where odd relative angular momenta are involved, then the yield indicated in Fig. 13 for the reaction producing Be^8 is about where it might be expected on a qualitative basis.

IV. CONCLUSION

The alpha-particle spectra from Li^6+Li^6 contain irregularities which are not yet fully explained. Of special interest is the mechanism involved in the production of alpha peak No. 3. The gamma-ray spectrum indicates a singular lack of the $(T=1)$ states of Be^8 which can be explained by assuming that Li^6 is in the form $\alpha+d$.

ACKNOWLEDGMENTS

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Slow Neutron Cross Sections for He^3, B, and Au

J. ALS-NIELSEN AND O. DIETRICH
The Danish Atomic Energy Commission, Research Establishment Risö, Roskilde, Denmark
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The He^3 neutron cross section was measured for neutron energies from 0.0003 to 11 eV. In this energy region no deviation from the $1/v$ law can be found from the data. The cross section at 2200 m/sec was found to be $\sigma(He^3)=5327_{-9}^{+10}$ b. As an instrumental check the cross sections of natural boron and of gold were also measured and the results agree with the most accurate existing data. The absorption cross sections at 2200 m/sec were found to be $\sigma_a(B)=759.1\pm2.0$ b and $\sigma_a(Au)=98.6\pm0.2$ b.

1. INTRODUCTION

THE total neutron cross section of He^3 was measured for neutron energies from 0.0003–11 eV to obtain more accurate data than available until now.[1]

As an instrumental check the total cross sections of Au and B were also measured and compared with values obtained in other laboratories.[2–4] There were two purposes for the measurement of the He^3 cross section: To show that He^3 might be the best primary standard material for neutron standardization, and for use in determination of the absolute efficiency of a He^3 counter.

The most important property of a standard material is that it possesses an accurately measurable $1/v$ absorption cross section (no resonances). This can generally be deduced from the total cross section by subtraction of the scattering cross sections.

Gold and boron have mainly been used as primary standards, but these both entail some disadvantages.

The major disadvantage of gold is a strong resonance at 4.9 eV; and furthermore the correction for the scattering cross sections (especially the incoherent part) is not too accurate.[2]

The chemical properties of boron imply that the sample must generally be a compound, of which the scattering cross section is rather inaccurately determined for thermal neutron energies on account of the chemical binding.[5] The determination of the B^{10} density is quite complicated and requires an accurate measurement of the isotopic and chemical compositions in the sample.

He^3 is in practice not seriously contaminated by He^4, the cross section of which is also very small. Being a monoatomic gas, no coherence effects from chemical bindings or from lattice configuration can take place. Up to at least 10 eV no trace of resonances has been observed. The cross section is of such a size that a sample length of roughly 10 cm, at a pressure of 1 atm, gives suitable transmission for thermal neutrons, and therefore the determination of the He^3 density consists of a straightforward pressure and temperature measurement and a sample length measurement. All these properties qualify He^3 as an excellent material for neutron cross section standardization.

In a He^3 proportional counter of proper geometry, the absolute efficiency in a neutron beam can be determined very accurately. The detection efficiency, i.e., the ratio between the number of (n,p) processes and the number of counts, can be determined with an accuracy of better than 0.3%,[6] and, by measuring the He^3 pressure carefully and knowing the (n,p) cross section, the absolute

[1] L. D. P. King and L. Goldstein, Phys. Rev. **75**, 1366 (1949).
[2] F. T. Gould, T. I. Taylor, W. W. Havens, Jr., B. M. Rustad, and E. Melkonian, Nucl. Sci. Eng. **8**, 453 (1960).
[3] A. Deruytter, G. Debus, K. Lauer, H. Moret, and A. Prosdocimi, EUR. 12. e, 1962 (unpublished).
[4] G. J. Safford, T. I. Taylor, B. M. Rustad, and W. W. Havens, Jr., Phys. Rev. **119**, 1291 (1960); Nucl. Sci. Eng. **9**, 99 (1961).
[5] P. A. Egelstaff, J. Nucl. Energy **5**, 41 (1957).

efficiency is determined. Such a counter can then be used in the measurements of many partial neutron cross sections.

