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IMPACT PARAMETER AND SOURCE SELECTED CORRELATION FUNCTIONS WITH A 4π MULTIDETECTOR.

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Abstract

For the first time in the domain of (light charged) particle interferometry in nuclear physics, we report a complete study of proton and deuteron correlation functions with both impact parameter and emission source selections. The correlations were determined for the system ^{129}Xe + ^{nat}Sn at 45 and 50 AMeV using the 4π multidetector INDRA at GANIL as an event selector as well as a particle correlator. Very short emission times are found for all the selections indicating possible contributions from a fast and preequilibrium process.

The correlation function of light charged particles at small relative momentum is a well-known tool to characterize the dynamical properties of nuclear matter produced in heavy ion collisions in terms of source size and emission time determinations [1-8]. In the domain of intermediate energies, the energy relaxation results from an interplay between one and two-body collisions causing the coexistence of pre-equilibrium and equilibrium emission regimes. For preequilibrium emission short time-scale characteristics will cause the nuclear final state interaction to dominate the correlation pattern and offer a sensitivity to the source size itself, justifying a usual zero lifetime assumption [1]. For equilibrium emission, Coulomb interaction will dominate due to long effective distances between emitted nucleons, and will result in a sensitivity to average emission time whereas reasonable assumptions are usually made for the source size itself [4,6]. Thus, due to the fact that the measurement integrates particles

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emitted all along the reaction time, most of the earlier quantitative space and time characterizations of the sources using this technique contain averaging effects and subsequent distortions. This is the originality and one of the main goals of this work to avoid most of these distortions through appropriate selections of the origin of the emission processes. Indeed, by using a 4π detector as an impact parameter and projectile-like and target-like source selector, we have been able, for the first time, to analyze the size and time characteristics of well characterized emitting sources for different excitation energies [9].

We have measured two-proton, two-deuteron and proton-deuteron correlation functions for the $^{129}\mathrm{Xe} + {}^{Nat}\mathrm{Sn}$ collisions at 45 and 50 AMeV at the GANIL facility. To improve statistics, events obtained at 45 and 50 AMeV for the same class in transverse energy (see below) were added. This system is quite interesting because the available excitation energy reaches 12 MeV/u and it consists of almost 250 nucleons so that we can expect large multiplicities for light particles. Moreover this system has been extensively simulated by dynamical codes such as Landau-Vlasov or QMD [10, 11], and is largely otherwise studied by the INDRA collaboration [12, 13, 14, 15]. Regarding the largely debated [16] energy dissipation process in violent collisions, a recent study [12] of light charged particles and intermediate mass fragments emitted in the Xe+Sn collisions has for instance shown that a sizeable fraction originates from the mid-rapidity region which might have important consequences for the estimation of the excitation energy of remnant products ; nevertheless, the analysis could not distinguish between a prompt emission from the early participant zone (after a few elastic nucleon-nucleon collisions) or a (delayed) emission from a neck of matter between the two separating spectators. In all cases the spatial extent of this mid-rapidity source is expected to be smaller than the composite system geometry whereas distinctive time developments between the two above processes are expected to be reflected in the two-particle correlation function [2].

The reaction products were detected by the 4π multidetector INDRA [17] which can measure the heaviest fragments as well as light particles with a large efficiency. The 4π array covers 90% of the solid angle. It performs a charge identification from Z=1 up to Z=60 and a mass identification for Z=1, 2, 3. The array is composed of three different types of detectors : Ionization Chambers (ChIo), silicon detectors (Si) and ICs scintillators. The ChIo-Si telescopes are used for the identification the slower fragments and the Si-ICs for the fast fragments. The fast and slow components of the scintillator signal allow to perform the mass separation of light charged particles. The identification threshold for protons and deuterons, which is about 6 MeV, and the small relative angle between the edges of two adjacent detectors (around one degree) allow us to investigate correlation functions at low relative momentum [18]. As compared to the classical compact detectors used in interferometry, the azimuthal symmetry of the present 4π array provides a considerable improvement of the number of particle combinations in a given momentum range, plus the possibility to get a wider relative momentum range which permits a good normalization of the correlation function and inspection of possible kinematical or multi-source production, usually not accessible.

