1960

Photoproduction of beryllium-7

Melvin Smith Foster

Iowa State University

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PHOTOPRODUCTION OF BERYLLIUM-7

by

Melvin Smith Foster

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
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DOCTOR OF PHILOSOPHY

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In Charge of Major Work

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Dean of Graduate College

Iowa State University
Of Science and Technology
Ames, Iowa

1960
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I. INTRODUCTION

A. History of Photonuclear Reactions

Experimental and theoretical investigations of the phenomena of photonuclear reactions has been the subject of a large number of studies since the first observed photodisintegrations of deuterium and beryllium. These reactions were observed by Chadwick and Goldhaber (1, 2) using the 2.62 and 1.8 Mev $\gamma$-rays from ThC" and RaC.

From this modest beginning, expansion of the field has been made possible largely through the development of artificial sources of photons of high energy, commonly bremsstrahlung from accelerators or $\gamma$-rays from one of several $(p, \gamma)$ reactions.

The most common reactions which have been studied from the start are the $(\gamma, n)$ and $(\gamma, p)$ reactions (3). Furthermore, most of the theoretical interpretations which have been forwarded concern themselves with these reactions, and perhaps rightly so, for the cross section for these reactions are larger, in general, than others. These reactions are similar for all isotopes studied in that they all exhibit a pronounced resonance peak (or several peaks) when the cross section is studied as a function of photon energy. For a summary of these and other developments in the field of photonuclear reactions, reference is made to the review articles of Strauch (4), Levinger (5), Titterton (6) and Wilkinson (7), along with
the bibliography of Toms (8).

Less common are the reactions in which more than one nucleon is emitted. The particles emitted in these "exotic" reactions vary all the way from the deuteron to Li$^8$ and N$^{17}$ (9 - 21). Also to be mentioned are the reactions in which multiple particle emission occurs, such as ($\gamma$, 2n) and ($\gamma$, 2p). While it is true that some of these type reactions have been effected with photons from very high energy machines, it is noteworthy that Li$^8$ emission has been observed using x-rays with a modest energy of only 26.7 Mev.

B. Purpose of Investigations

In considering the light elements ($Z < 10$) a singular isotope is the beryllium isotope of mass seven. This isotope has a half-life of approximately 53 days—by far the longest of the neutron-deficient isotopes in this region—and decays by electron capture to Li$^7$, 12 per cent of the time through the 477 kev isomeric level of Li$^7$ and from thence to the ground state by gamma emission (22). Thus the method of counting immediately suggested in this case is the scintillation method (23, 24, 25). The nuclide Be$^7$ has been studied widely and has even been postulated as an intermediate in nucleogenesis in stars to explain the abundance of lithium as determined by spectroscopic analysis (26).

In view of the fact that Be$^8$ is unstable with a half-life
in the neighborhood of $10^{-15}$ seconds and $B^8$ a half-life of only 0.6 seconds (27), $Be^7$ may not be produced by a simple photonuclear reaction. It is seen that even the simplest photoproduction, $Be^9(\gamma, 2n)Be^7$, must involve either the simultaneous emission of two neutrons or an excited neutron-emitting state of $Be^8$.

Therefore, it was decided to determine if beryllium-seven might be produced in a medium-energy bremsstrahlung beam. Target materials chosen for this study were beryllium, boron, carbon, oxygen and aluminum.

C. Literature Search

Beryllium-seven has been produced in a bremsstrahlung beam by Lokan (28), who bombarded a block of beryllium metal in a bremsstrahlung beam of 30 Mev maximum energy for a total of sixteen hours. The maximum counting rate attributed to $Be^7$ was 10 c.p.m. The integrated cross section for the reaction $Be^9(\gamma, 2n)Be^7$ was estimated.

No other photonuclear reactions producing beryllium-seven were found to have been reported. However, a number of other reactions producing $Be^7$ were reported in addition to the most common method of producing the isotope, the cyclotron reaction $Li^7(p, n)Be^7$ (29).

Dickson and Randle (30) and others have reported the production of $Be^7$ from carbon targets bombarded by protons of
from 32 to 156 Mev energy. This same type of spallation re-
action has been reported to produce Be\(^7\) from beryllium,
nitrogen, oxygen, fluorine, sodium, aluminum, copper, silver
and gold (31 - 37). In addition, carbon spallation by 90 Mev
neutrons (38), oxygen irradiated by high energy deuterons (39)
and aluminum bombarded by 160 Mev \(^{16}\)O nuclei (40) have been
reported to produce beryllium. However, Be\(^7\) was not noted as
a reaction product in high nvt irradiated beryllium (41).
Turkevich and Sugarman (42) have postulated the formation and
subsequent capture of beryllium in copper irradiated with 2.2
Bev protons to explain the observed yields of As\(^{70}, \, 71\) and 72.
In the proton spallation reactions, the yield of Be\(^7\) could not
be explained on the basis of a nuclear evaporation model, and
was postulated to be ejected directly from the target nucleus.

Photon interactions with beryllium have been studied by
many—for example Kliger, et al. (43) and Nathans and Halpern
(44). The theory of this type interaction has been treated by
Guth and Mullen (45).

The photodisintegration of boron has been studied experi-
mentally by Rochat and Stoll (46) and others (47 - 50).

The interaction of gamma radiation and carbon nuclei has
been studied by many workers. The \((\gamma, \, n)\) reaction has been
studied by Barber, et al. (51) and others (52 - 58). In addi-
tion, alpha emitting states of carbon have been observed by
gamma excitation (59 - 67) as well as other reactions (68 -
Photoreactions in oxygen which produce neutrons (73), alpha particles (74 - 78) and other particles (79 - 82) have been reported previously.

