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NEW MEASUREMENTS OF DIFFERENTIAL CROSS SECTION FOR ELASTIC SCATTERING PROCESS OF $^{16}O(p,p)^{16}O$ AT ASTROPHYSICAL ENERGIES

Abstract. The overview and analysis of existing literature experimental data on elastic scattering of protons by ^{16}O nuclei are carried out. The experimental complex and measuring methods of the work are described in detail. The results of the new measurements of elastic p^{16}O scattering in previously unexplored areas of the energy of the incoming particles from 0.6 to 1.0 MeV and angular range of 19°-159° are presented. A comparison of the data with the differential cross sections, calculated according to the Rutherford formula is conducted. In the overlapping areas the results of this work are consistent with the literature data. Also, the differential cross sections of the $^{27}Al(p,p)^{27}Al$ process at the same energy and angular ranges were measured. It is shown that, with the 4% accuracy, the obtained cross sections of $^{27}Al(p,p)^{27}Al$ coincide with Rutherford case. We describe a new method of obtaining the absolute values of the differential cross sections. The experimental data of presented work can be useful for calculations of the processes occurring in hybrid nuclear reactors and fusion devices.
Keywords: Experimental set-up, UKP-2-1 accelerator, elastic scattering, differential cross sections, $^{16}O(p,p)^{16}O$.

Introduction. Currently, there are experimental information on the differential cross sections of elastic scattering of protons by nuclei ^{16}O in the $E_{p,\,lab.} < 3.5$ MeV obtained at the following angles and energy ranges: $\theta_{c.m.} = 171.5^{\circ}$, $E_{p,\,lab.} = 0.4 - 2$ MeV, error of 10% [1]; $\theta_{c.m.} = 161.2^{\circ}$, $E_{p,\,lab.} = 0.6 - 2.0$ MeV, error of 10% [2]; $\theta_{c.m.} = 170.6^{0}$, $E_{p,\,lab.} = 0.8 - 2.5$ MeV, error of 4% [3]; $\theta_{c.m.} = 93.6^{\circ}$ and 123.1°, $E_{p,\,lab.} = 0.5 - 3.5$ MeV, error of 5% [4]; $\theta_{c.m.} = 142.3^{\circ}$ and 178.1°, $E_{p,\,lab.} = 0.6 - 2.5$ MeV, error of 5% [5]. In all the papers the excitation functions were measured in steps about 50 keV. For reliable phase shift analysis and the parameters of the optical potential determination for p + ^{16}O system at $E_{p,\,lab.} < 1$ MeV it is desirable to have also the angular distribution of the cross sections for the $^{16}O(p,p)^{16}O$ in the $E_{p,\,lab.} \leq 1000$ keV in steps of 200 keV for $\theta_{c.m.} \approx 40^{\circ} - 160^{\circ}$ in steps of $10^{\circ} - 20^{\circ}$. The energy range of $E_{p,\,lab.} \leq 1000$ keV is important because the processes in thermonuclear installations flow at very low energies.

Experimental methods and results. Therefore, new experimental data on elastic scattering of protons by nuclei oxygen at low energies were measured on electrostatic tandem accelerator UKP-2-1 (scheme of UKP-2-1 is shown in Fig.1) of Institute of Nuclear Physics of the Republic of Kazakhstan (Almaty) [6 - 8]. Protons were accelerated to energies $E_{p,\,lab.} = 600–1040$ keV. The value of the beam current was limited by stability of the target and load characteristics of the electronic apparatus and was ranging from 1 to 80 nA. Calibration of protons energies in the beam was made according to reactions with narrow, well-separated resonances [9, 10]. For this purpose we used $^{27}Al(p,\gamma)^{28}Si$ reaction at $E_{p,lab.} =$ 632, 773, 992, 1089 keV and $^{19}F(p,\alpha\gamma)^{16}O$ at $E_{p,\,lab.} = 340$ keV. The accuracy of beam calibration was equal to ±1 keV. Energy spread of the beam was determined by the width of the front of $^{27}Al(p,\gamma)^{28}Si$ reaction yield curve near resonance at $E_{p,\,lab.} = 992$ keV (resonance width < 0.1 keV) and did not exceed 1.2 keV [11 - 13].

