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Charged particle spectrometer for the investigation of nuclear reactions induced by fast neutrons

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Abstract. A spectrometer for detecting charged particles has been developed, designed for high-precision research in nuclear physics and applied tasks. The instrument is based on a two-section ionization chamber with a Frisch grid, providing high detection efficiency, nearly isotropic solid angle (~4π), and minimal background noise levels, which is critically important for reliable determination of small reaction cross-sections. The relevance of this development is driven by growing interest in studying neutron-induced reactions related to nuclear energy development, radiation protection, and fundamental research into nuclear structure, as well as the lack of modern spectrometers capable of working with both solid and gaseous targets without loss of efficiency. The device is effectively used in systematic studies of charged particle emission reactions induced by fast neutrons on light and medium-mass nuclei. It enables obtaining energy distributions of reaction products, total and differential cross-sections, as well as angular distributions of charged particles. A key advantage of the spectrometer is its ability to work with both solid and gaseous samples, significantly expanding its application scope in scientific research.
Keywords: charged particle spectrometer, fast neutrons, alpha particle spectra, detector, nuclear reactions.

Introduction

Neutron-induced nuclear reactions play a key role in the release of nuclear energy and are described by nuclear data such as total and differential cross sections. Comprehensive, systematic and accurate nuclear data serve as a bridge between fundamental research [1-3] and engineering applications, being of great importance for nuclear engineering, applications of nuclear technologies [4], nuclear astrophysics [5-7] and other fields. In nuclear energy, α-particles from (n,α) reactions, accumulating as helium bubbles, cause damage such as embrittlement and swelling of structural materials [8]. In nuclear astrophysics, (n,α) reaction cross sections are typically used in calculations of element evolution processes in the Universe.

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Previous measurements of these reactions in the MeV-range of neutron energies were performed mainly using activation methods. This method, although simpler in practice, is feasible only in specific cases when residual nuclei produced by charged particle emission are unstable [9-11]. The key research challenges are due to, first, the probability of the studied processes because of small reaction cross sections and limited sample quantity (in the case of isotopically enriched materials), and second, the complex background characteristic of neutron sources in this energy range. As a result, standard detector methods are either inapplicable or do not provide a comprehensive analysis of the processes. Moreover, such measurements do not allow obtaining energy spectra and angular distributions of emitted charged particles.

To expand our research to (n,p) reactions, we have constructed a new double ionization chamber. The new spectrometer can withstand higher working gas pressure, has the capability to study reactions on both solid and gaseous targets, which allows expanding the range of studied nuclei. Furthermore, the volume of the new spectrometer is smaller, and this has reduced the amount of required working gas. The developed detector and measurement methodology, in our view, are optimally suited for investigating (n,α) and (n,p) reactions with neutrons in the MeV range and allow obtaining both energy spectra and angular distributions of reaction products.

The methodology

The detection system was based on a ionization chamber with a common cathode design, offering a large solid angle and high detection efficiency for charged particles, as shown in Fig.1. Adjusting the gas pressure was essential to optimize the stopping of different particles: alpha particles, which have shorter ranges, were best detected at low pressures, while tritons, with longer ranges, required higher pressures. This allows the working gas pressure to be selected and adjusted for each measurement to reduce background reactions. Another big advantage of this detector is its low sensitivity to gamma background.

Figure 1 (a) shows the internal structure of the spectrometer. The detector consists of a cylindrical stainless steel chamber with a diameter of 29.2 cm and a height of 28.2 cm, comprising two parallel sections with a common cathode. The anodes are made of two aluminum plates with a thickness of 0.1-0.2 mm. The detector grids consist of parallel gold-plated tungsten wires with a diameter of 0.1 mm and a pitch of 2 mm, soldered onto rectangular frames made of copper-clad fiberglass laminate. The chamber design allows for adjustable spacing between the grids and electrodes over a wide range.

