JOINT INSTITUTE FOR NUCLEAR RESEARCH

Veksler and Baldin Laboratory of High Energy Physics

FINAL REPORT ON THE START PROGRAMME

Analysis of short-range tracks produced in boron-enriched nuclear emulsion exposed to thermal neutrons at the IBR-2 reactor in 2025

Supervisor:
Dr. Pavel Igorevich Zarubin

Student:
Elif Nur Gün,
Hacettepe University, Türkiye

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Abstract

This study investigates the detection of thermal neutrons (~0.025 eV) via the $^7B(n,\alpha)^7Li$ reaction using a boron-10-enriched nuclear emulsion. When exposed to the neutron flux of the IBR-2 reactor, the emulsion records short-range tracks from alpha particles and ^7Li ions produced by thermal neutron capture. These tracks were observed and photographed with MBI-9 and Olympus BX63 microscopes. These charged secondary particles produce high ionization density tracks (~5–10 μm) that can be detected with submicron spatial resolution. These tracks are analyzed with ImageJ programme to obtain the track lengths.

Keywords: Nuclear emulsion, thermal neutrons, $^{10}B(n,\alpha)$ reaction, IBR-2 reactor, short-range tracks, neutron imaging

1. Introduction

1.1 Nuclear Emulsion Technique

The nuclear emulsion technique is a sensitive and efficient method for detecting and analyzing particles by recording their tracks in a specially prepared photographic nuclear emulsion. This technique has played a crucial key role in many groundbreaking discoveries in nuclear physics, even including the identification of pions and the study of cosmic rays. [1] A nuclear emulsion consists of a dense suspension of silver halide microcrystals in a gelatin matrix coated on a glass or plastic base. When a **charged particle** passes through the emulsion, it ionizes the medium along its path, creating a latent image that can be revealed through chemical enhancement. This track is observable under an optical microscope, contains valuable information about the particle's **energy, charge, mass, and range**. Because of its high spatial resolution (often to fractions of a micron), the nuclear emulsion technique still remains as an important and powerful tool in research fields ranging from fundamental particle physics to space radiation measurements. [2]

1.2 History of Nuclear Emulsion Technique

At the time when nuclear emulsion technology was emerging, the world was in the final stages of World War II. People were struggling to recover from the effects of the war and the resulting depression. At such a time, there weren't enough people to conduct and lead research in particle physics. Those in this field were mostly recent graduates or staff members returning from the war. While many had the enthusiasm and passion for research, they lacked a sufficient physics background. A field of research that could be conducted under these conditions and didn't require complex requirements had to be found. Physicists decided that this field was to study cosmic rays, because studying cosmic rays and obtaining consistent data didn't require expensive or complex equipment. They decided that nuclear emulsion was the most suitable method. Not only was it inexpensive and easy to use, but it also didn't require extensive research expertise from those conducting the study. Because the researchers were enthusiastic about science but lacked extensive knowledge, this method was ideally suited for the study. All they had to do was locate nuclear photographic emulsions onto a mountain and expose them to cosmic rays for a period of time. The mountains' altitude provided an exposure to cosmic rays ten times more intense than at sea level. After the exposure, these layers were developed and washed. After being developed, emulsions would reveal the tracks of charged particles that traversed them. [3]

This method quickly yielded very consistent and valuable results and quickly became a household name in the scientific world. Young and enthusiastic physicists gathered at a large conference in Bristol. They presented their presentations and shared and discussed experimental data. Then, to take the experiment to the next level, they decided to expose the emulsions to higher exposure. A large hot air balloon was prepared for this purpose. They believed this method would make the statistics more consistent. The goal was to capture more cosmic rays at higher altitudes. [3, 4]

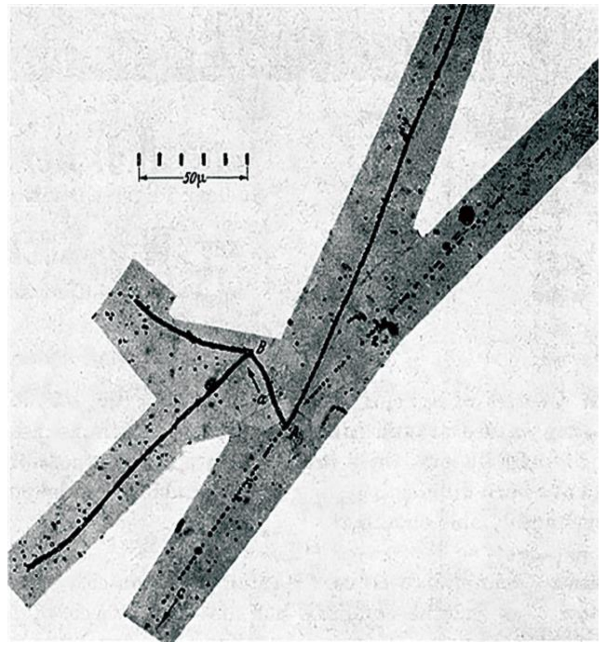


Figure 1: A balloon ready for the ascent - July 1953

Figure 2: First clear observation of the existence of the τ meson in a nuclear emulsion exposed to cosmic rays

Previously, it seemed that a new decay mode, or perhaps a known decay mode for a new parent mass, was found almost every month. However, it is now understood that the most common decay modes are quite limited in number and have very precise mass values. In these emulsions, each layer was in direct contact with the next, so that after exposure, traces of secondary particles could be followed from one layer to the next over much greater distances. These emulsions provided a significant improvement in measurement precision, allowing us to uniquely identify particles and calculate a particle's energy by measuring its range.

