Characteristics of the fragments produced in central collisions of $^{129}$Xe+$^{nat}$Sn from 32 to 50 AMeV

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I. INTRODUCTION

Multiple intermediate mass fragment (IMF) production in central heavy-ion collisions is related to the properties of nuclear matter under extreme conditions. Many different models have been proposed in order to explain the observed fragment production, and both theoretically and experimentally the situation is not clear. Models with widely differing basic hypotheses can be equally good at describing the same data such as charge distributions, mean energies and angular distributions. In order to gain further understanding it is therefore necessary to have more detailed information on the multifragmentation process.

One aspect of the reactions for which different models give very different predictions is the excitation energies of what we will call from now on the ‘primary fragments’: in other words the nuclei present around $\sim 100$ fm/c after the collision, which are not necessarily the same as those arriving in the detectors a few 10's of ns later. In Quantum Molecular Dynamics (QMD) simulations or Microcanonical Metropolis Monte-Carlo model (MMC) calculations the primary fragments are rather cold i.e. they are almost unaffected by subsequent secondary decays and arrive unchanged in the detectors. In the former case, the (lack of) excitation energy in the nascent fragments is determined by the collision dynamics, whereas in the latter case it is an assumption of the model when calculating the statistical weights of the partitions. On the other hand, Antisymmetrised Molecular Dynamics (AMD) and Stochastic Mean Field (SMF) simulations...
both predict moderately “hot” primary fragments in reactions around the Fermi energy, with $E_{\text{pr}}^* \sim 2\text{–}3\text{ AMeV}$ [1, 2, 13]. Finally, the Statistical Multifragmentation Model (SMM) [14] and the microcanonical multifragmentation model of [15, 16] allow primary fragments to be excited, the actual value in any given calculation being determined by energy conservation and the statistical weight given by the associated level density parametrization. This latter may or may not take into account the level density limitation in isolated nuclei at high excitation [17], equivalent to excluding from the primary partitions levels with very short lifetimes or introducing an effective limiting (maximum) temperature for hot nuclei [18, 19].

Our previous experimental work [20] has shown that the reconstruction of the average size and excitation energy of the primary fragments is possible by means of fragment-light charged particles (IMF-LCP) relative velocity correlation functions. A constant value of the excitation energy of the primary fragments has been deduced at about 3 AMeV for the Xe + Sn system at 50 AMeV. It was also possible to deduce the multiplicities of the secondary particles evaporated by the primary fragments. More recently analogous results and conclusions have been obtained for central collisions of Kr + Nb at 45 AMeV [21]. An important question arises from these studies: what is the evolution of the fragment excitation energies and secondary LCP multiplicities as a function of incident energy? The experimental answer to this question may permit to distinguish between different scenarios and assumptions made by different models. It should give a strong test of the validity of some of their basic hypotheses.

In this paper we extend the previous study [20] to a wider incident energy range, from 32 to 50 AMeV for central collisions of the Xe + Sn system measured with the 4$\pi$ INDRA detector [22, 23, 24]. Excitation functions for the fragment excitation energy and the fraction of secondary emitted LCP correlated to the fragments will be shown. We will give in section 2 a brief description of the detector, the way we select the events and an overview of the fragment production. We will describe in section 3 the method employed to extract the LCP’s correlated to each fragment. The method used for the decorrelation in this work is different from the previous one [20] but gives almost the same results. The experimental results are then given in section 4. In section 5 a comparison of the deduced primary excitation energy and secondary LCP multiplicities to SMM calculations is given. We then discuss the results in section 6.

II. EXPERIMENT

A. Experimental set-up

The experiment was performed at GANIL with the multidetector INDRA [22, 23, 24]. This charged product detector covers about 90% of the 4$\pi$ solid angle. The total number of detection cells is 336 arranged according to 17 rings centred on the beam axis. The first ring (2°–3°) is made of fast NE102/NE115 phoswich detectors. Rings 2 to 9 cover the angular range from 3° to 45° and are made of three detector layers: a low pressure gas- ionisation chamber, a 300 μm thick silicon detector and a 14 to 10 cm thick CsI(Tl) scintillator. The remaining 8 rings cover the angular range from 45° to 176° and have two detection layers: ionisation chamber and 7.6 to 5 cm thick CsI(Tl) scintillators. For the studied system Xe + Sn, fragments with Z up to 54 are identified in the forward region. Beyond 45°, the charge resolution is one unit up to Z=16 and few charges above. Over the whole angular range, a very good isotope identification is obtained for Z=1 to Z=3, except for particles with low energies where ambiguities are unresolved.

