Determination of the freeze-out temperature by the isospin thermometer

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The high-resolution spectrometer FRS at GSI, Darmstadt, provides the full isotopic and kinematical identification of fragmentation residues in relativistic heavy-ion collisions. Recent measurements of the isotopic distribution of heavy projectile fragments led to a very surprising new physical finding: the residue production does not loose the memory of the N/Z of the projectile ending up in a universal de-excitation corridor; an ordering of the residues in relation to the neutron excess of the projectile has been observed. These unexpected features can be interpreted as a new manifestation of multifragmentation. We have found that at the last stage of the reaction the temperature of the big clusters subjected to evaporation is limited to a universal value. The thermometer to measure this limiting temperature is the neutron excess of the residues.

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I. INTRODUCTION

Different mechanisms of fragment production can be studied within peripheral nucleus-nucleus collisions: Spallation and fission have been under investigation for many years. In the last decade a so-called multifragmentation reaction, which leads to the total disintegration of heavy nuclei into light and intermediate-mass fragments (IMF) arouse large interest [1–3]. Originally it was motivated by studying the liquid-gas type phase transition in nuclear matter [4, 5], as well as the role of thermal and spinodal instabilities in the disintegration of finite nuclei. At high-energy collisions the multifragmentation share was found to correspond to 10–20 % of the total reaction cross-section, and its contribution to the yield of the IMF (with charges Z=3–30) is crucially important. With increasing excitation energy of the thermal source, the transition from the evaporation and fission decay mechanisms to the multifragmentation is smooth: The probability for the formation of one compound nucleus decreases, whereas the multifragmentation appears first as a freeze-out state with two hot fragments and progressively involves three, four, and many fragment channels with increasing excitation. In this mechanism, a considerable part of the available excitation energy goes into the disintegration of the system, but not into increasing the temperature of the fragments [5].

II. EXPERIMENTAL INVESTIGATION OF THE REACTION MECHANISM

Multifragmentation is the field of intense investigation of the ALADIN (GSI, Darmstadt) collaboration [1], with an instrument whose total acceptance allows for the full counting of the produced fragments and their correlations. This precious information could be analyzed as in figure 1 (left), where a study of ^{238}**U** impinging on a copper target at 1 A GeV [1, 6] is shown: for each collision we have a collection of fragments of different Z, we chose the two residues having the highest Z and plot one against the other for each event. The fission products, individuated by two fragments of about half the projectile charge, are well separated. The region of multifragmentation, characterized by high multiplicity, small impact parameter and identified in the low-Z corner shows a gradual transition towards more and more peripheral collisions, where fragments of about half the projectile charge are correlated to very light residues like lithium, beryllium or boron. The aim of this paper is to discuss the possibility that the heavy fragments could provide a complementary information on the multifragmentation process.

By concentrating on the heavy residue, we can take advantage of the high-resolution spectrometer FRS (GSI, Darmstadt) [7], which was designed to obtain exclusive information on the heavy fragments. The precise kine-