2. Track Formation Mechanism in Nuclear Emulsions

Nuclear emulsions are a type of solid-state particle detector that offers high resolution. Nuclear emulsions are preferred for analyzing nuclear reactions and neutron applications because they can directly visualize and measure the tracks of short-range, high-LET (linear energy transfer) particles. The ability to identify particles through emulsions is a significant advantage. [5, 6, 7]

When a **charged particle** traverses boron-enriched nuclear emulsion (mostly AgBr crystals in gelatin), it ionizes atoms along its path, liberating electrons in latent image centers with the reaction;

$$\mathrm{Ag}^{+} + e^{-} \rightarrow \mathrm{Ag}^{0}$$

The ionization energy loss (dE/dx) is governed by the Bethe-Bloch formula:

$$\frac{dE}{dx} = \frac{4\pi e^{4} z^{2} Z\rho}{m_e v^{2}} \left(\ln \frac{2m_e v^{2}}{I} - \ln(1-\beta^{2}) - \beta^{2} \right)$$

Where:

- **z: Charge of the incident particle.**
- **Z: Atomic number and mass of the emulsion**
- ***I*: Mean excitation potential**
- ***β=v/c***
- **m=Rest Mass**

The resulting small silver particles create a visible image on the emulsion. As a result, after the photo emulsion is developed with a developer solution (usually an amidol developer), the "grains" transform into metallic silver particles. The fixer, by removing unreacted AgBr, ensures the tracks are permanent. Ultimately, track formation is a complex process that relies on both the kinetics of nuclear reactions and the chemical reactions of photographic emulsions. [1, 6, 7]

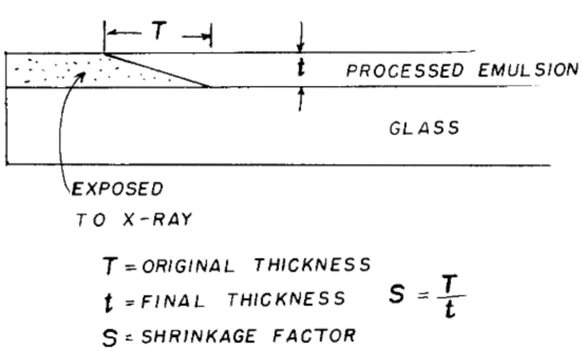
The thickness of the emulsion layer plays a crucial role in determining the overall effectiveness and sensitivity of nuclear emulsion detectors. A thicker emulsion layer significantly enhances the detector's capability to record extended segments of particle trajectories, particularly those entering the emulsion at steep angles relative to the surface. This increased thickness allows for more comprehensive path reconstruction, improving the accuracy and reliability of particle track analysis. [7]

Following the development process, the precise measurement of particle traces becomes possible through a well-defined mathematical relationship. The length of a developed track can be calculated using the following expression:

$$L = \sqrt{X^2 + Y^2 + (Z \cdot S)^2}$$

Where X, Y and Z are the differences of the coordinates of the event. S is the shrinkage factor of the emulsion layer. The shrinkage phenomenon occurs due to the removal of undeveloped silver halide crystals during the chemical development process. As these components are washed away, the emulsion undergoes a reduction in volume, leading to a compressed final state. The shrinkage factor S is defined as:

$$S = \frac{V_{\text{initial}} - V_{\text{removed}}}{V_{\text{gelatin}}}$$



2.1 Nuclear Track Emulsion Technique in Thermal Neutrons

Thermal neutrons are low energy (generally 0.025 eV and 2200 m/s) and slow moving neutrons. Their names come from their thermal equilibrium with atoms at ambient temperature. These neutrons are formed by the elastic scattering slowing down of high energy neutrons (e.g., fission neutrons) in moderator materials (water, graphite, heavy water, etc.). The probability of thermal neutrons interacting with nuclei is inversely proportional to their speed (1/v). Therefore, slow neutrons have a higher capture cross-section. For example $^3He(n, p)^3H \rightarrow$ 5330 barn (at 0.025 eV) and $^6Li(n, \alpha)^3H \rightarrow$ 940 barn. Due to their lower energy, they are only efficiently captured in high-cross-section materials.Because neutrons carry no electric charge, their interaction with matter occurs entirely through nuclear forces. This characteristic prevents them from leaving a direct trace in the emulsion. The operating principle of NTE relies on the ionization tracks created by charged particles in AgBr crystals. However, since uncharged neutrons cannot trigger this mechanism, their detection is achieved by examining the secondary particles that leave this trace. [6]The following reaction is the primary reaction that occurs when a thermal neutron enters a boron-enriched emulsion. The boron captures a neutron, resulting in the formation of lithium and helium. Because the secondary particles are charged, they can leave traces in the emulsion and be studied. Applications of neutron capture could be used in boron neutron capture therapy, neutron detectors and neutron imaging films. [9]

$$^{10}B+n\rightarrow {}^{7}Li+{}^{4}He \qquad Q=2.31\ MeV$$

- **^{10}B = Boron-10 (stable isotope)**
- ***n* = Thermal neutron (low energy, ~0.025 eV)**
- **^{7}Li = Lithium-7 (stable isotope)**
- **^{4}He (α) = Alpha particle (helium nucleus)**
- **2.31 MeV = Total energy released (Energy is distributed between Li and He)**

