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Neutron experiments with a tandem accelerator

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Abstract

The Wisconsin tandem accelerator is used part of the time for experiments in neutron physics. In these experiments the properties of neutrons from charged-particle reactions as well as the interaction of neutrons with nuclei are studied. Some of the techniques used and some of the results obtained are described.

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1. Introduction

In 1960 the second tandem accelerator designed and constructed by the High Voltage Engineering Corporation went into operation at the University of Wisconsin. This accelerator has been used about a third of the time for experiments in neutron physics. These experiments involved both studies of the properties of neutrons from charged-particle induced reactions and studies of the interaction of neutrons with nuclei. These two problems are closely related, since one has to use charged-particle reactions to produce monoenergetic neutrons.

Special equipment had to be constructed for measurements of the spectra and of the polarization of neutrons from charged-particle reactions.

2. Neutron Spectrometer

For the measurement of neutron spectra a time-of-flight spectrometer was constructed by Lefevre and Borchers¹⁾. The tandem accelerator offers the advantage that the ion source is readily accessible, but the negative ion source has the disadvantage of producing a small current compared to conventional accelerators.

Figure 1 shows the layout of the spectrometer schematically. It was originally hoped that it would be feasible to pulse the beam

before injection into the accelerator, but the negative ions have such a large spread in velocity that the beam pulse spread out between the chopping at the low energy end and arrival at the target. Sharp beam pulses could be obtained only by chopping the beam after acceleration.

In order to increase the beam intensity a klystron-type beam buncher was installed near the ion source. This buncher is shown in fig. 2. It consists of cylindrical sections between which rf is applied. It is constructed so that it can be used with either protons or deuterons.

The whole system produces bursts with peak currents of the order of $20 \mu\text{A}$ and duration of less than 2 nsec.

In fig. 3 the performance of the system is illustrated by results obtained by Borchers²⁾ on the neutrons from proton bombardment of Li^7 . Two groups of neutrons are produced which differ in energy by about 0.4 MeV and have an energy about 2 MeV lower than the proton bombarding energy.

The time-of-flight system has been used not only as a spectrometer but also as a monochromator. Since at the higher bombarding energies it is impossible to obtain strictly monoenergetic

neutrons from the source, the time-of-flight system is used to select one group of neutrons in the presence of other groups in a manner shown schematically in fig. 4. Only pulses caused by neutrons arriving at the detector at the desired time are passed by a gate into the counting device.

The effect of the monochromator is shown in fig. 5. Here the pulse height distribution of α -particle recoils produced by neutrons from the bombardment of deuterium by 11-MeV deuterons is shown. In addition to the 14-MeV monoenergetic neutrons, the source produces break-up neutrons of lower energy. The gating system eliminates the effect of such neutrons of lower energy.

3. Polarimeter

The second device which was built for neutron experiments with the tandem accelerator is a neutron polarization analyzer.

This instrument was designed and constructed by Dubbeldam and Walter³⁾, and is shown schematically in fig. 6. The neutrons the polarization of which is to be measured are scattered by helium in a gas cell, and the asymmetry in the scattering is measured. In order to reduce background, coincidences between the recoiling α -particles and the scattered neutrons are observed, as first suggested by Pasma⁴⁾.

A solenoid⁵⁾ placed between the target and the helium cell serves to rotate the spin of the neutrons and, at the same time, acts as a collimator. By measuring the ratio of the counting rates of the two scintillators for rotation of the neutron spin, once through 90° in one direction, then through 90° in the other direction, instrumental asymmetries caused, for example, by different responses of the two scintillators, may be eliminated.

The points in fig. 7 show the measured asymmetries as a function of solenoid current for 2-MeV partially polarized neutrons⁶⁾; the solid curve gives the expected variation of the asymmetry with current.

4. Neutron-Producing Reactions

The reactions used most frequently to produce monoenergetic neutrons are listed in table 1 together with the reaction energies. As the bombarding energy is increased other neutron-producing reactions become energetically possible. In the fourth column the thresholds for the competing reactions listed in the third column are given. The last column of table 1 shows the range of energies within which each reaction produces strictly monoenergetic neutrons in the forward direction.

One of the first experiments with the tandem accelerator was

to study how important the admixture of other neutrons to the monoenergetic group is for each of the reactions. Some of the results for the $\text{Li}(p, n)$ reaction obtained by Borchers²⁾ with the time-of-flight spectrometer are shown in fig. 8. While at low proton energies only about 10% of the neutrons belong to the group which leaves Be^7 in an excited state, this fraction becomes much larger at higher energies. At the highest energies the second excited state of Be^7 at 4.53 MeV is also frequently formed.

In the case of the $\text{T}(p, n)$ reaction the threshold for a tertiary reaction is 8.4 MeV. Up to the highest bombarding energy at which measurements were performed the tertiary reaction has a rather small cross section. At 13 MeV this cross section was found⁷⁾ to be 5 mb/sr versus about 30 mb/sr for the monoenergetic neutrons⁸⁾.

At one time it was hoped that a tandem accelerator could be used to produce monoenergetic neutrons around 12 MeV using the $\text{D} + \text{D}$ reaction. Unfortunately it has turned out that for this energy the break-up reaction has a neutron yield⁹⁾ about equal to that of the monoenergetic neutrons¹⁰⁾ as shown in fig. 9.

For the $\text{D} + \text{T}$ reaction there is also a large contribution from the break-up process. There is, however, a larger energy

difference between the maximum energy of the continuum and the monoenergetic group. Figure 10 shows a time spectrum for neutrons from the $D + T$ reaction for a bombarding energy of 8.2 MeV ⁸⁾. The peak at the high-energy end of the continuum was found to occur at all bombarding energies and observation angles and may be interpreted¹¹⁾ in terms of an excited state of He^4 at about 20 MeV .

Even if the reactions produced strictly monoenergetic neutrons, at high enough bombarding energy the charged particles striking materials other than the intended target will produce other neutrons. Figure 11 shows the results of some studies¹²⁾ of the neutron and γ -ray yields from the proton bombardment of various materials which might serve as target backings. Although it is possible to use neutron detectors which discriminate against γ -rays, high γ -ray yields are undesirable because the discrimination circuit takes time to reject pulses caused by γ -rays. It appears that ordinary ice produces relatively few neutrons and γ -rays, and for this reason it has been used frequently at our laboratory as a backstop.

5. Sources of Polarized Neutrons

The suitability of all the source reactions listed in table 1 as sources of polarized monoenergetic neutrons was studied for the

bombarding energies available with the tandem accelerator. It was found that all four reactions produce neutrons with appreciable polarization at some angles for all bombarding energies. The results^{13, 14)} obtained for the T(p, n) reaction for c. m. angles near 50° are shown in fig. 12. Over most of the energy range the polarization of the neutrons is high enough to be useful. Near 5 MeV bombarding energy where the polarization changes sign at this angle, the neutrons emitted at larger angles show a substantial polarization.

The first reaction which was observed to produce polarized neutrons was the D + D reaction. The polarization of these neutrons has been measured at many laboratories at many energies and angles. Figure 13 shows the result of some of these measurements.¹⁵⁾ As may be seen, the results obtained at most laboratories lie on a smooth curve (lower dashed line). These experiments were performed at Columbia University¹⁶⁾, at Orsay¹⁷⁾, at Washington University¹⁸⁾ and at the Institute for Theoretical and Experimental Physics in Moscow¹⁹⁾. Measurements made at our laboratory^{3, 20)} (upper dashed curve) are in complete disagreement with the results obtained at the four other laboratories. Recent measurements at Cracow²¹⁾ are, however, in agreement with the Wisconsin results. Likewise recent

measurements at the Atomic Energy Institution in Moscow²²⁾ at somewhat higher energies lie on an extrapolation of the curve through the Wisconsin data and are not consistent with the lower curve. The cause of the discrepancy between the two dashed curves is not understood.

6. Examples of Results Obtained

A few examples of measurements in neutron physics performed with the Wisconsin tandem accelerator are shown in the following figures.

The first neutron experiments which were done with this machine were measurements of the total cross sections of some light nuclei as a function of neutron energy. Since earlier measurements had shown sharp resonances in the total cross section of carbon up to about 8 MeV, it was expected that the tandem accelerator would enable one to observe similar structure at higher neutron energies. Figure 14 shows the results obtained²³⁾. Up to 3.4 MeV the curve is based on earlier Wisconsin data. Above 8 MeV no sharp structure was observed for carbon although the energy resolution used in the experiments was good enough so that such structure should have been observable if it were present. For none of the other light nuclei which were studied were any sharp resonances found above 10 MeV.

Another example of neutron experiments is a study of the polarization of neutrons in $n-\alpha$ scattering as a function of energy and angle²⁰⁾. In fig. 15 results obtained at six neutron energies are compared with calculations based on various proposed phase shifts²⁴⁻²⁷⁾. The agreement between experiments and calculations is good except at the highest energy of 23.7 MeV.

The final example is chosen from the investigations of neutron spectra from charged-particle reactions. With the time-of-flight system neutron spectra from the proton bombardment of Rh were studied. Some of the results²⁸⁾ are shown in fig. 16. It is customary to present such data by plotting $\log [N(E_n)/E_n]$ versus E_n . According to Weisskopf's statistical theory²⁹⁾ such a plot should produce a straight line. The slope of the line determines a quantity T , called the nuclear temperature, and should be independent of bombarding energy. At the higher bombarding energies the lines in fig. 16 show a break. This is attributed to neutrons from the $(p, 2n)$ reaction. The quantity T appears to increase with bombarding energy, contrary to expectation, a behavior already previously observed³⁰⁾ for (α, n) reactions.

