Compound System Formation at $E_{c.m.}$=36 MeV in $^{14}N + ^{12}C \rightarrow ^{6}Li + ^{20}Ne$

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Angular distributions of ^{6}Li produced in the reaction $^{14}N + ^{12}C \rightarrow ^{6}Li + ^{20}Ne$ have been measured at a center-of-mass energy of 36 MeV. Data were taken for the reactions $^{12}C(^{14}N, ^{6}Li)^{20}Ne$ and $^{14}N(^{12}C, ^{6}Li)^{20}Ne$ in order to cover the complete angular range ($16° \leq \theta_{c.m.} \leq 165°$). The angular distributions are symmetric about $\theta_{c.m.}=90°$ and closely follow a $(\sin\theta)^{-1}$ dependence. This is interpreted as indicating that the reaction proceeds primarily through compound-nucleus formation.

Recent experiments[1,2] indicate that many heavy-ion reactions proceed through a compound-nuclear shape resonance or quasimolecular state at relatively high excitation energies. The main evidence for such compound processes is the correlated resonancelike structure in the elastic scattering and reaction excitation functions. On the other hand a large number of similar reactions have been interpreted as proceeding via direct or semidirect transfer of one of more nucleons. (See, for example, Scott *et al.*[3] and Middleton, Garrett, and Fortune.[4]) These reactions are characterized by forward-peaked differential cross sections and by a selectivity in populating final states.

Previous reports[5,6] on the reaction $^{12}C(^{14}N, ^{6}Li)^{20}Ne$ have been interpreted in terms of the direct transfer of eight nucleons which were assumed to be coupled into quartet configurations. Marquardt, Von Oertzen, and Walter[5] have reported angular distribution for six transitions in the angular range $10° \leq \theta_{c.m.} \leq 70°$ at a ^{14}N bombarding energy of 52 MeV.

In order to obtain information on the reaction mechanism involved in the reaction $^{14}N + ^{12}C \rightarrow ^{6}Li + ^{20}Ne$, we have measured angular distributions of the ^{6}Li reaction products covering the entire angular range from $16° \leq \theta_{c.m.} \leq 165°$. The observations were made at the backward angles by exchanging the roles of projectile and target. This procedure allows one to overcome the severe experimental problem normally encountered in measuring differential cross sections over a wide angular range using a single target and incident beam of approximately equal masses.

Beams of 76.1-MeV ^{14}N and 67.2-MeV ^{12}C from the Harwell variable-energy cyclotron were used to bombard targets of ^{12}C and ^{14}N, respectively. This corresponds to a center-of-mass energy of about 36 MeV and a compound-nucleus excitation in ^{26}Al of 51 MeV. The ^{6}Li reaction particles were detected using a double E-ΔE particle identification system.[3]

