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Collisions of Neutrons with Atomic Nuclei

T. W. Bonner, *The Rice Institute, Houston, Texas*

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The velocity variation of the target areas of nuclei for neutrons has been investigated for neutrons obtained by bombardment of Be, B, and F with Po-alpha-particles. The target area of hydrogen was found to increase rapidly with a decrease in the velocity of the neutrons. The target area of carbon and nitrogen also increased with a decrease in the velocity of the neutrons, but not so rapidly as did that of hydrogen. The absorption of neutrons by lead was found to increase with the velocity. This anomalous absorption of lead can be explained by assuming that faster neutrons make relatively more inelastic collisions with the nuclei. Cosmic-ray bursts can be explained on the basis of this assumption. The neutrons from fluorine were found to be slower than those from boron, and the average range of the recoil protons produced by them was estimated to be about 2 cm in air. These slower neutrons were found to be more penetrating in lead than those from either beryllium or boron.

THESE experiments were undertaken to investigate the relation between the scattering of neutrons and their velocity. Neutrons of different velocities were obtained by bombarding beryllium, boron and calcium fluoride with α-particles from polonium. Measurements were made of the ionization currents produced in different gases by the neutrons from each of these sources. The relative target areas of the gaseous atoms were calculated from the ionization measurements. Measurements of the absorption of the neutrons in several solid materials were also made and the absolute values of the target areas of the atoms in the solids were calculated. The relative target areas of gaseous atoms for neutrons from beryllium have previously been determined by the writer.[1] In the previous experiments the ionization due to γ-rays emitted along with the neutrons from beryllium was not completely eliminated. For this reason a redetermination of the ionization of gases by these neutrons was made, the effect of γ-rays being eliminated.

While this work was in progress, Chadwick[2] reported that the collision area of a hydrogen atom is about twice as large for the slower neutrons from boron as for the faster neutrons from beryllium. The experiments described below confirm this result.

Experimental Procedure

A diagram of the apparatus used is given in Fig. 1. The ionization chamber was cylindrical in shape and had a length of 24 cm and a diameter of 14 cm. The walls were of iron and had a thickness of 1 cm. A Lindemann electrometer F and compensating condenser E were used to measure the ionization currents. The method was the same as that used in the previous work.

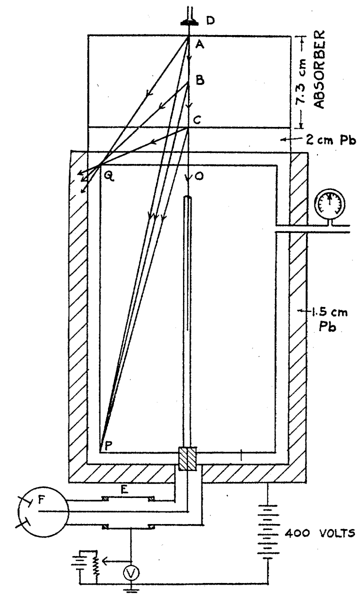

FIG. 1. Diagram of apparatus.

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[1] T. W. Bonner, Phys. Rev. **43**, 871 (1933).

[2] J. Chadwick, Proc. Roy. Soc. **A142**, 1 (1933).

Neutrons were emitted at D when the α-particles from about 7 millicuries of polonium struck a layer of either beryllium, boron, or calcium fluoride on a slide. The ionization current was measured first with the slide removed and then with it in place. The difference between the two currents was taken to be the current due to the neutrons. The current with the slide removed is due to radiation from the walls of the chamber, γ-rays, and cosmic rays. This current was usually of the same order of magnitude as that due to the neutrons.

When Be is bombarded by α-particles, a penetrating γ-radiation is emitted along with the neutrons.[3] In order to eliminate the ionization produced by these γ-rays, the radiation was filtered by 6 cm of lead, which absorbed the γ-rays almost completely but diminished the number of neutrons by only about 40 percent. The radiations from B and CaF_2 were filtered by 3 cm of lead before entering the chamber. In this case it was not necessary to use so great a thickness of lead, since the γ-rays from B and F are not so penetrating as those from Be.