References

- 1) H. W. Lefevre, R. R. Borchers and C. H. Poppe,
Rev. Sci. Inst. 33 (1962) 1231
- 2) R. R. Borchers and C. H. Poppe,
Phys. Rev. 129 (1963) 2679
- 3) P. S. Dubbeldam and R. L. Walter, Nuclear Physics 28 (1961) 414
- 4) P. J. Pasma, Nuclear Phys. 6 (1958) 141
- 5) P. Hillman, G. H. Stafford and C. Whitehead,
Nuovo Cim. 4 (1956) 67
- 6) W. Benenson, Ph.D. Thesis, University of Wisconsin (1962)
- 7) C. H. Holbrow, R. R. Borchers and C. H. Poppe,
Bull. Am. Phys. Soc. 6 (1961) 429
- 8) W. E. Wilson, R. L. Walter and D. B. Fossan,
Nuclear Phys. 27 (1961) 421
- 9) H. W. Lefevre, R. R. Borchers and C. H. Poppe,
Phys. Rev. 128 (1962) 1328
- 10) J. E. Brolley and J. L. Fowler, Fast Neutron Physics,
(Interscience Publishers, New York, 1960), p. 80
- 11) C. H. Poppe, C. H. Holbrow and R. R. Borchers,
Phys. Rev. 129 (1963) 733
- 12) R. R. Borchers, J. C. Overley and R. M. Wood, Nucl. Inst.
and Methods, to be published

References

(continued)

- 13) R. L. Walter, W. Benenson, P. S. Dubbeldam and T. H. May,
Nuclear Phys. 30 (1962) 292
- 14) C. A. Kelsey, B. Hoop and P. Vander Maat,
Nuclear Phys., to be published
- 15) W. Haerberli, Progress in Fast Neutron Physics, (University
of Chicago Press, Chicago, 1963), p. 309
- 16) J. A. Baicker and K. W. Jones, Nuclear Phys. 17 (1960) 424
- 17) P. Avignon, Y. Deschamps and L. Rosier, Journ. Phys. Rad.
22 (1961) 563
- 18) W. W. Daehnick, Phys. Rev. 115 (1959) 1008
- 19) I. S. Trostin and V. A. Smotryaev, J.E.T.P. 44 (1963) 1160
- 20) T. H. May, R. L. Walter and H. H. Barschall,
Nuclear Phys. 45 (1963) 17
- 21) H. Niewodniczanski, J. Szmider and J. Szymankowski,
Journ. Phys. Rad., to be published
- 22) N. V. Alexeev, U.R. Arifchanov, N. A. Vlasov, V. V. Davidov
and L. N. Samoilov, J.E.T.P., to be published
- 23) D. B. Fossan, R. L. Walter, W. E. Wilson and H. H. Barschall,
Phys. Rev. 123 (1961) 209

References

(continued)

- 24) D. C. Dodder and J. L. Gammel, Phys. Rev. 88 (1952) 520
- 25) J. D. Seagrave, Phys. Rev. 92 (1953) 1222
- 26) J. L. Gammel and R. M. Thaler, Phys. Rev. 109 (1958) 2041
- 27) K. W. Brockman, Jr., Phys. Rev. 110 (1958) 163
- 28) C. H. Holbrow and H. H. Barschall, Nuclear Phys.
42 (1963) 264
- 29) J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics,
(John Wiley and Sons, New York, 1952)
- 30) V. A. Sidorov, Nuclear Phys. 35 (1962) 253

Table 1

Neutron producing reactions

| Reaction | Q (MeV) | Competing reaction | Threshold (MeV) | Range of monoenergetic neutrons at 0° (MeV) |
|--|------------|---|--------------------|--|
| $\text{Li}^7(\text{p}, \text{n})\text{Be}^7$ | -1.6 | $\text{Li}^7(\text{p}, \text{n})\text{Be}^{7*}$ | 2.4 | 0.12 to 0.65 |
| $\text{T}(\text{p}, \text{n})\text{He}^3$ | -0.76 | $\text{T}(\text{p}, \text{np})\text{D}$ | 8.4 | 0.29 to 7.58 |
| $\text{D}(\text{d}, \text{n})\text{He}^3$ | +3.3 | $\text{D}(\text{d}, \text{np})\text{D}$ | 4.5 | 2.45 to 7.70 |
| $\text{T}(\text{d}, \text{n})\text{He}^4$ | +17.6 | $\text{T}(\text{d}, \text{np})\text{T}$ | 3.7 | 14.0 to 20.7 |

Figure Captions

- Fig. 1 Layout of tandem accelerator showing the neutron time-of-flight system (ref. ¹).
- Fig. 2 Three-gap beam buncher. λ is the distance that ions will travel in one rf period. In order to bunch H^- ions electrodes P_1 and D_1 and electrodes P_2 and D_2 are connected. To bunch D^- ions electrodes P_1 and P_2 are grounded (ref. ¹).
- Fig. 3 Time spectra of neutrons emitted at 0° from the bombardment of Li by protons of energies at 4, 7, and 9.75 MeV. The two peaks are due to neutrons leaving the residual nucleus in the ground state and in the first excited state at 0.43 MeV (ref. ²).
- Fig. 4 Gating arrangement to select a particular neutron group.
- Fig. 5 Pulse height distribution of He-recoils from neutrons produced by 11-MeV deuterons incident on deuterium. Squares show the distribution caused by all neutrons. Circles show the effect of gating by the arrangement of fig. 4, i. e., the recoil distribution caused by the monoenergetic neutron group of energy 14 MeV.

Figure Captions
(continued)

- Fig. 6 Neutron polarization analyzer. The polarization vector P_1 can be turned through 90° in either direction by the magnetic field H . Recoiling α -particles are detected in the gas scintillator A. Neutrons scattered through θ_2 are observed in the scintillation detectors B and C. The ratio of the coincidences between A and B to that between A and C is used to obtain the asymmetry and hence P_1 (ref. 3).
- Fig. 7 Asymmetry as a function of solenoid current. 2-MeV neutrons from the reaction $T(p, n)He^3$ are scattered by α -particles. The solid curve is calculated (ref. 6).
- Fig. 8 Zero-degree differential cross section for neutrons from $Li^7 + p$. The upper points refer to neutrons leaving Be^7 in the ground state, the lower points to leaving Be^7 in the first excited state at 0.43 MeV (ref. 2).

Figure Captions
(continued)

- Fig. 9 Zero-degree differential cross section for the production of neutrons from deuterons incident on deuterium. The dashed curve shows the cross section for the production of monoenergetic neutrons and is taken from ref. ¹⁰⁾, the solid curve gives the cross section for the break-up process and is based primarily on data reported in ref. ⁹⁾.
- Fig. 10 Time spectrum for neutrons from 8.23-MeV deuterons incident on tritium, taken from ref. ⁸⁾.
- Fig. 11 Neutron and γ -rays yields from thick targets of various materials bombarded by protons (ref. ¹²⁾).
- Fig. 12 Polarization of neutrons from the T(p, n) reaction as a function of proton energy (ref. ¹³⁾ and ¹⁴⁾).
- Fig. 13 Polarization of neutrons from the D(d, n)He³ reaction. The figure is taken from ref. ¹⁵⁾. The upper dashed curve connects Wisconsin measurements (ref. ³⁾ and ²⁰⁾). The lower dashed curve connects measurements at other laboratories, open triangles ref. ¹⁶⁾, open-square ref. ¹⁷⁾, open diamond ref. ¹⁸⁾, half-open square ref. ¹⁹⁾.

Figure Captions
(continued)

- Fig. 14 Total neutron cross section of carbon (ref. ²³).
- Fig. 15 Asymmetry in the scattering of polarized neutrons by α -particles. The data are taken from ref. ²⁰. Curves are fits to the data based on various sets of phase shifts (refs. ²⁴⁻²⁷) as explained in ref. ²⁰.
- Fig. 16 Spectra of neutrons from the Rh(p, n) reaction at a neutron emission angle of 80° and proton bombarding energies E_p . Nuclear temperatures T of Pd¹⁰³ are given for each plot. The three triangles in the lower left-hand plot indicate the energy resolution of the spectrometer. The arrows indicate the maximum energy of neutrons from the (p, 2n) reaction (ref. ²⁸).

