PHYSICAL REVIEW C VOLUME 10, NUMBER 5 NOVEMBER 1974

Light particle and gamma-ray production in $^{12}C + {}^{14}N$ interactions*

C. Olmer, R. G. Stokstad,† D. L. Hanson, K. A. Erb, M. W. Sachs, and D. A. Bromley
A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520
(Received 3 July 1974)

Angular distributions were measured for particle groups populating low-lying levels in the reactions $^{12}C(^{14}N, d)^{24}Mg$, $^{12}C(^{14}N, p)^{25}Mg$, and $^{12}C(^{14}N, \alpha)^{22}Na$ at E_{lab}=20 and 25 MeV. Excitation functions were also measured for low-lying γ-ray transitions in ^{24}Mg, ^{25}Mg, ^{24}Na, ^{21}Ne, ^{21}Na, and ^{18}F produced by ^{12}C bombardment of ^{14}N at E_{lab}=14–33 MeV. The excellent agreement of Hauser-Feshbach statistical model predictions with these results indicates that the light particle production from the $^{12}C + {}^{14}N$ interaction reflects a dominant compound nuclear interaction mechanism.

[NUCLEAR REACTIONS $^{12}C + {}^{14}N$ compound reactions, light particle emission and subsequent γ-ray decay, statistical model calculations. $^{12}C(^{14}N, d)$, $(^{14}N, p)$, $(^{14}N, \alpha)$, E_{lab}=20, 25 MeV, measured $\sigma(\theta)$; $^{14}N(^{12}C, \gamma)$, E_{lab}=14–33 MeV, measured E_γ, $\sigma(E_\gamma)$.]

I. INTRODUCTION

An interesting aspect of the study of any nuclear interaction has been the determination of the relative importance of direct and compound nuclear processes. This has been particularly true of heavy ion interactions. Some of these, such as $^{12}C(^{16}O, \alpha)^{24}Mg$ are now believed to proceed primarily by compound nucleus formation and decay, and experimental results are often well reproduced using a statistical model.[1,2] Other reaction data, such as those from the $^{12}C(^{14}N, {}^{13}C)^{13}N$ and $^{12}C(^{14}N, {}^{12}C)^{14}N$ reactions have been successfully analyzed in terms of direct one- and two-nucleon transfer.[3] However, for reactions which might be interpreted as proceeding via the transfer of large numbers of nucleons (e.g. 8- and 12-nucleon transfer), only the most qualitative types of analysis have been possible.[4-6]

An example of the difficulties encountered in such analyses is provided by previous investigations[7] of the $^{12}C + {}^{14}N$ interaction. The experimental data from these studies, spanning a wide range of bombarding energies and involving a variety of exit channels, have led to a number of conflicting interpretations. One of the first investigations was that of Almqvist, Bromley, and Kuehner[8] of γ-radiation yields from the bombardment of ^{14}N by 20 MeV ^{12}C ions. The most prominent lines in their spectra [obtained with a NaI(Tl) detector] correspond to the deexcitation of the first 2^+ and 4^+ levels in ^{24}Mg. γ rays from states in ^{22}Na, ^{25}Mg, and ^{25}Al, which could be reached by the energetically allowed emission of α particles, protons, and neutrons, respectively, as shown in Fig. 1, were either not observed or very weak. These results led the authors to speculate that an intense deuteron yield might be responsible for the observed γ-ray transitions, and that this explanation in turn could imply a strong direct component for the transfer of a ^{12}C cluster in the $^{12}C(^{14}N, d)^{24}Mg$ reaction.

A subsequent measurement was made by Nomura, Morinaga, and Povh[9] using a Ge(Li) detector to observe γ rays emitted when 25 MeV ^{14}N ions were incident on a ^{12}C target. In contrast to Ref. 8, these results were interpreted in terms of the evaporation of one or two particles from the compound nucleus. Based on the observed γ-ray yields, the authors concluded that the compound nuclear decay channels were distributed as follows: two α, 45%; two proton, 30%; proton plus neutron and/or deuteron, 21%; and single α-particle emission, 4%.

It is clear from the reaction thresholds shown in Fig. 1 that a statistical compound nuclear reaction mechanism would favor proton emission over deuteron emission for these low bombarding energies. Once ^{25}Mg is thus formed, however, neutron emission to states in ^{24}Mg would be the dominant mode of decay for the numerous low spin levels above the neutron threshold in ^{25}Mg. Thus, successive p-n emission would be expected to dominate deuteron emission if compound nucleus formation predominates.

The present work is directed toward an understanding of the problems raised by the foregoing experimental results. We have investigated the γ-ray and charged particle yields in the $^{14}N + {}^{12}C$ system at low center-of-mass energies, and as a part of our analysis, Hauser-Feshbach[10] statistical-model calculations have been performed and compared with our data. It is found that our experimental results are well explained by this statistical model.

