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# FRAGMENTATION OF TARGETS IN MUON-NUCLEUS INTERACTIONS AT (420 ± 45) GeV – STRONG TWO-PARTICLE AZIMUTHAL CORRELATION

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We present new data on target fragmentation in muon-nucleus interactions at (420 ± 45) GeV. A two-dimensional emission-angle – azimuthal-angle plot of target fragments does not indicate preferential emission of target fragments. We also present an investigation on the two-particle short-range angular correlation among the target fragments in azimuthal-angle space. The experimental data have been compared with MC simulated events to extract dynamical correlation. The data exhibit strong two-particle correlation among target fragments in azimuthal space.

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## 1. Introduction

One of the most interesting questions in the field of high-energy interactions is the nature of correlation among the produced particles. It is still an open question whether the particle production processes are basically weakly correlated phenomena or whether strong correlations are present. The matter is further complicated by the fact that conservation laws impose certain kinematical correlation which can not always be separated from correlations of a more dynamical nature. The study of correlation among the produced particles provides significant features of nuclear interactions and a rich source of information. Several studies using well known two-particle correlation function have been reported in different type of interactions [1 – 4].

The slow target-associated particles, which are emitted in high-energy interactions, are quantitative probes of the cascading processes in spectator parts of the target nucleus [5]. However, since the true dynamics of target-evaporated low-energy particles is not known, the study of black tracks still remains interesting [6 – 12]. In the emulsion experiment, the black-track-producing particles are evaporated from the excited target remnant in a late stage of collision whereas the grey-track-producing particles are mainly protons knocked out of the target nucleus in the later stage of collision [13]. The black tracks are identified as target-evaporation particles in a model referred to as the 'evaporation model' [14]. According to this model, the particles corresponding to 'shower' and 'grey' tracks are emitted from the nucleus very soon after the instant of impact, leaving the hot residual nucleus in an excited state This emission of particles takes place relatively slowly. In order to escape from this residual nucleus, a particle must await a favourable statistical fluctuation, as a result of random collisions between the nucleons within the nucleus, which takes the particle close to the nuclear boundary, travelling in an outward direction and with a kinetic energy greater than its binding energy. After the evaporation of this particle, a second particle is brought to the favourable condition for evaporation and so on, until the excitation energy of the residual nucleus is so small that the transition to the ground state occurs by the emission of $\gamma$-rays. In the rest system of the nucleus in this model, the emission of the evaporation particles is isotropic in nature. The evaporation model is based on the assumption that statistical equilibrium has been established in the decaying system, and that the life time of the system is much longer than the time taken to distribute the energy among the nucleons within the nucleus. In a recent study [15], it has been shown that the angular distribution of target fragments from relativistic heavy-ion interactions could not be explained very satisfactorily by the evaporation model. A few works have been performed where it was observed that target fragments seem to be emitted preferentially in a correlated fashion. So, the concept of the evaporation model has not been universally accepted. Many of the features of the black tracks can not be trivially explained and they put severe constraints on the model. The study of two-particle correlation presents significant features of the nuclear interaction and is a potential source of information. These correlations can provide direct information about the late stage of the reaction when nuclear matter is highly excited and diffused [16]. The correlation which prevails at the early stage of interaction can not be expected to survive in the final state due to the rigors of the initial violent dense stage. The late diffused and deconfined stage is still far from normal unexcited nuclear matter. In the past, all experiments have been reported with hadron-hadron, hadron-nucleus and nucleus-nucleus interactions. The detailed study is required in the case of lepton-nucleus interactions to measure two-particle correlation among target fragments. Thus, the analysis of the angular distribution of the so called target-evaporated particles as a diagnostic indicator of the dynamical phenomenon is essential.

This work presents new data on the angular distribution in two-dimensional space for target-associated slow particles and possible two-particle correlations among target fragments in muon-nucleus interactions at (420 $\pm$ 45) GeV to trace out the existence of short-range correlation.

## 2. Experimental details

The correlation study is performed with the help of the emulsion technique because of the high spatial resolution with $4\pi$ geometry.

