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CROSS SECTIONS FOR THE $D(d,n)He^3$ AND $D(d,p)H^3$ REACTIONS FROM 14 TO 110 KEV

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PHYSICS

ABSTRACT

In this experiment the following differential cross sections were measured, all at 90^o in the laboratory system, over the range of 14 to 110 kev deuteron energy:

(1) The absolute differential cross section of the D(d, p)T reaction

(2) The ratio: $\dfrac{\text{differential cross section of D(d,p)T}}{\text{differential cross section of D(d,n)He}^3}$

(3) The ratio: $\dfrac{\text{differential cross section of D(d,p)T}}{\text{differential cross section of D(T,n)He}^4}$

The experiments used the gas target-thin window-decelerator technique reported in LA-1479 with deuterium and tritium-deuterium as target gases. Using the angular distribution of Wenzel and Whaling,(5) resulting cross sections include

$\sigma_{D\text{-}D_p}$ at 90 kev, 13.4 mb, $\sigma_{D\text{-}D_n}$ at 90 kev, 13.1 mb

$\sigma_{D\text{-}D_p}$ at 15 kev, .079 mb, $\sigma_{D\text{-}D_n}$ at 15 kev, .074 mb

with over-all accuracy $\pm 3\%$ at 100 kev, $\pm 5\%$ at 15 kev. The total D-D cross section gives a straight line Gamow plot over the lower half of the energy range, corresponding to a relation

$$\sigma_{D\text{-}D_{total}} \text{ (barns) } = \frac{2.88 \times 10^2}{E} e^{-45.8E^{-1/2}}$$

I. INTRODUCTION

The reactions studied here are:

$$(D\text{-}D_n) \qquad D + D \longrightarrow He^3 + n + 3.29 \text{ Mev}$$
$$(D\text{-}D_p) \qquad D + D \longrightarrow T + p + 4.03 \text{ Mev}$$

As part of a program of redetermining the light element cross sections at low energies, these measurements of $\sigma_{D\text{-}D_p}$, $\sigma_{D\text{-}D_p}/\sigma_{D\text{-}D_n}$, and $\sigma_{D\text{-}D_p}/\sigma_{T\text{-}D}$ were undertaken. At the time the experiment was started, $\sigma_{D\text{-}D_p}$ was known below 100 kev deuteron energy from thick target measurements using an uncertain value for the stopping power of heavy ice(1) and a brief advance report of results by a thin target method.(2)

The correction for the neutron branch depended on the same measurements, and on the branching ratio measurements $\sigma_{D\text{-}D_n}/\sigma_{D\text{-}D_p}$ of Pepper,(3) McNeill, Thonemann, and Price,(4) and McNeill and Keyser.(5)

The D-D reactions show appreciable angular anisotropy even at the lowest energies, and a knowledge of this depended on the thick target measurements of Bretscher,(1) from which the angular anisotropy as a function of energy is obtained rather indirectly.

More recently, $\sigma_{D\text{-}D_p}$ and the angular distribution have been reported on more fully by Moffatt, Roaf, and Sanders,(2) who provided independent data. The measurements reported here were made at 90° in the laboratory system and the total cross sections were calculated using the recently reported angular distributions of Wenzel and Whaling.(6) (The latter work was carried out in coordination with the present work and succeeded it in time.)

The apparatus used for measuring $\sigma_{T\text{-}D}$ (LA-1479) was used in these experiments, the only modification being in the nature of the filling gas, and in the proportional counter system for detection of the He^3 and tritons instead of alpha particles.

The D-D reaction was treated in several parts:

1. An absolute determination of the 90° differential cross section of the $D\text{-}D_p$ branch from 15 to 110 kev was made by counting the tritons.

2. The ratio $\sigma_{D\text{-}D_p}/\sigma_{D\text{-}D_n}$ was measured from 15 to 110 kev, by counting tritons and He^3's simultaneously with a six channel analyzer.

3. An absolute determination of the cross section of the $D\text{-}D_n$ branch was attempted by counting the He^3's.

4. Finally, as a check of the internal consistency of this experiment with the T-D experiment reported previously, the ratio $\sigma_{T\text{-}D}/\sigma_{D\text{-}D_p}$ was determined independently. A known mixture of deuterium and tritium gas was prepared and the He^4's from the T-D reaction and the tritons from the $D\text{-}D_p$ reaction were counted simultaneously.

II. APPARATUS

The apparatus used is shown schematically in Fig. 1. This apparatus has been discussed fully in the report of the measurement of the T-D cross section (LA-1479) and will be described only briefly here.

The analyzed deuteron beam from the Cockcroft-Walton accelerator entered the target chamber through a thin ($\sim$5 kev) SiO window after collimation by a series of apertures. The target chamber contained the target gas, deuterium, at a pressure of about 1 mm Hg. The target chamber was electrically insulated and protected by a guard ring, and so was essentially a Faraday cage which collected the beam current passing through the SiO window into the gas. The beam was then measured with a current integrator. The reaction particles which came off at 90° with respect to the direction of the incident beam were collimated and counted by two proportional counters. The counter collimators defined the volume of the target gas in which reactions were detected. The deuterium gas was stored in a uranium reservoir and its purity was checked after each run by mass spectrographic analysis. The pressure of the gas was measured by a Consolidated Engineering Company micromanometer which was calibrated with a fluid manometer. The energy lost by the beam in passing through the window could be measured by means of a decelerator. The energy of the beam of deuterons in the target volume was then calculable from the high voltage of the accelerator (as measured by a high precision resistance stack and potentiometer), the energy lost by the beam in the SiO window, and the energy lost in the target gas in going from the window into the volume seen by the counters.

The original target chamber and counter collimators had been contaminated with tritium in the T-D experiments and it was necessary to replace them, since the T-D cross section is so much larger ($\sim$350 times) than the cross section of the D-D_p reaction that a small tritium contamination would give a large He^4 background. The design of the collimators for the counters was slightly modified when the target chamber was replaced.

III. ABSOLUTE DETERMINATION OF THE D-D_p CROSS SECTION

In the D-D reactions there are the three charged reaction particles, H, T, and He^3, which can be detected by a proportional counter. It is necessary then to identify positively each of the counter pulse groups with the corresponding reaction particle and to count only the desired group.

For the D-D_p branch it was determined that the tritons could conveniently be detected with the same counter windows and gas pressure which were used in the T-D experiment.

Table I shows the energies lost by the reaction particles in passing through the mica windows of the counters and the energies lost in the gas of the counters. In Fig. 2 the pulse height distribution that was obtained with the counters is shown. The tritons were well resolved and separated from the protons. The protons were, however, barely detected above the noise, while the He^3's do not get into the counter at all. A very small counting rate of alpha particles from the T-D reaction showed that there was a slight tritium contamination.

A test of the identification of the pulses as protons and tritons was obtained in the following way. At these bombarding energies the protons and tritons come off in almost opposite directions in the laboratory system. Since the top and bottom counters are located opposite each other, it was possible to count these pairs of reaction particles in coincidence in those cases where both particles entered a counter. When this was done coincidences occurred, giving a check on the identification of the particles.

The one other reaction particle which could be detected in the counters was the neutron from the D-D_n branch. This neutron has an energy of 2.47 Mev and could cause recoils in the gas of the counters. To measure the number of these recoils, the counters were provided with shutters which could be drawn across the counter windows thus preventing any charged particles from entering the counter. It was found that 0.3% of the pulses assigned to the tritons were due to neutron recoils and the number of tritons detected were so corrected.

The experimental procedure and treatment of the data are discussed in LA-1479. The only differences in the two experiments were the different angular distributions of the reaction products and the modified solid angle factors because of the new counter collimators.

