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EXPERIMENTAL EVIDENCE OF NON-SEQUENTIAL MECHANISM IN THE PRODUCTION OF THREE INTERMEDIATE MASS FRAGMENTS IN THE Xe + Cu REACTION AT 45 MeV/u

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Experiment performed at GANIL

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Experimental evidence of non-sequential mechanisms in the production of three intermediate mass fragments in Xe+Cu reaction at 45 MeV/u[1]

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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 prediction of a statistical sequential binary decay model starting from equilibrated sources (from incomplete fusion systematics or from dynamical calculations at several impact parameters). The experimental data disagree with such predictions, indicating mechanisms different from sequential binary decay.

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 the hot and compressed nuclear matter. The importance of these processes lies on the fact that they could indicate the existence of a novel mode of nuclear disassembly consisting in the simultaneous emission of more than two massive fragments.

In this energy regime the multifragment disintegration has been recently observed [1], indicating, in the case of central collision, mechanisms which are not compatible with statistical decays of nuclear systems at normal densities. At higher energies, observing the IMF production in the projectile fragmentation [2], a transition from evaporation to total disassembly of the projectile has been shown.

These are the most recent results of a very strong experimental effort [3] with the aim of studying the production of more than two massive fragments in a very large range of incident energies. To this end several large acceptance apparatus have been built in many laboratories [4].

In this line, with the aim of detecting IMF in reverse kinematics experiments, we have built a large acceptance apparatus with low energy thresholds and good position resolution, able to measure with sufficiently high accuracy the atomic number, the energy and the emission angle of the nuclear products coming from the heavy ion interactions at intermediate energies [5]. This apparatus is made of 48 three-element telescopes in the angular range from $\theta_{min} = 3^o$ to $\theta_{max} \approx 26^o$; each telescope is made of an axial ionization chamber (IC), a two dimensional position sensitive solid state detector [6] $500 \mu m$ thick, and a CsI scintillator.

The measured energy resolutions are around 1% for Si detectors and are of a few percent for the IC and the CsI. 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 ΔE - E method has been used for the atomic number Z determination and a good resolution from Z=2 to Z=54 has been achieved.

To understand if the process of multifragment production proceeds through a sequential decay or it is due to a simultaneous breakup of a hot system, 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).

We present here preliminary results obtained bombarding a Cu target (2.3 mg/cm^2) with a 45 MeV/u ^{129}Xe beam from the coupled cyclotrons of GANIL[2]. The geometrical efficiency in the angular range $0^o - 23^o$ is 68 %, essentially limited by the central hole and the IC window frames. Simulations have been performed, in order to estimate the multiple-event efficiency and no significative distorsion introduced by the apparatus has been found [7]. If one assumes, for sake of simplicity, an isotropic distribution for events of multiplicity greater than 2, the efficiency for the detection of the 3-fold events results of the order of 30 %. The ratio between 3- and 4-fold events has been experimentally found to be 18.4 and there are very few 5-fold events. Some recorded 3-fold events can originate from 4-fold events where one of the fragments is not detected. The calculated ratio for 4-fold events between three fragments and four fragments detected should be around 1.9. So at most $\frac{1.9}{18.4}$ of the 3-fold detected events are actually incomplete 4-fold events, i.e. 90 % are *real* 3-fold events.

[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 ($\approx$ 50%) of the telescopes ($\theta > 5^o$).

In Fig. 1a) the experimental distribution for the three-fold events in the $(\frac{Z_{min}}{Z_{tot}}, \frac{Z_{max}}{Z_{tot}})$ plane [8] is shown. Z_{tot}, Z_{min} and Z_{max} are the sum, the minimum and the maximum value of the charge of the three observed fragments, respectively. An enhancement is present in the upper corner, which corresponds to a high probability for the production of 3 fragments of nearly the same mass. As a first step these results have been compared to the prediction of a statistical sequential binary decay of an equilibrated source (Gemini code [9] with the inputs from the Viola systematics for the incomplete fusion [10]) filtered by the acceptance of our apparatus [7] (see Fig. 1b)). This model well describes experimental results obtained with more asymmetric systems, as the La + C,Al at 47 MeV/u [11].

For the reaction measured in the present experiment, however, the disagreement is evident; this could be due to different reasons, such as the dependence of the formation of the equilibrated hot systems (fragment sources) on the impact parameter, or to the fact that the statistical binary decay assumption could be not valid for this reaction and a sudden formation of several IMF in central collisions might be considered.

