PHYSICAL REVIEW VOLUME 67, NUMBERS 5 AND 6 MARCH 1 AND 15, 1945

Heavy Particle Groups From the Neutron Disintegrations of Nitrogen and Neon†

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(Received November 29, 1944)

Studies of the $_7N^{14}$ (n, α) $_5B^{11}$ reaction by the method of Wilhelmy seem to indicate the emission of heavy particle groups from nitrogen as a result of resonance transmutation by fast neutrons from a Ra+Be source. The total energy of the alpha-particle plus recoil nuclei lies at 1.33, 1.64, 1.94, 2.15, 2.64, 2.98, 3.82, 4.14, and 4.48 Mev. The data are in good agreement with those of other experimenters and it appears unlikely that the maxima in the distribution curve are caused by statistical fluctuations, but are intimately connected with nuclear transformations. Neon yields three alpha-particle groups at 0.85, 1.05, and 1.68 Mev in the energy range 0.25–2.5 Mev by a similar study. It appears probable that the reaction $_{10}Ne^{20}$ (n, α) $_8O^{17}$ is responsible for the 1.68-Mev group. The association of these groups with the intermediate nuclei Ne^{21} or Ne^{23} is not unique as long as it is not clear which excited states of the end nuclei can occur, and as long as accurate mass values of all the nuclei involved in these reactions are not known. Hydrogen gave a smooth distribution curve, as was expected.

I. INTRODUCTION

THE study of neutron disintegrations of nuclei with the emission of heavy particles is expected to yield data necessary for the development of an adequate theory of nuclear structure. There are several experimental methods which can be used for this purpose, among these being a promising method first proposed and tried by Wilhelmy.[1] This method consists of an ionization chamber coupled to a linear amplifier and recording oscillograph. The dimensions of the ionization chamber must be large enough to utilize the full range of the heavy particles resulting from the transformation. By means of this method, large amounts of statistical data can be collected and, even without direct knowledge of the actual neutron energies of individual processes, keys to transformations can be obtained.

Nuclear transformations by resonance penetration of the nuclear potential barrier by means of charged particles of discrete energies[2] have been known for some time. Prior to the work of Wilhelmy, resonances with fast neutrons had not been observed because of the difficulty of obtaining a homogeneous, step-wise source of fast neutrons. Wilhelmy, however, used a continuous source of fast neutrons and was able to obtain these resonances in the case of (n, α) and (n, p) processes.

In Wilhelmy's method, neutrons from a continuous source irradiate the target gas in the ionization chamber. If discrete groups are emitted, the energy distribution of the resulting particles, when measured, shows peaks. There is evidence that such emission resonance correlates with a penetration resonance of the neutrons,[3] and the energy of the incident neutron can be calculated from the energy balance of the reaction. With each resonance, there occurs an excited state of the intermediate nucleus, the energy of which can be measured.

II. FUNDAMENTAL ASSUMPTION

The range of nuclear particles is a function of the charge, gas pressure, and initial energy, whereas the total number of ions formed is only a function of the initial energy. Thus the average energy of ion pair formation in a given gas is nearly independent of the kind of ionizing particles and, approximately, of their velocities.

III. PURPOSE OF EXPERIMENTS

A. Nitrogen

Heretofore, the disintegration of nitrogen by neutrons has been studied from two points of

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[1] E. Wilhelmy, Zeits. f. Physik **107**, 769 (1937).
[2] For example, see the work of W. Maurer, Zeits. f. Physik **107**, 721 (1937).
[3] W. Maurer, Zeits. f. Physik **107**, 721 (1937).

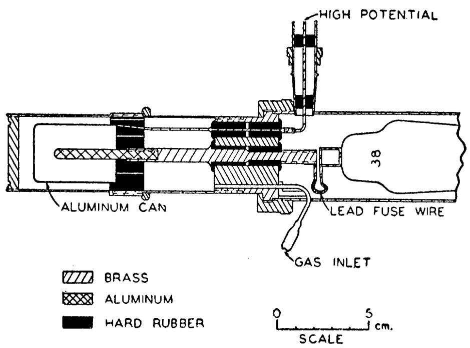

FIG. 1. Ionization chamber.

view: (1) reaction energies and kind of emitted particles; and (2) number, energy, and types of groups.

With respect to the second, Wilhelmy[1] has shown the existence of five energetically distinct groups. He used both Po+Be and Rn+Be neutron sources and apparently detected the alpha-particle groups from the reaction ${}_7N^{14}$ (n, α) ${}_5B^{11}$.

Comparat and Thibaud[4] using Rn+Be neutrons, repeated the work using greater resolving power, and made measurements at energies below the range of Wilhelmy's observations. Their statistics, however, are poor, leaving their data open to some question. Hansen,[5] in studying the range-velocity relation for boron, also investigated the reaction ${}_7N^{14}$ (n, α) ${}_5B^{11}$ with D+Be neutrons. In the overlapping energy region, their results are substantially in agreement.