The formula used to compute the cross section is:

$$\sigma = 4\pi I_{(90)} g_{(\theta)} h_{(E)}$$

where $I_{(90)}$ is the yield at 90° in the laboratory system, $g_{(\theta)}$ is the correction factor to counter solid angle for motion of the center of mass, and $h_{(E)}$ is the correction factor for the angular anisotropy of the reaction products in the laboratory system. The factor $g_{(\theta)}$ was applied although it has a maximum value of only 1.02. $h_{(E)}$ has the form:

$$h_{(E)} = \frac{1}{\left(1 + \frac{C_2}{2} + \frac{3C_4}{8} + p^2\left(\frac{3C_2}{2} - \frac{30C_4}{8}\right)\right)}$$

where C_2 and C_4 are experimentally determined coefficients of Legendre polynomials taken from Wenzel and Whaling[6] and

$$p^2 = \left| \cos^2 \theta_{c.m.} \right|_{\theta_{lab} = 90^\circ} = \frac{3E}{8000 + E}$$

A plot of $h_{(E)}$ as a function of energy is shown in Fig. 3.

A plot of the cross section as a function of the energy for the $D\text{-}D_p$ reaction is shown in Fig. 4. The lowest energy at which the cross section was measured was determined by the yield and the growth of the SiO windows, i.e., the longer running time required to obtain a sufficient number of counts at low energies caused greater uncertainty in the determination of the energy loss in the SiO window. The experimental accuracy is estimated at $\pm 3\%$.

IV. THE $D\text{-}D_n$ CROSS SECTION

The $D(d,n)He^3$ reaction may be detected by counting either the neutrons or He^3 recoils. It was decided to count the He^3 particles because of the higher precision of counting charged particles. The He^3 particles, however, have a range of only 0.4 cm air, and thin counter windows were required to transmit them. The windows used were zapon of 0.1 cm air equivalent.

Table II shows the energies lost by the three charged particles from the D-D reactions in the thin zapon window. The energies lost by the various particles in the counter gas with a counter filling of 3 cm Hg pressure of argon-CO_2 mixture are also shown in this table. It was possible to detect both the tritons and He^3's simultaneously. The He^3's were stopped in the counter gas and the tritons passed through the counter volume. Thereby a test was provided on the identification of the pulses, because the He^3's not only gave larger pulses than the tritons but their pulse heights were not appreciably changed by small changes of the counter gas pressure, while the triton pulse heights were almost proportional to the pressure.

Another check on the assignment of the particles was to look for coincidences between the two pulse groups. No coincidences should occur between the tritons in one counter and the He^3's in the other and no coincidences were observed.

The pulse height distribution obtained with this thickness of zapon as the window and a counter pressure of 3 cm Hg is shown in Fig. 5. The tritons and He^3's are well separated from each other and from noise.

The thin zapon windows were found to have a serious disadvantage in that it was impossible to make them gas-tight. Since the pressure in the counters was higher than that in the target chamber, the deuterium gas quickly became contaminated with argon. Not only was the target gas contaminated but at the higher bombarding energies the deuterons in the beam were scattered by the argon into the counters with enough energy to traverse the counter windows. These deuterons gave a large number of very small pulses, and pile-up of these pulses occurred which rendered the counters inoperable.

It was found that a better procedure was to measure the ratio of $\sigma_{D\text{-}D_n}/\sigma_{D\text{-}D_p}$ by counting protons and He^3's simultaneously and combining their ratio with the previously measured $\sigma_{D\text{-}D_p}$ to give $\sigma_{D\text{-}D_n}$. Such a procedure has the advantage that the ratio is, to a first order, independent of impurity and pressure of the target gas, these factors appearing only as they affect the small correction for energy lost by the deuteron beam in passing through the target gas. The greater allowable margin of error in the knowledge of the target gas density permitted use of a continuous flow of target gas which swept out the argon and kept the amount of scattering down to acceptable limits.

The experimental results are shown in Fig. 6. Each point plotted represents the average of about 5 experimental points. The ratio at 20 kev is 0.94 and increases as the energy increases to a value of 0.99 at 100 kev. The experimental error is estimated at 1.5%. The $D\text{-}D_n$ cross section derived from this curve and Fig. 4 is shown in Fig. 7.

The total D-D cross section was obtained by adding $\sigma_{D\text{-}D_p}$ (Fig. 4) and the product of $\sigma_{D\text{-}D_p}$ and $\sigma_{D\text{-}D_n}/\sigma_{D\text{-}D_p}$ (Fig. 6). The resulting total cross section is shown in Fig. 8 and as a Gamow plot in the dashed line of Fig. 9.

In calculating the theoretical slope of this curve, $\sigma_{D\text{-}D_{total}} = \frac{A}{E} e^{-44.40 E^{-1/2}}$, the finite height of the coulomb barrier is allowed for[7] and this introduces a departure from the zero energy slope (44.40 kev-barns $\text{kev}^{-1/2}$) amounting to 0.2% at 10 kev and 7.2% at 100 kev. The theoretical curve is shown as the solid curve of Fig. 9.

It is doubtful whether the accuracy of the experimental points could justify drawing a line through them with so small a curvature as the theory predicts, so the best straight line through the experimental points was drawn. The slope of this line is 45.8 kev-barns $\text{kev}^{-1/2}$ and the value of A is 2.88×10^2.

An absolute determination of the cross section was attempted for the $D\text{-}D_n$ branch at a few energies. Because the absolute measurement required an exact knowledge of the gas purity and pressure, the argon could not be flushed out continuously. The argon contamination built up to as much as 15%, leading to uncertainty in the knowledge of gas composition. The experimental procedure was the same as that used for the $D\text{-}D_p$ and T-D measurements. The results are shown in Fig. 10. In this figure the points plotted are calculated from the absolute $D\text{-}D_n$ and $D\text{-}D_p$ cross section measurements, while the solid line represents the direct ratio measurement. The agreement with the ratio experiment is within the experimental error but the scatter of the points shows that the values of $\sigma_{D\text{-}D_n}$ obtained independently of $\sigma_{D\text{-}D_p}$ are not as accurate as those obtained from the ratio measurement.

V. THE RATIO $\sigma_{T\text{-}D}/\sigma_{D\text{-}D_p}$

There were two reasons for making an independent measurement of the ratio $\sigma_{T\text{-}D}/\sigma_{D\text{-}D_p}$:

1. The ratio $\sigma_{T\text{-}D}/\sigma_{D\text{-}D_p}$ obtained from the absolute measurements of LA-1479 and this report is in rather serious disagreement with previous measurements.[1]

2. The ratio measurement provided a test of the internal consistency of the T-D and $D\text{-}D_p$ cross section measurements.

In this experiment the alpha particles from the T-D reaction and the tritons from the $D\text{-}D_p$ were counted simultaneously, using a known mixture of tritium and deuterium gas as a target. The ratio of the counting rates for these two particles, when corrected for the concentrations of the gases in the mixture, gave the ratio of the cross sections directly. This measurement, as in the $D\text{-}D_n/D\text{-}D_p$ ratio experiment, was independent of the beam current and pressure and temperature of the target gas.

In order to obtain comparable counting rates from the two reactions, it was necessary to have a gas mixture containing a relatively small percentage of tritium, since the T-D cross section is about 350 times larger than the $D\text{-}D_p$ cross section. Comparable counting rates were required because if the counting rate for the alpha particles were much larger than that for the tritons the tail of the alpha pulse height distribution would fall on the triton pulse height distribution, giving an appreciable error in the ratio. It was decided to use a mixture in which the ratio D/T was about 400.

We are indebted to Wesley Jones of Group CMR-4, who prepared the gas mixture used by mixing accurately known volumes of the two gases. The ratio of the gases was known to about 0.5%. However, at least two factors changed the ratio of the gases in the target chamber.