The energy calibration of the CsI(Tl) scintillators was obtained for light charged particles (LCP) by means of the elastic and inelastic scattering of secondary LCP beams (p, d, t, $^3\text{He}$, $^4\text{He}$) produced by the fragmentation of a 95 AMeV $^{16}\text{O}$ beam on a thick C target. These particles were then momentum selected by the “alpha magnetic spectrometer” of GANIL and scattered in a C or Ta target installed in the INDRA reaction chamber. For Z ≥ 3 fragments, the energy calibration was made by using the $\Delta E/E$ technique. A typical energy resolution was about 4%. The energy threshold was a few 100 keV for light particles, 0.7 AMeV for Z=3 and 1.4 AMeV for Z=35. A complete technical description of INDRA, its calibration and its electronics can be found in [22, 23, 24, 25, 26, 27].

B. Selection of central collisions

Two selections have been made to isolate central collisions. The first one is the requirement of quasi-complete events by accepting in the off-line analysis only events having total detected charge ($Z_{\text{tot}}$) ≥ 80% of the initial total charge of the system. The second is the use of the flow angle ($\theta_{\text{flow}}$) selection [28]. This angle is a global observable defined as the angle between the beam axis and the main direction of emission of matter in each event as determined by the energy tensor calculated from fragment ($Z \geq 3$) c.m. momenta [29]. It has been shown for heavy ion reactions in the Fermi energy range [25, 30, 31] that events with small $\theta_{\text{flow}}$ are dominated by binary dissipative collisions. On the other hand events with little or no memory of the entrance channel should be isotropic, thus favouring large $\theta_{\text{flow}}$ ($P(\theta_{\text{flow}}) \sim \sin \theta_{\text{flow}}$). Quasi-complete events having $\theta_{\text{flow}} \geq 45°$ for 50 AMeV bombarding energy and $\theta_{\text{flow}} \geq 60°$ for the three other systems correspond to an isotropic emission of the IMF in the centre of mass of the whole system. These events are compatible with decay of a compact object which could take place after fast emission of a direct light particle component. Indeed the velocity of the fragments
are evenly distributed around the centre of mass velocity \( \mathbf{v}_c \). By taking into account the detection efficiency and other biases due to the selection we have estimated the cross sections for ‘isotropic central collisions’ to decrease from 115±20 mb at 32 AMeV to 85±10 mb at 50 AMeV. More details about this event selection for Xe + Sn collisions at 32–50 AMeV incident energy and the extraction of the cross sections can be found in [32].

### C. Overview of fragment production in central collisions

Before determining the characteristics of the fragments, let us first show an overview of their production in central collisions of Xe + Sn from 32 to 50 AMeV. Figure 1 shows their charge distributions normalised to the number of events so that the four bombarding energies can be compared. The production of small fragments \( (Z \leq 10) \) increases with incident energy. For the charge range 10 to 15 the four distributions exhibit a kind of “plateau”. In this range the fragment production rates are roughly equivalent whatever the incident energy is. Finally the charge distributions evolve from a broad shape at lower incident energy, where residues up to the size of the projectile are observed, toward an almost exponential form at 50 AMeV, favouring the production of lighter fragments. Moreover figure 2 where the distributions of the heaviest fragment in the event are shown, confirms this behaviour. Here again the distribution at 32 AMeV is very broad, its average value is \( < Z_{\text{max}} > = 25 \), it decreases to smaller \( < Z_{\text{max}} > = 15 \) at 50 AMeV. It is important to notice that, even with this strong evolution in the charge distribution, the mean fragment multiplicity does not change too much with the incident energy.

It evolves from 5 to 7 fragments with \( Z \geq 3 \) only.

Concerning the kinematic characteristics of the fragments, figure 3 shows an example of the fragment angle-integrated centre of mass kinetic energy spectra for Li, O and P nuclei produced in central collisions of Xe + Sn at 32 and 50 AMeV. The distributions are broad; they are broader for the heavier elements. Comparing the spectra obtained at 32 and 50 AMeV, we observe easily that their shape, in particular the slopes of their exponential tails, are different. The distributions are broader and harder at 50 than at 32 AMeV.

We finally present in figure 4, for the four incident energies, the mean centre of mass kinetic energy of the fragments as a function of their atomic number. It increases with the charge \( Z \) and then saturates beyond \( Z = 15 \). It also increases with the bombarding energy but very little. We wondered whether this observation is true for central collisions in general, or is rather dependent on our selection. In fact it is the mean kinetic energy of the heaviest fragment which “saturates” while that of the other fragments increases monotonously with \( Z \). The \( \theta_{\text{flow}} \) selection we use is derived from fragment kinetic properties and therefore its effect on observables such as e.g. fragment energies and angular distributions must be taken into account in events selected in this way. Nevertheless this selection has little influence on the study of individual fragment characteristics such as excitation energy and secondary decay, whatever the mechanism of their formation.
III. EXTRACTION OF SECONDARY EVAPORATED LIGHT CHARGED PARTICLES

The main aim of this work is to extract the intrinsic properties of the fragments independently of the mechanism responsible for their formation. Are they excited? If so what are the associated LCP evaporated from the parents? Reconstructing the primary fragments assumes that we are able experimentally to isolate the secondary contribution. This is possible if the fragments formed are not too excited, so that the time scale associated with their decay is much greater than the time scale of their production. The origin of the fragments is still an open question but is not the subject of this paper.