The ionization produced by the neutrons from the three different sources was measured in H_2, N_2, He, A and CH_4 for pressures varying from 1 atmosphere to 300 lbs./sq. in. Absorption measurements were also made for the neutrons from B, Be and F in graphite, paraffin and lead.

The neutrons emitted from beryllium when bombarded by α-particles from polonium do not all have the same velocity. According to Chadwick[2] there are two main groups of neutrons emitted from a thin layer of beryllium. The more intense group has a velocity of 2.8×10^9 cm/sec., while the other group has a velocity of 4×10^9 cm/sec. When a thick layer of beryllium is used, as in the present experiments, the slowing down of the α-particles as they pass through the beryllium causes the velocities of the neutrons emitted to have a distribution which varies downward continuously from a definite maximum. The average velocity is probably about 3×10^9 cm/sec. The neutrons from B have a continuous range of velocities with a maximum of 2.5×10^9 cm/sec. The average velocity from a thick layer of B is given by Chadwick as "rather less than 2×10^9 cm/sec.".

RESULTS

The ionization-pressure curves for Be-neutrons are given in Fig. 2, while the corresponding curves for B-neutrons and F-neutrons are shown in Fig. 3. The data on three sample values of the ionization currents are given in Table I. The ± values indicated are the probable errors calculated in the ordinary way from the relation: probable error $=0.6745[\Sigma(T-\overline{T})^2/n(n-1)]^{\frac{1}{2}}$.

TABLE I.

	Time T in sec. for 15 divisions deflection due to residual current	Time T_1 in sec. for 15 divisions deflection due to residual current +neutron current	Neutron current $1/T_1-1/T$
Ionization due to neutrons from boron Gas: hydrogen Pressure: 285 lbs./sq. in.	214, 210, 211, 207, 197, 206 *av.* 207.7 ± 1.5	89, 82, 85, 87, 82, 81, 86, 86, 81, 89 *av.* 84.8 ± 0.7	0.00698 ± 0.00010
Ionization due to neutrons from fluorine Gas: hydrogen Pressure: 302 lbs./sq. in.	196, 197, 207, 200, 206, 189, 187, 191, 184, 191 *av.* 194.8 ± 1.6	143, 151, 139, 139, 142, 133, 136, 136, 138, 136 *av.* 139.3 ± 1.1	0.00205 ± 0.00006
Ionization due to neutrons from fluorine Gas: nitrogen Pressure: 294 lbs./sq. in.	75.2, 80.8, 76.6, 77.4, 78.2, 81.4, 75.0, 77.6, 75.0, 76.6, 73.8, 79.4, 75.2, 81.0, 79.8, 76.4, 74.0, 78.2, 82.0, 81.8 *av.* 77.76 ± 0.39	74.6, 76.8, 78.0, 74.4, 73.0, 72.4, 74.2, 79.0, 80.9, 77.8, 75.8, 74.0, 77.6, 72.2, 74.4, 75.6, 78.8, 77.2, 74.0, 75.2 *av.* 75.75 ± 0.34	0.00034 ± 0.00007

The accuracy of the ionization currents produced by fluorine neutrons in nitrogen and argon is not very great, since the neutron currents in these cases were only a small fraction of the natural leak. The probable error in these two cases was about 20 percent. The natural leak at 300 lbs./sq. in. pressure was approximately 51.2 ions per cc per sec. in N_2, 79.3 ions per cc per sec. in A, 21.0 ions per cc per sec. in H_2, and 30.1 ions per cc per sec. in He. At 300 lbs./sq. in. pressure the ionizations due to fluorine-neutrons were, respectively, 1.4, 2.0, 8.4, and 5.0 ions per cc per sec. in N_2, A, H_2 and He, while the ionizations due to boron-neutrons in these gases were 5.9, 11.1, 29.4 and 13.8 ions per cc per sec., respectively. The ionizations produced by beryllium-neutrons were several times larger than those produced by boron-neutrons. There is less ionization in a given gas produced by the neutrons from B than from Be and still less from F. The ratios of the relative ionizations produced by the three neutron sources depend on the gas used in the chamber. The relative amounts of

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[3] Becker and Bothe, Naturwiss. **20**, 41 (1932).

