Observation of ^{12}C cluster transfer by angular correlation measurements

R. W. Zurmühle, Z. Liu, D. R. Benton, S. Barrow, N. Wimer, Y. Miao, C. Lee, J. T. Murgatroyd,* and X. Li
Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania 19104-6396

V. Z. Goldberg and M. S. Golovkov
I. V. Kurchatov Institute of Atomic Energy, 123182 Moscow, Russia
(Received 18 November 1993)

Angular correlations between deuterons and alphas in the reaction $^{12}C(^{14}N,d)^{24}Mg^*(\alpha)^{20}Ne$(g.s.) at beam energies of 30, 33, 36, and 42 MeV have been used to investigate the reaction mechanism. Evidence for possible ^{12}C cluster transfer to the 13.45 MeV 6^+ state in ^{24}Mg is presented. The transfer of $^{12}C(2^+)$ clusters seems to be the dominant process. In addition to the correlation measurements, deuteron angular distributions were measured at 33 and 42 MeV and an excitation function at a lab angle of 8° was obtained between 30 MeV and 45 MeV in 3 MeV steps. The angular correlations, deuteron angular distributions, and the excitation function were fitted using the finite range distorted wave Born approximation (FRDWBA) and the Hauser-Feshbach formalism of compound nucleus formation.

PACS number(s): 25.70.Hi, 25.70.Gh, 24.60.Dr

I. INTRODUCTION

It has long been generally accepted that compound nucleus formation [1,2] is the dominant reaction mechanism in heavy-ion reactions which involve the rearrangement of many nucleons, such as in the $^{12}C(^{14}N,d)$ reaction [3–6], even though some possible multinucleon transfers were proposed [7]. Angular distribution and excitation function measurements were used to obtain various nuclear parameters, such as nuclear temperature, level density, critical angular momenta, etc., in the framework of the Hauser-Feshbach model. However, it has been shown by Artemov *et al.* [8] that angular distributions of multinucleon transfer reactions are rather insensitive to the reaction mechanism (statistical and direct reaction models) and therefore such studies may be of limited use in distinguishing between them. Angular correlation techniques [9] have previously been used to study 12 nucleon transfer to the 13.45 MeV 6^+ state of ^{24}Mg in the $^{12}C+^{14}N$ system [10,11], but conflicting conclusions about the reaction mechanism were arrived at in these two experiments. Representatives from the two groups collaborated on the current work, and a consensus has been reached.

If the deuterons in the reaction $^{12}C(^{14}N,d)^{24}Mg$ are detected at 0° with respect to the beam axis and the ^{24}Mg nucleus decays to spin zero fission fragments, then the projections of all orbital angular momenta along the beam direction vanish and the spin projection of the residual ^{24}Mg can only assume the values $m = 0, \pm 1$, and ± 2. The population parameters $p(m)$ can be determined experimentally by studying the decay of ^{24}Mg into the spinless α nucleus and the ground state of ^{20}Ne, which accounts for roughly 25% of the total decay strength. Compound nucleus formation and $^{12}C(2^+)$ cluster transfer can populate all these magnetic substates while in the ^{12}C(g.s.) cluster transfer only the $m = 0$ substate can be populated (under the assumption that the rather weak spin-orbit interaction is negligible). For compound nucleus formation, the population of spin projections can be calculated from the Hauser-Feshbach formalism [12]. Recent calculations [13] of compound nucleus formation using the Hauser-Feshbach formalism with various couplings of spins have generated results that depend only slightly on the choice of model parameters as well as the incident beam energy, with $p(0)$:$p(1)$:$p(2) \approx$ 0.4:0.4:0.2. Contributions from a direct ^{12}C(g.s.) transfer would increase the $p(0)$ population parameter. The population parameters for $^{12}C(2^+)$ transfer are calculated within the framework of the finite range distorted wave Born approximation (FRDWBA) [14,15] (see Sec. III). These calculations show that for $^{12}C(2^+)$ direct transfer the values of $p(m)$ have substantial dependence on the ^{14}N beam energy if more than one value of the orbital angular momentum contributes. This kind of behavior has been observed in our recent measurements, and it is in sharp contrast to that of compound nucleus formation and to direct ^{12}C(g.s.) transfer, where the values of $p(m)$ are stable over a wide range of the beam energy. Angular correlation measurements are therefore a powerful tool in distinguishing between these reaction mechanisms.

