ISSN 2518-1483 (Online),
ISSN 2224-5227 (Print)

2017 • 3

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫНЫҢ

БАЯНДАМАЛАРЫ

ДОКЛАДЫ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН

REPORTS

OF THE NATIONAL ACADEMY OF SCIENCES
OF THE REPUBLIC OF KAZAKHSTAN

ЖУРНАЛ 1944 ЖЫЛДАН ШЫҒА БАСТАҒАН
ЖУРНАЛ ИЗДАЕТСЯ С 1944 г.
PUBLISHED SINCE 1944

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫНЫҢ
БАЯНДАМАЛАРЫ **2017 • 3**

«Қазақстан Республикасы Ұлттық ғылым академиясының баяндамалары»
ISSN 2518-1483 (Online),
ISSN 2224-5227 (Print)

Меншіктенуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» Республикалық қоғамдық бірлестігі (Алматы қ.)
Қазақстан республикасының Мәдениет пен ақпарат министрлігінің Ақпарат және мұрағат комитетінде 01.06.2006 ж. берілген **№5540-Ж** мерзімдік басылым тіркеуіне қойылу туралы куәлік

Мерзімділігі: жылына 6 рет.
Тиражы: 2000 дана.

Редакцияның мекенжайы: 050010, Алматы қ., Шевченко көш., 28, 219 бөл., 220, тел.: 272-13-19, 272-13-18,
http://nauka-nanrk.kz. reports-science.kz

Типографияның мекенжайы: «Аруна» ЖК, Алматы қ., Муратбаева көш., 75.

ДОКЛАДЫ **2017• 3**
НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН

Доклады Национальной академии наук Республики Казахстан»
ISSN 2518-1483 (Online),
ISSN 2224-5227 (Print)

Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан» (г. Алматы)
Свидетельство о постановке на учет периодического печатного издания в Комитете информации и архивов Министерства культуры и информации Республики Казахстан **№5540-Ж**, выданное 01.06.2006 г.

Периодичность: 6 раз в год.
Тираж: 2000 экземпляров

Адрес редакции: 050010, г.Алматы, ул.Шевченко, 28, ком.218-220, тел. 272-13-19, 272-13-18
http://nauka-nanrk.kz. reports-science.kz

Адрес типографии: ИП «Аруна», г.Алматы, ул.Муратбаева, 75

REPORTS **2017 • 3**
OF NATIONAL ACADEMY OF SCIENCES OF THE
REPUBLIC OF KAZAKHSTAN

Reports of the National Academy of Sciences of the Republic of Kazakhstan.
ISSN 2224-5227
ISSN 2518-1483 (Online),
ISSN 2224-5227 (Print)

Owner: RPA "National Academy of Sciences of the Republic of Kazakhstan" (Almaty)
The certificate of registration of a periodic printed publication in the Committee of Information and Archives of the Ministry of Culture and Information of the Republic of Kazakhstan N 5540-Ж, issued 01.06.2006

Periodicity: 6 times a year
Circulation: 2000 copies

Editorial address: 28, Shevchenko str., of.219-220, Almaty, 050010, tel. 272-13-19, 272-13-18,
http://nauka-nanrk.kz / reports-science.kz

Address of printing house: ST "Aruna", 75, Muratbayev str, Almaty

REPORTS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN
ISSN 2224-5227
Volume 3, Number 313 (2017), 20 – 27

UDC 539.17

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ERRORS IN THE TOTAL REACTION CROSS SECTIONS AND ENERGIES OF INCIDENT PARTICLES MEASURED USING MODIFIED TRANSMISSION TECHNIQUE

Abstract. When determining the values of the total reaction cross sections and the energy of the particles of a beam of weakly bound nuclei, there are always statistical and systematic errors. The former depend on the data collected, the latter – on the components of the experimental setup. A thorough study of the used equipment and components, such as targets and detectors, makes it possible to evaluate and minimize the effect of systematic errors.

