INDICATIONS FOR FAST BREAK-UP PROCESSES IN RELATIVISTIC ION-PROTON COLLISIONS

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Abstract

Emission velocities and formation cross sections were recently measured with high resolution in the collision of ^{136}Xe projectiles with protons and titanium target nuclei, respectively, at an incident energy of 1 A GeV. The results revealed the formation of very excited systems even in proton-induced reactions, and the possibility of the onset of fast break-up processes, in competition with standard fission-evaporation decays.

1 INTRODUCTION

In relativistic ion-ion collisions, when very high excitation energies are reached by the spectators, above about 2.5 MeV/u, processes of multiple disassembly of the collision remnants set in, exhibiting high light-fragment multiplicity, a corresponding increase of formation cross sections for decreasing mass of the residues, and a widening of the kinetic energy spectra of the emitted particles. In reducing the excitation energy of the fragmenting system, the predominance of these characteristic features fades. In particular, the light-fragment multiplicity drops and the de-excitation of the hot remnants tend to favor a binary decay. When the excitation energy is too low for sustaining fast (binary or multiple) break-up processes the general de-excitation picture has the character of fission-evaporation decay.

We have indications that the remnants of proton-induced collisions at an incident energy of around 1 A GeV are possible appropriate "laboratories" for investigating the transition from fission-evaporation toward multifragmentation [1]. Differently from ion-ion collisions, where mechanical effects due to compression energy could prevail, in proton-ion reactions, the excitation of the system results mainly in thermal energy [2,3]. In this case, the influence of fast break-up processes on the total production cross section reduces to a minor portion and should have the nature of a mainly binary decay. The investigation on the nature of this "minor portion" of the total reaction cross section, reflecting a possible relation with fast break-up processes, was a goal of a recent experiment, dedicated to the collision of ^{136}Xe projectiles on protons at 1 A GeV. Also the collision on a titanium target was measured with the same beam, in order to have a reference to compare to, for very excited disintegrating systems.

2 EXPERIMENTAL SIGNATURES

2.1 *Experimental details*

A primary beam of ^{136}Xe was accelerated by the SIS (GSI, Darmstadt) and directed on a liquid hydrogen target and a titanium target, respectively. The reaction products were analyzed in inverse kinematics by the magnetic spectrometer FRS [4]. The isotopic identification of the residues was extended from ^{6}Li up to the mass of the projectile. From the magnetic rigidity of the residues (measured with a relative uncertainty of $\pm 5\cdot 10^{-4}$ for individual reaction products) the dependence of the isotopic cross section on the emission velocities was deduced.

2.2 Shapes of the longitudinal velocity spectra

The evolution of the shape of the measured velocity spectra as a function of the mass is shown in Fig. 1, for the reactions ^{136}Xe+p and ^{136}Xe+$^{(nat)}$Ti, respectively. The measured longitudinal velocity distribution accounts for the portion of emitted fragments selected by the acceptance of the spectrometer, that is around ±15 mr with respect to the laboratory frame. Therefore, when light fragments are emitted with large velocities, only very small angles are selected so that, if isotropic emission is assumed in the centre of mass frame, the measured velocity spectrum is very similar to the distribution of absolute velocity v, divided by the corresponding spherical surface $4\pi v^2$. This representation is very effective in revealing how the Coulomb repulsion acted in the emission mechanism.

Generally, the velocity spectra related to the ^{136}Xe+$^{(nat)}$Ti collision exhibit a bell shape, except for very light elements, which manifest a tendency toward a two-component distribution. Undoubtedly different are the spectra associated to the proton target. The lighter residues (Li, Be) are emitted according to a two-humped spectrum, peaked for very forward and very backward velocities. This is a signature of a mainly binary split of the decaying nucleus. Following the evolution of the spectra up to heavier masses, the two-humped shape gradually disappears while a second Gaussian-like component prevails. This bell-shaped component is very similar to the spectra observed in the ^{136}Xe+$^{(nat)}$Ti reaction. An additional peculiar feature is the shift of the Gaussian component with respect to its two-humped companion (N to Si). Somehow surprising is the direction of this shift toward higher velocities. In reconstructing the ^{136}Xe+p collision, the difference of the two components constituting the spectra seems to point to two decay processes involving at least different kinematical mechanisms.

