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LOS ALAMOS, NEW MEXICO

CONTRACT W-7405-ENG.36 WITH THE
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Report written:
October 15, 1954

LA-1853

This document consists of 18 pages

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TOTAL NEUTRON CROSS SECTION OF He^3

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PHYSICS AND MATHEMATICS
(M-3679, 15th edition)

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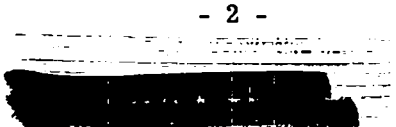
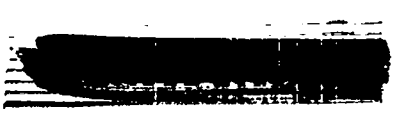


ABSTRACT

The total neutron cross section of He^3 has been measured over the energy range from 200 kev to 22 Mev in good geometry. The main feature of the curve is a maximum at 2 Mev, superimposed on a decrease in cross section that is otherwise monotonic with increase in energy. Where the known $He^3(n,p)T$ cross section overlaps these measurements, it comprises about one-third of the total cross section and has a similar variation with energy. The total elastic scattering cross section is obtained from the difference between the total cross section and the (n,p) cross section for neutron energies from 600 kev to 4 Mev.



1. Introduction

Because of the very strong binding of the last nucleon in He^4, the interaction of neutrons with He^3 can be interpreted in terms of the characteristics of the alpha particle at high excitations, i.e., from about 20.5 Mev to about 35 Mev for the range of these measurements.

The compound states formed by the scattering of neutrons from He^3 and H^3 are two members of an isotopic spin triplet, with $T_Z = 0$ and $T_Z = +1$, respectively. The third, with $T_Z = -1$, corresponds to protons incident on He^3, or excited states of Li^4. It should be of interest to compare the properties of the members of this triplet because of their bearing on the charge independence of nuclear forces. This triplet has the unique property that in addition to the substitution of an n-n for p-p bond (the property of mirror nuclei), there is one n-p bond substituted for one n-n or p-p bond. The total scattering cross section is obtained from the difference between the total cross section and what is known of the total reaction cross section. No direct measurements of the elastic scattering of neutrons from He^3 have been reported as yet.

These measurements may be regarded as part of an informal program of fundamental nuclear measurements of the very light nuclides which have been carried out by various members of the Los Alamos Scientific Laboratory in recent years, a program which has been facilitated by access to large quantities of H^3 and He^3.

2. Method and Procedure

The total cross section of He^3 for monoenergetic neutrons has been calculated from the results of a measurement in good geometry of the neutron transmission T of a vessel filled with He^3, according to the formula

$$T = e^{-N\sigma}$$

where N is the number of He^3 nuclei per square centimeter of sample, and σ is the cross section to be determined.

The vessel was cylindrical, 1 meter long, 7/8 inch i.d., with a 1/16-inch wall, welded end-cups 0.100 inch thick, a filling line of flexible capillary tubing, and double valves, all of stainless steel. A detailed description of the design and testing of the vessel is to be found in a report by R. L. Mills and F. Edeskuty.[1] This cell was used earlier for the measurements of the total neutron cross section of tritium.[2]

Filling of the vessel and subsequent recovery of the He^3 were carried out by T. R. Roberts. An account of this work is given in Appendix A.

Determinations of the number of nuclei per square centimeter of the sample were carried out by PVT measurements and by weighing, together with a mass-spectroscopic analysis of the sample. This work was done by Roberts and Mills. A report by Mills describing the work is given in Appendix B. The filling pressure was 1450 psi, corresponding to 1.47 moles of He^3. The impurities were less than 0.4 per cent of the number of He^3 moles.

Monoenergetic neutrons were generated by the large Van de Graaff, using the reaction $T(p,n)He^3$ for the neutron energy range from 0.14 to 4.25 Mev. For the range from 4.25 to 8.03 Mev the reaction $D(D,n)He^3$ was used, and for the range from 14.2 to 21.4 the reaction was $T(D,n)He^4$. In all cases gas targets were used, sealed off with 1/20-mil nickel foil.

The target-to-detector distance was 152 cm, with the gas vessel midway between them. The detector was a stilbene scintillator, 3/4 inch in diameter and 1 1/2 inches long, coupled to a Dumont 6467 photomultiplier, which was followed by a linear amplifier and scaler. The same detector system was used for all the data; only the amplifier gain, photomultiplier voltage, and scaler bias were changed with energy.

Backgrounds were taken with a copper bar 24 inches long in place of the cell, and with the target evacuated. The amplifier gain and scaler bias were set so that the counting rate with the copper bar in place was 1 per cent or less of the counting rate without the bar. The flux with sample out was taken with a dummy evacuated cell in lieu of the sample.

Sufficient counts were taken to assure an over-all rms error of not more than 1 per cent in the transmission.

