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Effect of Excited-state Decays on the Measured Angular Distribution of the $^{12}C(\gamma, p)^{11}B$ Reaction

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Abstract

The angular distribution of photoprotons from ^{12}C as measured directly and as deduced from the inverse reaction are compared. A discrepancy is revealed; it is resolved by proposing a small cross section for proton decay to excited states of ^{11}B. The size of this cross section is inferred from the data.

Introduction

The differential cross section of the reaction $^{12}C(\gamma, p_0)^{11}B$ may be expressed as a sum of Legendre polynomials:

$$\frac{d\sigma}{d\Omega}\left(E,\theta\right) = \sigma(E)\left(1+\sum_{l=1}^{n} a_l(E)\,P_l(\cos\theta)\right), \qquad (1)$$

where θ is the angle between the direction of the incident photon and the emitted proton, in the centre of mass system. Since the coefficient a_2 depends primarily on the angular momentum quantum numbers of protons emitted from the dominant electric dipole states of ^{12}C, an accurate determination of its value would provide a sensitive indication of the particle configuration in these states.

The angular distribution of protons in the $^{12}C(\gamma, p)^{11}B$ reaction has been investigated by Frederick and Sherick (1968) using several different bremsstrahlung energies and also by Allas *et al.* (1964) via the inverse reaction $^{11}B(p, \gamma_0)^{12}C$. In Fig. 1 the values of a_2 determined by Frederick and Sherick at 32·1 MeV are compared with those obtained by Allas *et al.* Despite the large statistical scatter in the data of Allas *et al.*, significant differences between the two sets of results are apparent in the photon energy region between 22 and 25·5 MeV. These differences may be explained by a contribution to the results of Frederick and Sherick from protons which leave ^{11}B in an excited state.

Non-ground-state Proton Contributions

When a ^{12}C nucleus absorbs a photon of energy E_γ and emits a proton of energy E_p, leaving the ^{11}B nucleus in its ground state, the proton and photon energies are related by

$$E_\gamma = \tfrac{12}{11}E_p + Q, \qquad (2)$$

where Q is the threshold of the reaction. However, when a proton of energy E_p is

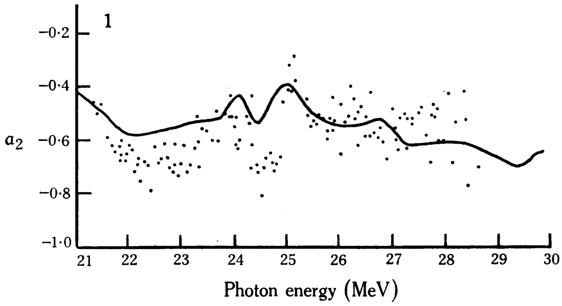
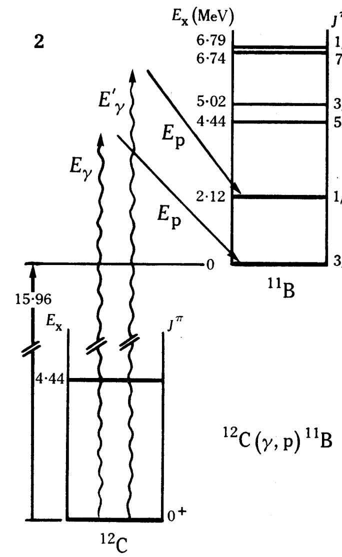


Fig. 1 (*left*). Values of a_2 for $^{12}C(\gamma, p)^{11}B$. The curve is a smooth fit to the data determined by Frederick and Sherick (1968) using 32·1 MeV bremsstrahlung while the points are those obtained by Allas *et al.* (1964) from the inverse reaction.



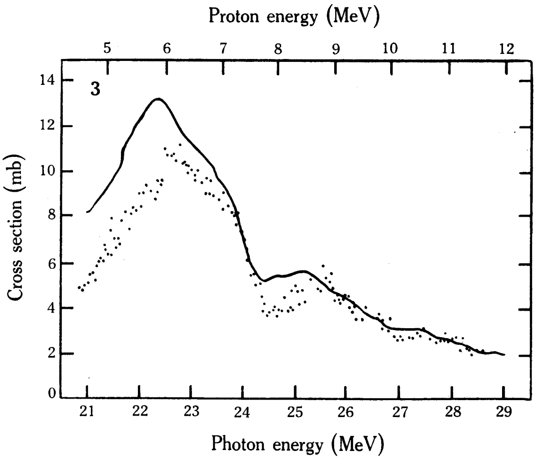


Fig. 2 (*right*). Some energy states involved in photoproton emission from ^{12}C.

