Fusionlike reactions of ^{40}Ar up to 1.36 GeV: Prethermalization and postthermalization particles and fragments

M. T. Magda,[1] E. Bauge,[1,3,*] A. Elmaani,[1,†] T. Braunstein,[1] C. J. Gelderloos,[1,‡] N. N. Ajitanand,[1] John M. Alexander,[1] T. Ethvignot,[1,3,§] P. Bier,[1] L. Kowalski,[2] P. Désequelles,[3] H. Elhage,[3] A. Giorni,[3] S. Kox,[3] A. Lleres,[3] F. Merchez,[3] C. Morand,[3] P. Stassi,[3] J. B. Benrachi,[3] B. Chambon,[4] B. Cheynis,[4] D. Drain,[4] and C. Pastor[4]

[1]*Departments of Physics and Chemistry, State University of New York at Stony Brook, Stony Brook, New York 11794*

[2]*Department of Physics and Geoscience, Montclair State College, Upper Montclair, New Jersey 07043*

[3]*Institut des Sciences Nucléaires de Grenoble, Institut National de Physique Nucléaire et de Physique des Particules–Centre Nationale de la Recherche Scientifique/Université Joseph Fourier, 53 Avenue des Martyrs, 38026, Grenoble Cedex, France*

[4]*Institut de Physique Nucléaire de Lyon, Institut National de Physique des Particules–Centre National de la Recherche Scientifique/ Université Claude Bernard, 43, Blvd. du 11 Novembre 1918, 69622 Villeurbanne, Cedex, France*

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Heavy residual nuclei are shown to result from the most violent (i.e., central) collisions for ^{40}Ar + Ag reactions of up to 1.36 GeV; their average velocities are ≳80% of the c.m. velocity. Angular and energy distributions for ^{1,2,3}H, ^{3,4}He, and Li are measured in coincidence with these heavy nuclei. The dominant light particle components are nearly isotropic in a frame of reference having the velocity of the heavy residues. In addition there are forward-peaked high-energy components of the H, He, and Li emission attributable to prethermalization emission. Fractional abundances of these prethermalization components increase markedly with increasing incident energy. Mass and momentum balance preclude the presence of a projectilelike fragment and thus indicate fusionlike reactions with large but incomplete linear momentum transfer. The remainder of the momentum is carried away by the spray of forward-peaked ejectiles. For 1.36 GeV ^{40}Ar ~1/2 of the 900 MeV available is completely thermalized, and ~1/2 goes into prethermalization emission after strong collisional mixing.

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Fusion in central collisions between complex nuclei has been extensively studied at near-barrier energies by measurements of heavy residual nuclei, e.g. [1] and also by evaporated particles, e.g. [2]. The fusion-evaporation residues for ≲10*A* MeV have been observed to have almost complete linear momentum transfer, which for ≳10*A* MeV gives way to only partial momentum transfer and is termed incomplete fusion, e.g. [3]. By contrast, very heavy reaction pairs such as Au+Pb follow mainly binary reaction paths. For ≲10*A* MeV (somewhat above barrier) their central collisions are dominated by deeply inelastic scattering to give highly excited target and projectilelike fragments, e.g. [4]. Even for ~29*A* MeV (well above barrier) there is evidence for persistence of the binary reaction character [5]. A number of papers imply the expectation that essentially all reactions at intermediate energies (~30*A* MeV) have this binary character [3]. The results of this study bear on this controversial point.

In this work we report results for ^{1,2,3}H, He, and Li emission along with heavy residual nuclei for 7*A* to 34*A* MeV ^{40}Ar+Ag. The evaporation residues from fusion reactions are clearly exhibited for 7*A* MeV along with strong evaporation components for H and He. With increasing beam energy we find that such fusionlike reactions continue to be important even up to 34*A* MeV ^{40}Ar, but that they are associated with an increasing amount of prethermalization emission of H, He, and Li as well as copious postthermalization emission. The mass and momentum balance exclude additional projectilelike fragments in this central collision group.

