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**EVENT SEARCHING ALGORITHMS
IN MESOPTICAL FOURIER TRANSFORM
MICROSCOPE
FOR NUCLEAR RESEARCH EMULSION**

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1. INTRODUCTION

Design and principle of the Mesooptical Fourier Transform Microscope (MFTM) for nuclear research emulsion are given in /1/. Modelling experiments and computer calculations which support additionally the real efficiency of the MFTM and its advantages over a traditional optical microscope are described in /1-4/. These investigations have been used in /5/ to construct an experimental prototype of the MFTM. It contains an optical part, a photoelectric device to pick up the optical information, motor-driven carriages for moving the nuclear emulsion layer and a reading system for position indication of this layer. The results of the first investigations with some test-objects and the metrical properties of this MFTM prototype are presented in /6/. The detailed analysis of the optical part and the general theory of the MFTM are given in /7/. The microstructure of the optical signals at the exit of the MFTM has also been treated. Some experiments to improve metrical properties of the MFTM and to observe particle tracks in a real nuclear emulsion are described in /7/. The electronic part of the MFTM, its working control and algorithms for reading out the output information are also mentioned in /7/.

The MFTM is an example of a device containing a mesooptical element. The term "mesooptics" which has been introduced in /8/ covers the class of optical imaging systems by means of which we can transform a given object into the image of higher space dimensionality. The review of possible applications of mesooptical devices in various experiments of high energy physics and the principle of event searching algorithms in the MFTM were presented in /9/. The concentration of geometrical information about straight line particle tracks in small light spots at the exit of the MFTM is a new feature which opens new scopes for increasing the speed of nuclear emulsion searching and for finding the nuclear interaction ("event"). If the particle tracks are issued from a common centre (apex) the output signals of the MFTM are lying on the sinogram. When this apex is beyond the MFTM field of view the corresponding output signals are lying approximately on a

straight line. In ^{/8/} it has been noted that the depth of focus problem inherent to all traditional optical microscope is solved completely in the MFTM.

In this paper we give a detailed description of the relationship between the spatial position of the straight line particle tracks in the nuclear emulsion and the output signals of the MFTM as well as of the event searching algorithm based on the output signals of the MFTM.

2. THE RELATIONSHIP BETWEEN THE PARTICLE TRACK POSITION AND THE OUTPUT SIGNALS OF THE MFTM

Figure 1 shows the optical scheme of the MFTM. As has been explained in ^{/1-7/} a straight line particle track that is inside the field of view of the MFTM is transformed into two light spots which are in the output plane of the MFTM and on the line perpendicular to the direction of the particle track. These two light spots are the output signals of the particle track in the MFTM. The position of these output signals does contain the full geometrical information on the straight line particle track segment. The locus of all output signals forms a ring of width DM and of average radius R , where D is the diameter of the field of view of the MFTM, M is the linear magnification of the MFTM, and R is the radius of the focal circle, i.e. the circle determined by the meso-optical image of a pinhole placed in the optical axis of the MFTM in the median plane of nuclear emulsion layer (the plane $z = 0$).

To find the relationship between the particle track position and the MFTM output signals we introduce the coordinate systems shown in Fig.2. In accordance with ^{/7/} we use the cartesian coordinate systems for input (x_1, y_1) and

output (x_3, y_3) planes perpendicular to the optical axis of the MFTM and with the axis Ox_1 and Ox_3 mutually parallel and of the same direction. Let us introduce a polar coordinate system (r, ϕ) for the input plane (Fig.2a):

$$r = \sqrt{x_1^2 + y_1^2}, \quad (1)$$

$$\phi = \text{arctg}(y_1/x_1).$$

The focal ring and two output signals corresponding to the particle track shown in Fig.2a are given in Fig.2b. Let us introduce the eigencoordinate system for two half planes $y_3 > 0$ and $y_3 < 0$ and the notations

$$\rho_1 = \Delta R_1/M, \quad \rho_2 = \Delta R_2/M, \quad (2)$$

where ΔR_1 and ΔR_2 are positive if the output signals are outside the central focal circle.

