

down. We also give here the factor by which the transition probability of the single j nucleon should be multiplied in order to obtain the probability of the transition considered. The even-even nucleus has $T=1$ and $T_z=1$, say, whereas for the odd-odd nucleus $T_z=0$ and T is either 1 or 0; the transition probability is the same for the two cases. The factor defined above is

$$2(2j+1)(2J+1)W(jJjJ'; jk)^2, \quad (11)$$

where J' is of the initial state and J is of the final state. In case one of the J, J' vanishes the other must be equal to 1 (if $k=1$) and the result is, for initial $J'=1$, final $J=0$: $2(2j+1)/3(2j+1)=\frac{2}{3}$, and for initial $J'=0$, final $J=1$: $2(2j+1)3/3(2j+1)=2$. Both of these factors are of order of magnitude of unity and all such transitions should be favored. A similar conclusion is also the result of the supermultiplet theory, and both these theories account for the cases in which the ft value is low (He^6 , C^{10} , and F^{18})⁹ and both have difficulty

⁹ And also Al^{26} for which neither J nor J' are known; in this case the correcting factors for the reasonable possibilities are as follows:

$J' \setminus J$	0	2	4
1	2/3	128/105	
3		162/245	32/49
5			2/7

in explaining the high ft values of such transitions as of P^{30} , Cl^{34} , and K^{38} .*

The other cases of odd-odd to even-even transitions, where $N \neq Z$ in the odd-odd nucleus, are not favored and should be forbidden according to the supermultiplet theory. It is interesting to calculate the matrix elements in jj coupling in the case that in the odd-odd nucleus there are a j' nucleon and a j hole. The ratio between the transition probability in this case to the probability of the single nucleon transition $j' \rightarrow j$ is given by

$$n^{\frac{1}{2}}(2j'+1)(2J+1)W(jJj'J'; jk)^2, \quad (12)$$

where n is the number of nucleons in the closed j shell $-2(2j+1)$. J must vanish and J' must be equal to 1 (for $k=1$) in which case the factor (12) becomes simply $(2j'+1)/3$. The only cases to which this result is applicable are B^{12} and N^{12} for which $j=\frac{3}{2}$ and $j'=\frac{1}{2}$ and the correction factor is $\frac{2}{3}$. This is not enough to explain the high ft values of these transitions ($\log ft = 4.17$ and > 4.3 , respectively).

The author would like to express his sincere thanks to Professor E. P. Wigner and Professor E. Feenberg for many helpful discussions.

* Note added in proof.—A super-allowed transition between the ground states of Cl^{34} and S^{34} is reported to have been found in the E.T.H., Zurich.

Thermal Neutron-Proton Capture

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(Received March 19, 1953)

Measurement of the thermal neutron capture cross section of hydrogen has been effected by a comparison with boron using the technique of pile oscillation. The 2200-m/sec value obtained, 0.332 b, has a 2 percent uncertainty resulting primarily from the effect of neutron moderation by hydrogen. However, the result indicates an exchange moment contribution to the cross section of $\sim 6 \pm 3$ percent.

INTRODUCTION

THE thermal $n-p$ capture cross section is of theoretical interest¹⁻⁵ in studying the nucleon-nucleon interaction; $n-p$ scattering data from thermal energies to ~ 5 Mev in conjunction with the deuteron binding energy allow one to fix the so-called "effective singlet and triplet ranges."⁶ It is the near equality of $n-p$ and $p-p$ singlet ranges ($2.4 \pm 0.3 \times 10^{-13}$ cm and $2.7 \pm 0.2 \times 10^{-13}$ cm, respectively) that suggests charge

independence of nuclear forces. $n-p$ capture, in addition to involving the singlet and triplet range, also involves an exchange moment.⁷ This has the effect of increasing the $n-p$ capture cross section by ~ 5 percent. Owing primarily to the large ratio of scattering to absorption (~ 150) the uncertainty in the measured value of the $n-p$ capture cross section⁸ is also ~ 5 percent. It is the object of the present work to improve on the accuracy of this measurement in order to better estimate the exchange moment contribution to the $n-p$ capture cross section. An improved technique has become available for this purpose since the recent refueling of the heavy-water reactor at the Argonne National Laboratory.

