even-even nuclei in the region with which we are concerned here. It is seen that the point found for Kr^{80} fits well into the general pattern. Moreover, it further supports the rule[5] that addition of 2 protons to a nucleus has only a slight effect on the energy of the first excited state except for proton numbers near a closed shell: Se^{78} has a first excited state of 0.60 ± 0.025 Mev, deduced by Kinsey and Bartholomew[8] from the energy difference of the two capture γ rays of highest energy observed from $(Se^{77}+n)$.

[8] B. B. Kinsey and G. A. Bartholomew (private communication). This will appear in the *Canadian Journal of Physics*.

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Neutron Total Cross Sections at 20 Mev

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With the $T(d,n)He^4$ reaction as a monoenergetic source of neutrons of about 20 Mev, the total cross sections of 13 elements have been measured by a transmission experiment. These cross sections vary approximately as $A^{\frac{2}{3}}$ as is to be expected from the continuum theory of nuclear reactions. The cross section for hydrogen at 19.93 Mev is 0.504 ± 0.01 barn. This result, together with other results at lower energies, seems to require a Yukawa potential in both the singlet and triplet *n-p* states and a singlet effective range that is lower than that obtained from *p-p* scattering data.

INTRODUCTION

UNTIL very recently most work on neutron cross sections at energies from 10 to 25 Mev was done with sources such as $Li^7(d,n)Be^8$ which do not produce monoenergetic neutrons. Therefore, to obtain results ascribable to a particular neutron energy it was necessary to use an energy-sensitive detector. The two methods most commonly used were (1) detection of recoil protons of a particular energy emitted in a given direction from a hydrogenous radiator[1] and (2) use of a threshold detector such as $C^{12}(n,2n)$.[2,3] Both of these methods suffer from rather severe defects. The first has very low efficiency if one wishes to obtain good energy resolution, while the second gives only a complicated average of the cross section over the energy region above the effective threshold.

With the production of sufficient quantities of tritium, the $T(d,n)He^4$ reaction can now serve as an intense source of high-energy monoenergetic neutrons, thus releasing one from the troublesome detector problem. With a 3.5-Mev accelerator, for example, it is possible to obtain neutrons from 12 to 20 Mev with a homogeneity that is determined essentially by the target thickness and hence by the source strength required. Because of the low-energy resonance in $T(d,n)$, Cockcroft-Walton accelerators are particularly well suited to produce high intensities of 14-Mev neutrons by this reaction. Coon *et al.*[4] have recently published a survey of the total cross sections of over 50 elements for 14-Mev neutrons, while Poss *et al.*[5] have also reported a few measurements of total cross sections at this energy.

Using this reaction as a source of monoenergetic neutrons in the 20-Mev region, we have measured the total cross sections of a number of elements to an accuracy of about 3 percent and the total cross section of hydrogen to 2 percent. The results vary approximately as $A^{\frac{2}{3}}$, as is to be expected from the continuum theory of nuclear reactions of Feshbach and Weisskopf.[6]

PROCEDURE

Fast neutrons of the order of 20-Mev energy were obtained by bombarding a tritium gas target with deuterons from the large Los Alamos electrostatic accelerator. To obtain a sufficiently high neutron flux, the tritium pressure was usually such that it produced an energy loss of about 200 kev for the deuterons traversing the target. This variation in deuteron energies throughout the target produced a corresponding spread in neutron energies which was much larger than the spread due to other causes. The average neutron energy was calculated from the dynamics of the reaction, including a small correction for relativistic effects. The corrections to the deuteron energy for the energy loss in the target and the nickel entrance foil were calculated from calibrations made with the proton beam.

The detector was a stilbene scintillation counter placed 148 cm from the target at 0° to the deuteron beam. To keep the background low the counter was biased to count only neutrons of about 14 Mev or higher. A similar scintillation counter at 30° to the

[1] W. Sleator, Jr., Phys. Rev. **72**, 207 (1947).
[2] R. Sherr, Phys. Rev. **68**, 240 (1945).
[3] Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Report of an International Conference on Fundamental Particles **1**, 97 (1947).
[4] Coon, Graves, and Barschall, Phys. Rev. **88**, 562 (1952).
[5] Poss, Salant, Snow, and Yuan, Phys. Rev. **87**, 11 (1952).
[6] H. Feshbach and V. F. Weisskopf, Phys. Rev. **76**, 1550 (1949).

beam served as a monitor for the neutron flux, while a precision current integrator was used to measure the deuteron beam incident on the target.