The cross section of the MFTM is given in Fig.3 where nine particle tracks directed perpendicular to the plane of figure are shown. In our design of the MFTM the photoelectric

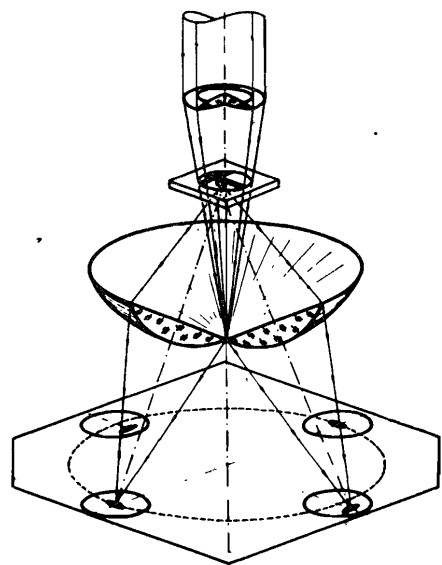


Fig.1. The principal optical scheme of the MFTM with a meso-optical lens.

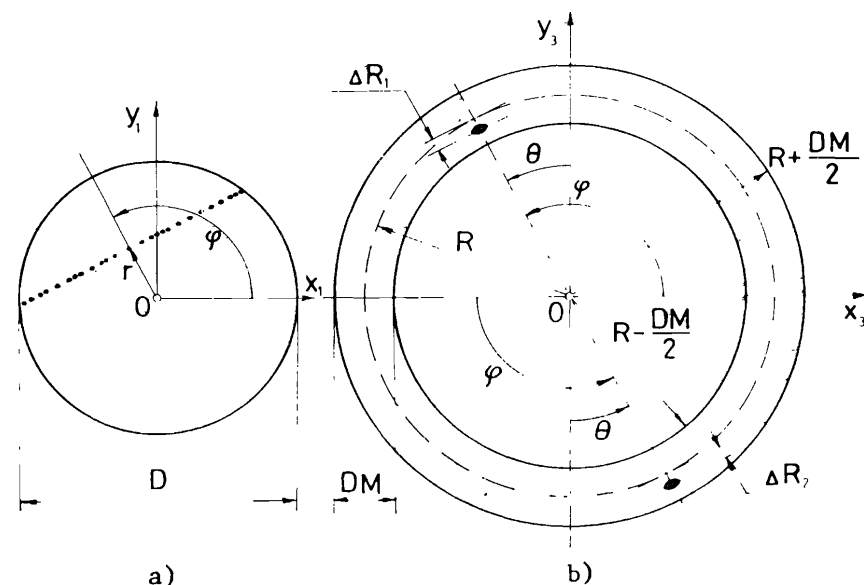


Fig.2. The coordinate systems for input and output planes of the MFTM.

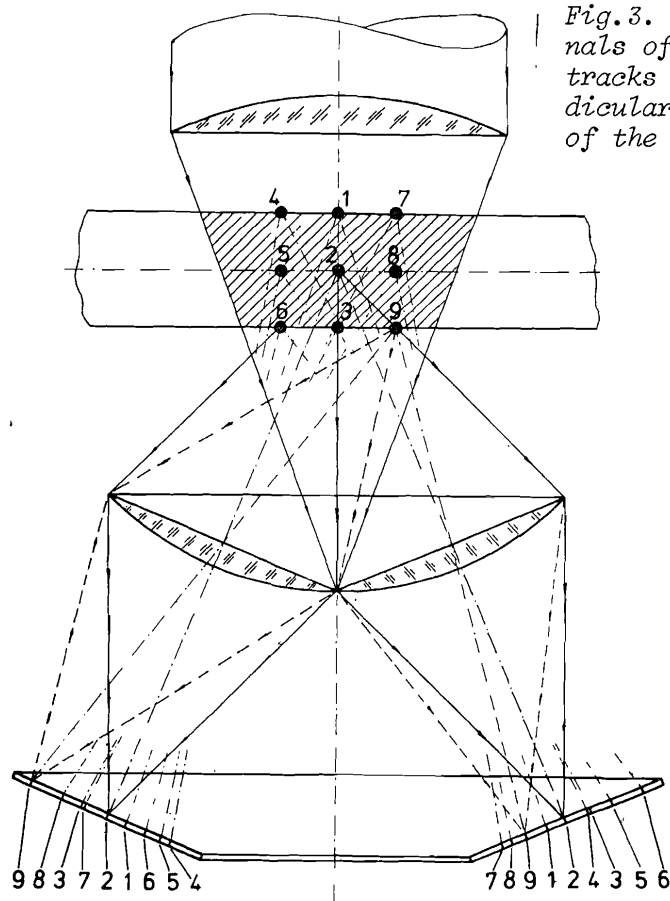


Fig.3. The output signals of nine particle tracks directed perpendicularly to the plane of the figure.

pick-up device is positioned perpendicularly to the light fallen on it, therefore the output ring forms a truncated cone.