II. EXPERIMENTAL PROCEDURE

Separate measurements of γ rays and of particles from the $^{12}C+^{14}N$ interaction were made at a variety of entrance channel energies. Absolute γ-ray yields were measured using a ^{12}C beam and nitrogen gas target over a range of ^{12}C energies, $14 \leq E_{lab} \leq 33$ MeV. Charged particle angular distributions for the population of low-lying states in ^{22}Na, ^{24}Mg, and ^{25}Mg were measured using 20 and 25 MeV beams of ^{14}N incident on a 40 $\mu g/cm^2$ natural carbon foil.

The target for the γ-ray measurements consisted of a nitrogen-filled gas cell, 1.4 cm long, with a 0.51 mg/cm^2 nickel entrance window. The gas pressure was typically 174 Torr, corresponding to a thickness of 0.40 mg/cm^2. The beam was stopped by a tantalum insert within the electrically isolated gas cell, and in-beam measurements of background were made by evacuating the cell. The number of incident ^{12}C ions was determined both from the integrated beam current and from the number of ^{12}C ions backscattered from the nickel foil entrance window into a silicon surface barrier detector fixed at 154°. A 36 cm^3 Ge(Li) detector was placed at 0° with respect to the beam and 6.3 cm from the center of the gas cell. A subsequent measurement with calibrated γ-ray sources, positioned at the center of the target volume, determined the absolute photopeak efficiency of this Ge(Li) detector.

The charged particle measurements were made simultaneously at two angles with two ΔE-E silicon surface barrier detector telescopes. The ΔE detector was 100 μm thick, while the E detector was 4000 μm thick and actually consisted of two 2000 μm detectors, one behind the other. The ΔE detector thickness was chosen for optimum identification and separation of the protons and deuterons, which were the particles of major interest in this work. As a result, low energy α particles were stopped in the ΔE detector and the α particles could be identified at forward angles only. The laboratory energy resolution, typically 350 keV, was determined mainly by target thickness and kinematic broadening. The normalizations for the measurements at different angles were based on the elastic scattering observed in a silicon surface-barrier detector fixed at 30°. The data were accumulated using an IBM 360/44 computer and stored event by event on magnetic tape. These data were subsequently processed off line, and the various particle species were identified and separated.

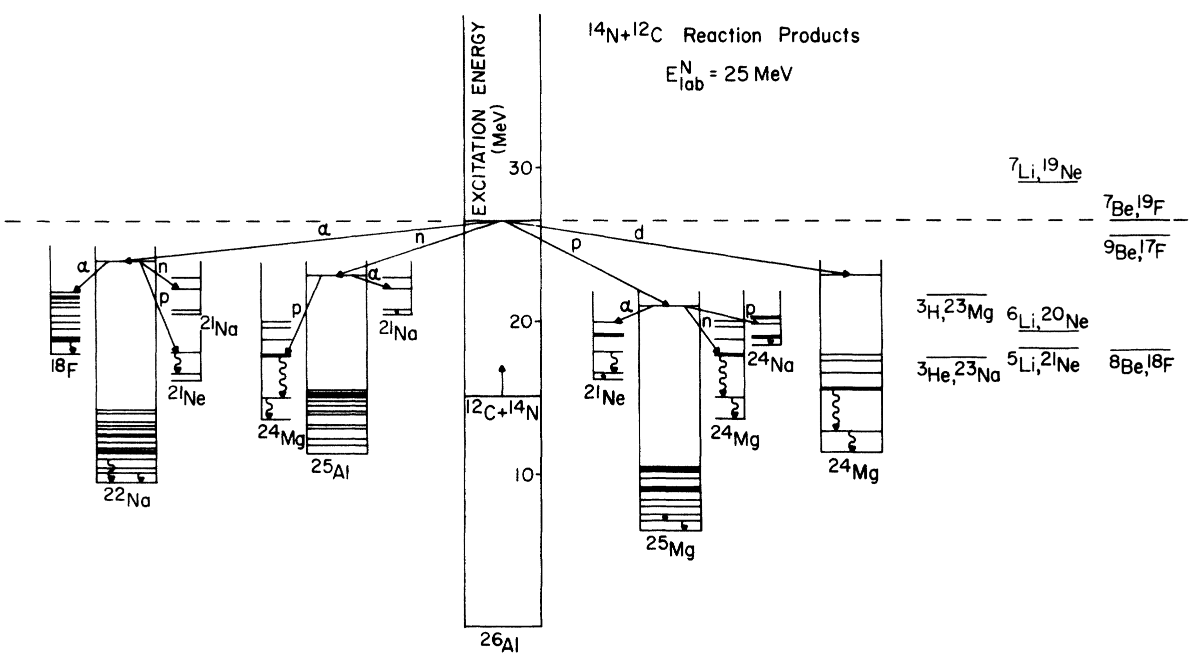

FIG. 1. Reaction channels which are energetically available for the decay of the ^{26}Al compound nucleus. Indicated γ-ray transitions were observed in the present experiment.