Hansen questions whether the maxima he observed have physical meaning or are caused by statistical fluctuations. As a check, he applied the χ^2 test and found "that if the points were represented by the smooth curve, then the chance that the deviations were as large as those observed was about 3 in 10." He concludes that this does not prove that the smooth curves are not the best representations of the points. Hansen points out that although it is unlikely that an event which has 3 changes in 10 of happening should happen in six consecutive runs, a possible interpretation might be that all six runs are equally bad.

As a result of these data there was some doubt as to the reality of the groups, and the nitrogen work was repeated by a similar method, but with a 200 mC Ra+Be neutron source.

B. Neon

The disintegration of neon by neutrons has been studied by Jaeckel,[6] and Harkins, Gans, and Newson[7] with a cloud chamber and by Gailer,[8] using the method of Wilhelmy.[1] Jaeckel observed only 34 neon disintegration tracks in the Wilson chamber, with only one observed disintegration ascribed to the ${}_{10}Ne^{22}$ (n, α) ${}_8O^{19}$ process. The other tracks were ascribed to the ${}_{10}Ne^{20}$ (n, α) ${}_8O^{17}$ reaction, as were the eleven forks observed by Harkins, *et al.* Gailer observed five groups which he ascribed to alpha particles.

The statistics of the cloud chamber data are few and the results indicate (1) no proton reactions, and (2) no mutually consistent values of the energy of reaction of the transformation.

The five groups observed by Gailer in the 1–6 Mev energy region are produced by alpha-particles because protons of about 2 Mev, or greater, had too great a range to yield their total energy in his chamber and so produced no sharp maxima. At most, the first maximum, i.e., the 1.76 Mev group, if considered as a proton group, is in

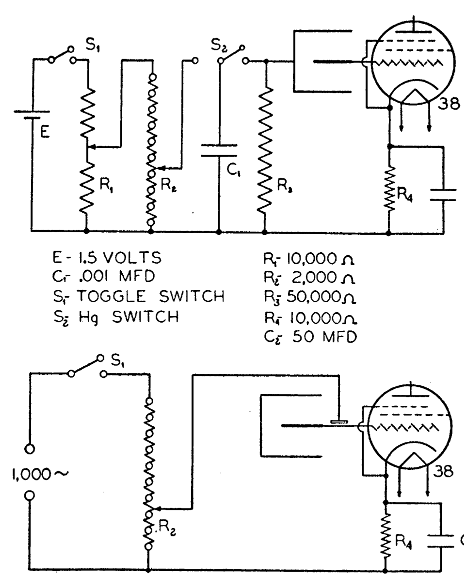

FIG. 2. Pulse generators for testing linearity of amplifier.

[4] P. Comparat and J. Thibaud, J. de phys. et rad. [7] 10, 161 (1939).
[5] W. Hansen, Ph.D. Thesis, Yale University (1941).
[6] R. Jaeckel, Zeits. f. Physik 96, 151 (1935).
[7] W. Harkins, D. Gans, and H. Newson, Phys. Rev. 47, 52 (1935).
[8] K. Gailer, Zeits. f. Physik 110, 605 (1938).

question. But, as Gailer states, this is highly improbable because no protons have been observed in the previous Wilson chamber experiments on neon.[6,7]

In view of this, it was thought desirable to repeat the work on neon in the 1–2.5 Mev energy region with Wilhelmy's method in order to check and clarify the work of the others, and to attempt to observe additional groups, if any.

IV. APPARATUS

The neutron source was a 200 mC radium bromide plus powdered beryllium mixture contained in a brass cylinder 2 cm in diameter and 4 cm high. A lead jacket 0.5 cm thick was placed around the brass cylinder to absorb the soft gamma-rays. The source and lead jacket were put in a cylindrical lead bucket of 5 cm wall thickness, and in addition, a lead block 5 cm thick was always kept between the source and ionization chamber. Thus there was always 10.5 cm of lead between the source and ionization chamber for the absorption of the gamma-rays.

The ionization chamber had the form of concentric cylinders, as shown in Fig. 1. The outer cylinder was an aluminum can which formerly had contained 35 mm film, the inner electrode was an aluminum rod, and both electrodes were inserted in a cylindrical block of hard rubber. This combination was encased in a brass tube which was screwed to a brass housing in which the first amplifying tube was placed. The tube and the housing were separated by a brass plug through which the insulated electrodes and gas inlet tube passed. The gas inlet tube had a needle valve and pressure gauge attached.

TABLE I. Comparison of proton recoil counts obtained with working chamber and calibration chamber.

Chamber 1	Chamber 2
2652 counts/5 minutes	2650 counts/5 minutes
2711	2600
2630	2686
2601	2643
2600	2700
2638	2636
2696	2621
2677	2634
2619	2676
2690	2642
2627	2691
2670	2603
31,811 Total	31,982 Total

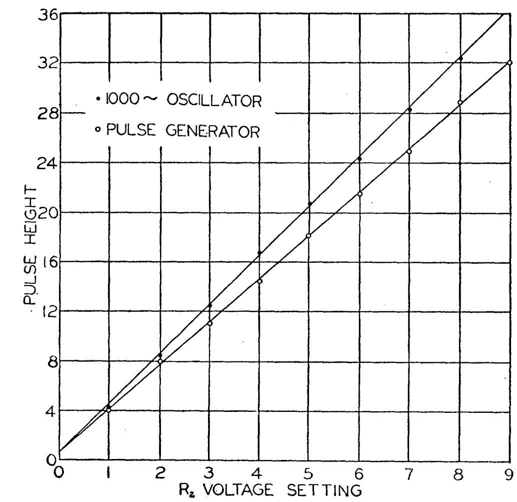

FIG. 3. Graph of oscilloscope pulse height against gang switch setting $R2$.