3. Results

The cross sections obtained as a function of energy are summarized in Table 1, in curve 1 of Fig. 1 on a log-log scale, and in Fig. 2 on a linear scale. The neutron energies given correspond to the average energy of a neutron generated in the gas target. The spread in neutron energy given in Table 1 is due to the target thickness and corresponds to half the thickness of the target. This spread is to be interpreted as half the effective spread in neutron energy, except for the two lowest energy points. At those energies the bias of the detector and the shape of the yield curve discriminated against the lower-energy neutrons, so that the spread in effective energy is less than the spread in neutron energy, perhaps only two-thirds as much.

The observed transmissions range from 0.44 to 0.83. The uncertainty in the cross section associated with the 1 per cent standard error of the transmission, which is due to statistical uncertainty, is 2 per cent for the lowest transmission and 5 per cent for the highest. Other sources of uncertainty in the cross-section including effect of He^3 impurities, uncertainty

TABLE 1

TOTAL NEUTRON CROSS SECTION OF He^3 AS A FUNCTION OF ENERGY

E_n, Mev	ΔE_n, Mev	σ_t, barns	E_n, Mev	ΔE_n, Mev	σ_t, barns
0.14	±0.050	3.44	4.25	±0.016	2.58
0.28	±0.040	3.12	4.85	±0.100	2.40
0.39	±0.050	2.92	5.44	±0.075	2.28
0.505	±0.047	2.82	5.97	±0.063	2.19
0.736	±0.042	2.75	6.50	±0.057	2.04
0.955	±0.038	2.85	7.00	±0.052	2.01
1.17	±0.035	2.95	7.52	±0.046	1.90
1.39	±0.032	3.09	8.03	±0.035	1.86
1.60	±0.030	3.20	14.8	±0.250	1.14
1.77	±0.027	3.20	16.0	±0.400	1.04
2.02	±0.025	3.23	16.9	±0.200	1.02
2.22	±0.023	3.28	17.6	±0.120	0.96
2.42	±0.021	3.08	18.2	±0.090	0.88
2.63	±0.021	3.06	18.8	±0.075	0.93
2.83	±0.020	2.97	19.3	±0.060	0.88
3.04	±0.019	2.95	19.9	±0.055	0.87
3.23	±0.019	2.85	20.4	±0.050	0.87
3.44	±0.018	2.86	20.9	±0.045	0.88
3.64	±0.018	2.74	21.4	±0.040	0.81
3.84	±0.018	2.66			
4.05	±0.017	2.57			

