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THE GAMMA-RAY SPECTRUM FROM RADIATIVE CAPTURE
OF THE FIRST RESONANCE NEUTRONS IN ^{149}Sm

By

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ABSTRACT

A 37-cc lithium-drifted germanium detector has been used in conjunction with the CNAEM neutron crystal spectrometer to examine the gamma-ray spectrum arising from neutron resonance capture in ^{149}Sm . The effective gamma-ray energy resolution of 0.6–2.4 keV allowed 17 transitions to be examined in the energy range between 109 and 1806 keV following the capture of 0.0976 eV resonance neutrons in ^{149}Sm . The spectrum is interpreted in terms of the levels in the compound nucleus, ^{150}Sm . An analysis of the reduced intensities of 38 E1 transitions which consist of 9 secondary and 29 primary transitions indicates that they have a cumulative Porter-Thomas distribution. A similar analysis has been applied to 15 M1 transitions which consist of 4 secondary and 11 primary transitions.

INTRODUCTION

The resonance-neutron-capture spectra are useful in making isotopic assignments in nuclear energy levels of a natural element. A lithium-drifted germanium detector has been used in conjunction with the ÇNAEM neutron crystal spectrometer^(1,2) to examine the gamma-ray spectrum arising from neutron resonance capture in ^{149}Sm . The energy of the first neutron resonance for ^{149}Sm , 0.0976 eV, is very close to the 0.07 eV peak energy of the Maxwellian for the count-rate spectrum of the ÇNAEM spectrometer⁽²⁾. Therefore, sufficient gamma-ray intensities were obtained for the spectrum. The reduced gamma-ray intensities are subject to the Porter-Thomas distribution⁽³⁾. Since the number of the secondary E1 and M1 transitions is small, a cumulative Porter-Thomas distribution was applied to these transitions together with the primary transitions given by Buss and Smither⁽⁴⁾.

EXPERIMENTAL DETAILS

The source of neutrons used in this research was a swimming pool reactor (TR-1) of 1 MW power located at Çekmece Nuclear Research and Training Center (ÇNAEM), İstanbul, Turkey. 47 g of powdered Sm_2O_3 inside an aluminum container, 4×5×1.5 cm, with 1 mm walls, was placed at an angle of 45° to the monochromatic neutron beam obtained from the spectrometer. A detailed description of this spectrometer has been given before^(1,2). The spectrometer resolution was 1.405 $\mu\text{sec/m}$ using the $\text{Be}(10\bar{1}1)$ crystal planes as a monochromator. The energy of the monochromatic neutrons was 0.0976 eV, i.e., the resonant energy^(5,6) of the first neutron resonance in ^{149}Sm . A 37-cc Ge(Li) detector with a resolution of 3.9 keV at 1.33 MeV was used for gamma-ray detection. In order to reduce the background produced by neutrons scattered from the sample, a 4-cm of Li_2CO_3 shield inside an aluminum container was placed between the sample and the detector holder. 47 g of Sm_2O_3 contains 40.53 g of pure natural samarium element,

and the isotopic abundance of the ^{149}Sm in natural element is 13.83 %.

The pulse-height spectra from the Ge(Li) detector were recorded in a 4096-channel analyser. The energy calibration was based on the 662-keV line⁽⁷⁾ of ^{137}Cs , and on 1170 and 1330-keV lines⁽⁷⁾ of ^{60}Co . These three energy values with their corresponding channel numbers of 1490, 2649, and 3010 were fitted to the following calibration curve

$$(E)^{1/2} = (E_0)^{1/2} + c \ln(1 + n/d), \quad (1)$$

where n is the channel number. This equation for the calibration curve has been derived in Appendix I. Using the three points mentioned above, the three parameters of the calibration curve were obtained as follows:

$$(E_0)^{1/2} = 10.42246394 \text{ (keV)}^{1/2}, \quad c = 34.41177184 \text{ (keV)}^{1/2}, \quad d = 2659.751837.$$

Fig. 1 shows the spectrum of resonance-neutron-capture gamma rays.

DETERMINATION OF GAMMA-RAY ENERGIES AND INTENSITIES

The peak positions are determined by direct examination of the pulse-height spectra and also with the help of a calculator program. This program, after subtraction of a background term, makes a skew Gaussian⁽⁸⁾ fit to the peak. The function is of the form

$$I = I_0 \exp(-(E - E_0)^2 f/G^2),$$

where $0 < f \neq 1$ for $E < E_0$, $f = 1$ for $E \geq E_0$, and E_0 and I_0 are the energy and height of the peak respectively, and f is the degree of skewness.

The absolute intensity of a gamma-ray transition from an initial state i to a final state f is proportional to the gamma-ray peak area,

$$(\pi)^{1/2} I_0 G (1 + 1/(f)^{1/2})/2.$$

Therefore, the relative intensity of a gamma-ray transition can be written in the following form:

$$I_f = I_0 G (1 + 1/(f)^{1/2})/2,$$

where G is $(2)^{1/2}$ times the standard deviation of the Gaussian distribution.