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⁵ E. E. Salpeter, Phys. Rev. **82**, 60 (1951).

⁶ Hafner, Hornyak, Falk, Snow, and Coor, Phys. Rev. **89**, 204 (1953).

⁷ N. Austern and R. G. Sachs, Phys. Rev. **81**, 710 (1951).

⁸ W. J. Whitehouse and G. A. R. Grahm, Can. J. Research **A25**, 261 (1947).

METHOD

(a) Enriched Heavy-Water Reactor

The Argonne National Laboratory's heavy-water reactor has recently had its fuel rods of normal uranium replaced with rods of enriched U^{235} Al alloy. In addition to generating a larger ratio of thermal to epithermal neutron flux, a former difficulty in interpreting a pile absorption cross section for a moderating substance has been eliminated. A strong moderator, such as hydrogen, when inserted into a normal uranium fueled reactor, exhibits an absorption cross section which is less than its actual value. This is because a fraction of the epithermal neutrons which would have been absorbed in the 7-ev absorption resonance of U^{238} during moderation is able to escape this energy band and enter the thermal region where fission can take place. This phenomenon is termed resonance escape (p), the probability for which is increased by the presence of a good moderator. As an example of the magnitude of this effect, the apparent capture cross section of hydrogen is ~ 75 percent of its actual value when measured in a pile in which p is ~ 0.9 . In the present enriched reactor, however, $(1-p)$ is $\sim 10^{-5}$. This insures that the above effect is negligible. A smaller moderation effect still exists, however, and this will be discussed in (d) of this section.

(b) Pile Oscillator

The pile oscillator⁹ is a mechanical device which periodically inserts and removes from the pile a sample to be measured. The resulting oscillating component of pile flux is observed via the current it produces in a BF_3 ionization chamber. This is taken as a measure of sample absorption. Calibration is effected by similarly oscillating a known quantity of some standard material such as boron.

The pile flux is composed of a thermal-Maxwellian and an epithermal $1/E$ distribution. A pile absorption cross section σ_{pile} measured by comparison with a $1/v$ absorber such as boron is given, therefore, by

$$\sigma_{pile} = \sigma_a^{(th)} + kC_r \Sigma_a^{(r)}. \quad (1)$$

Here k is the ratio of epithermal to thermal flux; C_r is the relative statistical weight of resonance to thermal neutrons; $\Sigma_a^{(r)}$ is the resonance absorption integral other than that resulting from $1/v$ absorption. Only in the case of two $1/v$ absorbers is a pile-oscillator comparison exact. In any other case it is necessary to make supplementary measurements of the resonance absorption integral.

Since the present work is one of comparing two $1/v$ absorbers, hydrogen and boron, no difference in absorption cross-section behavior exists. However, a marked difference in scattering cross section σ_s and slowing down power ξ does exist, and this will be shown

⁹Harris, Muehlhause, Rasmussen, Schroeder, and Thomas, Phys. Rev. **80**, 342 (1950).

to be equivalent to an effective negative absorption integral for hydrogen.

(c) Simple Scattering

By "simple scattering" the authors wish to indicate the effects of elastic scattering other than moderation. A sample which is not oscillated from the exact flux center of the pile generates an in-out scattering effect. That is, a sample which is off center will make a first-order change in the spatial neutron distribution, which in turn will cause a first-order change in the spatial neutron statistical weight. This effect is proportional to the neutron flux gradient at the sample in-position. It can be made equal to zero, therefore, by oscillating the sample from that point in the pile for which the gradient of the flux is zero or the flux itself is a maximum. The flux center is determined by oscillating boron as a function of in-position. The in-position yielding the maximum absorption effect is taken to be the flux center. This is actually the maximum of the product of the flux and its adjoint, both of which peak at the same position.