**(1) Exposure.** In this emulsion experiment, we have exposed stacks of G5 nuclear emulsion plates to the main muon beam at (420 ± 45) GeV in FERMI LAB (U.S.A.) [17]. The emulsions were allowed to warm to room temperature for 4 hours before the exposure. The two boxes were levelled to about ± 2 mrad. The beam intensity on the emulsion was monitored with a scintillator telescope with a circular aperture of 1.25 cm (in more detail: a counter with a 1.25 cm diameter hole in anticoincidence with two counters 2.5 cm × 2.5 cm). The density of the integrated exposure is $0.98 \times 10^6$ muons/cm$^2$ at the centre, tapering off quadratically to 0.60 at 5 cm from the centre (the edge of the emulsion sheets). The beam was deliberately defocussed with quadrupoles to get a fairly even density on all parts of the emulsion.

**(2) Scanning and measurement.** The scanning of the events was done with the help of a high-resolution Leitz Metalloplan microscope provided with an on-line computer system using objectives 10× in conjunction with a 10× ocular lens. The scanning is done by independent observers to increase the scanning efficiency which turns out to be 98 %.

Criteria for selecting the events were:

(i) The events within 20 $\mu$m thickness from the top or bottom surface of the plates were not analysed.

(ii) The beam track did not exceed 3° from the mean beam direction in the pellicle.

All the tracks were classified as usual:

(a) The target fragments with ionization $> 1.4\, I_0$ ($I_0$ is the plateau ionization) produced either black or grey tracks. The black tracks with the range $<$ 3 mm represent target evaporation (the light nuclei evaporated from the target) of $\beta < 0.3$, singly or multiply charged particles.

(b) The grey tracks with a range $\geq$ 3 mm and having velocity $0.7 \geq \beta \geq 0.3$ are mainly images of target recoil protons of the energy range up to 400 MeV.

(c) The relativistic shower tracks with ionization $< 1.4\, I_0$ are mainly produced by pions and are not generally confined within the emulsion pellicle. They are believed to carry important information about the nuclear reaction dynamics. The azimuthal angle ($\phi$) in the laboratory frame, of all black tracks, is calculated by taking the space coordinates $(x, y, z)$ of a point on the track, another point on the incident beam and the production point, by using oil-immersion objectives (100× in conjunction with a 10× ocular lens). The detailed characteristics for each event was thus obtained. The emulsion technique possesses the highest spatial resolution and thus is most effective in studying correlations. Following the above selection procedure, we have chosen 353 events in our sample plate of muon-nucleus interactions.

## 3. *Method of analysis*

Figure 1 presents a plot of $(1 + \cos\theta)$ vs. $\phi$ $(0 \leq (1 + \cos\theta) \leq 2$ and $0° \leq \phi \leq 360°)$ of target fragments from muon-nucleus interactions at (420±45)

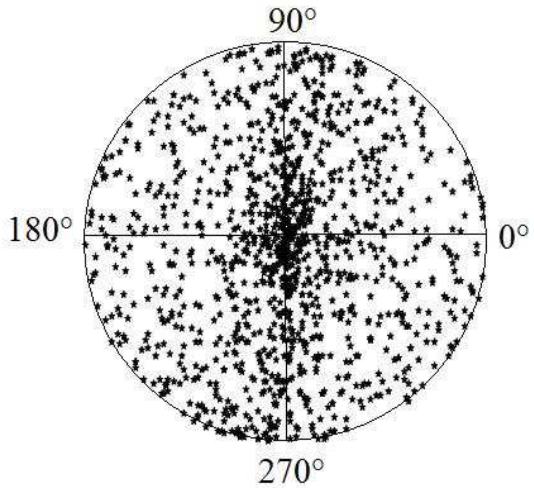



*Fig. 1. Plot of* $(1+\cos\theta)$ *vs.* $\phi$ $(0 \leq (1+\cos\theta) \leq 2$ *and* $0^\circ \leq \phi \leq 360^\circ)$ *of target fragments from muon-nucleus interactions at (420 ± 45)* GeV.