II. EXPERIMENT

One of the greatest difficulties in a correlation experiment using a heavy-ion reaction is to obtain coincidence data with adequate statistics for a process with a small cross section, with the additional constraint of having

*Current address: Wayne State University, Detroit, MI 48202.

to use a thin target to obtain good energy resolution for the observed particles. In our correlation measurements of the $^{12}C(^{14}N,d)^{24}Mg$ reaction, a 30 $\mu g/cm^2$ self-supporting ^{12}C target was bombarded with ^{14}N beams of 30, 33, 36, and 42 MeV from the University of Pennsylvania Tandem Van de Graaff Accelerator. The deuterons at 0° were momentum analyzed in a double focusing magnetic spectrometer with an acceptance angle of ±3.5° in the horizontal plane and ±1.8° in the vertical plane. They were detected with a 10 cm×2.5 cm double sided position sensitive silicon detector placed in the focal plane which was covered with a 42 mg/cm^2 Ta foil to stop beam particles that otherwise may strike the detector. The magnetic spectrometer was also used to measure deuteron angular distributions at 33 and 42 MeV from $\theta_{lab} = 0°$ to 24° in 4° steps and the excitation function from 30 to 45 MeV in 3 MeV steps for $\theta_{lab} = 8°$. The momentum analyzed particles were identified by their energy and position on the focal plane detector, which was related to the excitation energy of the residual ^{24}Mg nucleus. Examples of energy and position spectra for the spectrometer centered at 0° are shown in Figs. 1 and 2, respectively.

The α particles from the decay $^{24}Mg \to ^{20}Ne+\alpha$ were detected by two 5 cm×1.7 cm silicon detectors, each divided into 25 strips, one on either side of the beam. To extend the measurements to smaller angles, the target was moved from the center of the scattering chamber to a position 5 cm upstream along the beam direction. The total angle coverage of the position sensitive detectors extended from laboratory angles of 8.5° to 70° (13° to 120° in the center of mass for the 33 MeV beam energy). At the small angle setting, the α detectors were covered with a 9 mg/cm^2 Ni foil at 33 MeV and a 10.7 mg/cm^2 Ni foil at 42 MeV to stop elastically scattered beam particles. The relative solid angles of the strips of the α detector were determined from a calibration with an α source placed in the two target positions. The average angle was calculated for each strip. Because of the rectangular shape of the strips, this average angle is somewhat larger than the center angle of a strip in the reaction plane. This correction varies between 0° and 2° from the largest to the smallest angle. Random coincidences were typically at a level of less than 10% of the counts in the 13.45 MeV 6^+ peak, and the d-α angular correlation was calculated for the background on one side of the peak and subtracted from the d-α angular correlation for the 13.45 MeV 6^+ peak.

For some recent runs, an annular detector subdivided into ten segments was provided by the Kurchatov Institute of Atomic Energy of Russia. Each annulus had a width of 2 mm and was separated from adjacent segments with 1 mm wide inactive masks. The annular detector covered an angle range from 4.6° to 19.3° in the labo-