The external view of the cathode is shown in Figure 1 (b). The cathode, shared by both sections, is equipped with a rotating sample holder disk mounted between two aluminum plates with 48 mm diameter apertures. The design features five positions on the disk, each accommodating two samples in a "back-to-back" configuration, enabling the simultaneous loading of up to ten samples for various purposes: α-sources for energy calibration, test samples, background measurement samples, ^{238}U samples for absolute neutron flux determination, and others. The rotation mechanism allows for sample changes during experiments without opening the chamber, ensuring identical conditions for primary, background, and calibration measurements.

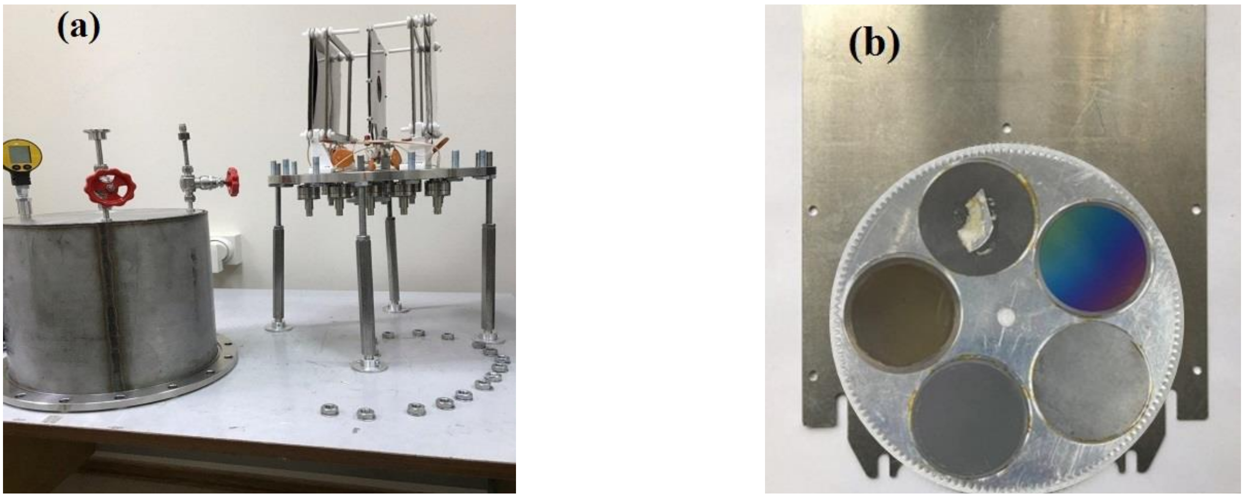

Figure 1. (a) Internal structure of the spectrometer, (b) internal structure of the cathode

Selection of Working Gas

When selecting the composition of the working gas mixture, the following fundamental physical processes affecting the accuracy of measuring energy lost by charged particles in the gas were considered: ion recombination and electron capture by molecules of the primary gas and impurities. Special requirements for the gas mixture are also determined by the operating conditions in a fast neutron field. The considerable cross-sections of (n,p) and (n,α) reactions for the chamber filling gases lead to background nuclear reactions. These reactions occurring with nuclei of the gas mixture components produce additional α-particles, which complicates the extraction of the useful signal from the nuclear reactions under study on the sample.

Noble gases (Ar, Kr, etc.) are typically used as working gases in ionization chambers [12-13]. To improve detector characteristics, mixtures containing small additives of CO_2, methane, and others are employed. However, in our case, methane-containing mixtures are rarely used due to the background caused by recoil protons, despite their high drift velocity. The $Ar+CO_2$ mixture is also not always suitable due to the presence of oxygen in carbon dioxide, which has a large (n,α) reaction cross-section at neutron energies above 3 MeV. Therefore, it is relevant to identify new effective mixture gases that would expand measurement capabilities.