Our experiment was performed with the AMPHORA 4π multidetector [6] and the double cyclotron at Grenoble. Light charged particles (or LCP's), ^{1,2,3}H and ^{3,4}He, and Li fragments were measured in 140 CsI detectors that covered ~85% of 4π sr. Thresholds were determined to be ~2 MeV per nucleon for $Z \leqslant 3$. Heavy residual nuclei were identified by light output and time of flight from eight 200 μm plastic scintillators mounted in front of CsI crystals in a plane from 4° to 14° from the beam. Values of Z for the heavy fragments were not obtainable, but the velocity spectra compare well with data from other studies of heavy residual nuclei [7–9]. Right-left symmetry for heavy fragment detection along with large angular coverage for LCP's minimizes the classic problem of kinematic biasing for LCP's in coincidence with fragments.

Figure 1 shows typical velocity distributions for the fragments with and without a gate on the largest LCP multiplicities (multiplicity bite of ~1/2 for 7*A* MeV, ~1/10 for $>27A$ MeV). The high-multiplicity gate screens out most of the

*Present address: Centre d'Etudes de Bruyères-Le-Châtel, Service de Physique et Techniques Nucléaires, Boîte Postale No. 12, 91680 Bruyères-Le-Chatel, France.

†Present address: Battelle Memorial Institute, 505 King Avenue, Columbus, OH 43201.

‡Present address: Physics Department, University of Colorado at Boulder, Box 446, Boulder, CO 80309.

§Permanent address: Centre d'Etudes de Bruyères-Le-Châtel, Service de Physique et Techniques Nucléaires, Boîte Postale No. 12, 91680 Bruyères-Le-Chatel, France.

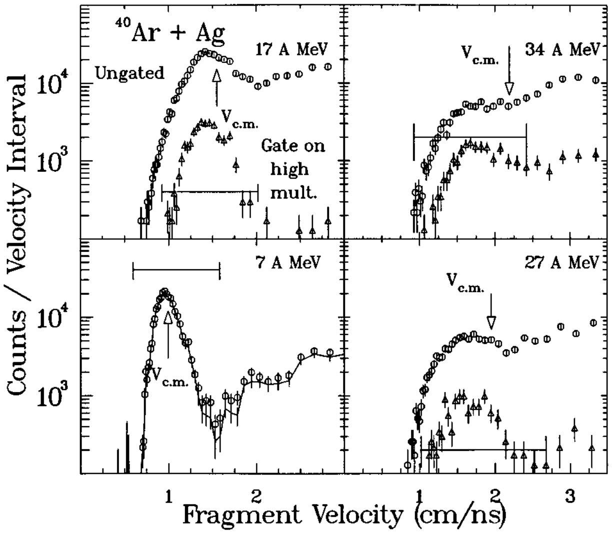

FIG. 1. Velocity spectra of heavy fragments emitted at $\theta_{\mathrm{lab}} = 7.9°$ from Ag bombarded by ^{40}Ar at the energies indicated: ⊙ ungated; △ and — gated on higher values of the H, He multiplicities. The c.m. velocity is shown by an arrow, and the velocity region used for subsequent gates is shown by the horizontal line; results in Figs. 2–5 are insensitive to detail in these velocity gates.

high velocity tail due to projectilelike fragments from deeply inelastic reactions. Clearly it is the low-velocity group of fragments that is associated with the more violent collisions or the most central collision group. For 7*A* MeV ^{40}Ar the velocity distribution of these fragments has a peak very near to the c.m. velocity, which is a well known feature of evaporation residues (ER's) from fusion reactions e.g. [10]. This group of heavy fragments with peak velocity slightly less than the c.m. velocity persists for all bombarding energies. For 27*A* MeV ^{40}Ar+Ag their summed cross section is approximately a barn [7,8], and their average mass number is $A\sim 90$ with half width at half maximum of ~ 15 [8,9].

We have measured angular distributions for ^{1,2,3}H, He, and Li in coincidence with these low-velocity fragments. Figure 2 shows such angular distributions for ^{1}H at each energy while Fig. 3 shows results for ^{1,2,3}H, He, and Li for the 34*A* MeV beam. From these curves one can allocate a part of the total multiplicity to a heavy nuclear emission source. For this purpose we have drawn calculated curves from simulations of particle evaporation from hot emitter nuclei [11] moving with velocity distributions taken from those of the residual nuclei shown in Fig. 1. The fraction of projectile mass transferred to the target was assigned according to a randomly selected value of the velocity ratio ($V_{\mathrm{fragment}}/V_{\mathrm{c.m.}}$). Statistical model parameters ($a = A/10$, $J_{\max} = 100\hbar$, $\mathfrak{I} = \mathfrak{I}$ rigid sphere) were chosen to fit the energy distribution of particles observed at $\sim 90°$, and then the angular distributions were individually normalized to the backward hemisphere data. Shapes of these calculated angular distribution curves are essentially independent of the details of evaporation model parameters; it is the reaction kinematics (i.e., emitter velocity and ejectile velocity) that are dominant. The integrated multiplicity under these curves can be assigned to emission after thermalization; this identification is also consistent with the shapes of measured and calculated energy spectra for ^{1}H, ^{2}H, and ^{4}He at large angles, as shown