For the case of very weak peaks it was not possible to be able to make a Gaussian fit to the peak. In that case the peak positions and the relative intensities were determined using the following relations:

$$\text{Area:} \quad A = \sum_n I_n,$$

$$\text{Mean:} \quad n_0 = \sum_n I_n n / A,$$

$$\text{Standard deviation:} \quad dn = \left(\sum_n I_n n^2 / A - n_0^2 \right)^{1/2},$$

where n is the channel number, I_n is the net counts in the n^{th} channel above background line, n_0 is the channel number which gives the position of the peak, and sums are over the channel numbers of the peak region. In this way, the relative intensity of the peak, the peak energy, and the standard deviation from the peak energy are given by the following relations:

$$I_\gamma = A/(\pi)^{1/2}, \quad E_\gamma = E_0 = E(n_0), \quad dE = E_0(n_0 + dn) - E_0,$$

where the function $E(n)$ is given by Eq. (1).

By using a modified independent-particle model, Blatt and Weisskopf⁽⁹⁾ have estimated the probability of a gamma-ray transition of order ℓ from an initial state i to a final state f . The absolute intensity of a gamma-ray transition is proportional to this probability. Therefore, the relative intensity of a gamma-ray transition can be written in the following form:

$$I_\gamma = C E_\gamma^{2\ell+1} D(E_i)/D(E_f), \quad (2)$$

where

$$E_\gamma = E_i - E_f \quad (3)$$

is the energy of the emitted gamma ray, $D(E_i)$ is the spacing of levels of the same spin and parity as the initial state i near E_i and $D(E_f)$ is the spacing of levels of the same spin and parity as the final state f near E_f .

For the nuclear level density $1/D(E)$, the formula⁽¹⁰⁾

$$1/D(E) = (1/T) \exp((E - E_0)/T) \quad (4)$$

can give a good fit to the experimental data. The experimental values of the energies of excited states of ^{150}Sm given by Buss and Smither⁽⁴⁾ were fitted to the formula (4) using the method of least squares. The parameters obtained from the analysis are $E_0 = 118.5$ keV and $T = 585.4$ keV. Using Eqs. (3) and (4), Eq. (2) can be rewritten in the following form:

$$I_Y = C E_Y^{2\ell+1} \exp(-E_Y/T), \quad (5)$$

where C is the so-called reduced intensity. For the case of E1 or M1 transitions the reduced intensity is given by the formula

$$C = I_Y \exp(E_Y/585.4) / E_Y^3. \quad (6)$$

The relative intensities of the transitions observed in resonance-capture experiments presented in this paper can be interpreted in terms of the simple scheme indicated in Fig. 2. The $\frac{7}{2}^-$ ground state of ^{149}Sm leads to 3^- and 4^- capture states for s-wave neutrons. The resonance neutrons of energy 0.0976 eV are captured into 4^- states only⁽¹¹⁾. Hence, for the case of primary dipole transitions the initial state 4^- depopulates in a uniform manner to the three possible final states of spin 3, 4, and 5. For the case of secondary dipole transitions the initial states of spin 3, 4, and 5 depopulates to the five possible final states of spin 2, 3, 4, 5, and 6, thus, as indicated in Fig. 2, the relative transition intensities will be proportional to m . Therefore, Eq. (6) must be replaced by the following equation:

$$C = I_Y \exp(E_Y/585.4) / (m E_Y^3), \quad (6a)$$

where m can take the integer values of 1, 2, and 3, corresponding to the spin values of (2,6), (3,5), and (4) respectively.

DISTRIBUTION OF THE REDUCED INTENSITIES

The statistical distribution of the partial radiative widths is expected to have the Porter-Thomas⁽³⁾ form. This had been a subject of intense study from the time of the first measurements of resonance capture spectra⁽¹²⁾. A measurement by Rae et al.⁽¹³⁾ of 88 E1 transitions following capture of thermal neutrons and resonance neutrons of energy 34, 130, and 175 eV in ¹⁹⁹Hg, were analysed using the χ^2 -test to fit the chi-squared distribution to the histogram of the data. The class of chi-squared distributions is described by the formula⁽³⁾

$$P_n(x) dx = ((n/2)^{n/2} / \Gamma(n/2)) x^{(n-2)/2} \exp(-nx/2) dx, \quad (7)$$

where $x = S / \bar{S}$, n is a quantity called the number of degrees of freedom, S is the reduced partial radiative width which is proportional to the reduced intensity and $\bar{S}$ is the mean partial radiative width. The result found was $n = 0.96^{+0.24}_{-0.17}$; this encompasses the Porter-Thomas form ($n = 1$). An exponential distribution ($n = 2$) was not compatible with the data⁽¹³⁾.

The Porter-Thomas distribution is given by the formula

$$P(x) dx = (2\pi x)^{-1/2} \exp(-x/2) dx, \quad (8)$$

where $x = C / \bar{C}$, C is the reduced intensity, and $\bar{C}$ is the mean reduced intensity and given by

$$\bar{C} = \frac{1}{N} \sum_{i=1}^N C_i, \quad (9)$$

where N is the total number of reduced intensities of E1 or M1 transitions and C_i is the i^{th} reduced intensity which satisfies the condition

$$C_1 < C_2 < \dots < C_i < \dots < C_N.$$

On the other hand, $x_i = C_i / \bar{C}$ satisfies the following conditions:

$$\sum_{i=1}^N x_i = N, \quad (10a)$$

$$x_1 < x_2 < \dots < x_i < \dots < x_N. \quad (10b)$$

Therefore, the number of reduced intensities up to C_i is i and given by the formula

$$i = (N + t) f(x_i), \quad (11)$$

where

$$f(x) = \int_0^x P(x) dx, \quad (12)$$

i.e., cumulative Porter-Thomas distribution which satisfies the condition $f(x) \leq 1$ and t is a slowly varying function of N . For a given N , all x_i and t can be calculated uniquely using Eqs. (10a) and (11). Some values of t obtained from calculations are listed in Table I.