In this paper, for the first time, the guidelines and basic principles for determining the errors in the total cross reaction sections and the beam energy in the course of the experiment are described in detail, and the determination of their errors in a particular experiment is demonstrated.

Keywords: statistical and systematic errors, total reaction cross section, γ-spectrometer.

Introduction. The total error of the final quantity is not only the statistical error of the recorded events. It must include the errors in determining all other quantities used in the calculation formula, for example, the errors in the measurement of the thickness of the target, the distance to the source and others. These errors are systematic errors. Systematic errors are caused by the imperfection of instruments, incorrect installation of the device, displacement of the scale, inaccurate setting of the instrument pointer in the zero position, low sensitivity of the instrument, neglect of external factors affecting the result of measurements (thermal, electric and magnetic fields, pressure, humidity and others) approximate equations and constants used to calculate the desired quantities, and other factors [1].

Systematic errors unlike statistical errors are not described by the methods of mathematical statistics. They can be reduced by examining the instruments used in the experiment and introduction of corrections in the results of measurements.

In this paper, we would like to give an example of the determination of systematic errors by the example of measuring the total cross section of nuclear reactions.

The two main experimentally determined parameters of the nuclear interaction are the values of angular distributions of the differential cross sections (ADDCS) of elastic scattering and total reaction cross sections (TRC). The method of determination of errors of angular characteristics and angular distributions of the differential cross sections of elastic scattering is described in detail in [2, 3].

Let us determine errors in the measurement of total reaction cross sections. The values of the total reaction cross sections are measured indirectly, i.e., using the results of direct measurements of particle fluxes I_0 and I incident on the target and passing through N target nuclei without interaction, respectively.

The total reaction cross section

The TRC value is connected with the intensities of particle fluxes I_0 and I by the equation:

$$\sigma_R = (I_0 - I)/N \cdot I_0 . \quad (1)$$

The equation (1) shows that for the direct measurement of the total reaction cross section σ_R it is necessary to simultaneously measure two quantities, namely, the difference $(I_0 - I)$ and the corresponding intensity of the flux I_0. This method, called the «transmission method», is most commonly used to measure TRC.

Experimental setup. In our experiment, where we measured the total cross sections for the interaction of ^{6}He, ^{8,9}Li with the nuclei of ^{28}Si, ^{9}Be, ^{59}Co and ^{181}Ta, we used the modified transmission technique based on the use of a multilayer telescope with semiconductor silicon detectors combined with a 4π-geometry scintillation gamma-spectrometer [4, 5]. This technique provides a direct measurement of the number of events in the reaction $\Delta R = (I_0 - I)$, normalized to the flux intensity I_0. The number of events in the reaction ΔR was determined by registration of radiation at least in one of the six detectors of the γ-spectrometer in coincidence with the starting semiconductor detector of the telescope.

The experiment was conducted at the U-400M accelerator in the G. N. Flerov Laboratory of Nuclear Reactions, JINR (Dubna). The secondary beam of ^{6}He and ^{8,9}Li nuclei of intensity $I_0 \sim 10^3\ s^{-1}$ in the energy range E = (5 –30) MeV/nucleon was obtained as a product of the fragmentation reaction of the primary beam of ^{11}B nuclei (E = 32 MeV/nucleon) on ^{9}Be target. The secondary ^{8,9}Li-beam was formed using the elements of the magnetic system of the ACCULINNA fragment separator equipped with the eight-meter *TOF* transport line for particle identification.

In the input and output parts of the separator channel, thin plastic scintillation detectors, which identified particle energy by energy release *dE* and by the time of flight *TOF*, were mounted. Multipole focusing elements provided further transportation of ^{6}He and ^{8,9}Li beam to the low-background separator cabin.

This experiment took into account the experience and corrected methodological errors of the previous works. The attempts of joint application of a full geometry γ-spectrometer and transmission technique had a number of significant shortcomings and gave only estimates and only for «energy-integrated reaction cross sections».

One of the disadvantages of this method is that the main source of gamma and neutron background (telescope *E*-detector of the full beam stop) was placed in the sensitive area of the γ-spectrometer, so that it fixed γ-radiation from the events both in the test target and in the E-detector material, where the number of nuclei is several orders of magnitude larger than that in the target.

