Reaching the Capacity of a Composite Nucleus for Energy and Spin Containment

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The reaction 1080-MeV $^{40}Ar + ^{238}U$ has been studied via correlated fission fragments and He particles. Between $\frac{1}{3}$ and $\frac{1}{2}$ of the reaction cross section goes into fusionlike events to form composite nuclei excited to 500–800 MeV. The probability for such high-energy containment drops dramatically for ^{40}Ar projectiles between 27 and 44 MeV/u. Evaporative He particles for fusionlike events (multiplicity ≈ 1.5) have been found to arise predominantly from the massively excited composite nuclei.

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The new GANIL (Grand Accelerateur National d'Ions Lourdes) facility at Caen has been designed to deliver a wide variety of heavy projectiles in the energy range of (for example) 20–80 MeV/u for ^{40}Ar. Over this span of energies one expects to see a rapid decline of the fusionlike nuclear reactions that epitomize slow collective rearrangements in a mean nuclear field.[1] In their place at higher energies, one expects an increasing dominance of fast, nucleon-nucleon collision cascades.[2] Indeed, for the reactions 44-MeV/u $^{40}Ar + ^{58}Ni$ or ^{197}Au, a dramatic change has been observed in the yield patterns of projectilelike fragments produced in peripheral collisions.[3] The N/Z distributions indicate that fast fragmentation reactions (44 MeV/u) have mostly replaced the deeply inelastic reactions (at $\lesssim 10$ MeV/u).

In this work our particular interest (and that of several complementary studies[4,5]) has involved a search for the upper bounds of energy (and spin) that can be contained by a relatively long-lived thermalized composite nucleus. We have chosen the reaction 1080-MeV $^{40}Ar + ^{238}U$ which, for complete fusion, would produce excitation energies of ≈ 800 MeV. The observation of binary fission, subsequent to fusion, provides a well-established benchmark for the formation of such a "long-lived" composite nucleus.[6,7] We do observe a large probability for fusing collisions, and we establish that evaporative He is abundantly emitted by the composite nuclei.

Measurements were made of the correlated fission fragments[5–10] and their additional correlations with He particles.[11–15] This technique has proved to be very useful for getting an overview of the occurrence of various reaction types and their time scales.[14] The experimental arrangement (sketched in Fig. 1) consisted of three silicon detectors, any one of which served as a fission-fragment trigger. In addition, a position-sensitive avalanche detector (sweeper) was used to record the in-plane and out-of-plane angles of the correlated fission fragment. Light charged particles were measured in five telescopes, each comprised of three Si detectors (of thickness 50-150, 500–1000, and 5000 μm). In this Letter we will mainly consider the information from double coincidences between the fission fragments and from triple coincidences between two fragments and a He particle. (Even though He isotopes were not always separated, > 85% of them