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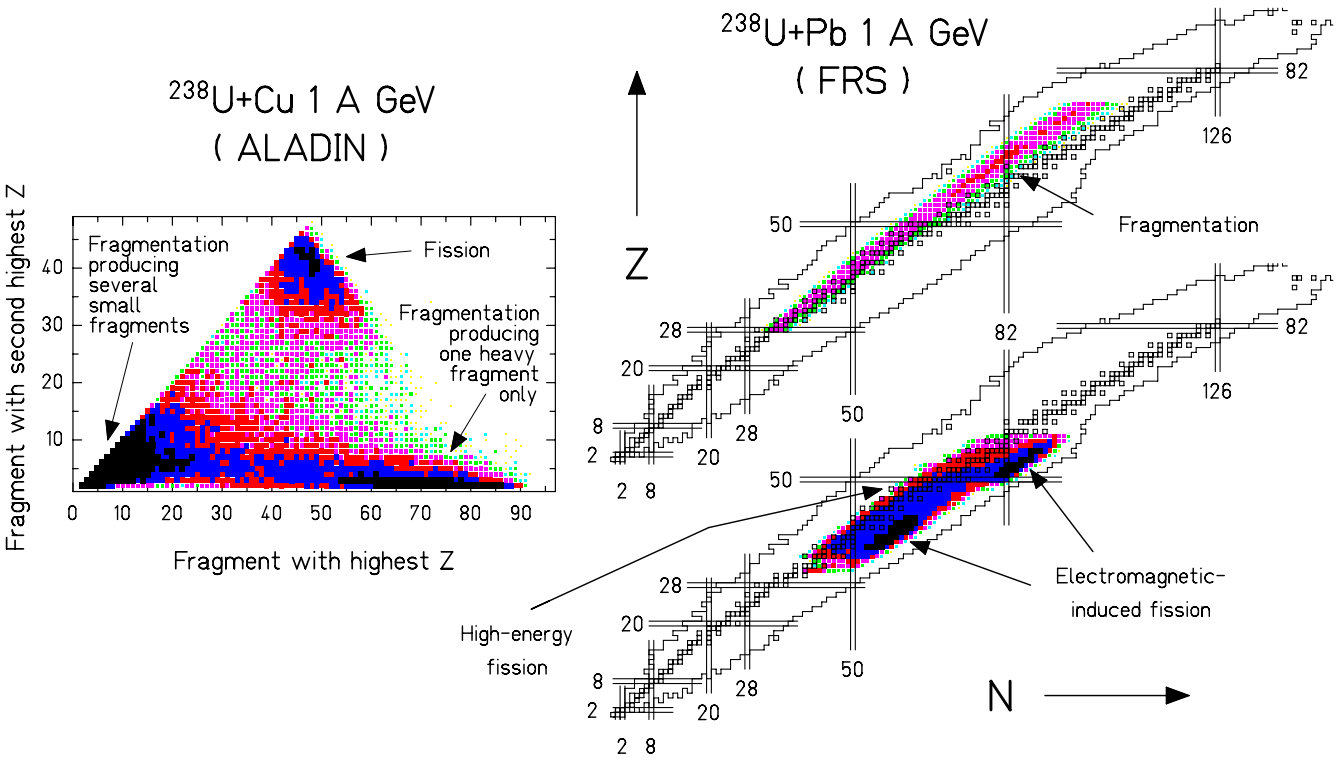

FIG. 1: Comparison between the experimental investigations that could be performed with ALADIN and with FRS. Left. ALADIN provides the measurement of the multiplicity and the correlation between the emitted particles for each event. Right: FRS provides the full isotopic and kinematical identification of one fragment for each event: it is possible to reconstruct the reaction process.

matical identification of the FRS provides unambiguous information on the de-excitation process that generated the observed residues: the measurement of the velocity distribution of each fragment enables to clearly disentangle fragmentation and fission products. In addition, the measurements of the energy loss and the mass-to-charge ratio lead to the full isotopic identification. A very systematic overview is shown in picture 1 (right) for the collision of ^{238}**U** with lead at 1 A GeV [8]: we can clearly recognize the region of electromagnetic-induced fission: this process originates from low-excited projectile-like prefragments and, consequently, produces very neutron-rich residues. The area of high-energy fission, generated by more excited prefragments, is less neutron rich. Fragmentation products, expected to originate from a long evaporation process starting from very highly excited prefragments, populate the neutron-deficient side of the isotopic chart. This analysis, based on the knowledge of the reaction process, establishes a connection between the isotopic distribution of the residues and the excitation energy introduced at the beginning of the evaporation. In the following, we will restrict this analysis to fragmentation only and continue to study how the neutron excess can provide indications on the reaction mechanism.

III. STUDY OF THE NEUTRON EXCESS OF THE FRAGMENTATION RESIDUES

The classical model describes fragmentation as a two-stage process [9]: highly excited prefragments are generated in an initial fast stage, usually described as an abrasion process (e.g. for nucleus-nucleus collisions) or an intra-nuclear cascade process (mostly for hadron-nucleus collisions). The time required by the fast stage is of the order of 20 to 50 fm/c. The resulting prefragment, whose neutron-to-proton ratio is initially close to the projectile, will then experience a sequential decay (or evaporation) dominated by neutron emission. The role of the second process is to change the neutron-to-proton ratio and to guide the isotopic production towards a universal evaporation corridor, where the initially more favourite neutron emission is finally balanced by proton emission. If the excitation energy introduced by the fast stage were entirely removed by sequential decay, the evaporation would be long enough for the residues to end up in the universal corridor and lose the memory of the projectile.

