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Photoproton reaction in beryllium-9

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PHOTOPROTON REACTION IN BERYLLIUM-9

by

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I. INTRODUCTION

If a photon is traveling through matter there are several ways in which it can interact with the material and lose energy. These interactions of electromagnetic radiation with matter have been studied by physicists for a long time. The parts of the problem involving interactions between photons and electrons, such as Compton scattering or photoelectric absorption, and some reactions between photons and the nucleus, such as pair production, are now well understood. However, other parts of the problem, especially those involving the internal structure or forces of the nucleus, have not yet been fully explained (1, pp. 692-710).

One of the processes involving the photonuclear interaction is the process of photo-disintegration. This is the case in which the photon energy exceeds the energy required to separate a proton, neutron, or a group of nucleons from the nucleus. The photon can then be absorbed by the nucleus and a nucleon or group of nucleons will be ejected (1, p. 673). The first experimental evidence of photo-disintegration was reported by Chadwick and Goldhaber (2) in 1934 when they found that neutrons were produced when they bombarded deuterium with 2.6 Mev gamma rays from ThC\(^{233}\). Except for a few cases, photon energies of 8 Mev or more are necessary to produce photo-disintegration. Therefore, until the advent of particle accelerators that could accelerate electrons to high energies,
and then produce bremsstrahlung radiation, experimental work in the photo-disintegration of nuclei was limited to the use of a few naturally occurring high energy gamma rays or gamma rays obtained from \((p, \gamma)\) reactions. However, since the advent of electron betatrons and synchrotrons with high intensity bremsstrahlung beams, work has been done on the photo-disintegration of almost all of the stable isotopes.

The present theories will predict the general features of the photo-disintegration process, but a more complete understanding is hampered by the difficulty of the theoretical calculations and the lack of good experimental information, especially for photon energies above 25 Mev (3).

In Chapter II a brief review of photonuclear reactions is given. For a more complete review of photonuclear work, one is referred to the book by J. S. Levinger (3) and review articles by De Sabbata (4), Bishop and Wilson (5), and Kinsey (6). In Chapters III-VII the \(\text{Be}^9(\gamma,p)\text{Li}^8\) experiment performed at Iowa State University is discussed.
II. GENERAL REVIEW OF PHOTONUCLEAR REACTIONS

A. Photonuclear Reactions

The definition of a photonuclear reaction used in this review will be the same as that used by Toms (7) and includes only those reactions leading to the photo-disintegration of the nucleus. This definition includes those photonuclear reactions in which a nucleon, nucleons, or aggregate of nucleons are emitted from the nucleus and excludes such reactions as the resonant scattering of photons and photomeson production.

Interest in photonuclear disintegration work is usually confined to the photon energy range below the threshold for the production of \( \pi \) mesons. The quantities of interest in this energy region are:

1. The threshold of the reaction;
2. The cross section and the integrated cross section;
3. The angular distribution, energy, and branching ratios of the disintegration products;
4. The breaks in the yield curve.

The threshold of a reaction is the smallest value of the bombarding energy at which a reaction can take place (1, p. 414). The thresholds of photonuclear reactions were originally of interest in the determination of masses of the different elements and their isotopes. However, with the accuracy
in mass numbers now available by other means, the thresholds of photonuclear reactions are generally used to calibrate the energies of particle accelerators (8, 9).

The cross section, $\sigma$, of a reaction is defined as

$$\sigma = \frac{\text{transitions/second}}{\text{photon flux}}$$

and is measured in cm$^2$/nucleus (3, p. 7). The cross section is proportional to the probability that a photon will react with a nucleus and is strongly dependent on the type of nucleus and the energy of the photon. The integrated cross section, $\sigma_{\text{int}}$, is defined as

$$\sigma_{\text{int}} = \int_{0}^{\infty} \sigma(k) dk$$

where $k$ is the photon energy (3, p. 7). Since the region of interest is limited by the meson threshold, the upper limit of the integral is usually placed at 150 Mev. Also, since there can be no reaction below the threshold or binding energy of the particular nucleon in which one is interested, the lower limit is replaced by the threshold energy (3, p. 7). The equation for the integrated cross section then becomes

$$\sigma_{\text{int}} = \int_{\text{threshold}}^{150 \text{ Mev}} \sigma(k) dk.$$  

The angular distribution of the disintegration products is dependent on the spins and parities of the initial state, of the excited state reached by photon absorption, and of the
state reached in the final nucleus. The angular distribution is also dependent on the orbital angular momentum of the emitted particle and on the multipole order of the absorbed photon. Some of these items are either known or can be easily calculated. The photons absorbed into the nucleus are almost entirely El radiation. Therefore the parity of the excited state must be of the opposite sign compared to the parity of the ground state and the total angular momentum of the two states must differ by 0, ± 1 (not 0→0) (3, pp. 102-103).

The energies of the decay products give the energy difference between the excited states in the original nucleus reached by photon absorption and the final states reached by nucleon emission (1, pp. 402-403). The branching ratios of the decay products, such as the ratio of deuterons to protons, will give information as to the various mechanisms of photo-disintegration (10), the probability of the decay by the different possible decay modes, and the width of the excited level (1, p. 399).

Breaks in the yield curve are sometimes observed when a bremsstrahlung beam is used to measure the cross section. The procedure for measuring the cross section with a bremsstrahlung beam is to measure the yield or number of reactions per dosage of radiation as a function of the peak photon energy in the bremsstrahlung beam. From this yield curve the cross section can be calculated by a process such as the one
described later in this report. If the yields are measured with small photon energy intervals ($\Delta k < 0.20 \text{ Mev}$) and plotted as a function of peak photon energy, breaks or discontinuities in the slope of the yield curve are sometimes observed (11, 12, 13). These breaks are associated with the discrete high energy nuclear levels sometimes found in light nuclei. However, because of the difficulty in calibrating the energies of particle accelerators and in obtaining sufficient energy stability, it has been only recently that there has been any agreement between the different laboratories on the energies of these observed breaks. In the case of $^{16}$O and several other nuclei there is now not only agreement between the energies of the breaks, but there is also a correlation between the breaks and the known energy levels in the nucleus (14, 15, 16).

B. Theory of Photonuclear Cross Sections

Theoretically the gross features of the total cross section, $\sigma(k)$, and the integrated total cross section $\sigma_{\text{int}}$ up to 150 Mev can be computed from several different nuclear models. The usual phenomenological process for photodisintegration is to think of the photon as entering the nucleus, losing its energy to one or more nucleons, and raising the nucleus to some excited level. If more than one nucleon shares the photon's energy, there are a great many
states in the nucleus that can be excited. While in the excited state the nucleus decays by the emission of one or more nucleons, and since there are usually several different modes of decay possible, the problem then becomes one of statistical mechanics (1, pp. 397-407).

The models usually used to give the nuclear energy levels are the shell or independent particle model and the collective model. Neither of these models is literally correct, but both are useful in discussing photonuclear reactions. Both of these models will predict a maximum or giant resonance in the cross section corresponding to E1 photon absorption into a large number of overlapping compound energy levels in the nucleus (3, pp. 80-97). Using dipole sum rules based on the different models, it has been shown that these models will give approximately the same results for the energy, $k_m$, of the giant resonance and identical values for the integrated cross section. These theoretical calculations give for the energy of the resonance $k_m \sim 100 A^{-1/3}$ Mev (3, p. 66). However, this result is for medium and heavy nuclei and is not valid for light nuclei.

The theoretical calculations give for the integrated cross section

$$\sigma_{\text{int}} = 0.060 \frac{N Z}{A} \text{ Mev-mb}$$

provided the nuclear Hamiltonian is velocity independent (3, p. 66). Using dispersion theory, Gell-Mann et al. (17)
gives for the integrated cross section

\[ \sigma_{\text{int}} = 0.060 \frac{NZ}{A} (1 + 0.1 \frac{A^2}{NZ}) \text{ Mev-mb} \]  

which matches the experimental results better. This result is derived for heavy nuclei but also seems to give fair results for light nuclei. The integrated cross section calculated from shell model theory can be increased by considering two-body exchange interactions or by introducing a velocity-dependent component into the nuclear potential (18). However, it should be pointed out that the numerical value of this increase is dependent upon the Hamiltonian and wave functions that one assumes and that these quantities are not accurately known.

Another quantity which one might compute from theory is \( \gamma \), the full width of the resonance at half maximum. Except in a few cases, however, the sum rules are not sufficiently complete nor accurate enough to compute this value (3, p. 66).