1. To avoid breaking the fragile SiO window it was necessary to admit the gas to the target chamber slowly through a needle valve. Fractionation of the gas occurred in the needle valve by selective diffusion. Thus early samples from the gas reservoir gave high values of $\sigma_{D\text{-}D_p}/\sigma_{T\text{-}D}$ being enriched in deuterium, while later samples gave lower values. The fractionation was reduced by inserting a small volume between the reservoir and target chamber which could be filled to full reservoir pressure and then emptied completely into the target chamber.

2. The SiO windows in the target chamber had small leaks into the high vacuum and fractionation occurred at these leaks because deuterium leaked through more readily than tritium. Because of this the gas in the target chamber was progressively enriched in tritium.

Because of these fractionation effects the measurement of the ratio $\sigma_{T\text{-}D}/\sigma_{D\text{-}D_p}$ was not as accurate as originally intended.

Both the alpha particles from the T-D reaction and the tritons from the D-D_p were counted simultaneously. The counters had 1.5 mg/cm^2 mica windows and were filled to a pressure of 10 cm Hg as they had been in the T-D and D-D_p measurements. There was good separation of the alpha pulses from the triton pulses and from background.

The experimental values for the ratios are shown in Fig. 11. The smooth curve is the result of dividing the experimental values for the cross section of the T-D reaction by those of the D-D_p reaction reported here. The agreement between the ratio measurement and the ratio of the absolute measurements is within 1.5%.

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Table I

ENERGY LOSS OF T-D AND D-D REACTION PRODUCTS IN COUNTER WINDOW AND GAS

Particle	Energy (Mev)	Energy Lost in Window (Mev)	Energy Lost in Counter (Mev)
Alpha particle from D-T	3.5	1.42	1.94
Proton from $D\text{-}D_p$	3	.13	.12
Triton from $D\text{-}D_p$	1	.73	.27
He^3 from $D\text{-}D_n$	.82	.82	-

Stopping power of window = 1 cm air.

Stopping power of counter gas = .92 cm air.

Table II

ENERGY LOSS OF D-D REACTION PRODUCTS IN COUNTER WINDOW AND GAS

Particle	Energy (Mev)	Energy Lost in Window (Mev)	Energy Lost in Counter (Mev)
Alpha particle from D-T	3.5	.12	.39
Proton from $D\text{-}D_p$	3	.01	.04
Triton from $D\text{-}D_p$	1	.07	.19
He^3 from $D\text{-}D_n$	.82	.24	.56

Stopping power of window = .1 cm air.

Stopping power of counter gas = .3 cm air.

