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- 1) *Collisions of neutrons with atomic nuclei. By T.W. Bonner. 1933.*
2) *The production of neutrons from fluorine. By T.W. Bonner. 1933.*
3) *Dependence of the absorption of neutrons on their velocity. By T.W. Bonner. 1933.*
4) *Luminosity of a flame containing sodium vapor. By T.W. Bonner. 1932.*
By Tom Wilkerson Bonner

Committee.

Exam. May 14

- MEMORANDUM Wilson ✓
(1) Bryan ✓
(2) Evans ✓
(3) Ford ✓
(4) Garrison ✓
(5) Heaps ✓
(6) Mott-Smith ✓
(7) Tsanoff ✓
(8) Weiser.

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- (1) ~~(2)~~ Emission of Neutrons from Fluorine And Beryllium, by T.W. Bonner. (Reprinted from The Physical Review, Vol. 45, No. 6, 425, March 15, 1934.)
(3) Ionization of Gases by Neutrons, by T.W. Bonner. (Reprinted from The Physical Review, Vol. 43, No. 11, June 1, 1933.)
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Collisions of Neutrons with Atomic Nuclei

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(Received December 9, 1933)

EXPERIMENTAL PROCEDURE

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- α -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 re-determination of the ionization of gases by these neutrons was made, the effect of γ -rays being eliminated.

While this work was in progress, Chadwick² 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.

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 P and compensating condenser E were used to measure the ionization currents. The method was the same as that used in the previous work. 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 Chadwick² 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

FIG. 1. Diagram of apparatus.

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

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	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 $\pm$ 0.00010
Gas: hydrogen Pressure: 285 lbs./sq. in.			
Ionization due to neutrons from fluorine	196, 197, 207, 200, 206, 189, 187, 191, 184, 191 av. 194.5 ± 1.6	143, 151, 139, 139, 142, 133, 136, 136, 138, 136 av. 139.3 ± 1.1	0.00205 $\pm$ 0.00006
Gas: hydrogen Pressure: 302 lbs./sq. in.			
Ionization due to neutrons from fluorine	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 ± 0.30	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 $\pm$ 0.00007
Gas: nitrogen Pressure: 294 lbs./sq. in.			

$\pm$ values indicated are the probable errors calculated in the ordinary way from the relation: probable error = $0.6745[\Sigma(T - \bar{T})^2/n(n-1)]^{1/2}$.

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 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 range of the protons

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.

ejected by F-neutrons is of the order of 2 cm in air at one atmosphere, which is the same as that produced 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 H₂ to be concave upward at low pressures. The ratio of ionization by Be-neutrons in H₂ 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 N₂ curves were more nearly linear and also higher with respect to H₂ 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 N₂ 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 N₂ much more than in He and H₂, resulting in the shifting of the A and N₂ curves lower with respect to the He and H₂ curves. The H₂ 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

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

Gas	C	R	CR	kCR	Atom-ic nu- cleus	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 -particles⁵; E_m =relative maximum energies given to nuclei⁶; 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 H₂ 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 H₂ 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 H₂ 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 $k = e^{-n_2 l}$ where k is the percent of unscattered neutrons, n_2 is the number of absorbing nuclei per cc and l 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 of lead is found to increase as the velocity of the neutrons 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

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

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

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 Pegram¹⁰ 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 why 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 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 triple coincidences in counters ^{out of kind} has been found by Rossi¹³ 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.

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

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

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

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

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.

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

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

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).

The Energy Distribution of the Neutrons from Fluorine

From experiments on the ionization currents in hydrogen produced by neutrons from Be, B and F, Bonner¹ concluded that the neutrons from fluorine must have a considerably smaller average energy than those from beryllium or from boron. Curie and Joliot,² on the other hand, concluded that fluorine neutrons must be of high energy since they found them to be weakly absorbed by lead. Accordingly, it was desirable to make, if possible, a direct measurement of the energy of the fluorine neutrons.

It appeared that the methods of energy measurement which have been used for beryllium and boron neutrons were not especially suitable, since the intensity of the fluorine radiation is so small. It seemed entirely impractical to use recoil protons from paraffin, observed with either a counter or a cloud chamber. Indeed it seemed not feasible to observe recoil atoms with any arrangement of an ordinary cloud chamber on account of the excessively large number of photographs which would be necessary to record a reasonable number of tracks. In order to increase this number a special cloud chamber was constructed which allowed the gas pressure to be increased by a factor of more than ten. In this experiment it was used with hydrogen at a pressure of 12.9 atmospheres, so that more than a tenfold increase in sensitivity was attained. The experiment then consisted in measuring by the usual method the range of the recoil protons produced in the gas.

The source of neutrons consisted of a ten millicurie polonium source of α -particles bombarding a piece of fluorite. It was placed near the side wall of the chamber. The tracks were photographed with the usual stereoscopic camera arrangement and were reconstructed by projection.

About 9000 pairs of photographs were taken, on which 205 recoil protons were found. The ranges of these protons

were measured and were then converted to air-equivalent by making use of the differential stopping-power data obtained by Gurney.³ The number of observed recoil protons as a function of the range is shown in the curve of Fig. 1. From the curve it appears that the maximum range

discrete energies, rather than with a continuous distribution. The values of the maximum range for these groups are given in Table I and are indicated in Fig. 1. The velocity and energy corresponding to these ranges are given in succeeding columns of this table.

TABLE I.

