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Study of $p + d \rightarrow\ ^3A + \pi$ reactions in the Δ-resonance region

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Abstract. A stack of annular detectors made of high-purity germanium was used to measure $p + d \rightarrow\ ^3\mathrm{He} + \pi^0$ and $p + d \rightarrow\ ^3\mathrm{H} + \pi^+$ differential and total cross-sections at beam momenta from 900 MeV/c to 1050 MeV/c. The total cross-sections are consistent with Δ-excitation. The differential data consist of two components. One corresponds to large momentum transfer from the projectile to the pion, the other to small momentum transfer. The former shows an independence of the slope as a function of the momentum transfer t (scaling). The scale parameter is different for π^+ and π^0 emission which violates isospin symmetry. The second component which is almost isotropic is in agreement with isospin symmetry. It is approximately a quarter of the total yield in the Δ-resonance region.

PACS. 25.10.+s Nuclear reactions involving few-nucleon systems – 25.40.Qa (p,π) reactions – 25.70.Ef Resonances

1 Introduction

The study of pion production in $p+d$ collisions is expected to provide information about the underlying reaction dynamics. Various reaction mechanisms involving different number of nucleons as well as the response of the bound residual nuclei to high momentum transfers should be considered. The deuteron is a loosely bound system making it an ideal case for the use of impulse approximation. Also the knowledge of wave functions for $A = 2$ and $A = 3$ nuclei allows a more accurate treatment. At the experimental side, data for $pd \rightarrow\ ^3\mathrm{He}+\pi^0$ reaction exist near threshold ($\eta < 0.5$) where only the S-wave pion production is important and near the resonance region ($\eta \simeq 1.5$) where the Δ-resonance is the dominant one. The data in the intermediate region, where S-D interference is expected to be large, are missing. The present experiments are performed to bridge the gap between these two intervals. The simultaneous detection of $pd \rightarrow\ ^3\mathrm{H} + \pi^+$ is also performed to investigate one of the most interesting aspects of strong interaction —the isospin invariance.

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2 GEM detectors and target system

The experimental technique and methods are unique and differ from the ones used to study the above-mentioned reactions. This new experimental design enabled a large-angular-acceptance (full-solid-angle) measurement with a very good energy resolution [1]. The measurements were performed with the Germanium Wall of the GEM detector system. It is a stack of annular diodes made of high-purity

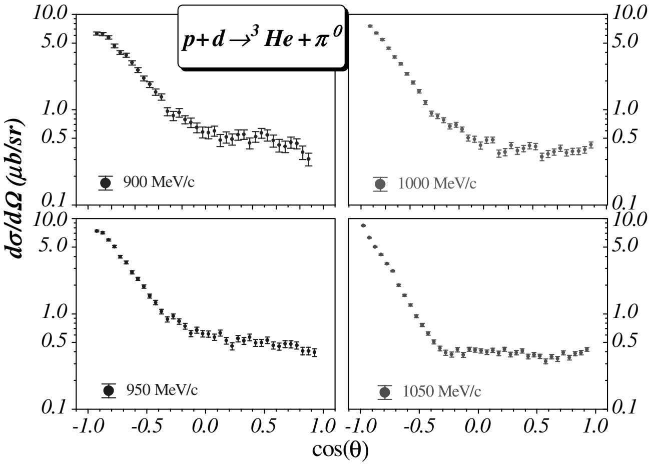

Fig. 1. Differential cross-sections for the $p + d \to {}^3\text{He} + \pi^0$ reaction as a function of the cosines of the angle of the recoiling ^{3}He. The beam momenta are indicated in the figure. All quantities are in the cm system.

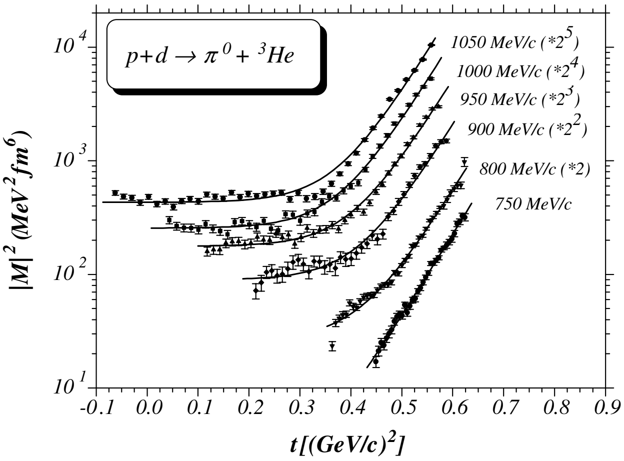

Fig. 2. Matrix elements squared fitted by eq. (1). The data are shown by dots and the fitted functions by solid curves. The laboratory beam momenta and scale factors are given next to the appropriate data.

