BREAKUP DENSITY IN SPECTATOR FRAGMENTATION

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Abstract

Proton-proton correlations and correlations of p-α, d-α, and t-α from spectator decays following ^{197}Au + ^{197}Au collisions at 1000 AMeV have been measured with an highly efficient detector hodoscope. The constructed correlation functions indicate a moderate expansion and low breakup densities similar to assumptions made in statistical multifragmentation models.

1 Introduction

Multifragmentation is strongly favored by heavy nuclei with densities lower than saturation density. Therefore, the observation of expansion is a prerequisite for the existence of dilute nuclear systems. The observation of radial collective flow in central collisions of heavy nuclei [2] provides evidence for rapid expansion. For the fragment decay of spectators produced in collisions at relativistic energies, the case studied in this work, significant radial flow has not been observed [3]. Here evidence for expansion has been obtained, indirectly, from model comparisons. Interferometry provides a tool to determine experimentally the space-time extent of the breakup volume, which is defined by the last collisions of the emitted particles. For short particle-emission times, which are expected for the present case of spectator decays at relativistic energies, it yields information about the volume of the source.

2 Experimental Setup

Beams of ^{197}Au with an incident energy of 1000 MeV per nucleon were provided by the heavy-ion synchrotron SIS and directed onto ^{197}Au targets of 25-mg/cm^2 areal thickness. One multi-detector hodoscope, consisting of a total of 96 Si-CsI(Tl) telescopes in closely-packed geometry, covered the angular range θ_{lab} from 122° to 156° with the aim of selectively detecting the products of the target-spectator decay. Each telescope consisted of a 300-μm Si detector with 30 x 30 mm^2 active area, followed by a 6-cm long CsI(Tl) scintillator with

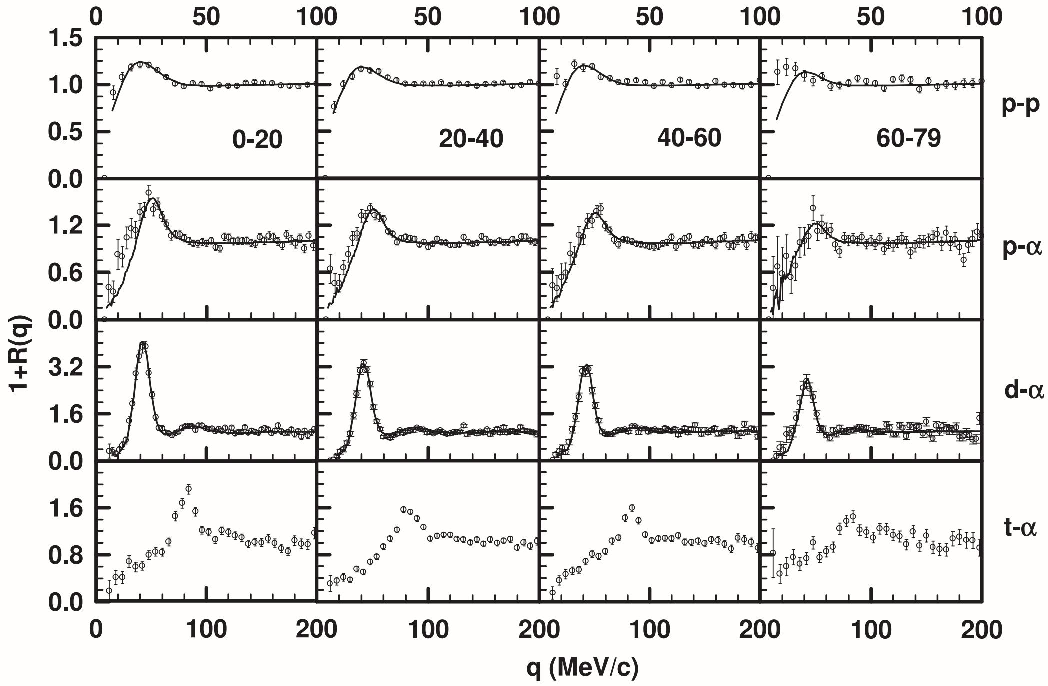

Fig. 1. Correlation functions constructed for p-p, p-^{4}He, d-^{4}He, and t-^{4}He (from top to bottom) for spectator decays following ^{197}Au + ^{197}Au collisions at 1000 MeV per nucleon and sorted into four bins of Z_{bound} as indicated. Note that the scale of the abscissa is different for the top row (p-p correlations) and the remaining three rows of panels.

