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The Thermal Neutron Capture Cross Section of Hydrogen

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The thermal neutron capture cross section of hydrogen has been measured to be 0.329±0.004 b at 2200 m/sec. This was done by measurement of the reduction in the neutron activation rate of NaI in a water solution when boron of a known absorption cross section was added to the solution.

I. INTRODUCTION

The cross section for the thermal neutron capture of hydrogen (σ_H) is directly related to various parameters connected with the neutron-proton interaction potential. An accurate determination of this cross section might contribute to the resolution of questions concerning the shape of the *n-p* well[1] or might permit an evaluation of the effect of the Sach's type of magnetic interactions.[2] With these ideas in mind, a series of experiments was performed in order to determine σ_H to an accuracy of approximately one percent.

The method most commonly used for measuring σ_H is the integration technique of Frisch, Halban, and Koch.[3] This method requires the determination of the neutron density in an essentially infinite solution, at a series of distances from a source of neutrons located near the center of the tank which holds the solution. The solutions used are distilled water and distilled water containing a small amount of boric acid. The neutron density is measured by use of BF_3-filled chambers, boron-lined chambers, or manganese foils. In all of these cases, the effect of the detector is difficult to ascertain to the degree of accuracy which would lead to a one percent accuracy for σ_H.

Frisch, Halban, and Koch[3] obtained a value of σ_B/σ_H of 1940±100, whereas Fenning, Halban, and Seligman[4] obtained 2160±30. In each of these experiments, no correction was made for detector perturbations on the neutron density. In a similar experiment by Kubitschek,[5] this correction was made using manganese foils, and a value of 2380±70 was obtained. A value of 1954±24 has been reported by Schulz and Goldhaber.[6] The most recent result obtained by the integration technique is from the very careful experiment of Whitehouse and Graham.[7] Their result is 2270±30. However, an upper limit of three percent for the error caused by detector perturbation effects is not included in this estimate of accuracy.

In view of the wide variation in the value of σ_B/σ_H, we have sought a procedure which would lead to about a one percent accuracy in this ratio. Furthermore, since there are significant variations in the isotopic abundances[8] of boron, a careful determination of the capture cross section of the boron used in such an experiment was thought desirable.

Muehlhause[9] has recently determined σ_B/σ_H at this laboratory using the pile oscillator technique. He used a boron sample of known cross section and obtained a value for σ_H of 0.332±0.007. However, this method involves the use of certain pile constants which are difficult to evaluate.

II. METHOD

As has been implied, the present measurement consists of a comparison of the hydrogen capture cross section with that of a boron sample of known cross section. The method used for the boron to hydrogen comparison is similar in principle to that of references 3–7. It involves a study of the competition between capture in boron and hydrogen in a solution containing a neutron source. The activation of a constant amount of NaI in the solutions is used as a measure of the captures in hydrogen.

For purposes of understanding the experiment, assume that a constant source of neutrons is placed at the center of a large tank. The tank must be large enough so that when the appropriate solutions are added to the tank, all of the source neutrons are absorbed in the solutions, i.e., there is no leakage of neutrons from the tank. Two solutions are used: NaI in H_2O and $NaI+H_3BO_3$ in H_2O. Each solution is placed in the tank in turn and irradiated. The solution is continually stirred during irradiation, and a sample of it is later counted. If the irradiation time is the same in the two parts of the experiment, then the ratio of iodine activities in the two cases is

$$R=\frac{\left(\dfrac{N_I\sigma_I}{N_{NaI}\sigma_{NaI}+N_H\sigma_H}\right)}{\left(\dfrac{N_I'\sigma_I}{N_{NaI}'\sigma_{NaI}+N_H'\sigma_H+N_B'\sigma_B}\right)}. \tag{1}$$

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[1] E. E. Salpeter, Phys. Rev. **82**, 60 (1951).

[2] N. Austern and R. G. Sachs, Phys. Rev. **81**, 710 (1951).

[3] Frisch, Halban, and Koch, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **15**, 1 (1938).

[4] Fenning, Halban, and Seligman, British Atomic Energy Project Report BR-135 (1943), unpublished.

[5] H. Kubitschek, Manhattan District Project Report CP-972 (1943), unpublished.

[6] L. G. Schulz and M. Goldhaber, Phys. Rev. **67**, 202 (1945); L. G. Schulz, Ph.D. thesis, University of Illinois (1945), unpublished.

[7] W. J. Whitehouse and G. A. R. Graham, J. Research **A25**, 261 (1947).

[8] Thode, Macnamara, Lossing, and Collins, J. Am. Chem. Soc. **70**, 3008 (1948).

[9] C. O. Muehlhause *et al.* (to be published).

