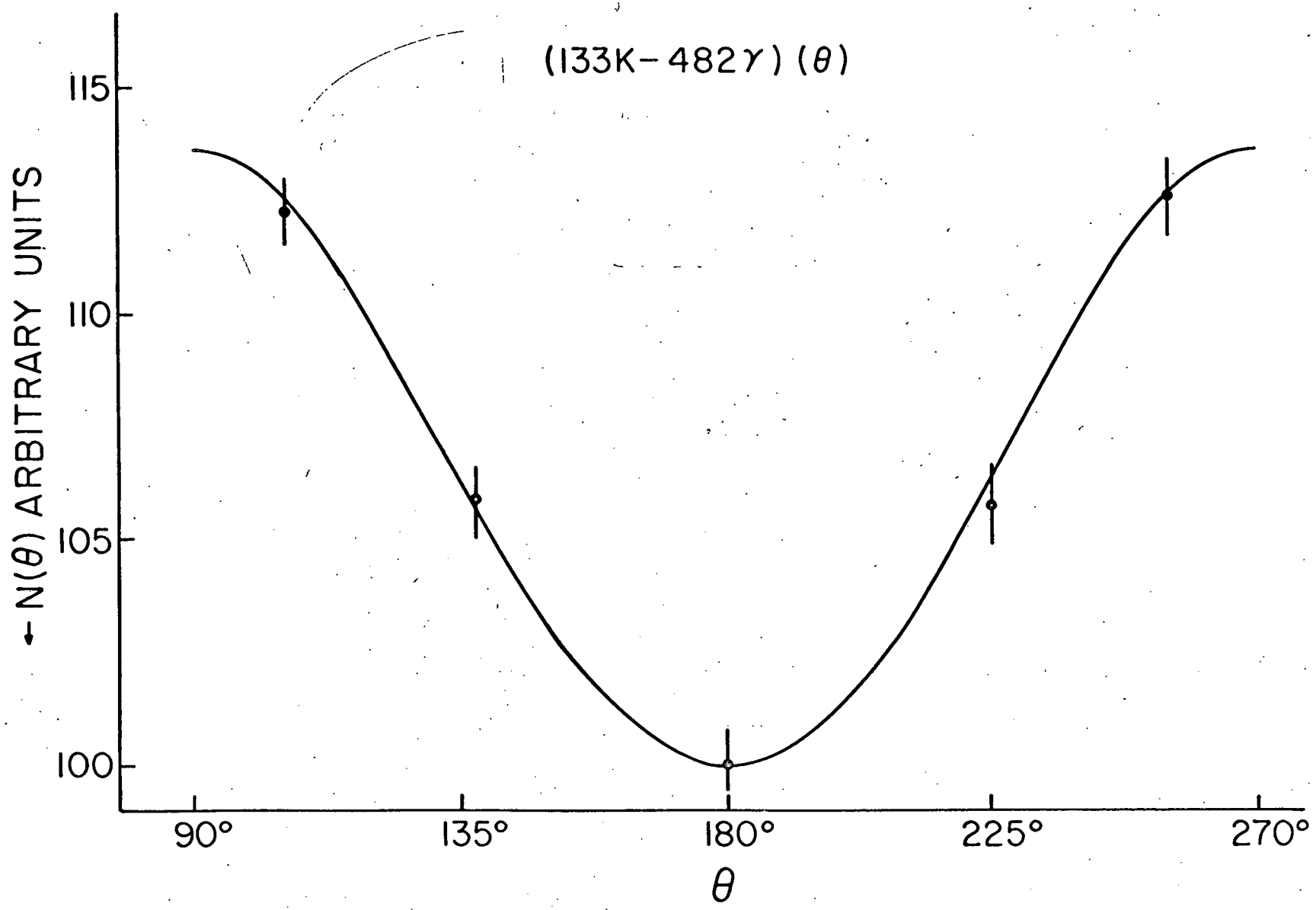

1024
Hf-181
45 day
1/2⁻[510]
β⁻
3.9
(3/2⁺)
618.9
615.0
1/2⁺[411]
133.02
136.86
482.0
5/2⁺[402]
482.0
476.0
618.9
615.5
345.85
136.25
9/2⁺
136.25
6.25
9/2⁻[514]
6.25
0
7/2⁺[404]
Ta-181