Buss and Smither⁽⁴⁾ have measured the average intensities of 46 primary gamma transitions to low-lying levels in ^{150}Sm when the neutron-capture process takes place in a large number of neutron resonances; and they have inferred the multipolarity of the radiation, and thus the parity of the final state, and limited the spin of the final state to within two choices. Comparing the experimental values of the energies of excited states of ^{150}Sm given by Buss and Smither⁽⁴⁾ and by Smither⁽¹⁴⁾, with the experimental values of the energies of the emitted gamma rays observed in resonance-capture experiments presented in this paper and using the Eq. (3), it has been inferred that the 17 experimental transitions presented in this paper were secondary transitions. 9 of these 17 transitions are E1 transitions, 4 of them are M1 transitions and the other 4 of them are E2 transitions. The numbers of the primary E1 and M1 transitions given by Buss and Smither⁽⁴⁾ are 29 and 11 respectively. Hence, the total number of the E1 transitions is 38 and the total number of the M1 transitions is 15.

The neutron-capture transition data for the first neutron resonance in ^{149}Sm are summarized in Table II. The first two columns give the energies and intensities of the secondary gamma transitions following

resonance capture in the $^{149}\text{Sm}(n,\gamma)^{150}\text{Sm}$ reaction; the intensities of transition are expressed as number of transitions per 1000 captures. The fourth column gives the reduced intensities calculated by using Eq. (6a). The transition multipolarities are listed in column five.

For $N = 38$ and $N = 15$ the values of x_i obtained from theoretical calculations are listed in Tables III and IV respectively. For the case of E1 transitions each of the 9 values of reduced intensities was calculated from the experimental data for $m = 1, 2, 3$, by using Eq. (6a). According to Eq. (6a) the dependence of C_i on m can be expressed as $C_i(m) = C_i(1)/m$. Since the value of $C_{38}(1)$ given in Table II is too big according to Porter-Thomas distribution values given in Table III, the first approximation to the mean reduced intensity was taken as $\bar{C} = C_{38}(3)/x_{38}$. Using this value of $\bar{C}$, 27 experimental values of $x_i(m) = C_i(m)/\bar{C}$ were calculated. Comparing the experimental $x_i(m)$'s with the theoretical x_i 's given in Table III, 9 sets of the values of x_i , of $x_i(m)$, and of i , and finally one value of m for each set were chosen such that $|x_i(m) - x_i|$ was a minimum for each set. Using the relations

$$\bar{C}_i = C_i(m)/x_i, \quad \bar{C} = \frac{1}{9} \sum_i \bar{C}_i, \quad \text{and} \quad x_i(m) = C_i(m)/\bar{C},$$

a better approximation was obtained. The results are shown in Table V. Fig. 3 shows the cumulative Porter-Thomas distribution of intensities of 38 E1 transitions including 9 experimental values. In the same manner, the results for M1 transitions are shown in Table VI. Fig. 4 shows the cumulative Porter-Thomas distribution of intensities of 15 M1 transitions including 4 experimental values.

Partial level scheme for ^{150}Sm , derived from the resonance-capture spectrum reported in this paper in conjunction with previously published studies^(4,14), is shown in Fig. 5.

DISCUSSION

The spin assignments given in Tables V and VI are inferred from Fig. 2, using the m values obtained from Eq. (6a) and the cumulative Porter-Thomas distributions given in Tables III and IV. Since these assignments depend on a probability distribution, in some cases they do not give accurate results. For example, spin assignments for the levels at 1071.8, 1357.7 and 1793.7 keV are different from that given in previously published studies^(4,14). Moreover, there is an ambiguity between two assignments for the levels at 1071.8 and 1357.7 keV. However, a 3^- or 5^- assignment for the level at 1357.7 keV is consistent with the result given in Refs. (4) and (15). On the other hand, the 2^+ assignment is recommended by Buss and Smither⁽⁴⁾ and is consistent with the result for the level at 1416.8 keV. The 3^- or 2^- assignment⁽⁴⁾ is also consistent with our result for the level at 1760.3 keV. A level is observed in the (d,d') reaction^(4,15) at 1819 keV. The strength of the proton group is proper to a 2^+ or 4^+ state. Hence, a 2^+ or 6^+ assignment for the level at 1818.9 keV gives comparable results with those given in Ref. (15) and the 2^+ assignment is probably correct. Buss and Smither concluded that any assignment except 2^+ , 3^+ , 4^+ , or 5^+ would be possible for the level at 2223.7 keV. This conclusion is correct compared with a 2^+ or 6^+ assignment. Finally, a 2^- or 6^- assignment for the level at 2233.5 keV is consistent with a 2^- , 3^- , 4^- , or 5^- assignment given in Ref. (4).

