Compound nature of the reaction $^{12}C(^{14}N,^{6}Li)^{20}Ne$†

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It is found that the statistical model accounts rather well for the absolute cross sections measured recently for the reaction $^{12}C(^{14}N,^{6}Li)^{20}Ne$ at $E_{c.m.} \sim 24$ and ~ 36 MeV and for the integrated ^{7}Be yields observed in the $^{12}C + ^{14}N$ reaction at $E_{c.m.} = 16$–28 MeV. These results demonstrate that compound-nucleus formation followed by the emission of complex particles such as ^{6}Li or ^{7}Be occurs with sizable cross sections in these reactions.

[NUCLEAR REACTIONS $^{12}C + ^{14}N$ compound reactions, complex particle emission, statistical model calculations. $^{12}C(^{14}N,^{6}Li)$, $E_{c.m.} = 24$, 36 MeV, calculated $\sigma(\theta)$; $E_{c.m.} = 36$, 55 MeV, calculated ^{6}Li evaporation spectra shapes. $^{12}C(^{14}N,2p)$, $(^{14}N,\alpha)$, $(^{14}N,^{7}Be)$, $E_{lab} = 12$–60 MeV; calculated integrated yields.]

I. INTRODUCTION

One of the attractive features of heavy-ion-induced reactions is the opportunity which they present for the study of nuclear correlations through the simultaneous transfer of many nucleons to the target or projectile in a direct process. A carefully documented example of this is the ^{12}C-$(^{12}C, \alpha)^{20}Ne$ reaction, in which certain states in ^{20}Ne appear to be populated preferentially through transfer of eight nucleons.[1] The $^{12}C(^{14}N, ^{6}Li)^{20}Ne$ reaction, however, represents a more controversial situation. In two recent experimental studies of this reaction,[2,3] it was argued that the compound-nucleus amplitudes would be expected to be small, and that the data constitute evidence for direct eight-nucleon transfer. A more recent publication by Belote *et al.*[4] presents evidence suggesting that the reaction proceeds primarily via compound-nucleus formation. In particular, angular distributions for the $^{12}C(^{14}N, ^{6}Li)^{20}Ne$ reaction at $E_{c.m.} \sim 36$ MeV (see Fig. 1) exhibit an approximate symmetry about $\theta = 90°$ (c.m.) which is well reproduced by a $(\sin\theta)^{-1}$ angular dependence.[4] This is presently the main evidence which has been advanced for the compound nature of the reaction.[4] In addition to the shape of the angular distributions, however, both the relative and absolute values of the cross sections to the various excited states of ^{20}Ne and the shape of the ^{6}Li particle spectrum contain significant information concerning the mechanisms involved. A comparison of quantitative predictions of a compound-nucleus or statistical model to these data was therefore undertaken in an attempt to elucidate the nature of these reaction mechanisms and to clarify several of the points raised in Refs. 2–4. The results of this comparison are a further demonstration that compound-nucleus formation is the predominant mechanism in this reaction.

II. STATISTICAL MODEL CALCULATIONS

Average compound-nucleus cross sections were calculated with the Hauser-Feshbach[5] expression

$$\bar{\sigma}_{\alpha\alpha'} = (\pi/k_\alpha^2) \sum_{J,\pi} \frac{(2J+1)}{(2I+1)(2i+1)} \times \frac{(\sum_{l,s} T_l^\alpha)_{J,\pi} (\sum_{l',s'} T_{l'}^{\alpha'})_{J,\pi}}{[\sum_{c'',l'',s''} T_{l''}^{c''}]_{J,\pi}} \quad (1)$$

using the computer code STATIS.[6] The notation for Eq. (1) follows Vogt *et al.*,[5] in which the unprimed quantities refer to the incoming channel c, primed quantities to the exit channel c', and the sum in the denominator runs over all possible outgoing channels. The quantum numbers of each channel c are $c = (\alpha, I, i, s, l, J, \pi)$, where α labels the pair of particles and their state of excitation, I and i are the ground-state spins of the target and projectile, s is the channel spin, l the orbital angular momentum, and J^π the total angular momentum and parity. The effects of spin-orbit forces, isospin, and γ-ray decay are expected to be small for the present calculations and have been neglected. The expression for the differential cross section used in the code STATIS differs from (1) only in the introduction of angular momentum recoupling coefficients,[5] and hence is not reproduced here.