The proton beam passed through collimation system (two collimators with diameters of 1.5 mm and placed 420 mm apart) and was formed on the target (located at a distance of 100 mm from the last collimator) into a spot with diameter of 2 mm. In order to minimize the number of protons scattered from the end faces of the collimators thickness of the front wall near the holes were brought to 0.1 mm. Faraday cup (a tube with a diameter of 15 mm and a length of 150 mm), located at a distance of 120 mm from the target, was connected to a current integrator, which sent a digital pulse to a scaler, once it collected a portion of charge (0.1 or 10 nC). Photo of scattering chamber is presented in Fig. 2. Accumulated charge was determined with an error of not more than 1.5%. To minimize carbon laydown on a target during the measurements we used pumping system consisting of ion and turbomolecular pumps, and inside the scattering chamber nitrogen traps system was installed (see Fig. 3a, 3b). A typical pressure in the chamber was $1.5*10^{-6}$ torr.

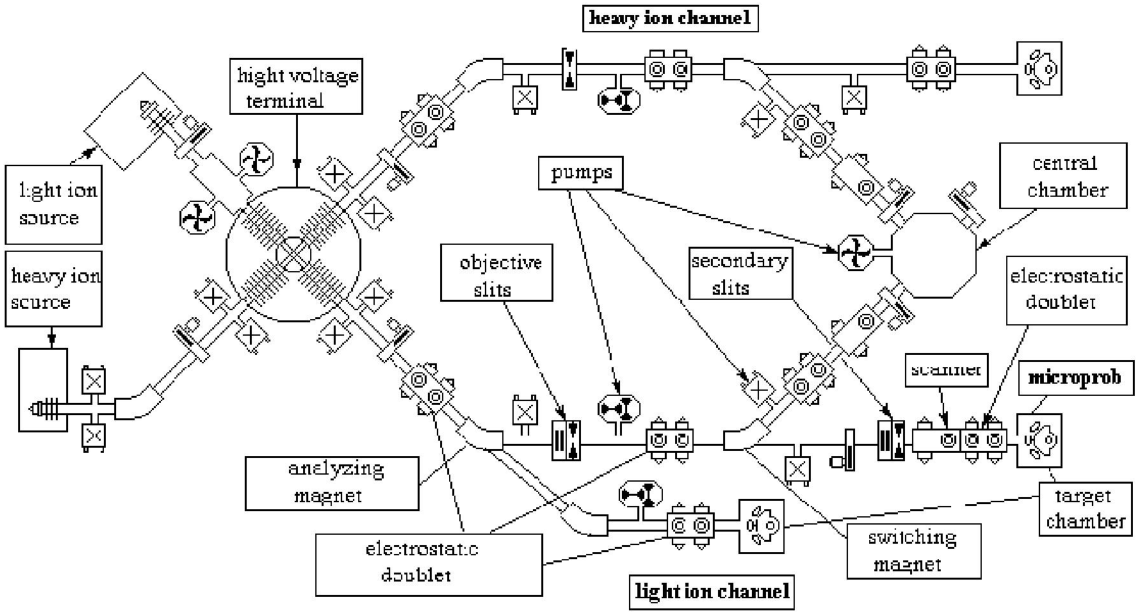

Fig. 1 - Tandem accelerator UKP-2-1 contains two independent channels for beam transportation united by one accelerating potential. This figure shows a scheme of the tandem. Cascade Kokroft-Wolton type generator ensures accelerating voltage up to 1MV. Analyzing magnet that includes NMR stabilization of magnetic field has mass resolution M/ΔM ≈ 200

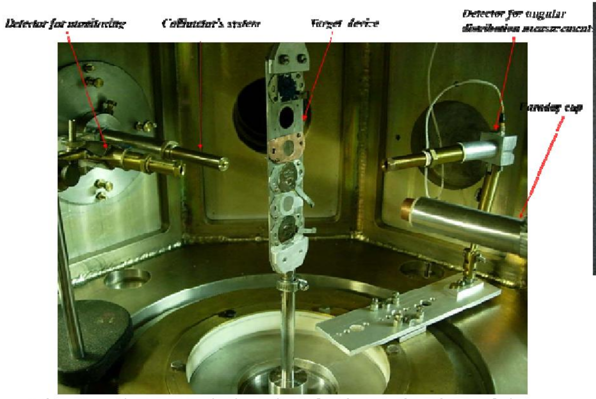

Fig. 2 - The central chamber for investigation of the scattering processes and reactions with charged-particles production