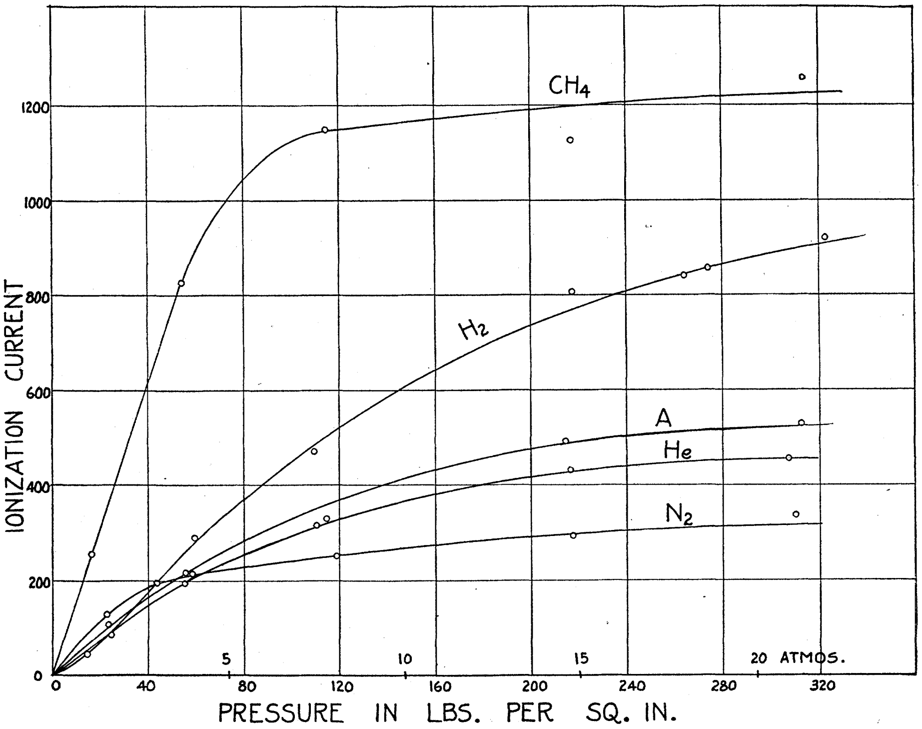

FIG. 2. Ionization currents produced by Be-neutrons.