A. Correlation functions

In the previous section it was shown that on average about 6 fragments are produced in central collisions of Xe + Sn at different energies. However the production of LCP is much more important, on average their number reaches 28 particles for the 50 AMeV beam energy. There are at least three different stages to produce these particles: i) in the early stage of the collision, in this case we call them primary particles; ii) at the same time as the formation of the fragments; iii) they can be emitted from the excited primary fragments, we call those the secondary particles. Correlation functions are a powerful tool for extracting small signals. This is the method we used to extract, on the average, the LCP emitted from each fragment. With the help of simulations we have developed a correlation technique to extract possible signals [11, 20, 33].

Figure 5 shows the relative velocity distributions: i) for $\alpha - P$ pairs taken from the same events, ii) for the uncorrelated events obtained by taking the fragment from a given event and the light particle from another event, iii) the correlation function defined as the ratio of the correlated and uncorrelated relative velocity distributions, iv) the difference correlation function defined as the difference between the correlated and uncorrelated distributions. In this work to decorrelate the relative velocity between the fragment and the LCP pairs we used the event mixing procedure [34]. In this example, for each phosphorus found in an event having a number of alphas $N_a$ we take randomly $N_a$ alphas emitted in $N_a$ other events.

This technique is different from the one reported in ref. [20] where Li nuclei were used to decorrelate the events. The problem with such a technique is that the Li can be the product of the known resonance of $^7Be$ which decays to $^6Li + p$ and increases the background, thus decreasing the yield of true correlated protons. However the final result is almost the same (within the error bars) as the old method of decorrelation of events based on Li.

As we can see, the example presented in figure 5 exhibits a bump around 2.5 cm/ns relative velocity in the...
correlation function and difference function which may be related to the evaporation of an $\alpha$ particle from a parent of phosphorus. The behaviour of this correlation encourages us to make such an analysis. However it is necessary to simulate the background in order to extract the signal.

B. Simulation of the background shape

The objective of this simulation is not to reproduce the data, it is more to have an idea about the shape of the background. We used a modified version of the SIMON event generator [35] to simulate a scenario deduced from BNV [36] calculations. Two steps are assumed in these simulations. The first step is the cooling of the initial fused system through a sequential light particles (LP) emission process (primary LP), the second is the fragmentation of the smaller remaining source where the remaining excitation energy is shared between a fixed number of primary fragments (typically 6 to 7 fragments). Then the primary fragments decay sequentially while moving apart under Coulomb forces plus an initial radial velocity. This simulation reproduces reasonably well the global experimental features. In particular the kinematic observables are well reproduced (see for example ref. [29].)

The calculated relative velocities are shown in Figure 6a (thick lines) for Mg-p pairs and for input parameters which reproduce data for the 32 AMeV Xe + Sn central collisions. Since in this version of SIMON we know which particle is emitted from which fragment, we plotted in the same figure the different contributions: the primary contribution (dotted histogram) that we call contribution 1, the evaporated protons from all other fragments except the parents of magnesium (dashed histogram) that we call contribution 2 and finally the protons emitted from the parents of detected magnesium fragments (hatched-dashed histogram) called contribution 3. As expected, the latter contribution is very small, it represents the protons truly correlated to the magnesium nucleus that we must extract from the data. Figure 6b shows the uncorrelated relative velocity for Mg-p pairs reconstructed by mixing the calculated events. Figure 6c and 6d show the Mg-p correlation function (the ratio of the correlated and uncorrelated relative velocity distributions of fig 6a and fig 6b) and the difference function (the difference of the latter distributions), respectively. In the same figures are plotted the associated true backgrounds (dashed histograms) calculated by dividing (subtracting) the sum of contributions 1 and 2 by the uncorrelated distribution (of
The hatched areas represent the contribution of secondary emission from the parents of magnesium (contribution 3). The shape of the background shown in figure 6.c is well fitted by the function:

\[ R(V_{rel}) = A - \frac{1}{BV_{rel} + C} \]  

(1)

where A, B and C are parameters which differ for each fragment-LCP pair. In fact only 3 coordinates are needed to solve this equation, we then used particular points from figure 6.d to do so. The first one corresponds to the first point at which the difference function is equal to zero (at small relative velocity). The second point used is the local minimum seen at small relative velocity (around 2.5 cm/ns) in the difference function (fig.6.d) which corresponds to the minimum relative velocity allowed by the Coulomb barrier. The third one corresponds to the first point where the difference function is equal to zero just after the second minimum, in this region the secondary evaporation vanishes.

