Doctoral Thesis

A Study of the photodisintegration of C-12 into three alpha-particles

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Publication Date:
1953

Permanent Link:
https://doi.org/10.3929/ethz-a-000088905

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A Study of the Photodisintegration of $^{12}\text{C}$
Into Three Alpha-Particles

THESIS
PRESENTED TO
THE SWISS FEDERAL INSTITUTE OF TECHNOLOGY
ZURICH
FOR THE DEGREE OF
DOCTOR OF NATURAL SCIENCE
BY
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Accepted on the recommendation of
Prof. Dr. P. Scherrer and Prof. Dr. G. Busch

Research Publication Services
General Electric Research Laboratory
Schenectady, New York, U.S.A., 1953
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I. INTRODUCTION

The first photonuclear disintegration was accomplished by Chadwick and Goldhaber in 1934. They used a small ionization chamber filled with deuterium and observed that protons were ejected from the deuterium when it was exposed to gamma-rays from thorium C. Later, Szilard and Chalmers, using gamma-rays from radium, produced a (γ, n) reaction in Be⁹. No other photonuclear disintegrations by natural gamma-rays appeared to be possible at this time because the binding energies of all other stable nuclei are greater than the gamma-ray energies available from natural sources.

A practical artificial source of gamma-rays of higher energy (≈18 Mev) was found in the reaction Li⁷ (p, γ) Be⁹ reaction. This process was first observed by Traubenberg, Eckardt, and Gebauer and independently by Lauritsen and Crane. Bothe and Gentner, using this artificial gamma-ray source, produced a number of (γ, n) reactions, while Waffler and Hirzel observed several (γ, p) reactions.

The successful construction of high-energy electron accelerators such as betatrons and synchrotrons opened up new possibilities for the study of photonuclear effects. G. C. Baldwin and H. W. Koch, using the bremsstrahlung of a 22-Mev betatron, determined (γ, n) thresholds for a number of nuclei. Baldwin and Klaiber extended this work, using the G-E 100-Mev betatron, and made qualitative studies using radiochemical techniques of other reactions such
as \((\gamma, p)\) and \((\gamma, \text{pn})\). They noted a resonance-like effect in the energy dependence of the \((\gamma, n)\) and photofission cross sections. Other exploratory work was done by Perlman and Friedlander,\(^{(18)}\) who studied the relative yields of the \((\gamma, n)\) reaction using the General Electric 100-Mev betatron. They noted no substantial difference in yields between the 50- and 100-Mev bremsstrahlung. J. L. Lawson and M. L. Perlman\(^{(19)}\) found similar results for copper and carbon. E. R. Gaerttner and M. L. Yeater\(^{(20)}\) constructed a fast recycling cloud chamber with a pulsed magnetic field. This chamber is especially well suited for work with pulsed accelerators such as the G-E 100-Mev betatron. They have made exploratory studies of photodisintegration reactions in helium, carbon (methane), nitrogen, and oxygen.\(^{(21,22)}\)

From the exploratory investigations cited, the following general conclusions may be drawn.

1. \((\gamma, n)\) and \((\gamma, p)\) reactions are the most probable.
2. In light elements, \((\gamma, n)\) and \((\gamma, p)\) reactions are about equally probable.
3. In heavier elements, the \((\gamma, n)\) reaction is the more probable.
4. Disintegrations with multiple particle emission have been observed, such as \((\gamma, 2n)\), \((\gamma, 2p)\), \((\gamma, 2\text{pn})\), \((\gamma, 3\text{pn})\), \((\gamma, \text{a n})\), \((\gamma, 2p, 3n)\), \((\gamma, 3\text{a})\).\(^{(23)}\)

Of these multiple disintegrations, one has been studied quite intensively, namely, the \(^{12}\text{C}(\gamma, 3\alpha)\) reaction. H. Hänni, V. L. Telegdi,
and W. Zünti\textsuperscript{(24)} have noted and studied this process in photographic emulsions (see Fig. 1). The photons in this case originated from the reaction $\text{Li}^7 (p, \gamma) \text{Be}^8$. Later, Goward, Telegdi, Zünti, and Wilkins,\textsuperscript{(25-27)} using the bremsstrahlung of a 25-Mev betatron, extended this investigation. They found a peak in the cross section for the $\text{C}^{12} (\gamma, 3\alpha)$ reaction at a photon energy around 18 Mev, followed by a sharp drop (see Fig. 2). They also correlated specific Be\textsuperscript{8} excitation levels (see Fig. 3) with this reaction and observed an indication of a possible re-increase in the cross section above 20 Mev. However, they were not able to make a thorough investigation of the cross section above 20 Mev because of the energy limitation of the betatron used.

The work described here was undertaken primarily to determine the energy dependence of the $\text{C}^{12} (\gamma, 3\alpha)$ total cross section above 20-Mev photon energy. The results of this investigation are: the discovery of a second "resonance" for the $\text{C}^{12} (\gamma, 3\alpha)$ reaction around 27-Mev photon energy of the order of $2.5 \times 10^{-28} \text{cm}^2$ at the maximum; and evidence for a Be\textsuperscript{8} excitation level around 17 Mev, not previously reported.\textsuperscript{(28)}
Fig. 1 Distribution of the sum of alpha-particle energies for C$^{12}$ stars produced by gamma-radiation from the Li$^7$(p, $\gamma$) Be$^8$ reaction. (V. L. Telegdi and W. Zünti)

Fig. 2 Distribution of the sum of alpha-particle energies for stars produced by bremsstrahlung from a 25-Mev betatron. (Goward, Telegdi)

Fig. 3 Distribution of E* values of stars produced by 25-Mev bremsstrahlung. (Telegdi, Goward)
II. APPARATUS AND EXPERIMENTAL PROCEDURE

A. X-ray Source

The General Electric 100-Mev betatron was the source of high-energy photons. The betatron was operated at the full 100-Mev peak energy. As a result, the spectrum in the region most interesting for this experiment (10 to 50 Mev) could be estimated with good precision. The output of this machine consists of 60 pulses of bremsstrahlung per second caused by high-energy electrons impinging upon a 5-mil tungsten target; the duration of each pulse is approximately one microsecond. The energy and the number of electrons accelerated in the machine per acceleration cycle can be continuously and independently varied.

The maximum x-ray intensity at the 100-Mev level, measured by a Victoreen thimble ionization chamber encased in a cylindrical lead envelope of 1/8-inch wall thickness and at one meter distance from the target, amounts to approximately 4000 R/min. The relation between the Victoreen readings as obtained above and the photon spectrum at the 100-Mev level can be approximated by the following relation:

\[ N(E) \, dE = 1.8 \times 10^7 R \, (dE/E) , \]

where N is the number of quanta of energy E (Mev) in the interval dE (Mev) per cm² corresponding to a gamma-ray intensity R in roentgens. This machine is exceptionally stable; if adjusted to a
particular energy and intensity level, it will operate for long periods at nearly constant output without readjustment. This is well demonstrated in Fig. 4 where the output level is recorded as a function of time.

B. Exposure of Photographic Emulsions

It was decided to follow the technique used by Telegdi and Goward\(^{(24,25)}\) in detecting the \(^{12}\text{C} (\gamma, 3\alpha)\) reaction and use nuclear emulsions. Type E1, Ilford emulsion, 200 microns thick, were selected. The exposures were made as follows:

At a distance of 4.5 m from the target, the exact center of the beam was first determined by exposing a large (13 inches by 15 inches) photographic plate. The intensity of the radiation in the center of the beam was measured by placing a Victoreen thimble ionization chamber encased in a lead cylindrical envelope of 1/8-inch wall thickness in the center of the beam at 4.5 m from the target. The machine was operated at the 100-Mev level. The intensity finally used was 50 R/min in the center of the beam at 4.5 m from the target.

The nuclear plate to be exposed was placed in a light-tight paper envelope and held by means of adhesive tape in the center of the beam 4.5 m from the target. Plates were exposed in two different positions; namely, with the beam incident normal to the emulsion surface (Fig. 5) and with the beam incident parallel to the emulsion surface (Fig. 6). The 100-Mev bremsstrahlung beam produced by
Fig. 4  Gamma-radiation output from G-E 100-Mev betatron as a function of time.

Fig. 5  Position of emulsions with respect to x-ray beam.
the 5-mil tungsten target has a half width of approximately 2 degrees. Thus, at a distance of 4.5 m, the intensity of radiation varied approximately in the ratio of 2:1 in moving 15 cm off the beam center. Since the plates used were of standard size (1 inch by 3 inches), the exposure over the entire area of the plate did not vary appreciably. After some experimentation, it was found that exposures of 150 to 220 R produced satisfactory results in conjunction with the following development technique. This technique is similar in many respects to a technique described by V. L. Telegdi. (27)

C. Processing of Photographic Emulsions

The plates were first soaked for 40 minutes in distilled H₂O at 40°F with no agitation. Then for 20 minutes they were soaked in amidol developer at 40°F. There was agitation for the first two minutes only. Next, the plates were immersed in amidol developer diluted 1:2 at 65°F for 20 minutes with intermittent agitation. The plates were then subjected to a short rinse in water at 65°F. After being rinsed, they were immersed for 20 minutes in acid hardener at 40°F (dilution 1:10) and intermittently agitated. The plates were then fixed in a 30 per cent hypo at 65° to 70°F for four hours with agitation. The agitation was provided by bubbling nitrogen through the fixer. The hypo was changed after the first 15, 30, and 60 minutes and hourly thereafter. The plates were next washed in running water at 65°F while lying in a horizontal position in the bottom of a large tank. They were dried in a 50 per cent relative humidity atmosphere. Finally, the edges of the
plates were painted with araldite cement (Ciba Company) to prevent peeling.

