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FEMTOSCOPY AND DYNAMICS IN HEAVY-ION COLLISIONS AT INTERMEDIATE ENERGIES*

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An overview of the present status in particle femtoscopy applied to heavy-ion collisions at intermediate energies is presented. Information about dynamics of particle emission can be obtained by means of two-particle correlation functions constructed with protons, intermediate mass fragments and complex light particles. The latter are more difficult to be treated due to the complexity of final state interactions and the effects induced by the interplay between thermal and collective motion. Some source size measurements with two-proton and deuteron–alpha correlation functions are presented. Correlation techniques are also used to study sequential emissions of light particles by unbound states in ^{12}C and ^{10}C, showing that femtoscopic techniques can provide tools to explore spectroscopy as well as dynamics.

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1. Introduction

Momentum correlations between light particles and complex fragments have improved our understanding of heavy-ion collision dynamics over the last two decades [1, 2]. At intermediate energies the overall scenario is complex due to the existence of different emission time scales. Both directional and angle-averaged correlation functions have provided tools to disentangle fast and slow emitting sources and to extract some of their properties [3, 4]. Intermediate mass fragments are expected to be produced in later stages of the reaction and their correlations provide information about the space-time properties of multifragmentation phenomena, their links to a nuclear liquid-gas phase transition [5–8]. Also, light particle-complex fragment correlations have been used to put constraints on secondary decays by primary

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fragments [9, 10]. In the second and third sections of this contribution we focus on some results and the present status of femtoscopy studies at intermediate energies with light and intermediate mass fragments. The last section of these proceedings deals with another important perspective offered particle correlation techniques providing access to important properties of unbound nuclear systems abundantly produced during the dynamical evolution of the reaction. These unbound systems live temporarily and decay by breaking-up into their stable constituents. Detecting these decay products in coincidence allows one to access spectroscopic information of their parent nuclei in one single experiment. This idea has been recently exploited by different groups [11–13] and promises to provide important perspectives for the future extension of heavy-ion collision studies to reactions induced by exotic beams.

2. Femtoscopy and space-time probes at intermediate energies

Two-proton correlation functions are often analyzed with imaging techniques [14] to extract the space-time profile of the emitting source, $S(r)$, defined as the probability distribution for emitting a pair of protons with a space-time separation r in their center of mass frame [4, 14, 15]. This almost model-independent approach has provided important physics information about proton emission processes at intermediate energies. Not only the source size can be extracted, but also the relative contributions between fast and slow emitting sources. This perspective is particularly important since several observables can be contaminated by secondary decays and require special considerations. Furthermore, the full profile of the source can be directly compared to predictions of transport theories [16].

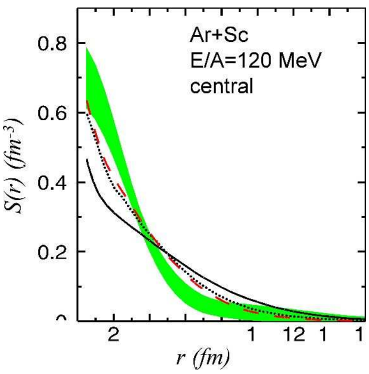

Fig. 1. Grey (colored) band: imaged source function from central Ar + Sc collisions at $E/A = 120$ MeV and proton total momenta $P = 200$–400 MeV$/c$. Lines: BUU emitting sources obtained when using free (solid line) and reduced (dotted and dashed lines) nucleon–nucleon cross-sections (see [16] for details).

Figure 1 shows a source profile (colored band on line) deduced from central Ar + Sc collisions at $E/A = 120$ MeV and for proton pairs with total momenta $P = 200$–400 MeV [16]. The lines correspond to two-proton source calculated with BUU simulations and with different choices for the nucleon–nucleon cross-section, σ_{NN}. It is clearly observed that the shape of the source is sensitive to details about an important transport property such as σ_{NN} (see [16] for details). Reduced nucleon–nucleon cross-sections (dotted and dashed lines) provide source profiles that are closer to the experimental results. Other studies of two-proton correlations in the context of microscopic model simulations have also suggested that these observables are sensitive to the density dependence of the symmetry energy in the nuclear EOS [17].

3. Towards complex particle correlations

In this section we review the status of present research activities aimed at studying correlations between complex particles. In the first part of the section we focus on the case of correlations between intermediate mass fragments (IMF), *i.e.* particles with charges $Z > 2$, while the second part of the section is devoted to the case of light particle correlations ($Z \leq 2$).