In our improved modification of the experiment, all basic background γ-sources are minimized and placed beyond the sensitive area of the γ-spectrometer, and in the physical installation the events ensemble was chosen so that γ-spectrometer played the main role in their analysis, and the *E*-detector was not a background γ-source. The other part of events, pretending to be nuclear reactions, was selected by the transmission method, where the γ-spectrometer analysis plays a secondary role. Therefore, this physical installation provides two separate exposures $\Theta >> 0^0$ and $\Theta \sim 0^0$ with the corresponding intensities of ^{8,9}Li beam, γ-spectrometer functions, etc.

4π-geometry CsI(Tl) scintillation *γ*-spectrometer was installed in the low background cabin in the additional Pb-protection. The studied target, in particular, *dE* Si-detector, was placed in the center of the *γ*-spectrometer (see Figure 1). The other *dE* and *E* detectors of the semiconductor telescope were placed along the beam axis, before and after the studied target, beyond the sensitive zone of the *γ*-spectrometer.

The target (*dE* - detector) was placed in the central zone of the γ-spectrometer, whereas all other telescope detectors, in particular, identifiers dE_0 and dE_1, detectors-identifiers of reaction products dE_3 and *E* detector of full beam stop were located in the (n-γ) – protection beyond the sensitive zone of the γ-spectrometer. The experimental technique using 4π- scintillation γ-spectrometer is described in detail in [4, 5].

Semiconductor dE_0, dE_1 detectors and active collimator dE_{AK} were placed before the target and used for identification of ^{6}He and ^{8,9}Li nuclei, and their separation from the other particles-products of the secondary beam. Recording of information started for each event when a particle passed through the detector dE_1. Different thicknesses of dE_0 and dE_1 detectors allowed the experimenters to change and measure the energy of ^{8,9}Li particles incident on the target for each event of particle passage.

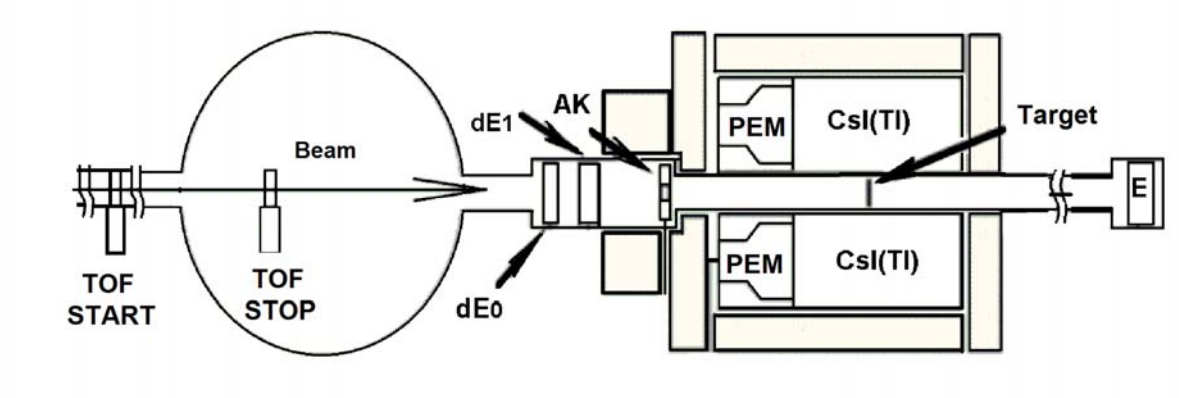

Figure 1 –The scheme of the experiment on measuring reaction cross sections by 4π- scintillation γ-spectrometer

The secondary beam of ^{6}He and ^{8,9}Li nuclei successively passed the following parts of the installation:

- the group of plastic scintillator *TOF* – *d*E detectors of ACCULINNA separator;
- the group of semiconductor detectors dE_0, dE_1 for additional identification of the beam particles and reduction of their energy;
- the active collimator detector AK;
- the target located in the center of 4π-geometry CsI(Tl) γ-spectrometer in the (n-γ)- protection;
- the *E* detector located along the beam axis behind the target.