The experiments were performed with 2100 volts on the positive electrode of the ionization chamber. This high voltage was supplied by a separate power pack—a half-wave rectifier of conventional design.

A negative feed-back linear amplifier, developed by Waddel[9] was used. The Waddel circuit was modified slightly in the first amplification stage by (1) the introduction of degenerative feed-back and (2) having the control grid tied to ground by a 106,700 megohm resistor.

The recording by an oscillograph was made upon a continuously moving film. A Sept f:3.5 lens with Super XX 35 mm film was found satisfactory in conjunction with a Pl screen in a DuMont type 164 oscilloscope. The films were projected on a screen which had a fixed scale and counted visually. Electrical counting by means of photo-cell, biased thyratron, and scaling circuit was first tried, but was unsuccessful because the film density of the tracks was not uniform and the photo-cell circuit could only be adjusted for one particular film contrast at a time. In addition, pulses very close together could not be resolved and were recorded as a single count.

As it is important that the amplifier be linear, the response of the amplifier was tested by means of the pulse generators shown in Fig. 2. In the upper circuit of Fig. 2, condenser C_1 is charged

[9] R. Waddel, Rev. Sci. Inst. 10, 311 (1939).

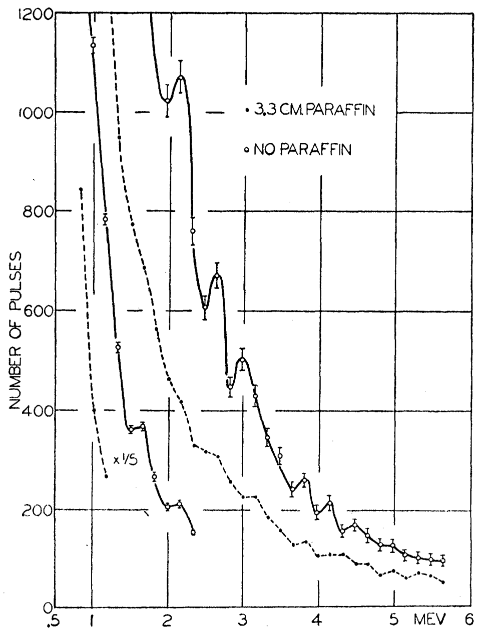

FIG. 4. Upper curve is a plot of number of pulses against E_{a+B} for ${}_7N^{14}$ (n, a) ${}_5B^{11}$ reaction. Dotted lower curve is plot of number of pulses against pulse size, with 3.3 cm paraffin between source and detector. Nitrogen pressure is 336 cm Hg.

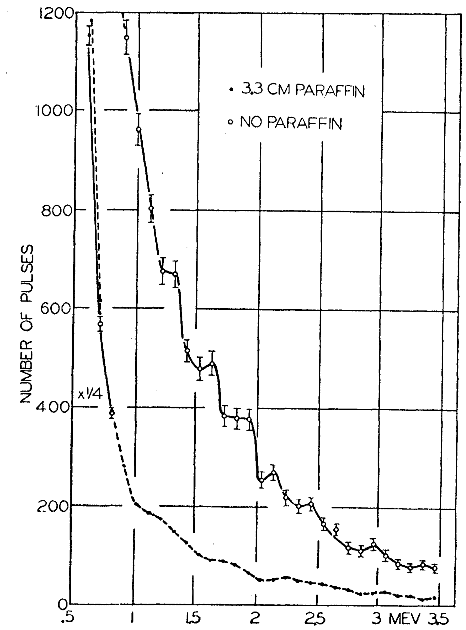

FIG. 5. Upper curve is a plot of number of pulses against E_{a+B} for the ${}_7N^{14}$ $(n, a)_5$ B^{11} reaction. Dotted lower curve is plot of number of pulses against pulse size, with 3.3 cm of paraffin between source and detector. Nitrogen pressure is 76 cm Hg.

by battery E through potential divider R_1 and gang switch R_2, and then discharged through resistor R_3. Gang switch R_2 had 10 arms, each of which consisted of a 200 ohm resistor. The voltage across C is thus a linear function of gang switch setting R_2. In the lower circuit of Fig. 2, sinusoidal oscillations from a 1000 cycle tuning fork oscillator were fed through gang switch R_2 to the grid of the ionization chamber by means of capacity coupling. Figure 3 shows the plot of oscilloscope pulse height against gang switch setting R_2, and it is seen that the circuit response is linear in both cases.

For the purpose of determining the size of oscilloscopic pulses in terms of Mev, pulses from the monoenergetic Po alpha-particles were used, the Po being placed inside the chamber. To prevent contamination of the ionization chamber, two identical ionization chambers were built and used. One of them, the calibration chamber, contained the weak Po alpha-source, while the other did not, the latter being used as the working chamber.