Proton Emission from Fluorine (Chadwick and Constable)				Neutron Emission from Fluorine				
R_p (cm)	$E_p/10^6$ e.v.	ΔE_p	R_α (cm)	R_n (cm)	$V_n/10^8$ cm/sec.	$E_n/10^6$ e.v.	ΔE_n	$R_{\alpha n}$ (cm)
36	6.55		3.9	10.5	2.20	2.54		3.9 (assumed)
47	6.13	0.42	3.9	7.8	2.01	2.11	0.43	3.9 (assumed)
40	5.58	0.55	2.7	4.9	1.74	1.59	0.52	2.7 (assumed)
33.5	5.07	0.51	2.2	2.8	1.45	1.10	0.49	2.3
30.5	4.77	0.30	2.7	—	—	—	—	—
25	4.26	0.51	2.2	—	—	—	—	—

R_p = Range of disintegration protons

E_p = Energy of protons.

ΔE_p = Energy difference between proton groups.

R_α = Range of α -particles producing disintegration.

R_n = Maximum range of recoil protons.

V_n = Neutron velocity.

E_n = Neutron energy.

ΔE_n = Energy difference between neutron groups.

Since the α -particles producing the disintegrations have a continuous range of energy from their maximum to zero (because a thick target was used) it seems probable that the discrete energy groups in the neutron emission are produced by the penetration of the α -particle into the nucleus through resonance levels. Such a resonance phe-

nomenon has been observed in the other type of disintegration of fluorine where a proton is emitted. The latest work on this subject is that of Chadwick and Constable.⁴ Since both types of disintegration depend on the entrance of the α -particle into the fluorine nucleus, it was expected that the resonance levels should be the same in both cases. Accordingly, we have looked for a correlation between the proton groups and the neutron groups. It cannot be expected that the actual energies of the groups shall be the same in both cases since the disintegration reactions are entirely different. However, the energy differences between successive groups should be the same if the same resonance levels are involved. The energy differences for both cases are given in Table I. The corresponding differences for the two cases are seen to agree as well as could be expected. It will be noted that the two groups of lowest energy for the neutron disintegration are missing. It is probable that they exist but have not been found because of poor resolving power at the shorter ranges. Further evidence that the same resonance levels are effective comes from the fact that the emission of neutrons from fluorine begins when the α -particle has a range of 2.3 cm.⁵ This value agrees with the range of 2.2 cm corresponding to the lowest resonance level which Chadwick and Constable observed in the proton disintegration.

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L. M. MOTT-SMITH

The Rice Institute,
Houston, Texas,
March 30, 1934.

⁴ J. Chadwick and J. E. R. Constable, Proc. Roy. Soc. A135, 48 (1932).

⁵ T. W. Bonner, Phys. Rev. 45, 425 (1934).

FIG. 1. Range distribution of the recoil protons from fluorine neutrons.

of the recoil protons is about 10.5 cm of air, giving the maximum energy of fluorine neutrons to be 2.5×10^6 e.v. This value is considerably less than the maximum energy of neutrons from beryllium and confirms Bonner's result.

It is seen that the curve shows distinct peaks which we believe definitely means that the neutrons are emitted with

¹ T. W. Bonner (to appear in the May 1st Physical Review).

² I. Curie and F. Joliot, J. de Phys. et le Rad. 4, 278 (1933).

³ R. W. Gurney, Proc. Roy. Soc. A107, 340 (1925).

The Energy Distribution of Neutrons from Boron

In a previous letter,¹ we have presented energy measurements of the neutrons from a polonium-fluorine source. These measurements were carried out by observing the tracks of the recoil protons produced in a cloud chamber containing hydrogen at high pressure. By means of this method of measurement we were able to show that in the case of this element there were several neutron groups of different energy. In fact this method seemed particularly suitable for detecting neutron groups when they exist. Accordingly, experiments using this same method have been carried out for the neutrons emitted from boron when bombarded by α -particles from polonium.

4000 pairs of photographs have been taken with this source of neutrons. 2000 of these photographs were taken with hydrogen in the chamber at a pressure of 12.9 atmospheres, the remainder with methane (CH₄) at the same pressure. In both cases only tracks of recoil protons were used; those due to the carbon atoms in the methane at this pressure were too short to be measurable or to be confused with the proton tracks. It was convenient to use the two gases because with hydrogen a large number of the faster protons collided with the walls of the chamber and thus

FIG. 1. Range distribution of recoil protons from Po-B neutrons.

could not be measured, while with methane the proton tracks of lower energy were too short to be measured with sufficient accuracy. With hydrogen, 162 tracks were measured; with methane, 210. The observed ranges were converted to their equivalent length in air by using, in the case of hydrogen, the stopping-power data from Gurney;² and for methane, the data given by Van der Merwe.³ The value of the relative stopping-power which was used in this conversion depends somewhat on the range of the proton. The value adopted at our longest range for the stopping-power of hydrogen at one atmosphere relative to air is 0.211. The corresponding stopping-power for methane was taken to be 0.83. The curves of Fig. 1 show the distribution-in-range of the observed recoil protons. As in the case of fluorine, the curves show distinct maxima and minima which we believe cannot be caused entirely by statistical fluctuations but must principally be due to the

existence of groups of neutrons of different energy. From Fig. 1 it is seen that six groups are indicated by the methane curve, while two additional groups are shown by the hydrogen curve below the 7.0 cm range where the methane curve ends. Where the two curves overlap, the hydrogen curve also shows peaks corresponding to the groups of higher energy, and the positions of the minima on this curve correspond approximately with those of the methane curve. The hydrogen curve alone would not be convincing on account of the small number of tracks, but considered in conjunction with that for methane strengthens the evidence for the existence of the groups.