APPENDIX I

THE CALIBRATION CURVE FOR THE Ge(Li) DETECTOR

The resolution of a gamma-ray spectrometer at energy E is often expressed in terms of $\Delta E/E$, where ΔE is the full width at half maximum of a gamma peak. ΔE is a function of the energy, being given by

$$\Delta E = k E^{1/2}, \quad (A1)$$

where k is a constant of the Ge(Li) detector. On the other hand, the calibration curve is given by

$$E = f(n), \quad (A2)$$

where n is the channel number of the pulse-height analyser corresponding to the gamma-ray energy E . Then the full width at half maximum of a gamma peak is given by

$$\Delta E = f'(n) \Delta n, \quad (A3)$$

where Δn is the full width at half maximum of a gamma peak when the variation of gamma-ray intensity with respect to channel number is taken into account. Then Δn is also a function of the channel number, i.e.,

$$\Delta n = g(n), \quad (A4)$$

and thus, Eq. (A3) can be rewritten as follows:

$$\Delta E = g(n) f'(n). \quad (A5)$$

Combining Eqs. (A1), (A2) and (A5), we obtain the following differential equation:

$$g(n) \frac{dE}{dn} = k E^{1/2}.$$

The variables in this differential equation can be separated as follows:

$$\frac{dE}{E^{1/2}} = \frac{k}{2} \frac{dn}{g(n)}.$$

Integrating this equation we obtain

$$(E)^{1/2} = \frac{k}{2} \int \frac{dn}{g(n)} + C, \quad (A6)$$

where C is the constant of integration.

As a first approximation, the function $g(n)$ in Eq. (A4) can take the following form:

$$\Delta n = a n + b. \quad (A7)$$

Inserting Eq. (A7) in Eq. (A6), we obtain

$$(E)^{1/2} = \frac{k}{2} \int \frac{dn}{an + b} + C,$$

or

$$(E)^{1/2} = k/(2a) \ln(an + b) + C. \quad (A8)$$

Using the initial condition $f(0) = E_0$, the constant of integration can be determined as follows:

$$(E_0)^{1/2} = k/(2a) \ln(b) + C.$$

Thus, Eq. (A8) takes the final form

$$(E)^{1/2} - (E_0)^{1/2} = k/(2a) \ln(1 + an/b). \quad (A9)$$

Defining the new parameters $c = k/(2a)$ and $d = b/a$, Eq. (A9) becomes identical with Eq. (1):

$$(E)^{1/2} = (E_0)^{1/2} + c \ln(1 + n/d). \quad (1)$$

TABLE I. Some values of t defined by Eq. (11).

N	t
1	0.46479
2	0.46921
9	0.47729
10	0.47775
11	0.47815
15	0.47937
38	0.48245

TABLE II. Resonance-capture data on transitions in ^{150}Sm . The gamma-ray energies and their probable errors are listed in column one. The intensities of transition in reaction $^{149}\text{Sm}(n,\gamma)^{150}\text{Sm}$ expressed as number of transitions per 1000 captures are listed in column two. The relative values of the reduced intensities in column four are calculated by using Eq. (6a) and normalized to 1000 for the intensity of the 187.7-keV line. The transition multipolarities are listed in column five.

E_γ (keV)	I_γ photons per 1000 neutron captures	$\Delta I_\gamma / I_\gamma$ (%)	C	Multipolarity
704.6 $\pm$ 1.5	2.63	8	16.07	E1
645.7 $\pm$ 1.6	0.06	65	0.46	M1
632.3 $\pm$ 2.2	0.17	41	1.24	M1
570.8 $\pm$ 1.2	0.02	128	0.18	E1
561.9 $\pm$ 2.4	0.16	51	1.55	E1
461.7 $\pm$ 1.0	0.07	48	1.01	E1
456.9 $\pm$ 1.2	0.06	49		E2
441.5 $\pm$ 1.9	0.08	122		E2
390.5 $\pm$ 1.2	0.47	12	9.91	E1
376.9 $\pm$ 1.1	0.21	12	4.73	E1
357.8 $\pm$ 0.6	0.09	1.4	2.35	M1
310.2 $\pm$ 0.9	0.49	2		E2
273.1 $\pm$ 0.8	0.83	4		E2
270.4 $\pm$ 0.9	0.73	6	37.51	M1
237.9 $\pm$ 0.7	3.42	8	244.73	E1
220.2 $\pm$ 1.0	0.16	11	13.75	E1
187.7 $\pm$ 0.7	7.48	9	1000.00	E1

TABLE III. The values of x_i obtained from theoretical calculations
for the case of $N = 38$.

i	x_i	i	x_i	i	x_i
1	0.00106	14	0.22375	27	1.08141
2	0.00425	15	0.25987	28	1.20464
3	0.00958	16	0.29945	29	1.34354
4	0.01707	17	0.34276	30	1.50161
5	0.02675	18	0.39008	31	1.68366
6	0.03868	19	0.44177	32	1.89666
7	0.05289	20	0.49822	33	2.15111
8	0.06947	21	0.55991	34	2.46402
9	0.08847	22	0.62740	35	2.86555
10	0.11000	23	0.70137	36	3.41750
11	0.13416	24	0.78263	37	4.28179
12	0.16107	25	0.87218	38	6.23330
13	0.19088	26	0.97125		

TABLE IV. The values of x_i obtained from theoretical calculations
for the case of $N = 15$.

i	x_i	i	x_i	i	x_i
1	0.00657	6	0.25671	11	1.12252
2	0.02645	7	0.36130	12	1.47362
3	0.06019	8	0.49167	13	1.97259
4	0.10873	9	0.65429	14	2.77795
5	0.17353	10	0.85914	15	4.65471

TABLE V. The values of experimental $x_i(m)$ with their corresponding theoretical values of x_i for the case of E1 transitions.

