Reaction mechanism of pn and d emission in certain heavy-ion-induced nuclear reactions

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The competition between pn and d evaporation leading to production of the same residual nucleus has been calculated in the framework of the Hauser-Feshbach theory for nine heavy-ion-induced nuclear reactions, each at several bombarding energies, for target-projectile combinations resulting in compound nuclei $12 \leq A \leq 40$. The observed very good agreement between the experimental and the statistically predicted relative cross sections for pn and d emission indicates that both these exit channels proceed via evaporation from a compound nucleus.

I. INTRODUCTION

Considerable experimental information is gradually becoming available on the competition between pn and d exit channels leading to the production of the same residual nucleus in heavy-ion-induced nuclear reactions.[1-4]

The most interesting conclusion therein is that the relevant relative cross sections in a series of nuclear reactions, far from being uncorrelated, follow a systematic trend according to which the competition between pn and d emission depends only on the maximum energy available for excitation to the $A-2$ residual nucleus[2,4] irrespective of the interacting heavy-ion system.

This systematic behavior was, in turn, utilized to extract a phenomenological relationship[2] according to which competition between pn and d emission may be predicted in experimentally uncharted nuclear reactions of interest. In fact this predictive formalism has been already employed in the literature, e.g., Ref. 5, in the study of related phenomena such as projectile breakup studies, comparison with theory, or utilization of Doppler-shift measurements. It is believed, however, that the range of applicability of the pn to d competition in the study of additional nuclear properties will be broadly extended if the reaction mechanism of both pn and d exit channels causing the observed competition systematics is ascertained.

The majority of the nuclear reactions at the bombarding energies employed in the previous experimental studies of competition[2,4] are generally considered to proceed via compound-nucleus formation. Indicatively, a detailed study of the $^{12}C+^{14}N$ reaction,[6] in which γ-ray and particle cross sections are compared with statistical-model predictions, has demonstrated that the d as well as the pn emissions are dominated by compound nucleus components.

A relevant experimental study,[3] furthermore, has provided convincing experimental evidence that the neutron-proton pair is almost exclusively produced via successive evaporation from a compound nucleus, as opposed to production from unbound-deuteron disintegration suggested by previous experiments.[7] The above considerations, however, do not ensure that in all reactions both pn and d exit channels proceed via the same reaction mechanism. In fact, it is well documented that (^{6}Li,d) reactions, certain of which are included in the present study, may proceed via direct ^{4}He transfer in contradistinction to other exit channels of the same ^{6}Li-induced reaction which may proceed via evaporation from a compound nucleus.

Hence, in order to estimate the role of compound-nucleus processes in the measured relative cross sections for pn and d emission, extensive Hauser-Feshbach calculations are performed for nine heavy-ion-induced nuclear reactions. These theoretical predictions are compared with the relevant experimental data in order to identify the reaction mechanism with which both these exit channels proceed, causing the observed systematic behavior.

II. COMPARISON OF STATISTICAL MODEL CALCULATIONS WITH THE EXPERIMENTAL RESULTS

In order to obtain a theoretical estimate of the competition between pn and d emission, the cross sections for the production of a residual nucleus by (pn + np) and d emissions were calculated, as a function of bombarding energy, in the framework of the Hauser-Feshbach theory, using the code STAPRE.[8]

In these calculations the contribution from the emission of the light particles (p, n, d and α) and γ-rays has been taken into account for each sequence of the reaction in populating specific residual states.

Previously known[9] excited states and branching ratios were explicitly considered in the calculations. For the density of the rest of the states the backshifted Fermi gas model[10] was used assuming the Lang formula.[11] The parameters entering that model are the single particle level density parameter α, the fictive ground state position Δ, and the effective moment of inertia J_{eff}. As expected, the calculated competition ratio was found to depend very sensitively on the level density parameters and in particular on α. Since the intention of the present study was to identify the reaction mechanism of both pn and d emission through the comparison between measured and calculated emission competition, no level density parameter fitting was employed in order to obtain better agreement between theory and experiment. On the contrary, the pa-

rameter values used in the present calculations were exclusively adopted from the relevant literature whereby they had been derived in independent studies of fusion evaporation reactions. These references are listed in the third column of Table I corresponding to the nuclear reaction for which theoretical calculations have been performed listed in the first column. Only for those nuclear reactions, such as $^{6}Li+^{6}Li$, for which no previous level density parameters were available, was a qualified guess of their value attempted. Thus, from this point of view we expect that the present calculations represent, if not parameter-free, at least parameter unbiased results.

