The Disintegration of Nitrogen by Neutrons

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Nitrogen disintegrations produced by neutrons have been observed in a cloud chamber filled with nitrogen at reduced pressures. All of the observed disintegrations are attributed to one of the following reactions:

$$_7N^{14}+{_0n^1}\rightarrow{_5B^{11}}+{_2He^4},\quad {_7N^{14}}+{_0n^1}\rightarrow{_7C^{14}}+{_1H^1},\quad {_7N^{14}}+{_0n^1}\rightarrow{_2He^4}+{_2He^4}+{_3Li^7}.$$

The first of these reactions is found to go for "slow neutrons" as well as fast ones. The value of the energy of disintegration for this reaction is 2.33 ± 0.26 MEV. For fast neutrons, the results are similar to those of Kurie, with nearly a constant amount of energy (3.1 MEV) appearing in the disintegration forks. The second and third reactions occur less frequently than the first one.

THE disintegration of nitrogen by fast neutrons was first observed by Feather.[1] He obtained photographs of forked tracks in a cloud chamber which was traversed by neutrons, and interpreted the two branches of the forks as tracks of the two disintegration products. Further experiments of this kind have been done by Harkins, Gans and Newson,[2] Meitner and Philipp[3] and by Kurie.[4]

Most of the nitrogen disintegrations were attributed to the reaction

$$_7N^{14}+{_0n^1}\rightarrow{_5B^{11}}+{_2He^4} \tag{1}$$

but some forks were observed where one of the disintegration particles seemed to be singly charged. The two possible reactions proposed to explain this type of fork were:

$$_7N^{14}+{_0n^1}\rightarrow{_6C^{13}}+{_1H^2}, \tag{2}$$

$$_7N^{14}+{_0n^1}\rightarrow{_6C^{14}}+{_1H^1}. \tag{3}$$

In the experiments described below we have shown that reaction (1) takes place for slow neutrons as well as for fast ones. A preliminary report of this work has been given in a Letter to the Editor.[5] We have also found that reaction (3) is responsible for some of the observed disintegration forks. One trident was observed, which we have attributed to the reaction

$$_7N^{14}+{_0n^1}\rightarrow{_2He^4}+{_2He^4}+{_3Li^7}. \tag{4}$$

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[1] N. Feather, Proc. Roy. Soc. **A136**, 709 (1932); **142**, 689 (1933).
[2] Harkins, Gans and Newson, Phys. Rev. **44**, 945 (1933).
[3] Meitner and Philipp, Naturwiss. **20**, 929 (1932); Zeits. f. Physik **87**, 484 (1933).
[4] F. N. D. Kurie, Phys. Rev. **45**, 904 (1934); **47**, 97 (1935).
[5] Bonner and Brubaker, Phys. Rev. **48**, 469 (1935).

EXPERIMENTAL PROCEDURE

In these experiments the Pyrex glass ring of the cloud chamber was replaced by a thin brass one, as the boron in the Pyrex absorbs slow neutrons strongly. The chamber was filled with nitrogen and saturated water vapor at reduced pressure. The calculated stopping power of the gas in the chamber (0.60) was checked by measuring the ranges of polonium alpha-particles. By comparing their mean lengths in the chamber to their known mean range of 3.805 cm at standard conditions, we experimentally determined the stopping power to be 0.592. Three stereoscopic images of the tracks were photographed through an f 3.5 lens; illumination was provided by a 2000-watt movie flood lamp. Examples of nitrogen disintegrations photographs are given in Figs. 1 and 2.

DISINTEGRATIONS BY SLOW NEUTRONS

From Bethe's[6] values of the masses, reaction (1) appears to be exothermic by 1.5 MEV, and hence should be expected to take place for slow neutrons in a manner similar to that of lithium and boron. In fact, Chadwick and Goldhaber[7] reported a small but definite increase in the number of counts from a nitrogen filled ionization chamber when the source of neutrons and the chamber were surrounded by paraffin.

If the disintegration is produced by a neutron with nearly zero energy, the $_5B^{11}$ and $_2He^4$ particles recoil in opposite directions and appear

[6] H. Bethe, Phys. Rev. **47**, 633 (1935).
[7] Chadwick and Goldhaber, Nature **135**, 65 (1935).

