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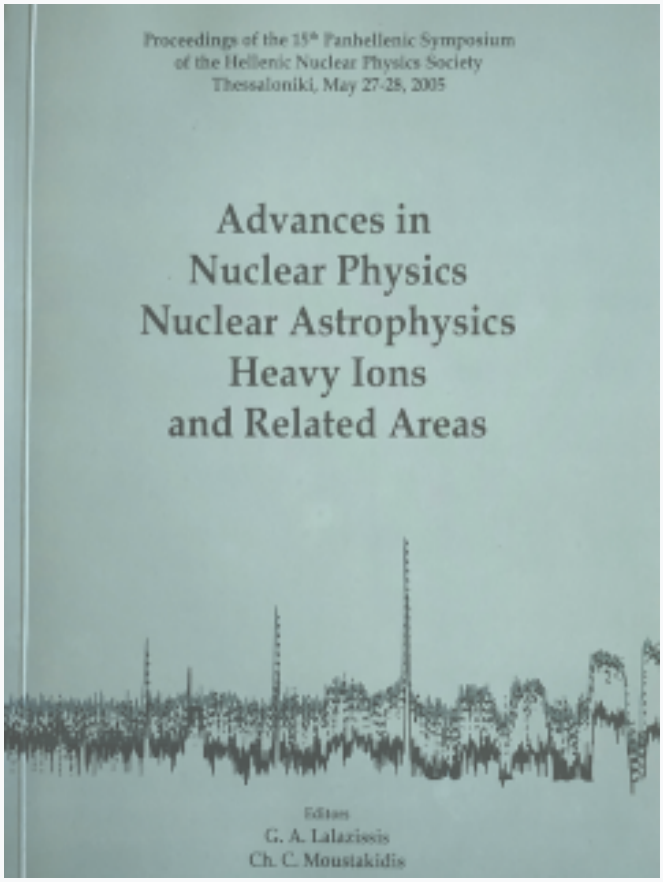

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Sequential binary decay of highly excited ^{40}Ar*

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Abstract

The sequential statistical binary decay of the highly excited compound nucleus ^{40}Ar* is described with an extended evaporation formalism implemented in a Monte-Carlo multi-step statistical model code. Asymmetric mass splittings involving nucleon emission up to symmetric binary ones are treated within the evaporation formalism, in a unified manner. Emission of heavy fragments in their ground and excited (particle-bound or unbound) states is considered. The evolution of the final mass distributions from ^{40}Ar* is studied as a function of the initial excitation energy, in the range from 45 up to 405 MeV. The population of final states originating from the decay of intermediate mass fragments in particle-bound and particle-unbound states (side-feeding) is discussed. Results are compared with an alternative description in which the time-dependent decay process is described by rate equations for the generation of different fragment species.

Complex fragment emission in low and intermediate energy nuclear reactions is a topic of experimental and theoretical interest. The emission of complex or Intermediate Mass Fragments (IMF) in the decay of compound nuclei formed in complete or incomplete fusion reactions has been established [1].

Binary mass splittings (and their associated secondary decay processes) have been incorporated in the statistical model. Statistical model treatments dealing with this issue could be classified as (a) "Consistent" in which both the binary decay and the evaporation stages are described within the same evaporation formalism (e.g. Weisskopf [2] or Hauser-Feshbach [3,4], and (b) "Hybrid" treatments in which binary divisions are treated in the framework of the transition stage theory and particle emission

by Hauser-Feshbach [5]. Besides long computation times, "consistent" treatments often involve coupling of two codes; one to determine the primary partitions and another one to calculate the secondary decays. Furthermore, it is occasionally assumed that binary decays occur at the first decay step (or one of the first few decay steps) of the deexcitation cascade [2,3]. Although such an assumption seems reasonable at relatively low excitation energies, it cannot be justified at high energies.

Alternative treatments have also been developed. For example, J. Richert and collaborators [6,7] describe the disassembly of an excited nucleus as a time-dependent process in which clusters are emitted sequentially. The dynamics is described by rate equations for the generation of different species and the rate at which the system deexcites and expands isotropically in space. Decay rates were treated with the Weisskopf formalism [8]. As an application, the sequential decay of $^{40}Ar^*$ was studied as a function of the initial excitation energy. The final mass distributions revealed interesting features of the compound nucleus decay, without providing however, a clear understanding of the way IMF emission affects the final mass distributions as well as certain aspects of their evolution with excitation energy [6].