Transmission coefficients for emitted light particles were obtained from optical model calculations using parameters proposed by Perey and Perey.[19] The corresponding coefficients for the heavy ions in the entrance channel were calculated according to the equations used in Refs. 20 and 21. Of the two entrance channel transmission coefficient sets thus calculated that one which best reproduced relevant experimental fusion cross section values available in the literature was selected to be used in the statistical model calculations of emission competition.

The calculated cross sections of production of the residual nuclei by pn, np, and d emission as well as the ratio σ_{pn}/σ_{d} are given in the last columns of Table I, corresponding to the bombarding energies listed in the second column. The calculations were not carried out at random bombarding energies but rather within the energy range actually employed in the corresponding experimental measurements. These results demonstrate that for any nuclear reaction the calculated σ_{pn}/σ_{d} ratio increases progressively with increasing bombarding energy, qualitatively in agreement with a similar energy dependence observed in the experimental results.[2] A detailed comparison, between theory and experiment, however, will be attempted below.

In order to estimate the effect of compound-nucleus processes in the pn and d exit channels, the statistical-model predictions of relative cross sections for pn and d evaporation are compared in Fig. 1 with relevant experiment data.

The representation used in this figure, whereby the logarithm of the ratio σ_{pn}/σ_{d} is plotted as a function of the maximum excitation energy available to the residual nucleus, is identical to that originally used[2] to identify the

TABLE I. Results of Hauser-Feshbach calculations for the production by pn and d emission of the residual nuclei commensurate with the indicated reactions at the specified bombarding energies.

Reaction	$E^{c.m.}$ (MeV)	Ref. level density parameter was adopted from	σ_{pn} (mb)	σ_{np} (mb)	σ_{d} (mb)	$\frac{\sigma_{pn}+\sigma_{np}}{\sigma_{d}}$
$^{12}C+^{12}C$	13.8	12	2.1	5.8	3.2	2.5
	15.8		9.7	11.9	3.7	5.8
$^{12}C+^{28}Si$	17.1	13	1.4	0.6	0.029	69
	22.1		1.9	0.5	0.009	268
$^{6}Li+^{16}O$	7.2	14,15,16	28.8	17.6	11.2	4.1
	9.2		72.0	41.5	20.7	5.5
	10.2		78.5	47.1	18.9	6.6
$^{7}Li+^{12}C$	7.4	13	17.0	66.4	45.0	1.9
	9.4		24.2	82.8	38.4	2.8
$^{6}Li+^{30}Si$	8.6	12,17	17.1	32.8	3.0	16.6
	10.1		30.9	50.3	3.9	20.8
	11.6		54.7	77.3	4.8	27.5
$^{16}O+^{16}O$	15.2	12,18	16.8	28.2	5.9	7.7
	17.7		25.9	43.0	5.3	13.0
	20.2		30.1	46.2	4.0	18.0
$^{16}O+^{12}C$	11.0	16	2.4	6.3	5.7	1.5
	12.0		6.6	9.3	7.8	2.0
	13.5		13.8	12.8	9.6	2.8
	16.0		25.0	16.6	9.1	4.6
$^{16}O+^{13}C$	12.3	16	6.4	2.7	0.6	14.7
	13.1		7.3	3.0	0.7	15.3
	14.6		8.3	3.2	0.7	16.4
$^{6}Li+^{6}Li$	7.3	see text	27.7	24.7	138.4	0.4
	10.9		49.7	44.6	149.2	0.6
	13.3		57.4	52.2	138.0	0.8

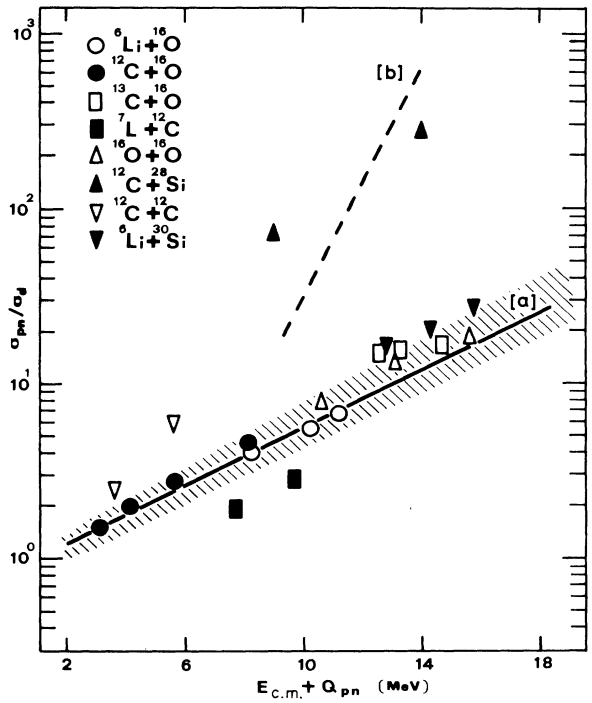

FIG. 1. Comparison between the experimental systematics (solid line) and $\sigma_{pn}/\sigma d$ values as predicted by Hauser-Feshbach calculations (data points). The shaded area about the solid line represents the experimental uncertainty. The broken line (b) represents the competition in the reaction $^{12}C+^{28}Si$ which was observed to deviate from systematic.

