and neutron beams is given by

$$\frac{Q'_{T(e)}}{Q_{T(p)}}=\frac{I'_{T(e),T}}{I_{T(p),T}}=\frac{k_x}{k_n}\frac{I'_{A(e),G}}{I_{A(p),G}}=K\cdot r/n \quad (23)$$

where $K=k_x/k_n$, and r and n are the exposures of the x-ray and neutron beams measured in roentgens and n units, respectively. This equation holds for measurements made per unit volume or per unit gram of the materials. Since k_x is approximately unity, K is the inverse of k_n, whose value was discussed in the preceding section.

If, after the relative ionizing energies of x-ray and neutron beams have been so determined, disproportionate biological actions occur, they must result from the strikingly opposite character of the ionic distribution resulting from the two agents, i.e., the widely spread and relatively weak ionization along the paths of the electrons scattered by x-rays, and the concentrated and dense ionizations along the paths of nuclei recoiling from neutrons. As reported by Aebersold and Lawrence, inequalities in biological sensitivities have been observed in most investigations, the relative sensitivities apparently resulting from the physiological condition of the irradiated material.

The authors gratefully express their appreciation of the interest and valuable assistance given them by members of the Radiation Laboratory, particularly Dr. K. McKenzie, and thank Professor E. O. Lawrence and the staff of the Laboratory for their cooperation in making available long periods of cyclotron time. The work was made possible by the generous support of the Rockefeller Foundation and the Josiah Macy, Jr. Foundation. One author was enabled to participate in the research through a fellowship awarded by the Finney-Howell Foundation, the other through a grant from the Trustees of Smith College.

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Activity of N^{16} and He^{6}

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An interrupted flow method of handling short lived gases is described. By use of the method, pure N^{16} and pure He^{6} are readily produced. Geiger counter measurements on the N^{16} give a period of 7.3 ± 0.3 sec. Presence of gamma-rays having energy greater than 5 Mev is demonstrated with a cloud chamber and absorption measurements. A lower limit to the end point of the N^{16} spectrum is derived from absorption curves, and an upper limit fixed by excitation measurements. By taking into account the barrier of N^{16} against emission of a proton, and excluding the electron self-energy, the maximum electron energy of the decay may be set at 10 ± 0.5 Mev. The electron absorption curves show the beta-spectrum to be complex with a softer component having an end point at approximately 4 Mev corresponding to decay to an excited state of O^{16} in the region of 6 Mev. The He^{6} period found is 0.85 ± 0.05 sec., and its end point 3.5 ± 0.6 Mev, in agreement with Bjerge and Bröstrum.

Part I. N^{16}

A. INTRODUCTION

N^{16} WAS reported in 1934 by Fermi[1] and his co-workers and also by Livingston, Henderson, and Lawrence.[2] Both groups found a negative electron emitter with lifetime of nine or ten seconds formed by the bombardment of fluorine with neutrons, and both assigned it to the reaction $F^{19}(n|\alpha)N^{16}$. In 1936 Fowler, Del-

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[1] Fermi, Amaldi, d'Agnostino, Rasetti, and Segrè, Proc. Roy. Soc. **A146**, 483 (1934).

[2] Livingston, Henderson, and Lawrence, Phys. Rev. **46**, 325 (1934).

sasso, and Lauritsen[3] produced the same activity by bombarding nitrogen with deuterons, assigning it to $N^{15}(D|P)N^{16}$. From 110 cloud-chamber tracks consisting mainly of positrons from Na^{24} mixed up with a few electrons from N^{16}, they concluded the nitrogen spectrum extended to 6 Mev. Concurrently, two other measurements on this same activity were published. Nahmias and Walen[4] reported both $F^{19}(n|\alpha)N^{16}$ and $F^{19}(n|P)O^{19}$ and showed that the former reaction proceeded with slower neutrons than did the latter, in agreement with the existing assignments. Their nitrogen period was 8.4 ± 0.1 sec. Naidu and Siday[5] produced the nitrogen activity by neutrons on fluorine and obtained a cloud-chamber histogram of some 250 tracks. The inspection end point was 6.5–7.0 Mev; a high energy tail extending to between 10 and 13 Mev they attributed to systematic errors in curvatures which result because the magnetic field was only 1000 gauss.

In 1937 Chang, Goldhaber, and Sagane[6] discovered the reaction $O^{16}(n|P)N^{16}$ (period 8 sec.). They found a good yield with neutrons from 450-kev deuterons on lithium, a detectable amount from the deuterons on boron, but nothing from the deuterons on beryllium, showing fast neutrons were required for the reaction. No positive chemical identification of N^{16} has been made because of its short lifetime,[7] but the various reactions producing an inert gas make the assignment seem unquestionable.