Exact theoretical calculations over the giant resonance have been completed on the doubly magic nucleus \( ^{16}O \) (19). These theoretical results agree extremely well with the results of the \( ^{16}(\gamma,p)^{15}N \) (20, 21), \( ^{15}(p,\gamma)^{16}O \) (22, 23), and \( ^{16}(\gamma,n)^{15}O \) (24) experiments.
C. Review of Methods Used in Cross Section Measurements

In order to measure the cross section of photonuclear reactions as a function of the photon energy, one must know four things:

1. The energy of the incident photons;
2. The number of photons in the incident beam;
3. The number of target nuclei;
4. The number of reactions or events that occur.

The ideal way of measuring the cross section is to use a monoenergetic photon source. However, the only monoenergetic photons readily available are from naturally occurring gamma ray sources or are from the radiative capture of nucleons such as certain \((p,\gamma)\) reactions. These sources of monochromatic photons are limited to fairly low energies \((E < 20\) Mev\), low intensities, and are not continuously variable. Work is currently being carried on at several laboratories with nearly monochromatic photon beams produced by particle accelerators, but at the present time the intensity of such beams is low (25).

The only readily available, continuously variable, high intensity source of high energy photons is bremsstrahlung radiation from high energy electron accelerators. Such a photon source complicates the analysis of the experiment since the beam contains photons with a continuous distribution of energies ranging from the peak kinetic energy of the electrons
down to zero energy (26). The yield or number of reactions that occur when a bremsstrahlung beam is used is given by

\[ \alpha(x) = \gamma_s \int_{0}^{\infty} N(x,k) \sigma(k) \, dk \]  

(6)

where

\[ \alpha(x) = \text{yield or number of events which occur per unit dose of radiation}, \]
\[ x = \text{peak photon energy in the beam}, \]
\[ \gamma_s = \text{number of target nuclei per cm}^2 \text{ of sample}, \]
\[ N(x,k) = \text{number of photons of energy k per unit range of k per unit dose of radiation}, \]
\[ \sigma(k) = \text{cross section for the desired reaction in cm}^2 \text{ per nucleus at energy k}, \]
\[ k = \text{photon energy (27)}. \]

The peak photon energy, x, is also equal to the kinetic energy of the electron beam producing the photons. Since the cross section below threshold of the reaction is zero, the lower limit of the integral is usually replaced by the threshold energy and since there are no photons with energy greater than x, the upper limit is usually replaced by x. Equation 6 then becomes

\[ \alpha(x) = \gamma_s \int_{\text{threshold}}^{x} N(x,k) \sigma(k) \, dk. \]  

(7)

This equation can be solved for \( \sigma(k) \) if all of the other quantities are known. One method for the solution is described in Chapter V of this paper.
If the intensity of the photon beam is exceedingly small the number of photons can be counted directly with a scintillation counter (25). However, when using bremsstrahlung radiation as the photon source, the beam intensity is usually much too high to allow the use of this method. Instead, the dosage of radiation is usually measured with a calibrated ionization chamber.

The number of target nuclei in the target is easily calculated if the physical dimensions, density, chemical composition and ratio of isotopes are known.

The number of reactions that are produced during a bombardment can be measured in a number of ways. One method that is commonly used is to detect the emitted particles. This method has the disadvantage in that there is no way of distinguishing between single or multiple particle reactions. That is, if one is detecting neutrons, there is no way of differentiating between the neutrons from the \((\gamma,n)\), \((\gamma,2n)\), \((\gamma,pn)\) or higher order reactions if more than one reaction is energetically possible. The cross section measured in such an experiment is actually

\[
\sigma(\gamma,xn) = \sigma(\gamma,n) + \sigma(\gamma,pn) + 2\sigma(\gamma,2n) + \ldots
\]

(3, p. 34).

Henceforth in this paper, any cross section measured by detecting the emitted particle will be designated as \(\sigma(\gamma,xn)\) or \(\sigma(\gamma,xp)\).
An alternative method of measuring the number of photo-disintegrations that occur can be used if the daughter nucleus is radioactive. In this case the induced beta or gamma activity can be detected and each decaying nucleus corresponds to one photo-disintegration. This method has the advantage in that one photonuclear reaction can be studied at all photon energies. It is also possible, if the half-life of the radioactivity is long enough, to remove the irradiated sample from the bombarding position and count the activity in some location with a low background. However, even with this method it is still possible to measure more than one type of photonuclear process if more than one of the energetically possible reactions lead to a radioactive nucleus. In many cases there is usually some difference in the features of the radioactivities that will make it possible to distinguish between them and allow a person to study one of the photonuclear reactions separately.

Both of these methods of detecting the yield from a photon bombardment have the disadvantage in that it is not the total photon absorption cross section that is being studied, but only the cross sections for certain of the individual processes. It is only the total photon absorption cross section that can be quantitatively compared with theory. Qualitative features such as the shape of the cross section curve can be checked by measurement of the individual photo-
nuclear processes involved, but quantities such as the integrated cross section, \( \sigma_{\text{int}} \), require knowledge of the total photon absorption cross section. An experiment to measure total photon absorption directly is exceedingly difficult, but the total cross section can be obtained by adding together the cross sections of all of the individual photonuclear processes if they are known (3, pp. 32-36).

D. Review of Experimental Cross Sections

A survey of experimental cross sections will show that all cross sections have the same general features. They all have a peak or giant resonance at a photon energy \( k_m \sim 20 \) Mev. This resonance is due to El photon absorption into a great number of overlapping energy levels in the nucleus. The energy of the giant resonance, \( k_m \), varies with the type of nucleus; the peak falling at higher energies for light nuclei and at lower energies for intermediate and heavy nuclei. This dependence of \( k_m \) on the size of the nucleus is proportional to \( A^{-0.3} \) for \( A > 20 \) (28). This agrees fairly well with the theoretical values where \( k_m \) is proportional to \( A^{-1/3} \) (3, pp. 62-65). The height of the giant resonance ranges from a few millibarns (one barn = \( 10^{-24} \) cm\(^2\)) to several hundred millibarns. The large values of the cross section are usually associated with the heavier nuclei. The width of the giant resonance at half maximum, \( \Gamma \), varies from a few Mev for magic
number nuclei to 10 Mev for the deformed nuclei (3, p. 35). In the case of some highly deformed nuclei the splitting of the giant resonance into two peaks has been seen (29).

The integrated total absorption cross section has been approximated by the sum of the \((\gamma,n)\) and \((\gamma,p)\) integrated cross sections. The values of these integrated cross sections are usually given for an upper limit of 25 Mev, the peak energy of most electron accelerators. (The upper limit is usually shown in parentheses following the symbol \(\Sigma_{\text{int}}\).)

For the heavier nuclei \(\Sigma_{\text{int}}\) (25) is found to be about 30 percent higher than the classical theoretical value but to agree well with the results of dispersion theory (3, p. 35). However, for light nuclei \(\Sigma_{\text{int}}\) (25) falls far below the classical theoretical value. In light nuclei much of the integrated cross section may be contained in a long high energy tail above the giant resonance, but there is little experimental data on photonuclear cross sections above 25 Mev with which to verify this idea. Jones and Terwilliger (30) have measured the \((\gamma,xn)\) cross sections to above the meson threshold for eleven different nuclei ranging in \(Z\) from 4 to 92. Their work shows that all of the materials bombarded have a small high energy tail but that the relative height of the tail was much greater for the lighter elements. In their work, Jones and Terwilliger made no corrections for multiple neutron reactions and at least part of the high energy tail
may be attributed to the overestimation of the cross section for the multiple neutron decays. A small high energy tail has also been found on the $^{12}_C(\gamma,p)^{11}_B$ and $^{12}_C(\gamma,n)^{11}_C$ cross sections by other experimenters (31, 32, 33).

These high energy tails have been explained by a direct interaction between the incoming photon and one nucleon. In this case one nucleon absorbs all of the photon's energy and is immediately emitted from the nucleus rather than two or more of the nucleons sharing the energy, raising the nucleus to some compound excited level, and then statistically decaying. This idea has also been used in angular distribution experiments to successfully explain a strong forward peaking in the distribution of emitted high energy nucleons (3, pp. 104-119).
III. BERYLLIUM-9 PROBLEM

A. The $\text{Be}^9(\gamma,p)$ Cross Section

After the preceding discussion, one may ask what can be learned by measuring the $\text{Be}^9(\gamma,p)\text{Li}^8$ activation curve and cross section. First one can measure the usual features of the cross section such as the shape, peak value and energy of the giant resonance. Second, the integrated cross section can then be computed and when added to the $\text{Be}^9(\gamma,xn)$ cross section, the sum will give a value that can be compared with theory.

