ELASTIC SCATTERING OF PROTONS FROM ^{12}C, ^{16}O, ^{27}Al

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ABSTACT

The differential elastic scattering cross sections for protons from ^{12}C nuclei have been measured for incident proton energies from 150 to 1203 keV, believed to be accurate to 10%, using a recently constructed precision scattering chamber. Excitation functions have been measured at the centre-of-mass angles 90^0 and 170^0 and angular distributions from 10^0 to 170^0 have been measured at 231, 344, 402, 443, 457, 470, 747, 975 and 1203 keV. The 1/2+ state in ^{13}N was observed near 457 keV in p-^{12}C scattering. A set of parameters has been derived for a global optical potential from elastic p-^{12}C scattering with present range of energy. The optical model predictions were tested with data from present experiment.

1. INTRODUCTION

Low and ultra-low energy nuclear physics is becoming more important because of the rapid development of nuclear astrophysics 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 evolution of the Universe and individual stars (cosmological nucleosynthesis), and 2) stellar energy dynamics during the synthesis of light elements' nuclei. 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 evolution stars accurate total cross sections and total cross sections of elastic scattering and non-elastic processes 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 and below the Coulomb barrier; moreover it is resonant.

H.N. Juckson *et al.* [1] have reported detailed measurements of the absolute differential cross section for the elastic scattering of protons by ^{12}C. The cross sections were measured at fixed angles ($\theta_{c.m.} = 169.2^0$, 148.9^0, 127.8^0 and 106.4^0) with the energy increasing in small steps. The quantity and accuracy of the data were sufficient to permit extraction of the experimental S wave phase shift from 400 to 1400 keV.
The purpose of this work is to present the information about absolute differential cross sections for the elastic scattering of protons by ^{12}C at the energy range, given at the center-of-mass system, from 213.2 to 1110.5 keV and optimal parameters of interaction potentials obtained from the analysis of the $^{12}C(p,p)^{12}C$ differential cross section angular distributions.

2. EXPERIMENTAL METHODS AND RESULTS

The electrostatic tandem accelerator UKP-2-1 at the Institute of Nuclear Physics in Almaty was used for our studies over the energy range from 150 to 1203 keV with proton beam currents from 1 to 150 nA. The characteristics of the accelerator have been described in a previous publication [2] and are available in the website http://www.inp.kz/structure/ukp/ukp.php?u=1#ac.

The energy calibration of the accelerator was tested during the course of the experiments using the well-known resonances [3, 4] of $^{27}Al(p,\gamma)^{28}Si$ at E_R = 632, 773, 992, 1089 keV and of $^{19}F(p,\alpha\gamma)^{16}O$ at E_R = 340 keV and is known to a precision of ± 1 keV. The proton energy spread of the accelerator is below 1.2 keV.
The photo of the experimental setup for our proton detection is shown in Fig. 1. The proton beam passed through beam-defining Collimator's system - two collimators (1.5 mm diameter) 42 cm downstream, and was formed onto the target (10 cm distance from last collimator) into a spot of about 1.5 mm diameter. The protons have been detected by means of solid-state detector, at a distance of 24 cm from the beam spot on the target and angles from 10^0 to 170^0 in the laboratory, in steps of 10^0. A second detector, placed at 160^0 with respect to the incident beam, was used as a monitor. A great care in the definition and collimation of the

proton beam allowed us to obtain an angular indeterminacy less than 1% in these experiments. The Faraday cup (cylinder: 1.5 cm diameter, 15 cm length) placed at a distance of 12 cm from the target was connected to a current integrator which shut off the counter recording circuits as soon as a predetermined charge (10 or 0.1 nanocoulombs) had been collected. So, the beam current was integrated, to within an uncertainty of 1.5%.