TABLE I. γ-ray transitions from $^{12}C + ^{14}N$ interaction.

Transition [a]	Light reaction products	E_γ^{TRAN} (MeV)	Mean lifetime	Doppler broadened and shifted?	$E_\gamma^{OBS\,b}$ (MeV)
$^{18}F[1.122(5^+) \to 0.937(3^+)]$	2α	0.185	218 ns	No	0.185
$^{21}Na[0.332(\frac{5}{2}^+) \to g.s.(\frac{3}{2}^+)]$	$n+\alpha$	0.332	14 ps	Yes	0.340
$^{21}Ne[0.350(\frac{5}{2}^+) \to g.s.(\frac{3}{2}^+)]$	$p+\alpha$	0.350	20 ps	Yes	0.360
$^{25}Mg[0.975(\frac{3}{2}^+) \to 0.585(\frac{1}{2}^+)]$	p	0.390	14 ps	Yes	0.403
$^{24}Na[0.473(1^+) \to g.s.(4^+)]$	$2p$	0.473	29 ns	No	0.471
$^{22}Na[0.583(1^+) \to g.s.(3^+)]$	α	0.583 [c]	352 ns	No	0.583
$^{25}Mg[0.585(\frac{1}{2}^+) \to g.s.(\frac{5}{2}^+)]$	p	0.585 [c]	4.9 ns	No	0.585
$^{18}F[0.937(3^+) \to g.s.(1^+)]$	2α	0.937	68 ps	No [d]	0.937
$^{24}Mg[1.369(2^+) \to g.s.(0^+)]$	$(p+n;d)$	1.369	1.8 ps	Yes	1.413
$^{21}Ne[1.746(\frac{7}{2}^+) \to 0.350(\frac{5}{2}^+)]$	$p+\alpha$	1.396	230 fs	Yes	1.442
$^{24}Mg[4.123(4^+) \to 1.369(2^+)]$	$(p+n;d)$	2.754	55 fs	Yes	2.836
$^{24}Mg[4.239(2^+) \to 1.369(2^+)]$	$(p+n;d)$	2.870	100 fs	Yes	2.964

[a] Energies, spins, parities, and lifetimes are from F. Ajzenberg-Selove, Nucl. Phys. A190, 1 (1972) and P. M. Endt and C. van der Leun, Nucl. Phys. A214, 1 (1973).

[b] Observed γ-ray energies from spectrum for $E_{^{12}C} = 30$ MeV.

[c] These states were unresolved.

[d] This state is fed predominantly by the long lived 5^+ state at 1.22 MeV.

III. EXPERIMENTAL RESULTS

The energies and assignments of observed γ-ray transitions which originated in the $^{12}C + ^{14}N$ interaction are listed in Table I. Listed are only those transitions whose photopeaks were sufficiently large and free of background to permit the extraction of a peak area. Several peaks in the γ-ray spectrum are Doppler-shifted and Doppler-broadened. For those transitions proceeding from states having lifetimes of less than a nanosecond, the observed γ-ray energies are larger by an amount consistent with the Doppler shift expected on the basis of the reaction kinematics, the length of the gas cell, and the long stopping times of ions moving in a gas.

Excitation functions for γ-ray transitions in a number of residual nuclei are shown in Figs. 2 and 3. The data points are plotted at the energy of the beam at the center of the gas cell, which was determined using the stopping power tables of Northcliffe and Schilling.[11] The horizontal bars indicate, for each bombarding energy, the range of energy available in the entrance channel as the projectile traverses and loses energy in the gas cell. The vertical error bars include contributions from uncertainties in detector efficiency, the number of incident ions, and background subtraction. The measured excitation function shown in Fig. 3(a) is for the sum of the 0.583 and 0.585 MeV γ-ray tran-

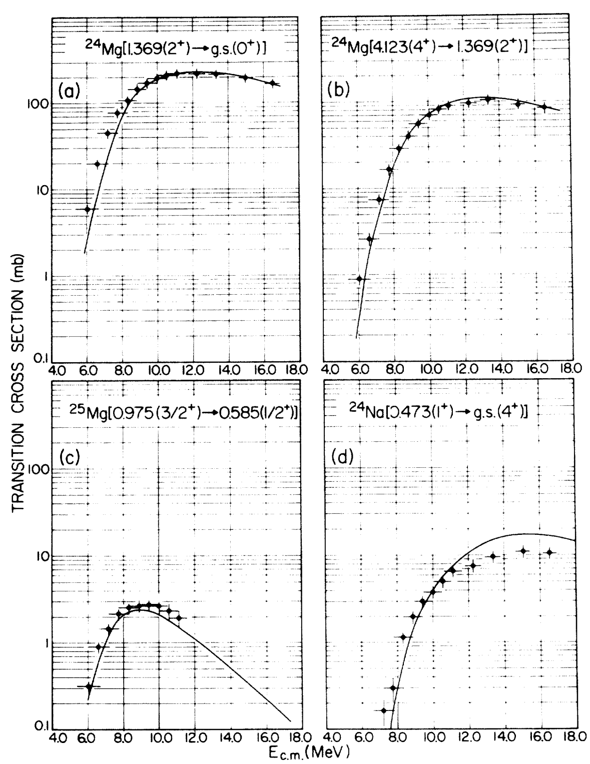

FIG. 2. Measured excitation functions for γ-ray transitions in ^{24}Mg, ^{25}Mg, and ^{24}Na. The solid lines are Hauser-Feshbach predictions.

