corresponding distribution of the π^- experiment. The average number of prongs is significantly higher in the present case. This is qualitatively explained by assuming a primary nucleon-meson interaction in the absorption process. The reaction yields an energetic proton in the case of π^+ absorption and an energetic neutron in the other case. Charged particle emission is favored in π^+ absorption even without secondary collisions in the nucleus, while, if an α-particle model is justified, multiple charged particle emission is extremely likely. More data on π^+ meson capture, such as is being gathered at Columbia,[11] will be very valuable.

The cross section for the scattering of π^+ mesons on hydrogen as measured by Anderson *et al.*, imply a low cross section at 45 Mev. Yet even the upper bound for the cross section found in this experiment is low enough to show that multiple collisions within the nucleus are unlikely for π^+ mesons, as is also the case for π^- mesons.[20,23] It is reasonable then that no inelastic scatters were found.[5,10]

In contrast to Part I of this experiment on π^- mesons, few nuclear scatters were found. Though the statistical errors are large, it is striking that the estimated mean free path for scattering is significantly higher in the present experiment, a fact which is not reasonably explained by the slightly higher energy. The relative measurements are in qualitative agreement, however, with the Columbia emulsion investigations.[9–11]

TABLE III. Summary of results.

	Proton control technique	Usual scanning procedure	Either[a] technique
Total path length scanned (cm)	191	711	902
Number of disappearances in flight	0	0	0
Number of stars	1	10	11
Number of scatters greater than 30°	0	5	5
Number of scatters greater than 90°	0	1	1
Mean free path for stars (cm)			82+17
Mean free path for total nuclear interaction (cm) (assuming symmetry about 90°)			69±13
Mean free path corresponding to nuclear area (cm) (for emulsion)			23

[a] The errors are probable errors.

We wish to thank Dr. Chaim Richman and Dr. Miriam Cartwright for their help in exposing the plates. Mrs. Edith Goodwin scanned the plates with the extreme care that is necessary for an accurate experiment.

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Search for Betatron Induced, Low Z, Activities of Short Half-Life

RAYMOND K. SHELINE*
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

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B^8 has been observed as a 0.61±0.11 sec positron emitter produced by the following reactions: $B^{10}(\gamma,2n)B^8$, $B^{11}(\gamma,3n)B^8$, and $C^{12}(\gamma,p3n)B^8$. Li^9 has been observed as a 0.19±0.05 sec beta minus emitter produced by the reaction, $B^{11}(\gamma,2p)Li^9$. Irradiation of elements from $Z=3$ to $Z=9$ with a 0–50 Mev gamma-ray spectrum failed to induce any other short-lived activities. In spite of this, B^{13}, C^9, and O^{13} are not ruled out as short-lived activities. Li^4 is not produced in observable amounts through the reaction $Li^6(\gamma,2n)Li^4$ if it has a half-life between 0.1 sec and 1 min; it is probably particle unstable.

I. INTRODUCTION

An investigation was undertaken to survey the field of short-lived radioactivities among the elements with $Z<12$ with particular emphasis on elements with $Z<8$. It seemed highly probable that any new radioactive isotopes found in this region would be short-lived because most of the isotopes which had not been observed would lie considerably away from the stability region of equal neutrons and protons. Equipment was set up specifically to observe activities of short half-life, i.e., in the region from 0.1 sec to several hours. Then an attempt was made to observe as many betatron-produced short-lived activities as possible.

Since B^8 and Li^9 had been observed only recently, confirmation of their existence from a betatron irradiation seemed significant. B^8 has been observed as a delayed alpha-emitter by Alvarez.[1] He found that it decays by a 13.7-Mev positron with a 0.65-sec half-life to the same excited state of Be^8 as does Li^8; the B^8 was produced by the following nuclear reactions: $B^{10}(p,H^3)B^8$, $Be^9(p,2n)B^8$ and $C^{12}(p,n\alpha)B^8$.

The positrons from B^8 have been observed in this laboratory in the current study from the gamma-ray betatron irradiations of B and C. During these same irradiations, a 0.19-sec negative beta-activity was also observed. Gardner, Knable, and Moyer[2] have described

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* Present address: Chemistry Department, Florida State University, Tallahassee, Florida.