The $\text{Be}^9(\gamma,xn)$ cross section includes the $\text{Be}^9(\gamma,n)\text{Be}^8$, $\text{Be}^9(\gamma,pn)\text{Li}^7$, $\text{Be}^9(\gamma;2n)\text{Be}^7$, $\text{Be}^9(\gamma,3n)\text{Be}^6$, $\text{Be}^9(\gamma,2p)\text{He}^7$, $\text{Be}^9(\gamma,3p)\text{H}^6$, $\text{Be}^9(\gamma,2pn)\text{He}^6$, $\text{Be}^9(\gamma,2np)\text{Li}^6$, $\text{Be}^9(\gamma,\alpha)\text{He}^5$, and higher order processes. $\text{H}^6$, $\text{He}^5$, and $\text{He}^7$ are all neutron unstable and so would be counted in a $(\gamma,xn)$ experiment (34, 35). If the integrated $(\gamma,xn)$ cross section is added to the $\text{Be}^9(\gamma,p)\text{Li}^8$, $\text{Be}^9(\gamma,d)\text{Li}^7$, $\text{Be}^9(\gamma,\text{H}^3)\text{Li}^6$, and $\text{Be}^9(\gamma,\text{He}^3)\text{He}^5$ integrated cross sections, the sum is then an approximate value of the total integrated absorption cross section. This sum will be larger than the total integrated cross section because the multiple neutron emission cross sections are over evaluated in a $(\gamma,xn)$ experiment. However, of the multiple neutron reactions, the most probable is generally the lowest order process or the $\text{Be}^9(\gamma,2n)\text{Be}^7$ process, and Foster (36)
has reported the integrated cross section to 45 Mev for this reaction to be only $5 \pm 2$ Mev mb.

Chizhov and Kul'chitskiï (37) have shown that the ratio of high energy ($E > 15$ Mev) deuterons to protons from the photo-disintegration of Be$^{9}$ is only a few percent and that the number of $H^{3}$ particles is almost zero. Therefore the ($\gamma$,d), ($\gamma$,H$^{3}$), and ($\gamma$,He$^{3}$) processes can be neglected since the probability of the He$^{3}$ reaction is probably on the same order of magnitude as the probability of the ($\gamma$,H$^{3}$) reaction. Thus the sum of the ($\gamma$,$xn$) and ($\gamma$,$p$) integrated cross sections will approximate the total integrated absorption cross section.

Jones and Terwilliger (30) have measured the Be$^{9}$($\gamma$,$xn$) cross section for photon energies from 13.5 Mev to above the meson threshold. Their data show a long high energy tail on the Be$^{9}$($\gamma$,$xn$) giant resonance. Nathans and Halpern (38) have reported the Be$^{9}$($\delta$,$xn$) cross section from threshold to 24 Mev, but their peak value for the giant resonance is only 3/4 of the value reported by Jones and Terwilliger. Even so, this is not in disagreement when one considers the experimental errors of 15 to 25 percent that are usually associated with this type of experiment. Together the two experiments give a value for the Be$^{9}$($\gamma$,$xn$) integrated cross section and show that most of it comes from the long high energy tail.

Haslam et al. (39) has measured the Be$^{9}$($\gamma$,$p$)Li$^{8}$ cross
section to 26 Mev by measuring the beta particles from the Li^8 decay. They reported the usual giant resonance with a peak value of 2.7 mb at 22.2 Mev. They also reported a Li^8 yield of 2.3 x 10^4 counts/mole/r at a bremsstrahlung energy of 24 Mev. Cohen et al. (40) measured the Be^9(γ,xp) reaction with nuclear emulsions and reported a proton yield of 5.8 x 10^4 protons/mole/r at a bremsstrahlung energy of 23.5 Mev. Cohen et al. concluded that half of the proton yield was due to (γ,p) reactions and half due to (γ,np) reactions. Haslam et al. were limited by the peak energy of their betatron to bremsstrahlung energies less than 26 Mev. Therefore, they could not report on the existence of a high energy tail on the Be^9(γ,p)Li^8 cross section such as Jones and Terwilliger (30) had reported for the Be^9(γ,xn) cross section. The existence of such a tail above 26 Mev would add a considerable amount to the integrated cross section and so is important.

In this experiment the Be^9(γ,p)Li^8 activation curve was measured and the cross section and integrated cross section computed to 57 Mev, the peak energy of the Iowa State University synchrotron. The integrated cross section for the Be^9(γ,p) reaction was added to the Be^9(γ,xn) integrated cross sections as reported by Jones and Terwilliger (30) and Nathans and Halpern (38) and the sum compared to the integrated total absorption cross section computed from theory.
B. Breaks in the Activation Curve

Since Be\textsuperscript{9} is a light nucleus, one might expect to see breaks or discontinuities in the slope of the activation curve. These breaks correspond to photon absorption into discrete high energy nuclear states. Several discrete high energy levels have been reported for Be\textsuperscript{9} (35). The data of Haslam et al. (39) were not taken in small enough energy intervals to detect any breaks in the yield curve and the data of Cohen et al. (40) showed no proton groups with energies greater than 2 Mev. Two preliminary experiments performed at Iowa State University indicated the existence of breaks in the Be\textsuperscript{9}(\gamma,p)Li\textsuperscript{8} activation curve. However, the energy stability of the synchrotron and the high background counting rates made the accurate determination of the energies of the breaks impossible.

Since these initial attempts at measuring the energies of breaks in the yield curve, much work has been done to improve the energy stability of the Iowa State University synchrotron. At the present time the short time stability is approximately ± 0.01 Mev while the long time stability is ± 0.07 Mev. However, the long time instabilities can be corrected to ± 0.02 Mev. This stability was enough to resolve most of the breaks in the Be\textsuperscript{9}(\gamma,p)Li\textsuperscript{8} activation curve.

However, even with this energy stability, the present methods of analyzing the breaks are usually inadequate. If
the stability and resolution of the equipment (particle accelerator, dosage monitors, and detection equipment) is very good, the breaks sometimes appear as scallops in the activation curve (15). However, the breaks usually appear only as a slight change in the slope of the activation curve. In this case the usual practice is to draw a straight line through as many points on the yield curve as possible on each side of the suspected break. The intersection of the two lines is then taken as the energy of the break (15, 16). A bad feature of this method is that if two breaks or narrow energy levels are close together, they can easily be analyzed as one broad level and vice versa. A second and more objectionable feature of this method is that it relies too strongly on the judgment of the experimenter.

Geller (24) has analyzed the $^{16}(\gamma, n)^{15}$ and $^{14}(\gamma, n)^{13}$ activation curves using a method based on the second difference of the yields. This method approximates the average relative cross section and when applied to the yield curves resolved several resonances in the $^{14}(\gamma, n)^{13}$ and $^{16}(\gamma, n)^{15}$ cross sections. These resonances correspond to photon absorption into known energy levels. This method is a big improvement in analyzing the breaks in yield curves since the breaks now appear as resonances in the cross section. However, actually computing the cross sections on a digital computer is no harder than using Geller's method.
Therefore, the first portion of the $^{9}\text{Be}(\gamma,p)^{8}\text{Li}$ yield curve was measured in 0.046 MeV steps and the cross section computed. Thus the problem of analyzing breaks in a yield curve was reduced to analyzing peaks or resonances in the cross section.
IV. EXPERIMENTAL PROCEDURES AND EQUIPMENT

A. Development of Method

The $^{9}\text{Be}(\gamma,p)^{8}\text{Li}$ reaction was studied by measuring the yield of $^{8}\text{Li}$ when a metallic beryllium target was bombarded by a bremsstrahlung beam from one of the Iowa State University synchrotrons. The yield of $^{8}\text{Li}$ was determined by detecting the beta particles from the 0.85 sec, 13 Mev beta decay of the $^{8}\text{Li}$.

Haslam et al. (39) measured the $^{9}\text{Be}(\gamma,p)^{8}\text{Li}$ yield curve by bombard ing a metallic beryllium target for a period of several seconds. The betatron beam was then turned off and the beta particles from the $^{8}\text{Li}$ decay detected by Geiger counters until the activity died out and then the process was repeated. The disadvantage of this method is that many of the beta particles, those that decay during the bombarding period, are not detected. If the bombarding period is long compared to the half life of the $^{8}\text{Li}$, these undetected decays form a major fraction of the total number of $^{8}\text{Li}$ nuclei formed. The chief advantage of this method is the low background because the particle accelerator is off during the counting period.

An alternative to the method used by Haslam et al. (39) is to count during the bombarding period. During the acceleration period of the synchrotron, the radiation level is so high that it will jam the detectors. However, since synchro-
trons are pulsed machines, the detectors can be gated off during the acceleration period and beam burst, and allowed to count only between the beam bursts. Simple calculations show that the counting rates can be increased by a factor of ten by using this method instead of the method used by Haslam et al. This increase in counting rate is somewhat offset by an increase in background. However, with the techniques used in this experiment the increase in background was kept to only two to three times normal room background.

