Photoproduction of Beryllium-7

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ABSTRACT

The nuclide Be^7 has been produced by photoactivation of Be^9 , B and Cl^{12} using the bremsstrahlung beam of an electron synchrotron operated at 45 Mev. Integrated cross sections for the formation of Be^7 have been estimated by comparison with the $\text{Ta}^{181}(\gamma, n)\text{Ta}^{180m}$ reaction. The reaction $\text{Cl}^{12}(\gamma, 2p3n)\text{Be}^7$ has also been observed in irradiations at 30, 35 and 40 Mev maximum energy. Its yield has been compared with that of the $\text{Cl}^{12}(\gamma, n)$ reaction at 45 Mev. The reaction $\text{Al}^{27}(\gamma, 2p3n)\text{Na}^{22}$ was observed at 45 Mev.

1. INTRODUCTION

Experimental and theoretical investigations of the phenomena of photonuclear reactions have been the subject of a large number of studies since the first observed photodisintegrations of deuterium and beryllium¹. The most

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common reactions which have been studied are the (γ, n) and (γ, p) reactions. Less common are the "exotic" reactions in which two or more nucleons are emitted as the result of photoexcitation.

A singular neutron-deficient isotope in the region of $Z < 10$ is the beryllium isotope of mass seven. It is separated from the other known beryllium isotopes by the completely unstable Be^8 nucleus. Also, it has recently been observed as a spallation product in a number of high energy processes². Beryllium-7 decays by K-capture with a 477 kev gamma-ray accompanying 12% of the decay processes.

The production of Be^7 by the $\text{Be}^9(\gamma, 2n)$ reaction has been reported by Lokan³, who bombarded a block of beryllium metal in a bremsstrahlung beam of 30 Mev maximum energy for a total of 16 hours to obtain a counting rate of only 10 counts per minute. To our knowledge no other photonuclear reactions producing Be^7 have been reported.

It was the purpose of this investigation to determine if Be^7 might be produced in a medium energy bremsstrahlung beam using as target materials the light elements, beryllium, boron, carbon, oxygen and aluminum. It was also desired to estimate the yields of the reactions relative to other photonuclear reactions of known yields.

The number of radioactive nuclei, $N(E_0)$, formed during an irradiation at a particular bremsstrahlung maximum energy

E_0 , is given by

$$\alpha(E_0) = \eta \int_0^{E_0} \sigma(E) N(E_0, E) dE \quad (1)$$

where η = the number of target nuclei, $\sigma(E)$ = the cross section as a function of photon energy E , and $N(E_0, E)$ = the number of photons per unit area between E and $(E + dE)$.

For two photonuclear processes which peak sharply at $E_{\max}(1)$ and $E_{\max}(2)$, the ratio of the yields may be used to estimate the ratio of the integrated cross sections. Using the assumption that the bremsstrahlung spectra is proportional to $\frac{1}{E}$, the ratio of yields is estimated as

$$\frac{\alpha_2}{\alpha_1} = \frac{\eta_2 E_{\max}(1) \int_0^{E_0} \sigma_2 dE}{\eta_1 E_{\max}(2) \int_0^{E_0} \sigma_1 dE} \quad (2)$$

In cases in which $\int_0^{E_0} \sigma_1 dE$ is known, the integrated cross section for the other reaction may be calculated. For comparison of the cross sections, the reaction $Ta^{181}(\gamma, n)Ta^{180m}$ was chosen. The detailed work of Carver and co-workers^{4,5} was used as standard for this purpose. In addition, the work of Barber, et al⁶ in determining the cross section of the $C^{12}(\gamma, n)C^{11}$ reaction was used as a secondary standard in some of the irradiations of carbon.

In order to determine the number of nuclei of sample and monitor in the beam, it was necessary to assume that equal areas

of each were struck by the beam. Once this had been established, the number of nuclei of each type was estimated from the densities, molecular weights and isotopic abundances.

The average yield ratios per target nucleus were calculated relative to the $\text{Ta}^{181}(\gamma, n)\text{Ta}^{180m}$ and $\text{C}^{12}(\gamma, n)\text{C}^{11}$ reactions.