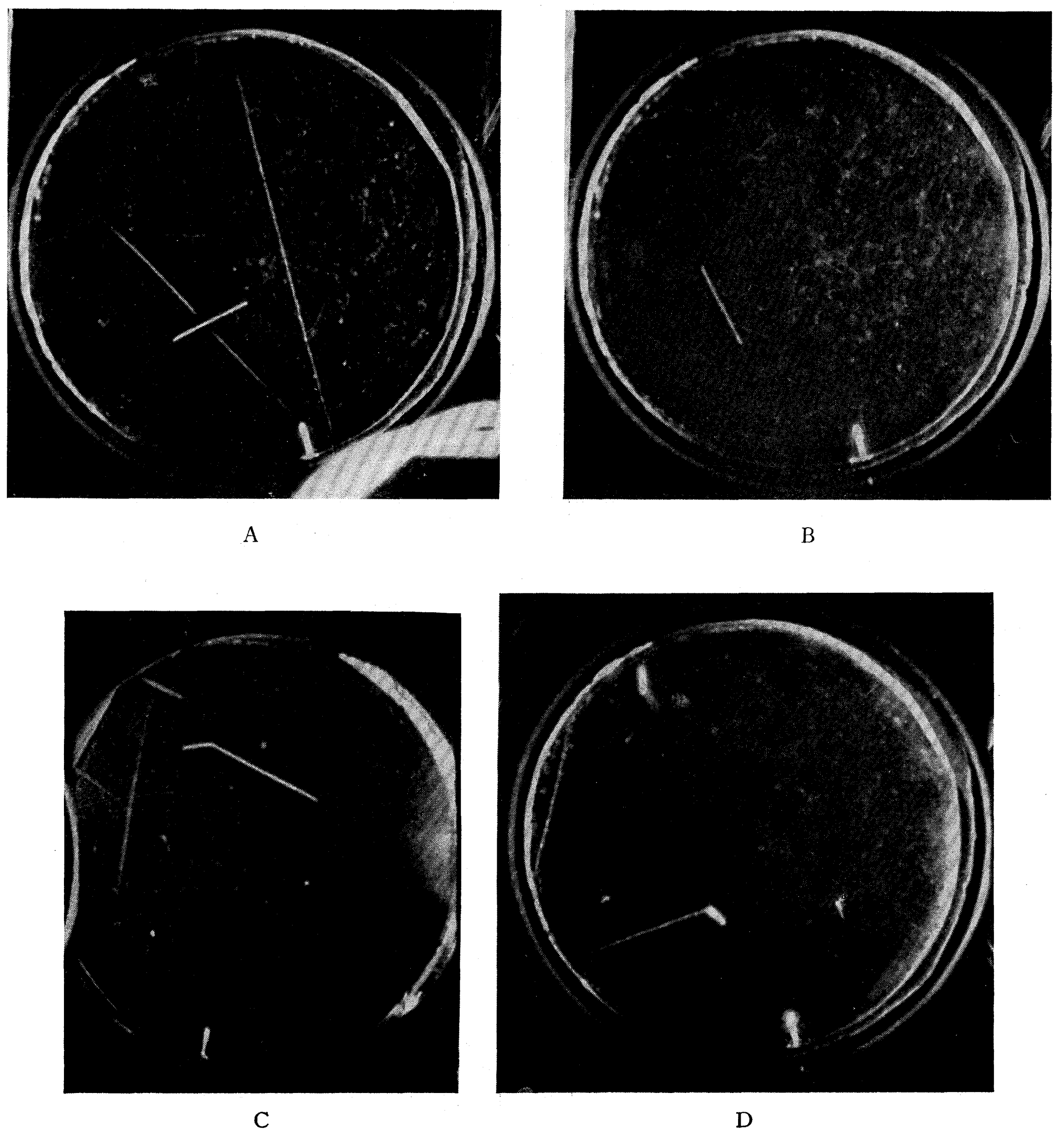

FIG. 1. A, B—The short straight tracks on both pictures are those of nitrogen disintegrations by slow neutrons. C, D—The disintegration fork on C is the ordinary type due to the reaction $N^{14}+n^1\rightarrow B^{11}+He^4$. The fork on D is due to the reaction $N^{14}+n^1\rightarrow C^{14}+H^1$.

as a single straight track in a cloud chamber. These tracks should all have the same length (neglecting straggling) as the energy contributed by the slow neutrons is negligible.

In our experiments we have used three different sources of neutrons: $Be+H^2+$paraffin, $Be+H^2$, and $Li+H^2$. In the first experiment a paraffin sphere with a radius of 7.5 cm surrounded the source and additional paraffin was placed around the chamber, so that a considerable number of slow neutrons were present. We have taken 9000 stereoscopic photographs of the chamber and on these have observed many straight tracks beginning and ending in the chamber, as well as several hundred forked nitrogen disintegration tracks. The range distribution of the straight tracks for the different neutron sources is given in Fig. 3. All tracks were measured regardless of their orientation in the chamber. Three different types of tracks are