Ge. The first detector (ΔE, quirl) is position sensitive segmented with 200 Archimedes spirals of opposite orientation on the front and rear sides. Each spiral from the front side crosses one spiral on the rear side defining thus 40000 pixels of sizes between 0.01–0.1 mm^2. The quirl detector is 1.3 mm thick with a 5.8 mm diameter hole in the centre. It was followed by two E detectors (pizzas) segmented into 32 wedges. Each of these pizzas was 15 mm thick. The detector system accepts particles emitted between 50 and 290 mrad. In the present experiment a thinner 2.2 mm liquid-deuterium target was used compared to the 6.4 mm applied in previous one [2].

3 Results on $p + d \to {}^3\text{He} + \pi^0$ and $p + d \to {}^3\text{H} + \pi^+$ reactions

The counts were lumped for each CMS angular bin as a function of CMS momenta or missing mass. Gaussian and smooth polynomial were fitted to the resulting spectra in order to separate the background. Finally the integrated counts in the Gaussians were converted to differential cross-sections. For ^{3}He the results are illustrated in fig. 1.

The proper theoretical description of data taken in full-solid-angle arrangement may lead to a revision of the deuteron model, *e.g.* to match the angular distribution the isovector component should be included into the deuteron [3].

The CMS angular distributions of ${}^3A$ at lower energies are backward peaked —with an almost exponential slope. With increasing collision energy an isotropic component appears. This happens at large momentum transfers from the projectile to the ion. In order to study these two components the matrix element squared $|M(t)|^2 \propto \mathrm{d}\sigma/\mathrm{d}t$, t being the four-momentum transfer squared from proton to pion, was fitted with a function

$$|M(t)|^2 = a \exp(bt) + c. \qquad (1)$$

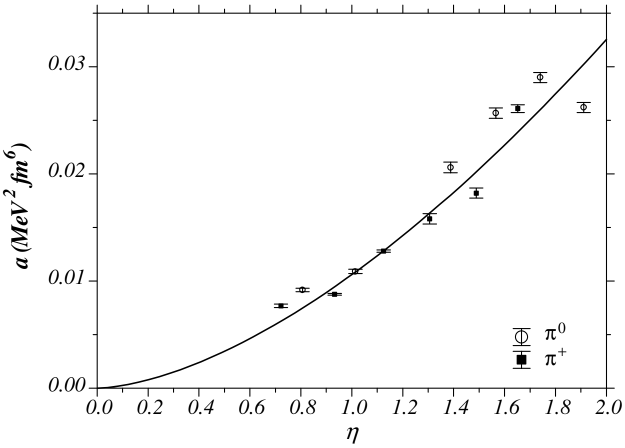

Fig. 3. The fit parameter a as a function of the pion centre of mass momentum $\eta = p^*_\pi/m_\pi$ with fixed value for b. The solid curve is to guide the eye.

The fit results in rather parallel slopes (see fig. 2):

$$b = 16.87 \pm 0.17\ (\mathrm{GeV}/c)^{-2} \quad (\chi^2/\mathrm{ndf} = 0.5) \quad \text{for} \quad \pi^0,$$
$$b = 18.71 \pm 0.34\ (\mathrm{GeV}/c)^{-2} \quad (\chi^2/\mathrm{ndf} = 3.2) \quad \text{for} \quad \pi^+.$$

The errors of the slope values b are 1% for π^0 and 2% for π^+ although the dimensionless variable $\eta = p^*_\pi/m_\pi$ changes more than 1 unit for π^0.

In the fitting procedure further on parameter b was fixed and a and c varied freely. The results are shown as functions of the dimensionless variable η. The values of a, as can be seen in fig. 3, increase with increasing pion CMS momenta and at a given beam energy they are slightly smaller for π^+ than for π^0.

The fitted values for c seem to fulfill the isospin symmetry. The fit results for ${}^3\text{He} + \pi^0$ final states in fig. 4 are multiplied by isospin factor 2. Obviously, the results obey this symmetry within the error bars. A smooth curve is fitted to the data to guide the eyes. The maximum at $\eta \approx 1.3$ is below the Δ-resonance.

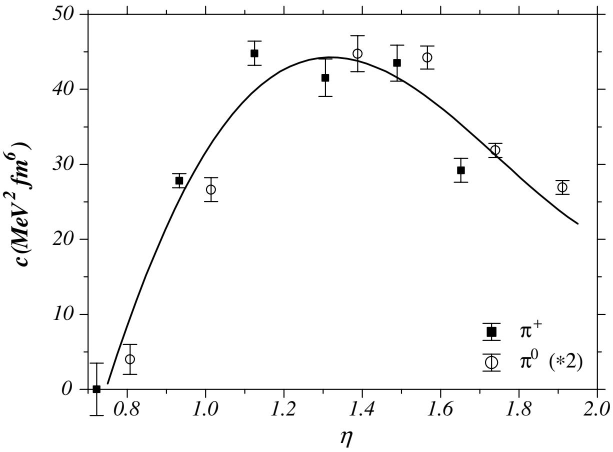

Fig. 4. Same as fig. 3, but for the parameter c.

