order to determine the absolute number of neutrons passing through the proportional counters from the number of recorded counts, spherical neutron sources of known intensity and various energies between 0.03 and 4.25 Mev were placed at the same distance from the counters as was the C^{14} target.[19] In this manner a conversion factor of 0.0028 was estimated and found to be nearly energy independent. The total number of neutrons emitted from the C^{14} target at a given proton voltage and ion current can be determined from the recorded number of neutron counts, the conversion factor, and the angular distribution relationship stated. Knowing the number of C^{14} nuclei in the target area where the beam hits, one calculates the cross section of the process to be about 0.7 barn for the top of the first resonance.

The cross section, $\sigma_{p,n}$, is related to that of the inverse $N^{14}(n,p)C^{14}$ process, $\sigma_{n,p}$, by the principle of detailed balance:[14]

$$\sigma_{p,n}/\sigma_{n,p}=[(2s_n+1)(2s_N+1)/(2s_p+1)(2s_C+1)]\cdot[P_n^2/P_p^2], \quad (10)$$

where s and P denote spin and momentum in the center of gravity system and subscripts denote the individual nuclear particles involved. The spins of n, $p(H^1)$, N^{14}, and C^{14} are known to be $\frac{1}{2}$, $\frac{1}{2}$, 1 and 0,[20] respectively. Since the masses of n and p and of N^{14} and C^{14} are about the same, Eq. (10) becomes

$$\sigma_{p,n}=3[(E_p-E_t)/E_p]\sigma_{n,p}, \quad (11)$$

an equation which involves only quantities measurable in the laboratory system, where E_p and E_t are the proton energy and the threshold energy of the $C^{14}(p,n)N^{14}$ reaction. For E_p at 1.14 Mev and using a vlaue of 0.085 barn for $\sigma_{n,p}$ from Barschall and Battat,[18] $\sigma_{p,n}$ was calculated to be 0.11 barn which is about $\frac{1}{6}$ of that estimated from our experiments.

[19] Boron trifluoride proportional counter calibrated at Argonne National Laboratory by Dr. D. J. Hughes and associates.

[20] F. A. Jenkins, Phys. Rev. **73**, 639 (1948).

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Total Cross Sections of Nuclei for 90-Mev Neutrons*

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Total cross sections of H, D, Li, Be, C, N, O, Mg, Al, Cl, Cu, Zn, Sn, Pb, and U for 90-Mev neutrons have been measured, using the 184-inch cyclotron as a source and carbon disks as detectors. Experimental details are described, and a brief discussion of some of the theoretical implications of the results is given.

I. INTRODUCTION

DATA on the total cross sections of nuclei for neutrons are of considerable importance, since they furnish the most direct evidence from which the sizes of nuclei can be computed. If a nucleus is thought of as simply an opaque sphere of collision radius R (which includes an "effective radius" of the incident neutron), then the total cross section σ_t is given by:

$$\sigma_t=2\pi R^2, \quad (1)$$

so long as the de Broglie wave-length of the neutron is not too large compared to the nuclear diameter.** Deviations from this simple law can result from several causes. When the neutron energy is only a few Mev, resonance levels in the compound nucleus produce irregular variations in σ_t. At energies of 25 Mev[1] and 14 Mev,[2] the resonances are not very important, as would be expected from the fact that the excitation ener-

* The results of this work were published in a Letter to the Editor, Phys. Rev. **72**, 1264 (1947).

** See the Appendix for fuller discussion.

[1] R. Sherr, Phys. Rev. **68**, 240 (1945).

[2] Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Nuovo Cimento **3**, 203 (1946).

gies of the compound nuclei are now of the order of 30 Mev where the levels are presumably close together, and the values obtained by these authors show a regular variation with A. This regularity appears in the form that a plot of R (computed from (1)) against $A^{\frac{1}{3}}$ is a straight line, or at least nearly so. The simple interpretation of this is that nuclear matter has a nearly constant density, so that the true nuclear radius is proportional to the cube root of the number of nucleons; the intercept of the line at $Z=0$ represents the effective neutron radius which must be added. Comparing the data of Sherr at 25 Mev with the more accurate values of Amaldi *et al.* at 14 Mev, it appears that there is probably no significant difference between them. The latter data can be represented rather well by the line:

$$R=(1.3+1.37A^{\frac{1}{3}})\times 10^{-13}\text{ cm}, \qquad (2)$$

which was drawn giving small weight to the values for Be and S, which do not fit on a smooth curve, and ignoring an apparent slight decrease in slope in the region of the heaviest elements. A fuller discussion of the fitting of a curve to these data is given by Amaldi and Cacciapuoti.[3] In any case, the above expression probably gives a good approximation to the actual geometrical radii of nuclei, plus an additive constant representing the effective neutron radius.

