PROCEEDINGS OF SCIENCE

Charge Symmetry Breaking in the Reaction $dd \to {}^4\mathrm{He}\,\pi^0$ with WASA-at-COSY

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The presented analysis concentrates on the charge symmetry breaking reaction $dd \to {}^4\mathrm{He}\pi^0$. The aim is to provide experimental results for comparison with chiral perturbation theory (ChPT) to study effects induced by quark masses on the hadronic level. In this paper the second measurement of the $dd \to {}^4\mathrm{He}\pi^0$ reaction at $Q = 60$ MeV using an improved WASA detector setup aiming at higher statistics is described. The total and differential cross sections have been determined. The preliminary result of the total cross section is $\sigma^{\mathrm{tot}}_{\mathrm{prel}} = (74.3 \pm 6.8(\mathrm{stat.})^{+1.2}_{-10.1}(\mathrm{syst.}) \pm 7.7(\mathrm{norm.}))$pb. The angular distribution has been described up to second order in $\cos\theta^*$ with a function of the form $\mathrm{d}\sigma/\mathrm{d}\Omega = a + b\cos^2\theta^*$, where θ^* is the scattering angle of the pion in the c.m. coordinate system. The obtained preliminary parameters a and b are $a_{\mathrm{prel}} = \left(1.55 \pm 0.46(\mathrm{stat})^{+0.32}_{-0.8}(\mathrm{syst})\right)$ pb/sr and $b_{\mathrm{prel}} = \left(13.1 \pm 2.1(\mathrm{stat})^{+1.0}_{-2.7}(\mathrm{syst})\right)$ pb/sr.

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1. Introduction

Isospin symmetry is one of the fundamental symmetries of Quantum Chromodynamics. In the Standard Model, it is broken because of the electromagnetic interactions and the mass difference of the lightest quarks [1, 2]. Studies of reactions in which these two isospin symmetry violating sources can be disentangled allow access to quark mass ratios [2]. On the hadronic level, the isospin breaking observables are dominated by the pion mass difference, which is an almost purely electromagnetic effect. Therefore, in general, it is difficult to get access to the quark mass difference. For a special case of isospin symmetry breaking, namely charge symmetry breaking (CSB), the pion mass difference term does not contribute. Charge symmetry is a rotation of 180° in isospin space around second axis, interchanging up and down quarks.

The corresponding CSB observables, namely the forward-backward asymmetry A_{fb} in the $np \to d\pi^0$ reaction [3] and the total cross section of the reaction $dd \to {}^4\mathrm{He}\pi^0$ close to the threshold [4] have been measured. The first theoretical results based on Chiral Perturbation Theory [5, 6, 7, 8] showed that the relative importance of the various charge symmetry breaking mechanisms is very different compared to $np \to d\pi^0$. It occurred that the πN re-scattering term, which is formally leading for both of these reactions, is suppressed in $dd \to {}^4\mathrm{He}\pi^0$ due to selection rules in spin and isospin space. A measurement of higher partial waves in $dd \to {}^4\mathrm{He}\pi^0$ can provide a non-trivial test of our understanding of isospin symmetry breaking [6]. In order to provide the necessary experimental input a program was initiated using the WASA-at-COSY setup [9].

In June 2008 an initial two-week long high-luminosity run dedicated to the measurement of the $dd \to {}^4\mathrm{He}\pi^0$ reaction took place. The main goal of this experiment was to obtain the total cross section at excess energy $Q = 60$ MeV [10]. These first data, however, did not provide decisive information on the differential distribution. The measurement described in this paper is the next stage of the WASA-at-COSY program aiming at the precise determination of the differential cross section.

2. Experiment and Data Analysis

The experiment was performed at the Institute for Nuclear Physics at the Forschungszentrum Jülich located in Germany. A high intensity deuteron beam with a momentum of $p_d = 1.2\,\mathrm{GeV}/c$ ($E_d = 350$ MeV) was provided by the Cooler Synchrotron COSY. The particles produced in the collisions of the beam with frozen deuteron pellets were detected in the modified WASA detector setup.

The WASA facility is designed to study the production and decays of light mesons. It allows to identify and fully reconstruct both charged and neutral particles. It has a geometrical acceptance close to 4π. The detector setup consists of three major parts, namely, the pellet target system, the Forward Detector (FD), and the Central Detector (CD). The beampipe goes through the whole detector setup and crosses perpendicularly the pellet target tube in the middle of the Central Detector.