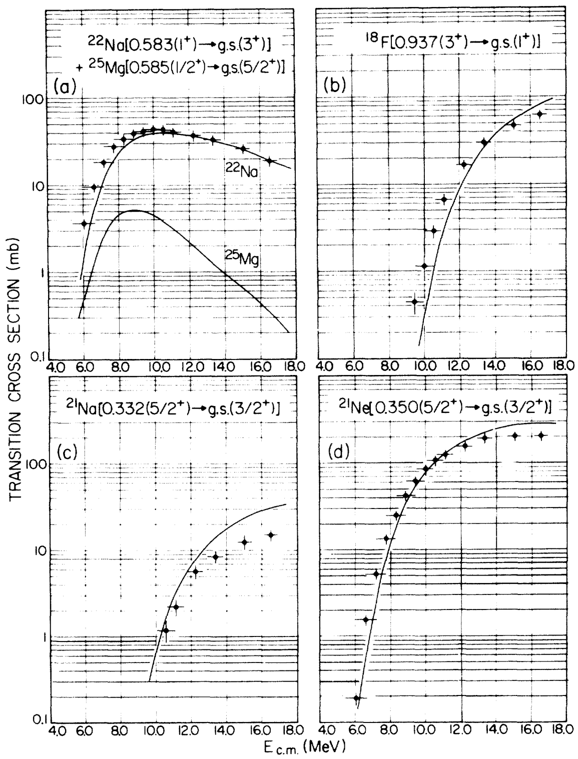

FIG. 3. Measured excitations functions for γ-ray transitions in ^{22}Na, ^{18}F, ^{21}Na, and ^{21}Ne. The solid lines are Hauser-Feshbach predictions.

sitions in ^{22}Na and ^{25}Mg, respectively.

The absolute γ-ray yields have been computed on the assumption of isotropic angular distributions. The error introduced by this assumption is probably not significant for the present purpose. Assuming that the nuclear spin of the residual nucleus is completely aligned perpendicular to the beam axis, maximum corrections of +250% and −18% would need to be applied to the cross sections for the $2^+\rightarrow 0^+$ and $4^+\rightarrow 2^+$ transitions in ^{24}Mg, respectively. However, the fact that these measurements are done at relatively low bombarding energies (for which a maximum of 10 units of angular momentum are brought in) and that these states are reached by either successive evaporation of two particles or emission of a deuteron suggest that any such alignment of the residual nucleus will be strongly attenuated. If the coefficients for the P_2 and P_4 terms in the expression for the angular correlation were attenuated by 60 and 80%, respectively, the above corrections are altered to −14 and −22%. Such corrections are sufficiently small that they may be neglected for the present work. The effects of cascade summing, which removes events from the photopeaks, have been estimated and found to be less than ten percent.

Angular distributions for charged particles populating low-lying states of ^{24}Mg and ^{25}Mg at the two ^{14}N bombarding energies are shown in Figs. 4 and 5. Measurements were made at eight laboratory angles from 25° to 140°. An over-all error of ±30% is estimated for the absolute normalization; the errors shown in the figures reflect only the uncertainties in determining the peak areas. Significantly, all of the angular distributions show an approximate symmetry about 90° in the center of mass, suggesting that the reaction mechanism is predominantly compound nuclear in origin.

TABLE II. Comparison of charged particle cross sections and statistical-model predictions.

	$^{12}C(^{14}N,d)^{24}Mg^*$			$^{12}C(^{14}N,p)^{25}Mg^*$		
		σ_{TOT}			σ_{TOT}	
E_N (MeV)	E_{cx} (MeV)	Expt (mb)	Theor (mb)	E_{ex} (MeV)	Expt (mb)	Theor (mb)
20	g.s.	0.33	0.34	g.s.	0.30	0.58
	1.369	1.07	1.31	0.585	0.11	0.20
	4.123 + 4.239	2.04	2.58	0.975	0.28	0.38
	5.236	0.93	1.09	1.612 + 1.965	0.78	1.21
	6.010	0.76	1.22	2.564 − 2.801	0.88	1.16
	6.432	0.26	0.17	3.405 + 3.414	0.74	1.05
				3.901 − 4.354	1.42	2.22
25	g.s.	0.15	0.24	g.s.	0.16	0.33
	1.369	1.01	1.04	0.585	0.06	0.09
	4.123 + 4.239	1.94	2.36	0.975	0.15	0.19
	5.236	0.86	0.94	1.612 + 1.965	0.49	0.73
	6.010	0.97	1.25	2.564 − 2.801	0.52	0.66
	6.432	0.19	0.11	3.405 + 3.414	0.48	0.74
				3.901 − 4.354	0.94	1.43