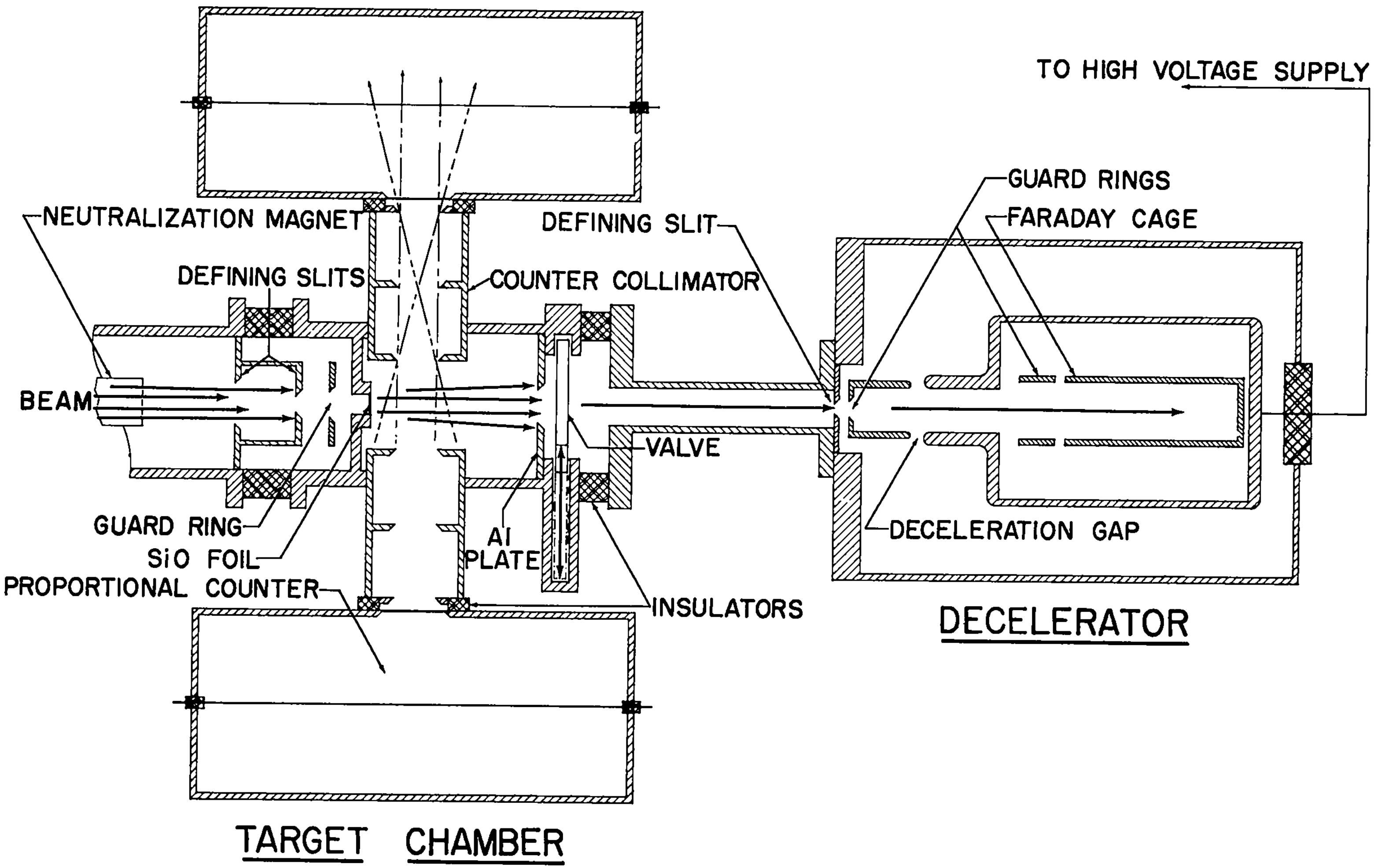

Fig. 1. Target chamber and decelerator for measurement of the T-D cross section

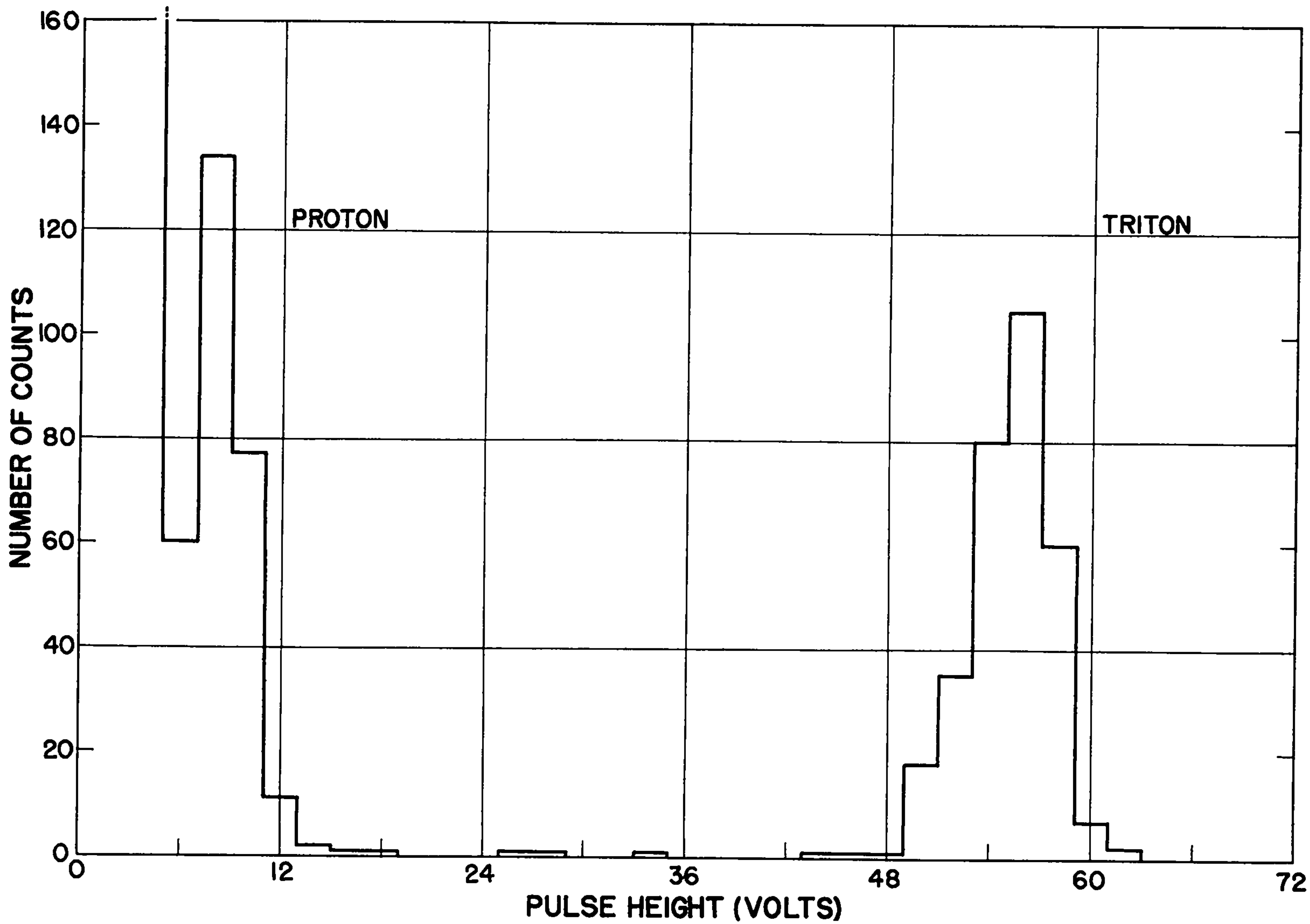

Fig. 2. Pulse height distribution. D-D_p experiment.

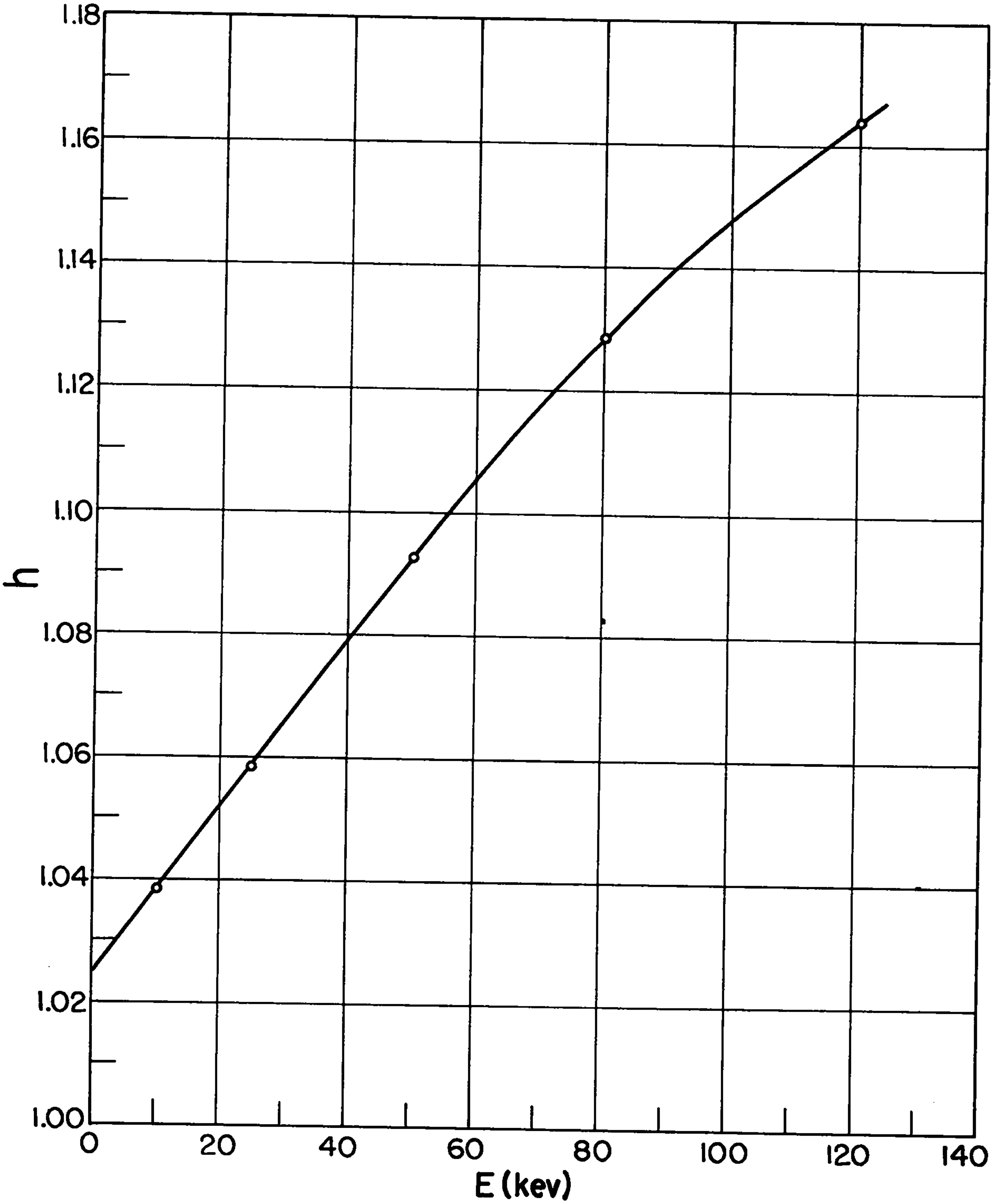

Fig. 3. Correction for angular anisotrophy in the laboratory system, $h_{(E)}$ (after Wenzel and Whaling)

