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LOW ENERGY CROSS SECTIONS FOR THE D-D and D-T REACTIONS

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Previous computations of cross sections for the D-D and D-T reactions were dependent upon the knowledge of the energy loss of deuterons and tritons in D_2O ice targets. The values for $\frac{dE}{dx}$ in the proton energy range of 0-40 kev were very uncertain and it was virtually impossible to estimate a probable error for the cross sections. Recent experimental work at the University of Nebraska[(1)] on the energy loss of protons in H_2 and O_2 have been sufficiently consistant to correct the results of the measurements of Bretscher, French, and Sidel.[(2),(3)]

The following discussion does not describe the methods used by this laboratory in making the $\frac{dE}{dx}$ measurements nor attempt to evaluate the resultant cross sections. It was felt that a new estimate of the cross sections would be of sufficient interest to warrant the rather unusual procedure of using the results of the $\frac{dE}{dx}$ measurements prior to a complete description of methods.

(1) Unpublished.
(2) Bretscher, French, and Sidel. Phys. Rev. 73, 815 (1948).
(3) Bretscher and French, Phys. Rev. 75, 1154 (1949).

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The energy loss of protons in the energy range of zero to forty kilovolts has been found to follow the relation

$$\frac{dE}{dx} = \frac{3}{2k} E_p^{\frac{1}{3}}$$

or the extrapolated range may be expressed as

$$R = k E_p^{\frac{2}{3}}$$

Assuming that the molecular stopping power of H_2O may be found by adding the atomic stopping powers of two atoms of H and one atom of O, the energy loss of protons in H_2O may be expressed by

$$\left.\frac{dE}{dx}\right)_{H_2O} = \left.\frac{dE}{dx}\right)_{H_2} + \frac{1}{2}\left.\frac{dE}{dx}\right)_{O_2}$$

$$= \frac{3}{2} E_p^{\frac{1}{3}} \left[\frac{1}{k_{H_2}} + \frac{1}{2}\frac{1}{K_{O_2}}\right]$$

This is assumed also to hold for D_2O since the electronic configuration of the H_2O and D_2O molecules are nearly the same.

The energy loss of a deuteron of energy E_D will be the same as the energy loss of a proton of energy E_p if the condition $V_p = V_D$ is satisfied. Therefore a deuteron of energy $2E_p$ will lose the same amount of energy per unit path length as a proton of energy E_p. The expression for the energy loss of a deuteron in water vapor may be written

$$\left.\frac{dE}{dx}\right)_{H_2O} = \frac{3}{2}\left(\frac{E_D}{2}\right)^{\frac{1}{3}}\left(\frac{1}{K_{H_2}} + \frac{1}{2K_{O_2}}\right)$$

The applicable values of k obtained experimentally are

$$K_{H_2} = 11.1 \ CM/KEV^{1/3}, \quad K_{O_2} = 7.40 \ CM/KEV^{1/3}$$

for the gas at 1 mm pressure and 15°C.

Reducing the above expression results in the relationship,

$$\left.\frac{dE}{dx}\right)_{H_2O} = .243 \ E_c^{1/3} \ KEV/CM$$

The expression for the cross section used by Bretscher et al[2] is

$$\sigma(E) = \frac{1}{A} \frac{dN}{dE} \frac{dE}{dx}$$

Since this paper failed to tabulate the values of $\frac{dN}{dE}$ as a function of energy, the simplest method of correcting the data is to multiply each cross section derived by Bretscher by the ratio

$$\left.\frac{dE}{dx}\right)_{H_2O}^{N} \div \left.\frac{dE}{dx}\right)_{H_2O}^{B}$$ where the numerator

is the value obtained at Nebraska and the denominator is the value used by Bretscher. Since all Bretscher's data had to be taken from a graph, the computations (Table 1) might be of greater value if the values of $\sigma(E)$ and $\left.\frac{dE}{dx}\right)_{H_2O}^{B}$ were taken from Bretscher's original data.

Following the same method as before, the energy loss of a triton of energy E_t will be the same as the energy loss of a proton of energy E_p if $V_p = V_t$. Therefore the energy loss of a triton of energy $3 E_p$ will be the same as the energy loss of a proton of energy E_p. The expression for the energy loss in H_2O is

$$\left.\frac{dE}{dx}\right)_{H_2O} = \left(\frac{E_T}{3}\right)^{\frac{1}{3}} \frac{3}{2} \left(\frac{1}{K_{H_2}} + \frac{1}{2K_{O_2}}\right)$$

$$= .213 \; E_T^{\frac{1}{3}}$$

The original paper by Bretscher and French[3] tabulates the values of $\frac{dN}{dE}$ and $\frac{dE}{dx}$ used in computing the cross section. The computations (Table 2) are therefore more straightforward than in the previous case.