This classical picture is in contradiction with recent experimental data on fragmentation of neutron-rich projectiles. The isotopic cross-sections of ^{238}**U** fragments,

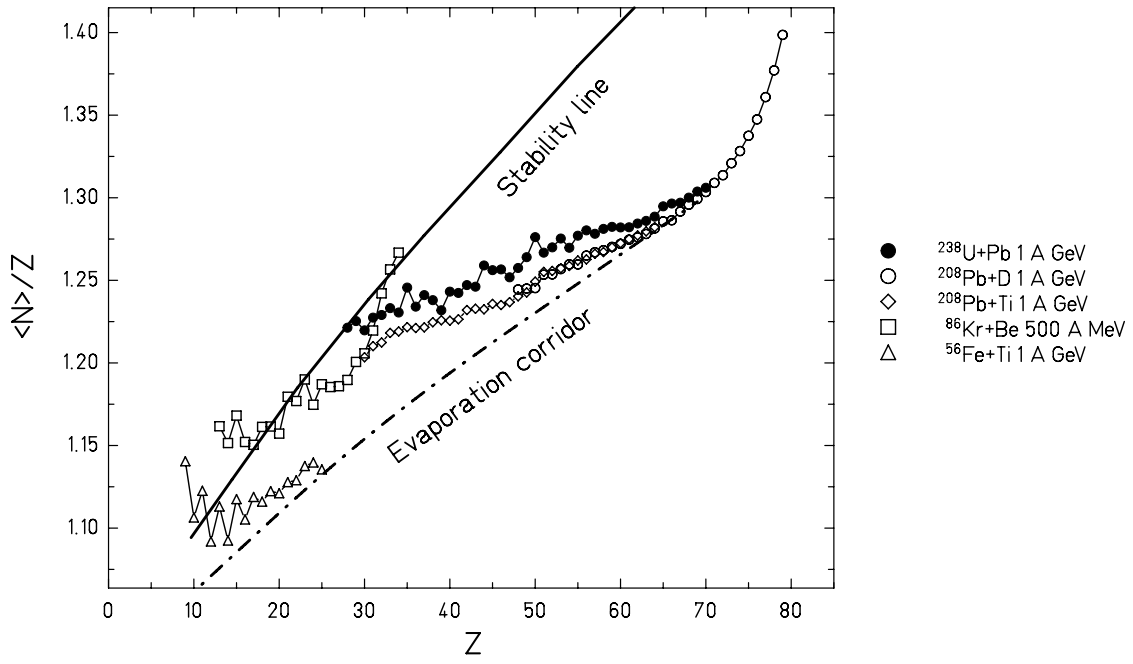

FIG. 2: Collection of experimental data showing a deviation from the evaporation corridor. The projectiles have different neutron excess. ^{56}**Fe** [10] is not neutron rich and its residues approach the evaporation corridor. ^{86}**Kr** [11] does not reach the corridor. The lead system, ^{208}**Pb** on deuterons [12] and ^{208}**Pb** on **Ti** [13], shows a clear deviation from the corridor. The ^{238}**U** system [8] deviates and is more neutron rich than ^{208}**Pb**. The evaporation corridor has been reproduced with the two-stage model (the abrasion code ABRA coupled with the evaporation code ABLA).

produced in a lead target at 1 A GeV [8], show an increasing deviation from the corridor (represented by the two-stage model calculation [9] in figure 2) for decreasing Z towards higher neutron numbers. As presented in figure 2, the measured fragmentation residues of ^{238}**U** even have the tendency to cross the stability line; this is very surprising because, with respect to β stability (equal Fermi levels of protons and neutrons), the evaporation of protons is suppressed by the Coulomb barrier.

The increasing deviation from the evaporation corridor indicates that, for collisions expected to be more and more violent, less and less excitation energy is available for the evaporation stage; evidently, in the classic picture of the fragmentation mechanism, an intermediate process that removed this excess of energy is missing.

Figure 2 presents the evolution of the mean neutron-to-proton ratio of the residues produced by the fragmentation of different systems. We infer that there is an ordering of the residues in relation to the neutron excess of the projectile: the isotopic distributions of different fragmenting systems do not collapse on the same universal evaporation corridor, but they are more neutron rich for more neutron-rich projectiles, showing an evident memory effect related to the neutron-to-proton ratio of the projectile.

