HIGH-RESOLUTION STUDY OF THE REACTION $C^{12}(p, 2p)B^{11}$ AT 50 MeV*

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The $(p, 2p)$ reaction has been extensively studied at energies between 40 and 440 MeV.[1] These studies have given valuable information on the gross shell structure of nuclei, but difficulties in obtaining good energy resolution have limited the use of the reaction for detailed spectroscopic investigations.

We have studied the reaction $C^{12}(p, 2p)B^{11}$ at 50 MeV using solid-state counters for detection of the outgoing protons and have, for the first time in this type of reaction, obtained energy resolution sufficient to distinguish between individual states of the final nucleus.

A carbon target was bombarded with 50-MeV protons from the Berkeley 88-inch cyclotron. Proton pairs from the $(p, 2p)$ reaction were detected in two counter telescopes, each consisting of a pair of lithium-drifted silicon detectors: a 0.024-inch "ΔE" detector and a 0.120-inch "E" detector. The circular collimators defining each solid angle subtended 6.9×10^{-3} sr at the target. Electronic circuits selected only those events in which the outgoing particles, identified as protons with energies between 9 and 25 MeV, produced a fast coincidence between all four counters. The resolution of the summed energy spectra (the total energy deposited in all four detectors) was better than 350 keV. Figure 1(a) shows a summed energy spectrum which is fairly typical and illustrates that the transition to the ground state of B^{11} is predominant. We have measured angular correlations for this transition with the telescopes placed at equal angles, θ, on opposite sides of the incident beam direction.

Figure 2 shows the differential cross section for the ground-state transition as a function of θ for events in which $|E_1-E_2| < 5$ MeV, where E_1 and E_2 are the energies of the two detected protons. This angular correlation differs markedly from those obtained at higher energies: (a) There are more oscillations, presumably diffraction effects due to localization of the interaction in the nuclear surface. (b) The cross section rises quickly at small angles, possibly due to the rapid rise of the proton-proton scattering cross section at low energies. Recent distorted-wave calculations seem to reproduce the major features of the correlation.[2]

The inset in Fig. 2 shows three spectra of (E_1-E_2) for the ground-state transition. The absence of sharp structure in these spectra (which as a consequence of our geometry must by symmetrical about $E_1 = E_2$) indicates that the reaction does not proceed through long-lived proton-unstable excited states of C^{12}.

The (E_1-E_2) spectra do, however, show slowly varying structure near the minima of the angular correlation. At these points the cross section averaged over $|E_1-E_2| < 5$ MeV is not a good approximation to that for equal energy sharing. There we have drawn smooth lines through the spectra to obtain the cross section for $E_1 = E_2$; the results are given by the dashed

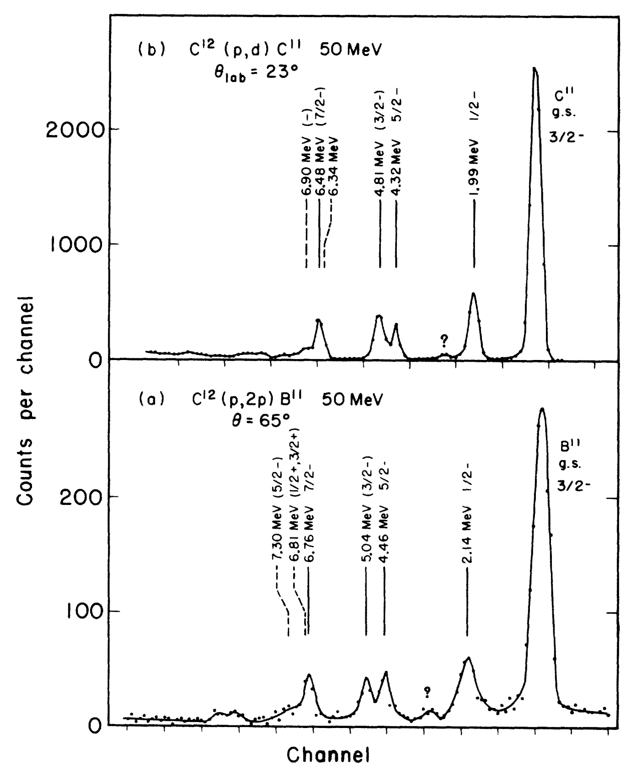

FIG. 1. (a) A summed energy spectrum (E_1+E_2) for the reaction $C^{12}(p,2p)B^{11}$ at 50 MeV. The positions of known excited states of B^{11} are indicated. (b) A deuteron energy spectrum from the reaction $C^{12}(p,d)C^{11}$ at 50 MeV. The positions of known excited states of C^{11} are indicated.

