NOTAS DE FÍSICA

VOLUME VII

Nº 13

A STUDY OF THE $Na^{23}(d,n)Mg^{24}$ REACTION WITH NUCLEAR EMULSIONS

by

J. M. F. Jeronymo and E. Lerner

CENTRO BRASILEIRO DE PESQUISAS FÍSICAS

Av. Wenceslau Braz, 71

RIO DE JANEIRO

1961

Notas de Física - Volume VII - Nº 13

A STUDY OF THE $Na^{23}(d,n)Mg^{24}$ REACTION WITH NUCLEAR EMULSIONS

J. M. F. Jeronymo* and E. Lerner**
Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro

(Received March 13, 1961)

ABSTRACT. - Neutrons from the $Na^{23}(d,n)Mg^{24}$ reaction produced by 2 Mev deuterons have been detected and their energies have been measured in nuclear emulsions by the proton recoil method.

The energy and the Q-value spectra of neutrons emitted at 0º, 5º, 25º, 35º, 45º, 60º and 85º to the deuteron beam are given. The ground state Q-value is found to be $Q_G = 9.56 \pm .12$ Mev, and execited levels are found at $E_i =$ $= 1.40 \pm .16$; $4.24 \pm .14$; $5.27 \pm .14$; $6.09 \pm .14$; $7.68 \pm .13$ and $8.63 \pm .13$

---

* On leave of absence with fellowship at Centre d'Études Nucléaires de Saclay, France.

** Now at Department of Physics of the Faculdade de Filosofia, Ciências e Letras da Universidade de São Paulo.

Mev, which are in good agreement with the published data and the precision comparable to that obtained taking the averages of other author's values.

* * *

1. INTRODUCTION.

An experiment was designed with the purpose of obtaining the energy spectra and the angular distributions of the neutrons arising from the reaction $Na^{23}(d,n)Mg^{24}$.

The energies of the excited levels of Mg^{24} have been obtained by different methods and by several authors.[1-14] The pertinent data on levels up to 9 MeV excitation energy are summarized in Table I.

The angular distribution of the neutrons arising from the $Na^{23}(d,n)Mg^{24}$ reaction have been investigated by Calvert et al.[1] with 9 MeV deuterons and by El Bedewi et al.[2] with 8 MeV deuterons.

In this paper we report our results on the energy levels of Mg^{24} using 2 MeV deuterons.

2. EXPOSURE AND NEUTRON DETECTION.

A target of metallic sodium evaporated over a tantalum foil, was bombarded with deuterons from the Van de Graaff generator of the University of S. Paulo. Table II gives the main characteristics of the beam and of the target.

The experimental arrangement of the exposure is shown in Fig. I.

Nuclear plates were located at several angles to the deuteron beam in such a manner that the emulsion planes were vertical and their longest axis of symmetry pointed to the center of the target.

The neutrons were detected with 200 micron Ilford C 2 emulsions, 4×2 inches, and their energy and relative intensity were obtained by the well known proton-recoil method. [15,16]

3. SCANNING AND TRACK SELECTION.

The area searched for protons was limited to the central region of each plate as shown by the shaded portion in Fig. 2.

The plates were "area scanned" with an oil immersion objective 53 × and binocular eyepieces 10 ×. We have not done any rescanning so as to check on possible bias against short tracks.

In order to be accepted for energy measurements a track had to satisfy the following requirements:

a) To have a projected length ℓ greater than 40 microns. This limit was chosen to bias against the large number of tracks of low energy and because of the poor energy resolution which is obtained for shorter ranges.

b) To have an initial direction within the limits

$$-20^{\circ} \leqslant \theta \leqslant +20^{\circ}$$

$$-15^{\circ} \leqslant \varphi \leqslant +15^{\circ}$$

These criteria correspond to a cut-off neutron energy of 2,45 MeV. The solid angle defined by these limits will contain only 11% of the scattered protons. This limitation was introduced in spite of the loss in statistics which ensues from it, due to the better energy resolution which is obtained and because it reduces the proportion of background (caused by stray neutrons and (n,p) reactions).

4. MEASUREMENTS.

For each accepted track the following quantities were measured (Fig. 3).

a) The projected length ℓ . For all tracks this length was measured with a calibrated eyepiece scale.

b) The azimuthal angle θ between the first 40 microns of the track projection in the emulsion plane and the x-direction. This angle was measured with an eyepiece protractor graduated in intervals of one degree.

c) The difference D between the depth of the track at its origin and at a point 40 microns away (projected distance).

The distance, 40 microns, was chosen as a compromise between the necessity of having a large distance for good precision in depth and angle measurements and the limitation imposed by multiple scattering which would, on long tracks give an appreciable change between the measured chord angle and the required initial tangent angle.

All measurements of depth have been performed with gauges specially adapted to our microscopes, in an air conditioned room at 25 ± 1 °C and 55 ± 5% relative humidity.

5. NEUTRON ENERGY SPECTRA.

For each measured recoil proton we have calculated the corresponding neutron energy, using a "shrinkage factor" of 2.3, and the range-energy curve due to Gibson et al. [17]

The histograms of the number of detected neutrons per 100 KeV energy intervals, for the seven angles of observation, are shown in Figs. 4 to 6.

Some figures also give the histograms for background plates, exposed scanned and measured in the same manner as the "normal" plates, except that the target consisted of a clean tantalum foil, similar to the one supporting our sodium target. It can be seen that the background, mostly due to $D^2(d,n)He^3$ reaction, can be neglected so that we did not subtract it from the "normal" histograms.

The most probable contaminants in the target are C^{12}, O^{16} and N^{14}. The first two have negative Q value for the (d,n) reactions, and do not contribute in the energy range studied. N^{14} produces only one neutron group in this energy range, which was not observed.

The energy spectra of neutrons leaving the target differ from the energy spectra of detected protons because of:

a) variation of the (n,p) scattering cross-section with the energy of the incident neutrons,

b) energy dependent absorption of the neutrons in the emulsion and in the glass backing,

c) escape probability of the recoil proton.

Corrections for the effects listed above* were applied in order to obtain the spectra shown in Figs. 7 and 8.

6. Q-VALUES SPECTRA.

In Fig. 9 is displayed the Q-value spectrum which results from the addition of the data of Figs. 7 and 8, weighted according to the relative intensities.

To obtain relative cross-sections, the normalized neutron flux should be multiplied by the appropriate factor K_i which is given, for each angle, in the corresponding figure.

This factor K_i was normalized to unity at 0º, and to obtain the absolute flux of neutrons in number of particles/steradian/100 KeV, it must be multiplied by 14×10^8.

In Table III we summarize the results obtained from the analysis of our Q-value spectrum (Fig. 9).

A correction has been applied for the estimated relative humidity of our plates at time of esposure (70 ± 10%) since Gibson's range--energy curve is valid for a relative humidity of 35%.

The errors quoted in Table III take into account the uncertain-

---

* The procedure for these corrections was suggested by Professor C. Lattes.

ties in the relative humidity, beam energy and statistics.

Comparing our results with those of other workers (see also Table I) one sees that, with the exception of Mandeville's data, the agreement is very good. There is no indication in our spectra, for the presence of levels L_1, L_2 and L_4 found by Mandeville.[3]

The levels L_5[Q = (5,336 ± .026) MeV] and L_6 [Q = 5.225 ± .026) MeV] cannot be resolved in our Q-values distributions where they show up as a single peak.