Fig.3a - Nitrogen trap

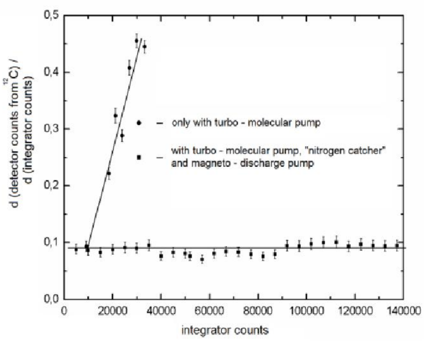

Fig. 3b - The carbon deposition during bombardment of target by incident protons

In order to detect the scattered protons we used surface-barrier charged particles detector (diameter of bounding diaphragm before detector was 2 mm, sensitive area thickness - 0.2 mm). The detector was placed at a distance of 240 mm from the target and was able to move in an angular range from 10° to 170°. The error in determining the angle of the detector location did not exceed ± 0.2°. The detector was equipped by the protective tube, which, for all its positions excluded registration of protons scattered from the end face of the last collimator and from the Faraday cup. A second similar detector was placed at an angle of 160° relative to the incident beam and was used to monitor the stability of the target. The energy resolution of detectors was equal to 15 keV. Detailed description of the experimental setup for the study of the processes with the charged particles produce in the UKP-2-1 can be found in [14], and in its references.

An aluminum oxide film (Al_2O_3), used as a target was made using the electrolytic method. Protons energy losses (for incident protons energy of $E_{p,lab.}$ = 992 keV) after passing the target (Al_2O_3) were determined by width at half-height of the yield curve of $^{27}Al(p,\gamma)^{28}Si$ reaction near resonance at $E_{p,lab.}$ = 992 keV (the target was placed exactly perpendicular to the incident beam) and were found to be 5.4±1.2 keV, which corresponds to the thickness of the target 28±6 μg/cm² [15,16]. Such target thickness satisfied the requirements of mechanical and thermal strength, and at the same time, practically did not affect on the spectral line broadening, except for spectral lines obtained at $\theta_{lab.}$ = 70°, 90°, 100° at $E_{p,lab.}$ = 600 keV, where broadening due to the target thickness is equal to the broadening due to the detector energy resolution.

Signals from the detectors were amplified and transmitted to two 2024-channel analyzers. Electronics dead time did not exceed 3%. At each proton energy value, the ratio of the area of the peak from the stationary detector because of $^{16}O(p,p)^{16}O$ and $^{27}Al(p,p)^{27}Al$ scattering to the reading of the integrator counter was a constant within 4% for all positions of the movable detector. Laboratory energy given in this work corresponds to laboratory protons energy in the center of the target thickness.

An example of protons elastic scattering from target nuclei spectrum obtained at $E_{p,lab.}$ = 1000 keV is given in Fig. 4. The peaks from elastic scattering of protons from ^{12}C, ^{16}O and ^{27}Al nuclei are clearly seen in the figure. The presence of a peak from $^{12}C(p,p)^{12}C$ process in the spectrum is due to the carbon laydown on the target surface.

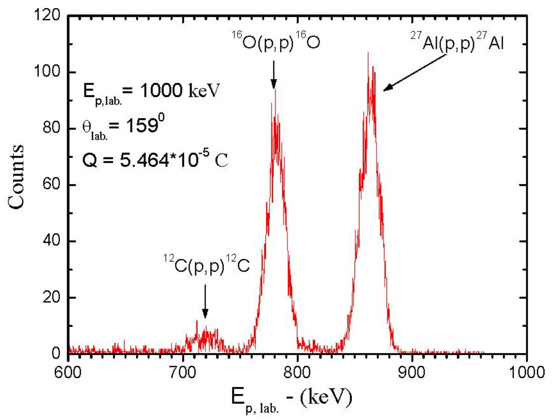

Fig. 4 - Energy spectrum of protons elastically scattered from target nuclei

The angular distributions of the $^{16}O(p,p)^{16}O$ were measured at incident protons energies $E_{p,lab.}$ = 600, 800 and 1000 keV at angles $\theta_{lab.}$ = 19, 39, 60, 70, 90, 100, 120, 140, 150, and 159 degrees. Excitation functions of the $^{16}O(p,p)^{16}O$ were measured in the energy range of $E_{p,lab.}$ = 600–1040 keV with a step of 20 keV for two angles 90° and 159° in laboratory system. The target was installed perpendicular to the incident beam for detector positions at angles $\theta_{lab.}$ = 39°, 60°, 120°, 140°, 150° and 159°, and for detector positions at $\theta_{lab.}$ = 70°, 90°, and 100° – at an angle of 45°.

By the yield of elastic $^{16}O(p,p)^{16}O$ scattering, we implied the ratio of the sum of counts in the spectral peak (without preliminarily subtracted background, which we linearly approximated by a trapezoid) to the reading of the integrator counter. Statistical error in the determination of the yields (including errors introduced by background subtracted) was less than 3.5% for all positions of the detector and energies of incident protons.