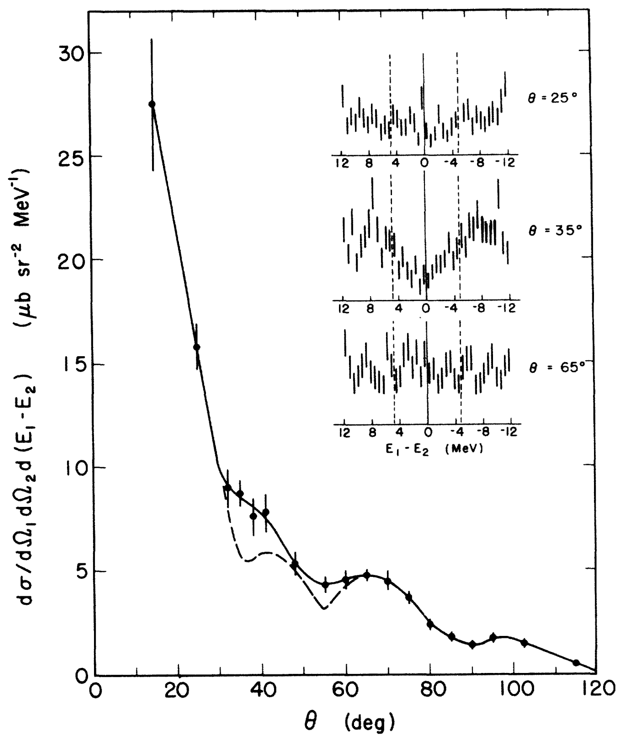

FIG. 2. The differential cross section $d\sigma/d\Omega_1 d\Omega_2 \times d(E_1-E_2)$ for the reaction $C^{12}(p, 2p)B^{11}$(g.s.) at 50 MeV as a function of θ. The cross section has been averaged over the region $|E_1-E_2| < 5$ MeV indicated by the vertical dotted lines on the (E_1-E_2) spectra shown in the inset. The dashed line is an approximation to the cross section for equal sharing of energy between the outgoing protons, obtained as described in the text.

line in Fig. 2. The effects of angular resolution on the angular correlation have not been extracted.

It will be seen from Fig. 1(a) that four excited states of B^{11} are produced with appreciable intensity. The states of spin $\frac{5}{2}^-$ and $\frac{7}{2}^-$ are particularly interesting since, in order for them to be produced by simple removal of a proton from C^{12}, it is necessary for the C^{12} ground state to contain large admixtures of $1f$ particles. While calculations do indicate the presence of $1f$ admixtures in C^{12}, it is by no means clear whether the quantity is sufficient.[3]

Alternatively, it is tempting to consider the possibility that these four states may have the character of a $p_{3/2}$ proton hole coupled to the 2^+ first excited state of C^{12} at 4.43 MeV. Their formation would then naturally proceed through a double excitation process, i.e., pickup of a $p_{3/2}$ proton accompanied by inelastic scattering of either the incoming or one of the outgoing protons. This mechanism is plausible since the 4.43-MeV state in C^{12} is known to be strongly excited by inelastic proton scattering at these energies.[4] Double-excitation processes of this type have been suggested by Penny and Satchler[5] and have recently been invoked to interpret an anomalous angular distribution in the reaction $Cr^{52}(d,p)$.[6] The production of the $\frac{1}{2}^-$ state at 2.14 MeV would be enhanced by simple removal of a proton from the $(p_{3/2})^{-2}(p_{1/2})^2$ admixture present in the ground state of C^{12}. We might also expect significant configuration mixing between the $\frac{3}{2}^-$ excited state and the ground state.