GeV. The plot reveals no significant clustering of target fragments in an angular emission zone. Further in-depth analysis of the data is required to look for any azimuthal correlation. For this we take the help of standard two-particle correlation function, the details of which are described below.

We investigated the two-particle correlation by using the following correlation function

$$C(z_1, z_2) = \frac{1}{\sigma_{\rm in}} \frac{{\rm d}^2\sigma}{{\rm d}z_1{\rm d}z_2} - \frac{1}{\sigma_{\rm in}^2} \frac{{\rm d}\sigma}{{\rm d}z_1} \frac{{\rm d}\sigma}{{\rm d}z_2}\,,$$

where $\sigma_{\rm in}$ is the inelastic cross section and ${\rm d}\sigma/{\rm d}z$ is the single-particle distribution.

The normalized correlation function is defined by

$$R(z_1, z_2) = \left( \frac{1}{\sigma_{\rm in}} \frac{{\rm d}^2\sigma}{{\rm d}z_1{\rm d}z_2} - \frac{1}{\sigma_{\rm in}^2} \frac{{\rm d}\sigma}{{\rm d}z_1} \frac{{\rm d}\sigma}{{\rm d}z_2} \right) \Big/ \left( \frac{1}{\sigma_{\rm in}^2} \frac{{\rm d}\sigma}{{\rm d}z_1} \frac{{\rm d}\sigma}{{\rm d}z_2} \right).$$

For black particles, $z_i = \phi_i$, the azimuthal angle, where $i = 1$ and 2. The normalized two-particle correlation can be defined as

$$R(\Phi_1, \Phi_2) = \left( \frac{1}{\sigma_{\rm in}} \frac{{\rm d}^2\sigma}{{\rm d}\phi_1{\rm d}\phi_2} - \frac{1}{\sigma_{\rm in}^2} \frac{{\rm d}\sigma}{{\rm d}\phi_1} \frac{{\rm d}\sigma}{{\rm d}\phi_2} \right) \Big/ \left( \frac{1}{\sigma_{\rm in}^2} \frac{{\rm d}\sigma}{{\rm d}\phi_1} \frac{{\rm d}\sigma}{{\rm d}\phi_2} \right)$$

$$= N_1 \frac{N_2(\Phi_1, \Phi_2)}{N_1(\Phi_1) N_1 \Phi_2)} - 1\,. \qquad (1)$$

Equation (1) is referred to as the diagonal form of the correlation function. $N_1(\Phi)$ is the number of black particles with $\Phi$ between $\Phi$ and $\Phi + \mathrm{d}\Phi$ and $N_2(\Phi_1, \Phi_2)$ is the number of pairs of black particles within the intervals $\Phi_1$ and $\Phi_1 + \mathrm{d}\Phi_1$ and $\Phi_2$ and $\Phi_2 + \mathrm{d}\Phi_2$, while $N$ is the total number of inelastic interactions in the sample.

The idea of using the correlation function of the above forms goes back to the work of Krikwood [18] in statistical physics. $R = 0$ implies the absence of the correlation, i.e. the case of completely independent particle emission.

## 4. *Monte Carlo simulation*

The simulation was done based on the following assumptions:

(i) Particles of all types are emitted independently of each other.

(ii) The multiplicity distribution in each ensemble of Monte Carlo events reproduces multiplicity spectrum of the real ensemble.

(iii) Due to scanty knowledge of the energy and momentum of the system, we used the random sampling method on the corresponding distribution to generate Monte Carlo events. We have compared the experimental data in muon-nucleus interaction for black tracks with Monte Carlo simulated events. By comparing the inclusive correlation function, $R$, obtained from the experiment and $R_\mathrm{m}$ obtained from Monte Carlo simulated events, one can search for the dynamical correlation.