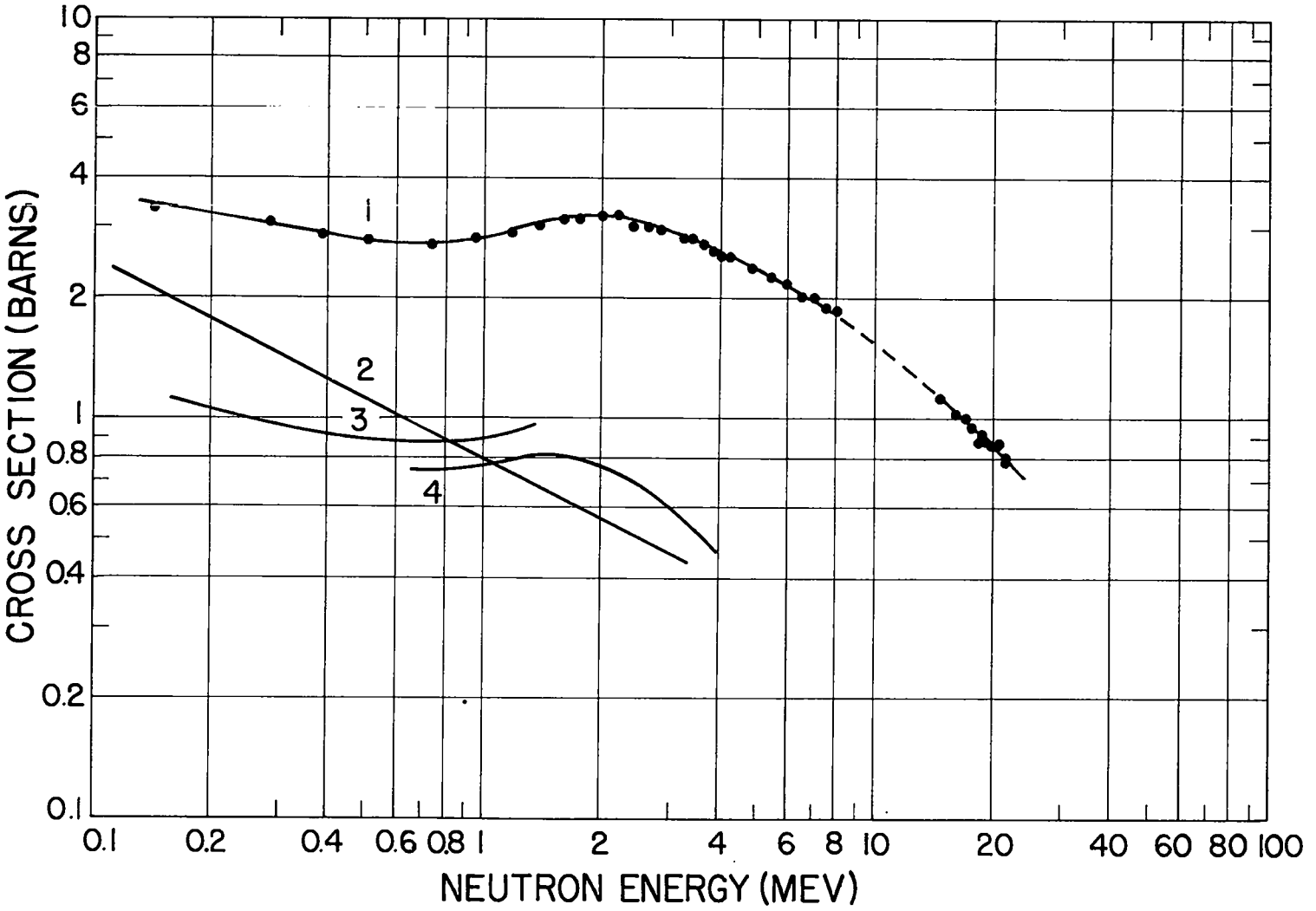


Fig. 1. Curve 1 is the measured total neutron cross section of He^3. Curve 2 is the total neutron cross section extrapolated from thermal data. Curves 3 and 4 are the reaction cross sections for $He^3(n,p)T$ calculated from the data on the inverse reaction.

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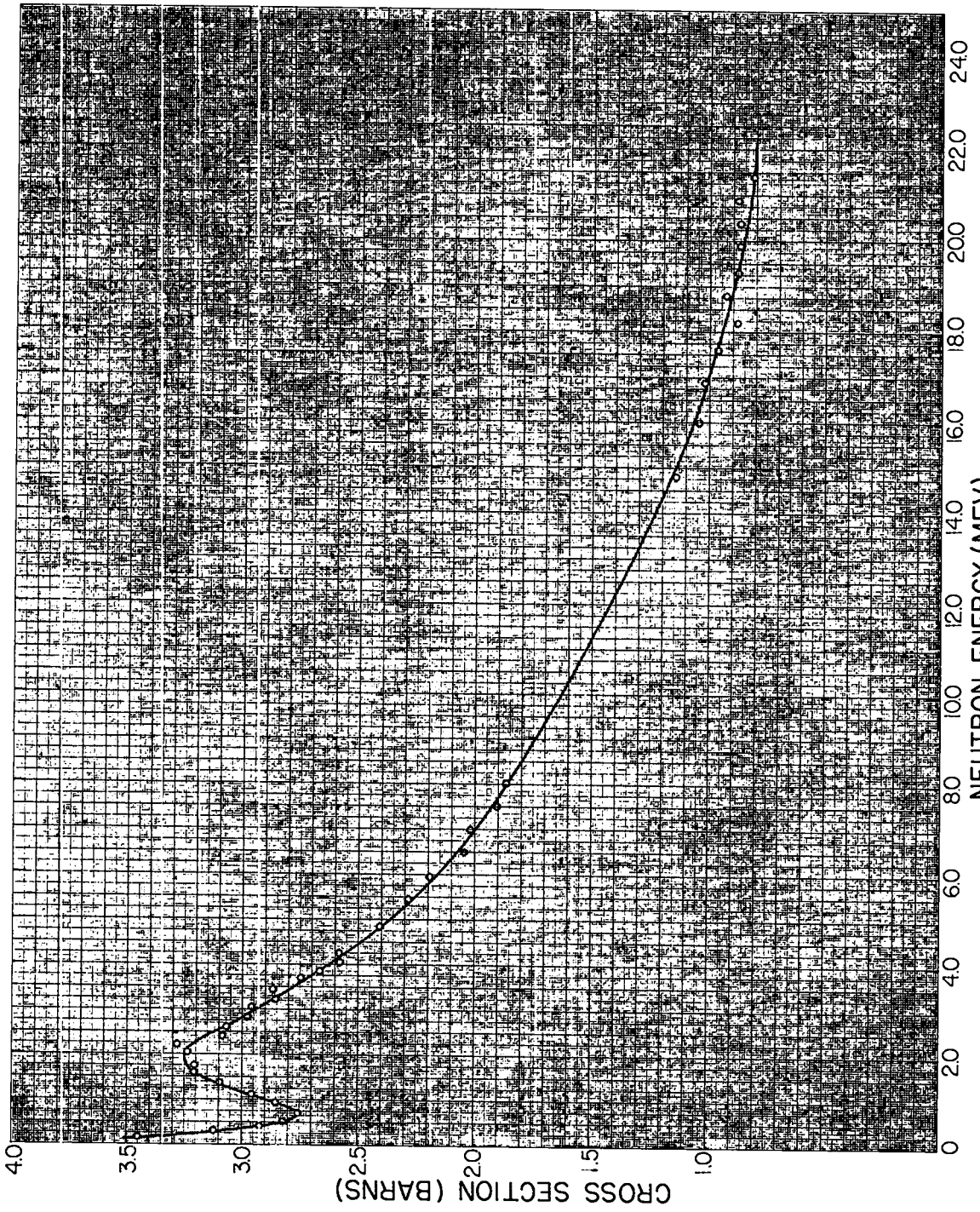