In order to validate the method employed to estimate the background several tests have been made. We summarize the two most important tests that we already reported in ref. [30]:

a) We compared the number of protons deduced by subtracting from the difference function (fig.6.d) the real background and the background evaluated by the parametrisation of (Eq.1). We recover 91% of the evaporated protons from Mg and 84% of evaporated protons from all prefragments.

b) The second check is related to the possible upper limit of the method. We performed SIMON simulations assuming higher excitation energies in the primary fragments. For 7.5 AMeV excitation energies we recovered 81% of evaporated protons. This result indicates that the fraction of all evaporated protons recovered by this method is rather insensitive to the excitation energies of the primary fragments.

Because the experimental shape of the correlation function as well as the difference function (Fig.4) have the same behaviour as those in our simulation, we applied the same method to the experimental data to remove the background. From this simulation and method developed above we are able to isolate the LCP evaporated by the primary fragments.

C. Application to the data

Figure 7 shows the experimental correlation function, the difference function and the velocity distribution of α particles evaporated from parents of P fragments. From the mean value of the distribution we can deduce the average kinetic energy of α particles evaporated. Its integral normalised to the total number of phosphorus nuclei provides the average multiplicity of α particles evaporated from parents of P fragments.

FIG. 7: P-α correlation measured in central collisions of Xe+Sn at 32 AMeV. (a) correlation function. (b) difference function. (c) velocity spectrum of alphas in the centre of mass of the Phosphorus fragment, obtained from the subtraction of the difference function (data point in b) and the background (dashed line in b).

The uncertainties of the extracted quantities are mainly related to the uncertainty of taking the three points which define the background. In practice the first minimum in the difference function is easy to locate: the corresponding error is small (see fig.6.b). The two other points are more difficult to extract, with the possibility of significant uncertainties. We then decided to take intervals around each point which are divided into a number of bins. Considering all possible combinations of one bin in the first interval and another in the second leads to a distribution of multiplicities. This distribution has a narrow gaussian shape. We then consider the mean value of this distribution as the average multiplicity and its half-width as the error due to the method.
IV. EXPERIMENTAL RESULTS

A. Average multiplicities and kinetic energies of the LCP correlated to the fragments

We applied the method described above for all fragment-LCP pairs made by combining LCP isotopes \( p, d, t, ^3\text{He} \) and \( \alpha \) particles and a range of fragments emitted in central collisions between Xe and Sn at four incident energies, 32, 39, 45 and 50 AMeV. However due to a small cross section for heavy fragment production which implies a low statistics (see figs. 1 and 2) we performed these analyses for a limited range of fragment charges depending on the beam energy. Thus the maximum fragment charge we studied at 32 AMeV was 30, 27 at 39 AMeV, 22 at 45 AMeV and 20 for 50 AMeV. The extracted average LCP multiplicities and their average kinetic energy are given in figures 8 and 9 as a function of the charge, \( Z_{\text{IMF}} \), of the detected fragments and for the four bombarding energies. The average multiplicities increase with the fragment size. The multiplicities are low and do not exceed a value of 1.5 which implies that the excitation energy of the corresponding primary fragments is moderate. For a given light charged particle, the multiplicity seems not to change with the beam energy. From the spectra of the LCP evaporated from the parents of the detected fragments we can extract the mean kinetic energy. This is shown in figure 9. It increases slightly with the charge of the fragment for the four incident energies and in particular for proton and alpha particles. Notice that the kinetic energies of \(^3\text{He}\) are high compared to the values of the other particles. The observed effect may be due to the higher identification threshold energy for \(^3\text{He}\).

B. Reconstruction of the size and excitation energy of the primary fragments

To reconstruct the charge of the primary fragments we used the LCP multiplicities correlated to each fragment as described in the last paragraph. Therefore the average charge of the primary fragment, \( < Z_{\text{pr}} > \), is given by the sum of the detected fragment and all evaporated LCP’s charge weighted by their corresponding multiplicities. \( < Z_{\text{pr}} > \) is then given by the relationship:

\[
< Z_{\text{pr}} > = Z_{\text{1MF}} + \sum z_i < M_i >
\]

where \( Z_{\text{1MF}} \) is the detected fragment charge, \( z_i \) and \( < M_i > \) are the charge and the average multiplicity of the evaporated particle \( i = p, d, t, ^3\text{He} \) and \( \alpha \).

In order to reconstruct the mass of the primary fragments, a quantity needed to deduce the excitation energy, we made two extreme assumptions: the first one is that the primary fragments are produced in the valley of stability, the second assumes that they are produced with the same N/Z ratio as the composite initial system (N/Z conservation assumption). However, as mentioned above
the INnRA detector does not resolve the fragment isotopes, we therefore made an additional assumption which supposes that the Z-identified detected fragments have a mass corresponding to their valley of stability isotope. In the framework of these assumptions we deduce from the primary fragment masses the number of neutrons evaporated from the primary fragments.