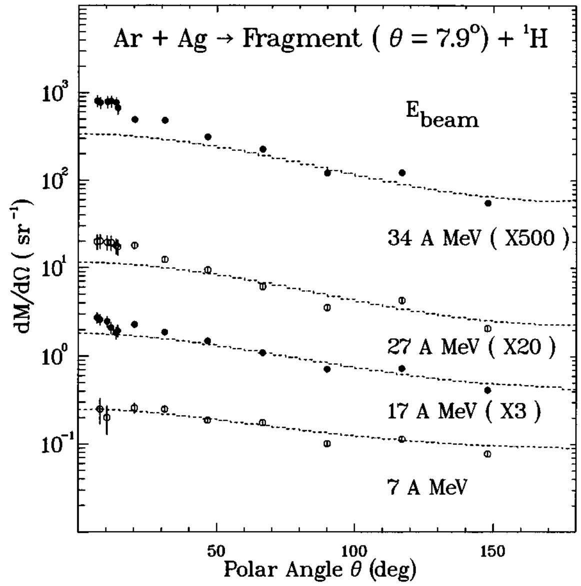

FIG. 2. Angular distributions for ^{1}H gated by heavy fragments at 7.9°. Smooth curves are from simulations of evaporation from emitters moving with velocity distributions taken from Fig. 1. Each one is normalized to the data at back angles. Error bars shown are statistical only.

in Fig. 4. It is also clear from Figs. 2–4 that there are significant forward-peaked LCP components that have high energy and are not attributable to emission from the same thermalized emitters. Angular integrations have been made individually for ^{1,2,3}H, He, and Li to determine both the total observed multiplicities as well as those components attributable to postthermalization emission. The differences are designated as prethermalization emission; evaporation from projectilelike fragments can be ruled out as discussed below.

The multiplicities for H, He, and Li are shown in Fig. 5 with separate indications for prethermalization and postther-

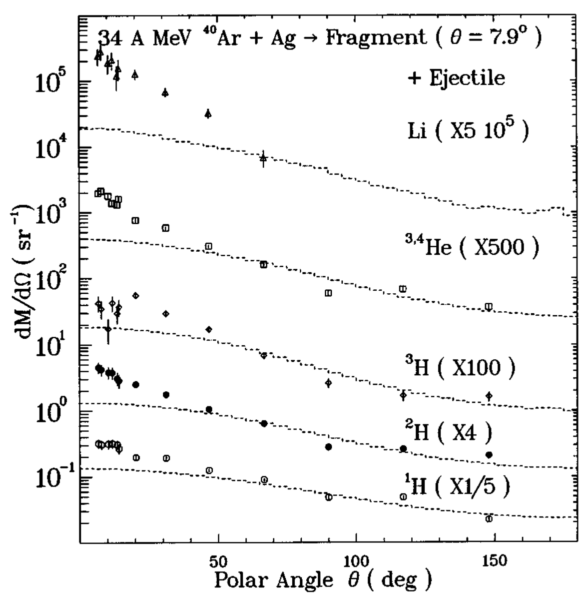

FIG. 3. Same as Fig. 2 but for various ejectiles for 34*A* MeV ^{40}Ar+Ag. The ^{3,4}He isotopes are combined; Li was assigned to $A=7$.

