Balance of Mass, Momentum, and Energy in Splintering Central Collisions for ^{40}Ar up to 115 MeV/Nucleon

Rulin Sun,[1] E. Colin,[1,4] N. N. Ajitanand,[1] John M. Alexander,[1] M. A. Barton,[3] P. A. DeYoung,[3] K. L. Drake,[3] A. Elmaani,[1,*] C. J. Gelderloos,[6,†] E. E. Gualtieri,[2] D. Guinet,[4] S. Hannuschke,[2] J. A. Jaasma,[3] L. Kowalski,[5] Roy A. Lacey,[1] J. Lauret,[1] E. Norbeck,[7] R. Pak,[2] G. F. Peaslee,[3] M. Stern,[4] N. T. B. Stone,[2] S. D. Sundbeck,[3] A. M. Vander Molen,[2] G. D. Westfall,[2] L. B. Yang,[7] and J. Yee[2]

[1]*Department of Chemistry, State University of New York at Stony Brook, Stony Brook, New York 11794*
[2]*National Superconducting Laboratory, Michigan State University, East Lansing, Michigan 48824*
[3]*Departments of Chemistry and Physics, Hope College, Holland, Michigan 49423*
[4]*Institut de Physique Nucléaire de Lyon, Institut National de Physique Nucleaire et de Physique des Particules–Centre National de la Recherche Scientifique, UniversitéClaude Bernard, 43, Boulevard du 11 Novembre 1918, 69622 Villeurbanne, Cedex France*
[5]*Department of Physics and Geoscience, Montclair State College, Upper Montclair, New Jersey 07043*
[6]*Nuclear Physics Laboratory, University of Colorado, Boulder, Colorado 80309-0446*
[7]*Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242*
(Received 1 September 1999)

For central collisions of (17–115)A MeV ^{40}Ar + Cu, Ag, Au, an overall balance is determined for the average mass, energy, and longitudinal momentum. Light charged particles and fragments are separated into forward-focused and isotropic components in the frame of the heaviest fragment. Energy removal by the isotropic component reaches 1–2 GeV. For such high deposition energies, statistical multifragmentation models predict much more extensive nuclear disassembly than is observed.

PACS numbers: 25.70.Pq, 25.75.Ld

Central collisions between mass asymmetric heavy nuclei of ~(10–100)A MeV deposit substantial amounts of energy into a core nuclear system, e.g., for ~100A MeV ^{40}Ar + Ag one finds ≳1 GeV (or ~10 MeV/nucleon [1]). One expects that the addition of energy to a nuclear system will cause it to expand in size and ultimately lead to its disassembly, but we do not yet have a systematic picture of the evolution from nuclear evaporative decay to such disassembly [2]. In this spirit we study the reactions of Cu, Ag, and Au with ^{40}Ar from (17–115)A MeV. What are the roles of nuclear stopping vs transparency in these reactions? What fragments carry away the undissipated energy in forward focused emission, and what ejectiles remove energy via isotropic emission from the very highly excited core nucleus? These are the questions that we address in this survey experiment.

In this communication we focus on the multiplicities, the angular distributions, and the average energies of the charged ejectiles. As in [1] we select violent central collisions via the highest 15% of the multiplicity distributions and require that each event include ≥75% of the system charge and ≥70% of the incident momentum. We group the various ejectiles into two components: (a) an isotropic component in the frame of the heaviest fragment, and (b) a forward-directed component in this frame [3,4]. We determine the average linear momentum for various ejectile types of each component and hence characterize the residual system after the forward ejections and prior to the isotropic emission. Similarly, we determine the energy removal by the ensemble of isotropic ejectiles and hence characterize the excitation energy of this isotropic emission ensemble (usually taken as thermalized and equilibrated). This is the first study to present such a complete mass energy and momentum balance for mass asymmetric reactions at intermediate energies.

