Multifragment emission in reactions of ^{84}Kr on Ag and Au at 17.7, 27, and 35 MeV/nucleon

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CR 39 solid state nuclear track detectors have been used to study the reaction products of 17.7, 27, and 35 MeV/nucleon ^{84}Kr on Au and Ag. The visual detectors allow studying interactions producing two or more correlated intermediate mass fragments in the final state. The characteristics of these events are such that they probably arise from a fragmentation process of the quasitarget or some intermediate zone. The cross sections of 3, 4, and (5+6) correlated fragments increase with increasing ^{84}Kr incident energy for both targets.

INTRODUCTION

For many years, solid state nuclear track detectors (SSNTD) have been used in the study of heavy ion interactions.[1–6] There have been reported, the so-called multipronged events where up to six correlated heavy fragments have been observed, using this technique, in ^{238}U+U, Pb, and Au reactions at 10 and 16.5 MeV/nucleon.[7] Similar information has also been reported more recently with other kinds of detection.[8–13] In general, experimental data concerning three-body production mechanisms agree independent of the method of observation. The fact that the deep inelastic (DI) mechanism is progressively replaced by other mechanisms such as evaporation,[14] sequential fission,[15] multifragmentation process described in the statistical liquid drop model,[16] and in percolation processes,[17] at higher energies makes it important to study the evolution of multifragment event cross sections at higher energies. At less than 10 MeV/nucleon most of the events observed are binary or ternary ones arising from fission after complete or incomplete fusion of the projectile with the target.

We have measured the cross section for multipronged events as a function of ^{84}Kr projectile energy on Ag and Au targets for bombarding energies of 17.7, 27, and 35 MeV/nucleon. In this work we show that the contribution of higher multiplicity events increases with increasing bombarding energy. This could be a consequence of a new type of mechanism.

EXPERIMENTAL

The incident ^{84}Kr beams were delivered by the UNILAC of the GSI in Darmstadt, Germany, at 17.7 MeV/nucleon and by GANIL in Caen, France, at 27 and 35 MeV/nucleon with beam fluxes on the order of 10^6 Kr ions/cm^2. All Ag and Au targets were bombarded perpendicular to their surfaces. The targets consisted of layers of 1–2 mg/cm^2 of Ag or Au evaporated on one surface of the SSNTD CR 39 (Ref. 18) detectors. This arrangement produced a 2π detection geometry in the laboratory system. The target thickness was determined with an accuracy of about 5%.

Chemical development was carried out in 5N NaOH at 60 °C. The chosen etching time of 4 h produced well developed tracks that still remained distinct from tracks of the incident beam. The number of beam particles was determined by counting their tracks directly on the detector surface. Combined with the number of multipronged events and the target thickness, this allowed calculation of the cross sections.

RESULTS AND DISCUSSION

Under our etching conditions the threshold of detection in CR 39 was about 8 MeV cm^2/mg. It was not possible to detect tracks less than 3 μm long. Figure 1 illustrates the domain in which fragments can be detected. All particles to the right of the boundary can be detected while those to the left (cross-hatched region) escape detection. In multipronged events there is also an angle limitation of about 5° around the beam axis where it is not possible to observe tracks. Around 90° to the beam there is also a small angle limitation (from $\approx$87° to 90°, with our etching conditions). An overall charge resolution of $\pm$5 charge units was obtained up to $Z\approx45$. Beyond this point, the Z determination is less precise. It should be emphasized that our thresholds lie below those obtained currently in other detection systems (see, for example, Granier *et al.*;[9] these authors give efficiencies limits in their work).

Among all events, we have selected those with two or more visible fragments issued from the same reaction. As can be seen in Fig. 2, we have classified as 3-pronged events all reactions having three detected fragments as well as those having two fragments with relative projected angle on the detection plane less than 175° (indirect events). Due to momentum conservation, these latter events are associated with a third fragment which escapes detection. Moreover, some 4- and 5-pronged events were