TABLE I.

Maximum range of recoil-proton group (cm)	Velocity of neutron group ($\times 10^9$ cm/sec.)	Energy of neutron group ($\times 10^6$ e.v.)
23.8	2.82	4.16
19.3	2.64	3.65
15.2	2.46	3.17
12.2	2.29	2.75
9.3	2.12	2.35
7.5	1.98	2.05
5.8	1.84	1.77
3.5	1.57	1.29

The maximum ranges corresponding to the eight observed groups are shown in Fig. 1 and are tabulated in Table I. In Table I are also given the velocity and the energy of the neutrons which correspond to the recoil protons of these ranges. The maximum energy of the neutrons from boron is found to be 4.2×10^6 e.v., a value somewhat higher than the value of about 3.3×10^6 e.v. found by previous observers. The new value of the maximum energy lowers the mass of the neutron which is obtained by Chadwick⁴ from the reaction $B^{11} + \alpha = N^{14} + n$. Using the value 3.35×10^6 e.v., he finds the mass of the neutron to be 1.0067; introducing our value, we obtain 1.0058. However, we feel that there is considerable doubt as to whether the mass of the neutron can be calculated from this reaction because there is the possibility that the neutrons of maximum energy are due to B^{10} .

Following the same argument which was given in our letter on the neutrons from fluorine, we considered the possibility of correlating the neutron groups with the groups from the proton disintegration of boron. However, with boron this cannot be done at present because of complications caused by the existence of the two isotopes. It is generally believed that only B^{10} disintegrates with the emission of a proton, while the neutron disintegration has been ascribed to both B^{10} and B^{11} . Thus it is possible that the eight neutron groups we have observed are due partly to B^{10} and partly to B^{11} , and in this case we would not be able to assign the various groups to their proper isotope. It is also possible that only B^{11} disintegrates with neutron emission, in which case no correlation is expected. If, on the other hand, only B^{10} undergoes neutron disintegration, a correlation would be expected, but we find that a correlation is impossible because in the proton disintegration of B^{10} only three groups have been observed.⁵ This result may be interpreted to mean either that some of the proton groups of B^{10} have not been detected or that B^{10} cannot alone be responsible for the neutron emission.

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T. W. BONNER

The Rice Institute,
Houston, Texas,
April 2, 1934.

¹ T. W. Bonner and L. M. Mott-Smith, Phys. Rev. **45**, 552 (1934).

² R. W. Gurney, Proc. Roy. Soc. **A135**, 48 (1925).

³ C. W. Van der Merwe, Phil. Mag. **45**, 379 (1923).

⁴ J. Chadwick, Proc. Roy. Soc. **A142**, 1 (1933).

⁵ F. Heidenreich, Zeits. f. Physik **86**, 675 (1933).

Emission of Electrons from Fluorine and Beryllium

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Emission of Neutrons from Fluorine and Beryllium

The purpose of this experiment was to investigate the emission of neutrons from fluorine and beryllium as a function of the velocity of the alpha-particles producing the disintegration. A diagram of apparatus is given in Fig. 1.

FIG. 1. Diagram of apparatus.

The source of alpha-particles was about 10 millicuries of polonium on a silver disk of 0.3 cm radius. Powdered calcium fluoride or beryllium was spread on a portion of a glass sphere of 3.8 cm radius. The residual range of the alpha-particles was varied by changing the pressure of the air inside the bell-jar. Since calcium has been found to give no appreciable emission of neutrons, the effects observed when calcium fluoride was used in this experiment are due to neutrons emitted from fluorine. An ionization chamber containing hydrogen at 20 atmospheres pressure was used to measure the ionization currents. Less than 5 percent of the current produced by the radiation from Po+F could have been due to γ -rays emitted along with the neutrons.

Fig. 2 shows the curves of the ionization produced by the neutrons from fluorine and beryllium as a function of the residual range of the alpha-particles. The beryllium-neutron curve is similar to that reported by Curie and Joliot.¹ The fluorine-neutron ionization current becomes zero when the residual range of the alpha-particles is less than 2.3 cm in air. Thus alpha-particles with ranges of more than 2.3 cm are necessary to produce neutrons from fluorine. An alpha-particle of this range has an energy of 3.7×10^6 e.v.

FIG. 2. Emission of neutrons from beryllium and fluorine. (Fluorine ordinates have been multiplied by 16.)

The maximum energy of the neutrons emitted by Po+Be is of the order of 12×10^6 e.v., which is greater than the energy of the exciting alpha-particles. Thus the nuclear reaction is possible for alpha-particles of any velocity, and so there is no alpha-particle velocity below which there is no emission of neutrons. The emission of neutrons from beryllium has been observed by Crane, Lauristen and Soltan² when the energy of the alpha-particles was as low as 500,000 volts. However with boron¹ and fluorine there is a definite threshold alpha-particle velocity for the emission of neutrons.

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Rice Institute,
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February 19, 1934.

¹ I. Curie and F. Joliot, J. de Phys. et Radium 4, 278 (1933).

² Crane, Lauristen and Soltan, Phys. Rev. 44, 514 (1933).

Ionization of Gases by Neutrons

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Ionization of Gases by Neutrons

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The ionization currents produced in hydrogen, helium, nitrogen, methane, ethylene and argon by the neutrons from beryllium have been measured for gas pressures from 5 to 80 atmospheres. The relative diameters of the atomic nuclei have been calculated from the relative ionizations. Assuming that the radius of the neutron is small compared to the radii of the atomic nuclei, the

relative radii of the nuclei are found to be $r_H = 1.0$, $r_N = 1.9$, $r_C = 2.8$, and $r_A = 4.1$. The target areas of $a_H = 1.0$, $a_{He} = 2.0$, $a_N = 3.5$, $a_C = 8.0$, and $a_A =$ roughly as their atomic numbers. The pressure-curves for neutrons are found to differ from curves in the same gases.