Optical-model parameters used to calculate the transmission coefficients T_l^α for the 10 major channels considered in the calculation are presented in Table I. Insofar as possible, they are obtained from analyses of elastic scattering data.[7–11]

The quantity $[\sum_{c'',l'',s''} T_{l''}^{c''}]_{J,\pi}$ in the denominator

TABLE I. Optical-model parameters for the $^{12}C + ^{14}N$ reactions.

	V	$R_0 = r_0 A^{1/3}$	a_0	W	$R_i = r_i A^{1/3}$	a_i	R_{Coulomb}	Ref. No.
$^{25}Al + n$	$48.2 - 0.3E_{\text{c.m.}}$	3.66	0.65	11.50[a]	3.66	0.47	0.0	7
$^{25}Mg + p$	$52.2 - 0.3E_{\text{c.m.}}$	3.66	0.65	11.50[a]	3.66	0.47	3.66	7
$^{24}Mg + d$	61.2	4.08	0.57	17.40[b]	3.14	0.85	4.08	8
$^{22}Na + \alpha$	54.4	4.76	0.53	9.80[b]	4.76	0.53	3.92	9
$^{21}Na + ^{5}He$	54.4	4.76	0.53	9.80[b]	4.76	0.53	3.92	9
$^{21}Ne + ^{5}Li$	35.5	$1.42A_T^{1/3}$	0.92	7.94[a]	$1.71A_T^{1/3}$	0.89	6.79	10
$^{20}Ne + ^{6}Li$	35.5	$1.42A_T^{1/3}$	0.92	7.94[a]	$1.71A_T^{1/3}$	0.89	6.79	10
$^{19}F + ^{7}Be$	35.4	$1.74A_T^{1/3}$	1.05	11.50[a]	$2.13A_T^{1/3}$	0.62	6.79	10
$^{18}F + ^{8}Be$	35.4	$1.74A_T^{1/3}$	1.05	11.50[a]	$2.13A_T^{1/3}$	0.62	6.79	10
$^{14}N + ^{12}C$	14.0	$1.35(A_1^{1/3} + A_2^{1/3})$	0.35	$0.4 + 0.1E_{\text{c.m.}}$[b]	$1.40(A_1^{1/3} + A_2^{1/3})$	0.35	6.58	11

[a] Surface absorption potential.

[b] Volume absorption potential.

of Eq. (1), representing the total number of channels open for the decay of the compound nucleus, was evaluated using discrete levels of known spin and parity up to an excitation energy E_{CUT} in each residual nucleus (see Table II). From E_{CUT} to the highest allowed energy, the sum was replaced by an integral over states in the continuum calculated using a level density formula given by[12]

$$\rho(U,J) = \frac{(2J+1)}{12a^{1/4}(U+t)^{5/4}(2\sigma^2)^{3/2}} \times \exp\left[2(aU)^{1/2} - \frac{(J+\frac{1}{2})^2}{2\sigma^2}\right],$$
$$\rho(U,J,\pi) = 1/2\rho(U,J). \quad (2)$$

In Eq. (2) the quantity $U = E - \Delta = at^2 - t$ is the excitation energy corrected for the pairing energy Δ, t is the nuclear temperature, and $\sigma^2 = \mathcal{I}_r t/\hbar^2$ is the spin cutoff factor with $\mathcal{I}_r$ the rigid-body moment of inertia. Values listed in Table II for the single-particle level-density parameter, a, are those given by Facchini and Saetta-Menichella,[13] who use the pairing energy corrections of Gilbert and Cameron.[14]

Confidence in the choice of optical-model and level-density parameters was gained from the good agreement found in a comparison of calculated and measured[15] absolute cross sections for certain $^{12}C + ^{14}N$ induced reactions at low energies ($E_{\text{c.m.}} \sim 10$ MeV) where compound-nucleus formation is known to be predominant. In particular, cross sections for the population of low-lying states by p, d, and α emission were reproduced to within (and usually much better than) a factor of 2.

