PHYSICAL REVIEW VOLUME 82, NUMBER 3 MAY 1, 1951

Total Cross Section of Helium for Fast Neutrons*

S. BASHKIN,† F. P. MOORING, AND B. PETREE
University of Wisconsin, Madison, Wisconsin
(Received December 19, 1950)

The total neutron cross section of helium has been determined at energies from 40 kev to 4.9 Mev by comparison of the transmission of neutrons through a helium-filled cylinder with the transmission through an identical empty cylinder. The observed cross section increases smoothly from 0.8 barn at 40 kev to 6.7 barns at 1.15 Mev, and then decreases smoothly to 2.3 barns at 4.9 Mev. No splitting of the peak at 1.15 Mev was observed.

I. INTRODUCTION

THE differential cross section for the scattering of neutrons by helium has been studied on several occasions. Staub and Stephens[1] found a resonance for the backward scattering at about 1-Mev neutron energy and attributed it to a p-level in the He^5 nucleus. This resonance was also observed by Gaerttner, *et al.*[2] Further work by Staub and Tatel[3] indicated that the half-width of the resonance was about 0.4 Mev and seemed to show a doublet structure with a splitting of about 0.3 Mev.

Barschall and Kanner,[4] using monochromatic neutrons, obtained the angular distribution of neutrons at energies of 2.5 and 3.1 Mev. Wheeler and Barschall[5] found that those angular distributions could be interpreted as a superposition of outgoing S, $P_{\frac{1}{2}}$, and $P_{\frac{3}{2}}$ waves, with large phase shifts between the $P_{\frac{1}{2}}$ and $P_{\frac{3}{2}}$ waves.

Hall and Koontz[6] obtained angular distributions at several neutron energies between 0.6 and 1.6 Mev. Their data were fitted with parabolas derived on the assumption that only s- and p-waves were important in the scattering. By extrapolating the parabolas to zero scattering angle and determining the areas under the curves, Hall and Koontz obtained a value for the total cross section at each energy. These total cross section values gave a slight indication that the resonance at 1 Mev is split.

II. EXPERIMENTAL

In the present experiment, the total neutron scattering cross section of helium has been determined from 40 kev to 4.9 Mev by measuring the neutron transmission of a helium-filled cylinder. Conditions were such that neutrons scattered through an angle greater than 6° could not enter the detector. This geometry was obtained by compressing purified helium to 8000 psi in a thin-walled steel vessel. Figure 1 shows the details of the container and the experimental arrangement.

Neutrons having energies between 40 kev and 2.1 Mev were produced by the $Li^7(p,n)Be^7$ reaction, while above 3 Mev the $D(d,n)He^3$ reaction was used. In both cases the charged particles were accelerated in an