The experiment was performed in three parts. In the first part the relative yield of $\text{Li}^8$ per dose of radiation as a function of bremsstrahlung energy was measured in energy intervals of 0.046 Mev. The object of this part of the experiment was to determine the threshold of the reaction, and to determine if any low energy resonances could be seen in the cross section. A total of 13 runs was made in this part of the experiment with bremsstrahlung beam energies ranging from 16 to 21 Mev. The repeated measurements in this energy region were necessary because of the low counting rates and relatively high background.

The object of the second part of the experiment was to measure the yield as a function of bremsstrahlung energy from threshold to 57 Mev, the peak energy of the synchrotron, and to determine the shape of the cross section. For this purpose, the yield per dose of radiation as a function of
bremsstrahlung energy was measured in steps of 0.94 Mev. A total of six runs was made in this part of the experiment and the data added together. A large fraction of the time was again spent in the low energy part in order to improve the counting statistics in this region.

The third part of the experiment was to determine the absolute yield of Li\(^8\) at one energy. In this way, the yield curve of parts one and two could be normalized to give the absolute value for the cross section and integrated cross section. For this part of the experiment, the solid angle of the detectors, the duty cycle of the gated detectors, and the total number of beta particles striking the crystal had to be measured.

B. Synchrotron and Bremsstrahlung Beam

The source of bremsstrahlung radiation used in this experiment was one of the Iowa State University electron synchrotrons. The energy calibration of the synchrotron was determined by measuring the threshold of the Be\(^9\)(\(\gamma\),p)Li\(^8\) reaction and the injection voltage of the electrons into the synchrotron as a function of integrator settings. The integrator is the energy selection device of the synchrotron and triggers the knock-out coils when the electrons have reached a predetermined energy. The knock-out coils then drive the electrons onto a molybdenum target where they lose energy
the form of bremsstrahlung radiation. The integrator settings are a linear function of the electron momentum, $p$, (8) and using the relativistic equation,

$$p^2c^2 + m_0^2c^4 = m^2c^4$$

(9)

one can compute the relationship between the electron kinetic energy and the integrator settings. This energy calibration was checked by measuring the $17.24 \pm 0.03$ Mev break in the $^0_{16}(\gamma,n)^{15}$ yield curve to be $17.19 \pm 0.05$ Mev. By repeated measurements of these points and two sharp breaks found in the $^{9}_{Be}(\gamma,p)^{18}_{Li}$ activation curve, the short time energy stability of the synchrotrons was ascertained to be $\pm 0.01$ Mev. Over long periods of time energy shifts as high as $\pm 0.07$ Mev were noted but these could be corrected to $\pm 0.02$ Mev by remeasuring the electron injection voltage and one other easily measured known energy point.

The bremsstrahlung beam was collimated as shown in Figure 1. The first collimator was a stainless steel tube, 7/16 inches inside diameter, 7 inches long, and surrounded by one inch of litharge. The second collimator was a lead wall, 8 inches thick and 16 inches high with a one inch diameter hole in it. The beam size at the beryllium target was 1.1 inch in diameter.
Figure 1. Experimental arrangement used in bombardment of the beryllium and in the detection of the Li$^8$ beta particles.
LEAD
BOPAX
AND
PARAFFIN
SYNCHROTON DONUT
MO TARGET
TRANSMISSION CHAMBER
DETECTOR 1
DETECTOR 2
N.B.S.
CHAMBER
CATHODE FOLLOWER AND GATING CIRCUIT
EXPERIMENTAL APPARATUS
C. Detection System for Beta Particles

The Li\textsuperscript{8} beta particles were detected with two scintillation counters arranged as a coincidence telescope. Figure 1 shows the arrangement of the detectors. The first detector used a plastic scintillator, 60 mils thick, viewed endwise by the photomultiplier tube. The second detector used a 1 inch x 2.5 inch diameter anthracene crystal. After amplification the signals from both detectors were fed to integral discriminators and the outputs of the discriminators were used to drive a coincidence circuit with a resolving time \( \sim 1 \mu \text{sec} \). Figure 2 is a block diagram of the electronics in the detection system. The discriminator on the first detector was adjusted to just eliminate the photomultiplier tube noise. The discriminator on the second detector was adjusted to reject the 3.5 MeV beta particles from the decay of He\textsuperscript{6} which could be formed from the Be\textsuperscript{9}(\gamma,2\text{pn})He\textsuperscript{6} or Be\textsuperscript{9}(\gamma,\text{He}\textsuperscript{3})He\textsuperscript{6} reactions. The number of counts in both the second detector and the coincidence counter were recorded during the runs. However, only the coincidence counts were used when plotting the yield curves and computing the cross sections.

The detectors were shielded as shown in Figure 1. The roof of the house consisted of four inches of lead, two inches of borax and paraffin, and one inch of copper. The lead and copper were used to stop charged particles and photons while the paraffin and borax shielding were used to thermalize and
Figure 2. Block diagram of the electronic circuits
absorb neutrons. The amount of shielding used in the house was limited by the small space that was available in this beam position. It was because of the limited amount of space available for shielding that it was decided to use a coincidence telescope to reduce the background.

The efficiency of the coincidence telescope, that is the ratio of real coincidence counts to real counts in the anthracene detector was 75 per cent. The ratio of background counts in the coincidence telescope to those in the anthracene detector was 10 per cent. Thus the coincidence telescope was particularly helpful in the region near threshold where the ratio of real to background counts is small. The coincidence telescope background consisted of cosmic showers, accidental coincidences, and the radiation emitted when a neutron was absorbed in one of the detection crystals or nearby shielding.

Another source of background, photoelectric electrons and photons scattered by the beryllium target during the beam burst, was eliminated by gating the detectors. Both of the photomultiplier tubes were gated off during the synchrotron acceleration period and beam burst. The detectors were gated on approximately one millisecond after the beam burst, allowed to count for 11.0 milliseconds and were then gated off until the next beam burst. Figure 2 also shows the gating equipment where the integrator output signal triggers both the electron knock-out equipment of the synchrotron and the delays in the
scintillation counter circuits. Figure 3 shows the timing cycle for one period. The two detectors were gated on and off at different times to prevent the possibility of any feed-through pulses from the gating signal arriving at the coincidence circuit at the same time and looking like a real coincidence count.

Figure 4 is the schematic diagram of one of the gated photomultiplier tubes and the white followers. The circuit is a modified design of one used by Bureau (41) in measuring an isomeric transition in W$^{181}$. A flip flop circuit was designed such that the plates of the tubes varied from +270 volts in one stable position to -60 volts in the other stable condition. The plate of one of the flip flop tubes was dc coupled to the third dynode of the photomultiplier tube. Thus the detector was gated off by a negative voltage applied to the first three dynodes of the phototube. In the on or counting condition, the third dynode was held at +270 volts and the photomultiplier operated in its normal capacity. The major fault of such a phototube gating circuit is that the gating pulses are fed through the phototube and cannot be distinguished from a real count at the anode. This difficulty was overcome by taking a part of the gating pulse, shaping and inverting it, and feeding it to the grid of the White follower where it canceled the gating pulse being fed through the photomultiplier tube. In this way, the gating pulses that
Figure 3. Diagram showing timing sequence of the gated beta detectors during one cycle of synchrotron operation
MAGNETIC FIELD OF SYNCHROTRON

- Zero Time
- Electrons Ejected into Synchrotron
- Electron Knockout and Photon Beam Burst

- 0.9 millisecond
- Detector 1 on 12.2 millisecond
- Detector 2 on 12.0 millisecond
- 10 millisecond

175 milliseconds

57.1 Cycles per Second
Figure 4. Schematic diagram of gated photomultiplier tube, pulse shaper and inverter, and White follower.
leaked through were reduced in size to about 20 millivolts while the real counts were as high as 2 volts for a $^{60}$Co source and the anthracene crystal. The 6AN8 tube was used as an inverter, shaper, and isolation stage while the 6AU8 was used as a White follower to drive the coaxial cable.

D. Targets

As seen in equation 6, page 10, the yield is proportional to $\gamma_s$, the number of target nuclei per cm$^2$ of target. Therefore a thick target with a large $\gamma_s$ increases the yield and is extremely useful in improving the counting statistics, especially in the range near threshold where the ratio of real to background counts is low. However, maximum target size is limited by two factors. First, the target cannot be so large that it absorbs a large fraction of the beta particles from the $^{7}$Li decay. Second, the target cannot be so thick that it significantly changes the energy distribution of the bombarding photons since this will change the shape of the yield curve.