The Gamow plot of the experimental points follows the theoretical slope to a somewhat higher energy (Figure 4). If the Gamow formula, modified by a resonance factor, is applied to the data as Bretscher and French have done, the resonance peak is also shifted to a higher energy. Although it is not always clear when one obtains a "best fit," a similar analysis was made to the revised data and a good fit was obtained with the following parameters,

$$E_R = 160 \text{ KEV} \qquad \Gamma = 113 \text{ KEV}$$

The points derived from this calculation are plotted on Figure 4.

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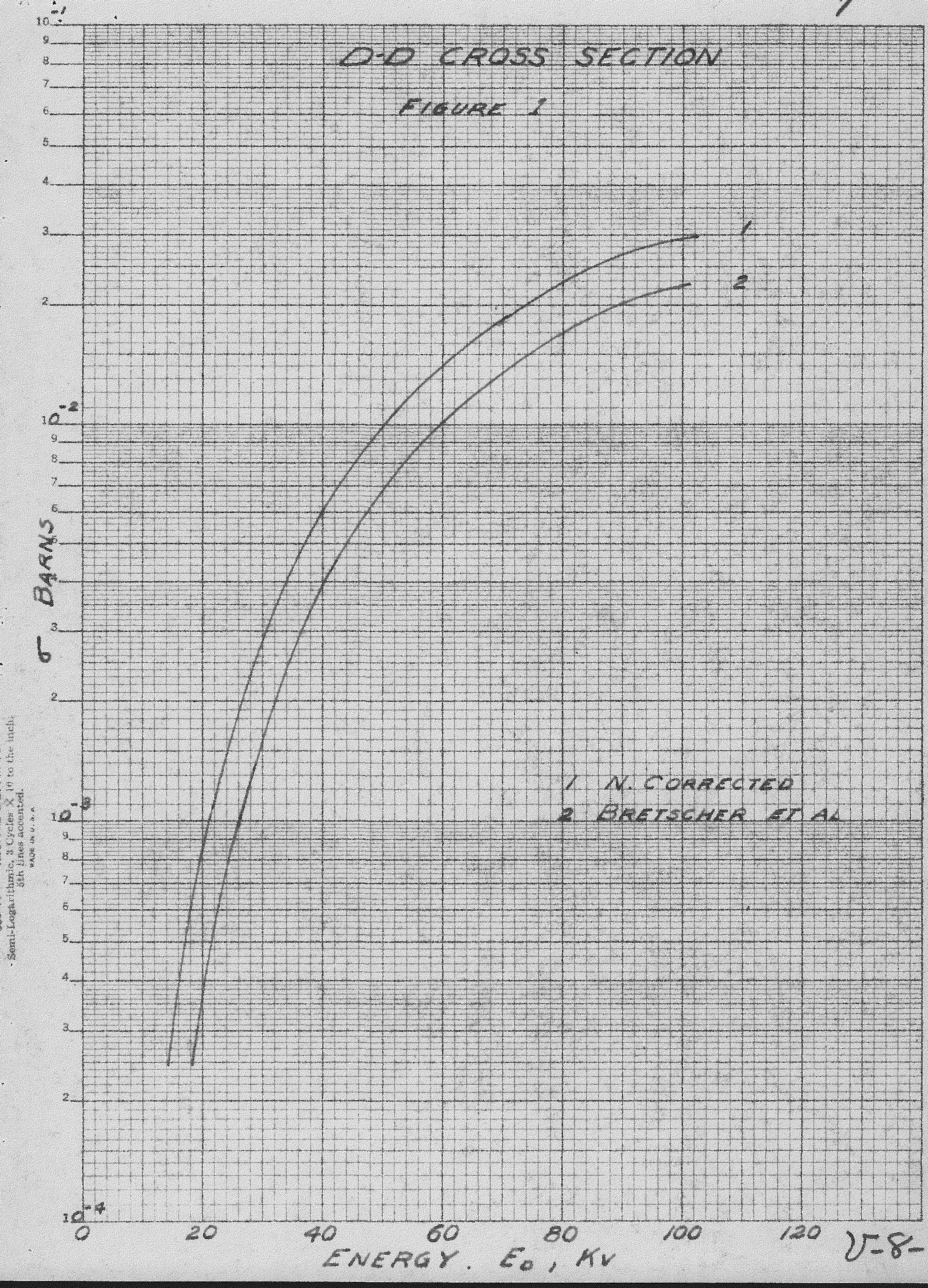
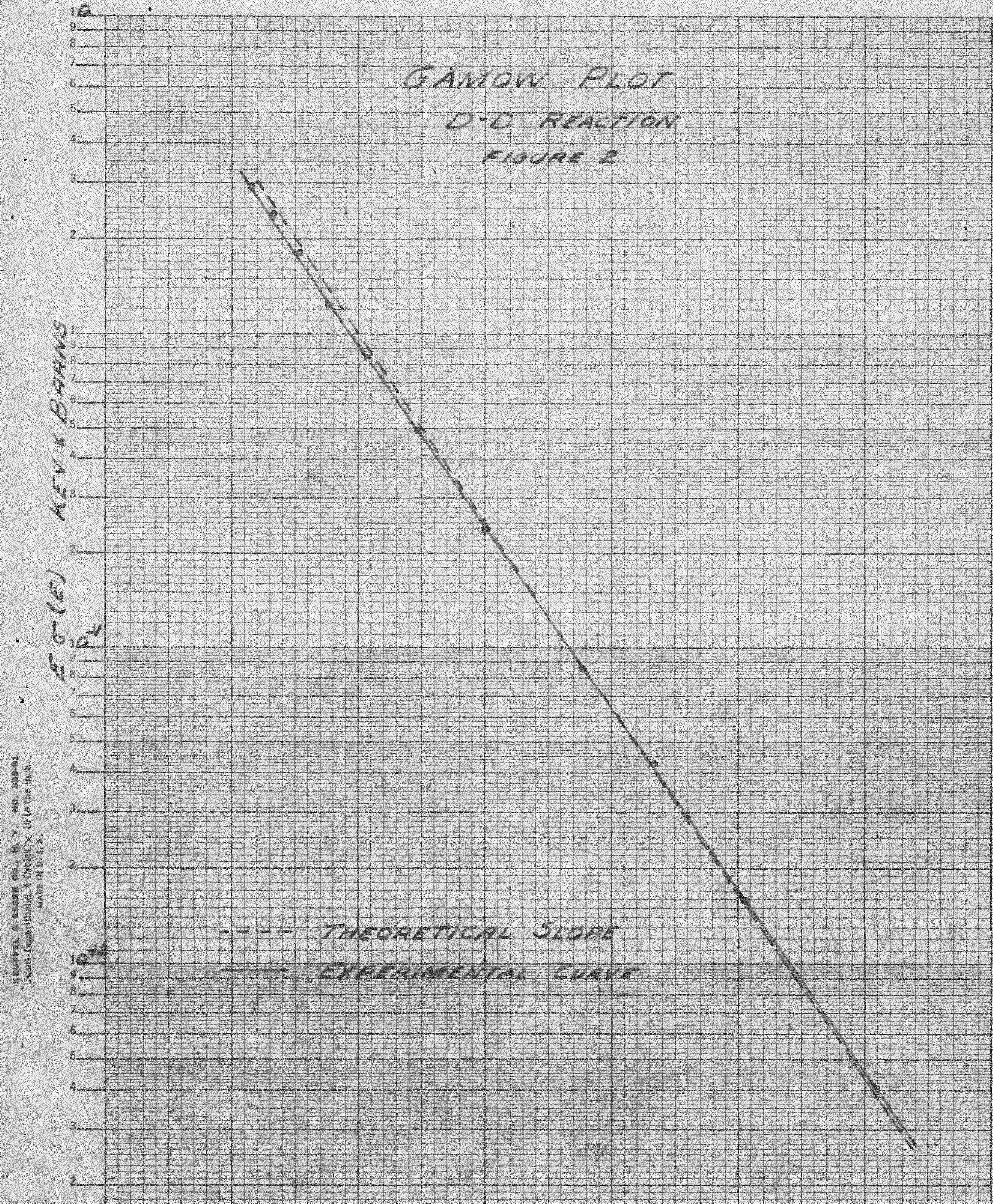
$E_{D\,KEV}$	$E_{T\,MEV}^{-\frac{1}{2}}$	$\left.\frac{dE}{dx}\right)_{H_2O}^{B} \frac{KEV}{CM}$	$\left.