One might expect that at higher neutron energies the collision radii would be about the same as at 14–25 Mev, except for a possible slight decrease in the effective neutron radius; actually the results of this paper show that the collision radii for the light elements lie considerably below the line (2), while those for the heavy elements tend to approach it. The interpretation of this fact brings in a new concept, that of nuclear transparency. We say that the effective collision radius as defined by (1) is smaller than the geometrical radius because neutrons have a certain chance of passing through a nucleus without suffering any deflection, and that this chance is greater for the smaller nuclei.

The very lightest nuclei, H and D, do not fit into the scheme discussed above. The deuterium nucleus, because of its small binding energy, can hardly be considered as a close-packed system like the nuclei of mass 4 and above. Both the H and D cross sections decrease with increasing energy much more than those of the other nuclei investigated, as will be seen by comparison of our results with those of Salant and Ramsey,[4] Ageno *et al.*,[5] Sleator,[5a] and Sherr.[1]

II. OUTLINE OF METHOD; NATURE OF SOURCE AND DETECTOR

The cross sections were determined by measuring the attenuation of the neutrons on passing through blocks of various materials, under conditions of good geometry. The neutron source was a $\frac{1}{2}$-inch thick Be target mounted on the probe of the 184-inch cyclotron; deuterons passing through this target produce a neutron beam by the process of "stripping."[6,7] The neutron energy can be estimated from the theory of this process. First, the mean energy of the neutron set free in a stripping process is very nearly half the deuteron energy, which is taken to have an initial average value of 190 Mev;[6] then the energy lost by the deuteron in the target must be taken into account. The estimated loss in traversing the target is 20 Mev; since stripping may occur at any depth, the mean loss to the deuteron before stripping is 10 Mev, and half of this is taken away from the neutron. Therefore the mean neutron energy is $190/2-5=90$ Mev. There is a distribution in energy caused primarily by the internal relative velocity of the particles in the deuteron before stripping, which leads to a momentum distribution for neutrons emitted in the forward direction of the following form:

$$P(p)\sim[1+(p-p_0)^2/M\epsilon_d]^{-2}, \qquad (3)$$

where p is the forward momentum, p_0 its mean value, M the proton mass and ϵ_d the deuteron binding energy. The points where the probability is down to half its maximum value are given by $(p-p_0)^2=(\sqrt{2}-1)M\epsilon_d$; the neutron energies at these points are then given approximately by $E_0\pm[2(\sqrt{2}-1)\epsilon_d E_0]^{\frac{1}{2}}$, where E_0 is the energy

[3] E. Amaldi and B. N. Cacciapuoti, Phys. Rev. **71**, 739 (1947).

[4] E. O. Salant and N. F. Ramsey, Phys. Rev. **57**, 1075 (1940).

[5] Ageno, Amaldi, Bocciarelli, and Trabacchi, Phys. Rev. **71**, 20 (1947).

[5a] W. Sleator, Jr., Phys. Rev. **72**, 207 (1947).

[6] A. C. Helmholz, E. M. McMillan, and D. C. Sewell, Phys. Rev. **72**, 1003 (1947).

[7] R. Serber, Phys. Rev. **72**, 1008 (1947).

corresponding to p_0. This puts the half-value points at 90 ± 12.8 Mev, and makes the half-width of the distribution equal to 25.6 Mev. If the additional spread as a result of the ranges of initial deuteron energies and energy losses is added according to the law for random distributions, the half-width is increased slightly to about 28 Mev. The distribution given by Eq. (3) falls off rapidly for large energy deviations from E_0; for example, it says that only 3 percent of the total number of neutrons have energies below 60 Mev, and 3 percent have energies above 125 Mev.