Fig. 3 (*left*). Cross sections for $^{12}C(\gamma, p)^{11}B$. The curve is a smooth fit to the data of Frederick and Sherick (1968) and the points are from Allas *et al.* (1964).

emitted leaving ^{11}B in a state of excitation energy E_x, the energy of the absorbed photon E'_γ is given by

$$E'_\gamma = \tfrac{12}{11}E_p + (Q + E_x) = E_\gamma + E_x . \tag{3}$$

This situation is depicted in Fig. 2. The number $Y(E_p)$ of protons produced with energy E_p depends on the cross section for the photoproton reactions to the ground state and to excited states in ^{11}B, and on the energy distribution of the photons incident on the ^{12}C target. Thus

$$Y(E_p) = \sigma_0(E_\gamma)N(E_\gamma) + \sigma_1(E_\gamma + E_1)N(E_\gamma + E_1) + \sigma_2(E_\gamma + E_2)N(E_\gamma + E_2) + \dots , \tag{4}$$

where $N(E)$ is the number of incident photons of energy E, $\sigma_0(E)$ is the (γ, p_0) cross section at excitation energy E in ^{12}C, $\sigma_n(E)$ is the cross section at excitation energy E for the photoproton reaction to the nth excited state of ^{11}B with excitation energy E_n, and E_p and E_γ are related by equation (2). The photoproton cross section $\sigma'(E_\gamma)$, deduced on the assumption that only ground state transitions occur, is related to the actual cross sections by the relation

$$\sigma'(E_\gamma) = \sigma_0(E_\gamma) + \sigma_1(E_\gamma + E_1)\frac{N(E_\gamma + E_1)}{N(E_\gamma)} + \sigma_2(E_\gamma + E_2)\frac{N(E_\gamma + E_2)}{N(E_\gamma)} + \dots . \tag{5}$$

In analyzing their $^{12}C(\gamma, p)^{11}B$ experiment, Frederick and Sherick (1968) assumed that photoproton decay to excited states in ^{11}B was negligible. Fig. 3 shows a comparison between the cross section deduced by Frederick and Sherick on this basis of ground state proton emission and that derived from the data of Allas *et al.* (1964) using the principle of detailed balance.* The differences between the cross sections in Fig. 3 indicate that it is not valid to ignore non ground state protons. The two cross sections have been normalized in the photon energy region between 27·5 and 28·5 MeV, where few non ground state photoprotons are expected because of the endpoint energy used. The figure suggests a significant number of protons with energies below 7 MeV and between 7·5 and 8·7 MeV which leave ^{11}B nuclei in excited states. These are wrongly assigned by Frederick and Sherick as coming from excitations below 23·5 MeV and between 24·2 and 25·5 MeV. The cross section and angular distribution coefficients subsequently deduced by them are distorted.

Accepting the above distortion, it is possible to deduce the magnitudes and shapes of the cross sections for photoproton emission to excited states in ^{11}B, in such a way as to account satisfactorily for the differences in Figs 1 and 3. Some further experimental information about these cross sections can be obtained from the work of Medicus *et al.* (1970), who measured the spectrum of decay γ-rays from the excited states of ^{11}B. Their data were taken when ^{12}C was irradiated with bremsstrahlung of different endpoint energies so that estimates could be made of the cross sections to different excited residual states from several regions of the dipole giant resonance of ^{12}C. Two important conclusions can be made from the values listed in Table 3 of their paper. Firstly, only the first three excited states have significant population following photoproton emission and, secondly, in each case the cross section to each of these states has its maximum above 27 MeV. Thus it follows that most non ground state protons with energies between 7·5 and 8·7 MeV (those responsible for the extra strength between 24 and 25·5 MeV in the photoproton cross section reported by Frederick and Sherick 1968) very likely derive from decays to the $5/2^-$ state at 4·44 MeV and the $3/2^-$ state at 5·02 MeV in ^{11}B. The excess protons with energies between 5 and 7 MeV probably come from decays to the first excited state in ^{11}B at 2·12 MeV, with possible contributions from decays to states at 6·74 and 6·79 MeV.