\frac{dE}{dx}\right)_{H_2O}^{N} \frac{KEV}{CM}$	$\frac{\left.\frac{dE}{dx}\right)_{H_2O}^{N}}{\left.\frac{dE}{dx}\right)_{H_2O}^{B}}$	$\sigma(E)$	$E\sigma(E)$
15	8.20	.225	.600	2.66	$2.7 \cdot 10^{-4}$	$4.05 \cdot 10^{-3}$
20	7.10	.300	.659	2.20	$7.9 \cdot 10^{-4}$	$1.58 \cdot 10^{-2}$
25	6.34	.370	.710	1.92	$1.71 \cdot 10^{-3}$	$4.28 \cdot 10^{-2}$
30	5.78	.425	.756	1.78	$2.85 \cdot 10^{-3}$	$8.55 \cdot 10^{-2}$
40	5.00	.530	.831	1.57	$5.97 \cdot 10^{-3}$	$2.39 \cdot 10^{-1}$
50	4.46	.610	.894	1.47	$9.85 \cdot 10^{-3}$	$4.93 \cdot 10^{-1}$
60	4.08	.680	.950	1.40	$1.40 \cdot 10^{-2}$	$8.40 \cdot 10^{-1}$
70	3.77	.730	1.00	1.37	$1.78 \cdot 10^{-2}$	$1.25 \cdot 10^{-1}$
80	3.54	.780	1.05	1.34	$2.28 \cdot 10^{-2}$	$1.82 \cdot 10^{-1}$
90	3.33	.820	1.09	1.33	$2.66 \cdot 10^{-2}$	$2.39 \cdot 10^{-1}$
100	3.16	.860	1.13	1.31	$2.88 \cdot 10^{-2}$	$2.88 \cdot 10^{-1}$