Spectra were measured at seven angles. The

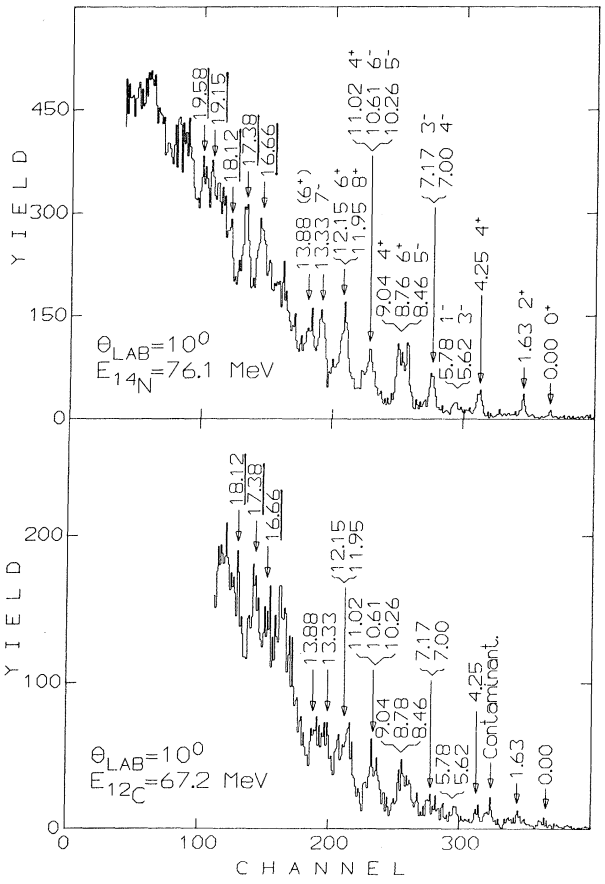

FIG. 1. Spectra for the reaction $^{14}N + ^{12}C \rightarrow ^{6}Li + ^{20}Ne$ at $E_{c.m.}=36$ MeV. The excitation energies (in MeV) and the spin and parity assignments, except for the underlined energy values, are adopted from those reported in Ref. 7. Levels identified by underlined energies may correspond with previously reported levels (Ref. 7).

scattering angle θ is here defined as the angle between the ^{14}N direction of motion and that of the outgoing ^{6}Li, i.e., for $^{12}C(^{14}N, ^{6}Li)^{20}Ne$ a forward laboratory angle for the detected ^{6}Li corresponds to a forward center-of-mass angle. For the case of ^{14}N incident on ^{12}C, data at $\theta_{lab} = 10°$, 15°, 20°, and 35° were obtained using a solid carbon target and at $\theta_{lab} = 10°$ using a thin-window gas cell containing CH_4 gas at 96 Torr pressure. The data for ^{12}C incident on ^{14}N were taken at $\theta_{lab} = 10°$, 20°, and 30° using the gas cell filled with N_2 gas at 90 Torr pressure.

In Fig. 1 the spectra at $\theta_{lab} = 10°$ for the reactions $^{12}C(^{14}N, ^{6}Li)^{20}Ne$ and $^{14}N(^{12}C, ^{6}Li)^{20}Ne$ are compared. Levels up to an excitation of 19.6 MeV are identified. The results are in good agreement with previously reported spectra at $E(^{14}N) = 60$ MeV[6] and $E(^{14}N) = 52$ MeV.[5] Also of particular interest in the present spectra are the strong states at 16.66, 17.38, 18.12, 19.15, and 19.58 MeV. These states may correspond to those quoted in Ref. 7.

The angular distributions for twelve ^{6}Li groups are shown in Fig. 2. The overall relative cross section for all the runs is correct to better than ±15%, and the absolute scale, established by the gas target run, is accurate to about ±30%. The error bars on the data arise from statistics and background only.

The following observations were made: (1) All the angular distributions appear to be symmetric about 90°. (2) All the transitions appear to be very similar in shape even though they populate states with spins ranging from 0 to 8. The data at this bombarding energy are also in good agreement with the approximate $2J+1$ strength rule

