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Production of three nearly equal mass fragments in the Xe+Cu reaction at 45 MeV/u ☆

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An experimental study of three intermediate mass fragment production in the reaction Xe+Cu at 45 MeV/u is presented. Results are compared with the predictions of a conventional statistical binary decay model starting from equilibrated sources obtained both from incomplete fusion systematics and from dynamical calculations at several impact parameters. The inclusive experimental data agree with the dynamical predictions, whereas a disagreement between the exclusive data and the calculations has been found.

The experimental study of the emission of intermediate mass fragments (IMF) in intermediate energy (20–100 MeV/u) heavy ion reactions is one of the methods allowing for a deeper understanding of the behaviour of hot and compressed nuclear matter. In this energy regime the multifragment disintegration has been recently observed [1,2], indicating, in the case of central collisions, mechanisms which are not compatible with conventional statistical decays of nuclear systems at normal densities. At higher energies, observing the IMF production in the projectile fragmentation [3], a transition from evaporation to total disassembly of the projectile has been shown. These are the most recent results of a strong experimental effort [4] with the aim of studying the production of more than two massive fragments over a large range of incident energies. To this end several large acceptance multi-detector systems have been built in various laboratories [#1].

With the aim of detecting IMF in reverse kinematics experiments we have built on this line a large acceptance apparatus with low energy thresholds and a good position resolution, able to measure with good accuracy the atomic number, the energy and the emission angle of the nuclear products coming from the heavy ion interactions at intermediate energies [6]. This apparatus is made of 48 three-element telescopes in the angular range from $\theta_{\min} \approx 3°$ to $\theta_{\max} \approx 26°$; each telescope consists of an axial ionization chamber (IC), a two-dimensional position sensitive solid state detector [7] 500 μm thick, and a CsI scintillator. The energy resolutions with a 30.7 MeV/u Xe beam, stopped in the Si detector, are 1% for the Si and 2% for the IC (263 MeV energy loss). The energy resolution of the CsI with a 43.8 MeV/u Ar beam is 2.2%.

The energy thresholds are essentially given by the energy losses in the IC. Typical values, when operating at 200 mbar CF_4, are around 2.5 MeV/u for all the detected fragments. the $\Delta E - E$ method has been used to determine the atomic number Z from 2 to 54.

☆ Experiment performed at GANIL, Caen, France.

[#1] The most recent apparatus are described in ref. [5].

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We present here the first results obtained by bombarding a Cu target (2.3 mg/cm^2) with a 45 MeV/u ^{129}Xe beam from the coupled cyclotrons at GANIL [#2]. The geometrical efficiency in the angular range 0°–23° was 68%, essentially limited by the central hole and by the IC window frames. Simulations were performed in order to estimate the multiple-event efficiency, and no significant distortion due to the apparatus was found [8]. If one assumes, for the sake of simplicity, an isotropic distribution for events of multiplicity greater than 2, the efficiency for the detection of the three-fold events is of the order of 30%. The ratio between three- and four-fold events was experimentally found to be 18.4 and there are very few five-fold events. Some recorded three-fold events can originate from four-fold events where one of the fragments is not detected. For four-fold events the calculated ratio between three- and four-fold detected fragments is around 1.9. So at most 1.9/18.4 of the three-fold detected events are actually incomplete four-fold events, i.e. 90% are *real* three-fold events.

Since exclusive observables can give more information on the reaction mechanism than inclusive ones, we focused the analysis on the Z correlation of three detected IMF ($Z>2$).

In fig. 1a the experimental distribution for the three-fold events in the ($Z_{\min}/Z_{\text{tot}}$, $Z_{\max}/Z_{\text{tot}}$) plane [9] is shown. Z_{tot}, $Z_{\min}$ and Z_{mas} are the sum, the minimum and the maximum value of the charge of