We have investigated the first point by coupling [12,13] a dynamical model based on the Landau-Vlasov equation to the statistical binary decay (Gemini code). The basic idea of this coupling is to follow the dynamics of the interaction for impact parameter from 0 to 8 fm, up to a time t^* (80-100 fm/c), when all primary excited systems have reached a statistical equilibrium condition, but they do not have yet started the de-excitation stage [14]. The excited system information is obtained from a coalescence model of the mean one body distribution in the phase space. Finally the de-excitation stage has been followed through sequential binary decays (Gemini code). Central impact parameters ($b \leq 2fm$) give a single excited system, whereas for more peripheral impact parameters two "sources" with different mass can be distinguished. In Table 1 the characteristics of these sources (referred to as "big" and "small" in the following) as a function of the impact parameter are presented, together with the values of the Viola systematics [10]. It has to be noted that the excitation energies of the Landau-Vlasov calculations are much lower than the excitation energy from the incomplete fusion systematics. The results of these calculations, filtered by the overall acceptance of the apparatus, seem to reproduce fairly well some inclusive data. The predicted total cross section for fragment production of any multiplicity is .995 b, in a reasonable agreement with the experimental value of 1.23 b. The statistical uncertainty is negligible and an error of 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 Fig. 2a) and b) respectively, are reasonably well reproduced by the calculations. The values of the cross sections are, on the contrary, very much underestimated by the Gemini calculations with the inputs from the Viola systematics. Going to more exclusive data the agreement disappears. From the Landau-Vlasov + Gemini calculations it results an efficiency for the detection of the "true" 3-fold events equal to the one found in previous Gemini calculations [7] for central impact parameters, as it was expected, decreasing for intermediate impact parameters and nearly vanishing for peripheral collisions. The calculated correlation ($\frac{Z_{min}}{Z_{tot}}, \frac{Z_{max}}{Z_{tot}}$), shown in Fig. 1c) is different both from the experimental data (Fig. 1a)) and from the one obtained by the Gemini calculations (Fig. 1b)). The upper part ($\frac{Z_{min}}{Z_{tot}} \simeq 0.3$) of the triangle 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 IMF in the three-fold events is presented, together with the results of the calculations, which, however, give values well above the experimental ones.

The discrepancies of these exclusive data seem to indicate a different mechanism responsible for three body events. We have furthermore investigated this point by performing calculations within the Landau-Vlasov approach at central impact parameter, extending the calculation to larger times. We studied the density profiles and the mean density of the system in the projectile-target overlap region ($\approx 4fm$ in radius) as a function of the time, in order to observe the onset of density dishomogeneities. Even if such dishomogeneities cannot be directly associated with the experimental observed fragments, they may however indicate that dynamical instabilities develop in the intermediate system, at variance with the usual compound nucleus assumption of statistical models.

In Fig. 3a) the time evolution of the nuclear density in the overlap region at b=0 fm, for the reaction Xe+Cu at 45 MeV/u, is shown. Fig. 3b) shows how the density profile in the plane perpendicular to the beam direction evolve with the time. As it can be seen, after the compression phase, the density of the system goes down as a function of the time and the system breaks up in fragments.

The apparent lack of agreement with the predictions of the binary statistical model and the indication given by the Landau-Vlasov at b=0 fm seems to suggest that the simultaneous multifragmentation of the Xe+Cu system at this energy could be an important mechanism for the complex fragment production.

In conclusion we would like to stress that the present analysis shows that correlations among IMF, together with more refined calculations, can give indications on the onset of a simultaneous breakup of nuclear systems. Therefore, from a theoretical point of view, further calculations are needed to describe the onset of multifragmentation. This work is in progress within a transport theory of fluctuations that goes beyond the one body average LV treatment [15]. In addition, from the experimental point of view, further measurements are needed to study this process and to understand the role played by the incident energy, the excitation energy and the mass asymmetry (or the total mass of the system).

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TABLES

TABLE I. Characteristics of the *sources* for the Xe + Cu reaction at 45 MeV/u

	big source				*small* source			
b(fm)	A	E*(MeV)	L	v/c	A	E*(MeV)	L	v/c
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 †	0.25				