(d) Moderation

Having determined the proper point in the pile from which to oscillate in order to eliminate errors resulting from simple scattering, it is impossible to avoid the effects of moderation. Moderation makes itself felt by causing epithermal neutrons to age (i.e., slow down) faster than they would otherwise age in the absence of the moderator. An aged neutron counts for more, i.e., has a higher statistical weight in the pile than it had in its previous less aged condition. Viewing the effect of moderation spatially rather than energetically, it may be regarded as one which pulls thermal neutrons closer to the center of the pile where they cause greater reactivity. At any rate moderation increases pile reactivity via the slowing down power ξ , the epithermal scattering integral Σ_s , and the change in statistical weight δC , effected by the moderation collisions.

Let us assume that at most a single scattering takes place. Then the moderation cross section σ_m is given by

$$\sigma_m = k\delta C_1 \Sigma_s, \quad (2)$$

where " k " is the quantity defined in (1) and δC_1 is the change in statistical weight C caused by one collision. The pile cross section of a moderator which is also a $1/v$ absorber is given, therefore, by

$$\sigma_{pile} = \sigma_a^{(th)} + \sigma_m. \quad (3)$$

The statistical weight C is given in terms of the geometry of the reactor and the reactor moderator,

$$C = 1 - K^2 \tau, \quad (4)$$

where K^2 is the so-called buckling constant, and τ is the age to thermal energies in the reactor moderator in question. The Argonne heavy-water reactor is in the

shape of a right cylinder, so that K^2 is given by

$$K^2 = \pi^2/H^2 + (2.405)^2/R^2, \quad (5)$$

where H is the effective height (including reflector savings) and R is the effective radius (includes reflector savings).¹⁰ For the reactor in question, K^2 has the value $6.96 \times 10^{-4} \text{ cm}^{-2}$, and

$$\tau = \tau_0 \log(\epsilon/\epsilon_{ih}), \quad (6)$$

where τ_0 has the value 7.15 cm^2 .

Therefore

$$\delta C_1 = -K^2 \tau_0 \xi, \quad (7)$$

and

$$\sigma_m = -kK^2 \tau_0 \xi \Sigma_s. \quad (8)$$

Equation (8) is an approximation and should only be used to indicate that σ_m varies as $\xi \Sigma_s$ for different samples. Experimentally one should observe σ_m for H^2 and He^4 and scale the results to the H^1 case. It is impractical to oscillate liquid He^4 , and the results on H^2 presented below are sufficiently inaccurate to make them useless in determining σ_m for H^1 . Another approach would be to change K^2 , but the small changes permissible are not worth while. Therefore (8) is used to estimate $\sigma_m(\text{H}^1)$. The authors consider this estimate to be their primary source of error.

APPARATUS

(a) Mechanical

The mechanical apparatus consists of a motor-driven cam and rocker-coupled arm which is periodically raised and lowered to two fixed positions. The amplitude of the end of the arm to which is attached a hanger rod and sample can is five feet. The total period is twenty seconds, during which time the sample rests in the in-position for 9.3 sec, transits out for 0.7 sec, rests in the out-position for 9.3 sec, and transits in for 0.7 sec.

The moving parts which enter the active portion of the pile are made of low neutron absorbing materials: hanger rod and sample can of Dow metal $FS-1$, bearings of graphite, hanger rod to sample can clamp of zirconium, and sample container bottles of either quartz or Teflon.

(b) Electrical

The detection system consists of a large enriched BF_3 ionization chamber placed in the thermal column of the reactor. The current resulting from neutron absorption is conducted into the bridge circuit shown in Fig. 1. The high sensitivity galvanometer shown is used as a null indicator for adjusting R_1 . A system of relays adds R_1 to R_0 during the sample in-time and shorts R_1 during the sample out-time. Except for a second harmonic, balance may be achieved by adjusting R_1 . Not

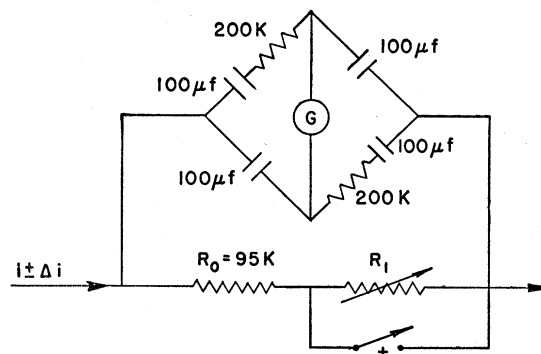


FIG. 1. Bridge circuit for measuring $\Delta i/i$.

shown are other switches controlled by relays which rectify the current through the galvanometer. R_1 , therefore, is a measuring of $\Delta i/i$, i.e., the ratio of oscillating to mean current value.