The neutrons were detected by measuring the activity induced in carbon disks according to the reaction $C^{12}(n,2n)C^{11}$. Details of the counting technique will be discussed later. The way in which the sensitivity of this detector varies with neutron energy is not well known experimentally, but we believe on the basis of theory[8] and experiments checking certain aspects of the theory of this and related processes[9–11] that the cross section is approximately constant above 60 Mev. It is certainly zero below 20 Mev, and may have a peak in the vicinity of 40 Mev. However, the number of neutrons between 20 and 60 Mev is small, and if we suppose that the detector sensitivity is nearly constant for the bulk of the effective neutrons, then the total cross section observed is simply the mean value averaged over the initial energy distribution. If the variation of the total cross section with energy can be represented by a straight line over the intense part of the neutron spectrum, then because of the approximate symmetry of the spectrum the measured cross section would correspond to the value at 90 Mev.

Recent experiments by J. A. Hadley *et al.* and H. F. York (both to be published) furnish some information on the energy distribution of the neutrons and on the carbon $(n,2n)$ excitation curve. Their results indicate that there are probably somewhat more low energy neutrons than are given by Eq. (3) and that the effective mean neutron energy as seen by the carbon detectors may be as low as 80 Mev. Therefore it should be understood that although the energy is given nominally as 90 Mev it would be more correct to say that it lies between 80 and 90 Mev.

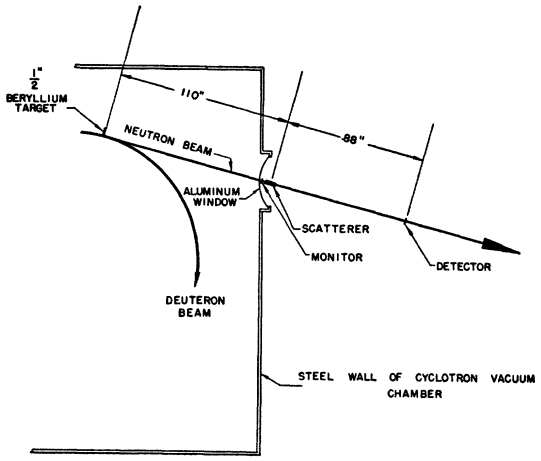

FIG. 1. Plan view of experimental set-up.

A plan view of the experimental set-up is shown in Fig. 1. The monitor, scattering block, and detector were mounted on supports made of thin dural, and were aligned along the axis of the neutron beam. A "neutron window" 32 inches in diameter, spun out of $\frac{1}{8}$-inch aluminum sheet, was set into the vacuum chamber wall, in order to reduce the background of scattered neutrons produced by the steel wall. The monitor and detector were carbon disks of $1\frac{11}{16}$-inch diameter and $\frac{1}{8}$-inch thickness. The alignment was done with the aid of a cathetometer; the axis was located by sighting on the target with the window removed, and the supports were then adjusted until cross-hairs mounted in rings having the same diameters as the scatterer and the carbon disks were on this line. The position of the axis had to be determined only once, since a mark was made on the window at its intersection with the axis, and a set of cross-hairs was fixed in a hole through the concrete cyclotron shield, through which the sighting was done. This procedure allows the achievement of very accurate collinearity. Since the greatest extent of the source is not over $1\frac{3}{4}$ inches and the detector diameter is a little less than that, it is clear that a $1\frac{3}{4}$-inch scatterer would intersect all the effective rays, but for safety a margin was allowed

[8] W. Heckrotte and P. Wolff, Phys. Rev. **73**, 264, 265 (1948).
[9] W. W. Chupp and E. M. McMillan, Phys. Rev. **72**, 873 (1947).
[10] E. M. McMillan and R. D. Miller, Phys. Rev. **73**, 80 (1948).
[11] E. M. McMillan and H. F. York, Phys. Rev. **73**, 262 (1948).

and the standard diameter of the scattering blocks was set at $2\frac{1}{2}$ inches. In a few cases the size was different for reasons connected with the availability of stock, but no diameter less than 2 inches was used.