On the assumption that decays to the second and third excited states in ^{11}B account for the excess protons with energies near 8 MeV in the work of Frederick and Sherick (1968), cross sections for decay to these states were deduced so that they best reconciled the differences in the cross section shapes in Fig. 3 and the angular distribution coefficients in Fig. 1. The resulting cross sections for decay to the 4·44 and 5·02 MeV states are shown in Figs 4*a* and 4*b*. They have been derived assuming values of the angular distribution coefficient a_2 of $+0\cdot5$ and $-0\cdot7$ respectively.

Discussion

Angular Distribution Coefficients

How well does the above assumption account for the differences in the angular distribution coefficients shown in Fig. 1? According to Bachelier *et al.* (1969) both the ground state of ^{11}B and the $3/2^-$ state at 5·02 MeV carry $p_{3/2}$ hole strength. The decays

* The present cross section differs from that presented in Fig. 8 of the paper by Frederick and Sherick, who appear to have omitted the momentum factor p_p^2/p_γ^2 in their calculation.

to both of these states from ^{12}C at excitation energies near 30 MeV therefore probably have similar angular distributions. The results of Frederick and Sherick (1968) show that a_2 is approximately $-0\cdot7$ for excitation energies near 30 MeV (see Fig. 1), so it is reasonable to assume that protons originating from this energy region but leaving

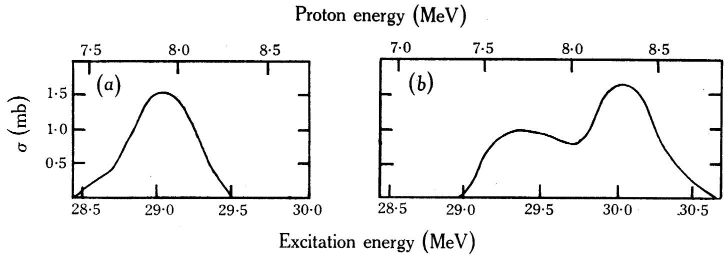


Fig. 4. Proposed photoproton cross sections for excited-state decay of ^{12}C to states in ^{11}B at (*a*) 4·44 MeV and (*b*) 5·02 MeV.

^{11}B in its 5·02 MeV state (as does the cross section in Fig. 4*b*) also have an a_2 value of $-0\cdot7$. These protons will have energies between 8·3 and 8·7 MeV and would contribute to the (γ, p) cross section and angular distribution between 25·0 and 25·5 MeV, as deduced by Frederick and Sherick. This would explain why the value of a_2 in this region is more negative than that deduced from the (p, γ_0) reaction. The difference between the value of a_2 deduced from the (γ, p) reaction and that deduced from the (p, γ_0) reaction between 24 and 25 MeV can be explained by a contribution in this region from non ground state protons with a positive a_2 value. Such a value of a_2 is feasible, since the cross section in Fig. 4*a* is postulated to decay to the $5/2^-$ state at 4·44 MeV in ^{11}B mainly via $d_{5/2}$ proton emission, which according to the tables of Carr and Baglin (1971) would result in an a_2 value of approximately $+0\cdot5$.