In the meridional cross section the MFTM can be considered as a double Fourier diffraction optical imaging system with a total angular aperture $2\alpha_{1/2}$. Let the z -axis be directed down along the principal optical axis of the MFTM and the median plane of the nuclear emulsion layer chosen as the $z = 0$ plane. The centres of the output signals corresponding to the particle tracks from "1" to "9" are also shown in Fig.3.

The particle track "2" is in the plane $z = 0$ and intersects the centre of the field of view at $r = 0$. The output signals of the particle track "2" are on the circle of radius R at $\rho_1 = \rho_2 = 0$. As is seen from Fig.3 the vertical or/and horizontal displacement of the particle tracks cause proper dis-

placements of the corresponding pair of output signals over the pick-up planes on both sides from the principal optical axis of the MFTM. In the course of rays tracing we must take into account the refraction of light rays issued from the nuclear emulsion layer. These effects, however, have been neglected in this paper as they can be ruled out or considerably diminished with the help of a large immersion bath with spherical surface put under the emulsion layer.

The relations between the input coordinate system (r, ϕ, z) and the output coordinate system (ρ_1, ρ_2, θ) can be constructed from simple geometrical considerations:

$$\left. \begin{aligned} \rho_1 &= z \sin \alpha_{1/2} - r \operatorname{sgn}(\pi - \phi) \cdot \cos \alpha_{1/2}, \\ \rho_2 &= z \sin \alpha_{1/2} + r \operatorname{sgn}(\pi - \phi) \cdot \cos \alpha_{1/2}, \end{aligned} \right\} \quad (3)$$

$$\theta = \begin{cases} \phi - \pi/2, & \phi < \pi, \\ \phi + \pi/2, & \phi > \pi, \end{cases} \quad -\pi/2 < \theta < \pi/2.$$

and

$$\left. \begin{aligned} r &= \frac{|\rho_2 - \rho_1|}{2 \cos \alpha_{1/2}}, \\ z &= \frac{\rho_1 + \rho_2}{2 \sin \alpha_{1/2}}, \end{aligned} \right\} \quad (4)$$

$$\phi = \begin{cases} \theta + \pi/2, & \rho_1 < \rho_2, \\ \theta - \pi/2, & \rho_1 > \rho_2, \end{cases} \quad 0 < \phi < 2\pi,$$

where $\operatorname{sgn}(x)$ is a sign function which appears in Eqs.(3) and (4) due to the fact that for $\phi > \pi$ the horizontal displacement in the cross section is of negative sign. The quantities $\theta, \Delta R_1$ and ΔR_2 are measured directly in the MFTM. The total data about the spatial position of the particle track can be deduced from these quantities with the help of Eqs.(3) and (4). The deep angle of the particle track can be estimated from two or more values of z -coordinates of the same particle track in the adjacent fields of view. The particle tracks with a very high angle ($> 60^\circ$) cannot be seen at all in the MFTM.

In the case when two or more particle tracks are mutually parallel a trivial ambiguity can arise. To separate actual and wrong particle tracks in the course of reconstruction we have to use some additional information and to accomplish corresponding signal processing. However, because of high angular resolution of the MFTM the probability of such cases is extremely low. As in our design of the MFTM $\alpha_{1/2} \approx 15^\circ$, the depth resolution is about four times worse than the horizontal resolution (Fig.3). Here we would like to stress that due to the fundamental feature of the MFTM the z-coordinate of the particle track is evaluated directly without any mechanical displacement in depth as it is the case in the traditional optical microscope.

