

# Study of nuclear multifragmentation induced by ultrarelativistic $\mu$ -mesons in nuclear track emulsion

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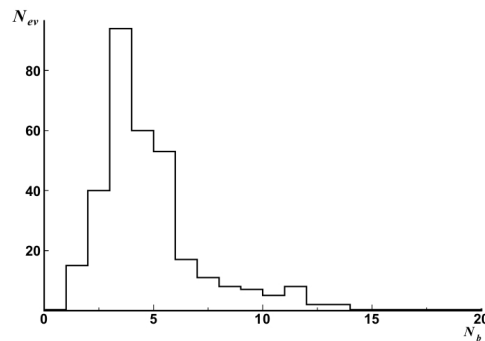
**Abstract.** Exposures of test samples of nuclear track emulsion were analyzed. The formation of high-multiplicity nuclear stars was observed upon irradiating nuclear track emulsions with ultrarelativistic muons. Kinematical features studied in this exposure of nuclear track emulsions for events of the muon-induced splitting of carbon nuclei to three  $\alpha$ -particles are indicative of the nuclear-diffraction interaction mechanism.

Possessing an excellent sensitivity and spatial resolution, nuclear track emulsions preserve their position as a universal and relatively cheap detector for surveying and searching investigations into nuclear and particle physics. The use of this classic procedure in beams from modern accelerators and reactors proved to be quite successful. In a number of important problems, the completeness of observations that is ensured by nuclear track emulsions remains inaccessible for electronic detection methods.

Test track-emulsion samples manufactured by the MICRON production unit of the Slavich Company JSC [1] are being presently irradiated within the Becquerel project [2]. The samples in question are created by casting emulsion layers 50 to 200  $\mu\text{m}$  thick onto glass substrates. The basic properties of this nuclear track emulsion are close to those of BR-2 nuclear track emulsions, which are sensitive to relativistic particles. The production of BR-2 nuclear track emulsions had been performed for more than four decades and was completed about ten years ago. The product emulsion [1] has already been used in the range-based spectrometry of  $\alpha$ -particles [3, 4].

Test irradiations were aimed primarily at a general quality control and a control of the emulsion sensitivity to relativistic particles, as well at a comparison of ranges of slow nuclei that have strongly ionizing low energies with the values calculated on the basis of the SRIM simulation code [5]. The present article combines the results obtained by analyzing recent exposures of nuclear track emulsions to ultrarelativistic muons. So wide a variety of experimental implementations, including those in [3, 4], became possible owing to the use of the new nuclear track emulsion, whose properties permitted applying the same strategy to coordinate measurements for tracks of length between several microns and several tens of microns. The





**Figure 1.** Distribution of nuclear stars with respect to the number of strongly ionizing  $b$  particles,  $N_b$ , in a track-emulsion sample irradiated with muons.

video data on the interactions studied in the track emulsion are available on the website quoted in [2].

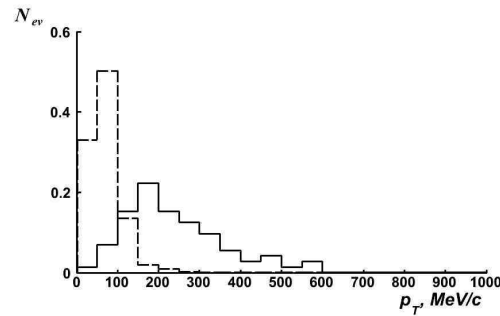
The deep-inelastic scattering of ultrarelativistic muons is a commonly recognized means for studying the parton structure of nucleons and nuclei. The irradiation of track emulsions with these particles makes it possible to study concurrently the multifragmentation of nuclei under the effect of a purely electromagnetic probe. Multiphoton exchanges or transitions of virtual photons to vector mesons may serve as a fragmentation mechanism. At CERN, a track-emulsion sample was exposed to 160-GeV muons. Earlier, comparable analysis was performed for NTE longitudinally exposed to 150 GeV [6]. The objective of the exposure described here was to study experimental loads in the vicinity of the beam axis and to assess preliminarily the character of muon interactions.

