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COMPETITION BETWEEN LIGHT CLUSTER AND CONSTITUENT MULTINUCLEON EMISSION IN HEAVY - ION NUCLEAR REACTIONS

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Abstract

Isoproduct competition, i.e. competition between cluster and multinucleon emission leading to the same residual nucleus, emerges as a general, interesting and useful characteristic of nuclear reactions. Common properties and factors underlying the competition between pn and d as well as between p2n, dn and t evaporation are recognized and discussed. The application of the isoproduct-competition method in the delineation of the mechanisms involved in ^{7}Li-induced reactions suggests that an additional mechanism, breakup-fusion, is involved even at very low energies. Finally, the competition associated with alpha emission in the ^{12}C + ^{16}O reaction demonstrates a strong contribution from composite ^{4}He emission which cannot be accounted for by either the systematics or standard statistical calculations.

1. Introduction

Perhaps the most interesting characteristic of heavy-ion induced nuclear reactions is the large number of exit channels which open up as a result of the large values of energy and angular momentum introduced by the heavy projectile into the entrance channel.

Although, however, general is the consensus that the *number* of emitted particles is large, the issue as to what *kind* of particles, and under what conditions, can be emitted with significant intensity remains outstanding. In that respect it should be noted that an aspect of nuclear reactions, the implications of which have not been fully realized, is that all reaction modes, other that single n and p emission, involve at least potentially more than one exit channel competing for the production of the same residual nucleus. For instance, a typical heavy-ion nuclear reaction can be symbolized as follows

$$
\begin{aligned}
{}^{12}\mathrm{C} + {}^{16}\mathrm{O} \quad &\rightarrow \quad {}^{27}\mathrm{Si} + \mathrm{n} \\
&\rightarrow \quad {}^{27}\mathrm{Al} + \mathrm{p} \\
&\rightarrow \quad {}^{26}\mathrm{Al} + (\mathrm{pn/d}) \\
&\rightarrow \quad {}^{25}\mathrm{Al} + (\mathrm{p2n/dn/t}) \\
&\rightarrow \quad {}^{24}\mathrm{Mg} + (\mathrm{2p2n/dpn/dd/.../\alpha}) \\
&\rightarrow \quad \mathrm{etc.}
\end{aligned}
$$

The notation used means that all exit channels included in a parenthesis can potentially contribute to the production of the commensurate residual nucleus. Thus, in any nuclear reaction almost all residual nuclei can be produced by cluster and / or constituent - multiparticle emission.

Let us, for the sake of brevity, introduce two abreviations related to the above discussion. For self evident reasons, we may call the exit channels leading to the same residual nucleus *isoproduct exit channels*. Similarly, the relative probabilities with which these exit channels participate in the production of the same residual nucleus may be called *isoproduct competition*.

According to the traditional wisdom isoproduct competition does not exist or at best it is insignificant. In evaporation reactions, this is because conventional assumption holds that a compound nucleus can emit only p, n and alpha particles. On the other hand, in direct reactions it is usually assumed that only composite particle emission is relevant.

The above tidy picture, however, has started to change. At low energies, for instance, it has been shown that compound nuclei can substantially emit deuterons [1], tritons [2] or even complex fragments [3], while on the other hand non-statistical multinucleon emission has been identified in direct, ^{4}He-transfer, reactions [2].

Apparently isoproduct competition constitutes a rather general property of nuclear reactions. The pertinent problem is to recognize the dynamical conditions which in each case determine the relative probability for either the cluster or the constituent-multiparticle emissions leading to the same residual nucleus. It is hoped that the delineation of the factors underlying isoproduct competition associated with various light-cluster emissions will offer not only a better understanding of nuclear reactions but also a better perspective to consider the emission of different clusters within a unified framework.

Below, the already existing data on the competition between pn and d as well as p2n, dn and t emission will be critically reviewed with the purpose to summarize the essential understanding obtained therein. Furthermore, involvement of isoproduct competition in direct alpha-transfer reactions will be evaluated and finally some preliminary results associated with isoproduct competition in the alpha-particle exit channel will be discussed.