The experimental two-particle correlation function is defined as the ratio of the true coincidence yield (Y_{12}) over the false coincidence yield (Y_{12}') versus the relative momentum q between the two particles.

$$C(q) = N\frac{Y_{12}}{Y_{12}'}$$

The false coincidence yield is obtained with the event mixing method [19]. The same event selections were used to construct both the numerator and the denominator. A particular effect to be carefully taken into account in the case of correlation functions built with a multidetector event is the possible influence of the relative velocities of multiple sources and their dispersion [9]. This can affect the correlation function in the sense that this dispersion is likely to distort the distribution of relative particle momenta when mixed events are reconstructed, as compared to genuine coincidence particles. This effect will be discussed later on. However it is not expected to affect significantly the results when well-characterized sources are considered. In this paper, we will consider only emission from projectile and target-like sources but their own sequential de-excitation process can produce the above effect as it will be presented below.

In order to correctly define the global variables described below, we have only investigated events for which at least 80% of the initial pseudo parallel (ZV) momentum is detected. To characterize the violence of the collision, we have used the variable defined as the sum of the transverse kinetic energy of all the Z=1, 2 particles. This quantity has been studied by the INDRA collaboration, which has shown that it was appropriate in this energy domain [12]. The transverse energy increases with the violence of the collision corresponding to a decreasing impact parameter. For our study we have separated the events in three classes, based on earlier INDRA results [12] : peripheral ($0 < E_T < 240$ MeV), intermediate ($300 < E_T < 400$ MeV) and central events (460 MeV $< E_T$ MeV). These values correspond to average reduced impact parameters of 0.8, 0.5 and 0.1 respectively. The emission source characteristics are determined in the ellipsoid reference frame which is calculated in an event by event analysis [20]. The characteristics of the ellipsoid are given by the eigenvalues of the momentum tensor defined by :

$$Q_{ij} = \sum_{(k=1)}^{m_{Z>2}} \frac{1}{P} p_i(k) p_j(k)$$

where $m_{Z>2}$ is the multiplicity of fragments with a charge greater than 2 and i and j two of the three components of the momentum of the particle k.

	Backward Source			Forward Source		
	E_{T1}	E_{T2}	E_{T3}	E_{T1}	E_{T2}	E_{T3}
Proton slope parameter (MeV)	6.2	8.1	10.5	5.6	8	10
Deuteron slope parameter(MeV)	8.2	11.5	13.7	8.2	10.3	12.1
Velocity (c)	0.03	0.07	0.08	0.29	0.26	0.25
Charge	37	33	33	40	36	36
Mass	89	76	76	94	84	84

Table 1 : Characteristics of the sources as a function of the transverse energy selections. E_{T1} means : $0 < E_T < 240$ MeV, E_{T2} : $300 < E_T < 400$ MeV and E_{T3} : 460 MeV $< E_T$. The mass is estimated by assuming that the source is in the valley of stability.

The thrust method [20] lets us separate the particles in two parts corresponding to a target-like and a projectile-like source [14]. We have next reconstructed the velocity distribution of these two sources by a kinematical calculation. The size of the projectile-like has been measured, following the method [12] which consists in assuming an isotropic emission, and taking into account only the particles and the fragments with a parallel velocity greater than the one of the forward source. The target-like charge has been calculated from the one of the projectile-like by assuming that the ratio (forward source)/(backward source) was the same than Xe/Sn. This method has been shown [12] to safely select the projectile-like emission above a reduced impact parameter value about 0.5. Conversely, in more central collisions, the projectile-like and the prompt emission from the participant zone present a large overlap in their rapidity distributions [21] and consequently the present velocity selection will contain both components.

Table 1 gives the characteristics of the two sources for the three selections in transverse energy. Correlation functions were built by taking into account only the particles with a parallel velocity greater (smaller) than the one of the forward (backward) source, in order to be sensitive to the thermal emission from these sources which is assumed to be predominant in this velocity region [12].

The extraction of proton and deuteron emission time scales have been performed by using a quantum model which assumes that the particles are emitted by a single thermalized source at normal density [22, 23]. The code calculates the correlation by taking into account the effect of the quantum statistics, the nuclear and Coulomb interaction between the two particles and the Coulomb interaction with the source (3-body effect). The geometrical and energy thresholds effects caused by the experimental apparatus are also taken into account by filtering the simulated events. One of the more noticeable effect is the statistical reduction of particles pairs at low relative momentum.