IV. A THERMOMETER BASED ON THE NEUTRON EXCESS

We can infer that the present data (figure 2) are closely related to the observation of multifragmentation. We will analyze the data with two models. First, a three-stage model is used, which describes the multifragmentation as an intermediate break-up stage after the high-energy nucleon-nucleon collisions and before the sequential decay in a rather schematic way. Secondly, we have chosen the Statistical Multifragmentation Model (SMM) as a dedicated model for multifragmentation, which is very effective in the description of the experimental data (see e.g. [5, 14]). The most intensively investigated signature for the onset of multifragmentation is the production of several about equal-size fragments. However, also in accordance with SMM, the fragments do not need to be necessarily about equal-size. In peripheral collisions, we could expect a disassembly of the hot primary fragment into a heavy residue, accompanied by clusters and very light nuclei: in this case, when one heavy fragment is observed in the FRS, we still have indication of the onset of the multifragmentation phenomenon [5].

The experimental data can be reproduced introducing an intermediate process that, right after the fast stage, removes part of the mass and energy. This stage can be described as a break-up process: the compression caused

by the high excitation energy and, eventually, by the collision dynamics provides a high internal pressure. A consequent expansion and disassembly of the system will remove part of the initial excitation energy. This process might be related to a liquid-gas-like phase transition. A fundamental assumption for the process is the conservation of the mean neutron to charge-number ratio $< N > /Z$. The nearly conservation of the $< N > /Z$ ratio is also predicted by SMM [15]. The break-up stage ends when the system reaches the freeze-out transition, and re-condensates in an ensemble of cooled fragments. If we assume that thermodynamic equilibrium is established in the system at the transition point, we can consider a freeze-out temperature as a major parameter of the reaction process. This parameter can in fact be defined as a limiting temperature, since no more than the corresponding excitation energy will be available for the sequential decay. As a result, also the length of the evaporation process will be limited and determined by this value. We assume that the sequential decay will start from an excitation energy corresponding to the freeze-out temperature.

The deviation of the experimental data from the universal corridor suggests a new tool to measure the length of the sequential decay and, consequently, the value of the freeze-out temperature. Between the fast stage and the evaporation stage a new step has been added in order to describe the effect of the break-up. We should observe that the treatment of the partitioning of the spectator into the break-up products affects the final cross section,

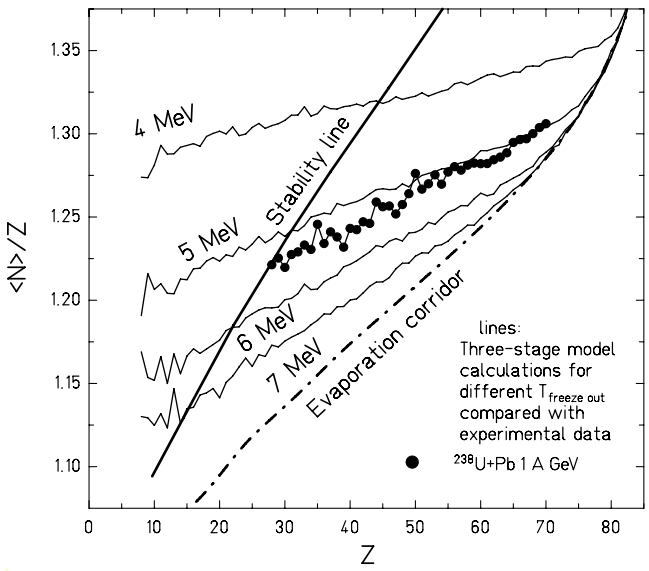

FIG. 3: The principle of the 'isospin thermometer'. The value of the freeze-out temperature is changed as a parameter of a three-stage model [9] calculation (ABRA followed by a break-up simulation and later by ABLA). The experimental data of fragmentation of ^{238}**U** are reproduced for a freeze-out temperature between 5 and 6 MeV.

