RICE UNIVERSITY

GAMMA-RAY SPECTRA FROM HE^3 REACTIONS WITH C^{12} AND N^{14}

by

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I. INTRODUCTION

Excitation curves of $C^{12} + He^3$ and $N^{14} + He^3$ reactions have been studied for He^3 bombarding energies from over 1 Mev to about 5 Mev through examination of the gamma rays with a NaI crystal scintillation spectrometer. Gamma-ray spectra were obtained by using a 256-channel pulse height analyzer. From the gamma-ray spectra the various gamma rays from (He^3,p) and (He^3,He^4) reactions have been identified. He^3 particles were accelerated by the 5.5 Mev Van de Graaff accelerator at the Rice University.

II. EXPERIMENTALS

A. TARGETS

Preparations

The carbon target used for excitation curves and gamma-ray spectra was made by first heat-cleaning a thin tungsten blank (diameter = 3/4 inch, thickness = 0.001 inch) in the induction heating target preparation system described by Givens[1] at high vacuum (5×10^{-5} mm Hg) and then heating it in the presence of 15 inches pressure spectroscopically pure Ethane (CH_3CH_3) gas for about 5 minutes at about 1300°C.

The carbon target used for the study of angular distribution was obtained from one made earlier with a tantalum backing.

The nitrogen target was made by first heating clean a tungsten blank (diameter = 3/4 inch, thickness = 0.0263 inch) in the induction heating system mentioned above at high vacuum (5×10^{-5} mm Hg). Cr was then evaporated on to it by using the apparatus described by Bernard[2]. Chemically pure CrN powder was put in a tungsten boat. Nitrogen was evaporated out first by slow heating. The temperature was then increased and Cr was evaporated on to the blank at high vacuum (4×10^{-5} mm Hg). The Cr target was then heated in the induction heating system in the presence of pure nitrogen gas (15 inches pressure, 15 minutes, 1300°C). The nitrogen gas was first passed through a liquid air trap to trap off all oil and water contaminations.

Target Testing

The thickness of the carbon target used for the study of angular distribution was obtained by observing the rise of the ratio curve of the ground state neutron threshold and the shift of resonance peak of $C^{12}(He^3,n)O^{14}$ reaction with the reported data[3]. It is about 300 Kev at a He^3 bombarding energy (E_{He^3}) of 3 Mev when the target is at an angle of 45° with the beam.

The thickness of the other carbon target is about 60 Kev at E_{He^3} = 3 Mev from the comparison of relative neutron yields.

The thickness of the nitrogen target can be obtained by running the 2 Kev wide resonance of $N^{15}(p, \alpha_1 \gamma_{4.43})C^{12}$ reaction at E_p = 0.898 Mev, since the target was made with natural nitrogen which contains 0.365% of N^{15}. An estimate of the target thickness can also be made from the approximate amount of Cr evaporated on to the blank. From this estimate the thickness of the nitrogen target used in the present experiment is about 80 Kev at E_{He^3} = 3 Mev.

Carbon contamination and deposition on the nitrogen target is a serious problem especially in the $N^{14}(He^3,n)F^{16}$ reaction. Measurement of the 2.31 Mev gamma-ray decay from the $C^{12}(He^3,n)O^{14}$ reaction is a good method for comparing the relative amount of carbon contamination.

B. PROCEDURES

Target and counter arrangement for excitation curves and spectra is shown in Fig. 1. The data were taken at the same time with the neutron measurement reaction $C^{12}(He^3,n)O^{14}$ or $N^{14}(He^3,n)F^{16}$.

The arrangement for angular distribution is shown in Fig. 2.

The 256-channel pulse height analyzer was calibrated, by using standard sources (PuBe, Na^{22}, Co^{60}), to obtain the relation between the energy scale of the pulse height and the channel number.

The biases of the two single channel pulse height analyzers were set by first running a differential bias curve. The biases for the excitation curves are shown on the spectra. In Fig. 3, the bias for curve I was set to count all pulses of energies higher than 3 Mev, the bias for curve II was set to count all pulses of energies higher than 4.5 Mev. The bias for the excitation curve in Fig. 11 was set to count all pulses of energies higher than 3 Mev.

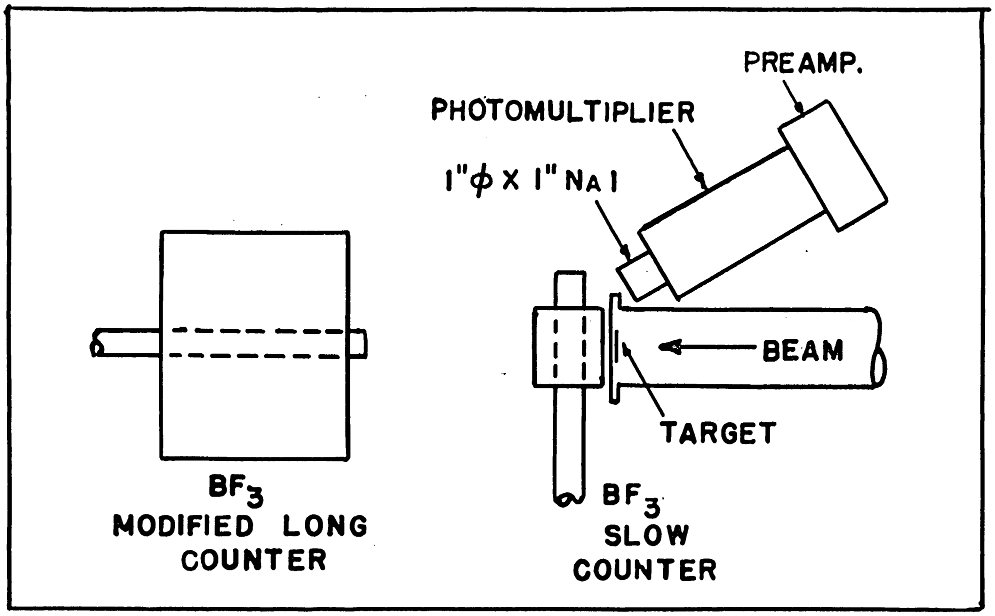


FIG. 1 TARGET COUNTER ARRANGEMENT FOR EXCITATION CURVES AND SPECTRA

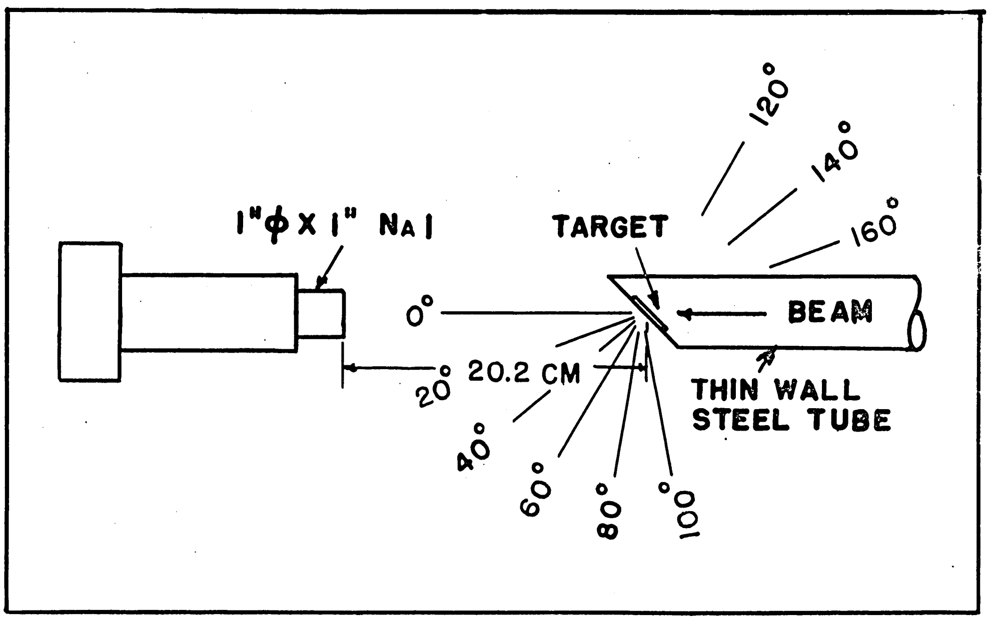


FIG. 2 TARGET COUNTER ARRANGEMENT FOR ANGULAR DISTRIBUTION

III. GAMMA-RAY SPECTRA FROM C^{12} + He^3

A. RESULTS

Excitation Curves

The gamma-ray excitation curves corresponding to two different bias settings are shown in Fig. 3. They both show a pronounced resonance at a He^3 bombarding energy of 3 Mev and two small peaks at 2.15- and 4.35- Mev bombarding energies. The positions labelled by A, B, ..., G are the expected resonance positions corresponding to the excited states of the compound nucleus O^{15} already reported(3,4,5).