Aluminum has been observed to emit neutrons (83, 84), protons (85), alpha particles (86) and combinations of these (87 - 89) as a result of gamma excitation.
II. THEORY OF TECHNIQUE

A. Basic Information Required

One of the difficulties in using a high energy electron accelerator as a source of photons for the quantitative study of photonuclear reactions is the bremsstrahlung distribution, which means that one must use a beam containing gamma energies from zero to the maximum electron energy as opposed to the ideal beam containing only monoenergetic photons. This maximum electron energy may be varied, and methods have been developed (90) for the solution of yield curves obtained from beams of varying maximum energy to give cross sections as a function of energy. If one is interested only in integrated cross sections, the situation is somewhat simpler, as will be seen.

For a photonuclear reaction, let:

\[ \alpha(E_0) = \eta_s \int_0^{E_0} N(E_0, E) \sigma(E) \, dE \]

\[ = \eta_s \int_0^{E_0} \frac{I(E_0, E) f_s(E)}{E F(E_0)} \sigma(E) \, dE \]  

(1)

where

\[ \alpha(E_0) = \text{number of product nuclei formed per unit of monitor response,} \]

\[ E_0 = \text{maximum electron energy,} \]

\[ E = \text{photon energy,} \]
\[ N(E_0, E) = \text{number of photons of energy } E \text{ per unit range of } E \text{ which enter the sample per unit of monitor response,} \]

\[ \sigma(E) = \text{cross section for the photoproduction of product nuclei from target nuclei in terms of unit area per nucleus at energy } E, \]

\[ I(E_0, E) = \text{a function at least proportional to the bremsstrahlung energy spectrum,} \]

\[ F(E) = \text{monitor response function which normalize the bremsstrahlung spectra to unit monitor response.} \]

In order to solve equation (1) it is necessary, then, to know not only the yield, \( \alpha(E_0) \), but also such other items as the number of target nuclei and the number of photons of given energy in the beam impinging upon the target.

B. Assumptions

Since many of the quantities in equation (1) are not known, it is usual to make certain simplifying assumptions. The Schiff (91) integrated-over-angles spectrum is assumed to be valid as corrected for absorption by material between the x-ray target and the sample with an additional correction for
the varying efficiency of the monitor for different photon
energies. In addition, it is assumed that the integrator, or
electron energy control device, does not affect the shape of
the spectrum of the beam.

For a comparison of the integrated cross sections of two
different photonuclear reactions, a simultaneous irradiation
of both target materials enables one to eliminate all monitor
considerations in calculating the ratio of the integrated
cross sections. Since in this work it was anticipated that
the cross sections would be very small, only integrated cross
section ratios were considered. If we assume that the two
photonuclear processes under consideration are sharply peaked
at \( E_{\text{max}}(1) \) and \( E_{\text{max}}(2) \) and the bremsstrahlung spectra is
proportional to \( 1/E \), then the ratio of yields is estimated as

\[
\frac{\alpha(2)}{\alpha(1)} = \frac{\eta_S(2) \int_{E_{\text{max}}(1)}^{E_0} \sigma(2) \, dE}{\eta_S(1) \int_{E_{\text{max}}(2)}^{E_0} \sigma(1) \, dE},
\]

where \( \eta_S \) may now be interpreted as the number of target nuclei
in the beam, assuming equal irradiation geometries.

For comparison of the cross sections, the reaction
\( \text{Ta}^{181}(\gamma, n)\text{Ta}^{180m} \) was chosen. The product nuclide has a half-
life (8.15 hours) which enables one to use this reaction as a
monitor in irradiations of less than eight hours length with
little error. The detailed work of Carver and co-workers
(92, 93) was chosen as the standard for this work.

In addition, the \( \text{C}^{12}(\gamma, n)\text{C}^{11} \) reaction was used as a secondary monitor in some of the irradiations of carbon. This reaction is one of the best-studied of all photonuclear reactions; the work of Barber, et al. (51) was chosen as standard.

To determine the number of nuclei of sample and monitor targets in the beam, it was necessary to assume that an equal area of each was struck by the beam. This is not an unreasonable assumption in view of the method of positioning each (see later). Once the area of sample in the beam had been established, the density of the materials, along with the atomic or molecular weight and isotopic abundance was used to estimate the number of nuclei of each type involved.
III. EXPERIMENTAL

A. Preliminary Experiments

In view of the fact that none of the reactions involved had been reported previously with the exception of the \( \text{Be}^9(\gamma, 2n)\text{Be}^7 \) reaction, preliminary experiments were performed to establish the existence of the reaction in several of the cases.

The first experiment involved the irradiation of boric acid to determine if \( \text{Be}^7 \) might be produced from a reaction with either the boron or oxygen. These preliminary experiments were all conducted by irradiation of the sample in a probe leading into the donut of the synchrotron and with the energy of the electrons a maximum for the machine conditions (about 45 Mev). The electrons were allowed to "peal out", that is the orbit was allowed to expand until the electrons struck the probe lining, which was uranium. These conditions mean that only a small fraction of the sample was positioned in the beam, leading to the formation of extremely low amounts of activity. In boric acid, no activity was found in the initial experiment which could be positively identified as \( \text{Be}^7 \). However, the irradiations were conducted under low flux conditions compared with the later experiments, and the only positive statement which might be made was that the integrated cross sections of the reactions involved were low.

Some beryllium metal turnings were irradiated for a
longer time than the boric acid previously irradiated to find out if the flux were high enough to induce even the Be\(^9(\gamma, 2n)\) Be\(^7\) reaction. This sample, after irradiation, contained enough Be\(^7\) to be counted on a single channel analyzer with a maximum peak height of 10 counts per minute.

