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STUDY OF η-MESON PRODUCTION IN $\mathbf{d}d \to {}^4He\eta$ REACTION

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Abstract The $\mathbf{d}d \to {}^4He\eta$ reaction has been investigated at 2.39 GeV/c beam momentum. The total cross sections for polarized and unpolarized beam have been measured as well as the differential cross sections for $cos\theta_{cm} > 0$. The cross-sections reveal strong anisotropy indicating excitation of higher partial waves at this energy.

1 Physics Motivation

Over the last years production of η meson in nucleon-nucleon interactions at energies close to threshold has been extensively investigated [1]. Extension

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of the measurements to meson production in proton-deuteron and deuteron-deuteron scattering has offered a good opportunity to study the possible multi step production processes [2, 3] as well as the possible existence of eta-nucleus quasi-bound states. Data on $pd \to {}^3He\eta$ [4–6] and $dd \to {}^4He\eta$ reactions obtained in several laboratories could be interpreted as suggesting existence of bound states in eta-helium system [7–9]. The goal of $\mathbf{d}d \to {}^4He\eta$ reaction investigation at 2.39 GeV/c beam momentum (reaction excess energy in the center-of-mass system $Q = 17.5\ MeV$) is to provide the absent measurements at energies well above the threshold and at different polarization modes of the beam. The polarized beams allow determination of the angular distributions of respective analyzing powers and relative magnitudes of higher partial waves admixtures to the production dynamics.

2 Experiment

The measurement of reaction $\mathbf{d}d \to {}^4He\eta$, has been performed with polarized deuteron beam delivered by the COSY accelerator in Forschungszentrum Jülich, Germany with deuteron beam momentum 2390 MeV/c (deuteron kinetic energy $T_d = 1160\ MeV$, excess energy in the center-of-mass system $Q = 17.5\ MeV$, eta c.m. momentum $(p_\eta)_{cm} = 134\ MeV/c$). Available polarization states during this first measurement were: unpolarized beam and polarized one with polarization states: P_z=–1/3 and $P_{zz} = \pm 1$. In a Cartesian coordinate system, vector and tensor polarizations are defined as: $P_z = (N_+ - N_-)/(N_+ + N_0 + N_-)$ and $P_{zz} = (N_+ - 2N_0 + N_-)/(N_+ + N_0 + N_-)$, where N_+, N_- and N_0 denote the number of deuterons with spin projection +1, –1 and 0, respectively. The axis of polarization is perpendicular to the accelerator ring. The vector polarization of the deuteron beam has been measured with a low energy polarimeter in the injection beam line utilizing elastic scattering from a carbon target and obtained values are: $P_z = -0.32 \pm 0.02$ for the case of $P_{zz} = +1$, and $P_z = -0.33 \pm 0.02$ for $P_{zz} = -1$. The tensor polarization has been determined in this experiment measuring of the $d\mathbf{p}$ backward elastic scattering reaction at θ_{cm}=180^0 [10]. Outgoing deuterons have been identified by energy losses and time-of-flight measurements in the focal plane of the Big Karl magnetic spectrometer. The P_{zz} has been obtained using our value for the above cross-section, and the value of tensor analyzing power T_{20} measured at 180^0 in broad energy interval including our energy. The measurement [10] has given the following values for the tensor polarization: $P_{zz} = -0.60 \pm 0.11 \pm 0.01$ for nominal tensor polarization –1 and $P_{zz} = 0.81 \pm 0.14 \pm 0.01$ for tensor polarization +1. Here the first error is statistical one and the second one accounts for systematics.

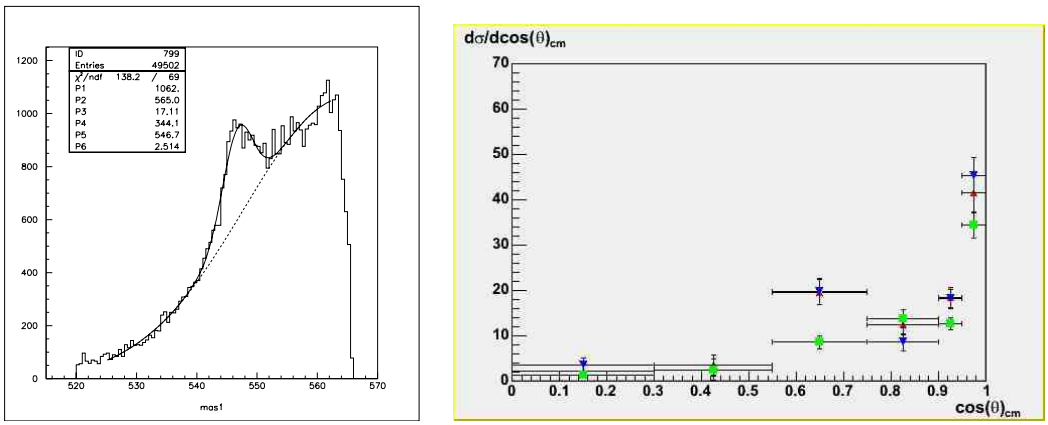

Figure 1: *Left panel:* Missing mass distribution for $P_{zz} = +1$. *Right panel:* Differential cross-sections for unpolarized and $P_{zz} = \pm 1$ beam.The blue down and red up triangles denote the differential cross-sections for tensor polarization -1 and +1 and the green squares denote the unpolarized differential cross-sections.