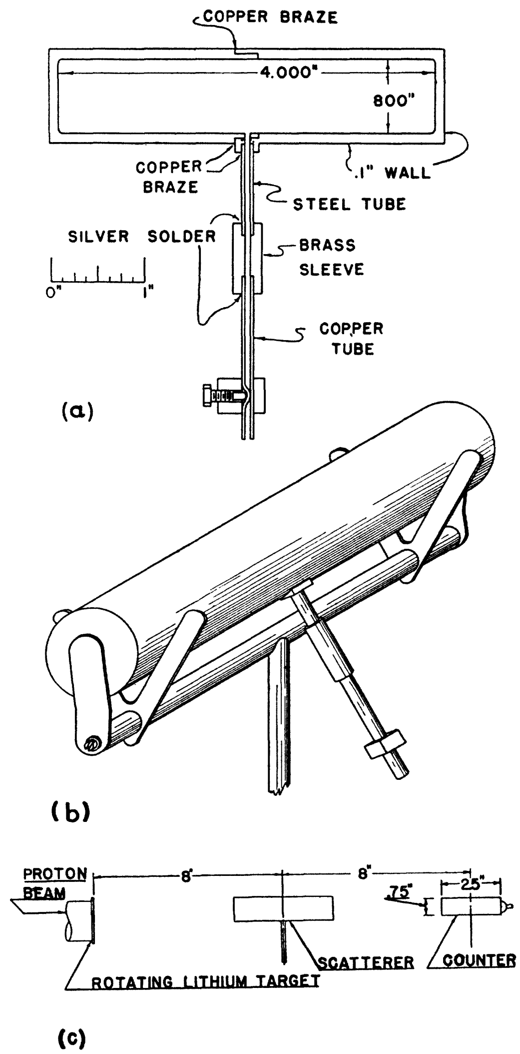

FIG. 1. (a) Helium cylinder. (b) Cylinder mounting. (c) Geometry for scattering experiment.

* This work was supported by the Wisconsin Alumni Research Foundation and the AEC.
† Now at Louisiana State University, Baton Rouge, Louisiana.
1 H. Staub and W. E. Stephens, Phys. Rev. **55**, 131 (1939).
2 Gaerttner, Pardue, and Streib, Phys. Rev. **56**, 856A (1939).
3 H. Staub and H. Tatel, Phys. Rev. **58**, 820 (1940).
4 H. H. Barschall and M. H. Kanner, Phys. Rev. **58**, 590 (1940).
5 J. A. Wheeler and H. H. Barschall, Phys. Rev. **58**, 682 (1940).
6 T. A. Hall and P. G. Koontz, Phys. Rev. **72**, 196 (1947).

electrostatic generator and defined in energy to 0.2 percent by an electrostatic analyzer. For the *d-d* work a deuterium gas chamber, separated from the analyzer's vacuum system by a $\frac{1}{10}$-mil thick nickel foil, replaced the rotating lithium target of Fig. 1. The finite target thickness produced an appreciable neutron energy spread. This spread was 60 kev for the 40-kev point and 30 kev for all other data up to 2.1 Mev. The neutron energy spread for the *d-d* work varied with energy, as is indicated in Fig. 2; the energies designated by the points are average energies weighted according to the variation of neutron yield[7] at 0° over the calculated energy spread.

The neutron detector was a hydrogen recoil proportional counter filled to a pressure of 150 mm of Hg for the 40-kev point and two atmospheres for all other work.

The scattering properties of the helium container were accounted for by inserting an identical empty container in the neutron flux. Background measurements of the neutrons scattered into the detector from the floor, walls, and similar objects were made by replacing the cylinder with a paraffin-boron carbide cone which absorbed the neutrons coming directly from the source towards the detector. If T be the transmission, N_s the number of counts with the sample cylinder in place, N_0 the number with the empty cylinder in place, and B the number of background counts, the cross section, σ, is found from

$$T=(N_s-B)/(N_0-B)=\exp(-n\sigma),$$

where n is the number of scattering centers per cm². In this experiment, n was found from the weight of the cylinder when filled and when empty and from the known dimensions of the cylinder.

In order to check against possible systematic errors,

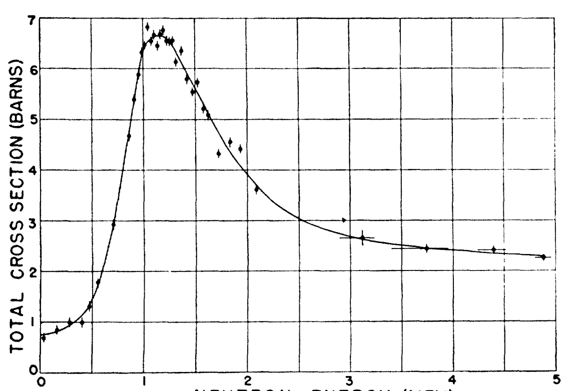

FIG. 2. Total neutron cross section of helium. The vertical bars indicate the statistical uncertainty in cross section. The horizontal bars on the four high energy points indicate the energy spread of the neutrons, which were obtained from the $D(d,n)He^3$ reaction. At all other energies the neutrons were obtained from the $Li^7(p,n)Be^7$ reaction, and the spread was 30 kev, except at the 40-kev point, where the spread was 60 kev.

