Separation of the Final States of the Residual Nucleus in the Pickup Reaction $C^{12}(p,d)C^{11}$ at 154 Mev

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The deuteron groups corresponding to different states of C^{11} in the (p,d) reaction on C^{12} at 154 Mev have been separated with a magnetic analyzer. A comparison with the known levels of C^{11} shows that only the $\frac{3}{2}-$ and $\frac{1}{2}-$ states (prominently the $\frac{3}{2}-$ ground state) seem to be formed to an appreciable extent. These results can be explained by the fact that at this energy the pickup of a more loosely bound high-momentum p-shell neutron should be the most probable; the observed states of C^{11} would then correspond mainly to a hole created in the p shell of C^{12} in its ground state. This gives the possibility in high-energy pickup reactions of exciting selectively certain states of the residual nucleus.

WE have been able to separate the deuteron groups corresponding to the ground state and different excited levels of the residual nucleus C^{11} in the pickup reaction (p,d) on C^{12} at 154.5 Mev. This was achieved with the new double-focusing magnetic analyzer with a radius of 170 cm and a deflection angle of 120° in the horizontal plane.[1] We used the 154.5-Mev proton beam of the Orsay synchrocyclotron. At this energy the (p,d) reaction can be considered in first approximation as the result of a direct interaction of the incident proton with only one nucleon of the target nucleus.[2–5] In order to be able to form an energetic deuteron, the picked-up neutron must have a relatively high momentum in the target nucleus just before the interaction.

A carbon target of 0.174 g/cm² was located in vacuum at the center of the reaction chamber of the analyzer. The beam was focused on the target to a spot about 12 mm wide and 20 mm high. The energy width of the beam was reduced by the partial introduction of an internal target in the synchrocyclotron so as to cut off part of the radial oscillations.[6] An ionization chamber was used as a monitor.

The solid angle used for the deuterons—defined by the entrance slits of the analyzer—was 1.3×10^{-3} sr. A fast coincidence telescope consisting of two plastic scintillators was placed at the image position of the spectrometer. A nuclear resonance probe, located in a field region which is made homogeneous, preliminarily calibrated with a Hall effect probe, gave the magnetic field value at the center of the analyzer. The field used in these measurements to analyze the deuterons was varied between 13 400 and 14 400 gauss, whereas the most energetic protons corresponded to about 11 000 gauss. Under the deuteron peaks there is a very small background formed by the continuous spectrum of tritons.

The energy spectrum of deuterons emitted at 20° (laboratory angle) is shown in Fig. 1. The abscissa scale gives the excitation energy of the residual nucleus C^{11}; the dashes indicate the position of the known levels of C^{11}.

The continuous deuteron spectrum which we had studied previously[7] begins at about 8 Mev.

The total width at half height of the most important deuteron peak is 1.2 Mev: this width represents the resolution which is at present limited by the energy width (approximately 0.9 Mev) and the optics of the primary beam; it should be possible to improve it in the future.

On Fig. 1 one can see several deuteron groups: (a) a first group corresponding to the ground state $(\frac{3}{2}-)$ of C^{11}—this group is clearly more important than the other ones—, (b) at 2.0 Mev corresponding to the first excited level at 2.00 Mev $(\frac{1}{2}-)$, (c) at 4.9 Mev corresponding to the third excited level at 4.81 Mev $(\frac{3}{2}-)$, (d) at about 7.0 Mev corresponding perhaps to the 6.90-Mev level.[8] Beyond there are probably several

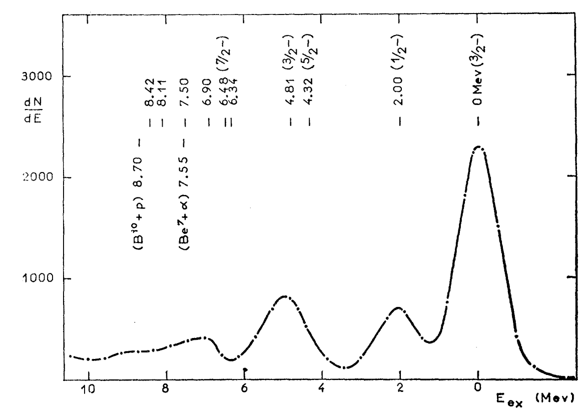

FIG. 1. Energy spectrum of deuterons emitted at 20° (lab) by a carbon target bombarded by 154.5-Mev protons. On abscissa: excitation energy of the residual nucleus C^{11}; on ordinate: arbitrary units. The dashes indicate the known levels of C^{11}.