Spectra

1) Spectra were taken at various bombarding energies. Some of them are given in Figs. 4 to 8.

2) The scale of gamma radiation energy, in Mev, on each spectrum was obtained from the calibration mentioned in the procedures. The error is about 4%.

3) General trend of the spectra:

a) For bombarding energies below that corresponding to the resonance D the general shape of the spectra is like that shown in Fig. 4 except that before resonance A the two peaks with electron energies of about 2.8- and 3.4-Mev are

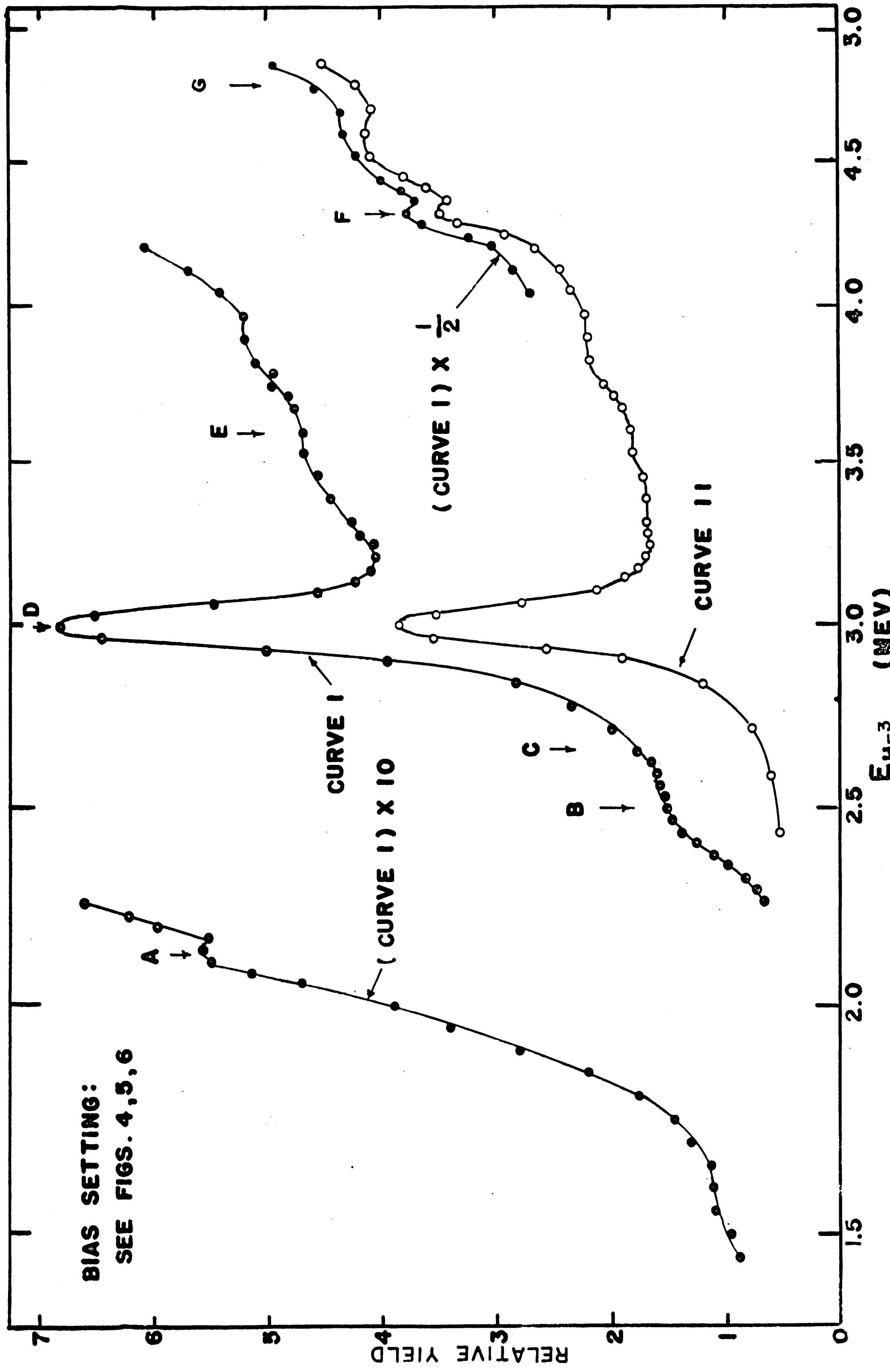


FIG. 3 γ-RAY EXCITATION CURVES FROM HE^3 BOMBARDMENT OF C^{12} TARGET

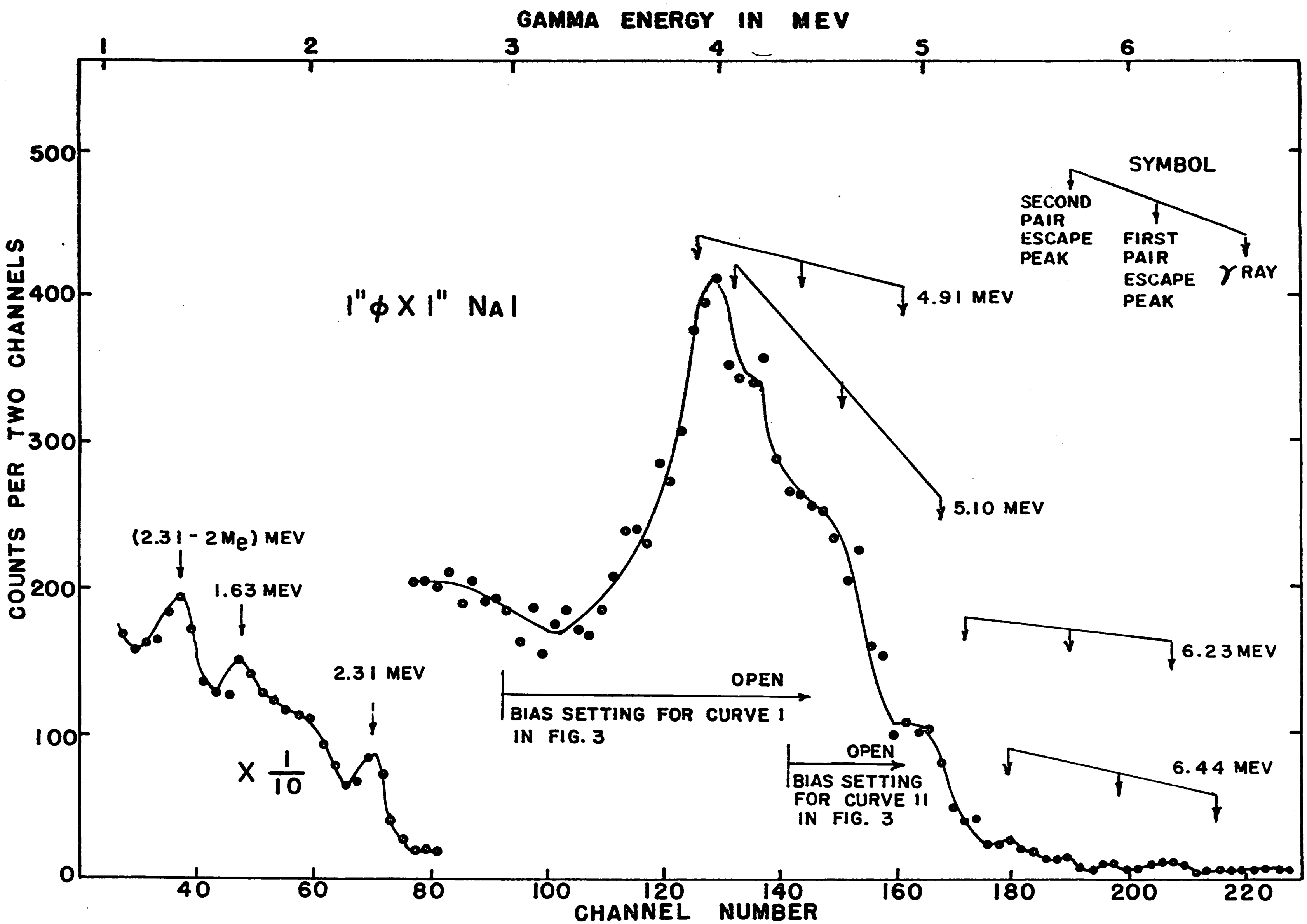


FIG. 4 $C^{12} + HE^3$ γ SPECTRUM, E_{HE^3} = 1.65 MEV

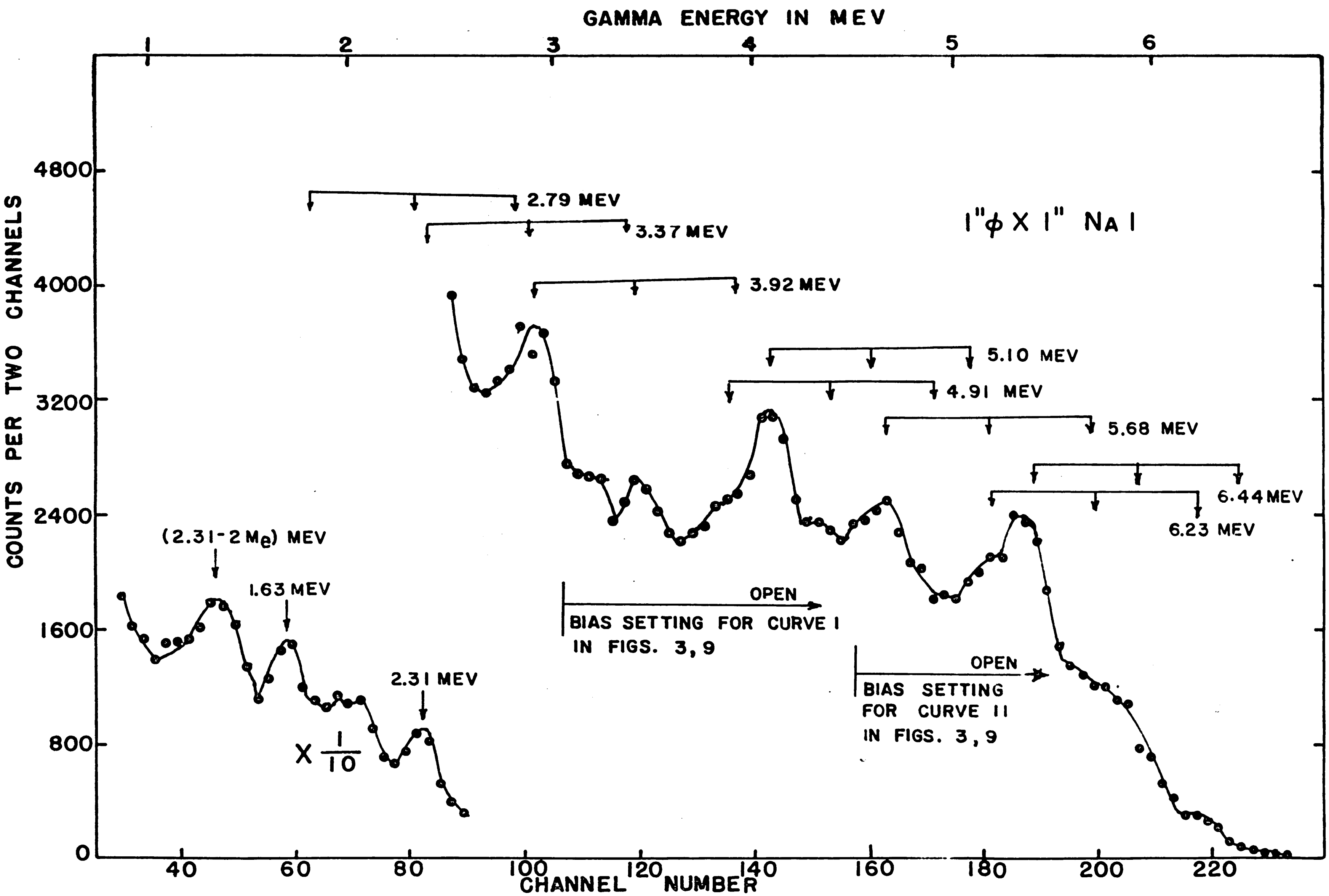


FIG. 5 $C^{12} + HE^3$ γ SPECTRUM, E_{HE^3} = 2.99 MEV (RESONANCE D)