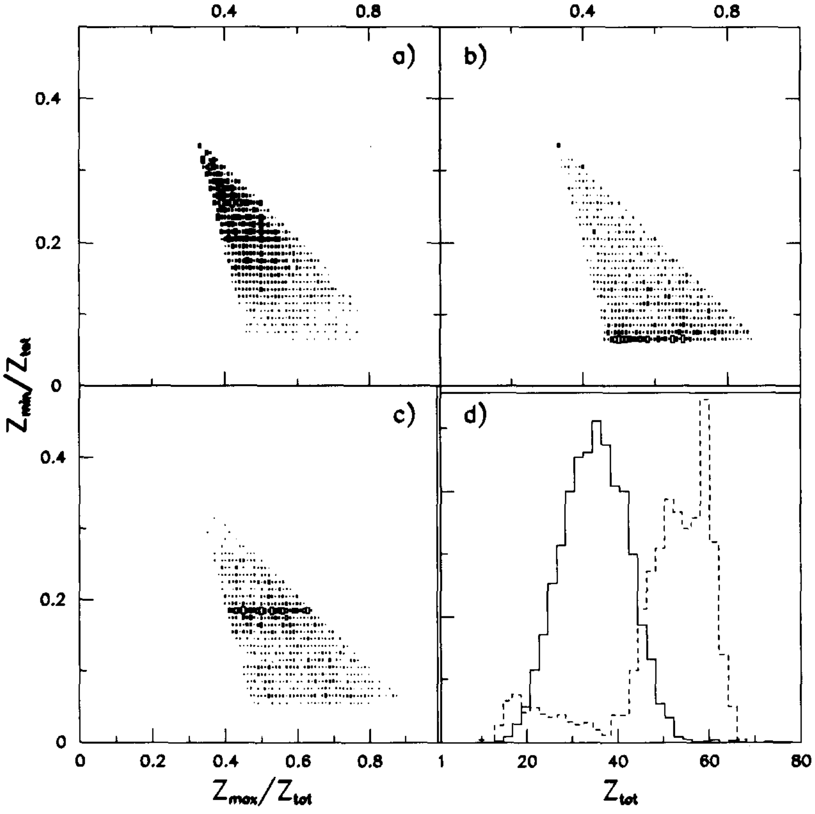

Fig. 1. $Z_{\min}/Z_{\text{tot}}$ versus $Z_{\max}/Z_{\text{tot}}$. (a) experimental results; (b) predictions by systematics+Gemini; (c) predictions by the coupling of dynamical and statistical approaches (for more details see text). (d) Sum of the charges of all IMF detected in three-fold events. The continuous line shows the experimental results, whereas the dashed one the predictions by the coupled dynamical and statistical approach.

[#2] The data have been collected with the trigger given by all the Si detector signals but, due to some technical problems, the Z identification has been made for only part (≈50%) of the telescopes ($\theta>5°$).

Table 1
Characteristics of the sources for the Xe+Cu reaction at 45 MeV/u.

b (fm)	Big source				Small source			
	A	E^* (MeV)	L	v/c (lab)	A	E^* (MeV)	L	v/c (lab)
0	151	800	11	0.21				
0.5	153	838	24	0.21				
1.5	154	907	63	0.21				
2	153	822	78	0.21				
3	129	543	68	0.22	14	64	2	0.15
4	123	490	71	0.23	25	64	5	0.12
5	126	348	71	0.25	31	139	10	0.10
6	119	297	63	0.26	41	136	16	0.08
7	116	183	51	0.28	46	123	20	0.07
8	121	140	36	0.28	50	92	20	0.05
syst.	162	1178	105 [a]	0.25				

[a] L_{max} corresponding to $b \approx 1.7$ fm.

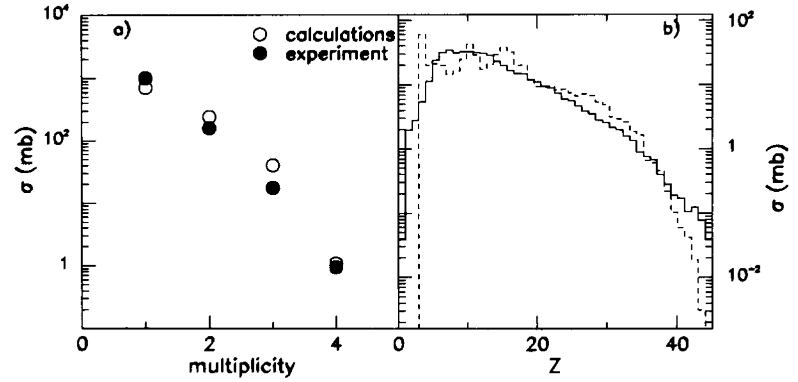

Fig. 2. (a) Cross sections as a function of the multiplicity for the overall apparatus. (b) Cross sections as a function of the charge of the detected IMF. The continuous line shows the experimental results; the dashed one the predictions by the coupled dynamical and statistical approach, filtered by the apparatus. No normalization has been applied.

the three observed fragments, respectively.