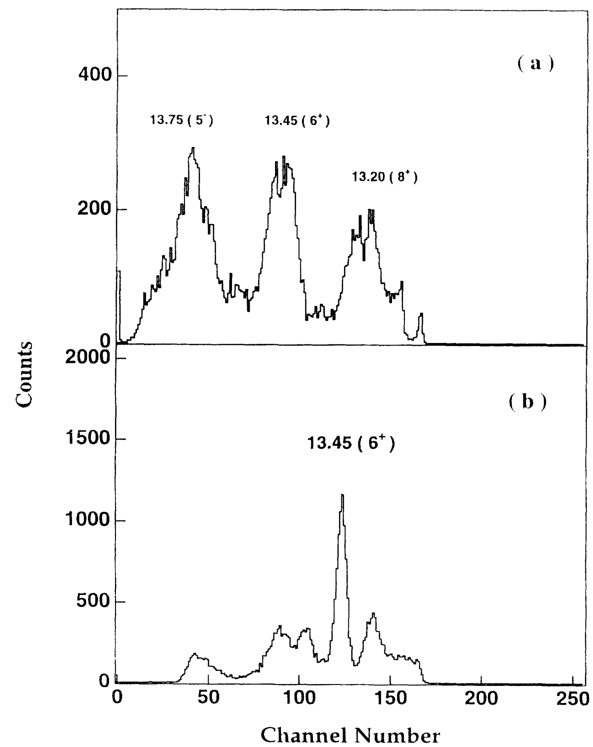

FIG. 2. Position spectra for deuterons from the position sensitive detector in the focal plane of the magnetic spectrometer in coincidence with α particles for beam energies of (a) 33 MeV and (b) 42 MeV. The peaks are labeled with their excitation energy in MeV and with J^π values of known states in ^{24}Mg.

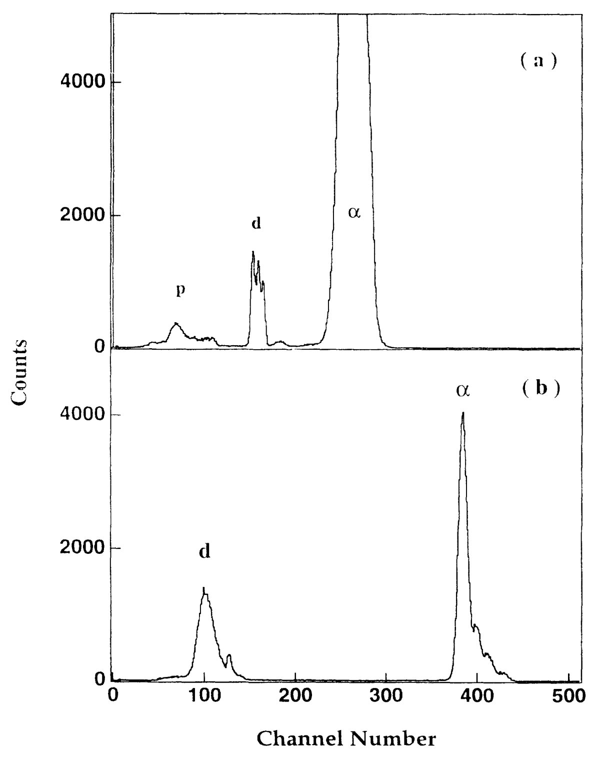

FIG. 1. Energy spectra from the position sensitive detector in the focal plane of the magnetic spectrometer at 0° for $^{12}C+^{14}N$ at beam energies of (a) 33 MeV and (b) 42 MeV. The peaks are labeled by particle types. For a beam energy of 33 MeV, the deuterons are fully stopped in the detector, while at 42 MeV they are not fully stopped, which accounts for the shift to the left in the deuteron energy between 33 and 42 MeV.

ratory system (from 7° to 34° in the center of mass for 33 MeV) and had a solid angle 2–3 times larger than the rectangular position sensitive detector. It was used to obtain small-angle correlation data at beam energies of 30, 33, 36, and 42 MeV.

A great deal of attention has been paid to the ability of the experimental setup to detect $l = 6$ minima in the angular correlations. The entire apparatus was subjected to a test experiment. The ^{12}C(^{12}C,α)^{20}Ne(6^+,excitation energy=8.78 MeV) reaction was used for this purpose. The α decay for this state is pure $l = 6$, $m = 0$. An extremely thin ^{12}C target was used to minimize contamination from known nearby levels. The measured angular correlation was best fit using the Legendre polynomials $l = 6$ and 1 with 97% $l = 6$ and 3% $l = 1$, which suggests that amplitude attenuation is not a major effect. For each strip in the position sensitive detector, the range of the center of mass angle varied by up to a few degrees from the average value. This variation is very small compared to the angular size of the oscillations in the angular correlation for any $l = 6$ spherical harmonic, and therefore folding of the calculated cross sections was not necessary. As is discussed in Ref. [11], the deuteron has a low center of mass energy and angular momentum, at most $l = 4$. For such low spins, the correction for deuterons slightly off 0° is negligible.