A

B

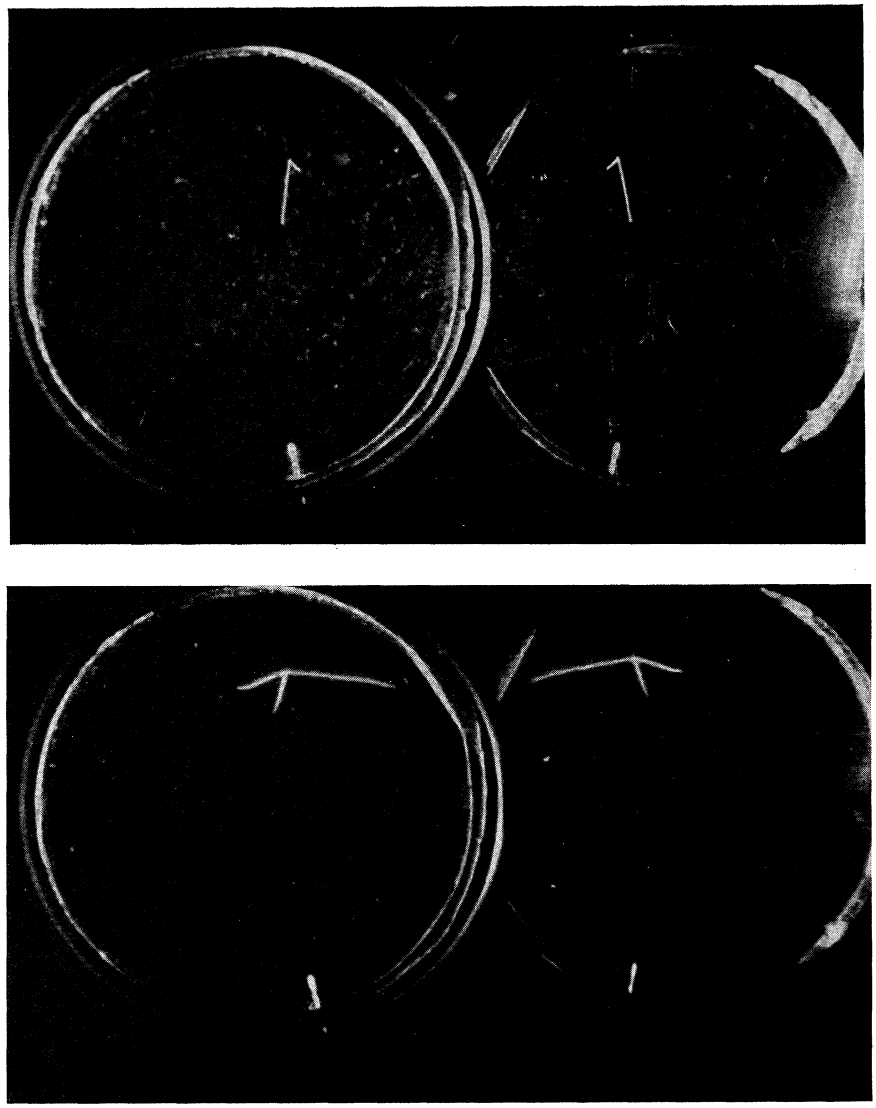

FIG. 2. A—A stereoscopic picture of a nitrogen disintegration where the measured ϕ was 51°. One of the particles must have been scattered in order for ϕ to appear so small. B—A disintegration of nitrogen into two alpha-particles and a Li^7 atom. This disintegration was produced by a 12.9 MEV neutron.

represented: those due to recoil protons, recoil nitrogen nuclei, and those due to the disintegration of nitrogen. The recoil protons result from the hydrogen in the water vapor. For all of the sources, the recoil protons will be responsible for a small number of tracks of all lengths in the interval measured. These will appear as a general background. The nitrogen recoils will be quite short, and their maximum range will depend on the maximum energy of the neutrons present. The neutrons from beryllium have a maximum energy of 4.42 MEV,[8] and should project nitrogen nuclei with a maximum range of 0.28 cm, which is in good agreement with the experiments. The neutrons from lithium have a maximum energy of 13.3 MEV,[9] and should project nitrogen nuclei with a maximum range of 0.51 cm. As only a small portion of the neutrons from lithium have

[8] Bonner and Brubaker, Phys. Rev. **47**, 910 (1935).
[9] Bonner and Brubaker, Phys. Rev. **48**, 742 (1935).

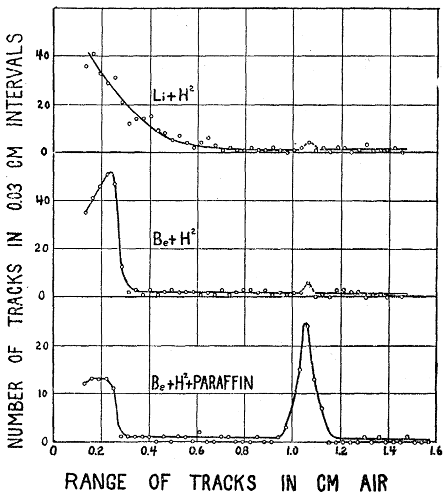

FIG. 3. Range distribution of the tracks in the nitrogen filled cloud chamber.

energies near the maximum, one can only estimate the maximum range of the recoil nitrogen nuclei; this estimate from the curve is consistent with the above-mentioned 0.51 cm.

The group of tracks with a mean range of 1.06±0.02 cm (15°C, 76 cm Hg) is due to the combined tracks of the alpha-particles and $_5B^{11}$ nuclei produced in the disintegration of nitrogen by slow neutrons. The curves show that very few tracks of this range were observed except when the neutrons were slowed down in the paraffin, indicating that very few (if any) "slow neutrons" are emitted from either of the sources.[10]

Table I gives the mean ranges, velocities, and energies of the $_5B^{11}$ and $_2He^4$ particles. We have used Bethe's range-velocity curve for alpha-particles.[11]

TABLE I.

NUCLEUS	RANGE	VELOCITY$\times 10^{-9}$	ENERGY IN MEV
$_5B^{11}$	0.22	0.329	0.62
$_2He^4$	0.84	0.907	1.71
	1.06		2.33

The range velocity curve for B^{11} has been computed from the nitrogen range velocity data[12] by means of Blackett's relation

$$R=k(M/Z^{\frac{1}{2}})f(v).$$

The probable experimental error of 0.02 cm in the determination of the range would introduce an error of 0.06 MEV in the energy. The probable error which is introduced by the inaccuracy of the range velocity curves for $_2He^4$ and $_5B^{11}$ particles of this energy is difficult to estimate, but perhaps is about 0.2 MEV.

Using the disintegration energy found in this experiment and Bethe's values for the masses of the other atoms appearing in reaction (1) we calculate the mass of $_7N^{14}$ to be 14.0085.

