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Possible dynamic effects in the particle decay of ^{59}Cu compound nuclei

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The slopes of the energy spectra of p, d, t, and α particles emitted from ^{59}Cu nuclei formed in the reaction of ^{32}S$+^{27}$Al at a bombarding energy of 150 MeV are described by statistical-model calculations in which the deformation is frozen during the first two steps of the deexcitation chain. The resultant fits to the high-energy portions of the spectra are comparable to those previously obtained by modifying the spin dependence of the level density, suggesting that dynamic effects may be important in evaporation from light nuclei.

In the last few years, a number of experiments have been performed to study angular momentum effects in the decay of light-mass compound nuclei formed in heavy-ion-induced complete fusion reactions at excitation energies around 100 MeV.[1-6] The experimental data, consisting of energy spectra, cross sections, and angular distributions of the emitted charged particles, have been compared with statistical-model calculations performed with modern statistical-model codes in attempts to ascertain properties of the emitting nuclei. The comparison with the model calculations may be used to check the degree of equilibration of the emitting system, or conversely, to study the shape and structure of the hot nucleus at high spin if the statistical evaporative origin can be demonstrated.

In particular, the decay of nuclei in the mass region $A \sim 60$ has been studied with the aid of the computer code CASCADE (Ref. 7) or its Monte Carlo version CACARIZO.[4] For spin regions where the rotating liquid-drop model[8] (RLDM) predicts near spherical shapes, experimental data for ^{67}Ga (Ref. 3) and ^{59}Cu (Refs. 4–6) compound nuclei are very well described by standard statistical-model calculations. When the angular momentum is increased to values for which the RLDM predicts significant deformations, important differences between the experimental and calculated spectra are observed. In particular, the calculations employing RLDM yrast lines[7,9] with standard level-density formulations and transmission coefficients lead to more high-energy and fewer low-energy (near barrier) α particles than experimentally observed. These differences between the calculation and experiment can be removed by the introduction of a spin-dependent modification to the relative level density and lower emission barriers.

This paper is devoted to the modeling of the level density. In previous works, the level density was increased as a function of the emitter spin J, by lowering the yrast line by a quantity $\Delta E(J)$. The lowering of the yrast line produces a level-density enhancement which was estimated to be ~ 100 in the case of ^{59}Cu at $J \sim 34\hbar$ and $E_x \sim 60$ MeV.[5] The origin of this effect is not clear. The absolute enhancements of the level density which appear to be required at the higher spins are as much as an order of magnitude greater than suggested by calculations of the variation of the level density with deformation[10-13] and also somewhat larger than estimates derived from observations of statically deformed nuclei.[14-16]

In fact, it is the spin dependence of the relative level density rather than the absolute value which is of particular significance in the deexcitation calculation. The approach used in Refs. 3–6 leads to a decrease in the rate at which the relative level density diminishes with increasing spin. This has the effect of reducing the rate of emission of higher-energy α particles relative that of nucleon emission.

An alternative approach which leads to a similar variation of the relative level density was reported in an earlier exploration of limiting models for decay from deformed nuclei.[17] In one of the limiting models explored in that work the deformation of the compound nucleus is assumed to be a frozen degree of freedom, i.e., it is assumed that there is no readjustment of shape of the nascent final nucleus and no change of collective to intrinsic excitation during the particle emission. The level density of the residual nucleus at spin J_{final}, which strongly affects the phase space for the statistical decay, is then computed using an yrast energy which includes the deformation energy of the parent nucleus and not, as usual, that predicted by RLDM for the daughter.

We have employed this idea in calculations of particle spectra using the code CASCADE. The structure of the CASCADE code does not allow us to maintain the deformation equal to that in the first step during the entire decay chain because the memory of the initial angular momentum is lost after each single decay step. However, since nucleon evaporation from ^{59}Cu carries away little angular momentum the deformations of ^{58}Cu and ^{58}Ni are practically equal to that of the parent ^{59}Cu. We present here both calculations with the deformation frozen for particles emitted from ^{59}Cu (first step) and calculations in which the deformation is also frozen for ^{58}Cu, ^{58}Ni (second step).