SAMPLES

(a) Containers

Good sample containers for general use are constructed of a material which is low in neutron absorption and also noncorrosive. Quartz (SiO_2) and Teflon (CF_2) satisfy these conditions. Most of the measurements presented herein employ sealed quartz bottles in the shape of a right cylinder of inside diameter 1.5 cm and of active length 15 cm.

(b) Boron Standards

Calibration material is taken from the Argonne stock of primary standard boric acid.¹¹ This boron is known to have a 2200 m/sec absorption cross section of $755 \pm 3 \text{ b}$. Since the relative abundance of B^{10} and B^{11} may vary depending upon the source from which it is obtained, it is important to employ a boron standard whose cross section is known from an absolute transmission measurement.

A known amount of boric oxide is prepared by igniting some boric acid. This is added to a known amount of high purity heavy water to make a known-concentration stock solution. The stock solution is then diluted by various amounts with additional heavy water to make the various boron standards to be used in the oscillator. A typical standard has a total macroscopic absorption area of $\sim 0.5 \text{ cm}^2$.

(c) Hydrogen Samples

Hydrogen is obtained in the form of multiply distilled light water from the Biology Division of the Argonne National Laboratory. This material is diluted by various amounts with heavy water to make the different hydrogen samples.

¹⁰ S. Glasstone and M. C. Edlund, *The Elements of Nuclear Reactor Theory* (D. Van Nostrand Company, Inc., New York, 1952).

¹¹ Kimball, Ringo, Robillard, and Wexler (unpublished Argonne National Laboratory data).

(d) Background Samples

Empty quartz bottles and quartz bottles with pure heavy water are also made available for "background" determinations.

TECHNIQUE OF MEASUREMENT**(a) Oscillation Point**

The central thimble or axial hole is chosen for oscillation measurements. Three samples are oscillated as a function of depth or in-position in this hole. These are: (1) a boron standard, (2) a heavy-water sample, and (3) an empty quartz bottle. From these the net effect of boron is calculated, and that position is chosen for which the effect of boron is a maximum. The exact location of this position is not critical but may be determined to within half an inch.

(b) Determination of k

k in (1) is determined essentially by measuring the cadmium ratio R_{Cd} (total activation over epithermal activation) of very thin gold (<0.1 mg cm⁻²). Two one-mil iron foils on which the gold is evaporated are placed in the pile at the oscillation point. One foil is covered with cadmium; the other foil is uncovered. The activity (Au¹⁹⁸) ratio is observed.

In addition, it is necessary to know the cadmium ratio of a $1/v$ absorber. This is measured by observing the cadmium ratio of a BF₃ counter in a beam outside the reactor, and in the same beam also observing the cadmium ratio for gold. Since the ratio $[R_{Cd}(Au)-1]/[R_{Cd}(B)-1]$ is invariant, the cadmium ratio for boron in the thimble may be calculated. k is then given by

$$k = \frac{\sigma_a^{(th)}(Au)}{\Sigma_a^{(v)}(Au)} \left\{ \frac{1}{R_{Cd}(Au)-1} - \frac{1}{R_{Cd}(B)-1} \right\}. \quad (9)$$

The measured results are $R_{Cd}(Au)=5.63$, $R_{Cd}(B) = 133 \sigma_a^{(th)}(Au)$ is taken to be 94 b, and $\Sigma_a^{(v)}(Au)$ to be 1180 b. This results in a k value of 0.0166.

(c) Check on K^2

A rough check on the calculated value of K^2 is made by making both axial and transverse static measure-

TABLE I. The apparent cross section of hydrogen uncorrected for moderation.