Livingston and Bethe[8] give the mass of N^{16} as 16.011 mass units with an uncertainty of ±0.002. This value apparently comes from the work of Harkins, Gans, and Newson[9] who, with a cloud chamber, measured thirteen recoil pairs which they attributed to the reaction $F^{19}(n|\alpha)N^{16}$. Q's computed from each pair ranged from $+0.7$ to -10.3 Mev, with most of the tracks yielding values between -2 and -5 Mev. Choosing only the latter group of tracks, one gets the mass of N^{16} listed by Livingston and Bethe. This mass indicates that the energy of the transition $N^{16}-O^{16}$ should be 10.2 Mev, while direct measurements have given a value of approximately 6 Mev for the disintegration electrons, with no gamma-ray reported. Since one of us (H.S.S.) was interested in studying the shape of beta-ray disintegration curves with a cloud chamber, it was considered advisable to resolve this 4-Mev discrepancy.

B. TREATMENT OF SAMPLE

(1) Gas System

Because of the difficulty of performing chemical separations before the disappearance of the activity, it seemed best to handle the radioactive nitrogen in the gaseous form, in order to achieve an immediate quantitative separation from all solid impurities. This also permitted ready transportation of the sample to a considerable distance from the cyclotron. The conventional continuous-flow method of transporting the gas proved rather unsatisfactory because of the difficulty of determining just what the cyclotron was doing when the gas sample at the measuring end of the line was bombarded. As all the measurements were made in the control room 120 feet from the cyclotron, the beam had to be interrupted during the measurements to remove the γ-ray background. Under such conditions of short bombardment, the ion current was usually quite unsteady. This fact, coupled with the inconvenience of measuring flow velocities and the large amounts of carrier gas wasted, made some other system desirable.

Following a suggestion of Dr. E. M. Purcell, a discontinuous flow method was used. In this scheme, the target is bombarded in a closed container filled with a quiescent gas at any desired pressure. At the end of the bombardment, a valve is opened permitting the gas to escape down an evacuated flow line to the receiving chamber at the other end; here it is confined by another valve, compressed to the pressure desired, and the measurements taken. To complete the cycle, the receiving chamber and line are evacuated and the target container refilled with the carrier gas. To permit remote

[3] Fowler, Delsasso, and Lauritsen, Phys. Rev. **49**, 561 (1936).
[4] Nahmias and Walen, Comptes rendus **203**, 71 (1936).
[5] Naidu and Siday, Proc. Phys. Soc. **48**, 332 (1936).
[6] Chang, Goldhaber, and Sagane, Nature **139**, 962 (1937).
[7] See, however, Polessitsky, Physik. Zeits. Sowjetunion **12**, 339 (1937), for attempts at identification by elimination.
[8] S. M. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 373 (1937). See also the computed value of 16.0114 by W. H. Barkas, Phys. Rev. **55**, 696 (1939).
[9] Harkins, Gans, and Newson, Phys. Rev. **47**, 52 (1935).

control, the valves were made in the form of solenoid-operated hose pinchers. The compressor was a flattened spheroid with a port on each end and a rubber disaphragm stretched diametrically across the center; the pressure of the carrier gas in the one cell thus was determined by the air pressure applied to the other cell.

A target chamber of 20 cu. in. volume containing hydrogen at 25 lb. per sq. in. gauge pressure, a $\frac{1}{16}$ inch I.D. flow line 120 feet long, and a receiving chamber with a volume of 10 cu. in. were used. Gas at a pressure of one atmosphere could be trapped in the receiver $2\frac{1}{2}$ seconds after the end of the bombardment. With a carrier of nitrogen or oxygen instead of hydrogen, 8 to 10 seconds were required to fill the receiver.

(2) Choice of Target

Direct bombardment of nitrogen with deuterons was not feasible because of the overwhelming quantities of O^{15} produced. In fact, bombarding ordinary tank helium with deuterons produced large amounts of O^{15}, N^{13}, and traces of longer-lived gases. Because of this, we used neutron bombardments. Neutrons directly on oxygen gave a moderate activity; however, because of some of the measurements contemplated, a solid target and hydrogen as a carrier were preferred. $Be(OH)_2$ prepared in high emanating form proved very satisfactory.[10]

The $Be(OH)_2$ was precipitated from an ammoniacal solution of $Be(OH)_2$ and repeatedly washed and centrifuged until the ammonium hydroxide content became so small that the precipitate started to go back into solution. It was then spread out into a layer on a sheet of glass, cut into small pieces, and air dried. Finally, each piece was blown clean of any fine particles which might clog the flow line and inserted into the bombardment chamber. About one hundred grams of the compound filled the chamber, volume 350 cc. The material was of such an ashy nature that it seemed expedient to insert a cotton plug in the flow line. With these precautions, no trouble was encountered with clogging of the line.

This target gave copious yields of both N^{16} and He^6 when bombarded with fast neutrons from deuterons on beryllium. With hydrogen gas as the carrier, we had no trouble from other activities; any impurities which may have been produced were of such long life as to be indistinguishable from the control room background. This is in contrast to our experience when silica gel was substituted for the $Be(OH)_2$; the yield of N^{16} dropped to about 10 percent mixed up with an equal activity of a forty-second period.