The level L_8 appears to be a composite one, as can be seen in Fig. 10 which shows the best fits one can obtain assuming one (Fig. 10a) and two gaussians (Fig. 10b) respectively, and taking the half-width of each gaussian to be equal to the average of the half-widths of levels L_7 and L_9 in the Q-value spectrum (F.W.H.M. = = 0.21 MeV).

An estimate of the best fit through "Chi-square" tests yields the probabilities:

$$P \leq 1\% \text{ for one gaussian.}$$

$$P \geq 10\% \text{ for two gaussians.}$$

Assuming L_8 to be due to two levels, the best fit is obtained for:

$$\langle Q_{8'} \rangle = 3.60 \pm .06 \text{ MeV}$$

$$\langle Q_{8'} \rangle = 3.04 \pm .06 \text{ MeV}$$

This is agreement with the results of Fisher[8] who reports the existence of two levels in the neighborhood of L_8, with excitation energies corresponding to the following Q-values:

$$\langle Q_{8'} \rangle = 3.57 \pm .10 \text{ MeV}$$

$$\langle Q_{8''} \rangle = 3.17 \pm .10 \text{ MeV}$$

7. EXCITED LEVELS: Q-VALUES AND ENERGIES CORRECTED THROUGH GROUND STATE DATA.*

The Barka's curve for adjusting measured ranges to equivalent ranges in a standard emulsion [19] was used to correct the range energy curve. A point of reference being that corresponding to the ground state Q value where the experimental Q_G value was compared to that calculated from Mattauch et al. [18]

With the aid of such a corrected range energy curve we have re-calculated the Q values and the corresponding errors for all excited states of Mg^{24}.

This is shown in Table IV.

8. ACKNOWLEDGEMENTS.

We are grateful to Professor C. Lattes for discussions and suggestions. We wish to thank Professor U. Camerini, who started this investigation, Professors O. Sala and E. Hamburger for the exposure and discussions and Miss

* This procedure was suggested by Professor C. Lattes.

Z. Calil and Miss E. N. Almeida who did the microscope work and helped with the calculations.

* * *

REFERENCES

1. J. M. CALVERT, A. A. JAFFE, A. E. LITHERLAND and E. F. MASLIM, Proc. Phys. Soc. (London) A 68, 1008 (1955).

2. F. A. EL BEDEWI and M. A. EL WAHAD, Nuclear Phys. 2, 385 (1957).

3. C. E. MANDEVILLE, Phys. Review 76, 436 (1949).

4. H. J. HAUSMAN, A. J. ALLEN, J. S. ARTHUR, R. S. BENDER and C. J. MC DOLE, Phys. Review 88, 1296 (1952).

5. D. J. DONAHUE, K. W. JONES, M. T. MC ELLISTREM and H. T. RICHARDS, Phys. Review 89, 824 (1953).

6. J. O. NEWTON, Phys. Review 96, 241 (1954).

7. C. J. BAKER, J. N. DODD and D. H. SIMONS, Phys. Review 85, 1051 (1952).

8. G. E. FISHER, Phys. Review 96, 704 (1954).

9. B. HIRD, C. WHITEHEAD, J. BUTTER and C. H. COLLIE, Phys. Rev. 96, 702 (1954).

10. G. W. GREENLESS, Proc. Phys. Soc. (London) A 67, 1107 (L) (1954).

11. LAWRENCE GRANBERG and JULES S. LEVIN, Phys. Review 103, 343 (1956).

12. ROBERT B. DAY, Phys. Review 102, 767 (1956).

13. R. H. HELM, Phys. Review 104, 1466 (1956).

14. D. M. VAN PATTER, W. C. PORTER and M. A. ROTHMAN, Phys. Review 106, 1016 (1957).

15. F. C. CHAMPION and C. F. POWELL, Proc. Royal Soc. (London) 183, 64 (1944).

16. LOUIS ROSEN, Nucleonics: I - vol. 11, nº 7, 32 (1953); II - vol. 11, nº 8, 39 (1953).

17. GIBSON and ROTBLAT, Nature, 173, 1180 (1951).

18. J. MATTAUCH, L. WALDMANN, R. BIERI and F. EVERLING, Annual Review of Nuclear Science, vol. 6, 179 (1956).

19. W. H. BARKAS, P. H. BARRET, P. CUER, H. HECKMANN, F. M. SMITH and H. K. TICHO, Nuovo Cimento, vol. 8, 185 (1958).

* * *

TABLE I

ENERGY LEVELS OF Mg^{24}

LEVELS	L_0 G.S.	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}	AUTHORS	REF.	REACTIONS	INCIDENT ENERGY
(E_x) EXCITATION ENERGIES (M.E.V.)		0.83	1.24		1.66	4.16				7.70	8.64	MANDEVILLE	3	$Na^{23}(d,n)$	1.4
				1.38 ± .02		4.13 ± .02	4.24 ± 02					HAUSMAN	4	$Mg^{24}(p,p')$	8.0
				1.371 ± 002 1.366 ± 004								DONAHVE	5	$Mg^{24}(p,p')$ $Al^{27}(p,\alpha)$	2.412 1.187
								5.23 ± .04				NEWTON	6	$Na^{23}(p,\gamma)$	0.742 → → 1.445
									6.38 ± .04			BAKER	7	$Mg^{24}(p,p')$	9.6
						4.2		5.1 ± .1	5.9 ± .1 6.3 ± .1			FISCHER	8	$Mg^{24}(p,p')$	9.9
				1.38 ± .02		4.11 ± .05			6.7 ± 2	7.7 ± 2		HIRD	9	$Na^{23}(p,\gamma)$	0.31
				1.38 ± .04		4.18						GREENLESS	10	$Mg^{24}(p,p')$	6.5
				1.38 .03								CRANBERG	11	$Mg^{24}(n,n')$	2.45
				(1.368)		(4.122)	(4.23)	5.1 * 5.5	6.3	7.5	8.4	CALVERT	1	$Na^{23}(d,n)$	8
												DAY	12	$Mg^{24}(n,n'\gamma)$	2.56
				1.37								HELM	13	$Mg^{24}(e,e')$	187
						(4.13)	(4.24)			7.45 ± .10	8.48 ± .10	EL BEDEWI	2	$Na^{23}(d,n)$	7.75
				1.366 ± 006								VAN PATTER	14	$Al^{27}(p,\alpha)$	4.655
AVERAGE Ex Mev		0.83	1.24	1.370 ± 0016	1.66	4.18 ± .014		5.23 ± .04	6.25 ± .06	7.50 ± .09	8.48 ± .10				
AVERAGE Q-VALUE Mev	9.465 ± 016	8.63	8.22	8.095 ± 016	7.80	5.28 ± .02		4.23 ± .04	3.21 ± .06	1.90 ± .09	.98 ± .10	MATTAUCH (G.S.)	18 (G.S.)		
SPIN PARITY	0 +			2 +		4 +	2 +			1 OR 2 +	1 OR 2 +	CALVERT	1		

TABLE II

BEAM AND TARGET DATA

DEUTERON ENERGY	1.96 ± 0.02 Mev
HALF-WIDTH OF THE ENERGY DISTRIBUTION OF THE BEAM	6 Kev
DIAMETER OF THE BEAM	1.6 mm
TOTAL EXPOSURE	10^4 μCOULOMBS
TARGET THICKNESS FOR 2 Mev DEUTERON	45 ± 15 Kev