2. EXPERIMENTAL

Target materials of metallic beryllium from the Beryllium Corporation, powdered boron from Fairmont Chemical Company, carbon spectrograph rods from National Carbon Company, "Fisher Certified Reagent" boric acid, "Baker's Analyzed" cupric oxide, 2S grade aluminum rods, and fused silica rods were used in these irradiations.

They were irradiated in a probe extending into the donut of the Iowa State University synchrotron which was operated at a maximum bremsstrahlung energy of 45 ± 2 Mev or as determined by an energy control device called the integrator. All irradiations were monitored by the use of tantalum foils of 0.0005 in. thickness which were wrapped around the sample. In the case of the powdered samples, the monitor foil was wrapped around the brass container used to hold the sample.

All samples in which Be^7 was anticipated were counted in a well-type $\text{NaI}(\text{Tl})$ scintillation counter to detect radiation with photon energy in excess of 40 kev. Gamma spectra were taken using an RCL 256 channel pulse height analyzer which was calibrated with standard activities of Be^7 , Na^{22} , Cs^{137} ,

Hg²⁰³, Mn⁵⁴ and Co⁶⁰. The tantalum monitor foils were counted in a conventional GM counting arrangement. Two foils were counted also with the scintillation counter used for the Be⁷ samples to obtain conversion factors for the two instruments.

3. RESULTS

Plots of the net counting rates for the tantalum monitor foils were examined visually to obtain half-lives and intercepts. The experimental points were very close to a straight line on a semi-log plot so that a least squares treatment was not considered necessary. The average of the tantalum half-life determinations was 8.19 hours which compares well with the accepted value of 8.15 hours⁷.

3.1 Beryllium Results

Two beryllium rods were irradiated for periods of 4 hours each in the bremsstrahlung beam at the maximum energy of the synchrotron (45 ± 2 Mev) and subsequently counted in the well-type scintillation counter. Data so obtained were analyzed using a weighted least squares treatment. The average of two values for the integrated cross section, $\int_0^{45 \text{ Mev}} \sigma(E) dE$, was determined to be $(6 \pm 2) \times 10^{-3}$ Mev-barns. This value may be compared with Lokan's value to 30 Mev of $(1.2 \pm 0.2) \times 10^{-3}$ Mev-barns³. The errors shown include those from the individual measurements and the estimated uncertainties in the integrated cross sections for the Ta(γ, n) reaction used for comparison.

3.2 Boron Results

Duplicate samples of powdered boron were irradiated at 45 Mev for periods of 6 hours each and counted as previously described. The integrated cross section for the production of Be^7 from boron was estimated with the help of Eq. (2) giving the results shown in Table I.

In the gamma-ray spectra of these samples, two peaks were visible, at 130 ± 20 and 830 ± 20 kev, which were considered most probably due to impurities. Qualitative spectroscopic analysis of the boron showed weak to moderate amounts of iron and lesser amounts of calcium, chromium, copper, magnesium, nickel, manganese, silicon and perhaps zirconium. It is possible that the peak at 130 kev is due to Mn^{54} which could have been formed from the iron or manganese impurity. Similarly the peak at 830 kev may be due to Co^{57} from the nickel impurity. It was felt that the contribution of these peaks was minimal and they were neglected for purposes of calculation.

3.3 Irradiation of Oxygen

Duplicate samples of orthoboric acid were converted to metaboric acid by drying at $103 - 105^\circ\text{C}$ for approximately 5 hours. They were irradiated in a bremsstrahlung beam of maximum energy 45 Mev and counted for Be^7 activity. The amount of Be^7 formed was compared with that expected from the calculated boron content and was not found to be appreciably larger. (See Table I).

However, since there was some doubt regarding the actual boron content of the sample, two other oxides were irradiated to establish more definitely whether or not Be^7 was produced from O^{16} . These compounds, cupric oxide, as powder, and silica, as a fused rod, were irradiated at 45 Mev. The gamma-ray spectra did not show any peak at 477 kev indicating that the $\text{O}^{16}(\gamma, 4p5n)\text{Be}^7$ reaction was not observed.

3.4 Carbon Results

Duplicate samples of carbon were irradiated at 45, 50 and 35 Mev maximum bremsstrahlung energy and a single sample at 30 Mev. The time of irradiation varied from 4 to 7 hours. Results of these experiments are summarized in Table I.