III. SCATTERING BLOCKS

The materials used can be divided into three classes: solids, liquids, and powders. Of the solids, C, Al, and Cu were machined from stock, and Sn and Pb from castings, to the standard $2\frac{1}{2}$-in. diameter. *U* was machined from stock to 2-in. diameter, and for Be a piece of existing 2-in. round stock was used. For Mg and Zn stacks of rectangular blocks forming 3-in. and 2-in. squares respectively were used. The most difficult to handle was Li, which we obtained in the form of rather rough $2\times2\times1$-in. blocks. These were carefully scraped clean under kerosene, then pressed in a die which brought them into an accurately rectangular shape, wiped free of kerosene and used before appreciable oxidation had occurred. Paraffin was used to get the H cross section by taking the paraffin-carbon difference; $2\frac{1}{2}$-in. disks were machined from clear bubble-free slabs of high quality paraffin and stacked together. The paraffin used was analyzed by the Chemistry Department and found to have a composition corresponding to $CH_{2.08}$.

The dimensions of the solid blocks were measured by micrometers and they were weighed to get the densities. In the case of Be the outer surface of the stock was not machined, so its density was determined by immersion in water. The measured densities are entered in Table I; it will be seen that they correspond very closely to the accepted values, with two exceptions. The density of the carbon is below the theoretical value for graphite, but this is to be expected and there is no doubt of the homogeneity and purity of the material. The density of the lithium is 6 percent high, indicating the presence of impurities. The error in the Li cross section will not be this large, however, since the impurities themselves do some absorbing; the mass absorption coefficients of the elements from Be to Cl are close enough to that of Li that any of these as impurities would give less than 1 percent error in the cross section.

The liquid absorbers were contained in thin-walled aluminum cells $2\frac{1}{2}$-in. in diameter by 11 27/64-in. long, with $\frac{1}{32}$-in. Al ends. One cell was filled with water, one with heavy water, and one was left empty to be used in the initial intensity and background determinations. The water cross section minus that of H gave the O cross section, and a direct comparison of the light and heavy water absorptions gave the D–H difference. One of these cells was also used to contain CCl_4 to measure the Cl cross section. The densities of the liquids were not measured, since their purity was known and the accepted values could be used.

The only powdered substance used was melamine ($C_3H_6N_6$), from which the N cross section was obtained. This was tamped into a $2\frac{1}{2}$-in. Al tube, taking care to get as nearly uniform packing as possible. The bulk density is of no interest; in the computations the surface density obtained from the inner diameter of the tube and the weight of melamine was employed.

IV. EXPERIMENTAL PROCEDURE

The experimental data were taken in a series of 18 runs, each run comprising the measurements taken on any one day or with any one particular experimental set-up. It was necessary to perform the alignment procedure for each run to make sure that the axes of the monitor, the absorber, and the detector lay along a common ray of the neutron beam from the cyclotron. It was not necessary to keep the longitudinal distances the same from run to run, but for convenience they were kept roughly the same, the run-to-run variation being only a few inches at the most.

A typical run took several hours to perform and included as many as 50 separate absorption measurements. Each measurement began with the insertion of a matched pair of carbon disks into the monitor and detector holders, a suitable length of absorbing material having been interposed. (Each pair of the monitor and detector carbon disks was matched in weight to within 0.2 percent.) This arrangement was then exposed to the neutron beam for 1.5 minutes, at the end of which time the carbon disks were taken to another building and the ratio of their activities counted. As the half-life of the induced activity in the carbon disks was only 20.5 minutes, i.e.,

small compared with the length of the run, it was necessary to begin the counting of the pairs of disks while other pairs of disks were being exposed. The time interval between the end of the exposure and the beginning of the counting varied from 4 to 30 minutes and was usually about 10 minutes.