The samples under study were placed in front of the target of the COMPASS experiment at a distance of about 25 cm from the beam axis (halo), where the intensity amounted to about  $10^6$  particles per centimetre squared per cycle. The track-emulsion samples  $9 \times 12$  cm in area and about 100  $\mu\text{m}$  in thickness were oriented both along and across the beam. A nine-hour irradiation in the case of the transverse orientation proved to be the most favourable for our analysis. So long-term an irradiation was possible owing to the smallness of the cross section for muon interaction and to a small effect of beam ionization in relation to the longitudinal arrangements of layers. The duration of the irradiation run was constrained for fear of overloads with tracks from interactions in the glass substrate. In principle, this duration could be increased by two orders of magnitude without causing complications for the ensuing analysis.

Scanning led to finding, in irradiated track emulsions, about 300 stars containing not less than three target fragments. The topology of stars was determined by the number of strongly ionizing  $b$  particles. Figure 1 shows the distribution of  $N_b$ . Although the solid angle within which tracks could be observed was limited, the formation of high-multiplicity stars involving almost one-half of the charge of heavy nuclei in the composition of the emulsion could be proven.

Seventy-two stars containing only triples of  $b$  particles stopped in the track emulsion were associated with the breakup process  $^{12}\text{C} \rightarrow 3\alpha$ . Alpha-particle ranges and spatial emission angles were determined on the basis of coordinate measurements for tracks. The mean  $\alpha$ -particle range was  $23.1 \pm 0.6 \mu\text{m}$  (RMS =  $8.4 \mu\text{m}$ ). The  $\alpha$ -particle energy was estimated on the basis of the SRIM model. Its mean value proved to be  $5.3 \pm 0.1 \text{ MeV}$  (RMS =  $1.3 \text{ MeV}$ ).

The fact that the interpretation of this group of events is unambiguous makes it possible to assess the character of their production on the basis of the total transverse momentum  $P_T$  of  $\alpha$ -particle triples. The distribution of  $P_T$  (see figure 2) is characterized by the mean



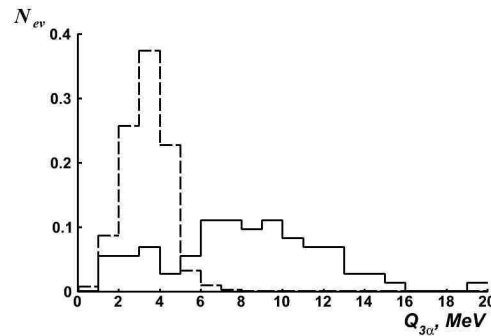
**Figure 2.** Total-transverse-momentum ( $P_T$ ) distribution of (solid-line histogram) 72 triples of  $\alpha$ -particles in a track emulsion irradiated with muons and (dashed-line histogram) 400 triples of  $\alpha$ -particles from the reaction  $n(14.1 \text{ MeV}) + {}^{12}\text{C} \rightarrow 3\alpha + n$  [3] (normalization to the number of events).

value of  $241 \pm 28 \text{ MeV}/c$  ( $\text{RMS} = 123 \text{ MeV}/c$ ). It is described by the Rayleigh distribution at the parameter value of  $190 \pm 13 \text{ MeV}/c$ . These parameter values are typical of the nuclear diffraction interaction. In the case of purely electromagnetic exchange, the  $P_T$  distribution would be concentrated in the range of  $P_T < 100 \text{ MeV}/c$ . It is useful to compare this distribution of  $P_T$  with the substantially narrower distribution of  $P_T$  for the reaction  $n(14.1 \text{ MeV}) + {}^{12}\text{C} \rightarrow 3\alpha + n$  (see figure 1 in [3]). The latter is characterized by the mean value of  $69 \pm 4 \text{ MeV}/c$  ( $\text{RMS} = 38 \text{ MeV}/c$ ) and by the Rayleigh distribution parameter value of  $55 \pm 28 \text{ MeV}/c$ .