3.1. What have we gained from IMF–IMF correlation function studies?

One of the most interesting points that have attracted the interest of the intermediate energy community has certainly been the opportunity of extracting space-time information about multifragmentation phenomena [1]. In particular, disentangling simultaneous and sequential complex fragment emission mechanisms and their implications on the expected liquid-gas phase transitions and phase diagrams in nuclear matter has been extensively explored by means of correlation functions between intermediate mass fragments (IMF) [1, 5, 6, 8]. These correlation functions are mostly dominated by the Coulomb final state interaction between the massive fragments, due to their large charge number. Muti-body Coulomb trajectory approaches have been applied to determine both the size and the emission time of these fragments that are believed to be formed in the late stage of the reaction, when most of the signals carrying information about a liquid-gas phase transition are expected to occur [18]. IMF–IMF correlations have therefore been studied in central collisions between quasi-symmetric systems at increasing incident energies [5] and in peripheral asymmetric reactions at relativistic energies [8]. Several important signatures of hierarchical fragment emission have been extracted in central collision studies. These signatures show that fragment emission processes may occur sequentially according to their charges, masses and velocities ([1] and Refs. therein).

A sequential binary splitting would correspond to cluster emission from the surface of an excited source (similar to fission), considered as the liquid phase. This process is associated with long emission times of the order of 10^{-20}–10^{-21} sec, necessary for shape deformation. In contrast, if multifragmentation corresponds to a simultaneous breakup of nuclear matter undergoing a phase transition, the system is expected to fall apart over shorter times (10^{-22}–10^{-23} sec), comparable to the timescales involved in the growth of density fluctuations in the spinodal instability region of the nuclear phase diagram. Fragmentation phenomena of target-spectator fragmentation induced by light probes at relativistic energies are one of the best tools to investigate thermally driven phase transitions. In the study of π^-, $\overline{p}+$ Au at 8.0, 8.2, 9.2 and 10.2 GeV/c, IMF–IMF correlation functions from the decay of Au target spectators were studied [8]. The evolution of IMF emission times with the excitation energy per nucleon is represented in Fig. 2. Emission lifetimes decrease from $\tau \approx 500$ fm/c at excitation energies $E^*/A \approx 2.5$ MeV to a saturating value of about $\tau \approx 20$–50 fm/c for excitation energies above 5 MeV/nucleon. These results indicate a transition from a surface evaporation-like emission at low excitation energies towards a bulk simultaneous multifragmentation scenario above excitation energies of the order of $E^*/A = 5$ MeV [8]. The extracted emission times seem to be comparable with timescales of thermodynamical fluctuations leading to liquid-gas phase transitions in nuclear matter.

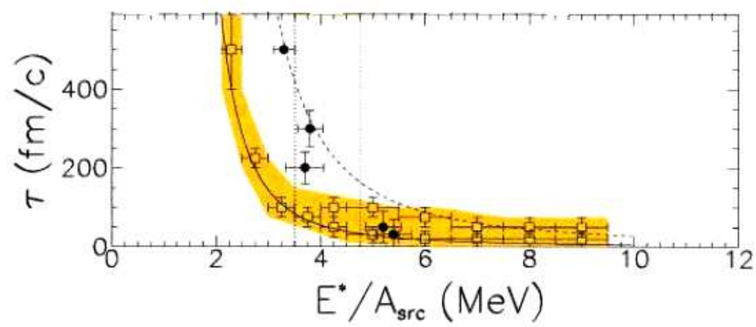

Fig. 2. IMF emission lifetimes as a function of the deposited excitation energy measured in target spectators decay induced by the bombardment π^- and p beams at incident momentum of 8.0 and 10.2 GeV/c (adapted from [8]).

Correlations between IMF and light charged particles (LCP) have been recently used to determine the excitation energy of primary fragments produced in the early stage of multifragmentation phenomena [9, 10]. These studies represent an important perspective in order to estimate the contaminations that are induced by the presence of secondary decays on reaction dynamics. These secondary decay contributions are indeed difficult to account for. In the case of LCP–IMF correlation functions, the Coulomb contribution is removed. Then one can estimate the excitation energies of primary fragments as well as the average number of evaporated secondary light particles [9, 10]. These studies have provided significant contributions and require large acceptance detector arrays.