In order to elucidate features of the compound nucleus deexcitation related to sequential binary decay, we developed a Monte-Carlo multistep code involving fragment emission in both ground and excited states (particle-bound or unbound). Decay widths of particles and clusters emitted in ground or excited bound states were calculated according to the Weisskopf formalism [8]. For fragment emission in unbound states, we employ a generalization of the decay width expression to the case when both fragments of a binary division process may be excited [6,9]. Pairing corrected level densities were calculated according to the Fermi gas model. Transmission coefficients for light particles and heavy fragments were calculated with the optical model with parameters interpolated from the compilation of Ref. [10]. Gamma-ray emission in the form of E1 transitions was taken into account

with a Lorentzian strength function characteristic of the giant resonance with parameters given in Ref. [11].

The Monte-Carlo procedure was implemented in the code MECO (Multiple fragment Evaporation COde) [12]. Events from the primary calculation (involving emission of unbound fragments) were fed again into MECO. Their deexcitation was calculated and the event structure was updated, in order to preserve correlations with the primary decay sequence. Statistical model calculations were performed for the deexcitation of ^{40}Ar*. A total of 172 decay channels were considered. They consisted of γ, n and the ground states of $^{1-3}$H, $^{3-4}$He, $^{6-8}$Li, $^{7-9}$Be, $^{10-12}$B, $^{11-15}$C, $^{13-17}$N, $^{15-19}$O, and $^{18-21}$Ne, covering the range from extreme asymmetric up to symmetric divisions. A total of 111 excited bound states were included for Li and heavier fragments. Unbound excited states were considered for B and all heavier fragments. Level densities were calculated with the Fermi gas model and an excitation energy independent level density parameter $a = A/8$.

Figure 1 shows the final mass distributions from ^{40}Ar* excited at 45.0, 101.25, 180.0, 281.25 and 405 MeV. These excitation energies correspond to initial temperatures of 3.0, 4.5, 5.0, 7.5 and 9.0 MeV (matching the calculations of Ref. [6]). They span a range from low up to extremely high energies, close to the complete dissociation limit. In all panels, the low-mass region corresponds to the emitted light particles and clusters. The evaporation residue mass distribution ($A \sim 30-35$) becomes broader and shifts down in mass, with increasing excitation energy. At the two highest excitation energies, it disappears; the system disintegrates mainly with the emission of unbound fragments. At the highest excitation energy, the mass distribution consists of the emitted particles and clusters with $A \leq 4$, and a small contribution from the secondary decays of the unbound fragments ($A \sim 10$).

Figure 1 may be compared with the results of Ref. [6]. There is an overall qualitative agreement, with the exception that our calculation shows a persistence of medium mass events ($6 \leq A \leq$