A second pair of samples was irradiated at 45 Mev for a period of 30 minutes and counted immediately in order that the C^{11} content might be determined and compared directly with the amount of Be^7 produced. The results from these irradiations are given in Table II. The discrepancy between the values estimated for the integrated cross sections in Table II is possibly due to inaccuracies in the determinations of the integrated cross sections with which comparison was made.

The gamma-ray spectra of these samples was identical with that of the standard Be^7 used for calibration processes. An example of the spectrum determined experimentally is shown in Figure 1. The average half-life of Be^7 as determined in all irradiations including both carbon series was 53 ± 2 days.

3.5 Irradiation of Aluminum

Duplicate samples of aluminum were irradiated for periods of 4 hours each with the synchrotron operating at maximum energy. After irradiation these samples were counted in a manner similar to that previously described. The gamma-ray spectrum was consistent with that of material known to be Na^{22} with no indication of the 477 kev Be^7 peak. It is possible that this peak could have been masked by the large 511 kev peak from the annihilation of the Na^{22} positron. However, at most only a very small amount of Be^7 was present since the shape of the peak did not appear to be distorted. The integrated cross section for the $\text{Al}^{27}(\gamma, 2p3n)\text{Na}^{22}$ reaction is given in Table I.

3.6 Calculations

The integrated cross sections listed in Table I were calculated using Eq. (2), the yield of $\text{Ta}^{180\text{m}}$ from the monitor foils and the published values^{4,5} of the integrated cross section for the reaction $\text{Ta}^{181}(\gamma, n)\text{Ta}^{180\text{m}}$. The yields relative to those of $\text{Ta}^{180\text{m}}$ (Table I, Column 6) were similarly calculated directly from the measurements. For the yields relative to those of C^{11} (Table I, Column 7) we used the results of the 30 minute irradiation of carbon in which the Be^7 yield was compared both to C^{11} and $\text{Ta}^{180\text{m}}$ (see Table II). The ratio of these numbers, $14 \times 10^{-2} / 16 \times 10^{-4}$, was used to convert yields compared to Ta^{181} to yields compared to C^{11} . Since the C^{11} to $\text{Ta}^{180\text{m}}$ ratio was determined at 45 Mev only, the latter calculation was not made for the irradiations of carbon at lower energies.

Table I Relative yields and integrated cross sections for formation of Be^7 and Na^{22}

Target material & run number	E_0 Mev	Product half-life, days	Activity at end of irradiation cts/min	$\int_0^{E_0} \sigma(E) dE$ Mev-mb	Yield, relative to $\text{Ta}(\gamma, n)=10^4$	Yield, relative to $\text{C}(\gamma, n)=10^2$
Be-(1)	45			4.9 ± 2.2		
-(2)	45			5.3 ± 2.4		
-(Av)		57	4530	5 ± 2	12 ± 2	11 ± 3
B-(1)	45			2.1 ± 1.0		
-(2)	45			1.8 ± 0.9		
-(Av)		52	953	1.9 ± 0.6	3.2 ± 0.6	3.0 ± 0.9
HBO ₂ -(1)	45			2.5 ± 1.2		
-(2)	45			2.0 ± 0.9		
-(Av)		56	108	2.2 ± 0.7	4.3 ± 0.5	4 ± 1
C-(1)	45			12 ± 6		
-(2)	45			12 ± 6		
-(Av)		51	1987	13 ± 4	18 ± 3	17 ± 5
C-(3)	40			7 ± 3		
-(4)	40			7 ± 3		
-(Av)		53	1080	7 ± 2	12 ± 2	
C-(5)	35			4 ± 2		
-(6)	35			4 ± 2		
-(Av)		54	707	4 ± 1	7 ± 1	
C-(7)	30	56	175	0.5 ± 0.2	1.1 ± 0.3	
Al-(1)	45			14 ± 6		
-(2)	45			8.8 ± 4		
-(Av)		2 yrs (Na-22)	1880	10 ± 3	14 ± 3	13 ± 4

Table II Relative yields of $\text{Cl}^{12}(\gamma, 2p3n)\text{Be}^7$ reaction, compared to different monitor reactions, $E_0 = 45 \text{ Mev}$