IV. COMPARISON OF STATISTICAL MODEL CALCULATIONS WITH THE EXPERIMENTAL RESULTS

The Hauser-Feshbach expression[10] for the angle-integrated and differential cross sections has been evaluated as described in Ref. 12. The optical model and level density parameters were unchanged from those used in Ref. 12 in a study of $^{12}C+^{14}N$ reaction data obtained at higher energies, and were generally taken from the literature. While no parameter changes were required in the present work, the lower bombarding energies used do lead to important differences in the dependence of the calculated cross sections on several of the input parameters. For example, at the lower energies the angular momenta involved in the $^{12}C+^{14}N$ interaction are considerably reduced from the values of interest in Ref. 12. As a consequence, the cross sections predicted at the present energies are much less sensitive to both the limiting angular momentum for fusion in the entrance channel[13] and the value of the spin cutoff parameter used in determining the angular momentum dependence of the level density in the residual nuclei. On the other hand, the calculations become more sensitive to the optical parameters for the $^{12}C+^{14}N$ entrance

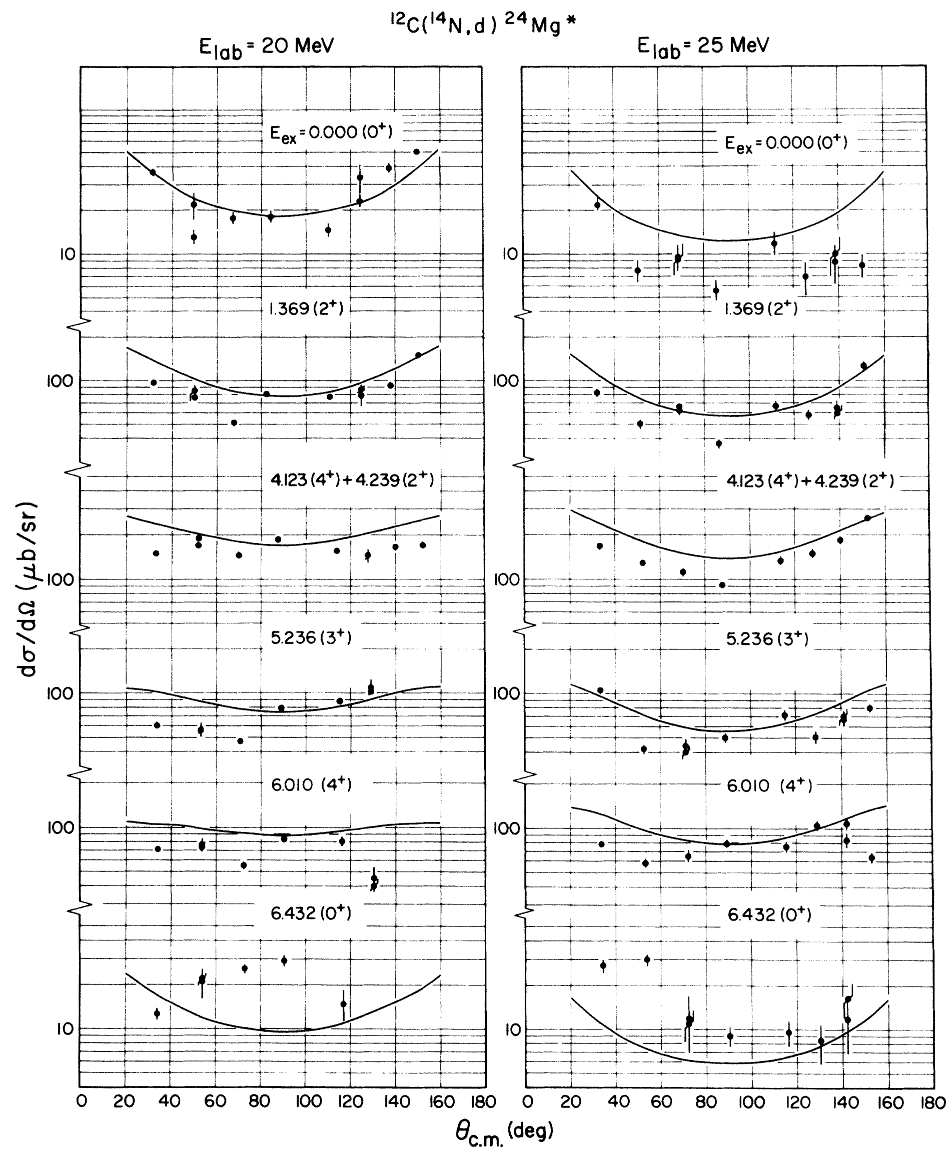

FIG. 4. Angular distributions for observed excited states in ^{24}Mg from the $^{12}C(^{14}N,d)^{24}Mg$ reaction at bombarding energies of 20 and 25 MeV. The solid lines are Hauser-Feshbach predictions.

channel.