Fig. 2. Linear plot of the total neutron cross section of He^3.

in the dimensions and contents of the cell, and inscattering by the sample, are estimated to have a combined effect not greater than 1 per cent at any cross section. The sum of the statistical and miscellaneous uncertainties at each energy is very close to 0.06 barns.

The most noteworthy feature of the results is the broad maximum centered at 1.9 ± 0.2 Mev, superimposed on a decrease that is monotonic with increasing energy. The general shape is similar to that which has been found by Coon et al.[2] for the total cross section of tritium, that is, a broad maximum in the Mev region, followed by a smooth drop at higher energies. At low energies the He^3 cross section increases, presumably because of the large $He^3(n,p)T$ contribution to the cross section at the lower energies.

In the region up to 4.35 Mev neutron energy, the only reactions of neutrons with He^3 energetically possible are elastic scattering, radiative capture, and the (n,p) reaction. If, following Flowers and Mandl,[3] it is assumed that the cross section for $He^3(n,\gamma)He^4$ is of the same order of magnitude as $T(p,\gamma)He^4$, that is, of the order of 10^{-28} cm^2, then the difference between the total neutron cross section and the (n,p) reaction cross section is essentially the elastic scattering cross section.

Curve 2 in Fig. 1 is an extrapolation on a 1/v basis of the total cross section for He^3 from measurements at thermal and subthermal energies by King and Goldstein.[4] This extrapolation provides a rough estimate of that part of the total cross section due to the (n,p) reaction. A more reliable estimate of the latter can be obtained from the principle of detailed balance by using the results of Jarvis et al.[5] and Willard et al.[6] for the inverse reaction $T(p,n)He^3$. These are given as curves 3 and 4, respectively, of Fig. 1. In the case of Willard's data, only that part of the results which corresponds to the experimental points is used. The extrapolation to threshold is presumed in error because it does not have the correct slope at threshold and corresponds to a decrease in the (n,p) reaction cross section with decrease in energy. A third set of data taken at this Laboratory[7] with improved background determinations corroborate Willards's results.[6] The discrepancy between Jarvis et al. and Willard et al. is therefore to be resolved in favor of the latter. Direct data on the reaction cross section obtained by Coon[8] are consistent with the data of curves 3 or 4.

The difference between the total neutron and the $He^3(n,p)T$ cross sections is given in Fig. 3, curve 1, using Willard's data. For comparison, curve 2 of Fig. 3 gives the curve of total neutron cross section for tritium as measured by Coon, Bondelid, and Phillips.[2] This is reasonably certain to be entirely due to elastic scattering up to the threshold for T(n,2n)D, 8.34 Mev.

At 4.36 Mev, the reaction $He^3(n,D)D$ becomes possible. From the data of McNeil and Keyser[9] on the inverse reaction, and the principle of detailed balance, the (n,d) reaction