C. PERIOD

For period and absorption measurements, an alcohol-filled Geiger counter and scale of thirty-two circuit were used. The counter was made of a 5-mil brass cylinder, $\frac{3}{4}$ inch by 3 inches long, waxed into glass ends and filled with argon and alcohol. Thresholds ranged from twelve to fifteen hundred volts, and plateaus were about one hundred volts wide. The scaling circuit was of the type described by Stevenson and Getting,[11] using four tubes per stage. The data were recorded by photographing a Cenco recorder and stop watch with a Ciné Kodak Special. Exposures were about one-fortieth of a second, at eight frames per second. By running the camera in bursts, we could catch the instant at which the Cenco counter moved to within a twentieth of a second, the smallest interval of the stop watch, thus making interpolation in the scaling circuit unnecessary.

To get pure N^{16} the target was bombarded to saturation in a gas whose pressure was adjusted to give an eight-second delivery time. (For optimum concentration, the delivery time should be one half-life.) Measurements were started ten seconds after the cyclotron dee voltage was cut off and continued for two to five minutes, sufficiently long to determine the background.

The usual method of presenting the decay curve by plotting the rate against the time leads to difficulties on short-lived samples. To make all points have the same statistical accuracy, one would like to include the same number of counts in each point, but this very soon makes the counting interval comparable with, or longer than, the half-life, and one cannot assign the

[10] We wish to thank Dr. E. Segrè for some helpful suggestions concerning the method and Dr. H. H. Anderson for assistance in the actual preparation of the $Be(OH)_2$.

[11] E. C. Stevenson and I. A. Getting, Rev. Sci. Inst. **8**, 414 (1937).

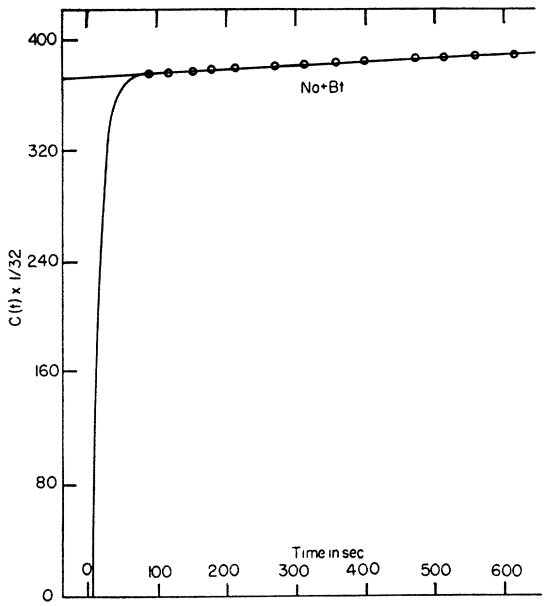

FIG. 1. $C(t)=N_0(1-e^{-\lambda t})+Bt$. Activity of N^{16}.

rate so measured to the midpoint of the interval. Since the camera essentially integrates the decay, it seemed expedient to plot the integrated form of the curve instead of the rate. Thus if $C(t)$ is the counter reading, then:

$$C(t)=N_0(1-e^{-\lambda t})+Bt,$$

where the first term on the right is the true activity and the second the background contribution. A direct plot of $C(t)$ against t gives N_0 and B from the asymptote intercept and slope, and a semi-logarithmic plot of the difference between the asymptote and $C(t)$ against t gives the half-life in the usual manner. Thus the half-life comes from a plot of $N=N_0(e^{-\lambda t})$ instead of from $A=A_0(e^{-\lambda t})$; the advantage is that we get our data from measuring $N(t)$ up to the instant t, which our camera records directly, instead of approximating $A(t)$ (the activity) by its average value over the interval. The precision of either method is of course limited by statistical fluctuations and background uncertainty.[12]

Figure 1 is a sample plot of $C(t)$ against t and shows how constant the background is a short distance (100 feet) from the cyclotron. Figure 2 is the decay curve, which is linear all the way from the initial rate of over 1100 counts per second. Of course, it is fortuitous that the last point lies on the curve, for a slight shift in the estimated asymptote of Fig. 1 will shift this point either up or down, as the rate at the tail is only five counts per second, or twice background.

The question as to the linearity of the counter over such a wide range is a serious one. To check this, we measured several decay curves of N^{16} and, with the same counter, one for Cl^{38}. The Cl^{38} was produced by bombarding NaCl with neutrons from 10.3-Mev deuterons on Be, taken at right angles to the beam, and was separated by precipitation with Ag and repeated washings. The Cl^{38} decay was linear from the starting rate of 160 counts per second, and gave the accepted period of 37 minutes.[13] The background of ten counts per second showed a 15-hour period and was assumed to be Na^{24}. The N^{16} curves agreed with many others we had measured, some with initial activities sufficiently high to block the recorder. Twelve pertinent runs were averaged, and these yielded a period for the N^{16} of 7.3 ± 0.3 sec.

