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Intermediate mass fragments from ^{40}Ar + ^{197}Au: Transition from the incomplete fusion to the participant spectator regime

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Inclusive cross sections of intermediate mass fragments from the reaction ^{40}Ar + ^{197}Au at $E/A = 30$ MeV and 220 MeV were measured with a low threshold and over a large range of angles. The integrated cross sections are about 2 b at both energies but the emission characteristics change considerably. The increased isotropy of the angular distributions and the strongly reduced Coulomb repulsion at the higher bombarding energy suggest that the emission process evolves towards fragmentation of excited spectator matter in central ion-ion collisions.

We report on the production of intermediate mass fragments (IMF's, defined as fragments with atomic number $Z \geq 3$) in the reaction ^{40}Ar + ^{197}Au at two bombarding energies, $E/A = 30$ MeV and 220 MeV. The lower energy is near the Fermi energy. Here the emission of IMF's starts to appear as a major mode of deexcitation in heavy-ion reactions [1]. The IMF cross sections rise rapidly and the element distributions broaden with increasing bombarding energy, but seem more directly correlated with the deposited excitation energy [2]. Multiple emission of IMF's may occur, but its features were found consistent with a sequential emission from the heavy composite nucleus that is formed in an incomplete-fusion-type reaction [2–5].

At $E/A = 220$ MeV, high above the Fermi energy, the total kinetic energy of the ^{40}Ar projectile of nearly 9 GeV is in the range where saturation effects were observed with lighter projectiles. The cross sections for IMF production in proton-induced reactions level off [6–8], and the elemental IMF distributions $\sigma(Z)$ in proton and heavy-ion (up to neon) induced reactions seem to attain nearly invariant shapes [8–11]. The present study, conducted with identical techniques at the two energies, is intended to follow the evolution of the argon-induced reaction into the relativistic regime of limiting fragmentation. It turns out that the results, although purely inclusive, have a bearing on the search for the proposed mechanism of multifragmentation [1,12].

The experiments were performed at the SARA facility in Grenoble and at the SATURNE facility in Saclay with ^{40}Ar beams of $E/A = 30$ MeV and 220 MeV, respectively. Self-supporting Au targets with areal densities of 1.0 and 5.0 mg/cm^2 were used. Arrays of six detector telescopes were placed around the target in the angular range $15° \leq \theta_{\text{lab}} \leq 120°$. Each telescope consisted of an axial-field ionization chamber, three silicon surface-barrier detectors of 50 μm, 300 μm, and 1000 μm thickness, respectively, and a scintillation detector [BGO at SARA, CsI(Tl) at SATURNE] viewed by a photodiode. The threshold energy for elemental identification of the detected fragments was in the range of $E/A = 1–2$ MeV.

As an example, the measured double-differential cross sections of carbon ions are shown in Fig. 1. Their exponential decrease with fragment energy and their forward peaking are expected for IMF emission in heavy-ion reactions. However, comparing the data from the two bombarding energies, we immediately observe two significant differences: At the higher energy the cross-section maxima which may be associated with the Coulomb repulsion from the emitting system are shifted to very small fragment energies. This is an important new feature and will be discussed in more detail below. Second, the slope parameters representing the tails of the fragment spectra are considerably larger, possibly reflecting properties of the initial collision dynamics.

Satisfactory descriptions of the data were obtained with fits employing two Maxwellian sources, a slow so-called target source and a faster intermediate-velocity source (Fig. 1, top). The sources move in the beam direction and emit isotropically in their rest frames. The spectra measured at $E/A = 30$ MeV and $\theta_{\text{lab}} = 15°$ deviate from the fits. But here, near the grazing angle $\theta_{\text{lab}} = 9°$, projectile fragments with velocities close to the beam velocity form distinct groups for $Z \simeq Z_{\text{proj}} = 18$. These groups gradually overlap with the low-velocity components as Z decreases. The carbon spectra at 15°, e.g., extend to $\simeq 300$ MeV with nearly constant intensity. We did not attempt to fit these spectra by including an