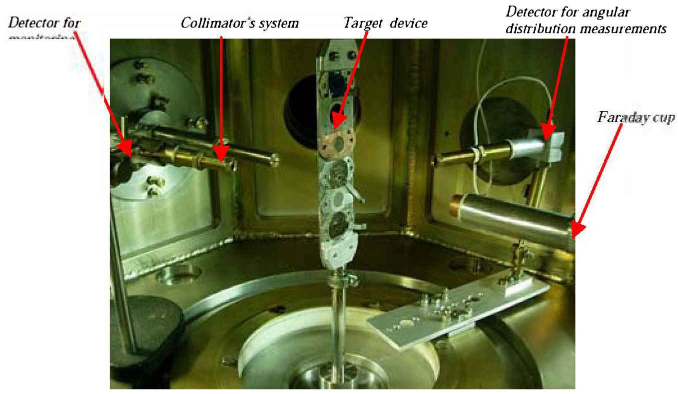

Fig. 1. The experimental setup for investigation of the scattering processes and reactions with charged-particles production.

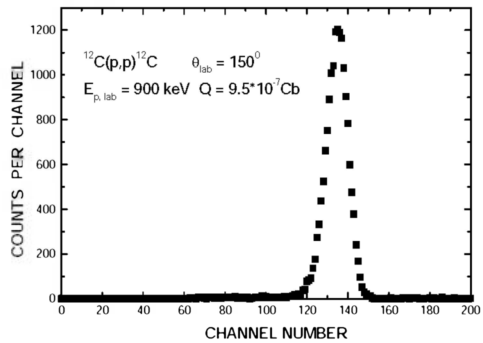

Fig. 2. The example of the proton – spectrum of the $^{12}C(p,p)^{12}C$ Elastic scattering, obtained by the charged-particle detector placed at the distance of 24 cm from the scattering region.

The target consisted of carbon foil 17.4 μg/cm^2 thick. The target thicknesses was taken from the shift of the resonance energy obtained by comparing the target yield curves over the $^{27}Al(p,\gamma)^{28}Si$ resonance at Ep = 992 keV (which has a total width of 0.10 keV) for an aluminum foil and an aluminum foil with the target placed before. Then stopping power tables [5] were used to obtain the atomic density of the carbon layer. This method allowed us to determine thicknesses of layers in the range of this experiment with an uncertainty less than 5%.

A Typical spectrum of protons is reported in Fig. 2. As one can see any impurities can be disregarded.
In the first part of the present experiment we measured the $^{12}C(p,p)^{12}C$ excitation function from 150 to 1203 keV at two different scattering angles of 90^0 and 170^0 in the center-of-mass system. At these angles observations were made every twenty keV except the region near 457 keV resonance of $^{12}C(p,\gamma)^{13}N$ reaction where measurements were made with the energy varying in five keV step. The good agreement of the present data for the excitation function at the angle of 170^0 with the data [1] for the same angle is shown in Fig. 3, with data from [1] read from the figure in that work.

Angular distributions were measured at incident proton energies E_p = 231, 344, 402, 443, 457, 470, 747, 975 and 1203 keV. The results are shown in Fig. 4, together with the optical-model predictions and Rutherford scattering.

The differential cross sections for the elastic scattering were determined using the relation

$$N_{p,scatt} = N_p\, N_C\, d\sigma/d\Omega \qquad (1)$$

where N_p is the number of incident protons, N_C is the number of ^{12}C atoms/sm^2 and $N_{p,\,scatt}$ is the number of counts, observed for the elastic scattering.

The overall uncertainties in the absolute cross sections reported here were no more than 10% and obtained, using the relation

$$\delta(d\sigma/d\Omega) = (\delta N_p^{\,2} + \delta N_{p\,,scatt}^{\,2} + \delta N_C^{\,2})^{1/2} \qquad (2)$$

where δN_p is the error in the determination of incident protons number (δN_p = 1.5%), $\delta N_{p\ scatt}$ is the error in the determination of the counts number, observed for the elastic scattering ($\delta N_{p,\,scatt}$ = 2 - 3%) and δN_C is the error in the determination of the ^{12}C atoms/sm^2 number (Uncertainties in the uniformity of thickness, counting statistic and determination of additional carbon deposition during bombardment lead to an overall uncertainty of δN_C = 8%).