3. AN EVENT SEARCHING ALGORITHM USING MFTM OUTPUT SIGNALS

As has been shown in §2, the spatial position of the particle track can be reconstructed directly from MFTM output signals. But this information is a primary one and the process of the spatial reconstruction can be omitted. The reason for this is that the main purpose of the MFTM consists in searching for nuclear interactions ("events") of several particle tracks issued from the common vertex. As will be proved later, the coordinates of this vertex can be found directly from the output signals without any reconstruction in 3 D-space of all particle tracks belonging or not belonging to the corresponding event. To explain this significant property of the MFTM let us introduce the coordinate system (θ, ρ) shown in Fig.4. The format (θ, ρ) is used for displaying the output signals of the MFTM for nuclear emulsion, where

$$\rho = \frac{\rho_2 - \rho_1}{2 \cos \alpha_{1/2}} = r \operatorname{sgn}(\rho_2 - \rho_1). \quad (5)$$

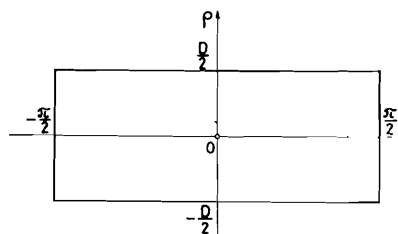


Fig.4. The cartesian coordinate system (θ, ρ) used for displaying the output signals of MFTM.

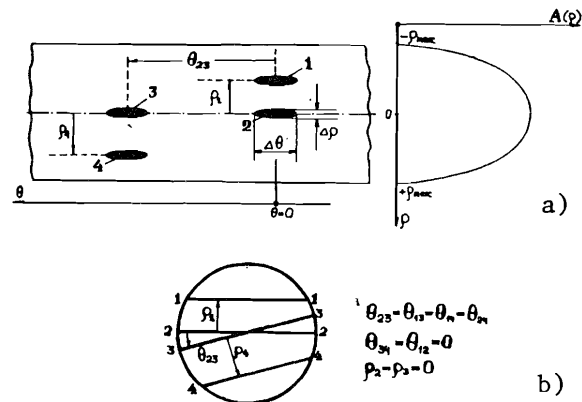


Fig.5. a) The output signals of the MFTM in the format (θ, ρ) corresponding to four particle tracks shown in b).

The (θ, ρ) coordinate system contains full information about the projection of the particle tracks onto plane $z = 0$ within the field of view of the MFTM.

The topological property for particle tracks issued from one vertex is conserved for any projection of this event. The vertex of the event found for two different projections can be considered as a real candidate of the event in 3D-space.

To illustrate more deeply this conclusion let us consider some examples of the events and their output signal configuration in the format (θ, ρ) . One of such output signal configurations for four particle tracks is shown in Fig.5a. The particle tracks "1" - "2" are seen on the traditional image in Fig.5b as mutually parallel and therefore their output signals have the same orientation angle θ . The radial coordinates of particles "2" and "3" are equal to zero as these particle tracks cross the centre of the field of view. The resolutions in θ - and ρ -coordinates are equal to $\Delta\theta$ and $\Delta\rho$ respectively.

A more lucid explanation of this property of the MFTM output signals can be attained by considering four configurations of particle tracks in the field of view which are shown in Fig.6. The first (upper) configuration contains three particle tracks which can be considered as primary beam particle tracks. The output signals have the same angular coordinates, but different radial coordinates. The second configuration contains four particle tracks, three of which are mutually parallel. The corresponding output signals in the MFTM are at the same angular orientation one over others. On the third configuration we can see an event. The primary particle track "1" interacts in nuclear emulsion with emission of two secondary particles. This event is a "falk". The third configuration goes into the fourth one after horizontal displacement of the field of view to a new position with new coordinates ρ in format (θ, ρ) .