E_γ (keV)	x_i	$x_i(m)$	i	m	J_f^π	E_f (keV)
570.8	0.00106	0.00109	1	3	(4^-)	1071.8
461.7	0.00958	0.00930	3	2	$(3^- \text{ or } 5^-)$	1357.7
561.9	0.02675	0.02844	5	1	$(2^+ \text{ or } 6^+)$	1416.8
376.9	0.08847	0.08703	9	1	$2^- \text{ or } 6^-$	1071.8
390.5	0.19088	0.18232	13	1	$2^- \text{ or } 6^-$	1760.3
220.2	0.25987	0.25288	15	1	$2^- \text{ or } 6^-$	2233.5
704.6	0.29945	0.29558	16	1	$2^- \text{ or } 6^-$	1357.7
237.9	4.28179	4.50211	37	1	$2^- \text{ or } 6^-$	2233.5
187.7	6.23330	6.13204	38	3	4^+	1793.7

TABLE VI. The values of experimental $x_i(m)$ with their corresponding theoretical values of x_i for the case of M1 transitions.

E_γ (keV)	x_i	$x_i(m)$	i	m	J_f^π	E_f (keV)
645.7	0.06019	0.06084	3	1	$(2^+ \text{ or } 6^+)$	1416.8
357.8	0.10873	0.10435	4	3	4^+	1793.7
632.3	0.17353	0.16555	5	1	$(2^+ \text{ or } 6^+)$	1818.9
270.4	4.65471	5.00620	15	1	$(2^+ \text{ or } 6^+)$	2223.7

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FIGURE CAPTIONS

- Fig. 1. The gamma-ray spectrum from radiative capture of the first resonance neutrons in ^{149}Sm .
- Fig. 2. Theoretical predictions of the gamma-ray branching ratios of primary and secondary transitions to low-lying levels following s-wave resonance neutron capture. m is a quantity which is proportional to the relative intensity of a secondary gamma-ray transition.
- Fig. 3. The cumulative distribution of the reduced intensities of the secondary E1 transitions. The curve is the cumulative Porter-Thomas distribution for the case of $N = 38$.
- Fig. 4. The cumulative distribution of the reduced intensities of the secondary M1 transitions. The curve is the cumulative Porter-Thomas distribution for the case of $N = 15$.
- Fig. 5. Partial level scheme for ^{150}Sm , derived from the resonance-capture spectrum reported in this paper in conjunction with previously published studies.