For use as a primary standard, as well as for the absolute counter purpose, an accuracy of the cross section of approx 0.2% is desirable. The methods for obtaining this accuracy are described in the following sections.

2. EXPERIMENTAL METHOD

The total cross section $\sigma(\lambda)$ is determined by a transmission measurement using the relation

$$T(\lambda)=e^{-N\sigma(\lambda)},$$

where $T(\lambda)$ is the transmission of a sample with N atoms per cm^2 for neutrons of wavelength λ.

The determination of $\sigma(\lambda)$ thus requires a monochromatic neutron beam, a transmission measurement, and a determination of N.

Monochromatization

A crystal spectrometer was used to extract a monochromatic neutron beam from the polyenergetic beam emerging from a horizontal tangential hole in the reactor DR 3 (for further details see Ref. 7). The wavelength is determined by the Bragg condition, $\lambda=2d\sin\theta$, where d is the distance between the reflecting planes in the single crystal and 2θ the angle between the monochromatic and the direct beams. In general, this wavelength only coincides with the actual average wavelength of the reflected neutrons if the wavelength distribution is symmetric. This distribution function is not directly measurable, but a symmetrical shape was aimed at by avoiding the occurrence of multiple scattering close to the wavelengths considered. An intensity scanning was therefore made and certain wavelengths selected around which no peaks or dips in the intensity were seen. The background count rate was measured by turning the crystal away from the Bragg orientation (for further details see Ref. 7). It appeared that the tangential reactor beam hole, with a water scatter, yielded fine background conditions.

Higher order contamination was completely avoided below 0.05 eV by means of a mechanical velocity selector, and for energies above 0.05 eV the higher order contamination was calculated and measured (for further details see Ref. 7).

It was possible to cover the energy range from 0.0003 to 11 eV by using mica, Be (100) and Be (121) reflecting planes. The lattice spacing for mica was measured by a transmission measurement of a Si powder sample around the Si cutoff wavelength (for further details see Ref. 7). The lattice spacings for the two planes (100) and (121) in Be were measured with x-ray techniques. The results were in agreement with published values. The following spacings were adopted: $d_{\text{mica}}=9.95$ Å, $d_{100}=1.9793$ Å, and $d_{121}=0.7323$ Å.

Transmission Measurement

The He^3 was contained in an Al box, and it was therefore necessary to correct for the transmission of the Al, and for the amount of air pushed out from the neutron beam by the box on insertion. The correction factor $T_{\text{Al}}/T_{\text{air}}$, which is the transmission of the evacuated Al box, was measured before the He^3 filling and agreement was found with calculated values.

A beam monitor was used as master for the counting time to avoid errors from reactor flux variations. Furthermore, the sample was inserted and removed from the beam in the following cycle: Out-in-in-out, and the counting time registered (method suggested by Gould *et al.*[2]), thus enabling comparison of the beam monitor method with the cycle method. Each cycle was repeated 20 times and the standard deviation for both methods was calculated and compared with the expected standard deviation from Poisson statistics. Good agreement of all three standard deviations was obtained, showing that reactor and electronic drift had negligible influence when using the methods described.

Sample Preparation

The He^3 Sample

The He^3 container is an Al box with internal dimensions of 5×12×36 cm (approx). The box can be turned so that three values of N (number of He^3 atoms/cm^2 along the neutron path) can be obtained with the same He^3 filling of approx $\frac{1}{2}$ atm absolute, yielding transmissions between 6% and 90% over nearly five decades of neutron energies from 0.0003 to 11 eV. N is determined as the product of the density n and the neutron path length l.

By simultaneous measurement of the He^3 pressure and temperature in the Al box, n is calculated from the gas equation using the small van der Waals constants measured for He^4. The pressure was measured in a Hg manometer with 19-mm-diam-wide glass tubes, whereby the capillary depression was negligible. A gas analysis on the Risö mass spectrometer showed 0.13% He^4 content, which was subtracted from the measured total pressure.