That both ionization chambers were identical was shown in the following way. Both chambers were filled with hydrogen to 273 cm Hg pressure. Under identical geometry, each chamber in turn was subjected to the source, and the proton recoils counted at five minute intervals. The number of counts obtained with each chamber is shown in Table I and it is seen that the total number of counts agree to within 0.95 percent.

Microphonic response to acoustical noise or vibration was minimized by (1) coupling the ionization chamber to the grid of the first amplifying tube with lead fuse wire; (2) connecting the ionization chamber and vacuum tube housing for the first amplifying stage rigidly together; and (3) clamping this entire assemblage rigidly to supporting iron rods which rested on sponge rubber placed on a concrete floor. In addition, the first amplifying tube was wrapped in cotton and fitted snugly in the vacuum tube housing.

The microphonic response to acoustical noise was so small that it permitted use of the apparatus during the passing of classes. It was also observed that clapping one's hands close to the ionization chamber, or stamping heavily on the floor near the ionization chamber, did not cause any increase in noise amplitude beyond the residual amplifier noise.

V. RESULTS

A. Nitrogen as Detector

Several reactions of the disintegration of the nitrogen nucleus with the emission of heavy particles are known.

The reaction (1) $_7N^{14}$ (n, a) $_5B^{11}$ yields a negative reaction energy Q of 0.25 Mev.[10] Burcham and Goldhaber,[11] have shown experimentally that this reaction cannot take place with slow neutrons.

The reaction (2) $_7N^{14}$ (n, p) $_6C^{14}$ yields a positive Q, and has been observed for fast neutrons by Kurie[12] and Bonner and Brubaker,[13] and for slow neutrons, by Bonner and Brubaker[13] and Burcham and Goldhaber.[11]

The reaction (3) $_7N^{14}$ $(n, 2a)$ $_3Li^7$ has been observed by Bonner and Brubaker[13] with very fast neutrons.

Also the reaction (4) $_7N^{14}$ (n, d) $_6C^{13}$ is energetically possible, according to Bonner and Brubaker.[13]

Tank nitrogen of purity 99.7 percent, or better, was used. With the source used, one would expect only reactions (1) and (2) to occur in any appreciable abundance.[14] The upper curve in Fig. 4 shows the result of a plot of the sum of the energies of disintegration products of nitrogen against number of associated oscillographic kicks. The curve shows several principal maxima at the energies 1.68, 2.15, 2.64, 2.98, 3.82, 4.14, and 4.48 Mev. The nitrogen pressure in the ionization chamber was 336 cm Hg.[15]

TABLE II. Comparison of maxima from $_7N^{14}$ (n, a) $_5B^{11}$ at 336 cm Hg and 76 cm Hg (Mev).

336 cm Hg	76 cm Hg	336 cm Hg. B_4C absorber
	1.33	1.25
1.68	1.64	1.68
	1.94	
2.15	2.15	2.15
2.64	2.46	2.64
2.98	2.96	2.98
3.82		
4.14		
4.48		

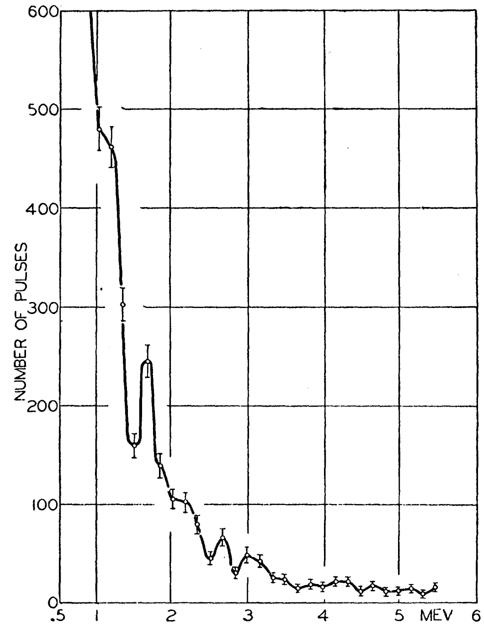

FIG. 6. B_4C absorber between source and chamber. Nitrogen pressure is 336 cm Hg.

The question then arises as to whether the observed heavy particle groups are proton groups or alpha-particle groups. To bring about a clear cut decision, the following series of experiments were performed.

First, a 3.3 cm paraffin plug was interposed between source and detector to slow down the impinging neutrons. Under these conditions, one expects proton reaction (2) to dominate. Hence if any of the groups were caused by protons, they should be enhanced, whereas the groups caused by alpha-particles should disappear. The dotted lower curve in Fig. 4 shows the result that none of the groups shows any enhancement, but, on the contrary, all the groups show a general disappearance.

If disintegrations occur in the gas of an ionization chamber, the number of disintegration particles may follow one or more courses. If the

[10] This value of Q (0.25 Mev) is calculated from the mass values of O. Hahn, S. Flügge, and J. Mattauch, Physik. Zeits. **41**, 1 (1940).

[11] Burcham and Goldhaber, Proc. Camb. Phil. Soc. **32**, 632 (1936).