Signal registration and analysis system of the alpha spectrometer

Signals from the alpha spectrometer are first amplified and then digitized using a PIXIE-16 digitizer. The electronics block diagram is shown in Figure 2. Two signals from the anodes and one from the common cathode of the ionization chamber (IC) are fed through charge-sensitive preamplifiers and fast amplifiers to four inputs of the digitizer. A fifth input is used to connect a neutron counter for neutron flux measurements.

The input signals are digitized by a 14-bit 250 MHz ADC (and an 11-bit 200 MHz ADC). Each event can be stored in memory. The PIXIE-16 supports spectroscopy in both independent and coincidence modes for pulses across different input channels.

Signals from the EJ-309 scintillation detector are fed into an 8-channel 12-bit 500 MHz digitizer (CAEN DT5730S), which serves as a neutron flux monitor and enables the separation of neutron and gamma-ray spectra.

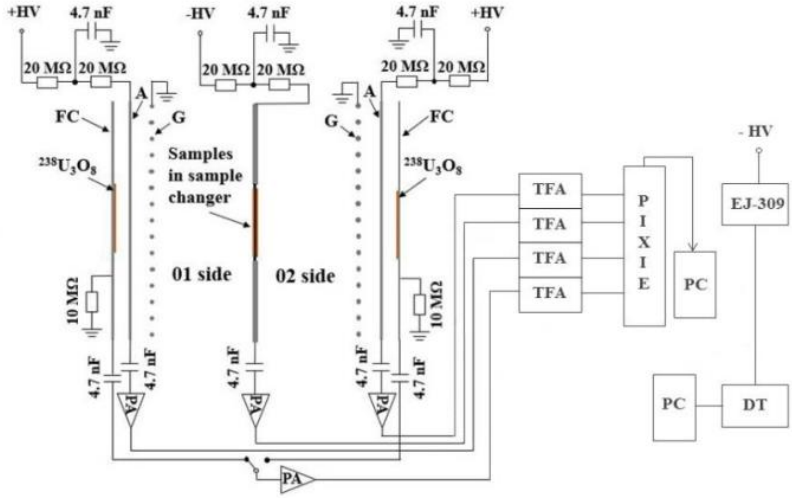

Figure 2. Schematic diagram of α-spectrometer with electronics:
FC – cathode of additional IC section with 238U; PA- charge-sensitive preamplifier;
A, G, C – anode, grid, cathode; CTU – trigger control; SA, TFA – fast amplifiers ORTEC 474;
PIXIE- digitizer PIXIE-16; DT – digitizer CAEN DT5730S; PC- personal computer

Application of α-spectrometer in the study of (n,α) reactions

The experimental setup shown in Figure 3 provided two configuration options: (a) for solid samples [14] (placed on the detector cathode) and (b) for gaseous samples with a collimator installed between the neutron source and the detection system. In measurements on solid samples, the collimator helps reduce background on the detector components, but the neutron flux also decreases due to the geometry. In the case of measurements on gas samples, the collimator helps define the irradiated volume of gas, which subsequently aids in data processing. Neutron flux monitoring was performed by a ^{3}He detector positioned along the beam axis, while system calibration was carried out using a reference ^{238}U target mounted on the rotating cathode disk. Fast quasi-monoenergetic neutrons were produced via the D(d,n) nuclear reaction using a gas target, achieving a neutron flux of approximately 10^5 neutrons per second.