Nitrogen disintegrations of this type (with slow neutrons) are no doubt largely responsible for the nitrogen cross section of 11.3×10^{-24} sq. cm for slow neutrons as observed by Dunning, Pegram, Fink and Mitchell.[13] This is approximately 100 times as large as the cross section for disintegration by fast neutrons.

DISINTEGRATION BY FAST NEUTRONS

Several hundred disintegration forks similar to those shown in Fig. 1C were photographed on the films exposed in the experiments described above. From this number 91 forks could be accurately measured both in regard to the lengths of the tines and to the angle between them. Table II gives the results of such measurements. The measured lengths of the tracks were 1.69 times as long as the range because the stopping power was 0.592.

The proper disintegration energy, $(E_{He}+E_B-E_n/15)$, which we shall call E, is the disintegration energy which an observer at rest relative to the center of mass would measure. Fig. 4 gives the distribution of E. The maximum at 3.1 MEV is in agreement with the results of Kurie.[4] We have shown that the Q for slow neutrons is 2.06 MEV;[14] hence the most probable energy which the neutrons contribute is approximately 1 MEV. From the curve it is evident that very few neutrons contribute more than 2 MEV. However, from the calculated energies of the neutrons producing the disintegrations, we find that most of the disintegrations were

[10] This agrees with our previous results with indium (Phys. Rev. **48**, 470 (1935)) which indicated that there were no slow neutrons emitted by a $Li+H^2$ source.

[11] We wish to thank Professor Bethe for communication of the values used in Table I which are based on his new range velocity curve for low energy alpha-particles.

[12] P. M. S. Blackett, Proc. Roy. Soc. **A135**, 132 (1932).

[13] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **48**, 265 (1935).

[14] We obtained this lower value of Q by using the range-velocity curve for alpha-particles which was used in computing alpha-particle energies in Table II.

TABLE II. *Data on nitrogen disintegration forks.* R_{He} = range alpha-particles; R_B = range ${}_5B^{11}$ particles; E_{He} = energy of alpha-particles in MEV;** E_B = energy of ${}_5B^{11}$ particles in MEV; ϕ = angle between two tines; E_n = calculated energy of neutron in MEV.