The total cross sections σ_t were obtained from transmission measurements by means of the relation:

$$T = e^{-n\sigma_t},$$

where n is the number of target nuclei per square cm of beam. In making the transmission measurements, samples 2.54 cm in diameter were placed midway between the source and detector. To measure the effect produced by neutrons scattered from the walls and floor of the room a long copper bar with essentially zero transmission was placed at the sample position. The counting rate with this in place was always less than 1.5 percent of the rate obtained from the direct neutron beam. A second correction must be made for neutrons (and any possible gamma rays) that are produced by (d,n) reactions where the deuteron beam strikes the collimating diaphragms, entrance foil, etc. This correction was obtained by replacing the tritium in the target cell with hydrogen and repeating the transmission measurements. In order to remove all tritium from the target it was necessary to flush it out several times with hydrogen. The removal of the tritium was considered satisfactory when the monitor counting rate no longer decreased with further flushing. The detector counting rate was then a maximum of 3 percent of the rate obtained with tritium in the target.

TABLE I. Total cross sections. Unless otherwise indicated the cross-section accuracy is ±3 percent. The accuracy in the neutron energy is ±0.025 Mev.

Element	E_n (Mev)	Neutron energy spread (Mev)	σ_t (barns)	Sample form
H	19.93	0.26	0.504±0.01	gas
He	17.97	0.44	0.848	gas
	19.00	0.32	0.816	
	20.07	0.25	0.770	
C	17.20	0.54	1.39	graphite
	19.00	0.32	1.45	
	20.07	0.25	1.52	
F	19.00	0.32	1.84	Teflon
Al	19.00	0.32	1.84	metal
Si	19.00	0.32	1.94	compacted powder
Fe	19.00	0.32	2.23	metal
Cu	19.00	0.32	2.56	metal
Br	17.20	0.54	3.12	liquid
	19.00	0.32	2.98	
	20.07	0.25	2.96	
Zr	19.00	0.32	3.60	metal
Pb	19.00	0.32	5.96	metal
Bi	19.00	0.32	5.69	metal
U	17.97	0.44	6.14	metal
	19.00	0.32	5.94	
	20.07	0.25	6.29	

For the hydrogen and helium measurements the sample was a cell 100.0 cm long and 2.38 cm in diameter filled with the gas to a pressure of about 2000 psi. The filling was done by R. L. Mills and F. Edeskuty, who also determined the amount of gas present by weighing the cell full and empty. For the hydrogen filling an independent check was made by accurate PVT measurements. The two methods agreed to $\frac{1}{2}$ percent. A mass-spectroscopic analysis of the hydrogen showed a purity of 99.75 percent, with deuterium being the principal contaminant. No special analyses of the other samples were made since they were known to have a purity of better than 99 percent and the accuracy expected from the cross sections did not justify this procedure.

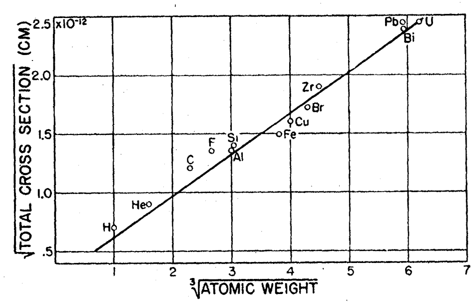

FIG. 1. The square root of the total cross section as a function of the cube root of the atomic weight. Neutron energy = 19 Mev. The straight line is the function $(\sigma_t)^{\frac{1}{2}} = (2\pi)^{\frac{1}{2}}(r_0 A^{\frac{1}{3}} + \lambdabar)$, $r_0 = 1.4 \times 10^{-13}$ cm.

RESULTS

The results of the total cross-section measurements are summarized in Table I. Generally, several series of measurements were made from which the cross section could be calculated, and these always agreed within 2 or 3 percent. Since the possible errors arising from other causes are considerably less than this, we believe that these cross sections are good to 3 percent.

A correction for in-scattering has been applied using the formula for in-scattering given in the appendix. Because of the good geometry used in these experiments the correction was never larger than 1.4 percent, and for the lighter elements it was negligible. The increased correction necessitated by the long length of the gas cell in the hydrogen and helium experiments has been calculated, but it is still negligible. The effects of multiple scattering were also considered and were found to be so small as to produce no detectable effect.

The cross sections are displayed graphically in Fig. 1, where we have plotted the square root of the total cross section as a function of the cube root of the atomic number. The solid curve is the function $(\sigma_t)^{\frac{1}{2}} = (2\pi)^{\frac{1}{2}} \times (R + \lambdabar)$, which is the asymptotic form of the expression for the total cross section given by the theory of Feshbach and Weisskopf.[6] Deviations from this curve are not significant, since the theory has already proved to be inadequate to explain the variation of total cross sections at lower energies.[7] A more refined theory has recently been announced,[8] which gives better agreement with the lower-energy data, and perhaps it will be satisfactory at these energies also.