The *E* detector was located beyond the γ-spectrometer and recorded the beam particles having passed the target.

Figure 2 shows the two-dimensional spectra: the dependence of energy losses in dE_0 on *TOF* (left) and energy losses in the detectors dE_0 and dE_1 (right). Compact grouping of points in the two-dimensional spectra shows a reasonably good separation of ^{6}He- and ^{8,9}Li-isotopes.

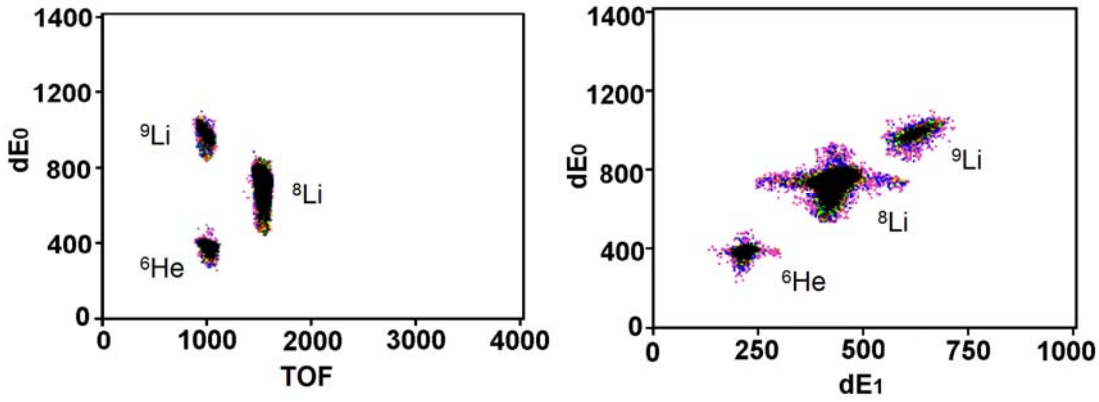

Figure 2 – Two-dimensional spectra of identification detectors dE_0 and dE_1: energy losses in dE_0 and *TOF* (left) and energy losses in the detectors ($dE_0 \times dE_1$). (right). The spectra demonstrate good separation of ^{6}He and ^{8,9}Li nuclei formed as products of (^{11}B + ^{9}Be) reaction

Gamma spectrometer with 4π-geometry recorded γ-quanta in coincidence with the starting dE_1-detector. For each event, the system recorded information about the energy of γ-quanta and the time of their registration.

The number of events-reactions $\Delta R = (I_0 - I)$ was determined by registering radiation at least in one of the γ-spectrometer detectors in coincidence with the starting dE_1 detector. Thus, the total cross section of the reaction was calculated by (4) using the results of measurement of I_0 and ΔR values.

The errors in determining the total reaction cross sections. Expression (1) shows that for direct measurement of the total reaction cross section σ_R it is sufficient to measure two quantities, namely, the difference $(I_0 - I)$ and the corresponding flux value I_0, simultaneously.

In accordance with formula (1), the main contribution to the error of the TRC value is made by statistical errors and errors in determining the target thickness (in the calculation it is the number of target nuclei).

The absolute error is calculated from the expression:

$$\Delta\sigma_R = \sigma_R \cdot \delta \ . \tag{2}$$

The relative error of the measurement result δ is determined by the expression:

$$\delta = \sqrt{(\delta N)^2 + (\delta\varepsilon)^2 + (\delta h_{\text{tar}})^2 + (\delta h_{\text{det}})^2} \ , \tag{3}$$

where δN is the statistical error, $\delta\varepsilon$ is the error determined by the efficiency of detectors, δh_{tar} is the error in determining the target thickness, δh_{det} is the error in determining the thickness of detectors. Let us consider these errors.