R_{He}	R_B	E_{He}	E_B	ϕ	E_n	$E_{He}+E_B$	$E_{He}+E_B-E_n/15$
			NEUTRON SOURCE: $Be+{}_1H^2$				
0.53	0.35	0.86	1.52	173	4.9	2.38	2.08
0.95	0.36	1.72	1.56	155	4.4	3.28	2.99
0.83	0.19	1.47	0.50	51*	18.4*	1.97	—
0.94	0.37	1.70	1.66	155	4.8	3.36	3.06
1.16	0.13	2.11	0.26	146	3.1	2.37	2.07
0.81	0.30	1.43	1.11	153	3.0	2.54	2.34
1.47	0.20	2.64	0.53	149	2.9	3.17	2.98
0.82	0.39	1.45	1.82	154	6.4	3.27	2.97
0.91	0.30	1.64	1.15	148	3.6	2.79	2.55
1.81	0.18	3.14	0.48	150	3.8	3.62	3.37
0.93	0.22	1.68	0.65	148	2.1	2.33	2.19
1.08	0.12	1.96	0.22	143	3.3	2.18	1.96
1.78	0.17	3.10	0.39	141	5.3	3.49	3.19
1.25	0.23	2.28	0.71	146	2.9	2.99	2.80
1.48	0.34	2.65	1.44	142	5.9	4.09	3.79
0.53	0.29	0.86	1.07	133	6.5	1.93	1.63
1.35	0.13	2.45	0.26	145	4.0	2.71	2.44
1.23	0.33	2.24	1.36	148	4.1	3.60	3.32
2.12	0.24	3.61	0.77	142	5.5	4.38	4.08
2.22	0.23	3.72	0.68	135	7.5	4.40	4.10
0.96	0.13	1.74	0.26	156	1.7	2.00	1.89
1.11	0.30	2.02	1.15	144	4.2	3.17	2.89
2.13	0.24	3.61	0.74	146	4.6	4.35	4.05
0.90	0.33	1.62	1.36	150	4.2	2.98	2.70
1.07	0.38	1.95	1.77	152	4.4	3.72	3.43
1.83	0.14	3.19	0.28	175	3.3	3.37	3.15
0.90	0.18	1.62	0.45	160	0.8	2.07	2.02
1.78	0.17	3.10	0.42	140	5.5	3.52	3.22
1.26	0.21	2.30	0.62	145	3.0	2.92	2.72
1.54	0.21	2.75	0.62	143	3.9	3.37	3.11
2.48	0.14	4.01	0.30	143	7.7	4.31	4.01
1.41	0.40	2.55	1.93	150	5.8	4.48	4.18
0.83	0.46	1.47	2.48	162	8.9	3.95	3.65
1.64	0.23	2.90	0.68	130	7.1	3.58	3.28
0.95	0.40	1.72	1.93	149	7.2	3.65	3.35
1.41	0.29	2.55	1.07	138	5.6	3.62	3.32
1.12	0.30	2.04	1.11	130	7.6	3.15	2.85
2.17	0.14	3.66	0.28	146	6.6	3.94	3.64
0.83	0.43	1.47	2.14	175	6.3	3.61	3.31
0.68	0.17	1.16	0.39	130	3.3	1.55	1.33
1.19	0.17	2.16	0.39	173	0.8	2.55	2.50
1.00	0.36	1.83	1.56	142	6.8	3.38	3.08
1.64	0.12	2.90	0.24	140	5.9	3.14	2.84
1.58	0.23	2.81	0.71	148	3.2	3.52	3.30
1.17	0.35	2.13	1.48	145	5.6	3.61	3.31
1.60	0.09	2.84	0.13	138	6.5	2.97	2.67
			NEUTRON SOURCE: $Be+{}_1H^2$				
1.54	0.30	2.75	1.15	143	4.8	3.90	3.60
2.12	0.25	3.57	0.83	141	5.7	4.40	4.10
1.08	0.23	1.96	0.68	148	2.4	2.64	2.48
0.84	0.41	1.49	1.98	161	6.2	3.47	3.17
1.46	0.38	2.63	1.77	146	6.1	4.40	4.10
0.87	0.44	1.55	2.24	163	7.4	3.79	3.49
1.14	0.46	2.07	2.48	165	6.6	4.55	4.25
1.96	0.23	3.36	0.71	144	4.7	4.07	3.77
1.11	0.43	2.02	2.19	158	6.3	4.21	3.91
			NEUTRON SOURCE: $Li+{}_1H^2$				
1.42	0.40	2.56	1.87	133	11.3	4.43	3.67
0.83	0.37	1.47	1.61	162	4.4	3.08	2.79
0.43	0.38	0.66	1.77	156	8.7	2.43	1.85
1.13	0.27	2.06	0.95	144	3.6	3.01	2.77
1.19	0.20	2.16	0.53	128	5.8	2.69	2.31
1.01	0.34	1.84	1.44	154	3.7	3.28	3.04
1.19	0.16	2.16	0.36	148	2.7	2.52	2.34
1.17	0.50	2.13	2.87	136	16.5	5.00	4.10
1.44	0.37	2.60	1.66	157	3.3	4.26	4.04
1.28	0.49	2.33	2.74	158	8.7	5.07	4.49
0.98	0.57	1.78	3.45	136	21.8	5.23	4.33
2.25	0.23	3.75	0.68	137	7.1	4.43	3.95
1.00	0.43	1.82	2.16	136	12.3	3.98	3.16
0.63	0.47	1.06	2.61	130	18.5	3.67	2.77
1.05	0.17	1.91	0.42	156	1.5	2.33	2.23
1.05	0.29	1.91	1.07	140	4.8	2.98	2.66
0.87	0.35	1.55	1.48	157	4.1	3.03	2.75
0.69	0.40	1.18	1.87	141	10.3	3.05	2.36
0.63	0.28	1.06	1.03	147	3.7	2.09	1.85
1.31	0.56	2.39	3.40	172	9.5	5.79	5.16
0.77	0.43	1.35	2.19	168	7.2	3.54	3.06
1.57	0.24	2.80	0.74	136	5.6	3.54	3.16
1.41	0.17	2.55	0.39	141	4.1	2.94	2.66
0.94	0.12	1.70	0.22	137	3.3	1.92	1.72
2.13	0.34	3.58	1.44	147	4.9	5.02	4.70
0.83	0.38	1.47	1.77	139	8.9	3.24	2.65
0.59	0.30	0.98	1.11	142	5.2	2.09	1.75
1.53	0.64	2.74	4.13	168	13.0	6.87	6.00
0.94	0.12	1.70	0.22	143	2.7	1.92	1.74
0.81	0.40	1.43	1.93	175	4.7	3.36	3.05
0.84	0.40	1.49	1.89	149	7.7	3.38	2.86
0.41	0.42	0.62	2.09	163	11.1	2.71	1.97
0.71	0.59	1.22	3.68	156	19.8	4.90	4.00
2.55	0.17	4.10	0.39	167	4.4	4.49	4.20
0.46	0.33	0.72	1.36	148	6.4	2.08	1.66

* One of the particles must have been scattered.
** We used the Cavendish Laboratory range-velocity curve for alpha-particles in these computations since Bethe's new curve which was used in the last section was not available.

caused by neutrons with energies above 2 MEV.[15] Thus we find that some kinetic energy disappears. This is in agreement with the work of all the others[1–4] who have studied this reaction. To account for this lost energy, Kurie has proposed the emission of a gamma-ray in a radiative capture of the neutron. Feather has suggested that this energy goes into the excitation of the ${}_5B^{11}$ nucleus.

Before trying to decide this question let us first consider how accurately we can calculate both the energy appearing in the forks and the energy of the neutron producing the disintegration. The energies of the ${}_5B^{11}$ and ${}_2He^4$ particles will include errors due to three causes: (1) experimental errors in measurement of track lengths; (2) errors due to straggling in ranges of tracks with equal energies and (3) errors in the range-velocity curves for the particles. All three of these possible errors are more important for

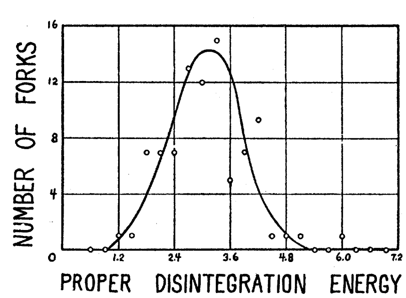

FIG. 4. The distribution of the proper energies ($E_{He}+E_B-E_n/15$) in MEV of the nitrogen disintegration forks.