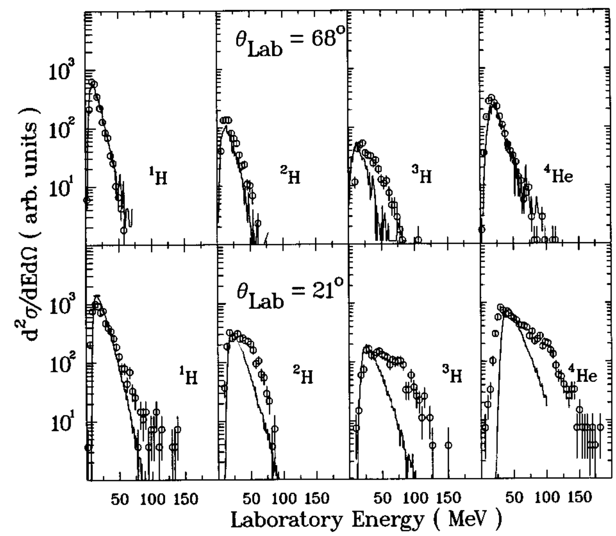

FIG. 4. Laboratory energy distributions of various ejectiles for 27A MeV ^{40}Ar (very similar to those for 34A MeV). Smooth curves are from simulations of evaporation from emitters moving with velocity distributions from Fig. 1.

malization components. It is clear that for the 7A MeV beam the LCP's are mainly evaporative and that the associated heavy fragments (Fig. 1) are mainly the ER's after essentially complete fusion; this result confirms a large body of earlier work [2]. For this near-barrier energy the small component of forward-peaked LCP's (~10%) makes for only a very small deviation from complete fusion and its concomitant 100% linear momentum transfer. However, the forward-peaked LCP components increase steadily with increasing beam energy and can account for the velocity gap in Fig. 1 between the calculated c.m. velocity and the observed peak velocities of the heavy residual nuclei.

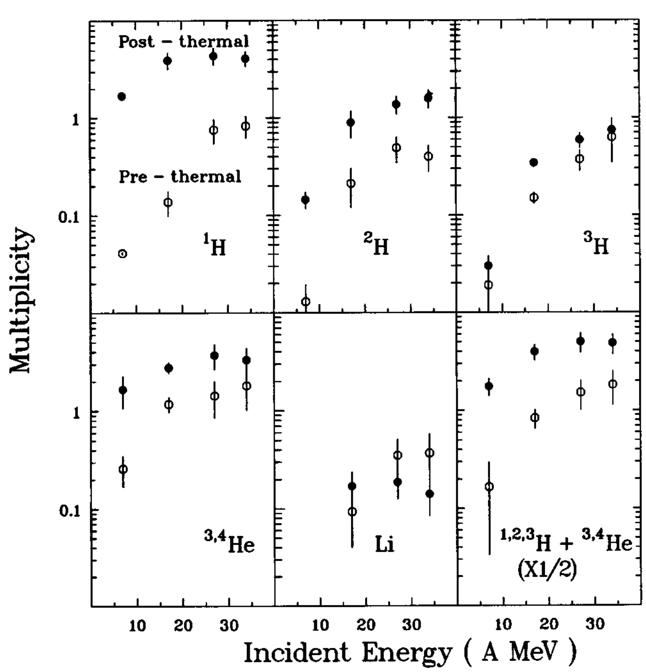

FIG. 5. Ejectile multiplicities for prethermalization and postthermalization components from heavy fragments at 7.9°. Only statistical uncertainties are shown.

TABLE I. Average multiplicities (M) and mass losses (ΔA) for 34A MeV ^{40}Ar+Ag.

	Prethermalization		Postthermalization	
	M	ΔA	M	ΔA
^{1}H	0.8	0.8	4.1	4.1
^{2}H	0.4	0.8	1.6	3.2
^{3}H	0.6	1.8	0.7	2.2
$^{3+4}$He	1.8	7.2	3.3	13.2
Li	0.4	3	0.2	1
IMF's [a]	0.4	5	0.2	2
n	0.8 [b]	0.8	8 [c]	8
Total	5.2	19	18	34

[a]Data taken from M.T. Magda *et al.*, Phys. Rev. C **45**, 1209 (1992).
[b]Estimated from reaction systematics [A. Oberstedt *et al.*, Nucl. Phys. **A548**, 525 (1992)].
[c]Estimated by ratio of neutrons to LCP's from statistical-model calculations [11].