The recipes for the developer and hardener are as follows:

**Amidol Developer**

- Amidol, 750 mg
- Sodium sulfite, 3.0 g
- Water, 250 cc

**pH Adjuster**

- Potassium bisulfate (KHSO₄), 500 g/liter
- Add ~1.2 cc of KHSO₄ to 250 cc of amidol developer to adjust pH to 6.7

**Acid Hardener**

**Solution (a)**
- Sodium sulfite anhyd. 12.5 g
- Glacial acetic acid 18.8 cc
- Distilled H₂O 65.0 cc

**Solution (b)**
- Pot. Alum. 25 g
- Distilled H₂O to 190°F 160 cc

When Solution (b) has cooled below 70°F, mix Solutions (a) and (b) and dilute to 250 cc with distilled water.

**D. Scanning of Photographic Emulsions**

For scanning and measuring, a Bausch and Lomb binocular research microscope, type E.D.R., was used. For scanning, 5X eyepieces and a 40X Bausch and Lomb fluorite 4.3-mm, 1.0 N.A. oil-immersion objective were used. For measuring, 15X eyepieces
with 60X Spencer apochromat 3-mm, 1.3 N.A. oil-immersion and 90X Bausch and Lomb apochromat 2-mm, 1.30 N.A. objectives were used.

It was established by measurement that the calibration of the vertical movement mechanism of the microscope used required a correction factor $S_2$ (see Fig. 7). As can be seen, this correction factor is practically constant in the range from 4 to 10 turns of the vertical fine control from the bottom and amounts to 1.1.

The shrinkage factor for Ilford E1, 200-micron emulsions was determined by two independent methods. The first method consisted of processing one half of a slide and determining by direct microscope measurements the thickness of the treated and the untreated emulsion. The shrinkage factor $S_1$ was 2.11. The second method used was similar to the first except that the measurements were made by means of a micrometer. The shrinkage factor obtained in this way was substantially the same as the factor obtained by the first method, namely 2.12. Consequently, $S_1 = 2.1$ was used.

Thus, the factors to be used in the range of 4 to 10 turns from the bottom in order to obtain the true vertical coordinate $Z$ from the measured vertical coordinate $Z_m$ of a track is:

$$S = S_1 S_2,$$

where $S_1$ is a factor determined by the shrinkage of the emulsion. In order to obtain the true vertical coordinate $Z$ from the measured vertical coordinate $Z_m$, the following relation must be used:

$$Z = SZ_m = 2.3Z_m.$$
Fig. 7 Correction factor for the vertical micrometer of the microscope.

Fig. 8 Nomenclature used in analysis of stars.
Measurements of distance in a plane parallel to the stage of the microscope (x, y plane) were made by using an eyepiece micrometer, previously calibrated with a BSL stage micrometer with the 60X and 90X objectives. Projections of angles in the XY plane were measured by means of a protractor attached to the rotating stage of the microscope.

The plates were systematically scanned and all nuclear events with two or more tracks were recorded. Events with three prongs (three-prong stars) were carefully examined and all stars having three alpha-tracks in a configuration not obviously precluding momentum balance were measured. The measurements resulted in the following data for each star (see Fig. 8): \( R_1', R_2', R_3' \), the three projected lengths of the three alpha-tracks upon a plane parallel to the stage of the microscope (x, y plane); \( \pm Z_1, \pm Z_2, \pm Z_3 \), the elevations of the end points of the three alpha-tracks with respect to the center of the star. In the case of scattered tracks, or very long track length, elevations of sections of these tracks were determined and then appropriately added. In addition, angles between \( R_1', R_2', \) and \( R_3' \) were measured. The angles were designated as follows:

\[
\alpha' = \hat{\phi} R_1', R_2', \\
\beta' = \hat{\phi} R_2', R_3', \\
\gamma' = \hat{\phi} R_3', R_1'.
\]
III. ANALYSIS

A. Identification of \( C^{12} \) Stars

1. General

Since the reaction under consideration here is a \( C^{12} (\gamma, 3\alpha) \) reaction, only stars having potentially three alpha-tracks must be considered. (In some instances, one of the three alpha-tracks may be very short, or two alpha-tracks may nearly coincide; some tracks may be badly scattered or unfavorably located in the emulsion, such as in or nearly in a vertical plane.) However, not every three-pronged alpha-star is necessarily a \( C^{12} \) star. For example, a reaction like \( C^{12} (n, 3\alpha n) \) would also produce a three-pronged alpha-star. Thus, the above criterion is necessary but not sufficient.

An additional important criterion for a \( C^{12} (\gamma, 3\alpha) \) star is the momentum balance. Since the \( C^{12} \) nucleus is at rest in the laboratory system before interaction with the gamma-quantum, the momentum of the gamma-quantum must be preserved after the interaction. Thus, \( \mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3 - \mathbf{p}_\gamma = 0 \), where \( \mathbf{p}_1, \mathbf{p}_2, \) and \( \mathbf{p}_3 \) are the momentum vectors in the laboratory system of the three alpha-particles forming a star and \( \mathbf{p}_\gamma \) is the momentum of the interacting gamma-quantum. It is convenient to express momenta in units where the mass is expressed in atomic mass units and the energy
in Mev.† The energy $E_Y$ of the interacting photon and its momentum $p_Y$ are, by use of the following expressions:

$$E_Y = E_1 + E_2 + E_3 + Q; \quad p_Y = \frac{E}{43.1},$$

where $E_1$, $E_2$, and $E_3$ are the kinetic energies in Mev of the three alpha-particles obtained by means of the range-energy relation\(^{(32)}\) and $Q$ represents the energy of the reaction and is equal to approximately 7.3 Mev.

The above expression for the computation of $E$ holds provided the $^{12}$C nucleus after absorbing the gamma-quantum disintegrates without emission of another gamma-quantum. Since, in general, the emission of a particle from an excited nucleus is much more probable

\[ p = mv = \sqrt{2mE} \text{ in cgs, if } E \text{ is in ergs, } m \text{ in grams. Since one atomic mass unit is } 1.66 \times 10^{-24} \text{ g and } 1 \text{ Mev} = 1.6 \times 10^{-6} \text{ ergs, the momentum unit employed is equal to } \]

$$\sqrt{2 \times 1.6 \times 10^{-6} \times 1.66 \times 10^{-24}} \text{ cgs units.}$$

The momentum of a gamma-quantum of energy $E'$ in ergs is

$$p_Y = \frac{hv}{C} = \frac{E'}{3 \times 10^{10}} \text{ in cgs units;}$$

and, in the units employed,

$$p = \frac{E \times 1.6 \times 10^{-6}}{\sqrt{2 \times 1.6 \times 10^{-6} \times 1.66 \times 10^{-24}}} = \frac{E}{43.1},$$

where $E$ is the energy of the photon expressed in Mev. The momentum of an alpha-particle is correspondingly given by $p = 2\sqrt{E}$. 
than the emission of a gamma-quantum, (31) the above relation may be assumed to hold here. No other reaction can be postulated in an unloaded Ilford E1 emulsion which would produce three-pronged alpha-stars with momentum balance. Thus, the criteria used here for selecting \( \text{C}^{12} (\gamma, 3\alpha) \) stars are: it must be a three-pronged alpha-star, and there must be a reasonably good momentum balance. That is, \( \Delta p \), defined as the absolute value of the momentum unbalance vector, must be small.

\[
\overrightarrow{p_1} + \overrightarrow{p_2} + \overrightarrow{p_3} - \overrightarrow{p_\gamma} = \Delta p
\]

A finite \( \Delta p \) is to be expected because of experimental limitations. The experimental limitations are set by limits in the precision of the range measurements of alpha-tracks, and by limits in the precision of the range-energy relations for nuclear emulsions (straggling, emulsion shrinkage, inhomogeneity of emulsion, etc.).

The disintegration of \( \text{C}^{12} \) may conceivably proceed in two different ways:

1. \( \text{C}^{12} (\gamma, \alpha) \text{Be}^{8*} \rightarrow 2\alpha + \alpha \), or

2. \( \text{C}^{12} (\gamma, 3\alpha) \),

where * denotes an excited state of \( \text{Be}^{8} \). Which process was responsible for a particular star cannot be answered positively; however, some indications can be gathered from the following consideration.
In case the first process is involved, it is of course not known which of the three alpha-tracks was caused by the alpha-particle first emitted. There are three choices, and for each such choice it is possible to compute the "corresponding" $^{9}$Be excitation level. Consequently, for each star there are three such "possible" excitation levels $E^*$, designated hereafter as $E_{12}^*$, $E_{13}^*$, and $E_{23}^*$. $E_{12}^*$ designates the case where the $^{9}$Be emitted Particles 1 and 2 (arbitrary designations—see Fig. 8); thus, in this case, Particle No. 3 would have been the particle emitted by $^{12}$C. One of these energy levels is the correct one, provided Process 1 was responsible for this reaction. If Process 2 was responsible, none of the $E^*$ values would have any significance. The relation between values of $E^*$ and the measured quantities of a star can be derived with the help of Fig. 9, which shows a momentum diagram for a star. The quantity $p_1$ is the momentum vector of the "first" particle in the laboratory system, while $p_2$ and $p_3$ are the momentum vectors of the remaining two alpha-particles in the laboratory system arising from the $^{9}$Be disintegration. The quantities $p'_1$, $p'_2$, and $p'_3$ are the above vectors transformed to the Center of Mass coordinate system; $2p_{Be}$ is the momentum vector of the $^{9}$Be nucleus due to recoil; and $p'_{2Be} = p'_{3Be}$ are the momenta of the two alpha-particles in the $^{9}$Be coordinates system arising from the $^{9}$Be disintegration. Since it can be assumed that the momentum of the interacting gamma-quantum $p_\gamma$ is equally distributed among the three particles, the following vector relations hold:
Fig. 9  Momentum diagram used for computation of $E^*$.  

$$p_3' + \frac{p_y}{3} = p_3,$$

$$p_2' + \frac{p_y}{3} = p_2,$$

$$p_1' + \frac{p_y}{3} = p_1.$$

It can be seen directly from the diagram that $AC = A'C' = p'_{2B} + p'_{3B} = S'$, but

$$2 \times \frac{S^*}{4} \times 1/4 = \frac{S^*}{8} = 2 \times \left(\frac{p_2 + p_3}{2}\right)^2 1/4 = E_{23}^*,$$

where $E_{23}^*$ is the kinetic energy released in the disintegration of $\text{Be}^a$ and $S = p_2^2 + p_3^2 - 2p_2p_3 \cos \gamma$. Since $p = \sqrt{4E}$,
\[ S^2 = 4E_2 + 4E_3 - 8 \sqrt{E_2E_3} \cos \gamma, \]

and hence

\[ E_{23}^* = \frac{S^2}{8} = 1/2(E_2 + E_3 - 2 \sqrt{E_2E_3} \cos \gamma). \]

(This relation holds also when the momentum of the gamma-ray is not distributed equally among the three alpha-particles. However, the two alpha-particles arising from Be^8 must have equal amounts of momentum from the gamma-ray.)