[7] G. T. Hunter and H. T. Richards, Phys. Rev. **76**, 1445 (1949).

the transmission of an identical cylinder containing purified hydrogen at 10,000 psi was measured at several energies so that the cross section thus obtained could be compared with other determinations of the hydrogen cross section.[8, 9]

III. RESULTS

The results of the measurements are shown in Fig. 2; the vertical bars indicate the statistical uncertainty, and the horizontal bars (on the *d-d* points) the neutron energy spread.

The extrapolated thermal cross section of 0.8 barn disagrees with the 1.25 barns reported by Carroll[10] and the 1.4 barns reported by Harris.[11] This discrepancy is not now understood.

The resonance at 1.15 Mev fails to show any splitting such as Staub and Tatel[3] found in the differential cross section for back scattering. It is believed that the 300-kev splitting of the $P_{\frac{3}{2}}$ and $P_{\frac{1}{2}}$ levels proposed by these authors to fit their data would have been clearly resolved in the present work. From 650 kev to 2.1 Mev the data of Fig. 2 should be corrected to account for the low energy neutrons[12] from the excited state of Be^7. The percentage of low energy neutrons is not well known over this energy range, however, and it was not considered advisable to correct the data at this time. Such a correction would increase the cross section between 650 kev and 1.45 Mev, and decrease it between 1.45 and 2.1 Mev. If one assumes the low energy neutrons to be 10 percent of the main group, this correction will increase the cross-section peak at 1.15 Mev to 7.4 barns, and decrease the cross sections at 1.6 and 2.1 Mev to 4.8 and 3.6 barns. The hydrogen cross sections measured at several neutron energies near 1.1 Mev agree well with the established values.[8]

The cross sections at 3.1, 3.7, 4.4, and 4.9 Mev were obtained with neutrons from the $D(d,n)He^3$ reaction. It was found, by replacing the deuterium in the target chamber with hydrogen, that about 5 percent of the neutron counts were from reactions other than $D(d,n)He^3$. The hydrogen cross sections determined at these energies are about 10 percent higher than the values of Bailey, *et al.*[9] who estimate their accuracy at five percent. Thus, it seems likely that the extraneous neutrons were predominantly of low energy. From this fact alone one cannot conclude whether the low energy neutrons increased or decreased the observed cross section of helium, because neutrons of about 1.15 Mev would reduce the observed transmission, whereas neutrons of less than 500-kev energy would increase it.

[8] Lampi, Freier, and Williams, Phys. Rev. **80**, 853 (1950).
[9] Bailey, Bennett, Bergstrahl, Nuckolls, Richards, and Williams, Phys. Rev. **70**, 583 (1946).
[10] H. Carroll, Phys. Rev. **60**, 702 (1941).
[11] S. P. Harris, Phys. Rev. **80**, 20 (1950).
[12] Johnson, Laubenstein, and Richards, Phys. Rev. **77**, 413 (1950).

The effect is small, however, and at worst could cause the observed cross sections to be in error by about 10 percent.

We wish to thank Professor R. J. Roark of the Department of Mechanics, who kindly discussed designs for the high pressure cylinders, and Professor D. J. Mack of the Department of Mining and Metallurgy, who suggested suitable cylinder materials and x-rayed the cylinders for flaws. Professor J. R. Roebuck gave valuable advice concerning the production of high pressures and the properties of materials subjected thereto. We also wish to thank C. H. Johnson, L. J. Koester, D. W. Miller, and R. E. Peterson for help in many phases of this experiment.