The detector setup used in the experiment, shown in Fig. 1, was optimized compared to the original version of WASA used during the first $dd \to {}^4\mathrm{He}\pi^0$ measurement. The main goal of the modification was to get access to the time-of-flight information of forward going particles. Thus, all the detectors which were located between the Forward Proportional Chamber and the

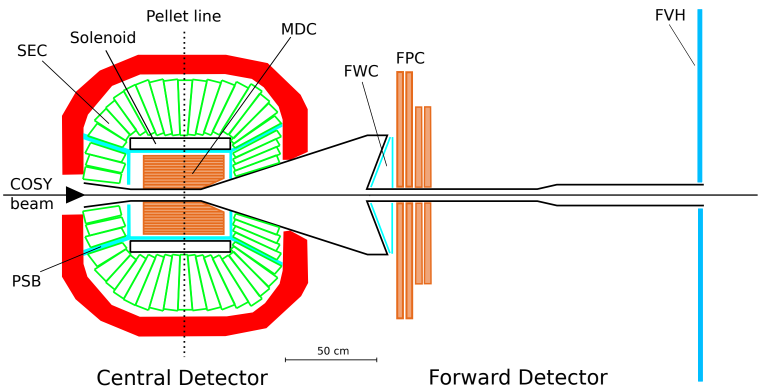

Figure 1: Schematic side view of the WASA detector setup used in the experimentt. All the detectors between the Forward Proportional Chamber and the Forward Veto Hodoscope were removed during the modification in 2013. The Forward Detector consists of two layers of the Forward Window Counter (FWC), four planes of the Forward Proportional Chamber (FPC), and one layer of the Forward Veto Hodoscope (FVH). In the Central Detector a tracking detector, called Mini Drift Chamber (MDC), is surrounded by the Plastic Scintillator Barrel (PSB), the solenoid, and the Scintillator Electromagnetic Calorimeter (SEC). The most outer part of the Central Detector is the iron yoke (marked in red). The COSY beam enters the detector setup from the left side. Adapted from [9].

Forward Veto Hodoscope were removed (see Fig. 1). In this detector configuration the slow ^{4}He from the $dd \to {}^4\mathrm{He}\pi^0$ reaction can reach the last layer of the Forward Veto Hodoscope instead of stop in the first thin scintillator layer after the Forward Proportional Chamber. The time-of-flight information provides an independent method for the energy loss calibration, and improves the separation between the signal $dd \to {}^4\mathrm{He}\pi^0$ and the main background $dd \to {}^3\mathrm{He}n\pi^0$ reaction.

The main trigger required a high energy deposit in at least one element of the first and the second Forward Window Counter layer together with at least one cluster originating from a neutral particle in the Central Detector. The whole beamtime was divided in two five-week long parts.

The experimental pattern of the signal reaction is a forward-going ^{4}He particle and two photons originating from the decay of the neutral pion in final state. The most important background sources are the $dd \to {}^3\mathrm{He}n\pi^0$ and $dd \to {}^4\mathrm{He}\gamma\gamma$ reactions. Since ^{3}He and ^{4}He have similar energy losses in the Forward Window Counters and similar time-of-flight, the suppression of the $dd \to {}^3\mathrm{He}n\pi^0$ reaction is the most challenging. Moreover, the cross section of this reaction is about five orders of magnitude larger than the signal cross section. The double radiative capture $dd \to {}^4\mathrm{He}\gamma\gamma$ is an irreducible physics background.

As the first step of the analysis, the time-of-flight and energy loss in the Forward Windows Counters have been used in the reconstruction of kinetic energy of the outgoing ^{3}He and ^{4}He particles by matching their patterns with Monte Carlo simulations. In addition, the azimuthal and horizontal angles have been reconstructed by the Forward Proportional Chamber, providing full four-vectors of the outgoing helium isotopes. In the Forward Detector at least one track has been required. Moreover, at least two well reconstructed clusters of crystals with energy originating from neutral particles have been required in the Central Detector.