The results of this computation are indicated in Figures 1 and 2.

$E_{T_{KEV}}$	$E_{T_{MEV}}^{-\frac{1}{2}}$	$\left.\frac{dE}{dx}\right)_{H_2O}^{N}$	$\frac{dN}{dE}\cdot 10^{-4}$	$\frac{dE}{dx}\frac{dN}{dE}$	$\sigma(E)$	$E\sigma(E)$
15.0	8.20	.524	.152	.080	$1.90\cdot 10^{-3}$	$2.85\cdot 10^{-2}$
17.5	7.56	.554	.330	.183	$4.40\cdot 10^{-3}$	$7.70\cdot 10^{-2}$
20	7.09	.577	.630	.364	$8.70\cdot 10^{-3}$	$1.74\cdot 10^{-1}$
25	6.32	.623	1.68	1.05	$2.50\cdot 10^{-2}$	$6.25\cdot 10^{-1}$
30	5.78	.662	3.55	2.35	$5.59\cdot 10^{-2}$	1.68
35	5.34	.697	6.25	4.36	$1.04\cdot 10^{-1}$	3.63
40	5.00	.729	9.90	7.22	$1.72\cdot 10^{-1}$	6.87
45	4.71	.758	14.7	11.14	$2.65\cdot 10^{-1}$	11.93
50	4.46	.784	20.0	15.68	$3.73\cdot 10^{-1}$	18.66
55	4.25	.809	26.1	21.12	$5.03\cdot 10^{-1}$	27.67
60	4.08	.833	33.3	27.74	$6.60\cdot 10^{-1}$	39.60
65	3.92	.856	42.0	35.95	$8.56\cdot 10^{-1}$	55.64
70	3.77	.878	50.2	44.08	1.05	73.43
75	3.64	.899	60.0	53.94	1.28	96.30
80	3.53	.918	68.5	62.88	1.50	118.8
85	3.42	.937	80.0	74.96	1.78	151.6
90	3.33	.954	91.0	86.81	2.07	185.9
95	3.24	.971	103.	100.0	2.38	226.1
100	3.16	.988	115.	113.6	2.70	270.4
105	3.08	1.005	129.	129.7	3.09	324.0
110	3.01	1.020	138.	140.8	3.35	368.5
115	2.94	1.035	151.	156.3	3.72	427.8
120	2.89	1.050	164.	172.2	4.10	491.8
125	2.82	1.065	177.	188.5	4.49	560.9

The results of this computation are indicated in Figures 3 and 4.


D-D CROSS SECTION
FIGURE 1
σ BARNS
ENERGY, E₀, Kv
1 N. CORRECTED
2 BRETSCHER ET AL
0
20
40
60
80
100
120
KEUFFEL & ESSER CO.
359-71 Semi-Logarithmic, 3 Cycles X 10 to the inch. 5th lines accented.
MADE IN U.S.A.