photodiode readout. The distance to the target was 60 cm. The products of the projectile decay were measured with the time-of-flight wall of the ALADIN spectrometer [3] and the quantity Z_{bound} was determined event-by-event. Z_{bound} is defined as the sum of the atomic numbers Z_i of all projectile fragments with $Z_i \geq 2$. It reflects the variation of the size of the primary spectator system.

3 Correlation Functions

Examples of correlation functions constructed for the four types of coincidences p-p, p-α, d-α, and t-α are shown in Fig. 1, sorted into four bins of Z_{bound} as indicated. The uncorrelated yields were obtained with the technique of event-mixing and normalized in the range of large relative momenta $70 \leq q \leq 100$ MeV/c (p-p) and $150 \leq q \leq 200$ MeV/c (p-α, d-α, and t-α). The off-line thresholds were set at $E_{lab} \geq 20$ MeV for all particles p, d, t, and α and all hodoscope detectors. The shapes of the correlation functions are sensitive to

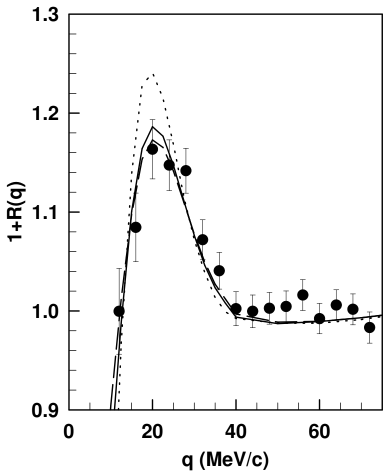

Fig. 2. Proton-proton correlation function for the interval $20 \leq Z_{bound} \leq 40$ in comparison with the predictions of the Koonin-Pratt formalism before (dotted) and after (full line) applying the experimental filter, and after taking into account the three-body effect of the Coulomb repulsion from the emitting source (dashed line). All calculations were performed for spherical sources with radii $R = 8.2$ fm.

the threshold. For p-p, e.g., the suppression at small q tends to disappear if the threshold is set at $E_{lab} \geq 10$ MeV or lower, presumably as a result of increasing contributions from evaporation and sequential decay. These long-lived components are suppressed if higher thresholds are chosen [4]. A striking feature of the data is the overall stability of the peak heights as a function of Z_{bound} which indicates source extensions that do not change dramatically with impact parameter.

4 MC-simulations

The analysis of the p-p correlation functions was performed with the Koonin-Pratt formalism [7] in the zero-lifetime limit. The analysis in this form includes the effects of quantum statistics and of the nuclear and Coulomb final-state interactions but it ignores the long-range Coulomb repulsion of the two protons from the emitting source. Therefore, Coulomb trajectory calculations and calculations with the three-body quantum model of Lednicky et al. [8] were performed. A uniform sphere with radius R and statistical momentum distributions corresponding to the measured kinetic-energy spectra were assumed for the proton source; the model results are slightly dependent on the particle momenta through the applied experimental filter. The quality of the obtained results and the sensitivity to the radius parameter R is illustrated in Fig. 2 for the case $20 \leq Z_{bound} \leq 40$. The most satisfactory description of the data is obtained with $R = 8.2$ fm (full line). The height and the width of the resonance peak are rather well reproduced. For comparison, the results of the Koonin-Pratt calculation for the same radius without filtering (dotted line) are also shown. The filtering effect corresponds to a radius change of