THE object of the experiments described in this paper was to find the relative amounts of ionization produced in different gases by neutrons. When neutrons collide with nuclei of gaseous atoms contained in an ionization chamber, energy is transferred from the neutrons to the nuclei. A recoil atom formed in this manner then produces a large number of ions in the gas.

Experiments on the relative ionization produced by neutrons in argon, nitrogen and helium containing 20 percent air have been described by Curie and Joliot¹ with an ionization chamber containing these gases at atmospheric pressure. In the present experiments the relative ionization currents due to neutrons have been determined for argon, helium, nitrogen, hydrogen, methane and ethylene over a range of pressure of from 5 to 80 atmospheres.

The diagram of apparatus (Fig. 1) shows the ionization chamber *B*, the inside dimensions of which were $5 \times 5 \times 10$ cm. The iron walls of the ionization chamber were one cm thick. The electrode was insulated by amber with a guard ring which was so arranged that the insulators were not in the electrical field across the ionization chamber. The chamber was made pressure

tight with sealing wax between the metal and amber surfaces. A Lindemann electrometer *C* operated at a sensitivity of 50 divisions per volt was used to measure the currents. In order to eliminate insulation leakage a null method

employing a potentiometer and a compensating condenser (*D* in Fig. 1) was used. The electrometer needle was always kept potential by changing the potential of condenser. A potential of 400 volts supplied by "B" batteries was applied across the ionization chamber.

A two-inch lead shield surrounded the ionization chamber, except on the top side. This shield also increased the number of neutrons entering the chamber, since a constant number of the neutrons are scattered in the chamber from the lead.

The polonium, used as a source of particles, was deposited on a silver disk 9 mm in diameter. The silver disk is shown in Fig. 1 directly above the ionization chamber. The polonium had an activity of roughly 1000 curies. A thin slab of beryllium was mounted on a slide (*A* in Fig. 1) so that it could be pushed under the source of polonium or out of the range of the alpha-particles. 4 mm of lead interposed between the source of neutrons and the ionization chamber.

The pressure in the chamber was measured by a Heise pressure gauge *E* which could be operated accurately to 2 lb. per sq. in.

The ionization chamber was thoroughly emptied by successively filling to 70 atmospheres and emptying it three times. The gases were passed through a P_2O_5 drying tube and a trap of tubing containing glass wool before the

¹ I. Curie and F. Joliot, *J. de Physique et le Radium* 4, 1, 21 (1933).

FIG. 1. Diagram of ionization chamber.

admitted to the ionization chamber. Measurements were made first at 80 atmospheres and then at the lower pressures.

In determining the ionization due to the neutrons, the ionization produced when the beryllium was out of the range of the alpha-particles was measured first, and then the ionization when the beryllium was directly under the polonium. The ionization in the first case was that due to γ -rays from the polonium source, cosmic rays, and radioactivity of the chamber. To determine the ionization due to the neutrons the first current was subtracted from the second. In these experiments the ionization due to the neutrons was several times that due to the other radiations.

The variation of the current with the potential applied to the ionization chamber was determined with different gases at 80 atmospheres. It was found that when the potential was changed from 200 to 400 volts there was an increase in the ionization current of only a few percent. In the subsequent measurements alternate readings were made with the chamber at a potential of +400 volts with respect to the electrode and then -400 volts and the mean of the two currents was used.

The capacity of the system was determined by comparing it with that of the compensating condenser and was found to be 9.6 e.s.u. The number of ion pairs per cc per second was

$$(9.6 \times 12) / (50 \times 300 \times 4.77 \times 10^{-10} \times 250 \times t)$$

where 250 cc was the volume of the chamber; 12,

the number of divisions deflection of the electrometer; 50, the sensitivity of the electrometer in divisions per volt; and t , the time in seconds required for this deflection.

Under the given experimental conditions the ionization by the less penetrating γ -rays,² emitted along with the neutrons was found to contribute only a small percentage of the total ionization. This was shown by getting the ionization in CH_4 , H_2 , and N_2 with an additional lead absorber of 2.2 cm thickness. The 2.2 cm of lead cut down the amount of ionization by 23 ± 5 percent in CH_4 , 26 ± 5 percent in H_2 , and 30 ± 5 percent in N_2 . If the γ -rays produced a considerable part of the total ionization, then the apparent absorption coefficient would have been much larger when using CH_4 and N_2 than when using H_2 in the chamber.

Fig. 2 shows the ionization currents produced at different pressures by the neutrons in CH_4 , C_2H_4 , A, H_2 , N_2 , He. Similar data given in Table I show the relative ionization in these

TABLE I. Ionization due to γ rays in arbitrary units.

Gas	10 atmos- pheres	20	40	80	80 for γ -rays	80 for neutrons
N_2	1.00	1.76	2.56	3.55	3.55	3.78
He	0.223	0.438	0.774	1.27	5.70	2.02
H_2	0.184	0.342	0.544	0.850	4.61	3.32
A	1.64	3.15	5.49	8.91	5.44	6.16
CH_4	0.956	1.60	2.38	3.64	3.81	2.16
C_2H_4	1.42	2.29	3.52	—	—	—

² Becker and Bothe, *Naturwiss.* 20, 41, 757 (1932).

