Results on two-, three-, and four-body events from the $^{100}\text{Mo} + ^{100}\text{Mo}$ and $^{120}\text{Sn} + ^{120}\text{Sn}$ collisions around $E/A = 20\text{ MeV}$

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Received April 30, 1991; revised version July 8, 1991

Events with 2, 3 and 4 heavy-fragments ($A \geq 20$) have been detected in the reactions $^{100}\text{Mo} + ^{100}\text{Mo}$ at $E/A = 18.7, 23.7\text{ MeV}$ and $^{120}\text{Sn} + ^{120}\text{Sn}$ at $E/A = 18.4\text{ MeV}$. The experiments were performed with an array of 12 detectors which together covered a large fraction of the forward hemisphere and allowed a high detection efficiency for these events. Masses and energies of all fragments have been reconstructed by means of an improved version of the kinematic coincidence method. The probabilities $P_3$ and $P_4$ of producing 3- and 4-body events were found to depend mainly on the dissipated energy rather than on the bombarding energy, thus indicating that their origin lies more in the decay properties of the excited fragments than in the dynamics of the interaction. Emission of light particles from the composite system is shown to become more relevant with increasing bombarding energy and may explain the drop of the $P_3$ and $P_4$ curves at high energy losses. Small deviations of the $P_3$ and $P_4$ curves at 23.7 $A\text{ MeV}$ from those at lower bombarding energies were used to estimate the amount of a possible pre-equilibrium light particle emission as a function of impact parameter.

PACS: 25.70.−z; 25.70.Lm

1. Introduction

The general features of heavy-ion nuclear reactions at low bombarding energies ($E/A \leq 10\text{ MeV}$) are well known. Reaction classes such as fusion-fission, quasi-fission, deep-inelastic and quasi-elastic scattering result in exit channels containing two heavy fragments. Apart from these binary reactions, the other major class of reactions is fusion-evaporation where the exit channel is characterized by only one heavy fragment. Reactions which produce 3 or 4 heavy fragments in the exit channel are usually strongly suppressed.

One exception to this general rule is the sequential-fission phenomenon. If one of the colliding nuclei is heavy enough, then after a quasi-elastic or deep-inelastic interaction this nucleus can undergo a fission step producing a 3-body exit channel. If both colliding nuclei are heavy, then 4-body exit channels can be produced with reasonable probability. The phenomenon of sequential fission has been well studied for very heavy nuclei and has been used as a probe to measure the spin and linear momentum transferred in the collision.

As the bombarding energy increases above $E/A = 10\text{ MeV}$, heavy fragment multiplicities greater than two are observed with increasing abundance. The role of sequential and instantaneous (multi-fragmentation) mechanisms in explaining these many-body exit channels is presently a subject of much debate. It can be expected that the processes are governed by different time scales concerning: (i) the interaction time of projectile with target, (ii) the equilibration of different degrees of freedom, (iii) the lifetime of the highly excited nuclei and (iv) the time of competing deexcitation modes, where the evaporation of nucleons can be very fast, but the dynamical process of fission is expected to be rather slow. Certainly, the sequential-fission phenomenon in dissipative collisions must still be present, at least at moderate energy losses. The larger possible excitation energies available at the higher bombarding energies should greatly amplify the fission probability for less fissile deep-inelastic fragments. Thus sequential fission may also be important for reactions between light and/or medium heavy nuclei at these larger bombarding energies.

A limited number of experiments have already investi-
gated sequential-fission reactions in collisions between medium mass nuclei at bombarding energies between $E/A = 10$ and 15 MeV. Awes et al. [1] have shown that the probability for 3-body events in the $^{58}\text{Ni} + ^{58}\text{Ni}$ reaction at $E/A = 15.3$ MeV is consistent with the statistical fission of one of the deep-inelastic fragments. In contrast, Glässel et al. [2] find larger 3-body probabilities than expected from statistical fission calculations for the $E/ A = 12.5$ MeV $^{129}\text{Xe} + ^{125}\text{Sn}$ reaction. They find other evidences also suggesting that the fission step is not completely decoupled from the initial deep-inelastic interaction and conclude that the sequential-fission step in this reaction is of a non-equilibrated nature. Studies of 3-body events in $E/A = 15$ MeV $^{40}\text{Ar}$ induced reactions on targets from $^{27}\text{Al}$ to $^{90}\text{Zr}$ [3, 4] have been interpreted as resulting from a more instantaneous breakup mechanism with competition from sequential-fission processes for the heavier targets.