It must be pointed out that high resolution devices are expected to better reveal the importance of nuclear final state interactions in fragment–fragment observables. The relevance of high angular resolution in experimental measurements can be clearly appreciated in Ref. [21], where position sensitive wire chambers have been used to improve the determination of fragment momentum vectors. High resolution devices promise to provide a comparable angular resolution that will help improving our extraction of detailed space-time information from IMF–IMF and light particle–IMF correlation functions.

3.2. Nuclear final state interaction and position–momentum correlations

Understanding particle emission requires studying also correlation functions between light complex particles. Since the very early studies on this subject ([19] and Refs. therein), proton–proton emitting sources sizes appeared larger than emitting sources accessed by deuteron–alpha correlation functions. These early studies were mostly conducted on inclusive data. Recently, it has been shown that light complex particle correlations can be strongly affected by position–momentum correlations induced by collective motion and therefore requiring exclusive measurements [15] with gates on impact parameter. In Ref. [15] it was shown that the interplay of collective motion and the geometry of the source affects both its size and the line-shape of the corresponding correlation function. These effects are responsible of the distortions encountered in the literature [19]. By taking them properly into account, one can quantitatively access d–α correlation functions and their emitting sources. The effects of collective motion are enhanced when more massive particles are studied (due to the decreasing relative contribution of thermal velocities as the mass of the particle increases [15]). No large effects on the line-shape of proton–proton correlation functions should be expected. In any case, position–momentum correlations contribute to apparently shrink the emitting source.

Deuteron–alpha and proton–proton correlation functions measured in $\mathrm{Xe} + \mathrm{Au}$ collisions at $E/A = 50$ MeV are shown in the left and right panel of Fig. 3, respectively. These data refer to fast particle pairs mostly probing the earlier stages of the reaction. The lines correspond to best-fits of the correlation functions with a Gaussian emitting source in the Koonin–Pratt equation. Effects of collective motion are properly taken into account in order to fully reproduce the shape of these observables (see [15]). The resulting size of the Gaussian emitting sources are about 2.2 fm and 5.6 fm for d–α and p–p pairs, respectively. A smaller d–α source size is also obtained when gating on particles pairs with lower total momenta. The d–α emitting source appears smaller than the proton–proton emitting source, even after having corrected them by taking the shrinking effects of collective motion into account. This preliminary results seem to confirm the fact that proton sources might be larger (or more long-lived) than other particle emitting sources (see early studies in [19]). This difference in source sizes could also be attributed to an effect of emission chronology in heavy-ion collisions: different particles may be emitted at different times and by different locations in the dynamically evolving source. Studies on this chronology problem have been performed both experimentally and theoretically and represent an important research topic since different particles are expected to be produced over different time windows. Clearly more precise and exclusive studies need to be performed in order to confirm this complex scenario of particle emission. This fascinating scenario also suggests that studying several particle species in the same reaction is key to fully understand heavy-ion dynamics.

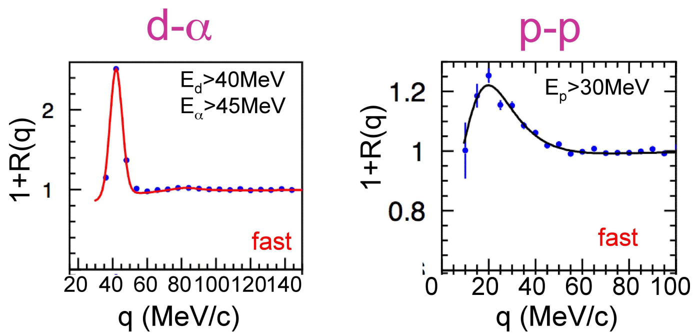

Fig. 3. d–α (left panel) and p–p (right panel) correlation functions measured in central Xe + Au collisions at $E/A = 50$ MeV (see text for the explanation of the meaning of solid lines).

4. Correlations as spectroscopic tools in heavy-ion collisions

Heavy-ion collisions can also be used to explore the spectroscopic properties of unbound states. Indeed, during the dynamical evolution of the system, several unbound nuclear species are produced and decay. Their unstable states can be identified and explored by detecting all the products of their decay in coincidence with an experimental setup characterized by a high angular and energy resolution. A typical example of this kind of analyses has been shown in Ref. [11] where p–^{7}Be correlation functions have been measured in the same reaction system, Xe + Au at $E/A = 50$ MeV, used to study the data shown in Fig. 3. These correlation functions allowed the authors of Ref. [11] to extract information about the spin of internal states in the parent decaying nucleus ^{8}B nuclei. This works has shown that a collision between two heavy-ion can be certainly considered as a tool to access not only nuclear matter properties, but also important spectroscopic information on several unbound states all produced in one single experiment. Some of these unbound states might even belong to exotic nuclei that could otherwise be explored only in dedicated experiments with radioactive beams.