PHYSICAL REVIEW VOLUME 82, NUMBER 3 MAY 1, 1951

Neutron Capture γ-Rays from Lead and Bismuth

B. B. KINSEY, G. A. BARTHOLOMEW, AND W. H. WALKER*
Division of Atomic Energy, National Research Council of Canada, Chalk River, Ontario, Canada
(Received November 20, 1950)

Only two strong γ-rays have been detected with a pair spectrometer during the bombardment of lead thermal neutrons. The weaker of the two is due to capture in Pb^{206} and has an energy of 6.734±0.008 Mev, and the stronger is due to capture in Pb^{207} and has an energy of 7.380±0.008 Mev. Apart from a very weak γ-ray with an energy of 6.90±0.05 Mev, no other radiation has been detected. The 6.9-Mev γ-ray may be due to the excitation of a hitherto unknown state in Pb^{208}, or it may be due to an impurity.

Bismuth produces a γ-ray with an energy of 4.170±0.015 Mev. The breadth of the coincidence peak is about 70 kev greater than would be expected for a homogeneous radiation. The γ-rays revealed by the coincidence spectra of lead and bismuth have intensities of about one quantum per capture.

The binding energies of four neutrons in Pb^{210} (RaD) have been calculated using the above experimental data and compared with that computed from the decay of Pb^{210} and its products. The latter exceeds the former by 0.37±0.07 Mev. The origin of this discrepancy is discussed.

The binding energy of Pb^{210} is shown to be less than the energy of disintegration of RaC″, and experiments are described which prove that if neutrons are produced in the decay of the latter, the yield is less than one neutron per two hundred and fifty disintegrations.

No γ-ray with the binding energy of Pb^{205} (6.4±0.2 Mev) was detected. Pb^{205} is shown to be unstable against electron capture to Tl^{205} by about 300 kev. Both Bi^{208} and Bi^{209} are shown to be unstable for α-decay by 3.25 Mev.

I. INTRODUCTION

A PRELIMINARY report on the energies of the γ-rays produced by capture of slow neutrons in lead and bismuth has already been published.[1] The present paper contains details of this work. The method of energy and intensity measurement will be discussed elsewhere.

A sample of the material to be examined is placed in a high neutron flux in a hole which traverses the concrete radiation shield of the pile. Gamma-rays from the pile are prevented from passing down the hole by a block of bismuth 5 in. long. The pair spectrometer is placed outside the concrete shield, and a series of lead collimators limits the γ-radiation reaching the spectrometer to that emitted from the central region of the sample. In this way, unwanted radiations emitted by the lining of the hole are eliminated.

II. RADIATIONS FROM LEAD

The first measurements with lead were made with two samples, one of chemically pure metallic lead, and the other of litharge (PbO) in a Dural container. The spectra obtained are shown in Fig. 1. It will be seen that the two characteristic peaks at 6.7 and 7.4 Mev appear in the same proportion in the spectra of both samples; and, in addition, the 7.7-Mev aluminum capture γ-ray appears in the litharge sample. Now, it is improbable that an impurity which might be responsible for the weaker of the two peaks should be present in both samples to the same extent; for this reason both radiations have been ascribed to lead. Since the energy released by neutron capture in the even mass number isotope will be less than that produced by the adjacent odd isotope, the γ-ray with the least energy is ascribed to capture in Pb^{206} and the γ-ray with the greatest energy to capture in Pb^{207}.

This assignment is confirmed by the more detailed

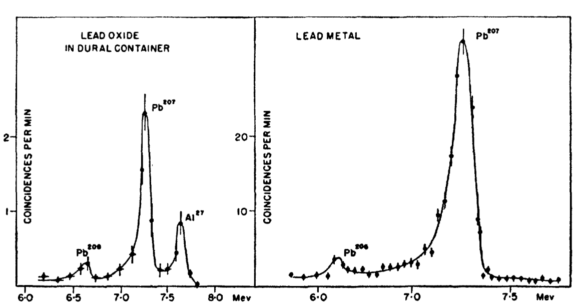

FIG. 1. Coincidence spectra for lead oxide, in a Dural container, and for lead metal, obtained with the pair spectrometer.

* Now at McMaster University, Hamilton, Ontario.
[1] Kinsey, Bartholomew, and Walker, Phys. Rev. 78, 77 (1950).