The temperature was measured by one thermocouple inside the gas inlet to the Al box. Two thermocouples placed on the outer side of the Al box indicated the order of magnitude of a possible temperature gradient. The thermocouples were calibrated against a Pt resistance thermometer with an accuracy better than 0.05°C.

[6] J. Als-Nielsen and A. Bahnsen, Risö Report No. 60, 1963 (unpublished).

[7] J. Als-Nielsen and O. W. Dietrich, Risö Report No. 59 (to be published); O. W. Dietrich and J. Als-Nielsen, Risö Reports Nos. 72 and 73, 1964 (unpublished).

When thermal equilibrium was obtained, indicated by the three temperatures and the pressure reaching constant values, the two thermocouples on the outer side both showed approximately 0.25°C lower temperature than the thermocouple placed in the He^3 gas. The latter temperature was used in the gas equation and the temperature gradient contributed a greater part of the uncertainty of $+0.1\%$ and -0.02% on n, the value of which was

$$n=1.1779_{-0.02\%}{}^{+0.1\%}\ He^3\ \text{atoms/cm}^3.$$

A leak test of the Al box indicated that not more than 0.1% of the He^3 could leak out per year, and a transmission measurement repeated two months after the first run showed no significant change.

The internal dimensions of the Al box were determined by measuring the wall thickness of the Al windows (approximately 1 mm) and by measuring the outer dimensions after filling with He^3. In fact, the length was measured at each center point of a net of squares (6×10 squares each 5×5 mm^2), and the average value l and the standard deviation Δl were calculated over the beam area. The correction factor[8] for fluctuations in N over the beam area $[1+(\sigma/2)(\Delta N^2/N)]$, showed that the fluctuations in N had negligible effect. The results of the length measurements were

$$l=\ 49.08\ \text{mm},\quad \Delta l=0.03\ \text{mm},$$
$$l=118.29\ \text{mm},\quad \Delta l=0.02\ \text{mm},$$
$$l=358.83\ \text{mm},\quad \Delta l=0.07\ \text{mm}.$$

The Au Samples

A careful measurement of the geometrical shape and weighing of two gold samples gave the results:

Sample I: $N=(8.6436\pm0.0007)\ 10^{21}$ atoms/cm^2,

Sample II: $N=(3.5779\pm0.0003)\ 10^{21}$ atoms/cm^2.

The direct measurements of thickness showed that fluctuation correction would be negligible. The gold delivered by J. Matthey and Company, England, was so pure that impurity correction was also negligible.

The B Sample

The sample of natural boron was a B_2O_3 solution in heavy water. The concentration of the solution in g of B_2O_3 per 100 g of solution was 1.67712 ± 0.00018. The B^{10} content in the natural boron was $(19.81\pm0.02)\%$.

The solution was encapsuled in a cylindrical quartz cell with a cell length of (2.003 ± 0.001) cm and a diameter of approximately 5 cm. To correct for the D_2O solvent and the quartz cell, two similar quartz cells were measured, one filled with D_2O and one with He. The samples were prepared by the Central Bureau for Nuclear Measurements, Euratom, Geel, Belgium, where the sample transmissions have been measured by "time-of-flight" technique (for further details of the samples and the "time-of-flight" measurements, see Ref. 3).

[8] O. D. Simpson, N. H. Marshall, and R. C. Young, Nucl. Instr. Methods **16**, 97 (1962).