The experiment was performed with beams of (8–115)A MeV ^{40}Ar from the K1200 cyclotron at Michigan State University. Thin targets of Cu, Ag, or Au were bombarded, and charged ejectiles were detected from ~0.5°–162° in the 4π array [1,5–7]. An important aspect of this experiment was the use of 45 Si detectors (~3 cm × 3 cm × 140 μm) mounted ≈70 cm from the target in front of 45 plastic telescopes at polar angles of 3°–18°. Energy and time-of-flight signals from these detectors provided mass determinations (resolution 5%–10%) for fragments of $A \geq 10$. As described in [1] we use these data to characterize the heaviest fragment in terms of its mass and longitudinal velocity; experimental details are given there. For data acquisition a minimum of two hits were required for $18° < \theta < 162°$ (thresholds 17 and 12 MeV for ^{1}H and ^{4}He)

For mass asymmetric reactions in the near-barrier energy domain of ≲20A MeV it has long been conventional to resolve light ejectile emission into an isotropic and a forward-peaked component, e.g., [3,4], commonly termed the evaporation and direct components. For incident energies greater than ~30A MeV, experiments have often been performed with near 4π detector arrays that give a wonderful view of the light or fast ejectiles [2]. Often these arrays are not sensitive to the low-velocity heavy fragments. Without such heavy fragment detection one has no independent handle on a source velocity for isotropic emission; therefore, it has not been possible to resolve these two components with good confidence or even consistency.

The multisource fits to particle spectra generally have employed a very large number of free parameters, which give a substantial vulnerability to systematic errors.

In Ref. [4] heavy fragment velocities were measured and used, along with a 4π array for light particles, to resolve H, He, and Li fragments into isotropic and forward-directed components. Here we have followed the same procedure. The various ejectiles were transformed into the moving frame (MF) of the average heaviest fragment as illustrated for several cases in Fig. 1. This moving frame (MF) has a smaller longitudinal velocity than the reaction c.m. due to the forward focusing of the lighter ejectiles (Figs. 3 and 4 in Ref. [1]). Results are similar for each target and energy. An isotropic component, with angle independent energy spectra, was observed for each reaction for polar angle $\gtrsim 100°$ in the heavy fragment frame [8]. This component was subtracted from the complete set of emissions in 4π sr (both corrected for acceptance and threshold) to obtain the resultant average multiplicity and energy of the forward component. Energy and angle-integrated multiplicities for the two components are displayed in Fig. 2. Neutrons were not detected in this experiment; however, a number of measurements in the literature [9–12] have been used, in conjunction with our data, to estimate their average multiplicities for Ar + Cu, Ag, Au.

The overall balance of average mass, energy, and momentum is shown in Fig. 3. Panels a–c show the average mass removed by the forward-peaked and isotropic components along with the average mass of the heaviest residual fragment. Several points should be noted. (1) The sums of the average experimental masses are consistent with the total system masses of $A = 104$, 148, and 237 for Ar + Cu, Ag, and Au, respectively. (2) The mass of the forward-peaked component decreases as target mass increases. (3) The mass removed by isotropic emission increases as the target mass increases.

Panels d–f show the average energy removal by isotropic components (IE) and by forward focused components (FE) separated by ejectile type. (1) Again, there is consistency between the sums of the observed averages and the total available energy. (2) The summed energy removal by forward focused components decreases as the target mass increases. (3) The energy removal by isotropic emission increases as the target mass increases.

Panels g–i show the average momentum balance for each reaction separated by ejectile type. The two unshaded bars indicate the average longitudinal momentum of the heaviest fragment along with the average momenta (over 4π sr) for its associated isotropic ejectiles. Shaded bars represent the average momenta for forward-peaked components of the type indicated. There is consistency between the arrows for the incident momenta and the sums of the exit channel momenta. The isotropic components are dominant for the lowest energies where complete and incomplete fusion are well known, and the compound-nucleus model rules. This pattern has been well established by studies of heavy fragment velocities, e.g. [13]. However, for beam energies of $\gtrsim 44A$ MeV, the forward-peaked components dominate, and the momentum is widely spread over many ejectile types. For this reason the term splintering central collisions was introduced [1].