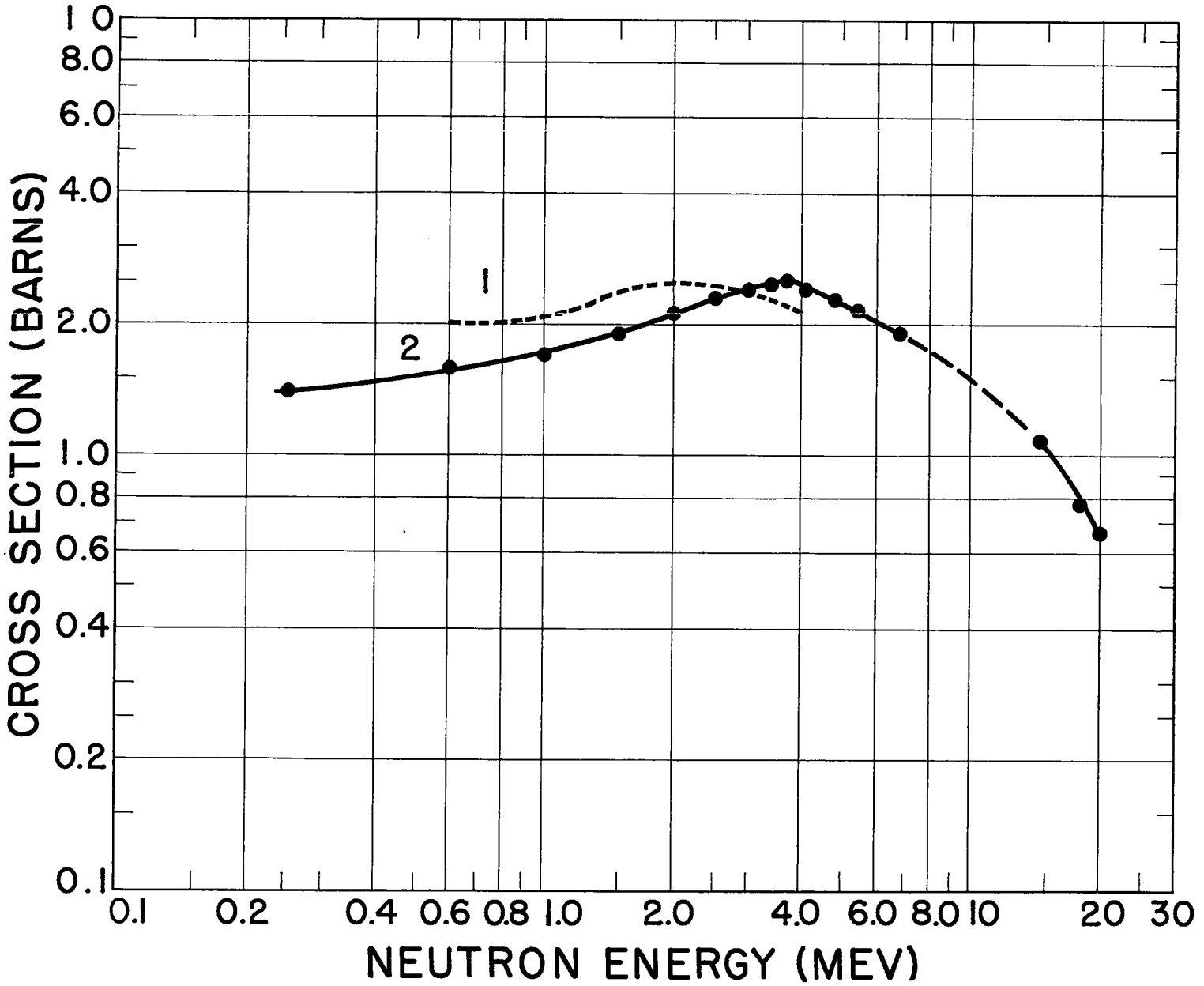

Fig. 3. Curve 1 is the total neutron elastic scattering cross section for He^3. Curve 2 is the total neutron cross section of tritium.

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accounts for 0.004 barn at a neutron energy of 4.50 Mev. From Hunter and Richards[10] data and detailed balance, the (n,d) reaction accounts for 0.097 barn at 6.4 Mev neutron energy, or about 5 per cent of the total. It seems likely that above 4.35 Mev the (n,p) reaction continues to account for an appreciably larger percentage of the total cross section than this, so that further data on the $He^3(n,p)T$ reaction are necessary to extend knowledge of the elastic cross section.

It is noteworthy that the reaction and total cross sections have maxima at the same energy, within experimental error, and, have similar general shapes down to 400 kev. Their ratio varies smoothly from 0.38 to 0.22, with increasing energy. It is interesting, too, to note that the peak cross sections for elastic scattering of neutrons from H^3 and He^3 are equal within the over-all uncertainty of about 0.1 barn. The energies at which the maxima occur differ by about 2 Mev.

4. Discussion

The only theoretical interpretation of these data made thus far is by J. Gammel. He has suggested, tentatively, that the maximum in the scattering at 2 Mev may be interpreted as a p-wave resonance with $J = 2$. This gives a maximum at resonance of about 2.6 barns, compared to the experimental value of 2.45 barns. The same interpretation has been placed on the maximum of the tritium results.

The results on the elastic scattering are of interest in connection with the frequently made suggestion that the $He^3(n,p)T$ reaction be used as a neutron spectrometer.[11] The chief source of background in such an instrument arises from elastic scattering, and these data provide a basis for estimating quantitatively the importance of this background.

APPENDIX A

He^3 CELL FILLING AND RECOVERY

By T. Roberts

The gas vessel was filled with He^3, using a modification of the cryogenic pump technique described by Mills and Edeskuty[1] in connection with the tritium filling of the same vessel. The main difference was that the He^3 was supplied in 12-liter cans at an average pressure of about 400 mm Hg instead of uranium pots. In order to condense most of the He^3 into the pump, the surrounding He^4 bath was cooled by pumping to about 1.2°K, at which temperature the vapor pressure of He^3 is about 20 mm.

