

MEASURING ANGULAR DISTRIBUTION OF DIFFERENTIAL CROSS-SECTIONS OF ELASTIC SCATTERING OF PROTONS BY 1P-SHELL NUCLEI AT ASTROPHYSICAL ENERGIES

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Introduction

Low and ultra-low energy nuclear physics is becoming more important because of the rapid development of nuclear astrophysics [1] where both differential and total cross-sections of elastic scattering are used actively alongside the optical potential parameters derived from their analysis.

Today nuclear astrophysics is faced with two major problems: 1) generation of chemical elements, from hydrogen to uranium, during the evolution of the Universe and the individual stars (cosmological nucleosynthesis), and 2) stellar energy dynamics during the synthesis of nuclei of light elements. In order to create adequate models of nucleogenesis in proton-nuclear and helion-nuclear collisions, and exothermic synthesis at low and ultra-low energies, which are characteristic of the synthesis and other nuclear reactions in evolving stars, accurate total cross-sections σ_t and total cross-sections of elastic scattering σ_{el} and non-elastic processes σ_{in} at low and ultra-low energies are needed. Parameters of nucleus-nucleus interaction potentials are applied in virtually all such calculations.

There is no information on elastic interaction of protons with light nuclei near or below the Coulomb barrier; moreover it is resonant.

The purpose of this research was to study angular distributions of differential cross-sections of elastic scattering of protons by a number of 1p-shell nuclei at low energies with a high accuracy of measuring the angle and energy, and determining the optimum parameters of optical potentials by analysis of data for a wide range of energies, with further calculation of integral and total cross-sections. Another goal was to determine how the cross-sections are influenced by structural peculiarities of light target nuclei.

Experiment

The angular distribution of differential cross-sections of elastic scattering of protons by ^{12}C , ^7Li and ^{16}O nuclei was measured using a beam in a UKP-2-1 accelerator at a projectile proton energy of $E_p = 350 \div 1050$ keV (at 350, 400, 450, 550, 750 and 1050 keV), which are of interest for nuclear astrophysics. At each energy level the angular distributions were measured at angles ranging from 30° to 170° with an increment of 10° .

Experiments to obtain angular distributions of elastic scattering differential cross-sections of protons by 1p-shell nuclei and further calculation of optical potentials for the nuclei require thin self-supporting targets of the respective isotopes (carbon, lithium and oxygen). A number of targets with ^{12}C , ^7Li and ^{16}O layers with a thickness of $\sim 20 \mu\text{g}/\text{cm}^2$ were made using the technique of vacuum evaporation by local heating of the specimen with a spot electron beam or direct heating of the spray.

Carbon was sprayed onto glass plates with previously placed layers of salt. After annealing for 12 hours at 150°C , the carbon films were removed from the glass plates and placed to specially prepared frames. For depositing zirconium oxide (to make oxygen targets), a magnetron target of high-purity metal (99.99 weight % Zr) was used; with the metal being produced by electron-beam melting. Zirconium was sprayed onto the support in an efflux of oxygen (20%) and argon (80%).

The lithium targets were made by spraying on a carbon support and later transferring to the central chamber through a special vacuum lock.

The thickness of the targets was measured using a special resonant chamber in the proton tube of the UKP-2-laccelerator, where the energy loss of the proton beam was measured when the beam passed through a self-supported target in the central chamber. The reaction $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ with a narrow resonance at $E_R=992$ keV was used and γ -quanta having an energy of $E_\gamma = 1779$ keV were registered. The thickness of the targets was determined by the shift of the resonance due to the energy lost by protons passing through the target placed before the aluminum film. This method allows the thicknesses of $10 \div 100 \mu\text{g}/\text{cm}^2$ to be measured with a minimum accuracy of 5%.