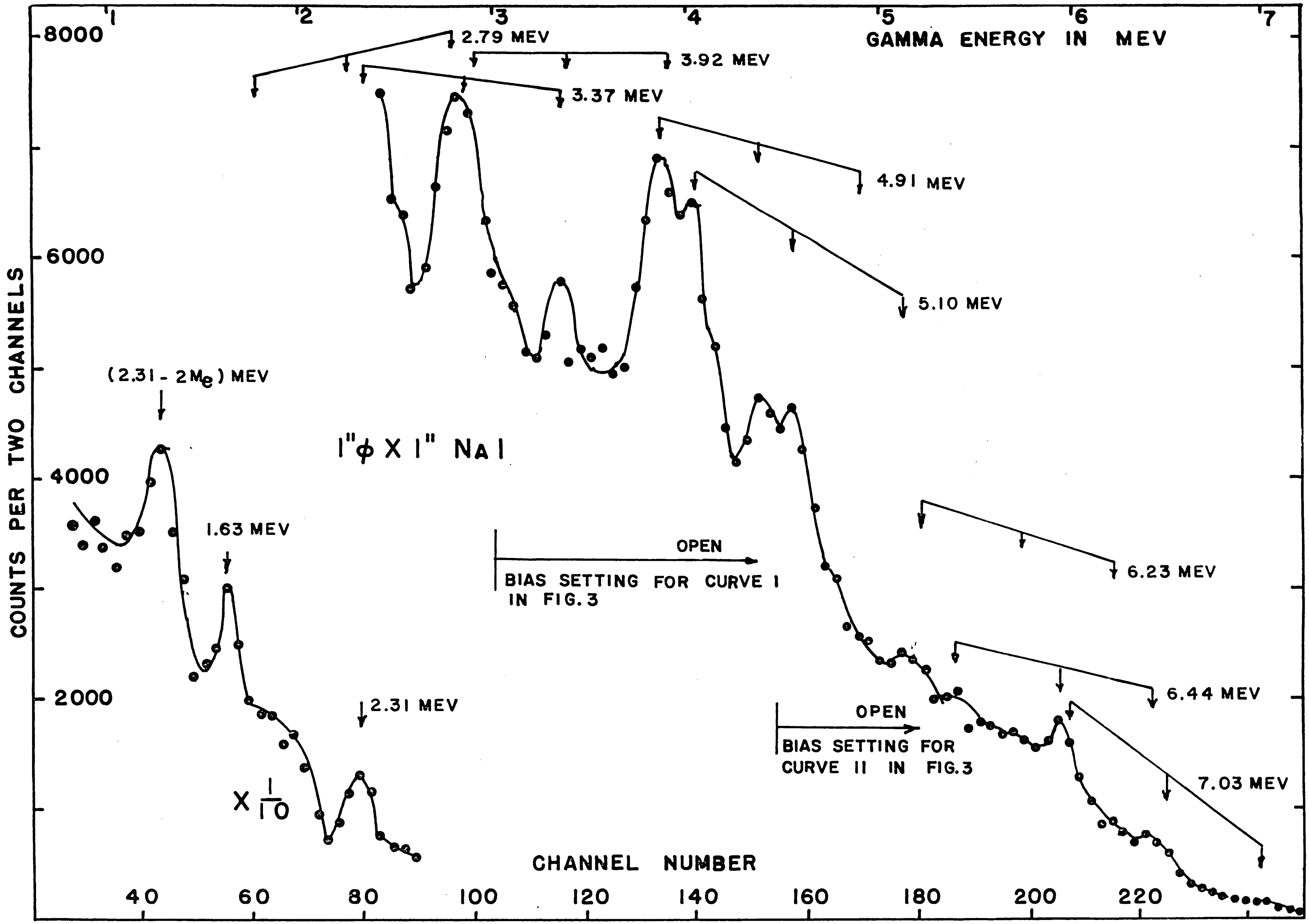


FIG. 6 $C^{12} + HE^3$ γ SPECTRUM, $E_{HE^3} = 4.23$ MEV

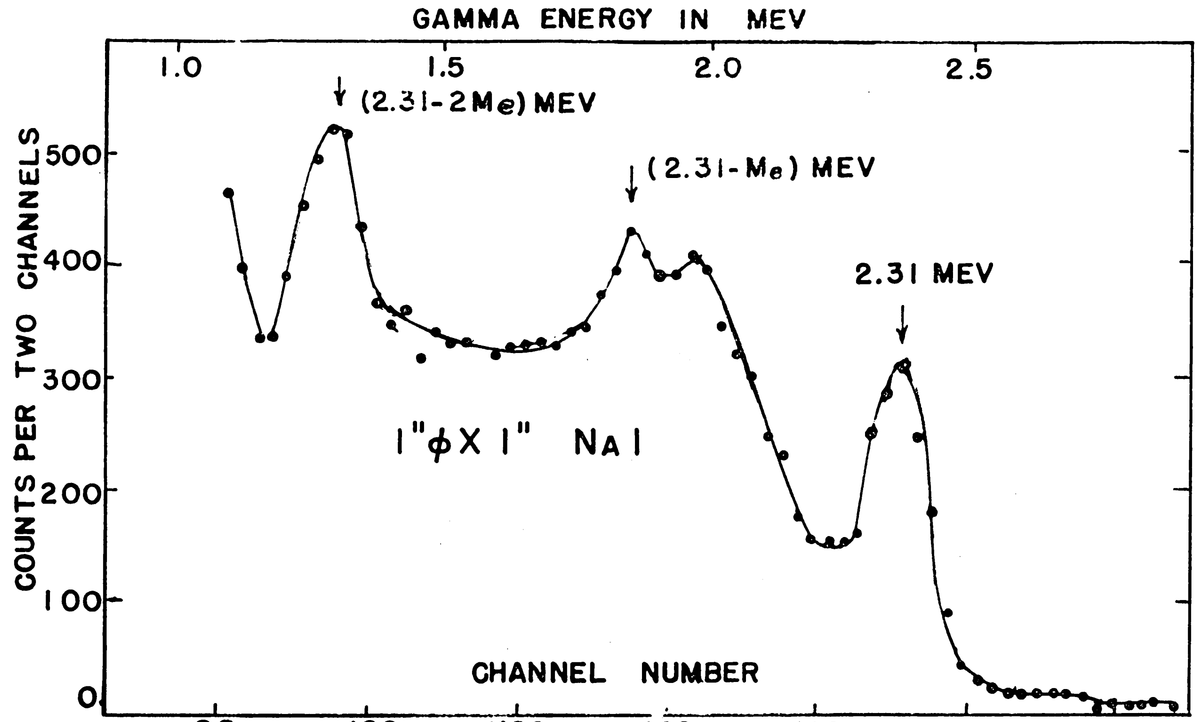


FIG. 7 $C^{12} + HE^{3}$ DECAY γ SPECTRUM

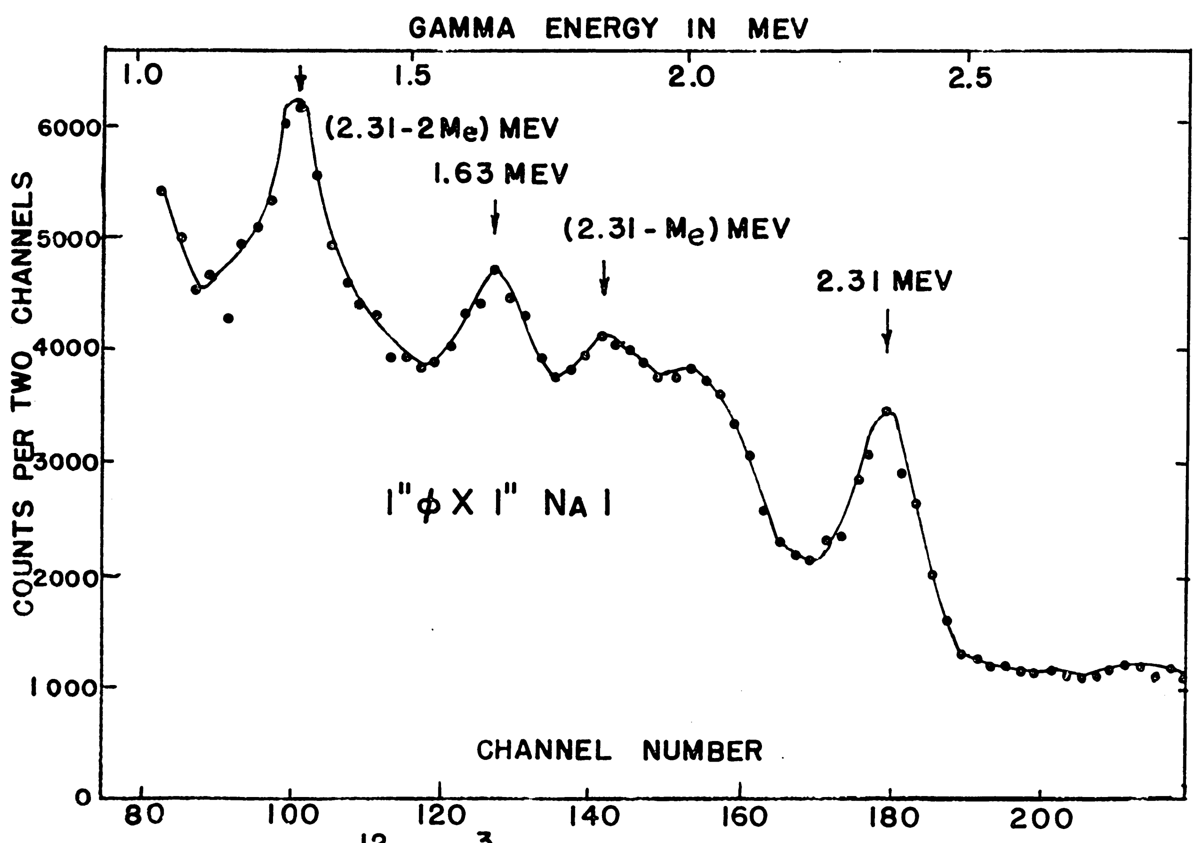


FIG. 8 $C^{12} + HE^{3}$ γ SPECTRUM, E_{HE^3} = 2.45 MEV not observable and there are very few pulses with energies higher than 5.5 Mev. The 2.8 Mev peak corresponds to the overlapping of (1) the 2.79 Mev gamma ray from the 5.10 to 2.31 transition in N^{14}, and (2) the first pair escape peak of the 3.37 Mev gamma ray from the 5.68 to 2.31 transition in N^{14}, and (3) the second pair escape peak of the 3.92 Mev gamma from the 6.23 to 2.31 transition in N^{14}. The 3.4 Mev peak corresponds to the overlapping of (1) the 3.37 Mev gamma ray and (2) the first pair escape peak of the 3.92 Mev gamma ray. The high energy pulses corresponds to the gamma rays with energies higher than 5.1 Mev. After resonance A the intensities of these two peaks and the high energy pulses increase gradually.

b) The spectra around resonance D show a resonant change for pulses corresponding to electron energies higher than 5 Mev. The spectrum taken on the resonance D, Fig. 5, shows a very large increase in intensity compared with those spectra taken below and above the resonance D. This indicates that the resonance D is mainly due to gamma rays with energies of 6.23- and 6.44- Mev.

c) The intensities of gamma radiation with energies above 6.44 Mev increase gradually after resonance D (see Fig. 6) and the other spectra taken show larger rate of increase at resonance F.