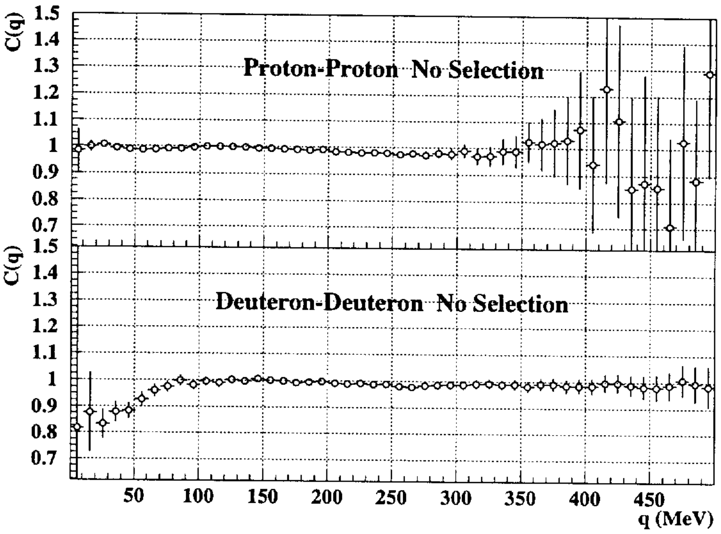

Fig. 1 Two-proton and two-deuteron correlation functions without any selection measured with INDRA in the reaction Xe+Sn at 45 and 50 AMeV.

Two-deuteron and two-proton correlation functions without any kind of selection are represented in Fig. 1. The functions are plotted on a large relative momentum scale, with all the relative momentum combinations available from the 4π detector. The main objective of this plot is to show that the denominator which is used here for the normalization works in a very reliable way.

The two-deuteron correlation function shows an anticorrelation effect mainly due to Coulomb repulsion [24]. The balance between repulsive Coulomb and attractive nuclear interactions leads to a well-known resonance located around 20 MeV/c in the case of proton-proton correlation function [1]. The peak is not very pronounced which indicates a large effective distance separating the two emitted particles. In fact, as stressed above, such a function represents a time average over all possible emission processes as well as an average over all sources and impact parameters.

Fig. 2 shows the two-deuteron correlation function for the two selected sources and for the three impact parameter selections. In the low momentum range and for more central collisions, one observes a stronger anti-correlation due to a larger repulsive interaction. Calculations using the above assumptions with the best agreement are also plotted with the corresponding average separation times : 30±10, 10±5 and 0 fm/c (simultaneous emission) for the backward source, 200±70, 50±10 and 10±5 fm/c for the forward source respectively. As expected for an almost symmetric system, the extracted times and the behavior of the forward and the backward correlation functions are close for intermediate and central collisions.

