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DIGITAL PROCESSING OF PHOTOS FROM A 4π TRACK DETECTOR

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A measuring complex with a digital data bank of stereo photos of photonuclear reactions on ^{4}He, ^{12}C, ^{14}N, and ^{16}O nuclei got from a 4π track detector has been created. The file name was formatted into a certain type of record, which included information about the experiment and the position in the data bank. A graphical application was presented that allowed semi-automatic determination of points along tracks of different lengths and curvatures. Methods and algorithms allowing to transfer into the camera system and perform event reconstruction were developed. Additional programs for the physical analysis of the reconstructed events and the graphical representation of the obtained results were created.

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INTRODUCTION

Till now, significant progress has been achieved in experiments on the study of photonuclear reactions on light nuclei [1, 2]. The main results have been obtained using 4π track detectors, in which the observed tracks corresponding to the trajectory of particle moving have been recorded. In most detectors, the tracking system is placed in a magnetic field; that leads to bending the trajectories of charged particles and makes it possible to determine their momentum and charge sign. Significant advantages of track detectors are the simplicity of their design and the possibility of measuring the kinematic parameters of particles in a wide range of energies and angles. This allows, when comparing the predictions of different models of the photon–nucleus interaction, to give preference to one of them.

At the same time, the facilities that must be used to extract information from track detectors are also of great importance. Therefore, simultaneously with the development of the technique of track detectors, methods for automating measurements have been also developed. In recent years, there is progress in the creation of precision measuring equipment with digital registration methods [3–5], as well as the use of the computational capabilities of modern computers. The creation of such automated systems is of great importance since it provides high-quality experimental data and significantly extends the sphere of problems for which solving this experimental technique can be effectively used.

The study of photonuclear reactions on the nuclei of s- and p-shells using a track detector (diffusion chamber placed in a magnetic field) was intensively carried out at the NSC KIPT [6–8]. The chamber was filled with saturated gas (helium or a mixture of helium and methane (nitrogen, oxygen)). In the experiment, during sessions of irradiating the camera with bremsstrahlung photons, the working area of the camera was photographed with two 2-lens cameras. A large amount of information about multiparticle photoreactions was accumulated. Obtaining physical information was carried out in several independent stages using special technical devices – a stereo magnifier and semiautomatic devices of the PUOS type. Unique software was used to reconstruct the events. However, the processing technique had been put into working condition for a long time [9, 10], and the question of its modernization, renewal or radical change arose.

The information obtained during the registration of photonuclear reactions was stored on photographic films, and this allowed the development of a procedure of digitizing the existing archive of stereo frames with subsequent digital data processing. The use of modern computer technologies permitted to improve the accuracy in determining the kinematic parameters of particles and significantly speed up the procedure of physical data accessing. It should be noted that, most often, image processing is interpreted as a technique for improving the quality and recovering lost or corrupted data for visual viewing [11, 12]. But we presented algorithms for mathematical processing of objects in a digital image with further visualization of the results.

The purpose of this work was to create a modern efficient measuring complex for accessing data about the events of photonuclear reactions. For this, it was necessary to perform a number of tasks aimed at creating a digital method for reconstructing tracks:

- ✓ realization of the transition from highly specialized measuring instruments to a PC with minimization of the operator's work;
- ✓ development of algorithms for digital measurement of points along the tracks, that accelerated the procedure for collecting physical information, as well as processing the results obtained;
- ✓ creation of universal software that can be installed on any PC; that permitted, if necessary, to use several workstations for measuring events.

1. CREATION OF A DIGITAL BANK OF STEREO PHOTOS

For now, a digital bank of stereo photographs of photonuclear reactions was created by digitizing photographic films. Digital data were obtained with a G429 slide scanner for 35 mm film with a resolution of ~17 Megapixels. For working with the digitized images, a computer code was worked out. A scheme was developed for filling the bank of data and their primary processing (as a rule, the result of scanning was a set of files with *.jpg extension). A structure for storing images in the form of a hierarchy of directories, subdirectories, and files was created. For files corresponding to a photo frame, the format of name recording was adopted. It included the necessary information about the belonging of this file to a specific experimental session.