Actually when measuring the absolute number of counts it is desirable to have a target so thin that all of the betas escape and are counted. However, for such a thin target, $\gamma_s$ is so small that the counting rate is very small and so a compromise must be made. The target used for measuring the absolute counting rate in this experiment was a sheet of
metallic beryllium, 2 x 2 x 0.044 inches. The target was placed at an angle of 45° with both the axis of the beam and with the axis of the detector. This target was large enough in area to subtend the whole beam at the target position and thin enough to stop very few of the beta particles.

When measuring the relative cross section, a thicker target can be used. The number of beta particles escaping the target is proportional to the number of parent nuclei formed. Therefore since only the relative yield curve is needed to compute the relative cross section, one can use a thicker target and improve the counting statistics. The thick target used in this experiment for measuring the relative yield curves was 3.63 x 3.25 x 1.44 inches with the 3.63 inch side placed parallel to the axis of the photon beam as shown in Figure 1. The effect of such a large target on the photon distribution in the beam was calculated using the absorption coefficients given by Davisson (42). It was found that the number of photons in a 60 Mev bremsstrahlung beam with energies greater than 16 Mev was reduced by ~ 10 percent after the beam had traversed 3 inches of beryllium. However, the ratio of the number of 16 Mev to 60 Mev photons in the beam is changed by less than 3 percent. Thus the actual shape of the bremsstrahlung beam above 16 Mev is changed very little and the last part of the large target sees the same relative number of high and intermediate energy photons as the first
part of the target.

The background for the relative yield curves was determined by substituting an aluminum target for the beryllium target. The thickness of the aluminum target was adjusted so that both the aluminum and beryllium targets had the same number of nuclei per unit area. For the measurement of the absolute counting rate a nickel target was used for the background measurement. Aluminum was not used for this measurement because of the $\text{Al}^{27}(\gamma,n)\text{Al}^{26}$ reaction which then decays with a 3 Mev positron. In the measurement of the relative yield curve, the discriminators were set above this energy. However, in the absolute measurements the discriminator levels were set as low as possible and this activity would have added to the background. Therefore nickel which produces only long lived or low energy beta activities was used for the background target.

E. Dosage Monitoring Equipment

During the measurements of the relative yield curve, radiation dosages were monitored with a sealed, thin walled, transmission chamber. The transmission chamber was located as shown in Figure 1 and was large enough to subtend the whole beam. The electric charge collected by the transmission chamber was measured with a vibrating reed electrometer which recorded the voltage as the charge was collected on a
capacitor consisting of the transmission chamber, coaxial cable, and the electrometer itself. The capacitance was measured with a laboratory type impedance bridge. The charge collected was the product of the voltage and the capacitance of the system.

Before or after each run the beryllium target was removed and the response of the transmission chamber was checked against the response of a second ionization chamber of the National Bureau of Standards design. This N.B.S. chamber was built according to the National Bureau of Standards design and specifications and was designed so that it could be built by any laboratory and yet give the same response as the chambers built and calibrated by the National Bureau of Standards. The N.B.S. chamber destroys the shape of the bremsstrahlung beam and so must be used after the target. Therefore, since the large beryllium target removed approximately 10 per cent of the high energy photons from the bremsstrahlung beam the N.B.S. chamber could not be used directly during the runs. The position of the N.B.S. chamber is shown in Figure 1. During the runs in which the transmission chamber response was calibrated against the N.B.S. chamber response, the N.B.S. chamber was monitored by a current integrator. The current integrator was dc coupled to the N.B.S. chamber and amplified and then integrated the current from the chamber. The calibration and stability of both the vibrating reed electrometer
and the current integrator were checked during the experiment and corrections made in the dosages. One important change was made in the operation of the N.B.S. chamber. The National Bureau of Standards used dry air in their chamber, but because of the usually high humidity in the Iowa air, this condition was hard to meet. Instead, the chamber was flushed with dry nitrogen before the run and nitrogen was allowed to trickle through the chamber during the run. This change in the operating condition of the N.B.S. chamber was both measured and calculated and found to increase the charge collected per dose of radiation by 7 percent. The accuracy of the dosage was determined to be 3 percent with the biggest source of error being the calibration of the N.B.S. chamber.

During the measurement of the absolute counting rate, the dosage measurements were made directly with the N.B.S. chamber since the thin beryllium target had little effect on the number of photons in the bremsstrahlung beam. Also, during this part of the experiment the N.B.S. chamber was monitored with a new vibrating reed electrometer instead of the current integrator. The new electrometer provided more sensitivity and greater stability than the other circuits.

F. Stability of the Detection and Dosage Monitoring Equipment

During this experiment, as in any experiment, instabilities were noted in the equipment. In experiments, such as
the $\text{Be}^9(\gamma,p)\text{Li}^8$ experiment, where data from many runs taken on as many different days must be added together, instabilities, especially in the gain of the detection equipment, must be small. Such long time stability in scintillation detectors is difficult to achieve. Instead of attempting to remove all of the instabilities in the detection equipment a system of normalizing the data was devised to reduce the instabilities. During the runs in which data were taken, one point on the yield curve was repeated once every half hour. This point was then used as a normalizing point. The normalization factors were plotted as a function of time and the normalization factor for any other yield point could then be read from the graph. The point chosen as the normalization point was the yield at 38.12 Mev. This point is in a relatively flat portion of the yield curve so that the small instabilities in energy did not affect the yield. This method of normalizing the data corrected for instabilities in both the detection equipment and the dosage monitoring equipment. Counting rate changes as high as 12 percent were noted in the detection equipment, but by normalizing, these changes were reduced to less than one percent.

G. Measurement of the Absolute Counting Rate

The measurement of the absolute counting rate was made with a 28 Mev bremsstrahlung beam. This bombarding energy,
just below the $^{9}\text{Be}^{(\gamma,2pn)}\text{He}^{6}$ threshold, was picked in order to maximize the $^{9}\text{Li}$ counting rate while at the same time keeping the number of 3.5 Mev betas from the $\text{He}^{6}$ decay at a minimum. Because the first detector attenuated and even completely stopped some of the beta particles from the beryllium target and prevented them from being counted, the scintillation telescope was removed and the betas were counted directly with the large anthracene crystal. This increased the background but since the bombarding energy was high, the ratio of real counts to background was also relatively high and so the increased background did not present a problem. It was impossible to set the discriminator level of the scintillation detector to correspond to zero beta energy and count all of the betas coming from the target because of phototube noise and the sharp rise in background as the discriminator energy settings approached zero. But since the area under a beta spectrum corresponds to the total number of counts, the ratio of counts for any discriminator level to the total number of counts will be given by the ratio of area above the discriminator level to the total area. Therefore, the beta spectrum was measured and plotted to as low an energy as possible, $E = 0.4$ Mev. The measured spectrum is shown in Figure 5. The spectrum was extrapolated to zero beta energy and the relative areas measured to give the total number of counts striking the crystal.
Figure 5. Beta-ray spectrum from $\text{Li}^8(\beta)\text{Be}^8$ decay; ratio of total area to area above discriminator level is equal to the total number of beta particles striking the detector to the number of beta particles counted.
Li\textsuperscript{8} Beta Spectrum
△ Measured Spectrum
○ Spectrum After Background Has Been Subtracted Out

RELATIVE NO. OF BETA PARTICLES PER UNIT TIME

ENERGY OF BETA PARTICLES (MEV)
The duty cycle of the gated scintillation counter was measured with an oscilloscope whose horizontal sweeps had been calibrated with a crystal controlled time calibrator. In order to measure the absolute counting rate it was also necessary to know the solid angle subtended by the scintillation detector. This quantity was approximated by assuming a point source and measuring the distance from the center of the target to the face of the anthracene crystal. It was also assumed that the crystal was 100 percent efficient, that is that any beta particle striking the crystal lost enough energy in the crystal to be detected. The accuracy of these methods of measuring the absolute counting rate was checked by measuring the counting rate of a Ru\textsuperscript{106} source. The source had previously been calibrated using a 4π solid angle counter. The two values for the counting rate of the source agreed within experimental accuracy.
V. ANALYSIS OF DATA

A. Cross Section Analysis

The relationship between the photonuclear cross section and the yield obtained with a bremsstrahlung beam has been given by equation 7, page 10, as

$$\lambda(x) = \gamma_s \int_{\text{threshold}}^{x} N(x,k) \sigma(k) \, dk.$$  

The term $N(x,k)$ is the radiation spectrum and is the product of three factors: first, the bremsstrahlung spectrum that is produced by the electrons in the synchrotron losing their energy; second, the absorption of the photons when they pass through the donut walls, air, and transmission chamber; third, a function which normalizes the spectrum to unit monitor response (27). The expression $N(x,k)$ can be written

$$N(x,k) = \left( \frac{\Phi(x,k)}{k} \right) \frac{f_s(k)}{F(x)}.$$  

$\frac{\Phi(x,k)}{k}$ is a term that is proportional to bremsstrahlung spectrum produced by the electrons. The shape of this spectrum is angle dependent, but Penfold and Leiss (27) have shown that if $\theta_0$, the maximum accepted angle between the photon and incident electron, is of the order of $m_o c^2/x$ or larger, then the shape of the bremsstrahlung spectrum converges to the integrated over angles spectrum given by Schiff (26). If the effects of the multiple scattering of
the electrons in the radiating target are also included, the
shape of the spectrum will approach the Schiff spectrum even
more closely. In this experiment the maximum value of
\( \frac{m_0 c^2}{x} \) is 0.0294 radians while \( \theta_0 \) is approximately 0.014
radians. Therefore the \( \phi(x,k)/k \) used in the analysis of
the data was taken as a term proportional to the integrated
over angles spectrum given by Schiff.