III. FINITE RANGE DWBA CALCULATIONS

A total of eight angular correlations in the FRDWBA formalism were calculated using the computer code DWUCK5 [16], one for each of the possible angular momentum configurations of the direct ^{12}C transfer relevant to the current work. Two states of the transferred ^{12}C nucleus were considered: the ^{12}C ground state ^{12}C(g.s.) and the lowest lying 2^+ state ^{12}C(2^+).

In the transfer of ^{12}C(g.s.), the orbital angular momentum of the ^{12}C(g.s.)$\otimes^{12}$C(g.s.) cluster is $l = 6$, while for the ^{12}C(2^+) transfer the orbital momentum can take one of three values, $l = 4, 6, 8$, which yields a total of four combinations of the intrinsic ^{12}C spin and the orbital angular momentum. For each of these four combinations, the angular correlation was calculated for the two configurations of the ^{12}C and deuteron coupling in the ^{14}N projectile: $L = 0$ and 2 relative orbital momentum. The strengths of the two relative orbital momentum states were taken from Cohen-Kurath two-particle coefficients of fractional parentage (CFPs) [17] and were 0.596:−0.122 for ^{12}C(g.s.)$\otimes d$, and 0.389:0.807 for ^{12}C(2^+) $\otimes$ d for (L = 0, 2), respectively. The final angular correlation is an incoherent sum of all different l transfers for the two ^{12}C clusters.

The structure of the J=6^+ state in ^{24}Mg at 13.45 MeV of excitation is not well known, and therefore the relative strength of ^{12}C(g.s.)$\otimes^{12}$C(g.s.) and ^{12}C(g.s.)$\otimes^{12}$C(2^+) was left as an adjustable parameter.

Optical model parameters used in the calculations are listed in Table I. An upper limit of integration length, $R_{\max} = 15$ fm, and a maximum number of partial waves, $L_{\max} = 25$, were used. The optical model parameters were based on calculations done in Refs. [1,3,4], but the well depths were modified slightly in the current work.

IV. RESULTS AND DISCUSSION

Angular correlations for the ^{12}C(^{14}N,$d\alpha$)^{20}Ne(g.s.) reaction proceeding through ^{24}Mg*(6^+, 13.45 MeV) as the intermediate state, for deuterons measured at 0°, are shown in Fig. 3 for two beam energies. Fits indicated in the figure are incoherent sums of spherical harmonics,

$$\frac{d\sigma}{d\Omega} = \mathbf{P}(0)|\mathbf{Y}_6^0|^2 + \mathbf{P}(1)|\mathbf{Y}_6^1|^2 + \mathbf{P}(2)|\mathbf{Y}_6^2|^2.$$

The experimental population parameters are obtained from best-fit matrix inversions. The experiment shows different behavior for the two beam energies of 33 and 42 MeV. This difference is reflected in the population parameters for the best fits which are summarized in Table II. Also plotted in Table II are the calculated population parameters for direct ^{12}C(2^+) transfer and for compound nucleus formation (see below). Forward angle data were obtained with the annular detector at two additional beam energies, 30 and 36 MeV. They are shown together with best fits in Fig. 4. They also support the observation that the shape of the correlation is changing rapidly as a function of beam energy.

The statistical model substate population parameters are taken from calculations which were published in Ref. [8]. These calculations cannot reproduce such rapid changes with beam energy. In order to explore the ability of FRDWBA calculations to reproduce such a strong energy dependence of the population parameters and angular correlations, we have performed calculations at six different beam energies in 3 MeV steps between 30 and 45 MeV. We simplified the calculations by only including the transfer of ^{12}C(2^+) clusters and neglecting the contributions from ^{12}C(g.s.) cluster transfer. Justification for this approximation comes from the fact that in the ground state wave function of ^{14}N the configuration ^{12}C(2^+)$\otimes d$ is about 10 times more probable than that of

TABLE I. Optical model parameters applied in the calculations. $R = R_0 A_1^{1/3}$ for ^{24}Mg+d and ^{12}C+d; $R = R_0(A_1^{1/3} + A_2^{1/3})$ for ^{12}C+^{14}N and ^{12}C+^{12}C.