A typical sample is shown in Fig. 1. The text in the line is the file name. So, for example, the first line corresponds to a file named Npl001app1k001l, containing the following information: N is nitrogen (target nucleus), pl001 is the film number corresponding to a certain target density and gas mixture concentration, app1 is the stereo camera number, k001 is the frame number on film and l – left stereo pair. 4 directories corresponding to the four target nuclei – ^{4}He, ^{12}C, ^{14}N и ^{16}O – have been created. In total, there are about one million stereo images in the data bank.

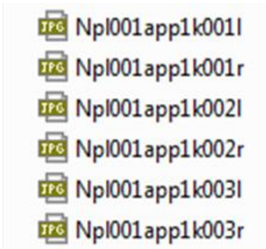

Fig. 1. Typical file names in the digital bank of data

Image processing methods involve working with raster images, the smallest unit of resolution of which is a pixel, that is characterized by the intensity or depth of color. Track camera images are grayscaled, i.e. the distribution of pixel intensity refers to gray color gradation. That is, a pixel can have some tint of gray (from 0 to 255). In our case, after scanning, the frame has a black and white image with a resolution of 5040×3360 pixels. In a computer, a digital image is stored only as a two-dimensional array of numbers in one format or another. As a matter of fact, a two-dimensional image is a visible field, which is a certain distribution function of intensity or color on a plane. From a mathematical point of view, it is a two-dimensional matrix $f[x, y]$, where x and y are an integer describing the number of the column or row of the matrix in which the given element is located. Each element of a digital image (a cell of a rectangular matrix) has an integer value proportional to the intensity $I[x, y]$ at a given point in the plane. The intensity range is from 0 (black) to 255 (white).

For processing digitized images, a graphical application has been created that allows obtaining physical information directly on a computer without using any additional measuring devices. It was written in Python [13] on the platform of the Tkinter graphics library, using complementary modules PIL, SciPY, and NumPy. PIL (Python Imaging Library) is a multifunctional library of image processing that allows one to perform the necessary manipulations with an image as well as accessing to each individual pixel. SciPy is an open-source library of high-quality scientific tools, including signal processing, statistics, and many other data analysis tools. NumPy is a library for working with large-scale arrays, which has a large set of high-level mathematical functions for operations with these arrays.

The created application has an optional cycle of interaction generated by user actions such as key-in, keystroke, or cursor moving. For each potential event, a function is assigned corresponding to a specific graphical component (widget) that can be placed on the application canvas. The top panel contains a number of widgets that allow the operator to enter the necessary service information, and the bottom panel contains widgets that allow the operator to control the measurement process. When certain parameters are selected, the images of both stereo pairs are automatically loaded in sequential mode. On the screen is the visible part of the image, and scroll bars allow one to move around the entire image. The top panel of the application displays current information about the file that is loaded for processing.

2. LOCALIZATION OF THE STUDY AREA. REPER CROSS

The working volume of the track detector was photographed by two (1st and 2nd) two-objective (left (l) and right (r) objective) cameras located parallel to each other. On the glass plates, to which the photographic film was pressed when photographing, reference crosses were applied. The distance between the crosses located on the line perpendicular to the beam was 120 mm, and between the crosses along the beam was 100 mm. The presence of the crosses permitted to set the image in the position that it had when photographing, as well as to control the quality of measurements and take into account film shrinkage.

The coordinates of the lines forming the crosses were measured on the frame at first. The obtained information was used to determine the starting point of the coordinate system on the frame during event reconstruction, the image rotation angle, and to estimate the measurement accuracy.