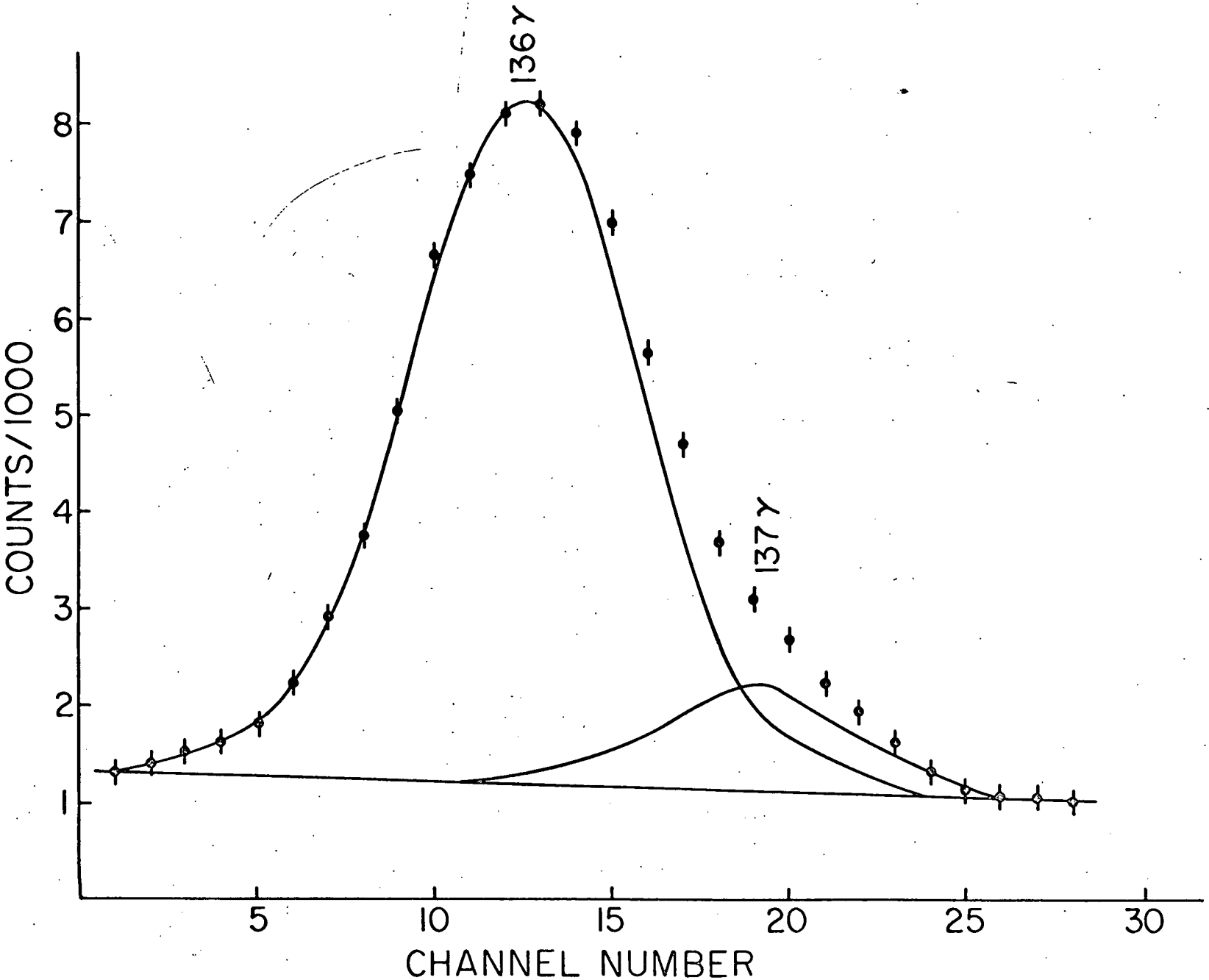

133 keV
singles
coincidences
137 keV
Counts
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
370
380
390
400
410
420
430
440
CHANNEL NUMBER

