Cross sections of $^4$He interaction with protons at 5 GeV/c

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Abstract

The total and topological $^4$He protons interaction cross sections as well as the cross sections of the separate $\alpha p$ interaction channels and the differential cross sections $d\sigma/dt$ of the elastic $\alpha p$ scattering were measured using the 2m hydrogen bubble chamber exposed to a separated beam of $\alpha$ particles from the ITEP synchrotron at 5 GeV/c (the kinetic energy of the initial protons in the nuclear rest frame was $T_p = 620$ MeV). The data obtained have been compared with the results of the previous experiments and with the theoretical predictions based on the Glauber-Sitenko multiple-scattering theory.

The systematic investigations of the nuclear reactions in the few-nucleon systems at intermediate energies have been carried out in ITEP for the last few years by making use of the lightest nuclei ($^3$H, $^3$He, $^4$He) as a beam and a liquid-hydrogen bubble chambers (80 cm and 2 m) as a target (see e.g. [1] for bibliography and background). In [1] we reported the data on the cross sections of $^4$He interaction with protons and $\alpha p$-elastic scattering below the pion production threshold in the elementary NN process. The momentum of the $^4$He nuclei averaged over the bubble chamber fiducial volume was equal to 2.7 GeV/c (the kinetic energy of the initial protons in the nuclear rest frame was $T_p = 220$ MeV). Now we
present some new data on the αp interaction cross sections at 5 GeV/c ($T_p = 620$ MeV) where the pion production is strong enough. The data on the cross sections of the separate $^4$He-p interaction channels at this energy range were obtained for the first time. The data on the total and differential cross sections of the αp scattering were compared with the results of the previous experiments at the considered energy range as well as the Glauber-Sitenko multiple-scattering theory predictions. Note that the present experiment is the only one based on non-electronic techniques at this energy range.

The 2m liquid-hydrogen bubble chamber was exposed to a separated beam of α-particles from the ITEP synchrotron at 5 GeV/c momenta. About 120000 pictures were received with an average of about 8 initial particles for the chamber extension. About 18000 events were measured. The peculiarities of the experimental procedure can be found in [1].

The total cross section is defined as follows

$$\sigma_{\text{tot}} = \frac{1}{n l} \frac{1}{1 - \frac{N_{\text{int}}}{N_0}}$$  \hspace{1cm} (1)$$

where $n$ is the number of hydrogen nuclei in 1 cm$^3$, $l$ is the fiducial length, $N_0$ is the number of initial tracks, $N_{\text{int}}$ is the total number of interactions in the fiducial volume taking into account the systematic loss of two-prong events.

The two- and three-prong αp events were identified with the help of kinematic analysis and track ionization measurement. A correction was introduced for the loss of two-prong events with a large dip angle. This correction was determined from the distribution on the angle between the plane of the event and the plane passing through the initial track and the vector directed along the magnetic field in the chamber. The loss of inelastic two-prong events was $\sim 14\%$. The loss of the elastic scattering events with short recoil-proton track for $|t| < 0.03$ (GeV/c)$^2$, where the differential cross sections have not been determined, was evaluated extrapolating the data in the interval 0.035 < |t| < 0.1 (GeV/c)$^2$ on the exponential function to the region $|t| < 0.03$ (GeV/c)$^2$. The differential elastic cross section for $|t| < 0.01$ (GeV/c)$^2$ has not been measured due to poor statistic.

The topological cross sections, the number of events in each channel and the cross sections of the αp reactions at 5 GeV/c are presented in Table 1 (only statistical errors are indicated).

The total αp-interaction cross section is equal to $121.5 \pm 2.9$ mb (the error is statistical only). The systematic error in the absolute normalization of the cross section is $\sim 3\%$.

The differential cross sections of the αp elastic scattering at 5 GeV/c are presented in Table 2. These data can be very well parameterized by the exponential function $\frac{d\sigma}{dt} = Ae^{Bt}$ with $A = (9.4 \pm 0.5) \times 10^2$ mb/(GeV/c)$^2$ and $B = 31 \pm 1$ (GeV/c)$^{-2}$ ($\chi^2/\text{NF} = 0.4$).
Table 1: Topological cross sections and the cross sections of separate $\alpha p$ interaction channels at 5 GeV/c momentum ($T_p = 620$ MeV).