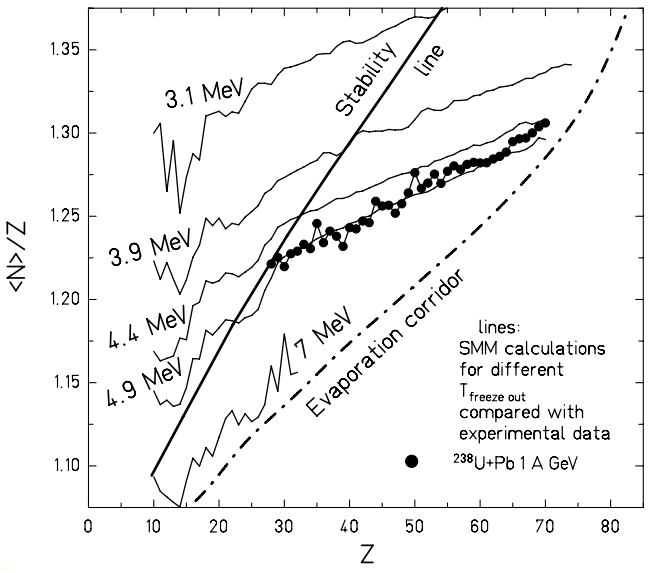

FIG. 4: Set of calculations performed with SMM[5] for different values of the excitation energy at break-up corresponding to mean temperatures of 3.1, 3.9, 4.4, 4.9 and 7 MeV .

but has no effect on the neutron excess of the isotopic distribution of the residues; the quantity $< N > /Z$ of the residues is only sensible to the value of the freeze-out temperature. This assumption motivates the calculation shown in figure 3, where the experimental data of fragmentation of ^{238}**U** on a lead target are compared with a set of calculations. The treatment of the partitioning was simplified by a parameterisation; the description of the neutron excess of the residues is determined by the freeze-out temperature as the only free parameter of the calculation: when this parameter has low values, the break-up is dominating and the residues are too neutron rich. Inversely, for high values, the break-up tends to be suppressed and the isotopic production ends up in the evaporation corridor.

The measurement fixes the freeze-out temperature in a range between 5 and 6 MeV. Missing the complete data for systems covering a wide range of the neutron excess, we still cannot determine whether the freeze-out temperature is a constant value or a function of N/Z. However, the choice of around 5 MeV provides a very satisfactory reproduction of the available data [16].

A more elaborate physical description of the partitioning is provided by SMM. In Fig. 4 we present the results of a series of SMM calculations for the disintegration of a ^{238}U source. The excitation energy at break-up was taken as a parameter. The calculation was performed for excitation energies of 1, 1.5, 2, 2.5 and 8 MeV, corresponding to mean temperatures of 3.1, 3.9, 4.4, 4.9 and 7 MeV, respectively. With increasing temperature the break up generates more excited fragments, and the mean neutron excess of the residues approaches the evaporation corridor. This calculation led to about the same

results as presented in Fig. 3: also in this case a remarkable agreement with the data is obtained for a freeze-out temperature of around 5 MeV. An important finding is the independence of the temperature from the mass of the residues. The observed universality is an indication that the limiting freeze-out temperature is rather independent of the initial conditions.

V. EFFECT OF THE BREAK-UP ON THE MASS-DISTRIBUTION

We investigate now the effect of the break-up in recent data of fragmentation of ^{56}**Fe** [10] in a proton target at 1 A GeV, measured in inverse kinematics at the FRS. This is an interesting case to study the generality of the break-up process and its extension to cases where the excitation energy of the system is neither high enough to be dominated by thermal instability, nor too low to exclude some break-up events. However, ^{56}**Fe** is not neutron rich and the isotopic distribution is not expected to deviate from the evaporation corridor. To observe the effect of thermal instability, we should then look for a different signature like, for instance, the mass distribution.

As was established in previous studies (see e.g. references in [5]), in reactions where a considerable energy is transferred to the thermal source, the multifragmentation influences essentially the yield of the residues. The ALADIN fragmentation data provide a typical example of multifragmentation obtained in peripheral nucleus-nucleus collisions at high energy [14]. It was also found that this process takes place in reactions induced by high-energy protons. In Figure 5, we present the results of the analysis performed in [17] concerning inclusive yields of fragments from tantalum [18] and gold [19] targets. The theoretical calculations were done within cascade, evaporation, and fission models which ignore the multifragment break-up stage, and, alternatively, with the same models including the multifragmentation additionally. In the last case the INC (Dubna version) and SMM were used. We can clearly see that fragments with $A = 10-60$ can be explained only by multifragmentation. However, the yield is not fully reproduced with the INC+SMM calculations. An additional correction of the parameters (masses and excitation energies) of the after-cascade residual nuclei is necessary. We can attribute this additional preequilibrium process to the expansion of the residues toward the freeze-out volume [5].

