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From Sequential Processes to Multifragmentation in Proton Reactions with Gold

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ABSTRACT

The distribution of relative angles between the intermediate mass fragments has been measured and analyzed for thermal multifragmentation in *p* + Au collisions at 2.1, 3.6 and 8.1 GeV. The analysis has been done on an event by event basis. The multibody Coulomb trajectory calculations of all charged particles have been performed starting with the initial break-up conditions given by the combined model with the revised intranuclear cascade (INC) followed by the statistical multifragmentation model. The measured correlation function was compared with the calculated one to find the actual time scale of the intermediate mass fragment (IMF) emission. It found transition from sequential evaporation for *p*(2.1 GeV) + Au to simultaneous multibody decay of a hot and expanded nuclear system in case of *p*(8.1 GeV) + Au.

Keywords: Multifragmentation; Correlations; Emission

1. Introduction

The main decay mode of very excited nuclei ($E^* \geq 4$ MeV/nucleon) is copious emission of intermediate mass fragments (IMF), which are heavier than α-particles but lighter than fission fragments. An effective way to produce hot nuclei is the reaction induced by heavy ions with energies up to hundreds of MeV per nucleon. But in this case, the heating of the nuclei may be accompanied by compression, rotation and shape distortion, which can essentially influence the decay properties of hot nuclei. The picture becomes clearer when light relativistic projectiles (protons, antiprotons, pions) are used. In this case, fragments are emitted by only one source—the slow moving target spectator. Its excitation energy is almost entirely thermal. Light relativistic projectiles provide therefore a unique possibility for investigating thermal multifragmentation.

The decay properties of hot nuclei are well described by statistical models of multifragmentation [1] and this can be considered as an indication that the system is in thermal equilibrium or at least close to that.

The time scale of fragment emission is a key parameter for understanding the decay mechanism of highly excited nuclei. Is it sequential and independent evaporation of IMF's or is it a multibody decay mode with almost simultaneous emission of fragments governed by the total accessible phase space? As was suggested by D.H.E. Gross in ref. [2], "simultaneous" means that fragments are liberated during a time interval which is smaller than the Coulomb acceleration time τ_c, when the kinetic energy of fragments amounts to ~90% of the asymptotical value. According to [2], τ_c is estimated to be (400 - 500) fm·c^{-1}. Fragments emitted within this time interval are considered being not independent as they interact via the Coulomb force while being accelerated in the electric field of the source. As a result, the yield of events with small relative velocities of the fragments (or small relative angles between them) is suppressed. The magnitude of this effect drastically depends on the emission time since the longer the time separation of the

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fragments, the larger their space separation and the weaker the mutual Coulomb repulsion. Thus, measurement of the IMF emission time τ_{em} (the mean time separation between two fragment emissions in a given event) is a direct way to answer the question as to the nature of the multifragmentation phenomenon.

The time scale for IMF emission is estimated by comparing the measured correlation function with the multibody Coulomb trajectory calculations with τ_{em} as a parameter. There are two procedures to measure the emission time: analysis of the IMF-IMF correlation function of the relative angle or the relative velocity.

The first measurements of the time scale for the thermal multifragmentation were performed for ^{4}He + Au collisions at 14.6 GeV by analyzing the IMF-IMF relative angle correlation [3,4]. It was found that τ_{em} is less than 75 fm·c^{-1}. The same procedure was used for the p + Au interaction at 8.1 GeV [5] when the emission time τ_{em} $\leq$ 70 fm·c^{-1} was found. A similar value was obtained by the ISiS collaboration of 4.8 GeV ^{3}He with the gold target [6]. In this paper, IMF-IMF relative angle correlations were studied. A general overview of the experimental activity in this field can be found in review paper [7].

In the present paper, the angle correlations of intermediate mass fragments have been studied for p + Au collisions at 2.1, 3.6 and 8.1 GeV.

2. Experimental

The experiment has been performed with the 4π setup FASA [8] installed at the external beam of the Dubna superconducting NUCLOTRON. The FASA device consists of two main parts:

1) The array of thirty ΔE-E telescopes, which serve as triggers for the read-out of the whole FASA detector system. These telescopes allow measuring the fragment charge and energy. The spatial distribution of fragments is also obtained.

2) The fragment multiplicity detector (FMD) including 58 thin CsI(Tl) counters (with scintillator thickness around 35 mg·cm^{-2}), which cover 81% of 4π. The FMD gives the number of IMF's in the event and their spatial distributions.

The fragment telescopes consist of a compact ionization chamber as the ΔE counter and a Si(Au) semiconductor detector as the E spectrometer. Effective thickness of the E detector was around 700 μ, which is enough to measure the energy spectra of all intermediate mass fragments. The ionization chambers have a shape of a cylinder (50 mm in diameter, 40 mm in height) and are made from polished brass. The entrance and exit windows are made from organic films (~100 μg·cm^{-2}) covered by a thin gold layer prepared by thermal evaporation. A gold wire 0.5 mm in diameter is used as the anode. The cathode (brass cylinder and mechanically supported thin entrance and exit windows) is surely grounded. Carbon fluoride CF_4 at the pressure 50 torr is used as a working gas.