Statistical error:

$$\delta N = \frac{1}{\sqrt{\langle N \rangle}} \approx \frac{1}{\sqrt{N}} \ , \tag{4}$$

where N is the number of events.

Table 1 – The number of events for different particles detected by the detectors. The error value for each value is $\sqrt{N}$

Run	**^{6}He**	**^{8}Li**		
69	100176	101677	^{28}Si 420 μm	
77	101889	105373	^{28}Si 200μm	
85	789070	943720	^{28}Si420 μm	
99	1735797	1149928	^{28}Si420 μm	
103	603406	475292	^{28}Si420 μm	
run	**^{6}He**	**^{8}Li**	**^{9}Li**	
12	1342089	291723		^{28}Si 510μm
24	69625	586099	13499	^{28}Si 510μm
32	180758	1747947	56384	^{28}Si 510μm
33	169484	1621098	42805	^{28}Si 510μm
37	248417	2119843	60880	^{28}Si 510μm

Table 1 presents the quantitative data from the spectra for ^{6}He- and ^{8,9}Li- particles interacting with ^{28}Si. The statistical error (4) in our experiment (Table 1) is less than 1%.

Error caused by the detector efficiency.

Efficiency of silicon semiconductor detectors. To identify beam particles we used semiconductor silicon detectors – penetrated (from 3 to 6 pieces) thin *dE*-detectors with a thickness of 200, 420, 510 μm and a 710 μm *E*-detector for total absorption.

Separation (selection) of the products of nuclear reactions by the one-dimensional spectra in the studied detectors leads to measurement errors and determines the accuracy of selection of events in nuclear reactions in the studied pair of detectors. These errors are not less than 1%.

Errors in determining the thickness of detectors. Table 2 presents the main characteristics of silicon semiconductor detectors used in the experiment.

The efficiency of registration of charged particles by semiconductor detectors is 100%.

Efficiency of γ-spectrometer. We used the γ-spectrometer assembled from six γ-detectors made of inorganic scintillator CsI (T1). Each detector consists of a scintillator in the form of a straight prism of 14 cm high, the base of which is a regular hexagon with the radius of the circumscribed circle of 10 cm, and a photomultiplier PMT-110, optically coupled to the end face of the CsI(Tl) prism.

Table 2 – Nominal characteristics of silicon semiconductor detectors used in the experiment. Values are given without errors from the manufacturer's data

Diameter of active area, mm	40
Diameter of semiconductor wafer, cm	10.16
Detector thickness, microns	200, 420, 510, 710
Dead layer, nm	50
Thickness of metal (aluminum) cover the entire active area of the detector, microns	0.5
Minimum energy threshold, keV	4 – electrons, 90 – protons
Energy resolution, keV	~ (50–70)

The surface of each scintillator is polished and coated with 150 μm-thick reflective film Tyvek® DuPont™, Wilmington, DE [6] in two layers. The scintillator is placed in the sealed enclosure from1mm-thick light-shielding plastic.

It is supposed that the γ-spectrometer covers the solid angle 4π (360^0). In practice, the solid angle covered by the detectors is less than 4π. Not all γ-quanta emitted in the reaction get to the detector. Moreover, even after getting into the detector, not all γ-quanta are recorded. For γ-spectrometry it is very important that the γ-quanta lose all their energy in the sensitive area of the detector and are registered in the peak of total absorption. Errors related to this process are not less than 1%.

The most important characteristics of γ-spectrometer, determining its efficiency, are the light output and energy yield of scintillators. Many different scintillators have been created. Table 3 lists the properties of some commonly used scintillators including CsI (TI), which was used in this experiment.