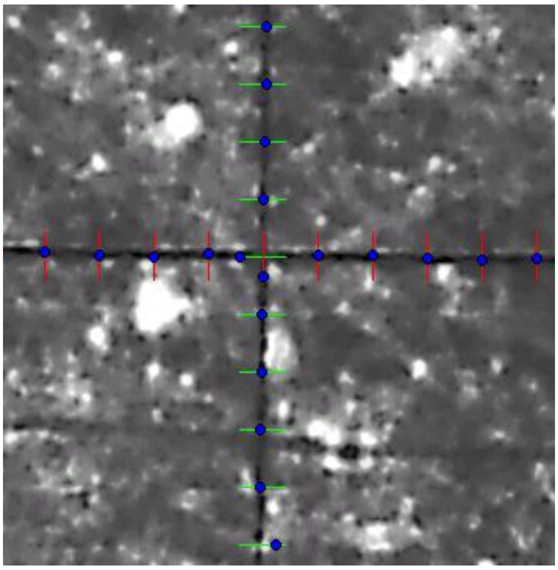

Fig. 2. Reference cross on the frame

The reference crosses were located in a strictly defined area of the photo. This made it possible to develop a method for automatically determining their coordinates, which significantly speeded up obtaining the information about the event compared to the methods using semi-automatic devices such as PUOS, where the coordinates of the crosses were measured manually.

For each stereo pair, a zone of crosses' location was determined, and, when loading an image by its name, the corresponding coordinates were automatically used. For each stereo pair of the corresponding camera, the position of the crosshairs of the reference crosses could be automatically determined. As seen in Fig. 2, the reference cross looks as dark lines on a gray background. Obviously, the row or column along which the pixels corresponding to the reference cross were located had a lower intensity compared to other rows and columns.

The average intensity of the entire row or column was defined as $I^{aver} = \frac{\sum_{i=1}^{n} I_i}{n}$, where n was the number of pixels, and I_i was the intensity of the i-th pixel.

On Fig. 3, the distribution of I^{aver} depending on the row number was shown as the solid line, and I^{aver} depending on the column number is shown as the dotted line. For ease of viewing, graph scales are given with the origin of coordinates at the beginning of the local area of the cross (0,0). The coordinates of the position of the minima in the distributions correspond to the coordinates of the center of the reference cross. On Fig. 2 this was the point that corresponds to the coordinates (3122,1764). At the same time, the coordinates of the crosshair found "manually" were (3121,1765), in good agreement with the automatic determination.

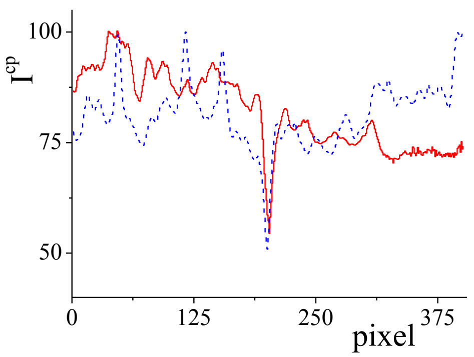

Fig. 3. Average intensity distribution for rows and columns in the area of the reference cross

To check the quality of the automatic measurements of the crosshairs, the positions of the reference crosses were measured for different films, frames, and stereo pairs. It was established that almost always the coordinates of the crosshairs (x_0, y_0) were automatically determined correctly. A slight deviation from the data received by the operator was due to the quality of the films (dirt, noise, background objects). To avoid frame losses due to their poor quality, the manual measurement of the coordinates of the reference cross was enabled (separate widget).

To put each frame in the position it had when photographing, one needs to measure the rotation angle of the entire digital matrix of this image. For this, the coordinates of the vertical and horizontal lines forming the cross were found in automatic mode. For example, for a horizontal line, the following algorithm was performed: moving along the line along the OX axis with a step δx and a fixed y_0, the coordinates of the points at the ends of the steps were determined. For each point on a vertical line with the same length of 15 pixels, a segment was taken on both sides of y_0 (in Fig. 3, solid lines are for horizontal points, dot lines are for vertical ones). On each segment, the point with the minimum value of intensity was found. The obtained set of points was fitted by a function like $y = a_y * x + b_y$. A similar procedure was performed along the OY axis for a line with a fixed x_0. The points were fitted with a function like $x = a_x * y + b_x$. The coefficients a_x and a_y were considered to be the rotation angles of the image. The lines of reference crosses are mutually perpendicular plotted on a glass plate with high accuracy. Therefore, the coefficients a_x and a_y must be equal within the measurement errors. For example, for Fig. 2 $a_x = -0.01131 \pm 0.00045$ and $a_y = 0.01185 \pm 0.00051$. The difference in the absolute values of the coefficients indicated the quality of the reconstruction of the reference cross. The angle of rotation was determined as the average of the absolute values of a_x and a_y.