Using the same counter telescopes as for the $(p, 2p)$ reaction, we have also studied the reaction $C^{12}(p,d)C^{11}$ with comparable energy resolution, producing analog states in the mirror nucleus. Figure 1(b) shows a spectrum for this reaction. The relative populations of the corresponding states in the two reactions are comparable. In particular, in the (p,d) reaction we find that the $(\frac{7}{2}^-)$ state at 6.48 MeV is more strongly produced than the neighboring state at 6.34 MeV. This supports our assumption that the unresolved doublet at 6.8 MeV in B^{11} for the $(p, 2p)$ reaction consists mainly of the $\frac{7}{2}^-$ state.

The $\frac{5}{2}^-$ and $\frac{7}{2}^-$ states have now been observed in a variety of single-nucleon pickup reactions on C^{12} up to 150 MeV.[7] Clarification of the role of the double-excitation process in these reactions is necessary to enhance their usefulness as spectroscopic tools.

We wish to thank W. R. Gibson, A. R. Johnston, and R. J. Griffiths[8] for sending us their results prior to publication. There seems to be no direct comparison that can be made between the two sets of results.

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INTRANUCLEAR CASCADE AND FERMI-MODEL BREAKUP CALCULATIONS ON THE PRODUCTION OF Li, Be, AND B ISOTOPES IN C^{12} BY 156-MeV PROTONS

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A complete calculation of the cross sections for the production of He^6, Li^6, Li^7, Li^8, Li^9, Be^9, Be^{10}, B^{10}, B^{11}, C^{10}, and C^{11} from 156-MeV proton-irradiated carbon has been performed using the hypothesis of a two-step mechanism of which the first step is the intranuclear cascade initiated by the incident proton and leading to a particular excited residual nucleus, and the second step is the breakup of the residual nucleus into various particles.

In all the following the term "residual nuclei" will refer to excited nuclei produced by the cascade, and "final nuclei" refer to nuclei left at the end of the two-step process.

I. The cascade.—We shall not describe here the Monte-Carlo cascade calculations on C^{12} which were recently discussed by Gradsztajn.[1] Let us only recall that the method used involved the possibility for any nucleon moving in the nucleus to have a probability P of colliding with an alpha cluster. In the present work 10 000 cascades have been calculated both for $P=0$ (no clusters) and for $P=0.40$. The frequency of occurrence of residual nuclei after the cascade is given in Tables I and II for $P=0$ and $P=0.40$, respectively. In Figs. 1 and 2 are shown the excitation energy spectra of these.

II. Breakup of highly excited residual nuclei.—The evaporation of particles, which is usually considered as a likely process of de-excitation in the case of heavy nuclei, cannot be used here due to the small number of nucleons in the residual nuclei. So we have applied to this problem a different statistical approach which

Table I. Frequency of occurrence of various residual nuclei as calculated from the cascade interaction of 156-MeV protons on C^{12} (taking $P=0$). Number of incident protons: 10 000.

Type of cascade	Residual nucleus	Number[a]	Type of cascade	Residual nucleus	Number[a]
p	N^{13}	0	$p, 2p2n$	B^9	158
p, n	N^{12}	253	$p, 2p3n$	B^8	10
$p, 2n$	N^{11}	121	$p, 2p4n$	B^7	1
$p, 3n$	N^{10}	15	$p, 3p$	Be^{10}	231
p, p	C^{12} [b]	604	$p, 3pn$	Be^9	117
p, pn	C^{11}	1550	$p, 3p2n$	Be^8	31
$p, p2n$	C^{10}	348	$p, 3p3n$	Be^7	0
$p, p3n$	C^9	36	$p, 4p$	Li^9	27
$p, 2p$	B^{11}	1.253	$p, 4pn$	Li^8	6
$p, 2pn$	B^{10}	709	$p, 4p2n$	Li^7	1

[a]Total, including the transparencies: 9777. The missing residual nuclei are produced by cascades with more than six emitted nucleons and are not useful for the breakup calculation.

[b]Not including 4306 transparencies.