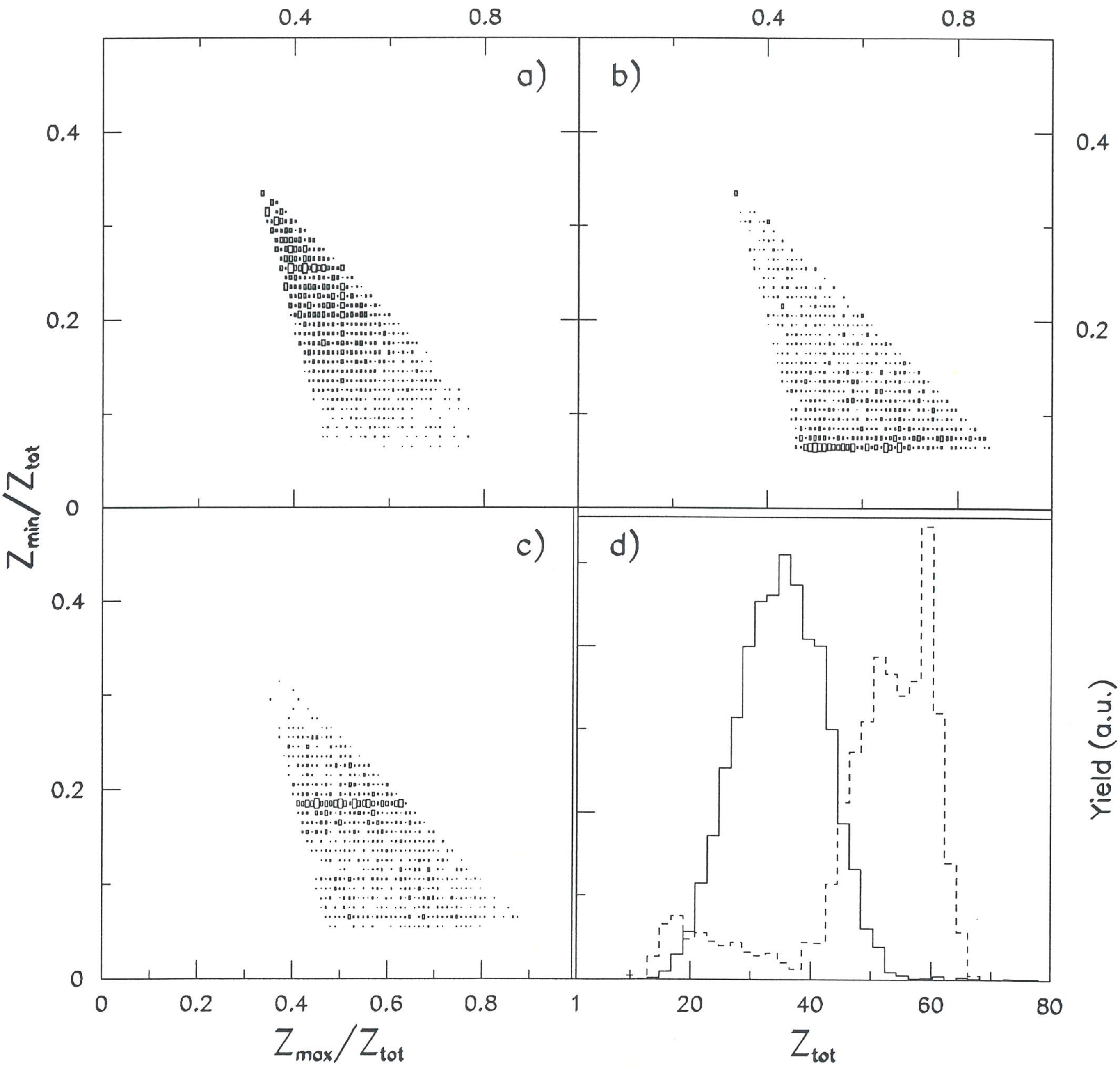
† L_{max}

FIGURES

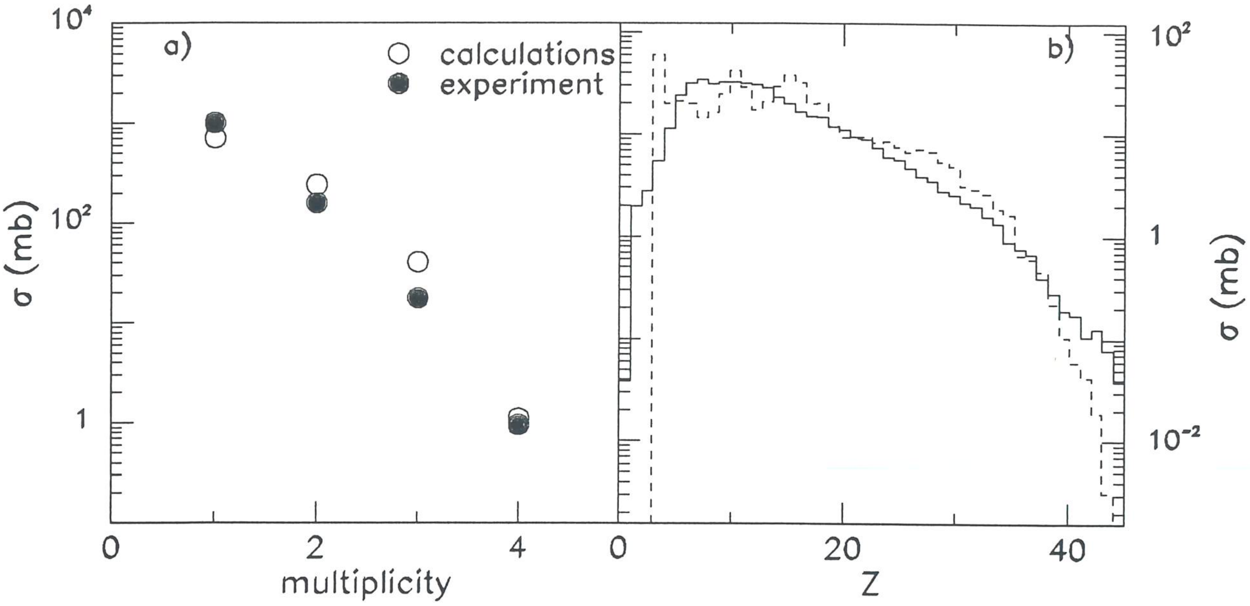
FIG. 1. $\frac{Z_{min}}{Z_{tot}} vs. \frac{Z_{max}}{Z_{tot}}$. a) experimental results; b) predictions by Gemini code; c) predictions by the coupling of dynamical and statistical approaches (for more details see text). d) Sum of the charges of all IMF detected in three-fold events. The continuous line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