Run	Cross section (barns)
1	0.3127
2	0.3125
3	0.3069
4	0.3145
5	0.3106
6	0.3139
7	0.3149
8	0.3061
Average	0.3115±0.003

ments of both the flux and the product of the flux and its adjoint. These data are fitted to the proper Bessel functions, and result in a value of K^2 of 6.8×10^{-4} cm⁻². Within the limits of error this value agrees with the one calculated from (5). The latter value is the one employed to calculate σ_m .

(d) Sample Measurements

Four different hydrogen samples are available: three as H₂O-D₂O solutions, and one as a B₂O₃-H₂O-D₂O solution. This latter sample is used to observe a possible local two-collision process; that is, to observe whether the presence of a moderating agent (H¹) increases the absorption by boron. Such an effect is expected to be small, and none is observed.

In all, eight complete runs of all hydrogen, boron, and blank samples are available, the measurements having taken place during two oscillator sessions which were over a month apart. This represents about thirty hours' observation time since each sample takes from twenty to thirty minutes to achieve balance. This much time is needed to eliminate pile drift during the measurement (i.e., while balancing the bridge). In effect it is necessary to first make a static balance and then a dynamic balance. The latter is about ten times more sensitive to the sample than the former, which is a major advantage of the oscillation method.

TREATMENT OF RAW DATA**(a) Electrical**

Since R_1 of Fig. 1 is in the circuit for one half of the cycle, it is necessary to convert R_1 to R_1' in order to obtain a value proportional to $\Delta i/i$. R_1' is given by

$$R_1' = 10^5 R_1 / (R_0 + \frac{1}{2} R_1), \quad (10)$$

where $R_0 = 95\,000\Omega$ and $R_1 \sim 2000$ to 7000Ω .

(b) Pile Power

Though R_1 is nearly independent of pile power (i), it is not entirely so. Observations are made always within 5 percent of the same mean current value, but when the mean current is purposely altered by 10 percent, a change of 1 percent in R_1 is observed. This is used to correct observations made at slightly different settings from the mean (~ 200 watts).

(c) Pile History

Observations are usually begun at the beginning of a week following a two-day shutdown from a high power (~ 250 kilowatts). The decaying "source strength" of the reactor causes a drift in the observed sample readings. Over any one day, measurements repeat to about a half-percent, but over the course of a week a drift in all readings of about 2 percent occurs. A "time correction" is made, therefore, by scaling daily sets to a "standard day." In this manner a high relative accuracy

is preserved, and at the same time proper averaging of sets is made possible.

(d) Nonlinearity

Since the samples are not infinitely dilute, a small but observable amount of self-protection exists. Readings (i.e., ohm values) are corrected on the basis of the following formula:

$$R'' = \frac{R_1'}{1 - R_1'/R_\infty} \quad (11)$$

Equation (11) is similar to the one used to correct for the dead time in counters. R_∞ is a parameter which should have the significance of being that number of ohms which corresponds to blackbody absorption by the sample. That is, $R_\infty \gg R_1'$, and should be given by

$$R_\infty = A_p (dR_1'/da)_{R_1'=0}, \quad (12)$$

where A_p is the projected area of the sample and $(dR_1'/da)_{R_1'=0}$ is the initial slope in ohms cm^{-2} of the boron calibration curve (ohms vs cm^2 absorption).

R_∞ and $(dR_1'/da)_{R_1'=0}$ are determined by fitting the boron calibration data to (11). The value of R_∞ is then checked by calculating A_p from the bottle shape (18.55 cm^2) and multiplying this by $(dR_1'/da)_{R_1'=0}$. The two figures agree to within 5 percent, R_∞ being $\sim 105 \text{ } 000\Omega$. Such agreement is good for a correction term which is always < 7 percent and usually ~ 4 percent.

EXPERIMENTAL RESULTS

(a) Deuterium

The application of (8) to deuterium in which the scattering cross section of deuterium is taken as constant and equal to 3.33 b from cadmium cutoff ($\sim 0.5 \text{ eV}$) to mean fission energy (1.5 Mev) yields a value for $\sigma_m(\text{H}^2)$ of -3.0 mb .