[15] This is consistent with an average neutron energy of 3.5 MEV for $Be+H^2$ and 3.9 MEV for $Li+H^2$, and a cross section for disintegration which varies only slowly with energy.

the shorter range $_5B^{11}$ tracks than for the $_2He^4$ tracks, and so when the amount of energy appearing in the $_5B^{11}$ particles is relatively large, the uncertainty in the proper energy is also large. For example, in the case where $E_{He}=3.72$ MEV, $E_B=0.68$ MEV and $E_{He}+E_B=4.40$ MEV, the probable error is only about 0.2 or 0.3 MEV, but in the case where $E_{He}=1.78$ MEV, $E_B=3.45$ and $E_{He}+E_B=5.23$ MEV, the probable error is of the order of 1 MEV.

The calculated energies of the neutrons are affected by the errors listed above as well as any error in the determination of ϕ. Errors in the determination of ϕ are due both to experimental errors in measuring the angle between the tines and to errors introduced when one of the particles is scattered through a small angle at a point so near the point of disintegration that it is unobservable. An example of this sort is given in the fork of Fig. 2A, where the angle ϕ was measured to be 51°, but from momentum considerations it must have been at least 134°. The neutron energy calculated from this fork was 18.6 MEV, which obviously was in error as there were no neutrons present with energies over 4.5 MEV. A check on the accuracy with which neutron energies can be calculated is obtained by knowing that the maximum energy of the neutrons from beryllium and lithium are 4.42 and 13.3 MEV, respectively. Quite a number of the calculated energies of the neutrons from beryllium were 2 or 3 MEV too high. This shows that an accurate determination of the neutron energy cannot be made from such disintegration data. However, it can be determined well enough to show that, with the lithium source, a considerable fraction of the disintegrations are produced by neutrons with energy above 8 MEV. In these cases, the disappearance of kinetic energy cannot be questioned.

An explanation of the distribution of E can be made by assuming that the excess energy which is carried into the reaction by the neutron goes into the excitation of the B^{11} nucleus. Cockcroft and Walton[16] have shown that B^{11} has excitation levels at 2.2, 4.5, and 6.8 MEV. These with perhaps a higher level, can account for the observed distribution if we assume that the boron nucleus is excited to the highest state possible, consistent with the alpha-particle having enough energy (>1.5 MEV) to get through the barrier of the N^{15}. This interpretation is clearly very artificial and unconvincing.

An alternative explanation of the distribution of proper energies has been proposed by Kurie, according to which the neutron is first captured by a radiative transition to a virtual level of N^{15}. This level corresponds to an energy greater by 1 MEV than that of $N^{14}+n^1$ and greater by about 3.1 MEV than $B^{11}+He^4$; the N^{15} is not stable and disintegrates into $B^{11}+He^4$. That part of the breadth of the energy distribution which is not conditioned by experimental errors in the determination of E, may be reasonably attributed to the short life of the N^{15}. This explanation is quite consistent with our results, and has only theoretical arguments against it. No reasonable model can be constructed for which the radiation emitted from the recoiling N^{14} is of the right order of magnitude to explain the observed cross sections for the process; on this theoretical basis a cross section of 1/1000 of that observed would have to be regarded as exceptionally large.[17]

The disintegrations by slow neutrons, which are presumably not of a radiative character, present no difficulties in interpretation, and are in fact analogous to those of lithium and boron by slow neutrons. The fairly large cross section observed for this process may here too be ascribed to the proximity of a virtual level of N^{15}.

Other Modes of Disintegration

Feather[1] and Kurie[4] reported another mode of disintegration in which one of the disintegration particles was singly charged. They suggested that these disintegrations took place according to reaction (2) or (3). With both the $Be+{_1H^2}$ and the $Li+{_1H^2}$ sources of neutrons we have observed forks of this type, an example of which is given in Fig. 1D. The data on the forks of this type, which were observed when the beryllium source was used, are given in Table III.

[16] J. D. Cockcroft, London Conference Report, 1934.

[17] Dr. Robert Serber has looked into this question theoretically, and we are indebted to him for telling us of his results. One essential reason for the small theoretically predicted cross sections is the impossibility, with any reasonable model, of having approximate resonance with a virtual level of N^{15} for the neutron, both before and after radiation.

TABLE III. *Ranges and energies of particles.*

Range Singly Charged Particle	Range Heavy Particle	Energies of Particles of These Ranges E_{H^1}	E_{H^2}	$E_{C^{13}}$	$E_{C^{14}}$	$E_{H^2}+E_{C^{13}}$	$E_{H^1}+E_{C^{14}}$
Neutron Source: $Be+{}_1H^2$							
2.42 cm	0.12 cm	1.04	1.4	0.2	0.3	1.6	1.3
>1.8	0.32	>0.87	>1.1	1.3	1.4	>2.4	>2.3
>3.4	0.20	>1.28	>1.6	0.6	0.6	>2.2	>1.9
>2.1	0.22	>0.95	>1.2	0.7	0.7	>1.9	>1.7
1.30	0.11	0.68	0.8	0.2	0.2	1.0	0.9
2.26	0.09	1.00	1.3	0.2	0.2	1.5	1.2
>1.4	0.18	>0.73	>0.8	0.5	0.5	>1.3	>1.2
0.25	0.35	0.26	0.2	1.6	1.7	1.8	2.0