The high-pressure filling line and glass vacuum line were similar to those shown in Figs. 6 and 7 of Mills and Edeskuty,[1] which are reported here as Figs. 4 and 5. The pressure gauge was a Heise 0 to 5000 psi gauge filled with mercury to reduce dead volume. A diffusion pump was connected to the high-pressure gauge manifold by only one autoclave valve in order to increase the pumping speed. The nine He^3 tanks furnished by LASL Group CMR-4 were interconnected by a low-pressure manifold of 1/8-inch copper tubing and were also connected to the main manifold by a high-pressure valve.

The cryogenic pump was designed to withstand 8600 psi, according to ASME specifications.[12] The pump had a volume of 87 cc and was made by drilling a 1 1/2-inch hole in a piece of 2 1/2-inch round 321-stainless steel stock. The plug had 1 3/4 standard fine threads. High-pressure tubing 1/4 inch o.d., 3/32 inch i.d., was used for the pump inlet tube to prevent the likelihood of air or tritium plugs. In order to warm the cryogenic pump to room temperature quickly, a 100-watt wire-wound resistor was taped to the pump.

The pump was pressure tested for 16 hours at 8600 psi and the pump, gauge, and high-pressure cell were tested for 60 hours at 1800 psi. To the limit of detectability, about 0.3 per cent, there was no loss in pressure in either experiment.

The only difficulties encountered concerned the sticking of valves on two He^3 tanks. It had been hoped, on the basis of labeled tank contents, that the cell could be filled to 1500 psi or more, but one tank was found to be empty, apparently because the valve stuck shut during the filling by Group CMR-4. The valve on another tank failed to open during the condensation, so that 1452 psi at a cell temperature of 28.5°C, was the maximum pressure that could be achieved.

The He^4 dewar contained about 5 1/2 liters, 3 1/2 of which were used up in pumping the He^4 bath down to 1.2°K and in condensing the He^3. Condensation was stopped when the storage-can pressure had fallen to 55 mm.