Channel	V (MeV)	R_{0R} (fm)	a_R (fm)	W (MeV)	R_{0I} (fm)	a_I (fm)	R_{0C} (fm)
^{12}C+^{14}N	100	1.19	0.48	27.4	1.26	0.26	1.24
^{24}Mg+d	109.5	1.35	0.86	7	1.45	0.681	1.4
^{12}C+^{12}C	*	1.17	0.75	0			1.4
^{12}C+d	*	2.18	0.825	0			1.4

TABLE II. Population parameters from different fits for d-α angular correlation function.

$P(m)$	Best fit 33 MeV	Best fit 42 MeV	FRDWBA 33 MeV	FRDWBA 42 MeV	Statistical model 33 MeV	Statistical model 42 MeV
$P(0)$	0.47±0.04	0.19±0.04	0.33	0.38	0.39	0.39
$P(1)$	0.26±0.02	0.55±0.02	0.26	0.46	0.36	0.36
$P(2)$	0.26±0.03	0.26±0.04	0.41	0.16	0.25	0.25
χ^2	3.27	1.15				

^{12}C(g.s.)$\otimes d$, as well as that the magnetic substate population parameter $P(0)$ is below the compound nucleus value at 42 MeV, which suggests a weak contribution from ^{12}C(g.s.) transfer. The results of the calculations are shown in Fig. 5 and summarized in Table III (the results for 33 and 42 MeV have been included in Table II under the column labeled "FRDWBA"). The qualitative changes in the angular correlation as a function of beam energy are well reproduced by these calculations. The fact that FRDWBA calculations can reproduce these changes while the statistical model is unable to do so constitutes strong evidence for the importance of the direct process in this reaction.

Figure 6 shows the cross section measurements for the ^{12}C(^{14}N,d)^{24}Mg reaction for beam energies from 30 to 45 MeV for θ_{lab}(deuteron) of 8°. Our setup was not ideally suited for this measurement because the Faraday cup for beam charge integration had to be placed inside the rather small scattering chamber and it was therefore too small to assure complete charge collection. The 10–15 % errors are mainly due to uncertainties in the integrated beam intensity. The solid curve is a FRDWBA calculation, again neglecting the transfer of a ^{12}C cluster in the ground state. The calculated cross sections are extremely sensitive to the depth of the imaginary potential. A decrease in the depth of the imaginary potential for entrance and exit channels of a few MeV results in an increase of the calculated cross sections of 10–50 times without much influence on the population parameters $p(m)$. Statistical model calculations of the excitation function are also shown in Fig. 6 and give results with an absolute magnitude at least a factor of 10 smaller than the measured cross section and show a rapid falloff above 35 MeV, and they are consistent with previous calculations of the Hauser-Feshbach cross section for this state