[1] The characteristics of this spectrometer will be published elsewhere.
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[8] The energies, spins, and parities are taken from A. N. James, A. T. G. Ferguson, and C. M. P. Johnson, Nuclear Phys. **25**, 282 (1961), and S. Hinds and R. Middleton, Proc. Phys. Soc. (London) **78**, 81 (1961).

TABLE I. Excitation energies and relative intensities measured at 20° (lab) at 154.5 Mev, and known characteristics of the levels of C^{11}.

Known energies in Mev, spins, and parities of C^{11} levels[a]	$0(\frac{3}{2}-)$	$2.00(\frac{1}{2}-)$	$4.32(\frac{5}{2}-)$	$4.81(\frac{3}{2}-)$	6.34	$6.48(\frac{7}{2}-)$	$6.90(-)$
Measured excitation energy in Mev	0	2.0 ± 0.1	···	4.9 ± 0.1	···	···	(7.0 ± 0.2)
Relative intensity	1	0.29 ± 0.03	<0.03	0.39 ± 0.03	···	···	(0.16 ± 0.03)

[a] See reference 8.

other unresolved groups which gradually merge in the continuous spectrum.

It is interesting to note that the second excited level at 4.32 Mev ($\frac{5}{2}-$) does not appear in our spectrum: The second and third levels would not be resolved with our present resolution, but the position of the maximum of the peak at 4.9 Mev corresponds very well to the third excited state of C^{11} and the width of the peak is not much larger than that of the ground state. The 4.32-Mev state, if it is excited at all by the (p,d) reaction at 154 Mev, is much less excited than the neighboring states. In the same way the levels at 6.34 and 6.48 Mev do not appear either.

Table I shows the excitation energies of C^{11} taken from our measurements, compared with the known energies, spins, and parities of the C^{11} levels,[8] together with the relative intensities of the various observed deuteron groups.

Austin *et al.* and Clegg *et al.*[9] have also observed, in studying the de-excitation γ rays of the levels of C^{11} excited by the reaction $C^{12}(p,pn)C^{11}$ at 120–150 Mev, that the C^{11} ground state is four times more excited than all the bound states together; this ratio is bigger than ours. On the other hand, they observe an appreciable production of the second level at 4.32 Mev ($J^{\pi}=\frac{5}{2}-$) which we do not observe. This is not surprising because the mechanisms of the (p,pn) and (p,d) reactions are different.

If the C^{11} and C^{12} nuclei can be correctly described by the shell model, the C^{12} ground state corresponding, for instance, to the $1s_{\frac{1}{2}}^4\, 1p_{\frac{3}{2}}^8$ configuration, the states of C^{11} excited by the (p,d) reaction would correspond to a neutron hole in the $p_{\frac{3}{2}}$ shell in consequence of the high momentum that the picked-up neutron must have to be able to form a high-energy deuteron. For an incident proton energy of 154.5 Mev, the probability of finding in the target nucleus a p-shell neutron possessing the right momentum necessary to form a deuteron at 20° is about 6 times larger than the probability of finding an s neutron of the same momentum[10]; also, because of their rather large absorption in nuclear matter, the emitted deuterons have a reduced probability of getting out from the inner part of the nucleus, and this makes still more probable the pickup of a p neutron in carbon.

Consequently, in deuteron pickup at high energy one favors very much the formation of states having a configuration with a hole in the neutron p shell. The levels observed in our measurements should correspond to such a configuration. The states which are not associated with such a hole should not appear, or should appear very weakly, in the deuteron spectrum; this seems to be the case for the second level of 4.32 Mev with an assumed spin and parity of $\frac{5}{2}-$. This is probably also the case for some higher levels, particularly at 6.34 and 6.48 Mev. Excitation of the first-excited state ($\frac{1}{2}-$) presumably means that one cannot use a pure jj coupling model.

This situation should be still more pronounced when the emission angle of the deuterons—and the mean momentum of the picked-up neutron—increases; at larger angles one favors further the pickup of a p-shell neutron over that of an s-shell neutron. The study of the deuteron angular distributions now in progress should bring new informations on the momentum of nucleons in different states and on the configuration of the different levels. Angular distributions of levels with similar configurations should be the same. Second-order mechanisms for the (p,d) reaction do not seem to be necessary to explain our present results.

The (p,d) reaction at this energy seems to allow the selective excitation of certain levels of the residual nucleus and to permit the configurations of the residual nuclear states to be related to the configuration of the target nucleus.

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