Figures 10 and 11 show the result of this reconstruction for the four incident energies. The values of the primary charge (fig.10, upper panel) obtained vary from 1 to 5 charge units larger than the detected fragment. The mass of the primary fragment depends on the assumption (fig.11, down panel). The average neutron multiplicities are deduced from the mass conservation, knowing the mass of the primary fragment, the detected fragment and the mass of the secondary light charged particle contribution. Figure 11 shows for the two assumptions the evolution of the number of neutrons for the four systems as a function of the deduced primary fragment atomic number. Whatever the beam energy, the multiplicity of neutrons reaches quite high values, up to 7 neutrons for the N/Z ratio conservation assumption. This is due to our assumption that detected fragments have their valley of stability mass. Clearly, when we also assume that the primary fragments are produced in the valley of stability, the deduced neutron multiplicity cannot be very high. Conversely, imposing an N/Z of 1.39 for nuclei with Z = 3-30 means that primary fragments have large neutron excess compared to the (valley of stability) detected fragments.

At this stage, the calorimetric procedure can be applied to reconstruct the average excitation energy of the primary fragments (<E^*_pr>). It is given by the relationship:

\[ <E^*_pr> = \sum M_{LCP} <E_{LCP}> + <M_n><E_n> - Q \]

where \(<E_{LCP}>> and \(<E_n>> are the average kinetic energies in the frame of the source (fragment) of the measured evaporated LCP’s and the deduced neutrons with the average multiplicity \(<M_n>>. The neutron kinetic energy \(<E_n>> is taken as the proton kinetic energy minus the proton Coulomb barrier. Q is the mass balance of the reaction.

Figure 12 shows the result of this procedure for the two scenarios and at the four bombarding energies. As expected from the deduced multiplicities (see paragraph IV A), the excitation energy increases with the size of the primary fragment for all bombarding energies and for the two assumptions. However, for the 32 AMeV system, \(<E^*_pr>> seems to saturate for the heavier fragments. We could wonder if this is due to limitations of the method. However, as we already mentioned in paragraph IV B, simulations have been performed at much higher excitation energy into the primary fragments showing that we recover more than 80% of the evaporated protons.

To decide between the scenarios for primary fragment mass, valley of stability or with the N/Z conservation hypothesis, we deduce from the primary fragment masses the number of neutrons evaporated from the fragment isotopes, we therefore made an additional assumption which supposes that the Z-identified detected fragments have a mass corresponding to their valley of stability isotope. In the framework of these assumptions we deduce from the primary fragment masses the number of neutrons evaporated from the primary fragments.

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To decide between the scenarios for primary fragment mass, valley of stability or with the N/Z conservation hypothesis, we deduce from the primary fragment masses the number of neutrons evaporated from the primary fragments. Two assumptions to reconstruct the masses are given: the open triangles correspond to the valley of stability case the black triangles represent the N/Z conservation hypothesis (see text).
FIG. 12: Average excitation energy of the primary fragments as a function of their atomic number for the central collisions of Xe+Sn at 32, 39, 45 and 50 AMeV. Left panels: the primary fragments have the same N/Z as the combined system. Right panels: the fragments are produced in the valley of stability.

assumption, extensive statistical calculations have been performed using the GEMINI [37] code, for the 50 AMeV system. In these calculations the input to the code was the experimental deduced primary charge, the fragment masses with the two assumptions and the associated excitation energies. The comparison to the experimental LCP multiplicities and kinetic energies suggests that the N/Z conservation assumption is the most reasonable scenario. Details of these calculations are given in ref. [20].

The linear trend of the $\langle E^*_{pr} \rangle$ with the primary charge indicates that the average excitation energy per nucleon, $\langle E^*_{pr} \rangle$ in MeV/nucleon, is constant whatever the size of the primary fragment. In figure 13 we verified the latter characteristic by plotting this variable. The horizontal lines in this figure represent the average value of the whole set of the primary fragments. Besides a few small charges the data points, within the error bars, lie on this straight horizontal line. Figure 14 shows the evolution of this value as a function of the bombarding energy. The vertical bars are the standard deviations from the mean values. They are small and do not exceed 1 AMeV, which supports the constancy of the value of $\langle E^*_{pr} \rangle$. For the N/Z conservation assumption the excitation energy per nucleon increases from 2.2 AMeV at 32 AMeV and saturates at 3 AMeV beyond 39 AMeV. For the valley of stability assumption, $\langle E^*_{pr} \rangle$ saturates also but at a lower value. The constancy of the fragment excitation energy per nucleon, $\langle E^*_{pr} \rangle$ for different fragment masses, seen in figure 13 has been interpreted in [20] as meaning that, on the average, thermodynamical equilibrium was achieved at the disassembly stage of the system. Only one bombarding energy (50 AMeV) was available in the previous work. On the other hand the saturation of $\langle E^*_{pr} \rangle$ beyond 39 AMeV beam energy (fig. 14) may indicate that the fragments reach their excitation energy limit (or limiting temperature) [18, 19].