[1] L. Alvarez, Phys. Rev. 80, 519 (1950).

[2] Gardner, Knable, and Moyer, Phys. Rev. 83, 1054 (1951).

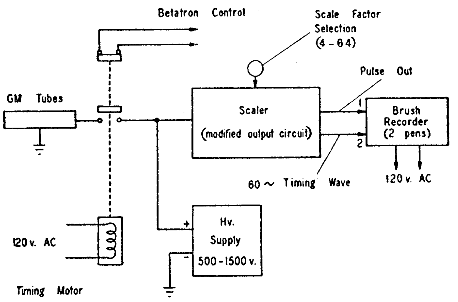

FIG. 1. Schematic diagram of apparatus used for controlling betatron and counting apparatus so that counting may begin milliseconds after the beam is turned off.

a new delayed neutron emitter, Li^9, with a 0.168-sec half-life. Whereas they have observed the delayed neutrons, the negative beta-particles have been observed directly in this laboratory.

II. EXPERIMENTAL

Several investigators[3,4] have found that heavy fragments (e.g., Li^8, Be^7) are expelled from nuclei on irradiation with high energy particles. Since many of these fragments have short half-lives, it would be necessary to distinguish between these processes (should they occur) and the production of new activities. Fortunately it was not possible in this study to observe this phenomenon when nuclei with $Z \geq 7$ were bombarded with a gamma-ray spectrum of 0–50 Mev or with a gamma-ray spectrum of 0–85 Mev.

Throughout the course of these experiments the principle problem was one of getting sufficiently high intensities of activities. Since the activities sought have short half-lives it was not possible to carry out chemical separations and the activities were to be identified by means of their half-lives and through the use of cross irradiations. Therefore, it was necessary to have enough of the activities produced to give good counting rates. Since γ-ray cross sections are notoriously low, an effort was made to maximize the total counts by (1) using a solid cylindrical target with its axis along the beam to intercept as large a percentage of the beam as possible; (2) using a large number of Geiger tubes arranged in a concentric circle around the target to increase the geometry; (3) summing the counting statistics of a number of consecutive runs; and (4) counting the sample within milliseconds after the beam was turned off.

The essence of the experiment was the following: a solid target in the form of a cylinder 20 to 25 cm in length was placed directly in the beam of the betatron in such a way that the beam center was focused along the axis of the cylinder. The target was counted in place immediately after turning off the beam with a concentric ring of 11 matched Geiger tubes two inches off the center of the beam but parallel to both the beam and the target. The Geiger tubes were shielded from the direct beam by 6 inches of lead. The betatron and the scaler were controlled by a motor-driven timing switch which executed the following duty cycle: betatron on, scaler off —3 sec; betatron off, scaler on —5 sec; betatron on, scaler off —3 sec, etc. The scaler pulse was fed directly to one pen of a two channel Brush recorder. The other pen was fed 60 cycle ac to act as a timer. In this way it was possible to irradiate a target for 3 sec and then count it within milliseconds after the beam was turned off for a period of 5 sec. The experimental arrangement employed is schematically illustrated in Fig. 1. The counters were of thin glass (35 mg/cm^2), 1 inch o.d., 12 inches long with an effective counting length of 25 cm. The targets were: lithium fluoride, a reagent grade chemical in the form of a pressed pill cylinder 8.25 inches in length and $\frac{5}{8}$ inch in diameter; elemental beryllium fabricated from fragments in the form of a crude cylinder 8 inches long and approximately 1 inch in diameter; elemental boron in the form of 4 cylinders 8.25 inches long and $\frac{3}{8}$ inch in diameter (the boron had 1.6 percent carbon as an impurity); and elemental carbon in the form of a cylinder 8 inches in