[12] F. Kurie, Phys. Rev. **45**, 904 (1934); **47**, 97 (1935).

[13] T. Bonner and W. Brubaker, Phys. Rev. **49**, 223 (1936).

[14] N^{15} has a concentration of 0.3 percent and so can be neglected.

[15] The background averaged about one count per minute and showed a random distribution. It was thus neglected in the calculations.

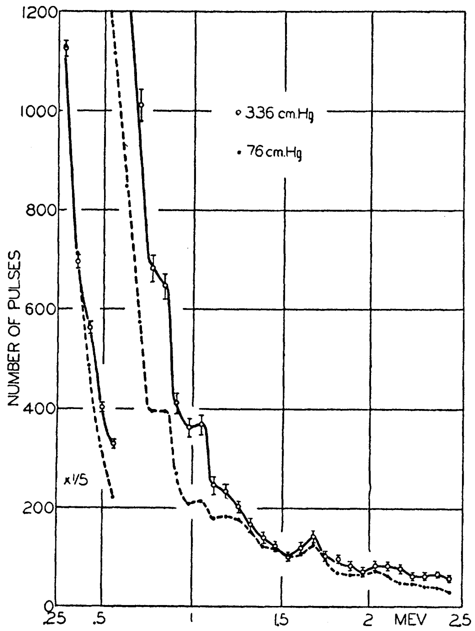

FIG. 7. The upper curve is a plot of number of pulses against pulse size. Neon pressure is 336 cm Hg. The lower dotted curve is a plot of number of pulses against pulse size with neon at a pressure of 76 cm Hg.

ranges of the disintegration particles are small compared with the dimensions of the ionization chamber, most of the particles will expend their total energy in the effective collecting volume, and, consequently, the edge effect will be small or negligible. On the other hand, if the ranges are about equal to or greater than the chamber dimensions, many will strike the walls with attendant reduction in the number of ion pairs formed. If now the pressure in the ionization chamber is lowered to the extent that the range corresponding to a definite group becomes comparable with the chamber dimensions, then this group tends to fade completely out of recognition. This is so because the specific ionization-range curve shows a maximum very nearly at the end of the range of the particles and this important portion vanishes in the case considered. At a given pressure, this fading out of groups occurs for protons rather than alpha-particles of equal energy because protons have the longer range.

The maximum depth of the ionization chamber is 4.3 cm. The stopping power of nitrogen is 0.99[16] that of air and thus the effective chamber depth with nitrogen becomes 4.2 cm. This value of range corresponds to a 1.45 Mev proton.[17] On the assumption that the highest energy group detected, the 4.48 Mev group, is an alpha-group, its range in nitrogen at 76 cm Hg is only 3 cm.[17] Thus if the pressure is lowered from 336 cm Hg to 76 cm Hg, all observed groups remain if they consist of alpha-particles, whereas all groups having an energy in excess of 1.45 Mev fade out if they consist of protons.

The result of such a study is shown in the upper curve of Fig. 5. Numerous maxima appear and the comparison of maxima at 336 cm Hg and 76 cm Hg, listed in Table II, shows good agreement. The reason more groups appear in the 0.5–3.5 Mev energy region at 76 cm Hg than in the corresponding energy region at 336 cm Hg is because of the difference in resolving power in the two cases. The resolving power at 76 cm Hg is 101,600 volts, whereas the resolving power of 336 cm Hg is 164,600 volts.

The experiment was repeated at 76 cm Hg with the 3.3 cm paraffin plug interposed between source and chamber. Under these conditions, the proton reaction should dominate. If all the groups previously detected were proton groups, only the 1.33 Mev group could be detected now, as its range alone in nitrogen (3.63 cm)[17] is less than the chamber dimensions. Thus the distribution should now show a group at 1.33 Mev, with the remainder of the curve smooth. One should also observe this same distribution if the 1.33 Mev group was caused by protons and the remaining groups caused by alpha-particles or by a mixture of alpha-groups and proton groups. If the 1.33 Mev group is caused by alpha-particles, however, the distribution should now be completely smooth.

The result is shown in the lower curve of Fig. 5 and the distribution is seen to be completely smooth.

A boron absorber (B_4C of boron thickness 0.56 g/cm^2) was placed next between source and detector to permit transmission only of the fast neutrons, and the distribution measured at a pressure of 336 cm Hg. The distribution is shown in Fig. 6 and it is seen that groups appear at 1.25,

[16] J. Hoag, *Electron and Nuclear Physics* (Van Nostrand Company, Inc., New York, 1938), p. 463.

[17] M. Livingston and H. Bethe, Rev. Mod. Phys. 9, 268 (1937).

1.68, 2.15, 2.64, and 2.98 Mev. Table II shows the comparison of maxima from nitrogen both with and without the boron absorber. The 1.25 Mev group very probably corresponds to the 1.33 Mev group observed at 76 cm Hg, while the remaining groups are in exact coincidence with previously observed groups at 336 cm Hg pressure.

From the above results it appears that the groups observed are affected by fast neutrons and are alpha-particle groups arising from the reaction $_7N^{14}$ (n, α) $_5B^{11}$.