FIG. 2. Ionization as function of pressure.

different gases by the γ -rays from 10 milligrams of radium placed several meters from the chamber and filtered by 5 cm of lead. The ionization produced by the neutrons in H_2 is a little larger than that in N_2 , while there is approximately four times as much ionization due to γ -rays in N_2 as in H_2 . In the case of H_2 , He, C_2H_4 , and CH_4 the ratio of ionization currents, due to the neutrons, at 80 atmospheres to the currents at 10 atmospheres is less than that for γ -rays. Now when the ionization currents are not proportional to the pressure of the gas, it means that there is a lack of saturation. Since neutrons collide with atomic nuclei, which in turn produce ions in short thick tracks, we might expect these ions to recombine more easily and thus be harder to saturate. This agrees with the data for H_2 , He, CH_4 , and C_2H_4 , but in A and N_2 it appears that it is slightly easier to saturate the ions produced by recoil atoms than those produced by γ -rays.

Since the neutron collides only with the nuclei of the atoms, a comparison of their sizes can be obtained. We have $I = k_1 n a A E / R$ where I denotes the number of ion pairs produced per 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 collision area

between neutron and 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; $-k_1$ being a constant. In the case of a gas containing two different kinds of atoms $I = I_1 + I_2$ where I_1 and I_2 are the ionizations due to the two different kinds of recoil atoms. In this case $I = k_1 n a_1 A_1 E_1 / R + k_1 n a_2 A_2 E_2 / R$. Since no data were available as to the average energy required to form an ion pair by the different recoil atoms in the six gases used, the average energy spent by an alpha-particle in producing an ion pair in each gas³ was employed in these calculations.

If we assume that the collisions made with nuclei by neutrons are perfectly elastic, we have for a head-on collision $v = 2MV / (m + M)$ where v is the velocity given to the nucleus; M , the mass of the neutron, which is taken to be 1.00 in these calculations; V , the original velocity of the neutron; and m , the mass of the nucleus. Thus the relative amounts of energy given to the various nuclei are $E_H = 1.00$, $E_{He} = 0.64$, $E_N = 0.250$, $E_C = 0.284$, and $E_A = 0.095$. For col-

³ Rutherford, Chadwick and Ellis, *Radiations from Radioactive Substances*, p. 82.

TABLE II. Ionization due to neutrons.

Gas	I	R_1	IR_1	I_1R_1	I_2R_2	$k \frac{I_1R_1}{a_1}$	$k \frac{I_2R_1}{a_2}$	Gas	E_1	A	Atomic No.	Atomic Weight
He	80.6	27.8	2240	2240	—	2240	—	N	0.250	3.5	7	14
H ₂	106	33.0	3500	3500	—	1750	—	He	0.640	2.0	2	4
A	113	25.4	2870	2870	—	2870	—	H	1.00	1.0	1	1
CH ₄	436	27.9	12200	7000	5200	1750	5200	A	0.095	17	18	40
C ₂ H ₄	468	26.8	12600	7000	5600	1750	2800	C	0.284	8.0	6	12
N ₂	87.1	35.0	3050	3050	—	1525	—					

I = ionization currents at 10 atmospheres (except for CH₄ and C₂H₄).

R_1 = average energy spent per ion pair for alpha-particles.

E_1 = relative energies given to nuclei.

a_1 = relative number of atoms of type 1 in chamber.

a_2 = relative number of atoms of type 2 in chamber.

A = relative collision area between neutron and nucleus.

lisions other than head on, the ratios of energy given to the various nuclei are the same as in the case of head-on collisions.

The values of the ionization I in Table II are those at 10 atmospheres where very nearly all the ions formed are drawn to the electrodes. But for CH₄ and C₂H₄ twice the value of I at 5 atmospheres is given instead. Table II gives these data on ionization and energies and the calculated value of the collision area A between the neutrons and nuclei. If we assume that the neutrons and nuclei are spherical we have

$$\pi(r_n + r_{He})^2 / \pi(r_n + r_H)^2 = 2.0$$

and $(r_n + r_{He}) / (r_n + r_H) = 1.4$, where r_n is the radius of the neutron and r_{He} and r_H are respectively the radii of the helium and hydrogen nuclei. If the size of the neutron is small compared to that of the nuclei $r_{He}/r_H = 1.4$, $r_N/r_H = 1.9$, $r_C/r_H = 2.8$, and $r_A/r_H = 4.1$. The relative target areas $a_H = 1.0$, $a_{He} = 2.0$, $a_C = 8.0$, $a_N = 3.5$, and $a_A = 17$ are roughly proportional to the atomic numbers. This suggests that the nucleus may be regarded as a group of separate protons and neutrons so that its target area is proportional to the number of protons it contains.

If we take the value 3.5×10^{-13} cm obtained by Chadwick⁴ as the radius of the carbon nucleus, then we get for the radii of the nuclei $r_H = 1.3 \times 10^{-13}$ cm, $r_{He} = 1.8 \times 10^{-13}$ cm, $r_C = 3.5 \times 10^{-13}$ cm, $r_N = 2.4 \times 10^{-13}$ cm and $r_A = 5.1 \times 10^{-13}$ cm. Although the neutron is probably considerably smaller than a proton, it seems worth while to consider what sizes are obtained for the nuclei if we assume that the radius of the neutron is equal to that of the proton. Using this hypothesis we get $r_H = 0.76 \times 10^{-13}$ cm, $r_{He} = 1.4 \times 10^{-13}$ cm, $r_N = 2.1 \times 10^{-13}$ cm, $r_C = 3.5 \times 10^{-13}$ cm, and $r_A = 5.5 \times 10^{-13}$ cm.