\( f_a(k) \) is the absorption factor, that is, the probability
that photons of energy \( k \) will be absorbed before reaching the
beryllium target. It is dependent upon the energy of the
photons and the amount and type of material that the photons
must penetrate before reaching the target. In this experi­
ment the photons must pass through the walls of the ceramic
donut in the synchrotron, the thin walled transmission cham­
ber, and about 40 inches of air before reaching the target or
N.B.S. chamber. When the targets are being bombarded, only
those photons with energy greater than the threshold energy,
16.89 Mev, are of interest. For the materials in the beam
the absorption coefficient is essentially constant for photons
between 15 and 60 Mev and so in this experiment, \( f_a(x) \) may be
considered equal to one. When the transmission chamber is
being calibrated against the N.B.S. chamber, the absorption
coefficient can again be neglected since absorption in the
donut walls, air, and transmission chamber will be small com­
pared to the absorption in the four inches of aluminum in the
forward part of the N.B.S. chamber.

The third term in $N(x,k)$ is $F(x)$, the monitor response function that normalizes the spectrum to unit monitor response. In this experiment, the unit of monitor response is 1 Mev of energy in the beam. The energy in the beam is

$$E(x) = \int_{0}^{x} N(x,k) \ k \ dk. \quad (11)$$

But, by definition, $N(x,k)$ produces 1 Mev of energy. Therefore

$$1 = \int_{0}^{x} N(x,k) \ k \ dk \quad (12)$$

and substituting for $N(x,k)$ we get

$$1 = \int_{0}^{x} \frac{\phi(x,k)}{k} \frac{1}{F(x)} \ k \ dk \quad (13)$$

where we have neglected the $f_g(k)$ because of the previous arguments. $F(x)$ is independent of $k$ and therefore can be removed from the integral giving

$$F(x) = \int_{0}^{x} \phi(x,k) \ dk. \quad (14)$$

If equation 10 is substituted for $N(x,k)$ in equation 7 the resulting equation is

$$\chi(x) = \eta_s \int_{\text{threshold}}^{x} \frac{\phi(x,k)}{k} \frac{1}{F(x)} \sigma(k) \ dk \quad (15)$$

where $f_g(k)$ has been considered constant and equal to one.
Again $F(x)$ can be removed from under the integral since it is independent of $k$ to give

$$\alpha(x)F(x) = \gamma_s \int_{\text{threshold}}^{x} \frac{\Phi(x,k)}{k} \sigma(k) \, dk.$$  \hspace{1cm} (16)

By rearranging the terms in the equation it becomes

$$Y(x) = \int_{\text{threshold}}^{x} \Phi(x,k) \Omega(k) \, dk.$$  \hspace{1cm} (17)

where

$$Y(x) = \alpha(x)F(x),$$
$$\Omega(x) = \gamma_s \frac{\sigma(k)}{k},$$
$$\Phi(x,k) = \text{a function proportional to the intensity of the Schiff integrated over angles bremsstrahlung spectrum.}$$

This is the reduced yield curve given by Penfold and Leiss (27, p. 8). In principle equation 17 can be solved by forming the appropriate combination of integrals and differentials of $Y(x)$. This procedure has been carried out by Spencer (43) who approximated $\Phi(x,k)$ by a comparatively simple function. However, the functional form of $Y(x)$ is not known and since $Y(x)$ is only measured for a limited number of points, only the average values of the cross section can be obtained from an experiment. The method of solution used in this experiment was the total spectrum method used by Diven and Almy (44) and by Johns et al. (45). In this method the integral is replaced by a sum:
\[ Y(x_j) = \sum_{k_1=\text{threshold}}^{x_j} \Phi(x_j, k_1) \Omega(k_1) \Delta k \]

where

\[ k_{i+1} = k_i + \Delta k \]
\[ \Omega(k_0) = 0 \]
\[ \Phi(x_j, k_1) = 0 \text{ for } k_1 > x_j \]

If the experimental data are then taken in energy steps of \( \Delta x = \Delta k \), the experimental yields can be written:

\[ Y(x_1) = \Phi(x_1, k_1) \Omega(k_1) \Delta k \]
\[ Y(x_2) = \Phi(x_2, k_1) \Omega(k_1) \Delta k + \Phi(x_2, k_2) \Omega(k_2) \Delta k \]
\[ Y(x_3) = \Phi(x_3, k_1) \Omega(k_1) \Delta k + \Phi(x_3, k_2) \Omega(k_2) \Delta k \]
\[ + \Phi(x_3, k_3) \Omega(k_3) \Delta k \]

where \( x_j \) is the electron kinetic energy, \( k_1 \) is the photon energy and \( x_j = k_1 \) when \( j = 1 \). This system of equations can be solved for \( \Omega(k_1) \), although the calculation of the \( \Phi(x_j, k_1) \) is a long and tedious job because of its complex form. Also, a set of values for \( \Phi(x_j, k_1) \) must be computed for each different value of \( \Delta k \) that one chooses to use in the calculations. The problem of calculating \( \Phi(x_j, k_1) \) and solving the equations for \( \Omega(k_1) \) was programmed for the Iowa State University Cyclone digital computer. The output of
the computer was equal to \((k_1 - 1/2 \Delta k) \sum (k_1 - 1/2 \Delta k)\) for each value of \(k\) from threshold to \(k_m\), the highest energy for which the yield was measured. Therefore from equation 17, the computer output equals \(\gamma_s \sigma(k_1 - 1/2 \Delta k)\). Dividing the computer output by \(\gamma_s\) then gives the cross section.

The integrated cross section, \(\sigma_{\text{int}}\) is given by equation 3, page 4, as

\[
\sigma_{\text{int}}(E) = \int_{\text{threshold}}^{E} \sigma(k) \, dk.
\]

If the integral is replaced by a sum, \(\sigma_{\text{int}}\) is approximated by

\[
\sigma_{\text{int}}(k_m) \sim \sum_{k=k_1}^{k_m} \sigma(k_1) \Delta k
\]

where \(k_m\) is the maximum energy for which the cross section was computed and \(k_1\) is equal to the threshold energy.

B. Smoothing of Data

The solution of the set of equations 19 is complicated by the addition of experimental error. The solution of the equations involve the difference of two numbers of the same order of magnitude; for example

\[
\Omega(k_2) = \frac{Y(x_2) - \Omega(x_2, k_1) \Delta \omega(k_1) \Delta k}{\Omega(x_2, k_2) \Delta k}
\]

where \(Y(x_2)\) and \(\Omega(x_2, k_1) \Delta \omega(k_1) \Delta k\) are the same order of
magnitude. When the difference of the two numbers is of the same order of magnitude as the experimental error in the reduced yield, then a large error can appear in the reduced cross section, \( \Omega \). In general, because of the nature of the curves, if \( \Omega(k_1) \) is too large, \( \Omega(k_{1+1}) \) will be too small. This results in an oscillating cross section rather than a smooth curve and the cross section must be smoothed.

In the past many different types of smoothing have been tried by different experimenters. Few have tried to smooth the cross section directly. Instead, the usual method is to smooth either the yield curve or the integrated cross section. Penfold and Spicer (12) simply drew a smooth curve through the yield points and analyzed the smooth curve for the cross section. Katz and Cameron (46) drew a smooth curve through the yield points and then took the differences between the yield points and the smooth curve. The differences were then plotted and smoothed also. The smoothed difference curve was then added to the smoothed yield curve and the resulting sum curve was used to compute the cross section. King et al. (47) improved on this method by first fitting a fourth degree equation to the yield curve by least squares and then taking the differences between the smooth curve and the yield points. The differences were then smoothed and added to the analytic curve, and the sum used to compute the cross section. These methods of smoothing are useful if the experimental error is
large. However, when the experimental error is relatively small, Penfold and Leiss (27) recommend computing the integrated cross section directly from the experimental yield curve without smoothing and then drawing a smooth curve through the integrated cross section curve. The smoothed cross section is then taken as the differences between points of the smoothed integrated cross section.

