Nuclear disassembly in violent central collisions at intermediate energies: (65−115)A MeV ^{40}Ar+Cu, Ag, Au

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Nuclear disassembly into light and intermediate mass ejectiles is searched for in ^{40}Ar + Cu, Ag, Au reactions of 17−115A MeV. Distributions in fragment mass versus velocity show that such nuclear disassembly does occur for 65−115A MeV. However, it is very rare, with much less abundance than reactions leading to a massive residual nucleus.

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Nuclear disassembly by multifragmentation has been predicted by statistical models for about two decades, e.g. [1], and has been of great interest ever since. Possibly the most dramatic experimental observation of such a process was reported by Marie *et al.* for the reaction Xe + Sn (50A MeV) [2]. In this reaction only ~1% of the collisions lead to nuclear disassembly. The most abundant exit channels for such mass symmetric reactions do not lead to disassembly, but seem to give two highly excited nuclei with memory of the target and projectile. Recent studies of the mass asymmetric reactions ^{40}Ar + Cu, Ag, Au (17−115A MeV) have shown clear examples that nuclear disassembly is not as extensive as predicted by multifragmentation models [3–5]. In this Brief Report we show that disassembly does indeed occur for the asymmetric reactions 65−115A MeV ^{40}Ar + Cu, Ag, Au, but that such processes are rare.

The experiment was done at the Michigan State University K1200 cyclotron with fragment and particle detection by the MSU 4π array. This setup included the basic ''soccerball'' array from ~18° to ~162° [6], the zero degree detector ~0.5° to 1.5° [7], the Maryland forward array 1.5° to 3° [8], and a set of 45 Si detectors (~3 cm×3 cm ×140 μm) [9] mounted ≈70 cm from the target in front of the 45 telescopes (~3−18°) of the high rate array [10]. Ionization chamber ΔE detectors were also used from 18° to 162° in front of each of the 170 telescopes in the ball [6]. The data from these Si detectors were corrected for pulse height defect [11] and analyzed to give masses (resolution ±5−10%) for the slow-moving fragments (A⩾10), while data from the other telescopes were analyzed to give atomic numbers and energies for fragments of Z~1−8 [3].

Figure 1 shows an overview of the properties of fragments with A⩾10 produced in the reaction 65A MeV ^{40}Ar + Ag [3]. The figure consists of six similar quadruplets, each for a different slice or cut on the observed multiplicity for charged ejectiles. The respective multiplicity cuts are indicated by the hatched areas in the top right panel of each set. The lower left panel of each set shows a contour map of fragment mass number A (divided by total system mass A_{sys}) versus its longitudinal velocity $V_\parallel$ (divided by the c.m. velocity $V_{c.m.}$). The other two panels of each quadruplet show projections from each map on the mass and velocity axes, respectively.

For the lowest multiplicity cut (top left), one sees the typical, fast-moving projectilelike fragment (PLF) and slow-moving targetlike fragment (TLF). As the multiplicity cut, i.e., the collision violence, is increased, the average velocities and masses of these two groups broaden and approach one another. Also the average masses decrease for each group, reflecting the mass loss that feeds the large multiplicities of charged particles, fragments, and neutrons. Similar results for other incident energies are given in [3].

Figure 2 shows the average mass numbers of the heaviest fragment (HF) from these Ar + Ag reactions as a function of the detected multiplicity for charged particles. For each incident energy the average mass $\langle A\rangle_{HF}$ of the HF decreases with increasing multiplicity of charged particles. Values of $\langle A\rangle_{HF}$ never drop below ~70 for incident energy ⩽44A MeV, indicating that nuclear disassembly is essentially absent. However, for incident energy ⩾65A MeV there is a steep decrease in $\langle A\rangle_{HF}$ for multiplicities ⩾25. Finally for multiplicities ⩾30 one may say that the HF masses have