[7] H. H. Barschall, Phys. Rev. **86**, 431 (1952).
[8] Feshbach, Porter, and Weisskopf, Phys. Rev. **90**, 166 (1953).

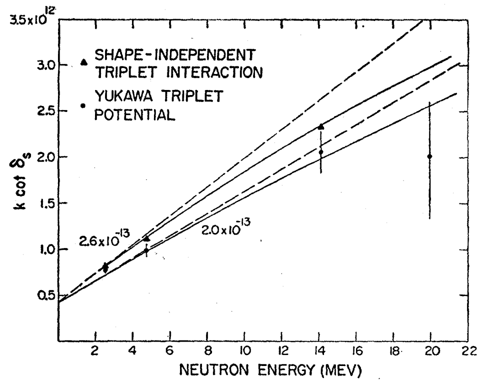

FIG. 2. $k \cot\delta_s$ for the singlet scattering state, calculated under the assumption of both a shape-independent triplet interaction and a Yukawa triplet potential. At 20 Mev, $k \cot\delta_s$ is practically independent of assumptions as to the nature of the triplet potential. The dotted and solid curves are the predictions of the effective range theory for the shape-independent and Yukawa potentials, respectively, for the two values of the singlet effective range indicated here.

More attention was given to the measurements of the total cross section of hydrogen. From five different determinations of the transmission, the cross section was found to be 0.504 ± 0.01 barn, where the error quoted is the standard deviation of the measurements. This error arises principally from the fact that the transmission was fairly high (0.734) and therefore the error in the cross section was several times the transmission error. With twice the hydrogen pressure this error could be reduced by a factor of two without increasing the counting time to any great extent. Other possible sources of error have been considered and are considerably less than that quoted here.

DISCUSSION OF *n-p* SCATTERING RESULTS

With the aid of the effective range theory for *s*-wave neutrons,[9,10] the results of the *n-p* total cross section have been compared with the most accurate experimental results obtained at lower energies. The other results used were (1) $\sigma = 2.525$ barns at 2.532 Mev (Fields, Becker, and Adair[11]); (2) $\sigma = 1.690$ barns at 4.749 Mev (Hafner, Hornyak, Falk, Snow, and Coor[12]); and (3) $\sigma = 0.689$ barn at 14.10 Mev (Poss, Salant, Snow, and Yuan[5]). Using the triplet scattering length and effective range given by Snow,[13] we have calculated $k \cot\delta_s$ for the singlet scattering at each of these energies for both a shape-independent triplet interaction and a Yukawa triplet potential. At 19.93 Mev the effect of *d*-wave scattering was considered, and a small correction for it was subtracted, using the results of calculations by Christian.[14] However, the *d*-wave contribution at this energy is actually negligible compared to our experimental error and could have been left out. Effects from *p* waves were not estimated since the symmetry in the scattering about 90° found at higher energies leads one to expect that they are very small.[14] It is interesting to note that the triplet phase shift is very close to 90° at this energy; consequently, the total cross section is practically independent of any assumptions as to the nature of the triplet interaction. Unfortunately, the singlet scattering is only about $\frac{1}{5}$ of the total cross section, and therefore a very precise measurement of the total cross section is necessary to get much accuracy in $k \cot\delta_s$.

The values for $k \cot\delta_s$ have been plotted in Fig. 2 as a function of neutron energy. The uncertainties indicated are those resulting from errors in the cross sections only and do not include any errors in the scattering parameters. From this graph it appears that the singlet effective range must be smaller than the value 2.6–2.7 $\times 10^{-13}$ cm obtained from *p-p* scattering data at low energies,[15] although if one assumes a shape-independent interaction for the triplet state a shape-independent singlet effective range of 2.6×10^{-13} cm is consistent with the three experiments at lower energies. Considering all the data, the best fit is obtained if one assumes a Yukawa potential for both the singlet and triplet states, with a singlet effective range of about 2×10^{-13} cm.

Since the low value for $k \cot\delta_s$ at 20 Mev is the main factor in the conclusions reached above, we must reconsider the possibility of a systematic error in the cross-section measurement. Of the various possibilities, the only one which could amount to more than a few tenths of a percent is in the measurement of backgrounds when the tritium in the target is replaced by hydrogen. In recent experiments some unusually high backgrounds were found to be produced by impurities in the hydrogen used as the replacement gas; however, at the time the total cross-section measurements reported here were made a different tank of hydrogen was in use and there was no suggestion of an abnormal background. If the hydrogen background measured then were ignored completely, the result would be a 2.7-percent decrease in the *n-p* cross section and a corresponding increase of 40 percent in $k \cot\delta_s$. Because the magnitude of this background depends on several unknown factors, among which are the bias used on the scintillation counter and the way in which the deuteron beam was focused, it is not possible to say how large it should have been.