2. The experimental method

In cases of isoproduct competition, although the entrance channel and the residual nucleus are the same, the competing exit channels are distinctly different reaction modes, demanding appropriate treatment for either their experimental identification or their theoretical description. The presence and effect, however, of competing isoproduct channels cannot be distinguished by the usual methods of cross-section measurements, such as detection of single γ rays or recoiling ions. These, instead, provide the sum of the cross sections of all the channels participating in the production of a specific residual nucleus. On the other hand, in direct reactions only partial cross sections, usually associated with emitted composite particles, are measured.

An experimental method suitable to quantify isoproduct competition, based on light charged particle-gamma coincidence techniques has been proposed [4] and extensively tested [1,5]. The discrete coincident γ rays are used on the one hand to identify the heavy residual nucleus of interest, and on the other hand to provide the intensities with the help of which the *relative cross sections* of the competing isoproduct exit channels are extracted. For particle detection and identification a DE-E counter telescope of silicon detectors of various thicknessess is used. That technique restricts the observation of the competition to the production of specific *individual* excited states, taking nevertheless into account both side- and cascade-feeding to these states. Clearly, however, information concerning the production of the ground state cannot be obtained.

3. Isoproduct competition in compound-nucleus reactions

It is expected that the mechanism of a nuclear reaction will strongly influence the manner as well as the relative cross sections with which clusters and constituent nucleons are emitted.

The heavy ion reactions at the energies employed in the relevant competition studies [1,2,5,6] are generally considered to proceed via evaporation from a compound nucleus. A few of those, however, such as ^{6}Li- and ^{7}Li- induced reactions, are as well expected to proceed via a direct interaction. The mechanism of the employed reactions was conclusively ascertained via a comparison with statistical Hauser-Feshbach calculations [2,6] which implicitly assume that a compound nucleus has been formed in the reaction as an intermediate unstable species. In such cases, the energy and angular momentum introduced by the projectile are shared among many nucleons of the intermediate compound nucleus. The latter subsequently emits those nucleons or clusters which as a result of random fluctuations concentrate enough energy to "evaporate" through the surface barrier.

In what follows the competition between pn and d as well as between p2n, dn and t evaporation in compound nuclear reactions will be discussed.

3.1 Competition between pn and d evaporation

With the development of the particle-gamma coincidence technique [4], the pn over d emission competion was very soon mapped in about 20 nuclear reactions, each at several bombarding energies, for target-projectile combinations resulting in compound nuclei $12 \leq A \leq 71$ [1,5,6].

The relevant data demonstrated that for a given nuclear reaction the relative probability for the pn contribution increases with increasing bombarding energy. Otherwise, however, an interconnection among the magnitude of the competition associated with different reactions was not discernible. On the contrary, at similar bombarding energies the ratio σ_{pn}/σ_d assumes widely different values for different target-projectile combinations.

However, with an association of the σ_{pn}/σ_d ratio with the maximum excitation energy, $E_{CM}+Q_{pn}$, available to the commensurate residual nucleus, shown in Figure 1, a systematic trend emerges, illustrating a nearly linear dependence for almost all of the reactions investigated. Specifically, 18 reactions were found to comply with the systematics, while the competition in the reactions ^{6}Li (^{6}Li, pn/d) and ^{28}Si (^{12}C, pn/d) was found to deviate significantly. In all 20 reactions, nevertheless, the relative probability for multinucleon emission consistently increased with increasing bombarding energy.

It has been found instructive to visualize the competition in terms of the phase space of residual states participating in the multinucleon and cluster evaporations. The number of states available to pn and d emission were calculated for several reactions as a function of bombarding energy using Newton's formula [7]. Some typical results are plotted in Figure 2 as a function of maximum residual excitation, where it can be seen that the ratio of cross sections and the relative phase space for pn and d emission have roughly similar slopes. This comparison suggests that the increase in pn relative to d emission observed with increasing bombarding energy in all the investigated reactions may be understood in terms of a parallel relative increase in the number of states available to the pn successive evaporation. Apparently, the phase space available to multinucleon emission increases with energy faster than that available to the cluster emission simply because more nuclei, intermediate and residual, are involved in the former than in the latter decay.

