The Disintegration of the Nuclei of Nitrogen and Other Light Atoms by Neutrons. I

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Disintegration experiments with N, C and Ne.—Thirty-one disintegrations of nitrogen have been found in 7600 pairs of photographs of a Wilson chamber through which neutrons were shot from a Be-Ms Th source. Of these, nineteen were disintegrations in which the neutron was captured according to the reaction

$$N_0^{14}+n_1^1 \rightarrow N_1^{15} \rightarrow B_1^{11}+He_0^4.$$

The distribution curve which shows the number of disintegrations for each velocity interval of the neutrons at capture exhibits a peak at 3.2×10^9 cm/sec. The lowest velocity which produces such a disintegration is 1.9×10^9 and the highest 5.5×10^9. The form of the curve is explained by the assumption that the probability that a neutron will be effective in producing disintegration increases rapidly with its velocity but that, as the velocity considered lies higher and higher above 3.2×10^9 cm/sec., the number of neutrons present at such a velocity decreases rapidly. The data are too few to show any indication of resonance. The highest energy found for a neutron at capture is 15.8×10^6 electron-volts, while, according to theory, it should be 14.7×10^6 provided the α-particle comes from Th C′.

Disappearance of energy and emission of γ-rays.—Without exception, for every disintegration of an atomic nucleus by capture of a neutron, kinetic energy (a) has been conserved or (b), much more often, disappears. It is assumed that this energy plus any energy in the form of mass which disappears, is converted into γ-rays. The values obtained suggest that the spectrum of these γ-rays is a line spectrum, which obviously may be superimposed upon a continuous spectrum. Conclusive evidence of this cannot be obtained until the accuracy of the work is increased by an increase in the range of the disintegration products.

Disintegration as related to scattering.—Nine disintegrations of the nitrogen nucleus were obtained in which it is probable that either (a) the neutron was first deflected by a nucleus and later disintegrated a nitrogen nucleus with capture or (b) the neutron was not captured.

Modified Wilson cloud track apparatus.—The features of a modified Wilson apparatus, which are considered essential to the accuracy of this work, are described.

Disintegrations of neon and carbon.—On June 12 thirteen disintegrations of neon nuclei were found in 3200 pairs of photographs. The kinetic energy which disappeared was found to vary from 5 to nearly 11 million electron-volts. The same number of photographs gave only 2 disintegrations in ethylene. Presumably these were disintegrations of carbon nuclei but it is possible that they were due to the oxygen of the water.

1. INTRODUCTION

THE recent discovery of the neutron has suggested several fundamental problems for investigation. Some of these may be outlined as follows: (1) The relation of the neutron to the structure of more complex nuclei. (2) The nature of the neutron and its relation to positive and negative electrons and to protons. (3) The emission of γ-rays associated (a) with the emission of neutrons from nuclei and also (b) with the disintegration of nuclei by the impact of neutrons. (4) The law of force between neutrons and other nuclei. (5) The validity or non-validity of the Harkins-Masson nuclear formula as a constitutional formula for all nuclei. This formula is discussed in Section 2.

The experimental investigation described in this paper has a bearing on all of these topics but the data thus far calculated relate to (1) the disintegration of light nuclei by fast neutrons, (2) the kinetic energy which disappears in the disintegration process and is presumably emitted as γ-rays and (3) the distribution of velocity for the neutrons effective in producing disintegration. The other data will be presented in later papers.

2. THE EMISSION OF NEUTRONS[1] FROM NUCLEI

In 1915, Harkins and Wilson[2] showed that the atomic weights and atomic numbers of the light

[1] Bothe and Becker, Zeits. f. Physik **66**, 289, 307 (1930); Curie, Comptes Rendus **193**, 1412 (1931); Joliot, Comptes Rendus **193**, 1415 (1931); Chadwick, Proc. Roy. Soc. **A136**, 692 (1932).

[2] Harkins and Wilson, Proc. Nat. Acad. Sci. **1**, 276 (1915); J. Am. Chem. Soc. **37**, 1383 (1915); Harkins,

elements of even atomic number may be represented by the assumption that such nuclei consist entirely of units with a charge of 2 and a mass of 4, which correspond both in charge and mass with helium nuclei (α-particles) (Table I).

TABLE I.

	He	Be	C	O	Ne	Mg	Si	S
Atomic number	2	4	6	8	10	12	14	16
Atomic weight predicted	4	8	12	16	20	24	28	32
Atomic weight determined	4	9	12	16	20	24	28	32
Composition of atom	He	He_2H	He_3	He_4	He_5	He_6	He_7	He_8

However, in the single case of the beryllium nucleus, it was necessary to assume the presence of a neutral nuclear particle or neutron with about the mass of a hydrogen atom. This gave rise to the idea that the neutron in the beryllium 9 nucleus takes the place of the third α-particle in the carbon nucleus and is essential to give stability. According to this view, Be^8 should have an unstable nucleus.

In a nuclear chart drawn at that time, Be^9 was found to lie on a higher level than the hypothetical Be^8 and this was expressed later by giving to Be^9 the isotopic number 1, while all the other atoms of Table I were assigned the isotopic number 0 (Fig. 1). According to the Harkins-

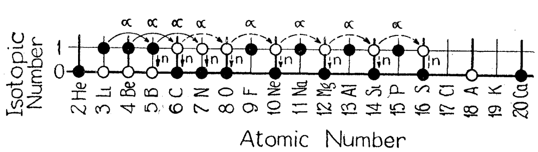

FIG. 1. Relations for the emission of neutrons by light nuclei on bombardment with α-particles.