After this reaction, we can see the traces formed in the emulsion. Microscopic analysis of the results is performed using high-resolution optical microscopes (Olympus BX63) and oil immersion techniques play a critical role in this process. Lens systems providing up to 90x magnification are generally preferred, and oil immersion provides higher resolution and clarity. Emulsion samples are placed on specially prepared plates and coated with oil immersion to eliminate any air gap between the objective lens and the sample. This minimizes light scatter and allows for sharper observation of the detailed structure of the scars. [10, 11]

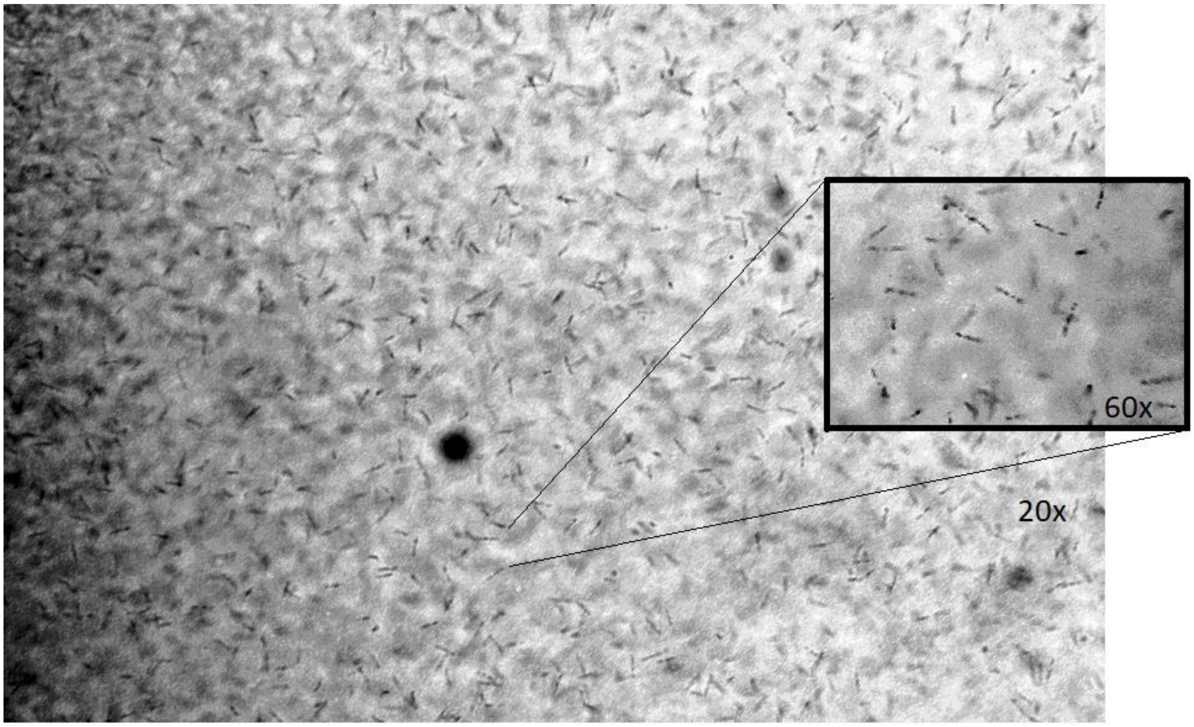


Figure 3: Traces in boron-enriched emulsion exposed to thermal neutrons, viewed with 20x and 60x lenses on MBI-9 microscope