linear unified behavior in the competition associated with several different reactions. This representation permits us to replace individual experimental competition data by their average behavior obtained by least-square fits to the measurements, thus facilitating the comparison. Specifically, the central solid line in Fig. 1 represents the average experimental competition associated with almost all the previously investigated nuclear reactions,[2,4] while the upper broken line describes the experimental competition in the reaction $^{12}C(^{28}Si,pn/d)$ which constitutes the only previously observed deviation from the systematic trend. Finally the shaded area circumscribing the solid line defines the experimental uncertainty of the average trend as obtained by the least-squares fit.

The theoretical statistical-model predictions of Table I are represented in Fig. 1 by the data points associated with the eight nuclear reactions identified in the upper left corner of the figure. Figure 1 demonstrates that the theoretical predictions are generally in agreement with the experimental data. The experimental systematics, in particular, are remarkably well reproduced by the theory. The theoretical predictions for the deviating reaction are as well, at least qualitatively, in agreement with the measurement.

The comparison between measured and statistically predicted competition serves to illuminate the reaction mechanisms involved in both pn and d emissions, since one expects that the ratio σ_{pn}/σ_d will be very different in cases of compound-nucleus evaporation or direct transfer. The overall agreement between theory and experiment indicates, therefore, that in the reactions included in this comparison at the bombarding energies employed the cluster and multiparticle emissions proceed via evaporation from a compound nucleus.

As has been expounded in the preceding section, the values of the input parameters used in the evaporation calculations were almost exclusively adopted from the relevant literature, whereby they have been derived in independent fusion reaction studies a fact that renders the observed agreement between theory and experiment even more conclusive.

With the exception of the $(^{6}Li,d)$ reactions, which will be discussed below, all the nuclear reactions at the bombarding energies employed here are generally considered to proceed via evaporation from a compound nucleus. The present results indeed verify that this is the dominant reaction mechanism causing the observed systematic behavior.

With respect to $(^{6}Li,d)$ reactions, three of which, $^{6}Li+^{6}Li$, $^{6}Li+^{16}O$, and $^{6}Li+^{30}Si$, are considered here, there exist ambiguities as to the nature of the reaction mechanism.

Angular distribution measurements for the reaction $^{6}Li+^{16}O$, previously investigated, lead to the conclusion that at 15 MeV the mechanism is predominantly compound nucleus,[22] while at 32 MeV a direct mechanism is dominant.[14] A measurement of the competition between pn and d emission in such reactions and comparison with evaporation calculations offers a practicable means to study the reaction mechanism as a function of bombarding energy. A limited application of the method may be illustrated in the interpretation of σ_{pn}/σ_d data associated with $^{16}O(^{6}Li,pn/d)$ previously measured[2] between 10 and 16 MeV bombarding energies. These experimental data, shown in detail in Fig. 2, are therein compared with the

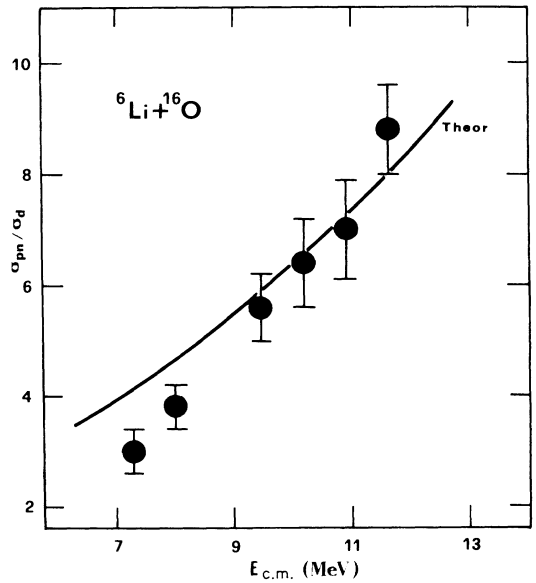

FIG. 2. Experimental relative yields for the production of ^{20}Ne by pn and d exit channels (data points) compared with Hauser-Feshbach predictions (solid line).

relevant evaporation model predictions, where an excellent agreement between theory and experiment is observed. Thus, it may be concluded that between 10 and 16 MeV in the reaction $^{16}O(^6Li,pn/d)$ both exit channels proceed essentially via the compound-nucleus mechanism, substantiating and extending the previous evidence[22] obtained at 15 MeV. Similarly, it may be concluded from Fig. 1 that between 9 and 11 MeV center of mass bombarding energy the $^{30}Si(^6Li,pn/d)$ reaction also proceeds essentially via evaporation from a compound nucleus.