An enhancement is present in the upper corner, which corresponds to a high probability for the production of three fragments of nearly the same mass. As a first step these results have been compared to the prediction of a statistical model calculation involving sequential binary decay of an equilibrated source at normal density (Gemini code [10] with the inputs from the Viola systematics for incomplete fusion [11], hereafter referred to as syst.+Gemini) filtered by the acceptance of our apparatus [8] (fig. 1b)). This model describes well the experimental results obtained for reactions like La+C, Al at 47 MeV/u [12], whereas discrepancies have already been pointed out for more symmetric systems [13], or for higher energies [1]. Even for the reaction measured in the present experiment the disagreement is evident. This could be due to different reasons, such as the dependence of the production yield and structure of the equilibrated hot systems (fragment sources) on the impact parameter, or a lack of validity of the statistical binary decay assumptions; e.g. a sudden formation of several IMF in central collisions might be considered.

We have investigated the first point by coupling [14,15] a dynamical model based on the Landau–

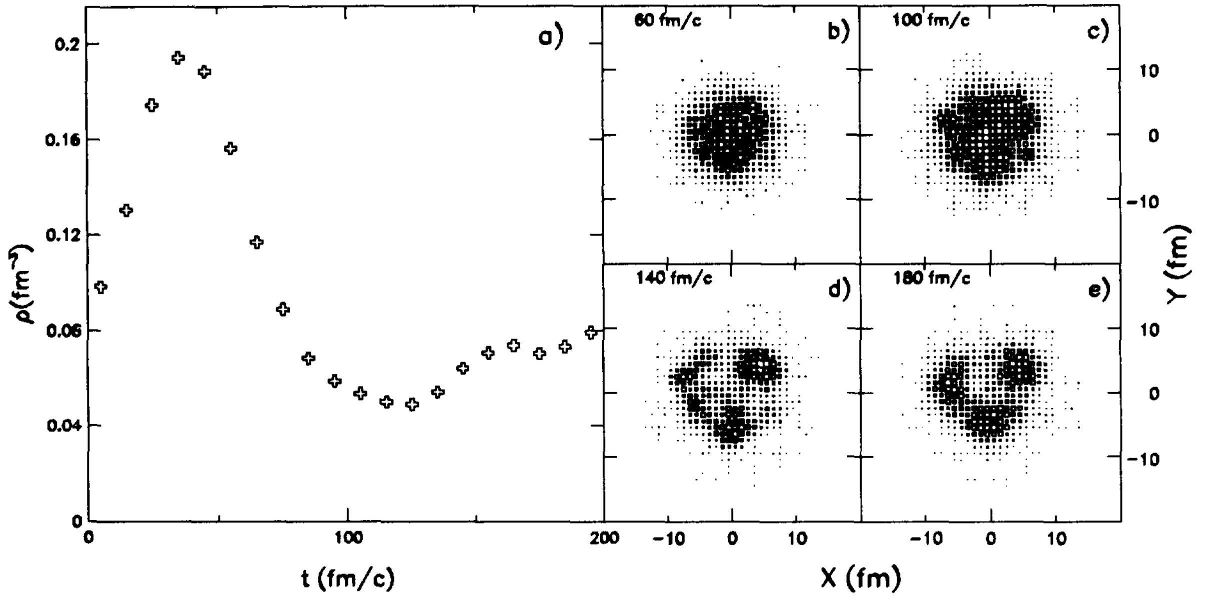

Fig. 3. (a) Evolution of the density in the overlap region as a function of time for the reaction Xe+Cu at 44 MeV/u; (b)–(e) density profiles in the plane perpendicular to the beam direction for different times.

