Angular momentum effects in preequilibrium cluster emission

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The preequilibrium emission of α particles was studied by observing the precompound decay of the $^{65}Zn^*$ composite system. Several entrance channels were used, covering a range of angular momenta up to about $40\hbar$. A model interpretation is presented which does not employ cluster preformation assumptions or parameters. The results suggest that angular momentum conservation governs preequilibrium cluster emission to a large extent.

The preequilibrium emission of clusters has been used[1-6] as a probe to obtain information on the preformation of clusters in nuclei. In these studies, existing preequilibrium models were supplemented by assumptions pertaining to the behavior of preformed clusters in nuclei, e.g., cluster state densities, and various preformation probability parameters were introduced. Parameter values were adjusted to fit experimental data and were compared to other sources of information on cluster preformation, such as the α decay of nuclei,[7] reasonability of coalescence radii,[8] and purely statistical coalescence.[3] All of these approaches, however, neglected the influence which the composite system angular momentum might bear on the emission of clusters versus that of nucleons.

In order to investigate angular momentum effects, the (average and maximum) angular momentum at which a composite system is produced may be varied by appropriate choices of the projectile energy and mass. This comes at the price, however, of simultaneously varying the excitation energy, the number of degrees of freedom excited in the target-projectile fusion, and the composite nucleus which is produced. As a consequence, several entrance channels are needed to disentangle the influence of one of these variations from that of any other, preferably entrance channels which will form one and the same composite system, as such a choice will minimize the influence of model parameters pertaining to the particular system, such as Coulomb barriers, level densities, etc.

For this purpose, we have supplemented existing preequilibrium data[8] on the $^{65}Zn^*$ composite system with the spectra of charged particles associated with several additional entrance channels summarized in Table I. In all of these experiments, conventional ΔE-E detector telescopes were used, substituting Si detectors by NaI scintillators where necessitated by the observable ejectile energies. Monitor counters were employed to calibrate the telescopes against elastic projectile scattering and obtain absolute cross sections. Particle identification was generally better than 2% (peak to valley ratio). Additional experimental details may be found elsewhere.[8-10] The particle spectra recorded at backward angles were used to construct the evaporative components of the data assuming an isotropic angular distribution. The results were well reproduced by a standard evaporation calculation[11,12] and subtracted from the total angle integrated spectra to yield preequilibrium emission spectra free of any appreciable equilibrium contamination.

In order to compare conveniently cluster and nucleon spectra resulting from various channels with one another, the ejectile energies were linearly scaled to have the high energy ends of the spectra (as determined by the reaction Q value, kinematics, and bombarding energy) and the evaporation peaks line up for any two spectra. The scaling was confined to the abscissae of the spectra and not extended to affect the bin sizes $d\epsilon_\alpha$ and $d\epsilon_p$ entering the ordinate. It was used both on the experimental data and the calculated spectra so that it does not affect the agreement between the two in any way. Rather, it just provides a convenient way of presentation, as after scaling, α and proton preequilibrium emission can be compared to one another by plotting emission cross section ratios

$$\sigma_\alpha/\sigma_p=\frac{d\sigma}{d\epsilon_\alpha}(\alpha,\epsilon)\Big/\frac{d\sigma}{d\epsilon_p}(p,\epsilon) \tag{1}$$

as a function of the scaled ejectile energy, ϵ, and data pertaining to different entrance channels can be shown in a common diagram.

Figure 1 shows experimental data obtained with the entrance channels listed in Table I and $\alpha+{}^{61}Ni$ data con-

TABLE I. Summary of systems investigated.

Entrance channel	Composite system
^{61}Ni + 50.7 MeV α	$^{65}Zn^*$ ($E^*=52.5$ MeV) (Ref. 9)
^{53}Cr + 82.1 MeV ^{12}C	$^{65}Zn^*$ ($E^*=77.6$ MeV) (Ref. 10)
^{51}V + 96.4 MeV ^{14}N	$^{65}Zn^*$ ($E^*=92.2$ MeV) (Ref. 10)