Due to the wide diversity of conclusions concerning the nature of the 3-body events in the above reactions, more systematic studies are needed to address the question of the relative role of the instantaneous and sequential mechanisms. It would also be useful to start investigations of 4-body and higher multiplicity events. At intermediate bombarding energies there is a definite need for more complete experiments, covering all major reaction channels, delivering results reaching beyond the incomplete momentum transfer data, which are based on the observation of one or two heavy fragments. Such data cannot give an overall energy-balance of the reaction, like the total kinetic energy loss TKEL, and it is often not clear if the missing momentum has to be attributed to pre-equilibrium nucleon emission or to fast evaporated particles or to a heavy-fragment decay. In view of these considerations, we have extended a systematic investigation [5] of many-fragment events in the $^{100}\text{Mo} + ^{100}\text{Mo}$ reaction from bombarding energies of $E/A = 12$–18 MeV up to $\approx 24$ MeV. An improved detector set-up permitted a large fraction of the solid angle for heavy fragments in the center-of-mass frame to be covered. This greatly increased the efficiency for detecting 3-body events and allowed meaningful results to be obtained for 4-body events as well.

This paper is the first of two papers reporting on the investigations of many-fragment events in symmetric reactions between $^{100}\text{Mo}$ nuclei at $E/A = 18.7$ and 23.7 MeV and between $^{120}\text{Sn}$ nuclei at $E/A = 18.4$ MeV. The experimental details and the general results are reported in this paper, whilst in a future paper [6] a detailed phase-space analysis of the detected 3-body events will be presented, which concludes that most 3-body events produced in non-central collisions are associated with a sequential-fission mechanism. In this paper, the general global properties of the 2-, 3- and 4-body events are discussed with special emphasis to the probabilities of the various event classes as a function of the dissipated kinetic energy. Some indications as to the sequential or instantaneous nature of all 3- and 4-body events are obtained from these probability curves. An attempt will be made to explain the features of the probability curves in terms of the excitation energy produced in the collision, which may allow the magnitude of the pre-equilibrium light particle emission to be inferred.

The contents of the present paper are as follows: the details of the experimental set-up and the method of extracting kinematical quantities are discussed in Sect. 2. The measured cross sections and probabilities of the 2-, 3- and 4-body events are presented in Sect. 3, while in Sect. 4 the implications of light particle emission from the composite system are discussed.

2. Experimental techniques

2.1. Experimental set-up

Two experiments were performed with symmetric systems. In the first experiment, beams of $^{100}\text{Mo}$ and $^{120}\text{Sn}$ at energies of 18.7 and 18.4 A MeV, respectively, were supplied by the Unilac accelerator of GSI-Darmstadt. The beam pulses reached the target at the repetition rate of 9 MHz and with a pulse width of about 500 ps.

In the second experiment, a $^{100}\text{Mo}$ beam of 23.7 A MeV was delivered by the GANIL accelerator in Caen. The repetition rate was 7.1 MHz and the pulse width was about 1 ns.

Both experiments were performed with one unique experimental set-up, which was first mounted in the large vacuum vessel of the “Z4” beam-line in Darmstadt, then transported to Caen and assembled in the “Nautilus” chamber.

The targets consisted of isotopically enriched foils of metallic $^{100}\text{Mo}$ and $^{120}\text{Sn}$, with a thickness of about 250 $\mu$g/cm$^2$. Both target foils were manufactured with a rolling technique to avoid the presence of a backing material.

The heavy fragments produced in these reactions were detected with the experimental set-up sketched in Fig. 1a. It consisted of twelve identical large-area position-sensitive parallel-plate avalanche counters (PS-PPAC), arranged in three groups and mounted in an axially symmetric configuration around the beam axis. The distance from the target was largest for the most forward-angle detectors and progressively smaller for the two more backward-angle detector groups. This choice of the distances not only provided longer flight-paths for the more forward-going particles, but also reduced the solid angle of the most loaded detectors, thus more evenly distributing the counting rates.

In the polar plot of Fig. 1b, each point corresponds to a fragment detected by one of the PS-PPAC in the reaction $^{100}\text{Mo} + ^{100}\text{Mo}$ at $E/A = 18.7$ MeV. In this representation, the distance of the point from the center of the plot represents the scattering angle $\theta_{lab}$ and the polar angle represents the azimuthal angle $\phi$. The detector groups match nicely and cover, altogether, about 75% of the solid angle in the forward hemisphere. It should be stressed that the forward hemisphere is the most important in this work as most of the products from symmetric reactions are expected to be emitted there. The advantages of such a large coverage of the physically relevant solid angle will be clear soon.