Analysis of experimental data on elastic scattering

The general approach to obtain information on the interaction potential complex particles with nuclei is phenomenological analysis of experimental data on elastic scattering based on the optical model of a nucleus. Such approach reduces the process of scattering by a multiparticle nucleus system to a simple process of scattering in a field of a complex optical potential $U(r)$ having the following form and value with the radial Woods -- Saxon relation:

$$U(r) = -V_R f(x_R) - i \left[W_V f(x_V) - 4W_D a_D \frac{df}{dr}(x_D) \right] + V_C(r), \quad (1)$$

where V_R and W_i are the depths of the real and imaginary parts of the potential with the radial relation $f(x_i) = (1 + \exp(x_i))^{-1}$, $x_i = (r - R_i) / a_i$, $R_i = r_i A^{1/3}$, $V_C(r)$ is the Coulomb potential of a uniformly charged sphere with a radius of $R=1,28A^{1/3}$ (fm). The potential only depends on the relative distance between the colliding nuclei and does not depend on the position of nucleons in the target nucleus.

Experimental data on elastic scattering of protons by such nuclei were analyzed applying the optical model and the standard software SPI-GENOA [2]. The parameters of the potential where the experimental and theoretical cross-sections match are found by minimizing the following value:

$$\chi^2 = \sum_{i=1}^N \left(\frac{\sigma_T(\theta_i) - \sigma_\Sigma(\theta_i)}{\delta\sigma_\Sigma(\theta_i)} \right)^2 \quad (2)$$

where N is the number of experimental points in the distribution, $\sigma_T(\theta_i)$ and $\sigma_\Sigma(\theta_i)$ are the calculated and measured differential cross-sections, correspondingly, for the angle θ_i , and $\delta\sigma_\Sigma(\theta_i)$ is the uncertainty of $\sigma_\Sigma(\theta_i)$.

In the research literature, experimental data on elastic scattering of protons by ^7Li nuclei were analyzed for energy values ranging from 0.45 to 155 MeV, by ^{12}C nuclei for energy values of 0.35-61.4 MeV and by ^{16}O nuclei for energy values of 0.35-135 MeV [3-7]. The initial values of the optical potential parameters were the values provided in the above-mentioned studies.

Global studies of the real and imaginary parts of the nuclear potential were done to find the relationships between the energy of incident protons and the mass numbers of the target nuclei. The optimal values of the radii of the optical potential were found (optical potential of protons on light nuclei). It was also shown that description of experimental data on elastic scattering of proton at energy values below 50 MeV is optimal with the surface absorption. The optimum depths of the spin-orbit potential were also found. It was shown that the spin-orbit interaction, if taken into account, effects only cross-sections at large angles.

Table 1 gives the values of optimum parameters of optical potentials for 1p shell nuclei for low energy levels, as found using the relationships, which are of interest for astrophysics.

Table 1. Optimum parameters of potentials of interaction between protons and light nuclei

E_p , MeV	Nucleus	V_R , MeV	r_R , fm	a_R , fm	W_D , MeV	r_{WD} , fm	a_{WD} , fm	V_{SO} , MeV	r_{SO} , fm	a_{SO} , fm
0.45	${}^7\text{Li}$	55.84	1.17	0.571	1.819	1.8	0.137	12.98	1.17	0.613
0.75		55.73	1.17	0.873	3.423	1.8	0.202	13.45	1.17	0.648
1.0		51.77	1.17	0.933	1.890	1.8	0.491	16.15	1.17	1.254
0.35	${}^{12}\text{C}$	62.23	1.15	0.584	9.651	1.25	0.320	6.656	1.15	0.296
0.40		61.15	1.15	0.695	9.651	1.25	0.241	6.656	1.15	0.316
0.45		60.89	1.15	0.698	11.10	1.25	0.208	8.272	1.15	0.306
0.55		55.26	1.15	0.858	11.99	1.25	0.164	7.774	1.15	0.288
0.75		54.83	1.15	0.861	12.36	1.25	0.178	7.814	1.15	0.888
1.05		51.16	1.15	0.972	12.98	1.25	0.268	8.992	1.15	0.612
0.350	${}^{16}\text{O}$	58.92	1.25	0.43	1.61	1.25	0.47	10.74	1.25	0.40
0.553		57.68	1.25	0.35	1.21	1.25	0.43	10.07	1.25	0.38
0.834		57.37	1.25	0.44	1.10	1.25	0.49	8.08	1.25	0.37
1.1		55.92	1.25	0.630	1.81	1.25	0.77	9.79	1.25	0.41