It is interesting that the linear momentum transfer to the heavy core nucleus (unshaded bars) decreases with energy more rapidly for Cu than for Ag, and the trend continues for Au. One can say that, for central collisions, the stopping power increases with target mass as is intuitively reasonable [1]. The INDRA Collaboration has presented

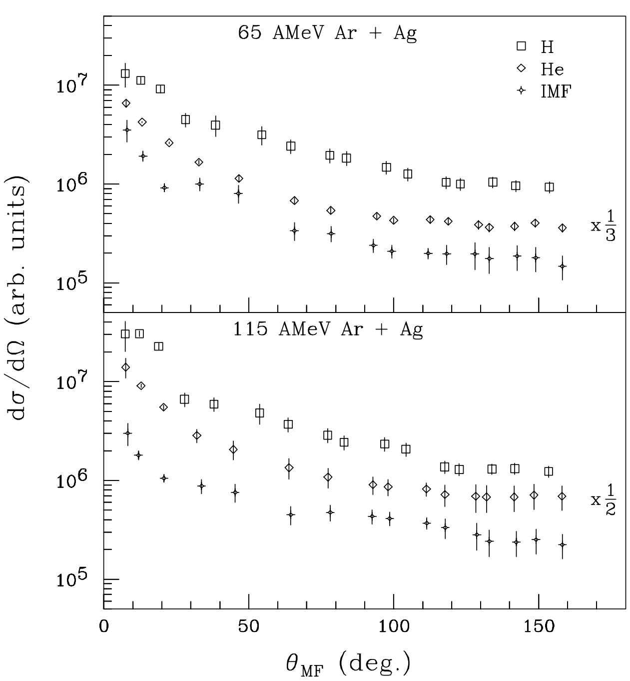

FIG. 1. Angular distributions for H, He, and IMFs ($3 \leq Z \leq 18$) in the moving frame (MF) of the average heaviest fragment for Ar + Ag reactions.

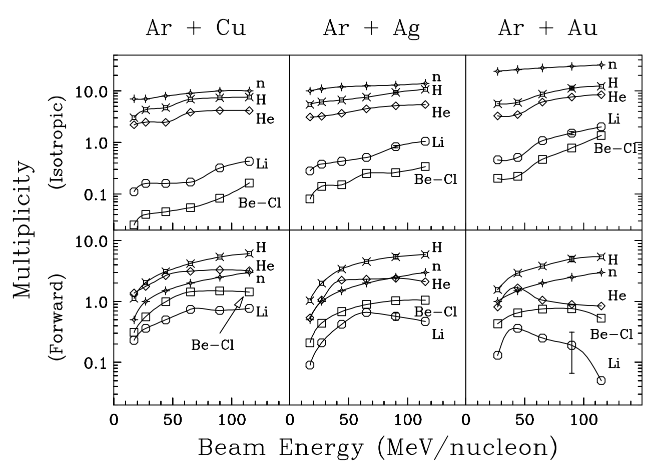

FIG. 2. Charged ejectile multiplicities from this work and neutron multiplicities from systematic extrapolations. Estimated overall errors are ~15%.

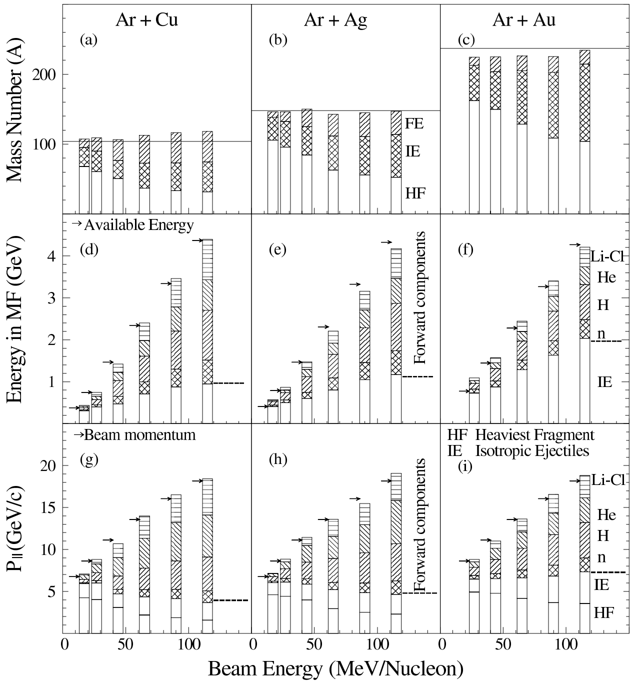

FIG. 3. (a–c) Average masses for the heaviest fragment HF, the isotropically emitted (IE), and forward-focused ejectiles (FE). (d–f) Average energy (moving frame) removed by forward-focused and isotropically emitted ejectiles for types as indicted. (g–i) Average longitudinal momenta (laboratory) for the isotropic and forward-focused ejectiles as indicated. Estimated errors are ~15%.

very different results that show essentially complete stopping followed by nuclear disassembly into particles and light IMF's, e.g. [14]. We see very similar disassembly behavior for $\lesssim 1\%$, of the reactions for $E_{\mathrm{beam}} \gtrsim 65A$ MeV, a very small fraction not inconsistent with [14]. In this work we accept a reaction fraction of ~15%, which, in summation, overwhelms such disassembly events.