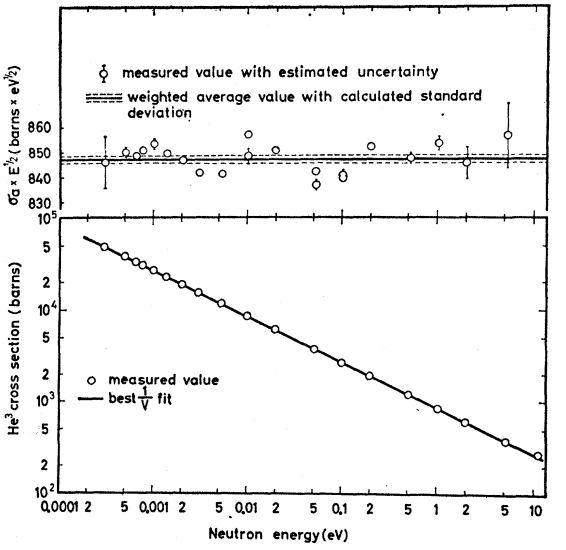

FIG. 1. The total cross section σ_t of He^3 versus neutron energy E. From the $1/v$ fit it is concluded that $\sigma_t=\sigma_a$ within the accuracy of the data. $\sigma_a\cdot E^{1/2}$ versus E is also shown. It is noted that the estimated uncertainties are only used in the weighing procedure to find the average value, the standard deviation of which is calculated from the actual spread of the data.

3. ANALYSIS OF DATA

Least-Squares fit

Experimental data (λ_i,σ_i), $i=1\cdots n$, are fitted to $\sigma=\alpha\lambda+\beta$ by the method of least squares, i.e., minimization of

$$S=\sum_{i=1}^{n}\left(\frac{\sigma_i-\alpha\lambda_i-\beta}{\Delta\sigma_i}\right)^2$$

with respect to α and β. All uncertainties are thus converted to uncertainties $\Delta\sigma_i$ on σ_i, leaving λ_i without any uncertainty.

With the estimate of $\Delta\sigma_i$, as described below, the least-squares fit was performed on a computer, and the values of the standard deviations of α and β were also calculated.

Estimate of $\Delta\sigma_i$

$(\Delta\sigma_i)^2$ is a sum of several contributions. The first term is experimentally found as the squared standard deviation when repeating each set of data as mentioned in the previous section. This will include fluctuations due to Poisson statistics, background conditions, and electronic drift. The next term is due to the uncertainty in first-order wavelength, composed of the uncertainty of crystal lattice spacing and Bragg angle determination. Other terms originate from uncertainty in the corrections for sample container, higher order con-

TABLE I. He^3 cross-section data.

Neutron wavelength λ in Å	Neutron energy E in eV	Total cross section σ_t in barns	Absorption cross section per Å σ_i in barns per Å	Sample length approx. in cm	repetition	Estimated uncertainties in % Contributions from wave-length	sample container	other corrections	Resulting $\Delta\sigma_i/\sigma_i$ in %
16.438	0.0003028	48639	2958.9	5	1.255	0.051	0.010	···	1.26
12.804	0.0004990	38062	2972.7	5	0.203	0.054	0.013	···	0.210
11.222	0.0006495	33310	2968.3	5	0.172	0.058	0.015	···	0.188
10.259	0.0007772	30529	2975.8	5	0.112	0.061	0.017	···	0.138
9.0278	0.0010036	26945	2984.7	5	0.212	0.064	0.019	···	0.222
7.6550	0.0013958	22748	2971.7	5	0.061	0.067	0.023	0.03	0.098
6.3535	0.0020259	18815	2961.4	5	0.142	0.071	0.027	0.055	0.170
5.1757	0.003054	15236	2943.8	5	0.061	0.070	0.033	0.068	0.120
3.9236	0.005313	11542	2941.7	5	0.069	0.081	0.073	0.044	0.136
2.8516	0.010058	8547.5	2997.4	12	0.060	0.016	0.12	0.041	0.141
2.8518	0.010058	8460.5	2966.7	5	0.206	0.016	0.27	0.059	0.345
2.0334	0.019782	6049.3	2975.0	12	0.054	0.025	0.125	0.035	0.143
1.2642	0.05118	3723.5	2945.3	36	0.102	0.040	0.063	0.050	0.136
1.2642	0.05118	3699.2	2926.1	12	0.101	0.040	0.18	0.078	0.223
0.90228	0.10047	2652.7	2940.0	12	0.110	0.020	0.20	0.083	0.244
0.90228	0.10047	2648.4	2935.2	36	0.094	0.020	0.028	0.060	0.117
0.64018	0.19954	1907.2	2979.2	36	0.071	0.030	0.041	0.068	0.111
0.40234	0.50524	1192.1	2962.9	36	0.208	0.047	0.061	0.042	0.226
0.28246	1.0252	842.9	2984.1	36	0.291	0.068	0.084	0.028	0.312
0.20433	1.9592	604.1	2956.5	36	0.726	0.094	0.118	0.024	0.740
0.12561	5.1843	376.2	2995.0	36	1.53	0.150	0.19	0.036	1.54
0.086092	11.036	276.3	3209.4	36	4.23	0.220	0.30	0.018	4.23