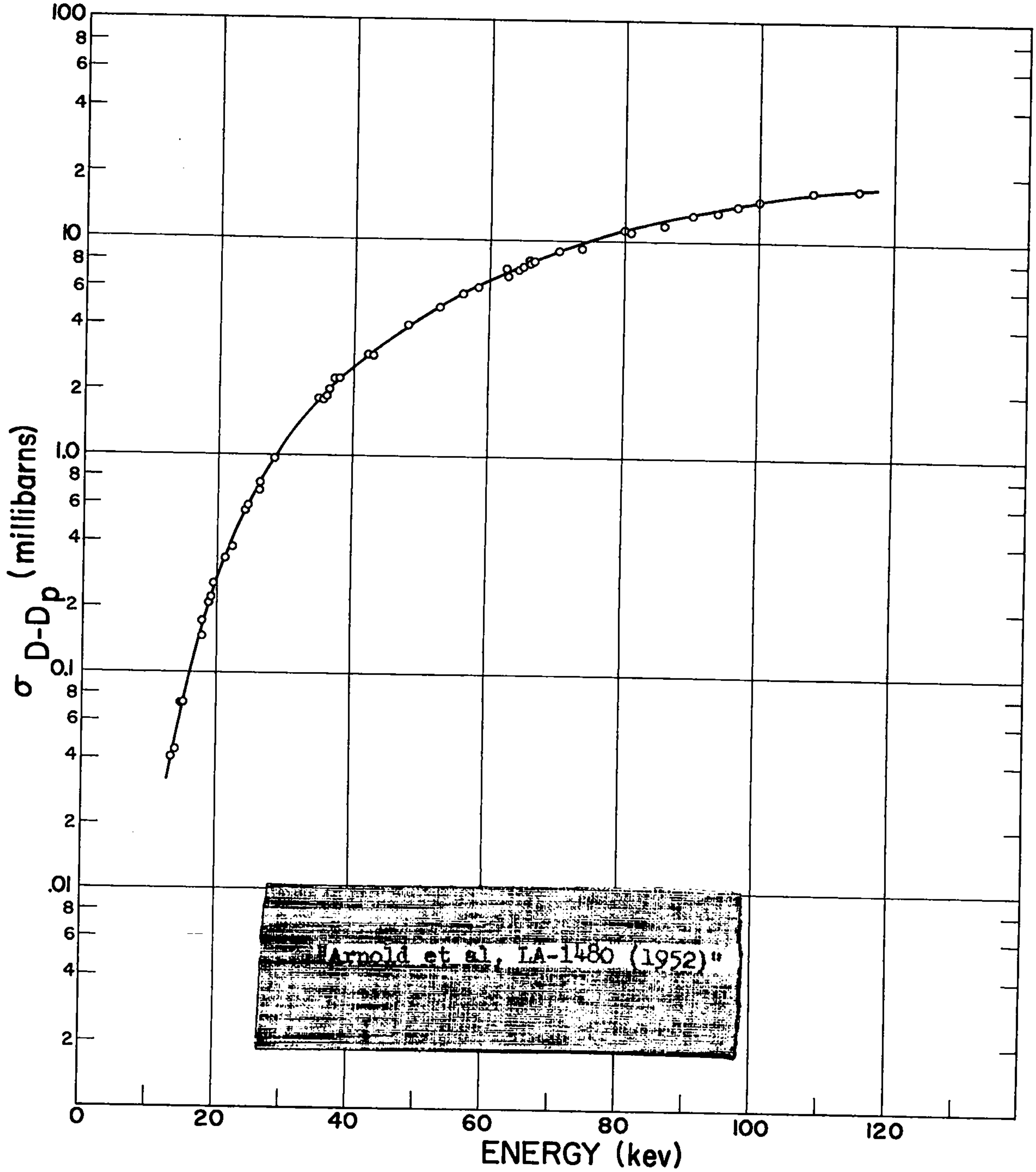

Fig. 4. D(d,p)T cross section

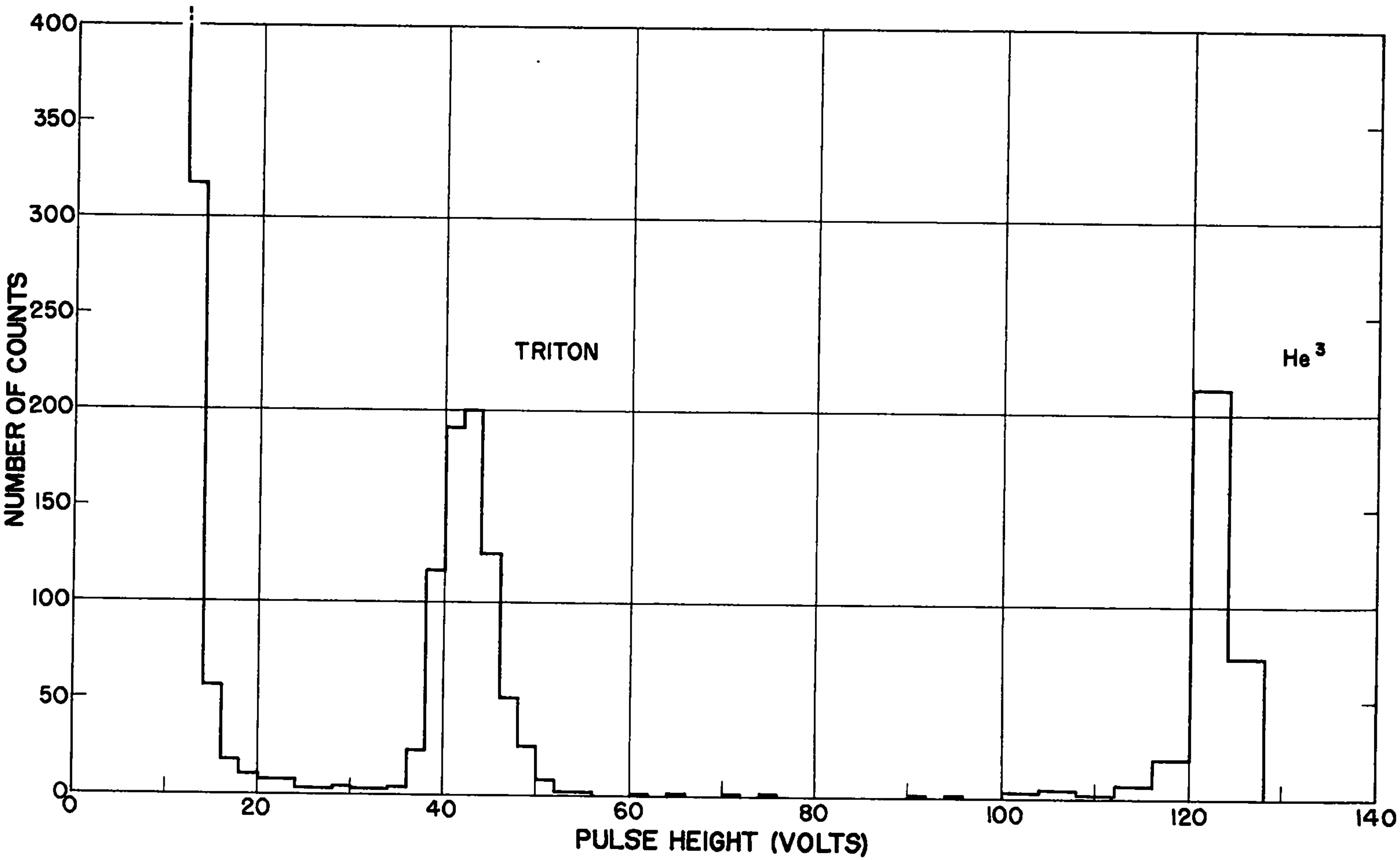

Fig. 5. Pulse height distribution. D-D_n experiment.