Masson[3] nuclear formula $(p_2e)_Z(pe)_I$ or $(np)_Zn_I$ the isotopic number (I) gives the number of neutrons not associated with protons. Thus in Fig. 1, the atoms Li^7, Be^9, B^{11}, etc., may emit neutrons without nuclear bombardment provided they lose energy in falling to the isotopic number 0. If such a nucleus is bombarded by an α-particle which is captured, the atomic number is increased by 2, and the kinetic energy of the α-particle, plus the energy of mass of the α-particle and the nucleus to which it becomes attached, should, in general, be sufficiently great to incite the emission of a neutron and the resultant decrease of the isotopic number to 0.

The possible reactions may be classified as belonging to three types. An outline of the reactions of type 1 follows:

$$Li_1^7 + \alpha_0^4 \rightarrow B_1^{11} \rightarrow B_0^{10} + n_1^1 \quad (1)$$

$$Be_1^9 + \alpha_0^4 \rightarrow C_1^{13} \rightarrow C_0^{12} + n_1^1 \quad (2)$$

$$B_1^{11} + \alpha_0^4 \rightarrow N_1^{15} \rightarrow N_0^{14} + n_1^1 \quad (3)$$

$$C_1^{13} + \alpha_0^4 \rightarrow O_1^{17} \rightarrow O_0^{16} + n_1^1 \quad (4)$$

$$O_1^{17} + \alpha_0^4 \rightarrow Ne_1^{21} \rightarrow Ne_0^{20} + n_1^1 \quad (5)$$

$$Ne_1^{21} + \alpha_0^4 \rightarrow Mg_1^{25} \rightarrow Mg_0^{24} + n_1^1 \quad (6)$$

$$Mg_1^{25} + \alpha_0^4 \rightarrow Si_1^{29} \rightarrow Si_0^{28} + n_1^1 \quad (7)$$

$$Si_1^{29} + \alpha_0^4 \rightarrow S_1^{33} \rightarrow S_0^{32} + n_1^1. \quad (8)$$

Here the superscript gives the atomic mass and the subscript the isotopic number. It may be noted that the isotopic numbers, which give the number of extra neutrons in the nucleus, are additive. Only in reactions (1) to (3) does the atom which is struck by the neutron represent the principal isotope of the element.

In a type 2 reaction the conditions are more favorable to the emission of a proton. Thus if N_1^{15}, F_1^{19}, Na_1^{23} or Al_1^{27}, captures an α-particle, the emission of a neutron would form, in each case, an atom of isotopic number zero which has not as yet been found to exist as a stable atom.

In a type 3 reaction an atom of isotopic number greater than one is involved. There is as yet no experimental evidence to indicate whether in this case neutrons of either atomic weight 1 or 2 would be emitted and those of the higher mass (2) should be extremely rare if they exist at all.

3. MODIFIED WILSON CHAMBER

The modified Wilson chamber used in this work was constructed in 1929 by Harkins, Gans and Wallace. The general design of the apparatus is shown in Fig. 2, in which D is the Wilson chamber, P a supplementary chamber filled with the same gas at the same pressure and J is a vacuum chamber which exerts a pull of more

J. Am. Chem. Soc. **42**, 1956–1997 (1920); Rutherford, Proc. Roy. Soc. **A97**, 374–400 (1920).

[3] Harkins, Phys. Rev. **15**, 73–95 (1920); J. Am. Chem. Soc. **42**, 1956–1997 (1920); Phil. Mag. **42**, 305–339 (1921); Masson, Phil. Mag. **41**, 281 (1921).

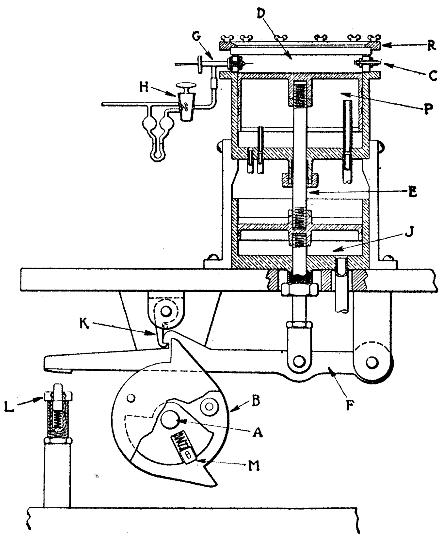

FIG. 2. Diagram of principal cloud chamber mechanism. *A*, axis for cam, and for electrical contacts (not shown) of timing mechanisms; *B*, cam used to trip catch *K*; *L*, shock absorber for principal expansion of chamber; *M*, shock absorber for half-expansion; *C*, opening for plug used as source of α-rays; *D*, Wilson chamber; *P*, supplementary chamber filled with same gas; *J*, vacuum chamber used to expand Wilson chamber; *G*, valve to control admission of gas and thermoelement of a coil of fine wire, used to determine temperature of chamber; *F*, lever used to control expansion of Wilson chamber.

than 200 kg. The Wilson chamber may be operated at gas pressures between 1000 and 40 mm of mercury. An important feature is that surge in the gas of the chamber is almost entirely eliminated by the use of metal and glass cylinders of the same diameter in the construction of the chamber.