In the first eleven runs absorption curves were plotted from measurements made on various thicknesses of absorbing material. These absorption curves, when corrected for background, were found to be exponential within experimental error as far as they could be followed into the background. This background activity induced in the carbon disks was caused by scattering of the neutron beam from the aluminum window in the cyclotron vacuum chamber, from the aluminum and dural trough which supported the absorber and the monitor disk, and from other neighboring materials. Another contributor to the background was the production of neutrons in parts of the cyclotron other than the $\frac{1}{2}$-inch beryllium target. The magnitude of the background reading was 5 to 6 percent of the activity induced when no absorber was interposed between the two carbon disks. It was measured by inserting a 32-inch length of copper rod in the absorber position; its diameter was equal to that of the usual absorbing samples. In the presence of no background this copper rod would have attenuated the beam to 2.5×10^{-7} of its undisturbed intensity. The substances on which absorption curves were run were paraffin, carbon, aluminum, copper, and lead. Figure 2 shows the absorption curves of copper and aluminum plotted on semi-logarithmic graph paper.

It having been shown in this way that the absorption of the neutron beam was indeed exponential, the remaining runs, upon which the final results were chiefly based, employed single lengths of absorbers and depended on repeated measurements for accuracy. The length of absorber used in each case was about one mean free path. Of course, before the experiment was actually run, it was impossible to tell exactly what length of absorber corresponded to one mean free path, but one could make reasonably good guesses by extrapolation or interpolation from previous measurements on other substances or by a quick run on some arbitrary length of the absorber in question.

For the calculation of the absorbing power of a typical substance, three ratios of detector to monitor activity had to be determined: (1) the ratio with no absorber between the carbon disks (the "blank" measurement), (2) the ratio with the length of absorber whose attenuation is being measured, and (3) the background ratio. Each of these ratios was measured several times to reduce the statistical errors. In the course of the repetitions the blank and the absorber ratios were measured alternately to keep the conditions as closely identical as possible. Not as many determinations of the background ratio were made because its contribution to the probable error was less than those of the other two ratios.

V. COUNTING TECHNIQUE AND CALCULATIONS

The basic measurement is the ratio of the activity of the detector disk to that of the monitor disk; calling this ratio r when the scattering block is in place, r_0 when it is absent, and r_b when the long copper block is in place

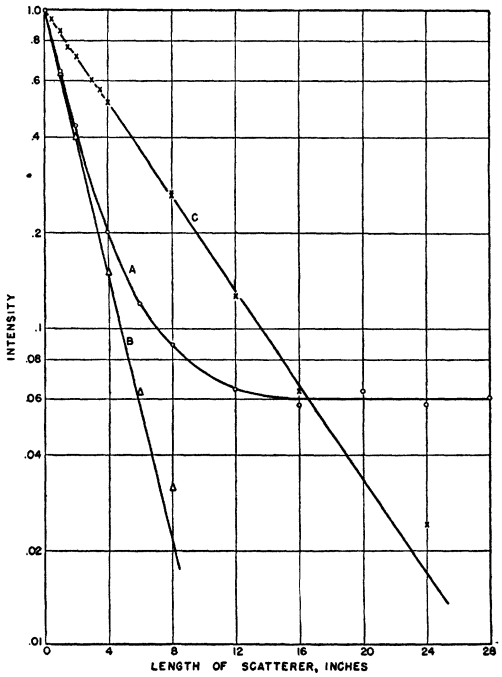

FIG. 2. Some attenuation curves. Curve A (circles): Copper scatterer, neutron background not subtracted. Curve B (triangles): Copper scatterer, background subtracted. Curve C (crosses): Aluminum scatterer, background subtracted.

TABLE I. Measured mean free paths.

Substance	Density ρ g/cm³	Mean free path λ (cm)	$\rho\lambda$ (g/cm²)
H_2O	0.998[a]	32.2	32.1
D_2O	1.105[a]	30.1	33.3
paraffin ($CH_{2.08}$)	0.918	35.3	32.4
melamine ($C_3N_6H_6$)	— [b]	—	34.4
CCl_4	1.595[a]	26.4	42.1
Li	0.567	64.7	36.7
Be	1.85	18.8	34.8
C	1.596	22.7	36.3
Mg	1.735	22.6	39.2
Al	2.711	14.8	40.0
Cu	8.91	5.33	47.5
Zn	7.078	6.94	49.1
Sn	7.28	8.26	60.1
Pb	11.33	6.70	75.9
U	18.8	4.18	78.6

[a] Density from tables. Other values were measured on the samples used.
[b] Only surface density measured on this sample. The individual errors are not given, but should be taken as about ±2 percent of λ and $\rho\lambda$. Corrections for scattering into the detector have been applied.