The method of smoothing used in this experiment was similar to that suggested by Penfold and Leiss (27). However, instead of drawing a smooth curve through the integrated cross section, a fourth degree equation was fitted by least squares through each adjacent seven points. The derivative of the curve was evaluated at the midpoint of the seven points. The group of points was then advanced one point and the process repeated until the derivative was evaluated at each point. This derivative of the smoothed integrated cross section was then taken as the smoothed cross section.

The question of which is the best method of smoothing and how much smoothing to apply is difficult to answer. In this experiment many different types of smoothing were tried, but the method described above seemed to give the best results without oversmoothing and removing some of the structure in the experimental curves that was considered significant. In order to compare different methods of smoothing, several different "known" cross sections were constructed from Gaussian
curves and straight lines. From these cross section curves, corresponding exact yield curves were computed. Then using a set of random numbers, deviations were made in the exact yield curve that corresponded to an experimental error with a standard deviation of one percent. The cross sections were then computed from these simulated yield curves and the different methods of smoothing applied. The advantage of using the simulated curves for comparing the different methods of smoothing was that the original cross section was known and could be compared with the smoothed curve. One cross section curve is shown in Figure 6. The smooth curve in Figure 6-a is the exact cross section and the histogram in Figure 6-a is the cross section computed from the exact yield curve. Figure 6-b shows the cross section computed from the yield curve when an experimental error is added to the exact yield curve. Figure 6-c shows the derivative of the seven point smoothed integrated cross section computed from the cross section in Figure 5-b.

C. Analysis of Errors

Errors in the measurement of the absolute cross section can be broken down into two parts, depending on how they enter into the measurement. The absolute cross section can be written as the product of two terms

\[ \sigma(k) = \sigma_{rel}(k) S \]  

(22)
Figure 6. Test cross sections

(a) Smooth curve is the known cross section; histogram is the computed cross section from the exact yield curve calculated from the known cross section.

(b) Unsmoothed computed cross section when one percent "experimental" error is added to the exact yield curve.

(c) Smoothed cross section using the method described in the text.
PHOTON ENERGY (Mev)

CROSS SECTION

1% STATISTICS ON YIELD CURVE

DIFFERENTIAL OF SEVEN POINT SMOOTH INTEGRATED CROSS SECTION

PHOTON ENERGY (Mev)
where $\sigma_{\text{rel}}(k)$ is the relative cross section, computed from the relative yield curves and $S$ is the term that normalizes the relative yield curve and hence the relative cross section to the absolute values. All of the errors in the experiment can then be classified into two groups: errors associated with the measurement and calculation of $\sigma_{\text{rel}}(k)$ and the errors in the determination of the normalization factor.

The error in $\sigma_{\text{rel}}(k)$ arises from the experimental error in measuring the relative yield curves. Errors in the relative yield curve come from three sources, the statistical fluctuation in the number of counts, drifts in the energy control equipment, and the drift in the beta detection and the dosage monitoring equipment. As was mentioned in one of the earlier sections, this latter source of error was reduced to less than one percent by normalizing the data. The statistical fluctuation in the yield curves can be reduced only by taking more data. However, there is a point beyond which it is no longer practical to keep taking data in order to improve the statistics because of the huge amount of time it would take.

In the energy region from threshold to 19.0 Mev, this error in $Y(x)$ was dominated by the statistical fluctuations in the number of counts. For yields at $x > 20$ Mev enough counts could be measured so that the drift of the experimental equipment caused most of the error and the error in these yield points was taken to be $\pm 1$ percent. For the energy
region between 19 and 20 Mev, the error was computed as the square root of the sum of the squares of the statistical error and the 1 percent experimental drift.

How the error in the relative yield curve affects the computed cross section can be seen by solving the first three equations of the set of equations 19 for \( \Omega(k_1) \), \( \Omega(k_2) \), and \( \Omega(k_3) \) in terms of the bremsstrahlung spectra and the reduced yields. The solutions are

\[
\begin{align*}
\Omega(k_1) &= \frac{Y(x_1)}{\Phi(x_1, k_1) \Delta k} \\
\Omega(k_2) &= \frac{Y(x_2) - \Phi(x_2, k_1) \frac{Y(x_1)}{\Phi(x_1, k_1)}}{\Phi(x_2, k_2) \Delta k} \\
\Omega(k_3) &= \frac{Y(x_3)}{\Phi(x_3, k_3) \Delta k} - \frac{\Phi(x_3, k_2) Y(x_2)}{\Phi(x_3, k_3) \Phi(x_2, k_2) \Delta k} \\
&+ \left[ \frac{\Phi(x_3, k_2) \Phi(x_2, k_1)}{\Phi(x_1, k_1) \Phi(x_2, k_2) \Phi(x_3, k_3) \Delta k} \right] Y(x_1).
\end{align*}
\]

Since the \( \Phi(x_j, k_1) \) are all computed values, there is no statistical error associated with them. Therefore
\[ E_1 = \frac{s_1}{\Phi(x_1, k_1) \Delta k} \]

\[ E_2 = \frac{1}{\Delta k} \left[ \frac{\Phi^2(x_2, k_1) s_2^2}{\Phi^2(x_1, k_1) \Phi^2(x_2, k_2)} + \frac{s_2^2}{\Phi^2(x_2, k_2)} \right]^{1/2} \]

\[ E_3 = \frac{1}{\Delta k} \left[ \frac{s_3^2}{\Phi^2(x_3, k_3)} + \frac{\Phi^2(x_3, k_2) s_2^2}{\Phi^2(x_2, k_2) \Phi^2(x_3, k_3)} \right. \]

\[ + \left( \frac{\Phi(x_3, k_2) \Phi(x_2, k_1)}{\Phi(x_1, k_1) \Phi(x_2, k_2) \Phi(x_3, k_3)} \right)^2 \frac{s_2^2}{s_1} \right]^{1/2} \]

where \( E_1 \) is the error in \( \Omega(k_1) \) and \( s_1 \) is the experimental error associated with \( Y(x_1) \). This method can be extended and used to solve for the error at any point for which the cross section is computed.

The second source of error in the absolute cross section comes from the determination of the normalization factor for the relative yield curves. The normalization factor is

\[ s = \frac{\alpha_{\text{abs}}}{\alpha_{\text{rel}}} \]  

The error in the relative yield at 28 Mev is one percent but the error in the absolute counting rate is considerably higher. The absolute counting rate is calculated from
\[ \alpha_{\text{abs}} = \frac{N(28)}{\text{dosage}} \cdot \frac{A_{\text{total}}}{A_{D > .6 \text{ MeV}}} \cdot \frac{T}{T_{\text{on}}} \cdot \frac{4\pi}{\Theta} \]

where

- \( N(28) \) = number of counts recorded at 28 Mev,
- \( \frac{A_{\text{total}}}{A_{D > .6 \text{ MeV}}} \) = ratio of total area under the beta spectrum to the area above the discriminator level,
- \( \frac{T}{T_{\text{on}}} \) = ratio of the total time of the run to the time that the counter was gated on,
- \( \frac{4\pi}{\Theta} \) = ratio of the total solid angle to the solid angle subtended by the detector.

The error in \( N \) is just the statistical fluctuations of the counting rate and is \( \pm 0.5 \) percent. The ratio of areas has an error of \( \pm 4 \) percent. The times were measured with an accuracy of \( 0.1 \) millisecond and the ratio has an error of \( \pm 1.25 \) percent. The largest error in the absolute counting rate comes from the measurement of the solid angle. This measurement has an error of \( \pm 8.5 \) percent. The error in the absolute dosage is \( \pm 3 \) percent, being mostly due to the calibration of the National Bureau of Standards designed ionization chamber. This gives for the absolute counting rate an error of \( \pm 10 \) percent.

Using these equations and the above information it is possible to assign a probable error to the computed cross section or integrated cross section.
VI. EXPERIMENTAL RESULTS

The yield curve from threshold to 20 Mev in steps of 0.046 Mev is shown in Figure 7. Examination of the yield curve shows several breaks or sudden changes in the slope of the curve. However, the energies of some of these breaks are hard to determine from just the yield curve. The integrated cross section was computed directly from the experimental points and is shown in Figure 8. The smoothed cross section was then calculated from the integrated cross section according to the procedure outlined in Section V and is shown in Figure 9. It should be noted that there are a number of resonances in this low energy cross section.