Figures 4 and 5 and Table II compare the results of the statistical-model predictions to the charged particle data obtained at $E_{c.m.}=9.2$ and 11.5 MeV. Good agreement is obtained for both the shapes and absolute magnitudes of the deuteron angular distributions. The predicted cross sections for low-lying levels in ^{25}Mg exceed the measured values by a factor of, typically, 1.5. Calculations of the α-particle yields agree with the limited experimental data to within ~10%. The fluctuations in the angular distributions relative to the smooth Hauser-Feshbach predictions may be attributed to the fact that the experimental data are not averaged over bombarding energy.

The measured γ-ray yields are perhaps better suited to a comparison with the statistical model since a much thicker target (typically 2 MeV) could be used, thus providing an energy averaged cross section. However, the calculation of the observed γ-ray intensities is not as simple as in the calculation of the charged particle yields because γ-ray feeding from higher excited states, and successive evaporation of protons, neutrons, and α particles

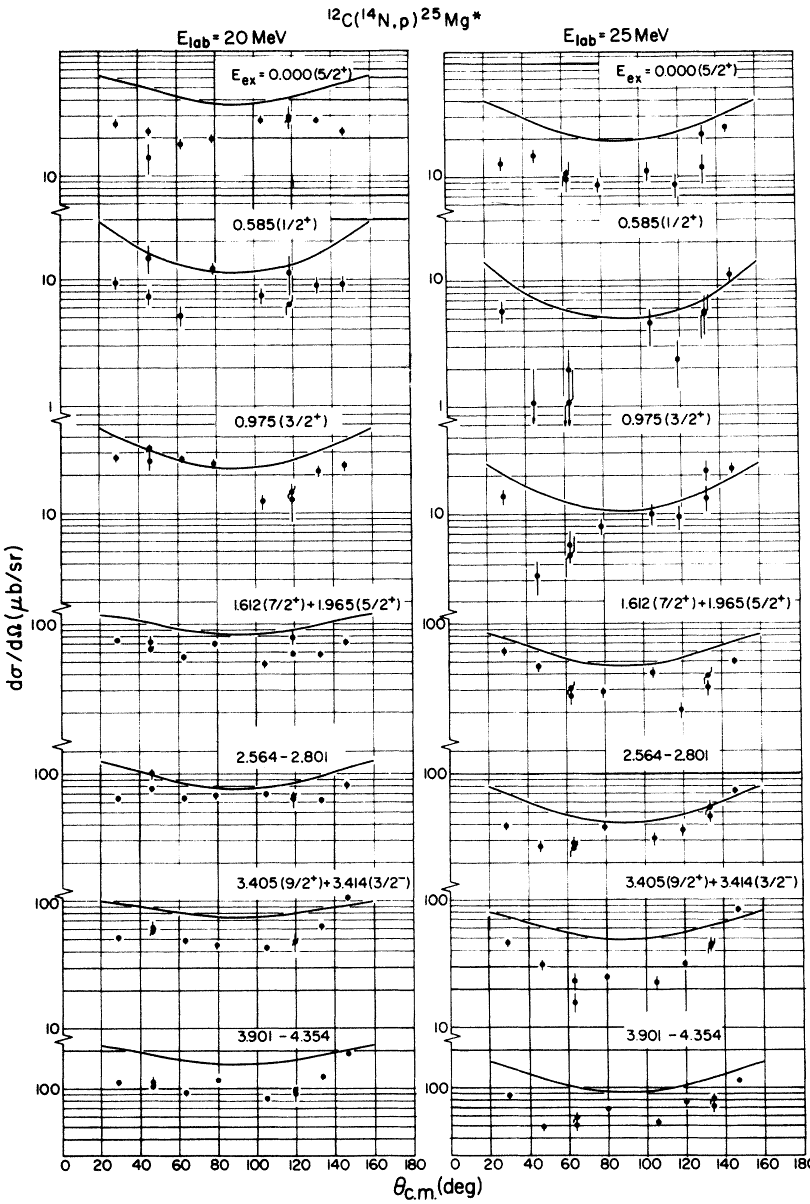

FIG. 5. Angular distributions for observed excited states in ^{25}Mg from the $^{12}C(^{14}N,p)^{25}Mg$ reaction at bombarding energies of 20 and 25 MeV. The solid lines are Hauser-Feshbach predictions.

contribute to the yield of a given γ-ray transition. The successive evaporation of particles was calculated without additional approximations, i.e., the population distribution of the intermediate compound nucleus was calculated as a function of excitation energy, angular momentum and parity, and these quantities were then considered explicitly in the statistical model calculation of the decay of the intermediate system. Theoretical cross sections for the intensity of a γ-ray transition in, e.g., ^{24}Mg were obtained by first calculating the separate cross sections for the population of individual states by proton-neutron, neutron-proton, and deuteron emission. Known or estimated γ-ray branching ratios were then folded with the sums of these separate cross sections to obtain the total γ-ray intensity for a given transition.