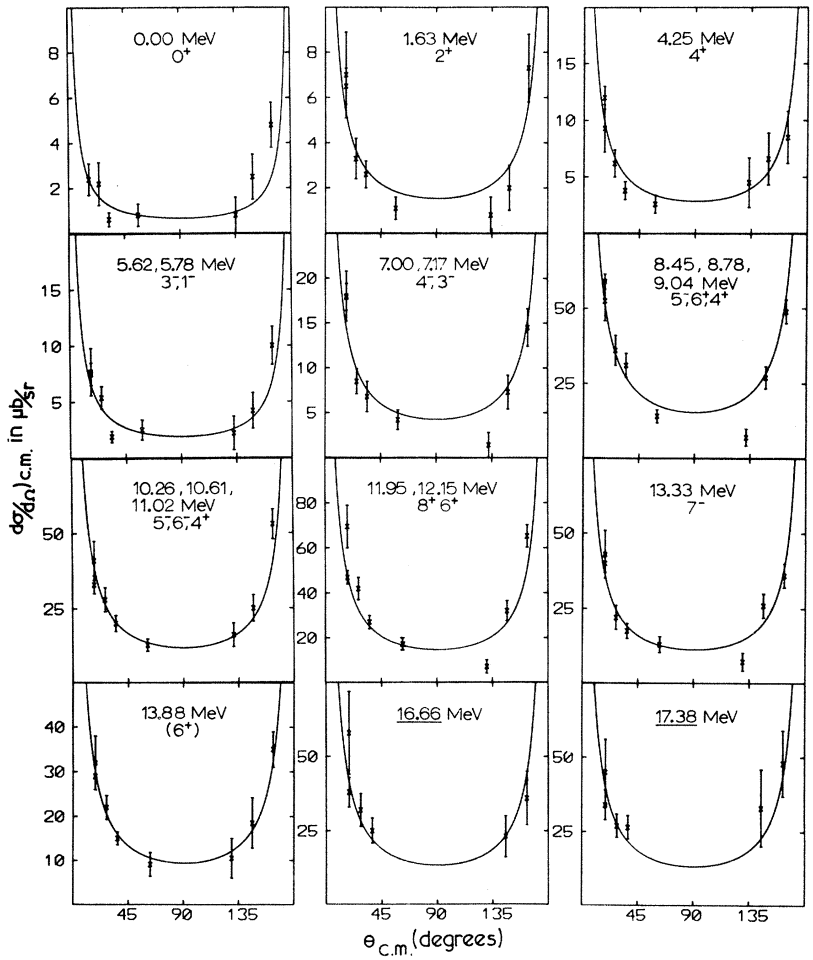

FIG. 2. Angular distributions for the reaction $^{14}N + ^{12}C \rightarrow ^{6}Li + ^{20}Ne$. Several of the angular distributions correspond to unresolved or partly resolved multiplets as indicated. The solid curves are $(\sin\theta)^{-1}$ fits. The energy and spin values are adopted from Ref. 7, except for the 16.66 and 17.38 transitions whose energies were determined in this work.

reported at the bombarding energy of 60 MeV.[6] (3) The present data are only in rough agreement with the shapes reported for $E(^{14}N) = 52$ MeV.[5]

Generally, it has been assumed[5] that this reaction is dominated by direct eight-nucleon transfer in this region of bombarding energy. It was then expected that the shapes of the angular distributions would be forward peaked since the amplitude for direct transfer of eight nucleons from ^{14}N on to ^{12}C should be large for forward angles whereas the amplitude for six-nucleon transfer from ^{12}C on to ^{14}N is expected to be smaller and backward peaked (recall the definition of θ).

However, as pointed out above, within normalization and statistical uncertainties, it was observed that all the angular distributions are symmetric about 90°. These observations strongly suggest that this reaction proceeds via compound nuclear excitation. To test this assumption further the angular distributions were compared with the predicted compound excitation shape[8] for decay with large angular momenta averaged over many values of L, namely $\sigma_c \sim (\sin\theta)^{-1}$. Excellent overall agreement was found between the data and this simple theoretical angular dependence.

One of the arguments used in the earlier work[6] for suggesting a direct mechanism was the apparent selectivity in exciting different bands. Within statistics, however, we observe an approximate $2J+1$ population of all states. In particular, the population of the SU(3) (9, 0) $K = 0^-$ band, based on the 5.78 MeV, 1^- level, does not appear to be anomalously weak. The best evidence for this is the strength of the 5^- member of the band at 10.26 MeV as deduced from a peak analysis of the triplet of states at 10.26, 10.61, and 11.05 MeV.

Data at higher bombarding energies, $E(^{14}N) = 120$ MeV and $E(^{12}C) = 114$ MeV, were also obtained to see if the reaction changes character at increasing energies. A more selective population of states would be consistent with an increasing direct transfer contribution. It was found, however, see Fig. 3, that the spectra were almost structureless and only a few transitions at most could be identified. At these energies the grazing angular momentum for the entrance channel is about $l \cong 28\hbar$ whereas the exit channel, with ^{20}Ne in its ground state, carries off only about $22\hbar$. This rather large momentum mismatch may be responsible for the very small cross-section observed below 15 MeV excitation.[9] At higher excitation the angular-momentum transfer