4) The decay gamma spectrum is shown in Fig. 7. A comparison with that when the beam is on (Fig. 8) clearly shows a gamma ray of 1.63 Mev from the reaction.

Angular Distributions

Fig. 9 shows two angular distribution curves at resonance D (E_{He^3} = 3 Mev) with the same biases as those for the excitation curves I and II in Fig. 3 (see Figs. 4,5,6 for bias setting). The distribution curve II is mainly due to gamma rays with energies of 6.23- and 6.44- Mev. The solid curves in Fig. 9 are the least-squares fit to the data of Legendre polynomial expansions including the fourth degree. The coefficients of the Legendre polynomials in these expansions are presented in Table I.

TABLE 1

Coefficients of the Legendre polynomials from the least-squares fit to the gamma-ray angular distribution data at resonance D (E_{He^3} = 3 Mev)

$$W(\theta) = W_0(1 + a_1P_1 + a_2P_2 + a_3P_3 + a_4P_4)$$

	Curve I	Curve II
a_1	0.010	- 0.001
a_2	0.223	0.261
a_3	- 0.049	- 0.042
a_4	- 0.125	- 0.137

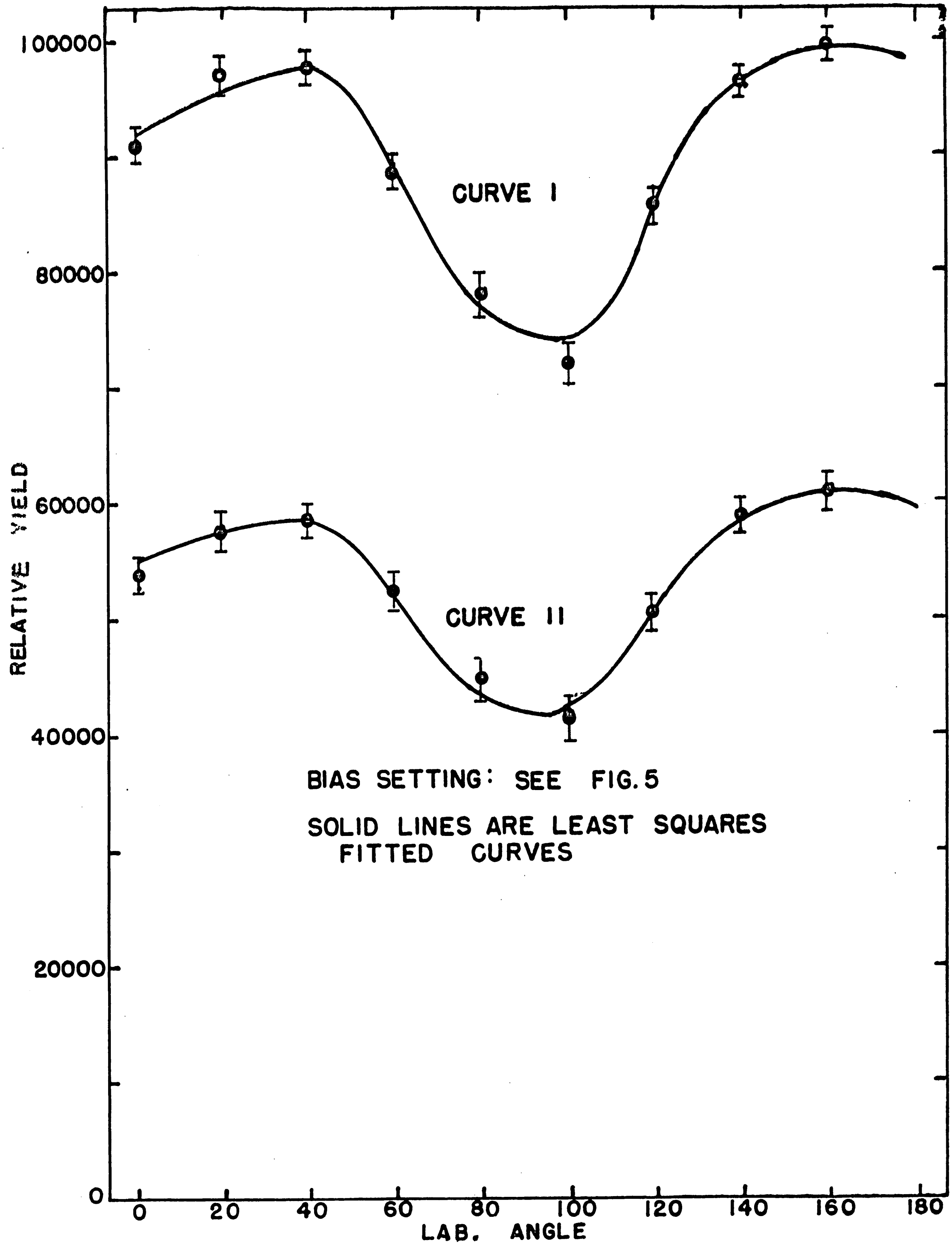


FIG. 9 $C^{12} + HE^{3}$ γ ANGULAR DISTRIBUTION
E_{HE^3} = 3.00 MEV (RESONANCE D)

B. DISCUSSION

Possible Reactions

The possible reactions which give the various gamma rays within the range of the present bombarding energies are shown in the energy level diagram (Fig. 10). These reactions are

$$C^{12} + He^{3} \longrightarrow O^{15} \longrightarrow N^{14} + p + 4.78 \text{ Mev}$$
$$\longrightarrow O^{14} + n \div 1.15 \text{ Mev}$$
$$\longrightarrow C^{11} + \alpha + 1.86 \text{ Mev}$$
$$\longrightarrow N^{13} + d - 3.55 \text{ Mev}$$

The reaction $C^{12}(He^{3},p)N^{14}$ contributes most of the observed gamma rays. In fact, the observed radiation of the spectra and the excitation curves are due to the decay of the excited compound nucleus through this channel.

The reaction $C^{12}(He^{3},\alpha)C^{11}$ is expected to give the 1.99 Mev gamma ray from the decay of the first excited state to the ground state and the 0.51 Mev annihilation radiation from the β^{+} decay of the ground state of the residual nucleus C^{11}. That the 1.99 Mev gamma ray is not observable may be due to its cross section's being relatively small compared with those of the gamma rays of nearly the same energy, e.g., 2.31 Mev gamma ray.

The reaction $C^{12}(He^{3},n)O^{14}$ gives a 2.31 Mev decay gamma ray from the residual nucleus through the following scheme