Table 3 – Comparative characteristics of some scintillators

Scintillator	light yield ϰ (%)	energy yield η	density ρ (g/cm^3)	$Z_{average}$	t(t_1) (ns)	λ_{max} nm	hλ_{max} (eV)	Refraction index
Anthracene ($C_{14}H_{10}$)	100	0.034	1.25	3.9	30(2)	447	2.77	1.62
Stilbene ($C_{14}H_{10}$)	50	0.030	1.16	4	4.5(0.1)	410	3.03	1.626
NE-102A, plastic	65	0.01	1.032	~ 5	2.4(0.6)	423	2.93	1.58
NaI(T1)	230 (anthr.) 100	0.16±0.01	3.67	~ 32	230(6)	415	2.99	1.85
CsI(T1)	171	0.06	4.51	~ 54	680(64%) 3.34(36%) (22)	540	2.30	1.80
BGO ($Bi_4Ge_3O_{12}$)	22	0.013	7.13	30	300	480	2.58	2.15

To determine the efficiency of the spectrometer, ideally calibrated springs were used. In such measurements, measures were taken to reduce the possibility of errors due to the measurement technique: the error in the geometric reproducibility of measurement conditions was reduced to 0.1%.

Usually, to determine the efficiency, a set of standard reference sources of *γ*-radiation and reference radio nuclides with a set of *γ*-lines of different energies E_i (such as ^{152}Eu, ^{133}Ba, ^{137}Cs and ^{241}Am), for which the initial specific activity A_0 (this specific activity is determined for the moment of manufacturing), are used. In our case, as the referenceγ-source ^{60}Co and ^{137}Cs were used.

The efficiency of registration of γ-radiation with energy E_i in predetermined conditions (geometry, sample) is determined by the formula:

$$\varepsilon(E_i) = \frac{N}{A_0^{tk} \cdot q \cdot t \cdot m \cdot K_c}, \quad (5)$$

where A_0^{tk} is the certified value of the specific activity of the source at the time of measurement; q is the output of *γ*-quanta per one beta decay; t is the time of measurement; m is the mass of the source; N_i is the number of counts in the spectrum during the time interval t; K_c is the self-absorption coefficient for radiation.

Usually $\varepsilon(E_i)$ and $K_c(E_i)$ are determined together experimentally:

$$\varepsilon(E_i)\cdot K_c(E_i) = \frac{N}{A_0^{tk}\cdot q\cdot t\cdot m} \tag{6}$$

A_0^{tk} for a concrete measurement is equal to:

$$A_0^{tk} = A_0\cdot\exp\left[-0.693\cdot(t_0 - t_k)/T_{1/2}\right], \tag{7}$$

where A_0 is the specific activity at the time of certification; $(t_0 - t_к)$ is the time elapsed since the certification before the measurement; $T_{1/2}$ is the half-life.

In our case, the efficiency of detection of γ-quanta was 80%.

Error in determining the target thickness. The success of the experiment on studying nuclear reactions depends on the properly selected targets. The most important requirement for the quality of the target is its thickness, uniformity and isotopic enrichment.

Determination of the reduced number of target nuclei depends on the target thickness. The error in determining the thickness of the target is caused by the instrumental error of the instruments used in measurements. To measure the thickness of the target, we used non-contact measuring instrument CHY-CB for thickness measurements with the instrumental error of 3%.

We used self-supporting targets from ^{28}Si with a thickness (500 ± 0.55) mm (Table 2), which simultaneously played the role of detectors, and passive targets of ^{9}Be, ^{59}Co and ^{181}Ta with thicknesses (200 ± 8), (65 ± 2.6) and (100 ± 4) mm, respectively.

The errors caused by the target uncertainty are 0.1, 8, 4, and 2.6% for ^{28}Si, ^{9}Be, ^{59}Co and ^{181}Ta, respectively.

Thus, the main contribution to the TRC errors is made by statistical errors; errors caused by the efficiency of detectors; as well as errors in the determination of thicknesses of targets and detectors.

The statistical errors introduced by the data collection system are small (Table 1) compared to other values.

Errors in determining energy values. The second important quantity in the experiments on determination of TRC values is determination of the error in the energy of incident and registered the secondary particles.

Errors in the determination of energy values are caused by two factors:

1) The initial energy spread of particles incident on the telescope.

Figure 3 shows a typical example of the energy resolution for the secondary beam of ^{6}He ions with an average energy equal to 100 MeV, which was determined by the energy losses in the detectors, in which the cross section was measured.