Figures 1-3 show the comparison between experimental and theoretical angular distributions of differential cross-sections of elastic scattering of protons; with the theoretical values being derived from the optical models for the ${}^7\text{Li}$, ${}^{12}\text{C}$ and ${}^{16}\text{O}$ nuclei.

The comparison shows a satisfactory match between the theoretical and experimental values, thus allowing their dependence on the energy and mass number to be considered with an adequate confidence.

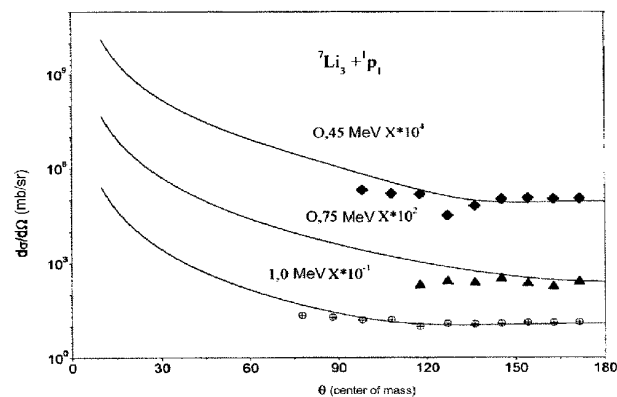


Fig 1. Angular distributions of differential cross-sections of elastic scattering of protons by the ${}^7\text{Li}$ nucleus. The symbols mark the experimental data, and the solid lines show the values computed using the optical model.