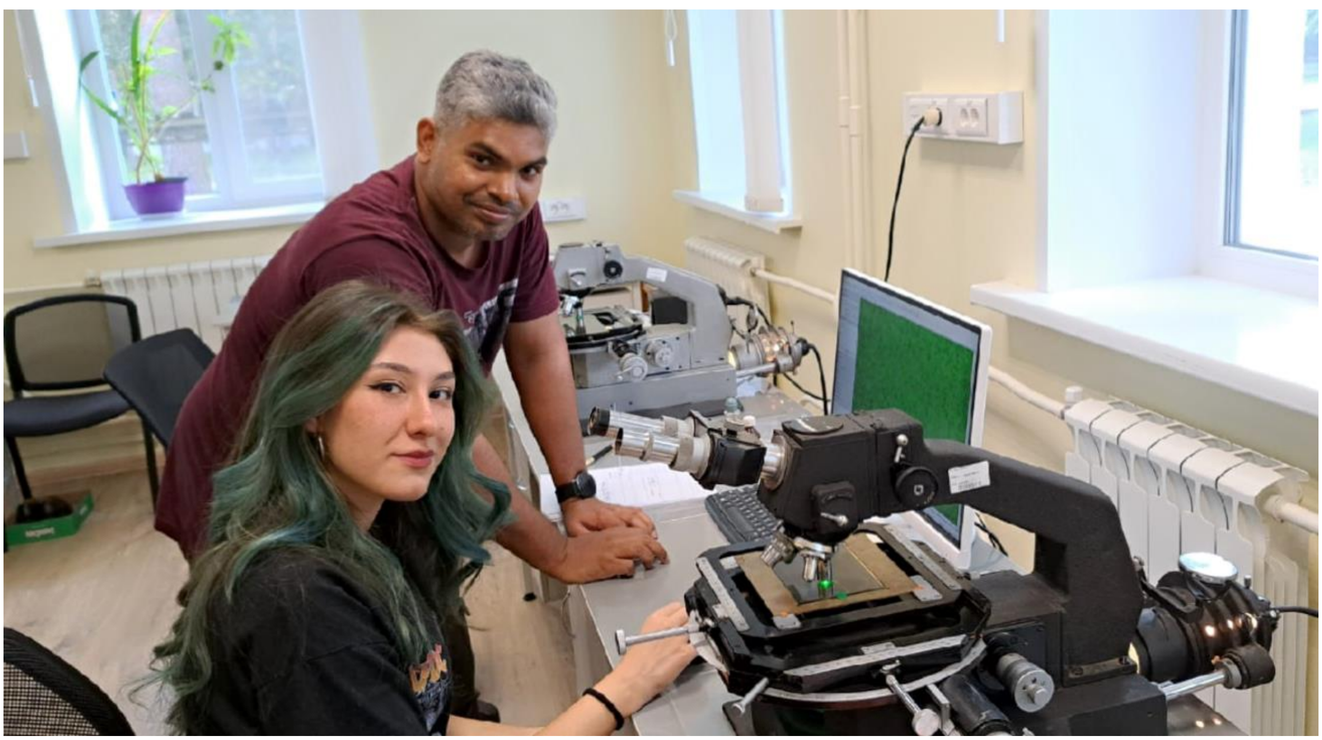


Figure 4: Examination of the traces with an MBI-9 microscope

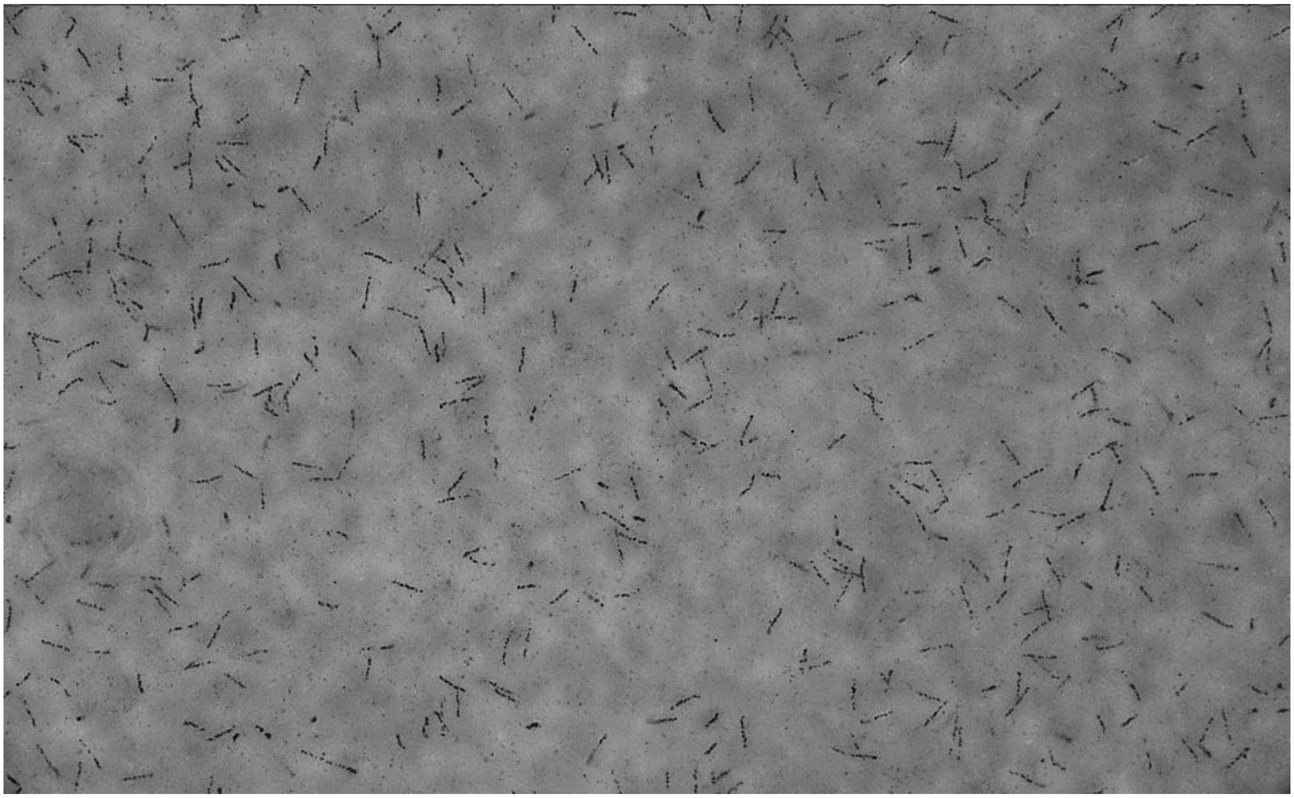


Figure 5: High resolution photograph of traces in emulsion taken with Olympus BX63 microscope

2.2 Analyzing the traces with ImageJ program

ImageJ is an image analysis program. It is frequently used, particularly in physics and materials science. Despite its simple interface, this program offers very powerful analysis tools and allows for detailed analysis. It is particularly useful for analyzing microscope images. When a photograph is first taken from a microscope, it is not entirely suitable for analysis. Some photo enhancements are necessary. ImageJ increases contrast and simplifies analysis. [12]