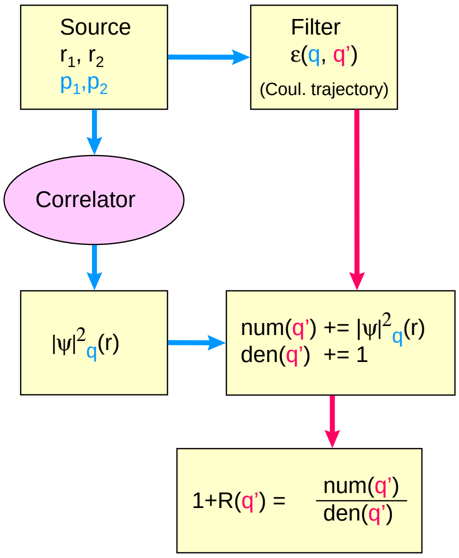

Fig. 3. Schematic view of MC-simulation of correlation functions in order to take filter effects and Coulomb boost into account.

$\Delta R \approx 0.3$ fm whereas the three-body effect due to the charge of the emitting source is almost negligible. This is expected for the present case, especially for the more central collisions which produce spectators of very moderate total charge (e.g. $Z_{source} \approx 45$ for $20 \leq Z_{bound} \leq 40$). In addition, because of the assumption of a simultaneous volume break-up, only the charge inside the volume corresponding to the radial position of the particle contributed to its acceleration. The same height of the correlation maximum was obtained with the three-body quantum model [8] and with the classical Coulomb trajectory calculations (dashed line), which are described below. The estimated overall uncertainty, mainly resulting from ambiguities of the normalization of the correlation function, is about 0.5 fm. The radii deduced for the four bins of Z_{bound} are all within 8 to 9 fm, values significantly but not substantially larger than the radius $R = 6.7$ fm of a gold nucleus at normal density 0.16 fm^{-3}. Besides the p-p correlations also those involving α particles were used to determine break-up radii by comparing to the numerical results of Boal and Shillcock [9].

In a MC-simulation, a pair of particles was chosen to be emitted randomly from an uniform sphere with radius R. Their velocities were sampled according to a Maxwell-Boltzmann distribution with a temperature T. The probability for this pair to exhibit a relative momentum q and a relative distance r is given by the square of the nuclear + Coulomb wavefunction. It is calculated for pp-correlation functions within the Koonin-Pratt formalism [7] and used for weighing the sampled pairs in the source which are averaged over the different relative distances r. This yields the correlation function $1+R(q)$. The technical procedure is sketched in Fig. 3. The averaging is performed by incrementing eventwise a relative momentum spectrum (numerator) by the probability of the pair. It is then normalized by another relative spectrum (denominator) which was incremented by a constant. The advantage of this method is the capability to correct eventwise for filter effects introduced by the detector system. The event pair passes the experimental filter which changes the original relative momentum q to the measured relative momentum q'. The measured relative momentum differs from the original one since particles are assumed to hit the middle of a detector. Further, their original momenta are changed in direction by multiple scattering within the target and the finite energy resolution of the detectors introduce a change of measured momenta. All this experimental smearing of relative momenta was taken into account by incrementing the relative momentum spectra with weight according to the original relative mometum q, applied in the bin of the measured relative momentum q' (Fig. 3).

The same procedure holds also for applying Coulomb corrections to the final particle momenta. Thereby, a classical Coulomb trajectory calculation takes the repulsion between emitting source and particle into account. Clearly, the original velocity of the emitted particle before the propagation has to be diminished by the push due to the Coulomb force. Each emitted particle feels only the repulsion of the source but not the repulsion of the other emitted particles. Since those corrections are small but time consuming in the MC-simulations, we neglected them for the final results. This approximation is justified all the more when a delay time before the decay of the scattering state is considered. This delay time, which is eg. for the singlet state of p-p correlations at a relative momentum of $q \approx 20$ MeV/c in the order of several hundreds fm/c, can be calculated from the phase shift of this state. It ensures that the particle pair decays at a certain distance from the source leading to even smaller corrections due to the Coulomb boost.