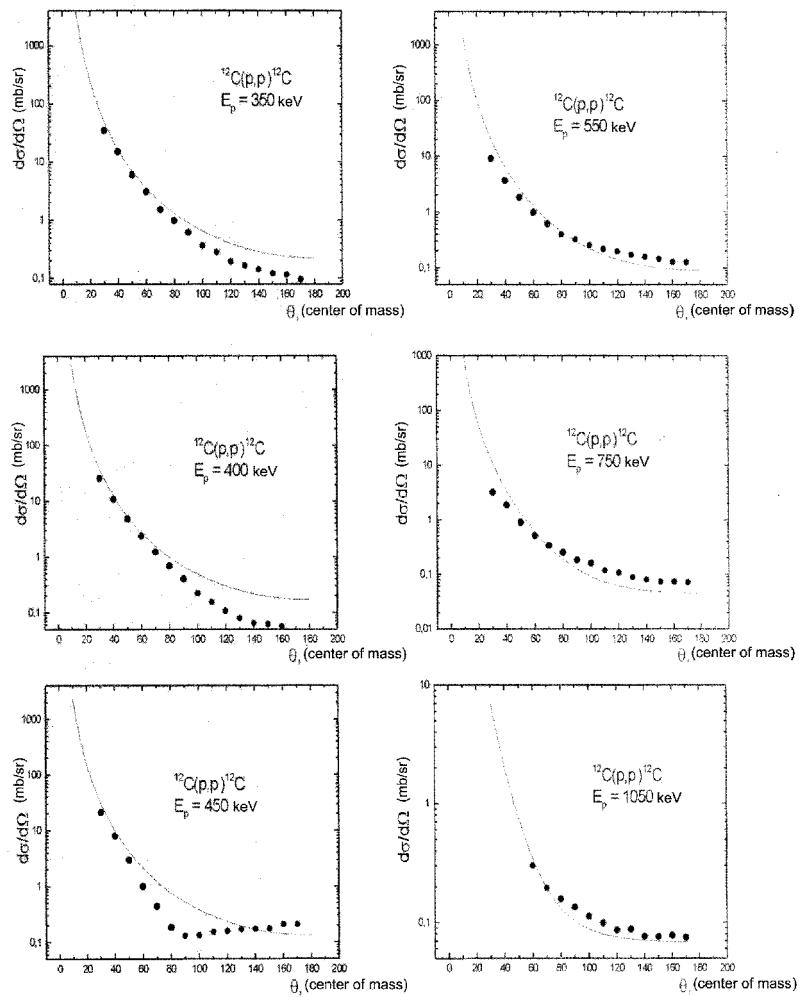


Fig 2. Angular distributions of differential cross-sections of elastic scattering of protons by the ^{12}C nucleus. The symbols mark the experimental data, and the solid lines show the values computed using the optical model

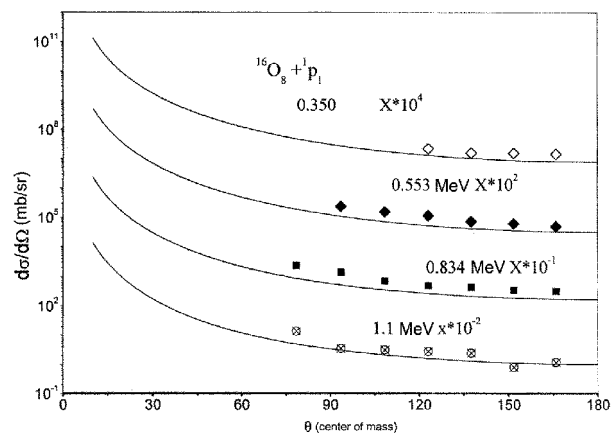


Fig 3. Angular distributions of differential cross-sections of elastic scattering of protons by the ^{16}O nucleus. The symbols mark the experimental data, and the solid line shows the values computed using the optical model.

Both international data and those collected by our team were systemized by total cross-sections of the studied nuclei using the optimum parameters of the optical potentials. With the energy level moving towards low and especially ultra-low values, sharp anomalies, such as narrow and wide resonance peaks, appear (e.g. see the total cross-sections of elastic scattering of protons by lithium and carbon nuclei in Figure 4.) In the upper part of Figure 4 the excitation levels of compound nuclei ^8Be and ^{13}N are shown. It is clear that the resonances generally match the energy levels of the compound nuclei, apparently being the main mechanism for forming the resonance in the excitation function.

Analysis of the specifics of the angular distribution of protons scattered by lightest nuclei shows that the angular distributions have the Fraunhofer form, except for the lowest energies.

In the study of the relationship between the tangent angular momentum and the trajectory and energy of the incident protons on the nuclei under consideration, a new phenomenon was revealed—a jump of the tangent angular momentum in the ultra-low energy range (Figure 5). This phenomenon can be explained by the influence of the Coulomb barrier. Indeed, calculation of the Coulomb barrier gives a value that matches the energy value at which the jump occurs.