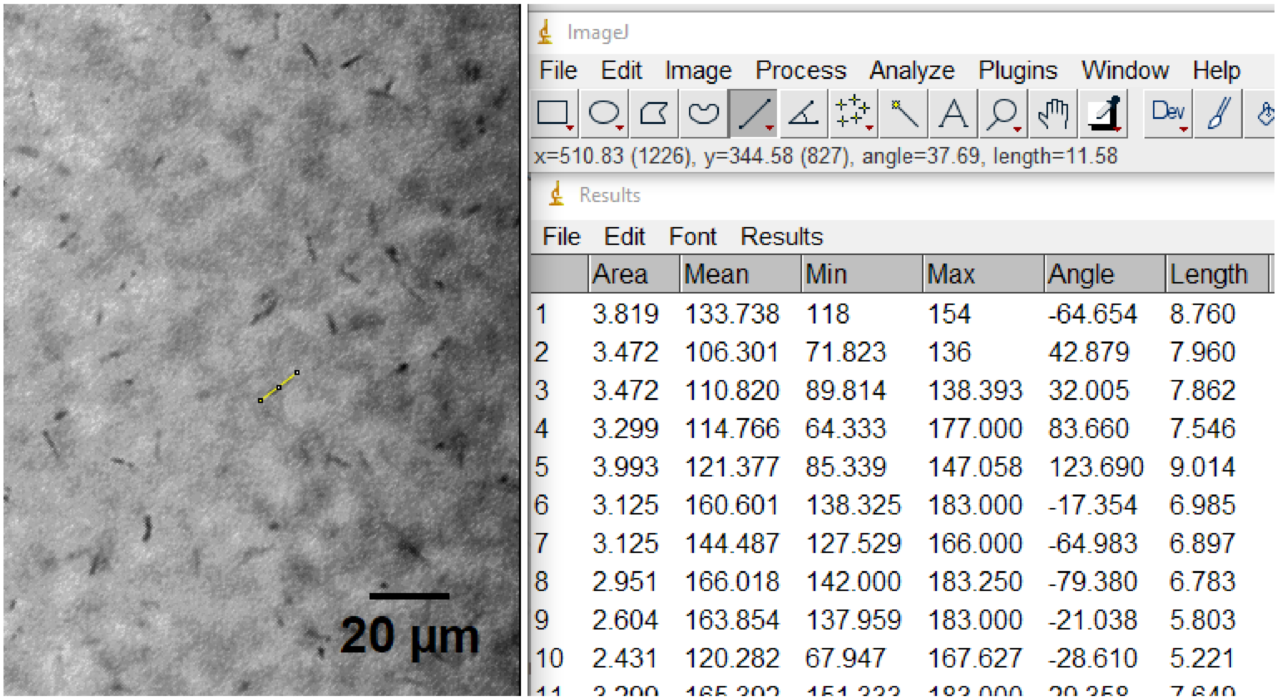


Figure 6: Analysis of traces with ImageJ program

When examining these tracks on the emulsion using ImageJ, certain points must be taken into account. Insufficient or excessive neutron fluence directly affects track density. Low fluence can lead to statistically insufficient data, while high fluence can lead to overlapping tracks. The optimal exposure time must be determined, and attention must be paid to the homogeneity of the neutron source. Incorrect microscope settings (illumination, contrast, objective magnification) may result in unclear visualization of tracks. High-resolution and contrast-rich images should be taken, and different magnifications should be tested. Dust, scratches, or imperfections in the emulsion can be mistaken for neutron tracks and incorrectly counted (especially if the program performs automatic counting instead of manual). Irregular shapes in the image should be removed. True tracks can be selected by applying the "Circularity" and "Size" filters. If the pixel-to-real size ratio (µm/pixel) is incorrectly entered, track size and density calculations will be inaccurate. Correct calibration should be performed using a micrometer slide. Furthermore, a correct scale must be selected. Cosmic rays or other radiation sources can create additional tracks. Background noise should be removed. Analysis of thermal neutron tracks in boron emulsion with ImageJ requires careful preparation, accurate image processing techniques, and statistical controls. This allows accurate and consistent results to be obtained.

2.3 Analysis Results

Additionally, data collected from a single area may not represent the entire sample. **Multi-field analysis** should be performed. Because the emulsion is not exposed to equal and homogeneous radiation throughout, traces vary in intensity across each area. Therefore, the areas with the highest concentration of traces should be identified, and an appropriate distribution should be determined.