We would like to thank Robert L. Mills and Frederick Edeskuty for filling the gas cells and determining the amount of gas present, and James H. Coon for the use of the gas cells and detection equipment.

[9] J. M. Blatt and J. D. Jackson, Phys. Rev. **76**, 18 (1949).
[10] H. A. Bethe, Phys. Rev. **76**, 38 (1949).
[11] Fields, Becker, and Adair, Phys. Rev. **89**, 908 (1953).
[12] Hafner, Hornyak, Falk, Snow, and Coor, Phys. Rev. **89**, 204 (1953).
[13] G. Snow, Phys. Rev. **87**, 21 (1952).
[14] R. S. Christian, Repts. Progr. Phys. **15**, 68 (1952).
[15] J. D. Jackson and J. M. Blatt, Revs. Modern Phys. **22**, 77 (1950).

APPENDIX

In-Scattering Corrections

Since there seems to be no general agreement as to how in-scattering should be treated we wish to derive here the corrections required for a transmission experiment.[16] We assume that the scattering sample is midway between the source and detector and that the incident and in-scattered neutrons make small angles with the axis of the system. Considering only singly scattered neutrons, the increase in transmission due to in-scattering is given by

$$T_1=\frac{4B}{(\frac{1}{2}L)^2}\int e^{-\mu z}f(0)\mu dz e^{-\mu(t-z)},$$

where $B=\frac{1}{4}\pi D^2=$ area of scattering sample, $L=$ source to detector distance, $t=$ thickness of scattering sample, $\mu=n\sigma_t$; $\sigma_t=$ total cross section, and

$$f(\theta)=\frac{1}{\sigma_t}\frac{d\sigma(\theta)}{d\Omega}.$$

After integrating this expression one can obtain a simple formula for the relative correction to be applied to the cross section, namely

$$\Delta\sigma/\sigma=4\pi(D/L)^2 f(0).$$

For the quantity $f(0)$ we have used $\frac{1}{2}(kR+1)^2/4\pi$, where k is the neutron wave number and $R=r_0A^{\frac{1}{3}}$ is the nuclear radius. The factor $(kR+1)^2/4\pi$ is obtained from the diffraction theory of Feld *et al.*[17] based on the continuum model; the factor $\frac{1}{2}$ arises from our assumption that half of the total cross section is due to diffraction scattering. There is excellent justification for using this diffraction theory. With the fast beam of the Los Alamos Fast Reactor as a source, Jurney[18] has measured the neutron angular distributions for a number of elements from iron to bismuth. In all cases the results were in very good agreement with the predictions of the theory for angles up to 60°. At the higher energies used in our experiments one would expect the theory to apply equally well.

Since in some experiments the effects of multiple scattering may be important we have considered them also. For elements which scatter principally in a narrow forward cone the increase in transmission caused by double scattering is

$$T_2=\frac{4B}{(\frac{1}{2}L)^2}\int\int e^{-\mu z}f(\theta)\mu dz[1-e^{-\mu(t-z)}]f(\theta)2\pi\sin\theta d\theta.$$

The expression in brackets, which is the probability that a second collision will occur, has been simplified by assuming that $\cos\theta\approx 1$. We have also neglected the attenuation of the neutrons after the second scattering. The ratio of the effects due to double and single in-scattering is now given by

$$\frac{T_2}{T_1}=\frac{2\pi\int f^2(\theta)\sin\theta d\theta}{f(0)}\frac{1-e^{-\mu t}-\mu te^{-\mu t}}{\mu te^{-\mu t}}.$$

An upper limit to this ratio can be obtained by letting $f(\theta)=f(0)$ within the first lobe of the scattering pattern and $f(\theta)=0$ outside. One then finds that for a uranium sample with a transmission of 0.5 the ratio of T_2/T_1 at 20 Mev is about $\frac{1}{2}$. A better estimate can be made by a numerical integration of the curves given in reference 17. This indicates that the ratio of $\frac{1}{2}$ may be an order of magnitude too large. Since in our experiments the greatest correction required for single in-scattering was 1.4 percent, we conclude that the correction for double in-scattering is negligible.

[16] The correct formula taking single scattering into account has previously been given by the following authors: Amaldi, Bocciarelli, Cacciapuoti, and Trabacchi, Atti accad. nazl. Lincei 1, 29 (1946); R. Ricamo and W. Zünti, Helv. Phys. Acta 24, 419 (1951); Hafner, Hornyak, Falk, Snow, and Coor, Phys. Rev. **89**, 204 (1953).

[17] Feld, Feshbach, Goldberger, Goldstein, and Weisskopf, Final Report of the Fast Neutron Data Project, NYO-636 (January 31, 1951) (unpublished).

[18] E. T. Jurney (private communication).