tamination, and dead time of BF_3 counter (the details of these corrections are described in Ref. 7).

4. RESULTS

In Table I the measured data (λ_i,σ_i) for He^3 are shown together with the different contributions to $\Delta\sigma_i$. The least-squares fit to $\sigma_t=\alpha\lambda+\beta$ gives the result $\alpha=2963.1\pm0.6$ b/Å, $\beta=-0.8\pm5.1$ b.

It is concluded from the small value of β that within the measured accuracy the total cross section σ_t is equal to the absorption cross section σ_a which is, however, known to obey the $1/v$ law rigidly. This conclusion is in agreement with the quoted scattering cross section of $\sigma_s(He^3)=(1.0\pm0.7)$ b.[9] In Table I σ_a/λ is therefore also shown and the weighted average and standard deviation are calculated to be

$$\sigma_a/\lambda=2962.6\pm5.1 \text{ b/Å}.$$

Adding the uncertainty on N, the final result for the absorption cross section at 2200 m/sec is

$$\sigma_a(He^3)=5327_{-9}^{+10} \text{ b at 2200 m/sec}.$$

The cross section as a function of energy is plotted in Fig. 1.

TABLE II. Au cross-section data.

Neutron wavelength λ in Å	Total cross section σ_t in barns	Absorption cross section per Å σ_a/λ (barns/Å)
16.438	900.8±9.0	54.76±0.54
12.804	698.3±0.8	54.49±0.07
11.222	611.5±1.4	54.43±0.13
10.259	559.9±0.7	54.51±0.07
9.0278	491.6±1.1	54.37±0.13
7.6550	417.2±0.5	54.40±0.07
6.3535	344.9±0.4	54.16±0.07
5.1757	279.8±0.4	53.88±0.08
3.9236	217.4±0.3	
2.8516	162.2±0.1	
2.0334	116.4±0.2	
1.2642	76.7±0.2	
0.90228	57.5±0.2	
0.64018	44.7±0.2	
0.40234	33.1±0.4	
0.28246	30.8±0.2	
0.20433	34.3±0.2	
0.08609	17.8±0.1	

The data for Au are shown in Table II. As in Ref. 2 the absorption cross section is deduced from the total cross section for $\lambda>5$ Å by subtraction of 0.03 b (from inelastic scattering), $1.7/\lambda$ b/Å (non-λ resonance contribution) and 0.5 b (from incoherent scattering). The latter term has an uncertainty of ±0.26 b, which is incorporated in the tabulated uncertainties of σ_a/λ. From the values of σ_a/λ, weighted with the inverse square of the uncertainties, an average value of 54.32 b/Å is calculated. The accuracy of this is composed of the weighted deviations from the average value (0.16%) and the contribution from the uncertainty in the systematic correction for incoherent scattering (0.062%). As the uncertainty of N is negligible, the final result for the Au absorption cross section at 2200 m/sec is:

$$\sigma_a(\text{Au})=98.6\pm0.2 \text{ b at 2200 m/sec},$$

which should be compared with the value 98.8±0.3 b from Ref. 2.

[9] D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report No. BNL 325, 1958 (unpublished).