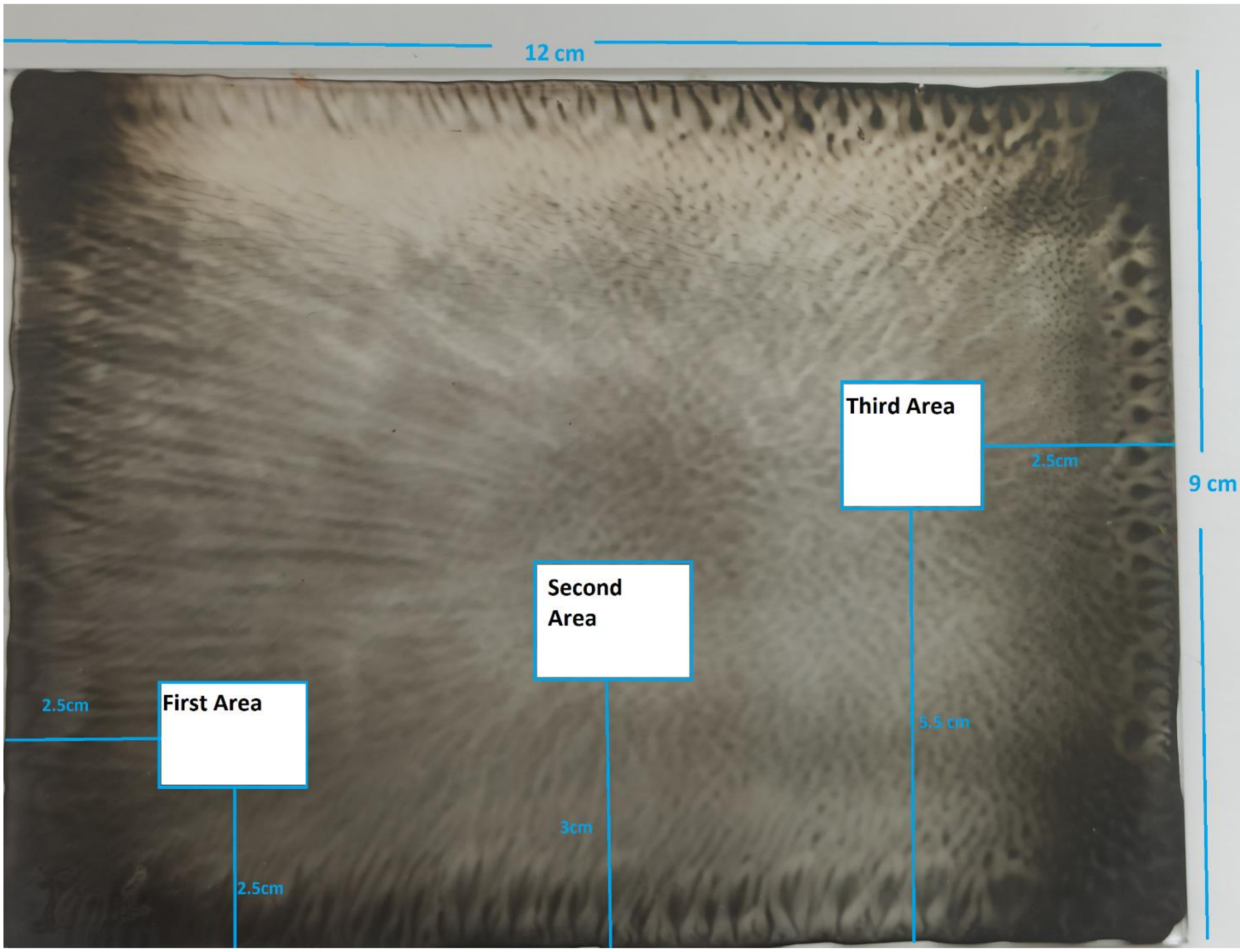
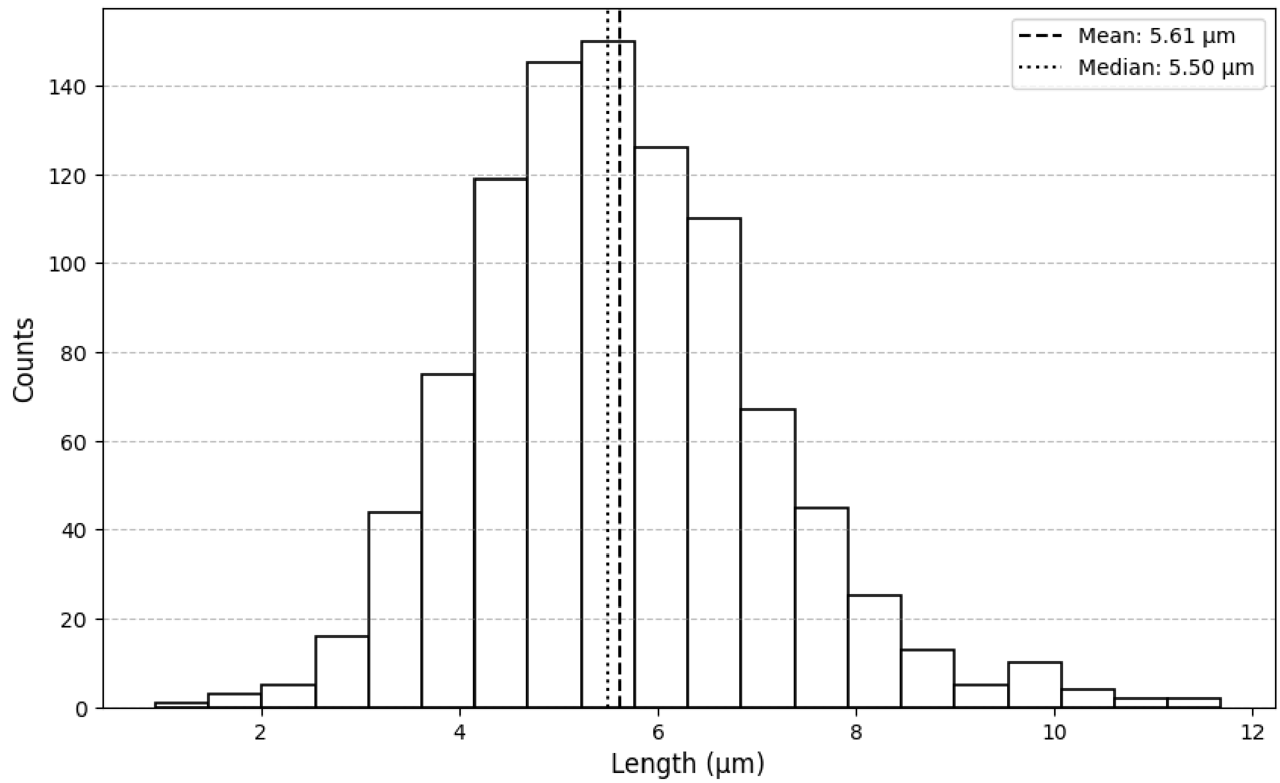
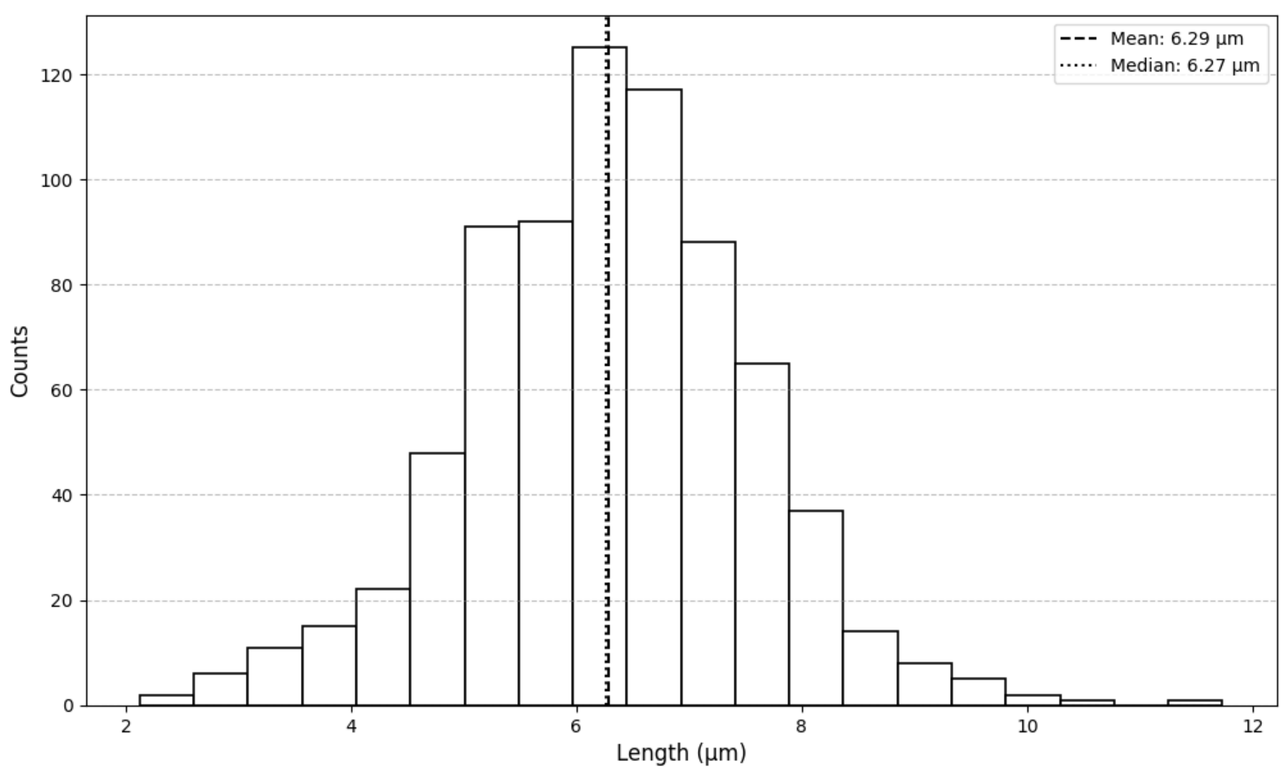