Vlasov equation to the conventional statistical binary decay (Gemini code). The basic idea of this coupling is to follow the dynamics of the interaction for impact parameters from 0 to 8 fm up to a time t^* (80–100 fm/c), when the primary excited system has reached a statistical equilibrium condition, but it has not yet started the de-excitation stage [16]. The excited system information (mass, charge, excitation energy, intrinsic angular momentum and laboratory velocity) is obtained from a coalescence model [14] of the mean one-body distribution in the phase space. Central impact parameters ($b \leqslant 2$ fm) give a single excited source, whereas for increasing impact parameters two equilibrated "sources", close in mass to the projectile and target, are found, reflecting the peripheral character of the interaction. In table 1 the characteristics of these sources (referred to as "big" and "small" in the following) are presented as a function of the impact parameter, together with the characteristics of the source from the Viola systematics [11]. Finally the de-excitation stage of the sources has been followed through sequential binary decays (Gemini code). The results of these calculations, filtered by the overall acceptance of the apparatus, seem to reproduce fairly well some of the inclusive data. The predicted total cross section for fragment production of any multiplicity is 0.995 b, in agreement with the experimental value of 1.23 b. The statistical uncertainty is negligible and an error on the order of 10% can be associated to the experimental cross section, due to the normalization to the Rutherford cross section. In addition the cross sections for various multiplicities and the inclusive $\sigma(Z)$, presented in figs. 2a and 2b respectively, are reasonably well reproduced by the calculations. We would like to stress that the cross sections are in contrast underestimated by roughly a factor 10 by the syst.+Gemini calculations. From the LV+Gemini calculations it follows that the intermediate impact parameters b-values (from 3 to 5 fm), not taken into account by the syst.+Gemini, are the most effective ones to reproduce the experimental cross sections, whereas more peripheral impact parameters give negligible contributions because of the 5° forward cone not covered by the detectors.

Going to more exclusive observables the agreement between the data and the LV+Gemini calculations disappears.

The calculated correlation ($Z_{\text{min}}/Z_{\text{tot}}$, $Z_{\text{max}}/Z_{\text{tot}}$), shown in fig. 1c is different both from the experimental data (fig. 1a) and from the one obtained from the syst. + Gemini calculations (fig. 1b). The upper part ($Z_{\min}/Z_{\rm tot} \simeq 0.3$) of the tri/angle is nearly empty and an enhancement is present corresponding to the emission of a quasi-target fragment together with two heavier fragments coming from the fission of the "big" source. Moreover, in fig. 1d the total charge of the IMF in the three-fold events is presented together with the results of the LV + Gemini calculations which, however, give values well above the experimental ones.

These discrepancies could be ascribed to the low excitation energy of the sources given by the Landau –Vlasov calculations (table 1). Higher excitation energies could in fact enhance the production of smaller fragments, reducing the total Z value in fig. 1d and populating the upper region of fig. 1c, thus improving the agreement with the experimental data. By arbitrarily increasing the excitation energy of the "big" source by 40% (thus reaching the E^*/A values of the systematics) no real improvement, however, has been found. The enhanced region in fig. 1c slightly moves up (10%) while the controid of the $Z_{\rm tot}$ distribution only decreases by five units when 20 units would be necessary. Thus, in the framework of the calculations we have performed, the excitation energy dies not seem to be the key to explain the discrepancies with the experimental data.

To obtain a deeper insight into the reasons of the failure of the LV + Gemini calculations we extended the Landau–Vlasov calculations to times larger than the equilibrium time. We studied, at $b=0$ fm, the mean density of the projectile-target overlap region (≈ 4 fm in radius) (fig. 3a) and the density profiles (fig. 3b) as a function of time. After the compression phase the density goes down to $\rho_0/3$ and keeps this value for ≈ 40 fm/c. Furthermore, there is a clear indication that dynamical instabilities appear a short time ($30\ {\rm fm}/c \approx 10^{-22}$ s) after the equilibrium: the system Xe + Cu may become unstabale well before the times assumed by the sequential binary statistical models we used. Thus we believe that, in order to follow the de-excitation stage of the equilibrated sources, calculations based on statistical simultaneous multifragmentation models [9,17,18], which also take into account the density of the intermediate systems formed in the reaction, are needed.

A further possibility to understand the exclusive data we presented could be related to improvements of the Landau–Vlasov model, and, in particular, to the attempt, still in progress [19], to go beyond the one-body average Landau–Vlasov treatment using a transport theory of fluctuations. In fact, at the present stage, Landau–Vlasov calculations cannot generate physical fragments. As a matter of fact, the physical fluctuations of the matter density, which lead to the aggregation regions of fig. 3b could be triggered by numerical round-off errors when the system is in the instability region. We think, however, that the sudden increase of fluctuations and the appearance of aggregation regions imply that the spinodal region has actually been reached by the intermediate system, and that they can be signals of a transition towards multi-fragmentation.

Finally, to account for the exclusive data such as those presented in this letter, both the formation and the de-excitation steps of the intermediate systems formed in a heavy ion reaction have to be further investigated theoretically.

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