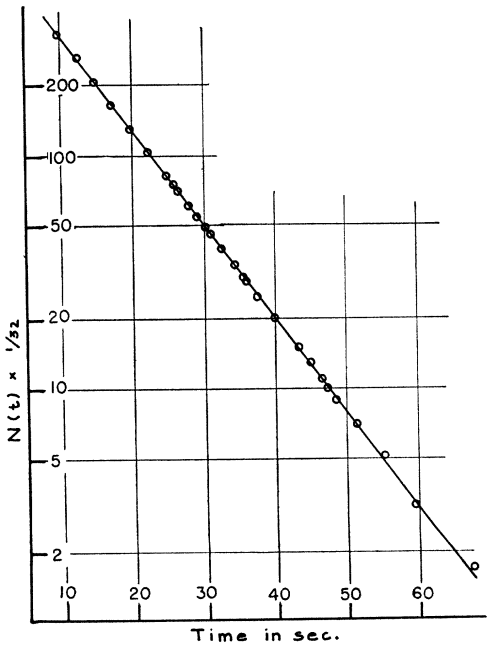

FIG. 2. Decay of N^{16}. $T_{\frac{1}{2}}=7.5$ sec.

[12] We wish to thank Professor S. Goudsmit for bringing this method of presenting the data to our attention.

[13] G. T. Seaborg, Chem. Rev. **27**, 199 (1940).

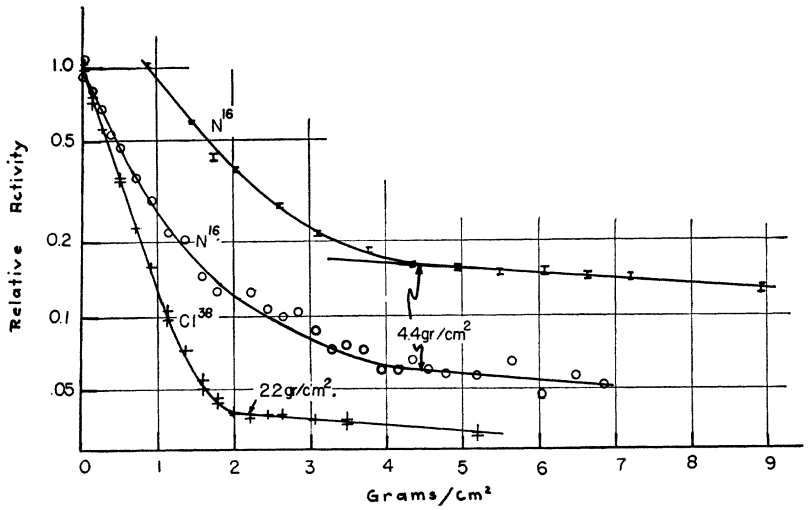

FIG. 3. Absorbtion curves. III N^{16}-cylindrical brass absorbers; O O O N^{16} sheet aluminum absorbers; + + + Cl^{38} sheet aluminum absorbers.

D. GAMMA-RAYS

It was possible to explain the discrepancy between the $N^{16}-O^{16}$ disintegration energy computed from mass values and that from beta-decay measurements by the presence of a hitherto unobserved gamma-ray.

The existence of gamma-rays from N^{16} was demonstrated by the presence of tracks inside a cloud chamber with the sample outside the $\frac{1}{4}$-inch glass walls. Insertion of a quarter inch of copper between the gas and the chamber failed to stop the tracks, showing conclusively they were not from high energy primary electrons. A histogram of the recoils from the chamber wall was made by using the field from a Helmholtz coil of $18\frac{3}{4}$-inch mean diameter, radial depth of $4\frac{1}{2}$ inches, axial depth $4\frac{1}{4}$ inches, and coil separation $9\frac{3}{8}$ inches. Calibration of the central field by Dr. G. E. Valley, using a conversion line from zinc in his beta-ray spectrograph, checked with the calculated field strength. Measurements on 125 N^{16} tracks gave a roughly uniform distribution which converged toward an upper energy limit of around 5 to 6 Mev.

A rough statistical analysis of the number of tracks in successive expansions at intervals of twenty seconds indicated the activity had the period expected. Attempts to get recoil pairs from a thin lead sheet inside the cloud chamber proved futile because of the weak intensity of the source; even with the thick chamber wall for the target, only two or three acceptable tracks per expansion were photographed.

The absorption coefficient of the gamma-rays in lead was measured. (See next section for description of the method.) By assuming monochromatic gamma-rays, the value of the coefficient obtained by measuring over a single half-thickness was 0.5/cm Pb. Since this is in the region of the absorption minimum for Pb, the gamma-ray may lie in the range between 2 and 7 Mev. No better measurements than this could be expected because the great thickness of absorbers required greatly reduced the intensity. With cyclotron beams of over 100 μamp., only 80 to 100 counts per bombardment were obtained through the thickest absorbers.

Additional evidence for the existence of a hard gamma-ray is obtained from the complete absorption curve in aluminum, Fig. 3. The gamma-ray intensity is about 7 percent of the total activity at zero absorber. Although there was no simple way of calculating the efficiency of the counter for 6-Mev gamma-rays, the observed intensity could reasonably be attributed to a single hard gamma-ray of this energy.