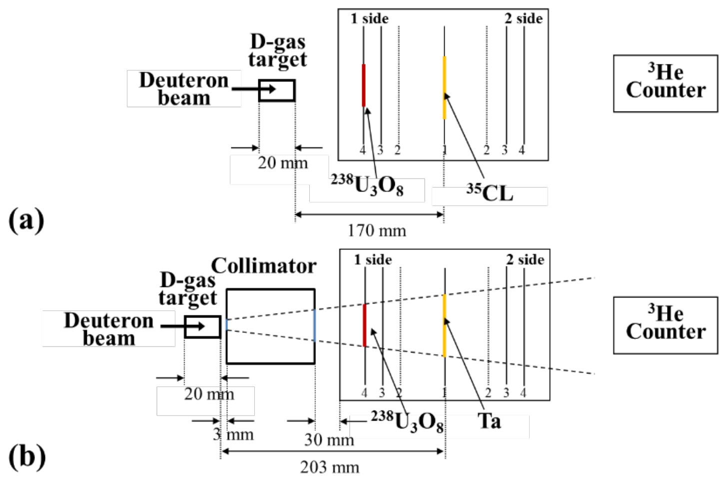

Figure 3. Schematic diagram of the experimental equipment setup, (a) for measurements on solid samples, (b) for measurements on gas samples with a collimator

Discussion

Measurements of (n, α) reaction

As an example, let's consider the study of the $^{35}Cl(n,\alpha)^{32}P$ reaction using neutrons with energy E_n= 5.0 ± 0.26 MeV. Also, studies of (n,α) on various nuclei using this detector are presented in the works [14-17]. The experiments were conducted with a Kr + 5% CH_4 gas mixture at 0.65 atm pressure. The rotating cathode disk contained: a ^{35}Cl target (707 μg/cm^2 thickness, 99.4% enrichment), an α-source for calibration, a tantalum substrate for background measurement, and a reference ^{238}U target (99.999% enrichment) for absolute neutron flux determination. The measurement results and their analysis are presented in Figures 4 and 5, showing α-particle spectra and corresponding distributions.

This methodology provided precise measurements of nuclear reaction parameters at fixed neutron energy with background control and equipment calibration. The rotating cathode with different samples allowed sequential recording of useful signals and background components under identical conditions. The obtained two-dimensional spectra can be used to determine the total cross section of the 35Cl(n,α)32P reaction [14].

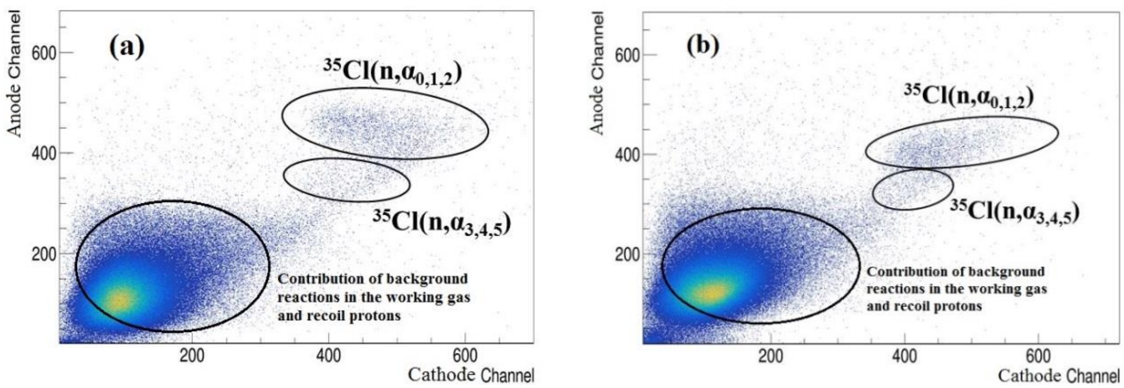

Figure 4. Experimental cathode-anode α-particle spectra from the $^{35}Cl(n,\alpha)^{32}P$ reaction at E_n=5.0 MeV: (a) forward-direction spectrum, (b) backward-direction spectrum. Both spectra include corrections for background reaction contributions