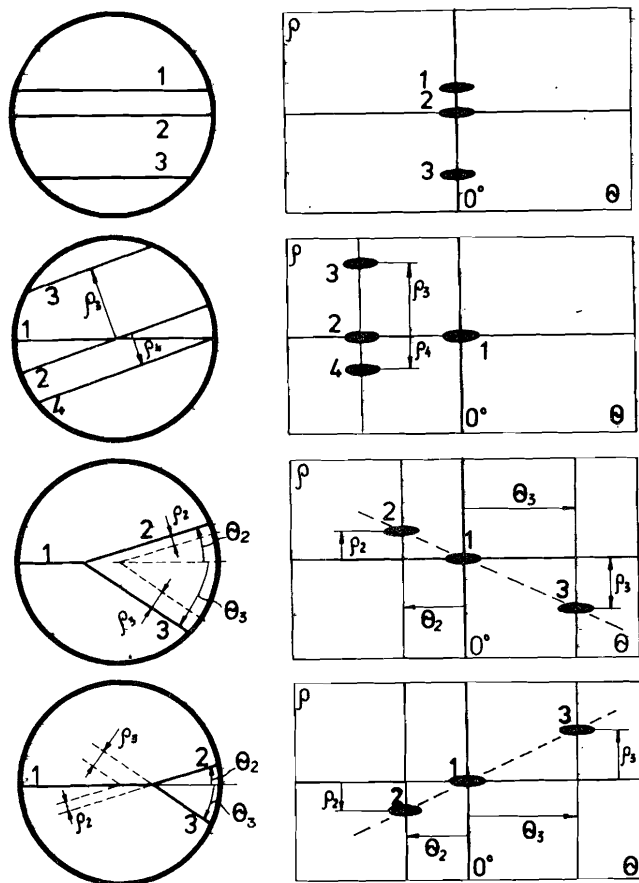


Fig. 6. Four typical configurations of particle tracks (left) and its output signals in the format (θ, ρ) (right).

It is easy to prove that the output signals of particle tracks forming an event are lying on the sinogram - the curve in the form of sinusoid. This conclusion is valid also for the case when the vertex is out of the field of view or beyond the nuclear emulsion layer. Let us consider the input plane with cartesian coordinates (x_1, y_1) or polar coordinates (r, ϕ) (Fig. 7). Let the vertex coordinates be (x_0, y_0) or (r_0, ϕ_0) . The fan of straight lines which pass through the vertex (x_0, y_0) can be described by the equation

$$x_0 \cos \phi + y_0 \sin \phi - r = 0 \quad (6)$$

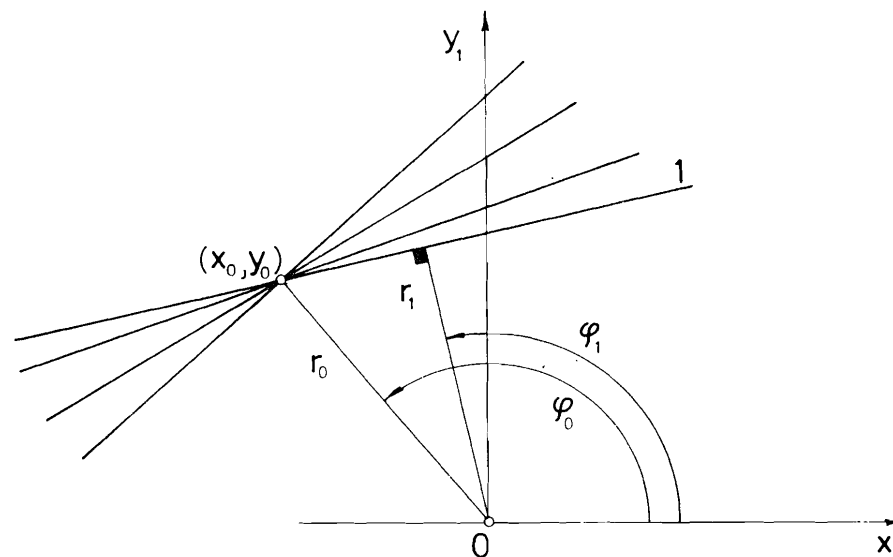


Fig. 7. The fan of straight lines in the coordinate system (x_1, y_1) or (r, ϕ) .

or in another form as

$$r = r_0 \cos(\phi_0 - \phi), \quad (7)$$

$$0 \leq r_0 \leq \infty, \quad -\pi/2 \leq \phi_0 - \phi \leq \pi/2.$$

In the format (θ, ρ) the equivalent equation takes the form

$$\rho = \rho_0 \cos(\theta_0 - \theta), \quad (8)$$

$$-\infty \leq \rho_0 \leq \infty, \quad 0 \leq \theta_0 \leq \pi,$$

where (θ_0, ρ_0) are the coordinates of the point common for all straight lines of the fan in the format (θ, ρ) .

In some experimental conditions the secondary particle tracks fill up only a part of the whole angular interval of θ and concentrated in a small angular interval around the angle $\theta = 0$. Due to this the distance between the vertex and the centre of the field of view can be large in comparison with the diameter of the field of view. In this case Eq. (8) goes into a simpler one.