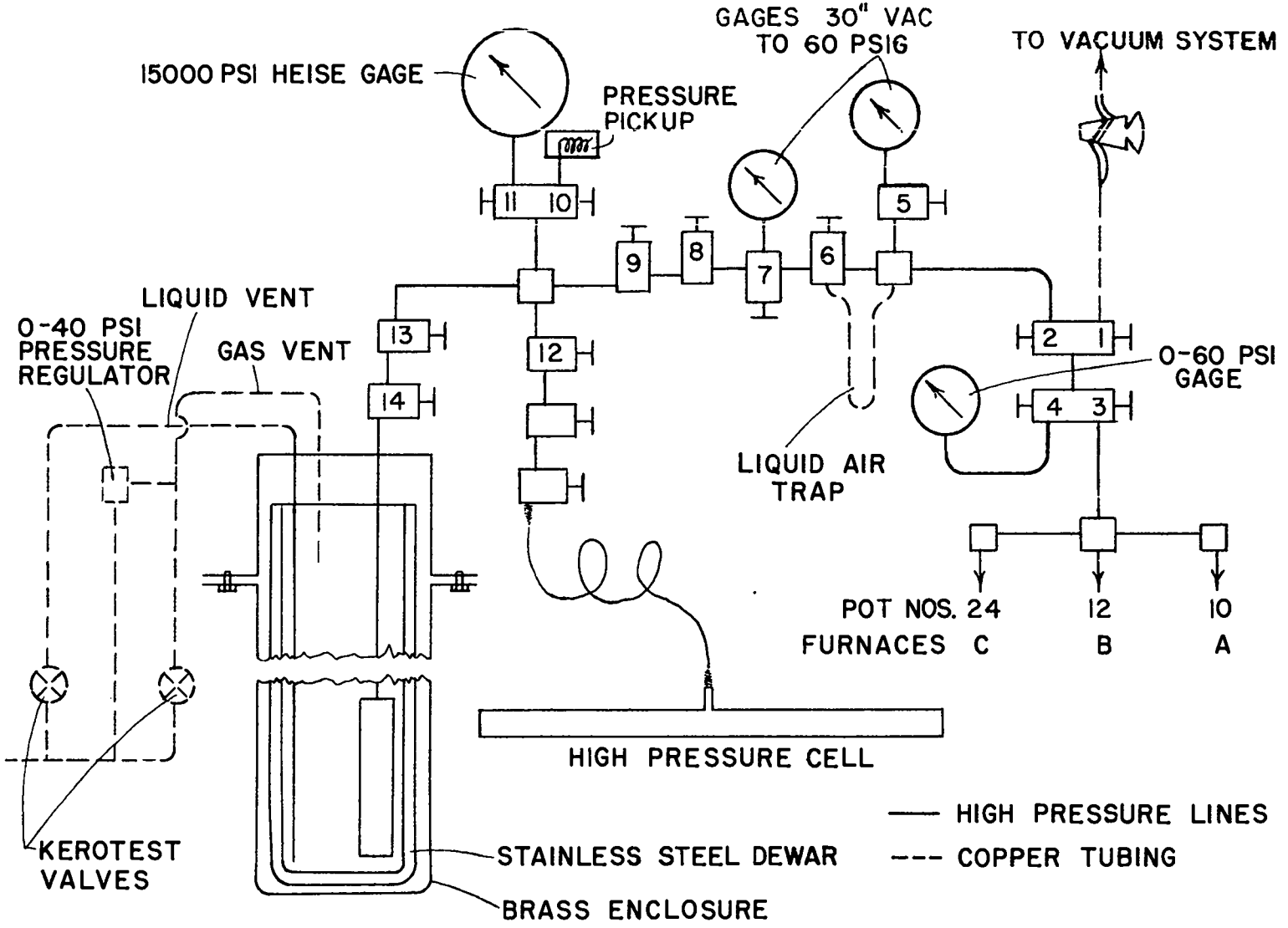

Fig. 4. High-pressure side of filling line.

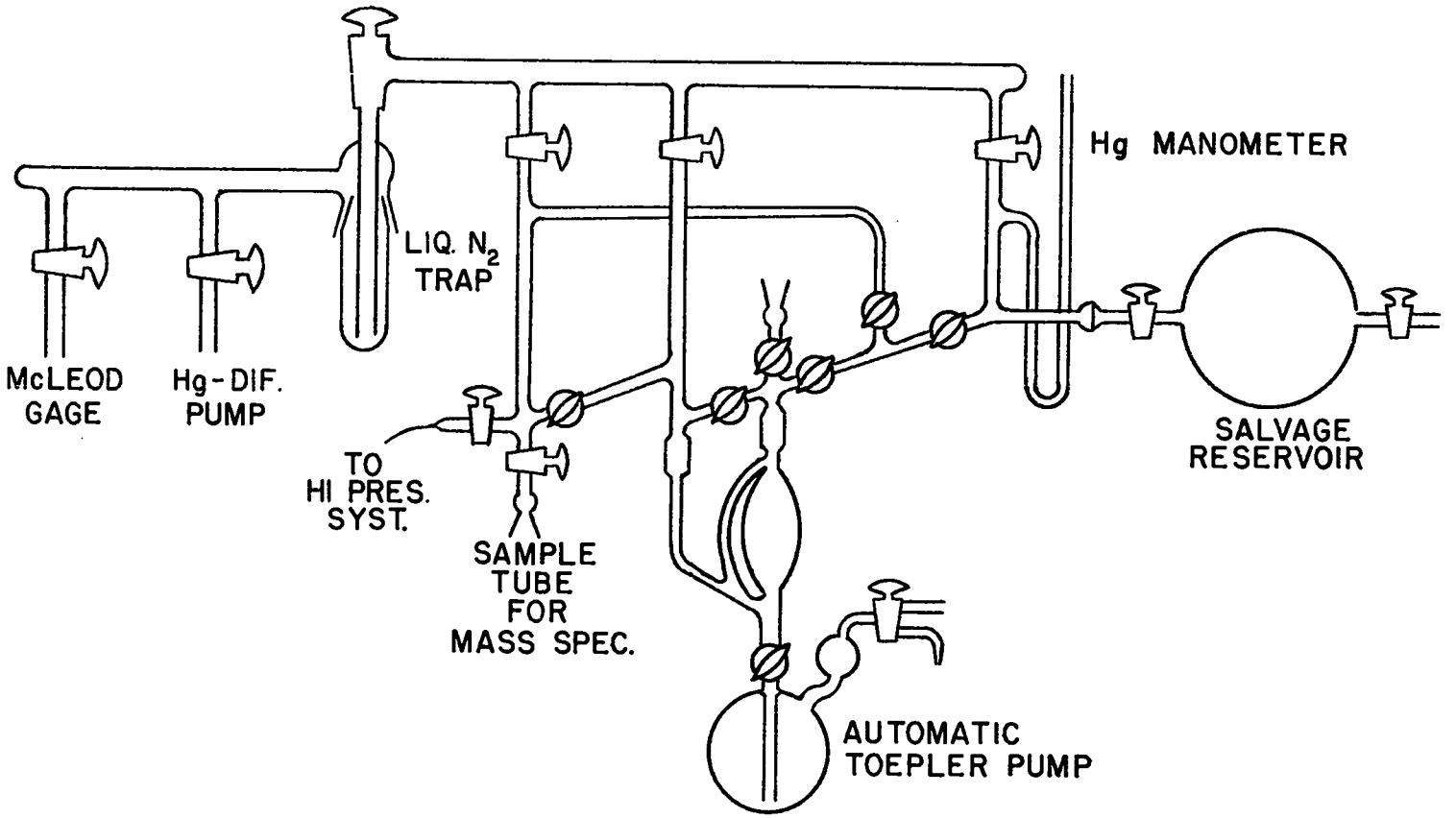

Fig. 5. Glass vacuum system.