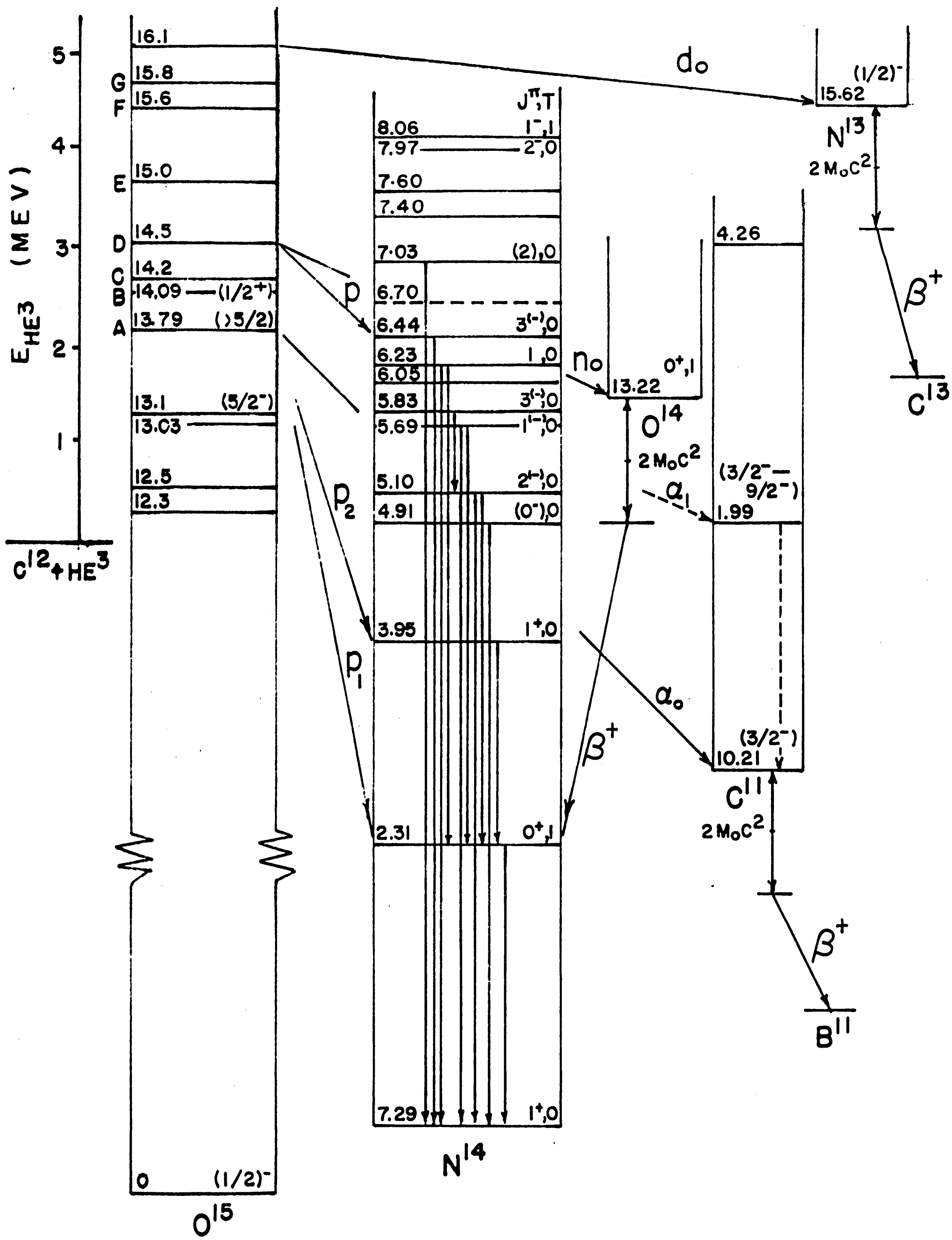


FIG. 10 ENERGY LEVEL DIAGRAM DESCRIBING THE HE^3 REACTIONS WITH C^{12}

$$O^{14}(\text{ground state}) \xrightarrow[99.4\%]{\beta^+} N^{14}(2.31 \text{ Mev state})$$

$$N^{14}(2{,}31 \text{ Mev state}) \longrightarrow N^{14}(\text{guound state}) + \gamma_{2.31 \text{ Mev}}$$

The measuring of this decay gamma ray provides a good method for comparing the relative amounts of carbon contamination in the nitrogen targets. In fact, it was observed[6] that the excitation curve of the 1.8 Mev β^+ decay and that of the 2.31 Mev gamma ray decay give a very good check to the total neutron yield of the reaction $C^{12}(He^3,n)O^{14}$. This 2.31 Mev decay gamma-ray spectrum is shown in Fig. 7. A comparison with the spectrum taken when the beam is on (Fig.8) clearly shows the 1.63 Mev gamma ray from the reaction $C^{12}(He^3,p\gamma)N^{14}$ (transition from the 3.945 Mev state to the 2.31 Mev state of the residual nucleus N^{14}).

The reaction $C^{12}(He^3,d)N^{13}$ with a negative Q value of - 3.55 Mev is expected to give only the 0.51 Mev annihilation radiation from the β^+ decay of the residual nucleus when the bombarding energy is higher than 4.5 Mev.

No gamma ray is expected from the reaction $C^{12}(He^3,He^{3\prime})C^{12}$ in the present range of bombarding energy.

Identification of Gamma Rays.

Peaks in the spectra are due to photoelectric, compton lines and pair escape peaks (lines 0.51- and 1.02- Mev lower in energy than the photo peak). The overlapping of many peaks from various gamma rays makes it difficult to identify some gamma rays. Limitation of resolution and fluctuation of gain make it difficult to distinguish closely situated gamma rays, e.g., 6.44- from 6.23- Mev and 5.10- from 4.92- Mev gamma rays.

The proper positions of all possible gamma rays are marked on each spectrum with an error of about 4%.

Excitation Curves

The positions of the expected resonances corresponding to the excited states of the compound nucleus O^{15} are labelled by A, B, ..., G in Fig. 3. The correspondence are listed in Table II (cf. page 196 of Ref. (4)).

TABLES II

Resonances in C^{12} + He^3

Position labelled in Fig. 3	E_{He^3}, lab. (Mev)	Reported data on resonance for	Excitation of O^{15} in Mev
A	2.15	p_o, n	13.79
B	2.52	p_o, p_1, p_2, p_3, n	14.09
C	2.7	p_1, p_2, n	14.2
D	3.0	p_o, p_1, p_2	14.5
E	3.6	"	15.0
F	4.4	"	15.6
G	4.8	"	15.9

The present results only show pronounced resonance at D and some indication of resonances at A, B, and F.

The general trend of the present excitation curves is different from those of proton yield of p_0, p_1, p_2 groups (cf. Ref. (5)).

A comparison of excitation curves II and I in Fig. 3 shows that the resonance peak D is mainly due to pulses with electron energies higher than 4.5 Mev. From bias setting shown in Fig. 5 we can see that these pulses are mainly from 6.23- or 6.44- Mev gamma ray or from both (because of experimental limitation these two gamma rays can not be distinguished definitely). Thus we see that the 14.5 Mev state of O^{15} has a relatively larger transition probabilities to 6.44 Mev state or 6.23 Mev state of N^{14} or to both compared with those to the nearby states of N^{14}. No report has been found about the excitation curves of proton groups to these states, otherwise it would be interesting to compare them with the present results.

The width of the resonance D is about 140 ± 25 Kev using 60 Kev at $E_{He^3} = 3$ Mev as the target thickness.

Angular Distribution

The angular distribution curve II (see Fig. 9) is mainly due to gamma rays with energies of 6.23- and 6.44- Mev. That of curve I is due to these two hamma rays as well as the lower energy gamma rays with energies above 3 Mev (mainly 4,92- and 5.10- Mev gamma rays). The

The similarity in shape of curves I and II is from the fact that the 6.23- and 6.44- Mev gamma rays have a relatively higher intensity at resonance D as can be seen from the spectrum taken at resonance D (Fig. 5).

Further analysis of the distributions consists of comparing the experimental results with that of the theoretical calculation. The expression for the angular distribution of a two stage particle reaction followed by gamma emission, (a,bγ), has been given by Kraus et al[8]. L. C. Biedenharn[9] and K. Siegbahn[10] also gave detail theoretical analysis on angular correlations.

IV. GAMMA-RAY SPECTRA FROM N^{14} + He^3

A. RESULTS

Excitation Curves

The excitation curve of gamma rays with energies greater than 3 Mev, mainly 4.43 Mev gamma ray, is shown in Fig. 11. The bias setting is shown on the spectrum in Fig. 12. This excitation curve shows a smooth rise with no indication of any resonance for the range 1.8- to 4.7- Mev of bombarding energies.