The question of whether a three-pronged alpha-star with a momentum unbalance \( \Delta p \) is to be considered a C^{12} (\( \gamma, 3\alpha \)) star is a basic experimental consideration in this work and is discussed in detail in the next section.

2. **Accuracy of Measurements**

The accuracy of the measured momenta depends on the following factors.

(a) Experimental accuracy achieved in measurements of ranges of alpha-tracks and of angles between alpha-tracks forming a star.

(b) Accuracy of determination of the shrinkage factor of the emulsion.

(c) Determination of the correction factor for the vertical micrometer of the microscope.

(d) Precision of range-energy relation\(^{(32)}\) (including straggling\(^{(33)}\)).
The factors listed in (a), (b), and (d) may be assumed to obey the normal error function $y = \left(\frac{h}{\sqrt{\pi}}\right) e^{-h^2 x^2}$. Thus, these factors may conveniently be specified by their respective rms values or precision indices $h$.

Assuming now that the above factors are known, it is possible to compute for the three alpha-particles forming a three-prong star the momenta $p_1$, $p_2$, and $p_3$, and the corresponding rms momenta errors $\Delta p_1$, $\Delta p_2$, and $\Delta p_3$. The momentum of the interacting gamma-quantum can also be computed together with its rms error $\Delta p_\gamma$. The momentum unbalance for a star is formally given in cartesian coordinates (laboratory system):

$$\Delta p_\text{s} = p_1 + p_2 + p_3 - p_\gamma = \Delta p_1 + \Delta p_2 + \Delta p_3 - \Delta p_\gamma.$$ 

The root-mean-square value of $\Delta p_\text{s}$ is, since cross-products vanish (assuming no correlation between the errors):

$$\Delta p_\text{s} = \sqrt{\Delta p_1^2 + \Delta p_2^2 + \Delta p_3^2 + \Delta p_\gamma^2}.$$ 

The scalar quantity $\Delta p_\text{s}$ may be interpreted as follows. Assume many identical stars distributed in the emulsion identically as far as the measuring processes are concerned. This assumption is important because the accuracy with which measurements on a star may be made depends not only upon the size and shape of the star but also upon the orientation of the star in the emulsion. This is so because the accuracy attained, for example, in range measurements in a plane parallel to the stage of the microscope ($x$, $y$ plane) is not necessarily
equal to the accuracy attained in range measurements perpendicular to the plane of the stage (z direction). Now, if we obtain \( \Delta p_S \) values for many such stars and compute from them an rms value, it will approach the \( \Delta p_S \) quantity obtained above. It is of interest to know what kind of distribution function will approximate the distribution of \( \Delta p_S \).

It is reasonable to assume that the components \( \Delta p_{sx}, \Delta p_{sy}, \Delta p_{sz} \) of the vector \( \Delta p_S \) with respect to a cartesian coordinate system, \( x, y, z \), are likely to obey the normal error function (Gaussian \( y = K e^{-\beta^2 x^2} \)), since no direction is preferred, and total deviations are the cumulative results of many small factors. Consequently, the distribution of the absolute value of the momentum unbalance vector \( \Delta p_S \) may be approximated by a function such as \( y = A (\Delta p_s)^2 e^{-\beta^2 (\Delta p_s)^2} \), where \( A \) is a constant to be determined by normalization and \( \beta \) is the "precision index" (Maxwellian distribution). Thus, if \( \Delta p_S \) is computed for a star according to the above considerations, it will completely specify the distribution function for the absolute values of the momentum unbalance vectors for many identical stars with a similar orientation in the emulsion as far as the measurements are concerned.

The rms value for \( \Delta p_S \) follows from

\[
\overline{\Delta p_S} = \Delta p_{rms} = \sqrt{\frac{\int_0^\infty (\Delta p_s)^4 e^{-\beta^2 (\Delta p_s)^2} \, d(\Delta p_s)}{\int_0^\infty (\Delta p_s)^2 e^{-\beta^2 (\Delta p_s)^2} \, d(\Delta p_s)}}
\]

\[
= \sqrt{1.5} \frac{1}{\beta}
\]
Hence,
\[ \beta = \frac{\sqrt{1.5}}{\Delta p_s} \]

That is, \( \Delta p_s \) determines the distribution function.

In addition to computing \( \Delta p_s \) from considerations of measuring precision, we obtain for the same star the actual absolute value of the momentum unbalance vector, \( \Delta p_a \), from the measurements of the star. (The method used to obtain this result is explained later.)

The conditions are shown in Fig. 10, where the Maxwellian distribution function for \( \Delta p_s \) for the star under consideration is indicated together with the actually obtained momentum unbalance \( \Delta p_a \). We define \( \eta = \Delta p_a / \Delta p_s \) as a new variable. Thus,
\[ \eta = \frac{\Delta p_a}{\sqrt{1.5/\beta}} \]

and
\[ \Delta p_a = \frac{\eta}{\beta} \sqrt{1.5} \]

We substitute now for \( \Delta p_a \) in the distribution function \( \frac{\eta}{\beta} \sqrt{1.5} \) and obtain \( y = C \eta^2 e^{-1.5\eta^2} \) where \( C \) is a constant.

It is interesting to note that the distribution in \( \eta \) applies to all \( C^{12} \) stars in the emulsion regardless of the alpha-particle range and directions or position of the star in the emulsion. This fact provides a convenient over-all check of all stars presumed to be \( C^{12} \) stars. If the values of \( \eta \) are computed for a number of correctly selected stars, and their distribution histogram plotted, it should approximate,
Fig. 10 Theoretical distribution of momentum errors \( \Delta p \) of alpha-particles.

Fig. 10a \( \Delta p_a \) as a function of \( \eta \).

Fig. 11 Histogram of \( \eta \) for 82 stars for 0.1 intervals and theoretical curve normalized to 82 stars.
reasonably well, a properly normalized Maxwellian distribution function with $\beta^2 = 1.5$. This actually has been done for 82 stars selected at random, and the results are given in Fig. 11.

3. Selection Methods Used

The selection method used is essentially the same as that discussed by Telegdi(27) and by Goward and Wilkins. (27a)

The distribution of $\Delta p_a$ for the three-pronged alpha-stars is plotted. This distribution shows a maximum around $\Delta p_a = 0.50$. This population increase is primarily attributed to $C^{12}$ stars. Such a distribution is shown in Fig. 30 for 154 stars with $\Delta p_a$ up to 1.60. As an independent test of reliability of selection, 82 stars have been selected at random from the 154 stars of Fig. 30 and the distribution in $\eta$ for these 82 stars has been plotted in Fig. 11. In addition, a properly normalized function $y = K \eta^2 e^{-1.5 \eta^2}$ has also been plotted in the same figure. As seen, the two functions match extremely well, indicating that the selection procedure is reliable.

The integral

$$\int_0^\eta Ky \, dy$$

has also been formed for the theoretical distribution $y = K \eta^2 e^{-1.5 \eta^2}$ and the actually obtained distribution in $y$ for the 82 stars. These are shown in Fig. 13. Again, the two functions show a very good match.

A somewhat more refined approach to the method of selection is as follows.
It is clear that a star that can be measured with a given accuracy is more likely to be a true $^{12} \text{C}$ star if $\eta$ is small. However, it is not quite sufficient to use the value of $\eta$ alone as a selection criterion, since a star that has a small $\eta$ but is poorly measurable is less likely to be a real star than a star with the same $\eta$ that is accurately measurable. The criterion for selection of stars should, therefore, take account both of measurability of the star and its actually determined momentum unbalance.

To put these ideas on a semiquantitative basis, the following is done:

By taking into account all inaccuracies inherent in the measurements, it is possible to predict for each particular three-pronged $^{12} \text{C}$ star the probability distribution and the "most probable" or the rms value of the momentum unbalance $\Delta p_s$. This is done with the help of methods described in Section B. A family of curves is computed (Fig. 12) giving squares of most probable momentum errors $\Delta p^2$ for individual alpha-tracks as a function of the momentum $p$ of the alpha-track and the angle the alpha-track forms with the $x, y$ plane (plane parallel to the emulsion). The theoretically predicted rms value of momentum unbalance for a star is then given by

$$\Delta p_s = \sqrt{\sum_{\nu=1}^{3} \Delta p^2_{\nu} + \Delta p^2_{\gamma}},$$

where $\Delta p_{\nu}$ is the predicted momentum error of the $\nu^{th}$ alpha-particle of a three-pronged star, and $\Delta p_{\gamma}$ is the momentum error of the gamma-quantum.
Fig. 12  Square of the rms of the momentum error for an alpha-particle as a function of momentum computed for $\Delta x = \frac{1}{2} \mu; \Delta z = \frac{1}{2} \mu; s = 2.3; \Delta s = 5 \times 10^{-2}; \Delta \alpha = \frac{1}{2} \degree$.

Fig. 13  Theoretically and experimentally obtained function $\int_0^\eta y \, d\eta = f(\eta)$ for 82 stars.
In general, this distribution will be different for every star, since it depends upon the ranges of the alpha-particles and their position in the emulsion. As discussed in Section 2, the distribution of $\Delta p_S$ can be expected to obey a Maxwellian distribution function (see Fig. 10). The criterion used for selection consists essentially of finding how well the actual momentum unbalance $\Delta p_a$ of a star (obtained as indicated in Fig. 10) fits the predicted distribution.