I am indebted to Dr. L. M. Mott-Smith for the use of the ionization chamber used in these experiments. I also want to thank Professor F. J. Hodges of the University of Michigan Hospital, Mr. C. B. Braestrup of the New York City Cancer Institute, and The State Institute for the Study of Malignant Disease, Buffalo, N. Y., for their gifts of old radon tubes. My thanks are due to Professor H. A. Wilson for the interest he has taken in this work and for many valuable suggestions.

⁴ J. Chadwick, Proc. Roy. Soc. A136, 703 (1932).

Dependence of the Absorption of Neutrons on Their Velocity

The purpose of this experiment was to see if the penetrating power of neutrons changes with their velocity. The absorption of neutrons obtained in three different ways was determined: (1) neutrons ejected in the forward direction from Be, (2) neutrons ejected backward from Be, (3) neutrons ejected forward from B. In all cases the alpha particles from polonium were used to produce the neutrons.

J. Chadwick¹ has found the maximum velocity of the neutrons in these three cases to be as shown in Table I. The average velocity of the neutrons emitted in these three cases will probably vary roughly as their maximum velocities.

An ionization chamber filled with hydrogen at 20 atmospheres pressure was used and the radiation was filtered by 2.5 cm of iron before entering the ionization chamber. Hydrogen was used since it gives a high ionization for neutrons but very little ionization for gamma-rays.² Diminution of the ionization current was determined when six centimeters of lead were interposed. The geometrical arrangement of the absorbers was the same in each of the three cases. The results are shown in Table I. It will be seen that over this range of velocities the faster neutrons are more easily absorbed by lead than the slower ones. It is suggested that this may correspond to the Ramsauer effect in electron absorption by inert gases where there is a similar range of velocities in which the penetrating power increases with decrease in velocity. It is likely that the absorption coefficient will decrease again for velocities higher than those here studied.

TABLE I.

Neutron group	Maximum velocity (Chadwick) (cm/sec.)	Decrease in ionization in 6 cm of lead (percent)
Be, forward	3.3×10^9	43.2 ± 1.8
Be, backward	2.7×10^9	36.1 ± 1.9
B, forward	2.5×10^9	32.0 ± 2.4

The different penetrating powers of the neutrons emitted from the other elements are probably due to their different velocities but measurements of their velocities have not been made. If we assume then that there is one velocity for which there is a maximum absorption and a decrease in absorption for either faster or slower neutrons, then for the extremely penetrating neutrons from fluorine³ we see that there are two possibilities: (1) that these neutrons are even slower than those from boron or (2) that they are much faster than those from Be in the forward direction; the former possibility seems the more likely of the two. Similarly the easily absorbed neutrons from lithium³ would probably be faster than those from Be.

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The Rice Institute,
Houston, Texas,
June 20, 1933.

¹ J. Chadwick, Proc. Roy. Soc. A136, 692 (1932).

² T. W. Bonner, Phys. Rev. 43, 871 (1933).

³ I. Curie and F. Joliot, Comptes Rendus 196, 397 (1933).

LUMINOSITY OF A FLAME CONTAINING SODIUM VAPOR

BY
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THE LUMINOSITY OF A FLAME CONTAINING
SODIUM VAPOR

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ABSTRACT

This paper contains an account of measurements of the variation of the luminosity of a sodium flame with the thickness of the flame and the concentration of the sodium salt solution sprayed into it. The reversal of the sodium lines by the layer of cool vapor at the front of the flame was eliminated by having no sodium in the front 3 cms of the flame. An improved form of sprayer was used in which the level of the solution and its concentration remained constant. It was found that the luminosity is a function of the product of the thickness of the flame and the concentration of the sodium in it or of the mass M of sodium per square cm. This result agrees with the previous results of Gouy, H. A. Wilson and Locher but not with the recent results of C. D. Child. The function of M is proportional to M when M is very small but increases less rapidly than M when M is large. Measurements of the variation of the luminosity with the thickness at the center of one of the D lines and at its edge showed that the absorption at the center is much greater than at the edge as was to be expected.

INTRODUCTION

THE first measurements of the luminosity of flames containing salt vapors were made by Gouy¹ in 1879–80, while more recent work has been done by Zahn,² H. A. Wilson,³ Locher,⁴ and Lundegardh.⁵ Gouy, H. A. Wilson, and Locher found that the luminosity of the surface of a sodium flame is a function of the product of the flame thickness and the concentration of the sodium salt solution sprayed into the flame or a function of the mass M of sodium per square cm. This function was roughly proportional to $(M)^{1/2}$ over a considerable range provided M is not too small. Recently C. D. Child⁶ has measured the luminosity of sodium flames, but his results do not show that the luminosity is a function of M . The experiments described below were undertaken to find out the reason for this discrepancy.

EXPERIMENTAL METHODS AND RESULTS

The burner used was a horizontal fused quartz tube 25 cm long and 3 cm in diameter with a straight slot 15 cm long and 2 mm wide cut in it parallel to its axis. One end of the burner was connected to a sprayer in which natural gas and air were mixed together along with spray of a sodium

¹ Gouy, Jour. de Physique 9, 19 (1880).

² Zahn, Deut. Phys. Ges. Ber. 15, 1203 (1913).

³ H. A. Wilson, Phil. Trans. Roy. Soc. A216, 63 (1916).

⁴ G. L. Locher, Phys. Rev. 31, 466 (1928).

⁵ Lundegardh, Zeits. f. Physik 66, 109 (1930).