The chamber is illuminated by a type of light not thus far used for this purpose. A 0.44 microfarad condenser at 30,000 volts is discharged through two Pyrex capillaries (Fig. 3) in series. These are filled with air at about 3 mm pressure. This type of discharge gives an intense

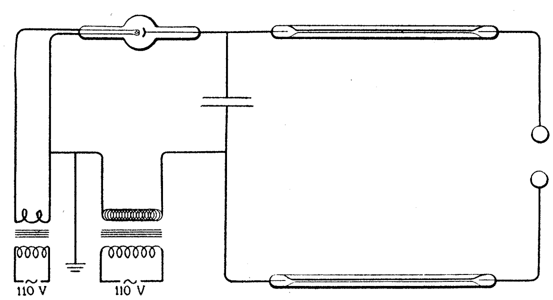

FIG. 3. Diagram of system for illumination of chamber.

continuous spectrum and has been used by Hopfield. However, considerable experimental work was done in order to produce the great increase in intensity needed to illuminate properly a Wilson chamber. This type of light, with sealed-in tungsten electrodes, is much better in many ways than those usually used with mercury to aid the discharge. One of these capillary lights is placed horizontally at each side of the chamber.

It was necessary to construct a device which would give a single discharge of the condensers through the lights at exactly the right moment. For this purpose a horizontal gap between two 8 cm steel spheres is closed by a heavy horizontal copper wire. This wire is fastened on the end of a long light insulating rod and rotates uniformly around a horizontal axis with a period equal to that of the chamber. The uniform rotation would give a discharge about two seconds after the completion of the expansion in the chambers. To reduce this to less than 1/100 second, a catch is released just before the piston reaches its lowest position. This allows a spring to act in such a way as to accelerate greatly the arm and to shoot the wire through the gap at such a high speed that an accurately timed single flash is produced. The other timing mechanisms of the chamber, such as the shutter for α-rays, are controlled by electromagnets.

4. SOURCE OF NEUTRONS

The neutrons were emitted from an intimate mixture of beryllium with a salt of either mesothorium, thorium X or radiothorium. These salts were used because the polonium source available was too weak for the purpose.

The initial velocities of the α-particles were thus, in units of 10^9 cm per second: 1.70, 1.94, 1.90, 1.97, 1.85 and 2.22, as compared with the value 1.68 for polonium. The use of such a composite source is not so disadvantageous as might appear at first sight, since with a single source, such as polonium, the initial velocity is in general decreased before the disintegration takes place, since the α-particle practically always passes through a considerable number of beryllium atoms before it hits a nucleus. The only disadvantage of such a source is that it gives a large number of γ-rays.

The dried radioactive salt and fine beryllium powder were ground into an intimate mixture in a small agate mortar. This mixture, in a very small flask about 7.0 mm in diameter, was put into a platinum vessel (Fig. 5, No. 12) with a wall 3.5 mm thick, which was inserted through a small opening in the top of the chamber. The platinum is used to absorb the softer γ-rays. If the platinum vessel is kept somewhat high the surge produced in the gas around it is not great enough to give any inaccuracy except very close to the platinum. It is obviously better to place the source entirely outside the chamber but the source available does not give enough α-particles to make this profitable.

5. Measurements and Calculations

According to the customary procedure, two photographs, nearly at right angles, are obtained for each disintegration and these are reprojected, according to a suggestion of Dr. A. v. Hippel, as applied by Curtis, by reprojecting the views in the same cameras in which they are taken. The cameras are fixed rigidly at the ends of a crossbeam of heavy channel iron which is attached at each end to a sturdy roller carriage which runs on a steel track. The camera system may be unclamped and rolled backward until it is in position for the reprojection upon an adjustable reprojection frame. This frame holds a tightly stretched sheet of onion skin paper and when the plane of this is properly adjusted, the two projections become practically identical. Then photographic paper is substituted and a photograph is taken from each camera. These two photographs thus obtained should be identical except that they may be optical images. The reprojection system was tested for accuracy by the use of fine lines ruled on aluminum, with a known angle between each pair of lines. The sheets of aluminum were photographed at various angles and positions in the chamber.

If ϕ is the angle which the track of the lighter disintegration particle makes with the invisible path of the neutron and θ the corresponding angle for the heavier particle, then only $\phi+\theta$ is directly obtainable from the projection. However, if momentum is to be conserved in the disintegration, then, $\sin\theta/\sin\phi = m_{\mathrm{He}}v_{\mathrm{He}}/m_{\mathrm{B}}v_{\mathrm{B}}$, in which m_{He} and v_{He} are the mass and the velocity of the lighter disintegration particle and m_{B} and v_{B}, of the heavier particle. Substituting this relationship in the trigonometric identity:

$$\tan\phi = \frac{\sin(\phi+\theta)}{\cos(\phi+\theta)+\sin\theta/\sin\phi}$$

we obtain:

$$\tan\phi = \frac{\sin(\phi+\theta)}{\cos(\phi+\theta)+m_{\mathrm{He}}v_{\mathrm{He}}/m_{\mathrm{B}}v_{\mathrm{B}}},$$

which enables us to calculate ϕ and θ and determine the path of the neutron, from a measurement of $\phi+\theta$ and of the ranges of the particles, which may be translated into velocities by means of range-velocity plots obtained as described by Feather.[4]

The values for the ranges (R), angles (ϕ and θ), velocities (v) kinetic energies (KE), decrease in kinetic energy ($-\Delta KE$) and decrease in total energy ($-\Delta E$), for the neutron (n), the helium nucleus (He) and the boron 11 nucleus (B), are given for 19 disintegrations by direct capture, and for nine in which the neutron was scattered in Table II.