TABLE III

SUMMARY OF Q AND E_x VALUES RESULTS FOR $Na^{23}(d,n)Mg^{24}$ REACTION

LEVEL	$Q \pm \Delta Q$	$\bar{Q} \pm \overline{\Delta Q}$	$E_x \pm \Delta E_x$	$\bar{E}'_x \pm \Delta\bar{E}'_x$
Ground	9.56±.12	9.465±.016	-	-
L_3	8.16±.11	8.095±.016	1.40±.16	1.37±.002
$L_{5,6}$	5.32±.08	5.28±.02	4.24±.14	4.18±.014
L_7	4.29±.07	4.23±.04	5.27±.14	5.23±.04
L_8	3.47±.06	3.20±.06	6.09±.14	6.25±.06
L_9	1.88±.05	1.90±.09	7.68±.13	7.50±.09
L_{10}	0.88±.04	0.98±.10	8.68±.13	8.48±.10

Q - value for each level, calculated from our data, using Gibson's curve converted to $e = 3.78 \pm .09$ gr/cm^3.

$\Delta Q \rightarrow$ is given by $\sqrt{\epsilon_S^2 + \epsilon_{RH}^2 + \epsilon_D^2}$

$\epsilon_S \rightarrow$ statistical

$\epsilon_{RH} \rightarrow$ Due to range-energy relation (e or R.H) uncertainty

$\epsilon_D \rightarrow$ Due to deuteron energy uncertainty

$\bar{Q} \rightarrow$ Average of the published Q-values

$\Delta\bar{Q} \rightarrow$ Error of the average

$E_x \rightarrow$ Level Energy

$\bar{E}'_x \rightarrow$ Average of the published values (Without the values given by Mandeville)

TABLE IV

GROUND-STATE CORRECTED Q AND E_x VALUES FOR $Na^{23}(d,n)Mg^{24}$ REACTION

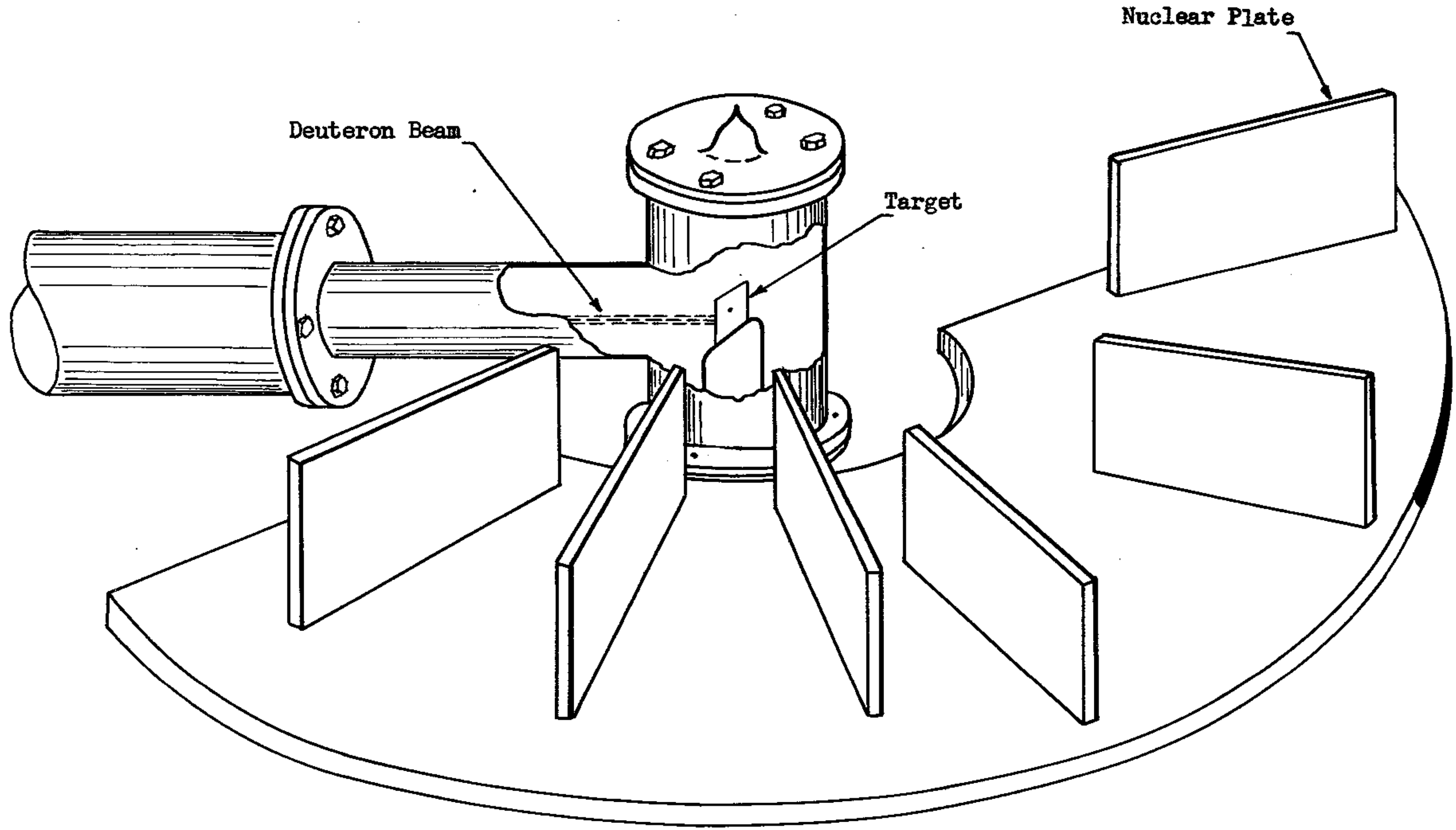
LEVEL	$\bar{Q}_G \pm \Delta\bar{Q}_G$ [a]	$\bar{Q} \pm \Delta\bar{Q}$ [b]	$\bar{E}_{XG} \pm \Delta\bar{E}_{XG}$ [c]	$\bar{E}_X \pm \Delta\bar{E}_X$ [d]
Ground	9.465±.016	9.465±.016	-	-
L_3	8.090±.031	8.095±.016	1.375±.035	1.370±.002
$L_{5,6}$	5.271±.023	5.280±.020	4.194±.028	4.180±.014
L_7	4.250±.021	4.230±.040	5.215±.027	5.230±.040
L_8	3.434±.020	3.210±.060	6.031±.026	6.250±.060
L_9	1.859±.018	1.900±.090	7.606±.024	7.500±.090
L_{10}	0.866±.017	0.980±.100	8.599±.023	8.480±.100
(L_8')	3.560±.020	3.560±.100	5.905±.026	5.900±.100
(L_8'')	3.006±.020	3.160±.100	6.459±.025	6.300±.100

a) Q-values using ground state calibration.

b) Average of published data.