⁶ C. D. Child, Phys. Rev. 38, 699 (1931).

chloride solution. The mixture was burned at the slot and gave a Bunsen flame 15 cm long, 6 cm high and about 1 cm thick. The inner cone was about 1 cm high. The air and gas supplies were regulated and kept at constant pressures indicated by manometers.

The burner and sprayer were similar to that described by H. A. Wilson,⁷ but an improvement was introduced which prevented errors due to the gradual change in the level of the solution in the sprayer and the slow increase in its concentration due to evaporation. The sprayer was connected to a large reservoir of the salt solution, and the solution was kept circulating through the sprayer and reservoir by means of a small air aspirator.

The brightness or luminosity of the flame, along a horizontal line parallel to the slot and about one half cm above the top of the inner cone, was measured with a Nutting spectrophotometer made by Hilger. A small incandescent lamp was used for comparison and the potential difference on it was kept constant during any one set of measurements. The thickness of the flame on the line along which the luminosity was measured was varied by means of a vertical black copper plate put across the flame. This plate was carried on a graduated slide so that its distance from the front of the flame could be varied and accurately measured.

When the sodium lines from this flame were examined with a plane grating in the third order, it was found that they were strongly reversed unless the solutions used were very weak. This reversal was evidently due to the absorption of the center of the sodium lines by cool sodium vapor at the front of the flame. This effect was eliminated by having no sodium in the front part of the flame so that all the sodium vapor was at the same temperature. A thin diaphragm was cemented into the quartz burner 3 cms from the front end of the slot and a mixture of gas and air only was passed into one end of the burner and the gas, air and salt spray into the other end. In this manner a uniform flame 15 cm long was obtained with no sodium in the front 3 cm but sodium in the remaining 12 cm. With this flame there was no reversal even when strong sodium solutions were sprayed.

In previous work on the luminosity of sodium flames, the light from a row of equal flames was measured and the number of flames in the row was varied. Each flame must have had a layer of cool vapor on each side so that there must have been strong absorption of the centers of the *D* lines by these cool layers. The previous experiments therefore do not give the way in which the luminosity varies with the thickness and concentration for a layer *all* at the same temperature. It was found that the removal of the cool reversing layer considerably altered the variation of the luminosity.

A diaphragm of 1.5 mm in diameter was placed at a distance of 30 cm from the collimator slit so that the width of the cone of light admitted to the slit was only 2.2 mm at the back of the flame; thereby making the intensity of illumination due to the different portions of the flame independent of their distances from the spectrometer. Since C. D. Child used a Lummer-Brodhun photometer in his experiments, he had to take into consideration

⁷ Electrical Conductivity of Flames, Rev. Mod. Phys. 3, 156 (1931).

the distance of the flames from the photometer as the intensity of illumination is inversely proportional to the square of the distance. The uncertainty in the determination of the effective distance of the flames from the photometer probably accounts for his results.

In performing the experiment, the standard lamp was so adjusted for each concentration of salt solution that the photometer readings would fall symmetrically around 45° where the photometer has its maximum sensitivity. When a second solution was used, the relative intensities of the standard lamp with the two different potentials was determined so that all the intensities could be compared with one another. The data on a sample run are given in Table I which shows the variation in intensity with change in thickness of a flame sprayed with a sodium chloride solution of 40 gm per liter.

TABLE I. (Voltage on standard lamp—3.03 volts).

Thickness of flame				
1.6 cm	2.6 cm	4.1 cm	6.6 cm	11.1 cm
56.0°	52.8°	47.0°	45.8°	38.3°
56.6	52.0	49.8	43.0	38.5
56.3	52.9	48.3	45.2	40.8
55.0	52.0	49.0	46.5	40.9
55.8	53.3	48.8	46.5	37.3
56.5	51.2	47.9	45.0	42.5
56.0	53.4	48.4	44.5	40.0
57.2	51.8	49.0	43.5	40.0
56.6	52.8	49.5	44.1	40.7
55.8	51.8	48.5	44.7	40.0
55.0	51.2	48.2	43.0	38.5
55.5	52.0	47.0	45.8	40.9
56.5	52.8	48.8	46.6	42.5
56.3	52.9	49.8	45.2	40.2
57.2	51.6	48.5	45.0	40.6
55.5	53.3	49.0	46.5	40.9
56.3	53.4	49.0	43.5	39.3
56.0	52.4	48.4	44.5	40.9
56.3	51.6	47.8	44.7	40.2
56.0	52.4	49.5	44.1	40.8
Av. 56.1°	Av. 52.4°	Av. 48.6°	Av. 44.9°	Av. 40.2°
Intensity (I) = 1.00	$I = 1.19$	$I = 1.41$	$I = 1.61$	$I = 1.87$

The intensities given in Table II were obtained in the same way and thus each intensity represents the average of twenty independent readings of the photometer.

When sodium carbonate solutions were used in place of sodium chloride, it was found that the luminosity due to an equal weight of sodium was the same for both salts, in keeping with the results of H. A. Wilson.