In order to make the relations of Table II as simple as possible, the relativity corrections, which are in general smaller than the errors in the work, are not included. If this correction is introduced, the values for the velocity and energy of the neutron are decreased by 1.7 percent for event 13A, by 1.2 percent for 12A and by still smaller percentages in all other cases. The values for atoms heavier than the neutron are not appreciably affected. The correction for the velocity and energy is the same since the value of the momentum is not affected by the relativity correction for the velocity and mass of the neutron.

6. The Velocity Distribution of Neutrons from Be^9 which are Effective in the Disintegration of N^{14}

According to Section 2, the neutron which is initially present in Be_1^9 is emitted from an unstable C_1^{13} nucleus formed by the capture of an α-particle. During this process a γ-ray may be emitted (Bothe and Becker[1]).

A second paper for which the experimental work is already completed, gives the distribution

[4] Feather, Proc. Roy. Soc. **A136**, 709 (1932); Nature **130**, 273 (1932).

TABLE II. *Disintegration of nitrogen N^{14}.* The letters in column 1 have the following significance: A indicates that both photographs of the disintegration are excellent; B indicates satisfactory photographs; C indicates that both views are not visible over the whole range of both particles but the angle between the two is visible on both. A. *By capture of a neutron* designates those disintegrations for which the direction of the neutron, as calculated on the assumption of conservation of momentum, passes directly through the source. B. *Related to a scattered neutron* indicates that the direction of the neutron as thus calculated does not pass through the source. *The values given under B are not valid if the neutron is not captured.*

No.	R_{He} (mm)	R_B (mm)	ϕ	θ	v_{He} (cm per sec. $\times 10^{-9}$)	v_B	v_n	$KE\cdot$He (ergs $\times 10^6$)	$KE\cdot B$	$KE\cdot n$	$-\Delta KE$	$KE\cdot$He (electron-volts $\times 10^{-6}$)	$KE\cdot B$	$KE\cdot n$	$-\Delta KE$	$-\Delta E$
								A. By capture of a neutron								
1 A	8.47	1.55	53.2°	92.9°	0.848	0.247	1.89	2.37	0.55	2.96	0.03	1.49	0.35	1.86	0.02	1.42
2 A	5.02	1.34	61.4	65.2	0.623	0.219	2.19	1.28	0.44	3.99	2.28	0.80	0.27	2.51	1.43	2.83
3 A	9.38	2.21	72.6	68.4	0.895	0.334	2.41	2.64	1.01	4.81	1.16	1.66	0.64	3.03	0.73	2.13
4 A	14.17	1.82	45.5	97.1	1.084	0.283	2.64	3.88	0.73	5.79	1.19	2.44	0.46	3.64	0.75	2.15
5 A	10.25	3.42	111.0	40.0	0.936	0.494	2.81	2.89	2.22	6.53	1.43	1.82	1.39	4.11	0.90	2.30
6 A	10.53	3.49	108.9	40.6	0.950	0.502	2.95	2.98	2.29	7.20	1.94	1.87	1.44	4.53	1.22	2.62
7 A	17.00	4.25	112.3	40.7	1.170	0.603	3.23	4.52	3.30	8.68	0.87	2.84	2.08	5.46	0.54	1.94
8 A	7.94	3.97	143.3	18.3	0.819	0.566	3.27	2.21	2.91	8.86	3.74	1.39	1.83	5.57	2.35	3.75
9 A	12.10	4.35	133.9	25.5	1.011	0.617	3.30	3.37	3.46	9.06	2.23	2.12	2.17	5.69	1.40	2.80
10 A	11.70	4.89	145.8	17.2	0.997	0.688	3.90	3.28	4.30	12.69	5.11	2.06	2.70	7.98	3.21	4.61
11 A	14.40	2.48	56.7	63.9	1.091	0.369	4.15	3.93	1.24	14.28	9.12	2.47	0.78	8.98	5.73	7.13
12 A	24.10	5.66	116.8	33.8	1.340	0.781	4.70	5.92	5.54	18.30	6.84	3.72	3.48	11.50	4.30	5.70
13 A	13.36	5.41	115.4	27.3	1.058	0.757	5.55	3.69	5.20	25.60	16.70	2.32	3.27	16.09	10.50	11.90
14 B	8.04	1.21	42.4	90.4	0.824	0.202	2.41	2.24	0.37	4.80	2.19	1.41	0.23	3.02	1.38	2.78
15 B	10.17	3.27	100.3	44.7	0.932	0.474	3.02	2.87	2.04	7.58	2.68	1.80	1.28	4.77	1.68	3.08
16 B	7.08	3.54	121.2	27.9	0.766	0.509	3.34	1.94	2.27	9.27	5.07	1.22	1.43	5.83	3.18	4.58
17 B	8.49	3.54	103.7	36.1	0.849	0.509	3.70	2.38	2.27	11.35	6.71	1.50	1.43	7.14	4.22	5.62
18 C	10.60	0.78	20.6	123.4	0.952	0.146	2.66	2.99	0.19	5.89	2.70	1.88	0.12	3.70	1.70	3.10
19 C	16.70	1.00	16.6	136.4	1.162	0.175	3.04	4.45	0.28	7.68	2.94	2.78	0.18	4.82	1.85	3.25
								B. Related to a scattered neutron								
20	8.49	1.77	62.6	82.9	0.849	0.276	1.93	2.38	0.69	3.08	0.01	1.50	0.43	1.94	0.01	1.41
21	8.49	1.27	41.3	104.2	0.849	0.210	1.97	2.38	0.40	3.23	0.45	1.50	0.25	2.03	0.28	1.68
22	10.06	0.87	25.6	113.0	0.927	0.158	2.65	2.84	0.23	5.82	2.76	1.78	0.14	3.66	1.73	3.13
23	10.40	2.55	76.1	61.6	0.942	0.378	2.87	2.93	1.30	6.85	2.62	1.84	0.82	4.30	1.65	3.05
24	10.00	2.01	59.5	70.5	0.924	0.307	2.98	2.82	0.86	7.39	3.72	1.77	0.54	4.65	2.34	3.74
25	14.71	1.37	33.0	101.8	1.104	0.223	3.18	4.02	0.45	8.41	3.94	2.53	0.28	5.28	2.47	3.87
26	4.95	3.54	143.2	15.3	0.616	0.509	3.41	1.25	2.27	9.64	6.12	0.79	1.43	6.06	3.84	5.24
27	7.63	1.96	55.8	53.3	0.800	0.300	3.75	2.11	0.82	11.69	8.76	1.33	0.51	7.35	5.51	6.91
28	24.10	1.00	15.0	134.0	1.340	0.175	3.81	5.92	0.28	12.08	5.88	3.72	0.18	7.59	3.69	5.09