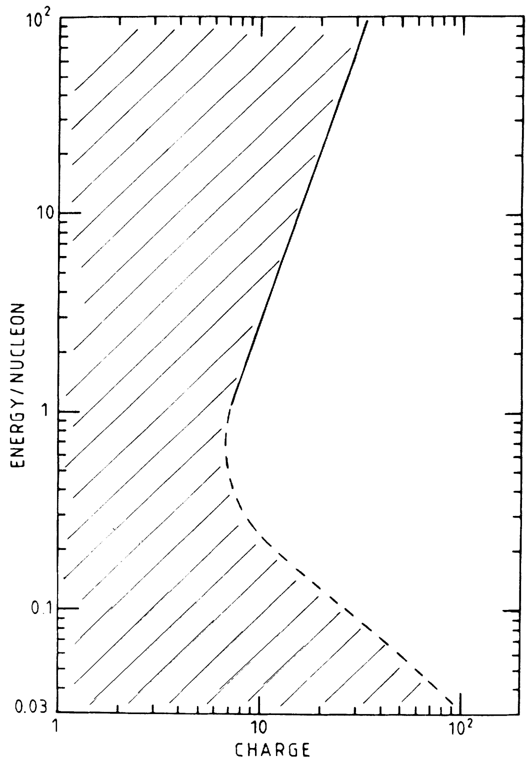

FIG. 1. CR-39 detection thresholds represented in an energy per nucleon versus fragment charge plot. In the hatched region detection efficiency is zero. The boundaries take into account the etching conditions leading to a 8 MeV cm^2/mg threshold (solid curve) and the shortest track (3 μm) which can be detected unambiguously (dashed curve).

found to be, respectively, 5- and 6-pronged events after the same analysis. The charge and energy of the detected fragments can be determined using our calibration based on the measurement of the geometrical track parameters (lengths, angles) and the etched tip radius.[19,20] As an example, we give the relationship between the angle θ relative to the beam axis and the charge for indirect 3-pronged events in Fig. 3 for the reaction ^{84}Kr+Au, and for events having three visible prongs in Fig. 4. The grazing angle for this reaction at 17.7 MeV/nucleon is 12.9°.

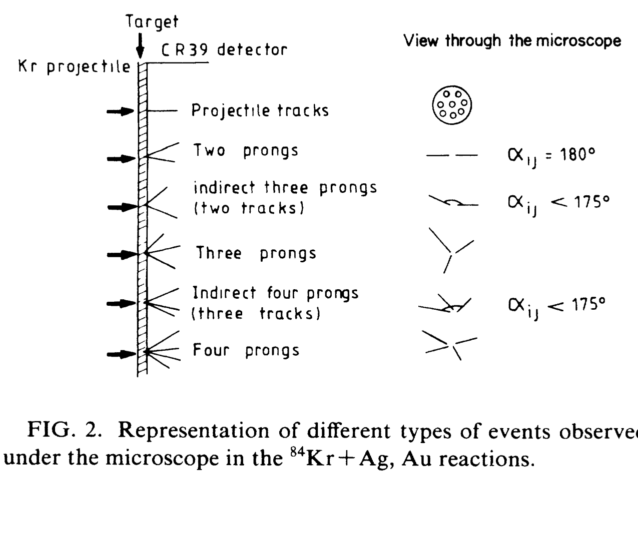

FIG. 2. Representation of different types of events observed under the microscope in the ^{84}Kr+Ag, Au reactions.

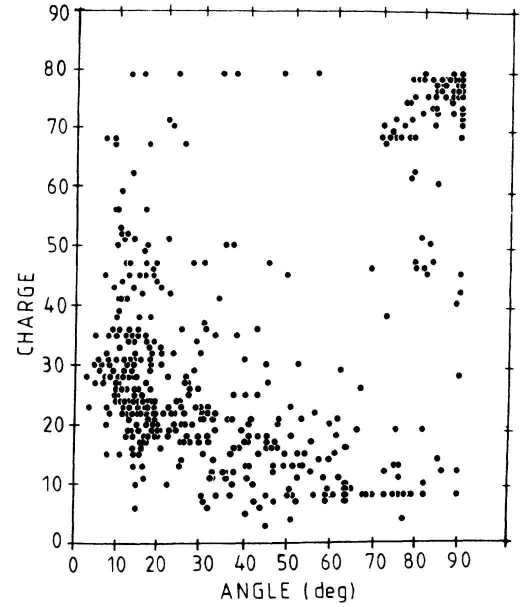

FIG. 3. Charge versus emission angle of 490 fragments issued from indirect three prongs in the ^{84}Kr+Au reaction at 17.7 MeV/nucleon.