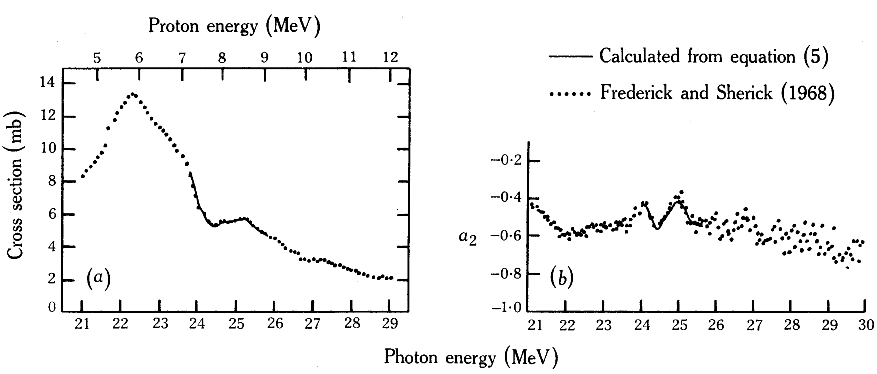


Fig. 5. Calculated (*a*) photoproton cross section as defined by equation (5) and (*b*) effective a_2 values, compared with the experimental points from Frederick and Sherick (1968) for the reaction $^{12}C(\gamma, p)^{11}B$.

Indeed, a calculation can be made of the cross section and angular distribution as determined by Frederick and Sherick (1968), by assuming the cross sections shown in Figs 4*a* and 4*b*, together with the ground state cross section and angular distribution coefficients as determined from the inverse reaction. When these cross sections are inserted into equation (5), together with an estimate of $N(E)$ for a bremsstrahlung beam of endpoint energy 32·1 MeV, as used by Frederick and Sherick, very good agreement is obtained with their cross section and angular distribution. The calculated curves are compared with the experimental points in Figs 5*a* and 5*b*.

Several Possible Sources of Error

The good agreement shown in Fig. 5 requires integrated cross sections to the 5·02 and 4·44 MeV states in ^{11}B of 1·4 and 0·9 MeV.mb respectively. These values are to be compared with 1·3 and 2 MeV.mb obtained from the work of Medicus *et al.* (1970) for the integrated cross sections between 27 and 33 MeV. Clear agreement is seen for the population strength of the 5·02 MeV state, but the measured cross section to the 4·44 MeV state is somewhat greater than the postulate suggests. This may be because the experimental value covers the energy region from 27 to 33 MeV and may include a cross section contribution from above the energy range of Frederick and Sherick (1968).

As stated above, the data shown in Fig. 3 were normalized between 27·5 and 28·5 MeV assuming that only ground state protons were present in this region of the data of Frederick and Sherick (1968). There may be, however, some protons in this region due to states in ^{12}C above 30 MeV decaying to the first excited state of ^{11}B. These would be excited weakly by the photons in the tip of the 32·1 MeV bremsstrahlung spectrum. Medicus *et al.* (1970) estimate the cross section for this decay mode, integrated between 27 and 33 MeV, to be 2 MeV.mb. This implies a maximum normalization error of 10%, which would increase the integrated cross sections derived from Fig. 4 by approximately 0·25 MeV.mb, and would shift the cross-section zero axis down by an amount between 0 and 0·3 mb. Fortunately a normalization error as large as 10% is unlikely since this would imply a cross section for decay to the 5·02 MeV state that is 50% larger than that reported by Medicus *et al.*

If the values of a_2 assumed in deriving the cross sections in Figs 4*a* and 4*b* are not constant over the resonances, the present analysis will be in error. In practice a large variation in a_2 over such a small energy region is unlikely, and at most the values would be expected to vary by $\pm 0{\cdot}05$. Allowing this range of variation, the overall shapes of the cross sections in Fig. 4 do not change significantly, although their magnitudes may vary by up to 20%.

Other Non Ground State Protons

There is insufficient information to deduce with any certainty the origin of the non ground state protons with energies below 7 MeV, which contribute to the photoproton cross section around 22 MeV. However, the de-excitation γ-ray measurements of Medicus *et al.* (1970) suggest an integrated cross section of about 3 MeV.mb for decay to the $1/2^-$ state at 2·12 MeV in ^{11}B from excitation energies in ^{12}C below 24·5 MeV. If these protons had an a_2 value of approximately $-0{\cdot}2$, this would account for the discrepancy between the cross sections and angular distributions as measured in the (γ, p) and (p, γ_0) experiments below 23 MeV.

Conclusions

The above discussion has shown that a relatively small contribution from excited-state protons can have a significant effect on the measured angular distribution of photoprotons. The postulates of this paper may be checked by a careful measurement of the differential photoproton cross section to the first few states of ^{11}B. A more accurate measurement of the differential cross section for the ^{11}B(p, γ_0)^{12}C reaction is also much needed.

Acknowledgment

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