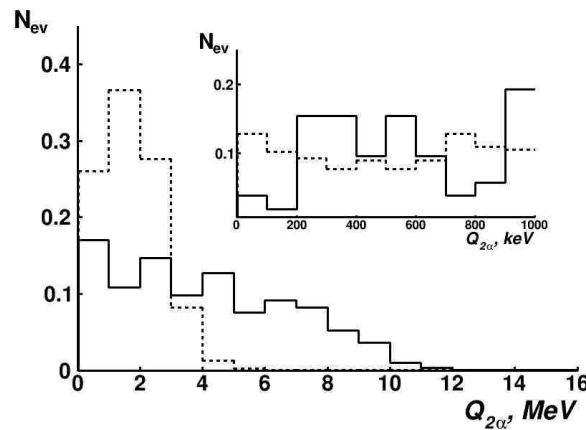
The distribution of the total energy of  $\alpha$ -particle triads,  $Q_{3\alpha}$ , in figure 3 is substantially broader than that in the case of the reaction  $n(14.1 \text{ MeV}) + {}^{12}\text{C} \rightarrow 3\alpha$  [7], the latter revealing distinctly the clustering features of the  ${}^{12}\text{C}$  nucleus. In the case being considered, the distribution of  $Q_{3\alpha}$  is concentrated above the  $\alpha$ -cluster levels of excitation of the  ${}^{12}\text{C}$  nucleus. The distribution of the energy of  $\alpha$ -particle pairs,  $Q_{2\alpha}$ , in figure 4 does not reveal any similarity in the spectra for the exposures being considered either. In the exposure to muons, there is virtually no signal from the decays of the ground state  ${}^8\text{Be}_{g.s.}$  in the range of  $Q_{2\alpha} < 200 \text{ keV}$  (see inset in figure 4), which manifest themselves as narrow  $\alpha$ -particle pairs [7]. The distribution of  $Q_{2\alpha}$  does not exhibit a peak from the decays of the first excited state  ${}^8\text{Be}^{2+}$  at 3 MeV. Moreover, this distribution of  $Q_{2\alpha}$  proves to be substantially broader than that in the case of the reaction  $n(14.1 \text{ MeV}) + {}^{12}\text{C} \rightarrow 3\alpha$  [7].

By and large, the  $P_T$ ,  $Q_{3\alpha}$  and  $Q_{2\alpha}$  distributions for the irradiation of nuclear track emulsions with muons are indicative of a hard character of the process without manifestations of the well-known structural features of the  ${}^{12}\text{C}$  nucleus, including the formation of  $\alpha$ -particle triples in the continuum region. We emphasize that the contribution of  ${}^{12}\text{C}$  breakup with a threshold of 7.36 MeV should have inevitably manifested itself in the channel being discussed ( $N_b = 3$ ). However, the circumstance that it is the nuclear diffraction mechanism rather than the soft electromagnetic mechanism that manifests itself for this channel, which possesses the minimum threshold, seems unexpected and deserves a theoretical analysis. The corroboration of this conclusion is of importance for interpreting not only multifragmentation under the effect of ultrarelativistic muons. It may also serve as a basis for interpreting the multifragmentation of relativistic nuclei in peripheral interactions not leading to the formation of target fragments (white stars).

These observations, which are of a preliminary character, indicate that a full-scale investigation of a complete muon-induced disintegration of nuclei on the basis of multilayered assemblies from thick layers of substrate-free nuclear track emulsion is highly promising. In order



**Figure 3.** Distribution of the total energy of  $\alpha$ -particle triples,  $Q_{3\alpha}$ , in a track emulsion irradiated with (solid-line histogram) muons and (dashed-line histogram) neutrons in the reaction  $n(14.1 \text{ MeV}) + {}^{12}\text{C} \rightarrow 3\alpha + n$  [3] (normalization to the number of events).



**Figure 4.** Distribution of the energy of  $\alpha$ -particle pairs,  $Q_{2\alpha}$ , in a track emulsion irradiated with (solid-line histogram) muons and (dashed-line histogram) neutrons in the reaction  $n(14.1 \text{ MeV}) + {}^{12}\text{C} \rightarrow 3\alpha + n$  [3] (normalization to the respective number of pairs).

to interpret reliably data obtained upon exposing track-emulsion layers to muons, it is necessary to test the hadron-background level at the places where the emulsion layers were irradiated.

## References

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