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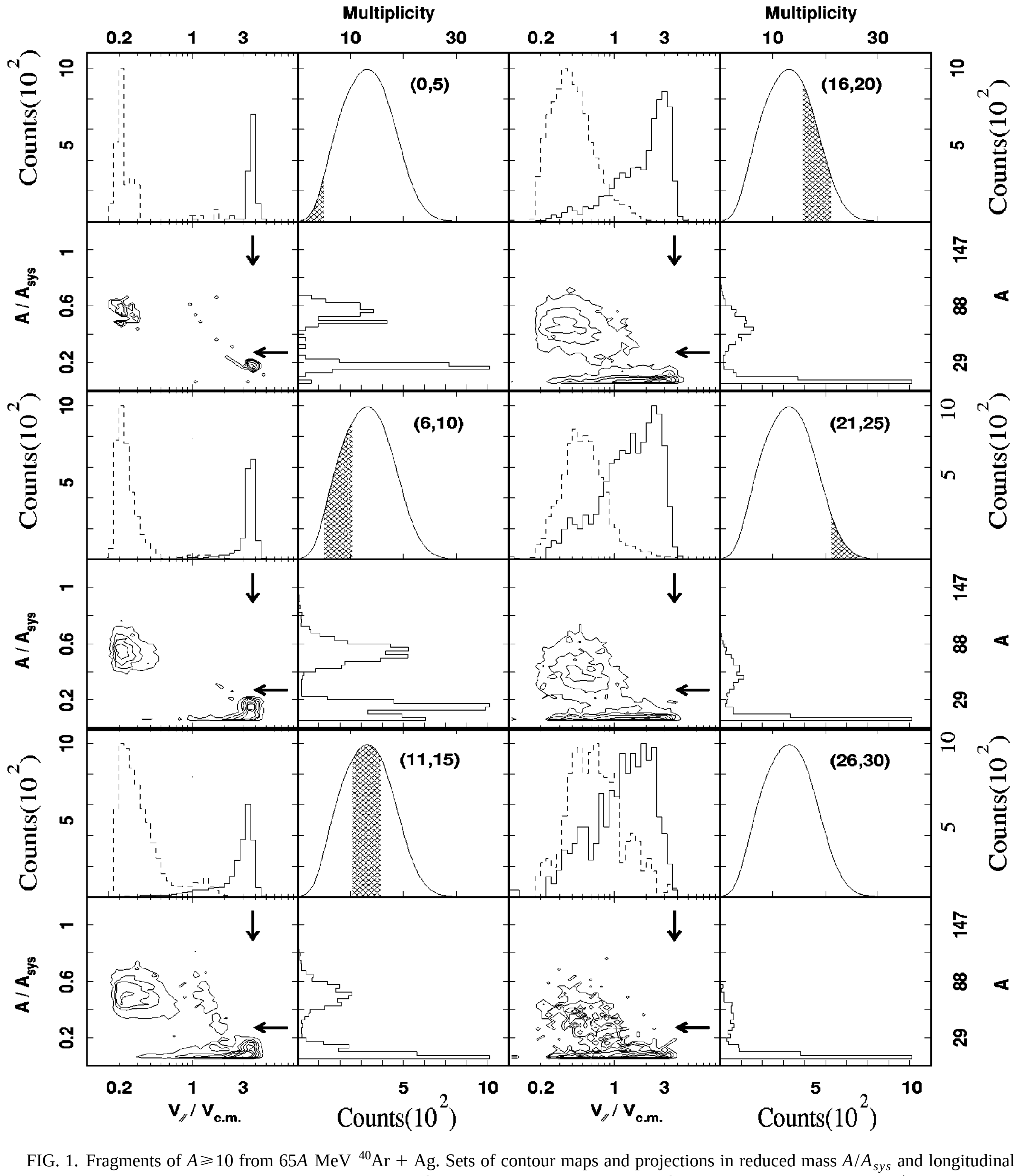