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The empty He^3 tank was useful in the recovery operation. After the cell filling, the cryogenic pump and high-pressure manifold were bled down to 14 mm pressure by a two-stage expansion, first into two of the tanks whose pressure was 55 mm, and then into the empty tank. The high-pressure manifold was then emptied with the Toepler pump.

After the cross-section measurements, the cell was reconnected to the high-pressure manifold and the pressure measured as 1441 psi at 27.9°C. The pressure drop was completely accounted for by the temperature change and the expansion into the empty manifold. The cell was then emptied to 500 mm pressure by expansion into seven of the tanks and a sample taken for mass spectrometer analysis. The cell contents then were expanded into the nearly empty tank to 32 mm and the remaining gas removed by Toeplering for three days.

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APPENDIX B

He^3 CELL CONTENT

By R. L. Mills

The total charge in the cell was computed by PVT relationships as indicated in Table 1 and from weight changes as shown in Table 2. Results of the mass-spectrographic analysis of the gas sample are entered in Table 3.

TABLE 1

CELL CONTENT AS DETERMINED BY PVT

Pressure, atm	Volume, cc	Temperature, ^{o}K	Cell Content, moles
98.80 ± 0.10	384.220 ± 0.077	301.6 ± 0.1	1.468[(a)]
			1.470[(b)]
			1.468[(c)]
			1.470[(d)]
		average	1.469 ± 0.002

(a) Computed from the virial equation

$$pv = RT\left[1 + B(T)/v\right]$$

using a value for B(T) determined from the equation

$$B = (1/T)^{1/4}\left[16.4873 - 74.09(1/T)^{1/2} - 24.6(1/T)\right] \text{ cc/g}$$

as given by F. G. Keys, Temperature, pp. 45-59, Reinhold Publishing Corporation, New York, 1941.

(b) Computed from the virial equation using for B(T) the value 11.38 cc/mole, interpolated from data reported by W. H. Keesom, Helium, Table 205, p. 38, Elsevier Publishing Company, Amsterdam, 1942.

(c) Computed from A. C. Johnson's equation of state

$$pv = 24875.08 + 11.802p - 0.001094p^2 \text{ cc atm/mole at } 30^{o}C$$

and corrected to 28.5°C. See "IV - Vapor Pressure, Specific Volume, PVT Data for H_2, N_2, O_2, CO, CO_2, Air, He, A, Hg," by S. Gratch, Trans. ASME, 70, 635 (1948).

(d) Computed from an interpolation of data reported by R. Weibe, V. L. Gaddy, and Conrad Heins, Jr., "The Compressibility Isotherms of He from -70 to 200° and at Pressures up to 1000 atm," J. Am. Chem. Soc., 53, 1721 (1931).

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TABLE 2

CELL CONTENT AS DETERMINED BY WEIGHT DIFFERENCE OF CELL

Wt. Cell Full Minus Tare, g	Wt. Cell Empty Minus Tare, g	Wt. of Gas in Cell, g	Cell Content, moles
4.476	0.017	4.459 ± 0.005	1.453 ± 0.002[a]
			1.478 ± 0.002[b]

[a] Based on an "average molecular weight" of 3.0685 for the gas mixture, as computed from the mass-spectrographic data of Table 3.

[b] Assuming pure He^3 with molecular weight 3.0170.

TABLE 3

MASS SPECTROGRAPHIC ANALYSIS OF CELL SAMPLE

Symbol	Mass Number	Mole %
He^3	3	99.62
N_2	28	0.20
H_2	2	0.05
HT	4	0.05
T_2	6	0.04
HD	3	0.02
DT	5	0.02

Computed cell contents in Tables 1 and 2 do not agree within the combined experimental errors. Such a discrepancy could easily arise if the gas sample analyzed in Table 3 was not truly representative of the cell content. For this reason the results of Table 1 have been used to compute the following concentrations, where L, the cell length, is 99.981 ± 0.005 cm, and N, Avogadro's number, is taken as $6.0228 \pm 0.0011 \times 10^{23}$:

$$(n/V) = 0.003823 \pm 0.000005 \quad \text{mole/cc}$$

$$(L)\,(n/V) = 0.3822 \pm 0.0005 \quad \text{mole/cm}^2$$

$$(N)(L)\,(n/V) = 2.302 \pm 0.003 \times 10^{23} \quad \text{molecules/cm}^2$$

$$(0.9962)(N)(L)(n/V) = 2.293 \pm 0.003 \times 10^{23} \quad \text{molecules } He^3/\text{cm}^2$$

$$(0.0020)(N)(L)(n/V) = 0.0046 \times 10^{23} \quad \text{molecules } N_2/\text{cm}^2$$

[redacted]

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