An important quantity entering into the statistical model for a heavy-ion reaction at much higher bombarding energies is the limiting angular momentum J_l beyond which compound-nucleus formation does not occur. This limiting angular momentum can depend on the dynamics of the entrance channel[16] but in any case cannot exceed the grazing angular momentum in the entrance channel or the maximum angular momentum J_c which the compound nucleus can support at the excitation energy fixed by the center-of-mass energy and Q value. Lacking precise knowledge of both J_l and J_c, we have made the somewhat arbitrary approximation $J_l \approx J_c$ and have estimated J_c by considering the moments of inertia $\mathcal{I}$ obtained by fitting rotational energy levels for the mass-26 nuclei ($\mathcal{I} = 0.55\mathcal{I}_r$), and have further assumed that $\mathcal{I}$ approaches the rigid-body value $\mathcal{I}_r$ at high excitation energies. Values of $J_c = 14$ and $18\hbar$ were used for $E_{\text{c.m.}} = 24$ and 36 MeV, respectively, and correspond to values of $\mathcal{I}$ equal to 0.7 and 0.8 of the rigid-body limit, where $\mathcal{I}_r = \frac{2}{5}mAR^2$ and R

TABLE II. Level density parameters for the $^{12}C + ^{14}N$ reactions.

Residual nucleus	^{25}Al	^{25}Mg	^{24}Mg	^{22}Na	^{21}Na	^{21}Ne	^{20}Ne	^{19}F	^{18}F	^{14}N
a/A[a]	0.148	0.148	0.149	0.167	0.152	0.152	0.152	0.152	0.152	0.152
Δ[b] (MeV)	2.67	2.46	5.13	0.0	2.67	2.46	5.13	2.67	0.0	0.0
E_{CUT}[c] (MeV)	5.06	5.00	10.07	4.36	6.51	5.77	9.50	5.94	4.96	
No. of discrete levels	18	18	28	19	20	20	19	23	22	

[a] Level density parameters from Ref. 13.

[b] Pairing energies from Ref. 14.

[c] Excitation energy in residual nucleus above which level density formula is used.

$=1.4A^{1/3}$ fm. These values of J_c are significantly less than the grazing angular momenta in the entrance channel (~17 and ~21$\hbar$, respectively); the flux in the surface partial waves is most probably accounted for by few-nucleon transfer reactions, inelastic scattering, and other direct processes. [The single-neutron transfer reaction $^{12}C(^{14}N, ^{13}C)$-^{13}N observed by von Oertzen *et al.*[17] at $E_{c.m.}=36$ MeV has cross sections in the 1–10 mb/sr range. As would be expected, a statistical calculation underestimates the cross section for this clearly direct reaction by a large factor of ~10^3.]

III. COMPARISON TO EXPERIMENTAL RESULTS

Predicted and measured[4] angular distributions for states in ^{20}Ne below 10 MeV excitation and populated at $E_{c.m.}=36$ MeV are compared in Fig. 1. The over-all agreement for the shapes and relative and absolute values of the cross sections is excellent. Figure 2 presents a similar comparison to experimental data[2] at $E_{c.m.}=24$ MeV. Since the statistical model overestimates the cross sections at this energy, the absolute theoretical values are shown divided by a factor of 2 (dashed line) in order to facilitate comparison of the shapes and relative magnitudes.

The energy spectrum of ^{6}Li particles at $E_{c.m.}=36$ MeV indicates[2-4] a number of selectively populated states which appear as resolved or partially resolved groups superimposed on a smoothly varying background [Fig. 3(a)]. These groups correspond most likely to high-spin states. The origin of the background above 10 MeV excitation is presumably the many closely spaced levels of lower spin which are not resolved in the experiment. At $E_{c.m.}\sim 55$ MeV, however, the ^{6}Li spectra[4] show little evidence of the selective population of high-spin states [Fig. 3(b)].