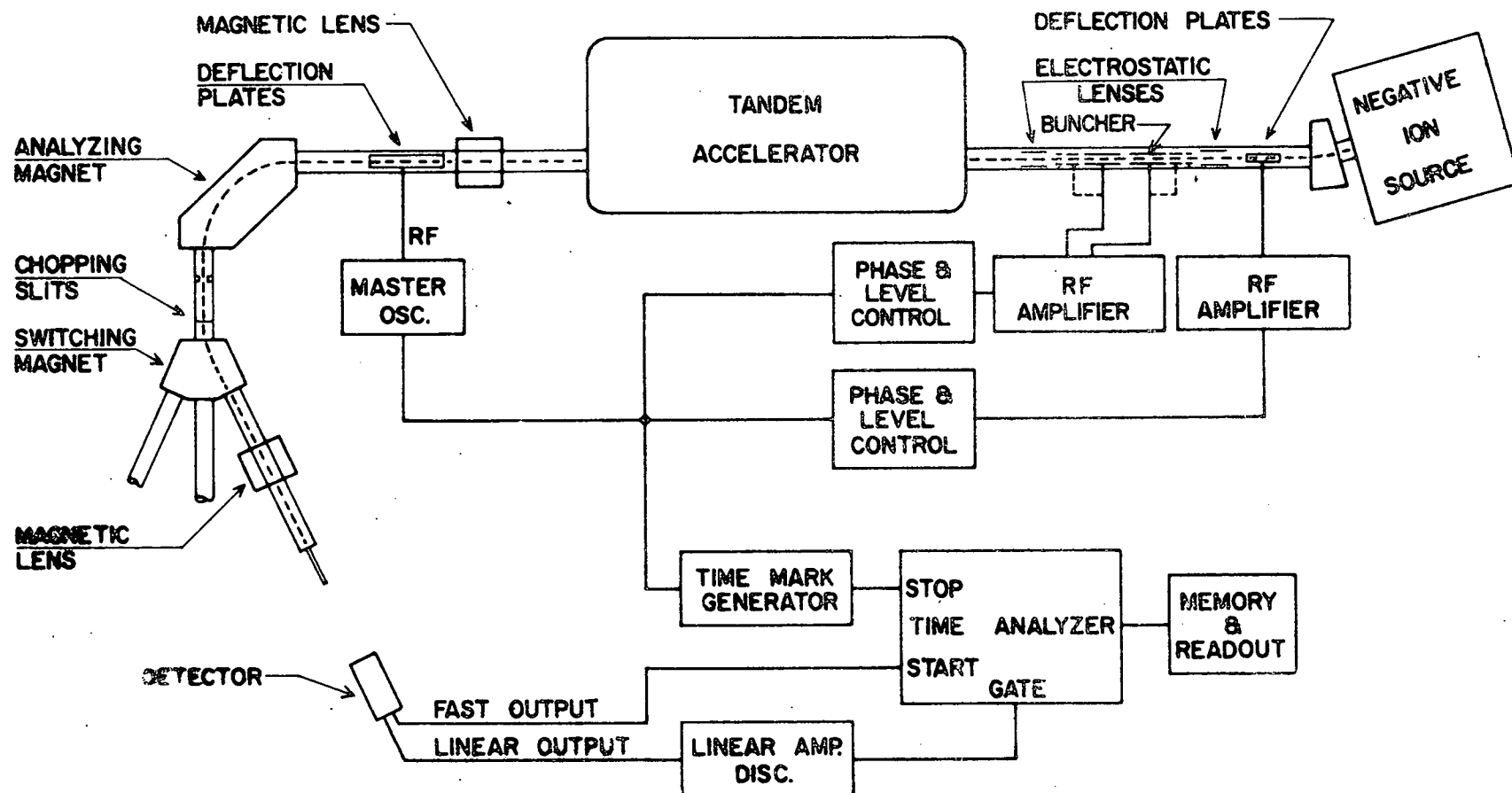


Fig. 1

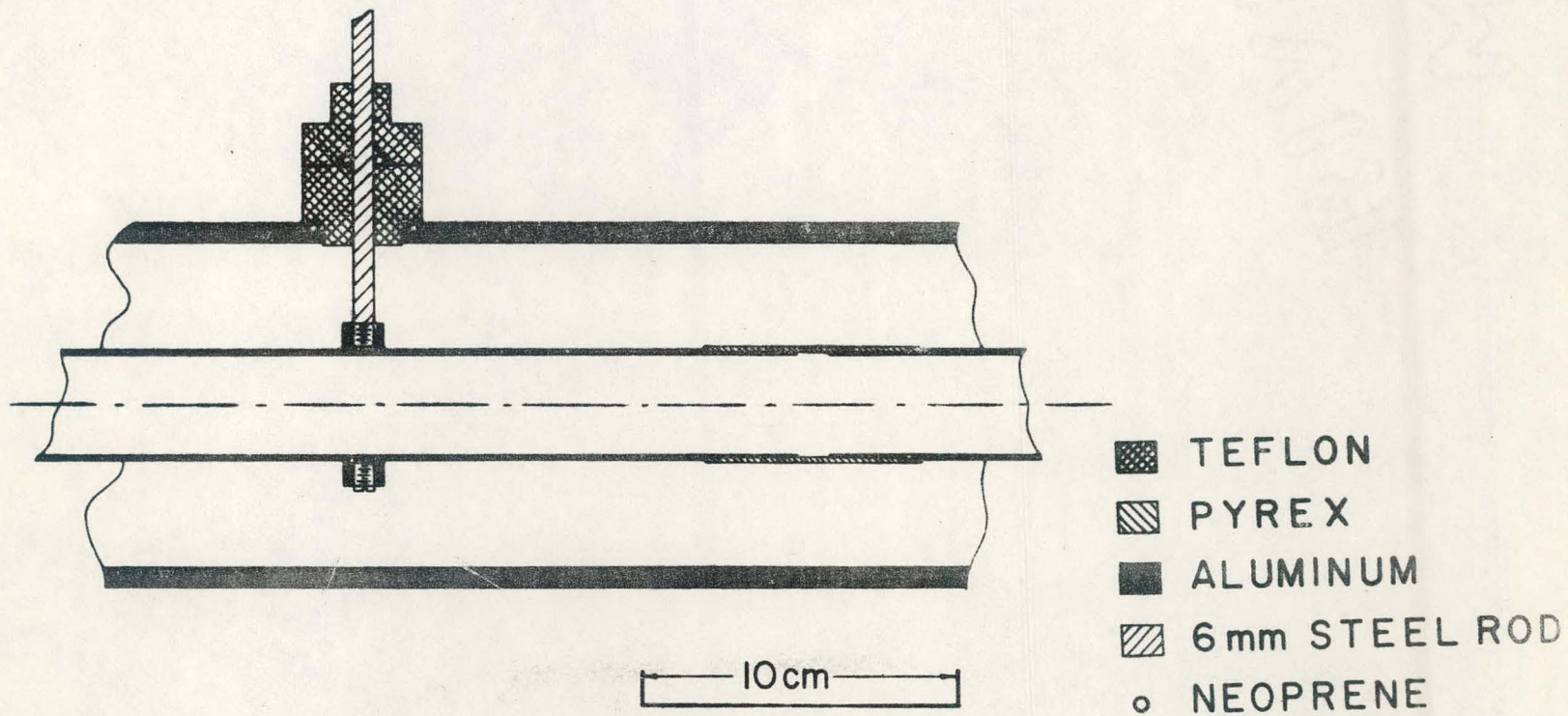
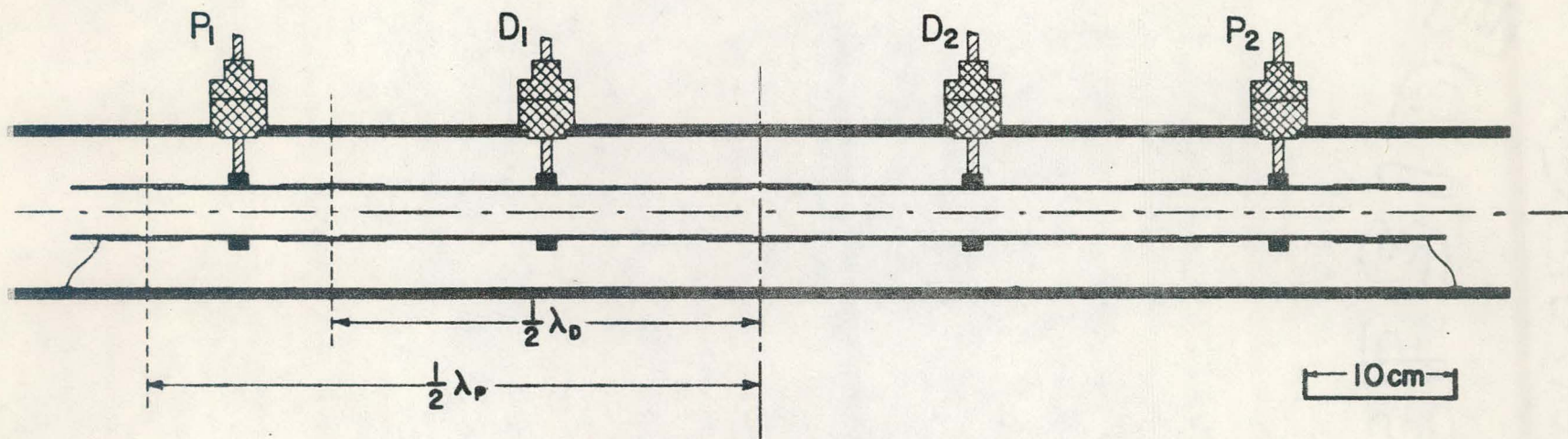