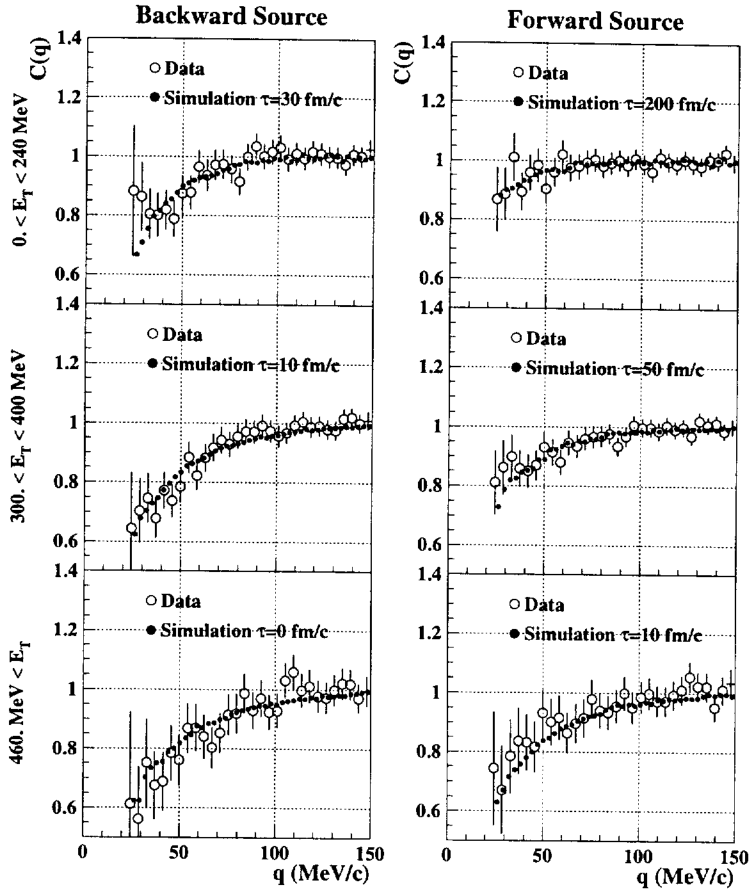

Fig. 2 The two-deuteron correlation functions for the three impact parameter selections. The left and the right panel respectively correspond to the backward and the forward source. The simulations with the best agreement are also plotted.

The emission times scales decrease from peripheral to central collisions. A first interpretation would be that this evolution agrees with the idea that the more excited the system is, the smaller the average emission time scale is. In the most peripheral collisions, the Coulomb anticorrelation is not very strong. This is qualitatively consistent with the idea of larger effective distances between two successive or coincident deuterons. Although the system is almost symmetric and the target and projectile are expected to have equivalent properties, we find a difference between the emission times of the two sources especially in the case of peripheral selection. In each case the amplitude of the fluctuation of the source velocity used in the quantum model agreed with experimental measurement. However, close inspection of the low momentum range reveals a rising trend below 40 MeV/c for the forward selection, mainly in the case of the intermediate transverse-energy selection, which may be responsible for the lowering of the anticorrelation effect quoted above. In order to see whether a purely kinematical explanation can be found, we have simulated the emission of a single source using the experimental velocity fluctuations. The same qualitative trend is obtained, namely an increase of the correlation function at low relative momentum. This kinematical effect has a very specific numerical consequence when building the correlation function : the relative momentum of mixed events (denominator) integrates the fluctuations of the source velocity which correspondingly induces higher values. Such an effect is not present in the relative velocity distributions of coincident particles originating, in the case of most peripheral collision mainly from a single (projectile or target) fragment. This difference between the two distributions produces an artificial ascent of the correlation function at low relative momentum where smaller relative velocities are demanded. This effect, which has not received attention so far, is revealed by the experimental possibility to isolate characterized sources with the 4π detector.

We present in Fig. 3 a comparison of our two-proton correlations for the forward source with a similar work performed at 31 AMeV with a dedicated detector by the MSU group [26]. As quoted above, it shows the large improvement of statistics in the medium and large relative momentum range together with a fairly good yield above the threshold.

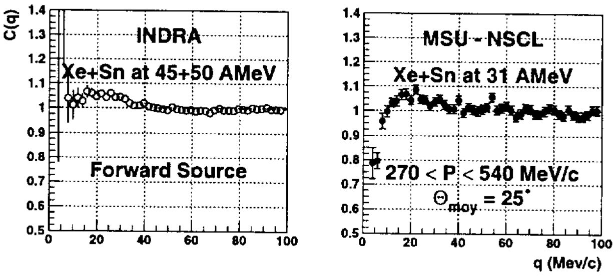

Fig. 3 The two-proton correlation function measured with INDRA compared to the one obtained with a hodoscope at MSU-NSCL in quite close conditions of experiment.

We have studied two-proton correlation function in the same conditions of selection for the two sources and for the three transverse energy gates. The correlation-functions, displayed in Fig. 4, are characterized by the known resonance [1] at q around 20 MeV/c. Fig. 4 contains fits with the quantum model calculations (full dots) together with the deduced average emission time scales. The estimation of the calculation above the resonance can be attributed [2, 5, 8, 23] to the absence of dynamical description of the emitting source in this type of static final state interaction.