For the selection of the $dd \to {}^4\mathrm{He}\pi^0$ candidates a kinematic fit technique has been used. For every event the $dd \to {}^4\mathrm{He}\gamma\gamma$ hypothesis has been fitted. No additional constraint on the invariant

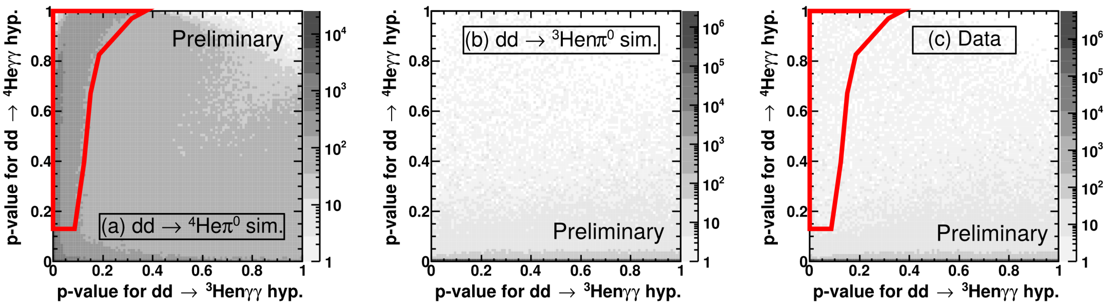

Figure 2: Two-dimensional distributions of the complementary cumulative distribution (p-value) from the kinematic fits of the $dd \to {}^4\mathrm{He}\gamma\gamma$ hypothesis and the $dd \to {}^3\mathrm{He}n\gamma\gamma$ hypothesis. Distributions for the $dd \to {}^4\mathrm{He}\pi^0$ (a) and $dd \to {}^3\mathrm{He}n\pi^0$ (b) simulations and data (c) are presented. The final two-dimensional cut applied in the analysis is presented with a solid line. Adapted from [11].

mass of the two photons has been required, not to artificially produce a fake π^0 signal. In case of more than one track in the Forward Detector or more than two neutral clusters in the Central Detector, the combination with the smallest χ^2 from the fit of has been chosen. For these events, the $dd \to {}^3\mathrm{He}n\gamma\gamma$ hypothesis also has been fitted.

A significant reduction of the $dd \to {}^3\mathrm{He}n\pi^0$ background was achieved using a cut on the two-dimensional cumulative distribution (p-value) from the kinematic fit. In Fig. 2 the p-value for the $dd \to {}^4\mathrm{He}\gamma\gamma$ hypothesis versus the p-value for the $dd \to {}^3\mathrm{He}n\gamma\gamma$ hypothesis is plotted for simulation of the $dd \to {}^4\mathrm{He}\pi^0$ (a) and $dd \to {}^3\mathrm{He}n\pi^0$ (b) reactions and for data (c). The $dd \to {}^4\mathrm{He}\pi^0$ events are uniformly distributed for the $dd \to {}^4\mathrm{He}\gamma\gamma$ hypothesis and are located in the low p-value region for the $dd \to {}^3\mathrm{He}n\gamma\gamma$ hypothesis. The events from the double radiative capture reaction have the same signature. The situation is opposite for the $dd \to {}^3\mathrm{He}n\pi^0$ reaction. The final cut is indicated with a solid line. It has been optimized to maximize the statistical significance of the π^0 signal in the final missing mass plot.

The four-momenta obtained from the kinematic fit with the $dd \to {}^4\mathrm{He}\gamma\gamma$ hypothesis have been used to calculate the missing mass for the reaction $dd \to {}^4\mathrm{He}X$. For events from the signal reaction, the missing mass should correspond to the π^0 mass. In Fig. 3 the missing mass spectra for the whole data sample is shown. On a flat broad background from double radiative capture $dd \to {}^4\mathrm{He}\gamma\gamma$ two peaks are visible. The first located at about 135 MeV comes from the signal reaction $dd \to {}^4\mathrm{He}\pi^0$. The second one corresponds to misidentified events from the background reaction $dd \to {}^3\mathrm{He}n\pi^0$. The missing mass spectra have been fitted with Monte Carlo templates. For the $dd \to {}^4\mathrm{He}\gamma\gamma$ channel a homogeneous 3-body phase-space distribution has been assumed, for the $dd \to {}^3\mathrm{He}n\pi^0$ contribution the obtained model from [12] has been used, and the contribution of the $dd \to {}^4\mathrm{He}\pi^0$ reaction has been generated with the angular distribution obtained in this analysis.

The missing mass fitting has been done as a function of the scattering angle θ^* of the outgoing π^0 in the c.m. coordinate system to determine the angular distribution. The data has been divided in four angular bins within the detector acceptance ($-0.9 \leq \cos\theta^* \leq 0.4$).

For acceptance correction the $dd \to {}^4\mathrm{He}\pi^0$ generator with obtained angular distribution has been used in an iterative procedure. The integrated luminosity has been calculated from the $dd \to {}^3\mathrm{He}n\pi^0$ reaction which was measured previously with WASA at $p_d = 1.2$ GeV/c [12].