Assume that in the emulsion scanned, there are $N_r$ true $^{12}\text{C}$ stars and $N_f$ three-pronged alpha-stars arising from other reactions. One such reaction, for example, may be the $^{16}\text{O} (\gamma, 4\alpha)$ reaction with one sufficiently short track to be overlooked. As previously explained, the momentum unbalance distribution for true $^{12}\text{C}$ stars in the interval $d(\Delta p_S)$ should be Maxwellian. Therefore, the average number of real stars that have a certain $\Delta p_S$ in the interval $d(\Delta p_S)$ and a certain $\Delta p_a$ in the interval $d(\Delta p_a)$ is

$$P_T d(\Delta p_a) d(\Delta p_S) = K_T \left(\Delta p_a\right)^2 e^{-\beta T \left(\Delta p_a\right)^2} f(\Delta p_S) d(\Delta p_S) d(\Delta p) .$$

Hence, $f_1 (\Delta p_S) d(\Delta p_S)$ gives the fraction of real stars with $\Delta p_S$ in the range $d(\Delta p_S)$. Thus,

$$\int_0^\infty f(\Delta p_S) d(\Delta p_S) = 1 .$$

Recalling that $\beta = \sqrt{1.5/\Delta p_S}$,
\[ K_r = N_r \frac{4}{\sqrt{\pi}} (\beta_r)^3, \]

where \( N_r \) is the number of \( C^1 \) stars in the volume scanned.

For false stars, \( \Delta p_a \) and \( \Delta p_s \) are also defined, since \( \Delta p_s \) is an indication of the precision with which the momenta of a star can be measured. We assume that the distribution of \( \Delta p_s \) for false stars is the same as that for real stars. Although this assumption is somewhat arbitrary, it is a reasonable one and should suffice to give a qualitatively correct understanding of the situation. It is assumed, furthermore, that the distribution of \( \Delta p_a \) for false stars is a very broad Maxwellian. Thus, the number of false stars in the range \( d(\Delta p_a) \) and \( d(\Delta p_s) \) may be written

\[
P_f = d(\Delta p_a) d(\Delta p_s) = K_f (\Delta p_a)^2 e^{-\beta_f^2 (\Delta p_a)^2} f(\Delta p_s) d(\Delta p_s) d(\Delta p)
\]

and

\[
K_f = N_f \frac{4}{\sqrt{\pi}} \beta_f^3.
\]

\( (N_f \) is the number of false stars in the volume scanned.\)

It is also assumed that for false stars \( \beta_f \) is very small and independent of \( \Delta p_s \). Therefore, the probability that a star with a given \( \Delta p_a \) and \( \Delta p_s \) is a real star is:

\[
p(\Delta p_a, \Delta p_s) = \frac{1}{1 + \frac{N_f}{N_r} (\beta_f)^3 e^{+\beta_r^2 (\Delta p_a)^2}}.
\]
(Since $\beta_f$ is small, we replace $e^{-\beta_f \Delta p_a^2}$ by unity.) Using expressions for $\eta$ and $\beta_r$, we obtain

$$P(\Delta p_a, \Delta p_s) = \frac{1}{1 + K(\Delta p_s)^3 e^{+1.5\eta^2}}$$

where

$$K = \frac{N_f}{N_r} \left( \frac{\beta_f}{\sqrt{1.5}} \right)^3.$$

Since the number of true and false stars, $N_r$ and $N_f$, respectively, and $\beta_f$ are unknown, the coefficient $K$ cannot be computed. However, some useful conclusions may be drawn about the dependence of $P(\Delta p)$ upon $\Delta p_a$ and $\eta$. It is apparent that all stars having equal values of $(\Delta p_s)^3 e^{1.5\eta^2}$ have the same probability of being true $C^{12}$ stars. Thus, in principle, it is possible to specify the probability of the selected stars being true $C^{12}$ stars by choosing the value of $P(\Delta p)$. This value then determines the maximum possible value $L$ of $(\Delta p)^3 e^{1.5\eta^2}$ for an acceptable star.

$$(\Delta p_s)^3 e^{1.5\eta^2} \leq L.$$

Recalling that $\eta = \Delta p_a/\Delta p_s$, this expression can be rewritten as

$$\Delta p_a \leq L^{1/3} \eta e^{-\frac{\eta^2}{2}}.$$

Since the ratio $N_f/N_r$ and $\beta_f$ are unknown, no reasonable estimate of $K$ can be made. However, this problem may be approached in a different manner.
Assume a star to be just acceptable if $\Delta p_a \leq 1.4$ and $\eta \approx 1$. These two assumptions determine a value of $L$. The validity of the assumptions can be later determined by computing values of $\eta$ for the stars under consideration and observing how well the resultant stars conform to a properly normalized Maxwellian function, $y = Ky\eta^2 e^{-1.5\eta^2}$, and noting how many stars are rejected that would improve or not diminish the degree of matching of the two functions. If, for example, $L$ were chosen too small, the distribution $y$ and $\eta$ would match well. However, a number of stars would be rejected that should have been accepted. Conversely, if $L$ were chosen too large, fewer stars would be rejected and, therefore, a larger number of false stars would be accepted, thus making a worse match between the distributions.

This procedure was carried out. The relation between $\Delta p_a$ and $\eta$ for $L^{1/3} = 2.3$ is shown in Fig. 10a.

$$\Delta p_a = 2.3 \eta e^{-1/2\eta^2},$$

The selection of stars is made simply by determining for each star its value of $\Delta p_a$ and $\eta = \Delta p_a / \Delta p_s$.

The quantity $\Delta p_s$ is determined from Fig. 12. Referring to the $\Delta p_a$, $\eta$ plane, stars represented by points lying within the area bound by the $\eta$ axis and the curve $\Delta p_a = 2.3 \eta e^{-1/2\eta^2}$ are accepted, whereas stars represented by points outside this area are rejected.
This method of selection differs from the one previously outlined (Telegdi(27) and Goward(27a)), where $\Delta p_a$ is essentially limited in value for acceptable stars, in the following respects:

If $\overline{\Delta p_S}$ is too large (indicating that the star is poorly measurable), the star is excluded unless $\eta$ is very small. In fact, if $\overline{\Delta p_S}$ is greater than $1^{1/3}$ ($=2.3$), the star is rejected regardless of the value of $\eta$. If the star is accurately measurable ($\overline{\Delta p_S}$ very small), then $\Delta p_a$ must be small for the star to be accepted.

However, since most stars have $\overline{\Delta p_S}$ neither very large nor very small, this criterion in practice is essentially equivalent to the one used by Telegdi(27) and Goward and Wilkins. (27a)

The distribution of $\Delta p_a$ for 154 stars is shown in Fig. 30. This distribution resembles also a Maxwellian function. Since this function should be a summation of many Maxwellian functions with different $\overline{\Delta p_S}$, one may conclude that the dispersion of the $\overline{\Delta p_S}$ is not large. About 90 per cent of the stars contributing to the distribution in Fig. 30 were acceptable according to the criterion of Fig. 10a. This again shows indirectly that the value chosen for $L$ is a reasonable one and that the identification of $C^{12}$ stars, using the momentum balance method, is valid.

As an illustration, photomicrographs of three different stars were made. The data for these stars are summarized in Table I.
TABLE I

<table>
<thead>
<tr>
<th></th>
<th>$E_\gamma$</th>
<th>$p_1$</th>
<th>$p_2$</th>
<th>$p_3$</th>
<th>$\alpha_1$</th>
<th>$\alpha_2$</th>
<th>$\alpha_3$</th>
<th>$(\Delta p_1)^2$</th>
<th>$(\Delta p_2)^2$</th>
<th>$(\Delta p_3)^2$</th>
<th>$\Delta p_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star in</td>
<td>16.3</td>
<td>2.8</td>
<td>4.3</td>
<td>3.1</td>
<td>0°</td>
<td>18°</td>
<td>15°</td>
<td>0.90</td>
<td>0.35</td>
<td>0.70</td>
<td>0.7</td>
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<tr>
<td>Fig. 31</td>
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<td></td>
</tr>
<tr>
<td>Star in</td>
<td>31.1</td>
<td>6.6</td>
<td>4.1</td>
<td>6.0</td>
<td>15°</td>
<td>16°</td>
<td>18°</td>
<td>0.05</td>
<td>0.35</td>
<td>0.07</td>
<td>0.45</td>
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<tr>
<td>Fig. 32</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Star in</td>
<td>40.4</td>
<td>8.7</td>
<td>3.8</td>
<td>6.4</td>
<td>10°</td>
<td>0°</td>
<td>5°</td>
<td>0.01</td>
<td>0.35</td>
<td>0.08</td>
<td>0.8</td>
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<tr>
<td>Fig. 33</td>
<td></td>
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</tr>
</tbody>
</table>

$E_\gamma$ = the energy of the interacting photon in Mev.

$p_1$, $p_2$, and $p_3$ = the momenta of the three alpha-particles forming a star. (The indices 1, 2, and 3 correspond to the track in the photomicrographs marked A, B, and C.)

$\alpha_1$, $\alpha_2$, and $\alpha_3$ = the angles formed by the three alpha-tracks forming a star with the $x$, $y$ plane.

$(\Delta p_1)^2$, $(\Delta p_2)^2$, and $(\Delta p_3)^2$ = the squares of the momentum errors of the three alpha-particles forming a star. These are obtained from Fig. 12.
Thus, the following results are obtained:

**Star of Fig. 31**

$$\Delta p_S = \sqrt{0.35 + 0.70 + 0.90} = 1.4; \quad \Delta p_a = 0.7;$$

$$\eta = 0.7/1.4 = 0.5.$$ Star is acceptable according to the relation in Fig. 10a.

**Star of Fig. 32**

$$\Delta p_S = \sqrt{0.05 + 0.07 + 0.35} = 0.69; \quad \Delta p_a = 0.45;$$

$$\eta = 0.45/0.69 = 0.65.$$ Star is acceptable according to Fig. 10a.

**Star of Fig. 33**

$$\Delta p_S = \sqrt{0.35 + 0.01 + 0.08} = 0.65; \quad \Delta p_a = 0.8;$$

$$\eta = 0.8/0.65 = 1.21.$$ Star is acceptable according to Fig. 10a.