(iv) The difference

$$R_\mathrm{d}(\text{dynamical surplus}) = R - R_\mathrm{m} \qquad (2)$$

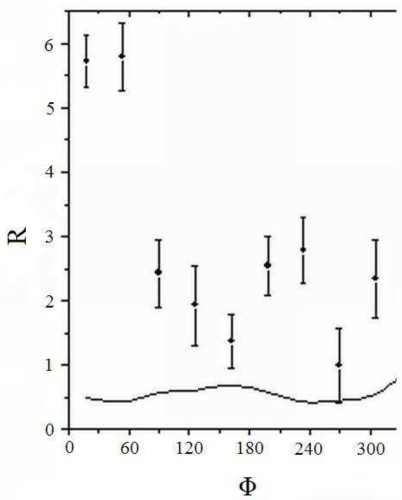
can be interpreted as a manifestation of the dynamical correlation.

## 5. *Results and discussion*

We have calculated the two-particle short-range correlation function ($R$) using Eq. (1). Figure 2 shows the normalized two-particle correlation function along with the Monte Carlo simulated values. The black dots in the figure represent the experimental values and the thick curve represents the best fitted values of the correlation function as calculated by Monte Carlo simulation. The figure indicates the existence of short range correlation over more or less entire $\phi$-space. The correlation is prominent at azimuthal angles around $\phi = 18°$ and $54°$.

Figure 3 illustrates the dynamical surplus obtained by relation (2), giving an idea of the magnitude of the short-range two-particle correlation among the target fragments.The errors shown are only statistical.

This analysis provides new data on two-particle correlation in the $\Phi$-space, which is not only interesting, but also extremely useful for the understanding the emission of target fragments in high-energy muon-nucleus interactions.



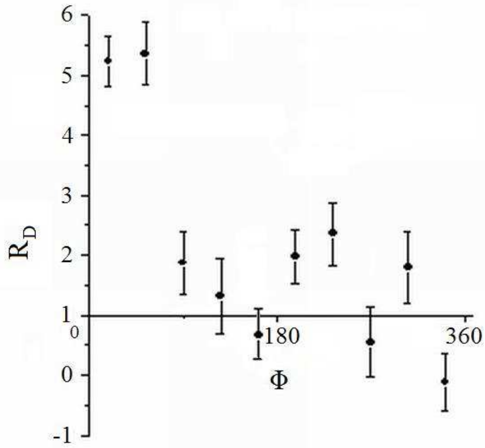




*Fig. 2 (left). Shows the normalized two-particle correlation functions at different azimuthal angles ($\phi$). The thick curve shows Monte Carlo simulated values.*

*Fig. 3. Shows the dynamical surplus, i.e., excess correlation over the Monte Carlo background in muon-nucleus interactions at (420 $\pm$ 45)* GeV.

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## Appendix

The variance of $R$ is given by

$$V(R) = \{\langle n^4\rangle\langle n\rangle^2 - 4\langle n^3\rangle\langle n^2\rangle\langle n\rangle + 4\langle n^2\rangle^3 - \langle n^2\rangle^2\langle n\rangle^2 + 2\langle n^2\rangle^2\langle n\rangle^2 - 4\langle n^2\rangle^2\langle n\rangle$$
$$+2\langle n^2\rangle^2\langle n\rangle^3 + \langle n^2\rangle\langle n\rangle^2 - \langle n\rangle^4\} \times \left[N\langle n\rangle^6\right]^{-1} \quad + \; 0(1/N^2) \quad \text{for} \quad \Phi_1 = \Phi_2\,.$$

The variance in $R$ [19] is calculated term by term and instead of giving the long algebraic expression of the net variance, we have computed it and shown the corresponding errors in the figures.

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## RAZBIJANJE JEZGRI U SUDARIMA S MIONIMA NA (420 $\pm$ 45) GeV – JAKA DVOČESTIČNA AZIMUTALNA KORELACIJA

Predstavljamo nove podatke o razbijanju meta u sudarima miona s jezgrama na $(420 \pm 45)$ GeV. Dvodimenzijski prikaz kut emisije – azimutalni kut ne pokazuje povezanost u emisiji krhotina mete. Predstavljamo također analize dvočestičnih kutnih korelacija kratkog dosega u azimutalnom smjeru. Usporedili smo podatke s Monte Carlo računima radi izvođenja dinamičkih korelacija. Podaci pokazuju jaku dvočestičnu korelaciju među krhotinama mete u azimutalnom smjeru.