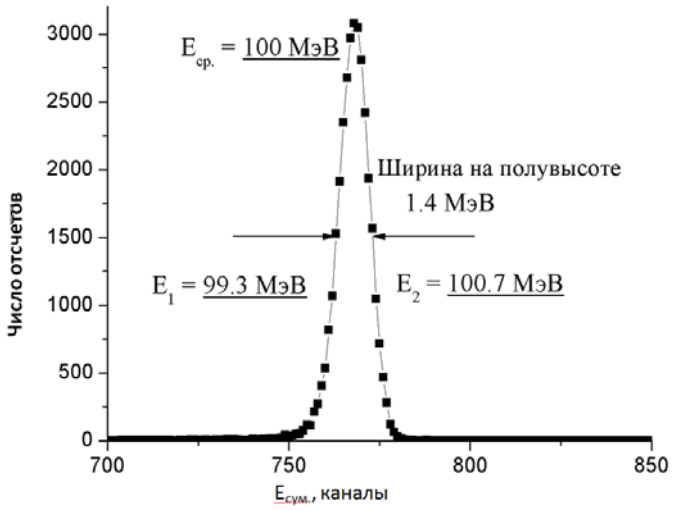

Figure 3 –A one-dimensional spectrum of the total energy loss of particles in the telescope detectors

Consider an example of finding the errors in determining energy. For this purpose let us use the data on the parameters of the primary beam in the given experiment (Table 4).

Table 4 – Parameters of the $_{11}B^{3+}$-primary beam

Parameter	Value
Date	(19.02.2014 – 20.03.2014)
Average flux on the target, nA	500.0
Beam energy, MeV/nucleon	40.0
Pure time of target irradiation, hours	655
Frequency, MHz	F = 15.01
Harmonic	n = 2
Magnet current, A	1893.90
Date	(14.01.2016 – 28.01.2016)
Average flux on the target, nA	200.0
Pure time of target irradiation, hours	178

Let an ion beam with the energy of E = (100 ± 0.7) MeV, with the lowest energy of ions E_1 equal to 99.3 MeV and the maximum E_2 = 100.7 MeV (energy value at the half maximum of the energy distribution) fall on the telescope. Suppose that the third telescope detector is used as a target, i.e. the detector in which the reaction cross sections are determined (see Figure 4).

After the first two detectors the average energy of ions, as a result of ionization losses, decreased to 93.5 MeV. The minimum ion energy became equal to 92.8 MeV, and the maximum – 94.3 MeV.

After passing through the target detector the average energy of ions became equal to 84.3 MeV, the minimum energy – 83.5 MeV, the maximum – 85.1 MeV.

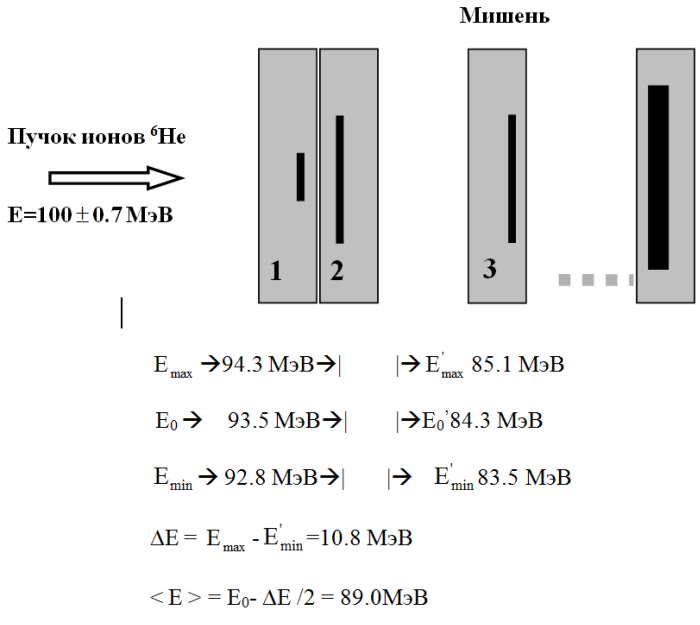

Figure 4 – An example of finding errors in the determination of ion energy

The difference between the maximum energy of ions before hitting the target and the minimum energy after its passage determines the energy error. This value was on average equal to 10%.