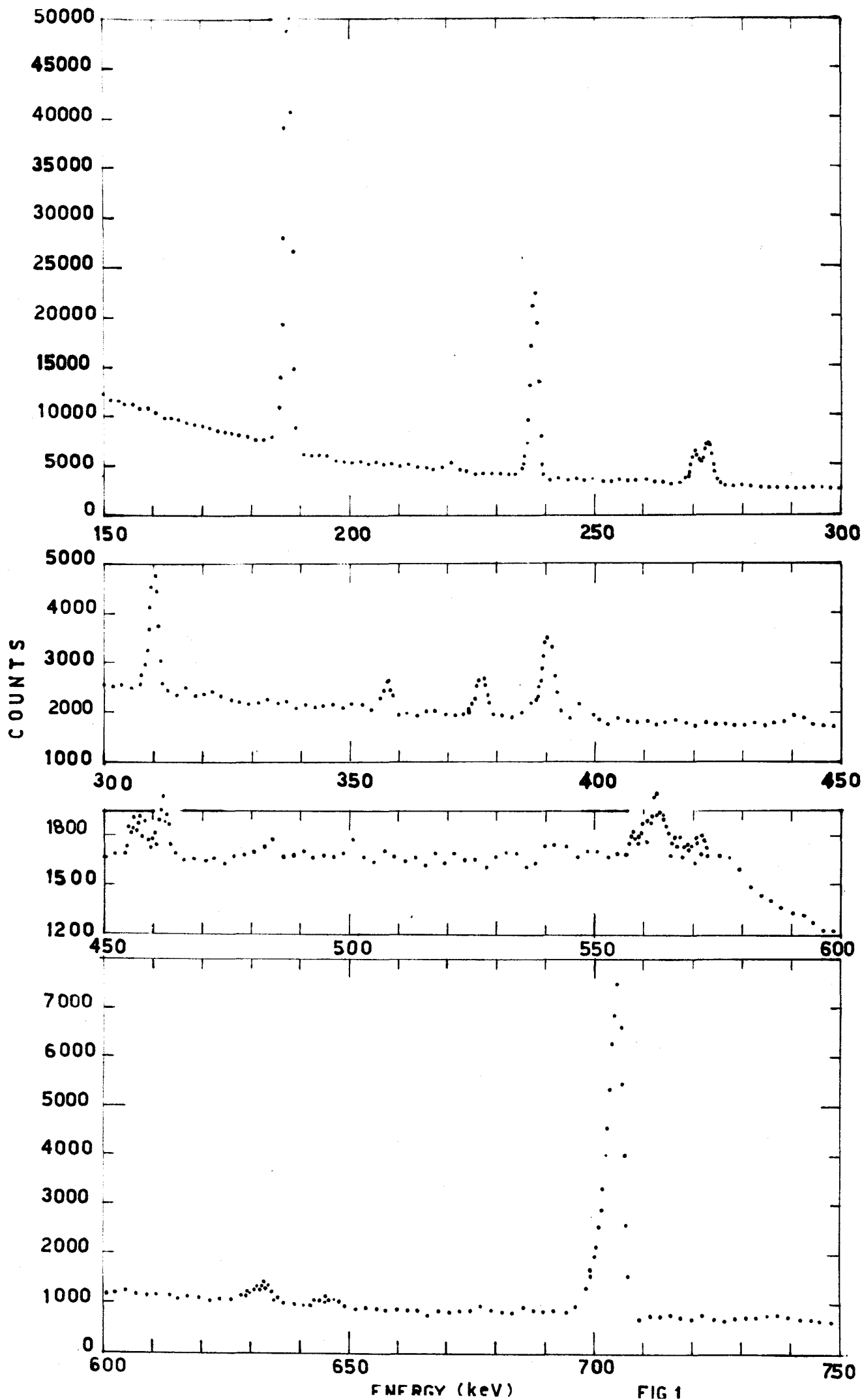
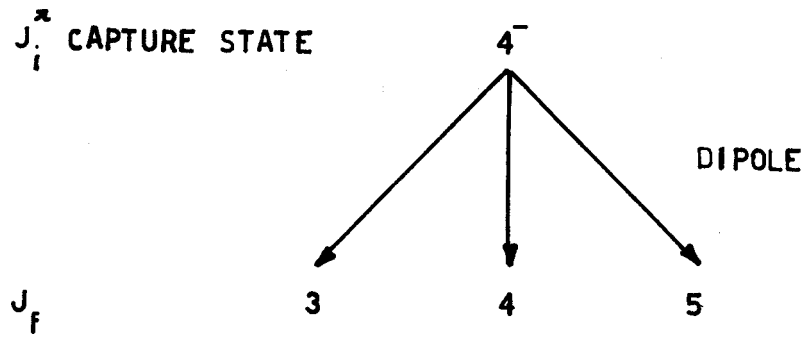