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 for part of the apparatus; the dashed one the predictions by coupled dynamical and statistical approach, filtered by the same detectors. No normalization has been done.

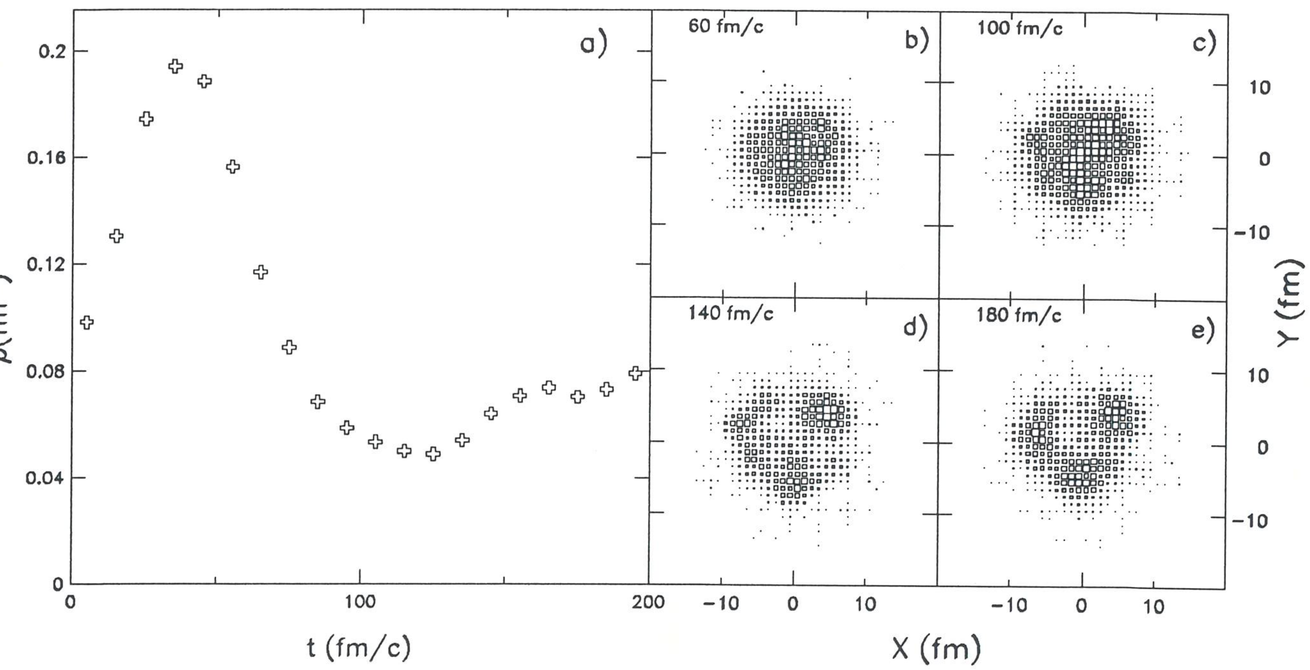
FIG. 3. a) Time evolution of the density in the overlap region as a function of the time for the reaction Xe+Cu at 44 MeV/u; b),c),d) and e) density profiles in the plane perpendicular to the beam direction for several values of the time.



a)
b)
c)
d)
0.4
0.8
0.4
0.8
0.4
0.2
0
0.4
0.2
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
20
40
60
80
Z_{min}/Z_{tot}
Z_{max}/Z_{tot}
Z_{tot}
Yield (a.u.)



a)
calculations
experiment
σ (mb)
multiplicity
b)
Z
σ (mb)


a)
b)
c)
d)
e)
60 fm/c
100 fm/c
140 fm/c
180 fm/c
ρ(fm⁻³)
t (fm/c)
X (fm)
Y (fm)
0.2
0.16
0.12
0.08
0.04
0
100
200
-10
10