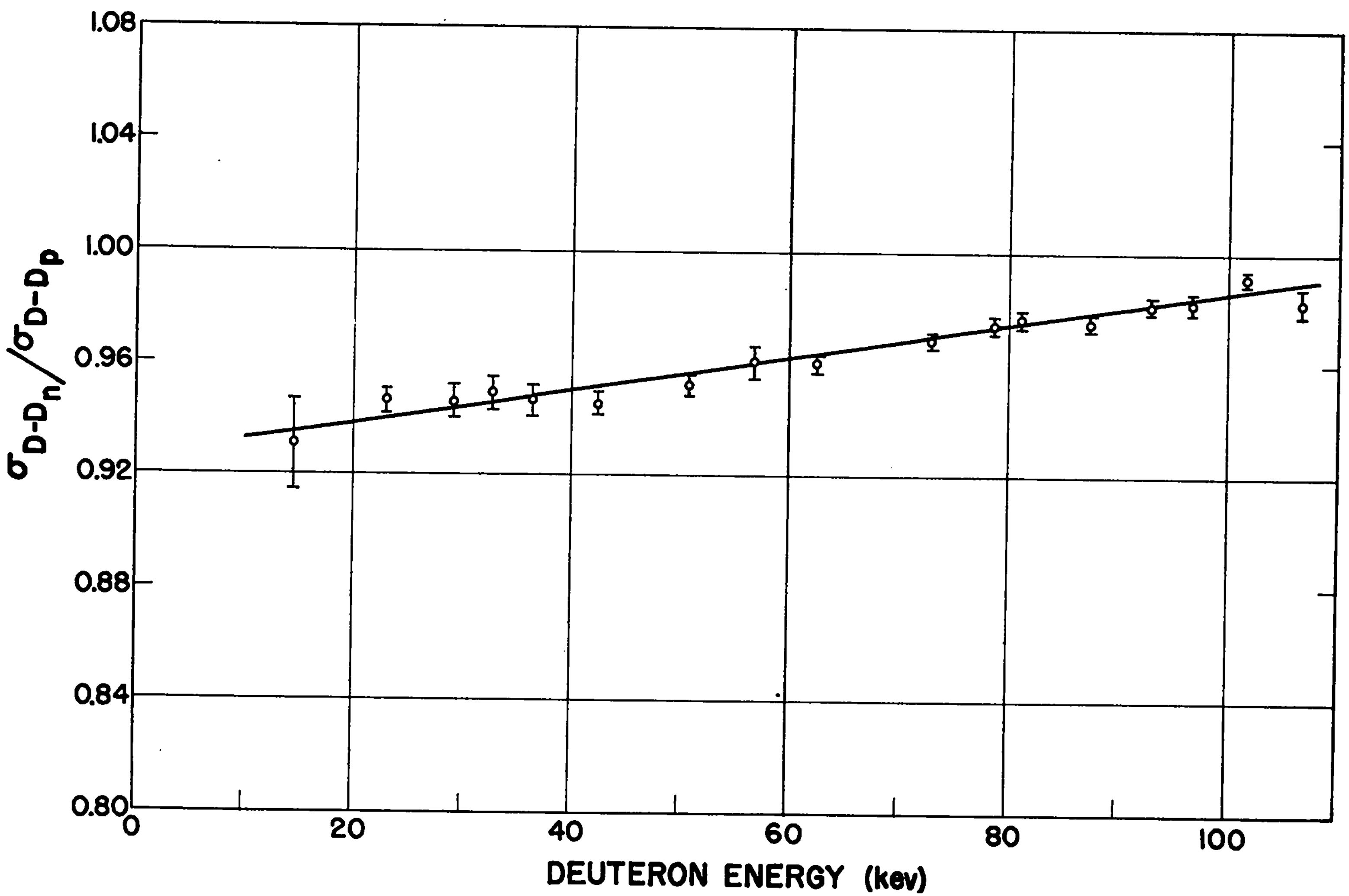

Fig. 6. Ratio $\frac{\sigma_{D-D_n}}{\sigma_{D-D_p}}$ vs energy

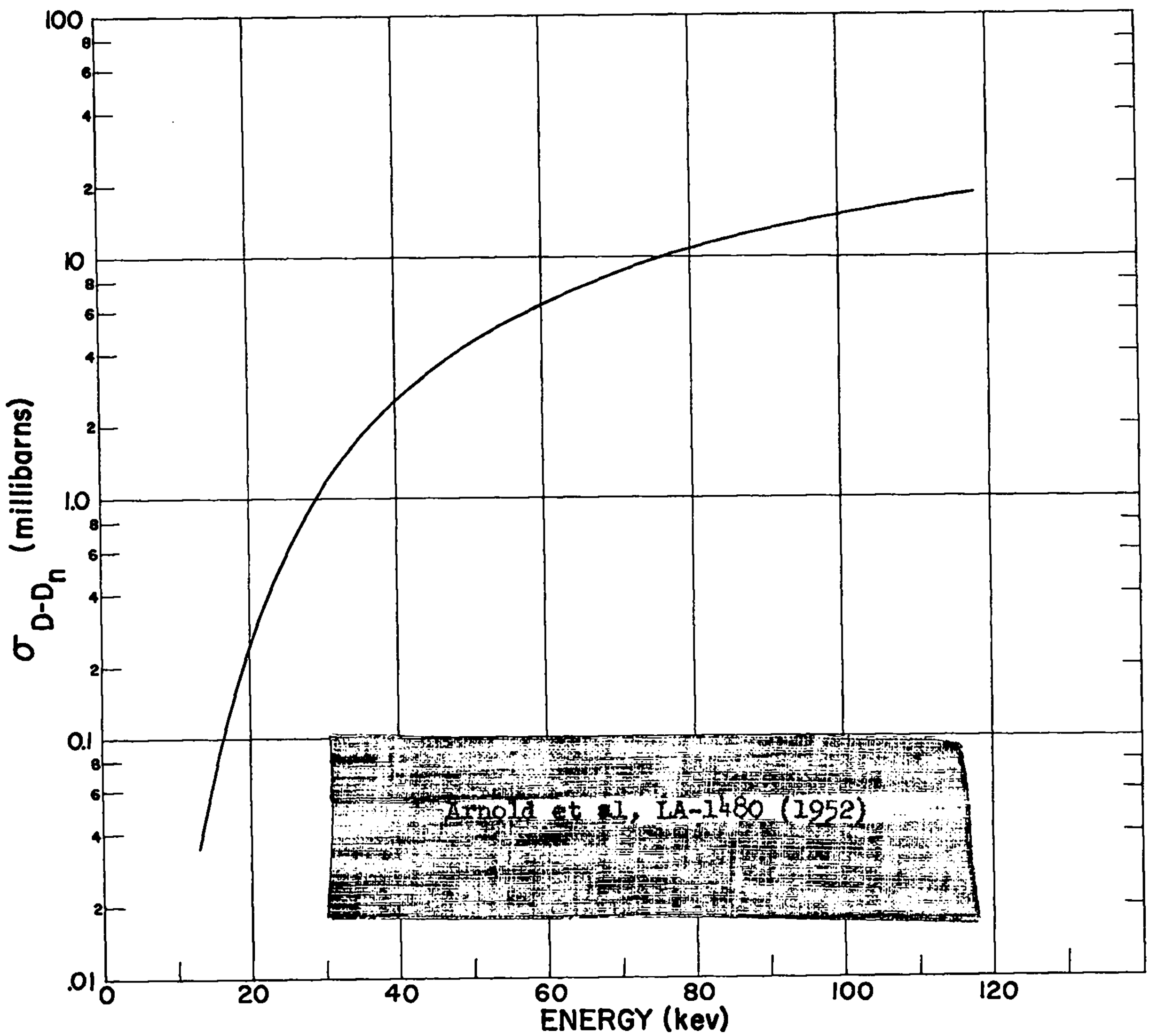

Fig. 7. $D(d,n)He^3$ cross section

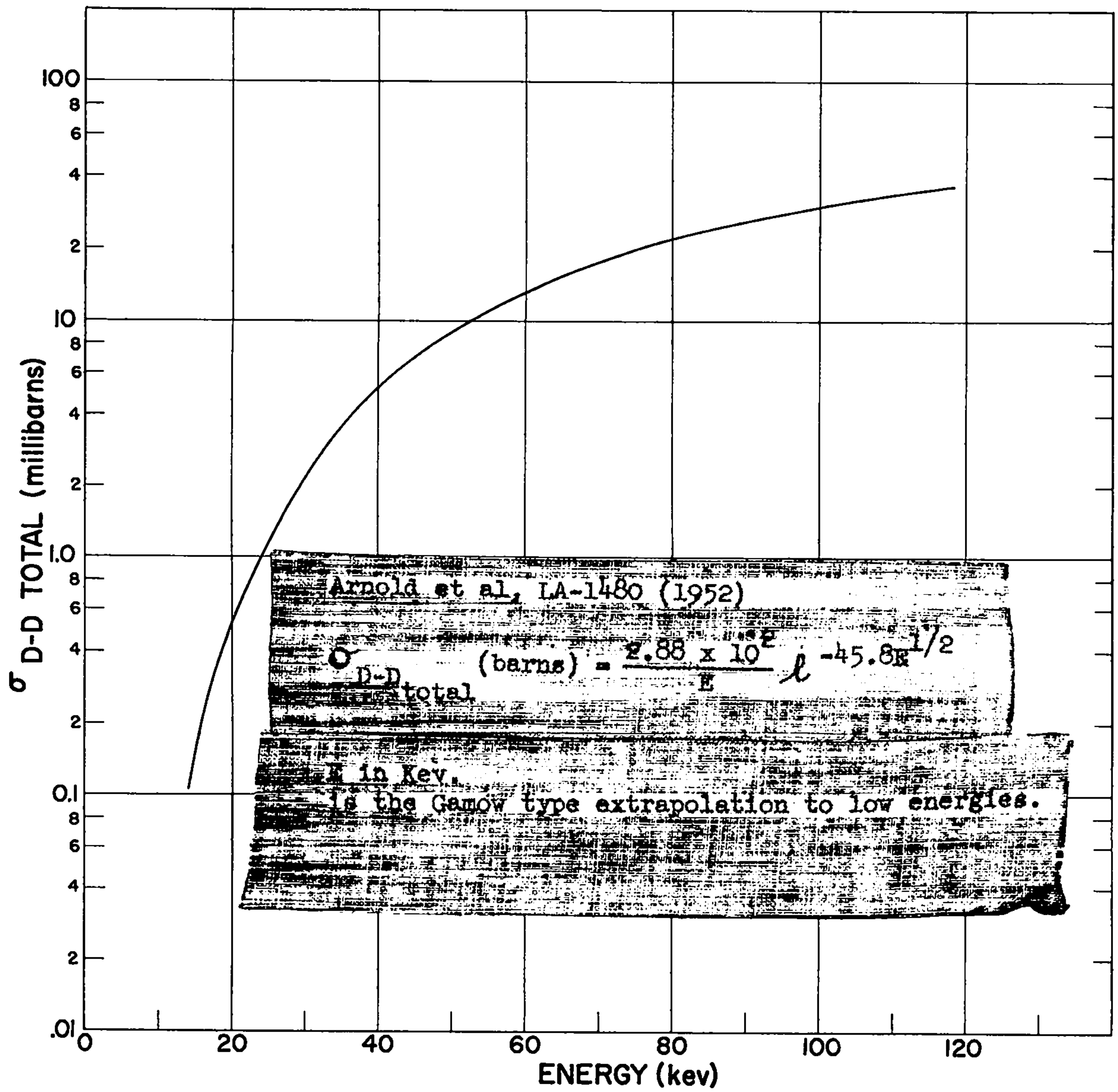