The mass 1.0067 used for the neutron in the calculation of this table is that determined by Chadwick, and may be too high.

of velocities for the neutrons emitted by a source which contains a mixture of beryllium powder with Ms Th or Th X or both. In this section there is exhibited the distribution of velocities for those neutrons which were found to disintegrate N_0^{14} atoms by capture in the reaction.

$$N_0^{14}+n_1^1 \rightarrow N_1^{15} \rightarrow B_1^{11}+He_0^4.$$

Table II gives the velocities of 19 such neutrons immediately before their capture, while Fig. 4 includes, in addition, values for 7 disintegrations found by Feather[4] and one by Meitner and Philipp.[5]

[5] Meitner and Philipp, Naturwiss. **20**, 929 (1932).

The distribution curve (Fig. 4) has a maximum at a velocity of about 3.23×10^9 cm/sec., which is almost exactly the maximum velocity found by Chadwick for neutrons from beryllium as emitted under bombardment by α-particles from polonium.

The distribution curve is found to be of somewhat the form of a Maxwell distribution curve. There is, thus far, no indication of resonance in the beryllium nucleus. The temperature equivalent to the distribution curve is about 4.6×10^{10} °K.

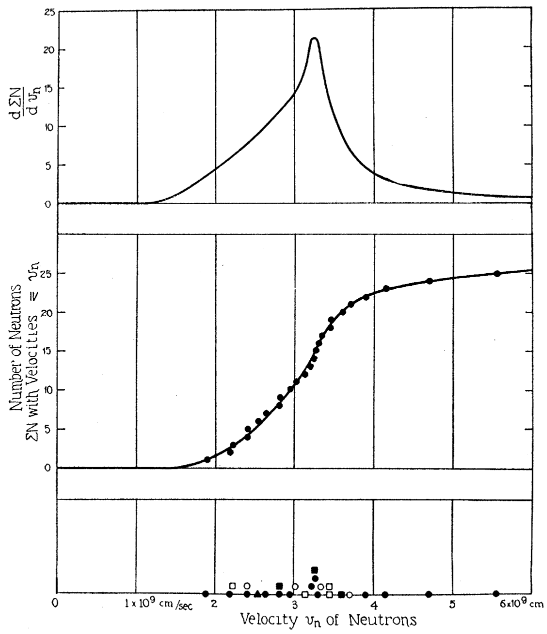

FIG. 4. Neutron velocities at impact for the disintegration of N^{14} by capture.

7. The Disintegration of Nitrogen Nuclei by Neutrons

Seven thousand six hundred pairs of photographs have now been taken in order to obtain a fairly accurate knowledge of the energy relations involved in the disintegration of nitrogen nuclei by neutrons. These have given 29 pairs of good photographs of such events, together with about 50 poorer photographs which have not been measured. On account of the ease of penetration of the neutron into the nucleus there seems to be no *a priori* reason, from this standpoint alone, to assume that low velocity neutrons should be ineffective but from the energy standpoint the higher velocities may be more effective.

The lowest velocity found by Feather for neutrons is 1.6×10^9 cm/sec. but, according to Meitner and Philipp, there are many low velocity neutrons ($KE=2.8\times10^5$ electron-volts, $v=0.62\times10^9$ cm/sec.) in the rays from Po-Be and if this is true such slow neutrons should not be absent in the experiments reported here, in which much faster α-particles have been used to produce the neutrons.

Our experiments on nitrogen, neon and carbon and those of Feather on oxygen, seem to indicate that the mean velocity of the neutrons which produce disintegration by capture, increases in the order of N_0^{14}, O_0^{16}, Ne_0^{20} and C_0^{12}. The energy needed to supply the (negative or positive) mass produced in the reaction increases in just this order.

It is not improbable that some neutrons may attach themselves to atomic nuclei without causing a disintegration. In such a case the isotopic number is increased by unity.

Fig. 5 shows two views, taken at an angle of 73.8°, for each of nine disintegrations by capture of the neutron and three in which the neutron was scattered either before or during the disintegration.

8. Disappearance of Kinetic Energy, Emission of γ-Rays and Possible Nuclear Energy Levels

The most interesting feature of the disintegrations by capture thus far obtained is that in every event *kinetic energy is conserved or else disappears*. This is also the general rule for what have been called non-capture events, provided these actually occur by capture.

The explanation of the above relation is very simple: kinetic energy is conserved if no γ-ray energy is emitted in the process, aside from that given by a loss of mass, while it disappears if it is transformed into γ-ray energy.