The shape of the ^{6}Li "background" yield may be calculated within the statistical model by using a level-density formula to approximate the spectrum of excitation in ^{20}Ne. The results of such a calculation at $E_{c.m.}=36$ and 55.4 MeV are compared to the experimental data in Figs. 3(a) and 3(b), respectively. The contribution from the two-step decay process $^{12}C(^{14}N, \alpha)^{22}Na^{*}(^{6}Li)^{16}O$ will be important only for very low ^{6}Li energies and has not been included in the calculated ^{6}Li yield. Since an absolute normalization for these spectra is not given in Ref. 4, the predicted yields have been normalized to the data. The predicted and measured shapes of the ^{6}Li spectra agree fairly well.

The absence of selectively populated groups in the ^{6}Li spectrum at $E_{c.m.}\approx 55$ MeV [Fig. 3(b)] also can be explained by the statistical model. At lower bombarding energies ($E_{c.m.}\lesssim 36$ MeV), a strong angular momentum mismatch between the maxi-

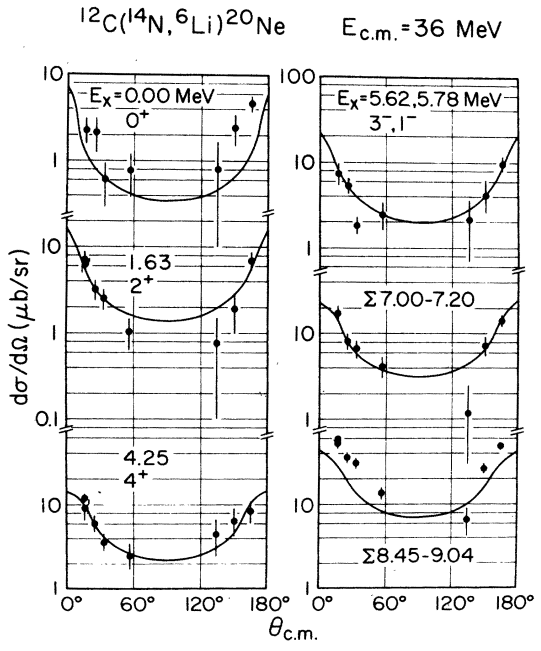

FIG. 1. Absolute Hauser-Feshbach statistical-model calculations compared with experimental angular distributions from Ref. 4 for low-lying states in ^{20}Ne populated by the $^{12}C(^{14}N,^{6}Li)^{20}Ne$ reaction at $E_{c.m.}=36$ MeV.

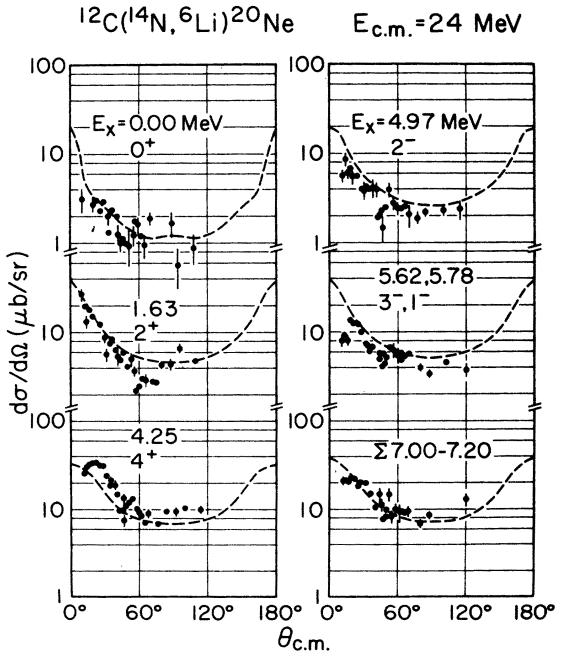

FIG. 2. Angular distributions for the $^{12}C(^{14}N,^{6}Li)^{20}Ne$ reaction at $E_{c.m.}=24$ MeV from Ref. 2. Statistical-model cross sections shown here by the dashed lines have been normalized downward by a factor of 2.