In Figs. 1–4 we compare the energy spectra of light

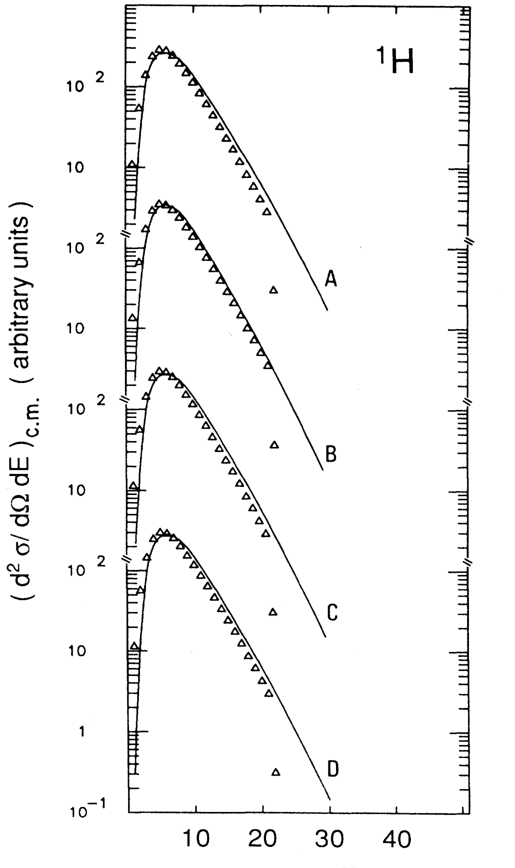

FIG. 1. Center-of-mass proton spectra (^{32}S+^{27}Al at $E_{\text{lab}}=150$ MeV, $\theta_{\text{lab}}=30°$) compared with CASCADE calculations. *A*, standard calculation; *B*, calculation with adjusted yrast line; *C* and *D*, standard calculations freezing the shape degree of freedom in the first (*C*) and in first and second (*D*) steps of the deexcitation chain.

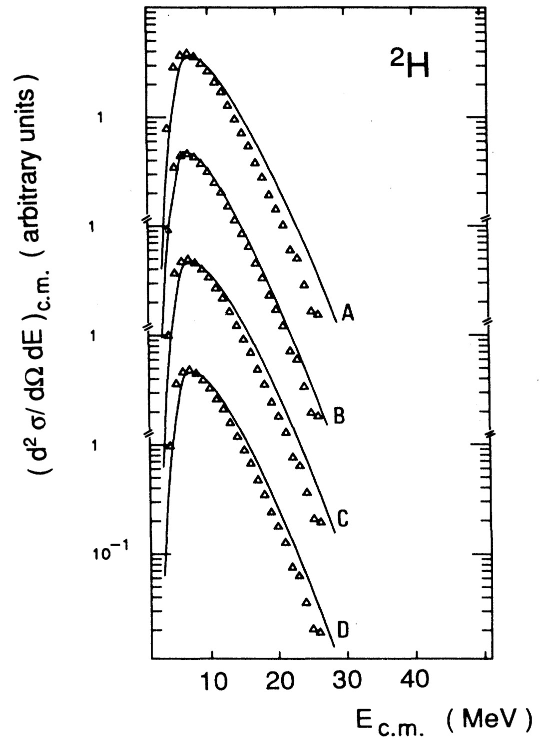

FIG. 2. Same as Fig. 1 but for deuterons.

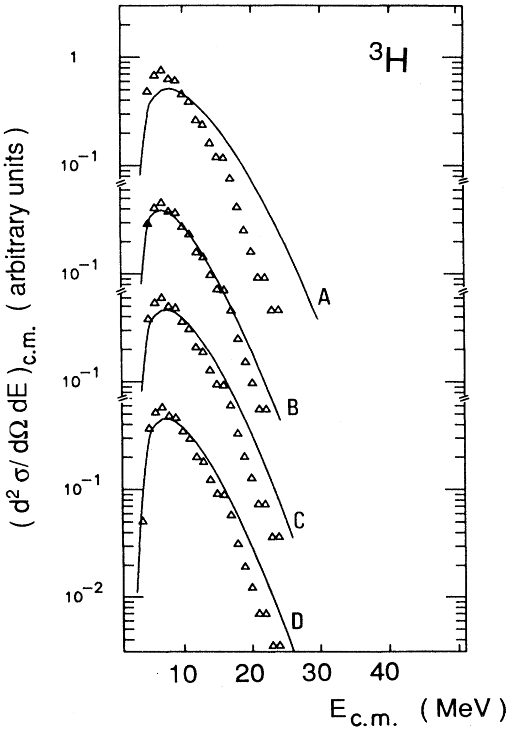

FIG. 3. Same as Fig. 1 but for tritons.