In Fig. 4 we look in more detail at the energy removed by the isotropic emission components. These components are generally termed as "postthermalization" or "equilibrium emission." It should be kept in mind that the condition of isotropy is necessary but not sufficient for complete equilibration. To obtain these values we have made a calorimetric sum of each ejectile's average multiplicity times its average separation and kinetic energies in the emitter frame. The separation energies have been taken from averages over calculated statistical model decay chains [15]; they result from a complex average and are rather insensitive to the detailed parameter set employed. As mentioned above, the neutron multiplicities have been taken from reported measurements where available [9–12], supplemented by systematic extrapolations based on ratios to the charged particle production observed here.

The magnitudes of the total energy removal (isotropic component) shown in Figs. 3 and 4 compare quite favorably with deposition energies inferred from average velocities of the heaviest fragment [1]. At the lowest incident energies, the ^{40}Ar projectile deposits the bulk of its energy via incomplete fusion with each target. As the beam energy is increased, the total energy deposited also increases to ~1 GeV for Cu compared to ~2 GeV for Au. In each case the main ejectiles for energy removal are the light particles n, H, and He with IMF's playing a relatively minor role. For $115A$ MeV ^{40}Ar + Cu collisions, Figs. 3 and 4 show that ~1/3 of the available energy (or ~13 MeV/source nucleon) is converted into isotropic emission compared to ~1/2 (or ~9 MeV/nucleon) for Au reactions. This energy is more than the total binding energy, but contrary to many expectations it does not lead to disassembly of the core nucleus into light particles and IMF's.

One way to characterize nuclear disassembly is by the average mass of the heaviest remaining fragment. In Fig. 5 we show these average masses for each reaction system; they are compared to average masses calculated by the Berlin [16] and Copenhagen [17] models for multifragmentation (using default parameters). The two models are generally consistent with each other (except for the lowest energy for Ar + Au, where Berlin allows binary fission to dominate). However, the experimental results are consistent with the models only at the lowest energies. The divergence between experimental and model calculations is very marked for reactions of $(65–115)A$ MeV.

For these calculations, initial conditions of energy, mass, and charge were taken from the isotropic components, as given in Fig. 3. Evidently these statistical models invest much more of the energy in nuclear disassembly and less for kinetic energy than is actually found in these reactions. A very similar result has been observed for the case of ^{197}Au + ^{12}C ($E/A = 1$ GeV) [18]; there about half of the isotropically removed energy (12 ± 2 MeV/nucleon) was found to be in excess of that for a thermalized system. For that reaction the extra-thermal kinetic energy was ascribed to a form of radial flow. More information on this aspect will be given in a future publication.

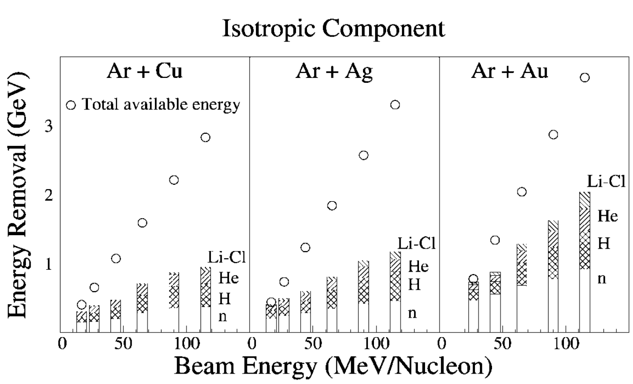

FIG. 4. Energy removal (moving frame) by the isotropic ejectiles as indicated. Overall errors are ~15%.

