mid-range as a function of H, T and the total electric field splitting in zero magnetic field. The calculations consisted in forming a partition function

$$Z=\sum_{i=1}^{6} e^{-E_i/kT},$$

in which the E_i are the energy levels[13] for cubic symmetry which depend on the magnetic field and on crystalline field splitting in zero magnetic field. The magnetic moment is

$$M=kT\partial \ln Z/\partial H.$$

The results of a sample calculation of two points for Fe^{+++} are given in Table I for the (100) direction.

The experimental determination of relative magnetic moments for potassium chromium alum in fields up to 50,000 gauss has shown with precision the creditability of space quantization of magnetic dipoles and the quenching of orbital angular momentum by compatibility of the Brillouin function, for $g=2$, with experiment. Even the small, second-order departure of the magnetic moment from the Brillouin function can probably be attributed, at least in part, to an effect of the crystalline field splitting on the magnetic energy levels, as is suggested by a preliminary calculation of the moment for Fe^{+++} at a few points. More detailed calculations of the effect of the crystalline field are being made and will be reported later.

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Total Cross Sections for 14-Mev Neutrons*

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The total cross sections of over 50 elements were measured in good geometry for 14-Mev neutrons. A plot of the square root of the total cross section *versus* the one-third power of the atomic weight shows deviations from the linear relationship predicted by statistical theory. The deviations are most pronounced for the heaviest elements.

INTRODUCTION

One of the methods for determining nuclear radii is based on measurements of the total cross sections of nuclei for fast neutrons. Nuclear radii are most likely to be calculable from such measurements if the neutron wavelength divided by 2π is small compared to the nuclear radius, but not small enough that the nucleus is transparent for the neutrons used. Neutrons of energies of the order of 20 Mev satisfy these conditions. Several measurements using neutrons of energies between 13 and 25 Mev have been published,[1–6] and have served to determine nuclear radii. Each investigation covers a relatively small number of elements. Measurements performed at different neutron energies and in different geometries are difficult to compare particularly because of the strong angular dependence of diffraction scattering about which only very limited experimental information is available.

All the published measurements at neutron energies of the order of 20 Mev are compatible with the assumption that for nuclei heavier than Be the nuclear radius is a linear function of the one-third power of the number of nucleons in the nucleus. The present investigation was undertaken to study possible deviations from this relationship as might perhaps occur in nuclei with closed shells. For this purpose the cross sections of all readily available elements were measured for neutrons of the same energy and in about the same geometry. The uniformity of the technique used for all the elements serves to increase the precision of the cross section *versus* atomic weight relationship and hence might facilitate the interpretation of the data.

PROCEDURE

Fast neutrons were produced by bombarding a thick Zr-T target with 220-kev diatomic deuterium ions. The direction of observation was at an angle of 88° with respect to the deuteron beam. In this direction the neutrons have an energy of 14.12±0.04 Mev, assuming a reaction energy of 17.58±0.02 Mev for the *d*-T reaction.

A *trans*-stilbene scintillator served as neutron detector. It was placed at a distance of 165 cm from the neutron source. In order to check the sensitivity of the detector to γ-rays or neutrons which do not come directly from the target, a copper bar, 1 in. in diameter and 25 in. long, was inserted between source and detector. It was found that the background counting

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* Work performed under the auspices of the AEC.

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rate in the presence of the bar divided by the counting rate produced by the direct neutron flux decreased as the setting of the pulse-height discriminator was increased. The discriminator bias was set high enough to keep the background below one percent. This setting corresponded to a proton recoil energy of about 10 Mev.

The neutron source strength was monitored both by counting associated α-particles from the d-T reaction and by a second scintillation neutron detector. No systematic differences between the two monitors were observed.

Total cross sections were measured by simple transmission experiments in good geometry. The samples were placed half-way between the source and detector. The thickness of the samples was chosen to give transmissions of about fifty percent. Most of the samples had a diameter of one inch. In this geometry the transmission experiment measures the total cross section except for neutrons scattered elastically (or inelastically with small energy loss) through angles less than about 2°. It is assumed that within this angle the neutrons scattered into the detector by the sample compensate those neutrons which are scattered out of the direct path from source to detector. If the scattering were isotropic, 0.02 percent of the scattered neutrons would hit the detector. The diffraction scattering will produce a forward maximum in the distribution of the elastically scattered neutrons which results for the heaviest nuclei in an intensity about seventy times larger than if the neutrons were scattered isotropically, so that the largest inscattering correction to be expected would be about 0.8 percent, assuming that elastic scattering constitutes one-half of all the interactions. A correction for inscattering of 0.13 σ_t percent was applied to the data, where σ_t is the measured total cross section in barns. This correction is based on a value of $k^2R^4/4$ for the differential scattering cross section in the forward direction[7] where k is the wave number of the incident neutrons and R the nuclear radius. Use of the value $(kR+1)^4/4k^2$, instead of $k^2R^4/4$, as indicated in a summary report by other authors,[8] would make the corrections for the heavy elements approximately a factor of two larger.