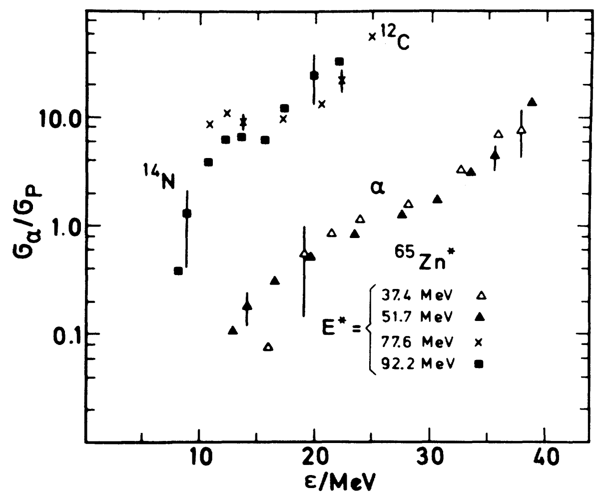

FIG. 1. Preequilibrium emission cross section ratios for α emission versus that of protons as a function of the scaled ejectile energy ϵ. Symbols refer to the entrance channels listed in Table I and used in Ref. 8.

tained in Ref. 8 in such a fashion. The (typical) experimental errors plotted include uncertainties introduced by subtracting out equilibrium components. The striking feature seen in Fig. 1 is that the preequilibrium emission of α particles compared to that of protons is strongly dependent upon the entrance channel mass asymmetry. Associated with the different mass asymmetries are markedly different ranges of angular momentum populated in the composite system, about 0–20$\hbar$ and 0–40$\hbar$ in the α- and heavy-ion-induced reactions, respectively. It is tempting to see whether the different angular momenta can explain the different α to proton preequilibrium emission cross section ratios.

Closed formula preequilibrium models calculate particle decay rates by applying the reciprocity theorem to the ejectile under consideration rather than the composite system as a whole. When this concept is to be extended to cluster emission, it requires knowledge of the probability at which clusters are available in the composite system and at which they are suitably excited to be emitted into the continuum. Such information is not available on an *a priori* basis. We propose to avoid this problem by applying reciprocity to the composite system as a whole, much in the spirit of the evaporation model. This requires that all of the residual states considered be accessible from any of the states considered for the composite system. We assume strong configuration mixing to meet this requirement. As this assumption is also made[13] in the exciton model (see, e.g., Ref. 14), it comes as no surprise that our formulation resembles a spin dependent exciton model formulation very closely. Two more assumptions are employed in order to facilitate numerical calculations. First, we assume that the orbital angular momentum of the ejectile, l, will always couple to the composite system spin, $J_{\rm CS}$, so as to minimize the residual spin, J_R, i.e.,

$$J_R = J_{\rm CS} - l \ . \qquad (2)$$

This is, perhaps, not unreasonable in view of the forward peaking of preequilibrium angular distributions observed experimentally, and it is supported by the spin alignment of yrast levels populated in preequilibrium reactions.[15] Second, we assume that the cluster to be emitted is entirely formed of excited particles (excitons) so that emission of a cluster of mass a_x from an n-exciton state will lead to an $(n - a_x)$-exciton state in the residual nucleus. As a consequence, no pickup of nucleons from below the Fermi energy is considered.

Under these assumptions, the particle emission rate may be written as (see Table II for notation)

$$\lambda_{n,x}(\epsilon_x, J_{\rm CS}, J_R) = \frac{2s_x+1}{\pi^2 \hbar^3} \epsilon_x \mu_x \sigma^l_{\rm inv}(\epsilon_x) \frac{\rho_{n-a}(U, J_R)}{\rho_n(E, J_{\rm CS})} \ , \qquad (3)$$

with

$$U = E - S - \epsilon_x \ ,$$

$$J_R = J_{\rm CS} - l \ ,$$

$$\sigma^l_{\rm inv}(\epsilon_x) = \pi \lambda\!\!\!^{-2}(2l+1)T_l \ ,$$

$$\rho_n(E,J) = \frac{g(gE)^{n-1}}{p!h!(n-1)!} \frac{2J+1}{2\sqrt{2\pi}\hat{\sigma}^3} \exp\left[-\frac{J(J+1)}{2\hat{\sigma}^2} \right] \ ,$$

i.e. using Ericson-type[16] particle hole level densities and a spin dependence suggested by Williams.[17] Considering only the particle emission decay channels, the preequilibrium spectrum arising from all n-exciton states of the composite system is given by

$$\frac{d\sigma}{d\epsilon_x}(n) = \sum_{J_{\rm CN}} \sigma_{J_{\rm CN}} \frac{\sum_{J_R} \lambda_{n,x}(\epsilon_x, J_{\rm CS}, J_R)}{\sum_x \int_0^E \sum_{J_R} \lambda_{n,x}(\epsilon_x, J_{\rm CS}, J_R) d\epsilon_x} \ , \qquad (4)$$

with $\sigma_{J_{\rm CN}}$ being the entrance channel partial fusion cross section (appropriately depleted for terms $n > n_0$). Obviously, the competition by internal nucleon-nucleon collisions is neglected completely in Eq. (4). This is not of crucial importance, however, as long as only ratios of