The yield curve from threshold to 57 Mev in steps of 0.94 Mev is shown in Figure 10. The integrated cross section and the cross section were computed directly from the experimental points and are shown in Figures 11 and 12 respectively. The oscillations in the cross section, caused by the experimental error in the relative yield curve, are readily seen in Figure 12. To remove the oscillations, the smoothed cross section was computed from the integrated cross section and is shown in Figure 13. A smoothed cross section using a quartic equation through nine points was also tried, but it did little to further remove the oscillations. Since the additional smoothing did not improve the curve significantly, only the curve with the least amount of smoothing is shown.
Figure 7. Yield curve for the $^9\text{Be}(\gamma,p)^{18}\text{Li}$ reaction for the energy interval 16.5 Mev to 20 Mev taken in steps of 0.046 Mev.
Be$^9$ (γ,p)Li$^8$ YIELD CURVE
Figure 8. Integrated cross section for the $^{9}{\text{Be}}^{(\gamma,p)}^{7}{\text{Li}}$ reaction for the energy interval 16.5 MeV to 20 MeV in steps of 0.046 MeV; no smoothing has been applied.
Figure 9. Smoothed cross section for the $^{9}\text{Be}(\gamma,p)^{8}\text{Li}$ reaction for the energy interval 16.89 Mev to 20 Mev; the smoothing applied is discussed in the text (the known levels in $^{9}\text{Be}$ are shown by the arrows with the horizontal bars indicating their widths).
Figure 10. Yield curve for the Be$^9(\gamma,p)$Li$^8$ reaction for the energy interval 16 Mev to 57 Mev taken in steps of 0.94 Mev.
Be$^9(\gamma, p)$Li$^8$ YIELD CURVE

RELATIVE YIELD

PEAK PHOTON ENERGY (MeV)
Figure 11. Integrated cross section for the $^{9}\text{Be}(\gamma,p)^{8}\text{Li}$ reaction; no smoothing has been applied.
$^9\text{Be}^9 (\gamma p) \text{Li}^8$
INTEGRATED CROSS SECTION
Figure 12. Unsmoothed cross section for the $\text{Be}^9(\gamma,p)\text{Li}^8$ reaction
$^{9}\text{Be} \ (\gamma, p) ^{8}\text{Li}$

UNSMOOTHED CROSS SECTION
Figure 13. Smoothed cross section for the Be$^9(^\gamma,p)$Li$^8$ reaction; the smoothing applied is discussed in the text (the dotted curve is the data of Haslam et al. (39))
Be\(^9\) (γ,p) Li\(^8\)
Smoothed Cross Section

[Graph showing the smoothed cross section for the reaction Be\(^9\) (γ,p) Li\(^8\) as a function of photon energy (MeV).]
VII. DISCUSSION OF EXPERIMENTAL RESULTS

A. Low Energy Data

Be$^9$ has several high energy, excited states that lie above the $\gamma$,p threshold (35, 48). These high energy levels are shown in Figure 7 with the horizontal bars indicating the known widths of the levels. There is a definite correlation between the resonances in the cross section and some of the known levels. Almost as noticeable as the correlation between the levels and resonances is the lack of a resonance corresponding to the known 17.28 Mev level. This level has been studied by bombarding Li$^7$ with $H^2$, forming Be$^9*$, and observing the protons, neutrons, or alpha particles that come from the reaction (35). In such reactions, the change in the angular momentum, $\Delta J$, between the ground state of Li$^7$ and the excited state of Be$^9$ can be 0, ± 1, ± 2, or more. Thus by taking the appropriate combinations of the spin, $I$, and orbital angular momentum, $l$, of the deuteron, the Be$^9*$ can be formed in states ranging from $J^\pi = 1/2^+$ to $5/2^-$ or $7/2^+$ for $l = 0$ or 1. In a photonuclear reaction this is not possible since most of the photons are absorbed by an El transition. Therefore, for photonuclear reactions, $\Delta J = 0, \pm 1$ (not 0→0) and the parity must change between the ground state and the excited levels. The angular correlation of the ground state alpha particles resulting from the breakup of the He$^5$ in the
Li⁷(d,α)He⁵ reaction indicates J = 3/2⁻ (49) or J = 5/2⁻ (50) for the level at 17.28 Mev. The ground state of Be⁹ is a 3/2⁻ state (35). Thus, the 17.28 level could not be excited by El photon absorption because there is no change in parity between the two levels.

A second discrepancy between the cross section and the known levels is noticeable at 17.8 Mev. The cross section indicates another level at this energy, but Ajzenberg-Selove and Lauritsen (35) do not list such a level in their energy diagrams. Baggett and Bame (51) and Bennett et al. (52) reported an excited state in Be⁹ at 17.8 Mev from their Li⁷(d,n)Be⁸ investigations. Bashkin (53) investigating the level later by a Li⁷(d,p)Li⁸ experiment could find no indication of this level and concluded that it did not exist. Because of this latter experiment, the level does not appear on the level diagrams.

It should also be noted that the existence of the levels at 18.1 Mev and 18.6 Mev are listed as being uncertain. The Be⁹(γ,p)Li⁸ cross section presented here would tend to verify the existence of these levels.

B. High Energy Data

The high energy cross section shown in Figure 13 shows that the giant resonance reaches a maximum at 23 Mev which agrees with the work of Haslam et al. (39). The peak value of
the cross section obtained in this experiment is $2.64 \pm 0.33$ mb which is also in good agreement with Haslam et al. who reported a value of $2.72 \pm 0.8$ mb. However, the shape of the rest of the cross section is quite different. The present experiment shows a high energy tail on the giant resonance while the cross section as reported by Haslam et al. drops rapidly after reaching its maximum as is shown in Figure 7.

The integrated cross section to 57 Mev is $41.4 \pm 4.6$ Mev-mb with much of the integrated cross section being contained in the high energy tail.

Using equation 5, the theoretical value for the integrated cross section up to the photomeson threshold is 187 Mev-mb. This value may be compared with the sum of the cross sections for the ($\gamma$,p), ($\gamma$,n), ($\gamma$,pn), ($\gamma$,2n) etc. reactions. The only measurement of the ($\gamma$,xn) cross section for Be$^9$ above 25 Mev is the work of Jones and Terwilliger (30). Taking the results of Figure 4 from their paper, the integrated ($\gamma$,xn) cross section to 57 Mev is $\sim 143$ Mev-mb. This is an over-estimate of the photoneutron cross section since no attempt was made to correct for multiple neutron reactions. However, this may not be too serious below 50 Mev since Foster (36) reported the Be$^9$($\gamma$,2n)Be$^7$ integrated cross section to 45 Mev to be $5 \pm 2$ Mev-mb. Adding the results of Jones and Terwilliger to the value for the ($\gamma$,p) cross section from this experiment gives $\sigma_{\text{int}}(57) \sim 184$ Mev-mb.
Nathans and Halpern (38) measured the Be\(^9\)(\(\gamma\),xn) cross section to 24 MeV and reported the giant resonance to be only three-fourths of the value found by Jones and Terwilliger (30). If Nathans and Halpern are correct, then a better estimate of the integrated cross section could be found by using only three-fourths of Jones and Terwilliger's value for the Be\(^9\)(\(\gamma\),xn) integrated cross section. In this case, the sum of the Be\(^9\)(\(\gamma\),p) and Be\(^9\)(\(\gamma\),xn) integrated cross sections to 57 MeV would be \(\sim 148\) Mev·mb.

In addition to these two values of \(\sigma_{\text{int}}\) (57), one can also set a lower limit on the integrated cross section to the meson threshold by making two approximations. First, using the data of Jones and Terwilliger (30) and assuming a neutron multiplicity of 5, the maximum value it can be, in the region between 57 MeV and the meson threshold, one gets for the corrected integrated cross section \(\sim 180\) Mev·mb. Or again using the lower values of Nathans and Halpern, this becomes \(\sim 135\) Mev·mb. The second assumption to be used is that the (\(\gamma\),p) cross section is zero above 57 MeV. Then if the integrated cross section to 57 MeV of the Be\(^9\)(\(\gamma\),p) reaction is added to 135 Mev·mb, one obtains a lower limit for the total integrated cross section, \(\sigma_{\text{int}}\), of \(\sim 180\) Mev·mb.

Thus it appears that the integrated cross section to the meson threshold will be at least as large as the theoretical value of 187 Mev·mb with most of the integrated cross section
lying above 26 Mev, the upper limit of most particle accelerators. It may be for this reason that most of the previous attempts at measuring the integrated cross sections of low Z nuclei gave values much smaller than the theory predicted.
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