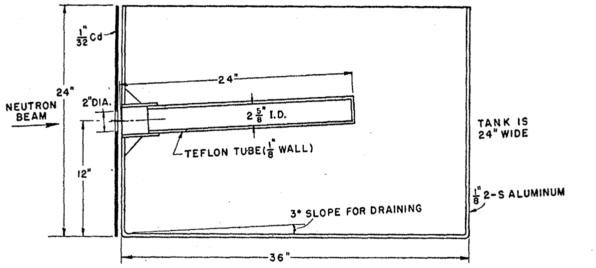

FIG. 1. A vertical cross section of the tank used in the neutron-proton capture experiment.

The various N's are the numbers of atoms/cm^3 of the different constituents, and the σ's are the capture cross sections. The unprimed N's refer to the no-boron experiment. The primed N's refer to the experiment with boron.

If N_{I} is made equal to N_{I}', then

$$R-1=\frac{N_{\mathrm{B}}'\sigma_{\mathrm{B}}+(N_{\mathrm{H}}'-N_{\mathrm{H}})\sigma_{\mathrm{H}}}{N_{\mathrm{NaI}}\sigma_{\mathrm{NaI}}+N_{\mathrm{H}}\sigma_{\mathrm{H}}}. \tag{2}$$

$(N_{\mathrm{H}}'-N_{\mathrm{H}})\sigma_{\mathrm{H}}$ is relatively very small. The NaI concentration is so chosen that $N_{\mathrm{NaI}}\sigma_{\mathrm{NaI}}$ is small. Thus, with small corrections, Eq. (2) readily leads to $\sigma_{\mathrm{B}}/\sigma_{\mathrm{H}}$.

III. PROCEDURES AND RESULTS

A beam of neutrons from the thermal column of the Argonne heavy water-moderated reactor was used as a source. There are two advantgages of the beam technique compared with the point source (e.g., Ra$-$Be) method. First, since a thermal beam is used, one can perform Cd-difference experiments and thereby avoid problems associated with leakage of fast neutrons and neutron capture at other than thermal energies. Second, the difficulty associated with neutron capture in the source itself is eliminated.

The neutron beam was brought into the large tank (Fig. 1) through the attached Teflon tube. The dimensions of the tank were so chosen that leakage of neutrons through the tank walls was less than 0.1 percent. The incident neutron beam was monitored by matched gold foils which were supported at the center of the entrance hole of the tank and were later measured for the Au^{198} activity induced. During and for an eight-minute period after an irradiation, the solution was well mixed by electric stirrers. As a check on the thoroughness of the mixing, a test was made by taking samples of solutions from various parts of the tank after only four minutes of stirring. No difference in the counting rates of these samples was observed.

The two solutions used in the experiment were prepared by dissolving reagent grade NaI in approximately 700 liters of distilled water and then adding reagent grade H_3BO_3 to half of the iodide solution. The concentrations of the boric acid (as B_2O_3) and sodium iodide were accurately determined by chemical analysis to be 2.681 g/l and 41.48 g/l, respectively. NaI, rather than the ordinarily used manganese salts, served as the neutron detector because of the former's chemical compatability with boric acid in aqueous solutions. Each solution was made slightly basic with a small volume of NH_4OH in order to prevent air oxidation of iodide. The 25-min I^{128}, the predominant activity formed in the neutron irradiation, was counted in two glass-jacketed annular Geiger counters, each of which held approximately 20 cc of solution. The stability of the counters was checked by use of a standard 50-day In^{114} solution. Dead-time corrections were determined by means of two solutions of active NaF which differed by a factor of five in concentration. Care was taken to have the specific activity of the Na^{24} sufficiently high so that the densities of the two solutions were practically identical despite dilution. The dead-time corrections caused a 0.14 percent change in R.

A rigid schedule of irradiation, cooling and counting times was maintained in order to secure comparable data. An irradiation lasted 36 minutes, and stirring continued an additional eight minutes before withdrawal of the two samples of the solution for counting. Three 12-minute counts were taken, begun exactly 15 minutes after the irradiation and spaced by one-minute intervals. Appropriate background corrections were made by counting samples of the solution taken from the tank just before the irradiation. The two solutions were irradiated alternately.

A set of data from one complete experiment appears in Table I. A cadmium difference for each solution was obtained by irradiating with, and then without, a Cd cover over the entrance hole.

IV. CORRECTIONS

To obtain the ratio of the boron-to-hydrogen capture cross sections from the ratio of the activities of the two solutions, several corrections must be applied. The first is for neutrons absorbed in the Teflon tube. The effective absorption area of the tube was measured by comparison with cadmium wires, using the danger coefficient method[10] in a reactor. In addition, the neutron flux was measured at several points along the tube during an irradiation. From these two measurements the number of neutrons absorbed in the tube was calculated, and the measured activity of the solution corrected by the ratio of this number to the total number entering the tank (about 0.007). The effect of these changes in the activities was an increase of 0.1 percent in the activity ratio of the two solutions.