In an effort to induce the C\(^{12}(\gamma, 2p3n)\)Be\(^7\) reaction, samples of graphite in the form of a spectrograph rod and lithium carbonate were irradiated\(^1\). At this time a well-crystal with improved geometry was made available for detection of the gamma radiation from the irradiated sample, and it was relatively easy to detect the characteristic 477 keV gamma-ray from the decay of beryllium-7, indicating that the desired reaction had occurred.

In a final preliminary experiment, a sample of amorphous boron powder was irradiated and counted using the well-type counter. This time, no difficulty was encountered in observing the beryllium gamma ray.

In addition to the gamma-ray energy determinations made of these samples, the half-lives were ascertained using a single-channel analyzer. The half-lives, while poor due to low counting rates, nevertheless demonstrated that beryllium-seven had been generated.

\(^1\)The notation for photonuclear reactions does not imply that only neutrons and protons are emitted, but that the target nucleus loses the indicated number of protons and neutrons in some form.
B. Materials

To determine the integrated cross sections of these reactions and others which might lead to Be\textsuperscript{7}, target materials of beryllium, boron, carbon, boric acid and aluminum were obtained.

The beryllium target material used in this investigation was obtained from The Beryllium Corporation, Hazleton, Pennsylvania, in the form of 1/4 inch extruded rod. The analysis furnished for this rod, specified as the highest purity available, is given below:

<table>
<thead>
<tr>
<th>Be Assay</th>
<th>98.60 %</th>
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<tr>
<td>BeO</td>
<td>1.34</td>
</tr>
<tr>
<td>C</td>
<td>.131</td>
</tr>
<tr>
<td>Fe</td>
<td>.1405</td>
</tr>
<tr>
<td>Al</td>
<td>.1140</td>
</tr>
<tr>
<td>Ni</td>
<td>.0212</td>
</tr>
<tr>
<td>Si</td>
<td>.0670</td>
</tr>
<tr>
<td>Mg</td>
<td>.0045</td>
</tr>
<tr>
<td>B</td>
<td>.00008</td>
</tr>
<tr>
<td>Li</td>
<td>&lt; .0003</td>
</tr>
<tr>
<td>Cd</td>
<td>.0001</td>
</tr>
</tbody>
</table>
| All other metallic impurities | < .04 max.

This rod was reduced to samples 7/16 inch in length and .230 inch in diameter, weighing approximately 0.5 grams.

The boron target material was obtained from Fairmont Chemical Company, Newark, New Jersey, and was specified as "99.5 % boron (powdered)." A qualitative spectroscopic analysis of this material showed weak to moderate amounts of iron and lesser amounts of calcium, chromium, copper, magnesium, manganese, nickel, silicon and perhaps zirconium.
The sample was contained in a holder of turned brass which will be described later.

The carbon target material was graphite in the form of spectrograph rods obtained from National Carbon Company. These rods were 1/4 inch in diameter and .500 inch long. Qualitative spectrographic analysis showed only traces of iron, copper and sodium as impurities.

The oxygen target material used was in the form of boric acid. It was felt that if the photodisintegration of oxygen had an appreciable integrated cross section, it would be obvious that the beryllium-seven formed was larger than that formed from the boron, since boric acid contains only 17.5% by weight of boron. The boric acid used was "Fischer Certified Reagent" grade which was furnished with the following analysis:

\[
\begin{align*}
\text{Cl}^- & \quad .003 \% \\
\text{PO}_4^{3-} & \quad .0008 \\
\text{SO}_4^{2-} & \quad .000 \\
\text{As} & \quad .0000 \\
\text{Ca} & \quad .005 \\
\text{Heavy metals (as Pb)} & \quad .0002 \\
\text{Iron} & \quad .0001
\end{align*}
\]

Samples of this material were contained in brass tubes, to be described later.

Aluminum samples were irradiated in the form of rods of .250 inch diameter by .500 inch length. This aluminum was
from a larger cylinder of 2S grade aluminum. Spectrographic analysis showed a moderate amount of iron impurity along with smaller amounts of calcium, chromium, copper, magnesium, silicon and perhaps zirconium.

The tantalum monitor foils were cut from a sheet obtained from Ethicon Suture Laboratories, New Brunswick, New Jersey. These foils were approximately .250 by .78 inch and .0005 inch thick. Spectroscopic analysis of this material was unsuccessful in that it was purer than the purest material on hand for comparison. These monitor foils were wrapped around the cylindrical samples in such a way that the beam passed through the foil both entering and leaving the actual target material. The ends were arranged in such a way that the points of impact of the beam were as far from the ends as possible.

Pellets of reagent grade potassium bromide 1/4 inch in diameter and approximately 7/16 inch long were pressed under a pressure of 7500 psi in a hydraulic press. These pellets were used in checking the bremsstrahlung beam position. Since these were only used in this connection, no analysis for purity was made.

Standard activities were employed to calibrate the multi-channel analyzer used to determine the gamma ray energy from the irradiated samples. Standard Be\(^7\) was obtained from Nuclear Science and Engineering Corporation, Pittsburgh,
Pennsylvania. This activity was cyclotron-produced by the \( \text{Li}^7(p, n)\text{Be}^7 \) reaction and was obtained carrier-free. Other activities used were \( \text{Na}^{22}, \text{Cs}^{137}, \text{Hg}^{203}, \text{Mn}^{54} \) and \( \text{Co}^{60} \).