FIG 1

PRIMARY TRANSITIONS



SECONDARY TRANSITIONS

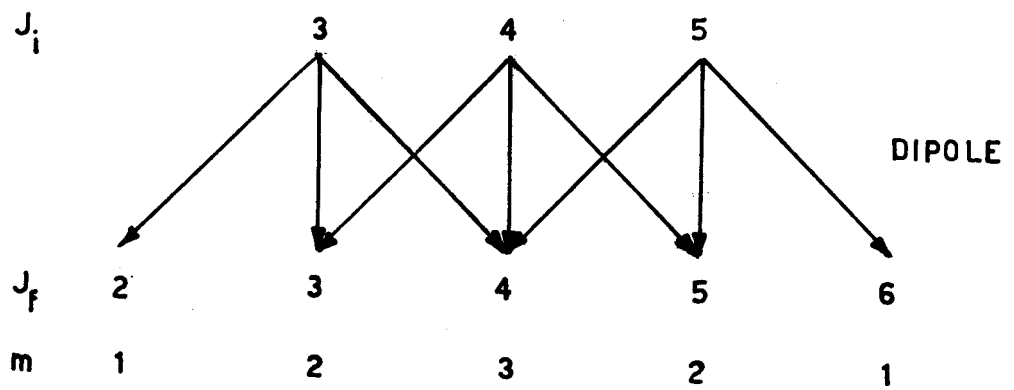


FIG. 2

FIG. 3

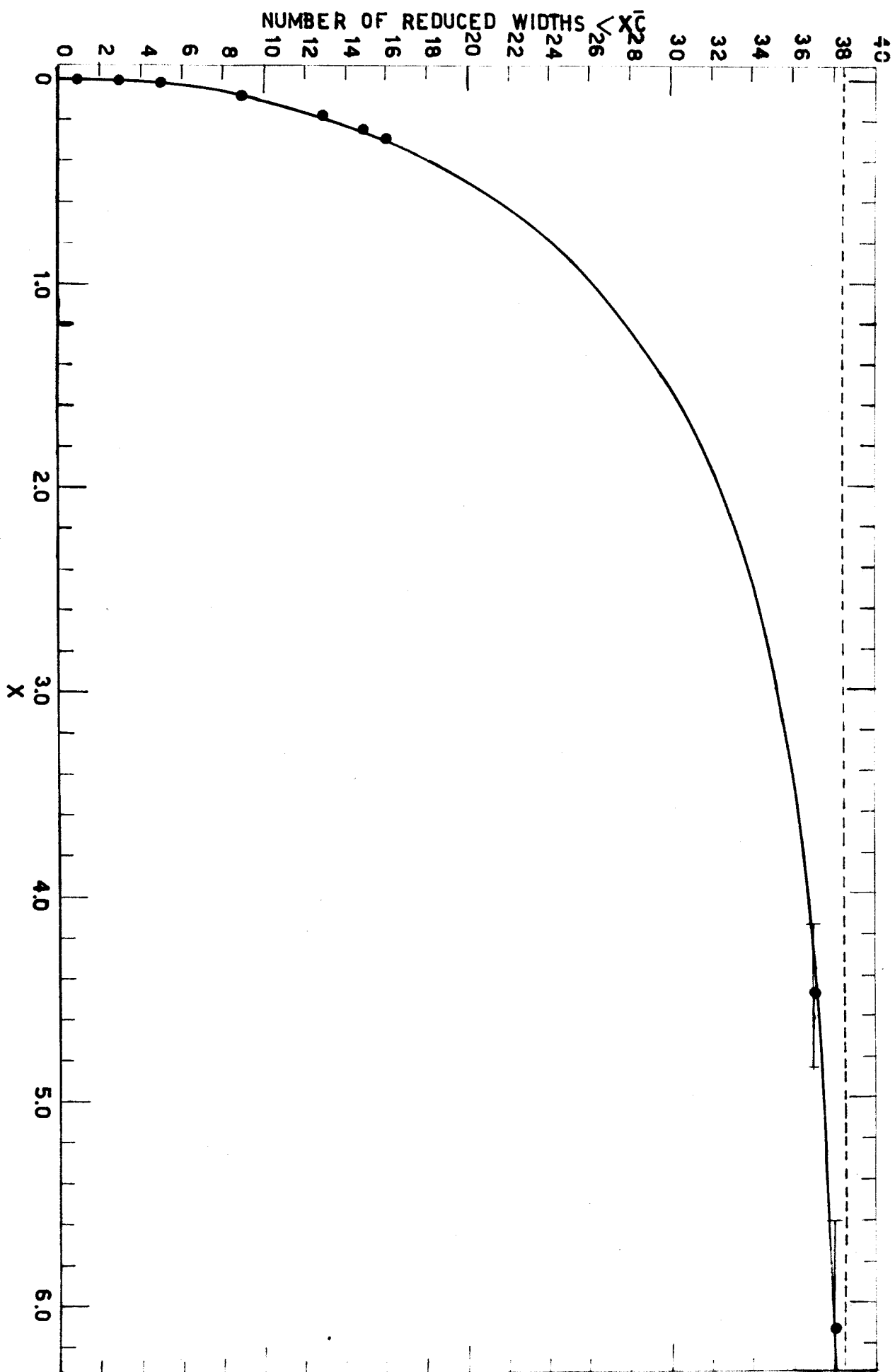
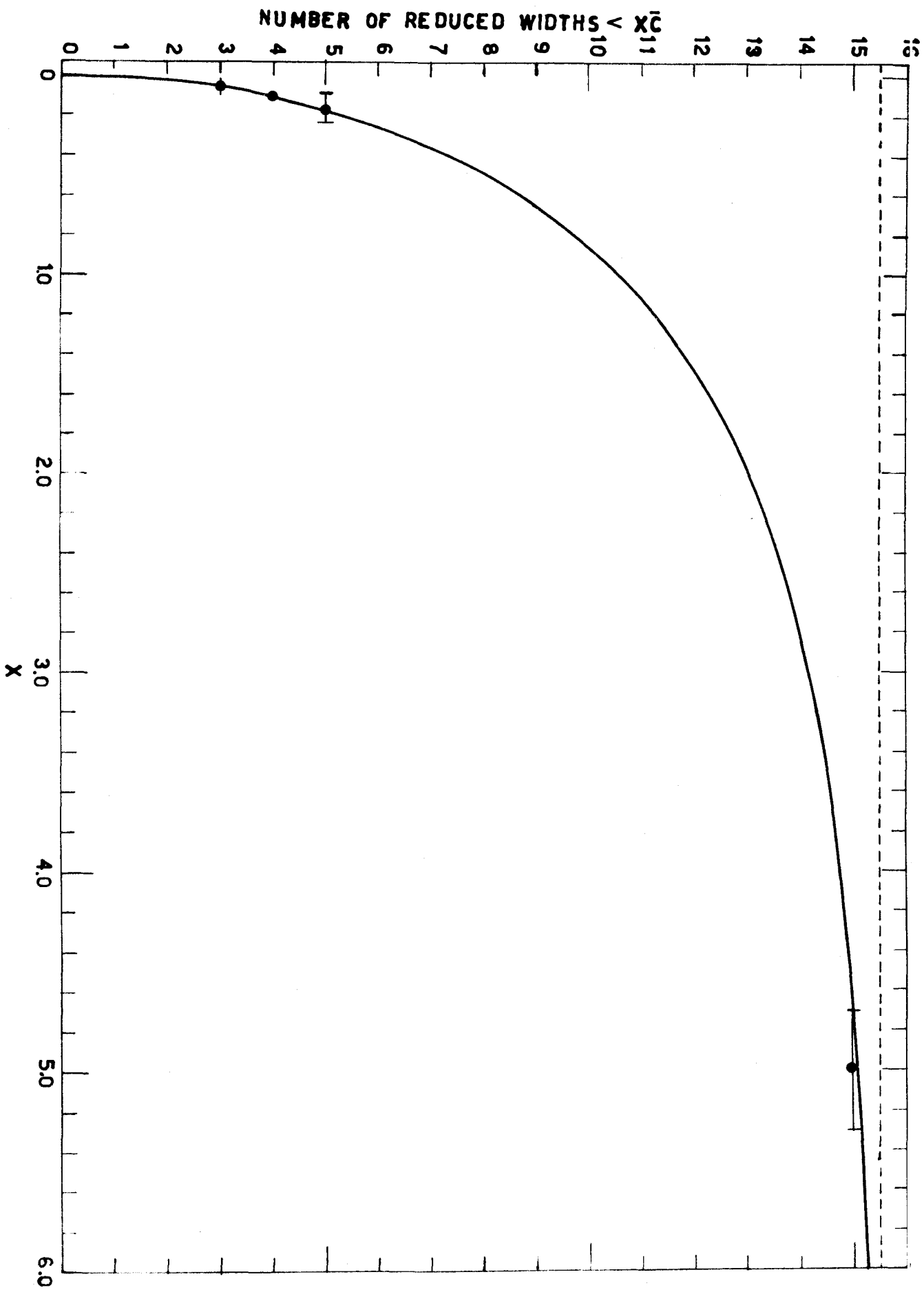