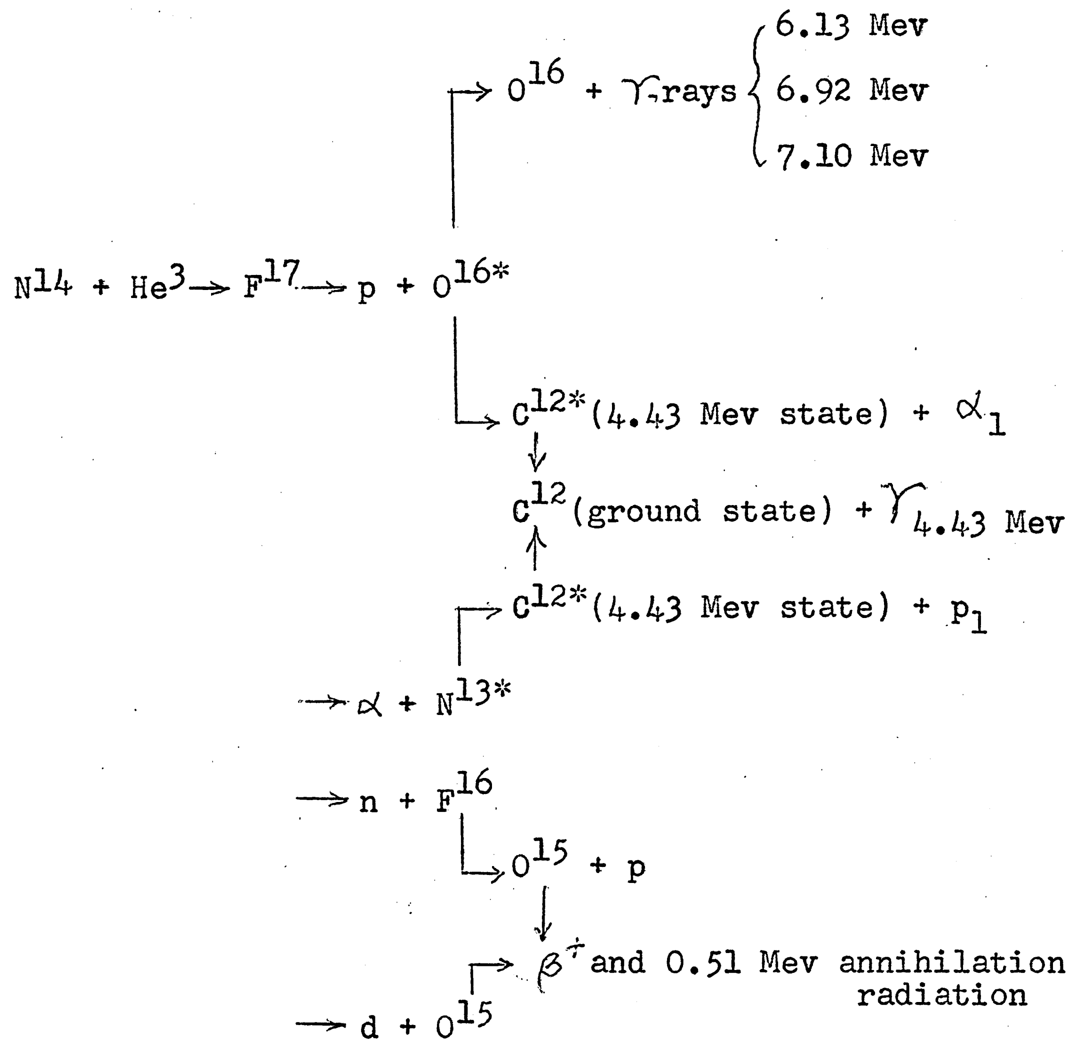
Spectra

The gamma-ray spectra taken at various bombarding energies all show the same general pattern as the one given in Fig. 12: a strong 4.43 Mev gamma ray and some weak radiations around 6 to 7 Mev.

B. DISCUSSION

Possible Reactions and Gamma Rays

The possible reaction channels and gamma rays of N^{14} + He^3 in the present range of bombarding energies are described in the energy level diagram shown in Fig. 13. They are as follows:



The identification of various gamma rays are marked on the spectrum (Fig. 12).

The observed high intensity of the 4.43 Mev gamma ray compared to those of the high energy gamma rays (6.13-, 6.92- and 7.10- Mev gamma rays) can be understood by noting the fact that there are many levels in O^{16} with excitations above 12.44 Mev and in states in N^{13} with excitations over 6.91 Mev which can decay to the 4.43 Mev state in C^{12} by