As another check on the gamma-ray energy, beta-beta coincidence measurements were taken on the gamma-recoil electrons. Various thicknesses of absorbers were inserted between the two coincidence counters to determine the range of these recoil electrons, but the high energy of

the disintegration electron spectrum made our results far less precise than those reported in other cases.[14] It was necessary to interpose a thick absorber in front of the first counter to cut off the primary electrons because their spectrum extended far beyond the gamma-ray energy; hence the source of the gamma-recoil electrons was a thick target and the otherwise sharp coincidence cut-off at maximum electron range was badly smeared. Measurements with five different absorbers, averaging around a dozen bombardments for each absorber, again showed the presence of gamma-rays of greater than 4 Mev.

E. ABSORPTION MEASUREMENTS

An absorption curve of the radiation emitted by N^{16} was taken by using a gas cell, with active volume of $1\times1\frac{1}{4}\times1\frac{1}{4}$ inches and $1\frac{1}{2}$-mil Al windows in front and in back, placed near the counter. A space was left for $1\frac{1}{4}$ inches of absorbers between cell and counter. The whole unit was surrounded by a 2-inch thick lead cylinder 6 inches in diameter. Each reading required a separate bombardment.[15] To provide adequate monitoring, the number of electrons passed through the absorber during the interval from ten to twenty-five seconds after bombardment was compared with the counts recorded during the interval from thirty to forty-five seconds with the absorber removed. Photographic recording again afforded precise reading. Figure 3 shows the curve obtained with sheet Al absorbers; the number of counts obtained during the absorption interval ranged from 2000, with no absorber, to 200 with the thickest, including the background of about fifteen counts as determined from decay curves. The gamma-ray absorption coefficient was measured at the same time.

Because of the surprisingly high activity of the tail, still 5 percent of the total activity after passing through 5 g/cm² of Al, we made a comparison run with Cl^{38}, approximating the same geometry by placing cotton wool soaked in neutron-activated chloroform inside the gas chamber for the source. The Cl^{38} end point agrees well with that reported by Watase and Itoh[16] of 2.3–2.4 g/cm² of Al. Their beta-ray spectrograph measurement gave an upper limit of 5.0 Mev for the chlorine electrons; the nitrogen electron energy must far exceed this. The Cl^{38} comparison run is shown on the same graph with the N^{16}. A third series of measurements made with cylindrical brass absorbers is also included on this graph. These last measurements were made by using a cylindrical shell gas chamber, 2-inches I.D. with $\frac{3}{8}$-inch wall spacing, and a set of telescoping brass absorbers to insert between the inner wall of the gas cell and the outside of the counter. The minimum absorber possible thus was 10 mils of brass for the chamber wall plus 5 mils for the counter; nevertheless the intensity was greatly increased. The curve for cylindrical absorbers gives the best indication of the end point; the lower limit to the spectrum end point is 4.4 g/cm², or 9.6 Mev, from the relation from Curran, Dee, and Petrzilka:[17]

$$E=2.19R,$$

where R is the range in g/cm².

A comparison of the N^{16} absorption curve taken with the Al absorbers against the similarly made Cl^{38} curve suggests that the N^{16} spectrum is complex. If one passes a straight line through the points on this N^{16} curve in the region from 2 to 4 g/cm² and subtracts the extrapolation of this line from the plotted points, he can get a very crude estimate of the intensity of the lower energy N^{16} spectrum. A reasonable estimate of the energy of the softer component obtained in this way is 3.5 Mev, and its abundance seems to be about three times that of the harder component.

F. EXCITATION THRESHOLD

As a further check on the disintegration energy, we tried to determine the threshold for the reaction $O^{16}(n|P)N^{16}$. The mass difference

[14] See for example Curran, Dee, and Strothers, Proc. Roy. Soc. **174**, 546 (1940).

[15] It should be born in mind that the best statistical accuracy feasible when taking measurements on short lived samples is necessarily poor. For a given initial activity the total number of disintegration electrons which are recorded decreases proportionately with the decrease in half-life.

[16] Watase and Itoh, Proc. Phys. Math. Soc. Jap. **22**, 626 (1940).

[17] Curran, Dee, and Petrzilka, Proc. Roy. Soc. **169**, 286 (1938).

TABLE I. Yields for various neutron energies.

	Minimum angle	Rate 9 sec. after bombardment He^6	Rate 9 sec. after bombardment N^{16}	$\frac{He^6}{N^{16}}$	E_n	N^{16} corrected to saturation at 50μ amp.
		(A) Neutrons from D on Be				
1.	90°	185/sec.	8.9/sec.	21	11.6 Mev	11/sec.
2.	90°	150	5.9	25	11.6	7.0
3.	90°	150	7.4	20	11.6	9.3
4.	90°	230	15	15	11.6	16
5.	90°	260	12	22	11.6	11
						Average = 11 ± 0.8
6.	70°	130	24	5.4	12.5	40
7.	70°	150	26	5.8	12.5	34
8.	70°	215	26	8.1	12.5	30
						Average = 35 ± 2
		(B) Neutrons from D on brass				
1.	90°	29	5.0	5.8	?	7.6
2.	90°	49	5.2	9.4	?	5.2
						Average = 6.4 ± 1
3.	70°	17	11	1.5	?	11

$N^{16}-O^{16}$ is given by

$$N^{16}-O^{16}=E_n'+(n-P),$$

where E_n' is the minimum neutron energy (in C. of G. coordinates) which will produce the reaction. Since $n-P$ is 0.78 Mev and $E_n' = (16/17)E_n$, the mass difference becomes

$$N^{16}—O^{16}=\frac{16}{17}E_n+0.78 \text{ Mev},$$

where E_n is the neutron energy in laboratory coordinates.