Fig. 2

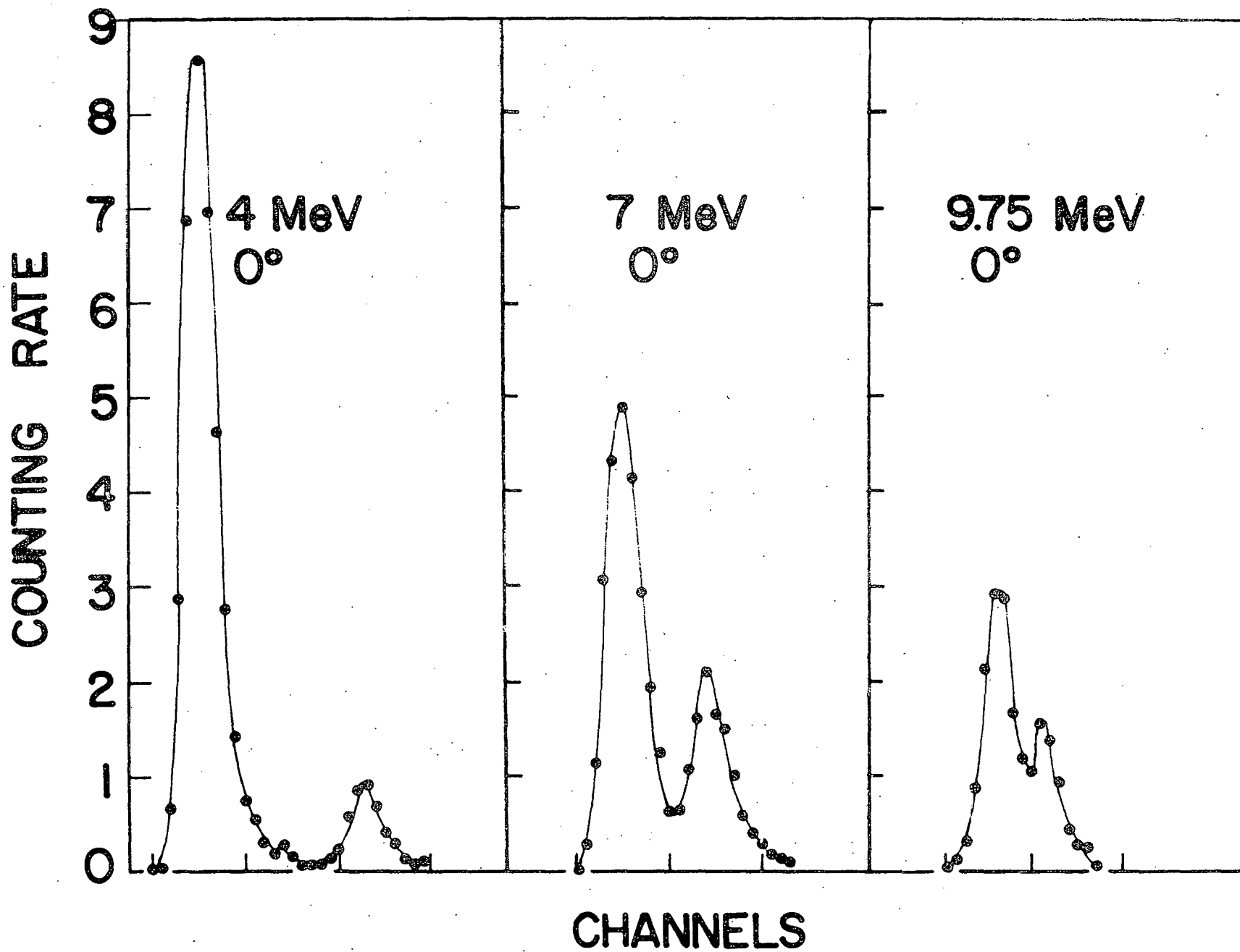


Fig. 3

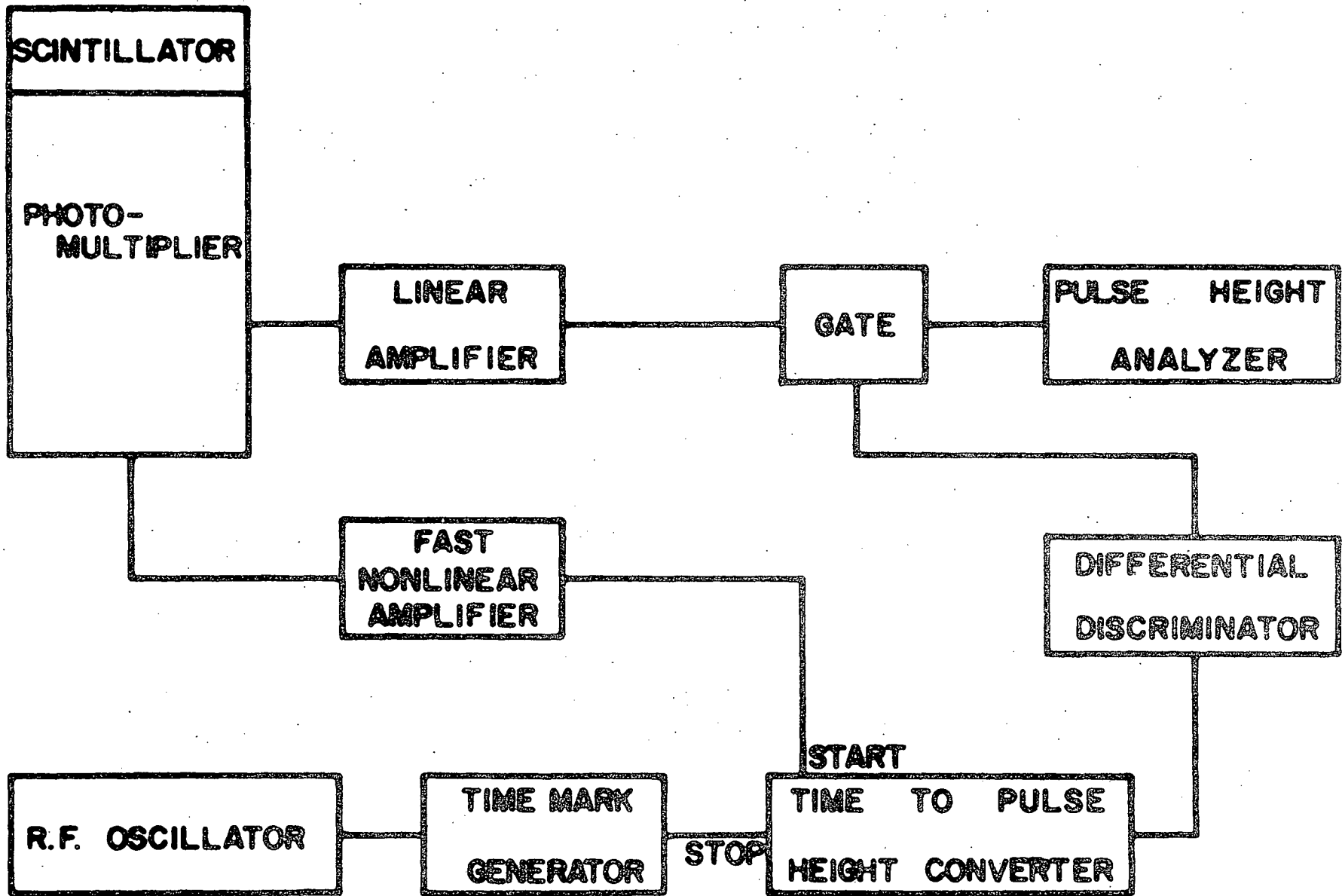


Fig. 4

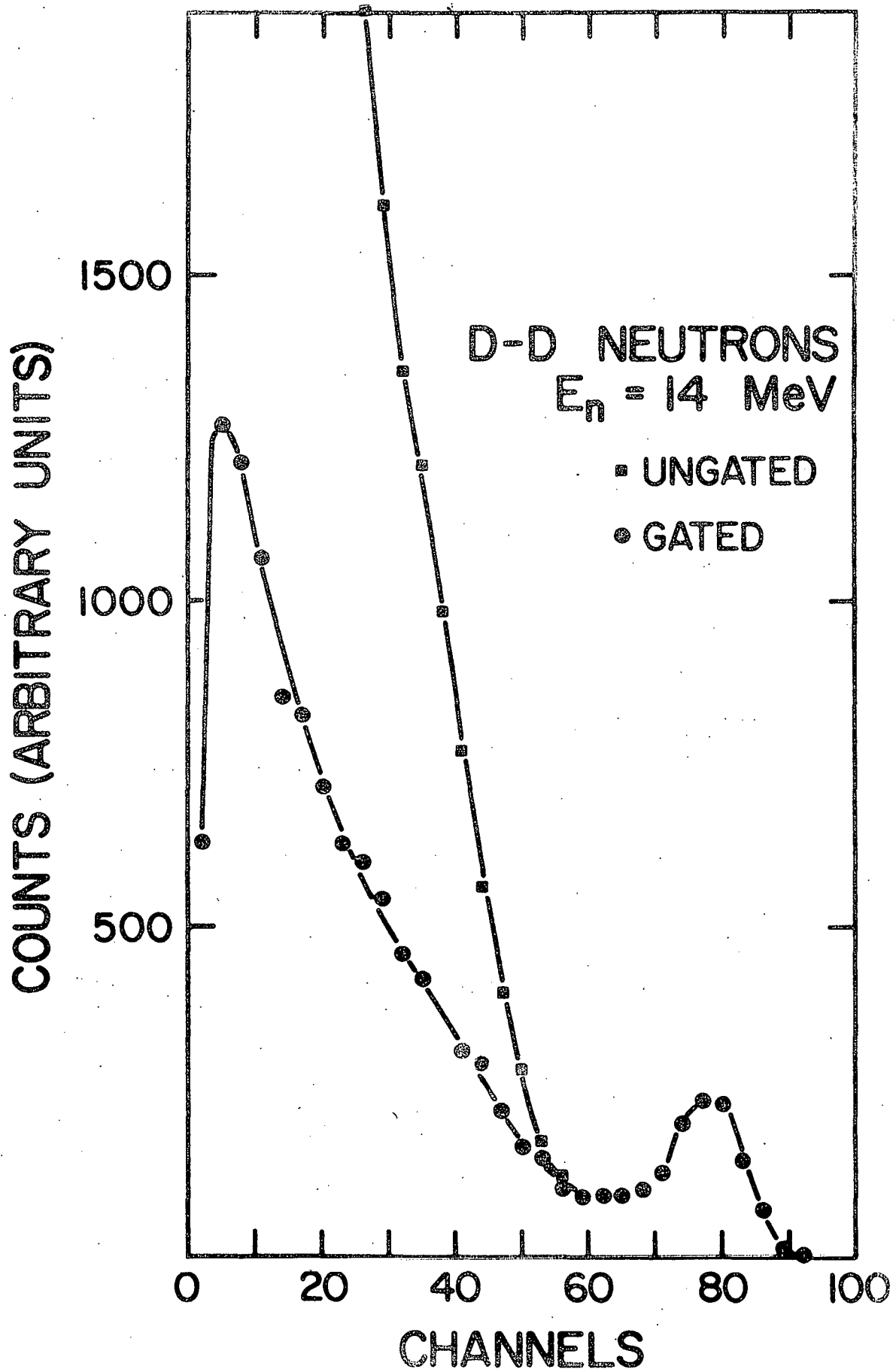


Fig. 5

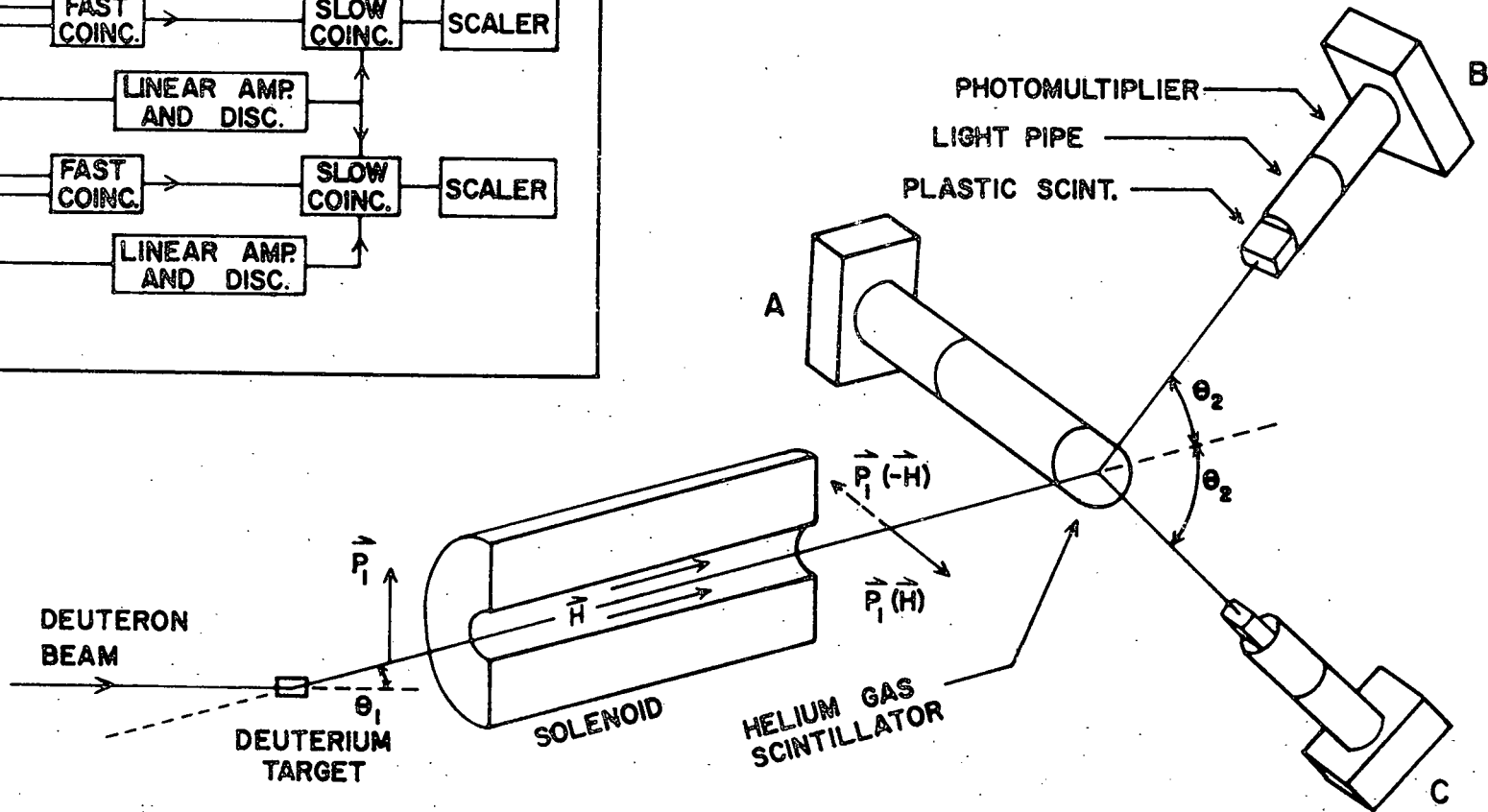
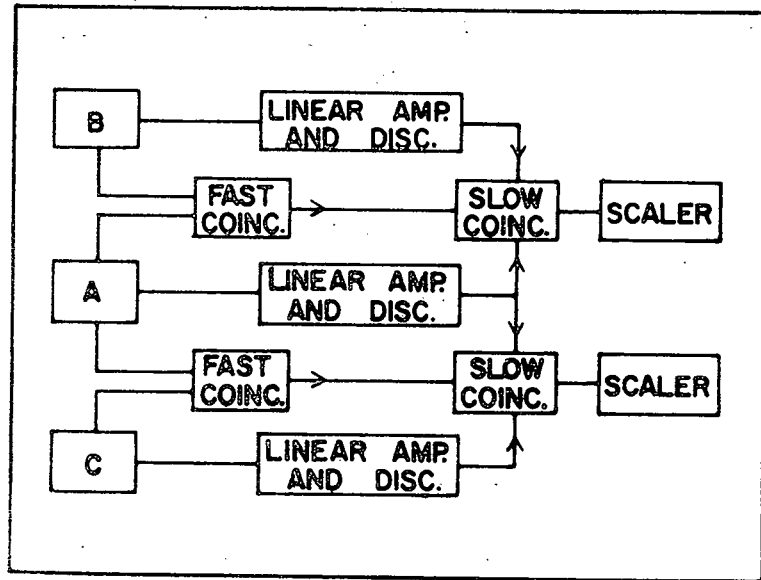