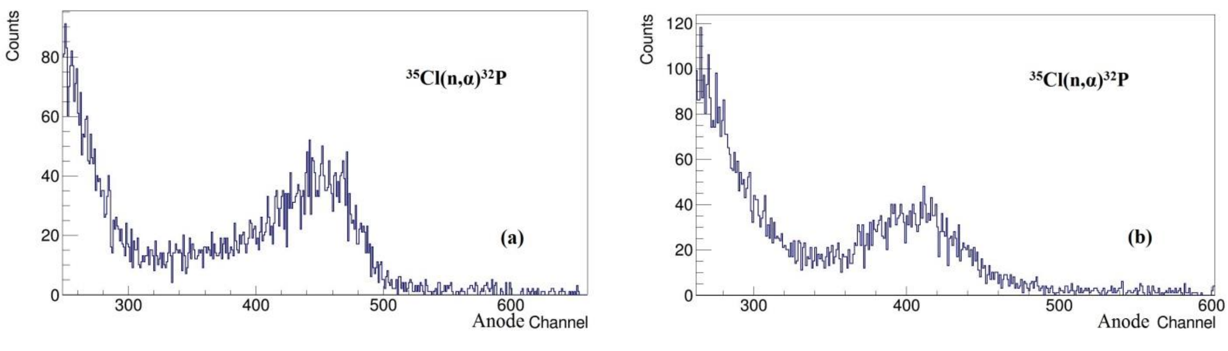

Figure 5. Anodic spectrum of α-particles from the reaction $^{35}Cl(n,\alpha)^{32}P$ at E_n=5.0 MeV, forward direction (a), backward direction (b), with the contribution of background reactions

Fission chamber

A key feature of this spectrometer is its capability for precision measurement of fast neutron flux using an integrated fission chamber. To implement this function, a highly enriched ^{238}U sample (99.999% enrichment) was mounted on the guard electrode of one spectrometer section, while the space between the anode and guard electrode was utilized as the detection chamber. The neutron flux was measured separately for each energy. The combination of the fission chamber and ^{3}He counter provided exceptional measurement reliability and accuracy, which is crucial for precision experiments with fast neutrons. The obtained neutron flux data were subsequently used for cross-section analysis of the studied nuclear reactions [14-17].

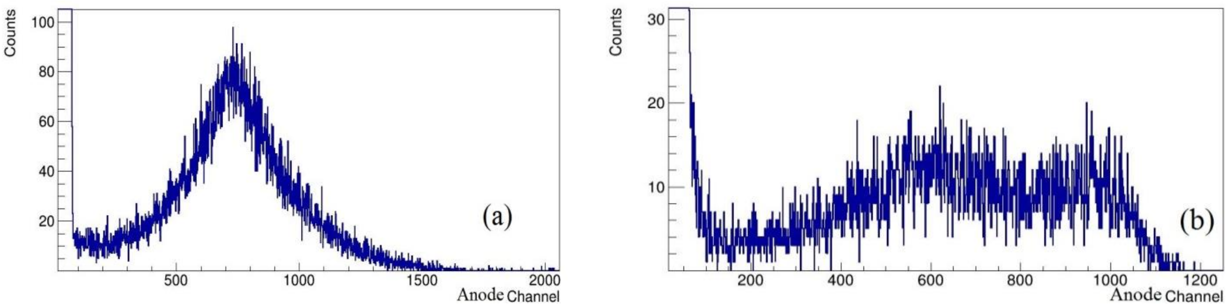

Figure 6. Spectra of fission fragments at E_n=5 MeV. (a) from the fission chamber; (b) from the spectrometer cathode

The uncertainty in the measured cross sections for the (n, α) reaction arises from multiple sources. The most significant contribution stems from the determination of the number of detected alpha particles, tritons. This includes both statistical errors and uncertainties related to background subtraction, as well as event selection criteria such as energy thresholds and valid–event–area cuts.