Thus, the total value of the TRC error is on average $\Delta\sigma_R \approx$ (5 – 8) %. The error in the determination of the incident particle energy is on average 10%.

Conclusion. When measuring the TRC values and in determining the beam particle energy, statistical and systematic errors are always present experimentally. The former depend on the data collected, the latter on the components of the experimental setup. A thorough study of the equipment and components used, such as targets and detectors, makes it possible to evaluate and minimize the effect of systematic errors. In the given example, the best value of the total error of the TRC value is, on the average, $\Delta\sigma_R \approx$ (5-8) %. The value of the total error in determining the energy of the incident particles is higher and averaged 10%.

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ӨЛШЕУ КЕЗІНДЕГІ МОДИФИКАЦИЯЛАНҒАН ТРАНСМИССИОНДЫ ӘДІС НЕГІЗІНДЕ – РЕАКЦИЯЛАРДЫҢ ТОЛЫҚ ӨЛШЕМДЕРІНІҢ ҚАТЕЛІКТЕРІН ЖӘНЕ ҰШЫП КЕЛУШІ БӨЛШЕКТЕРДІҢ ЭНЕРГИЯСЫ АНЫҚТАУ

Аннотация. Жұмыста ядролары әлсіз байланысқан бөлшек шоқтарының энергиясы және реакциялардың толық қимасының өлшемдерін анықтау барсысында статистикалық және жүйелік қателіктері анықталған болатын. Біріншісі терілген мәліметтерден, ал екіншісі – эксперименттік қондырғы құраушыларынан тікелей тәуелді. Қондырғыны және оның құраушыларын толық зерттеу, мәселен нысана және детектор сияқты бөлшектерін зерттеу жүйелік қателіктерді азайтуға мүмкіндік береді. Жұмыста алғаш рет эксперимент кезінде реакциялардың толық қимасының және бөлшек шоқтарының энергиясының қателіктерін анықтаудың, сонымен қатар белгілі бір экспериментте қателіктердің анықталғаны көрсетілген.

Түйін сөздер: статистикалық және жүйелік қателер, реакция толық қимасы, γ-спектрометрі.

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ПОГРЕШНОСТИ ВЕЛИЧИН ПОЛНЫХ СЕЧЕНИЙ РЕАКЦИЙ И ЭНЕРГИЙ НАЛЕТАЮЩИХ ЧАСТИЦ ПРИ ИЗМЕРЕНИЯХ МОДИФИЦИРОВАННОЙ ТРАНСМИССИОННОЙ МЕТОДИКОЙ

Аннотация. При определении величин полных сечений реакций и энергии частиц пучка слабосвязанных ядер, всегда присутствуют статистические и систематические погрешности. Первые зависят от набранных данных, вторые – от компонентов экспериментальной установки. Тщательное изучение используемого оборудования и компонентов, таких как мишени и детекторы, дает возможность оценить и минимизировать влияние систематических погрешностей. В статье впервые подробно представлены указания и основные принципы в определении погрешностей в полных сечениях реакций и энергии пучка в ходе эксперимента, а также продемонстрировано определение их погрешностей в конкретном эксперименте.

Ключевые слова: статистические и систематические погрешности, полное сечение реакции, γ-спектрометр.

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http://www.reports-science.kz/index.php/ru/

Редакторы *М. С. Ахметова, Д. С. Аленов, Т.А. Апендиев*
Верстка на компьютере *А.М. Кульгинбаевой*

Подписано в печать 01.06.2017.
Формат 60x881/8. Бумага офсетная. Печать – ризограф.
4,0 п.л. Тираж 2000. Заказ 3.

Национальная академия наук РК
050010, Алматы, ул. Шевченко, 28, т. 272-13-18, 272-13-19