The experimental and predicted results are compared in Figs. 2 and 3. Here, again, the over-all agreement is excellent over a range of bombarding energies. At the lower energies, where the cross sections change rapidly, the effective energy at which theory and experiment should be compared no longer corresponds to the center of the gas cell. Rather, this effective energy moves closer to the initial energy at the center of the gas cell. The discrepancy between the predicted values and some of the data at the higher energies [Figs. 2(d) and 3(c)] very probably arises from uncertainties in the branching ratios for states at high excitation energy in the residual nuclei or from angular correlation effects.

The ability to predict absolute cross sections for individual γ-ray transitions, as demonstrated in Figs. 2 and 3, suggests that the procedure we have followed could be reversed in other reactions, i.e., total reaction cross sections could be deduced from the combination of measured photopeak intensities and statistical model calculations of the fraction of the total reaction cross section which yields the observed γ ray.

Finally, Fig. 6 shows the predicted intensity of the various exit channels for the decay of the ^{26}Al compound nucleus as a function of bombarding energy. Also shown in the figure is the sum of all these processes, the total cross section for compound nucleus formation, and the total reaction cross section measured by Kuehner and Almqvist.[14] It may be seen that the calculation underestimates the total reaction cross section by about 20–30% in the energy region where the present measurements were made. This implies that all predicted cross sections in Figs. 2–5 and Table II should be raised by this amount. As may be seen by inspection of these figures, the conclusions regarding the good overall agreement of the predicted and experimental cross sections are not affected.

V. CONCLUSION

The angular distributions for the ^{12}C(^{14}N, p)^{25}Mg and ^{12}C(^{14}N, d)^{24}Mg reactions to low-lying states were found to be approximately symmetric about 90° in the center of mass. Moreover, statistical model calculations based on independently derived transmission coefficients and level density parameters are able to reproduce both the absolute magnitudes and the general shapes of these angular distributions. The statistical calculations also reproduce the observed γ-ray yields which result from combined single and successive particle emission. Since the statistical model can account for the weak deuteron yields, as well as the intense γ-ray transitions observed in ^{24}Mg, we conclude that statistical p, n evaporation from the ^{26}Al* compound nucleus is the main process populating these low-lying states in ^{24}Mg.

In summary, the general agreement of a statis-

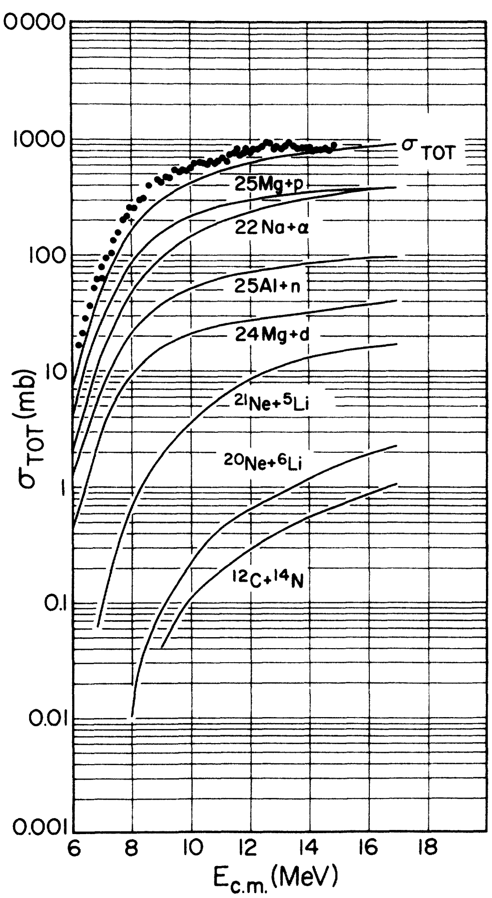

FIG. 6. The excitation function for the total reaction cross section as calculated using the Hauser-Feshbach theory. The individual contributions from the various exit channels are also shown. The dots indicate the total reaction cross section as measured by Kuehner and Almqvist (Ref. 14).

tical model with the observed charged particle and γ-ray yields at the energies considered here, leads to the conclusion that the reaction mechanism for light particle production from the $^{12}C+^{14}N$ interaction contains a dominant compound nuclear component. This result adds to the growing body of information which indicates that heavy ion reactions at low and moderate energies generally proceed via a compound nuclear mechanism when the amount of mass transferred as a result of the reaction is more than 4 amu.[15] Moreover, the success of the Hauser-Feshbach formalism in reproducing the average compound nuclear contributions to such reactions should assist in identifying those exceptional reactions which contain a significant direct component.