| Topology of event | Topological cross section (mb) | Channel | Number of events | Cross section (mb) |
|-------------------|--------------------------------|---------|------------------|--------------------|
| 2*                | 59.9±2.8                       | $^{4}\text{Hep} \rightarrow ^{4}\text{Hep}$ | 1695             | 31.4±2.8           |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{3}\text{Hepn}$ | 2507             | 22.2±0.4           |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{4}\text{Hep}\pi^+$ | 233              | 2.0±0.1            |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{4}\text{Hep}\pi^0$ | 295              | 2.6±0.2            |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{3}\text{Hepn}\pi^0(\pi^0)$ | 97               | 0.80±0.08          |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{3}\text{Hep}\pi^0$ | 59               | 0.50±0.07          |
| 3*                | 60.2±0.7                       | $^{4}\text{Hep} \rightarrow ^{3}\text{Hpp}$ | 1952             | 16.1±0.4           |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{d}\text{dp}$ | 335              | 2.8±0.2            |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{d}\text{dppn}$ | 2567             | 21.2±0.4           |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{d}\text{ppppn}(\pi^0)$ | 1394            | 11.5±0.3           |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{d}\text{Hd}\pi^+$ | 101              | 0.80±0.08          |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{d}\text{Hpp}\pi^+$ | 362              | 3.0±0.2            |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{d}\text{ddn}\pi^+$ | 79               | 0.65±0.07          |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{d}\text{dppn}\pi^+(\pi^0)$ | 128            | 1.10±0.09          |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{d}\text{ppppn}\pi^+(\pi^0)$ | 79              | 0.65±0.07          |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{d}\text{Hpp}\pi^0$ | 117              | 1.00±0.09          |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{d}\text{dp}\pi^0$ | 53               | 0.40±0.06          |
|                   |                                | $^{4}\text{Hep} \rightarrow ^{d}\text{dppn}\pi^0(\pi^0)$ | 93              | 0.80±0.08          |

$4^* - 5^*$ 1.4 ± 0.1
Table 2: Differential cross sections of the $^\alpha p$ elastic scattering at 5 GeV/$c$ ($T_p = 620$ MeV).

| $t$ (GeV/$c$)$^2$ | $\frac{d\sigma}{dt}$, mb/(GeV/$c$)$^2$ |
|-------------------|----------------------------------------|
| 0.035             | 311±19                                 |
| 0.045             | 246±15                                 |
| 0.055             | 172±13                                 |
| 0.065             | 134±12                                 |
| 0.075             | 97±10                                  |
| 0.085             | 70±8                                   |
| 0.100             | 52±5                                   |

For the theoretical interpretation of the elastic scattering data we use the Glauber-Sitenko multiple-scattering theory taking into account the spin-isospin structure of the NN scattering amplitude which is the simple generalization of the conventional Glauber theory for non-diffractive NN scattering.

The details of the present theoretical approach are given in [1]. In our present calculations we also use a parameterization of the $^4$He nuclear ground-state density in the gaussian form $\rho(r) \sim \exp(-r^2/R^2)$ with $R = 1.25$ fm [1].

Figure 1 shows the differential cross sections $\frac{d\sigma}{dt}$ of the $^4$Hep elastic scattering at 5 GeV/$c$ momentum ($T_p = 620$ MeV) and the results of calculations in the framework of the Glauber-Sitenko multiple-scattering theory taking into account the spin-isospin structure of the NN scattering amplitude (curve). For comparison, the $^4$He elastic scattering data at $T_p = 500$ MeV [3], 560 MeV [4], 587 MeV [5], 600 MeV [6], and 695 MeV [7] are also shown here. As can be seen from the Figure the shapes of the experimental distributions for all these experiments are quite similar. All data are in good agreement. Note that the independent experiments based on the different experimental techniques give very close results. The multiple scattering theory perfectly describes the shape of the distribution but the theoretical curve is slightly below the experimental data.

The total $^\alpha p$ cross section obtained in this experiment at $T_p = 620$ MeV ($\sigma_{tot} = 121.5\pm 2.9$ mb) is in good agreement with the result of [7] at $T_p = 563$ MeV, $\sigma_{tot} = 123.7\pm 0.9$ mb. Some discrepancy with the theoretical value for total cross section calculated through the optical theorem ($\sigma_{tot}^{th} = 113.4$ mb at $T_p = 620$ MeV) is caused by the accuracy of the theoretical scheme used here (see [1] for details).

The main results of the paper are as follows.
(i) Using a 2m ITEP liquid-hydrogen bubble chamber exposed to a separated beam of $\alpha$ particles with 5 GeV/c momentum ($T_p = 620$ MeV) we have measured the total, topological $\alpha p$ cross sections as well as the cross sections of separate $\alpha p$ interaction channels. The data on the cross sections of the $\alpha p$ reaction channels at this energy range were obtained for the first time. The value of total $\alpha p$ cross section obtained in present experiment is in good agreement with the data from the literature.

(ii) The data on the $\alpha p$ differential cross sections are in good agreement with the previous data at the considered energy range and with the multiple-scattering theory predictions as well.

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Figure 1: The differential cross section of the reaction $^4\text{He} \rightarrow ^4\text{He}$. ○ — our data ($T_p = 695$ MeV); ◊ — data from ref. 2 ($T_p = 500$ MeV); △ — data from ref. 3 ($T_p = 560$ MeV); ▽ — data from ref. 4 ($T_p = 587$ MeV); □ — data from ref. 5 ($T_p = 600$ MeV); ◯ — data from ref. 6 ($T_p = 695$ MeV). The solid line corresponds to the theoretical predictions (at $T_p = 620$ MeV) based on the Glauber-Silenko multiple-scattering theory taking into account the spin-isospin structure of the NN scattering amplitude.