FIG. 4



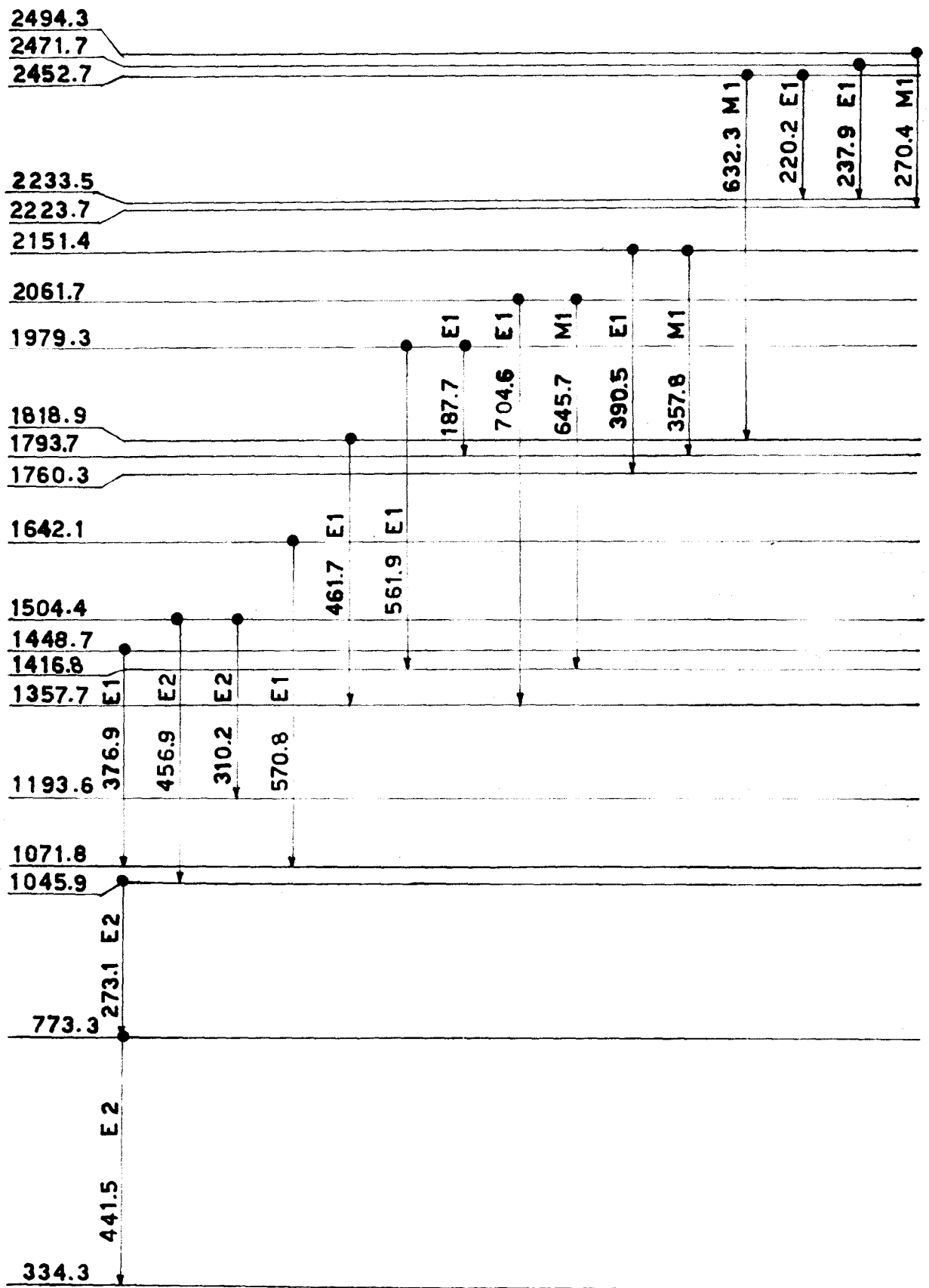


FIG. 5