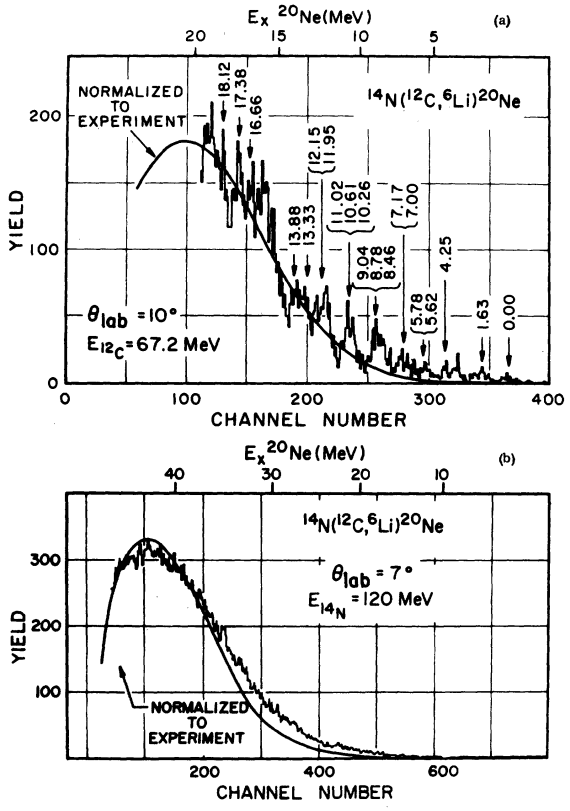

FIG. 3. (a) Statistical-model calculation of the shape of the ^{6}Li "evaporation" spectrum for $E_{c.m.}$ =36 MeV. The data are from Ref. 4. (b) Similar calculation for $E_{c.m.}$ =55.4 MeV. A maximum angular momentum in the compound nucleus of J_c =24 was used.

mum angular momentum in the compound nucleus and the maximum orbital angular momentum available to the ^{6}Li +^{20}Ne system requires that the residual states in ^{20}Ne have high spin. In going to higher bombarding energies, the maximum angular momentum of the compound nucleus J_c increases slowly whereas the increased kinetic energy available in the ^{6}Li +^{20}Ne channel results in an enhanced cross section for the lower-spin states in ^{20}Ne. Thus, it is a reduction in this angular momentum mismatch for a reaction proceeding through the compound nucleus which is responsible for the absence of selectively populated groups at very high bombarding energies.

IV. UNCERTAINTIES IN THE STATISTICAL CALCULATIONS

The cross sections evaluated with Eq. (1) are subject to uncertainties in the optical-model transmission coefficients, level densities of residual nuclei, and the angular momentum cutoff J_c. Each of these will be discussed in turn.

The transmission coefficients for the exit channels ^{6}Li +^{20}Ne and ^{7}Be +^{19}F were derived from the surface absorption parameters of Bethge, Fou, and Zurmuhle.[10] If their volume absorption parametrization of the ^{6}Li +^{20}Ne optical potential had been used, the calculated ^{6}Li cross sections would be increased by about 15% for $E_{c.m.}$ =24 MeV and reduced by about 25% for $E_{c.m.}$ =36 MeV.

A further uncertainty in the transmission coefficient concerns the effect of ^{6}Li dissociation and direct transfer reactions on the imaginary potential derived from analyses of elastic scattering data. Since breakup and direct transfer reactions remove flux from the ^{6}Li elastic scattering channel without compound-nucleus formation, the use of optical-model transmission coefficients obtained from fits to elastic scattering results in an overestimate of the compound-nucleus formation cross section. If, for example, the ^{6}Li imaginary potential depth is reduced by 50% in order to simulate the effects of breakup and direct reactions, the calculated cross sections for the reaction ^{12}C-(^{14}N, ^{6}Li)^{20}Ne at $E_{c.m.}$ =36 MeV decrease by about 30%. We expect that reasonable variations in the α-particle optical-model parameters will indicate uncertainties in the ^{6}Li cross sections of a similar magnitude (i.e., ~30%), since the α-particle yield is the dominant contribution to the denominator of Eq. (1).

At high energies, the choice of the ^{12}C +^{14}N optical-model potential has practically no effect on the predicted cross sections because the entrance channel transmission coefficients are limited by the amount of angular momentum which the ^{26}Al compound nucleus can support (yrast cutoff) to those whose l values correspond to complete absorption.