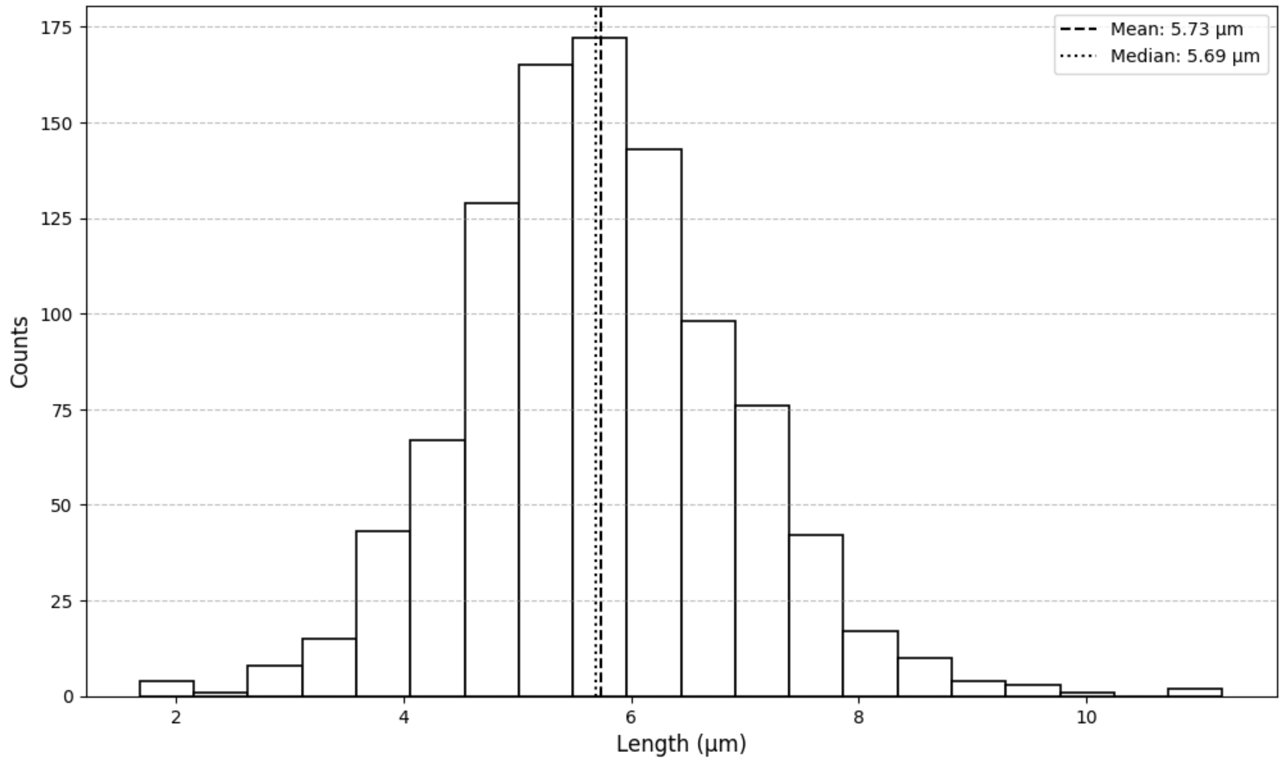
Figure 7: Representation of the multi-areas examined in the emulsion