This agrees with the work of Baldinger and Huber[18] who have shown that for neutron energies of 2.8 Mev, the (n, α) reaction has a capture cross section four times that of the (n, p) reaction.

B. Neon as Detector

Neon has three stable isotopes: $_{10}Ne^{20}$, $_{10}Ne^{21}$, $_{10}Ne^{22}$, which are found in an abundance percentages of 90, 0.27 and 9.73 respectively. One can discard $_{10}Ne^{21}$ from consideration and therefore only the following neutron heavy particle reactions need be considered: (1) $_{10}Ne^{20}$ (n, α) $_8O^{17}$, (2) $_{10}Ne^{22}$ (n, α) $_8O^{19}$, (3) $_{10}Ne^{20}$ (n, p) $_9F^{20}$, and (4) $_{10}Ne^{22}$ (n, p) $_9F^{22}$.

Up to the present, the oxygen, fluorine, and neon masses reported as having been measured accurately[10] are O^{16}, O^{17}, O^{18}, Ne^{20}, Ne^{21}, Ne^{22}, F^{19}. Thus only the energy of reaction Q for Eq. (1) can be calculated, and hence one cannot predict accurately what reactions are possible with the available neutron source. In order to analyze the reactions which are detected, indirect methods must be tried. Reaction (4) is very improbable because it yields an isotope which is three mass units higher than the heaviest naturally occurring fluorine isotope, F^{19}. Reactions (1), (2), and (3) may very well occur, especially (1) as its Q calculated[10] equals—0.43 Mev.

The first observation was made at a chamber pressure of 336 cm Hg. The energy of the recoil nucleus plus the associated heavy particle was plotted against number of transformations and the plot is shown in the upper curve in Fig. 7. Maxima appear at 0.85, 1.05, and 1.68 Mev.

To try to determine whether the groups are caused by alpha-particles or protons, the pressure in the chamber was reduced to 76 cm Hg and the experiment repeated. The stopping power of neon, relative to air, in the energy range under observation is 0.57.[19] Thus the effective depth of the chamber is $4.3 \times 0.57 = 2.45$ cm of air.[20] This corresponds to a proton energy of 1.02 Mev.[17] Thus with 76 cm Hg pressure of neon in the chamber, all proton groups of energy greater than 1 Mev should fade out, whereas the 0.85 Mev group, if it consists of protons, should diminish considerably because of the edge effect.

However, if the groups are caused by alpha-particles they should still show up after the pressure in the chamber has been lowered to 76 cm Hg. To show this, assume the 1.68 Mev group, the highest neon energy group detected, to consist of alpha-particles. Its range would be 0.9 cm,[17] whereas the effective depth of the chamber is 2.45 cm, or nearly three times as long.

The results at 76 cm Hg are shown in the lower curve of Fig. 7. This curve is nearly identical with the curve at 336 cm Hg and the observed groups are alpha-particle groups. The neon data are shown in Table III.

The 1.68 alpha-group can be compared with the 1.7 Mev alpha-group found by Gailer,[8] the 1.6 Mev alpha-group from $_{10}Ne^{21}$ reported by Murrell and Smith,[21] and the 1.75 Mev alpha-group found by Pollard and Watson[22] from $_{10}Ne^{21}$.

It thus appears likely that the reaction $_{10}Ne^{20}$ (n, α) $_8O^{17}$ is responsible for the 1.68 Mev alpha group observed here. The Q calculated for this reaction equals minus 0.43 Mev and hence is a fast neutron reaction. This fits in very well with the observed data.

The cloud chamber experiment of Jaeckel[6] and

TABLE III. Results of neon experiments, groups detected.

336 cm Hg	76 cm Hg
0.85	0.85
1.05	1.05
1.68	1.68

[18] E. Baldinger and P. Huber, Helv. Phys. Acta **12**, 330 (1939).

[19] Rutherford, Chadwick, and Ellis, *Radiations from Radioactive Substances* (Cambridge University Press, London, 1930), p. 97.

[20] Maximum chamber depth = 4.3 cm.

[21] Murrell and Smith, Proc. Roy. Soc. **173**, 410 (1939).

[22] E. Pollard and W. Watson, Phys. Rev. **58**, 16 (1940).

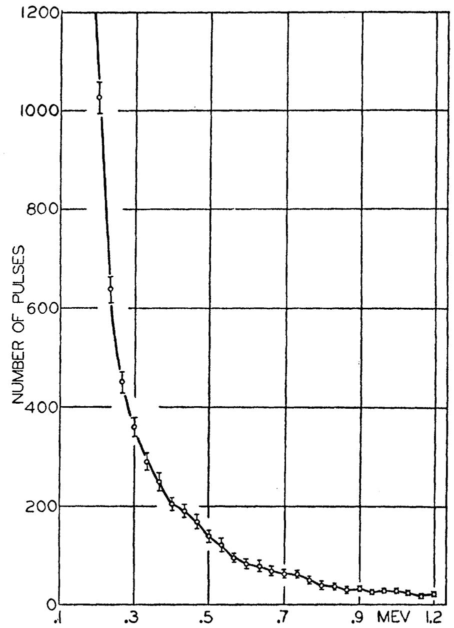

FIG. 8. Recoil proton distribution with hydrogen. Hydrogen pressure is 338 cm Hg.