The observed pile cross section must be corrected for (1) the absorption cross section of deuterium, (2) the absorption of a trace amount of hydrogen (~ 0.15 percent), and (3) the effect of displacing nitrogen in the atmosphere for the sample-in position. These corrections make for a considerable error in $\sigma_m(\text{H}^2)$, the result being $-2 \pm 1 \text{ mb}$.

(b) Hydrogen

The apparent cross section of hydrogen uncorrected for moderation is given by the average of the eight mentioned complete runs shown in Table I. The average value is 0.3115 b. The internal error in this number as obtained from the mean deviations is only ~ 1.0 percent. However, application of Eq. (8) for the evaluation of $\sigma_m(\text{H}^1)$ yields the value -0.0205 b . This gives for the 2200-m/sec absorption cross section of hydrogen

TABLE II. Shape independent ϵ -values for various assumed values of r_{0s} .

$r_{0s} < 10^{13} \text{ cm}$	$D < 10^{13} \text{ cm}$	ϵ (%)
2.6	1.080	7.9
2.5	1.055	6.7
2.4	1.030	5.5
2.3	1.005	4.3

the value 0.332 b, which is ~ 6 percent higher than the uncorrected value.

The final boron-to-hydrogen ratio is 2274, which compares favorably with the values of 2270 and 2292 reported elsewhere.^{8,12} Considering the uncertainty in estimating σ_m , however, the uncertainty in our figure is at least 2 percent. That is,

$$\sigma_a^{(th)}(\text{H}^1) = 0.332 \pm 0.007 \text{ b.}$$

The important theoretical quantity is not the cross section but the product of the cross section, and the corresponding velocity

$$\sigma_a^{(th)}(\text{H}^1)v = 7.30 \times 10^{-20} \text{ cm}^3/\text{sec.}$$

EXCHANGE MOMENT

If ϵ is the fractional contribution of the exchange moment to the capture cross section,⁵

$$[\sigma_a^{(th)}(\text{H}^1)v](1-\epsilon) = [\sigma_a^{(th)}(\text{H}^1)v]_0 \frac{[1-\gamma a_s + \gamma^2 a_s D]^2}{(1-\gamma a_s)^2 (1-\gamma r_{0T})} \quad (13)$$

$[\sigma_a^{(th)}(\text{H}^1)v]_0$ is the zero-range approximation of $\sigma_a^{(th)}(\text{H}^1)v$ and has the value $6.52 \times 10^{-20} \text{ cm}^3/\text{sec}$, and $\gamma = 2.318 \times 10^{12} \text{ cm}^{-1}$ is the so-called "reciprocal radius of the deuteron." $a_s = -23.68 \times 10^{-13} \text{ cm}$ is the singlet $n-p$ scattering length; $r_{0T} = 1.720 \times 10^{-13} \text{ cm}$ is the effective triplet $n-p$ range; and $2.6 \times 10^{-13} > r_{0s} > 2.3 \times 10^{-13} \text{ cm}$ is the effective singlet $n-p$ range. Also

$$D \simeq \frac{1}{4}(r_{0s} + r_{0T}). \quad (14)$$

Substituting the observed value of $\sigma_a^{(th)}(\text{H}^1)v$ into (13) yields

$$D \simeq 0.915 + 2.1\epsilon, \quad (15)$$

where D is now in units of 10^{-13} cm . Combining (14) and (15) for different values of r_{0s} yields Table II, where ϵ is expressed in percent.

Inspection of Table II with consideration for the error in $\sigma_a^{(th)}(\text{H}^1)v$ indicates that $\epsilon \sim 6 \pm 3$ percent. If, in fact, ϵ is only ~ 1 or 2 percent, the intrinsic singlet ranges² of the $n-p$ and $p-p$ interaction are outside the experimental limit of being equal. The inclusion of a variety of possible nuclear potentials in the above calculations only slightly increases the spread in ϵ -values. The authors are indebted to Dr. G. Snow for a discussion of this last point.

¹² Hamermesh, Ringo, and Wexler, Phys. Rev. **90**, 603 (1953).