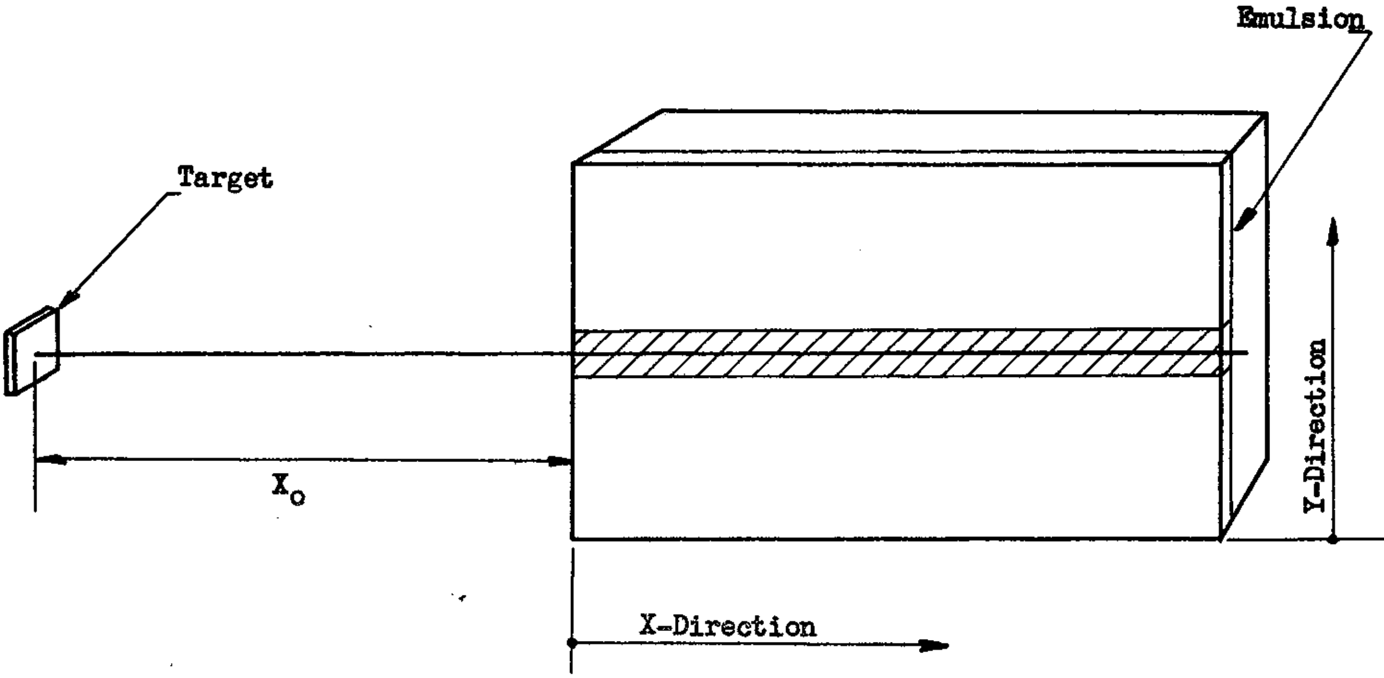
c) $E_{X_i} = Q_{Mattauch} - Q_{C_i}$

d) $\bar{E}_{X_i}$ = Average of published data.