Extensive Hauser-Feshbach calculations reproduced [6] remarkably well all the

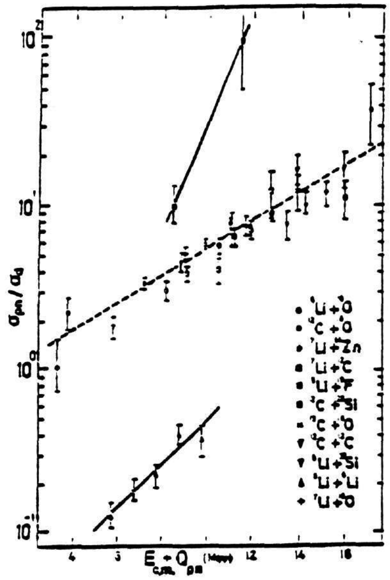

Figure 1. Experimental σ_{pn}/σ_d ratio values for various nuclear reactions as a function of maximum residual excitation

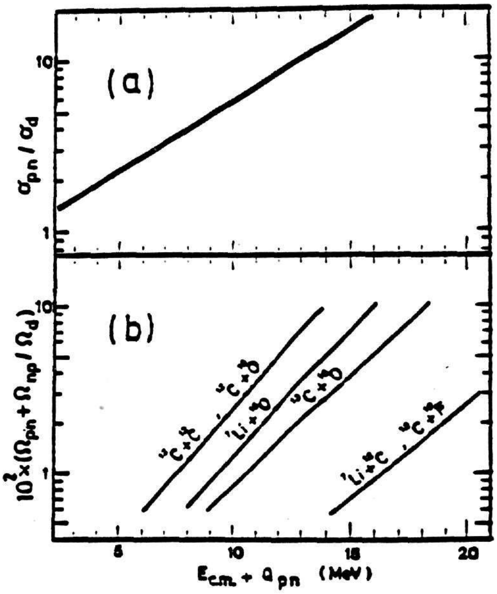

Figure 2. Comparison between the experimental systematics (a) shown in Figure 1 and calculated ratios of the number of levels available to pn + np emission over those available to d emission (b)

experimental data indicating that in all cases the cluster and multinucleon emissions proceed via evaporation from a compound nucleus, as opposed to a direct reaction mechanism.

3.2 Competition between p2n, dn and t evaporation

Measurements of the competition between p2n, dn and t evaporation have become recently available [2], for 6 heavy-ion-induced reactions, each at several bombarding energies, for target-projectile combinations resulting in compound nuclei $29<A<37$.

The properties of the above triple competition were found to be commensurate to those of the pn versus d evaporation. In particular, an association of the relative yields for p2n, dn and t evaporation with the maximum excitation energy available to the A-3 ressidual nucleus, shown in Figure 3, demonstrates again a systematic trend, irrespectively of the interacting system. According to these systematics triton cluster emission dominates at low excitation while the multinucleon p2n evaporation dominates at higher energies. At about 7 MeV of maximum residual excitation the A-3 residual nucleus is predominantly produced via p2n evaporation.

Again standard Hauser-Feschback calculations reproduced very nicely [2] the experimental competition between p2n, dn and t evaporation.

3.3 Consideration of the evaporation competition

The competition between cluster and constituent-multinucleon evaporation does not seem to depend on the interacting system. Thus, systematic trends, shown in Figures 1 and 3, were recognized, according to which the relative cross sections for cluster versus multinucleon evaporations are simply related to the maximum excitation energy available to the commensurate residual nucleus. These regularities encourage an attempt to identify common properties of different clusters, although, as it will be discussed below, it is not as yet clear whether the same factors are underlying the competition associated with emission of more massive clusters.

Firstly, with respect to the nuclear physics implications, it should be emphasized that, although the experimental systematics demonstrated in Figures 1 and 3 were very nicely reproduced by the relevant calculations, the factors causing that systematic behavior unfortunately are not as yet explicity recognized. Most likely, an unexpected interplay between density of levels and angular momentum values, which can cancel out the individual characteristics of different interacting systems, is suggested by these systematics.