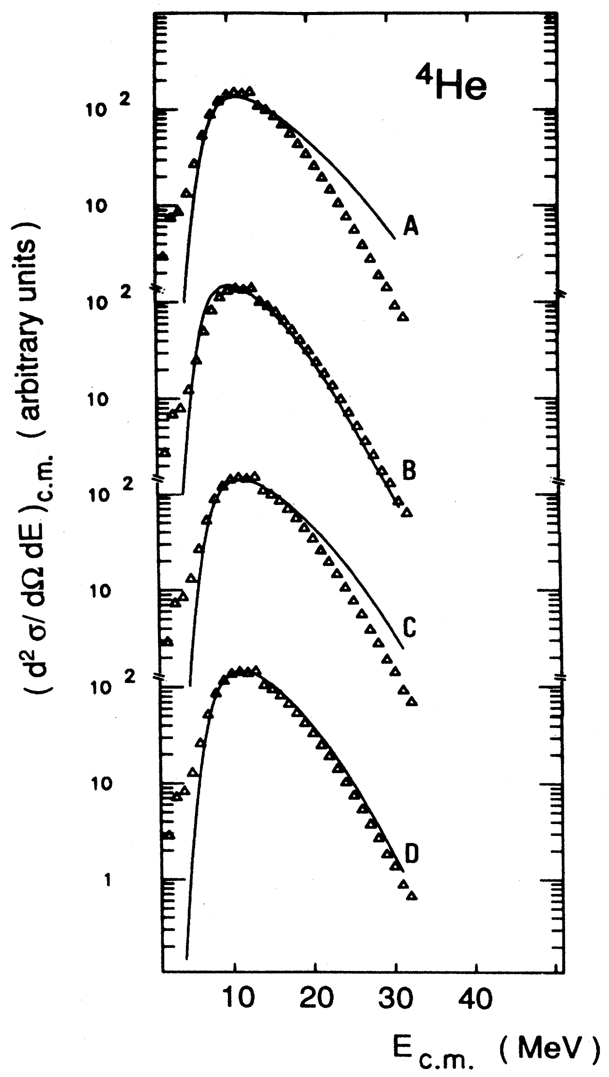

FIG. 4. Same as Fig. 1 but for α particles.

particles emitted in the decay of ^{59}Cu formed in the ^{32}S+^{27}Al reaction at 150 MeV with different model calculations. Type *A* refers to the standard statistical-model calculation (set 1 input to the CASCADE code in Ref. 6) whereas type *B* contains an adjusted yrast line (set 2 in Ref. 6). These calculations use the equilibrium deformation of the final nucleus at each decay step. Types *C* and *D* are calculations using the set 1 parameters but freezing the deformation degree of freedom, in *C* only during the first step of the cascade, in *D* in the two first steps as discussed above. Both data sets include transmission coefficients calculated with a reduced emission barrier. The barriers for α-particle emission in units of the barrier for emission from the spherical nucleus[6] are 0.92 in the calculations with set 1 (*A*, *C*, *D*) and 0.81 in that with set 2 (*B*). These reduced barriers provide the best fit to the spectra when taken together with the other assumptions of each calculation.

Figures 3 and 4 show that for the tritons and α particles the striking deviations between the experimental spectra and those resulting from the standard statistical model are removed in calculations employing frozen deformations. The type-*C* calculation is sufficient to describe the spectra of tritons, which are predominantly emitted in the first step of the decay. In the case of α particles, the type-*D* calculation yields a result not far from those obtained with an *ad hoc* adjusted yrast line. As evidenced in previous work, protons and deuterons are less sensitive to the spin dependence of the level density and therefore to this freezing of the nuclear deformation (see Figs. 1 and 2).

A more severe test of the models is shown in Fig. 5 where, following the procedure described in Ref. 5, cross sections of α particles emitted from the high-spin window $27\hbar \leq J \leq 39\hbar$ are compared with calculations. Here again, calculation *D* is seen to provide good agreement with the data.

It seems that the freezing of the nuclear deformation at the top of the decay chain is capable of removing the discrepancies between the shapes of experimental spectra and those predicted by the statistical model and provides an alternative approach to that of the level-density enhancement. Since level-density enhancements can be expected in deformed nuclei, attributing the observed spectra entirely to the dynamics of shape relaxation may not be appropriate. A complete calculation would take into consideration both the level density in deformed nuclei and the dynamics of the competing processes.

We note that to the extent that the dynamics of shape relaxation is important, compound nucleus decay is strongly dependent on the characteristic time scales of

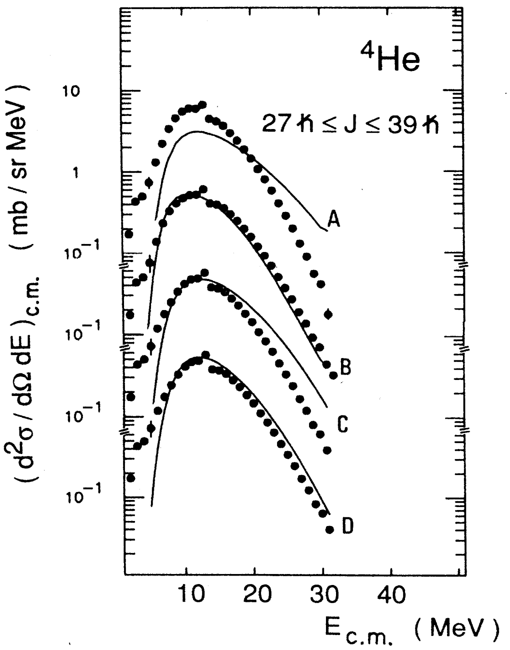

FIG. 5. Same as Fig. 1 but for the α particles emitted from the angular momentum window $27\hbar \leq J \leq 39\hbar$. These spectra are obtained by a subtraction procedure described in Ref. 5.

particle emission and collective shape changes.[18,19] Studies of these effects in light nuclei can perhaps provide complementary information to those determined from related effects being explored in heavy nuclei in which prefission particle emission is employed to probe the dynamics of shape evolution.[20] Such effects appear to become important at a temperature near 3 MeV (neutron emission lifetime of $\sim 10^{-21}$ s). We also note that the population of superdeformed nuclei as seen in intermediate mass nuclei may be governed by similar dynamics.

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