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 $r_H = 1.0$, $r_{He} = 1.4$, $r_N = 1.9$, $r_C = 2.8$, and $r_A = 4.1$. The target areas of the nuclei $a_H = 1.0$, $a_{He} = 2.0$, $a_N = 3.5$, $a_C = 8.0$, and $a_A = 17$, vary roughly as their atomic numbers. The pressure-ionization curves for neutrons are found to differ from the γ-ray 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 Joliot[1] 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 $5\times5\times10$ 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. Thus the electrometer needle was always kept at zero potential by changing the potential on the 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, to cut down the ionization due to local radioactivity. This shield also increased the number of neutrons entering the chamber, since a considerable number of the neutrons are scattered into the chamber from the lead.

The polonium, used as a source of alpha-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 15 millicuries. A thin slab of beryllium was mounted on a slide (A in Fig. 1) so that it could be put either just under the source of polonium or out of the range of the alpha-particles. 4 mm of lead was 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 read accurately to 2 lb. per sq. in.

The ionization chamber was thoroughly flushed out by successively filling to 70 atmospheres and emptying it three times. The gases were slowly passed through a P_2O_5 drying tube and a length of tubing containing glass wool before they were

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

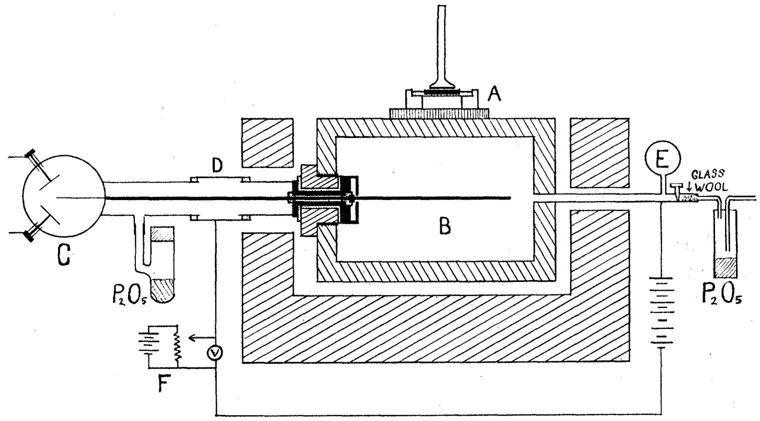

FIG. 1. Diagram of ionization chamber.

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 atmospheres	20	40	80	$\frac{80}{10}$ for γ-rays	$\frac{80}{10}$ 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).

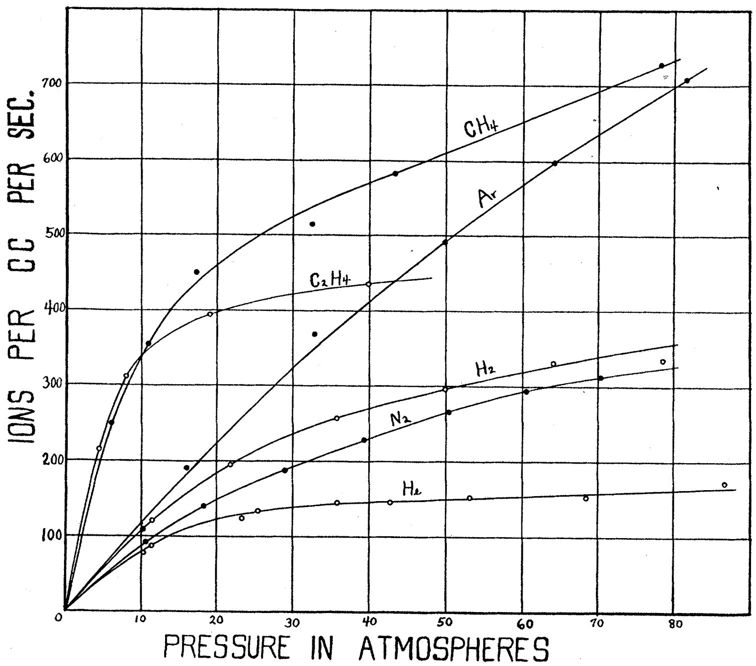

FIG. 2. Ionization as function of pressure.

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 $I=k_1naAE/R$ 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 $I=k_1na_1A_1E_1/R+k_1na_2A_2E_2/R$. 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 gas[3] 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_2H_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 CH_4 and C_2H_4).
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 CH_4 and C_2H_4 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 Chadwick[4] as the radius of the carbon nucleus, then we get for the radii of the nuclei $r_H=1.3\times10^{-13}$ cm, $r_{He}=1.8\times10^{-13}$ cm, $r_C=3.5\times10^{-13}$ cm, $r_N=2.4\times10^{-13}$ cm and $r_A=5.1\times10^{-13}$ 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 $r_H=0.76\times10^{-13}$ cm, $r_{He}=1.4\times10^{-13}$ cm, $r_N=2.1\times10^{-13}$ cm, $r_C=3.5\times10^{-13}$ cm, and $r_A=5.5\times10^{-13}$ cm.

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