4. **Determination of \(E_\gamma, \Delta p_S, \) and Intermediate Energy States of \(\text{Be}_8\)**

Given the data for a star which were obtained by microscope measurements in the form described previously, namely \(R_1', R_2', R_3', Z_1', Z_2', Z_3',\) and \(\alpha'\) and \(\beta',\) the energies \(E_1, E_2,\) and \(E_3\) of the three alpha-particles can now be found with the help of the range-energy relation. The range-energy relation used was supplied by Dr. J. Rotblatt(32)(see Fig. 14). The momenta \(p_1, p_2,\) and \(p_3\) of the three particles and the momentum of the photon \(p_\gamma\) may be computed (Fig. 21). In this work, energies are measured in Mev and momenta of alpha-particles in the units employed are \(p = 2\sqrt{E}.\) In these units, momenta of quanta are given by \(p_\gamma = E/43.1,\) where \(E\) is the energy of the gamma-quantum expressed in Mev. These units were discussed in detail on page 14. The energy \(E_\gamma\) is given by
where $E_{\alpha v}$ is the kinetic energy of the $v^{th}$ alpha-particle, $Q$ is the threshold energy of the $^{12}$C$(\gamma, 3\alpha)$ reaction, and is approximately equal to 7.3 Mev.

The value of threshold energy $Q$ for the $^{12}$C$(\gamma, 3\alpha)$ process is found as follows:

For the reaction $^{12}$C + $h\nu \rightarrow 3$He$^4$,

Mass of $^{12}$C = 12.00382,
Mass of He$^4$ = 4.00389,
Mass of 3He$^4$ = 12.01170,

$M_{^{12}}$ - $M_{3He}^4 = h\nu = 0.00788$.

But, one atomic mass unit = 931 Mev.

Consequently, $Q = h\nu = 7.34$ Mev.

For the reaction $^{12}$C + $h\nu \rightarrow \alpha +$ Be$^8$,

Mass of Be$^8$ = 8.00785,
$M_{Be^8} + M_{He^4} - M_{^{12}} = h\nu = 0.00793$.

Thus, $Q = 7.38$ Mev.

B. Numerical Evaluation

1. Evaluation of Experimental Data

A practical method had to be devised to find quickly and reliably, from the data obtained by microscope measurements, for each star, the kinetic energies of the three alpha-particles $E_1$, $E_2$, $E_3$. 

-33-
Fig. 14 Range-energy relation for alpha-particles.

Fig. 15 Determination of actual momentum unbalance $\Delta p_\alpha$.

Fig. 16 Illustration of graphical method used in analysis of star.
and $E_3$, energy of the interacting gamma-quantum $E_\gamma$, the possible Be$^8$ excitation levels $E^*$, and the momentum unbalance vector $\Delta p_a$.

Various methods were considered for processing the data obtained by microscope measurements. For example, a mechanical device could be constructed, similar to that suggested by Telegdi, which would represent a scale model of each star in space so that measurements of the true track length, $R_1$, $R_2$, $R_3$, and the corresponding angles could be measured directly on the model, and so that the "flatness" of a star could be examined easily. An actual momentum balance, however, would have to be done in addition.

It was finally decided that a graphical method, described below, gives accurate and quick results and, in addition, leaves a permanent record for each star which can be easily examined at any time. The method used is illustrated in Figs. 15 and 16. The projection in a plane parallel to the stage of the microscope ($x, y$ plane) of a star is drawn using an appropriate scale (say $1 \text{ cm} = 1 \text{ micron}$). The origin of the star is designated by $O$. The end points of the three alpha-track projections in the $x, y$ plane are $A'$, $B'$, $C'$. The length $OA' = R_1';$ $OB' = R_2';$ $OC' = R_3'$, and the angles $\alpha' = R_1'R_2';$ $\beta' = R_2'R_3'$, etc., are the quantities determined by microscope measurements.

The true ranges of the three alpha-particles are determined by turning the plane $OA'$, $OA$, which is perpendicular to the $x, y$ plane, into the $x, y$ plane. This results in a triangle $OA'(A)$. The distance
A' (A) is equal to Z and Z is equal to $Z_m S$, where $Z_m$ is the measured elevation (in microns) and $Z$ the true elevation in microns, and $S$ is discussed on page 10. The true alpha-particle range $R_x$ is thus equal to $O(A)$. The angle which the track makes with the plane of the drawing board ($x, y$ plane) is then $\delta_x$. Similarly, the tracks of the two remaining alpha-particles yield the ranges $R_2$ and $R_3$ and the angles $\delta_2$ and $\delta_3$. Using the range-energy relation of Rotblatt(32) (Fig. 14), the energies $E_1$, $E_2$, and $E_3$ of the three particles are determined. From this follows immediately the energy of the photon involved in the interaction

$$E_\gamma = \sum_{v=1}^{3} E_v + Q \ (Q = 7.3).$$

The momentum of the gamma-quantum is

$$p = \frac{\sum_{v=1}^{3} E_v + Q}{43.1}.$$

By means of a curve (Fig. 21) derived from the range-energy curve (Fig. 14) by the relation $M = 2 \sqrt{E}$, the momenta of the three alpha-particles $p_1$, $p_2$, and $p_3$ are quickly determined. These quantities are entered by using appropriate units in the previously described Fig. 16. The origins and directions of the vectors $p_1$, $p_2$, and $p_3$, of course, coincide with the origin and directions of the tracks $R_1$, $R_2$, and $R_3$. Thus, $p_1 = (P_1)O$; $p_2 = (P_2)O$; and $p_3 = (P_3)O$. Projections of the vectors $p_1$, $p_2$, and $p_3$ into the $x, y$ plane ($x, y$ components of $p_1$, $p_2$, and $p_3$).
and \( p_3 \) are now easily obtained. These vectors are designated by \( p'_1, p'_2, p'_3 \).

The momentum balance is now checked by forming (see Fig. 15)

\[
\sum_{v=1}^{3} (p'_v - p_{xy})
\]

and

\[
\sum_{v=1}^{3} (p_{yz} - p_z)
\]

and finally \( \Delta p_b = \Delta p_{xy} + \Delta p_z \). Since the gamma-radiation used was either parallel or perpendicular to the plane of the emulsion, in the first case \( \Delta p_z \gamma = 0 \) and in the second case \( \Delta p_{xy} \gamma = 0 \).

The three possible excitation levels of Be\(^{8} \) for each star were determined as follows: The problem (Fig. 16) reduces to a determination of the distance \( S_{12} \) in momentum space between the end points of two momentum vectors, say, for example, \( p_1 \) and \( p_2 \). Thus

\[
S_{12} = p_2 - p_1 \]

and

\[
E'_{12} = (S_{12})^2/8 \]

similarly, \( E'_{13} \) and \( E'_{23} \) are determined. The lengths \( S_{12}, S_{23}, \) and \( S_{31} \) are easily determined, as shown in Fig. 16. A plane perpendicular to the \( x, y \) plane is imagined constructed through the end points of two momentum vectors, say \( p_1 \) and \( p_2 \). Thus, the projection of \( S_{12} \) is a straight line between points \( M_1 \) and \( M_2 \). Its true length is obtained by turning the plane that is perpendicular to the \( x, y \) plane and contains \( M_1 \) and \( M_2 \) into the
Disintegrations involving the ground level of Be$^8$ had to be treated in some cases in a different manner. In some instances, the track caused by the first alpha-particle could be readily recognized and measured. However, the two tracks caused by the disintegration of the recoiling Be$^8$ nucleus were in some cases badly scattered, so that angle measurements necessary for the construction of a momentum diagram were impossible or at least quite unreliable.

The method used in such cases is illustrated in Fig. 17. It is assumed here that the momentum of the interacting gamma-quantum $p_\gamma$ is negligible. Let $P_R$ represent the portion of the momentum of an alpha-particle arising from Be$^8$ disintegration which is due to Be$^8$ recoil. The quantity $P_G$ represents the total momentum of an alpha-particle originating from the Be$^8$ disintegration.

From Fig. 17,

\[ 4E_2 = p_2^2 = p_G^2 + p_R^2 + 2p_Bp_G \cos \alpha; \]
\[ 4E_3 = p_3^2 = p_G^2 + p_R^2 - 2p_Bp_G \cos \alpha. \]

By adding the above equations: \( 4(E_2 + E_3) = 2(p_G^2 + p_R^2). \)

\[ p_R = \sqrt{2(E_2 + E_3) - p_G^2} \]
and

\[ p_G^2 = 4E^*/2 = 2E^*. \]
where $E^*$ is the energy released by disintegrating Be$^8$ and

$$p_R = \sqrt{2(E_2 + E_3 - E^*)}.$$  

For a legitimate $C^{12}(\gamma, 3\alpha)$ star, the momentum must balance. Thus, $p_1 = 2p_R$ or, since $p_1 = 2\sqrt{E_1}$, $2\sqrt{E_1} = 2\sqrt{2(E_2 + E_3 - E^*)}$.

Since $E^*$ is known ($\sim 0.1$ Mev) for this case, the scalar quantities only, $E_1$, $E_2$, and $E_3$, have to be determined by measurements. No measurements of angles are necessary. Thus, the momentum unbalance is $\Delta p_\alpha = 2 \left[ \sqrt{E_1} - \sqrt{2(E_2 + E_3 - E^*)} \right]$. The above relation may also be used for a quick estimation of the three possible Be$^8$ excitation levels $E_{12}^*$, $E_{13}^*$, $E_{23}^*$ for a star. From the above relation it follows that:

$$E_1 = 2(E_2 + E_3 - E_{23}^*);$$

$$E_{23}^* = E_2 + E_3 - \frac{1}{2}E_1 + (E_1 - E_1).$$

Thus,

$$E_{23}^* = E_1 + E_2 + E_3 - 1.5E_1,$$

and, substituting $E_1 + E_2 + E_3 = E_\alpha$ (total kinetic energy of the alpha-particles in a star), we obtain

$$E_{12}^* = E_\alpha - 1.5E_3 + \text{small correction},$$

$$E_{13}^* = E_\alpha - 1.5E_2 + \text{small correction},$$

$$E_{23}^* = E_\alpha - 1.5E_1 + \text{small correction}.$$

In disintegrations caused by higher energy quanta, say above 25 Mev, the momentum of the gamma-quantum should not be neglected. A practical relation can be obtained as follows.
Fig. 17  Momentum diagram of a star neglecting $p_\gamma$.

