Decay Process of Excited Fragments in $^{40}$Ar + $^{13}$C at 27.5 MeV/A

J. Richert and P. Wagner
Centre de Recherches Nucléaires et Université Louis Pasteur, Strasbourg, France

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We investigate the nature of the disassembly process leading to the mass and isotopic distributions of fragments which were recently measured in the reaction $^{40}$Ar on $^{13}$C at an energy of 27.5 MeV per nucleon. The experimental distributions of intermediate and heavy mass species are compatible with a sequential decay mechanism. Calculated isotopic distributions are also in satisfactory agreement with the experiment. A moment analysis of the mass distributions in the spirit of percolation theory is performed. We do not see the expected critical behaviour of the system as a function of the temperature. We present some arguments about the reasons for this behaviour.

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1. Introduction

Fragmentation of nuclei is now commonly observed in intermediate energy heavy ion reactions. Two different types of mechanisms have been proposed. The first one assumes a violent and quasi-instantaneous splitting of highly excited bound aggregates into particles and clusters of particles. Models following this mechanism have been proposed and an impressive amount of data has been quite successfully reproduced in this framework [1–9]. This mechanism is at variance with the more trivial evaporation process which cannot be excluded at least at low energy. There the disassembly is slow in time. An initial excited source may either simply evaporate particles and clusters of particles [10] or the process may even be of multisequential nature in the sense that the source may emit excited clusters which themselves decay further on into smaller pieces in a chain process [11–12].

Up to now it seems that there exists no precise experimental signal for the existence of pure sequential or multisequential evaporation processes in intermediate energy heavy ion physics although signs for this type of mechanism have been found [13–14]. Only multifragmentation models including possible final evaporation effects from primary fragments [2–7] have been directly confronted with the experiment.

Some time ago we applied our model [11] to the study of the argon projectile in $^{40}$Ar on $^{68}$Zn reactions [15–17]. A careful analysis of isotopic distributions showed that multisequential decay can be ruled out on ground of excitation energy consideration [18], the process is certainly fast and may effectively be explained in the framework of a simple minded abrasion-ablation picture [19].

Recently however, experimental mass and isotopic distributions were measured for the system $^{40}$Ar + $^{13}$C in reversed kinematics at 27.5 MeV/nucleon and an incomplete fusion mechanism was suggested [20–21]. The possible formation of a more or less equilibrated and long living intermediate system produced in the partial fusion of target and projectile is intuitively well adapted to a situation in which multisequential decay may play a non negligible role. We aim to analyse this point in the present paper. We shall briefly recall the essence of the model in Sect. 2, then give some details about the experimental analysis of the reaction mechanism in Sect. 3 and compare the measured mass and isotopic distributions from $^{40}$Ar + $^{13}$C with distributions which are obtained from different incompletely fused initial aggregates decaying through a multisequential process. In Sect. 4 we shall finally discuss the possible existence of a critical behaviour of sequentially decaying sys-
tems through a moment analysis which has already been introduced in the framework of a percolation approach to nuclear fragmentation [22].

2. Multisequential Decay

We sketch only briefly the essential features of the model. Details can be found in [11-12]. Define $P(i_x, i_v, t)$ as the yield of bound clusters with $i_x$ protons and $i_v$ neutrons at time $t$. The sequential break-up dynamics is described by the rate equations.

$$\frac{d}{dt} P(i_x, i_v, t) = \sum_{j > i} W_{j \rightarrow i} P(j_x, j_v, t)$$

$$- P(i_x, i_v, t) \sum_{j < i/2} W_{i \rightarrow j}$$

where $\{W_{j \rightarrow i}\}$ are the transition rates per time unit for a cluster $j(j_x, j_v)$ to decay into $i(i_x, i_v)$ and $j - i(j_x - i_x, j_v - i_v)$. The initial conditions are fixed by $P(i_x, i_v, 0) = \delta_{i_x, Z} \delta_{i_v, N}$ for a cluster with $Z$ protons and $N$ neutrons. The set of coupled (1) is integrated in time along with the equations of conservation of the total energy (kinetic, binding, excitation and Coulomb interaction between the fragments). This fixes, at each time step, the global excitation energy of the decaying system as well as an average radius of isotropic expansion which, in return, allows to calculate the Coulomb energy between the emitted fragments.

The model of [11] has been improved on several points. Recoil effects in the binary decay of clusters and the acceleration effects of the Coulomb field between the clusters in the calculation of the expansion dynamics have been taken into account. The corrections do not sensibly affect the actual calculation of the production yields.

3. Mass and Isotopic Distributions of Fragments Produced in $^{40}$Ar + $^{13}$C

The reaction $^{40}$Ar on $^{13}$C has been studied recently at 27.5 MeV per nucleon along with other systems and the possible reaction mechanism compatible with the observed mass distributions has been investigated [20-21]. One may figure out several processes, all leading to the formation of an excited system which decays into particles, light and intermediate mass fragments. These processes are essentially direct particle transfer from the projectile to the target like, for example, $^{40}$Ar($^{13}$C, $^9$Be)$^{44}$Ca* and $^{40}$Ar($^{13}$C, $^6$Li)$^{45}$Sc*, target break-up followed by the capture of one of the fragments by the projectile and complete fusion.

However incomplete fusion seems to be the most probable process [21]. The reaction goes in two steps. At the beginning of the collision preequilibrium particles and (or) clusters are emitted from the interacting ions and the remaining cluster forms an incompletely fused excited system which decays. The analysis performed under this assumption with a simple minded model [23] is consistent with the experimental analysis for final residue masses $A \geq 25$. It comes out that an average of 9 mass units is ejected in the first step and the remaining incompletely fused aggregate acquires an excitation energy corresponding to a temperature of 5–6 MeV in the framework of the Fermi gas model with $a = A/8$.

One may ask how the heavy cluster formed in this second step may decay. We suppose here that multisequential decay is at work. Since we have only vague experimental hints about the mass and excitation energy of the intermediate heavy cluster we choose the initial mass to lie between 42 and 48 and the excitation energy to correspond to a temperature $T_0 = 5$–6 MeV. The multisequential decay calculations are performed for fixed mass and temperature which is not completely realistic since several clusters with different masses and energies certainly contribute. This is however the best we can do since, as already mentioned above, neither the mass nor the energy distribution of the intermediate source are experimentally well known. Hence we look here at plausibility arguments for the existence of multisequential decay rather than at a precise comparison with the experiment which is unfortunately not available.

Last it should be mentioned that the incompletely fused system may acquire compression energy and that its mass itself may depend in some way on the impact parameter. The acquired angular momentum may play a role in the decay process. An estimate using the results from a well-known sequential decay model indicates that the effects might get sizable for $l > 30 h$ [24]. We could not take these effects into account in our model.

The calculation of mass distributions for different clusters and energies show the best agreement with the experimental distributions measured at $\theta = 7^\circ$ for $A \geq 25$ for initial clusters with masses $A = 44, 45$ and $T_0 \sim 5.5$ MeV. Figure 1 shows the final ($t = \infty$) distributions for the intermediate $^{44}$Ca*, $^{44}$K*, $^{45}$Ca* and $^{45}$Sc* species. A least square fit procedure has been used in order to compare the calculated and non-normalised experimental spectra. A close inspection of the Figures shows that the agreement is best for $A = 44$ (Ar + 4 particles) but is still good for $A = 45$. This is surprisingly consistent with the aforementioned predictions about the size and the excitation energy of the most probable incompletely fused remnant, i.e. 9 preequilibrium particles and $T_0 \geq 5$ MeV.