Fig. 8. Total D-D cross section. D(d,p)T plus D(d,n)He^3.

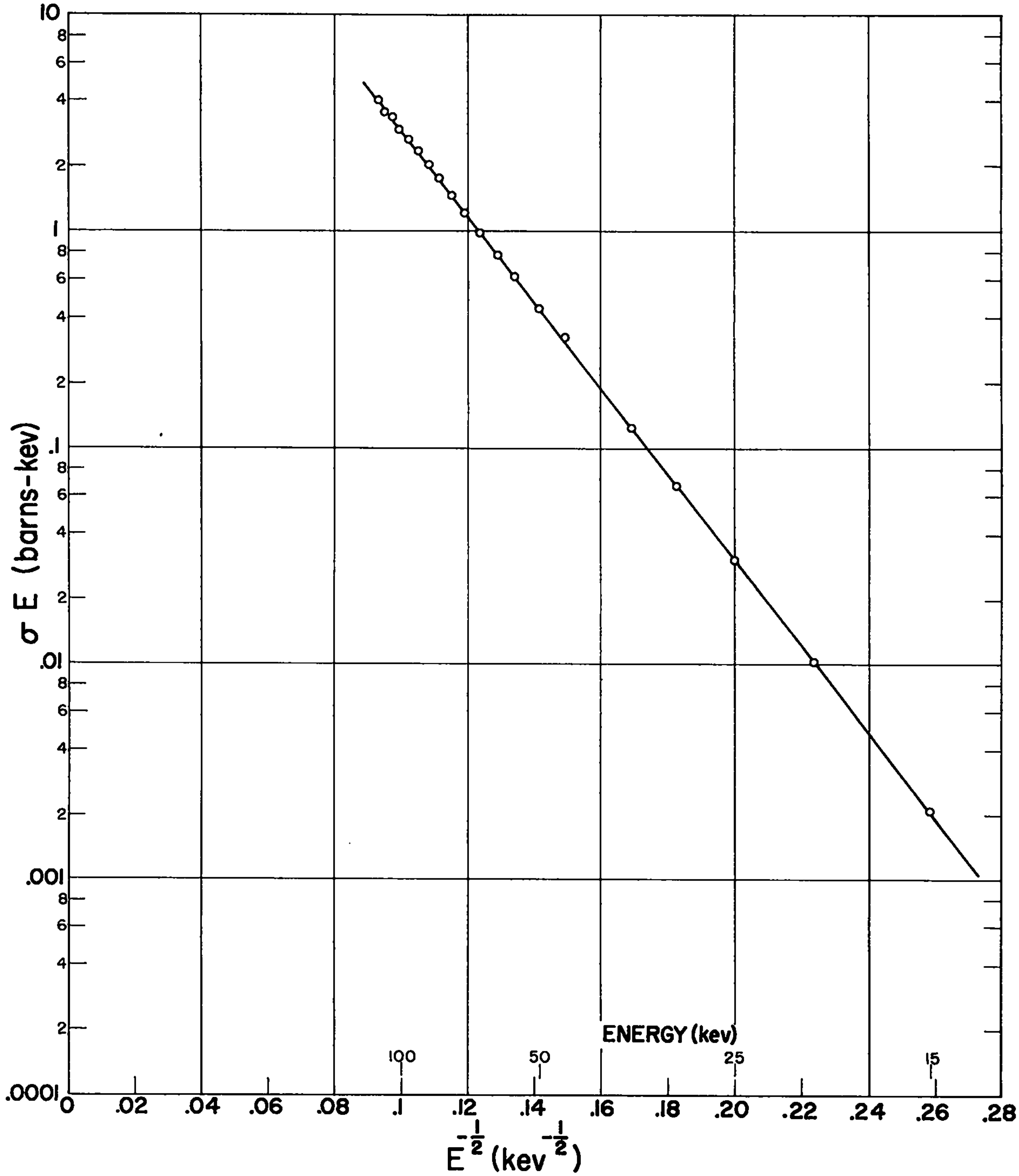

Fig. 9. Gamow plot. Total D-D cross section. $\sigma_{D\text{-}D_p}$ plus $\sigma_{D\text{-}D_n}$.