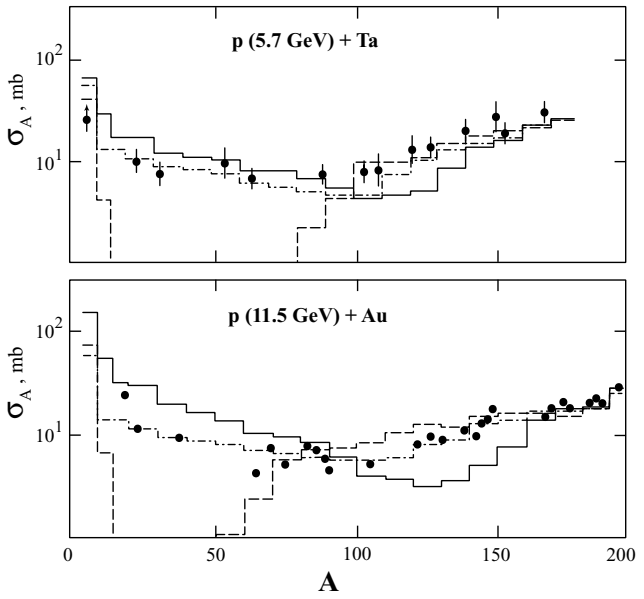

FIG. 5: Mass yields of fragments in the reaction shown in the figure. The dots denote the experimental data for tantalum [18] and for gold [19]. The histograms correspond to calculations. Dashed lines: cascade-evaporation model (break-up was disregarded). Solid line: calculation where the break-up is included. Mashed line: calculation with break-up included, with the addition of a preequilibrium process.

We applied the same investigation to study the reaction of ^{56}**Fe** on proton at 1 A GeV. Such a system is expected to produce a broad distribution of the residues in excitation energy depending on the impact parameter and fluctuations during the preequilibrium process. In general, nucleus-proton reactions at about 1 A GeV generate too low excited system to undergo a multifragmentation event but, nevertheless, ^{56}**Fe** is light enough to still reach the break-up temperature. A very indicative way to discriminate the possible break-up events is presented in figure 6 (left): the plot shows a collection of calculated prefragments, generated by the fast stage, distributed according to their mass and excitation energy. The region above the energy corresponding to a freeze-out temperature of 5 MeV is hot enough to undergo a break-up stage. The region below collects the prefragments expected to start the sequential decay immediately after the fast stage.

As shown in figure 6 (top), three intranuclear cascade codes (BRIC [20], INCL4 [21], ISABEL [22]) coupled with the same evaporation code (ABLA) reveal to severely under-predict the experimental data for the lighter half of the mass distribution (figure 6, top). Inversely, the introduction of a break-up stage (calculation performed with BRIC coupled with SMM) provides a satisfactory reproduction of the measurement. A slight discrepancy in the yields of fragments with mass numbers $A > A_{target}/2$ is probably caused by the discussed uncertainty of the parameters of the excited residues produced after the intra-nuclear cascade stage: the hybrid model used to reproduce the data is still too simple to correctly describe the transition from the fast stage to the break-up, and the inclusion of a preequilibrium process could be needed. In figure 6 (bottom) it is possible to observe that the light part of the mass distribution is mainly populated by break-up events. A very interesting result revealed by the experiment is the tendency for the cross sections to increase in the region of light masses: the only mechanism able to reproduce this characteristic