FIG. 1. Fragments of $A \geqslant 10$ from 65A MeV ^{40}Ar + Ag. Sets of contour maps and projections in reduced mass A/A_{sys} and longitudinal velocity $V_{\parallel}/V_{\mathrm{c.m.}}$. The observed multiplicity distribution for charged ejectiles is indicated for each quadruplet by shading (with respective multiplicity cuts of 0−5, 6−10, 11−15, 16−20, 21−25, and 26−30). A ''completeness condition'' was also used to require detection of 75% of the system charge and 70% of the incident momentum.

become so small that they would all be referred to as intermediate mass fragments (IMFs).

This is the situation corresponding to nuclear disassembly into light charged particles (LCPs), IMFs, and neutrons. The selected fraction of reactions is $\leqslant 1\%$, corresponding to detected charged ejectile multiplicity $\geqslant 30$. Very similar results are found for the reactions ^{40}Ar + Cu, Au. We conclude that this experiment does indeed confirm the presence of nuclear

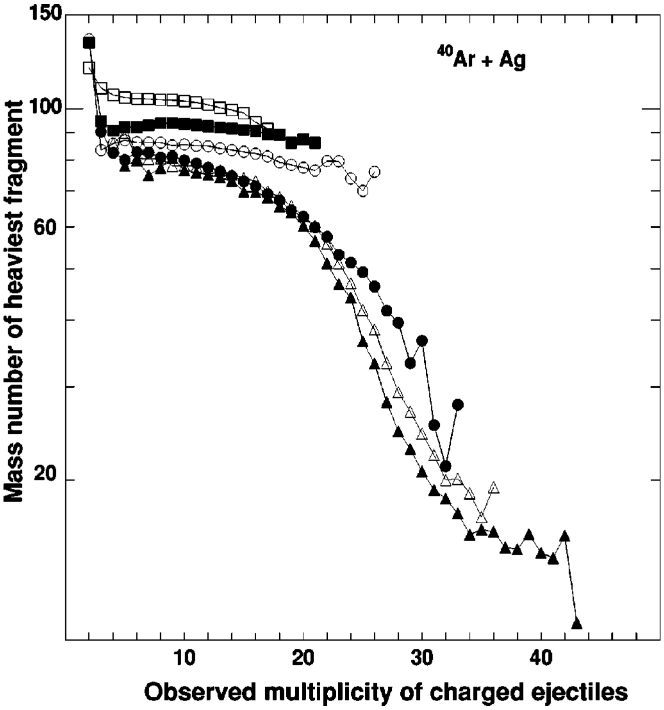

FIG. 2. Average mass of the heaviest fragment in each event versus charged ejectile multiplicity. ^{40}Ar + Ag reactions at various incident energies in MeV/nucleon: 17, open squares; 27, solid squares; 44, open circles; 65, solid circles; 90, open triangles; and 115, solid triangles. The completeness condition was used as in Fig. 1.

disassembly events in ^{40}Ar-induced reactions, but they are very rare indeed.

Our papers [3–5] have focused on sets of 15% of the events selected by the highest multiplicities. These reactions