TABLE III. B cross-section data.

Neutron wavelength λ in Å	Total cross section of (B_2O_3) in barns	Absorption cross section per Å σ_a/λ (barns/Å)
3.9236	3340.2	423.0±0.5
2.8518	2439.9	424.1±0.5
2.0334	1726.5	419.4±0.6
1.2642	1091.8	423.5±1.4
0.90228	775.2	417.9±1.4

The gold cross section as function of energy is plotted in Fig. 2, which also shows a smoothed curve of other reported data.[9]

The data for B are shown in Table III. As in Ref. 3, a constant value of 21 b for the scattering cross section of the B_2O_3 molecule is subtracted from the B_2O_3 total cross section. The uncertainty of this correction is estimated to be ±2 b,[5] because the energy dependence of the scattering cross section between 0.005–0.1 eV is unknown. This uncertainty is incorporated in the tabulated uncertainties of σ_a/λ. From the values of σ_a/λ, a weighted average value of 422.2 b/Å is calculated. As in the case of gold, the uncertainty of this value is composed of the weighted deviations from the average value (0.24%) and the weighted contribution from the uncertainty in the correction for molecular scattering (0.1%). As the uncertainty in N is negligible, the final result for the thermal absorption cross section of boron is

$$\sigma_a(\mathrm{B}) = 759.1 \pm 2.0 \text{ b at } 2200 \text{ m/sec},$$

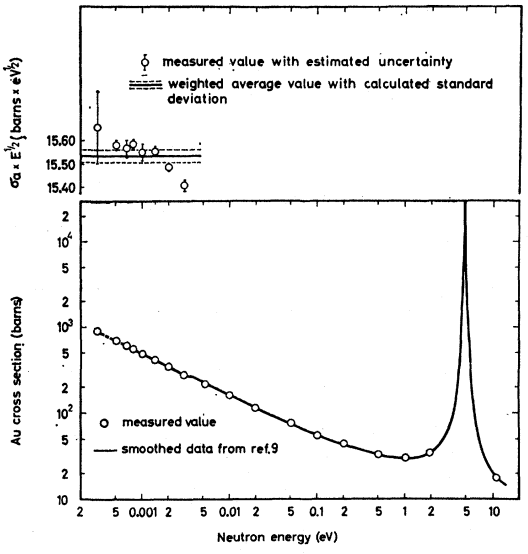

FIG. 2. The total cross section σ_t of Au versus neutron energy E. The absorption cross section σ_a is deduced from σ_t for $E<0.005$ eV. $\sigma_a \cdot E^{1/2}$ versus E is also shown.

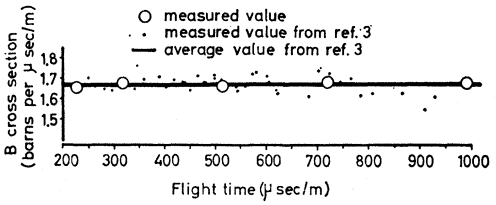

FIG. 3. Reproduction of part of Fig. 8 in Ref. 3 together with the authors' measured values of the boron cross section.

which should be compared to the value 760.8±1.8 b as stated in Ref. 3.

In order to compare the results at different wavelengths with Ref. 3, the data are converted to barns per μsec/m in Fig. 3.

The result is also in good agreement with other published values.[2,4]

5. CONCLUSION

It is evident from the data obtained that the He^3 total cross section obeys the $1/v$ law rigidly, at least up to 11 eV, and it is concluded that the total cross section in this region is equal to the absorption cross section with very good approximation.

The reliability of the He^3 cross-section measurement is confirmed by the agreement between the measured Au and B cross sections and previously published data.

It is noted that the Au cross section measurement is extended down to 0.0003 eV.

The uncertainty on the thermal B cross section is nearly the same as the uncertainty for the corresponding measurement in Ref. 3. As indicated in Fig. 3 the accuracy in our measurement is obtained by fewer measured points with lower spread than in Ref. 3.

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