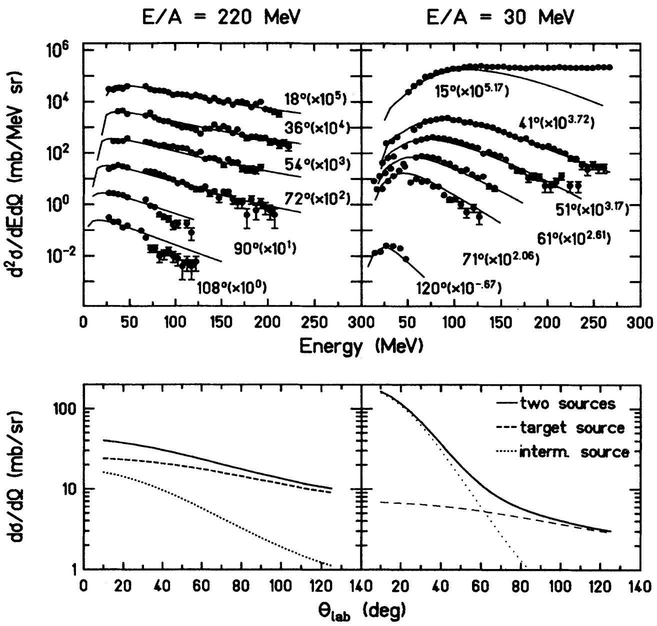

FIG. 1. Top: Double-differential cross sections for carbon ions produced at $E/A=220$ MeV (left-hand side) and 30 MeV (right-hand side). The lines represent the moving-source fits described in the text. Note the scaling by factors of 10 (top left) and by factors chosen to give an equivalent angular representation (top right). Bottom: Energy-integrated angular distributions as obtained from the moving-source fits. The dashed and dotted lines give the individual contributions of the target and the intermediate-velocity sources, respectively.

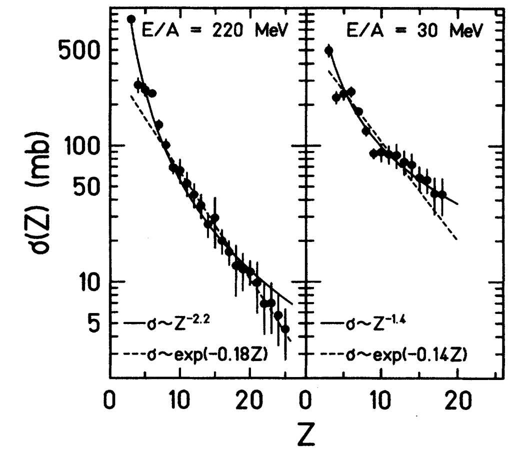

FIG. 2. Integrated cross sections $\sigma(Z)$ at the two energies. The solid and dashed lines represent the results of power-law and exponential fits, respectively. The fit parameters are indicated.

additional projectile source. For illustration, the fit parameters for three elements are given in Table I. Here N, T, and β denote the strengths, the temperatures, and the velocities of the sources, and the subscripts i and t indicate the intermediate-velocity and target sources, respectively. The errors are generally between 10% and 20% and reach up to 30% for the intermediate-velocity source at $E/A=220$ MeV. The errors of the Coulomb parameters E_C will be given in Fig. 3 (see below).

The moving-source parametrization was used to construct energy-integrated angular distributions which reveal a third significant change in the reaction characteristics (Fig. 1, bottom). At the lower bombarding energy the cross sections are strongly forward peaked, which shows that dynamical equilibrium has not been reached. At $E/A=220$ MeV the angular distributions are more isotropic and, thus, indicate emission from a nearly equilibrated source of slowly moving target matter. This difference is reflected in the relative intensities of the two sources fitted to the data (Fig. 1, bottom). The target source, which at $E/A=30$ MeV is only needed to reproduce the back-angle data, accounts for the major part of the cross section at $E/A=220$ MeV. Its velocities $0.02 \leq \beta_t \leq 0.03$ at this energy are far below the nucleus-nucleus center-of-mass velocity $\beta_{c.m.}=0.12$.

The moving-source description was further used to generate elemental cross sections $\sigma(Z)$ integrated over the $4-\pi$ solid angle. The results were found to depend weakly on possible ambiguities in the parameter sets as long as fits of comparable quality were produced by these parameters. The errors given in the figure include these uncertainties. The cross sections $\sigma(Z)$ reach values of up to several hundred millibarns for the smaller fragments and are very similar at the two energies (Fig. 2). Larger fragments with Z close to Z_{proj}, however, are more copiously produced at the lower energy even though the yields of the projectile source were not included in the integration (cf. Fig. 1). This may indicate that a friction-type damping mechanism, familiar from reactions

TABLE I. Moving-source parameters for lithium, carbon, and magnesium ions.

E/A (MeV)	Z	N_i (mb)	T_i (MeV)	β_i (%)	N_t (mb)	T_t (MeV)	β_t (%)	E_C (MeV)
30	3	360	15	12	135	8	4.1	20
	6	200	15	11	52	13	2.3	35
	12	45	18	11	41	16	4.5	45
220	3	260	62	15	560	22	2.9	17
	6	60	53	7	180	26	2.5	11
	12	. . . [a]	. . .	. . .	44	34	2.4	18

[a]For practical reasons one-source fits were applied to the $Z \geq 10$ spectra at $E/A=220$ MeV.

closer to the Coulomb barrier and not expected at $E/A=220$ MeV, may contribute to this group of fragments. Fits to the elemental cross-section distributions were achieved with both exponential and power-law descriptions (Fig. 2). The power-law function is clearly superior if the large yields of lighter fragments are to be reproduced. The rather small power-law exponent $\tau=1.4\pm0.2$ at $E/A=30$ MeV falls outside the range of τ values reported for reactions with lighter projectiles [2,9,10]. It results from the enhanced yields with $Z \simeq Z_{\rm proj}$.