C. Proportion of the evaporated light charged particles

In paragraph IV A we have extracted the average multiplicities of the secondary evaporated light charged particles for a given fragment. It is interesting to use this information in order to study the characteristics of the multifragmentation events. Indeed the LCP multiplicity per event can be another pertinent observable. Table I shows the secondary LCP multiplicities per event, the total LCP measured per event and the ratio of both quantities, for the four beam energies. The secondary LCP multiplicities per event are defined as the sum of the secondary evaporated LCP’s per fragment, extracted by the method described above, weighted by the measured fragment multiplicity per event, $M_{IMF}$. These values are plotted in figure 15 as a function of the beam energy.
The fraction of helium isotopes evaporated in the decay of the primary fragments is higher than for those of hydrogen. This difference is more pronounced at lower beam energy. We observe also that the maximum proportion of evaporated particles does not exceed on the average 35% of the total number of produced light charged particles. The proportion of secondary particles increases between 32 and 39 AMeV, which reflects the increasing of the excitation energy of the primary fragments as it is seen in figure 14. Then this fraction decreases for higher incident energies, it reaches 23% at 50 AMeV, while \( \langle e_{pr}^* \rangle \) saturates.

It should be noticed that the proportion of the secondary evaporated particles given is a lower limit, because we did not consider the contribution that can originate from the decay of unstable nuclei such as \(^8\)Be, \(^7\)Li etc. and the decay of short-lived excited states. We finally have to stress that the results we obtained with the method described above are given on the average.

V. COMPARISON WITH A STATISTICAL MODEL

An application of the experimental estimation of this secondary statistical component is to constrain the statistical multifragmentation models [5, 14, 15, 16, 39, 40, 41]. The comparison of the extracted quantities with these models provides a crucial test of some of their basic assumptions. Since in the MMMC [5] model the primary fragments undergo instantaneous decay with neutron emission only, it can not be used for comparison with the data.

We have chosen to compare our data, with more details, to the SMM model using input source parameters very close to the ones already optimised in previous works [32, 42, 43]. As shown there SMM provides a very good description of experimental fragment partitions. In the present paper we aim to analyse the general behaviour of excitation energy of primary fragments, therefore, for simplicity, the size of the initial source has been fixed to be \( Z=83 \) and \( A=198 \) for the four incident energies. This corresponds to \( N/Z = 1.39 \) which is the same ratio as the initial system. This choice is justified by some dynamical calculations of source parameters in this energy range [44, 45]. Although the \( N/Z \) ratio of the SMM primary fragments increases slightly with increasing \( Z \) of the fragments, it remains very close to the \( N/Z \) ratio of the initial source [46]. Therefore we will compare the results of these calculations to the extracted experimental results using the \( N/Z \) conservation hypothesis. The freeze-out volume has been fixed to three times the normal volume. Finally for each incident energy we used the excitation energy of the initial source as a free parameter. The thermal excitation energy values which reproduce best the charge distributions of the detected fragments are given in table 4.
TABLE I: Xe+Sn, central collisions: mean multiplicities of evaporated particles per event. For each energy and particle, $M_{ev.}$ is the multiplicity of evaporated particles, $M_{tot}$ the total multiplicity; $M_{ev.}/M_{tot}$ the percentage of evaporated particles.

| $E_{incident}$ (AMeV) | $^1H$ | $^2H$ | $^3H$ | $^3He$ | $^4He$ | $Z = 1$ | $Z = 2$ | $Z = 1\&2$ |
|----------------------|-------|-------|-------|-------|-------|--------|--------|--------|
| 32                   | 0.97  | 0.83  | 0.71  | 0.12  | 3.09  | 2.51   | 3.21   | 5.72   |
| $M_{tot}$            | 5.98  | 2.85  | 1.84  | 0.38  | 7.36  | 10.67  | 7.88   | 18.55  |
| $P_{ev.}$ (%)        | 16.22 | 29.12 | 38.59 | 31.58 | 41.98 | 23.52  | 40.74  | 30.84  |
| 39                   | 1.73  | 0.92  | 1.1   | 0.18  | 4.18  | 7.93   |        |        |
| $M_{tot}$            | 7.16  | 3.3   | 2.45  | 0.55  | 8.6   | 12.91  | 9.15   | 22.06  |
| $P_{ev.}$ (%)        | 24.22 | 27.95 | 44.69 | 32.36 | 46.49 | 23.52  | 45.64  | 35.94  |
| 45                   | 1.68  | 1.21  | 1.01  | 0.24  | 3.2   | 3.91   | 3.44   | 7.35   |
| $M_{tot}$            | 7.82  | 3.85  | 2.93  | 0.72  | 9.39  | 14.6   | 10.11  | 24.71  |
| $P_{ev.}$ (%)        | 21.48 | 31.51 | 34.61 | 33.89 | 34.03 | 26.76  | 34.03  | 29.73  |
| 50                   | 1.42  | 0.98  | 1.01  | 0.34  | 2.6   | 3.41   | 2.94   | 6.34   |
| $M_{tot}$            | 8.37  | 4.35  | 3.3   | 0.89  | 10.1  | 16.02  | 10.99  | 27.01  |
| $P_{ev.}$ (%)        | 16.99 | 22.51 | 30.45 | 37.98 | 25.71 | 26.71  | 23.48  |        |