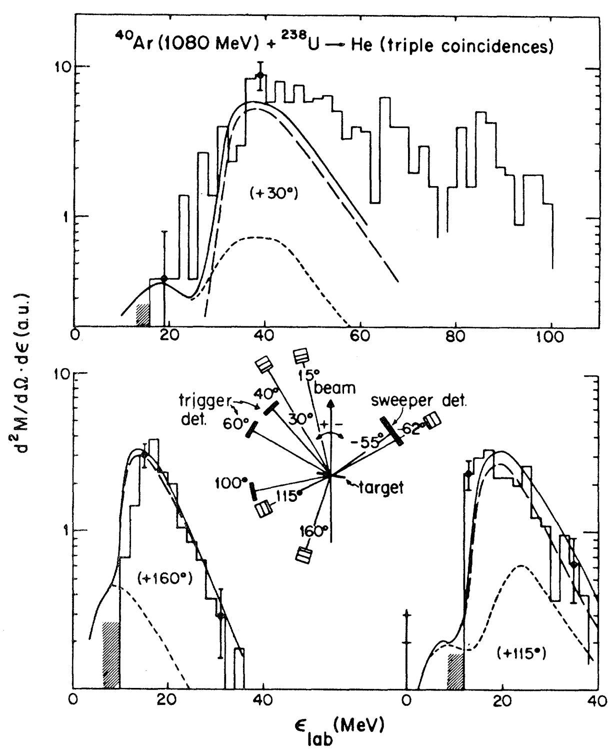

FIG. 1. Energy spectra for He in triple coincidence with a trigger fragment at 40° or 60° and a sweeper fragment in the position-sensitive avalanche detector. Smooth curves are from simulations for evaporation from fully accelerated fragments (short dashed line), from the composite nucleus (long dashed line), and their sum (solid line).

were ^{4}He.)

The fragment-fragment correlations from this work are shown in Fig. 2(b) as one combined projection on the in-plane folding angle θ_F. Qualitatively the broad peak at $\theta_F \approx 110°$ corresponds to very large momentum transfers to the composite nucleus followed by binary fission (i.e., a fusionlike process). This fusion peak is very similar to that observed at much lower beam energies [as shown in Fig. 2(c)]. The narrower peak at $\theta_F \approx 170°$ corresponds to sequential fission of the targetlike nucleus after a glancing collision and departure of a projectilelike fragment; hence there is very little momentum (and mass) transfer to the fissile nucleus. For *complete* fusion followed by isotropic evaporation, the average value of θ_F should be $\approx 96°$ (100° for uniquely symmetric fission) instead of 110°. In addition, the fusion peak is very broad. A straightforward Monte Carlo simulation[16] shows that this fusionlike peak cannot be accounted for by *complete* fusion even after considering the mass and energy distributions of the fission fragments and the evaporated particles. There must be some additional particle emission during the very first steps of the interaction. By comparisons to the simulations we estimate that, on average, about ten mass units and ≈ 200 MeV have escaped in a forward-peaked, light-particle spray.

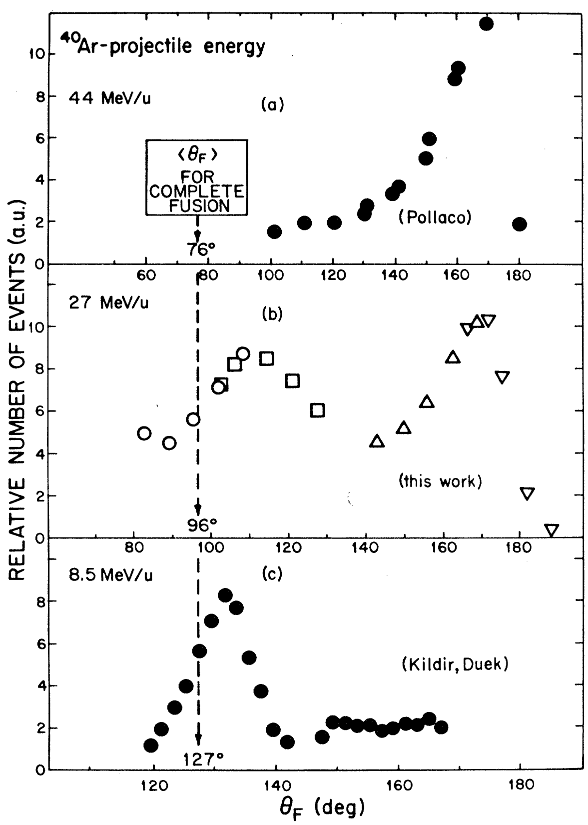

FIG. 2. Number of events vs folding angle θ_F ($\theta_{\rm trigger}+\theta_{\rm sweeper}$ for the two fission fragments): (a) 44-MeV/u ^{40}Ar+Th (Ref. 5); (b) 27-MeV/u ^{40}Ar+U (this work); (c) 8.5-MeV/u ^{40}Ar+U [Ref. 14 and M. Kildir *et al.*, Z. Phys. A **306**, 323 (1982)]. Additional data from the authors of Ref. 5 indicate the absence of a peak for very large momentum transfer. The symbols in (b) are for different trigger angles: 40°, open circles; 60°, squares; 100°, triangles and inverted triangles.