Harkins, *et al.*,[7] have not led to mutually consistent values of the total energy of reaction of the transformation. This means that the end nucleus originating from the intermediate nucleus, does not always return to the same excited state or ground state, but exists in various excited states. In this case there belongs to a definite state of the intermediate nucleus several energy groups of heavy particles which differ by the energy difference of the energies of the excited state of the end nucleus.

Thus the assignment of groups with the excited states of the intermediate nucleus, $_{10}Ne^{21}$ or perhaps $_{10}Ne^{23}$, is not unique as long as it is not clear which excited states of the end nucleus can occur.

C. Hydrogen as Detector

At a test to show that the detected groups were not caused by instrumentation, the chamber was filled with hydrogen to 338 cg Hg and the distribution measured. Groups are not expected from hydrogen, and the distribution should be smooth. Figure 8 shows the result of such an investigation, and the graph is seen to be smooth without trace of maxima or minima.

VI. THEORY

The details of the processes observed here can be considered best on basis of the Bohr conception of the course of nuclear reactions. In point of time, such reactions proceed in two steps.

First, the particle is captured and its energy distributed among the number of nuclear constituents. Thus there arises an excited intermediate nucleus, the lifetime of which is finite, i.e., greater than the time required by the particle to cross the nucleus.

Secondly, these excited intermediate nuclei can go to the ground state by gamma emission, or the entire excitation energy, or an essential part thereof, can be concentrated on a particular particle so that it may acquire sufficient energy to leave the nucleus.

On account of the long lifetime of the intermediate nucleus, its excitation states are fairly sharp. Thus the reaction occurs with appreciable probability only for certain well-defined energy ranges of the incident neutrons.

The different observed resonance groups of a nucleus may correspond either to the different excitation states of the intermediate nucleus, or the different excitation states of the transformed, end nucleus. The first will be assumed, and the calculations made on the basis of the end nucleus being in the ground state. This assumption, which will be discussed later, permits the determination of the energy of reaction Q from the masses.[10]

One can deduce the energy of the incident neutron E_n by adding to the energy of the observed group E_{a+B}, the energy Q, corresponding to the change in mass in the course of the reaction.

E_t, the absolute value of the resonance level in

TABLE IV. Summary of nitrogen data for $_7N^{14}$ (n, a) $_5B^{11}$.

E_a+B Observed particle and recoil nucleus (Mev)	Energy of reaction Q (Mev)	Neutron energy E_n (Mev)	E_a+B_0 Particle and recoil nucleus (Mev)	E_l Binding energy of a particle to N^{15} (Mev)	E_t, Term of intermediate nucleus N^{15} (Mev)
1.33	−0.25	1.58	1.23	11.0	12.23
1.64		1.89	1.51		12.51
1.94		2.19	1.77		12.77
2.15		2.40	1.99		12.99
2.64		2.89	2.45		13.45
2.98		3.23	2.77		13.77
3.82		4.07	3.55		14.55
4.14		4.39	3.85		14.85
4.48		4.73	4.16		15.16

relation to the ground state of N^{15} is determined by adding the binding energy E_1, of the alpha-particle in this nucleus to E_{a+B_0}, the observed neutron energy in a system of coordinates with the center of gravity at rest.

A calculation shows that

$$E_{a+B_0}=\frac{14}{15}E_n-Q.$$

Table IV contains a summary of the nitrogen data.

A test of the question as to whether the observed resonance groups correspond either to the different excitation states of the intermediate nucleus, or the different excitation states of the end nucleus, is possible in the case of nitrogen. If the boron nucleus is in the ground state, then, and only then, is it possible for the exact inverse process to be observed when boron is bombarded with alpha particles and the alpha penetration resonance results in neutron emission according to the process ${}_5B^{11}\ (a, n)\ {}_7N^{14}$. These resonance energies are expected to agree with the observed emission resonances if the motion of the center of gravity is taken into consideration. Maurer[2] carried out this investigation by measuring the energies of the inverse process ${}_5B^{11}\ (a, n)\ {}_7N^{14}$.

The alpha-particle energies obtained by Maurer must be transposed so as to be comparable with the inverse process observed here. If E_{a+B} is the resonance energy of the alpha-particle plus the boron nucleus found in the (n, a) process, Q the energy of reaction of this process, E_a the alpha-resonance energy in the (a, n) process, then

$$E_{a+B}=\frac{1}{14}(11E_a+Q).$$

Table V shows the comparison of data reported here (column 1) with those of Wilhemy,[1] Comparat and Thibaud,[4] Maurer,[3] and Hansen.[5]

There is obviously good agreement among the levels in common.

The fact that the same levels of resonance of ${}_7N^{15}$ are found by two processes which are the inverse of each other proves that in some cases, when one of these levels is excited, the B^{11} nucleus is emitted in its ground state [(n, a) process] as previously assumed.

TABLE V. Comparison of data on resonance energy, (E_{a+B}) given in Mev.