Fig. 18  Determination of $\Delta p_a$ used primarily for ground-state stars (momentum of the gamma-ray, $p_\gamma$ not neglected).
The momentum of the recoiling $\text{Be}^8$ nucleus $p_R$ in the Center of Mass System is equal to the momentum $p_1$ of the alpha-particle first ejected. The momentum $p_\gamma$ of the gamma-ray must be conserved in the Laboratory System. Therefore,

$$p_R + p_1 = p_\gamma$$

or

$$\Delta p_a \geq |p_R + p_1 - p_\gamma|$$

if $\delta$ is the angle formed between $p_1$ and $p_\gamma$ (Fig. 18).

$$p_1 - p_\gamma = \sqrt{p_1^2 + p_\gamma^2 - 2p_1 p_\gamma \cos \delta}$$

and

$$p_R = \sqrt{2 x 4(E_2 + E_3 - E^*)},$$

where $E^*$ is the excitation energy of $\text{Be}^8$. Thus,

$$\Delta p_a \geq 2\sqrt{2(E_2 + E_3 - E^*)} + 2\sqrt{2E_1 + (p_\gamma^2/4) - 2p_\gamma E_1 \cos \delta}.$$

This relation is convenient because only three range measurements ($E_1$, $E_2$, $E_3$) and one angle measurement ($\delta$) are necessary.

Chances are good that in a ground-state star the track of the first alpha-particle is well defined and the angle $\delta$ it makes with the gamma-ray can be measured with good precision.

The above relation could also be used for the determination of $\text{Be}^8$ excitation levels ($E^*_{12}$, etc.), particularly in cases where the angles between the projected tracks cannot be measured due to scattering or the unfavorable position of the star in the emulsion,
but where the angle between the gamma-ray and one of the tracks can be measured.

2. Numerical Estimates of Precision of Measurements

In order to make an estimate of the precision of the measurements, the measuring techniques used must be carefully analyzed. As already indicated, the measuring procedures used were as follows. First, the lengths of projections of the three alpha-tracks, forming a star, in a plane parallel to the stage of the microscope (x, y plane) are measured. This is done by means of an eyepiece micrometer calibrated with a Bausch and Lomb stage micrometer. Customary precautions were taken to compensate for the curvature of the field of view of the microscope by properly centering the tracks to be measured. The next measurement consisted of the measurement of the “elevation” of the tracks; these are coordinates (Z) perpendicular to the stage of the microscope (x, y) indicating the elevation differences of the three tracks with respect to the origin of the star. If the tracks were badly scattered or very long, they were subdivided into shorter sections, and separate elevation measurements were made for the various sections. The microscope used is provided with an accurately calibrated mechanism for measuring elevations. The final measurement is the determination of the angles between the projections in the x, y plane of the three alpha-tracks forming a star. This is done by means of the rotating stage provided in the microscope used.
Errors in determining the total range $R_v$ of a track. Errors in the determination of the range $R_v$ of an alpha-particle arise from errors $\Delta X$ in the determination of the length of the projection of the track $X'$ in the $x$, $y$ plane and errors $\Delta Z$ in the determination of its elevation $Z$, together with errors $\Delta S$ indicating errors and variation in the shrinkage of the emulsion used. Referring to Fig. 19, $R$ represents the "true" range and $R_m$ is the measured range of an alpha-particle. Thus, $R = iX + j(Z \cdot S)$ where $i$ and $j$ are unit vectors along the $y$ and $z$ axis and $S$ is the factor taking into account the shrinkage of the emulsion and the correction factor for the vertical micrometer. Consequently,

$$\Delta R = i\Delta X + j(Z \Delta S + S \Delta Z),$$

$$\Delta R_m = \frac{R \cdot \Delta R}{R}$$

$$= \frac{X \Delta X + Z S (Z \Delta S + S \Delta Z)}{R}$$

$$= \frac{X \Delta X + Z^2 S dS + Z S \Delta Z}{R},$$

or

$$\Delta R_m = \Delta X \cos \delta + (\Delta Z) S \sin \delta + R \frac{dS}{S} \sin^2 \delta.$$

We take the average of this expression, noting that the cross products vanish, and we obtain

$$\Delta R_m = \sqrt{\Delta X^2 \cos^2 \delta + \Delta Z^2 S^2 \sin^2 \delta + R^2 (\Delta S/S)^2 \sin^2 \delta}.$$
Fig. 19 Diagram showing inaccuracies of measurements in a plane perpendicular to the $x, y$ plane.

Fig. 20 Range error in per cent due to straggling as a function of energy. Derived from data of J. Rotblatt, Nature, 165, 387 (1950).
The function $\Delta R_m$ can be numerically computed by using experimentally determined values of $\Delta X$, $\Delta S$, $S$, and $\Delta Z$.

In addition, there is another error $\Delta R_S$ in range because of the straggling effect. This error may be assumed to be in the direction of $R_m$ and is a function of the range. Figure 20, giving the error in range due to straggling, was derived from data published by Rotblatt. (33) The total uncertainty in range is then

$$\Delta R_t = \sqrt{\Delta R_m^2 + \Delta R_S^2} = f(R, \delta).$$

The momentum of an alpha-particle is a function of its range $R$. 

$$p = p(R)$$

and

$$\Delta p = \frac{\delta p}{\delta R} \Delta R_t = p' \Delta R_t = f(p, \delta).$$

From the known range-energy relation, Fig. 14, we construct the momentum range curve, Fig. 21, and $\delta p / \delta R = p' = p'(R)$, Fig. 22.

From the above considerations, the component $\Delta p_m$ of the momentum error in the direction $R_m$ is determined.

Next, we consider the determination of momentum error perpendicular to $R_m$. From Fig. 19 it is seen that

$$(R_m \delta \delta)^2 + (\overline{\Delta R_m})^2 = \Delta R^2.$$

Thus,

$$\delta \delta = \frac{\Delta R^2 - \overline{\Delta R_m}^2}{R_m^2},$$
Fig. 21  Momentum of alpha-particle as a function of range.

Fig. 22  Derivative of momentum of alpha-particle with respect to range, $p'$, as a function of range.

Fig. 23  Diagram showing $\Delta p_r$. 
but
\[ \Delta R^2 = dX^2 + (SdZ + ZdS)^2 \]
and, consequently, \[ \bar{\Delta R} = \sqrt{(\Delta x)^2 + S^2(\Delta Z)^2 + Z^2(\Delta S)^2} \].

Hence,
\[ (\delta \delta)^2 = \frac{\Delta X^2 \sin^2 \delta + S^2 \Delta Z^2 (1 - \sin^2 \delta) + (dS/S)^2 R^2 \sin^2 \delta (1 - \sin^2 \delta)}{R_m^2} \].

Thus, the component of momentum error perpendicular to \( R_m \) (see Fig. 23) is:
\[ \Delta p_{\perp} = p \, d\delta \].

Errors owing to uncertainties in angle measurements. There is an additional error in momentum (\( \Delta p_{xy} \)) perpendicular to the plane defined by \( R \) and \( Z \), and thus parallel to plane \( x, y \). This error arises because of errors inherent in the measurement of angles \( \alpha', \beta', \) and \( \gamma' \) between the range components in the \( x, y \) plane of the three alpha-particles forming a star.

Since the momentum vectors of a star will form the same angles as the corresponding alpha-track ranges, the momentum error parallel to the \( x, y \) plane of the \( \psi \)th alpha-particle is given by
\[ \Delta p_{\psi xy} = p_\psi \cos \delta \, d\alpha', \]
and the square of the total error in momentum for an alpha-particle is
\[ \Delta p^2 = \Delta p_T^2 + \Delta p_m^2 + \Delta p_{xy}^2 = f(p, \delta) \].
Using the relationships discussed above, a family of curves is computed representing the square of the total momentum error \((\Delta p_t)^2\) for an alpha-particle as a function of the momentum \(p\) of the alpha-particle with the angle \(\theta\) that it forms with the \(x, y\) plane as a parameter (see Fig. 12). The computations were made using the following data, which have been experimentally determined.

\[
\Delta X = \frac{1}{2\mu} \text{ rms}
\]
\[
\Delta Z = 1\mu
\]
\[
S = 2.3
\]
\[
\Delta S = 5 \times 10^{-2}
\]
\[
\Delta \alpha' = 1/2^\circ
\]

The momentum error in a momentum balance of a star can then be easily and quickly obtained by using the curves of Fig. 12; namely, by forming

\[
\Delta p_S = \sqrt{(\Delta p_{t1})^2 + (\Delta p_{t2})^2 + (\Delta p_{t3})^2 + (\Delta p_\gamma)^2},
\]

where \(\Delta p_{t1}, \Delta p_{t2},\) and \(\Delta p_{t3}\) are total momentum errors for the three alpha-particles forming a star and \((\Delta p_\gamma)^2\) is the error of the momentum of the interacting gamma-quantum. The \(\Delta p_\gamma\) is negligible, as can be seen from

\[
p_\gamma = \frac{E_1 + E_2 + E_3 + 7.3}{43.1}
\]

and

\[
\Delta p_\gamma = \frac{1}{43.1} (\Delta E_1 + \Delta E_2 + \Delta E_3),
\]
Since \( p \alpha = 2 \sqrt{E}, \quad E = \frac{p}{2} \Delta p \).

Thus,

\[
(\Delta p_\gamma)^2 = \left( \frac{1}{2 \times 43.1} \right)^2 \left( p_1^2 \Delta p_{11}^2 + p_2^2 \Delta p_{12}^2 + p_3^2 \Delta p_{13}^2 \right),
\]

which becomes negligible because of its small numerical coefficient.