An integration of the folding-angle distribution between 80° and 130° provides a measure of the limits for the fusionlike cross section. The lower and upper limits are given respectively by the assumption of isotropic or $1/\sin\theta_{\rm c.m.}$ angular distributions for fission. An important part ($\frac{1}{3}$ to $\frac{1}{2}$) of the reaction cross section[17] is found for the fusion process; this implies the involvement of a large number of l waves in the entrance channel (0 to $260\hbar$ or $330\hbar$). For 8.5-MeV/u ^{40}Ar the fusion process also comprises $\approx \frac{4}{10}$ of the reaction cross section and spins of $0-124\hbar$ [Fig. 2(c)].[14]

The overall features of the folding-angle distributions are very similar for 8.5 and 27 MeV/u, in particular the form of the fusionlike peak. These correlation functions also strongly resemble the data obtained with lighter projectiles at similar and lower velocities ($\lesssim 30$ MeV/u).[6–10,15] On the contrary the present data (27 MeV/u) are dramatically different from those of Pollaco *et al.*[5] obtained with ^{40}Ar of 44 MeV/u. Figure 2(a) shows the markedly changed correlation function for 44 MeV/u; this difference must signal an important change in the nature of the nucleus-nucleus interaction mechanism. The distinct fusionlike peak (8.5 and 27 MeV/u) indicates that the bulk of the projectile was harnessed by the mean field of the composite nuclear system for a time period long enough for this object to exchange many particles and collectively deform into binary-fision-like decay. In fact, for the reaction 1080-MeV ^{40}Ar+^{238}U, more than ≈ 700 MeV must have been removed from the translational motion, and long-lived composite nuclei of 500–800 MeV of excitation must have been formed. Furthermore, this process comprises entrance channel l waves of 0 to $\approx 300\hbar$.

The disappearance of this fusion peak[18] over the relatively small velocity increase from 27 to 44 MeV/u indicates a rapid collapse of the capacity of the nucleus for energy and spin containment. Instead the fusion–binary-fission mode has largely disappeared and the intermediate reaction complex must have lost much of its mass and energy into exit channels of many smaller particles or clusters.

Evidently the wall of the mean nuclear field has been broken down for the major fraction of the reactions. The growth of leaks in this wall may also be reflected by the massive increase of direct He emission as discussed below (approximately twentyfold for a change of 8.5 to 27 MeV/u in ^{40}Ar energy).

Turning now to the triple-coincidence study of He, we show an interesting feature by plotting the differential multiplicities versus folding angle as shown in Fig. 3. Forward-directed He production arises from the whole range of momentum transfers, but with a distinct preference for intermediate-momentum-transfer collisions (Fig. 3, curves *a* and *b*), i.e., at the θ_F value for minimum abundance in Fig. 2. (Possibly the copious ejection of prompt particles has reduced the fissility of the residual nuclei.) By contrast, the He production at backward angles is decidedly disfavored in peripheral collisions. Evidently the massive energy deposition that characterizes fusionlike reactions strongly enhances the probability of this evaporationlike emission.

In Table I we give total multiplicities for He as a function of the transferred momentum. The in-plane multiplicities are rather well determined; in the absence of out-of-plane measurements we assume out-of-plane isotropy. (Strictly speaking, these multiplicities should therefore be designated