The level-density parameters a given in Ref. 13 were obtained from an analysis[13] in which a rigid-body moment of inertia given by $\mathcal{I}_r = \frac{2}{5}mAR^2$ and $R = 1.4A^{1/3}$ fm was used to parametrize the spin distribution of the level density. We have employed a somewhat larger moment of inertia, with radius $R = 1.5A^{1/3}$ fm in calculating the spin cutoff factor σ^2. This serves to increase the density of high-spin states in the residual nuclei and thereby reduce the compound-nucleus cross section for a particular state. The reduction for calculations at $E_{c.m.}$ =36 MeV is about a factor of 2. Since the value of $R = 1.4A^{1/3}$ fm used in Ref. 13 was obtained from a shell-model calculation of the average value of $\langle m_J{}^2 \rangle$ (the projection of the total angular momentum for states around the Fermi level), it is not unreasonable that a larger value of the moment of inertia should be appropriate in a statistical calculation where very high excitation ener-

gies and angular momenta are involved.[18] At low bombarding energies ($E_{c.m.} \sim 10$ MeV), this change in the radius has little effect.

The absolute cross sections at high bombarding energies are very sensitive to the choice of the yrast cutoff J_c in the compound nucleus. At $E_{c.m.} = 36$ MeV, the cross sections increase (decrease) by roughly a factor of 2 for an increase (decrease) of one unit in the value of J_c. This sensitivity is reduced at lower energies and corresponds to a factor of 1.75 at $E_{c.m.} = 24$ MeV.

An explicit consideration of isospin conservation[19] has not been included in the present calculation. This is equivalent to assuming that all levels populated in this reaction in the compound nucleus and in the residual nuclei have $T = 0$ or $T = \frac{1}{2}$ according to whether the residual nucleus is even or odd A. Under this assumption, the $T = 1$ state at 3.562 MeV in ^{6}Li should not be populated provided that the residual ^{20}Ne nucleus is left in a $T = 0$ state. It is interesting to note, in this regard, that in the ^{6}Li spectra of Refs. 2–4, no group appears which would correspond to ^{6}Li ($T = 1$, $E_x = 3.56$) + ^{20}Ne ($T = 0$, $E_x = 0$). Within the statistical precision of these spectra, isospin apparently remains a good quantum number in ^{26}Al even to excitation energies as high as 50 MeV.

V. DISCUSSION

The striking feature of these statistical calculations is that the predicted cross sections are comparable to or, at $E_{c.m.} = 24$ MeV, somewhat larger than, those measured. This result is in contradiction with arguments[2,3] that the compound system is unlikely to decay into $^{6}Li + ^{20}Ne$ and that the observed large cross sections therefore indicate a direct reaction. The prediction of relative yields is in excellent agreement with the data and the shapes of the ^{6}Li particle spectra are well reproduced. These results demonstrate that the reaction mechanism is predominantly compound. Furthermore, similar statistical calculations predict that the integrated ^{6}Li yield should be larger than the ^{7}Li, ^{7}Be, and ^{8}Be yields, in rough agreement with the observations in Refs. 2 and 3. The fact that the cross sections do not show strong fluctuations[2] is not necessarily inconsistent with compound-nucleus formation since fluctuations are expected to be damped by the entrance and exit channel spins of (at least) $1\hbar$. Finally, forward- and backward-peaked angular distributions and total cross sections with an approximate $2J + 1$ dependence are predicted by the statistical model. Thus many of the observed properties of these reactions (particularly when only forward-angle data have been measured) which have been cited as evidence for a direct mechanism are in fact well explained by the statistical model.

The recent measurements by Holub *et al.*[20] on ^{7}Be radioactivity produced in the bombardment of a thick carbon target by 16–58-MeV ^{14}N ions provide a significant test of the assumptions made in the statistical calculations described above. If the compound nucleus is indeed formed and reaches equilibrium, and if complex particles such as ^{6}Li are emitted through statistical processes, then the emission of ^{7}Be should also occur in a proportion governed primarily by the reaction threshold, transmission coefficients, and level densities. The experimental integrated yields for ^{7}Be, ^{22}Na (α-particle emission), and ^{24}Na (successive two-proton emission) are shown in Fig. 4 together with our statistical-model calculations. The excellent agreement shown here further indicates the importance of compound processes in the $^{12}C(^{14}N,^{6}Li)^{20}Ne$ reaction.