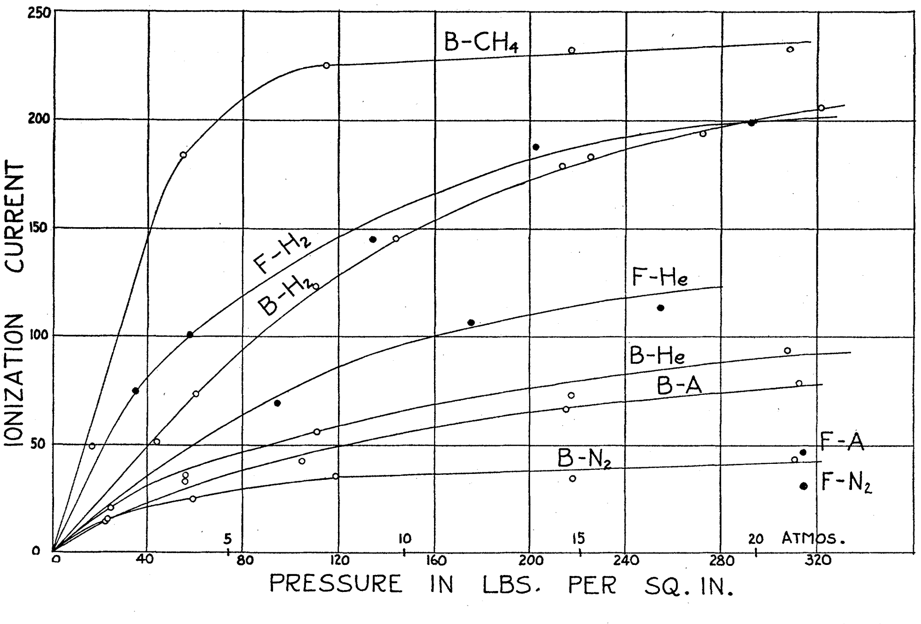

FIG. 3 Ionization currents produced by B- and F-neutrons. F-neutron ordinates have been multiplied by 3.5.

ionization depend both on the number of neutrons emitted and the energy of the neutrons.

The shapes of the ionization-pressure curves in N_2, He, and A are the same when produced either by Be- or B-neutrons, but in H_2, the Be-neutron ionization-pressure curve is steeper than that for B-neutrons. This is caused by the fact that the secondary protons ejected by the Be-neutrons have a longer range than those due to B-neutrons, and are not so completely absorbed in the chamber at low pressures. When the chamber is filled with 2 or 3 atmospheres of H_2, the protons ejected by Be-neutrons have a maximum range comparable to the length of the ionization chamber, and thus the protons do not lose all their energy before hitting the walls. The ionization-pressure curve for F-neutrons in H_2 is not so steep at about 80 lbs./sq. in. pressure as those for Be- and B-neutrons, which shows that the ejected protons from F-neutrons have a smaller range than those from either Be or B. The ratios of ionization at 300 lbs./sq. in. to that at 20 lbs./sq. in. is 12.4 for Be-neutrons, 8.0 for B-neutrons, and 4.1 for F-neutrons. From the curves obtained when H_2 was used in the chamber it is estimated that the average range of the protons ejected by F-neutrons is of the order of 2 cm in air at one atmosphere, which is the same as that produced in a head-on collision by a neutron of velocity 1.3×10^9 cm/sec.[4]

The presence of protons not completely absorbed in the chamber causes the ionization-pressure curve for Be-neutrons in H_2 to be concave upward at low pressures. The ratio of ionization by Be-neutrons in H_2 at 21 atmospheres to that at 1 atmosphere is 20.1, while the corresponding ratio for γ-rays is 19.4. Although these ratios are approximately the same, the γ-ray curve differs from the neutron curve, since the γ-ray curve is very nearly a straight line throughout this range of pressures, while the neutron curve is concave at low pressures and convex at higher pressures.

The ions formed by the recoil atoms are along thick straight tracks and are very hard to saturate, as is shown by the great deviation of the ionization-pressure curves from straight lines. Although the ions produced by neutrons are much harder to saturate than those produced by γ-rays, the relative ease of saturation in different gases of the ions due to neutrons is the same as for γ-rays. Nitrogen is much harder to saturate than either argon or helium.

The ionization-pressure curves for Be-neutrons given in Fig. 2 differ from those previously reported by the writer.[1] The main difference is that in the old experiments the A and N_2 curves were more nearly linear and also higher with respect to H_2 and He than in the present work. This difference is due to the presence of γ radiation along with the neutrons in the old experiments. In the old experiments the Be-polonium radiation was filtered by only the equivalent of about 1 cm of Pb. It was thought that under these conditions only a small part of the ionization was due to γ-rays, but it now appears that the γ-rays produced about 25 percent of the ionization in N_2 at 10 atmospheres pressure. The relative ionization contributed by the γ-rays increases as the pressure of the gas in the chamber becomes greater. This is caused by the fact that the ionization produced by the γ-rays is much more easily saturated than the ionization produced by neutrons. The filtering out of the γ-rays in the present experiment by 6 cm of lead decreases the ionization in A and in N_2 much more than in He and H_2, resulting in the shifting of the A and N_2 curves lower with respect to the He and H_2 curves. The H_2 curve in the previous experiments rises more rapidly at 20 atmospheres than in the present experiments. This is partly because of the fact that the ionization chamber in the earlier work was smaller, thus requiring gas at a greater pressure to absorb the long-range protons.