(background), the following relation holds:

$$(r-r_b)/(r_0-r_b)=e^{-l/\lambda}, \quad (4)$$

where l is the length of the scatterer and λ is the mean free path for the neutrons.

All counts were made concurrently; that is, the detector and monitor activities were counted over the same time interval on separate counters, eliminating the necessity of corrections for decay. Furthermore, each count was repeated with the detector and monitor interchanged between the two counters, in order to eliminate inequalities in counter sensitivity. The counter-to-sample distances were not equal for the two disks, but were chosen so that the ratio r_0 was about unity. This procedure allows more efficient use of the counting time, and does not affect the result since it multiplies all the activity ratios by a constant factor.

The counters used were mica window, bell-jar type counters, with lead shields, regulated power supplies, and scaling circuits of standard design. In all cases appropriate corrections for counter background and overlapping of counts were made. The counting rates were mostly in the range 2000 to 6000 counts per minute, and the counting periods one to three minutes, timed by a synchronous motor time meter interlocked with the counting switch.

The statistical errors may be estimated in the following way. A typical determination of r_0 involves about 5000 counts each on the detector and monitor, and an equal number with the samples interchanged, giving a mean error in r_0 of $1/(5000)^{\frac{1}{2}}=1.4$ percent. Similarly, in measuring r, the detector made about 2000 counts and the monitor about 5000, giving an error in r of $[\frac{1}{2}(1/5000+1/2000)]^{\frac{1}{2}}=1.9$ percent. Since the determination of r_b contributes a negligible error, and $l/\lambda\sim 1$, then according to (4) the error in a single determination of λ is just $((1.4)^2+(1.9)^2)^{\frac{1}{2}}=2.4$ percent. Finally, for each substance the determination was repeated about ten times, so that the mean statistical error in the final value for λ is a little less than 1 percent. It was found that the spread among individual determinations, even when made on different days or with different counters, corresponded to that expected from the counting statistics.

Where the cross-section values are derived from differences, as in the cases of H, D, O, N, and Cl, the errors are of course greater than those of the individual measurements. In taking the differences $CH_{2.08}-C$ and D_2O-H_2O, samples of nearly equal attenuation were used, and the readings were alternated between the samples. The numbers of separate determinations of these differences were 30 and 20 respectively.

The errors in the length and density measurements are believed to be less than 0.5 percent. Another possible source of error, the backscattering of neutrons from the absorber into the monitor, was found to be negligible in a special experiment designed to measure this effect. The errors given with the final results are

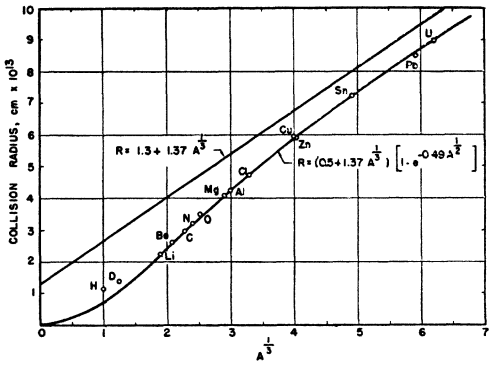

FIG. 3. Collision radii R, computed from the measured cross sections by Eq. (1), plotted against cube roots of mass numbers. The straight line represents an approximation to data obtained by other observers at 14–25 Mev; the curve is from an empirical formula fitted to the 90-Mev points, not including H and D.

the mean statistical errors, plus 1 percent added to allow for other unsuspected sources of error.

VI. CORRECTION FOR SCATTERING INTO DETECTOR

In spite of the very good geometry of this experiment, the errors arising from scattering of neutrons into the detector by the heavier elements are not quite negligible, on account of the small angular spread of the diffraction patterns at this neutron energy. Therefore, corrections were made for this effect, computed as outlined in the Appendix. The largest correction for this effect was 3 percent.

VII. RESULTS

The results are collected in Tables I and II.

TABLE II. Total cross sections.