The second correction is for the loss of neutrons which leave the tank through the entrance hole. These neutrons were measured by a gold foil placed in the entrance hole and covered by cadmium on the side toward the reactor. Since the gold foil used for this measurement was essentially identical to the one used to monitor the

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[10] Anderson, Fermi, Wattenberg, Weil, and Zinn, Phys. Rev. **72**, 16 (1947).

incident flux, the ratio of the activities of these two foils was a measure of the fraction of the neutrons escaping. The ratio of the activities was multiplied by the ratio of the areas of the entrance hole (the hole in the cadmium) and the escape area (an area slightly more than the area of the hole in the tank). This gave the ratio of leakage to absorbed neutrons. It turned out to be 0.016 for the solution without boron and so near to that for the other solution that the net effect on the ratio of the activities of the two solutions was only 0.06 percent.

As mentioned in the introduction, it was thought necessary to determine the capture cross section of the boron used in this experiment. This was done by comparing this boron with a standard whose absorption cross section had been measured absolutely. The standard used was another batch of boric acid whose absorption cross section had been determined by a transmission measurement[11] which was corrected for the rather small scattering cross section. The comparison of the borons was done by the danger coefficient method.

As can be seen from Eq. (2), a correction must be made for the absorption by the activator, NaI. Since the amount of activator was chosen so that the absorption would be about 5 percent of that of the hydrogen, it would only be necessary to know it to about 5 percent to make the error it contributes negligible. The published values of the Na and I absorption cross sections,[12] however, vary rather widely; so a new measurement using the standard boron mentioned earlier as a standard was thought desirable. A value of 7.4 barns for the NaI absorption cross section was obtained by the pile oscillator method.[13]

TABLE I. Sample data for one determination of R.

Solution in tank	Cd cover	Counter	Bkgd.	Counts per minute		
				1st	2nd	3rd
NaI	Yes	A	51	1848	1417	1121
		C	65	1913	1430	1077
NaI	No	A	76	23 566	16 526	11 735
		C	75	23 077	16 180	11 484
$NaI+H_3BO_3$	Yes	A	27	1178	877	691
		C	25	1117	859	703
$NaI+H_3BO_3$	No	A	50	9779	6975	4982
		C	49	9833	6925	4799

In addition to the corrections which have been discussed, another possible source of error is the energy dependence of the absorption cross sections. It is implicit in Eq. (2) that the neutron spectra in the two solutions are the same or else that the absorption cross sections of iodine, hydrogen, and boron all have the same energy dependence. There is at least the possibility that the spectra differ slightly in the two solutions, so the other assumption had to be made. There is much experimental evidence that boron is a $1/v$ absorber, and there are good theoretical reasons for thinking hydrogen is also. However, iodine has resonances near the thermal region, and there is no direct evidence on the energy dependence of its capture cross section in the thermal region. Accordingly it was decided to test the dependence of the activation of the solution on the neutron spectrum. The solution containing boron was irradiated at 16.5°C and at 60°C. The solution activities, for a given incident neutron flux, were the same within the estimated accuracy of the experiment—two percent. The difference in the spectrum in the solution containing boron and that in the solution without boron is expected to be small compared to the difference in this heating experiment. Therefore this experimental result furnishes a reasonable confirmation of the assumptions in Eq. (2).

V. RESULTS

The ratio of activity in the solution without boron to that in the solution with boron, corrected for the incident neutron flux, obtained from 9 runs, was 2.528±0.016. Applying the corrections that have been discussed and using Eq. (2), we obtained a ratio of standard boron-to-hydrogen capture cross sections of 2292±27. The measured standard boron cross section was 755±3 b at 2200 m/sec; thus the neutron capture cross section of hydrogen is

$$0.329 \pm 0.004 \text{ b at } 2200 \text{ m/sec.}$$

The sources of error in this measurement are believed to be as shown in Table II.

VI. DISCUSSION

In general, these results are in good agreement with earlier work;[5,7,9] in better agreement, in fact, than would be expected in view of the known variations in boron isotopic ratios, which might spoil comparisons with some of these measurements. The error in the ratio of boron-to-hydrogen capture cross sections is not notably better than has been obtained earlier,[7] but this experiment has reduced the uncertainty in the cross section of the boron used in the comparison.

TABLE II. The sources of error in the experiment. The errors listed are the contributions to the error in the hydrogen cross section, not the error in the item listed.