The relative target areas of the different nuclei were calculated from the relation $I = knaAE/R$ where I denotes the number of ion pairs produced in unit time; n, the number of neutrons passing through the chamber per unit time; a, the number of atoms per cc in the chamber, A, the target area between the neutron and the nucleus; E, the average energy given to the nucleus per collision; and R the average energy spent in the production of a pair of ions by the recoil nucleus.

The target areas calculated in this way are given in Table II. The value of C given is the

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[4] Calculated from the range-velocity curves of Blackett and Lees, Proc. Roy. Soc. **A134**, 665 (1932).

TABLE II. *Ionization due to neutrons from beryllium, boron and calcium fluoride.*

Gas	C	R	CR	kCR/a	Atomic nucleus	E_m	KA	A
Be-neutrons								
Hydrogen	217	33.0	7160	3580	H	1.00	35.8	1.00
Helium	73	27.8	2030	2030	He	0.640	31.7	0.89
Argon	92	25.4	2340	2340	A	0.095	24.6	6.9
Nitrogen	116	35.0	4060	2030	N	0.249	81.5	2.3
B-neutrons								
Hydrogen	48.7	33.0	1610	805	H	1.00	8.05	1.00
Helium	16.1	27.8	447	447	He	0.640	6.99	0.87
Argon	13.5	25.4	343	343	A	0.095	36.1	4.5
Nitrogen	14.3	35.0	500	250	N	0.249	10.0	1.2
F-neutrons								
Hydrogen	14.3	33.0	472	236	H	1.00	2.4	1.0
Helium	5.5	27.8	153	153	He	0.640	2.4	1.0
Argon	2.3	25.4	58	58	A	0.095	6.1	2.5
Nitrogen	3.5	35.0	123	61	N	0.249	2.4	1.0

C=ionization current at 20 lbs./sq. in. in arbitrary units; R=average energy spent per ion pair for α-particles[5]; E_m=relative maximum energies given to nuclei[6]; a=relative number of atoms in the chamber; A=relative target area between neutron and nucleus.

ionization at 20 lbs. per sq. in., at which pressure practically all the ions formed are drawn to the electrodes. The values of C in Table II for B- and Be-neutrons in hydrogen were calculated from the relation $C_{B(20)}=C_{B(300)}\cdot C_{F(20)}/C_{F(300)}$ in order to correct for the fact that the protons from Be- and B-neutrons are not completely absorbed in H_2 at 20 lbs. per sq. in. pressure. The above relation holds since at 300 lbs. per sq. in. pressure even the long-range protons are almost completely absorbed, and hence the lack of saturation in H_2 is the same for B-neutrons, Be-neutrons, and F-neutrons. The difference in the target areas for Be-neutrons given in Table II and those previously reported is largely due to the earlier results obtained with H_2 not being corrected for the long-range protons which are only partially absorbed in the chamber. The relative target areas of He, N and A with respect to each other are about the same as those previously reported, but the target area of H when corrected for the long range protons differs by a factor of about 2. The elimination of the γ-rays produced only a small change in the target areas.

It appears that the relative target areas of the argon and nitrogen nuclei with respect to hydrogen are smaller for slower neutrons.