The first striking feature is the close similarity of the extracted times whatever the source or the transverse energy selection is. The second interesting point is the small value of this average emission time scale ($\tau \approx$ 25-30 fm/c with an uncertainty of +/-5 fm/c). Like the above values for deuteron emission, these times are much shorter than the time (τ = 150 fm/c) when the two excited nuclei separate [11, 12, 21] (this time has been also found to be weakly dependent on the actual impact parameter). Even if one takes into account the uncertainty caused by our size determination, these times remain short. For instance in the case of peripheral collisions, a reduction of the forward source nucleon number by 25 %, in agreement with the determined contamination by mid-rapidity particles leads to a lifetime of 40 fm/c. These times, almost constant, are not compatible with an increase of excitation energy for more central collisions. Rather, these light particles characterize a prompt process of pre-equilibrium emission which covers a whole domain of rapidity [21]. Similar indication of mid-rapidity emission have been quoted in previous work : the various mid-rapidity particle yields measured in the Xe+Sn collision [12, 27] indicate that a larger fraction of deuterons (as compared to protons) originates from this fast process : its increasing importance for central collisions [11, 21] is compatible with the slight decreasing average-time here observed for the deuterons (Fig. 2)

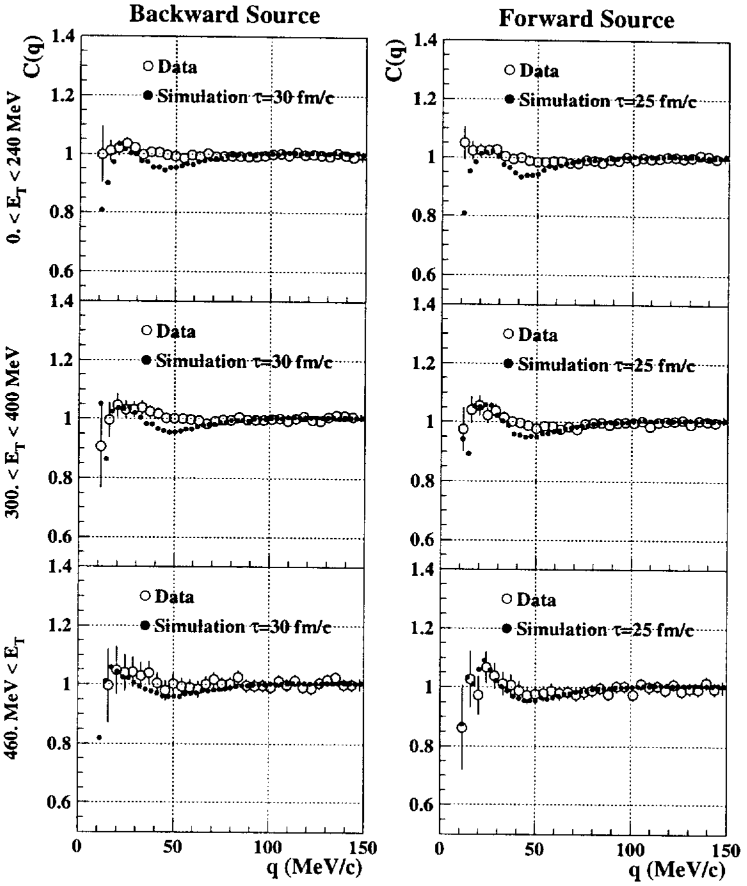

Fig. 4 The two-proton correlation functions for the three impact parameter selections. The left and the right panel respectively correspond to the backward and the forward source. The simulations with the best agreement are also plotted.

In summary we have studied the proton and deuteron correlations with the nuclear collisions ^{129}Xe + ^{Nat}Sn at 45 and 50 AMeV. The measurement has been performed using the 4π detector INDRA which allows via selections of impact parameters and emission sources, to estimate the source charges. From the measured correlations and a comparison with a quantum and three-body final state interaction theory, the evolution and the characteristics of the averaged emission time scales were deduced for protons and deuterons. The most striking conclusion is the observation of very short emission times for protons. This fact, together with the almost constancy of the measured emission time scale with the different selections of collision events, lead us to postulate the occurrence and the dominance of a fast preequilibrium emission process covering a large rapidity domain around a mid-rapidity origin. Although this process is expected to dominate in central collisions, our determinations show that it may also strongly contribute to the forward and the backward emission from two fragments of binary peripheral collisions

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