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 C^{12}
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
V. DISCUSSION AND CONCLUSION

As stated in the introduction, the main objective of this work is the investigation of the $^\text{C}\!\!\text{C}^1_2\, (\gamma, 3\alpha)$ cross section for photon energies above 23 Mev. This range was not covered in the earlier investigations of Telegdi, Goward, and Zünti(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 $\eta$ given in Fig. 11, and the function of $\int \eta y_{dn} = f(\eta)$ shown in Fig. 13, indicate that the actually obtained statistical distribution of momentum unbalances $\Delta p_\alpha$ is consistent with the theoretical distribution for $\Delta p_\beta$ computed on the basis of an independently determined accuracy of the measurement technique used. In addition, the distribution of $\Delta p_\alpha$ for most stars is given in Fig. 30.

The existence of two maxima in the cross section of the $^\text{C}\!\!\text{C}^1_2(\gamma, 3\alpha)$ 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
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 $\sigma = 2.6 \pm 0.5 \times 10^{-25}\text{cm}^2$ obtained here is somewhat larger than those obtained by Telegdi (about $1 \times 10^{-26}\text{cm}^2$) and Goward (approximately $2.5 \times 10^{-26}$) 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 $4 \times 10^{-28}$ cm$^2$; at 29 Mev, approximately $3.5 \times 10^{-28}$ 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. (39) This work represents further investigation of $(\gamma, \alpha)$ reaction in 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 $^{12}\text{C} (\gamma, \alpha + \gamma) \text{Be}^8_*$ with $\text{Be}^8_{**} \rightarrow 2\alpha$ and $^{12}\text{C} (\gamma, \gamma) \text{C}^{12}_* \rightarrow \text{C}^{12}_* \rightarrow 3\alpha$ 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 Be$^8$ excitation levels which, due to parity rules, emit first a gamma-ray, thus decaying to the ground level; then the Be$^8$ 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 Be$^8$ in the reaction $^{12}\text{C} (\gamma, \alpha) \text{Be}^8_*$, $\text{Be}^8_{*} \rightarrow 2\alpha$. 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$^7$ 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 Li⁷ (p,γ)Be⁸ 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 Be⁸ 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 Be⁸ 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 Be⁸ 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 ΔPa for most of the stars.

It is of interest to note that the cross section of the (γ, 3α) reaction in C¹² 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 \(^{11}\)C activity which resulted from \(^{12}\)C \((\gamma, n)\) 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 $^{12}$C ($\gamma$, 3$\alpha$) reaction. Goward(28) reports two peaks in the total cross section at 23 and 29 Mev for the $^{16}$O ($\gamma$, 4$\alpha$) reaction. It may be that there are similar reasons in $^{12}$C ($\gamma$, 3$\alpha$) and $^{16}$O ($\gamma$, 4$\alpha$) which produce such a response. Some possible explanations of this cross section response in $^{12}$C are as follows.

1. It is fairly reasonable to assume that the total photo-absorption cross section for $^{12}$C 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 $^{12}$C ($\gamma$, 3$\alpha$) reaction has the lowest threshold (7.3 Mev) of all possible disintegrations of $^{12}$C, it will be observed first with rising photon energy and, in fact, will form the beginning of the photoabsorption curve if we neglect $^{12}$C ($\gamma$, $\gamma$) process for $^{12}$C.

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 \( C^{12}(\gamma, 3\alpha) \) 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 \( C^{12} \) is given by H. A. Bethe to be 180 millibarns Mev. Experiments on \( (\gamma, n) \) and \( (\gamma, p) \) reactions with \( C^{12} \) 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 \( C^{12} \) 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:

$$\frac{\sigma_{\text{Quad}}}{\sigma_{\text{Dipole}}} = \left(\frac{r}{\lambda}\right)^2 = 1:100$$

3. Another possibility may be as follows: The $^{16}_{\text{C}} (\gamma, \alpha)$ process goes only through special states of the $^{16}_{\text{C}}$ 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 $^{16}_{\text{C}}$ 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 C$^{12}$(γ, 3α) reactions in the range above 23 Mev disintegrate via a Be$^8*$ 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.