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Experimental study of the $^{12}C(^3He, p)^{14}N$ reaction mechanism between 11 and 20 MeV bombarding energy

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The $^{12}C(^3He,p)^{14}N$ reaction mechanism has been studied by measuring the alignment of ^{14}N excited states using a particle-γ angular correlation technique. A collinear geometry has been used with simultaneous particle detection at 0° and 180°. Strong fluctuations of the nuclear alignments, observed between 11 and 20 MeV bombarding energy, reflect a complex reaction mechanism similar to that observed previously at lower energies.

[NUCLEAR REACTIONS $^{12}C(^3He,p\gamma)$, $11 \le E \le 20$ MeV; measured p-γ angular correlations. Deduced nuclear alignments. Comparison with direct interaction and Hauser-Feshbach theories.]

A study of the $^{12}C(^3He,p)^{14}N$ reaction mechanism for bombarding energies between 3 and 11 MeV has been presented in an earlier article,[1] where the p-γ angular correlations were measured at a large number of energies in order to obtain the population parameters of the ^{14}N bound levels. In that work the results indicated the importance of compound nuclear (C.N.) process but also that the cross section for the formation of the ^{14}N levels diminished rapidly with bombarding energy (Fig. 7 of Ref. 1), as predicted by the Hauser-Feshbach statistical model calculations, so that the direct interaction (D.I.) process could become dominant at energies somewhere above 11 MeV. It is the purpose of the present paper to describe experimental results where we have extended the measurements from 11 MeV up to 20 MeV, an energy at which the angular distributions of the proton groups have been fitted assuming a direct interaction mechanism.[2] In this way it was expected that the present study would bridge the region between which the C.N. and D.I. processes predominate.

Experiments have been performed using a ^3He beam delivered by the Strasbourg MP tandem Van de Graaff accelerator. The ^{12}C targets (thickness: 110 $\mu g/cm^3$) were deposited onto Ta, Ag, or Au backings of thicknesses ranging from $\frac{1}{10}$ to $\frac{2}{10}$ mm. These backings were chosen to be thick enough to stop the incident ^3He beam without degrading too much the energy of the protons coming from the $^{12}C(^3He,p)$ reaction and detected at 0°. The angular correlation method in the collinear geometry described by Litherland and Ferguson[3] has been used and the experimental setup was described previously.[1,4] The particles, detected simultaneously at 0° and 180° using two Si solid state detectors (full at 0° and annular at 180°), were observed in coincidence with NaI γ-ray detectors located at 0°, 45°, and 90°. The data corresponding to the six coincidence spectra were recorded on magnetic tape. The angular correlations obtained with only three γ detection angles are sufficient to determine the population parameters. This is due to the fact that the ^{14}N 3.95, 5.10, 5.69, and 6.21 MeV states decay to the $J^\pi = 0^+$ state at 2.31 MeV and so the corresponding transitions have a pure multipolarity. For the 7.03 MeV level, which decays almost completely to the ground state, the corresponding mixing ratio is known with high accuracy.[5]

The measurement of angular correlations can be an excellent tool to study the reaction mechanism, for example, in reactions as $(^6Li,d)$ or $(^7Li,t)$ on spin 0 targets where an alignment of the final nuclei in magnetic substates different from zero indicates directly the contribution of nondirect processes.[6] In other cases, as for example the $^{12}C(^3He,p)^{14}N$ reaction, the magnetic substates $|m| = 0, 1$ can be populated in the used collinear geometry but the corresponding alignments depend strongly on the reaction mechanism.[1] For example, using the Glendenning selections rules[7] for the direct two nucleon transfer reactions, the final levels in ^{14}N of natural parity and $T = 0$ can only be aligned in the $|m| = 1$ substates. This is the case for the $J^\pi = 1^-$ and $J^\pi = 2^+$ levels at 5.69 and 7.03 MeV, respectively. For the other levels, assuming a dominant L transfer value given in Ref. 2, a constant alignment in the $m = 0$ substate should be found [$P(0) = 0.33$ and 0.40 for the $J^\pi = 1^+$ and $J^\pi = 2^-$ levels, respectively]. In the present measurements of particle-γ angular correlations one obtains directly the magnetic substate populations. Therefore this method is a direct test of the reaction mechanism. A similar study was reported by Balamuth, Anastassiou, and Zurmühle[8] for the $^{40}Ca(^{3}He,p\gamma)^{42}Sc$ reaction.