Table 3. Principal sources of uncertainty and their estimated magnitudes

Source of Uncertainty	Relative Error (%)
$^{238}U(n,f)$ reference cross section	0.7
Determination of number of fission events	3.0
Alpha/triton event statistics	3.0–5.0
Background subtraction and neutron flux normalization	3.0
Atom number of ^{238}U in the $^{238}U_3O_8$ sample	2.0
Atom number of sample	2.0
Total combined uncertainty	7.5–9.8

Measurement of (n,α) reactions on gas samples

In this experiment, instead of a solid target, the working gas mixture Ar+1%CO was used as the target material. For measurements with gas samples, the experimental setup shown in Figure 3 (b) consists of four main components: a neutron source, a steel collimator with an internal copper cone, a spectrometer, and a ^{3}He counter [1]. A steel collimator positioned between the neutron source and the spectrometer serves to collimate the neutron beam and limit the irradiation area of the working gas within the spectrometer. Also, the study of (n,α) on a gas sample using this detector is presented in the paper [18].

The detector's active reaction volume is defined by the collimated neutron beam path, as illustrated in Figure 3 (b). Neutron fluxes were determined using the ^{238}U(n,f) reaction. The (n,α) events were identified through anode spectra measured by the spectrometer. Figure 7 presents both 2D and 1D projections of the obtained spectra. As evident from the figures, the spectrometer and electronics system effectively discriminates background reactions.

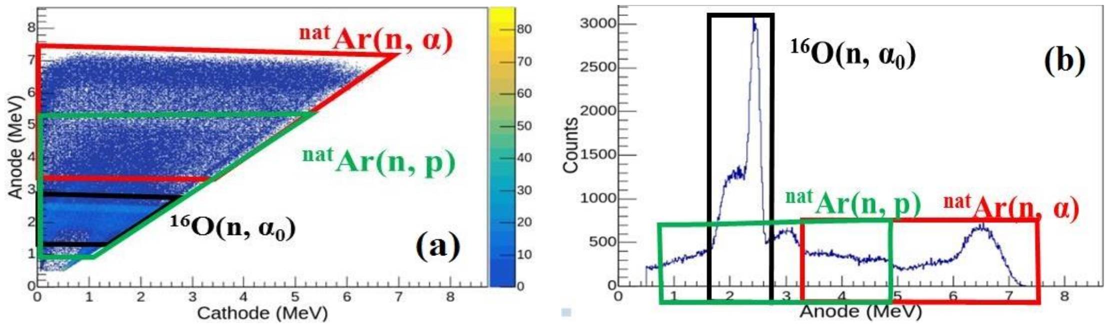

Figure 7. Two-dimensional spectrum of alpha particles (a) at E_n=5 MeV and one-dimensional spectrum (b)

Conclusion

The two-section ionization chamber spectrometer is a modern and highly efficient tool for studying nuclear reactions, particularly (n,α) reactions. An important advantage of this configuration is the ability to quickly change targets without the need to break the vacuum or alter operating parameters. This allows optimal use of beam time and economical consumption of expensive working gases (Kr, Xe, CF_4). Particularly noteworthy is the built-in fission chamber based on highly enriched ^{238}U, which provides precise measurement of neutron flux. The combination of this chamber with a ^{3}He counter enables exceptional measurement accuracy. Together with a modern event registration system, this detector makes it possible to obtain α-particle spectra corresponding to transitions to various energy levels of the daughter nucleus, as well as detailed information about angular distributions of nuclear reaction products. Experiments conducted with various targets (including gas samples) demonstrate the broad research capabilities of the setup. The results obtained make a significant contribution to understanding the mechanisms of nuclear reactions and can be used to verify theoretical models. Thanks to its characteristics, this spectrometer is a valuable tool for conducting research aimed at developing new nuclear technologies and improving the safety of existing ones. In particular, the data obtained can be used to improve nuclear reactor models and develop more effective radiation protection methods.