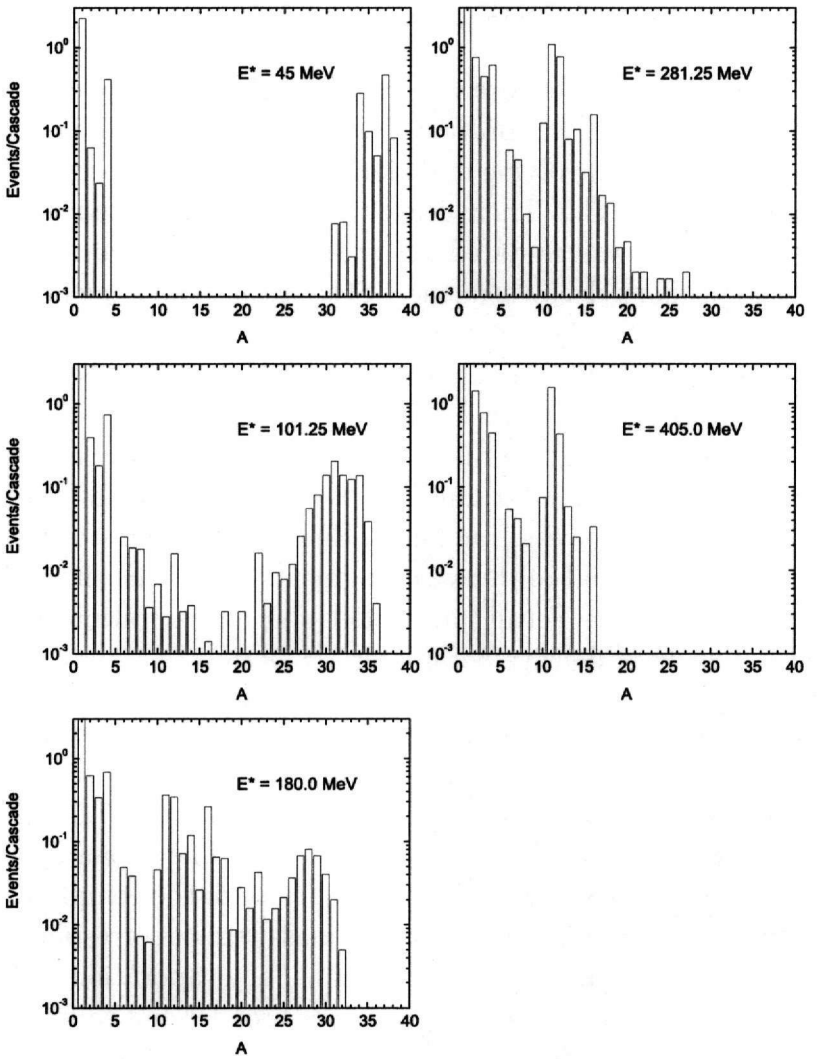

Fig. 1. Final mass distributions from the statistical decay of $^{40}Ar^*$, at the indicated initial excitation energies.

19). These differences can be attributed to the treatment of level densities and transmission coefficients. Specifically, the authors of Ref. [6] use a simple exponential level density form and classical (sharp-cutoff) inverse cross sections.

From an examination of the IMF multiplicity distributions per

cascade, we realize that at low excitation energies, emission of at most one IMF is possible, whereas at higher excitation energies, emission of one or two IMF's may occur with a higher probability. The decay step probability distributions show that at low excitation energies, first-chance IMF emission dominates. At higher excitation energies, the probability distributions attain similar shapes and IMF emission probabilities for decay steps up to the fifth are comparable. These results justify our multistep approach.

We also find that intermediate mass residues at T=4.5-6.0 MeV originate from emitted IMF's in bound states and involve deexcitation remnants of IMF's emitted in unbound states; a result which could not be deduced by the procedure of Ref. [6].

In contrast to the monotonic increase of the decay widths of $A \leq 4$ ejectiles with excitation energy, we find that decay widths of fragments with $Z \geq 3$ increase at low and decrease at high E*, after reaching a maximum. This is observed in both the ground and the excited state decay widths and implies that emission of the heaviest fragments may be more favourable at some intermediate rather than the highest excitation energies of the present study. This behaviour can be explained in terms of the drastic reduction of the level density parameter $a = A/k$ for mass partitions close to symmetry as opposed to minute changes caused by the emission of low mass ejectiles.

From an analysis of the excitation energy distributions of the unbound fragments it follows that their available excitation energy has not fully reached the complete dissociation limit, even at the highest excitation energy of ^{40}Ar*. This excitation energy deficit appears in the total kinetic energy of the emitted fragments.

Summarizing, we have developed a Monte-Carlo, multistep evaporation code, in which sequential binary decay and evaporation are treated in a unified framework. The deexcitation of ^{40}Ar* was studied in a wide excitation energy range, up to the limit

of complete dissociation. Our procedure is capable to trace the feeding of final residues from bound and unbound emitted IMF's. At the highest excitation energies of the present study, IMF's are predominantly emitted in particle-unbound states and their production is suppressed due to level density limitations. Our results on the final mass distributions qualitatively agree with the calculation of Ref. [6], based on a different approach. Some differences in the final mass distributions, predicted by the two methods, are attributed to different treatments of level densities and transmission coefficients.

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