If, as Heisenberg and Bohr assume, neutrons are not subject to the conservation law, there is no apparent reason to assume that the kinetic energy should not, in some events, be increased. However, this does not seem to occur.

The reaction involved is

$$\underset{14.008}{N_0^{14}} + \underset{1.0067}{n_1^1} \rightarrow N_1^{15} \rightarrow \underset{11.0110}{B_1^{11}} + \underset{4.00216}{He_0^4}.$$

If the mass data were entirely accurate $-\Delta m$ would be 1.5×10^{-3} mass units, or 1.4×10^6 e.v., with a probable error greater than the whole of Δm.

The total energy $(-\Delta E)$ which disappears, and presumably appears as γ-ray energy, is given by the equation: $\Delta E=\Delta m+\Delta KE$.

The values of $-\Delta E$ are given in the lowest one-dimensional plot of Fig. 6. The inked-in circles represent better photographs than those given in outline. The middle plot gives a weight of 2 to

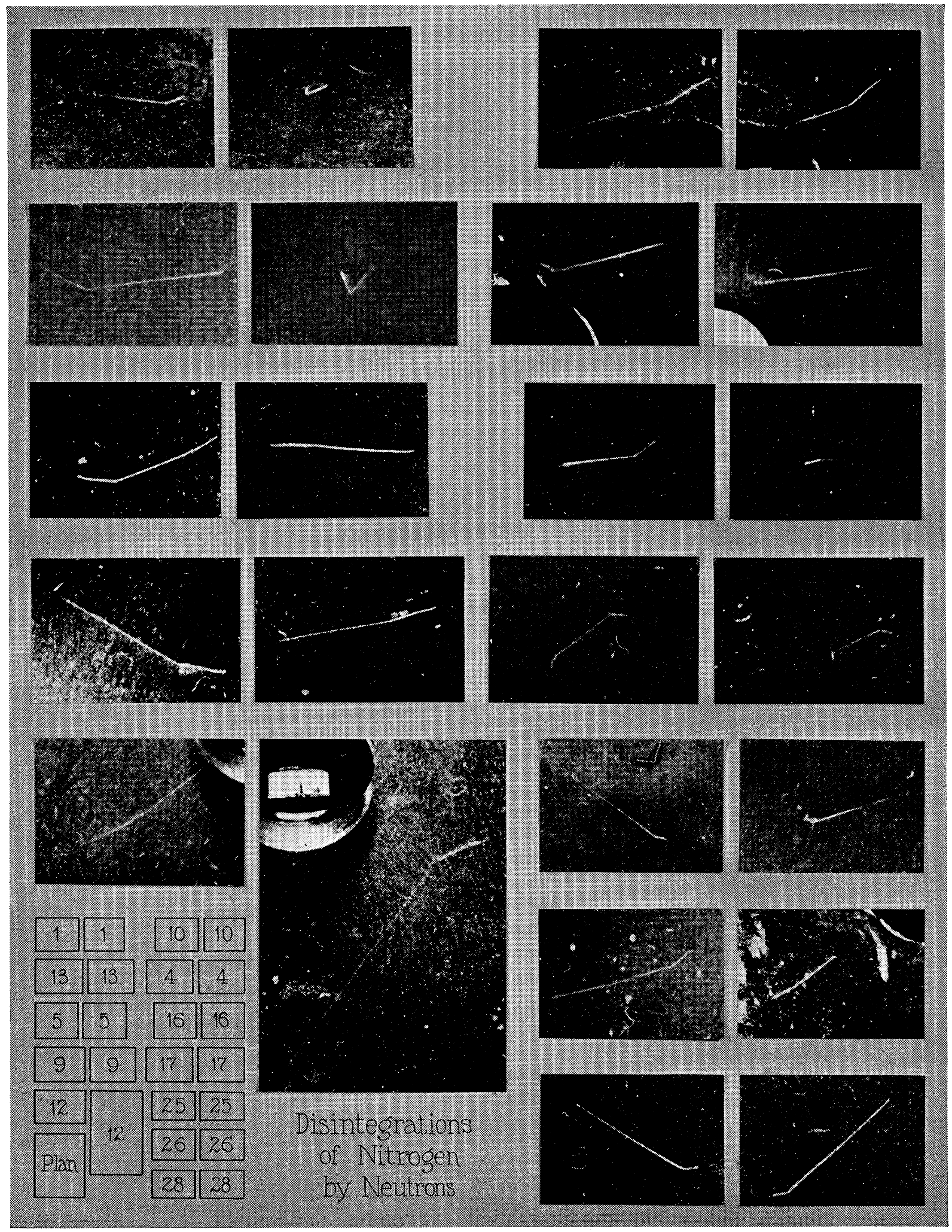

FIG. 5. Paired stereoscopic views of disintegration of nitrogen (by capture of neutron: 1, 13, 5, 9, 12, 10, 4, 16, 17: by scattered neutron: 25, 26, 28).

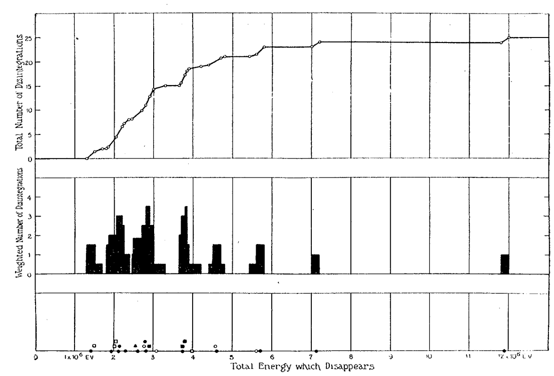

FIG. 6. Energy relations for disintegration of nitrogen nuclei by capture of a neutron.

each of the supposedly better values and of 1 to the others. The upper plot is the integral curve. It is not at all as smooth as the corresponding curve for the velocity of the neutrons.