Noting that ^{7}Be has about the same threshold for breakup as ^{6}Li, the good agreement found for ^{7}Be emitted with both low and high energies from the compound nucleus suggests that breakup effects for ^{7}Be and for ^{6}Li may not be a serious problem for the present calculation.

In conclusion, the over-all agreement with experiment obtained with the statistical model for the reactions $^{12}C(^{14}N,^{6}Li)^{20}Ne$ and $^{12}C(^{14}N,^{7}Be)^{19}F$ demonstrates that the formation of the statistical compound nucleus and subsequent emission of complex and loosely bound particles such as ^{6}Li and

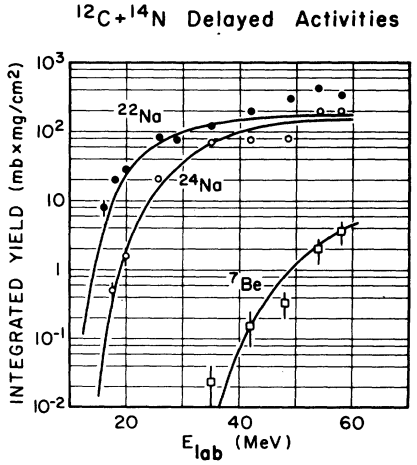

FIG. 4. Absolute statistical-model calculations compared with experimental integrated yields for various $^{12}C + ^{14}N$ reaction products (Ref. 20). The ^{24}Na yield has been calculated assuming the successive emission of two protons. The stopping powers given by L. C. Northcliffe and R. F. Schilling [Nucl. Data A7, 233 (1970)] were used in the calculation of the thick target yields.

^{7}Be occurs with sizable cross sections in this heavy-ion reaction. A similar conclusion for the case of α-particle bombardment of ^{12}C and ^{16}O has been drawn by Rudy *et al.*[21] (It was first emphasized by Cohen that the emission of complex particles as well as single nucleons reflects the degenerate fermion nature of the nuclear system.[22]) We emphasize that, while the over-all agreement shown in Figs. 1–4 cannot rule out the possibility of there being some direct component for eight-nucleon transfer to a particular state in ^{20}Ne, this agreement does point out the need for extreme caution in attempting to derive nuclear structure information from a direct reaction interpretation. Compound processes clearly account for the bulk of the reaction.

The success of the present Hauser-Feshbach calculations in quantitatively accounting for the observed yields in this particular heavy-ion reaction suggests that such calculations should be performed regularly as a part of the analysis of similar reaction data. The ability to reliably estimate (i.e., to within a factor of ~2) the compound contribution to a reaction often can be of considerable help in establishing whether the reaction mechanism is predominantly direct or compound. Recent examples of this are the reactions ^{12}C-(^{14}N, d)^{24}Mg (Ref. 23) and ^{16}O(^{14}N, ^{6}Li)^{24}Mg (Ref. 24).

Finally, we note that the compound process itself can provide valuable nuclear structure information; first, as a means for selectively populating high-spin states in ^{20}Ne. Secondly, the sensitivity of such reactions as ^{12}C(^{14}N, ^{6}Li)^{20}Ne to the limiting angular momentum for compound-nucleus formation might be exploited in further measurements to investigate this quantity and its relation to the moment of inertia and yrast levels at very high excitation in ^{26}Al.

Note added in proof: A recent calculation by Wilczynski [Nucl. Phys. A216, 386 (1973)] of the limiting orbital angular momentum for compound-nucleus formation yields the value $l_{\text{crit}} = 17$ for $^{12}C + ^{14}N$. Considering the entrance channel spin of $1\hbar$, this compares favorably with the value $J_c = 18$ which was used in our calculations at $E_{\text{c.m.}} = 36$ MeV.

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