Time scale of the thermal multifragmentation in p(3.6 GeV) + Au collisions

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Abstract - The relative angle correlation of intermediate mass fragments has been studied for p+Au collisions at 3.6 GeV. Strong suppression at small angles is observed caused by IMF-IMF Coulomb repulsion. Experimental correlation
function is compared to that obtained by the multi-body Coulomb trajectory calculations with the various decay time of fragmenting system. The combined model including the empirically modified intranuclear cascade followed by statistical multifragmentation was used to generate starting conditions for these calculations. The model dependence of the results obtained has been carefully checked. The mean decay time of fragmenting system is found to be $85 \pm 50 \text{ fm/c}$.

**Introduction** - The time scale of fragment emission is a key point for understanding decay mode of highly excited nuclei. Is it a sequential process of independent evaporation of IMF’s or that is a new multi-body decay mode with simultaneous emission of fragments governed by the total accessible phase space? As it was suggested in ref. [1], simultaneous means that the primary fragments are liberated at freeze-out during the time interval which is smaller than the Coulomb interaction time $\tau_c \approx 10^{-21}\text{s}$ (300 - 400 fm/c). In that case fragment emissions are not independent as they interact via Coulomb forces while accelerating in the common electric field. So, measuring the IMF emission time $\tau_{em}$ (i.e. the mean time interval between sequential fragment emissions), or the mean life time $\tau$ of fragmenting system is a direct way to answer the question about the nature of the multifragmentation phenomenon. There is a simple relation between these two quantities via the mean IMF multiplicity [2, 3].

Two procedures are used to determine experimentally the time scale of the process: analysis of the IMF-IMF correlation function in respect to the relative angle or relative velocity. The correlation function exhibits a minimum at $\vartheta_{rel} = 0(\nu_{rel} = 0)$ arising from the Coulomb repulsion between the coincident fragments. The magnitude of this effect drastically depends on the mean emission time, since the longer the time separation of the fragments, the larger their space separation and the weaker the Coulomb repulsion. The time scale for IMF emission is estimated by comparison the measured correlation function to that obtained by the multibody Coulomb trajectory calculations with $\tau$ (or $\tau_{em}$) as a parameter.

The first time scale measurements for the thermal multifragmentation have been done in [2, 3] for $^4He + Au$ collisions at 14.6 GeV by analyzing the IMF-IMF relative angle correlation. It was found that $\tau$ is less than 75 fm/c. Later on [4] a breakup time of order (20-50) fm/c was estimated via small-angle IMF-IMF relative velocity correlations for $^3He + Au$ interactions at 4.8 GeV and for p + Au at 8.1 GeV interaction by analyzing the IMF-IMF relative angle correlation is found to be $\tau \leq 70 \text{ fm/c}$ [5]. In this paper the data on the time scale measurements for the multi-fragment emission in
p + Au collisions at 3.6 GeV are presented. Emphasis is put on the question of the model dependence of the results obtained.

Comparison between experimental data and model. - The experiment has been performed with the 4π-setup FASA [6] installed at the beam of the Dubna synchrophasotron-nuclotron. The device consists of two main parts:

1) Thirty dE-E telescopes, which serve as triggers for the read-out of the system allowing the measurement of the fragment charge and energy distributions. The ionization chambers and Si(Au)-detectors are used respectively as dE and E counters.

2) The fragment multiplicity detector (FMD) including 58 CsI(Tl) counters (with a scintillator thickness averaging 35 mg/cm$^2$), which cover 89% of 4π. The FMD gives the number of IMF’s in the event and their angular distribution.

A self-supporting Au target (1.0 – 1.5) mg/cm$^2$ thick is located in the center of the FASA vacuum chamber. The beam intensity was around 7 · 10$^8$ p/spill (spill length - 300 ms, spill period - 10 s).

We used a refined version of the intranuclear cascade model (INC) [7, 8] to get the distributions of the target spectators over A, Z and the excitation energy. The primary fragments are hot and their deexcitation is considered by SMM [9] to get the final distributions of cold IMF’s in two break-up volume conditions: 1) freeze-out volume $V_f = 3V_o$; 2) Two characteristic break-up volumes [10]. The first volume $V_t = 3V_o$ corresponds to the stage of fragment formation, the second one $V_t = 5V_o$ is the freeze-out volume.

The model calculations (INC + SMM) fail to describe the data for the IMF multiplicities [11, 12]. One concludes that the cascade calculation overestimates the high energy tail of the residue excitation energy distribution. In order to overcome this difficulty the excitation energies are reduced event-by-event via parameter $\alpha$:

$$\alpha = \frac{< M_{exp} >}{< M_{INC+SMM} >}$$

where $< M_{exp} >$ - measured mean multiplicities for events with at least one IMF, $< M_{INC+SMM} >$ - calculated mean multiplicities for events with at least one IMF. The mass loss during "expansion" is fine tuned via parameter $(1 - \alpha)$ [12].

Events in model calculations (INC + $\alpha$ + SMM) with reduced excitation energies and reduced mass loss have been selected for IMF multiplicity $M > 2$ and at least one fragment has $Z > 6$. The "experimental
filter” was applied to be in the line with the experimental definition of the correlation function. For each fragment in a given event the starting time to move along a Coulomb trajectory has been randomly chosen according to the decay probability of the system: $P(t) \sim \exp(-t/\tau)$. The calculations were done for $\tau = 0, 100, 200$ and $300$ fm/c. The left panel of fig.1. shows the comparison of the measured correlation function (points) with the calculated ones in case of freeze-out volume $V_f = 3V_o$ for different mean decay times of the fragmenting system.

Two kind of calculations have been done by the models discussed above - INC + $\alpha$ + SMM. First calculations made with freeze-out volume $V_f = 3V_o$. Second one used two size parameters:

1. transition state $V_t = 3V_o$ corresponds to the stage of pre-fragment formation. Strong interaction between pre-fragments is still significant at this stage;

2. freeze-out volume $V_f = 5V_o$. At this configuration, fragments are well separated each other, they are interacting via the Coulomb force only.

In order to measure the IMF-IMF repulsion effect, the correlation function values at $\Theta_{rel} = 26^\circ$ is used. This quantity is shown in right panel of fig.1. as a function of $\tau$, the mean life time of the system. Upper line
corresponds to calculations with freeze-out volume \( V_f = 3V_o \). Lower line corresponds to calculations used two size parameters. 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 produced in \( p(3.6 \text{ GeV}) + \text{Au} \) reaction. The mean decay time of fragmenting system is found to be \( 85 \pm 50 \text{ fm/c} \).

**Conclusion.** - The distribution of relative angles between the intermediate mass fragments has been measured and analyzed for thermal multifragmentation in \( p + \text{Au} \) collisions at 3.6 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 breakup conditions given by the combined model with the revised intranuclear cascade (INC) followed by the statistical multifragmentation model. The distributions of the excitation energy and residual masses after INC has been empirically modified to reach agreement with the data for the mean IMF multiplicity. The correlation function was calculated for different values mean life time \( \tau \) of the system at different breakup volume conditions, and compared with the measured one to find the actual time scale of the IMF emission.

It was found good agreement of calculations and measured correlation function. Mean life time of the system is \( 85 \pm 50 \text{ fm/c} \) for \( p(3.6 \text{ GeV}) + \text{Au} \) reaction which is in accordance with the scenario of a simultaneous multibody decay of a hot and expanded nuclear system.

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