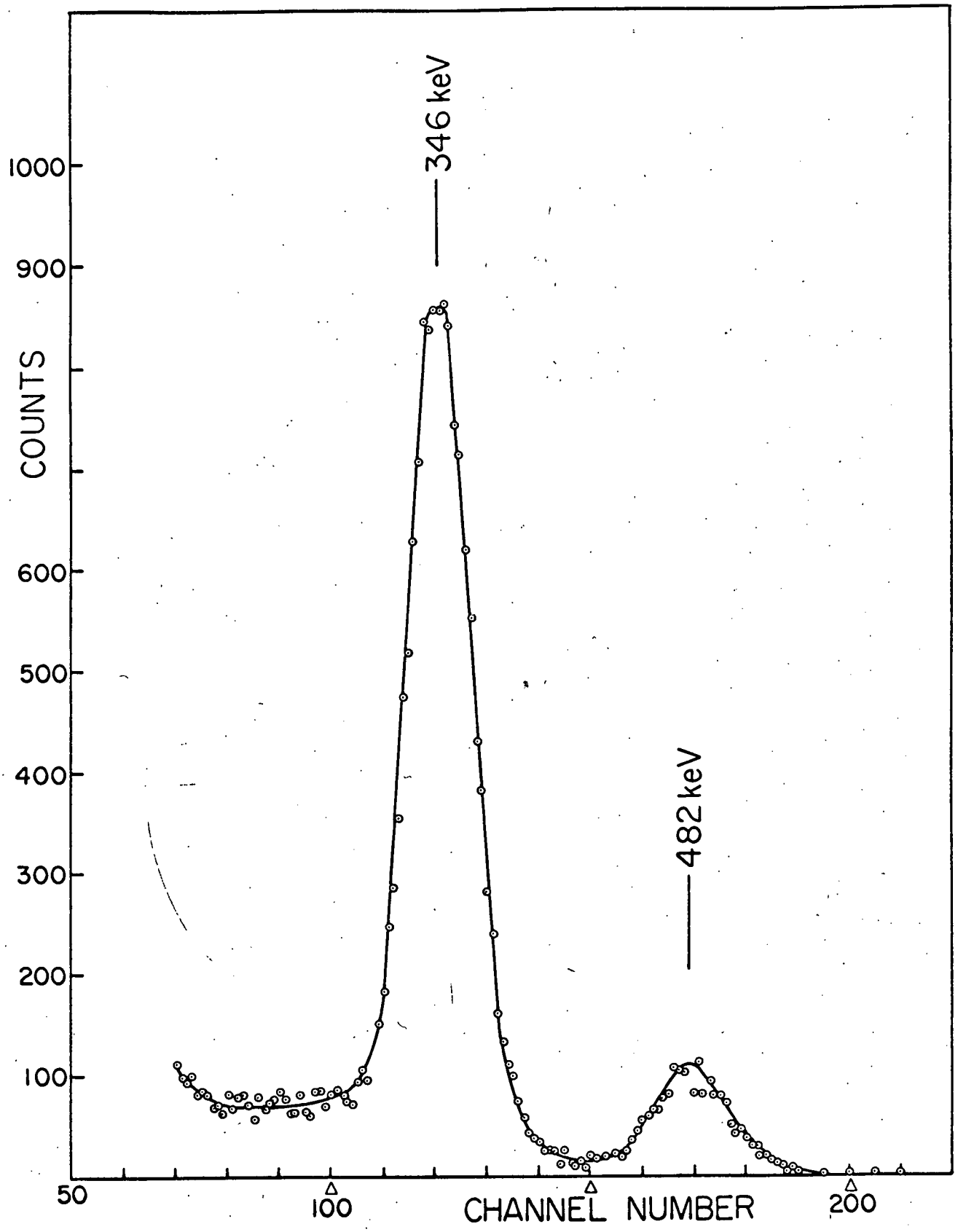

133 keV
136keV
singles
coincidences
Counts
25000
20000
15000
10000
5000
450
460
470
480
490
500
510
CHANNEL NUMBER


133 K
136+137 K
COUNTS/6400
9
8
7
6
5
4
3.0
3.1
3.2
3.3
CURRENT IN AMPS


7
6
5
4
3
2
1
COUNTS/100
133 K
137 K
3.0
3.1
3.2
CURRENT IN AMPS


(133K-482γ)(θ)
115
110
105
100
← N(θ) ARBITRARY UNITS
90°
135°
180°
225°
270°
θ


136Y
137Y
COUNTS/1000
CHANNEL NUMBER
1
2
3
4
5
6
7
8
5
10
15
20
25
30


346 keV
482 keV
COUNTS
1000
900
600
500
400
300
200
100
50
100
200
CHANNEL NUMBER