EXPERIMENTAL ARRANGEMENT FOR PLATES EXPOSURE

Fig. 1



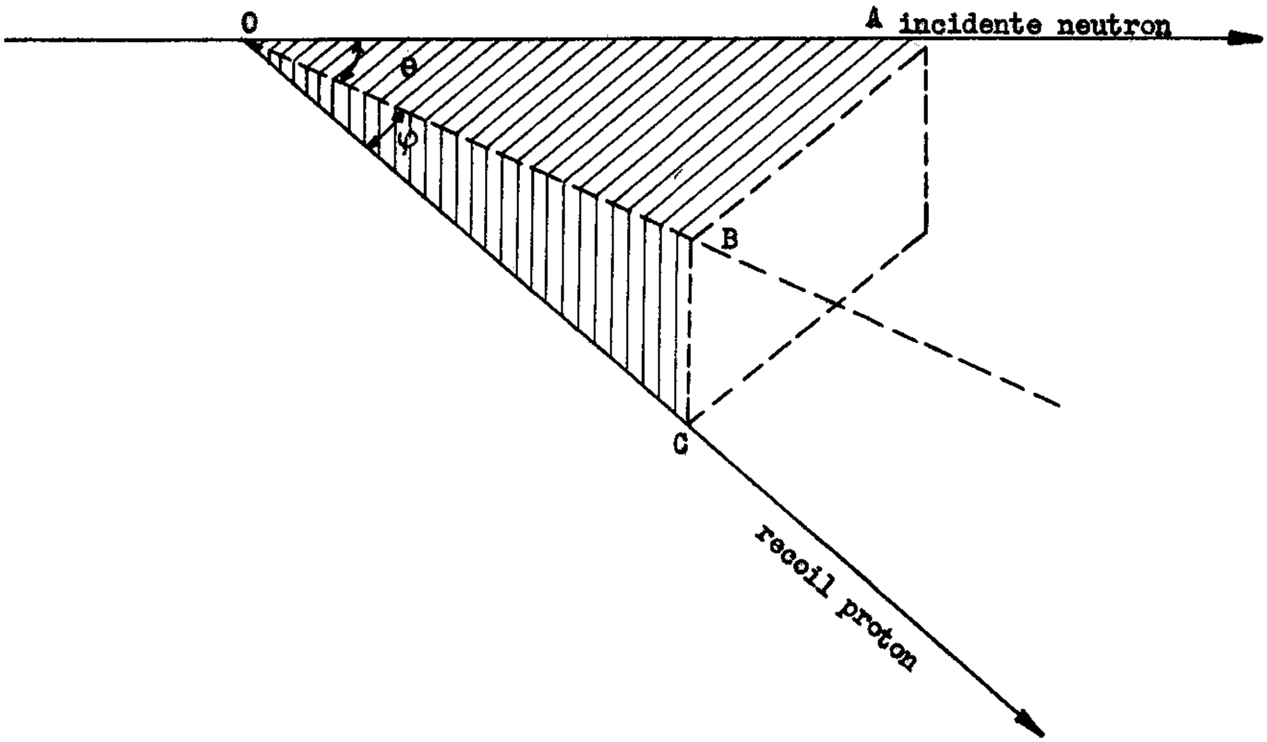
GEOMETRY OF EXPOSURE

Shaded Portion - 6mm Wide-Indicates the Area Searched for Protons

X_o = 72 mm For the Plates at 60° and 85°

X_o = 120 mm For the Other Plates

Fig. 2



DEFINITION OF THE ANGULAR CHARACTERISTICS OF A TRACK