We used neutrons given off from the beryllium target at various angles to the incident deuteron beam and secured an energy range from 14.7 Mev for straight ahead neutrons to 11.6 Mev for neutrons at right angles. As a monitor we took the activity of the He^6 produced in the same bombardment, for since its Q value is about 0.4 Mev,[18] its yield is roughly independent of the neutron energy over the narrow range of energies employed here. Hence its strength gives some indication of the neutron intensity.

Our target was the usual cylinder of $Be(OH)_2$, 3 inches in diameter by 3 inches long, placed as near the beryllium plate serving as the neutron source as was consistent with keeping a constant distance for all the desired angles. The target was bombarded for 30 seconds at a uniform beam and a decay curve taken starting seven seconds after the cyclotron was cut off. Analysis gave the N^{16} and He^6 decay curves. Table I (*A*) gives the results for neutron energies in the neighborhood of the threshold. The first column is the minimum angle between the deuteron beam and the beryllium target, the second and third columns the helium and nitrogen activities, respectively, nine seconds after bombardment. (Their periods were taken as 0.9 and 7.5 seconds for this work.) The fourth column gives the ratio He^6/N^{16}, likewise nine seconds after bombardment; the fifth column the maximum energy of any neutron which could hit any part of the $Be(OH)_2$; and the last column is the nitrogen yield corrected to saturation bombardment with a beam of 50μ amp of deuterons.

Table I (*B*) gives the same information for some runs made with a brass plate for the source of neutrons instead of the beryllium to check whether the neutrons responsible for the N^{16} really came from the beryllium plate. These data show that at a minimum angle of 90° a large part of the N^{16} may have come from stray neutrons, for here the Be source gave an average yield of 11 counts/second against an average with the brass of 6.4/sec. At a minimum angle of 70°, however, there is a big contribution from the beryllium, for here the latter gives an N^{16} activity of 35/sec. against 11/sec. for the brass. A further comparison of the bombardments at 90° shows that the neutrons from the brass, though less intense, have a slightly higher maximum energy than those from the beryllium since the N^{16}/He^6 ratio is three times as large for the brass as for the beryllium.

These excitation measurements show N^{16} was produced by neutrons emitted at an angle of at least 70° with the deuterons incident on the beryllium target. Since the deuterons had a range in air of 72 cm, including the Al foil, their energy was 10.3 Mev, and taking the Q value for the reaction $Be^9(D|n)B^{10}$ to be 4.2 Mev,[19] the neutrons producing the N^{16} had an energy less

[18] Bjerge and Bröstrum, Kgl. Danske Vid. Sels. Math.-Fys. Medd. **16**, No. 8 (1938).

[19] S. M. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 332 (1937).

than 12.6 Mev. This neutron energy gives a value $\leqslant$12.6 Mev for the mass difference $N^{16}-O^{16}$. If one takes into account the potential barrier of N^{16} for the emitted proton, this mass difference is lowered since at low proton energies the small probability of penetrating the barrier would greatly reduce the N^{16} yield even though the neutron energies were somewhat above the reaction threshold. The potential barrier of N^{16} for protons is given by

$$E=Ze^2/r_0A^{\frac{1}{3}}.$$

Taking $Z=7$, $A=16$, and $r_0=1.35\times10^{-13}$ cm, one finds $E=3.0$ Mev. This consideration would place the value of $N^{16}-O^{16}$ in the neighborhood of 10 Mev.

G. DISCUSSION

The absorption curve of the N^{16} disintegration electrons indicates a lower limit of 9.6 Mev for the maximum beta-ray energy. The excitation data give an upper limit of 12.6 Mev. Consideration of the potential barrier for the $n-P$ reaction suggests that this upper limit is probably too high by several Mev. We can conclude that $E_0=10\pm0.5$ Mev, in agreement with the value of 10.2 given by Livingston and Bethe and that a direct transition from N^{16} to the ground state of O^{16} occurs in about 25 percent of the disintegrations.

Our gamma-ray measurements showed the presence of photons with energies greater than 5 Mev coming from excited O^{16} nuclei. Studies of the reaction $F^{19}(H|\alpha)O^{16}$,[20] which also leads to excited states of O^{16}, have given sufficient information about the oxygen nucleus to permit us to make rather plausible postulates about our gamma-rays. There is an O^{16} level at 6.0 Mev which decays by pair emission[21] and another at 6.2 Mev which emits all its energy in a single photon. No lower levels are known, and their existence seems highly doubtful because of the great stability of the O^{16} ground state. We can reasonably assume our gamma-radiation consisted mainly, if not completely, of the known 6.2-Mev quanta.