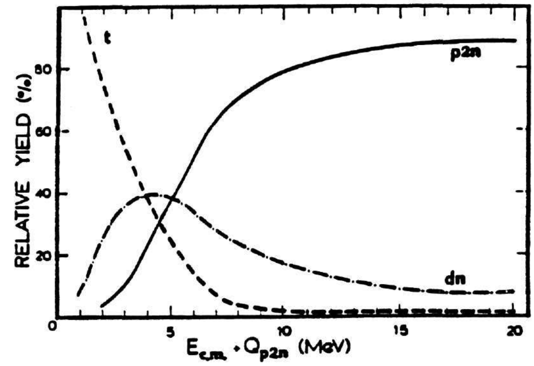

Figure 3. Systematics of the competition between p2n, dn and t evaporation

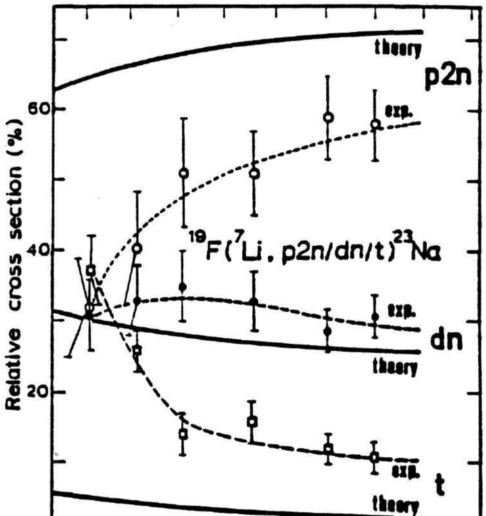

Figure 4. Experimental and statistically expected p2n, dn and t contributions

It is of course premature to try to understand the nature of the two deviations, shown in Figure 1, before understanding the nature of the systematics. Nevertheless, the facts that in the ^{12}C + ^{28}Si reaction the compound nucleus involved is a magic nucleus while the ^{6}Li + ^{6}Li is the lightest possible heavy-ion reaction may not be irrelevant.

Some comments with respect to common properties of the clusters is in order. Figures 1 and 3 clearly demonstrate that in both the evaporation of composite clusters is favored by low energy while with increasing energy the evaporation of constituent nucleons becomes dominant. A more carefull comparison of Figures 1 and 3 suggests, however, that the dissociation of d to its constituents takes place faster than the dissociation of t. This most probably results from the larger binding energy of the latter cluster, the overcome of which at relatively low energies supresses more drastically the phase space available to the multinucleon p2n than in the case of pn evaporation. At higher energies binding energy differences clearly become irrelevant. It seems that about 2 MeV of energy available per emitted nucleon is required before the multinucleon evaporation becomes dominant.

4. Isoproduct competition in direct heavy-ion reactions

In several instances, such as in ^{6}Li- and ^{7}Li-induced reactions as well as on quasimolecular resonances, the competition between cluster and constituent multiparticle emission has been found to deviate significantly from that expected from pure evaporation. The significance of these deviations as well as the information they may convey either about the mechanism of the reactions or about the structural peculiarities of the involved nuclei are not yet conclusively evaluated. Nevertheless, here we shall discuss some interesting, although preliminary, conclusions concerning p2n, dn and t emission associated with direct alpha-transfer reactions induced by ^{7}Li beams.

The triton cluster versus constituent-multinucleon competition has been studied in 5 ^{7}Li-induced reactions on ^{12}C, ^{16}O, ^{19}F, ^{30}Si and ^{51}V. In all these reactions the competition between p2n, dn and t emission was found to deviate from that statistically expected.