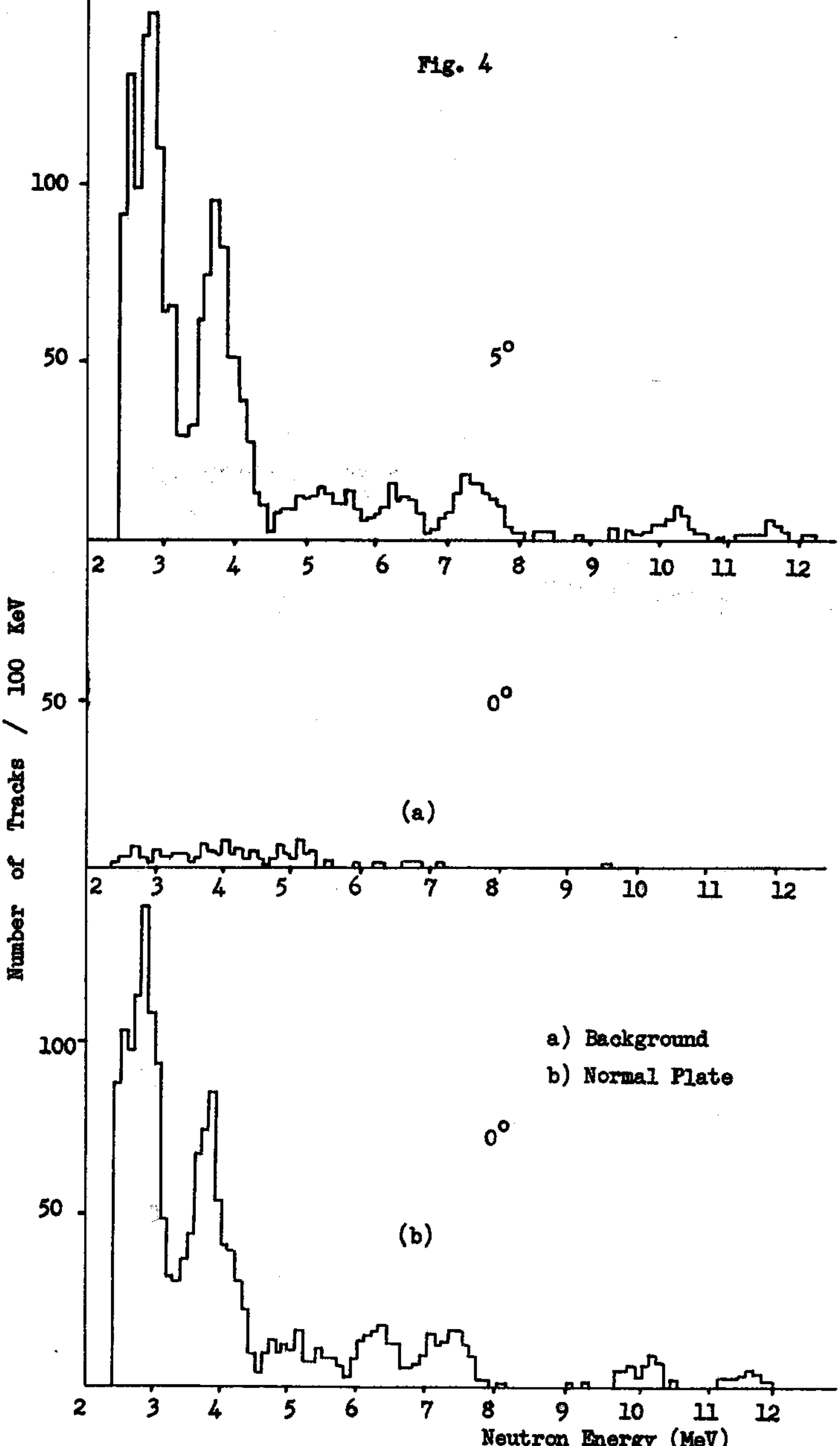
$$\widehat{AOB} = \theta$$

$$\widehat{BOC} = \varphi$$

$$\widehat{AOC} = \psi$$

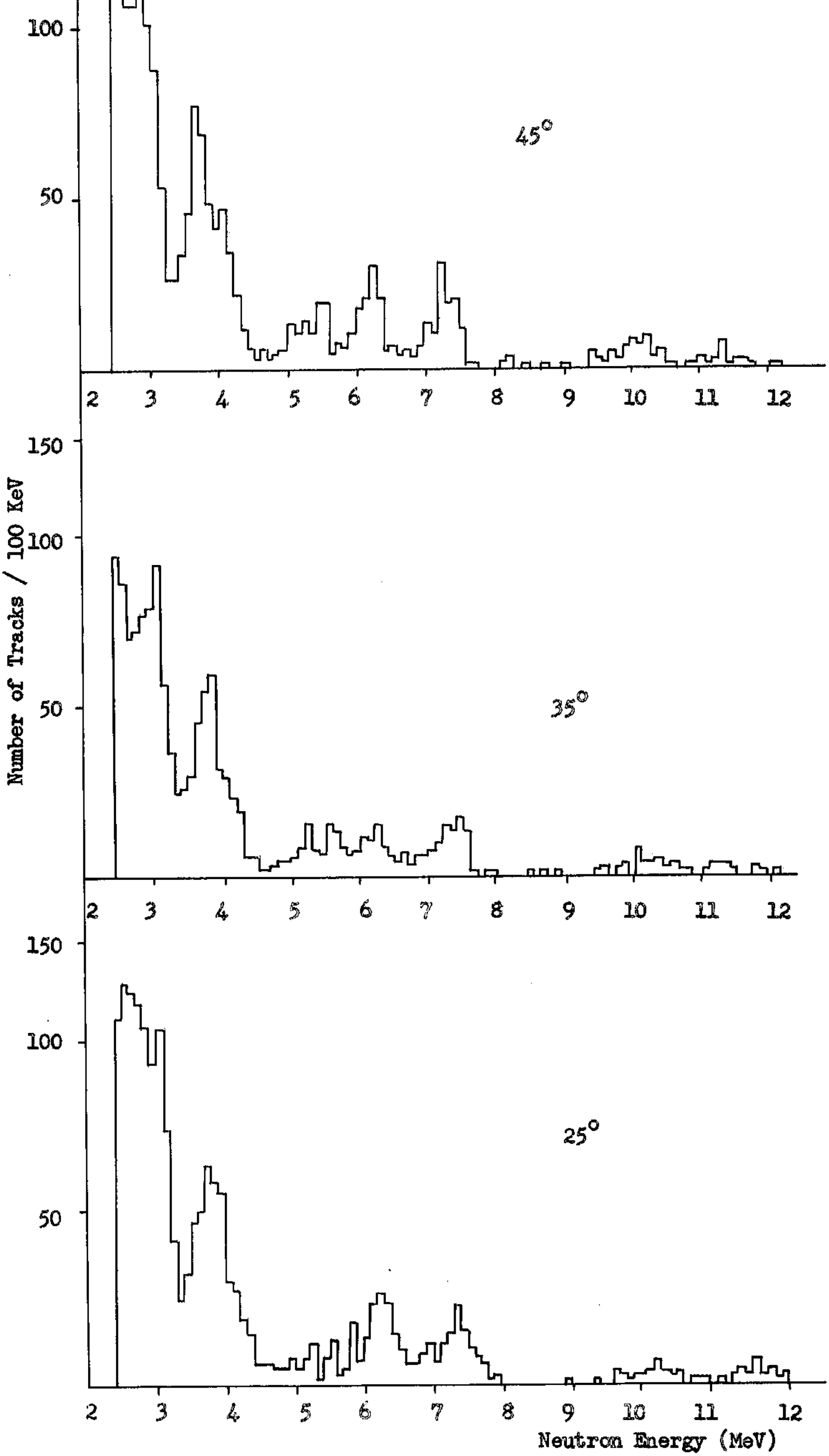
Fig. 3

Fig. 4



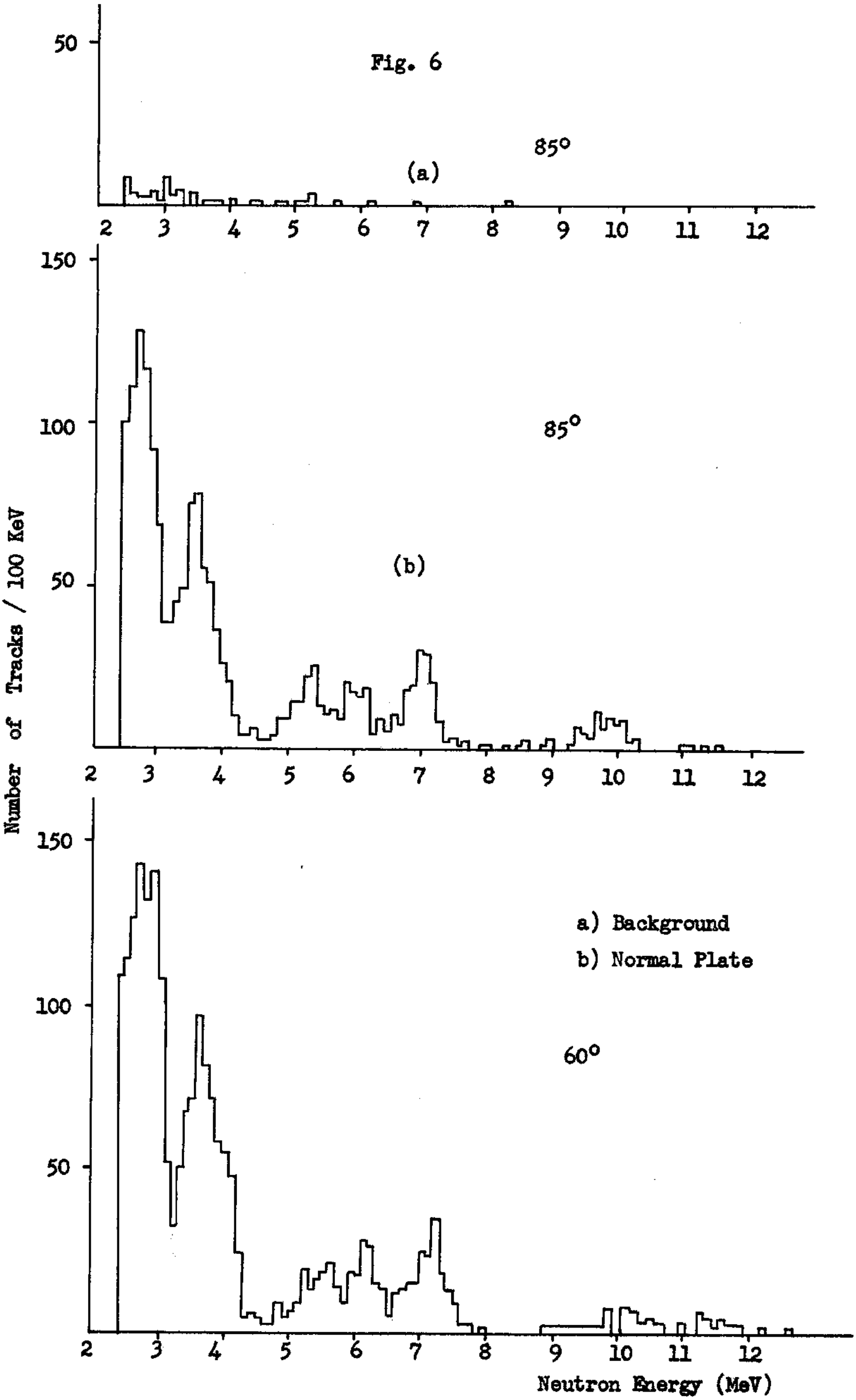
NEUTRON ENERGY HISTOGRAM (UNCORRECTED)

Fig. 5

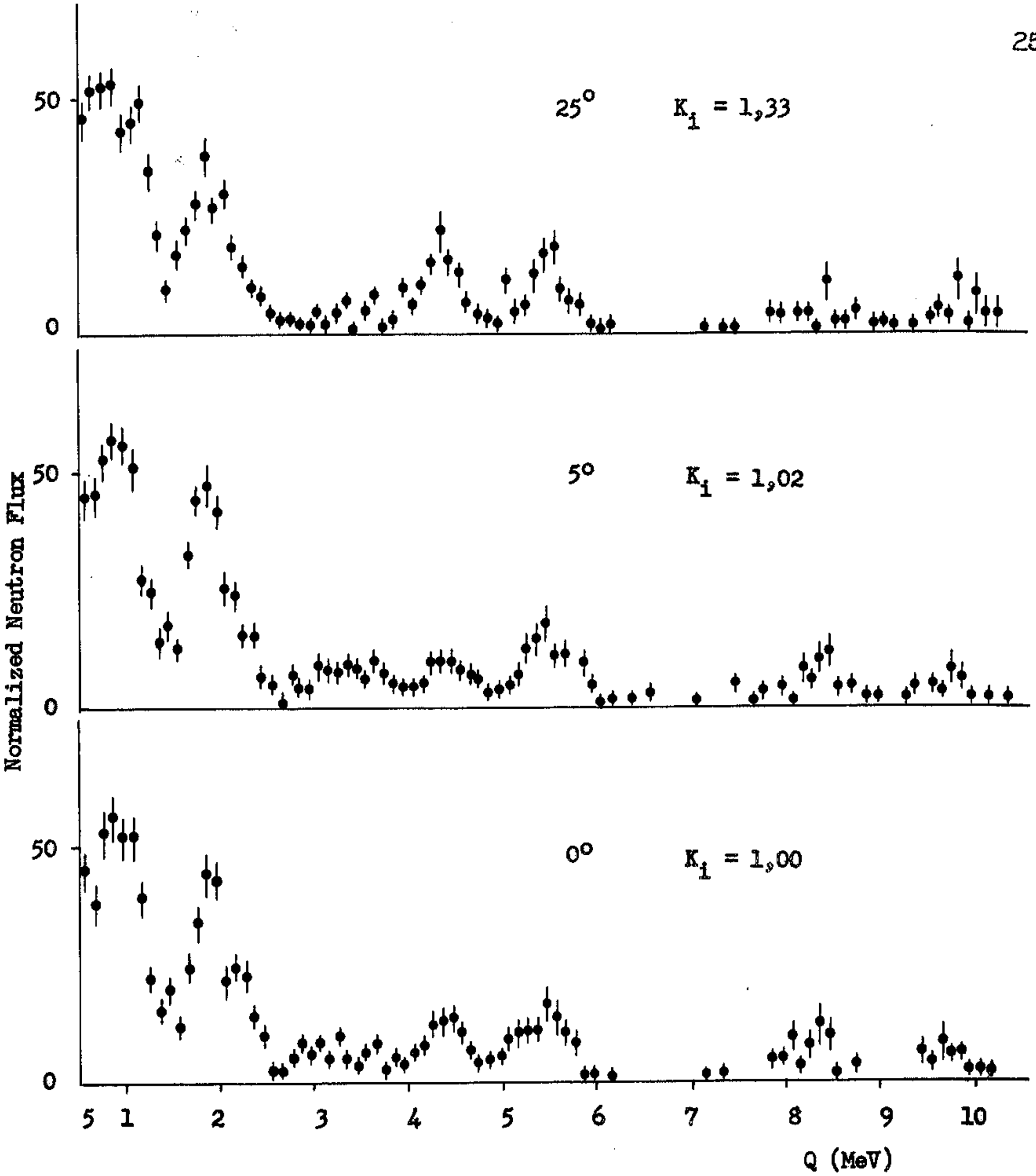


NEUTRON ENERGY HISTOGRAM (UNCORRECTED)