The middle plot of this figure suggests the existence of energy levels at about 1.4, 2.1, 2.85, 3.85, 4.6 and 5.7×10^6 e.v. These values are all subject to correction by $\pm k$, or the error in Δm.

To prove definitely or disprove the existence of these levels will require more accurate work. It is proposed to make the following changes in later work, with a more powerful source of α-rays. (1) The greatest error is due to the shortness of the track of the heavier atom (B^{11}). This will be lengthened by operation at a lower pressure or by admixture of helium or hydrogen. This will also increase the accuracy of measurement of the track of the α-particle. (2) The source should be removed from the center to one side of the chamber in order not to interfere with the photography and also to give a greater mean length of track of the neutron prior to capture. A source of error lies in the fact that the range-velocity relations for B^{11} are not known but are calculated on the basis of an empirical relation suggested by Blackett. (3) The thickness of the glass top of the Wilson chamber will be reduced as much as possible in order to reduce the scattering of neutrons. The floor of the chamber has already been made as thin as possible.

9. Disintegration of Nitrogen as Related to Scattering of Neutrons

Nineteen pairs of photographs have been found to represent disintegrations by capture, while for nine disintegrations the neutrons appear to be scattered, either before or during the disintegration.

The important question arises: are these nine disintegrations produced by capture of neutrons which have been scattered by the glass top, the copper-brass bottom of the chamber or other parts of the apparatus?

The only argument against this point of view lies in the fact that about one-third of all the disintegrations are of this type, that is, there seem to be half as many scattered as non-scattered neutrons, in the chamber.

Whether this is possible cannot be told with certainty until the data on the scattering of neutrons by various types of solids are more complete.

If the neutron is not captured, then the reaction may be:

$$N^{14}\rightarrow B^{10}+He^4,\quad \Delta m=0.0077 \text{ mass units} \tag{1}$$

$$N^{14}\rightarrow C^{13}+H^1,\quad \Delta m=0.0038 \tag{2}$$

$$N^{14}\rightarrow C^{12}+H^2,\quad \Delta m=0.0091. \tag{3}$$

However, (2) and (3) are excluded, at least in almost all of these events, by the fact that the track of the light atom has too great a line density of ions to be due to hydrogen. Thus the line density was, in all cases, almost as great as for the heavy atom.

The mass increase in (1) is 0.0077, as given by Aston's data. This corresponds to a gain of energy of 7.1×10^6 electron-volts. Thus the neutron must lose $(7.1\pm4.4)\times10^6$ electron-volts. The error of 4.4×10^6 electron-volts included here is the arithmetical sum of all of Aston's estimated errors, which are not likely to be all in one direction, so that the probable error is less than this.

The energy which must be supplied lies between 6 and 8×10^6 electron-volts if Aston's data are as accurate as is assumed by Chadwick. In disintegrations of this type the kinetic energies of B^{10} and He^4 commonly amount to 1 to 3×10^6 electron-volts, so that, in all, about 9×10^6 electron-volts should be obtained from the loss of kinetic energy of the neutron. There is thus, at present, no good explanation from the energy standpoint as to how such disintegrations by non-capture are able to occur, particularly in the work of Feather, who used the comparatively slow α-particles from polonium, and thus obtained neutrons of maximum energy 8×10^6 electron-volts as determined from recoil atoms but found such fast neutrons to be extremely rare. The maximum value calculated from mass values $=12.3\times10^6$ e.v.

The energy relation becomes perfectly normal if it is assumed that all of these events are caused by neutrons scattered by the nuclei in the apparatus and that the disintegration occurs by capture. In Table II the calculations for events 20 to 28 are made on this basis. The velocities of the neutron at capture calculated on this basis are found to be in general rather lower than those disintegrations known to occur with capture (1 to 19) of a non-scattered neutron.

10. Experiments on the Disintegration of Carbon by Fast Neutrons

If carbon 12 is disintegrated by capture, the reaction is

$$C^{12} + n^1 \rightarrow C^{13} \rightarrow Be^9 + He^4$$
$$12.0036 + 1.0067 \rightarrow 9.0155 + 4.00216$$

or $\Delta m = 0.0074$, which is equivalent to 6.9×10^6 e.v.

This corresponds to a velocity for the neutron of 3.6×10^9 cm/sec., so only neutrons of velocities higher than this should be effective in disintegrating carbon 12. However, (Fig. 4) only a very small fraction (possibly 1/5) of the fast neutrons from our source have velocities greater than this.

From this point of view the number of disintegrations obtained with carbon should be small. The experimental result agrees with this conclusion.

If the Be^9 nucleus is formed in an excited state by the disintegration process, which would correspond with the usual expectation, then an even higher velocity, say greater than 3.9×10^9 cm/sec. would be essential.

From this point of view the number of disintegrations in carbon would be about one-seventh (or less) of the number in nitrogen.

The number of pairs of photographs taken with ethylene (C_2H_4) in the chamber is 3200. Two very good photographs of disintegrations were obtained but neither of these represents the capture of a neutron which comes directly from the source. With this number of photographs, nitrogen should have given about 13 disintegrations. Since, however, only two were obtained it will need additional work to prove definitely that these were not due to the oxygen of the water used in the apparatus.