TABLE II. Definition of symbols.

s_x, μ_x, $\lambda\!\!\!^{-}$	Spin, reduced mass, and de Broglie wavelength of ejectile, respectively.
$\sigma^l_{\rm inv}$	Partial inverse cross section.
E, S, ϵ_x	Composite system excitation, separation energy, and ejectile channel energy.
g	Single particle level density.
p, h, n	Number of excited particles, holes, and excitons, respectively.
$\hat{\sigma}$	Spin cutoff parameter as determined from compound reaction studies.

cross sections for cluster versus nucleon emission are considered. It affects only the relative strength, with which the $n_0, n_0+2, \ldots$, etc. stages contribute to the total result. In summing up these contributions, we have estimated their relative strength by a conventional preequilibrium calculation,[12] which matches the observed proton spectra. Variations of these relative strengths within reasonable limits affect the results only marginally, as do[18] variations of the spin cutoff parameter $\hat{\sigma}$. The procedure used may be considered as effectively normalizing the calculation to the experimentally observed proton spectra.

The preequilibrium emission cross section ratios predicted by our calculations also depend on the initial exciton number, n_0, determined by the entrance channel, as one goes from a low value associated with the α projectile to high values describing the heavy ion entrance channels. A similar influence has already been observed in earlier treatments.[8] It is of comparable significance as that exerted by angular momentum conservation. Variation of n_0 within one entrance channel and reasonable limits, however, changes our results only within the margins stated below. We used $n_0=5$ and $n_0=12$, 14 for the α- and heavy-ion-induced reactions, respectively. These values were obtained from up-to-date conventional[12] preequilibrium calculations required to fit the proton spectra.

Figure 2 compares the results of both a spin dependent and a spin independent calculation to the experimental data. Clearly, the inclusion of angular momentum conservation changes the model predictions by more than an order of magnitude and gives much closer agreement with experimental data than a treatment neglecting angular momenta. In view of the model assumptions given above, we estimate that a variation of calculated results within a factor of 2–4 has no significance.

Figure 3 displays the total relative α and proton preequilibrium emission cross sections calculated as a function of the incident partial wave. Angular momentum conservation leads to a strong dominance of nucleon emission

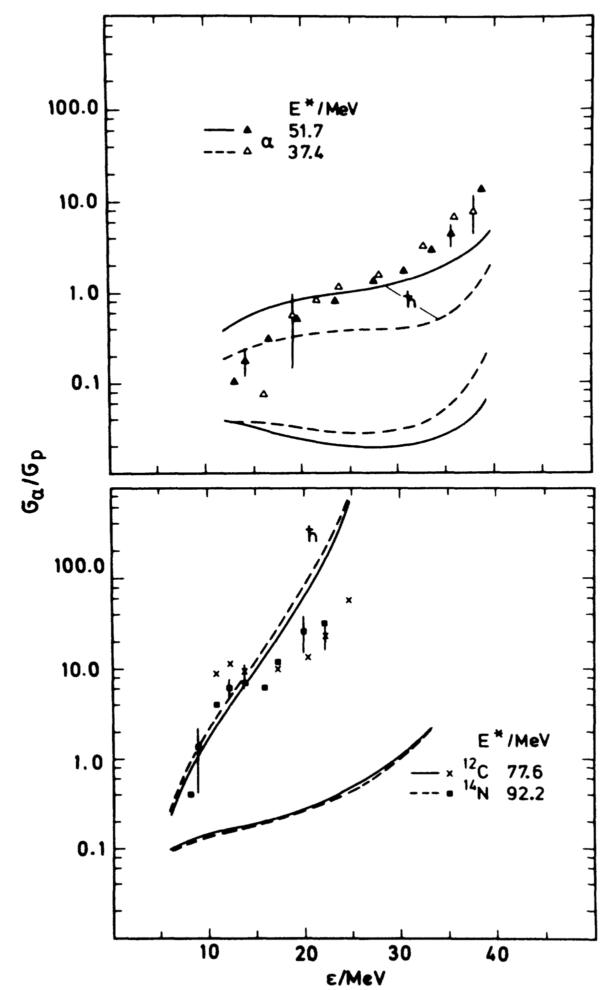

FIG. 2. Preequilibrium emission cross section ratios as given in Fig. 1 compared to model calculations. Spin dependent calculations are indicated by the symbol $\hbar$.