In summary, we have studied the mass, energy, and momentum balance in central collisions of ^{40}Ar with Cu, Ag,

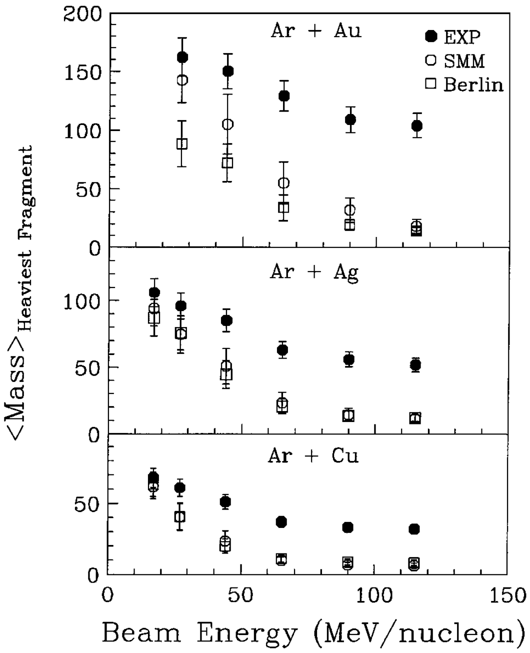

FIG. 5. Average mass of the heaviest fragments from the data and from model calculations as indicated.

and Au [(17–115)A MeV]. The average velocity of the heaviest fragment has been used to define the reference frame for isotropic emission from a highly excited system. Angular distributions have been used to separate each ejectile type into isotropic and forward-focused components in this moving frame. The forward-directed components carry away a large fraction of the energy via a spray of light ejectiles. The isotropic components give core nuclear excitations of ~1–2 GeV or ~8–13 MeV/nucleon for 115A MeV ^{40}Ar. Multifragmentation models predict that such a highly excited nucleus will essentially disassemble, leaving heaviest fragments with $A \leq 20$. Much heavier residual nuclei are actually found, indicating less energy utilization for disassembly and more in isotropic kinetic energy.

Financial support has been provided by the U.S. Department of Energy, the National Science Foundation, and the CNRS of France.

*Present address: Battelle Pacific Northwest National Laboratory, National Security Division, Box 999, K6-48, Richland, WA 99352.

†Present address: Hughes Space and Communications, P.O. Box 92919, Los Angeles, CA 90009.

[1] E. Colin *et al.*, Phys. Rev. C **57**, R1032 (1998).
[2] D. Durand, LPC Caen Report No. LPC C98-02, 1997, and references therein.
[3] C. J. Gelderloos *et al.*, Phys. Rev. C **54**, 3056 (1996).
[4] M. T. Magda *et al.*, Phys. Rev. C **53**, R1473 (1996).
[5] G. D. Westfall *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **238**, 347 (1985); M. Maier *et al.*, *ibid.* **337**, 619 (1994); R. Pak, thesis, Michigan State University, 1996.
[6] N. T. B. Stone, Ph.D. thesis, Michigan State University, 1996.
[7] D. E. Russ, Ph.D. thesis, University of Maryland, 1996.
[8] R. Sun, Ph.D. thesis, State University of New York at Stony Brook, 1999.
[9] D. X. Jiang *et al.*, Nucl. Phys. **A503**, 560 (1989).
[10] E. Crema *et al.*, Phys. Lett. B **258**, 266 (1991).
[11] B. Lott *et al.*, Z. Phys. A **346**, 20 (1993).
[12] B. Hurst *et al.*, Texas A & M University, Cyclotron Institute Report No. 97-06.
[13] H. Morgenstern *et al.*, Phys. Rev. Lett. **52**, 1104 (1984); V. E. Viola *et al.*, Nucl. Phys. **A502**, 531c (1989); F. Haddad *et al.*, Phys. Rev. C **53**, 1437 (1996).
[14] N. Marie, Ph.D. thesis, Université de Caen, France, 1995; N. Marie *et al.*, Phys. Lett. B **391**, 15 (1996).
[15] N. N. Ajitanand *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **376**, 213 (1996).
[16] D. H. E. Gross, Rep. Prog. Phys. **53**, 605 (1990).
[17] J. P. Bondorf *et al.*, Phys. Rep. **257**, 133 (1995).
[18] J. Lauret *et al.*, Phys. Rev. C **57**, R1051 (1998).