A self-supporting Au target (~1.5 mg·cm^{-2}) is located at the center of the FASA vacuum chamber supported by thin tungsten wires. The energy calibration of the counters was done periodically using a precise pulse generator and a ^{241}Am alpha source. The beam intensity was around 10^9 particles per spill. The beam spot was contenuously controlled by two multi-wire proportional chambers placed at the entrance and the exit of the FASA device. The beam intensity was measured by the special ionization chamber located 150 cm behind the target. The spill length was 1.5 s, the frequency of the beam bursts was 0.1 Hz.

3. Results of Measurements

We used a refined version of the intranuclear cascade model (INC) [9] to get the N, Z and the excitation energy distributions of the target spectators. Primary fragment are hot and their de excitation is considered by SMM [4] to get the final distributions of cold IMF's in two break-up volume conditions (freeze-out volume $V = 3V_0$ and freeze-out volume $V = 5V_0$). For each fragment in a given event the starting time to move along Coulomb trajectory has been randomly chosen according to the decay probability of the system: $P(t) \sim exp(-t/\tau)$. The calculations were done τ = 0, 100, 200 and 300 fm/c. The left panel of **Figures 1** and **2** show the comparison of the measured correlation function (points) with the calculated ones in case of freeze-out volume $V = 3V_0$ for different mean decay times of the fragmenting system. In order to measure the IMF-IMF repulsion effect, the correlation function values at $\theta = 26^\circ$ is used.

The quantity is shown in right panel of **Figures 1** and **2** as a function of τ, the mean life time of the system. Upper line corresponds to calculations with freeze-out volume $V = 3V_0$, lower line—calculations with freeze-out volume $V = 5V_0$. The crossing of the obtained lines with the band corresponding to the measured correlation function and its error bar ($\pm 3\sigma$) defines the mean life time of fragmenting nuclei. The mean decay time of fragmenting system is found to be 85 ± 50 fm/c in p(3.6 GeV) + Au and less then 100 fm/c in p(8.1 GeV) + Au reaction.

Calculations with freeze-out volume $V = 3V_0$ cannot describe experimental data in case of 2.1 GeV of protons but there is a good agreement in case of freeze-out volume $V = 4V_0$. We use Pirson criterion in order to compare experimental data and calculated one. According to χ^2 we make a plot of confidence level (CL) versus the mean decay time of the system (**Figure 3**).

This plot gives possibility to extract decay time of the system correspondent to selected confidence level. An example of such calculations is shown in **Figure 3**.

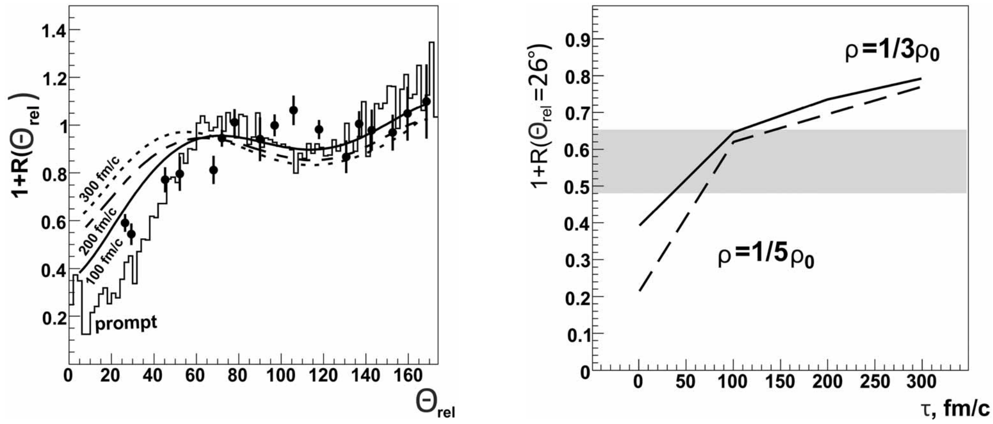

Figure 1. Left panel: Relative angle correlation function for IMF produced in p(3.6 GeV) + Au collisions. Points—experimental data. Histogram—INC + α + SMM calculations with prompt secondary disintegration. Lines correspond to—INC + α + SMM calculations with mean time of secondary disintegration 100, 200 and 300 $fm \cdot c^{-1}$. Right panel: Correlation function at $\theta_{rel} = 26^\circ$ versus the mean decay time of the system. The experimental value is given by the horizontal band, the lines are calculations using different decay time and freeze-up volume.