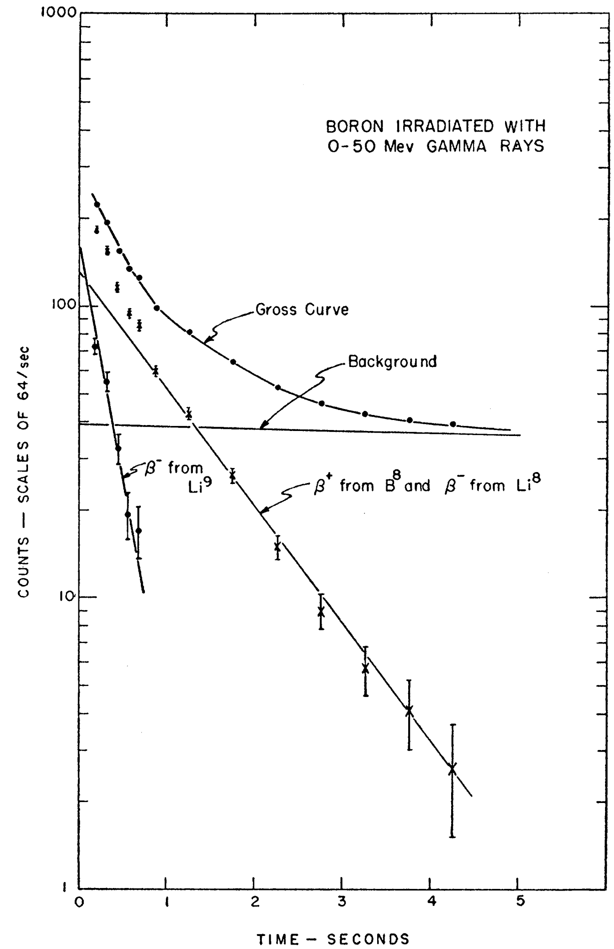

FIG. 2. Decay induced from the betatron irradiation of elemental boron with a 0–50 Mev gamma-ray spectrum.

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[3] S. C. Wright, Phys. Rev. 79, 838 (1950).

[4] L. Marquez, Phys. Rev. 81, 953 (1951).

length and 1 inch in diameter with no spectrographically observable impurities. Similar targets of NH_4I, V_2O_5, NaF, NaCl were available.

With the experimental arrangement schematically illustrated in Fig. 1 it was possible to observe half-lives in the region from 0.1 sec to 1 min. Some indication of shorter half-life activities was also possible. Using the more traditional lead shielded end window Geiger counter and a "rabbit" to transport the samples quickly after irradiation it was possible to check the half-life region from 1 minute to several hours.

III. EXPERIMENTAL RESULTS

In the irradiation of LiF with the University of Chicago 0–50-Mev betatron gamma-ray spectrum, a very considerable yield of He^6 was observed from the reaction $Li^7(\gamma,p)He^6$. The half-life observed over 6 half-lives was 0.86±0.03 sec in good agreement with previous investigators.[5–7] There was no indication of a short-lived activity indicative of Li^4 which might have been produced by the reactions $Li^6(\gamma,2n)Li^4$ or $Li^7(\gamma,3n)Li^4$. Therefore, it seems reasonable to conclude that Li^4, if it exists, does not have a half-life in the region from 0.025 sec to one min with the exception of the 0.85-sec region which is obscured by the He^6 activity.