As noted previously,[1] two descriptions of the compound nucleus formation are possible:
(i) The statistical Hauser-Feshbach model, which gives alignments varying very smoothly $[P(0) \simeq 0.5]$ with bombarding energy E_B. This description is supported by the fact that the bombarding energies of the present experiment correspond to an excitation region in ^{15}O from 20.87 to 28.15 MeV where there is a high level density.
(ii) The formation of only one ^{15}O state of a particular configuration (as doorway states for example) which contributes mainly to the formation of the final ^{14}N level at a given E_B. This description can account for the strong fluctuations observed, because the resulting alignments can be very different according to the spin of the intermediate ^{15}O state (see Table II in Ref. 1).

Angular correlations have been measured from 11 to 20 MeV by steps of 1 MeV. At the highest energy, $E_B = 20.1$ MeV, Mangelson, Harvey, and Glendenning[2] have measured and analyzed the angular distributions of all proton groups feeding the ^{14}N bound levels. Our new results are presented on Figs. 1–5 (points with error bars) along with those reported earlier for E_B between 3 and 11 MeV.[1] The parameter $P(0)$ represents the population of the $m = 0$ magnetic substate, i.e., $P(m = 0)$, and is related to $P(|m| = 1)$ through the relation $P(m = 0) + 2P(|m| = 1) = 1$. For the backward direction ($\theta_p = 180°$) it was not possible to extract the angular correlations at 19.0 and 20.1 MeV for experimental reasons, but at these energies the forward points are the most important. On each figure the direct interaction (D.I.) prediction is also indicated. For the unnatural parity levels this prediction corresponds to the predominant L character reported by Mangelson *et al.*,[2] i.e., $L = 0$ for the $J^{\pi} = 1^{+}$ levels at 3.95 and 6.21 MeV (Figs. 1 and 4) and $L = 1$ for the $J^{\pi} = 2^{-}$ level at 5.10 MeV. For the natural parity levels, $J^{\pi} = 1^{-}$ at 5.69 and $J^{\pi} = 2^{+}$ at 7.03 MeV only $L = 1$ and $L = 2$ transfers, respectively, are possible.

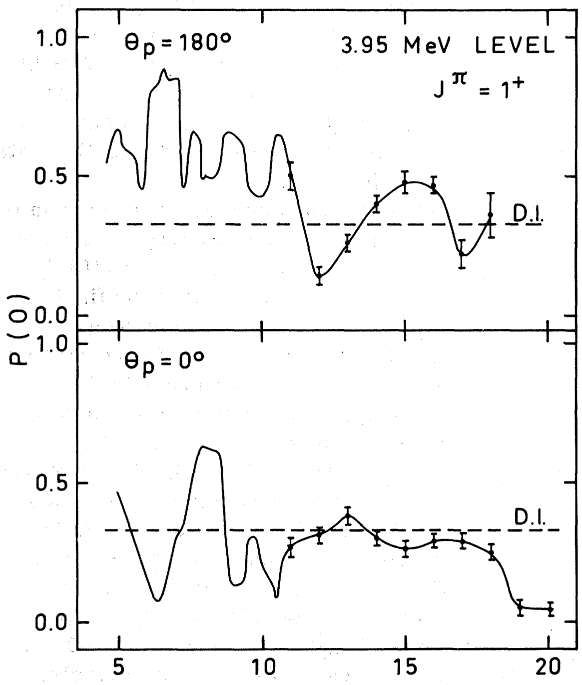

FIG. 1. Experimental variations of the alignment of the 3.95 MeV level, in the magnetic substate $m = 0$, as a function of incident energy for $\theta_p = 180$ and 0°. The theoretical prediction of the direct interaction (D.I.) theory is also shown. The lines are only a guide to the eyes.