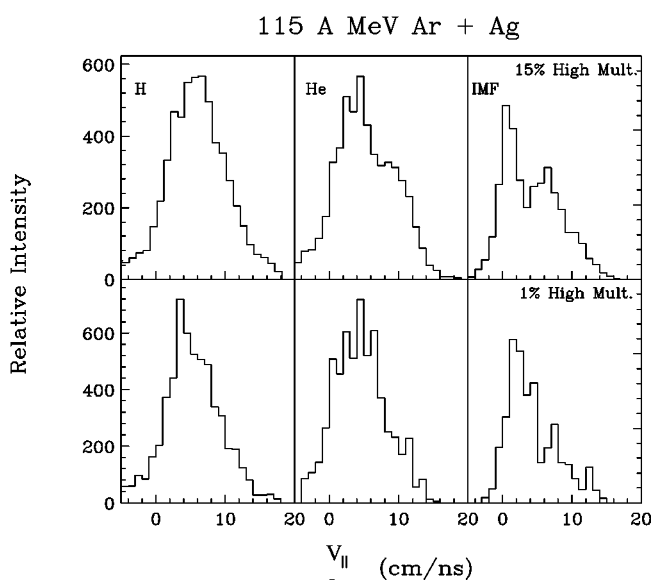

FIG. 3. Longitudinal velocity distributions of H, He, and IMF ejectiles from 115*A* MeV ^{40}Ar + Ag. Top (bottom) panels are for a multiplicity cut of the highest 15% (1%).

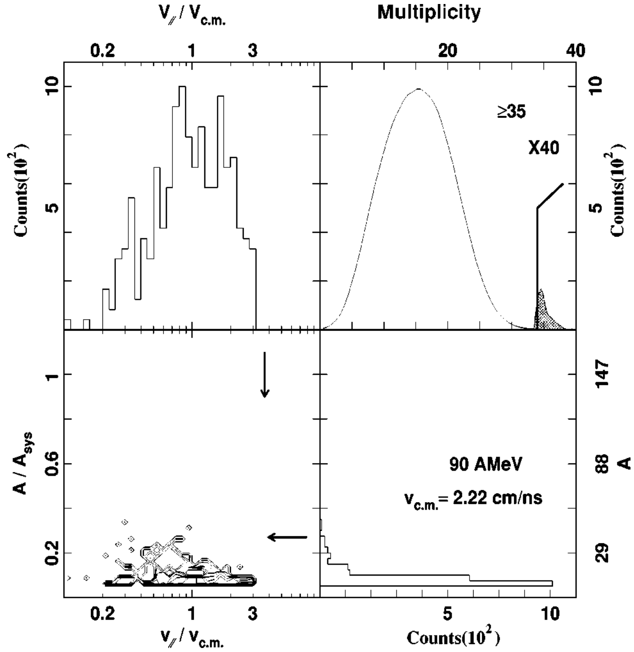

FIG. 4. Mass and velocity distributions as in Fig. 1 for 90*A* MeV ^{40}Ar + Au. Here the only selection applied was for the highest 1% of multiplicities.

have a substantial loss of momentum and energy into a forward focused spray of ejectiles comprised of neutrons, H, He, and IMFs. In Fig. 3 we show longitudinal velocity distributions of these ejectiles for the 15% cut (top panels) and the 1% cut (bottom panels). For the 15% sample the velocity distributions extend to ~15 cm/ns, much larger than the average velocity of the HF (~1.5 cm/ns) with average mass number of ~50. In the lower panels for the 1% sample, we see a strong reduction in the high velocity part of these velocity distributions. Much less energy is therefore carried away by the forward-peaked spray, and, therefore, more energy must be deposited into the reaction zone for the 1% set.

Similar results are shown in Fig. 4 for the reaction 90*A* MeV ^{40}Ar +Au. Here again one sees that the heaviest fragment masses are small (≤30). In addition the velocity distribution is almost symmetrically spread about the c.m. velocity. This would imply almost complete stopping or energy dissipation of ~4 GeV (or ~17 MeV/nucleon) in this small sample of the collisions. Surprisingly large energy depositions seem to be required to induce nuclear disassembly. Multifragmentation models predict disassembly for much smaller deposition energies [1,4,5].

To summarize we have shown the evolution of reaction properties with charged particle multiplicity for ^{40}Ar reactions. For the lowest multiplicities one sees typical two-body kinematics, with fast PLFs and slow TLFs. As the multiplicity cut is raised these mass groups approach and overlap one another. Finally for 65−115 *A* MeV ^{40}Ar + Cu, Ag, Au and a high multiplicity cut of ≤1%, one sees nuclear disassembly into light particles and IMFs which have a wide velocity distribution centered roughly about the c.m. velocity.

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