C. Equipment

The Iowa State synchrotron used for the irradiations was a type N machine with a rated maximum energy of 70 Mev. However, due to modifications, the maximum energy obtainable at the time of these experiments was \( 45 \pm 2 \) Mev. The energy control device has been discussed by Schupp (94) and Rawls (95).

The probe which contained the samples during irradiation extended into the cavity of the donut-shaped acceleration chamber (commonly called the donut) and consisted of a .375 inch inside diameter stainless steel tube with .010 inch walls and bottom. The bremsstrahlung target was an approximately .111 inch lead plate located one inch from the sample and monitor being irradiated. A system to destroy the beam stability quickly and "knock out" the electrons to the converter was used; this provided a beam flux approximately 10 times greater than the arrangement used during the preliminary experiments. This system is described by Bureau and Hammer in some detail (96).

The solid samples of beryllium, carbon and aluminum rod were centered in the probe by means of a plastic Synthane
(phenol-type resin) collar, and held in place by means of a setscrew in the collar. The samples of powdered boron and crystalline boric acid were contained in small turned brass containers with 10 mil bottoms and 40 mil walls. These samples were kept in place by a solid glass rod inserted into the container on top of the sample and the whole container with sample inserted into the same Synthane collar used for the solid samples.

The Ta$^{180m}$ samples were all counted with a Tracerlab TCG-2 End Window Geiger Tube with a window thickness of 1.7 mg/cm$^2$ contained in a Technical Associates Model AL 14A Lead Shield, backed by a Nuclear Instrument and Chemical Corporation Model 165 Scaler and Streeter-Amet Company "Ametron" Counter. The latter was used to automatically record the number of registers (of 64 counts each) every 15 minutes.

A single-channel analyzer was used to count the samples irradiated for half-life determination. This setup consisted of a Crystals, Incorporated well-type scintillation crystal of the NaI (Tl) type, constructed in the form of a right cylinder 2 inches by 2 inches with a 3/8 inch diameter hole drilled one inch into the crystal, followed by a cathode-follower preamplifier$^1$ which amplified the pulses from the RCA 6432A photomultiplier tube, a Baird Associates-Atomic Instru-

$^1$Design by B. Loupee, Instrument Shop, Ames Laboratory.
ments Company Model 215 Non Overloading Amplifier, a single channel differential-integral pulse height analyzer with the negative pulse output going to two Nuclear Instrument and Chemical Corporation Model 161 Scaling Units which were connected in series in such a way that one count on the mechanical register corresponded to $2^{10}$ counts. A separate regulated power supply (800-1200 volts) was used to supply the RCA 6432A photomultiplier tube. The crystal was shielded to reduce the background counting rate with at least four inches of lead bricks on each side.

For the determination of gamma-ray energy, the output from the cathode-follower preamplifier was connected to a Model 20611 Radiation Counter Laboratories, Incorporated, RCL 256 Channel Pulse Height Analyzer.

D. Procedure

For these irradiations, the beam position was ascertained to be at the center of the sample by irradiating a KBr pellet for approximately two minutes and visually checking the blue streak of color across the end of the cylinder. This blue mark, caused mainly by high energy electrons, both primary (not all electrons are converted to bremsstrahlung by the lead converter) and secondary, fades slowly at room temperature and is taken in position to be indicative of the position of the bremsstrahlung beam.
A sample of the target material with a tantalum monitor foil in place was then inserted into the probe and irradiated either at maximum energy or at an energy controlled by the integrator. After irradiation, the samples were placed in plastic test tubes and counted for residual gamma-ray activity after allowing the samples to cool for several hundred hours to allow any short-lived activities from impurities to die away. All counting for half-life and amount of Be\(^7\) formed was done with the single-channel analyzer in the integral position with the discriminator set at approximately 40 keV to exclude as much electronic noise as possible.

The tantalum monitors were centered carefully on cardboard holders and counted automatically on the G.M. setup for at least one half-life. In addition, two samples were counted immediately in the scintillation counting setup before G. M. counting to determine the relationship between counting rates on the G. M. setup and the scintillation counter.
IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Monitor Results

The counting rates from the Streeter-Amet counters were plotted as net counting rates on semi-logarithmic paper. The half-life and intercept were obtained analytically from lines drawn to provide the best visual fit to the points; a typical decay curve for a tantalum foil on the G. M. counting setup is given in Figure 1. It was felt that the points fell so close to a straight line that a least squares or similar mathematical analysis was not necessary. Figure 2 shows the decay of an irradiated tantalum foil determined with the scintillation counter while Figure 3 shows the gamma-ray spectrum of an irradiated foil. The average of the tantalum half-life determinations was 8.19 hours, which compares well with the accepted value of 8.15 hours (22). The determined half-lives were not corrected for any long-lived activities, such as Ta$^{182}$, which would have been formed by a Ta$^{181}$ (n, $\gamma$)Ta$^{182}$ reaction. It is estimated that this introduces an error not in excess of four percent.

B. Beryllium Results

Two beryllium rods were irradiated for periods of four hours each in the bremsstrahlung beam at maximum machine energy. These were subsequently counted in the well-type
Figure 1. Decay of irradiated tantalum foil as determined with G. M. counting setup
Figure 2. Decay of irradiated tantalum foil as determined with scintillation counter.
Figure 3. Gamma-ray spectrum of irradiated tantalum foil
scintillation crystal with the single channel analyzer described previously.

The data from this counting were analyzed by a weighted least squares treatment.