Fig. 6

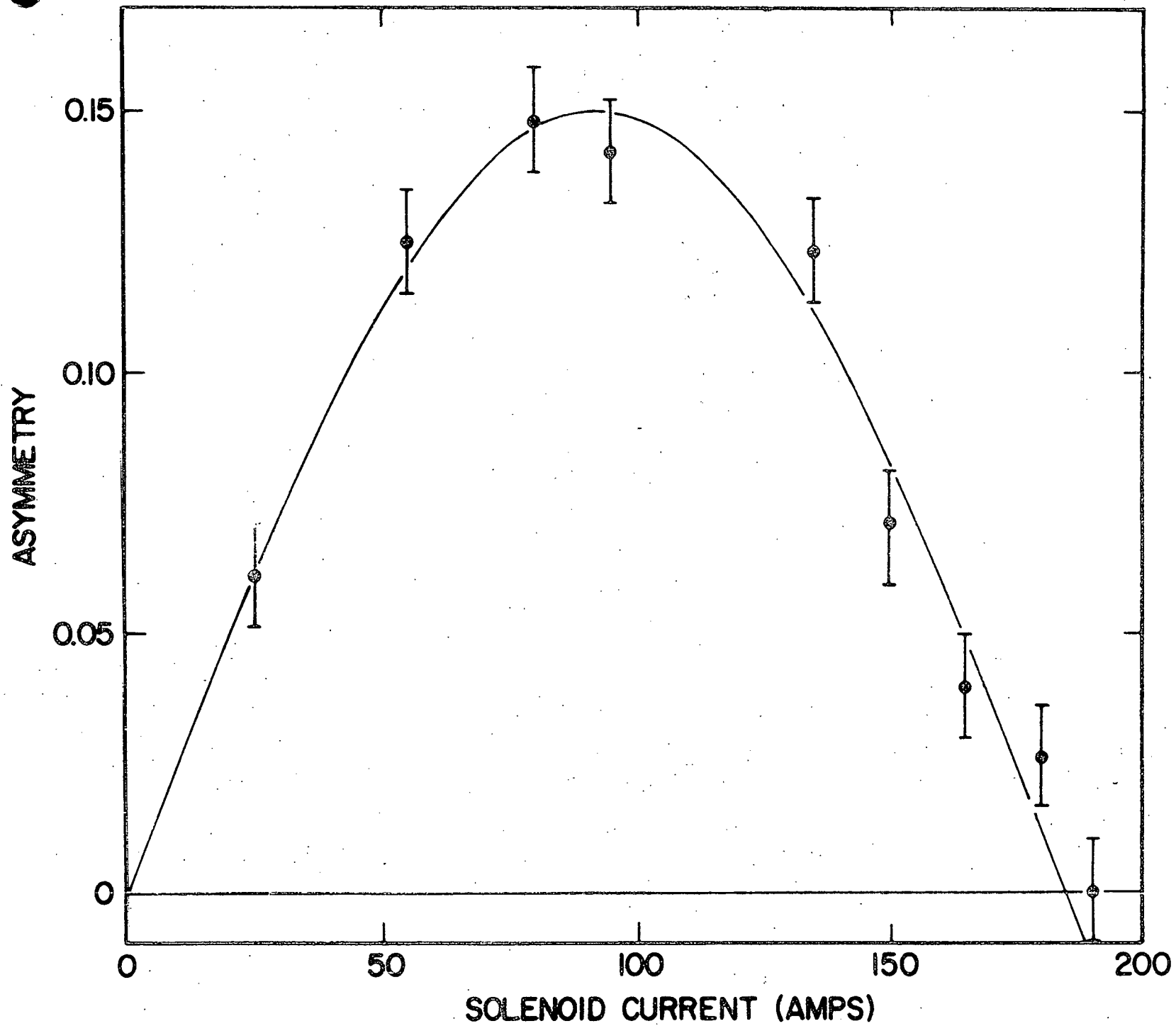


Fig. 7

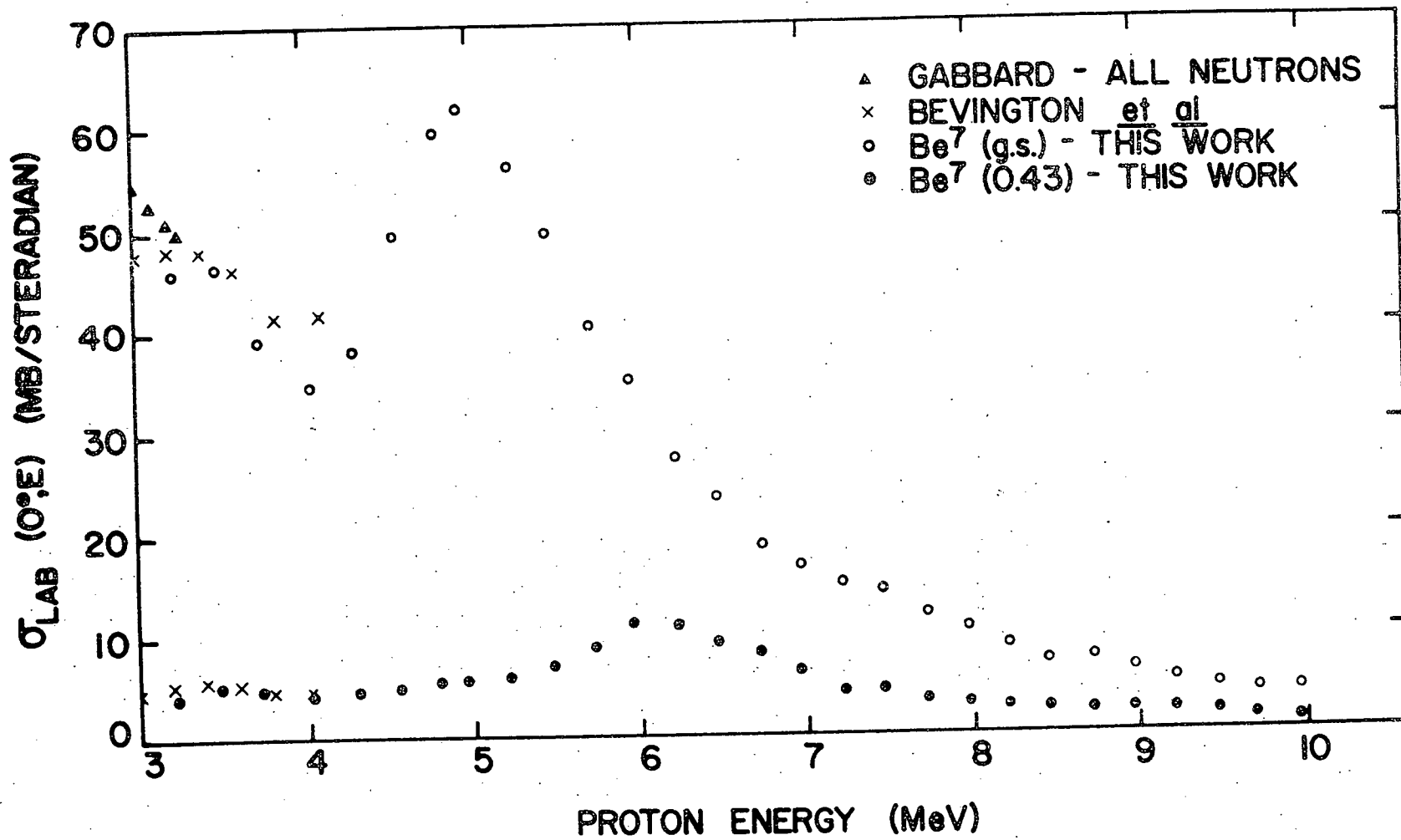


Fig. 8

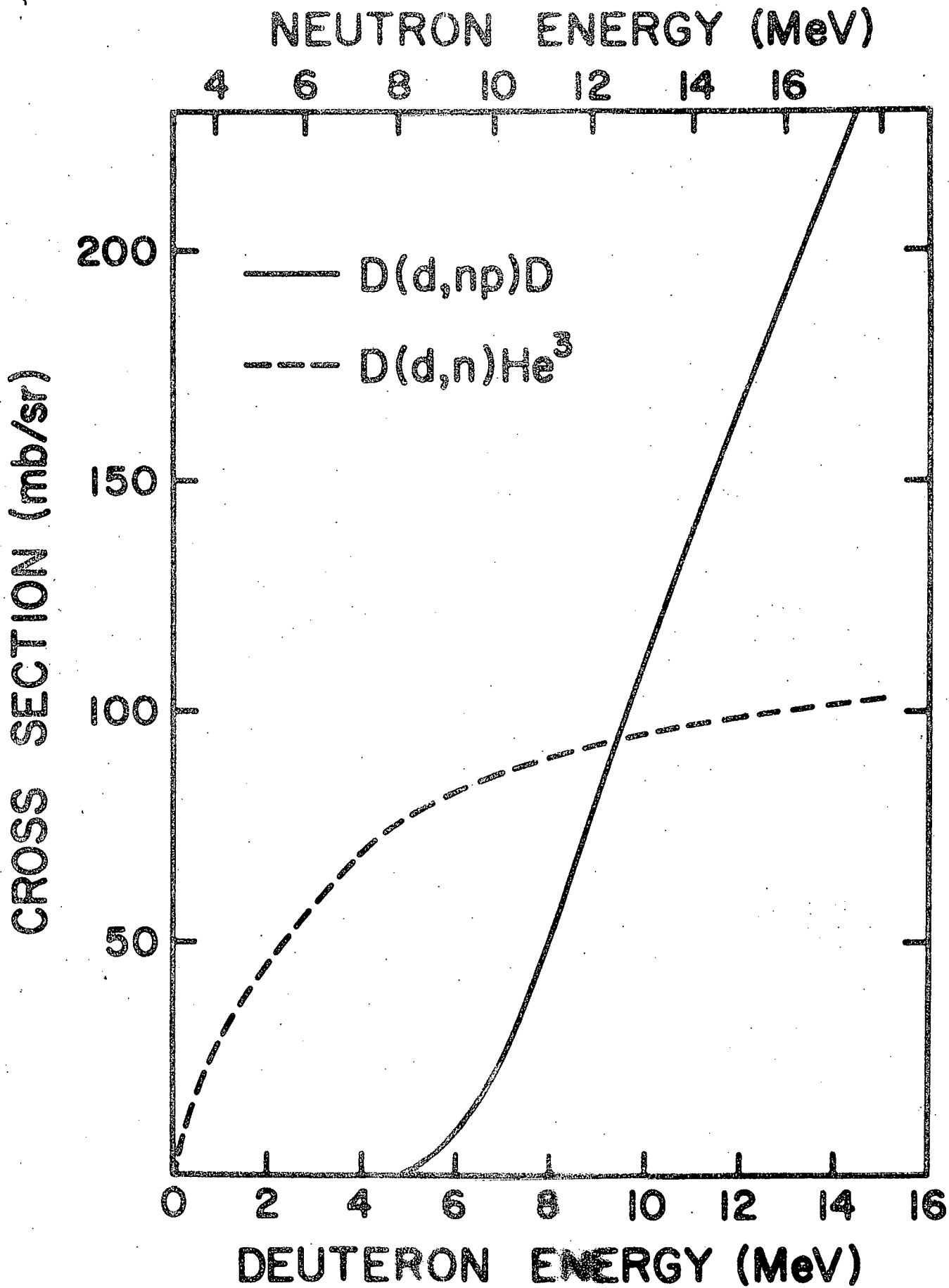