A. Characteristics of the primary fragments

We have used a version of SMM where we have access to the freeze-out configuration, i.e., to primary fragments' characteristics before secondary decay and Coulomb propagation. This standard version is described in [14].

The results of the SMM calculation, extracted directly from the freeze-out volume, are compared to the data in figure 16. The excitation energy of the primary fragments is globally well reproduced for the four incident energies.

Small deviations are, however, observed for large primary fragment charges in particular for the 32 AMeV case. The experimental saturation of the excitation energy is not reproduced. Quantitative comparisons with the experimental excitation energy per nucleon averaged over the charge range of the measured fragments, are presented in table II.

| Beam Energy (AMeV) | 32 | 39 | 45 | 50 |
|-------------------|----|----|----|----|
| Thermal excitation energy | 5. | 6. | 6.5 | 7. |
| $(E^*/A)_{exp}$ (MeV) | 2.26 | 3.02 | 3.26 | 3.13 |
| $(E^*/A)_{SMM}$ (MeV) | 2.97 | 3.26 | 3.39 | 3.55 |

TABLE II: Thermal excitation energies in AMeV used in SMM simulations. Experimental and calculated average excitation energies of the primary fragments produced in central collisions of Xe+Sn at 4 incident energies.

The values of the calculated $<e^*_p>$ show smooth increase with the beam energy while the data seems to saturate at 3 AMeV above 39 A.MeV.

B. Evaporated light charged particles

The contribution of the secondary evaporated LCP reflects the excitation energy of the primary fragments discussed in the previous paragraph. How do the small differences between the data and the calculation for the excitation energy affect the predicted LCP multiplicities? We compare in figure 17 the charge contribution of total evaporated LCP resulting from SMM to the data.
Evaporation

We found that by considering the relative velocities in the calculation, taking into account evaporation from heavier fragments, the total charge of evaporated particles increases significantly to be in agreement with the experimental values. The neutron multiplicity per event evaporated by the system Xe + Sn data, evaporative part of SMM calculations is presented by histogram and the freeze-out contribution by the dotted histogram.

The discrepancy is real, though, partly, it is caused by the increase of IMF at very large excitation energies, in the “falling” part of the “rise and fall” of multifragmentation. However, in the experiment this effect is observed when the maximum of multifragmentation is not yet reached. In the calculations this behaviour takes place because the number of evaporated particles increases, contrary to the experimental result. This could be a consequence of the secondary de-excitation prescription employed in SMM. An other possible reason would be an overexcitation of light primary IMF’s predicted by SMM. The decay of these IMF’s contributes considerably into LCP production and their share increases with the thermal energy.

The decrease of the experimental evaporated component at high energy could be alternatively understood if we consider the increasing effect of the collision dynamics. The direct emission of LCP increases with the incident energy while the proportion of the thermal contribution decreases. This could be mocked up in the SMM calculations by decreasing the thermal source size, but in no case be predicted by SMM.

It is worth noting the contribution of light charged particles produced at freeze-out as predicted by SMM. Figure 17 shows that this contribution increases with the beam energy more rapidly than that of the evaporated particles.

VI. DISCUSSION OF RESULTS

In this work we have directly measured the saturation of the thermal excitation energy deposited in fragments produced in central heavy-ion collisions between 32 and 50 AMeV, by associating with each detected cold fragment the light charged particles evaporated by the primary excited parent nucleus. This saturation at excitation energies of around 3 AMeV observed in section II (see figure 14) is accompanied by a saturation of the number of evaporated LCP, that leads to a decrease in the proportion of evaporated to all detected LCP, with increasing incident energy (see figure 15 or figure 17).

A similar saturation has been observed in an earlier work by Jiang et al. using a completely different experimental method, based on the measurement of neutron multiplicities. The authors claimed the saturation of the thermal energy deposited in hot nuclei formed in collisions of Ar + Au and Ar + Th in the energy range 27-77 AMeV. Their claim was based on the observation of a saturation of the multiplicity of evaporated neutrons, as well as that of the light charged particles detected in coincidence at backward angles, in central collisions at increasing beam energies. The neutron multiplicity saturates for the system Ar + Th around 30 AMeV at \( < M_n > = 35 \). Let us note in passing that we estimate the neutron multiplicity per event evaporated by the system Xe + Sn to be \( < M_n > = 23 \) at 39 AMeV.