Overman and Clark (97) list
\[ w = \left( \frac{R}{0.434\sigma} \right)^2 \]
as the weighting factor for the logarithm of the experimentally observed counting rate \( R \) in terms of \( R \) and its standard deviation \( \sigma \). This factor results directly from the fact that a weighting factor should vary inversely as the dispersion, \( \sigma^2 \). Standard treatment was used to determine the dispersion (see, e.g., Friedlander and Kennedy (98) for an elementary account).

Worthing and Geffner (99) list the formulas used for fitting a straight line of the form
\[ y = mx + b \]
by a weighted least squares method as
\[
m = \frac{\sum_{x} x \sum_{y} y - \sum_{x} \sum_{xy}}{(\sum_{x})^2 - \sum_{x} \sum_{x^2}} = \frac{X}{D} \tag{3} \]
and
\[
b = \frac{\sum_{x} x \sum_{wx} y - \sum_{wx} x^2 \sum_{y}}{D} \tag{4} \]
where \( x \) and \( y \) are the experimentally observed quantities and the subscripts for summations have been omitted. This method throws all the error on the variable \( y \), which is reasonable in
this case.

From the law of propagation of probable errors, which for $b$ is given by:

$$ p_b^2 = p_{y_1}^2 \sum \left( \frac{\partial b}{\partial y_1} \right)^2, \quad (5) $$

it may be shown that

$$ p_b = p_{y_1} \sqrt{\frac{\left(\Sigma wx\right)^2 \Sigma w^2 + \left(\Sigma wx\right)^2 - 2 \Sigma wx \Sigma wx^2 \Sigma w^2 x}{d^2}} \quad (6) $$

and, in like fashion

$$ p_m = p_{y_1} \sqrt{\frac{\left(\Sigma w\right)^2 \Sigma (wx)^2 + \Sigma w^2 (\Sigma wx)^2 - 2 \Sigma w^2 x \Sigma w \Sigma wx}{d^2}} \quad (7) $$

where by definition

$$ p_{y_1} = .675 \sqrt{\frac{n \Sigma w (y - mx - b)^2}{\Sigma w (n - 2)}} \quad (8) $$

The half lives and counting rates at the end of irradiation were calculated using these formulas to treat the experimental data. A plot of one of the decay curves for beryllium is shown in Figure 4. The line shown is that calculated by the weighted least squares method. The slope of the line corresponds to a half-life of $54.2 \pm 0.5$ days.

A graph of the gamma spectrum of an irradiated beryllium sample determined 58 days after the end of irradiation is shown in Figure 5. This spectrum was obtained in an accumulation of 25,000 seconds net live time duration using the 256 channel analyzer and may be compared with the standard Be$^7$ activity shown in Figure 6. Extra peaks in Figure 5 are
Figure 4. Decay of irradiated beryllium rod as determined with scintillation counter

$T_1 = 54.22 \pm 50 \text{ DAYS}$
Figure 5. Gamma-ray spectrum of irradiated beryllium rod
Figure 6. Gamma-ray spectrum of standard Be$^7$ activity
due to unknown impurity activities which are considered to be minimal and will be discussed later.

Using an estimate of the efficiency of the crystal for the decay involved (100), the experimentally determined density and the calculated number of target and radioactive nuclei produced during the irradiation, equation (2) may be used to estimate the integrated cross section for the Be\(^9\)(\(\gamma\), 2n)Be\(^7\) reaction. The average of two estimations was determined to be

\[
\int_0^{45 \text{ Mev}} \sigma(E) dE = (5 \pm 2) \times 10^{-3} \text{ Mev-barns.}
\]

This value may be compared with Lokan's (28) value of

\[
\int_{20.56}^{30} \sigma(E) dE = (1.2 \pm .2) \times 10^{-3} \text{ Mev-barns.}
\]

The errors shown in the results from this investigation are combinations of the estimated errors due to individual counting measurements and the estimated uncertainty in Carver and Turchinetz's (93) measurement of the Ta\(^{181}\)(\(\gamma\), n)Ta\(^{180m}\) integrated cross section, whereas the errors in Lokan's estimate are those assigned to the measurements only.

C. Boron Results

In the investigation of the B\(^{10}\)(\(\gamma\), p2n)Be\(^7\) and B\(^{11}\)(\(\gamma\), p3n)Be\(^7\) reactions, duplicate samples of powdered boron were irradiated at the maximum machine energy for periods of six
hours each. The samples were then transferred to plastic test tubes and counted as described previously. A plot of the decay observed for an irradiated boron sample is shown in Figure 7 with the calculated weighted least squares line shown. The half-life was calculated as $53.37 \pm 0.08$ days. Figure 8 shows the gamma spectrum of an irradiated boron sample as determined 54 days after the end of irradiation.

In addition to the $\text{Be}^7$ still present, Figure 8 clearly shows two other impurity peaks which do not appear in the standard $\text{Be}^7$ spectrum. These occur at $130 \pm 20$ kev and $830 \pm 20$ kev. The known impurities in the boron used have been given previously. The major contaminant was iron. The 830 kev peak is reasonably close to the 835 kev energy of 291 day $\text{Mn}^{54}$. This isotope may have been formed in the target material during the irradiation by a $\text{Fe}^{57}(\gamma, p2n)\text{Mn}^{54}$ reaction, since manganese was also an impurity, a $\text{Mn}^{55}(\gamma, n)\text{Mn}^{54}$ reaction or a combination of both. The lower energy peak at 130 kev may correspond to the $\text{Co}^{57}$ 136 kev gamma ray. This nuclide may have been formed due to a $\text{Ni}^{58}(\gamma, p)\text{Co}^{57}$ reaction. It is interesting to note that an impurity peak near 830 kev also occurs in the aluminum and beryllium spectra (which see). The analysis of these target materials also showed the presence of iron as a minor constituent. The odd backscatter peak in the beryllium rod spectra (Figure 5) may be due to the presence of $\text{Co}^{57}$ also, since beryllium was known to contain
Figure 7. Decay of irradiated boron sample on scintillation counter
Figure 8. Gamma-ray spectrum of irradiated boron sample
nickel as an impurity.