The total cross sections for IMF production $\sigma_{\rm IMF}=2.2$ b ($E/A=30$ MeV) and $\sigma_{\rm IMF}=2.3$ b ($E/A=220$ MeV), obtained by summing $\sigma(Z)$ from $Z=3$ up to $Z\leq 20$ and $Z\leq 25$, respectively, are very similar. The error, including the contribution from the absolute normalization of the experiments, amounts to about 25% in both cases. A rising trend of $\sigma_{\rm IMF}$ with incident energy is most likely at the lower bombarding energy [2]. One may therefore expect a maximum at some intermediate energy and a decrease or, at least, a leveling off around the higher bombarding energy as observed for reactions with lighter projectiles in the GeV energy range [6–9]. The magnitude of $\sigma_{\rm IMF}$, however, is considerably larger than the saturation value of about 0.5 b reported for proton-induced reactions [8].

The perhaps most interesting feature in the data is the shift of the maxima of the fragment spectra to very low energies at $E/A=220$ MeV because it implies that the emitting system exerts a drastically reduced Coulomb force upon the fragments. The effect manifests itself in rather small Coulomb parameters E_C in the moving-source description (Fig. 3). In fact, even $E_C=0$ is within the range of the systematic uncertainties, since only some of the spectra show indications of an actual maximum near the detection threshold. It is assumed in these fits that the Coulomb potential originates in the slowly moving target source and that its strength varies between $0.5E_C$ and $1.5E_C$ with equal probability [13]. At $E/A=30$ MeV the obtained E_C parameters are in qualitative agreement with those for the ^{12}C+^{197}Au reaction at comparable energies [13] and follow the trend expected from the fission systematics [14] assuming an initial $Z=79$. A slight reduction of E_C with respect to that prediction is easily understood since charged particles may be evaporated prior to the IMF emission [15]. The very low E_C values deduced for $E/A=220$ MeV, however, imply that here IMF's are not emitted from composite nuclei of similar size and excitation. Such nuclei, excited above the threshold for IMF emission [2] and resulting from incomplete-fusion-type reactions at the lower energy [5], do not seem to be produced in large quantities at $E/A=220$ MeV. The close to isotropic angular distributions indicate emission from spectator matter, but the heavy spectator nuclei from the more peripheral collisions are excluded by the small E_C. They may not be sufficiently excited as expected from, e.g., an abrasion-type mechanism. The bulk of the IMF's must, therefore, originate from more central collisions that lead to either rather small spectator systems or to systems which, driven

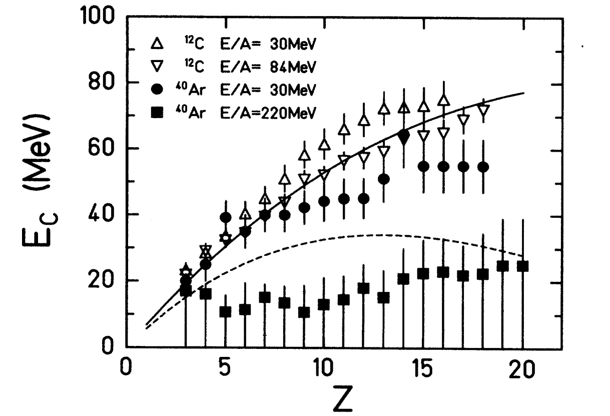

FIG. 3. Coulomb energies E_C obtained from moving-source fits to the fragment yields in ^{40}Ar (solid symbols) and ^{12}C (open symbols, from Ref. [13]) induced reactions on ^{197}Au. The solid and dashed lines represent the Coulomb energies expected from the fission systematics [14] for decaying nuclei of $Z=79$ and 39, respectively.

by thermal or compressional excitation [16], expand before releasing the IMF's.

A reduced Coulomb repulsion was first observed by Cumming *et al.* [17] and Poskanzer, Butler, and Hyde [18] in proton-induced reactions and since then reported for several proton- and light-ion-induced reactions at relativistic energies [9,19–22]. A weak dependence on the projectile mass is indicated by the data of Sullivan *et al.* [19] and of Warwick *et al.* [9]. Our data seem to continue this trend since the Coulomb peaks, as seen in the spectra (Fig. 1), are at even lower energies than in these earlier data with projectiles of $Z\leq 10$. Warwick *et al.* conclude from their coincidence data that IMF's result from the breakup of relatively cold spectator matter in central collisions [9]. In the ^{40}Ar+^{197}Au reaction studied here about 50% of the target nucleons remain spectators in the most central collisions, according to the fireball geometry [23]. The expected Coulomb repulsion for IMF emission from such a remnant of $Z=39$ is close to the upper limit of the observed effect but, apparently, not small enough to fully explain the data (Fig. 3). The assumption that the spectator system with $Z=39$ is distributed over the volume of the original gold nucleus will reduce the Coulomb repulsion by only $\simeq 15\%$. Further significant reductions may result, however, if (i) evaporation of a large number of light charged particles precedes the IMF emission [15,24], or if (ii) the spectator matter clusters and fragments are produced by volume instead of surface emission [25]. The latter process may require that the clusterization, as conjectured in multifragmentation scenarios [1,12], is accompanied by a collective expansion of the spectator system. In order to distinguish between these possibilities further systematic and, in particular, correlation studies [3,15] will be required.

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