From these data we cannot determine the maximum energy which appears in such forks, but we can say that at least 2 MEV appears when neutrons with energies up to 4.42 MEV are used. According to calculations from Bethe's masses, reaction (2) is endothermic by 4.7 MEV. Thus we must turn to reaction (3) to explain the singly charged particles.

$$ {}_7N^{14}+{}_0n^1\rightarrow{}_6C^{14}+{}_1H^1. \quad (3)$$

The C^{14} would probably be radioactive, going into N^{14} with the emission of an electron. However, such a radioactive C^{14} has not been observed. The upper limit of the mass of C^{14}, assuming that 2.0 MEV of energy appears in reaction (3) when 4.42 MEV neutrons are used, is 2.8 MEV more than that of N^{14}. Thus the maximum energy of the beta-particles from C^{14} is less than 2.8 MEV.

We have found one trident which we have attributed to the disintegration of nitrogen according to reaction (4). Fig. 2B shows a stereoscopic pair of photographs of the single disintegration of this type which we observed when we bombarded nitrogen with the high energy neutrons from $Li+H^2$. The energy appearing in the three forks is 4.8 MEV and the calculated energy of the neutron which produced the disintegration is 12.9 MEV. From a calculation of the masses involved, this reaction is endothermic by 7.0 MEV, which is consistent with the observed data.

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The Energy Distribution of Neutrons Slowed by Elastic Impacts

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The problem of finding the distribution in energy of particles of mass m, initially of the same energy, which have made n impacts with particles of mass M all initially at rest, is solved. It is supposed the impacts are elastic and the distribution in angle isotropic in a coordinate system in which the center of mass is at rest. If x is the ratio of the energy after n impacts to the initial energy then the chance that x lie in dx at x is $(\log 1/x)^{n-1}/(n-1)!$ for $m=M$. For unequal masses the expression is more complicated but easy to calculate. The results have some interest in connection with the slowing of neutrons by elastic impacts with other nuclei, especially with hydrogen nuclei.

In this note we work out the energy distribution of neutrons which, starting with the same initial energy, have made n impacts with other nuclei all initially at rest. We suppose the impacts are elastic and the scattering isotropic in a coordinate system in which the center of mass is at rest. The result is of some interest in connection with current researches on "slow" neutrons. The work grew out of a desire to understand a statement due to Fermi[1] that "It is easily shown that an impact of a neutron against a proton reduces, on the average, the neutron energy by a factor $1/e$."

Let the nuclei of the medium be all at rest and of mass M while the incident neutron is of mass m and energy, E_0. Then by a simple application of the conservation laws it is found that the neutron energy after an impact is given by $E_1=E_0(1-\alpha x)$

where $\alpha=4mM/(m+M)^2$ and $\cos\varphi=1-2x$, φ being the angle of scattering of the neutron in

[1] Amaldi, D'Agostino, Fermi, Pontecorvo, Rasetti and Segrè, Proc. Roy. Soc. **A149**, 522 (1935). See p. 524.