Again, using the estimates necessary, formula (2) was used to compare the sum of the integrated cross sections of the reactions $B^{10}(\gamma, p2n)Be^7$, $\sigma_a$, and $B^{11}(\gamma, p3n)Be^7$, $\sigma_b$, with that of $Ta^{181}(\gamma, n)Ta^{180m}$.

The average of duplicate estimations is

$$\int_0^{45 \text{ Mev}} \sigma_a(E)dE + \int_0^{45 \text{ Mev}} \sigma_b(E)dE = (1.9 \pm .6) \times 10^{-3} \text{ Mev-barns}.$$  

D. Irradiation of Boric Acid

Duplicate samples of metaboric acid were irradiated in containers similar to those used for the boron samples. The bombardments were carried out at maximum energy for periods of six and 4.5 hours, respectively.

In this phase of the investigation it was desired to look for the reaction $O^{16}(\gamma, 4p5n)Be^7$. Since boron has been proven to produce $Be^7$ upon irradiation, boric acid will give rise to a certain amount of $Be^7$ without any of the desired reaction in oxygen. However, it was felt that since two times as many oxygen nuclei as boron nuclei are present, any appreciable cross section for the $O^{16}$ reaction would be observable in the form of a larger amount of $Be^7$ than that formed from the boron alone.

A plot of the decay observed for an irradiated boric acid sample is shown in Figure 9. The line drawn is again the weighted least squares line, corresponding to a half-life of
Figure 9. Decay of irradiated boric acid sample on scintillation counter

\[ T_1 = 53.43 \pm 59 \text{ days} \]
53.43 ± .59 days. Figure 10 shows the gamma spectrum of an irradiated boric acid sample as determined with the 256 channel analyzer 52 days after the end of irradiation. The counting period duration used in obtaining this spectrum was 75,000 seconds net live time. Even so, the counting rate per channel for this sample is very low, accounting for the fluctuation of points. Note that in this case no extraneous peaks are shown.

The amount of beryllium-7 activity formed was compared with that expected from the boron content of the boric acid and was not found to be appreciably larger. The integrated cross section for the formation of Be\(^7\) from the boron in boric acid was estimated by comparison with the Ta\(^{181}\)(\(\gamma\), n) Ta\(^{180m}\) reaction as

\[ \int_{0}^{45 \text{ Mev}} \sigma(E) dE = (2.2 \pm .7) \times 10^{-3} \text{ Mev-barns}. \]

The two estimations made were not very close together and this fact is reflected in the estimated error shown. The cross section for the formation of Be\(^7\) from O\(^{16}\) was estimated to be too small to measure under present irradiation conditions. However, other target materials containing O\(^{16}\) should be irradiated.

**E. Carbon Results**

In the investigation of the C\(^{12}\)(\(\gamma\), an)Be\(^7\) reaction, ten different carbon samples were irradiated in two series of
Figure 10. Gamma-ray spectrum of irradiated boric acid sample
irradiations.

In the first series, duplicate samples were irradiated at 45, 40, 35 and 30 Mev maximum electron energy. These runs were monitored only with tantalum foils. The time of irradiation varied from four hours at 45 Mev to seven hours at 30 Mev, where the beam intensity is greatly reduced. Unfortunately, one of the samples irradiated at 30 Mev showed no activity upon conclusion of the irradiation. This has been attributed to the fact that the sample was not pushed completely to the end of the probe and thus was not in the bremsstrahlung beam during the irradiation. This possibility is strengthened by the fact that the tantalum monitor did not contain appreciable activity and no carbon-11 was detected with a portable survey meter used to survey the samples immediately upon removal from the synchrotron probe.

The counting data from these samples were analyzed in the same manner as for the other runs--an example of the decay curve for the irradiated carbon rods is shown in Figure 11 and an example of the gamma spectrum as determined 58 days after irradiation is shown in Figure 12. The clean spectra of the Be$_7$ formed in these samples is nearly as good as that of the standard Be$_7$ in Figure 6. A summary of the results of the first series of irradiations is given in Table 1 and a graph of the integrated cross section as a function of maximum bremsstrahlung energy is given in Figure 13. Each point in
Figure 11. Decay of irradiated carbon rod on scintillation counter
Figure 12. Gamma-ray spectrum of irradiated carbon rod
Figure 13. Integrated cross section for the reaction $^{12}\text{C}(\gamma, 2p3n)^7\text{Be}$ as a function of maximum bremsstrahlung energy.
Table 1. Integrated cross section for the reaction $^{12}\text{C}(\gamma, 2p3n)^7\text{Be}$ as a function of maximum bremsstrahlung energy

<table>
<thead>
<tr>
<th>Sample</th>
<th>$E_0$</th>
<th>$\int_0^{E_0} \sigma(E)dE$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>45 Mev</td>
<td>$(1.3 \pm .6) \times 10^{-2}$ Mev-barns</td>
</tr>
<tr>
<td>C2</td>
<td>45</td>
<td>$(1.2 \pm .6) \times 10^{-2}$</td>
</tr>
<tr>
<td>C3</td>
<td>40</td>
<td>$(7 \pm 3) \times 10^{-3}$</td>
</tr>
<tr>
<td>C4</td>
<td>40</td>
<td>$(7 \pm 3) \times 10^{-3}$</td>
</tr>
<tr>
<td>C5</td>
<td>35</td>
<td>$(4 \pm 2) \times 10^{-3}$</td>
</tr>
<tr>
<td>C6</td>
<td>35</td>
<td>$(4 \pm 2) \times 10^{-3}$</td>
</tr>
<tr>
<td>C8</td>
<td>30</td>
<td>$(5 \pm 2) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

this plot represents the average of two determinations with the exception of the point at 30 Mev, which, as explained before, represents only one determination.