Fig. 6

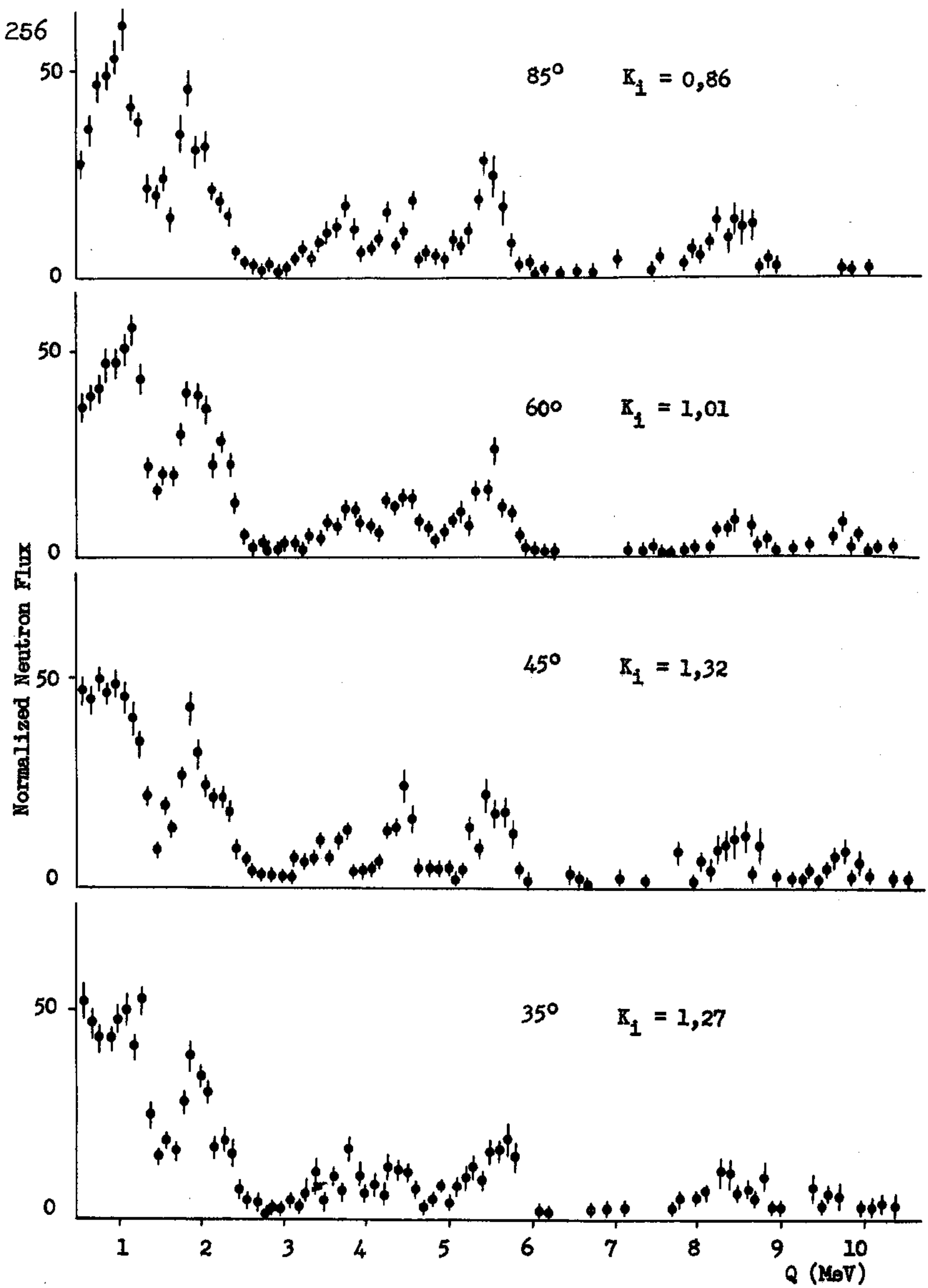


NEUTRON ENERGY HISTOGRAM (UNCORRECTED)