The large variations of the different nuclear alignments (Figs. 1–5) observed previously for $E_B < 11$ MeV are still present at higher energies and remain important up to $E_B = 20$ MeV. At the same time no evident correlation is observed between the alignment fluctuations in the backward and the forward directions. This could be under-

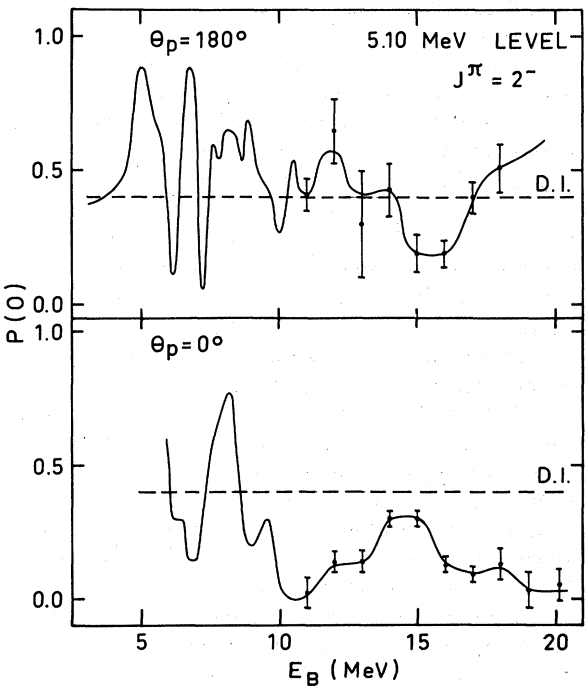

FIG. 2. Variations of the alignment of the 5.10 MeV level.

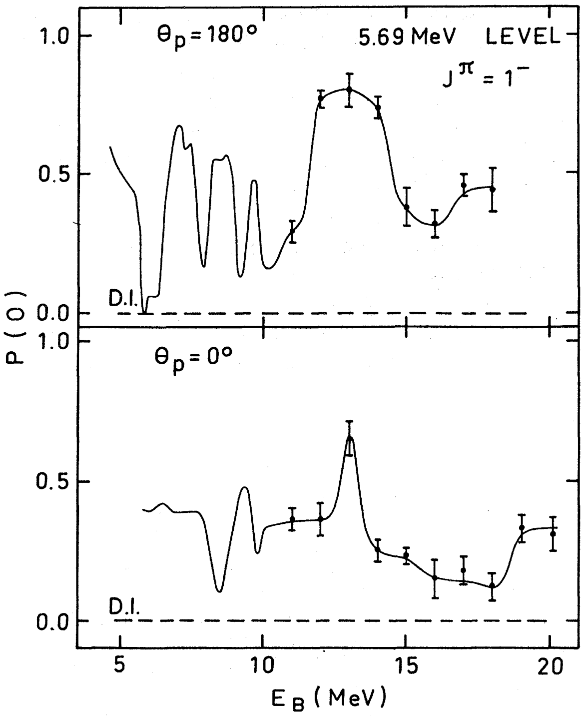

FIG. 3. Variations of the alignment of the 5.69 MeV level.

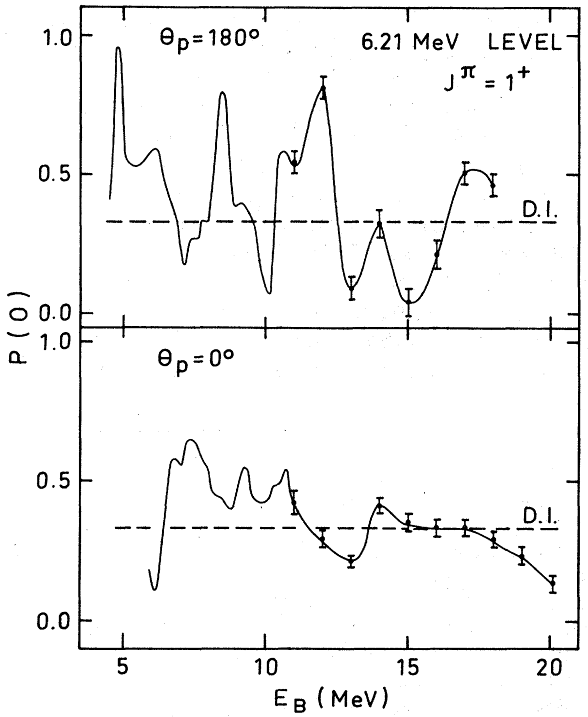

FIG. 4. Variations of the alignment of the 6.21 MeV level.

stood if the direct interaction dominates at $\theta_p = 0°$ which seems to be, for example, the case for the 7.03 MeV level, totally aligned in the $|m| = 1$ substates for $E_B \geqslant 13$ MeV (Fig. 5). In contrast, the results for the 6.21 MeV level diverge from the D.I. predictions for $E_B \geqslant 18$ MeV and $\theta_p = 0°$ (Fig. 4) though it has a dominant (*sd*) configuration.