The experimental behavior of the reaction ^{30}Si(^{7}Li, p2n/dn/t), which is

Table 1. Relative cross sections for the production by p2n, dn and t emission of the ^{34}S residual nucleus in the ^{7}Li + ^{30}Si reaction at the specified bombarding energies

E_{CM} (MeV)	Relative cross sections (%)					
	Experimental			Theoretical		
	σ_{p2n}	σ_{dn}	σ_t	σ_{p2n}	σ_{dn}	σ_t
13.0	10 ± 3	13 ± 3	77 ± 9	85.5	12.4	2.1
14.6	26 ± 4	20 ± 4	54 ± 5	86.6	12.0	1.4

demonstrated in Table I in juxtaposition with the statistical expectations, will help to discuss its essential features as influenced by the direct alpha-transfer mechanism expected to be present. The experimental data demonstrate that the ^{34}S residual nucleus is mainly produced via t emission, although it should be noted that the competing p2n and dn contributions are not at all negligible. The comparison of the experimental relative cross sections with those expected from pure evaporation clearly suggests that the experimental competition cannot be accounted for by pure evaporation. The experimental triton contribution in particular exceeds by more than an order of magnitude that expected from evaporation, clearly indicating dominant presence of direct components in the ^{30}Si(^{7}Li,t) reaction at both bombarding energies.

The presence of multiparticle p2n and dn exit channels in the experimental measurements suggests on first inspection coexistence of direct and evaporation mechanisms in the ^{30}Si(^{7}Li, p2n/dn/t) reaction. If, however, the p2n and dn emissions in this reaction resulted from pure evaporation, their relative cross sections should have been correctly predicted by the relevant statistical calculations. The experimental multiparticle contributions, however, are in striking disagreement with the statistically expected. The σ_{p2n}/σ_{dn} ratio for instance assumes experimental values 0.8 ± 0.3 and 1.3 ± 0.3 at 13.0 and 14.6 MeV, respectively, compared to 6.9 and 7.2 expected from pure evaporation. Clearly, therefore, in this reaction not only the cluster but also the multiparticle emissions proceed predominantly via a non-statistical mechanism.

Apparently the nature as well as the energy dependence of the physical mechanisms coexisting in ^{7}Li-induced reactions are not at all clear, suggesting that these issues remain outstanding in spite of the opposite views more often than not expressed or implied in the relevant literature.

With respect to the energy dependence, it should be noted that the relative probabilities for multiparticle emission are significantly larger at 14.6 than at 13.0 MeV (Table 1). That information by itself, however, does not necessarily ensure an increasing contribution from non-statistical multiparticle emission with increasing bombarding energy since it can be equally well undersstood as due to an enchancement of the evaporation component against the contribution from the coexisting ^{4}He direct transfer mechanism. In fact such an anomalous energy dependence of the competition between direct and compound-nucleus mechanisms has been previously suggested for the reaction ^{12}C(^{7}Li,t) where a larger compound-nucleus component seems to exist at 38 than at 25 MeV bombarding energy [8].

In order to resolve the above question detailed excitation functions of the competition between p2n, dn and t emission were obtained. Such data associated with the $^{19}F(^{9}Li,\ p2n/dn/t)$ reaction are demonstrated in Figure 4 together with the theoretical contributions expected from pure evaporation. Rather unexpectedly the deviations of the experimental data from the statistically expected are the largest at the lower bombarding energies. As the bombarding energy increases experimental and theoretical contributions tend to be aligned.

If one as usually assumes that only compound-nucleus and direct ^{4}He- transfer mechanisms contribute, the conclusion suggested by Figure 4 is inevitable. The increasing bombarding energy favors the compound-nucleus component against the direct-reaction contribution. The rest of the investigated ^{7}Li-induced reactions demonstrate a similar behavior with that shown in Figure 4. Thus, either in ^{7}Li-induced reactions the competition between compound-nucleus and direct reaction mechanism has an anomalous energy dependence or an additional mechanism is present.

Preliminary measurements of absolute cross sections for the production of ^{23}Na in the above reaction suggest that a third mechanism must be present. This in all likelihood is associated with breakup of the projectile followed by ^{4}He transfer to the target nucleus.

Such breakup modes are not, at least conventionally, anticipated at the relatively low energies employed, although it should be noted that the experimental method used is especially suited to single out reaction events even of very low probability as long as these lead to the production of the A-3 residual nucleus.

5. Isoproduct competition associated with ^{4}He emission

Very little if anything is known about the next in complexity competition between 2p2n, dpn, dd, tp and ^{4}He emission leading to the same A-4 residual nucleus.