Monitor reaction	$\int_0^{E_0} \sigma(E) dE$ Mev-mbarns	Yield, relative to $\text{Ta}(\gamma, n)=10^4$	Yield, relative to $\text{C}(\gamma, n)=10^2$
$\text{Ta}^{181}(\gamma, n)\text{Ta}^{180m}$ (1)	11 ± 5		
(2)	11 ± 5		
(Av)	11 ± 3	16 ± 3	
$\text{C}^{12}(\gamma, n)\text{C}^{11}$ (1)	14 ± 3		
(2)	16 ± 4		
(Av)	15 ± 3		14 ± 3

4. DISCUSSION

It is noteworthy that the yield ratios for the production of Be^7 from carbon are higher than those for its production from Be^9 . The yield ratio for the production of Be^7 and C^{11} from C^{12} shows that the reaction which gives rise to Be^7 is about 13% as probable as the (γ, n) reaction yielding C^{11} . This seems surprisingly high.

A calculation of mass thresholds for various types of reactions using the masses listed by Sullivan⁸ shows the following:

- a. For the reaction $\text{Be}^9(\gamma, 2n)\text{Be}^7$, $-Q_m = 20.6$ Mev.
- b. For the production of Be^7 from B^{10} and B^{11} the values of $-Q_m$ for all particle emission paths lie below 45 Mev, from 18.6 for the $\text{B}^{10}(\gamma, t)$ reaction to 38.6 for the $\text{B}^{11}(\gamma, p3n)$ reaction. The present data do not provide sufficient information for any decision regarding the pathway.
- c. For the production of Be^7 from C^{12} , the only paths which have mass thresholds below 45 Mev are the $(\gamma, \alpha n)$, (γ, He^5) and (γ, td) reactions with thresholds at 26.3, 27.2 and 43.9 Mev respectively. Since He^5 is unstable with respect to He^4 and a neutron, its emission as a single entity seems unlikely. Over the range of energies investigated the yield of Be^7 from carbon appeared to vary smoothly indicating that a single mechanism is involved for the reaction up to 45 Mev. This fact and the nearness of its threshold to 45 Mev would appear to eliminate the

(γ ,td) reaction from consideration. Thus the reaction by which Be^7 is produced from C^{12} appears to be the excitation of the C^{12} nucleus followed by the ejection of an alpha particle and a neutron. If the reaction proceeds with the alpha particle emission step first a neutron emitting state of Be^8 would be involved. If the neutron is emitted first an alpha emitting state of C^{11} would be involved. From the fact that the cross section of the $\text{C}^{12}(\gamma, 2p3n)$ reaction is considerably larger than that for $\text{Be}^9(\gamma, 2n)$ reaction (13 compared to 5 Mev millibarns) one could conclude that the two reactions do not involve the same intermediates. Hence the pathway involving neutron emission first to an alpha emitting state of C^{11} would appear to be the most likely for the photoproduction of Be^7 from C^{12} .

d. For the $\text{Al}^{27}(\gamma, 2p3n)\text{Na}^{22}$ reaction $-Q_m$ values range from 22.5 Mev for the $(\gamma, \alpha n)$ reaction to 50.8 Mev for the emission of neutrons and protons indicating that particles of larger than unit weight must be emitted.

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REFERENCES

1. J. Chadwick and M. Goldhaber, Proc. Roy. Soc. (London), Ser. A, 151, 479 (1935).
2. P. A. Benioff, Phys. Rev., 119, 316 (1960).
3. K. H. Lokan, Proc. Phys. Soc. (London), Ser. A, 70, 836 (1957).
4. J. H. Carver, R. D. Edge and K. H. Lokan, Proc. Phys. Soc. (London), Ser. A, 70, 415 (1957).
5. J. H. Carver and W. Turchinets, Proc. Phys. Soc. (London), Ser. A, 71, 613 (1958).
6. W. C. Barber, W. D. George and D. D. Reagan, Phys. Rev., 98, 73 (1955).
7. D. Strominger, J. M. Hollander and G. T. Seaborg, Rev. Mod. Phys., 30, 585 (1958).
8. W. H. Sullivan, Trilinear Chart of Nuclides, U.S. Gov't. Printing Office, 1957.

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Figure 1. Gamma-ray spectrum of irradiated carbon rod. Sample irradiated 4 hours with beam of maximum energy 45 Mev, counted for 7 hours.

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