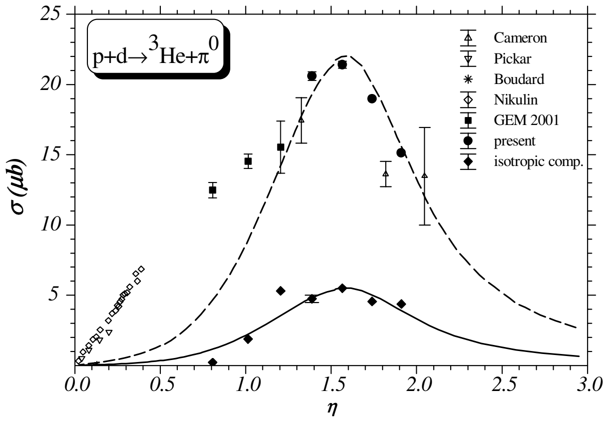

Fig. 5. Excitation function for the $p + d \to\ ^3\mathrm{He} + \pi^0$ reaction.

In the Glauber approach applied to meson production on nuclei [4] the steep raising component is due to coherent, while the almost isotropic component is connected with incoherent meson production. The slope parameter is in a simple relation with the strong absorption radius (R) of the optical model $R = 2\sqrt{b}\ \hbar c$. For π^0 channels one gets $R = 1.622 \pm 0.008$ fm and for π^+ the radius is $R = 1.708 \pm 0.016$ fm. It is interesting to note that a similar analysis of the elastic $p + d$ scattering at 1 GeV/c [5] yields $b = 15.4 \pm 1.3$ (GeV/c)$^{-2}$ and an absorption radius of 1.55 ± 0.07 fm.

Most models applied to the present reactions are variations of the so-called spectator model [6]. The t-dependence is due to a form factor containing the deuteron and ^3A wave functions and the more elementary $NN \to d\pi$ cross-section. One would naively expect R to scale with the ^{3}He and ^{3}H wave functions. However, the present finding is in contrast to the results for the charge radii from electron scattering [7] $r_{\mathrm{ch}}(^3\mathrm{He}) = 1.959 \pm 0.030$ fm $>$ $r_{\mathrm{ch}}(^3\mathrm{H}) = 1.755 \pm 0.086$ fm. Since the Coulomb energy between π^+ and ^{3}H is rather small, the present effect is more likely due to the Coulomb force between the two protons in the ^{3}He wave function. In the entrance channel we are dealing with the same system. Therefore, another possibility for the different radii may be different forces between the pions and the ^3A systems for the present partial waves involved.

Reaction cross-sections were extracted fitting Legendre polynomials to the angular distributions. The found cross-sections and the world data are shown in fig. 5 as functions of η for the case of the $p + d \to\ ^3\mathrm{He} + \pi^0$ reaction, where existing data are primarily in the threshold region. The present data are shown as full dots, those from refs. [8–11, 2] by the indicated symbols. The dashed and full curves are the $p + p \to d + \pi^+$ cross-sections scaled down by factors of 145.4 and 581.6, respectively. The points near the full curve represent the isotropic component of the cross-section. For the reaction $p+d \to\ ^3\mathrm{H}+\pi^+$ there were more data mainly from pion absorption. The excitation function in fig. 5 for the $p+p \to d+\pi^+$ reaction exhibits a wide peak around $\eta \simeq 1.6$ caused by Δ-excitation. The ^3A cross-sections follow in the peak region the same dependence.

The data points around the full curve correspond to the extracted contributions of the isotropic part and are approximately 25% of the reaction cross-section. The momentum dependence again follows the Δ-resonance excitation. The underlying reaction mechanism is presently unclear. It must be of a more complicated origin than the exponential part, since it is almost independent of the momentum transfer. Its onset at a certain collision energy and its coupling to the Δ may shed light on this reaction mechanism.

4 Summary

Diffferential and total cross-sections for the reactions $p + d \to\ ^3\mathrm{He} + \pi^0$ and $p + d \to\ ^3\mathrm{H} + \pi^+$ were measured in the Δ-excitation region. The CMS angular distributions show two components: one strongly increasing with momentum transfer to the pion and a smaller one almost independent of momentum transfer. Parametrization of

$$\mathrm{d}\sigma/\mathrm{d}t = \tilde{a}\exp(bt) + \tilde{c}$$

yields constant values of slopes, but different for the two reactions. The slope parameters seem to carry more isospin information than a_1. The reaction mechanism behind the $a_1 \simeq$ const must be of more complicated nature than the exponential part, since it is independent of momentum transfer. Its onset at $\eta \approx 0.9$ corresponds to the threshold for the free $NN \to d\pi$ and needs further studies.

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