Source	Error percent
Ratio of solution activities (based on statistics of 9 runs)	1.1
Standard boron	0.4
Comparison of borons	0.4
Analyses of boron	0.3
NaI capture cross section	0.2
Errors in other corrections	0.1
Total	1.3

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[11] Kimball, Ringo, Robillard, and Wexler (unpublished data).

[12] H. Pomerance, Phys. Rev. **83**, 643 (1951).

[13] Harris, Muehlhause, Rasmussen, Schroeder, and Thomas, Phys. Rev. **80**, 342 (1950).

It should be pointed out that this measurement and that of Muehlhause[9] are both dependent on the same standard boron cross section, so they only serve to check each other on the boron-to-hydrogen ratio. The standard boron cross section has as yet not been confirmed by other laboratories. Any change in the accepted value of this cross section will, of course, produce a proportionate change in the value of the capture cross section of hydrogen.

Because this experiment seems relatively free of uncertain corrections and the principal source of error appears to be the statistics of the activity ratio measurements of the two solutions, we believe that it would be entirely possible to reduce the error in σ_H to about $\frac{1}{2}$ percent. The effort involved in this would be warranted however only after there was more certainty in the capture cross-section standards.

It is a pleasure to express our gratitude to the following members of this laboratory: Dr. L. A. Turner for several suggestions on the method used in this experiment, to Dr. David Rose for his measurement of the NaI capture cross section, and to Mr. Ralph Bane and Mr. Ralph Telford for their careful boron and iodine analyses.

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Inner Bremsstrahlung Associated with *K* Capture in A^{37}[†][*]

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An investigation has been made of the inner bremsstrahlung accompanying *K* capture in A^{37}. The inner bremsstrahlung energy distribution was examined by absorption and scintillation spectrometer techniques and found to agree with that predicted by theory. A Kurie-type plot showed the maximum energy of the gamma-radiation to be 815±15 kev.

INTRODUCTION

THE theory of inner bremsstrahlung associated with beta-decay processes was extended to the case of *K* capture by Morrison and Schiff[1] in 1940. More recently, Jauch[2] has reviewed and improved the theory. The first experimental evidence for the existence of this inner bremsstrahlung was found by Bradt *et al.*[3] in the nucleus Fe^{55}. Later investigations on the same nucleus by Maeder and Preiswerk;[4] Jauch;[2] and Bell, Jauch, and Cassidy[5] have confirmed Bradt's conclusions and have also yielded further knowledge of the *K* capture transition energy and the gamma-radiation energy distribution. Up to the present investigation, Fe^{55} is the only nuclide shown to emit inner bremsstrahlung with *K* capture.

The theory shows, essentially, that the relative probability of photon emission per *K* capture is given by

$$\frac{dP}{P_0}=\frac{\alpha}{\pi m^2}\left(1-\frac{\omega}{W_0}\right)^2\omega d\omega \qquad (1)$$

and that the total number of photons emitted per *K* capture is given by

$$\int_0^{W_0}\frac{dP}{P_0}=\frac{\alpha}{12\pi}\left(\frac{W_0}{m}\right)^2. \qquad (2)$$

Here dP is the probability per unit time for photon emission, P_0 is the probability per unit time for K capture, ω is the energy of the photon, W_0 is the energy available for the transition, m is the rest energy of the electron, and α the fine structure constant. It has also been shown by Jauch[2] that it is possible to write (1) in such a form that a linear plot may be made of the experimental data. That is,

$$N(\omega)d\omega=C(\omega)\frac{\alpha}{\pi m^2}\frac{\omega}{W_0^2}(W_0-\omega)^2d\omega, \qquad (3)$$

where $N(\omega)$ is the number of photons having energy between ω and $\omega+d\omega$, and $C(\omega)$ is a slowly varying function (except at low energies) which is therefore treated as a constant. Upon simplification we have

$$K[N(\omega)/\omega]^{\frac{1}{2}}=W_0-\omega, \qquad (4)$$

where K is a constant. The intercept of this straight line on the energy axis will be W_0, the energy available for the transition.

HALF-LIFE

The A^{37} source was prepared by irradiating enriched argon gas for 30 days in the Brookhaven reactor. The

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[1] P. Morrison and L. I. Schiff, Phys. Rev. **58**, 24 (1940).

[2] J. M. Jauch, Oak Ridge National Laboratory Report ORNL 1102, 1951 (unpublished).

[3] H. Bradt *et al.*, Helv. Phys. Acta **19**, 222 (1946).

[4] D. Maeder and P. Preiswerk, Phys. Rev. **84**, 595 (1951).

[5] Bell, Jauch, and Cassidy, Science **115**, 12 (1952).