Helium nuclei from the reaction $\mathbf{d}d \to {}^4He\eta$ have been detected with Big Karl magnetic spectrometer [11]. Its momentum acceptance is $\pm 4.5\%$ of the central value and for this experiment the central value has been chosen in such a way that particles with $cos\theta_{cm} > 0$ are registered. Particle tracks are measured with two packs of multi-wire drift chambers allowing precise determination of their positions and angles in the focal plane.Two scintillator hodoscope layers located behind the focal plane, 3.8 m apart of each other, provide energy loss and time-of-flight measurement, as well as a start signal for the drift chambers. After selection of tracks belonging to alpha particles we have reconstructed their four-vectors at the target. Small correction, of about 2 MeV in average, for energy losses in the 4 mm thick liquid deuterium target has been applied, too. η - mesons in the final state have been identified by missing mass technique. An example is the spectrum onthe left panel of Fig. 1, where the distribution of events over the missing mass to the ${}^4He$ nucleus is shown. The peak is fitted with Gaussian and the background with a polynomial. Missing mass resolution is around 2.7 MeV, in agreement with our earlier experiments [13]. Particle flux on the target has been measured by luminosity monitors, independently for each polarization state and with systematic uncertainty of about 5–8%. For the unpolarized beam the total flux was 3.25x10^{13} particles and for $P_{zz} = +1$ and $P_{zz} = -1$ it was 2.25x10^{13} and 2.19x10^{13} particles, respectively. In order to find the angular distributions of the helium particles from the investigated reaction, we have divided the $cos\theta_{cm}$ interval $[0 - 1]$ into 6 angular bins for each polarization

state of the beam. In each bin a spectrum similar to that on the left panel of Fig. 1 has been constructed. Then we have fitted the spectrum by a Gaussian and polynomial background. Obtained this way number of η-mesons in each angular bin was used to evaluate respective differential cross-section.

According to the theory of observables in reactions with polarized particles the differential cross section of a reaction induced by polarized deuterons is:

$$\frac{d\sigma}{d\Omega}(\theta,\varphi) = \frac{d\sigma}{d\Omega}(\theta)_{unpol.} \times \left[1 - \frac{1}{2}\tau_{20}T_{20}(\theta) + \sqrt{2}\tau_{10}iT_{11}(\theta)\cos\varphi - \sqrt{\frac{3}{2}}\tau_{20}T_{22}(\theta)\cos 2\varphi\right] \quad (1)$$

where τ_{10} and τ_{20} are the vector and tensor polarization of the beam in irreducible tensor representation, T_{20}, T_{11}, T_{22} are the respective analyzing powers in the same representation. If we assume that close to threshold only S and P waves contribute to the reaction amplitude the analyzing powers can be expressed as:

$T_{11}(\theta) = \frac{3}{2\sqrt{10}}Im(a_0 a_1^*)sin\theta$,

$T_{20}(\theta) = \frac{1}{3}a_0 - \frac{9}{10}a_1^2 sin^2\theta$,

$T_{22}(\theta) = \frac{9\sqrt{3}}{40}a_1^2 sin^2\theta$,

where a_0 and a_1 denote amplitudes for S and P wave, respectively. Measuring the differential and total cross-sections one can extract T_{11}, T_{20} and T_{22}, partial wave amplitudes and, therefore, the scattering length of the reaction.

3 Results

We have obtained the following total cross-sections:

$\sigma_{tot}(unpol) = 14.32 \pm 1.18$ nb,

$\sigma_{tot}(P_{zz} = +1) = 20.79 \pm 2.05$ nb,

$\sigma_{tot}(P_{zz} = -1) = 20.32 \pm 1.96$ nb.

Errors are statistical only The systematic error is estimated to be of about 15%. Differential cross sections are plotted on Fig. 1

Apart from this measurement there are only three other measurements of $d + d \to {}^4He + \eta$ reaction available [7–9]. Two of them have been performed with unpolarized beam [7, 9] and one with polarized one [8]. In the SPES3 experiment [8] it is assumed that only S–wave is excited and the unpolarized cross section is 2/3 of the polarized one. However, the angular distribution obtained by ANKE group suggests the presence of higher partial waves [9].

The strong rise of measured differential cross sections with $cos\theta_{cm}$ seen in Fig. 1(right panel) also indicates an influence of higher partial waves. At our energy point which is 9.2 MeV above the last point of SPES3 measurement [8] the value of the polarized cross section we got is consistent with the value of 22.4 ± 1.6 nb measured by that group.

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