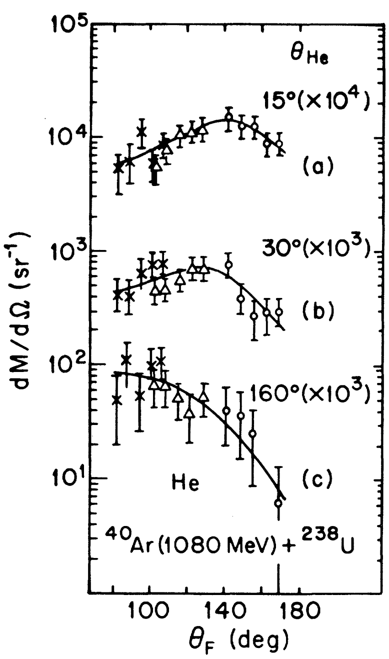

FIG. 3. Differential He multiplicity vs θ_F for various angles θ_{He}.

as upper limits.) Similarly, multiplicities have been deduced for the evaporationlike He particles from the data at backward angles. For the fusing collisions ($p_{\parallel}/p_{\text{projectile}} = 0.6–1$) we see that larger momentum transfers correspond to lower multiplicities for direct (or forward) emission and to higher multiplicities for evaporation. (Compare the slopes in Fig. 3.) It is likely that direct He production (along with n and ^{1,2,3}H) can account for most of the missing momentum in fusion. This cannot be true for the most peripheral collisions as the observed multiplicity of direct He actually decreases; here a "projectile residue" must carry away a sizable fraction of the initial momentum.[15]

For fusionlike fission the average multiplicity for evaporative He emission is about 1.5, a value about 15 times that observed[14] for 340-MeV ^{40}Ar + ^{238}U (and comparable to that[11] for 720-MeV ^{12}C + ^{238}U). Clearly a threefold increase in the deposited energy strongly enhances the evaporative He emission.

Another interesting aspect is shown by the He spectra in Fig. 1; reaction simulations[14] (to be discussed in detail in a forthcoming paper) are also shown. Figure 1 indicates that evaporation from the composite nucleus can account for the bulk of the data and that an upper limit for the fraction evaporated from the fully accelerated fragments can be set at $\approx 25\%$. However, for spherical composite nuclei with spins $\gtrsim 100\hbar$ the calculated evaporation spectrum has a long high-energy tail that is not compatible with the data. This result is due to the very appreciable spin-off energies that would characterize evaporation from rapidly rotating spherical composite nuclei.[19] As we do not observe such a high-energy tail in the ^{4}He spectra, we had to invoke a rather extensive deformation, i.e., a principal-axis ratio of $\gtrsim 1.5$ for prolate deformation. Such a large distortion of the composite nucleus reduces its rotational velocity and thus eliminates the high spin-off energies for ^{4}He. These evaporative processess thus provide an interesting

TABLE I. Multiplicities for He vs fractional momentum transfer.

$p_{\parallel}/p_{\text{projectile}}$	Total He	Evaporative He	Forward-peaked He
0.25	1.46	0.22	1.24
0.50	2.50	0.70	1.80
0.75	2.70	1.30	1.40
1.0	2.75	1.60	1.15

constraint on the properties of the emitters.

We conclude that composite nuclei of relatively long lifetime and ≈ 500–800 MeV of excitation energy have been formed in central collisions of 1080-MeV ^{40}Ar with ^{238}U. The formation of such long-lived composite nuclei at 27 MeV/u constitutes $\frac{1}{3}$–$\frac{1}{2}$ of the reactions but then drops to a much smaller value for 44 MeV/u.[5] The fusionlike collisions for 27 MeV/u are generally associated with several forward-peaked, light particles including ≈ 1.4 He. However, the maximum probability for direct He (≈ 1.8) occurs for $\approx 50\%$ momentum transfer. The maximum probability for evaporative He (≈ 1.5) occurs for 75–100% momentum transfer; most of this evaporative He arises from the massively excited composite nuclei. Further studies of these evaporated particles can be expected to give even more detailed information (average spin, temperature, size, and/or shape) concerning these very hot, long-lived composite nuclei,[19,20] near to their limit for energy and spin containment.

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[18]It is conceivable that "slow decay" by triple fission could have largely replaced the binary fission. This possibility cannot be definitely ruled out, but the consistent rarity of triple versus binary fission makes it very unlikely.

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