The Li fragments are particularly interesting as members of the heavily studied class of intermediate mass fragments (IMF's). In Fig. 3 their angular distributions are shown to exhibit even more decided deviations from the postthermalization calculations than do any of the LCP's. Such forward peaking (gated on central collisions) has been reported several times for reactions of light projectiles such as ^{14}N that can be easily imagined to generate Li as the remnant of a projectilelike fragment, e.g. [12,13]. For ^{40}Ar and heavier projectiles, a Li fragment as a central-collision remnant would require such enormous projectile abrasion that this is not such a natural presumption. Instead these IMF's are often presumed to be postthermalization in their origin, and their yields are generally compared to predictions from equilibrium models [14,15]. On the contrary, in this reaction of 34A MeV ^{40}Ar, the Li fragments are decidedly forward peaked as verified in Ref. [9] and thus seem to be mainly generated prior to complete thermalization. This conclusion of prethermalization emission has also been reached from time scale information deduced by small-angle correlation studies of Li-Li, ^{2}H-Li, and ^{3}H-Li pairs [16].

In Table I we give the pattern of multiplicities and mass losses for prethermalization and postthermalization processes for 34A MeV ^{40}Ar+Ag. Recall that we have gated on heavy residual fragments at $\theta = 7.9°$. These fragments have the velocity distribution shown in Fig. 1 and have average final mass of $A \sim 90$ [7–9]. The average mass loss in prethermalization processes is $\Delta A \sim 19$. These ejectiles have high energies and forward peaked angular distributions and account for the momentum loss that drives the observed differences between heavy fragment and c.m. velocities. The average mass loss in postthermalization processes is $\Delta A \sim 34$. Combining these two mass decrements the average residual mass is $40+108-19-34 \approx 95$, consistent with the observed average heavy fragment mass $A \sim 90$.

It is clear from the mass and momentum balance that there is no additional projectilelike fragment associated with these reactions. Instead, there is the spray of gently forward peaked ejectiles, as shown in Fig. 3, that retain a general preference for the direction of the light collision partner, and hence reduce the fragment velocities to somewhat less than $V_{c.m.}$. Apparently the ^{40}Ar projectile has been torn asunder in these rather central collisions, but its tremendous energy dissipation has not evolved all the way to complete thermalization. One might say that the projectile's energy is essentially all "dissipated" but that only ~1/2 to 2/3 of it is "completely thermalized" with the rest carried by the rather diffuse forward directed spray. There are indications that this general behavior may persist even to 70*A* MeV [9,17].

As shown in Fig. 5 the extent of such prethermalization emission increases with incident energy, and evacuates an increasing fraction of the available energy prior to complete thermalization in this central collision group. These prethermalization ejectiles do not have projectilelike velocities; they have very broad energy distributions and angular distributions extending from 0° to $\gtrsim$50°. Therefore it seems that even for these preequilibrium ejectiles there has been considerable collisional energy mixing even though their complete thermalization has not been achieved. In a separate study of 34*A* MeV ^{40}Ar+Ag, mean lifetimes have been reported for ^{1}H, ^{2}H, and ^{3}H as a function of ejectile energy in the c.m. [18]. These lifetimes vary continuously over a tremendous range from $\lesssim$50 fm/*c* for ^{1,2,3}H of high exit-channel energy to $\gtrsim$1000 fm/*c* for ^{1,2,3}H of much lower energy. Clearly the very long lifetimes for low-energy ^{1,2,3}H are due to extensively thermalized emission, and the very short lifetimes for high energy ^{1,2,3}H reflect much less collisional energy mixing (i.e., prethermalization emission). The following rough picture emerges for near central collisions. As the partners interpenetrate, the projectile is broken into a variety of clusters, some of which survive to traverse the target. The survivor population exits at times of order of traversal time (~50 fm/*c*) with great abrasion of mass left behind in a collision cascade toward thermalization. For reactions with such enormous total energy dissipation, the dynamical and statistical features of the reaction chain generate ejectiles with broad, continuous and overlapping angular, energy, and lifetime distributions. Clear cut delineation between the dynamical and statistical driving forces will be difficult to achieve, but their separate effects are clearly in evidence.

The general conclusion from these results is that fusion-like reactions occur for this mass asymmetric reaction over the whole energy range studied, 280–1360 MeV. They lead to very highly excited composite nuclei, which deexcite by both prethermalization and postthermalization emission of particles and fragments of low *Z*. These incomplete fusion reactions give straightforward pathways to very highly excited nuclear systems which are currently of great interest.

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