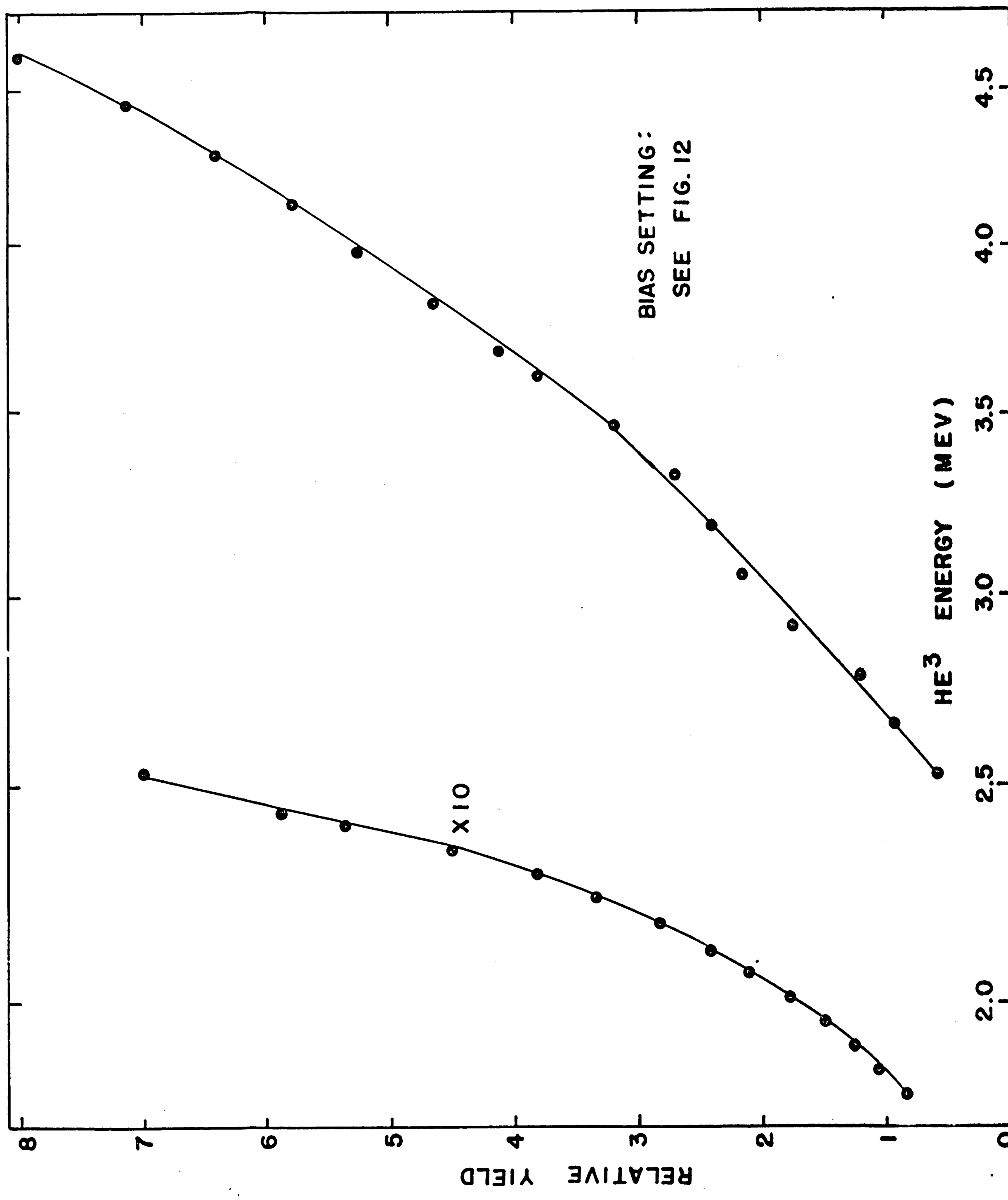


FIG.11 γ-RAY EXCITATION CURVE FROM HE^3 BOMBARDMENT OF N^{14} TARGET

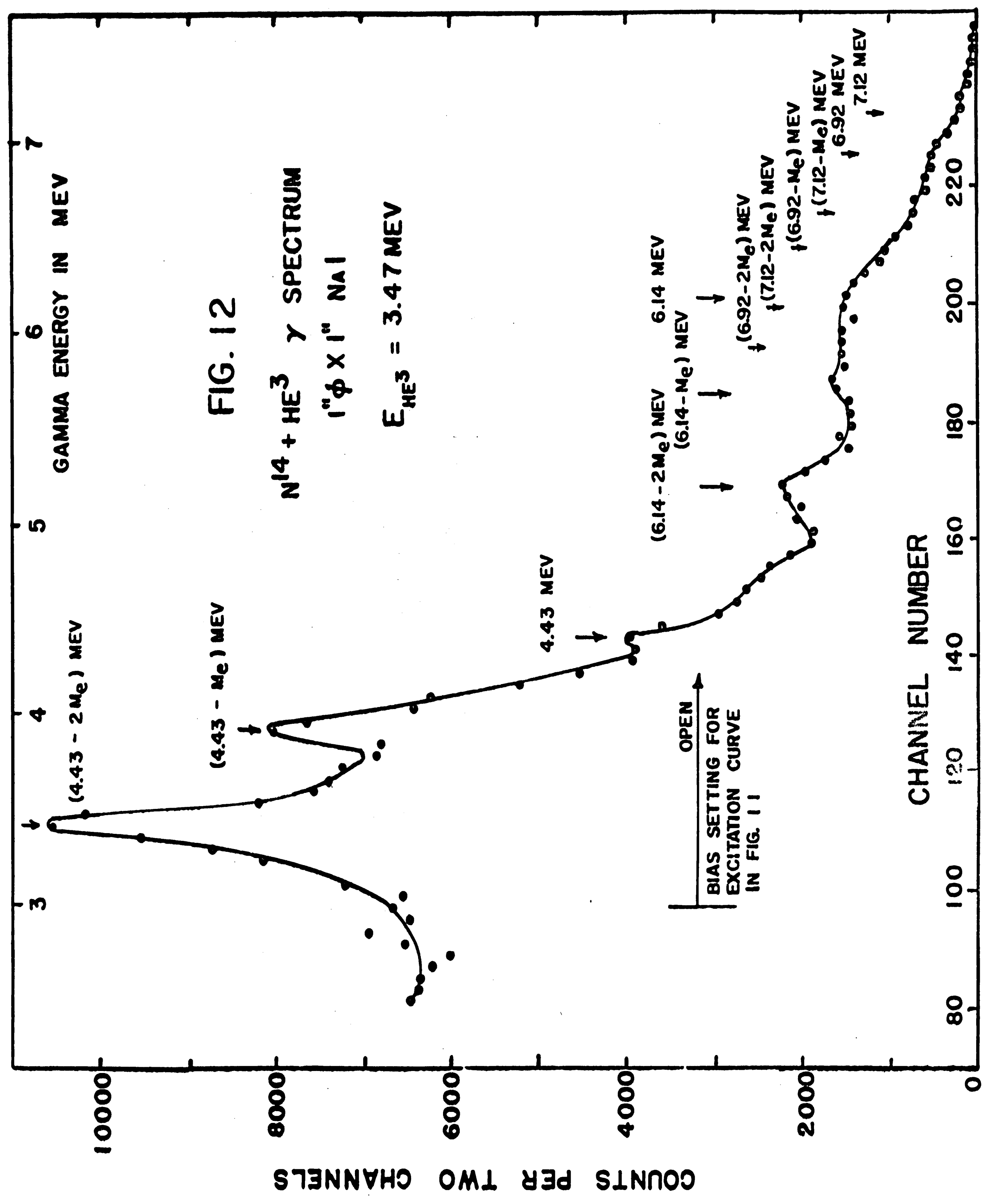


FIG. 12
$N^{14} + HE^3$ γ SPECTRUM
1"φ X 1" NaI
E_{HE^3} = 3.47 MEV
GAMMA ENERGY IN MEV
3
4
5
6
7
(4.43 - 2Me) MEV
(4.43 - Me) MEV
4.43 MEV
(6.14 - 2Me) MEV
(6.14 - Me) MEV
6.14 MEV
(6.92 - 2Me) MEV
(7.12 - 2Me) MEV
(6.92 - Me) MEV
(7.12 - Me) MEV
6.92 MEV
7.12 MEV
OPEN
BIAS SETTING FOR
EXCITATION CURVE
IN FIG. 11
CHANNEL NUMBER
80
100
120
140
160
180
200
220
0
2000
4000
6000
8000
10000
COUNTS PER TWO CHANNELS

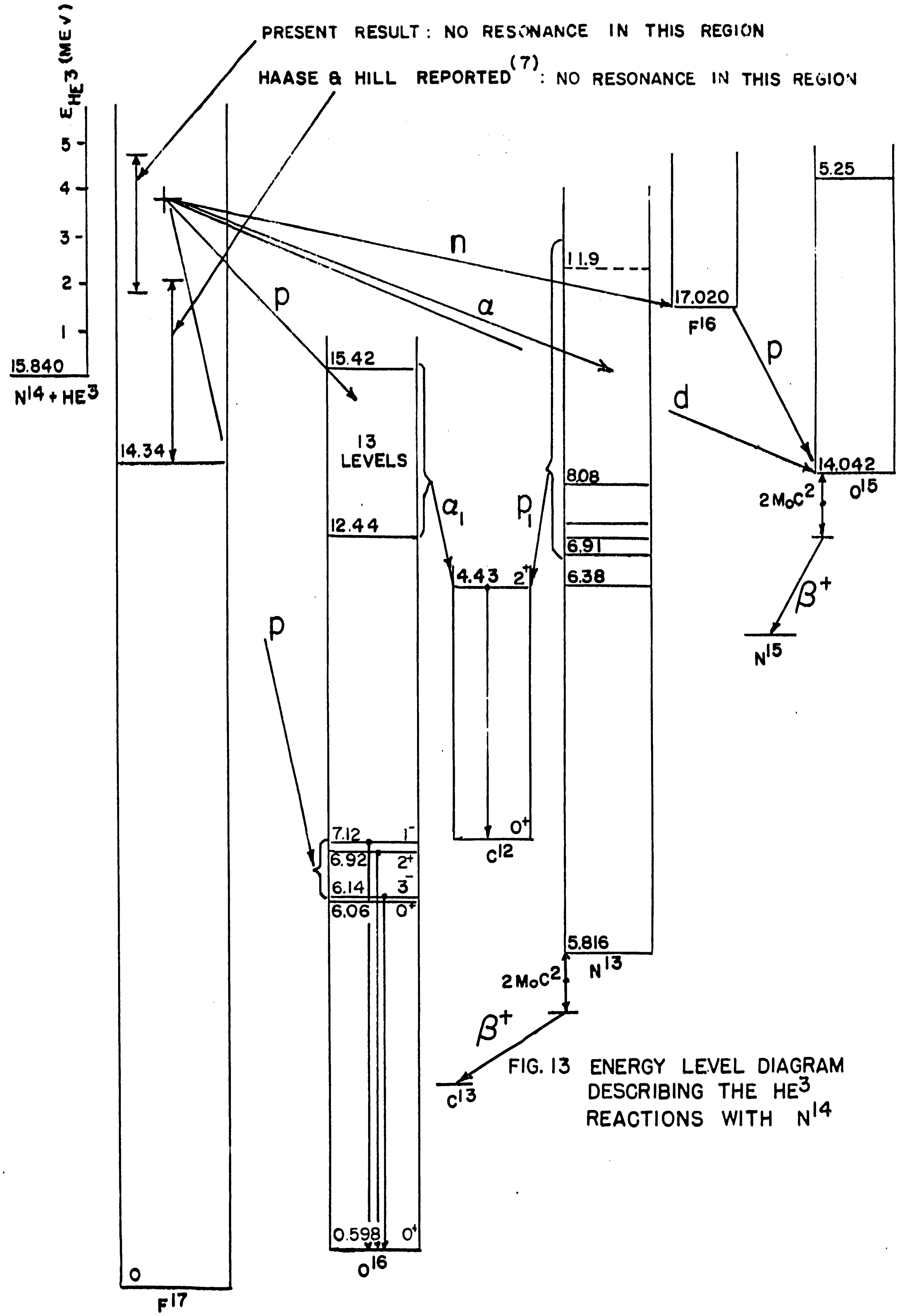


FIG. 13 ENERGY LEVEL DIAGRAM DESCRIBING THE HE^3 REACTIONS WITH N^{14}

α particle or proton emission.

Excitation Curve

The smooth rise in excitation curve indicates that there are no distinguishable resonances in the compound nucleus F^{17} for the present range of 1.8- to 4.7- Mev of bombarding energy, corresponding to 17,3- to 19.7- Mev of excitation in F^{17}. Haase and Hill reported(7) that in the reaction $O^{16}(p,\alpha)N^{13}$ there are no resonances besides that corresponding to the 14.6 Mev state of F^{17} for the bombarding energy range which correspond to excitations from 11.9- to 17.5- Mev.

V. REFERENCES

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