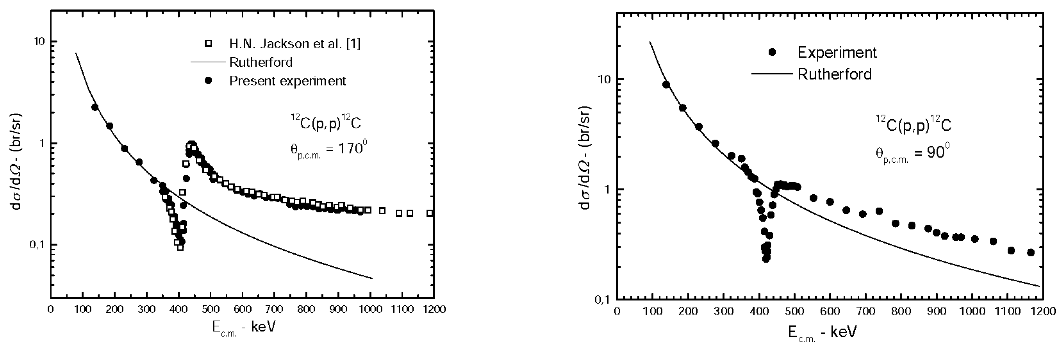

Fig. 3. Elastic scattering excitation functions of $^{12}C(p,p)^{12}C$ at $\theta_{c.m.}$ = 170^0 (left diagram) and $\theta_{c.m.}$ = 90^0 (right diagram). The lines are the result of Rutherford calculation, the circle solid points are the present experiment data, the square open points are the data obtained by H.N. Jackson et al. [1]. The uncertainties are approximately the size of the points and better than 10%.