Let the event contain n particle tracks with scattering angles δ_i , $i = 1, 2, \dots, n$ and with a mean value $\bar{\theta}$. Then we have

$$\rho_1 = \rho_0 \cos[\theta_0 - (\bar{\theta} - \delta_1)] =$$

$$= \rho_0 [\cos(\theta_0 - \bar{\theta}) \cos \delta_1 + \sin(\theta_0 - \bar{\theta}) \sin \delta_1].$$

If the condition

$$\max\{\delta_i\} < \Delta\theta \cdot 3 \quad (10)$$

is fulfilled, where $\Delta\theta$ is the angular resolution of the MFTM, then we have

$$\rho_1 \approx \rho_0 \cos(\theta_0 - \bar{\theta}) + \rho_0 \sin(\theta_0 - \bar{\theta}) \cdot \delta_1. \quad (11)$$

From Eq.(11) we can see that the output signals of the particle tracks issued from the vertex at small angles are lying on the straight line. For $\Delta\theta = 5' / 7'$ the Eq.(11) will be correct for angular cone of particle tracks of the order of 20° .

To illustrate Eqs.(8) and (11) just obtained let us consider four events presented in Fig.8. The first (upper) example consists of seven straight line particle tracks.

Only six of them come from common vertex lying beyond the field of view. The seventh particle track is not connected with the event. All these features are easily recognized on the (θ, ρ) -plot. The signals of the particle tracks which form the event are lying on the straight line. In the second example the vertex is near the centre of the field

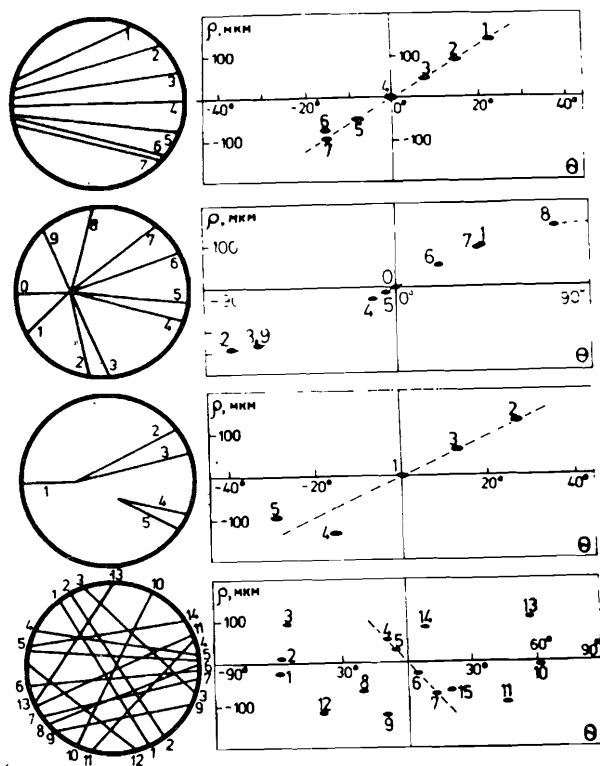


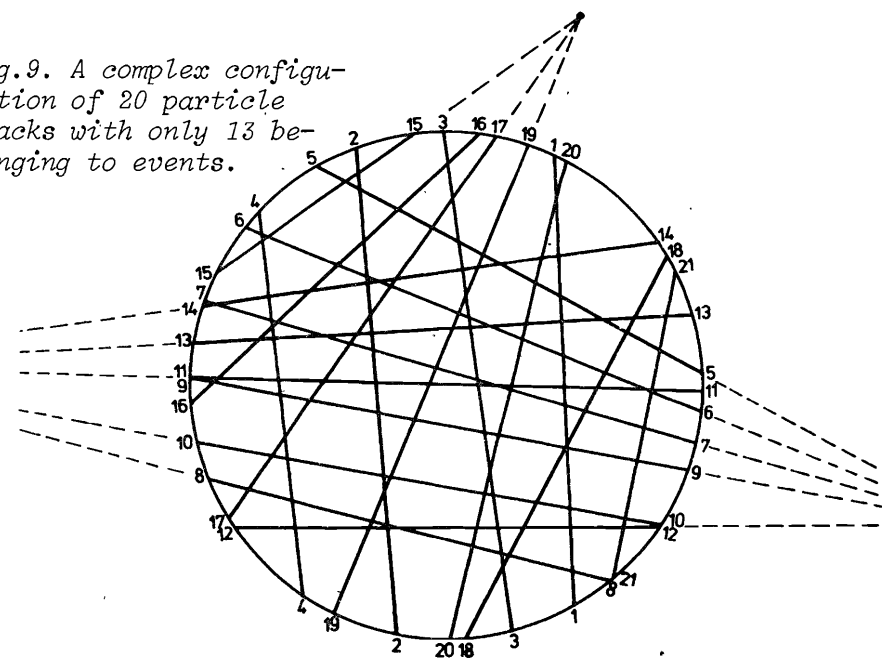
Fig.8. Four typical events observed in nuclear research emulsion (left) and corresponding sinograms (right).