Thus, an algorithm was developed and a program was created to automatically find the crosshairs (x_0, y_0) of the reference cross on the image and determine the rotation angle. These options allow us to set the image to the position that it had when photographing.

3. DETERMINATION OF PARTICLE TRACKS

When determining the coordinates of points along the track, a number of difficulties arise in comparison with the determination of the lines of the reference cross. The working volume of the diffusion chamber was filled with a gas mixture, that was both a target and a detection system. Even when using a hardener, there were many secondary electrons in the chamber, that created a significant background. Also, in the registration area, there could be several tracks simultaneously, which could intersect (Fig. 4). The chamber was in a magnetic field, and the tracks had a curvature whose radius depended on the charge and energy of the particle. Since the particles had only a positive charge in this experiment, the tracks were located on one side of the line connecting the beginning and end of the track.

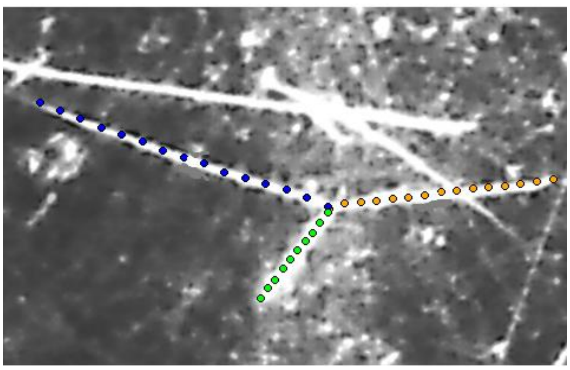

Fig. 4. Distribution of points along the tracks

In the developed application, a variant of the method of semi-automatic measurement of track coordinates was realized, which is schematically shown in Fig. 5. On the track image (dotted line), the first and last points of the track were manually plotted. This marked out the digitization area and determined the direction of motion. It is assumed that experimental point 1 coincides with the “first”. A line is drawn between the “first” and “last” points, and with a certain step (determined by the length of the track), an ancillary point 2′ is placed on it.

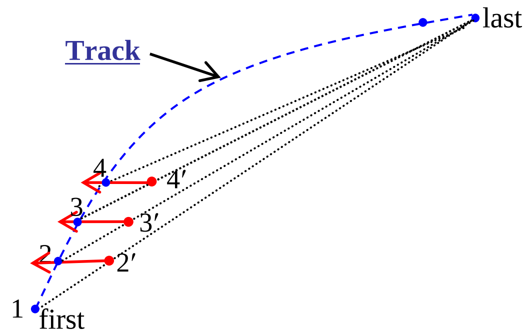

Fig. 5. Scheme of the algorithm for determining points along the track

In the experiment, the origin of the coordinate system was defined in the upper right corner, the *OX* axis was directed along the γ-quantum momentum (from top to bottom along the frame), and the *OY* axis was from left to right. The direction of the magnetic field was perpendicular to the frame (axis *OZ*). Therefore, the track was always on the left side of the line connecting the track end points. The vector was drawn from the ancillary point 2′ towards the track (see the red arrow in Fig. 4). It was considered that the maximum value of intensity among the pixels of this vector corresponded to the track coordinate. By this, experimental point 2 was determined. The new line was drawn between points 2 and “last”, and the next auxiliary point 3′ was placed at some distance. Again, the vector was drawn, and the location of the maximum value of intensity was considered to be the coordinate of point 3. And so on, in a loop, for the selected number of points. The points obtained in this way (2, 3, 4, etc.) satisfactorily described the track trajectory. The result of this algorithm is shown in Fig. 4 for real tracks.