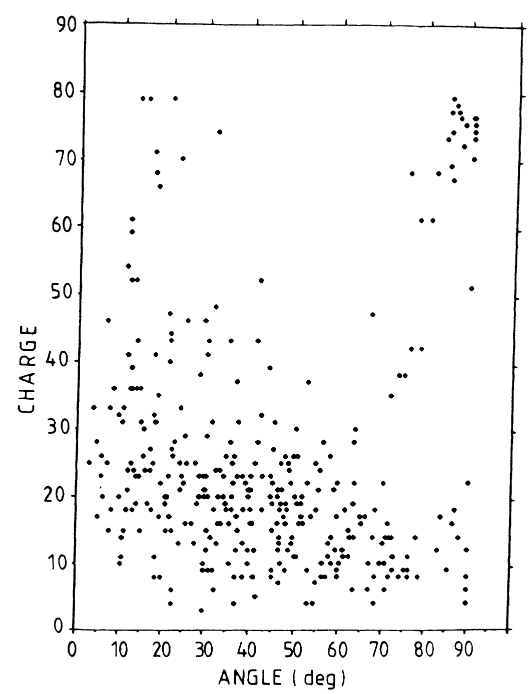

FIG. 4. Charge versus emission angle of 324 fragments issued from three prongs in the ^{84}Kr+Au reaction at 17.7 MeV/nucleon.

Figure 3 shows a group of fragments at $\theta \approx 85°$, $Z \approx 75$. The range of each of the fragments in these events corresponds to a very low energy (≈ 0.1 MeV/nucleon). They are identified as slow targetlike fragments. Most of these events are associated with fast fragments lying around $\theta = 14°$, $Z \approx 29$ having an energy about 85% of the total incident energy of 1.48 GeV. The missing energy corresponds to particles that escape detection. These events are assumed to have their origin in DI reactions. Around $\theta \approx 45°$, $Z \approx 15$ we observe a group with a different behavior. The two associated fragments have lower charges and larger emission angles. The total energy of the two fragments is about 200–600 MeV which implies that an important amount of energy escapes detection.

In Fig. 4 we show the events with three registered tracks. We also observe a small group ($\theta \approx 85°$, $Z \approx 75$) assumed to arise from DI reactions. The charge of the two associated fragments lies around 30 and $\theta \approx 14°$. Their total energy is slightly lower than the beam energy of 1.48 GeV.

Most of the other events of Fig. 4 have Z values lying around 20 and laboratory angles around 45°. The total energy of the three fragments is a few hundred MeV. Here again most of the incident energy escapes detection. We tentatively identify these low energy ternary fragments as resulting from targetlike or some intermediate zone fragmentation with some forward driving velocity as could be deduced from the angular distribution of Figs. 3 and 4. We attribute the same origin to the low energy indirect 3-pronged events of Fig. 3. In order to extract yields of ternary events leading to fragmentation, we have subtracted DI events in our measurements at 17.7, 27, and 35 MeV/nucleon. The resulting cross section for 3 prongs associated with a fragmentation process is shown in Fig. 5. Higher order 4-, 5-, and 6-pronged reactions also have low total energies and intermediate Z. Therefore, we identify these events as arising from the same processes. Angular distributions of fragments (shown in Figs. 3 and 4 for 3-pronged events not presented for 4, 5, and 6 prongs) indicate that the yield decreases from 45° to 90° and is very low around 90° in the lab. Thus a nearly 4π detection geometry can be assumed. The cross sections for these processes are shown in Fig. 5 for 3, 4, and (5+6) prongs. Figure 6 illustrates the cross sections obtained in the case of ^{84}Kr+Ag at 17.7 and 27 MeV/nucleon. No measurements were obtained for Ag targets at the 35 MeV/nucleon bombarding energy.

As can be seen from Figs. 5 and 6, the cross sections for multifragmentation processes leading to 3, 4, and (5+6) intermediate mass and low energy fragments in the final state increase with bombarding energy. The smaller the multiplicity, the greater the cross section. Events with 5 and 6 intermediate mass fragments appear to have a threshold around 15 MeV/nucleon bombarding energy. As an internal check of the experimental procedure, we have measured the total reaction cross section of ^{84}Kr+Au at 17.7 MeV/nucleon, taking into account all 1-, 2-, 3-, 4-, 5- and 6-pronged events, to be (4.1 ± 0.5) b.