Then, for a star, the expected total momentum unbalance is

\[
\overline{\Delta p_S} = \sqrt{\sum_{\nu = 1}^{3} (\Delta p_{\nu})^2},
\]

which is obtained from curves in Fig. 12.
IV. RESULTS

The results are summarized in the form of histograms. Figure 24 is a plot of the number of stars found in 1-Mev photon energy intervals produced by photons of increasing energy. This histogram is based upon 192 stars selected on the basis of criteria discussed in the preceding sections. The shaded areas represent stars believed to have been caused by $^{12}C$ disintegrations to the ground state of $^{8}Be$.

The distribution shows a gradual rise from a photon energy of approximately 12 Mev with a maximum at about 18 Mev. At this point there is a sharp drop followed by a relatively slow rise with a second maximum around 28 Mev, followed by a rapid drop above 30 Mev.

The actual cross section of the reaction is computed from this histogram as follows: The plates used to obtain the results were irradiated with an intensity of 150 R produced by electrons of 100 Mev. The scanned area $A$ was 1.95 cm$^2$; the volume $V$ scanned was $4.6 \times 10^{-2}$ cm$^3$. According to information supplied by Ilford, there are $0.27$ g/cm$^3$ of $^{12}C$ in $E_1$ emulsions. Thus, in the volume scanned we have $1.24 \times 10^{-2}$ g of $^{12}C$. There are $6.02 \times 10^{23}$ atoms per gram atom. Thus, the number $n$ of atoms of $^{12}C$ in the volume scanned is $6.2 \times 10^{20}$. It is assumed here that the number of photons $N_Q$ per energy interval $\Delta E$(Mev) at an energy $E$(Mev) produced by bremsstrahlung of 100-Mev electrons is
Fig. 24  Distribution of 185 C$^{12}$ stars as a function of gamma-ray energy for 100-Mev bremsstrahlung.
\[ N_q = 1.8 \times 10^7 \frac{\Delta E}{E} \text{ R number of quanta/cm}^2, \]

where \( R \) is the intensity of radiation in roentgens as measured by a Victoreen thimble ionization chamber encased in a lead cylinder of 1/8 inch wall thickness. The coefficient \( 1.8 \times 10^7 \) is given by Dr. G.C. Baldwin. (34)

We find 25 stars in the first peak located between 17 and 18 Mev. The number of quanta per cm\( ^2 \) for this energy interval is

\[ N_{Q_{17-18}} = 1.8 \times 10^7 \times \frac{150}{17.5} = 1.55 \times 10^8. \]

Since the number of events \( N \) equals \( \sigma n N_Q \), where \( \sigma \) is the cross section in cm\( ^2 \),

\[ \sigma_{17.5} = \frac{N}{n N_Q} = \frac{(25 \pm 5)}{6.2 \times 10^{20} \times 1.55 \times 10^8} = 2.6 \pm 0.5 \times 10^{-28} \text{ cm}^2. \]

For the second peak located at around 27 to 28 Mev,

\[ N_{Q_{27.5}} = 1.8 \times 10^7 \times \frac{150}{27.5} = 0.985 \times 10^8. \]

Hence,

\[ \sigma_{27.5} = \frac{(16 \pm 4)}{6.2 \times 10^{20} \times 0.985} = (2.6 \pm 0.7) \times 10^{-28} \text{ cm}^2. \]

The location of the first maximum should be accurate within 1/2 Mev; however, the location of the second maximum is considerably more uncertain with present statistics. It is in the range of 26 to 29 Mev,
as can be seen from the histogram. It is also reasonable to assume that the half width of the second peak is considerably broader than that of the first peak.

Because some of the stars located near the surfaces of the emulsion had one or more prongs leaving the emulsion, not all of the C\textsuperscript{12} stars found in the scanned volume could be identified. An estimate of how many stars were lost in this way was made as follows. Out of 354 three-pronged stars located entirely in the volume scanned, 83 were identified as C\textsuperscript{12}. In the entire volume scanned, 40 three-pronged stars had one or more prongs leaving the emulsion. Thus, about \((40 \times 83)/354 = 10\) were lost in this way. This number is not sufficiently large to influence in an appreciable way the above estimate of the cross section.

Figure 25 is a histogram of \(E^*\) values that represent possible Be\textsuperscript{8} excitation levels in Mev (three per star) for 75 stars (three tracks per star) found in the energy interval up to 23 Mev. This histogram does not contain the ground-state stars. The number of \(E^*\) values found in increasing 1/2-Mev energy steps are plotted.

In Fig. 26 is plotted the alpha-track range distribution for 34 stars found in the energy interval of 17 to 19 Mev; in Fig. 27 is reproduced a similar plot of 483 stars produced by the gamma-radiation of the Li\textsuperscript{7} (\(p, \gamma\)) reaction.\textsuperscript{(24, 27)} Figure 28 is a histogram similar to that of Fig. 25, but for stars found
in the energy range above 23 Mev (77 stars). Figure 29 is a histogram representing $E^*$ values for stars found in the energy interval of 26 to 29 Mev (35 stars).
Fig. 25  Distribution of $E^*$ energies (3 values/star) for 75 stars produced by quanta up to 23 Mev.

Fig. 26  Alpha-range distribution for 34 stars found in the energy interval of 17 to 19 Mev.

Fig. 27  Alpha-track range distribution for 483 stars. [V. L. Telegdi and W. Zünti(27)]
Fig. 28 Distribution of $E^*$ energies for 77 stars found above 23 Mev.

Fig. 29 Distribution of $E^*$ values (3 values/star) for stars found in the energy interval of 26 to 29 Mev.
V. DISCUSSION AND CONCLUSION

As stated in the introduction, the main objective of this work is the investigation of the C\textsuperscript{12} (γ, 3α) cross section for photon energies above 23 Mev. This range was not covered in the earlier investigations of Telegdi, Goward, and Zünti\textsuperscript{(25)} because the betatron available to them limited their work to lower photon energies (25-Mev betatron). For comparison with the results shown here, the stars studied at lower energy by the above-mentioned investigators are also recorded here. As will be seen, results obtained here for the photon-energy range up to about 23 Mev agree well with results obtained by Telegdi, Goward, and Wilkins, although the present results are based upon fewer events than those of Telegdi, Goward, and Wilkins.

The distribution in η given in Fig. 11, and the function of \[ f(\eta) \] shown in Fig. 13, indicate that the actually obtained statistical distribution of momentum unbalances Δp\textsubscript{a} is consistent with the theoretical distribution for Δp\textsubscript{S} computed on the basis of an independently determined accuracy of the measurement technique used. In addition, the distribution of Δp\textsubscript{a} for most stars is given in Fig. 30.

The existence of two maxima in the cross section of the C\textsuperscript{12}(γ, 3α) reaction (at about 18 Mev and 28 Mev) is believed to have been proven beyond reasonable doubt. In Fig. 24, which represents a histogram of star population as a function of photon energy, are
Fig. 30 Distribution of momentum balance errors $\Delta p_a$.

indicated the probable statistical errors. It is seen that the statistics are sufficiently good to resolve the two maxima in the cross section. This histogram up to a photon energy of about 23 Mev resembles closely corresponding histograms obtained by Telegdi and Goward using the 25-Mev betatron (see Fig. 2). The cross section value of $\sigma = 2.6 \pm 0.5 \times 10^{-28} \text{cm}^2$ obtained here is somewhat larger than those obtained by Telegdi (about $1 \times 10^{-28} \text{cm}^2$) and Goward (approximately $2.5 \times 10^{-28}$) and may be due to statistics. A more important reason for this discrepancy may be the difficulty of evaluating the x-ray spectrum at its upper energy limit. In
the present work, the upper energy limit is far above the maximum photon energy found to produce the \((\gamma, 3\alpha)\) reaction, and the spectral function used is therefore considerably more reliable.

A possibility of confusion with some other reactions is believed to be unlikely. For example, stars caused by the \(^{16}\text{O} (\gamma, 4\alpha)\) reaction with a sufficiently short alpha-track to be missed by the observer could not be numerous. According to Goward, the cross section for this reaction shows also two peaks (approximately at photon energies of 23 and 29 Mev), the two peaks having approximately equal amplitudes, with a cross section of approximately \(\sigma = 2.5 \times 10^{-28}\) cm\(^2\). Only a small percentage of these \(^{16}\text{O} (\gamma, 4\alpha)\) stars could have one alpha-prong sufficiently small to be missed.

After this investigation was completed, the author found a more recent investigation on the same subject by F. K. Goward and J. J. Wilkins. In this work, the authors pooled information obtained with bremsstrahlung of various electron accelerators ranging in energy from 21 to 70 Mev. Thus, a total of 1700 stars have been measured and analyzed. Presented are essentially only the final results in the form of the cross section curve for the \((\gamma, 3\alpha)\) reaction in \(^{12}\text{C}\) versus photon energy. The authors believe that they have discovered evidence of a fine structure in the cross section curve. The results would be more convincing if all the data were obtained with the same bremsstrahlung spectrum.
The location of the two main peaks in Goward's work (about 18 and about 29 Mev) agrees well with the results of the present work. The magnitudes of the cross section peaks in this latest work of Goward are estimated to be somewhat larger than in his previous work and are also larger than estimates of the present investigation. (Goward's present estimate of the cross section: at 18 Mev, approximately $4 \times 10^{-28} \text{cm}^2$; at 29 Mev, approximately $3.5 \times 10^{-28} \text{cm}^2$.) The slight discrepancy between Goward's work and the present work is probably not significant for this type of experiment. The present work cannot prove or disprove the existence of the fine structure indicated by Goward and Wilkins because of insufficient statistics. In view of Goward's results, it is clear that a very large amount of data is needed to resolve with certainty the fine structure they report.