Q-VALUES SPECTRA OF $Na^{23}(d,n)Mg^{24}$ REACTION

Fig. 7



Q-VALUES SPECTRA OF Na (d,n)Mg REACTION

Fig. 8

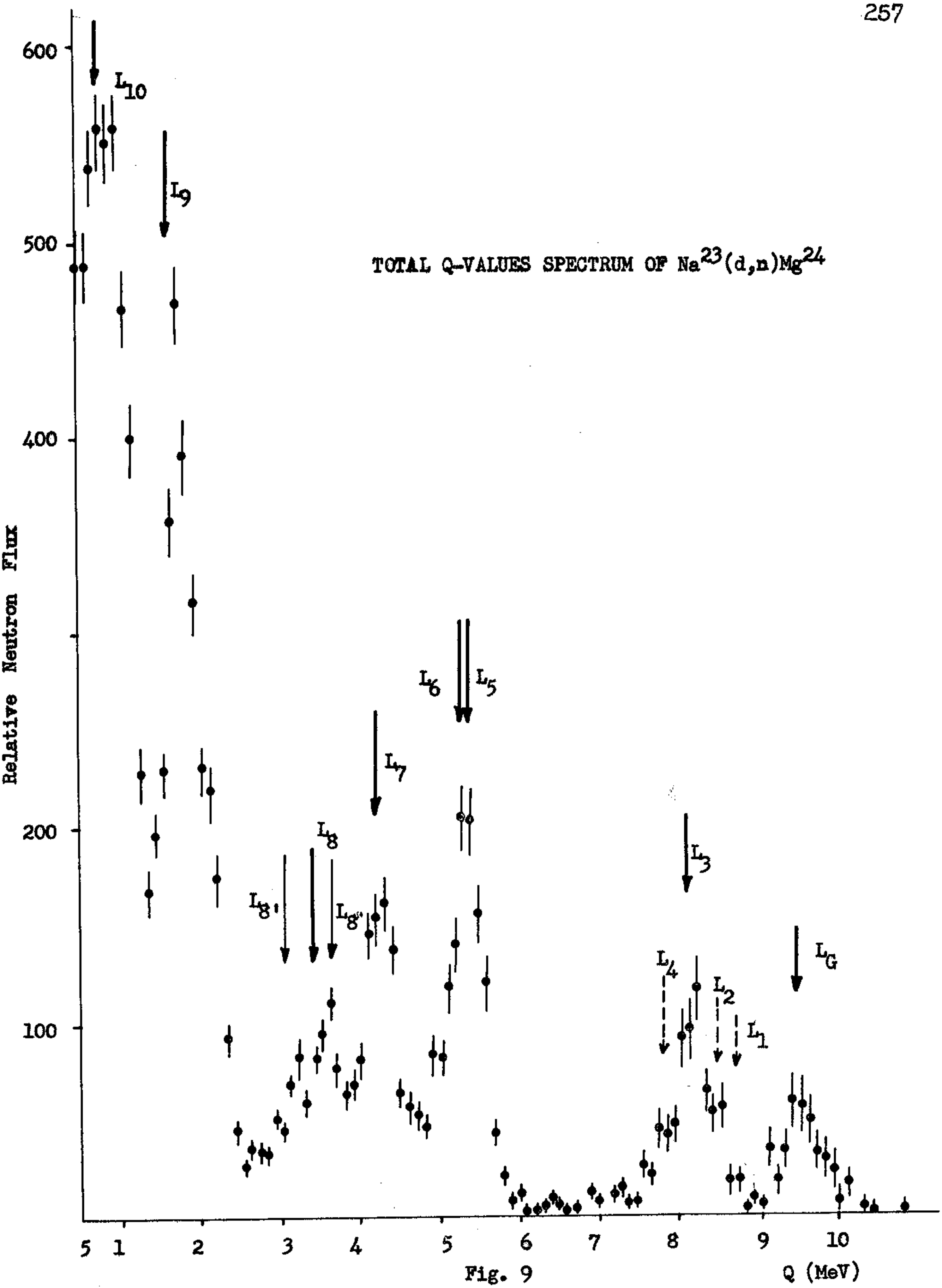
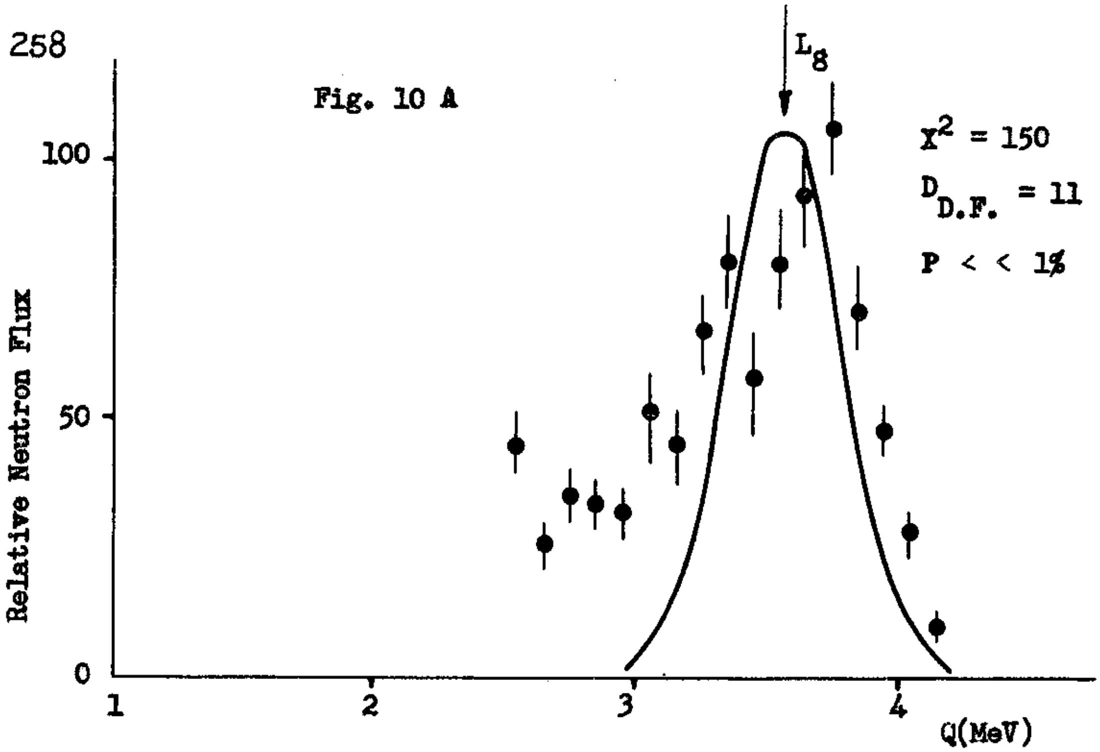
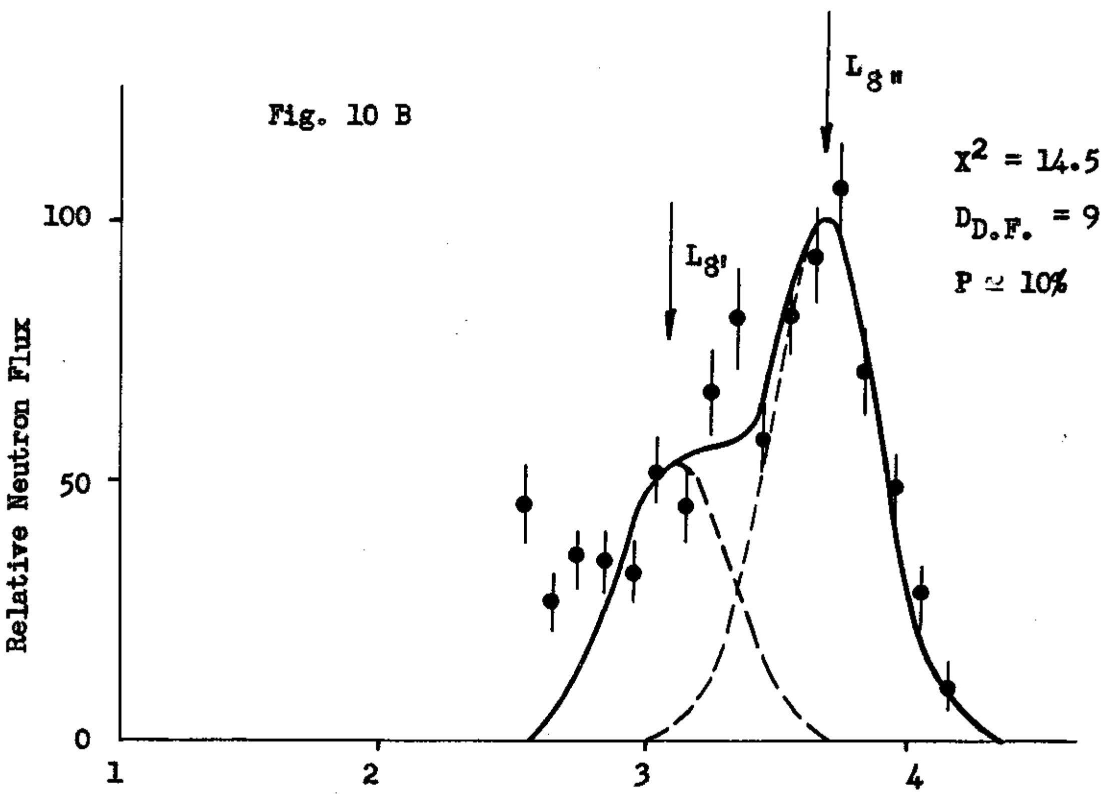

TOTAL Q-VALUES SPECTRUM OF Na23(d,n)Mg24
Relative Neutron Flux
600
500
400
200
100
L10
L9
L8
L8'
L8"
L7
L6
L5
L4
L3
L2
L1
LG
5
1
2
3
4
5
6
7
8
9
10
Q (MeV)

Fig. 9



GAUSSIAN FITS TO L 8



GAUSSIAN FITS TO L 8