A gamma-ray of this energy implies the beta-spectrum is complex, being composed of a spectrum with a maximum energy of 10 Mev corresponding to a direct transition to the ground state of O^{16} and another with a 4-Mev end point. Such an energy level scheme was suggested above in the interpretation of the absorption curve. The lower energy spectrum seems to be the more abundant, perhaps accounting for three-fourths of the transitions. Then the 7.2-sec. N^{16} decay is composed of a 4-Mev spectrum, period 10 sec., and a 10-Mev spectrum, period 30 sec., with a relative abundance of 3/1. If one takes He^6, 0.85 sec., $E_0=3.7$ Mev, as an example of an allowed transition inside a supermultiplet, then the 10-sec. decay should be an allowed transition with change of supermultiplet for it has roughly the same energy as the helium but is 1/12 as fast. The high energy group is then strongly forbidden, for it is 1/35 as fast as the He^6 while its energy is 2.7 times as great.

Incomplete as our data are, it is interesting to speculate on what conclusions the data permit about the states of the nuclear levels. The ground state of O^{16} is known to have zero spin and even parity. N^{16} probably has a high spin, then, for the strong selection rule against the direct transition from it to the ground state of O^{16} seems to imply a large change of angular momentum. A large spin for N^{16} is also consistent with the non-appearance of transitions from it to the pair-emitting level of O^{16}. This conclusion of high spin for N^{16} also implies a non-zero spin for the gamma-emitting level of O^{16}, for otherwise the transition between the two could not be the non-forbidden one observed.

The direct transition from N^{16} to the ground state of O^{16} seems to belong to the second of the forbidden types considered by Critchfield and Wigner,[22] the group comprised of transitions in which the finite size of the nucleus is important. Assigning the transition to this group may seem paradoxical in view of the lightness of the nucleus involved, but the shortness of the wavelengths of these extremely energetic emitted

[20] See Streib, Fowler, and Lauritsen, Phys. Rev. **59**, 253 (1941), for a summary and discussion of the radiations from the fluorine reactions.

[21] We tried to find positrons by passing the electrons through a magnetic field, but found that less than one-fourth of the electrons could be positive; the cloud-chamber work of Nahmias and Walen showed actually far fewer positrons than this were emitted, but could not rule out their presence.

[22] C. L. Critchfield and E. P. Wigner, Phys. Rev. **60**, 412 (1941).

particles far more than compensates for the small size of the nucleus. The interesting aspect of this group, from an experimental point of view, is that the Kurie plots should be concave toward the axis at the end corresponding to high electron energies. Although the total spectrum of N^{16} is double, measurement of the Kurie plot for the transition to the ground state of O^{16} should be possible because of the great difference of energies of the two spectra. Such a measurement should give telling evidence regarding the theory of Critchfield and Wigner.

Further work along this line has been postponed.

Part II. He^6

A. INTRODUCTION

In 1936, Bjerge,[23] and later Bjerge and Bröstrum,[18,24] reported a short-lived gas emitting negative electrons formed by the bombardment of beryllium hydroxide with neutrons. The period, found by flowing the gas in a carrier past the recorder and measuring the activity as a function of flow rate, was 0.8 ± 0.1 sec.; a cloud-chamber histogram gave the upper limit of the spectrum as 3.7 ± 0.5 Mev. They assigned the activity to He^6 as the only gas with this disintegration energy which could be so formed. Several other workers[25] have reported the same activity from neutrons on beryllium, but no attempt has been made to improve the precision of these measurements.

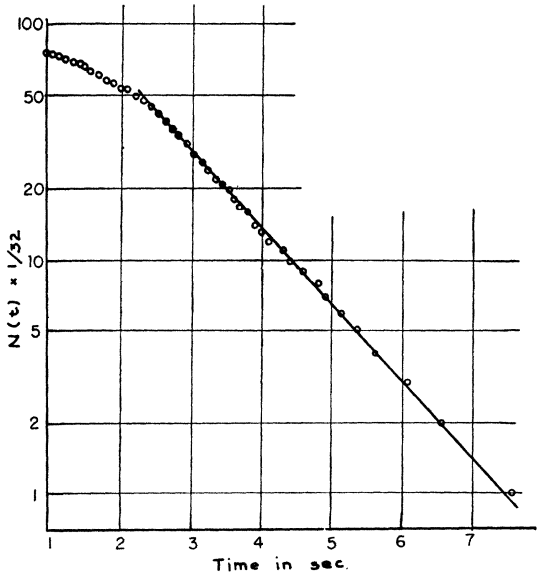

FIG. 4. Decay of He^6. $T_{\frac{1}{2}}=0.90$ sec.

[23] T. Bjerge, Nature **137**, 865 (1936).
[24] T. Bjerge and K. J. Bröstrom, Nature **139**, 400 (1936).
[25] G. T. Seaborg, reference 11, for complete bibliography.