In order to find the variation of target area with the velocity for different nuclei, absorption measurements were made with paraffin, carbon and lead. Hydrogen at 20 atmospheres pressure was used in the chamber when the absorption measurements were made, because the residual ionization in H_2 and its ionization by γ-rays are both very small. The absorbers used were cylindrical in form, 7.3 cm in thickness, and of the same diameter as the ionization chamber. In these measurements the thickness of the lead filter was 2 cm.[7] The data from the absorption measurements are given in Table III. The target areas were calculated by means of the relation $k=e^{-n_2At}$ where k is the percent of unscattered neutrons, n_2 is the number of absorbing nuclei per cc and t is the thickness of the absorber.[8] These measurements show that the target areas for both carbon and hydrogen increase with a decrease in the velocity of the neutrons, but that the target area of H increases much more rapidly than the target area of C. We should therefore expect the target area of N to vary a little less rapidly with the velocity of the neutrons than does that of carbon. The absorption in lead is found to increase as the velocity of the neutrons

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[5] Since no data were available as to the average energy R required to form an ion pair by the different recoil atoms in the gases used, the average energy spent by an alpha-particle in producing an ion pair in each gas was employed in the calculations. The values of R in different gases for electrons (mass$=1/2000m_H$) and for alpha-particles (mass$=4m_H$) are about the same. Thus it seems probable that the value of R in different gases is nearly independent of the mass of the ionizing particle and so would be approximately the same for H, N and A atoms as for alpha-particles.

[6] The ratio of the average energy given to the nucleus E to the maximum energy E_m may be different for the different nuclei, but due to insufficient data in regard to this point, no attempt was made to apply this correction.

[7] With this thickness of lead filter about 2 percent of the ionization produced by the Po-Be radiation was due to γ-rays. Thicker lead filters were not used in order to keep the geometrical arrangement the same when B-, Be- and F-neutrons were used.

[8] Due to the different amount of ionization produced by a slow and a fast neutron, this relation is strictly only applicable to the case (1) where the neutrons in the beam all have the same velocity or (2) where the neutrons have a range of velocity but over this range the absorption of the neutrons does not vary appreciably. In the present experiment the second condition is approximately satisfied.

TABLE III. *Absorption measurements of neutrons from Be, B and F.*

	Percent Absorbed by 7.3 cm Pb	*Percent Absorbed* by 7.3 cm paraffin	*Percent Absorbed* by 7.6 cm graphite	*Target Area* ($\times 10^{-26}$ sq. cm) A for Pb atom	*Target Area* ($\times 10^{-26}$ sq. cm) A for carbon atom	*Target Area* ($\times 10^{-26}$ sq. cm) A for hydrogen atom
Be-neutrons $v=3\times 10^9$ cm/sec.	43.6	44.0	32.0	239	72	73
B-neutrons $v=2\times 10^9$ cm/sec.	36.2	63.7	41.1	187	99	141
F-neutrons $v=1.3\times 10^9$ cm/sec.	29.1	81.2	46.3	143	116	253

increases; that is, the faster neutrons are more easily stopped than the slower ones. This agrees with the results previously reported by the writer.[9]

The relative target areas given in Table III differ from those in Table II. When Be-neutrons were used in the absorption experiments, the target area of a lead atom was calculated to be 3.3 times that of a hydrogen atom. When F-neutrons were used, the target area of a lead atom was only 0.6 times that of a hydrogen atom. Thus the relative target area of a lead atom was found to be smaller than that of an argon atom in both cases. The target area of a carbon atom, as obtained by absorption measurements with Be-neutrons, was the same as that of a hydrogen atom, while the target area of a nitrogen atom obtained from ionization measurements was 2.4 times that of the hydrogen atom. Thus the absorption measurements give lower relative target areas as compared to hydrogen than do the ionization measurements. This difference is probably caused by the fact that the measurements of a target area by absorption measurements and by ionization measurements are measurements of two distinct quantities.