The spectra where peaks from $^{12}C(p,p)^{12}C$, $^{16}O(p,p)^{16}O$ and $^{27}Al(p,p)^{27}Al$ processes significantly overlapped, were analyzed using information about the differential cross sections of $^{12}C(p,p)^{12}C$, taken from [17-20]. While the number of ^{12}C nuclei in the target was determined by spectrum closest to the analyzed one where peak from $^{12}C(p,p)^{12}C$ is well separated. For spectra with overlapping peaks yield of elastic $^{12}C(p,p)^{12}C$ scattering does not exceed 10% of yield of $^{16}O(p,p)^{16}O$.

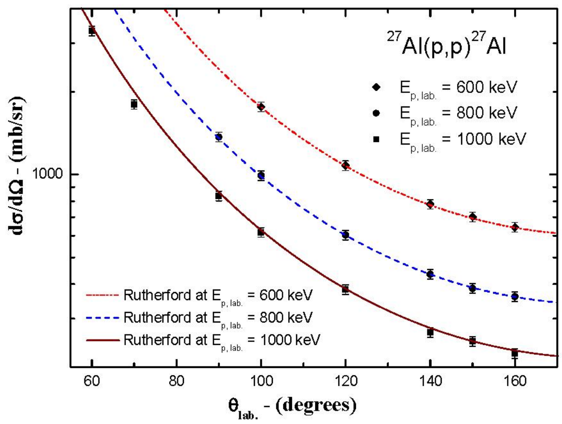

Fig. 5a - The differential cross section of the elastic scattering of protons on ^{27}Al with errors of 4%. Symbols are the experimental data of present work, the curves - calculations by the Rutherford formula

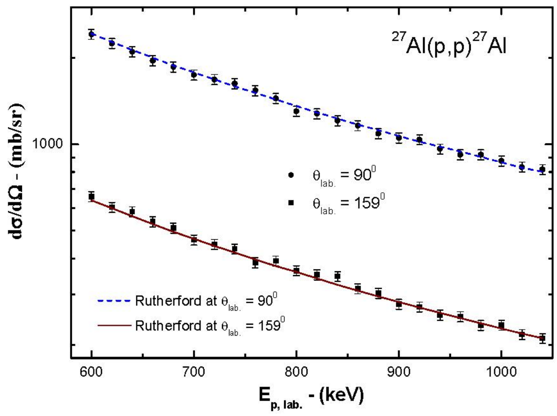

Fig. 5b - Excitation functions of the elastic scattering of protons on ^{27}Al with errors of 4%. Symbols are the experimental data of present work, the curves - calculations by the Rutherford formula

Differential cross sections of $^{27}Al(p,p)^{27}Al$ were assumed as purely Rutherford. Last assertion is based on the data shown in Figs. 5a,b, where the differential cross sections (Fig. 5a) and the excitation function (Fig. 5b) for the $^{27}Al(p,p)^{27}Al$ are given, which are the results of the processing the spectra, where the peaks from $^{27}Al(p,p)^{27}Al$ scattering are separated reliably (errors in the determining of the differential cross sections are about 4%). Finally, the differential cross sections of the $^{16}O(p,p)^{16}O$ were obtained with an error of about 5% by normalizing of $^{16}O(p,p)^{16}O$ yields to the normalization factor which was derived by normalizing of $^{27}Al(p,p)^{27}Al$ yields to the Rutherford cross sections for $^{27}Al(p,p)^{27}Al$.

Excitation functions and differential cross sections of elastic scattering of protons by ^{16}O, obtained in this work are given in Fig. 6a and Fig. 6b, respectively.

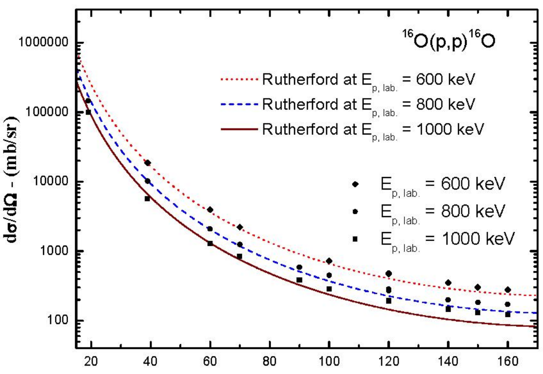

Fig. 6a - Angular distributions of the $p^{16}O$ elastic scattering. Symbols are the experimental data of present work, the curves - calculations by the Rutherford formula. The uncertainties are approximately the size of the points and about 5%