He^6 is of considerable theoretical interest.[26] It is a member of the group of nuclei containing $4n+2$ primary particles, whose decay rates are so anomalous. Two transitions in this group, He^6-Li^6 and $C^{10}-B^{10}$, are allowed and exceedingly rapid, while the transitions $Be^{10}-B^{10}$ and $C^{14}-N^{14}$ are highly forbidden, contrary to theoretical expectations. Moreover, the He^6-Li^6 transition itself is more allowed than any other known transition and seems almost to lie in a group by itself.

B. PERIOD

Our methods of producing, transporting, and measuring the He^6 activity were the same as those already described in the sections on N^{16}. The pressure of the carrier gas in the target chamber was 25 lb./in.^{2}, and counting was started two seconds after bombardment, the minimum time possible with the rather slow acting valves and compressor in the gas line. The period was measured with the Geiger counter calibrated against the Cl^{38} decay. No subtraction was necessary to eliminate the N^{16} activity since the beryllium neutrons at right angles to the deuteron beam were used. These were too slow to produce N^{16}. Checks to determine that the activity came from the beryllium were substitution of a target of silica gel for the $Be(OH)_2$ (this gave no gas of period shorter than N^{16}) and direct bombardment of beryllium with deuterons, which gave a weak gaseous activity of roughly one second period.

Another check on the identification was to filter the activated carrier gas through a Jena 3G3 sintered glass filter; this showed conclusively

[26] J. R. Oppenheimer, Phys. Rev. **59**, 908L, (1941). See reference 22 for a list of theoretical calculations on β-transitions in light nuclei.

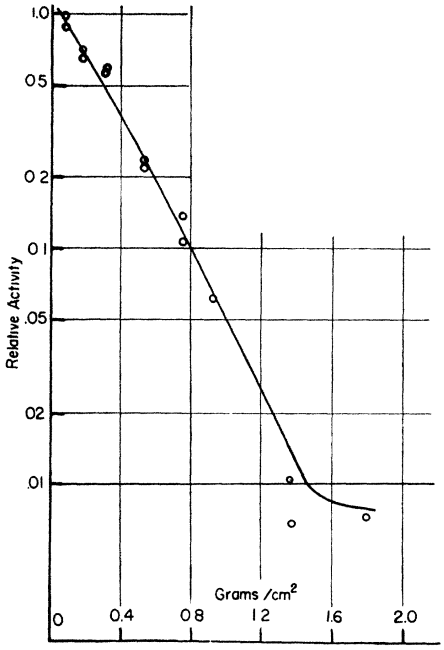

FIG. 5. He^6 absorbtion in aluminum.

the activity was not carried by fine particles of $Be(OH)_2$ dust, for the filter spacings of 20–30 microns passed the activity undiminished.

Figure 4 is a typical decay curve of pure He^6, again recorded photographically. The initial part of the curve, up to 2 sec., shows the build up as the gas flows over; the section from 2–2½ sec. shows the blocking of the counter when the gas is compressed; and the rest of the curve illustrates the rapid recovery of the counter and the purity of the decay. This curve was taken with the scale of 32 circuit. The statistics are actually worse than the graph would lead one to expect. Though the initial rate is high, 750 counts/sec. at 3 sec., the total number of counts recorded over the whole decay time from then on is only about $31 \times 32 = 1000$, as shown by the ordinate. Because of this difficulty, various decay curves differ amongst each other; our period, taken from an average of sixteen runs, is 0.85 ± 0.05 sec.

C. ABSORPTION

We ran an absorption curve on He^6 (Fig. 5) using the flat aluminum absorbers and the same geometry described in the work on nitrogen. The counts recorded in the interval from 2.2–4.0 sec. after bombardment with absorber interposed were compared with those from 4.5–6.0 sec. with no absorber. Again the neutron energy was too low to produce any N^{16} impurity. The estimated end point is 1.6 g/cm², giving a maximum energy of 3.5 ± 0.6 Mev. Because of insufficient data for this absorption curve, the existence of a gamma-ray cannot definitely be excluded. Judging by the concavity toward the axis of the absorption curve and the small intensity for the next to the last points, one would guess there are no gamma-rays. The high point at 1.8 g/cm², which might suggest a gamma-ray, is rather uncertain.

D. CONCLUSIONS

Our results are in substantial agreement with those of Bjerge and Bröstrum. A short lived gas emitting negative electrons is formed by medium energy neutrons on beryllium. Its period is 0.85 ± 0.05 sec., and its maximum energy found by absorption is 3.5 ± 0.6 Mev.

It is a pleasure to thank Professor K. T. Bainbridge for starting us on this work, and Dr. C. L. Critchfield for many valuable discussions. The extensive cooperation of Dr. Curtis, Mr. Bender, and Mr. Harpell of the Harvard Cyclotron Staff made this work possible. The Milton Fund gave generous grants for the construction of the cloud chamber, magnet, and Geiger counter circuits, and the W.P.A. furnished assistance in reducing the data.