In Fig. 1 the paths of neutrons scattered at the points A, B and C in the absorber are shown. It appears that neutrons can be scattered at A, B and C, respectively, through angles less than 12 degrees, 13 degrees, and 15 degrees, and still traverse the entire length of the chamber. When scattered through even larger angles than these, the neutrons still pass through a portion of the chamber unless they are scattered more than 34 degrees, 47 degrees and 67 degrees. The chance of a collision is proportional to the length of the path of the neutron in the chamber, so that the probability of a collision in the chamber is less for a neutron scattered through angles larger than 13 degrees. Thus the target areas found by such absorption measurements depend on the probability of scattering the neutron through a mean angle of more than about 25 degrees from its original direction, while in gases the target areas depend on scattering the neutron through any angle. Dunning and Pegram[10] have found that the relative number of neutrons scattered through small angles increases with the atomic weight of the scatterer. It follows then that the target areas of carbon and lead atoms calculated from absorption measurements should be smaller with respect to hydrogen than the target areas calculated from ionization measurements.

Another factor which increases the relative absorption by hydrogen absorbers as compared to carbon and lead absorbers is that neutrons scattered by hydrogen atoms lose a larger percentage of their energy per collision than those scattered by heavier atoms. Thus a neutron which is scattered by a hydrogen atom, but which still enters the ionization chamber, produces less ionization than a neutron scattered by a heavier atom. These two factors probably explain whv the target areas of lead and carbon found from absorption measurements are respectively smaller with respect to hydrogen than those of argon and nitrogen found from ionization measurements.

The absorption of neutrons is due both to elastic and inelastic collisions of the neutrons with the nucleus. When a neutron makes an

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[9] T. W. Bonner, Phys. Rev. **44**, 235 (1933).

[10] J. R. Dunning and G. B. Pegram, Phys. Rev. **43**, 497 (1933).

inelastic collision it gives all its energy to the nucleus, causing disintegration. If, on the other hand, the collision is elastic, the neutron loses only a portion of its energy to the nucleus. The amount of energy lost by the neutron in an elastic collision depends both on the directness of collision and the mass of the nucleus. The amount of energy lost by a neutron in a direct collision can be calculated if the conservation of energy and the momenta are assumed.[11] Only a small portion of the energy of the neutron is given to a nucleus whose mass is large compared to that of the neutron. In the case of lead, the amount of energy lost per collision varies from 0 to 1.92 percent, depending on how direct a collision is made.

The larger absorption in lead by the neutrons of high velocity can be explained if we assume that the faster neutrons are more likely to make inelastic collisions than the slower ones. Such an assumption seems likely as there is an increase in the number of inelastic collisions that α-particles and protons make when their velocities increase. In the absorption experiments with lead only a portion of the neutrons making a single elastic collision are deviated through a large enough angle to prevent their entering the ionization chamber, but none of the neutrons making inelastic collisions enter the chamber. Thus the faster neutrons making more inelastic collisions are more easily absorbed in lead than the slower neutrons.

Application to Cosmic-Ray Bursts

If we assume that a small portion of cosmic radiation at sea-level consists of high speed neutrons, we have an explanation of cosmic-ray Stösse. Practically all the collisions of these high speed neutrons in lead would be inelastic and would result in disintegrations. The secondary particles emitted from such a disintegration might include protons, neutrons and γ-rays. The absorption in lead for these high speed neutrons would be even larger than that obtained for Be-neutrons. Since the absorption coefficient of these neutrons would be larger than that for the rest of the cosmic radiation, the relative number of bursts would increase at higher altitudes as has been found to be the case.[12] The radiation producing coincidences in three counters out of line has been found by Rossi[13] to be absorbed approximately 69 percent by 7.2 cm of lead. This is about what one would expect for the absorption of neutrons with energy of the order of 50 million electron-volts from extrapolation of the absorption values for lower velocity neutrons.

In conclusion, I wish to thank Professor H. A. Wilson for the interest which he has shown in this work.

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[11] The conservation of energy and momenta was assumed by Chadwick in calculating the mass of the neutron, and has generally been accepted as true for elastic neutron collisions.

[12] A. H. Compton, Phys. Rev. **41**, 681 (1932).

[13] B. Rossi, Zeits. f. Physik **82**, 165 (1933).