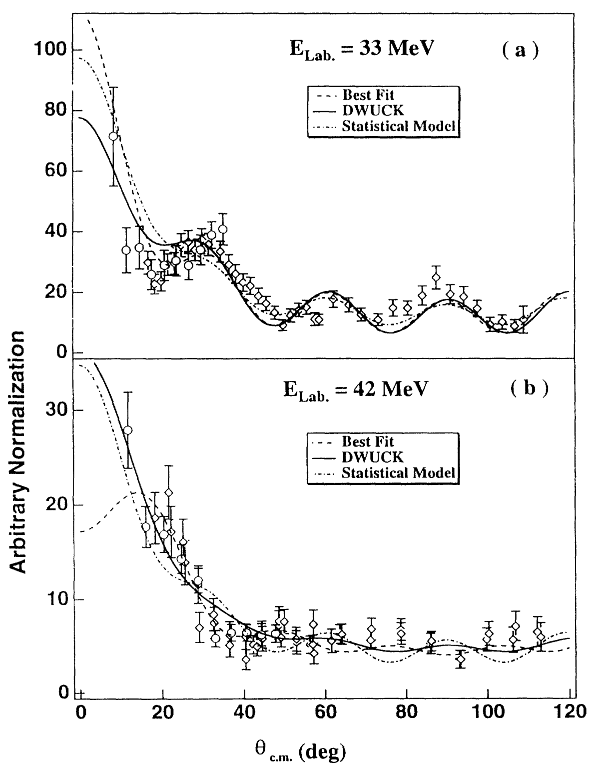

FIG. 3. d-α angular correlations for the ^{12}C(^{14}N,d)^{24}Mg (excitation energy= 13.45 MeV, $J^\pi = 6^+$) reaction at beam energies of (a) 33 MeV and (b) 42 MeV. Curves corresponding to the best-fit, FRDWBA, and statistical model calculations are indicated in the figures. The circle symbol indicates data taken with the annular detector and the diamond data taken with the position sensitive strip detectors.

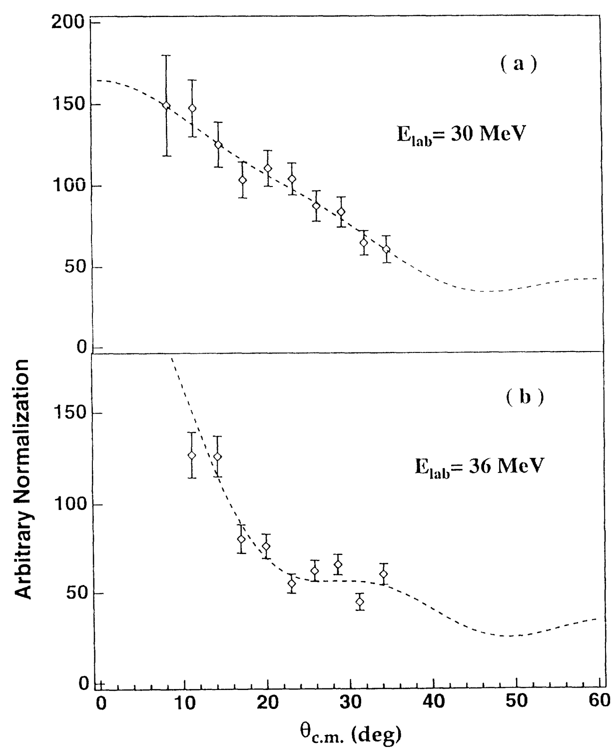

FIG. 4. d-α angular correlations for the ^{12}C(^{14}N,d)^{24}Mg (excitation energy=13.45 MeV, $J^\pi = 6^+$) reaction at beam energies of (a) 30 MeV and (b) 36 MeV. Dashed curves indicate the best fit.

TABLE III. Population parameters from FRDWBA calculations.

$P(m)$	30 MeV	33 MeV	36 MeV	39 MeV	42 MeV	45 MeV
$P(0)$	0.31	0.33	0.37	0.38	0.38	0.34
$P(1)$	0.28	0.26	0.38	0.44	0.46	0.42
$P(2)$	0.41	0.41	0.24	0.18	0.16	0.25

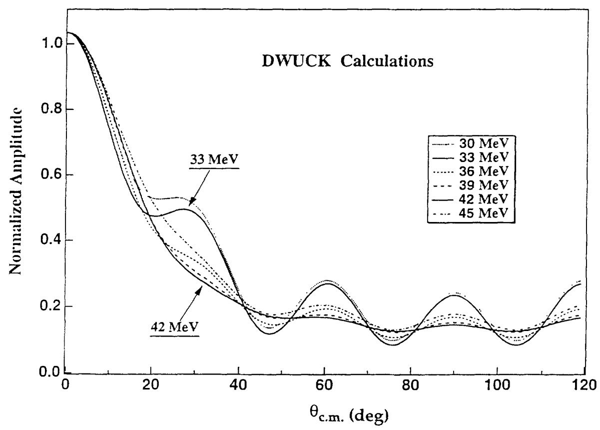

FIG. 5. Angular correlation functions from the DWUCK5 calculations for a ^{12}C(2^+) transfer where l, the orbital angular momentum between the two ^{12}C nuclei in ^{24}Mg, assumes all three possible values, namely, $l = 4, 6, 8$, each with equal strength and without any contribution from ^{12}C(g.s.) transfer. The corresponding population parameters are listed in Table III.