In the authors concluded that the observed saturation was due to the increasing inefficiency of the reac-
tion mechanism to deposit thermal energy in to the hot nuclei it produced, rather than it being related to reaching the limits of excitation energy or temperature that a nucleus may support. In discussing the results of the present work we must ask ourselves the same question, but the situation is complicated by the fact that here we are dealing with several heated nuclei per event which may themselves result from the break-up of some other heavy, hot system. Here we will present some elements which may help to find an answer.

Although the excitation energies of primary fragments remain constant for incident energies $\geq 39$ AMeV, the detected fragment partitions continue to evolve, becoming steeper with increasing bombarding energy (figure 1) while the average charge of the largest fragment varies from 25 at 32 AMeV to 15 at 50 AMeV (figure 2). This suggests that with increasing energy, above 39 AMeV, the average number and temperature of primary fragments produced in the reactions does not change, whereas their average size decreases. Moreover, in order to conserve the total mass of the system the number of light particles produced prior to secondary evaporation from fragments must also increase with increasing energy. If indeed the mechanism for thermal energy deposition saturates, then the energy not used in forming and heating fragments has to be evacuated by some other means, for example direct particle production. This would lead to such an increase in non-evaporated particle multiplicity. Some energy may also be locked up as kinetic energy of fragments due to some kind of collective motion, either isotropic (compression-expansion effects) or anisotropic (incomplete stopping).

It should be recalled that the decrease of fragment excited state lifetimes with the excitation energy can limit the mean excitation values obtained in this paper. However, simulations we have performed indicate that the effect of shorter lifetimes on the efficiency of the method is quite small for primary fragment excitation energies up to 7.5 AMeV.

It is interesting to compare our results with a recent compilation of limiting temperatures extracted from different experimental measurements \[49\]. It suggests that $T_{\text{lim}}$ decreases with increasing nuclear mass, in good agreement with calculations \[50, 51\]. The primary fragments considered in the present work (figure 1) have, at the very most, masses $A = 80$, while most of them have masses in the region $A = 10$–50. The corresponding limiting temperature from \[50\] is $T_{\text{lim}} = 9$ MeV or $E^*/A = 7.5$ AMeV. As these values are much higher than the 3 AMeV maximum excitation energy we find in our primary fragments, this would imply that the observed saturation is due to reaction mechanism and not related to $T_{\text{lim}}$.

However, in the same compilation limiting excitation energies $\leq 3$ AMeV are found for the heaviest nuclei with masses in the $A = 150$–200 range. If we suppose that fragments are produced by the break-up of some heavy composite system formed in the reaction (as in SMM calculations) then it is possible that the observed saturation of primary fragment excitation energies is due to the saturation of the excitation energy of the initial system, which attains its (mass-dependent) $T_{\text{lim}}$.

VII. CONCLUSION

We have presented in this paper the experimental results of the intrinsic properties of the fragments produced in the central collisions of Xe + Sn from 32 to 50 AMeV bombarding energy. Quantitative experimental determination of the size and excitation energy of the primary fragments produced at such collisions before their decay are given for the four beam energies. The comparison of these extracted quantities with models provides a crucial test of some of their basic assumptions.

The experimental methods used in this work are based on the relative velocity correlation functions between the detected fragment and light charged particles. Thus we have extracted the average multiplicity of the evaporated particles and their average kinetic energies in the centre of mass of the fragments. These two variables have been used in order to reconstruct the average charge, mass and excitation energy of the primary fragments.

Our results show that for a given beam energy, the excitation energy per nucleon is almost constant over the whole studied range of fragment charge. The statistical multifragmentation model, SMM, reproduces very well the internal excitation energy of the primary fragments. The average value of this quantity increase from 2.3 AMeV for a beam energy 32 AMeV to saturate around 3 AMeV for 39 AMeV and above.

We also deduced the proportion of evaporated light charged particles per event, amounting to 30% of the total measured LCP for the 32 AMeV reaction, increasing to 35% at 39 AMeV and decreasing down to 23% for 50 AMeV. Therefore the majority of light charged particles are not evaporated by excited primary fragments in these reactions. Neither the absolute values of this proportion nor its evolution are reproduced by SMM calculations assuming a constant size for the multifragmenting system.

The two last results may indicate either i) that the system which disassembles into fragments is not able to sustain more than 3 AMeV thermal excitation energy and the excitation energy of the fragments reflects the temperature limit of that system, or/and ii) that the mechanism of dissipation of beam energy in to thermal energy of hot nuclei saturates above $\sim 32$ AMeV, and the kinetic energy in excess is evacuated via direct particle production and collective motion of the fragments.

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