ACKNOWLEDGMENTS

The authors wish to thank Kenzo Sato, John Benjamin, and the operating crew at the Yale MP tandem accelerator for their diligent assistance during these measurements.

*Work supported under U.S. Atomic Energy Commission Contract No. AT(11-1)3074.
†Present address: Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830.
[1]M. L. Halbert, F. E. Durham, and A. van der Woude, Phys. Rev. 162, 899 (1967).
[2]L. R. Greenwood, K. Katori, R. E. Malmin, T. H. Braid, J. C. Stoltzfus, and R. H. Siemssen, Phys. Rev. C 6, 2112 (1972).
[3]W. von Oertzen, M. Liu, C. Caverzasio, J. C. Jacmart, F. Pougheon, M. Riou, J. C. Roynette, and C. Stephan, Nucl. Phys. A143, 34 (1970).
[4]N. Marquardt. W. von Oertzen, and R. L. Walter, J. Phys. (Paris) 32, 229 (1971); Phys. Lett. 35B, 37 (1971).
[5]K. Nagatani, M. J. LeVine, T. A. Belote, and A. Arima, Phys. Rev. Lett. 27, 1071 (1971).
[6]M. Conjeaud, S. Harar, E. DaSilveira, and C. Volant, J. Phys. (Paris) 32, 169 (1971).
[7]H. L. Reynolds and A. Zucker, Phys. Rev. 96, 1615 (1954); M. L. Halbert and F. E. Durham, in *Proceedings of the Third Conference on Reactions Between Complex Nuclei, Asilomar, Pacific Grove, California, 1963,* edited by A. Ghiorso, R. M. Diamond, and H. E. Conzett (Univ. of California Press, Berkeley, 1963), p. 223; R. M. Gaedke, K. S. Toth, and I. R. Williams, Phys. Rev. 140, B296 (1965); H. V. Klapdor, N. Marquardt, and H. Reiss, J. Phys. (Paris) 32, 217 (1971); J. N. Hallock, H. A. Enge, A. Sperduto, R. Middleton, J. D. Garrett, and H. T. Fortune, Phys. Rev. C 6, 2148 (1972); H. V. Klapdor and H. Reiss, J. Phys. (Paris) 33, 111 (1972); H. Voit, G. Ischenko, F. Siller, H.-D. Helb, Nucl. Phys. A179, 23 (1972); T. A. Belote, N. Anyas-Weiss, J. A. Becker, J. C. Cornell, P. S. Fisher, P. N. Hudson, A. Menchaca-Rocha, A. D. Panagiotou, and D. K. Scott, Phys. Rev. Lett. 30, 450 (1973); R. Holub, A. F. Zeller, G. R. Choppin, R. J. DeMeijer, and H. S. Plendl, *ibid.* 43B, 375 (1973); H. V. Klapdor and H. Reiss, Z. Phys. 262, 83 (1973).
[8]E. Almqvist, D. A. Bromley, and J. A. Kuehner, in *Proceedings of the Second Conference on Reactions Between Complex Nuclei, Gatlinburg, Tennessee, 1960,* edited by A. Zucker, F. T. Howard, and E. C. Halbert, (Wiley, New York, 1960), p. 282.
[9]T. Nomura, H. Morinaga, and B. Povh, Nucl. Phys. A127, 1 (1969).
[10]W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952); H. Feshbach, in *Nuclear Spectroscopy,* edited by F. Ajzenberg-Selove (Academic, New York, 1960), Part B, p. 625.
[11]L. C. Northcliffe and R. F. Schilling, Nucl. Data A7 (Nos. 3, 4), 233 (1970).
[12]D. L. Hanson, R. G. Stokstad, K. A. Erb, C. Olmer, and D. A. Bromley, Phys. Rev. C 9, 929 (1974).
[13]R. Bass, Phys. Lett. 47B, 139 (1973).
[14]J. A. Kuehner and E. Almqvist, Phys. Rev. 134, B1229 (1964).
[15]E. W. Vogt, D. McPherson, J. Kuehner, and E. Almqvist, Phys. Rev. 136, B99 (1964); J. Gomez del Campo, J. L. C. Ford, Jr., R. L. Robinson, P. H. Stelson, and S. T. Thornton, Phys. Rev. C 9, 1258 (1974); J. L. C. Ford, Jr., J. Gomez del Campo, R. L. Robinson, P. H. Stelson, and S. T. Thornton, Nucl. Phys. A226, 189 (1974). For a recent review of statistical compound processes in light nuclei, see R. G. Stokstad, in Proceedings of the International Conference on Reactions Between Complex Nuclei, Nashville, Tennessee, 1974 (North-Holland, to be published), Vol. II.