Whenever possible the samples were made of the pure element. In Table I the elements investigated are listed together with the form in which the element was used. Gas samples were contained in cylinders 40 in. long and $\frac{15}{16}$-in. inner diameter of stainless steel of $\frac{1}{32}$-in. wall thickness. The inscattering corrections for these samples, although larger than for nongaseous samples of similar atomic weight, were still negligible.

RESULTS

In Table I the measured total cross sections corrected for background and scattering into the detector are

TABLE I. Total cross sections for 14-Mev neutrons.

Z	Element	A	Sample form	σ_t (barns)	Previous reports	Reference
1	H	1	Gas		0.686±0.007	4
					0.689±0.005	5
2	He	4	Gas		1.02 ±0.02	4
3	Li	6	Cast	1.39±0.05		
3	Li	7	M[a]	1.45±0.03		
4	Be	9	M	1.53±0.03	0.65 ±0.04	1
					1.41 ±0.11	3
5	B	10	Powder	1.47±0.03		
5	B	11	Powder	1.40±0.03	1.16 ±0.13	1
6	C	12	Graphite	1.32±0.02	1.23 ±0.02	1
					1.24 ±0.06	3
					1.279±0.004	5
					1.29 ±0.02	6
7	N	14	Gas	1.59±0.03	1.7 ±0.1	5
					1.39 ±0.05	6
8	O	16	Gas	1.59±0.03	1.64 ±0.04	5
					1.61 ±0.04	6
8	O	16	H_2O	1.56±0.04		
9	F	19	CF_2	1.70±0.05		
11	Na	23	Compacted	1.71±0.03		
12	Mg	24.3	M	1.75±0.03	1.83 ±0.10	1
13	Al	27	M	1.73±0.03	1.92 ±0.09	1
14	Si	28.1	Compacted	1.83±0.04		
14	Si	28.1	SiO_2	1.90±0.13		
15	P	31	Cast	1.97±0.04		
16	S	32.1	Cast	1.92±0.04	1.58 ±0.10	1
17	Cl	35.5	CCl_4	2.00±0.05		
19	K	39.1	Compacted	2.24±0.04		
20	Ca	40.1	Compacted	2.19±0.04		
22	Ti	47.9	M	2.28±0.04	2.24 ±0.29	3
24	Cr	52.0	Compacted	2.45±0.04		
25	Mn	54.9	Compacted	2.54±0.05		
26	Fe	55.9	M	2.60±0.05	2.75 ±0.09	1
27	Co	58.9	Compacted	2.72±0.05		
28	Ni	58.7	M	2.67±0.05	2.62 ±0.09	1
29	Cu	63.5	M	2.96±0.06	2.86 ±0.15	1
					2.85 ±0.05	6
30	Zn	65.4	Cast	3.06±0.06	3.03 ±0.17	1
31	Ga	69.7	Cast	3.19±0.06		
34	Se	79.2	Powder	3.56±0.07	3.35 ±0.20	1
35	Br	79.9	Liquid	3.52±0.07		
38	Sr	87.6	Compacted	3.68±0.07		
39	Y	88.9	Y_2O_3	3.88±0.14		
40	Zr	91.2	Compacted	4.00±0.08	2.37 ±0.35	3
41	Nb	93.3	Compacted	4.02±0.08		
42	Mo	96.0	M	4.04±0.08		
47	Ag	107.9	Cast	4.34±0.09	3.82 ±0.13	1
48	Cd	112.4	Cast	4.44±0.09	4.25 ±0.13	1
49	In	114.8	Cast	4.53±0.09		
50	Sn	118.7	Compacted	4.68±0.09	4.52 ±0.14	1
51	Sb	121.8	Compacted	4.71±0.09	4.35 ±0.15	1
52	Te	127.6	Compacted	4.85±0.10		
53	I	126.9	Compacted	4.74±0.10		
56	Ba	137.4	Compacted	5.17±0.10		
57	La	138.9	Compacted	5.18±0.10		
58	Ce	140.1	M	5.08±0.10		
59	Pr	140.9	M	4.93±0.25		
73	Ta	180.9	M	5.24±0.10		
74	W	183.9	M	5.30±0.11		
78	Pt	195.2	Cast	5.36±0.11		
79	Au	197.2	M	5.31±0.11	4.68 ±0.9	1
80	Hg	200.6	Liquid	5.36±0.11	5.64 ±0.24	1
81	Tl	204.4	Cast	5.36±0.11		
82	Pb	206	Cast	5.40±0.11		
82	Pb	207.2	M	5.48±0.11	5.05 ±0.15	1
					4.97 ±0.27	3
83	Bi	209.0	Cast	5.46±0.11	5.17 ±0.17	1
90	Th	232.1	M	5.69±0.11	6.11 ±0.33	3
92	U	238.1	M	5.87±0.12		

[a] M denotes samples which were machined from bulk metal. Most of the cast and compacted samples were also machined to accurate dimensions.