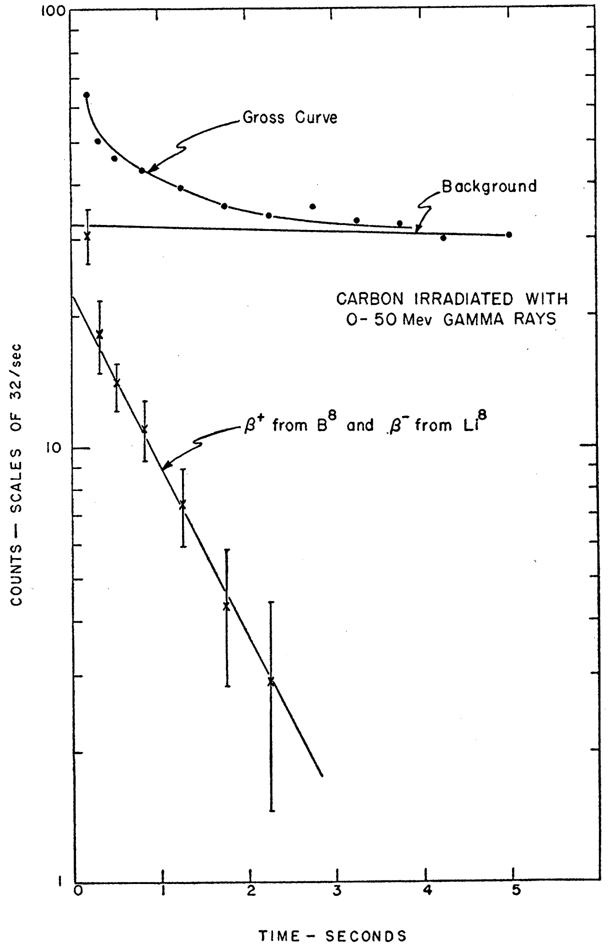

FIG. 3. Decay induced from the betatron irradiation of elemental carbon with a 0–50 Mev gamma-ray spectrum.

TABLE I. Thresholds for some of the various nuclear reactions considered,[a] calculated from known masses.

Reaction	γ-threshold E
$C^{12}(\gamma,H^3n)B^8$	46.0 Mev
$C^{12}(\gamma,d2n)B^8$	52.3
$C^{12}(\gamma,p3n)B^8$	54.5
$C^{12}(\gamma,He^3,p)Li^8$	43.0
$C^{12}(\gamma,d2p)Li^8$	48.5
$C^{12}(\gamma,3pn)Li^8$	50.7
$B^{11}(\gamma,3n)B^8$	38.4
$B^{11}(\gamma,He^3)Li^8$	27.1
$B^{11}(\gamma,dp)Li^8$	32.6
$B^{11}(\gamma,2pn)Li^8$	34.8
$B^{10}(\gamma,2n)B^8$	27.1
$B^{10}(\gamma,2p)Li^8$	23.4
$C^{12}(\gamma,3p)Li^9$	48.3
$B^{11}(\gamma,2p)Li^9$	32.3

[a] The mass of B^8 was assumed to be 8.0273; the mass of Li^9 was assumed to be 9.0313. Corrections were not made for potential barrier effects where charged particles are emitted.

The bombardment of elemental Be with 0–50-Mev gamma-rays produced Li^8 by the reaction $Be^9(\gamma,p)Li^8$. The activity was followed for six half-lives and gave the value 0.85±0.016 sec. Several runs were summed to give the best possible result (i.e., lowest probable error) because the value of this half-life was important in determining the half-lives of B^8 and Li^9. This value agrees with the more recent work of Rall and McNeill[8] and Baldwin,[9] and is lower and slightly outside the experimental error of Hughes *et al.*[10] No evidence for Be^6 from the reaction $Be^9(\gamma,3n)Be^6$ was found. However, Bethe[11] has suggested that Be^6 is not expected to be particle stable due to larger Coulombic forces than those in He^6.

The bombardment of elemental boron produced the decay curve shown in Fig. 2. When corrections were applied for the carbon activities induced from 1.6 percent carbon impurity, the resultant curve was easily resolved into the two half-lives of 0.75±0.03 sec and 0.19±0.05 sec. When the beta-particles from this bombardment were magnetically analyzed, it was found that 55±8 percent of the 0.75-sec half-life component were negative beta-particles and the rest were positrons. The 0.19-sec component consists entirely of negative betas. The following nuclear reactions are postulated to account for the activities observed: $B^{10}(\gamma,2p)Li^8$; $B^{11}(\gamma,2pn)Li^8$ or $B^{11}(\gamma,He^3)Li^8$—a 0.85-sec negative beta-emitter and $B^{10}(\gamma,2n)B^8$; $B^{11}(\gamma,3n)B^8$—a 0.61±0.11

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[9] G. C. Baldwin, Phys. Rev. **76**, 182A (1949).

[10] Hughes, Hall, Eggles, and Goldfarb, Phys. Rev. **72**, 646 (1947).

[11] H. A. Bethe, Phys. Rev. **54**, 436 (1938).

sec positron emitter. These two activities have such similar half-lives that they form the composite 0.75-sec half-life of 55 percent negative betas and 45 percent positrons shown in Fig. 2. $B^{11}(\gamma,2p)Li^9$ accounts for the negative beta-emitter shown in Fig. 2 with a 0.19 ± 0.05 sec half-life. Gardner, Knable, and Moyer[2] have suggested that the decay scheme for Li^9 is:

$$Li^9 \rightarrow Be^{9*} + \beta^- + \nu, \quad (1)$$

$$Be^{9*} \rightarrow Be^{8*}(2\alpha) + n. \quad (2)$$

If this suggestion is correct the neutrons should decay with the half-life of the parent, Li^9, with which they are in "immediate" equilibrium because their true half-life is very short relative to the half-life of Li^9. The half-life they report for the delayed neutrons, 0.168 sec, agrees within experimental error with the value observed in this laboratory for the negative betas, $(0.19\pm0.05$ sec).