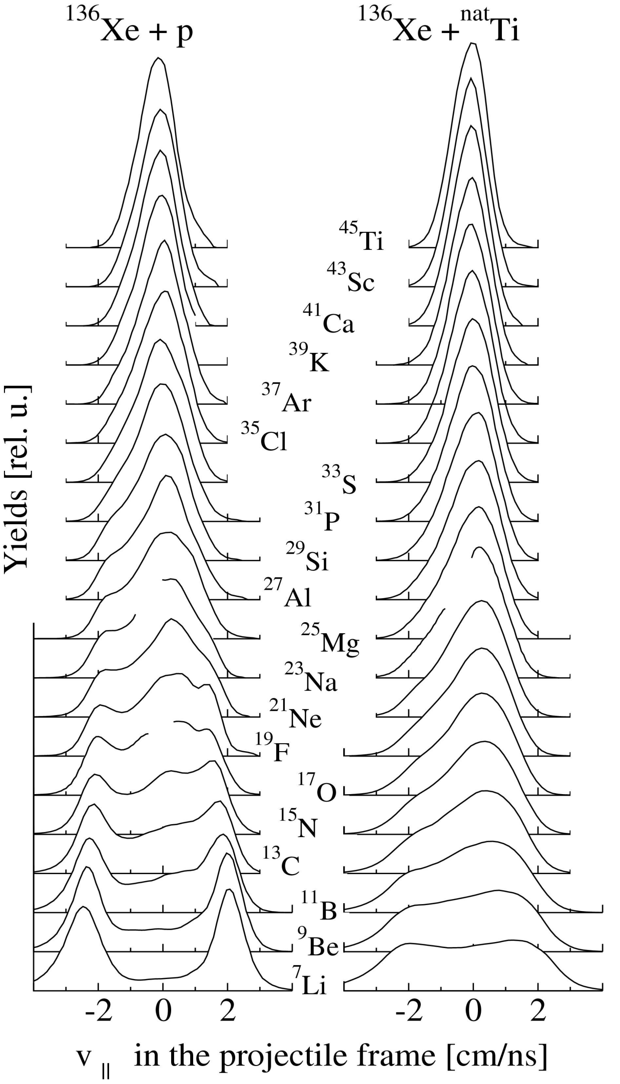

FIG. 1: Measured velocity spectra in the projectile frame for a selection of light residues produced in the reactions ^{136}Xe+p (left) and ^{136}Xe+$^{(nat)}$Ti (right), respectively.

2.3 Nuclide cross section

The full knowledge of the beam optics is the tool to determine the ratio of particles rejected due to the limited angular acceptance of the FRS [5]. From deducing this ratio and integrating the velocity spectra, the isotopic cross sections are obtained. In Fig. 2 the formation cross sections are presented as a function of the mass of the residues (full circles). The gross feature revealed by the mass distribution is the rapid growth of cross section for increasingly light fragments and, in the ^{136}Xe+p reaction, the presence of the large hollow centred around vanadium. In the ^{136}Xe+p collision, the evolution of the cross section with the mass could recall an asymmetric fission process. The depth of the hollow is sensitive in revealing the excitation energy involved in the reaction. In particular, in the transition from the ^{136}Xe+p reaction to the ^{136}Xe+$^{(nat)}$Ti fragmentation, increasingly hotter systems are reflected in a corresponding filling up of the hollow.

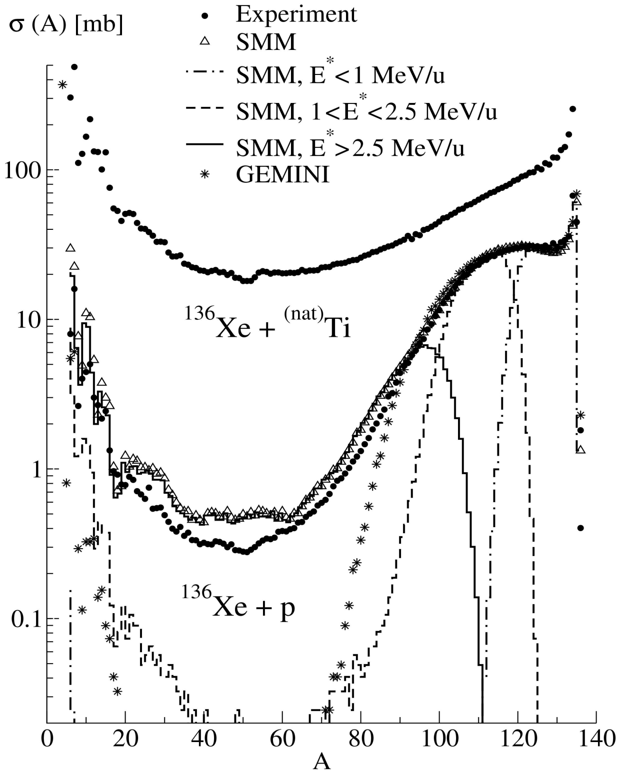

FIG. 2: Experimental cumulative production cross sections as a function of the mass number for the reactions ^{136}Xe+p (bottom) and ^{136}Xe+$^{(nat)}$Ti (top). Only for the ^{136}Xe+p system, comparisons to model calculations (SMM and GEMINI) are presented. The production obtained from SMM is also presented subdivided according to three excitation energy ranges of the source.

3 DISCUSSION

There is a fundamental difference between a fission decay from a compound nucleus and the simultaneous disassembly of a hot collision remnant. The difference is the kind of equilibration process followed by the system and its time evolution. If the excited nucleus is not too hot, the favored process of the system is a reordering of its configurations, i.e. occupations of excited single-particle levels by the nucleons around the Fermi surface. Rather seldom, compared to the thermal chaotic motion of the system, a nucleon or a cluster could pass above the energy of the continuum and leave the nucleus. This event, characteristic of a compound nucleus, is a rare process. If the system is very hot, many other unstable configurations are accessible and the compound-nucleus picture is no more valid. The predominant decay channel is a simultaneous disintegration of the system in several constituents.