Fig. 9

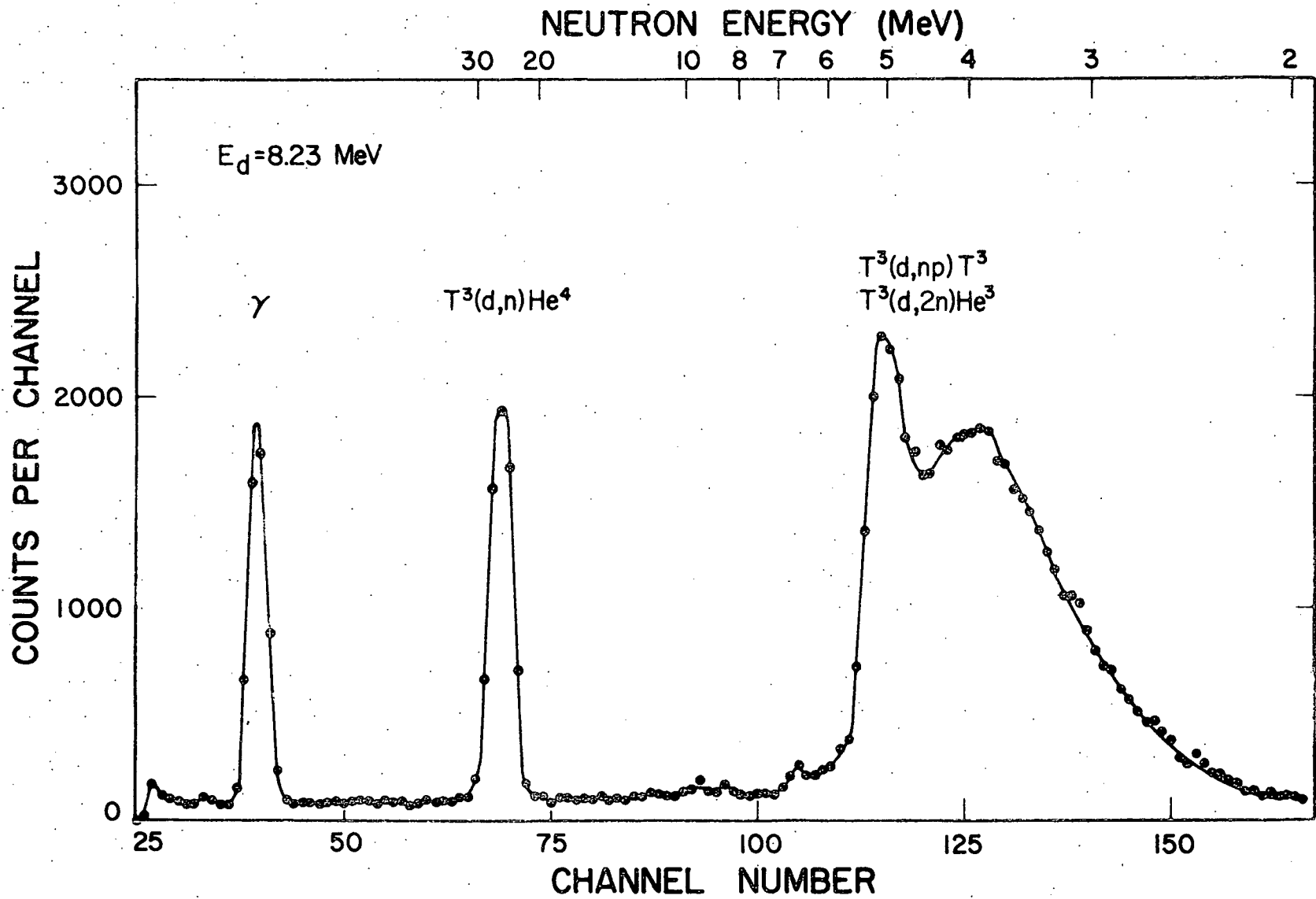


Fig. 10

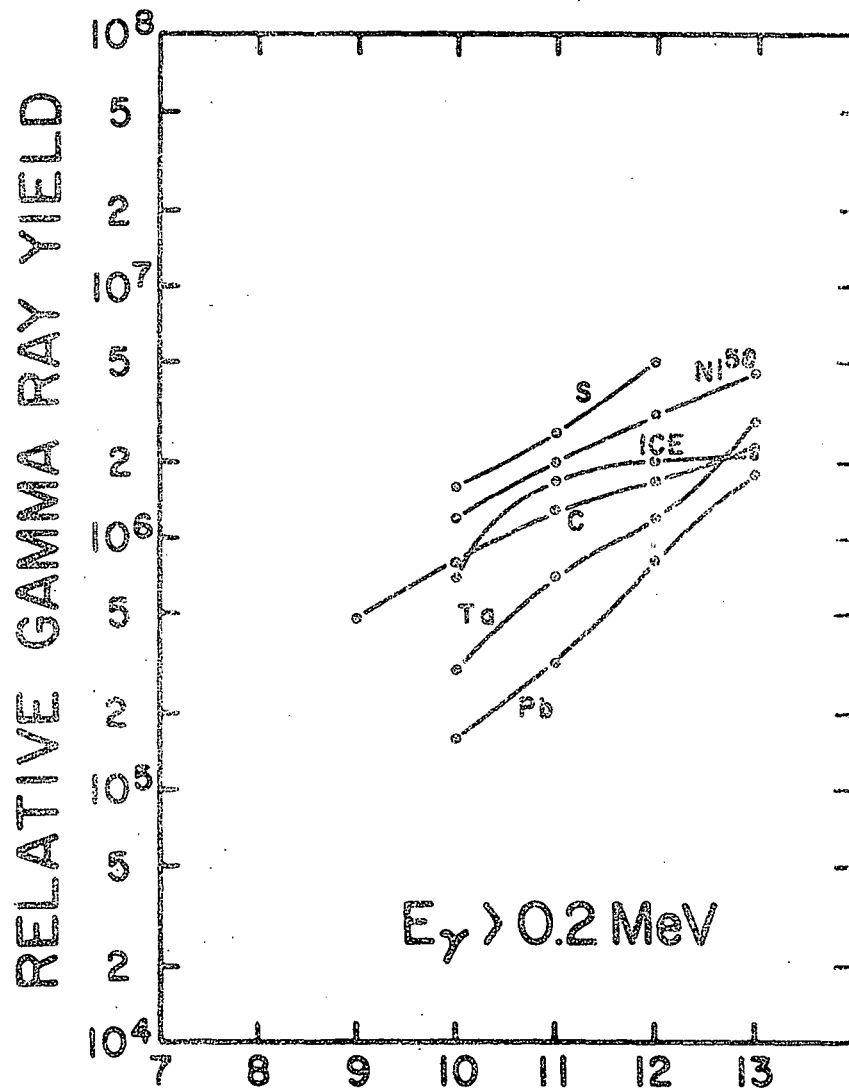
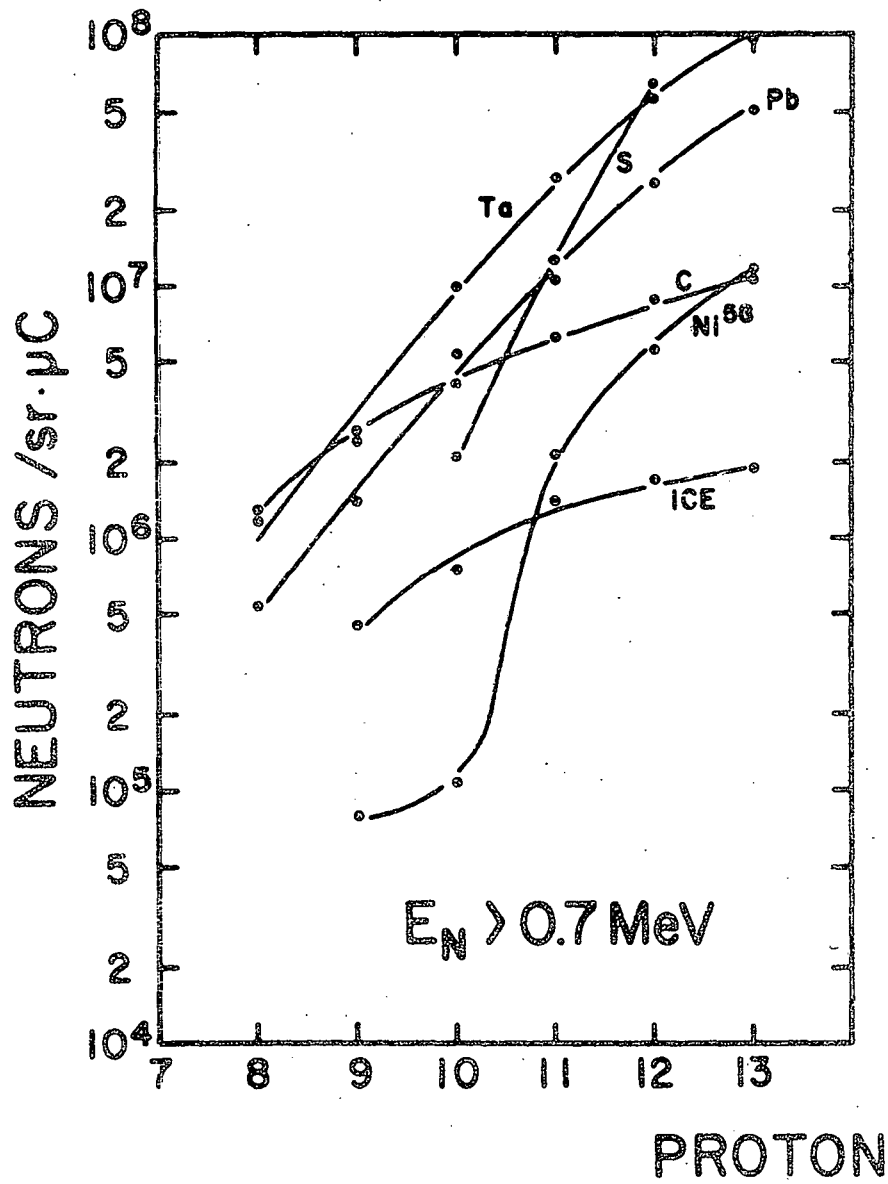