Fig. 1 shows the variation of the logarithm of intensity with the logarithm of ρd where ρd is varied from 4 to 83200. From this curve one concludes that the luminosity of the flame is a function of ρd and is independent of the distribution of the vapor. Since the luminosity of a flame sprayed with a dilute salt solution is almost proportional to ρd , there must be very little absorption under these circumstances. For a flame in which there is more sodium vapor present, the absorption becomes quite large. The square root relation be-

TABLE II. *Intensity of the D lines of sodium as compared with an incandescent lamp.*

Gm NaCl per liter	Concentration ρ in arbitrary units	Thickness d in cm	ρd	Intensity I
0.00532	1	4.1	4.1	4.83
0.00532	1	6.6	6.6	7.81
0.00532	1	11.1	11.1	12.50
0.0267	5	1.6	8.0	8.67
0.0267	5	2.6	13.0	13.5
0.0267	5	4.1	20.5	20.5
0.0267	5	6.6	33.0	28.2
0.0267	5	11.1	55.5	38.0
0.0800	15	1.6	24.0	20.7
0.0800	15	2.6	39.0	30.5
0.0800	15	4.1	61.5	41.3
0.0800	15	6.6	99.0	48.4
0.0800	15	11.1	167	64.3
0.400	75	1.6	120	55.1
0.400	75	2.6	195	68.9
0.400	75	4.1	308	82.1
0.400	75	6.6	495	99.7
0.400	75	11.1	832	128
4.00	750	1.6	1200	149
4.00	750	2.6	1950	189
4.00	750	4.1	3080	220
4.00	750	6.6	4950	265
4.00	750	11.1	8320	323
40.0	7500	1.6	12000	367
40.0	7500	2.6	19500	438
40.0	7500	4.1	30800	516
40.0	7500	6.6	49500	591
40.0	7500	11.1	83200	688

Fig. 1. Variation of the logarithm of intensity with the logarithm of ρd .

tween luminosity and ρd holds only over a limited range, and for the largest values of ρd used in these experiments the luminosity is approximately proportional to the cube root of ρd .

H. A. Wilson⁸ gave the theoretical relation for the luminosity of a sodium flame

⁸ H. A. Wilson, Proceedings Roy. Society A118, 362 (1928).

$$I = E \int_{-\infty}^{+\infty} (1 - e^{-n\gamma_0/(1+4m^2\Delta^2/k^2)}) d\Delta \quad (1)$$

where m = mass of vibrating electron; k = viscous resistance to motion at unit velocity; n = number of atoms; γ_0 = atomic absorption coefficient at the center of the line; Δ = variation in frequency from that of the center of the line; E = intensity of black body radiation at the temperature of the flame per unit range of Δ near the D lines. When $n\gamma_0$ is greater than 2 or 3, he gave the approximate value of this integral to be

$$I = Ek/m(\pi n\gamma_0)^{1/2}(1 - 1/4n\gamma_0 - 3/32n^2\gamma_0^2 - \dots). \quad (2)$$

An exact series for this integral can be gotten by expanding the integrand into the series

$$\frac{n\gamma_0}{1 + \frac{4m^2\Delta^2}{k^2}} = \frac{1}{2!} \frac{n^2\gamma_0^2}{\left(1 + \frac{4m^2\Delta^2}{k^2}\right)^2} + \frac{1}{3!} \frac{n^3\gamma_0^3}{\left(1 + \frac{4m^2\Delta^2}{k^2}\right)^3} - \dots$$

Fig. 2. Variation of luminosity for small values of ρd (circles represent experimental points).

Each term of this series can be integrated, so Eq. (1) becomes

$$I = En\pi k\gamma_0/2m(1 - n\gamma_0/4 + n^2\gamma_0^2/16 - 5n^3\gamma_0^3/384 + \dots). \quad (3)$$

For small values of $n\gamma_0$ Eq. (3) is approximately equal to

$$I = E \frac{k\pi}{2m} \frac{n\gamma_0}{\left(1 + \frac{n\gamma_0}{4}\right)} \quad (4)$$

The variation of the luminosity for small values of ρd is shown in Fig. 2. The experimental points fall approximately on the curve given by the equation $I = 1.09\rho d/(1 + 0.0112\rho d)$ which is of the same form as (4).

Since according to the theory the middle of the D lines is absorbed more than the edges, it seemed to be a good plan to test this assumption experimentally. High resolving power was obtained by viewing the D_1 line in the third order of a plane reflecting grating. Light from a standard lamp was made to fall on the upper half of the collimator slit by placing a right angle prism over this portion of the slit. The solid angle of light admitted to the spectrometer was again cut down by a diaphragm so that the illumination due to different parts of the flame would be independent of their distances. Shutters in the eyepiece were adjusted so that a narrow portion of the middle of the D_1 line was observed and the variation of the intensity of this portion

Fig. 3. Curve I shows variation of the intensity of the edge of the D_1 line; curve II that of the middle of the D_1 line with change in thickness of flame.

of the D_1 line was determined when the thickness of the flame was varied. The intensity of the light from the standard lamp was varied until it was of the same intensity as that from the flame and then the potential applied to the lamp was noted. The lamp was subsequently calibrated for the wave-length of the D_1 line for various applied potentials.

The spectrometer was then rotated through a small angle corresponding to a change of wave-length of 1.7 angstroms and the variation of the edge of the D_1 line noted for different flame thicknesses. Curve (2) of Fig. 3 shows the variation of intensity of the middle of the D_1 line with change in the thickness of the flame, while curve (1) shows the variation of the intensity of the edge of the D_1 line. The curves indicate that the middle of the line is absorbed much more than the edges in agreement with the theory.

The conclusion reached is (1) that the luminosity of a flame containing sodium vapor is a function of the mass of sodium per square cm contained in it and is independent of the distribution of the vapor, and (2) that the middle of the D_1 line of sodium is absorbed more than the edges.

In conclusion, I wish to acknowledge my indebtedness to Professor H. A. Wilson for the suggestion of this problem and my appreciation of his interest and many valuable suggestions made during the course of this work.