In the second series of observations, duplicate samples of carbon in the form of graphite rods were irradiated simultaneously with tantalum monitor foils at the maximum energy of the machine for a period of thirty minutes. These samples of carbon were counted in the scintillation counter soon after conclusion of the irradiation to determine the amount of $^{11}\text{C}$ formed during the irradiation. Thus it was possible to compare the $^{12}\text{C}(\gamma, 2p3n)^7\text{Be}$ reaction with both the $^{181}\text{Ta}(\gamma, n)^{180m}\text{Ta}$ and $^{12}\text{C}(\gamma, n)^{11}\text{C}$ reactions. A summary of
the results from these calculations is given in Table 2. Note that the integrated cross sections calculated using the tantalum monitor for comparison compare well with each other and with those determined in the longer runs, the results of which are given in Table 1. Those calculated by comparison with the $^{12}\mathrm{C}(\gamma, n)^{11}\mathrm{C}$ standard are approximately twice those calculated using the tantalum monitor. This difference is possibly due to the inaccuracy of the determinations of the integrated cross sections of the reactions with which comparison was made.

Table 2. Comparison of integrated cross sections for the reaction $^{12}\mathrm{C}(\gamma, 2p3n)^7\mathrm{Be}$

<table>
<thead>
<tr>
<th>Sample(s)</th>
<th>Monitor for comparison</th>
<th>$\int_0^{45} \sigma(E) dE$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C9</td>
<td>Ta</td>
<td>$(1.1 \pm .5) \times 10^{-2}$ Mev-barns</td>
</tr>
<tr>
<td>C9</td>
<td>C</td>
<td>$(1.4 \pm .3) \times 10^{-2}$</td>
</tr>
<tr>
<td>C10</td>
<td>Ta</td>
<td>$(1.1 \pm .5) \times 10^{-2}$</td>
</tr>
<tr>
<td>C10</td>
<td>C</td>
<td>$(1.6 \pm .4) \times 10^{-2}$</td>
</tr>
<tr>
<td>C9, C10</td>
<td>Ta</td>
<td>$(1.1 \pm .3) \times 10^{-2}$</td>
</tr>
<tr>
<td>C9, C10</td>
<td>C</td>
<td>$(1.5 \pm .3) \times 10^{-2}$</td>
</tr>
</tbody>
</table>
The average half-life of Be\textsuperscript{7} as determined in all irradiations including both carbon series was determined as 52.87 ± 2.36 days.

F. Irradiation of Aluminum

Duplicate samples of aluminum were irradiated for periods of four hours each with the synchrotron operating at maximum energy. After irradiation, these samples were counted in a manner similar to that previously described for the other samples. In this case, as is seen in the gamma spectrum taken 45 days after the end of irradiation and shown in Figure 14, no gamma-ray characteristic of Be\textsuperscript{7} was observed. It is possible that the 477 keV gamma-ray peak was masked by the large 511 keV peak from the Na\textsuperscript{22} position. However, this amount must be very slight, since the shape of the 511 peak does not appear to be distorted from that of the standard.

The decay of the aluminum samples, a sample of which is shown in Figure 15 along with the calculated weighted least squares line, is very long-lived—that shown being 1.87 ± .04 years. The gamma ray spectrum is consistent with that of standard Na\textsuperscript{22}, a gamma spectrum of which is shown in Figure 16. This nuclide, which could have been formed by an Al\textsuperscript{27} (γ, 2p3n)Na\textsuperscript{22} reaction, was not expected to be formed in appreciable quantities due to its long half life as compared
Figure 14. Gamma-ray spectrum of irradiated aluminum sample
Figure 15. Decay of irradiated aluminum sample as determined with scintillation counter

$T_{1/2} = 1.87 \pm 0.04$ YEARS
Figure 16. Gamma-ray spectrum of standard Na\textsuperscript{22} sample
with the length of irradiation. However, the cross section, calculated in the same manner as the others by comparison with the tantalum cross section, is

\[
\int_{0}^{45 \text{ Mev}} \sigma(E) dE = (1.0 \pm 0.3) \times 10^{-2} \text{ Mev-barns},
\]

which explains the high yield.

Note that in Figure 14 the impurity peak at 830 ± 20 kev is present once again. Also the activity at 130 ± 20 is present, though to a lesser extent (it is interesting in the case of aluminum that spectroscopic analysis did not show any nickel).

G. Discussion

One of the most interesting questions in the consideration of exotic photonuclear reactions is the question of possible mechanisms or reaction paths.

In the Be\(^9\)(γ, 2n)Be\(^7\) reaction, it would seem logical to assign the reaction to the emission of one neutron to an excited state of Be\(^8\), which can then emit a second neutron, yielding Be\(^7\) in either its ground or an excited state. If one trusts the compound nucleus theory, credulity is lent to the idea that a neutron emitting state of Be\(^8\) exists, for the Li\(^7\)(p, n)Be\(^7\) reaction is commonly used to produce Be\(^7\). Resonances in the cross section for the Li\(^7\)(p, n) reaction have been observed near threshold (101) and at \(E_p = 2.25\) Mev,
corresponding to excited, neutron-emitting states of Be\(^8\) at 22.5 and 23.85 Mev. These states are also known to emit protons, tritons and alpha particles. The neutron-emitting levels of Be\(^9\) are many, the lowest being at 1.665 Mev. The mass threshold for the photonuclear reaction studied in this investigation is calculated as 20.6 Mev.