Acknowledgement, conflict of interests

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The contribution of the authors

Chuprakov I.A. – significant contribution to the concept and design of the work; analysis and interpretation of the results, as well as writing the main text of the scientific article;

Gledenov Yu.M. – research management, approval of the final version of the article for publication;

Enkhbold S. – analysis and interpretation of the results, writing the text;

Bekbaev A.K. – theoretical calculations and analysis of the results;

Mukhametuly B. – participation in the experiment, performing data collection tasks, their preliminary processing and analysis;

Korshikov E.S. – conducting the experiment, preparing the experimental equipment and starting the data collection system, organizing and monitoring data collection during the entire experiment.

Temerbulatova N.T. – preparation and manufacturing of the test samples.

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Жылдам нейтрондар тудыратын ядролық реакцияларды зерттеуге арналған зарядталған бөлшектер спектрометрі

Аңдатпа. Зарядты бөлшектерді тіркеуге арналған спектрометр ядролық физикада және қолданбалы мәселелерде жоғары дәлдікпен зерттеу жүргізу үшін әзірленді. Құрылғының негізінде Фриш торлы екі секциялы иондалу камерасы жатыр, ол жоғары тіркеу тиімділігін, іс жүзінде изотропты кеңістік бұрышын (~4π) және фондық шулардың ең төменгі деңгейін қамтамасыз етеді, бұл реакциялардың кішігірім қималарын сенімді анықтау үшін өте маңызды. Дамудың өзектілігі ядролық энергетиканың, сәулеленуден қорғау жүйелерінің және ядролар құрылымын зерттеудің негізгі мәселелерінің дамуына байланысты нейтрон-индуцирленген реакцияларды зерттеуге деген қызығушылықтың артуымен, сонымен қатар қатты және газ тәрізді нысандармен тиімділікті жоғалтпай жұмыс істей алатын заманауи спектрометрлердің болмауымен түсіндіріледі. Құрал жеңіл және орташа массалардың ядроларында жылдам нейтрондар әсерінен туындайтын зарядты бөлшектердің ұшып шығу реакцияларын жүйелі зерттеуде тиімді қолданылады. Оның көмегімен реакция өнімдерінің энергетикалық таралуын, толық және дифференциалды қималарды, сонымен қатар зарядты бөлшектердің бұрыштық

таралуын алуға болады. Спектрометрдің маңызды артықшылығы – қатты және газ тәрізді үлгілермен жұмыс істей алуы, бұл ғылыми зерттеулерде оның қолданыс аясын айтарлықтай кеңейтеді.

Түйін сөздер: зарядталған бөлшектер спектрометрі жылдам нейтрондар, альфа бөлшектерінің спектрлері, детектор, нейтрондармен ядролық реакциялар.

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Спектрометр заряженных частиц для исследования ядерных реакций, вызванных быстрыми нейтронами

Аннотация. Разработан спектрометр для регистрации заряженных частиц, предназначенный для высокоточных исследований в ядерной физике и прикладных задачах. В основе прибора лежит двухсекционная ионизационная камера с сеткой Фриша, обеспечивающая высокую эффективность регистрации, практически изотропный телесный угол (~4π) и минимальный уровень фоновых помех, что критически важно для надежного определения малых сечений реакций. Актуальность разработки обусловлена растущим интересом к изучению нейтрон-индуцированных реакций в связи с развитием ядерной энергетики, радиационной защиты и фундаментальных исследований структуры ядер, а также отсутствием современных спектрометров, способных работать как с твердыми, так и с газообразными мишенями без потери эффективности. Прибор эффективно применяется в систематических исследованиях реакций с вылетом заряженных частиц, индуцированных быстрыми нейтронами, на ядрах легких и средних масс. С его помощью можно получать энергетические распределения продуктов реакций, полные и дифференциальные сечения, а также угловые распределения заряженных частиц. Важным преимуществом спектрометра является возможность работы как с твердыми, так и с газообразными образцами, что значительно расширяет область его применения в научных исследованиях.

Ключевые слова: спектрометр заряженных частиц, быстрые нейтроны, спектры альфа частиц, детектор, ядерные реакции.

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