In order to discern between the pertinence of these possible scenarios in describing the de-excitation process, we performed a complete reconstruction of the reaction by employing physical models. To simulate the initial non-equilibrium stage of the reaction, the intranuclear cascade model of Gudima and Toneev was used [6]. Subsequently, we treated the de-excitation stage of hot remnants employing the model GEMINI [7], where all asymmetric divisions of the decaying nuclei are considered in the calculation of the probability of successive binary decay configurations [8]. In comparing with the experimental data we remark a satisfactory agreement for the major cross sections, related to the heavy residues. On the contrary, a general underestimation in the intermediate-mass region invited us to look for a more complete model. For this purpose we turned to SMM [9], which is the extension of the statistical fission-evaporation decay toward higher excitation energies, treated by adding fast simultaneous break-up events as possible decay channels. At low excitation energies channels of production of compound-like nuclei prevail and SMM gives results similar to GEMINI. At very high energies, in SMM fast simultaneous multifragment disintegrations become dominant. The onset of the latter mode would explain the binary processes that we observe. In Fig. 2, the production related to different ranges of excitation energy of the hot remnants is shown. The total nuclide production is the sum of all these contributions. According to the calculation, intermediate-mass fragment formation is mainly alimented by very hot sources, exceeding 2.5 MeV/u.

The shape of the longitudinal velocity spectra of the lightest fragments and the velocities related to the maxima could recall fission. We could at least portrait the emission of the lighter fragments as a binary split of a heavy nucleus, rather close to the projectile. More difficult to combine with a fission barrier is the large width of the two peaks and the extension of the sides of the distribution to very high velocities (reflecting larger kinetic energy than released in an asymmetric fission process). In Fig. 3 a calculation performed with SMM gives a satisfactory reproduction of the spectrum for ^{7}Li. Two contributions can be selected in the simulation. A Gaussian like component is attributed to IMF (A>4) multiplicity equal to two. The Gaussian peaks are centred around the maxima. Another component, related to higher multiplicity (hardly exceeding three IMF) fills more the centre of the spectrum. Both the two contributions (for ^{7}Li as well as for the whole ensamble of light residues) reflect very high excitation energies of the source, distributed around 3 MeV/u. According to previous work [e.g.,10,11], and in line with other experimental indications [12,13], this excitation energy is often suggested as the threshold above which a compound nucleus can no more be formed.

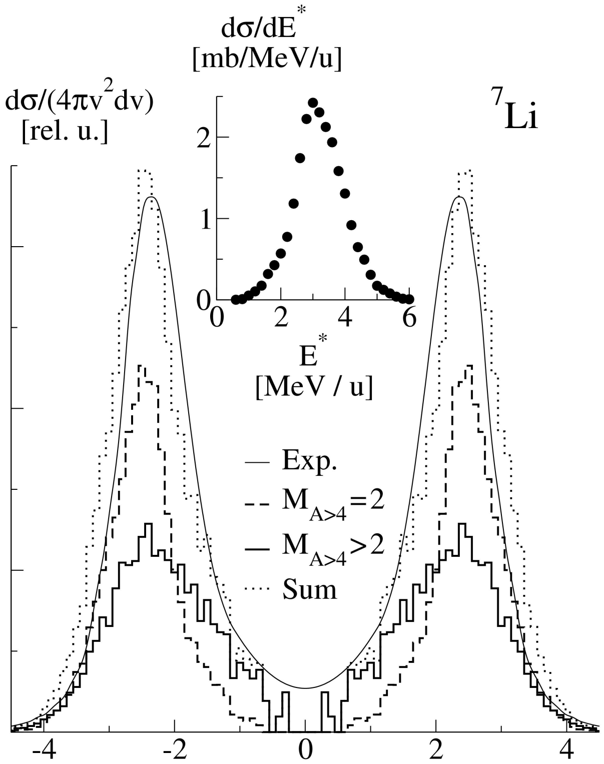

FIG. 3: Differential cross section of ^{7}Li as a function of the emission velocity v in the centre of mass, divided by the spherical surface of radius equal to v. The experimental spectrum, corrected for the spectrometer angular acceptance (straight solid line) is compared to SMM calculations (dotted line). The calculation is also subdivided in two components, related to IMF multiplicity equal (dashed histogram) or higher than two (solid histogram). In the insert, the differential cross section of ^{7}Li is shown as a function of the excitation energy of the emitting source.

4 CONCLUSIONS

We suggested that proton-induced reactions at 1 A GeV could carry indications of fast break-up processes.

In ^{136}Xe+p collisions, the measured high yields for the production of light and intermediate fragments could not be fully interpreted on the base of a statistical fission-evaporation model. The analysis of the longitudinal velocity spectra revealed a mainly binary character of the decay, together with features that could recall very excited systems, like the presence of an additional component centred around the beam velocity and the large width of the backward and forward emission peaks.

A fast break-up scenario would be more adapted in portraying the de-excitation process of the most strongly excited systems, and would explain the higher yields for light residues and the complex shapes of the velocity spectra.

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