Table 2. Relative cross sections for the production by 2p2n, dd, dpn, tp and ^{4}He emission of the ^{24}Mg residual nucleus in the $^{12}C + {}^{16}O$ reaction at 75 MeV bombarding energy

	Relative cross sections (%)	
Exit channel	Experimental	Theoretical
^{4}He	55 ± 10	6.6
tp	14 ± 3	37.0
dd+dpn	25 ± 5	44.5
2p2n	6 ± 2	11.4

Recently, however, that competition has been measured in the $^{12}C + ^{16}O$ reaction at bombarding energies well above the threshold for the disintegration of the alpha particle to its contituent nucleons.

Relevant experimental results obtained at 75 MeV bombarding energy are shown in Table 2 together with those expected from pure evaporation. Obviously theory and experiment are in a rather violent disagreement.

The above measurement corresponds to 10.6 MeV of energy available for excitation to the commensurate ^{24}Mg residual nucleus after 2p2n emission. According to the discussion presented in section 3.3 one qualitatively expects that at that excitation the composite ^{4}He evaporation would have been almost completely substituted by evaporation of the constituent multiparticles. While, however, that qualitative prediction is in rather good agreement with the results of the relevant statistical calculations (Table 2), this is not the case with the experimental data since the latter demosntrate an unexpectedly large probability for composite ^{4}He emission. Therefore, either the $^{12}C(^{16}O, \alpha)^{24}Mg$ reaction does not proceed via evaporation from a compound nucleus, or otherwise the factors underlying the isoproduct competition associated with ^{4}He evaporation are not any more the same with those identified to influence the isoproduct competition in the case of d and t evaporation.

If the disagreement between theory and experiment observed in Table 2 were due to the direct character of the reaction, one would normally expect that disagreement to be caused primarily by the composite ^{4}He emission. This seems to be presently the case. Specifically, in Table 3 which demonstrates a comparison between theory and experiment of the same reaction, where however the composite ^{4}He contribution has been ignored in both theoretical and experimental data, a rather reasonable agreement between theory and experiment is observed, suggesting that the disaray previously observed in Table 2 is in fact almost exclusively caused by the unexpectedly strong composite ^{4}He component seen in the experiment.

Table 3. Relative cross sections for the production by 2p2n, dd, dpn and tp emission of the ^{24}Mg residual nucleus in the $^{12}C + ^{16}O$ reaction at 75 MeV bombarding energy

	Relative cross sections (%)	
Exit channel	Experimental	Theoretical
tp	32 ± 6	39.6
dd+dpn	56 ± 10	47.6
2p2n	12 ± 4	12.8

Almost unanimous is the consensus in the literature that at the bombarding energies employed here the $^{12}C(^{16}O, \alpha)^{24}Mg$ reaction proceeds via evaporation from a compound nucleus, with the singular exception of one investigation [9] which has suggested otherwise. The present preliminary results lend support to the latter view. Certain reservations stem from the opinion that the standard statistical calculations, which were proven extremely successful in reproducing the isoproduct competition associated with d ant t evaporation, are not any more sufficient to describe the competition associated with ^4He evaporation. We are thus attempting to test the effect of various parameters which are not normally available in standard statistical calculations, such as deformation or even superdeformation which has been suggested [10] to characterize certain neighboring nuclei in this mass region.

Presently, nevertheless, the unexpectedly large relative cross section for composite ^4He emission observed in the reaction $^{12}C + {}^{16}O$ remains outstanding.

6. Conclusions

Isoproduct competition, i.e. competition between cluster and constituent -multinucleon emission leading to the same residual nucleus, emerges as a rather *general characteristic* certainly of compound-nucleus and very probably of direct heavy-ion reactions.

Furthermore, it seems to be a rather *interesting characteristic* demonstrating unsuspected, thought-provoking, properties.

Finally, it constitutes a rather *useful characteristic* which can be implemented in the study of additional nuclear properties, such as the reaction mechanism, projectile breakup, utilization of Doppler-shift measurements as well as conditions for a meaningful comparison between theoretical and experimental cross-section values and the optimum experimental conditions for the discovery of virtual clusters.

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