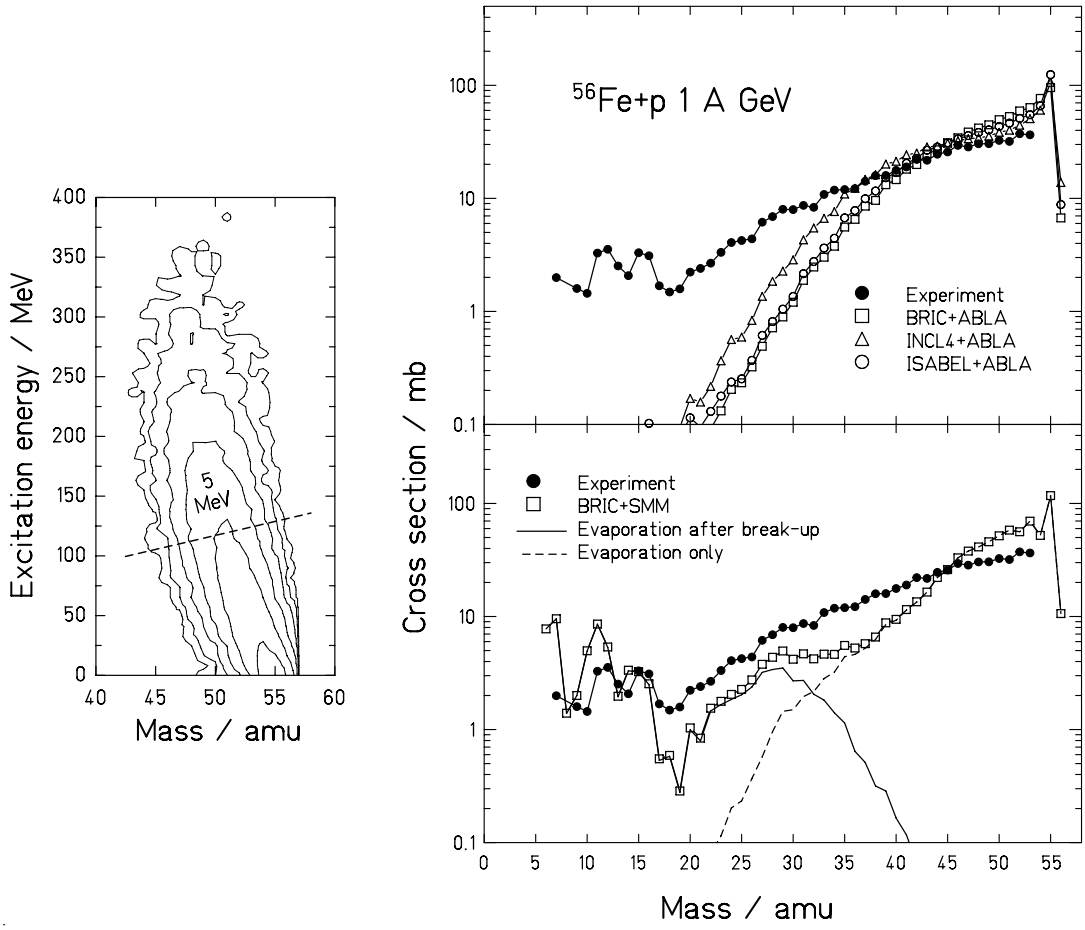

FIG. 6: Left. Prefragments produced right after the intra-nuclear cascade stage in the reaction ^{56}**Fe** on proton at 1 A GeV (calculation performed with INCL4 [21]). The dashed line indicates the excitation energy corresponding to a freeze-out temperature of 5 MeV. Right, top. Three intranuclear-cascade codes (BRIC [20], INCL4 [21], ISABEL [22]) coupled with the evaporation code ABLA do not reproduce the experimental data of ^{56}**Fe** on proton at 1 A GeV [10]. Right, bottom. The experimental data are reproduced if the break-up is considered. The calculation is performed coupling the intranuclear-cascade code BRIC with SMM.

seems to be a series of break-up events.

VI. CONCLUSIONS

The analysis of recent experimental data revealed the influence of multifragmentation to be more general than expected. In nucleus-nucleus reactions, the signature for the onset of multifragmentation is not only carried by the lightest fragments, but it extends towards the intermediate-mass fragments. The break-up process does not only describe the reactions at small impact parameter, but it should be taken into account in peripheral collisions as well. Moreover, the memory of the N/Z of the projectile reflected in the neutron excess of the residues is not only an experimental evidence of the generality of multifragmentation, but it is also a new tool to study the reaction mechanism. The study of the relation between the isotopic distribution of the residues and the break-up process opens up new possibilities of investigation: the combination between the isotopic identification (FRS) and the measurement of the multiplicity (ALADIN) can provide a new insight about the role of the impact parameter on multifragmentation.

In the case of nucleon-nucleus reactions, the impact of thermal instability is also more general then expected. We have experimental evidence that the fragmentation of light nuclei like ^{56}**Fe** in a proton target at 1 A GeV, shows similar features as in the case of proton-induced fragmentation of heavy nuclei at high energy (5–10 GeV range). Disregarding the break-up process in the complete description of nucleon-nucleus collisions could lead to an underprediction of the yields of the light residues by several orders of magnitude, even at beam energies around 1 A GeV.

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