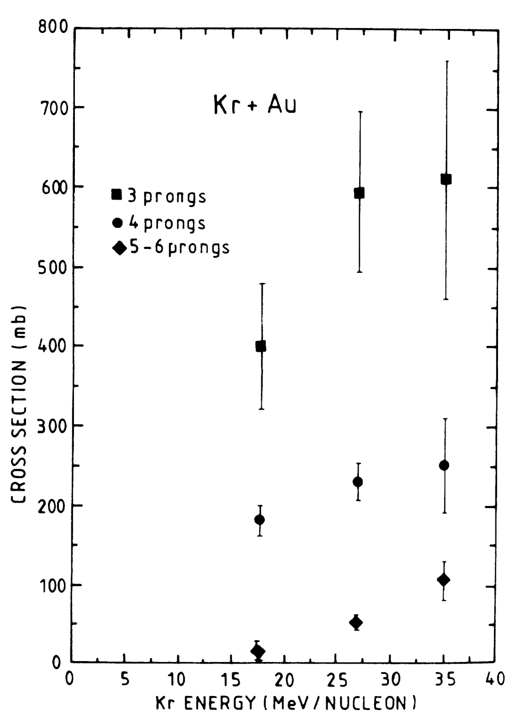

FIG. 5. Cross section of 3-, 4-, and (5+6)-pronged events versus incident Kr energy in the ^{84}Kr+Au reaction.

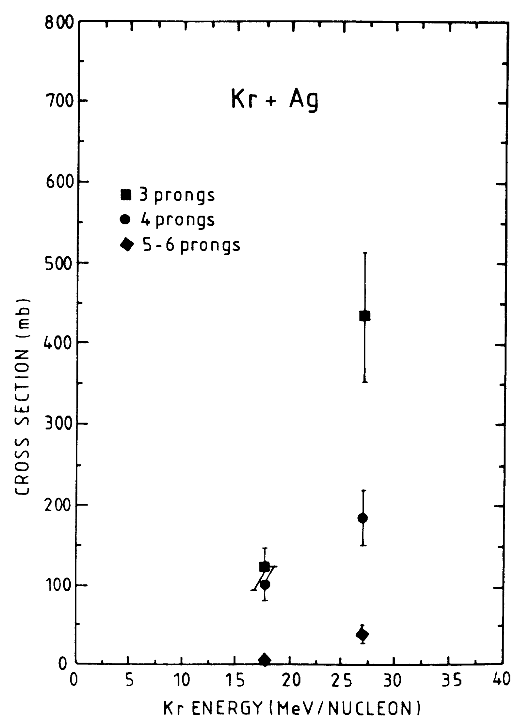

FIG. 6. Cross section of 3-, 4-, and (5+6)-pronged events versus incident Kr energy in the ^{84}Kr+Ag reaction.

TABLE I. Cross sections for 3-, 4-, 5-, and 6-pronged events as a function of bombarding energy for the ^{84}Kr+Au and ^{84}Kr+Ag reactions. The reaction cross sections are calculated from Ref. 21.

Energy (MeV/nucleon)	Total multipronged event cross section (mb)	Ratio to reaction cross section (%)
	^{84}Kr+Au	
17.7	575±105	13±3
27	874±130	17±3
35	966±240	18±5
	^{84}Kr+Ag	
17.7	230±46	6±2
27	659±130	15±3

The calculated cross section[21] is 4.6 b.

Table I shows the multipronged event cross sections as well as the percentages of the calculated reaction cross section for ^{84}Kr+Au and Kr+Ag. The total multiprong cross sections for ^{84}Kr+Ag rise faster than in the case of ^{84}Kr+Au.

CONCLUSION

In this work we have measured cross sections for higher order multiplicities involving several intermediate mass fragments in the ^{84}Kr+Au and ^{84}Kr+Ag reactions. Multiplicity as high as six could be measured. The characteristics found for events with three or more correlated fragments were a total charge of about 80 in the case of ^{84}Kr+Au and a total energy of about 20% of the bombarding energy. This leads us to assume that these events originate in a targetlike or in an intermediate zone fragmentation process in which the projectilelike fragment with the greatest part of the incident energy escapes detection. This is reasonable in consideration of the detector efficiency curve of Fig. 1.

The cross section for five and six correlated fragments as a function of bombarding energy clearly increases in going from 17 to 35 MeV/nucleon. This may indicate that we are in a region of mechanism transition which could be interesting to study. To our knowledge, the present results are the first cross sections for high multiplicity of intermediate mass low energy fragments obtained in this region of energy.

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