of view. The output signals of nine secondary particle tracks and of the primary particle track are lying on the sinogram. The third example is a more complex one. Two events are coupled by the neutral particle. The output signals of the particle tracks of the event are lying approximately on the straight line because of their small scattering angles. Two particle tracks coming from the decay of the neutral particle are disposed out of this straight line. The last example demonstrates the very high noise immunity of the MFTM. The event of particle tracks "4", "5", "6", "7" can be found in the background of fifteen particle tracks. A much more complex configuration of 20 particle tracks is presented in Fig.9. Only 13 particle tracks among 20 are forming three events. The output signals for this example are shown in Fig.10.

By using this property of the output signals and taking into account for the particular features of nuclear interactions we can construct both software and hardware for solving the inverse problem: to find the event and to determine the vertex coordinates (θ_0, ρ_0) from the set of output signals. In the case of small scattering angles we can use the angular scanning algorithm with eigenfunctions of angular scanning^{/10/}.

Output signals displayed in the format (θ, ρ) correspond to one projection of the event on the plane $z = 0$. Therefore the vertex coordinates thus found must be considered only as

Fig.9. A complex configuration of 20 particle tracks with only 13 belonging to events.



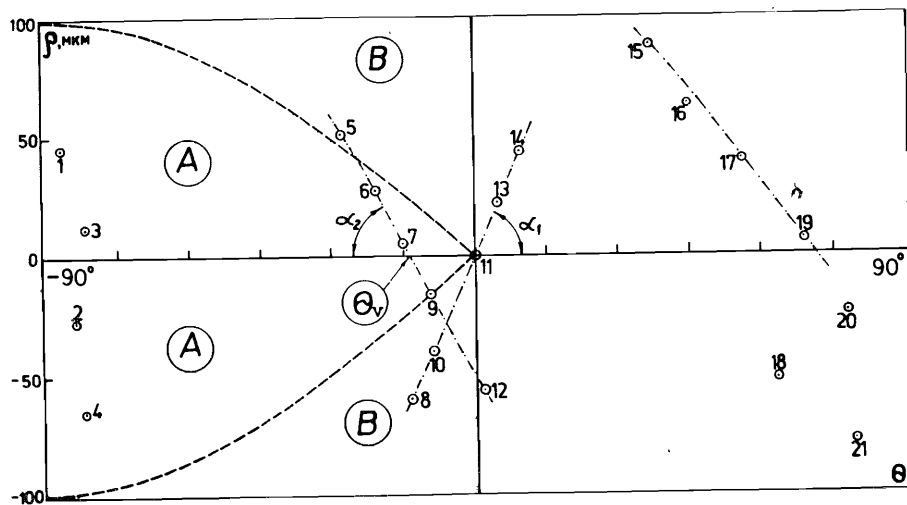


Fig.10. The output signals of 20 particle tracks shown in Fig.9 in the format (θ, ρ) .

a candidate of the event. To get more additional information about this event we must change the direction of projection line and thus to use the Steree-MFTM with two aspects.

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Алгоритм поиска событий в мезооптическом
фурье-микроскопе для ядерной фотоэмульсии

Рассмотрена связь между расположением в пространстве прямых следов частиц в ядерной фотоэмульсии и выходными сигналами мезооптического фурье-микроскопа /МФМ/. Показано, что эти выходные сигналы содержат информацию о z-координате следа частицы. Описаны алгоритмы поиска событий по выходным сигналам МФМ.

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Event Searching Algorithms in Mesooptical
Fourier Transform Microscope for Nuclear
Research Emulsion

The relationship between the spatial position of the straight line particle tracks in the nuclear research emulsion and the output signals of the Mesooptical Fourier Transform Microscope (MFTM) is treated. It is shown that these output signals do contain the information about z-coordinate of the particle track. Event searching algorithms based on the output signals of the MFTM are described.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Communication of the Joint Institute for Nuclear Research, Dubna 1987.