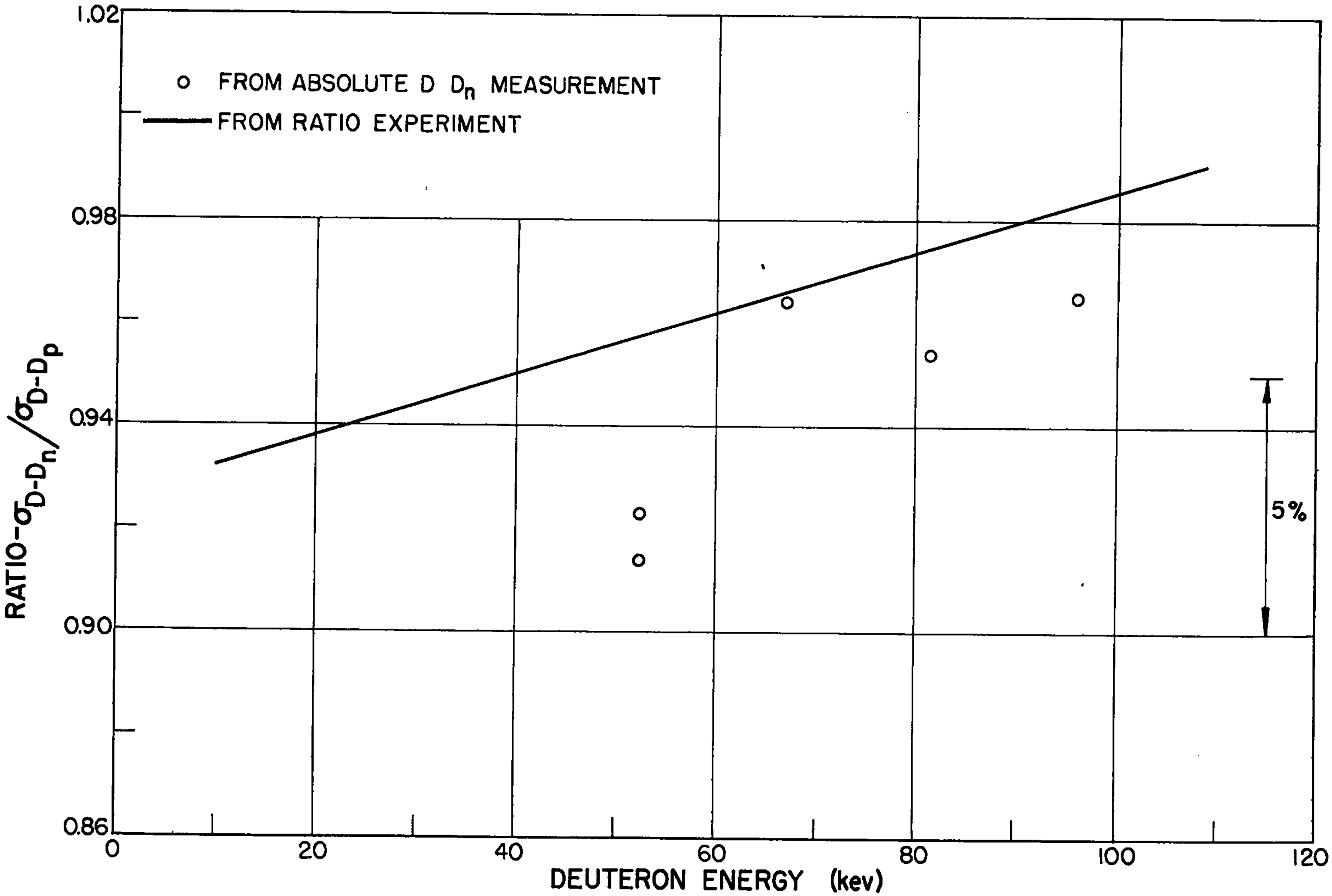

Fig. 10. Ratio $D\text{-}D_n/D\text{-}D_p$

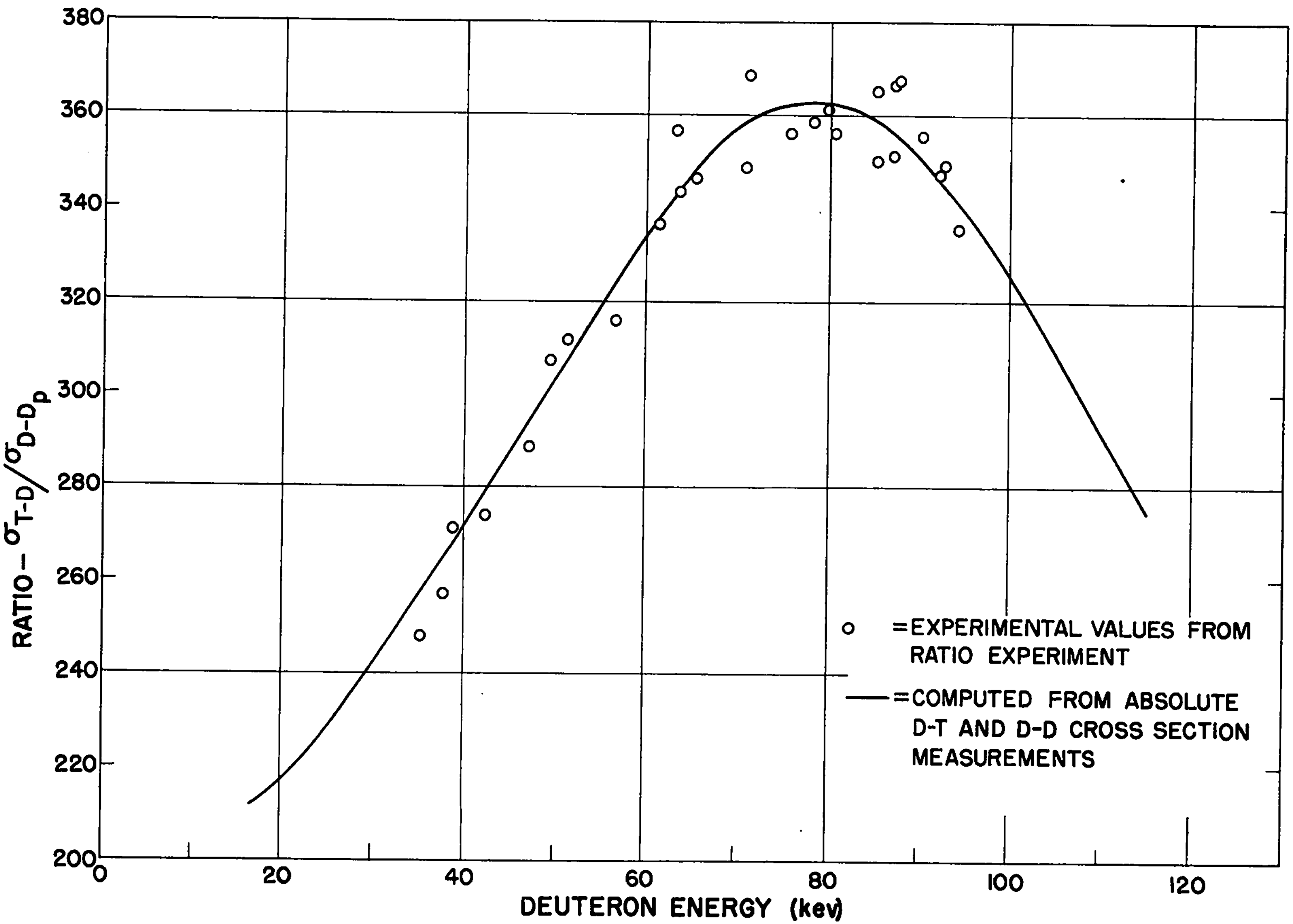

Fig. 11. Ratio $\frac{\sigma_{T-D}}{\sigma_{D-D}}$ vs energy