Substance	σ_t cm$^2\times10^{24}$	A mean mass no.	$A^{\frac{1}{3}}$	R cm$\times10^{13}$	R' cm$\times10^{13}$
H	0.083±0.004	1	1	1.15±0.03	0.72
D[a]	0.117±0.005	2	1.26	1.36±0.03	1.11
Li	0.314±0.006	6.94	1.91	2.24±0.02	2.26
Be	0.431±0.008	9	2.08	2.62±0.02	2.58
C	0.550±0.011	12	2.29	2.96±0.03	2.97
N	0.656±0.021	14	2.41	3.23±0.05	3.19
O	0.765±0.020	16	2.52	3.49±0.05	3.39
Mg	1.03 ±0.02	24.32	2.90	4.05±0.04	4.07
Al	1.12 ±0.02	27	3.00	4.22±0.04	4.25
Cl	1.38 ±0.03	35.46	3.29	4.69±0.05	4.74
Cu	2.22 ±0.04	63.57	3.99	5.94±0.05	5.85
Zn	2.21 ±0.04	65.38	4.03	5.93±0.05	5.90
Sn	3.28 ±0.06	118.70	4.92	7.22±0.07	7.21
Pb	4.53 ±0.09	207.21	5.92	8.49±0.08	8.60
U	5.03 ±0.10	238	6.20	8.95±0.09	8.99

[a] The difference D–H has an error of ±0.003. The collision radius R is computed from Eq. (1); R' is the corresponding value given by the empirical Eq. (5). The errors given are the statistical mean errors plus 1 percent.

VIII. DISCUSSION

The cross sections from Li to U can be compared with the results at lower energy, as given in Eq. (2), by plotting R against $A^{\frac{1}{3}}$. Such a plot is given in Fig. 3. It is apparent that the values lie on a smooth or nearly smooth curve, and can therefore be fitted by an empirical equation. Such an equation is:

$$R=(0.5+1.37A^{\frac{1}{3}})[1-\exp(-0.49A^{\frac{1}{3}})]\times10^{-13}\text{ cm}. \quad (5)$$

This is plotted on the figure, and the values are also entered in the last column of Table II. The form of this equation has no theoretical basis, but it may be useful for purposes of interpolation. The deviations of some of the points from the smooth curve are hardly statistically significant. After completing the measurements described above, some attenuation values were obtained with the same detectors and absorbers, but using the collimated neutron beam which emerges through a 2-inch hole in the concrete cyclotron shield. The values obtained were for carbon $\sigma_t=0.556\pm0.013$, and for copper $\sigma_t=2.13\pm0.04$. The two carbon values are in excellent agreement; the two copper values lie above and below the empirical curve, making us believe that the deviations from this curve are not significant.

It will be noted that the 90-Mev values tend to approach the lower energy values for large A, but become increasingly smaller than the latter as A becomes smaller. This is attributed to the transparency of the nucleus, the probability of penetration without collision becoming greater as the nuclear diameter becomes less compared to the mean free path of the neutrons in nuclear matter. This mean free path, computed using the measured H and D cross sections, is consistent with the degree of transparency shown by the other elements. Since a more complete discussion will be given in a paper to be published by the theoretical group of the Radiation Laboratory, these relations will not be developed further here.

As pointed out in Section II, the effective mean energy of the neutrons may be below the nominal value of 90 Mev by as much as 10 Mev. The energy is thus known with less accuracy than the cross sections. This uncertainty is not very important in making a theory to correlate the various cross sections, where one is dependent chiefly on internal consistency of the data, but it is important in comparing the cross sections with computed absolute values, or with values measured at other energies. In the cases of H and D which may be compared with theoretical calculations based on assumed nuclear force laws, the fact that the nominal energy of 90 Mev is possibly a little too high should be taken into account.

ACKNOWLEDGMENTS

The authors wish to thank Professor E. O. Lawrence for his encouragement in this work, the cyclotron operating crew for their assistance

in making the runs, and Miss Alice Dodson for her help in computing the data. This paper is based on work performed under Contract No. W-7405-eng-48 with the Atomic Energy Commission in connection with the Radiation Laboratory, University of California.