Fig. 11

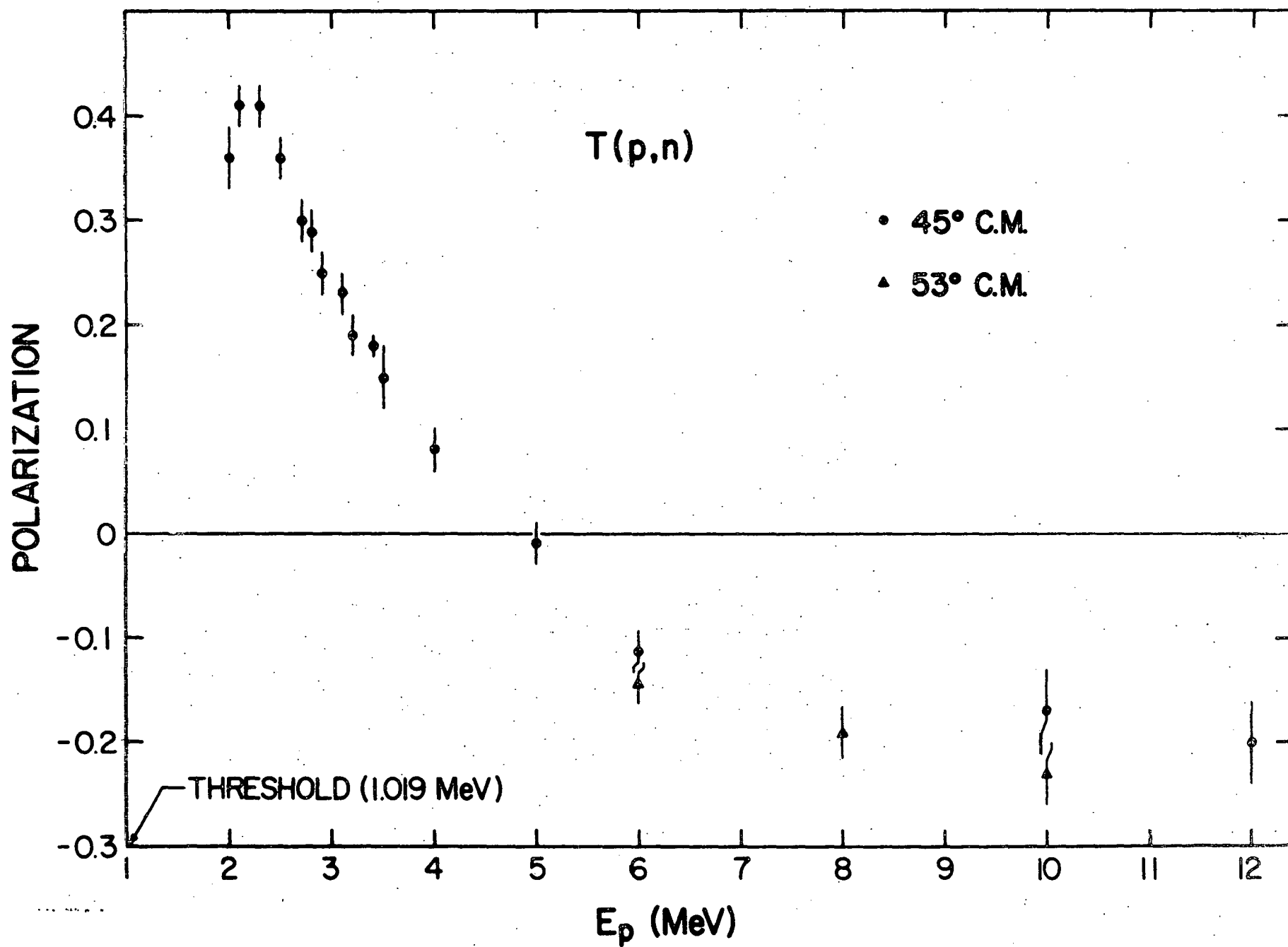


Fig. 12

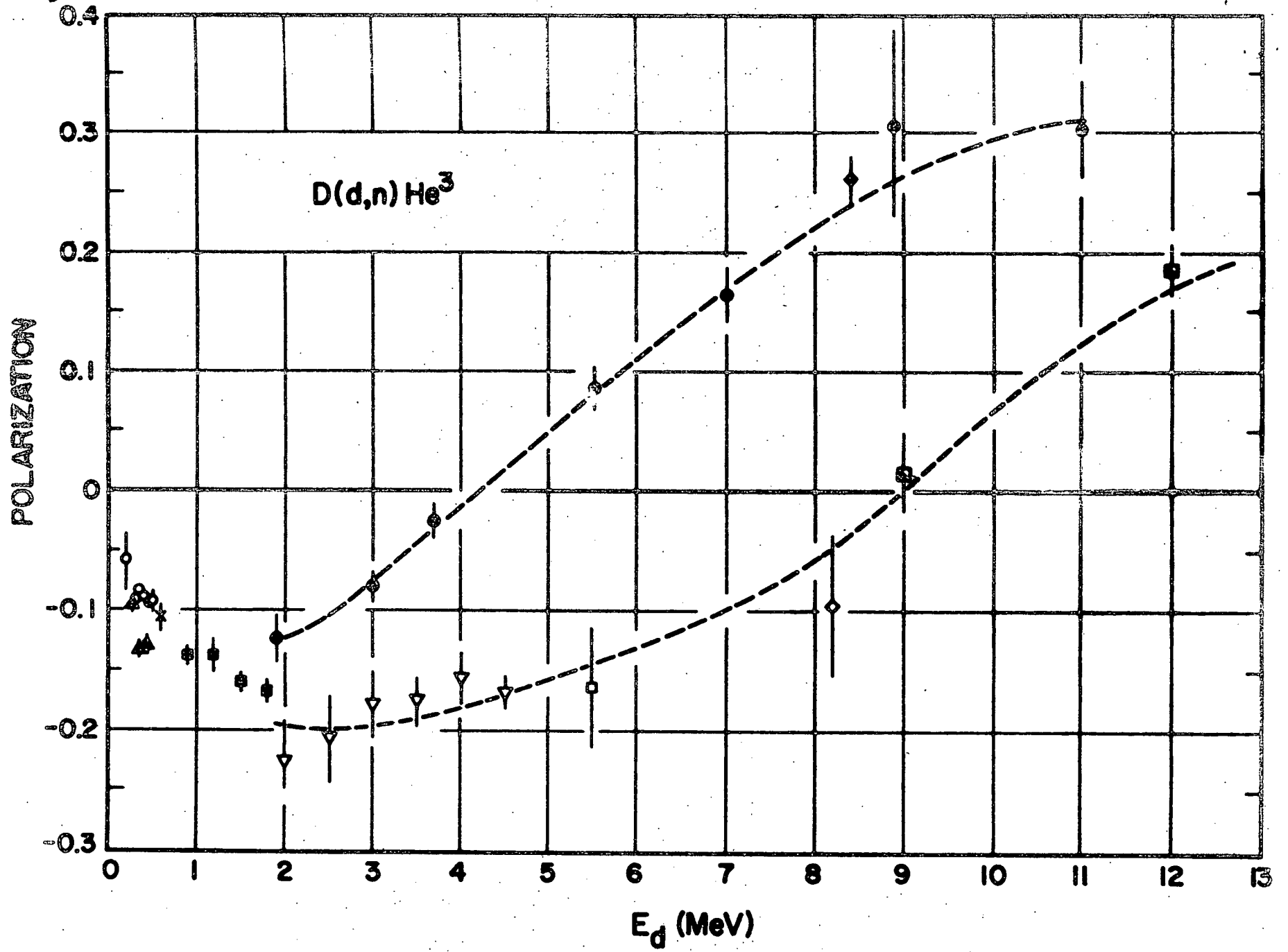


Fig. 13

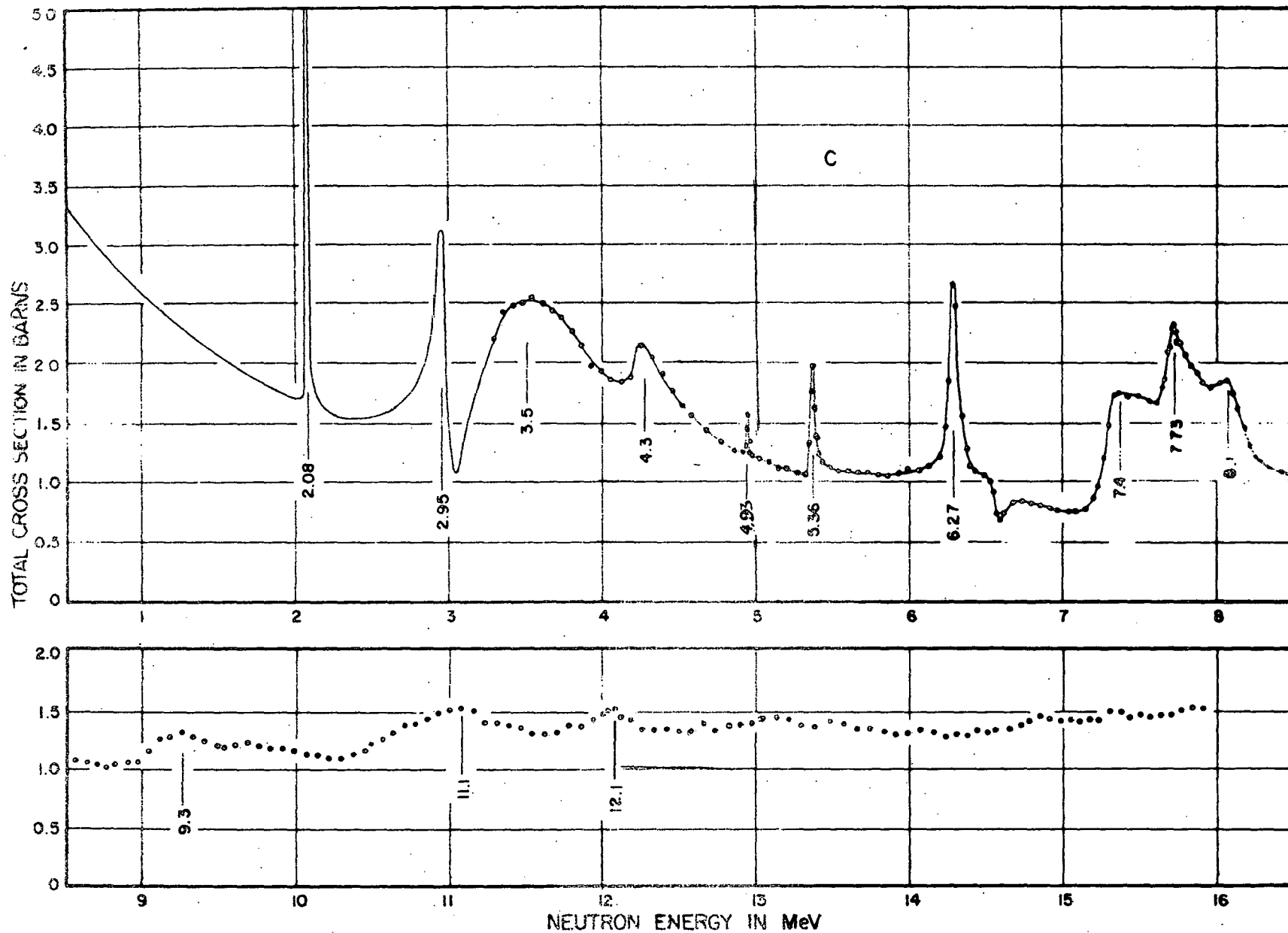


Fig. 14