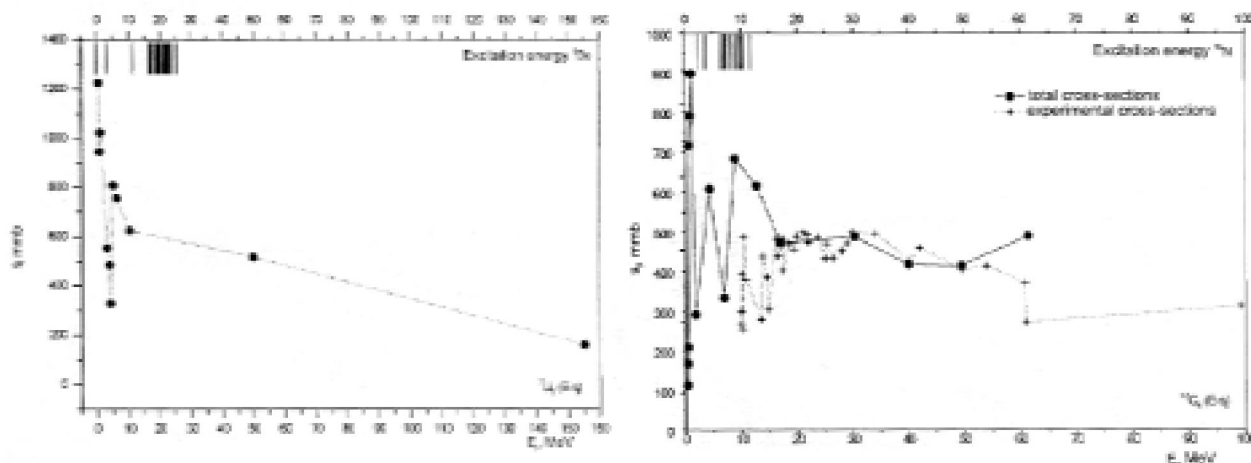


Fig 4. Total cross-sections of angular distributions of elastic scattering of protons by ^7Li (left diagram) and ^{12}C nuclei (right diagram)

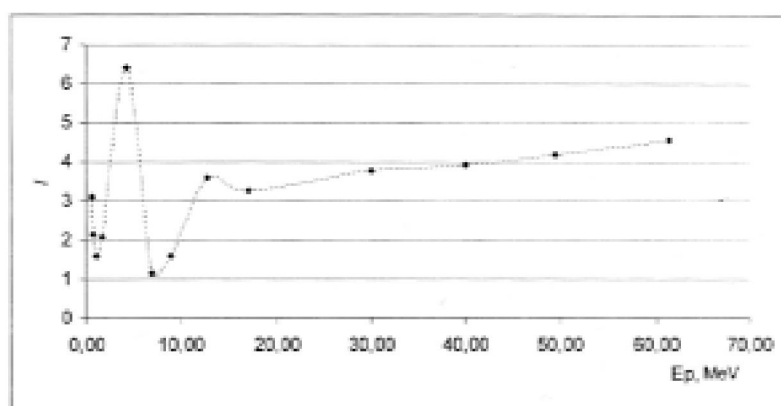


Fig 5. Relationship between the tangent angular momentum and the energy of incident protons

Conclusions

Experimental study of the differential and total cross-sections of elastic scattering of protons was conducted using an accelerated beam of protons in the UKP-2-heavy-ion accelerator. By gathering, analyzing and summarizing international data on elastic scattering of protons, regularities in the behavior of the mentioned cross-sections and parameters that characterize the structure and mechanism of the nuclear interaction were found. They are the following:

- For the first time experimental data on cross-sections of elastic scattering of protons by ${}^7\text{Li}$, ${}^{12}\text{C}$ and ${}^{16}\text{O}$ nuclei (angular distributions and excitation functions) were obtained for an energy range of 350-1000 keV.
- The optimum parameters of the nuclear potential for protons elastically scattered by 1p-shell nuclei were obtained; the general relationships between the optimum parameters of the optical model and the incident particle energy levels were approximated for the ultra-low energy range (100–1000 keV) taking in to account of the mass number of the target nuclei.
- Anomalies in total cross-sections (resonances), and their dependence on the energy of incident particles were found; they are explained by the presence of quantum levels of a compound nucleus system and by cluster specifics of the nuclear potential form.
- A new phenomenon of a jump in the angular momentum on the tangent line against the interaction trajectory surface was discovered, which is connected with the anomalous dependence of the radius of interaction between an incident proton and nuclei from the incident particle energy near the Coulomb barrier.

The results of this research may be used for obtaining systematic information on the differential and total cross-sections for energy levels from 300 keV to 155 MeV for any energy value by interpolating the optical model parameters taking account of the new data.

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