APPENDIX. CORRECTION FOR DIFFRACTION EFFECTS

In interpreting fast neutron scattering experiments, it has generally been assumed that the diffraction of the neutron waves by the nucleus accounts for a part of the total cross section equal to the projected collision area of the nucleus. This is a very reasonable assumption in cases where the neutron wave-length is short compared to the nuclear diameter, since the diffracted intensity is mostly in the forward direction and the situation approximates that of diffraction by a disk-like obstacle. Comparison with the well-known equivalent optical problem shows that the total diffracted flux is indeed equal to the flux intercepted by the obstacle, and that its angular distribution is given by:

$$d\sigma_d/d\omega=\left[\frac{RJ_1(kR\sin\theta)}{\sin\theta}\right]^2 \tag{6}$$

where $d\sigma_d/d\omega$ is the cross section per unit solid angle for diffraction at the angle θ, R is the collision radius of the nucleus, k is 2π times the reciprocal of the neutron wave-length, and J_1 is a Bessel function.

The total cross section σ_t should then be made up of the integrated cross section σ_d for diffraction plus an equal amount to take care of the neutrons that actually strike the nucleus, giving the usually assumed relation:

$$\sigma_t=2\sigma_d=2\pi R^2. \tag{7}$$

This should be strictly valid when $kR\gg1$, if the nucleus can be considered as an opaque obstacle. If the nucleus is partially transparent, as is apparently the case for lighter nuclei at 90-Mev neutron energy, the situation is more complicated, and both the magnitude and angular distribution of the diffraction can be altered. One can however still treat (7) as a definition of R in these cases, and use the diffraction formula (6) as a first approximation, with the understanding that the R so defined may be smaller than the actual nuclear radius.

In the cases to be considered here, we are dealing with 90-Mev neutrons, for which $k=2.15\times10^{13}$ cm^{-1}; the collision radius found for the uranium nucleus is 9.0×10^{-13} cm, giving $kR=19$. According to Eq. (6) the diffraction pattern for uranium falls to half intensity at $\theta=0.085$ radian, while the patterns for other elements will be wider.

At small values of θ, the diffraction per unit solid angle is given approximately by the first two terms in the series expansion for the Bessel function, thus:

$$d\sigma_d/d\omega\sim1/4k^2R^4[1-1/8(kR\sin\theta)^2]^2. \tag{8}$$

With the above preliminaries we can estimate the intensity diffracted into the detector in a typical attenuation experiment, set up as in Fig. 1. The method of calculation is similar to that of reference (2), appendix II. The source and detector are treated as points, since they subtend angles small compared to the width of the central diffraction peak. Because of the similarity of the treatment to that already published by Amaldi *et al.*,[2] only the result is given here. The intensity I_d diffracted into the detector, in terms of the intensity I that would be seen there in the absence of diffracted neutrons, is given by:

$$\left.\begin{aligned} I_d&=I(l/\lambda)(K-K^2)(1+l/8\lambda),\\ K&=(1/16\pi)k^2a^2(1/x_1+1/x_2)^2\sigma_t,\end{aligned}\right\} \tag{9}$$

where a is the radius of the scatterer, x_1 and x_2 are the distances from the center of the scatterer to the source and detector, l is the length of the scatterer, and λ is the mean free path of the neutrons in the scatterer. The term in K^2 comes from the second term of (8) and the term in $(l/8\lambda)$ from double scattering processes; their smallness indicates that higher order approximations are not necessary. Numerically we find for example in the case of lead $k=2.15\times10^{13}$ cm^{-1}, $a=1.25$ in., $x_1=110$ in., $x_2=88$ in., $\sigma_t=4.5\times10^{-24}$ cm^2, giving $K=0.027$. The relative error in λ is simply the error in the intensity times λ/l, and is therefore equal to I_d/I from (9) without the factor l/λ, giving an error of $0.027(1+1/8)=3.0$ percent. For lighter elements the error is obviously smaller, and for uranium it is smaller because the radius of the scattering block was only one inch.

In order to check the approximate validity of the formula used in making this correction, measurements were made of the scattering from rings of Cu and Pb placed around a long copper rod which intercepted the direct beam. Although not very precise because of the relatively high background, these results verified the computed scattering with sufficient accuracy for the purpose of making this small correction.