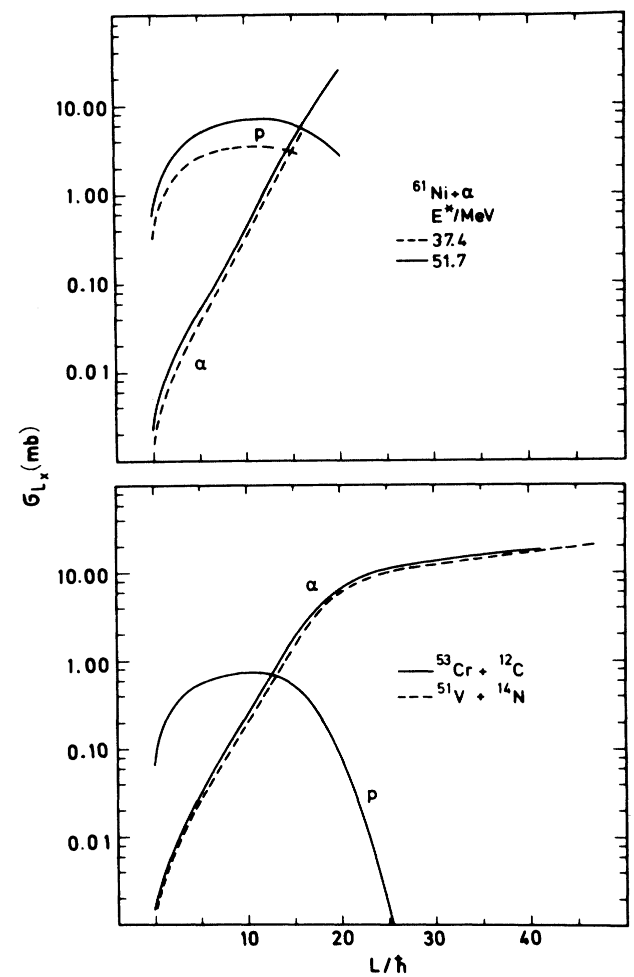

FIG. 3. Total preequilibrium emission cross sections σ_{LN} for α and proton emission as a function of the incident partial wave. Curves are calculated neglecting internal transitions and must be considered *relative* emission cross sections. They are drawn up to the grazing angular momentum.

for low partial waves and an even stronger cluster dominance for high partial waves. The range of angular momenta excited in the heavy-ion-induced reactions extends far into that cluster saturation region, whereas in the α-induced reactions the cluster domination region is hardly touched. Consequently, the α to nucleon emission ratios tend to be much higher for the heavy-ion-induced reactions, just as is found experimentally.

Angular momentum conservation, even if taken into account in a most basic form, strongly influences cluster versus nucleon preequilibrium emission. If it is included in model calculation, gross features of experimentally measured data are reproduced without any assumptions about preformation of clusters in nuclei. The inability of nucleons to carry off large amounts of angular momentum greatly reduces their emission in preequilibrium processes if high angular momenta are excited by the entrance channel. Preequilibrium emission of clusters is then greatly favored, and the similarity of the ^{12}C- and ^{14}N- induced data suggests that this is not attributable to an α substructure of the projectile.

Extended and more refined calculations in the framework outlined above are possible and present no conceptual difficulties. Extensions conceivable regard clusters other than α particles and additional entrance channels. The calculations may be refined by doing full angular momentum coupling, by explicitly including the internal decay rate competition, and by exploring effects in changes in the state densities involved.[17] There is no provision in our approach, however, for pickup-type reactions, in which the emitted cluster is formed of excitons *and* nucleons below the Fermi energy. This mechanism may be dominant for nucleon-induced reactions, for which inclusion of angular momentum conservation is less important.

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