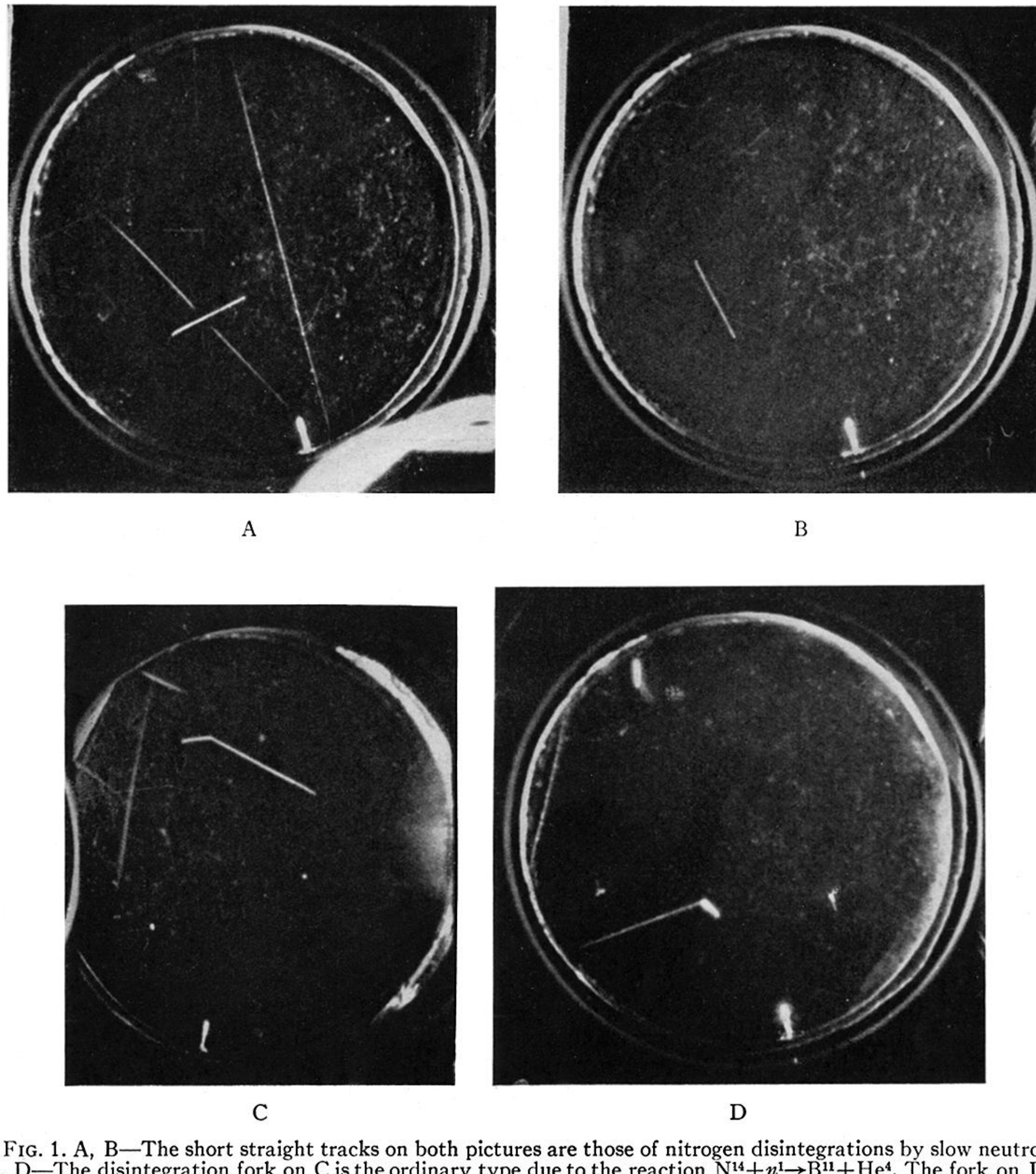
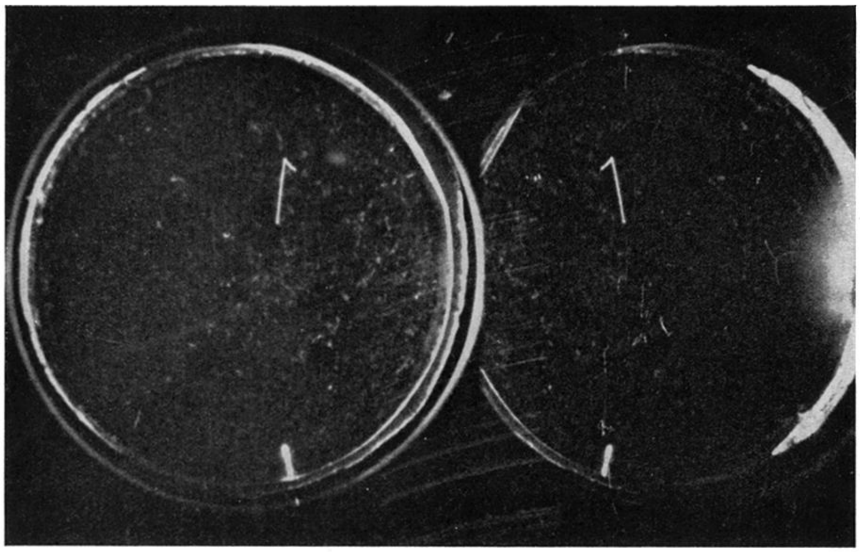


FIG. 1. A, B—The short straight tracks on both pictures are those of nitrogen disintegrations by slow neutrons. C, D—The disintegration fork on C is the ordinary type due to the reaction $N^{14}+n^1 \rightarrow B^{11}+He^4$. The fork on D is due to the reaction $N^{14}+n^1 \rightarrow C^{14}+H^1$.

A



B

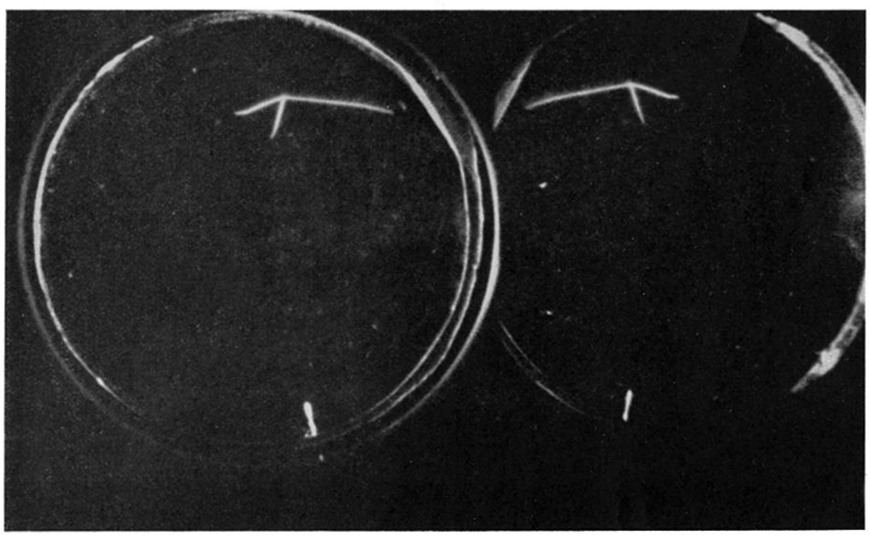


FIG. 2. A—A stereoscopic picture of a nitrogen disintegration where the measured ϕ was 51°. One of the particles must have been scattered in order for ϕ to appear so small. B—A disintegration of nitrogen into two alpha-particles and a Li^7 atom. This disintegration was produced by a 12.9 MEV neutron.