Another work was also recently reported by M. Eder and V. L. Telegdi. This work represents further investigation of $(\gamma, \alpha)$ reaction in $\text{C}^{12}$. The bremsstrahlung of a 32-Mev betatron was used. Eder and Telegdi conclude, in accordance with the present work, that the cross section reincreases strongly after the previously established resonance-like peak at about 18 Mev. They find some indication of a second maximum at about 26 Mev. However, the energy limitation of the spectrum used requires a rather drastic correction which is difficult to estimate accurately.
Confusion caused by reactions like $^{12}$C (γ, α + γ) $^8$Be* with $^8$Be** → 2α and $^{12}$C (γ,γ)$^{12}$C* with $^{12}$C* → 3α are unlikely simply because the above reactions are very improbable, since the emission of a particle by an excited nucleus is generally much more probable than the emission of a gamma-ray. There is, however, the possibility of $^8$Be excitation levels which, due to parity rules, emit first a gamma-ray, thus decaying to the ground level; then the $^8$Be disintegrates into two alpha-particles. Some of the ground-level stars may have been indeed caused by such events. Since the ground-level stars are not numerous, they could not seriously have affected the present estimate of the cross section.

In Fig. 25, a histogram for $E^*$ values is given for stars found in the photon-energy range up to 23 Mev. The $E^*$ values given are the three computed values for possible excitation energies of $^8$Be in the reaction $^{12}$C (γ, α) $^8$Be*, $^8$Be* → 2α. All three values for each star are plotted in units of 1/2 Mev. This histogram, which represents 75 stars, resembles strongly the histogram obtained by Telegdi et al. (see Fig. 3) using a 25-Mev betatron. The strongest pronounced $E^*$ value is definitely around 3 Mev, with another possible value around 7 Mev.

In addition, for a rough comparison with Telegdi's and Hänni's work using the 17.5-Mev photons produced by bombardment of Li* with protons, stars have been selected between 17 and 19 Mev, and a histogram of their alpha range distribution based
upon 34 such stars was plotted. This is shown in Fig. 26. In Fig. 27 is reproduced a histogram for alpha-track range distribution for 483 stars obtained by Telegdi\(^{(27)}\) from the Li\(^7\) \((p, \gamma)\) Be\(^8\) reaction, and the distribution of the three ranges for each such star is given. Although the statistics are necessarily poor, these two plots appear to be similar in character.

In Fig. 28 is a histogram of E* values similar to that in Fig. 25 but for 77 stars found in the photon range above 23 Mev. Ground-state stars are not included in this plot. Again, there is an indication for a 3-Mev level and a somewhat bigger indication for a level between 7 and 9 Mev. As indicated, the statistics are not strong. Nevertheless, since there are known Be\(^8\) levels of even parity at 7.5 and 9.8 Mev, these indications have some significance. The most definite and perhaps the most interesting indication is that of a possible Be\(^8\) level which has not been reported previously, namely, around 17 Mev. In Fig. 29 a similar plot of E* for 35 stars found in the energy range of 26 to 29 Mev is shown. Again, there is a definite indication of a Be\(^8\) level at 17 Mev. It would be of interest to improve statistics and to investigate more thoroughly this point. In Fig. 30 is given the distribution of \(\Delta p_a\) for most of the stars.

It is of interest to note that the cross section of the \((\gamma, 3\alpha)\) reaction in C\(^{12}\) decreases rapidly above 30 Mev (no stars at all were found above 54 Mev). This result is in general agreement with observations of other photonuclear effects. Baldwin and Klaiber,\(^{(17)}\)
using the bremsstrahlung of the General Electric 100-Mev betatron, have demonstrated the resonance-like character of the photonuclear effect. J. L. Lawson and M. L. Perlman(19) measured the C\textsuperscript{11} activity which resulted from C\textsuperscript{12} (\gamma, n) reaction induced by the bremsstrahlung of the G-E 100-Mev betatron. They expressed the photon intensity as the number of quanta/Mev-min at a photon energy of 30 Mev. The ratio of (\gamma, n) processes/min atom to the number of quanta/Mev-min is given as $1.5 \times 10^{-25}$ Mev-cm$^2$ ± 20 per cent. The same result was obtained with bremsstrahlung produced by both 50- and 100-Mev electrons.

Lawson and Perlman interpret their result by assuming a sharply peaked photo absorption curve versus photon energy. This assumption is also experimentally corroborated by R. Sagane,(38) Strauch,(36) and others. This type of behavior was also observed in many different nuclei in the energy range up to 100 Mev by M. L. Perlman and G. Friedlander.(18)

It is possible, however, that in the present experiment a weak resonance somewhere above 50 Mev could have been overlooked because of the decrease of bremsstrahlung intensity at higher energies.

An attempt to explain the resonance character of the photonuclear effect was made by Bethe and Levinger.(35) They find that so far the experimental results are in general agreement with their theory.
At the present stage of knowledge, it is impossible to explain the reason for the peculiar energy dependence of the total cross section for the \( C^{12}_2 (\gamma, 3\alpha) \) reaction. Goward(28) reports two peaks in the total cross section at 23 and 29 Mev for the \( O^{16}_2 (\gamma, 4\alpha) \) reaction. It may be that there are similar reasons in \( C^{12}_2 (\gamma, 3\alpha) \) and \( O^{16}_2 (\gamma, 4\alpha) \) which produce such a response. Some possible explanations of this cross section response in \( C^{12}_2 \) are as follows.

1. It is fairly reasonable to assume that the total photo-absorption cross section for \( C^{12}_2 \) has a peak somewhere between 25 and 30 Mev (Standard Compound Nucleus). Suppose this peak is actually at 28 Mev. This assumption has some experimental support: Strauch(36) quotes a value of 30 Mev; Baldwin and Klaiber(17) give a value of 30 Mev. According to Baldwin,(34) the value should be around 26 to 27 Mev. Since the \( C^{12}_2 (\gamma, 3\alpha) \) reaction has the lowest threshold (7.3 Mev) of all possible disintegrations of \( C^{12}_2 \), it will be observed first with rising photon energy and, in fact, will form the beginning of the photoabsorption curve if we neglect \( C^{12}_2 (\gamma,\gamma) \) process for \( C^{12}_2 \).

Since the \( (\gamma, p) \) reaction has a threshold of about 16 Mev, and \( (\gamma, n) \) about 19 Mev, the competition from these reactions causes the sharp drop in the \( (\gamma, 3\alpha) \) first cross section peak (approximately 18 Mev). Since,
however, the total photo cross section keeps on rising up to 28 Mev, the number of $^{12}_{\text{C}}(\gamma, 3\alpha)$ also rises, forming a "broad" maximum close to the energy where the total photoabsorption cross section shows a maximum.

A theoretical value for the total photonuclear cross section for $^{12}_{\text{C}}$ is given by H.A. Bethe to be 180 millibarns Mev. Experiments on $(\gamma, n)$ and $(\gamma, p)$ reactions with $^{12}_{\text{C}}$ are compatible with this result. The $(\gamma, \alpha)$ cross section is about one percent of the above. A rough estimate of the integrated cross section for $(\gamma, 3\alpha)$ in $^{12}_{\text{C}}$ from this work yields about 2 millibarns Mev, which is compatible with above estimates.

2. Another explanation may be as follows: The stars in the first peak are primarily produced by a dipole interaction. Those in the second peak are primarily produced by a quadrupole interaction. The drop at 18 Mev is still due to the $(\gamma, n)$ and $(\gamma, p)$ competition. In defense of this approach, one may say that the quadrupole interaction is more likely to interact directly with the alpha-particles of the system. The dipole interaction is more likely to interact with the protons or neutrons of the system than with alpha-
particles. The cross section ratio of electric quadrupole to electric dipole interactions is approximately:

\[ \frac{\sigma_{\text{Quad}}}{\sigma_{\text{Dipole}}} = \left( \frac{r}{A} \right)^2 = 1:100 \]

3. Another possibility may be as follows: The \(^{12}C\ (\gamma, \alpha)\) process goes only through special states of the \(^{12}C\) nucleus. These special states cannot disintegrate into neutrons or protons, and formation of these states can only take place by electric quadrupole (or magnetic dipole) radiation. This would be compatible with the small cross section. It must then be assumed as accidental that there are only two such special states producing the two maxima.

4. Another approach has been advanced by Telegdi.\(^{(37)}\) The first peak is caused by electrical quadrupole and magnetic dipole radiation with perhaps a small contribution of electrical dipole radiation. Using this assumption, Telegdi\(^{(35)}\) has calculated the expected range distribution for the alpha-particles and finds good agreement with the experimentally obtained range distribution. The re-increase in the cross section is attributed to another absorption mechanism such as the electrical dipole resonance. He notes that with E.D. absorption the direct disintegration of \(^{12}C\) into three alpha-particles becomes a more probable competitive reaction
mechanism. This, however, is not well supported by results obtained here (see Fig. 28) and also by Goward.\(^{(28)}\) These results indicate that a great number of \(^{12}\text{C} (\gamma, 3\alpha)\) reactions in the range above 23 Mev disintegrate via a Be\(^6\) level of about 17 Mev. Nevertheless, a certain number of these stars may indeed disintegrate directly into three alpha-particles.

Probably more information could be gained by the study of the angular distribution of the first alpha-particle with regard to the direction of the incident photon. This could be done by selecting ground-state stars only because of the certainty in recognition of the first alpha-particle.
ACKNOWLEDGMENT

The author wishes to thank Prof. P. Scherrer of the Swiss Federal Institute of Technology for suggesting the problem and for his continued interest in the experiment; Dr. C.G. Suits, Vice President and Director of Research, General Electric Company, for making available the necessary facilities of the G-E Research Laboratory and for supporting in full this research; Dr. E.E. Charlton for his encouragement and continued interest in the problem.

Drs. G.C. Baldwin, E.A. Gaerttner, M.L. Yeater, H. Hurwitz, Jr., W. Van der Grinten and other members of the G-E Research Laboratory, and Dr. H.A. Bethe of Cornell University, contributed through many helpful suggestions and discussions in bringing this research to a successful conclusion.

Mr. D.F. Barker assisted in the processing and scanning of the emulsions and has prepared the photomicrographs. Mr. R.E. Slovacek assisted in scanning the emulsions.
Figure 31: Photomicrograph of a C12 star produced by a 16.3-MeV gamma quantum.
Fig. 32 Photomicrograph of a $^{12}$C star produced by a 31.1-Mev gamma-quantum.
Fig. 33  Photomicrograph of a $^{12}C$ star produced by a 40.4-Mev gamma-quantum.
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