This thesis	Wilhelmy	Comparat and Thibaud	Maurer	Hansen
		0.60		
		0.75		
		0.90		
		1.05		
		1.25		
1.33	1.42	1.40	1.40	1.31
1.64		1.60		
		1.75		1.75
1.94	2.04	2.05	2.00	1.94
2.15		2.25	2.16	2.31
		2.55		
2.64	2.59	2.75	2.70	2.58
2.98		3.05		2.93
	3.21	3.30	3.25	3.18
			3.49	
			3.74	3.7
3.82			3.86	3.82
4.14				4.12
4.48				4.37
				4.68
	4.9			4.93

But one cannot conclude that all groups found correspond to resonance levels, as certain of the observed groups may correspond to transition groups, leaving the boron nucleus excited. The statistics have shown a very large majority of impulses corresponding in low E_{a+B} energies, indicating that the energy imparted by a fast neutron to the nitrogen nucleus is only partially concentrated on the emitted alpha-particle and consequently the boron nucleus remains excited at any possible excitation level. Two such levels are known for B^{11} at 2.1 Mev and 4.4 Mev.[23] In such a case, the energy of an observed group, E_{a+B}, represents the energy of the resonance level of N^{15} minus the excitation energy of a level of B^{11}. One should observe gamma-emission in such a case. The experimental set-up employed here was inadequate for the detection of these gamma-rays because of the intense gamma-ray spectra from the Ra+Be neutron source.

The terms of the intermediate nucleus have, in the average, an interval of about 0.30 Mev, and they lie moderately close. This is understandable as the terms lie very high above the ground term and according to Bohr, the term density increases rapidly, in general, towards the higher terms.

Theoretically, from Bethe's equation[24] the

[23] M. S. Livingston and H. Bethe, Rev. Mod. Phys. 9, 341 (1937).

[24] H. Bethe, Rev. Mod. Phys. 9, 85, Eq. 304 (1937).

spacing of the energy levels in N^{15} excited to 11 Mev has a value of about 0.1 Mev. The agreement between theory and experiment is thus quite good.

Cases in which neutron transformations can be observed in the reverse direction are rare. Consequently the process described here is often the only possible one to determine experimentally the excitation states of certain intermediate nuclei. To be sure, such an assignment of groups is only possible if one has at his disposal homogeneous neutrons of any desired energy.

VII. ACKNOWLEDGMENTS

Thanks are due Professor C. W. Van der Merwe for his encouragement and interest in the work and to Professors E. O. Salant and R. D. Present for helpful discussions. We appreciate the work done by Dr. I. I. Hudes, Mr. M. G. Levy, and Mr. V. L. Parsegian in helping us take the data, and thank the Graduate School of New York University for financial aid to one of us (H. I. Z.). We also wish to express our thanks to Dr. W. W. Hansen for permission to use his results.

PHYSICAL REVIEW VOLUME 67, NUMBERS 5 AND 6 MARCH 1 AND 15, 1945

Radioactive Xenons

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(Received December 9, 1944)

The investigation of the radioactive xenons growing out from radioactive iodines following uranium or thorium fission is summarized in this paper. Two complete chains have been established and identified with their mass numbers. They are:

(1) $_{51}Sb^{133}$ 10 min.$\rightarrow {}_{52}Te^{133}$ 60 min.$\rightarrow {}_{53}I^{133}$ 22 hrs.$\rightarrow {}_{54}Xe^{133}$ 5 days$\rightarrow {}_{55}Cs^{133}$

and

(2) $_{53}I^{135}$ 6.6 hrs. $\nearrow {}_{54}Xe^{135*}$ $\downarrow$ 10 min. $\searrow {}_{54}Xe^{135}$ 9.4 hr. $_{55}Cs^{135}$?

I. INTRODUCTION

THE investigation of radioactive xenon from iodine as a result of nuclear fission was started in 1939 and was discontinued at the end of 1941. Although parts of our results have been briefly reported in this journal[1,2] and some of the results have since been confirmed and further extended in different laboratories,[3] nevertheless, it seems desirable to give a systematic description of the whole situation as it stands now.

Our investigation concerning this problem consists mainly of three parts. First, we observed the radioactive xenons growing out of iodine and established their genetic relations with known fission chains. Second, by bombarding cesium and barium with fast neutrons, the mass numbers of these radio-xenons and consequently of the whole chains were identified. The last part was a tentative study of the nuclear isomerism in xenon.

II. EXPERIMENTAL PROCEDURE

(a) Material

The chemical form of uranium employed in this investigation was uranyl nitrate ($UO_2(NO_3)_2 \cdot 6H_2O$) or uranyl chloride (UO_2Cl_2), depending on the type of chemical manipulations required for carrying out a specific separation. The neutrons used in this investigation were

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1 E. Segrè and C. S. Wu, Phys. Rev. **57**, 552 (1940).
2 C. S. Wu, Phys. Rev. **58**, 926 (1940).
3 R. W. Dodson and R. O. Fowler, Phys. Rev. **57**, 966 (1940), H. Goette, Naturwiss. **28**, 449 (1940); W. Seelmann-Eggebert and H. J. Born, Naturwiss. **31**, 59 (1943); W. Seelmann-Eggebert, Naturwiss. **31**, 491 (1943).