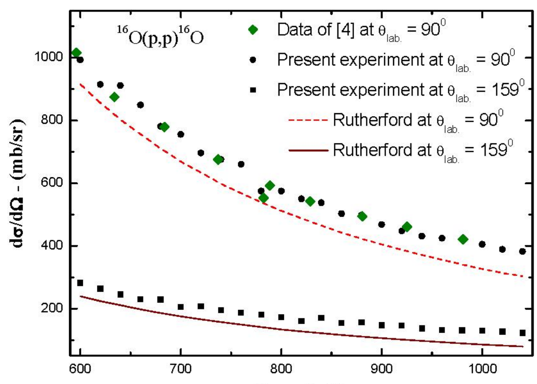

Fig. 6b - Excitation function of the $p^{16}O$ elastic scattering. Symbols are the experimental data of [4] and present work, the curves - calculations by the Rutherford formula. The uncertainties are approximately the size of the points and about 10% for work [4] and 5% for present work

Conclusion. Within the errors the results of our experiment coincide with the published data in the overlapping areas. At the angles of $\theta_{lab.} = 39^{\circ}, 60^{\circ}, 70^{\circ}$ and at the energies of $E_{p,\,lab.}$ = 600, 800 keV; and at

$\theta_{lab.}$ = 39°, 60° and at $E_{p,\ lab.}$ = 1000 keV the experimental cross sections coincide with Rutherford cross sections (with accuracy of 5%), while at the same energies and large angles, they are a little bit more than Rutherford. At the same time, for example, at $\theta_{lab.}$ = 159° and $E_{p,\ lab.}$ = 1000 keV the ratio of $\sigma_{ex.}/\sigma_R$ equal to 1.42 ± 0.07, which is in good agreement with published data.

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НОВЫЕ ИЗМЕРЕНИЯ ДИФФЕРЕНЦИАЛЬНЫХ СЕЧЕНИЙ ПРОЦЕССА УПРУГОГО РАССЕЯНИЯ $^{16}O(p,p)^{16}O$ ПРИ АСТРОФИЗИЧЕСКИХ ЭНЕРГИЯХ

Аннотация. Выполнен обзор и проведен анализ имеющихся в литературе экспериментальных данных по упругому рассеянию протонов на ядрах ^{16}O. Подробно описаны экспериментальный комплекс и измерительные методики настоящей работы. Представлены результаты новых измерений упругого рассеяния p^{16}O в неисследованных ранее областях энергий налетающих частиц от 0.6 до 1.0 МэВ и углового диапазона 19°-159°. Проведено сравнение полученных данных с дифференциальными сечениями, вычисленными по формуле Резерфорда. В перекрывающихся областях результаты настоящей работы согласуются с литературными данными. Также были измерены дифференциальные сечения процесса ^{27}Al(p,p)^{27}Al в тех же энергетическом и угловом диапазонах. Показано, что с точностью 4% полученные сечения ^{27}Al(p,p)^{27}Al совпадают с Резерфордовскими. Описана новая методика получения абсолютных значений дифференциальных сечений. Экспериментальные данные представленной работы могут быть востребованны для расчетов процессов происходящих в гибридных ядерных реакторах и термоядерных установках.

Ключевые слова: Экспериментальная установка, ускоритель УКП-2-1, упругое рассеяние, дифференциальные сечения, ^{16}O(p,p)^{16}O, ^{27}Al(p,p)^{27}Al.

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АСТРОФИЗИКАЛЫҚ ЭНЕРГИЯЛАРДА ^{16}O(p,p)^{16}O СЕРПІМДІ ШАШЫРАУ ПРОЦЕСІНІҢ ДИФФЕРЕНЦИАЛДЫҚ ҚИМАЛАРЫ БОЙЫНША ЖАҢА ӨЛШЕУЛЕР

Аннотация. ^{16}O ядроларынан протондардың серпімді шашырауы бойынша әдебиеттік мәліметтерге шолу жасалынды және алынған эпериментік мәліметтер талданды. Осы жұмыста эксперименттік кешен мен өлшеу әдістері толық сипатталған. Жұмыста 19°-159° бұрыштық диапазонда және 0,6 – 1 МэВ атқыланатын бөлшектің зерттелмеген энергия аймағында p^{16}O серпімді шашырау өлшеулерінің жаңа нәтижелері келтірілген. Резерфорд теңдеуімен есептелген дифференциалдық қима мен алынған мәліметтерге салыстырулар жасалынды. Жұмыста ұсынылған эксперименттік мәліметтер термоядролық қондырғыларда және гибритті ядролық реакторларда жүретін процестерді есептеулерде қолданылуы мүмкін.

Тірек сөздер: Эксперименттік қондырғы, УКП-2-1 үдеткіші, серпімді шашырау, дифференциалдық қима, ^{16}O(p,p)^{16}O, ^{27}Al(p,p)^{27}Al.