The presence of a resonance near $E_B = 17$ MeV has been observed at backward angles by Fortune *et al.*[9] and McEver *et al.*[10] in the $^{12}C(^3He, ^3He_0)^{12}C$ study. This can be related to the alignment changes observed for the five studied levels at $\theta_p = 180°$ and $E_B = 17$ MeV. Around $E_B = 20$ MeV, McEver *et al.*[10] have reported another structure in the excitation function of the elastic scattering; near this energy we measured at $\theta_p = 0°$ alignments diverging strongly from the D.I. prediction, except for the 7.03 MeV state. As we have suggested before,[1] these observations confirm the argumentation in favor of the presence of quasigiant resonances in ^{15}O.

From the particle angular distributions reported in the literature for the $^{12}C(^3He, p)^{14}N$ reaction by Sokol *et al.*,[11] Duray and Browne,[12] Holbrow, Middleton, and Focht[13] and Mangelson *et al.*[2] for $11 < E_B < 21$ MeV, it is difficult to extract precise information on the reaction mechanism. For example, nearly symmetric distributions around 90° are obtained for the 7.03 MeV level at $E_B = 10.5$,[1] 12,[12] and 20.1 MeV,[2] whereas very different alignments

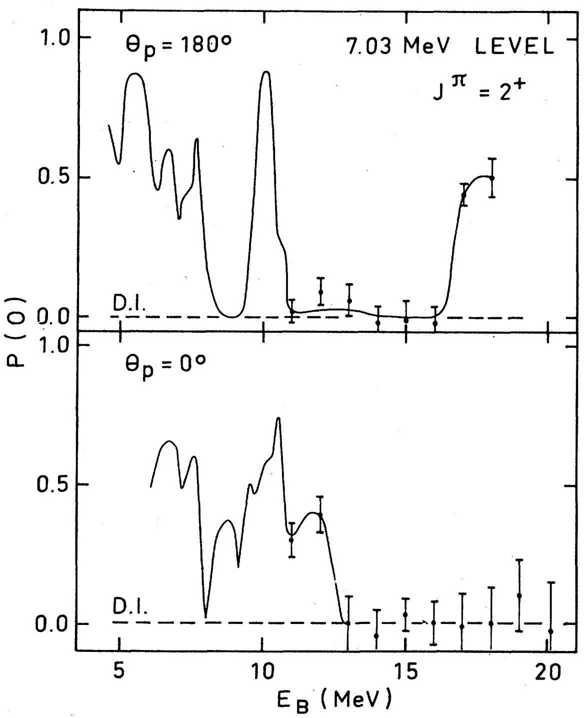

FIG. 5. Variations of the alignment of the 7.03 MeV level.

are measured at $\theta_p = 0°$. Backward peaking can be due to exchange phenomena but if such direct processes are dominant one would expect a nearly constant or slowly varying alignment also at $\theta_p = 180°$. In a recent work, Noé, Balamuth, and Zurmühle[14] have studied ^{14}N unbound levels between 8 and 10 MeV excitation in ^{14}N at $E_B = 12.0$, 13.5, and 14 MeV: though no systematic study of the alignment versus E_B has been done, it is interesting to notice that only for the $T = 1$ unbound states of ^{14}N at 8.91, 9.17, and 10.43 MeV the complete alignment in the $m = 0$ substate is in agreement with the D.I. predictions. This can be an indication that the direct transfer of a quasideuteron ($S = 0, T = 1$) is more favorable than for a deuteron ($S = 1, T = 0$).

Though we have extended our study of the $^{12}C(^3He,p)^{14}N$ reaction up to bombarding energies greater than 20 MeV, where direct processes are expected to become dominant, no simple conclusions emerge from our experimental findings. The population parameter $P(0)$ behaves in a similar way to that found at lower bombarding energies, and this is interpreted as the continuing importance of the compound nucleus formation even up to the highest energies studied here.

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