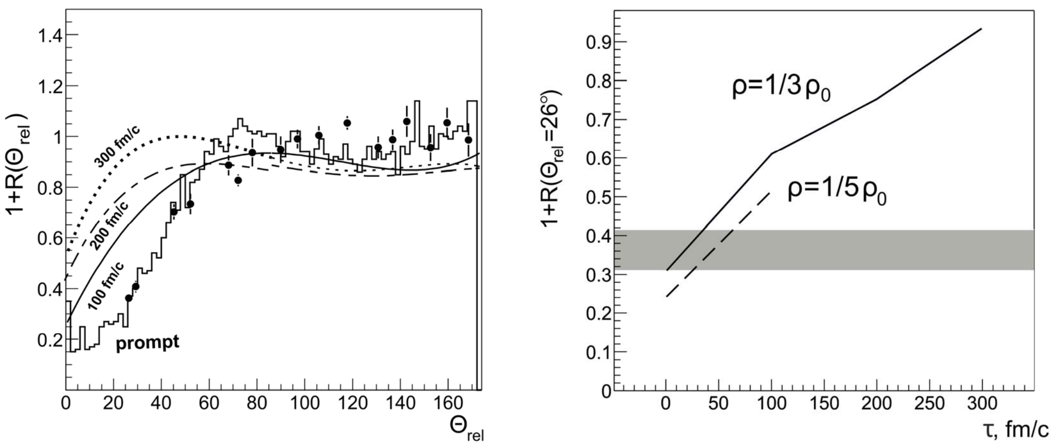

Figure 2. Left panel: Relative angle correlation function for IMF produced in p(8.1 GeV) + Au collisions. Points—experimental data. Histogram is INC + α + SMM calculations with prompt secondary disintegration. Lines correspond to INC + α + SMM calculations with mean time of secondary disintegration 100, 200 and 300 $fm \cdot c^{-1}$. Right panel: Correlation function at $\theta_{rel} = 26^\circ$ versus the mean decay time of the system. The experimental value is given by the horizontal band, the lines are calculations using different decay time and freeze-up volume.

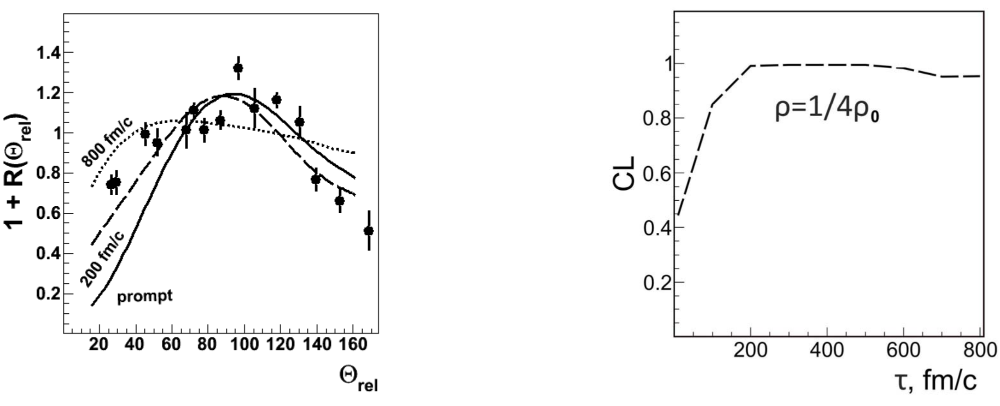

Figure 3. Left panel: Relative angle correlation function for IMF produced in p(2.1 GeV) + Au collitions. Points—experimental data. Solid line is INC + α + SMM calculations with prompt secondary disintegration. Dashed and doted lines are INC + α + SMM calculations with mean time 200 and 800 $fm \cdot c^{-1}$ of secondary disintegration. Right panel: Confidence level versus decay time of fragmenting system.

Measured lifetime of fragmenting system more than 140 fm·c^{-1} at 90% CL.

4. Conclusions

The correlation function in respect to relative angles between the intermediate mass fragments has been measured and analyzed for thermal multifragmentation in p + Au collisions at 2.1, 3.6 and 8.1 GeV of protons. The multibody Coulomb trajectory calculations of all charged particles have been performed starting with the initial break-up conditions given by the combined model with the revised intranuclear cascade followed by the statistical multifragmentation model. The excitation energy and residual masses after cascade have been empirically modified to reach agreement with the data for the mean IMF multiplicity. The correlation function was calculated for different values of mean life time τ of the system at different break-up volume conditions, and compared with the measured one to find the actual time scale of the IMF emission.

It was found that mean life time of the system for 3.6 and 8.1 GeV of protons is less than Coulomb interaction time. In case of 2.1 GeV of protons, mean life time of the system is more than Coulomb interaction time. So, we had transition from sequential evaporation for p(2.1 GeV) + Au to simultaneous multibody decay of a hot and expanded nuclear system in case of p(8.1 GeV) + Au.

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