GAMOW PLOT
D-D REACTION
FIGURE 2
THEORETICAL SLOPE
EXPERIMENTAL CURVE
$E\sigma(E)$ KEV x BARNS
$E_D^{-\frac{1}{2}}$ MEV
KEUFFEL & ESSER CO., N. Y. NO. 359-81
Semi-Logarithmic, 4 Cycles X 10 to the inch.
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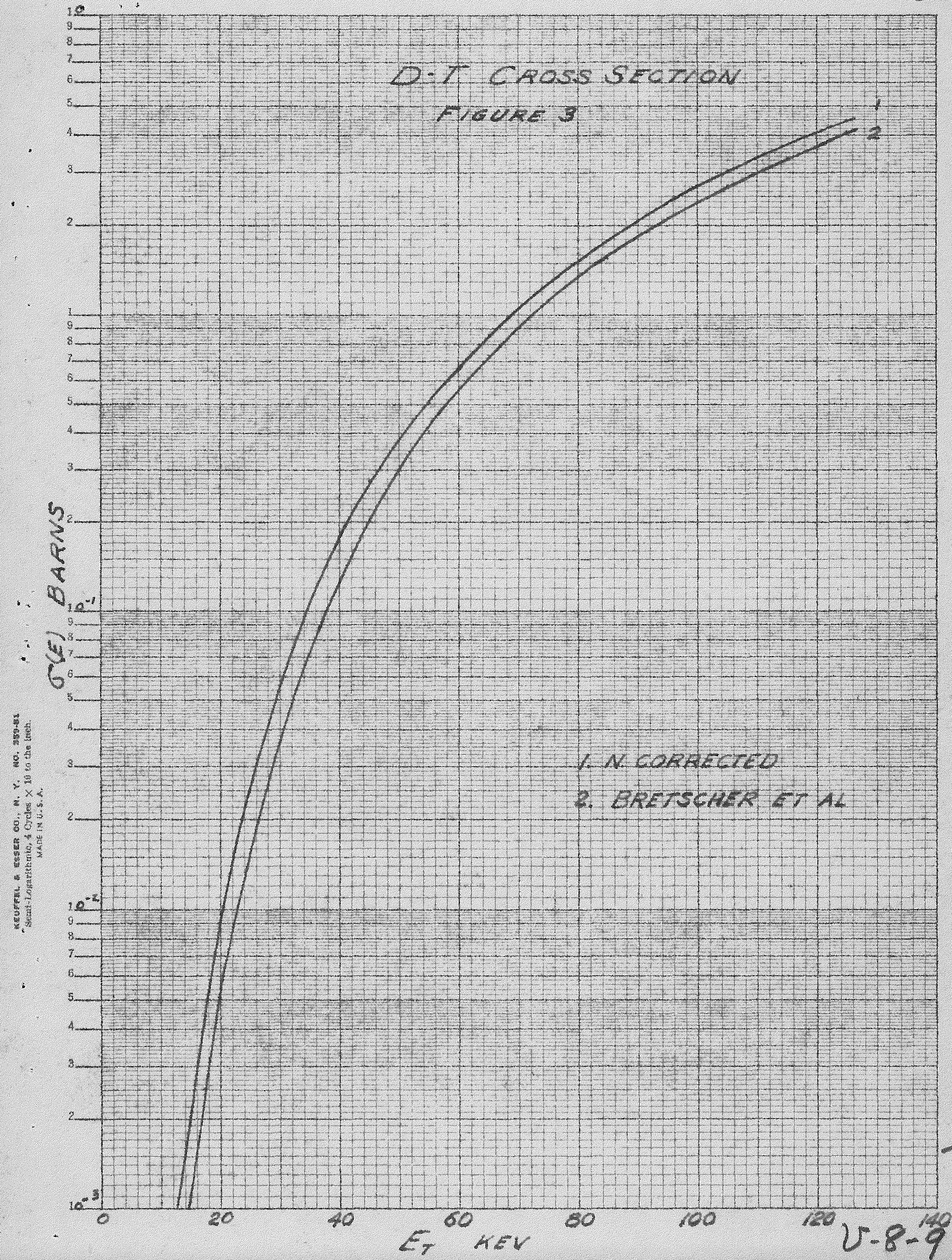
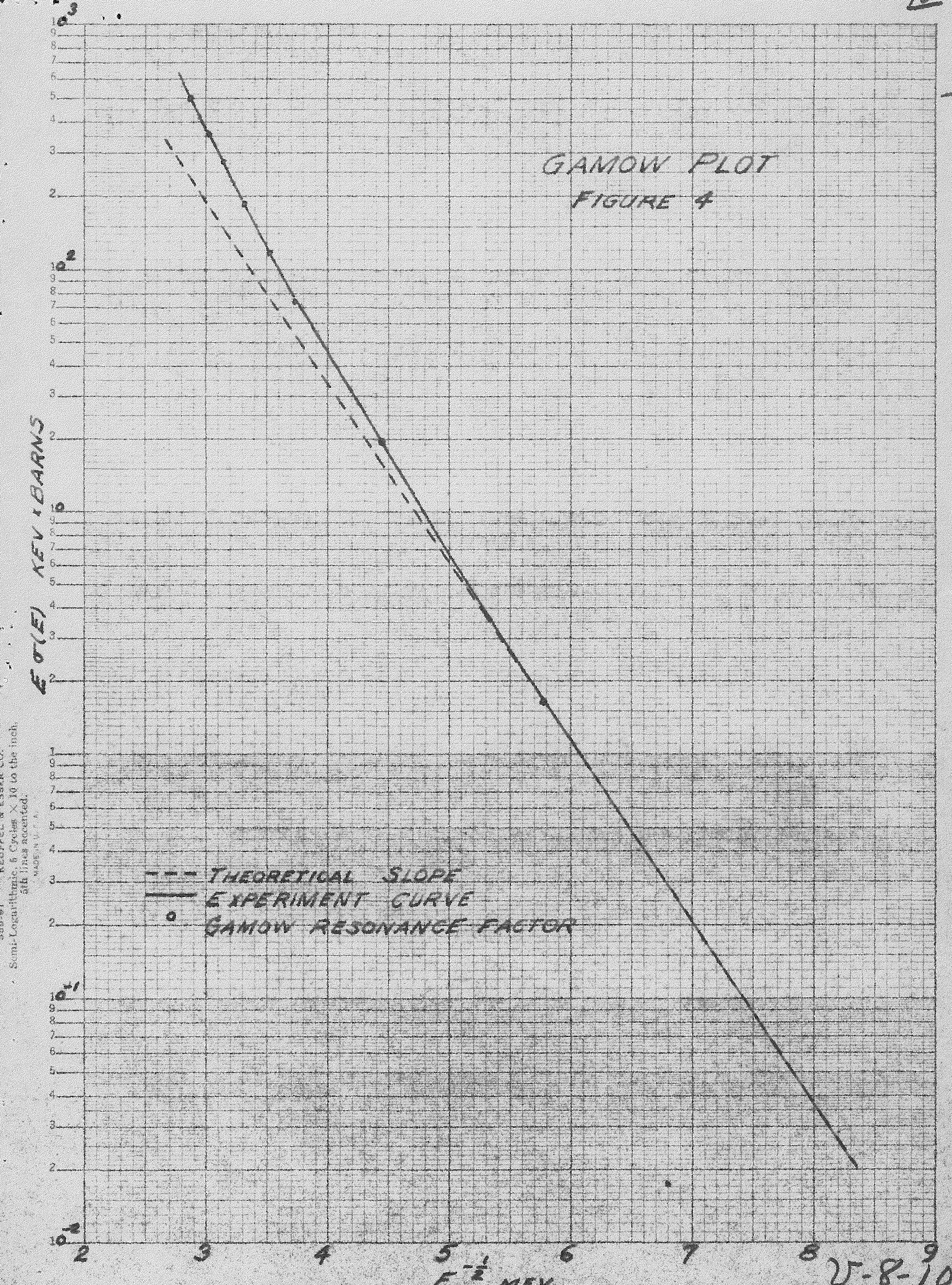


D-T CROSS SECTION
FIGURE 3
1
2
1. N. CORRECTED
2. BRETSCHER ET AL
σ(E) BARNS
E_T KEV
0
20
40
60
80
100
120
140
10^{-3}
10^{-2}
10^{-1}
10^0
KEUFFEL & ESSER CO., N. Y. NO. 359-81
Semi-Logarithmic, 4 Cycles × 10 to the inch.
MADE IN U.S.A.


GAMOW PLOT
FIGURE 4
$E\sigma(E)$ KEV × BARNS
$E_T^{-\frac{1}{2}}$ MEV
--- THEORETICAL SLOPE
— EXPERIMENT CURVE
o GAMOW RESONANCE FACTOR
359-91 KEUFFEL & ESSER CO.
Semi-Logarithmic, 5 Cycles × 10 to the inch, 5th lines accented.
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