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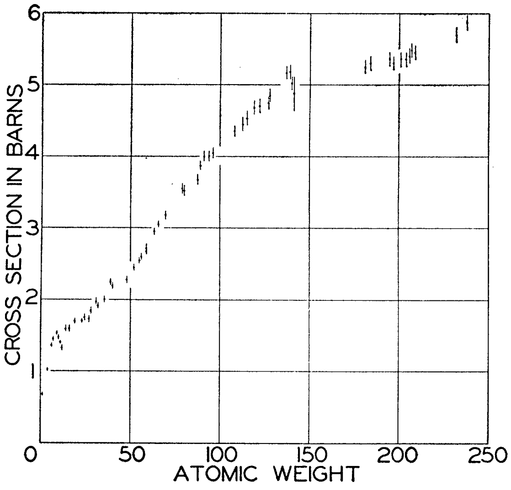

FIG. 1. The total cross sections of the elements for 14-Mev neutrons plotted against atomic weight.

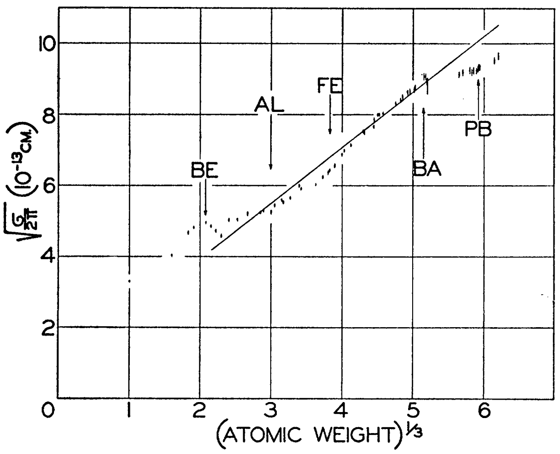

FIG. 2. Square root of the total cross sections divided by 2π plotted against the cube root of the atomic weight. The solid line represents the behavior predicted by the theory of Feshbach and Weisskopf under the assumption that the nuclear radius is given by $1.5\times A^{\frac{1}{3}}\times 10^{-13}$ cm.

tabulated, and in Fig. 1 the results are plotted against atomic weights. The statistical accuracy of the measurements is about one percent, except in the cases in which compounds were used and in the case of Pr where only a very thin sample was available. While precautions were taken to obtain samples of high purity and uniform density, errors introduced by the properties of the samples may be of the same order of magnitude as the statistical errors.

In the last two columns of Table I the results obtained previously by others are listed. While the agreement with the present data is within the experimental error in most cases, there are a few instances of rather large differences. These discrepancies may be due to the fact that some of the elements have only recently become available in pure form.

Feshbach and Weisskopf[9] have proposed a schematic theory of nuclear cross sections which should be applicable for neutrons of the energy used in the present experiment. According to this theory the square root of the total cross section should be approximately a linear function of the nuclear radius. To facilitate a comparison between the calculated and observed cross sections $(\sigma_t/2\pi)^{\frac{1}{2}}$ is plotted in Fig. 2 against the cube roots of the atomic weights, A. The solid line shown in Fig. 2 shows the dependence of the cross sections on nuclear radius calculated according to reference 9 with the assumption that the nuclear radius is related to the atomic weight by $R=1.5\times 10^{-13}\times A^{\frac{1}{3}}$ cm.

While the experimental points lie on a fairly smooth curve, systematic deviations from the calculated relationship between σ and A are apparent in Fig. 2. No appreciable improvement in the fit is obtained by changing the coefficient in the dependence of R on $A^{\frac{1}{3}}$. Deviations from the predicted curve might be expected for the lightest elements, since statistical theory is probably not applicable to them. Apart from the lightest elements the largest differences between calculated and observed cross sections occur for the elements above the rare earths.

There is no apparent effect of closed shells on the nuclear radius; for example, Tl, Pb^{206}, and Pb^{208} have within the experimental error the same total cross sections. This finding is at variance with the results of Lasday[3] and with the analysis by Curie[10] based on data taken at higher neutron energies.

It should perhaps not be surprising that the theory of Feshbach and Weisskopf does not give a precise quantitative fit to the experiments, since this theory is based on a rather special assumption about the radial dependence of the neutron wave function inside the nucleus. It would probably be possible to fit the data more quantitatively by a theory which has more adjustable parameters, as was done for example by Fernbach, Serber, and Taylor[11] to account for the experimental results at 90 Mev.

We are indebted to Professor F. H. Spedding for the loan of samples of yttrium oxide and praseodymium metal. We wish to thank Mr. L. K. Goodwin for help in preparing most of the samples and Dr. J. S. Wahl for building the detector.

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