Conclusions about the reaction mechanism demand, of course, a detailed individual treatment of competition data, such as that presented above. In a less rigorous way, however, if the experimental competition in a certain nuclear reaction is found to comply with the experimental systematics, one fairly safely may assume that that reaction proceeds via evaporation from a compound nucleus since it has been seen that this is the dominant reaction mechanism causing the systematic behavior.

The situation, however, becomes more ambiguous for reactions in which the competition deviates from systematics. One such reaction is the $^{12}C(^{28}Si,pn/d)$, whereby the relative probability for pn emission is significantly larger than average. It is difficult to visualize a reaction mechanism, other than compound nucleus, able to explain such a feature since one expects that in the discussed range of bombarding energies the presence of the direct-reaction mechanism would augment the emission of deuterons primarily. In fact, the Hauser-Feshbach predictions reproduce rather adequately the competition in the $^{12}C(^{28}Si,pn/d)$ reaction. It should be mentioned, nevertheless, that the calculations did not help us to explicitly recognize the factors causing the deviation from systematics. The fact, however, that the compound nucleus involved is a magic nucleus may not be irrelevant.

A second deviation of competition from the average trend has been identified in the reaction $^6Li(^6Li,pn/d)$. This reaction, which has been investigated experimentally in the course of the present study, constitutes the lightest system in which competition between pn and d emission has been measured. The experimental results, shown in Fig. 3, demonstrate that at five bombarding energies the ratio σ_{pn}/σ_d in that reaction is almost an order of magnitude smaller than the corresponding average trend, exhibiting an usually enhanced relative probability for deuteron emission, hinting, therefore of the possible presence of a direct component in the deuteron exit channel. Comparison with statistical model calculations, however, indicates otherwise. Specifically, evaporation calculations of relative cross sections for pn and d emissions, shown in Fig. 3 for two single particle level density parameter values, both reproduce rather satisfactorily the experimental measurements, although it should be noted that the predictions

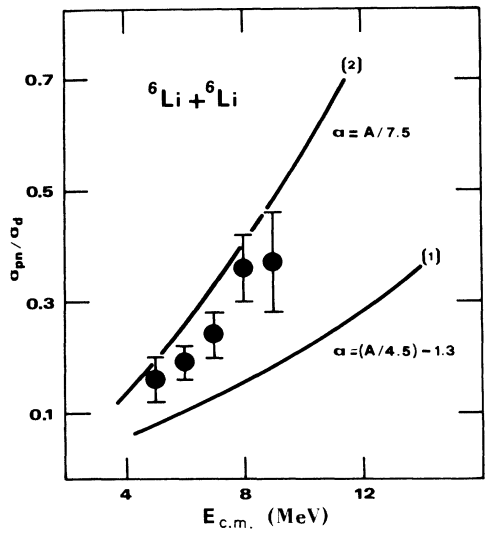

FIG. 3. Experimental relative yields for the production of ^{10}B by pn and d exit channels (data points) compared with Hauser-Feshbach predictions (solid lines) associated with two values of the level density parameter α.

corresponding to $\alpha = A/7.5$ are clearly in better agreement with experiment. The data of Fig. 3, therefore, strongly suggest that the $^6Li(^6Li,pn/d)$ reaction proceeds essentially via compound nucleus formation in spite of the unusually small experimental σ_{pn}/σ_d ratio. A certain reservation about the certainty of the above conclusion stems only from the fact that the values of the greatest input parameters necessary in the calculations are not available from independent studies. Thus, neither the fusion cross section for $^6Li+^6Li$ nor level density parameters for the nuclei involved are available in the relevant literature.

The case presented demonstrates convincingly that Hauser-Feshbach calculations of relative cross sections for pn and d emissions can account remarkably well for the experimental values. These calculations reproduce rather successfully both the experimental systematics and the two observed exceptions from the systematics, indicating that in all the investigated heavy-ion-induced reactions the cluster and multiparticle emissions both proceed via evaporation from a compound nucleus, as opposed to a direct reaction mechanism.

In light of the present conclusions, it will be very interesting to attempt to interpret certain nuclear phenomena, such as ^6Li- induced reactions at higher bombarding energies and nuclear reactions on quasimolecular resonances, in which the competition between cluster and multiparticle emission has been measured to deviate from that statistically expected.[23]

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