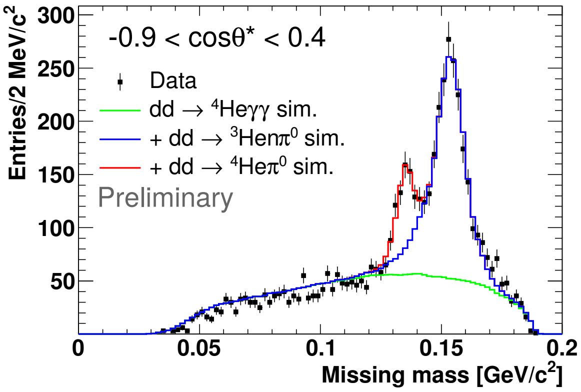

Figure 3: Missing mass for the $dd \to {}^4\text{He}X$ reaction for $-0.9 \le \cos\theta^* \le 0.4$. The spectrum is fitted with a linear combination of the simulated signal and background reactions: $dd \to {}^4\text{He}\gamma\gamma$ (green line), plus $dd \to {}^3\text{He}n\pi^0$ (blue line), plus $dd \to {}^4\text{He}\pi^0$ (red line). Adapted from [11].

3. Results and discussion

The total and differential cross sections for the $dd \to {}^4\text{He}\pi^0$ reaction at $Q = 60$ MeV have been determined. Due to the identical particles in the initial state, odd and even partial waves do not interfere and the angular distribution is symmetric with respect to $\cos\theta^* = 0$ and it can be described with the function $\text{d}\sigma/\text{d}\Omega = a + b\cos^2\theta^*$. In Fig. 4 the obtained angular distribution is presented. The preliminary parameters of the fit are:

$$a_{\text{prel}} = \left(1.55 \pm 0.46(\text{stat})^{+0.32}_{-0.8}(\text{syst})\right)\text{pb/sr}, \tag{3.1a}$$

$$b_{\text{prel}} = \left(13.1 \pm 2.1(\text{stat})^{+1.0}_{-2.7}(\text{syst})\right)\text{pb/sr}. \tag{3.1b}$$

Both parameters have common systematic uncertainties of about 10% from external normalization and about 2% from luminosity determination. The preliminary total cross section calculated as an integral over $\cos\theta^*$ from the fit of the angular distribution equals to:

$$\sigma^{\text{tot}}_{\text{prel}} = (74.3 \pm 6.8(\text{stat})^{+1.2}_{-10.1}(\text{syst}) \pm 7.7(\text{norm}))\text{pb}. \tag{3.2}$$

The statistical uncertainties for the parameters a and b as well as for the total cross section are of similar size as the systematical effects estimated by the variation of the selection cuts and the uncertainty of the luminosity determination.

The non-zero value for b is an indication of the importance of higher partial waves. Moreover, following the formalism from Ref. [13] and considering only s- and p-waves the parameter b can be presented as $b = -\frac{p_{\pi^0}}{p}\frac{2}{3}|C|^2 p^2_{\pi^0}$, where C is the p-wave amplitude. Up to this order, p-wave contributes with a negative sign. The observed positive parameter b can be explained only by a significant contribution of a d-wave.

4. Summary

These proceedings present an overview of the preliminary results of the measurements of the charge symmetry breaking $dd \to {}^4\text{He}\pi^0$ reaction at $Q = 60$ MeV with the WASA-at-COSY experiment. The obtained differential cross sections clearly show the importance of d-waves.

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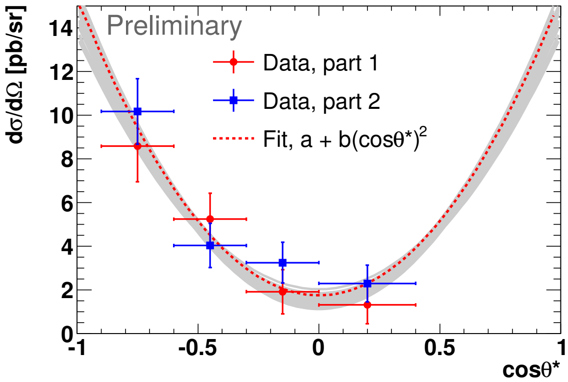

Figure 4: Preliminary angular distribution of the $dd \to {}^4\mathrm{He}\pi^0$ reaction. Data from the first and the second part of the beam time are shown separately (red and blue points). The result of the fit up to second order in $\cos\theta^*$ is shown with a red dashed curve. The systematic errors are presented as a gray band. Adapted from [11].

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