The coordinates of the points along the track were written in a separate file. Sequential reconstruction of the tracks of the same particle on all 4 image projections (1l, 1r, 2l, and 2r) gave the necessary information for a complete geometric reconstruction of the particle trajectory.

4. OBTAINING PHYSICAL INFORMATION ABOUT THE PHOTONUCLEAR REACTION

After measuring the coordinates of points along the tracks and reconstructing the event geometry, a numerical matrix of this event was created with information on the length, direction cosines *l*, *m*, *n* and curvature radius for each track. If the particle did not stop in the working volume of the chamber, the momentum absolute value *P* was determined from the curvature of the track; if it stopped, the particle energy and momentum were determined from the track length using the tabular range-energy dependence. As the verification of the reliability of the information obtained by digital processing, the kinematic parameters of the particles were compared by two methods: using the PUOS and the created digital application. The results are presented in the Table.

Comparison of kinematic parameters

	PUOS				Digital processing			
	l	*m*	*n*	*P*, MeV/c	*l*	*m*	*n*	*P*, MeV/c
proton	0.75	0.03	0.66	164.2	0.76	0.05	0.65	167.6
α-particle	-0.48	-0.84	0.19	100.4	-0.46	-0.87	0.22	104.1

The uncertainties of determination of the momentum and *l*, *m*, *n* were estimated as 4 MeV/c and 0.05, respectively. Within this uncertainty, the results of the two methods agree with each other.

Once the events are identified for a given reaction, a physical analysis is done.

An application for the analysis of the energy and angular dependences for the final particles in photonuclear reactions has been created. For each calculation block on the top panel of the application, a separate widget has been created with links to classes of needed mathematical operations with data.

The Matplotlib library was used as a tool for data visualization with two-dimensional graphics. The created application makes it possible to process data from the event matrix and immediately display the results as tables and graphs.

The application has been written in the framework of object-oriented programming (OOP) that facilitates carrying out a new calculation through varying a number of widget parameters with an immediate presentation of the output data on the graphs. Such applications significantly simplified the procedure of analyzing the physical characteristics of the reaction under study due to the interactive visualization of the obtained dependences.

CONCLUSIONS

An experimental complex for measuring and analyzing photonuclear reactions with a digital data bank of stereo frames of the corresponding reactions obtained from a 4π track detector has been created. A set of graphical applications has been developed permitting to reconstruct events and perform a physical analysis of the obtained data.

For digital processing of events recorded with track chambers, the following procedures were performed:

- a digital bank of photographic film frames was created with formatting a file name into a certain type of record, which includes information about the experiment and the position in the archive;
- an algorithm has been developed for automatic extraction of information about the reference cross on each

projection, and a program implementing this algorithm has been worked out;

- an algorithm has been developed for semi-automatic measurement of coordinates of points along the track;

- the software was created to organize the viewing and measurement of track coordinates.

The modernization of the measurement process has accelerated obtaining track coordinates through shortening manual work and avoiding usage of the outdated equipment and facilitated extracting the kinematic parameters of particles from the obtained digital bank of photo frames.

The measurements of the kinematic parameters of particle tracks were carried out by two methods – using the developed application and with special technical devices such as PUOS. The comparison of the results has shown that within the experimental uncertainty they are in a fair agreement.

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МЕТОДИКА ЦИФРОВОЇ ОБРОБКИ ФОТОКАДРІВ ІЗ ТРЕКОВОГО 4π-ДЕТЕКТОРА

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Створено вимірювальний комплекс із цифровим банком даних стереокадрів фотоядерних реакцій на ядрах ^{4}He, ^{12}C, ^{14}N та ^{16}O, отриманих з трекового 4π-детектора. Виконано форматування імені файлу в певний вид запису, що включає інформацію про експеримент і становище в банку даних. Представлено графічний додаток, що дозволяє в напівавтоматичному режимі визначати точки вздовж різних по довжині та кривизні треків. Розроблено методи та алгоритми, що дозволяють перейти в систему камери та виконати реконструкцію подій. Створено додаткові програми для фізичного аналізу відновлених подій та графічного представлення одержаних результатів.