In the case of possible photonuclear processes producing Be\(^7\) from a boron sample of mixed isotopic composition, mass differences from the data of Sullivan (27) for various reactions which might occur are:

<table>
<thead>
<tr>
<th>Reaction</th>
<th>(Q_m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^{10}(\gamma, T)Be^7)</td>
<td>-18.6 Mev</td>
</tr>
<tr>
<td>(B^{10}(\gamma, dn))</td>
<td>-24.8</td>
</tr>
<tr>
<td>(B^{10}(\gamma, p2n))</td>
<td>-27.1</td>
</tr>
<tr>
<td>(B^{11}(\gamma, nT))</td>
<td>-30.1</td>
</tr>
<tr>
<td>(B^{11}(\gamma, d2n))</td>
<td>-36.4</td>
</tr>
<tr>
<td>(B^{11}(\gamma, p3n))</td>
<td>-38.6</td>
</tr>
</tbody>
</table>

In the case of B\(^{10}\), the reaction most probable from a consideration of only the mass differences is the \(B^{10}(\gamma, T)Be^7\) reaction. In the other two cases, the mass difference is higher, but still well under the maximum energy in the bremsstrahlung beam used. Triton- and deuteron-emitting states of B\(^{10}\) have been reported from studies of the Be\(^9\)(p, T)Be\(^7\) and \(B^{10}(\gamma, d)Be^{8\ast}\) reactions. Except for the reaction paths which might lead through B\(^9\), the nuclides involved in the other cases have been discussed.
Excited states of $^{11}B$ are known which emit protons, neutrons, deuterons, tritons and alpha particles. The $^{11}B(\gamma, Tn)Be^7$ reaction may be favored because of the lower mass difference.

Some of the possible photonuclear reaction paths for carbon and the mass differences involved are:

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$Q_m$ (Mev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}C(\gamma, an)Be^7$</td>
<td>-25.4</td>
</tr>
<tr>
<td>$(\gamma, He^5)$</td>
<td>-27.2</td>
</tr>
<tr>
<td>$(\gamma, He^32n)$</td>
<td>-46.9</td>
</tr>
<tr>
<td>$(\gamma, n2d)$</td>
<td>-50.1</td>
</tr>
<tr>
<td>$(\gamma, 2p3n)$</td>
<td>-53.6</td>
</tr>
</tbody>
</table>

The first two are clearly shown as the only ones possible in using bremsstrahlung of 45 Mev maximum energy. The fact that the reaction is observed as low as 30 Mev indicates once again that only the first two may contribute to the cross section at that energy. It might be thought that the reaction $^{12}C(\gamma, an)Be^7$ would be rendered impossible at 30 Mev by the Coulomb barrier. This is not necessarily so.

The Coulomb barrier for photonuclear reactions is that energy necessary to remove the emitted charged particle from the interior of the compound nucleus (102). If the target nucleus is small (of low A) the Coulomb barrier should be small, if not negligible. For example, in the case of the $^{9}Be(\gamma, p)$ reaction, the yield curve does not approach the abscissa in a regular manner (with steadily decreasing slope)
but rather drops abruptly with increasing slope. The intercept, as carefully determined, is within 100 kev (the limit of the machine calibration) of the calculated mass threshold. Therefore, it appears as though the product particles may be "created" in juxtaposition and are merely repulsed by Coulomb force. This is reasonable because a low-Z nucleus cannot "contain" a proton (or other charged particle) in the normal sense of a point charge within a sphere. Alternatively, the low Z, low A particle ejected may exist in the surface of the target nucleus. For an interesting discussion of nucleon "clusters" in this connection, the reader is referred to references (103, 104, 105).

In the irradiation of aluminum, any production of Be would have been from nucleon clusters or photofission, since the most favorable reaction, Al\(^{27}(\gamma, P^{19}n)Be^{7}\), has a mass difference of 39.5 Mev. In the reaction observed, namely Al\(^{27}(\gamma, 2p3n)Na^{22}\), mass differences vary from 22.5 Mev for the (\(\gamma, \alpha n\)) reaction to 50.8 Mev for the (\(\gamma, 2p3n\)) reaction, indicating that in all probability particles of larger than unit weight are emitted.

V. SUMMARY

The integrated cross sections to 45 Mev for the production of Be\textsuperscript{7} from Be\textsuperscript{9} and boron containing the natural isotopic abundance of B\textsuperscript{10} and B\textsuperscript{11} have been estimated. In addition, the integrated cross sections for the production of Be\textsuperscript{7} from C\textsuperscript{12} have been estimated from threshold to 30, 35, 40 and 45 Mev. An attempt to produce Be\textsuperscript{7} from Al\textsuperscript{27} and O\textsuperscript{16} failed, but the production of Na\textsuperscript{22} from Al\textsuperscript{27} was observed and the integrated cross section to 45 Mev for this reaction was estimated.

These cross sections may be useful to nuclear theorists in testing various theories of photonuclear reactions and nuclear structure which may be advanced.

Further work on these reactions should include a detailed study of the energy dependence of the cross sections involved. In the case of the boron reaction, this study should be made on the separated isotopes, if possible. Further elucidation of mechanisms might be made through a determination of any tritium formed.
VI. LITERATURE CITED


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