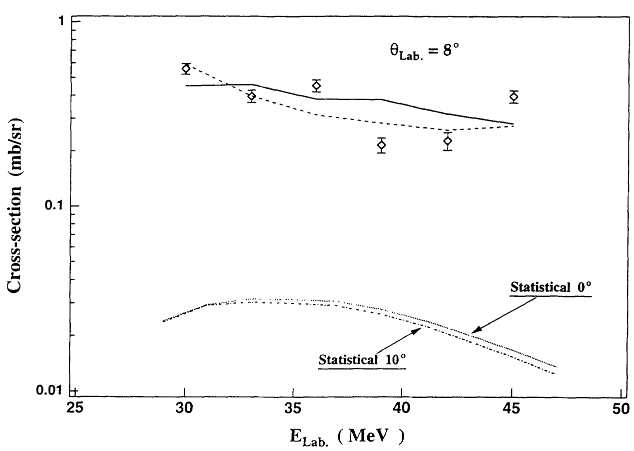

FIG. 6. Excitation function of ^{12}C(^{14}N,d)^{24}Mg (excitation energy=13.45 MeV, $J^\pi = 6^+$) for a fixed deuteron angle of $\theta_{\rm lab} = 8°$. The solid curve is a FRDWBA calculation with pure ^{12}C(2^+) transfer. The dashed curve is a fit using the relative strengths of $l = 4, 6, 8$ for the ^{12}C(2^+) transfer and of $l = 6$ for the ^{12}C(g.s.) transfer as free parameters. The resulting coefficients are 1.68, 1.7, and 0 for $l = 4, 6$, and 8, respectively, and 0 for the ^{12}C(g.s.) transfer. The curves labeled as statistical are the predicted excitation functions for a compound nucleus formation and have cross sections which are roughly an order of magnitude smaller than the experimental values.

in Refs. [3,8].

Deuteron angular distributions measured at 33 and 42 MeV are shown in Fig. 7. Calculations based on the FRDWBA with equal strength of $l = 4, 6, 8$ for ^{12}C(2^+) transfer and without ^{12}C(g.s.) transfer show rather good agreement. Their shapes are rather insensitive to the parameters in our calculations. Statistical model calculations produce angular distributions of similar shape in this angle range.

V. CONCLUSIONS

Our measurements of d-α angular correlations at various beam energies for the 13.45 MeV, 6^+ state of ^{24}Mg provide new evidence for the importance of direct ^{12}C cluster transfer in the ^{12}C(^{14}N,d)^{24}Mg reaction. There

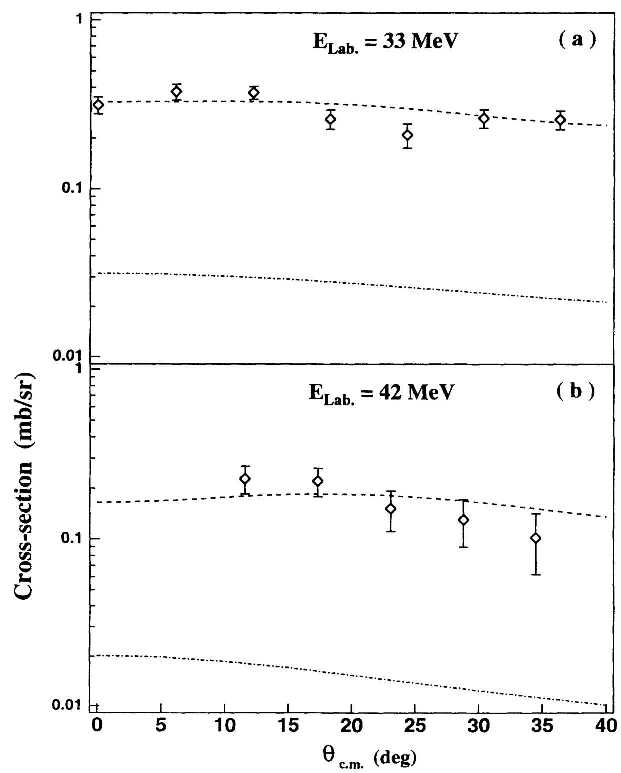

FIG. 7. Deuteron angular distributions for beam energies of (a) 33 MeV and (b) 42 MeV. The dashed curves represent DWUCK calculations without ^{12}C(g.s.) transfer, and the dot-dashed curves represent the predicted angular distribution cross sections for compound nucleus formation.