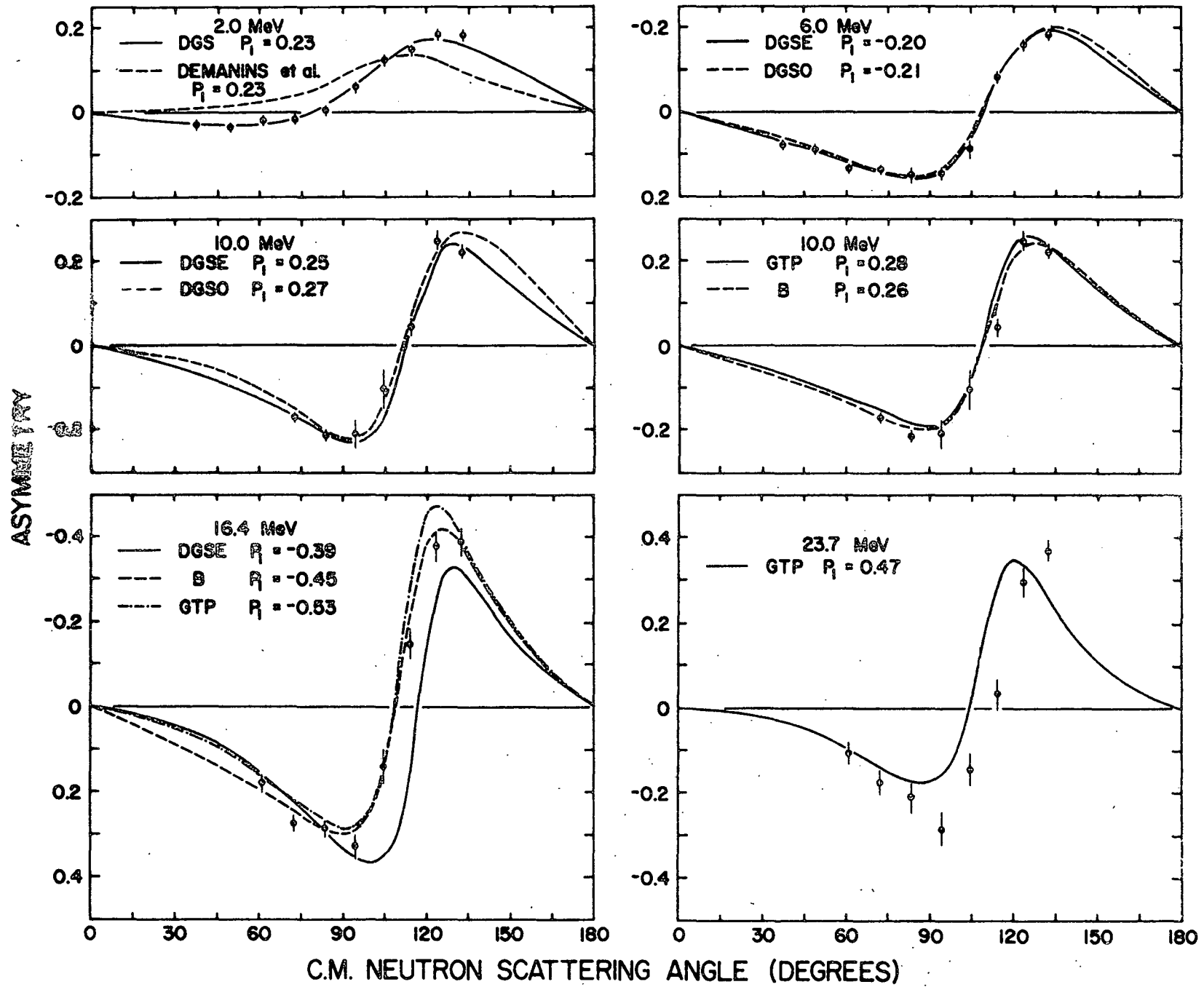


Fig. 15

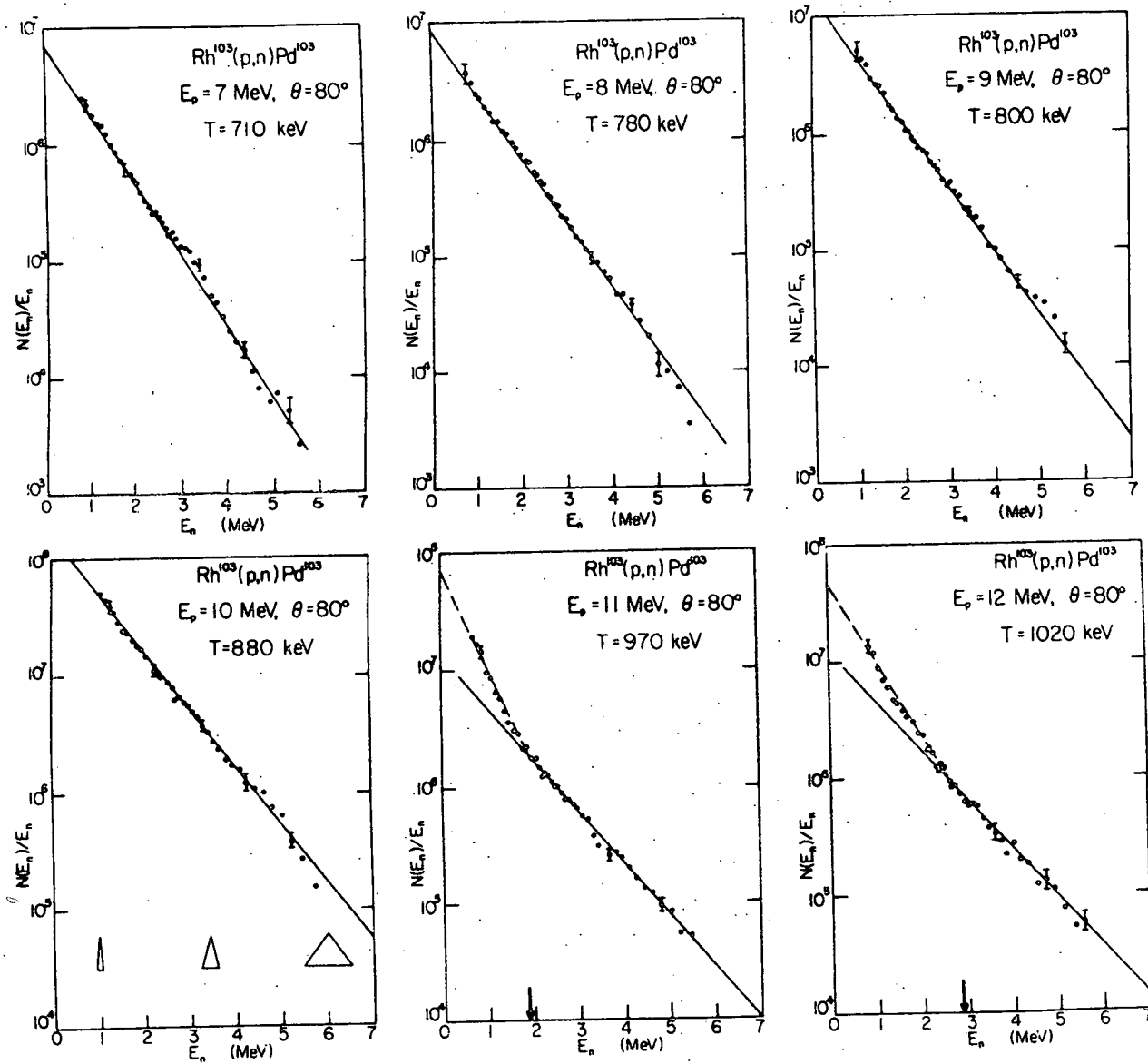


Fig. 16

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