Graph 1: Histogram plot of the traces obtained by the analysis of the first area



Graph 2: Histogram plot of the traces obtained by the analysis of the second area



Graph 3: Histogram plot of the traces obtained by the analysis of the third area

The analysis of short-range tracks in the boron-enriched nuclear emulsion was performed using ImageJ software to measure and classify the lengths of helium and lithium ion tracks produced by the $^{10}B(n,\alpha)^{7}Li$ reaction. The tracks were identified and measured across multiple sample areas to ensure statistical reliability and account for variations in thermal neutron irradiation. The histograms presented above (Graphs 1–3) display the distribution of track lengths for three distinct regions of the emulsion, providing insight into reaction uniformity. The majority of tracks fall within the expected range of 5–10 µm, consistent with the theoretical prediction for alpha particles and ^{7}Li ions from thermal neutron capture. Variations in track density between different regions suggest localized differences in neutron flux or boron concentration. The histograms shows a roughly Gaussian distribution, indicating a well-controlled exposure process. A small fraction of longer tracks (>10 µm) may correspond to higher-energy secondary particles or background interactions. The presence of a **hard background** (cosmic rays or natural radioactivity) contributes to minor irregularities in track distribution and emulsion surface imperfections. However, this does not significantly affect the primary neutron-induced signal. The multi-field analysis confirms that the emulsion responds uniformly to thermal neutrons, validating its suitability for neutron applications. [8, 6]

2.4 Conclusion and Discussion

The nuclear emulsion testing described in this research was not only conducted for fundamental research but also serves a critical purpose in applied physics, particularly in the development of boron neutron capture therapy (BNCT) and nuclear astrophysics. The emulsions analyzed here were produced as part of a collaborative project led by Prof. S.Yu. Taskaev at the Institute of Nuclear Physics. In this project, the emulsion stacks were specifically designed to detect epithermal (resonance) neutrons generated by a proton source, which are essential for advancing BNCT—a targeted cancer treatment that leverages the high cross section of boron-10 for thermal and epithermal neutrons. When boron-10 captures a neutron, it undergoes the $^{10}B(n,He)^{7}Li$ reaction, releasing helium and lithium ions that destroy cancer cells while sparing surrounding healthy tissue. The emulsions tested in this study confirm the proper production and sensitivity of the material for such applications, as they successfully recorded short-range tracks from thermal neutron interactions.

A critical aspect of track analysis in nuclear emulsions is accounting for their three-dimensional structure. Tracks propagate not only laterally (x-y plane) but also along the z-axis (depth), which complicates microscope-photograph based measurements. For instance, a track appearing shorter than expected may indicate its trajectory deviates significantly into the emulsion's depth, making full reconstruction challenging under standard optical microscopy. This z-axis penetration can obscure the true length and orientation of tracks, necessitating careful focal plane adjustments and oil immersion techniques to resolve overlapping or partially visible traces. Despite these challenges, the high spatial resolution of nuclear emulsions still allows for precise measurements, provided that track projections are analyzed with appropriate corrections for shrinkage and geometric effects.

Furthermore, these emulsions hold promise for future experiments in nuclear astrophysics, particularly in the study of proton-driven reactions simulating stellar nucleosynthesis processes. The preliminary results presented here, including multi-field analysis and track length distributions, demonstrate the emulsion's ability to resolve high-LET particle tracks despite the presence of a hard background. This background, likely originating from cosmic rays or other ambient radiation, contributes to the observed surface defects but does not affect the overall performance of the emulsion. By confirming the emulsion's response to thermal neutrons, this work supports its broader use in both medical and astrophysical research.

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