In case of the simulation of the p-α and d-α correlation function only unfiltered results for several source sizes were available [9]. Therefore, we replaced the correlator by the correlation function (the average weight) itself and interpolated different radii by assuming an r^{-3} scaling of the correlation function $R(q)$. The source radii were then found by a least squares analysis and the statistical rms-uncertainties of the radii are found by using the χ^2-test algorithm. The results are given in Table 1. Best fits are shown in Fig. 1 as solid lines. The figure also demonstrates the high sensitivity of these pronounced resonances of particle unbound states to the source extension. A suitable formalism should

Z_{bound}	0-20	20-40	40-60	60-79
pp	7.75 ± 0.1 (0.7)	8.2 ± 0.15 (1.4)	8.1 ± 0.15 (1.0)	8.8 ± 0.6 (3.2)
pα	9.5 ± 0.4 (3.3)	10.45 ± 0.35 (2.6)	10.9 ± 0.3 (0.8)	12.65 ± 0.8 (0.8)
dα	$8.4^{+0.15}_{-0.2}$ (0.7)	$9.25^{+0.05}_{-0.1}$ (1.2)	9.45 ± 0.15 (1.6)	$10.5^{+0.1}_{-0.15}$ (0.3)

Table 1: Extracted source radii and statistical uncertainties in fm by comparing pp, pα, and dα correlation functions to MC-simulations with a χ^2-test. The fit region of the correlation functions were q=10-35, 30-70, and 30-54 MeV/c for pp, pα, and dα correlation functions, respectively. The numbers in brackets denote the minimum χ^2 per degree of freedom.

therefore permit rather precise evaluations even for large sources. While the radii turn out to be fairly invariant, the derived densities decrease considerably with increasing centrality. This is caused by the changing number of spectator constituents. These spectator masses result from the calorimetric analyses reported in Refs. [10, 11]. The mean relative density decreases from $\rho/\rho_0 = 0.4$ for the peripheral collisions to values below $\rho/\rho_0 = 0.2$ for the most central bin with the smallest Z_{bound} (Fig. 4). The deduced values compare well with the densities assumed in the statistical multifragmentation model. The variation with centrality is similar to that resulting from using a fixed cracking distance as criterion for the placement of fragments inside the breakup volume [1]. The different freeze-out radii between the different correlated particles might reflect their different scattering cross section.

5 Summary

We employed the correlation-function technique to deduce source sizes of spectators, selected according to Z_{bound} a measure for their mass and excitation energy. Correlation functions constructed from proton-proton coincidences and from coincidences between protons, deuterons, or tritons with α particles consistently show that the breakup volume does not appreciably change with impact parameter even though the spectator mass varies considerably. For large source sizes only weak correlation maxima are expected. These maxima are for p-α and d-α correlations larger compared to p-p correlations and help to gain sensitivity for the break-up radius. A quantitative analysis yields results that are consistent with a moderate expansion and with low break-up

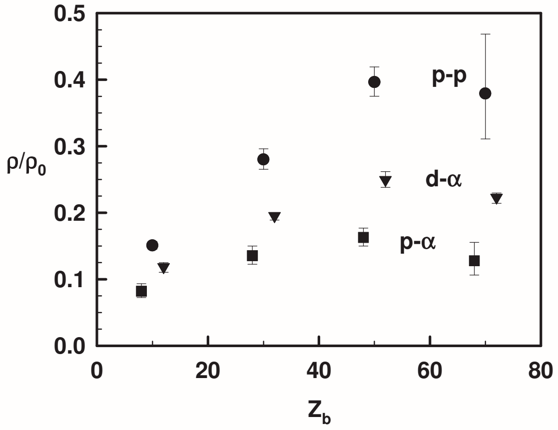

Fig. 4. Breakup density ρ/ρ_0 as obtained from the analysis of the p-p, p-α, and d-α correlation functions. The rapid decrease of the density with decreasing Z_{bound} reflects the changing mass of the spectator source.

densities as assumed in the statistical model scenarios. The variation of the density with impact parameter is caused by the changing spectator mass. The systematic uncertainties are large and many factors influence the correlation functions which makes it rather difficult to draw firm quantitative conclusions. On the other hand, the studied case of spectator decay at relativistic energies may be less critical in the sense that the source charge is moderate, collective motion nearly nonexistent, and the high kinetic-energy thresholds may have excluded long-lived components from the analysis.

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