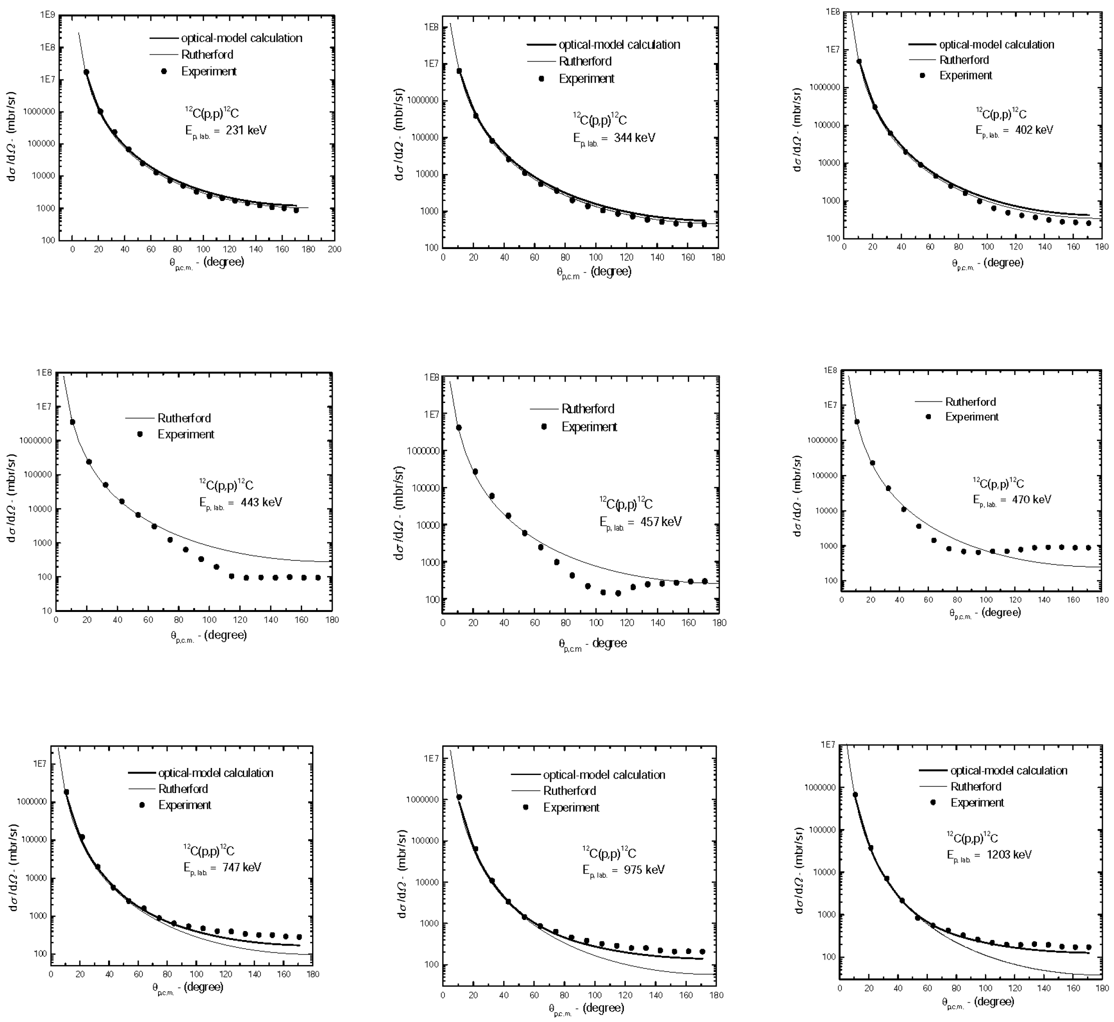

Fig. 4. Absolute differential cross sections for the elastic scattering of protons by ^{12}C. The points are the experimental data, the thin curves were calculated from the Rutherford expression, and the thick curves represent optical-model calculations obtained with the parameters given in Table 1. The uncertainties are approximately the size of the points and better than 10%.

3. ANALYSIS OF RESULTS

The angular distributions have been analyzed on the basis of the optical model. The parameters we have used are listed in Table 1. They have been determined by means of the code ECIS88 [6], assuming as starting set the parameters reported in work [7] and presented in the Table 2. No energy dependence of the parameters was taken into account, due to the small energy range covered by our measurements. The details of the calculation have been described in work [8].

The thick solid curves in Fig. 4 represent the results of these calculations. As is clear, the agreement between theory and experiment is satisfactory at all energies, except the energies near the 457 resonance of the $^{12}C(p,\gamma)^{13}N$ reaction.

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}, MeV
53	1.4	0.75	2	1.25	0.4	7	1.4	0.5

Table 1. Optical-model parameters from these calculations.

V_R, MeV	r_R, fm	a_R, fm	W_D, MeV	r_{WD}, fm	a_{WD}, fm	V_{SO}, MeV
53	1.4	0.75	7	1.25	0.4	6.2

Table 2. Optical-model parameters from work [7].

The optimal values of the radii of the optical potential were found (optical potential of protons on ^{12}C). It was also shown that description of experimental data on elastic scattering of proton at low energy is optimal with the surface absorption. The optimum depths of the spin-orbit potential were found. It was shown that the spin-orbit interaction, if taken into account, effects only cross-sections at large angles.

4. CONCLUSION

At the UKP-2-1 accelerator the differential elastic scattering cross sections for protons from ^{12}C have been measured for incident proton energies from 150 to 1203 keV, believed to be accurate to 10%.

A set of parameters has been derived for a global optical potential from elastic p-^{12}C scattering with present range of energy.

The obtained values of the optical potential parameters going to be used in the $^{12}C(p,\gamma)^{13}N$ reaction cross section calculations.

The complex phase shifts will be obtained to represent the elastic scattering cross sections.

5. REFERENCES

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