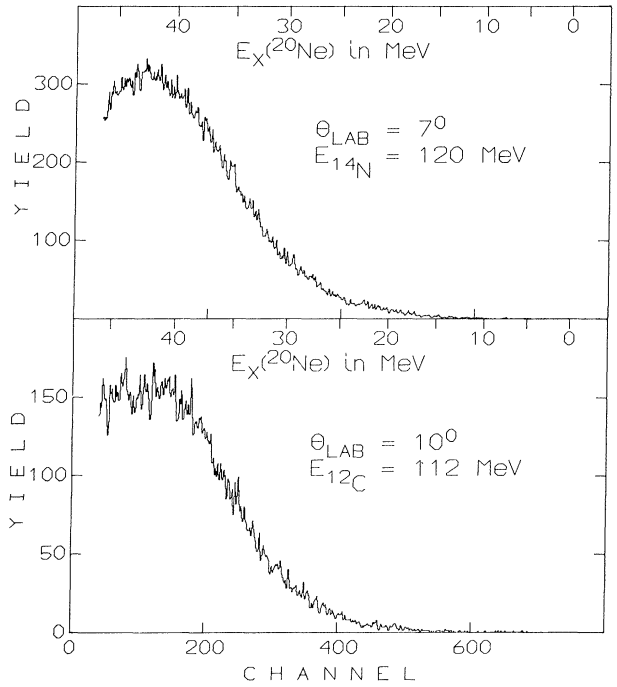

FIG. 3. Spectra for $^{14}N + ^{12}C \rightarrow ^{6}Li + ^{20}Ne$ at high bombarding energies. The small selectivity of this reaction for high bombarding energy should be compared with the results shown in Fig. 1. Although there is evidence for states even at high excitation, few levels could be unambiguously identified.

is more favorable, but the three-body breakup becomes progressively more pronounced and obscures any possible excitation. Furthermore, the density of high-spin states ($J = 10, 11, 12$) becomes very large (about 10 levels/MeV for $J = 11$ and 12 at 30 MeV excitation),[10] and because of our limited resolution, 430 keV full width at half-maximum, individual levels cannot be resolved. It is, therefore, difficult with the present data to make any quantitative argument regarding the reaction mechanism at the high incident energies.

The present experimental results indicate that the reaction $^{12}C(^{14}N, ^{6}Li)^{20}Ne$ proceeds through the compound system having 51 MeV of excitation in contradiction to the previous assumption that this reaction proceeds by direct eight-nucleon transfer. At present one can only speculate on the structure of such a high lying state in the compound system. Since, however, at the incident energy of this experiment, the grazing angular momentum is about $21\hbar$, it is likely that the compound system has high angular momentum. The lowest energy for an angular momentum state of $21\hbar$ in the compound nucleus ^{26}Al can be calculat-

ed from the expression for the yrast energy,[11] $E_J = (\hbar^2/2\mathcal{I})J(J+1)$, where $\mathcal{I}$ is the rigid body moment of inertia; E_J is found to be approximately 70 MeV. From this consideration one expects compound nuclear formation involving such high angular momenta to be inhibited. In fact calculations show that 21 units of angular momentum is greater than the compound nucleus ^{26}Al can support.[12] The compound system may therefore result from a temporary fusion of the ions in the incident channel.

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Measurements of the Quadrupole Moments of the First 2^+ States of ^{150}Sm and ^{194}Pt by the Reorientation Precession Technique

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We have observed the influence of the nuclear quadrupole moment on the γ-ray angular correlation following Coulomb excitation by heavy ions scattered through angles of about 90°. A prolate quadrupole moment precesses the γ-particle correlation in the opposite direction to that produced by a moment of oblate shape. The method has been applied to the first 2^+ states of ^{150}Sm and ^{194}Pt, which are found to be prolate, $Q = -1.25 \pm 0.2$ b, and oblate, $Q = +0.77 \pm 0.5$ b, respectively.

The rapidly growing body of data on static quadrupole moments Q of first 2^+ levels in even nuclei continues to have considerable impact on our understanding of these highly collective states which extend throughout the periodic table and include the closed shells. A number of recent articles review the theoretical and experimental situation.[1,2] The various techniques so far used measure the differential cross section for Coulomb excitation in such a manner that the diagonal quadrupole matrix element—a second-order effect—can be deduced from the data. Breit,