now exists evidence of 12 nucleon direct transfer, one of the largest number of nucleons transferred in a direct reaction observed to date. This could suggest the presence of quasimolecular configurations of $^{12}C\otimes^{12}C$ in the 13.45 MeV state in ^{24}Mg. Although the angular correlation measurements were conducted with deuterons detected at 0^0, we have gained insight about the relative contributions from different ^{12}C cluster states in the direct transfer. Fits to the angular correlations with FRDWBA calculations imply the dominance of $^{12}C(2^+)$ transfer in the reaction mechanism and the possible existence of selectivity of orbital angular momentum in the process, which is closely related to the structure of the state in ^{24}Mg. Further investigation of the $^{12}C(^{14}N,d)$ reaction with off 0° angular correlation measurements and a search for other quasimolecular states in ^{24}Mg may provide more parameter independent information on both the reaction mechanism and the structure of these states.

ACKNOWLEDGMENTS

The authors are very much indebted to H. T. Fortune and Z. Mao for valuable discussions and assistance in the DWUCK5 code calculations, and to R. Antonov and D. Essiam for help during data acquisition. This work was supported by a grant from the National Science Foundation. V. Z. Goldberg and M. S. Golovkov acknowledge the financial support of the Russian Foundation RFFI.

---

[1] N. Marquardt, W. van Oertzen, and R. L. Walter, Phys. Lett. **35B**, 37 (1971).
[2] T. H. Belote, N. Anyas-Weiss, J. A. Becker, J. C. Cornell, P. S. Fischer, P. N. Hudson, A. Menchaca-Rocha, A. D. Panagiota, and D. K. Scott, Phys. Rev. Lett. **30**, 450 (1973).
[3] H. V. Klapdor and H. Reiss, Z. Phys. **262**, 83 (1973).
[4] H. V. Klapdor, H. Reiss, and G. Rosner, Phys. Lett. **53B**, 147 (1974).
[5] C. Volant, M. Conjeaud, S. Harar, S. M. Lee, A. Lepine, and E. F. Da Silveira, Nucl. Phys. **A238**, 120 (1975).
[6] H. V. Klapdor, H. Reiss, and G. Rosner, Nucl. Phys. **A262**, 157 (1976).
[7] K. Nagatani, Phys. Lett. **35B**, 286 (1971).
[8] K. P. Artemov, M. S. Golovkov, V. Z. Goldberg, V. P. Rudakov, I. N. Serikov, V. A. Timofeev, M. Andrassy, D. Wolfahrt, G. U. Gersch, G. Lang, and E. Hentschel, Yad. Fiz. **44**, 893 (1986) [Sov. J. Nucl. Phys. **44**, 579 (1986)].
[9] A. E. Litherland and A. J. Ferguson, Can. J. Phys. **39**, 788 (1961).
[10] K. P. Artemov, V. Z. Goldberg, M. S. Golovkov, I. P. Petrov, V. P. Rudakov, I. N. Serikov, V. A. Timofeev, H. U. Gersch, and E. Hentschell, Phys. Lett. **149B**, 325 (1984).
[11] A. H. Wuosmaa, S. Saini, P. H. Kutt, and R. W. Zurmühle, Phys. Lett. B **172**, 297 (1986).
[12] T. D. Tomas, Annu. Rev. Nucl. Sci. **18**, 343 (1968).
[13] D. P. Grechukhin and D. V. Fedorov, Yad. Fiz. **51**, 353 (1990) [Sov. J. Nucl. Phys. **51**, 226 (1990)].
[14] R. Bock and H. Yoshida, Nucl. Phys. **A189**, 177 (1972).
[15] L. A. Chalton, Phys. Rev. C **8**, 146 (1973).
[16] P. D. Kunz, computer code DWUCK (unpublished).
[17] S. Cohen and D. Kurath, Nucl. Phys. **A141**, 145 (1970).