In a recent experiment performed at GANIL with the Indra multidetector array, three- and four-particle correlation functions have been used to study highly lying unbound states in ^{12}C and ^{10}C nuclei. These nuclei were produced as excited projectile-like fragments (PLF*) in ^{12}C+^{24}Mg peripheral collisions at $E/A = 53$ and 95 MeV [13]. Three-alpha particle correlation functions (Fig. 4) have been used to study the decay of excited states in ^{12}C and two-proton–two-alpha particle correlation functions (Fig. 5) have been studied to access information about the decay of ^{10}C excited states. The peaks in Figs. 4 and 5 correspond to such internal states in ^{12}C and ^{10}C, respectively. The correlation functions shown as filled circles are built using the standard event-mixing technique to construct the uncorrelated three- and four-particle yields. The open symbols correspond to correlation functions built by modifying the event-mixing technique. As an example, the open symbols in Fig. 4 represent the three-alpha correlation function obtained when two alpha particles are chosen from the same collision event while the third one comes from a different event [13]. In this way, part of

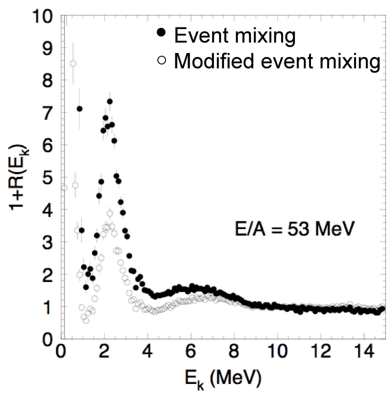

Fig. 4. Three-alpha correlation functions in C + Mg reactions at $E/A = 53$ MeV (filled dots). The open dots are obtained with a modified definition of the event mixing background (see text and Ref. [13] for details).

two-alpha decays of ^{8}Be unbound states are not removed from the uncorrelated yields and contribute to reduce the magnitude of resonance peaks in the resulting correlation function (see open symbols in Fig. 4). This attenuation of the peak magnitudes indicates that some of the peaks in the standard three-alpha particle correlation function (solid symbols) correspond to sequential decays of ^{12}C* proceeding through the production of intermediate unbound states in ^{8}Be. A similar procedure allowed us to estimate the relative contributions between simultaneous decays of ^{10}C* nuclei into two protons and two alphas and sequential processes producing intermediate states in ^{6}Be, ^{8}Be and ^{9}B [13]. Standard (filled circles) and modified (empty symbols) event-mixing techniques help disentangling different sequential decay paths in Fig. 5 and estimate their relative contribution to the total decay widths of the studied states. These estimates suggested that the decay width of ^{10}C unbound states is dominated by the sequential process $^{10}\mathrm{C}^* \rightarrow p + {}^9\mathrm{B} \rightarrow p + (p + \alpha + \alpha)$. The study of ^{10}C is particularly important since this nucleus has been recently suggested as a possible candidate for a Brunnian nuclear system [20] and high resolution experiments have been performed to study its properties [12, 20].

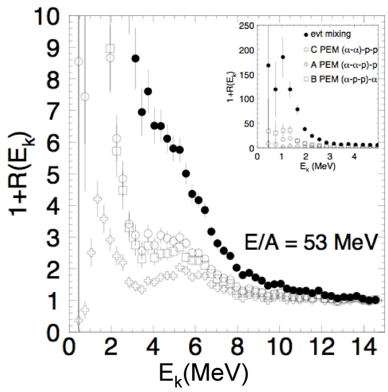

Fig. 5. 2α–$2p$ correlation functions in C + Mg reactions at $E/A = 53$ MeV (filled dots). The open dots are obtained with a modified definition of the event mixing background (see text and Ref. [13] for details).

These techniques open the promising perspective of using one single experiment to explore both dynamics and structure of nuclear systems far from stability. However, the angular and energy resolution of the employed experimental setup play a key role in order to extract quantitative information. In this respect, the construction of high resolution devices is expected to improve the use of correlation techniques to spectroscopic problems where a precise measurements of particle momentum vectors is required.

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