11. The Disintegration of Neon

The reaction involved in the disintegration of Ne^{20} by capture is

$$Ne^{20} + n^1 \rightarrow Ne^{21} \rightarrow O^{17} + He^4$$

$$(19.9967 \pm 0.0009) + 1.0067$$
$$\rightarrow (17.0032 - E + 0.003) + (4.00216 \pm 0.0004)$$

in which E represents the energy emitted as γ-radiation in the formation of O^{17} from N^{14} and He^4.

Note added July 25, 1933

The first photographs in neon, with a weak source of neutrons, gave no disintegrations but a stronger source, as reported to the American Physical Society on June 23, gave 13 disintegrations of neon nuclei. The values for four of these are given in Table III.

Table III. *Energy values for the disintegration of Ne_0^{20} by capture of the neutron.*

	1	2	3	4
v neutron $\times10^{-9}$ cm per sec.	3.9	4.5	5.3	5.1
KE neutron $\times10^{-6}$ e.v.	7.8	10.6	14.5	13.4
$-KE\times10^{-6}$ e.v.	5.0	5.9	10.6	6.9
Energy of γ-ray $\times10^{-6}$ e.v.	3.1	4.0	8.7	5.0

The kinetic energy which disappears in the reaction varies from 5.0 to 10.6, and the energy of the γ-rays presumably emitted from 3.1 to 8.7, in millions of electron-volts, while about 2×10^6 e.v. of energy is converted into mass.

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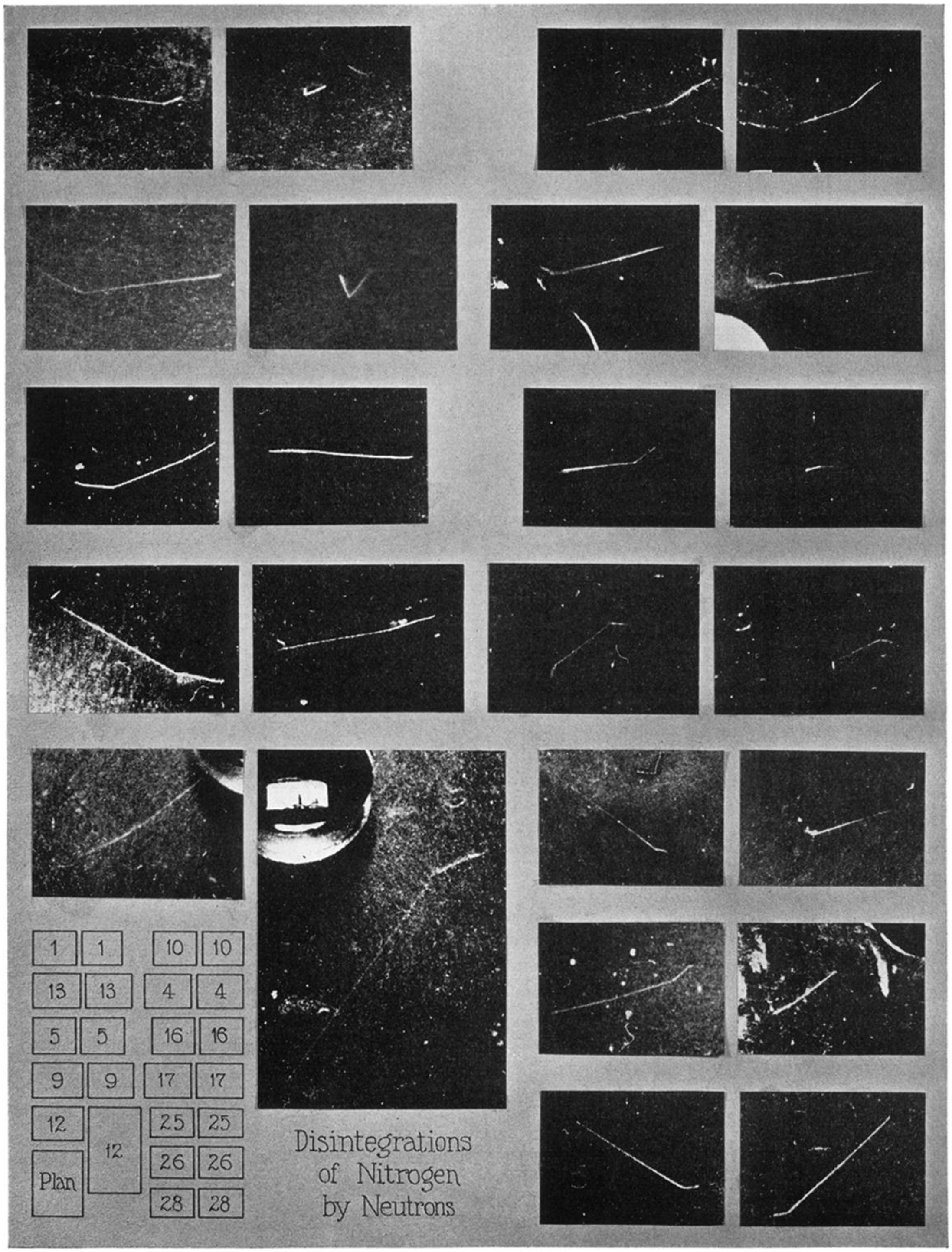

FIG. 5. Paired stereoscopic views of disintegration of nitrogen (by capture of neutron: 1, 13, 5, 9, 12, 10, 4, 16, 17: by scattered neutron: 25, 26, 28).