In the bombardment of elemental carbon some further evidence for B^8 was found. A composite half-life of 0.76 ± 0.12 sec was observed in which there were approximately equal numbers of negative betas and positrons. The decay curve is shown in Fig. 3. The first point gives a hint of a possible Li^9 activity in this decay curve also. However, because there were fewer counts it was not possible to verify the existence of Li^9 in this irradiation or to obtain an accurate value of the half-life of B^8. Table I summarizes the various nuclear reactions and thresholds in producing Li^8, B^8, and Li^9 from the gamma-irradiations of boron and carbon.

In addition to the above-mentioned activities the following nuclear reactions and activities were produced: $C^{12}(\gamma,2n)C^{10}$—a 20-sec positron emitter; $C^{12}(\gamma,n)C^{11}$—a 20-min positron emitter; $N^{14}(\gamma,n)N^{13}$—a 10-min positron emitter; $F^{19}(\gamma,2p)N^{17}$—a 4-sec negative beta-emitter; $N^{14}(\gamma,2n)N^{12}$ and $N^{14}(\gamma,2p)B^{12}$—an extremely short composite half-life; $O^{16}(\gamma,n)O^{15}$—a 120-sec positron emitter and $O^{16}(\gamma,2n)O^{14}$—a 77-sec positron emitter; and $Na^{23}(\gamma,3n)Na^{20}$—a 0.23-sec positron emitter.[12]

No activities were observed which might have been ascribed to C^9, B^{13}, or O^{13} although these species might have been produced by the following reactions: $C^{12}(\gamma,3n)C^9$, $N^{15}(\gamma,2p)B^{13}$, and $O^{16}(\gamma,3n)O^{13}$. Since in each of these cases either the isotopic abundance of the element irradiated was very low, or a three particle nuclear reaction was involved, the absence of an observable activity in the half-life interval from 0.1 sec to 1 min does not preclude its existence in this region.

CONCLUSION

The discovery of B^8 and Li^9 has given new impetus to the search for other low Z isotopes. In view of this research B^{13} offers the greatest promise, with C^9 and O^{13} as distinct possibilities also. Barkas[13] estimates the mass of B^{13} as 13.0207, which distinctly indicates particle stability. Furthermore B^{13} differs by one alpha-particle from both Li^9 and N^{17} which are delayed neutron emitters of 4.13 and 0.168 sec, respectively. B^{13} might then be expected to be a delayed neutron emitter of the order of 1-sec half-life. Barkas has also estimated the mass of C^9 as 9.036, which places it on the very edge of particle stability. (The sum of proton and B^8 masses is 9.0354.) If C^9 and O^{13} exist they might be expected to be delayed proton emitters by analogy with the delayed neutron emitters, Li^9 and N^{17}.

If Li^4 exists, it is possible to set limits on the energy of its positron from the following considerations. The mass of Li^4 must be greater than 4.02628 because otherwise B^8 would be essentially instantaneously unstable with respect to the products, $Li^4+\alpha$. It also must be less than 4.02631 because, if it were not, Li^4 would be unstable toward the emission of a proton and formation of He^3. Therefore, if a mechanically stable Li^4 exists it must go to He^4 by the emission of a positron of from 19.82 to 19.85 Mev. This is not only a narrow mass range into which to expect Li^4 to fall, but it also suggests that a positron of such high energy should have a short half-life, observable in these experiments. In view of these calculations, the work of Breit and McIntosh[14] on H^4, and the failure to find Li^4 in these irradiations, it seems probable that Li^4 is particle unstable.

It is a pleasure to acknowledge the help, advice, and interest of Professor W. F. Libby and Dr. R. W. Stoughton and the services of Mr. Charles McKinney and the betatron operating crew.

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