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Investigations of the charge symmetry conserving reaction dd $\rightarrow {}^{3}\mathrm{He}n\pi^{0}$ with WASA-at-COSY

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The investigation of charge symmetry breaking is one of the most important topics for the WASA detector at COSY. One of the planned studies focuses on the charge symmetry forbidden $dd \rightarrow {}^{4}He\pi^{0}$ reaction. Experimental results will be compared with predictions from Chiral Perturbation Theory (χPT) allowing to extract information on parameters proportional to the up and down quarks mass difference. First steps toward theoretical understanding of the $dd \rightarrow {}^{4}He\pi^{0}$ reaction have been taken. It was found that the existing data are not sufficient for a precise determination of the parameters of χPT and new data are required. These new data should comprise the measurement of the charge symmetry conserving $dd \rightarrow {}^{3}Hen\pi^{0}$ reaction in order to study the relevance of initial and final state interaction in $dd \rightarrow {}^{4}He\pi^{0}$. Therefore the investigation of the $dd \rightarrow {}^{3}Hen\pi^{0}$ reaction at a beam momentum of 1.2 GeV/c was performed. For the first time information on the total cross section and the differential distributions of this reaction were obtained. Various differential distributions exhibit rich structures indicating important contributions of higher partial waves. The differential distributions are compared to simple model expectations based on a phenomenological approach – the combination of a quasi-free reaction model and a partial wave expansion model for the three-body reaction.

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1. Introduction

The isospin and charge symmetries introduced by Heisenberg were considered accidental. They were introduced based on similarities of proton and neutron masses and interactions, however, it was known that these similarities are approximate and these symmetries are broken. Despite that, those symmetries are widely used in description of various nuclear and elementary particles processes. Presently charge symmetry breaking (CSB) is explained by the up and down quark mass difference and by their different electric charge. With this interpretation the study of charge symmetry for hadrons become one of the most challenging topics in hadron physics, since CSB observed for hadrons allows to access the mass difference of up and down quarks. Such interlink between the hadronic level and QCD motivated investigations in which a lot of attention was paid to the experimental and theoretical studies of CSB [1]. However, usually observed effects are dominated by the mass difference of neutral and charge pions, which originate from electromagnetic interaction. Therefore, it was not possible to relate the CSB effects to the quark mass difference. Only recently CSB was discovered in two reactions, which are free of this weakness. The first observation of $dd \to {}^4He\pi^0$ reaction was reported [2] for beam energies very close to the reaction threshold and at the same time data on the forward-backward asymmetry in $np \to d\pi^0$ reaction became available [3]. Those observations triggered advanced theoretical calculations in the framework of χPT and significant progress has been obtained in theoretical understanding of CSB [4].

Recent theroretical analysis of the $np \to d\pi^0$ reaction [5] successfully describes total cross sections, the overall shape of angular distributions and the analyzing power for pion production reactions $np \to d\pi^0$ and $pp \to d\pi^+$. However, it fails in reproducing the very tiny forward-backward asymmetry induced by CSB overestimating the data by 2.4 standard deviations. In the first calculations performed for the $dd \to {}^4He\pi^0$ reaction [6] using a very simplified model it was found that at leading order (LO) only charge symmetry violation in pion re-scattering contributes, there is no next-to-leading-order (NLO) contribution and some next-to-next-leading-order (NNLO) contributions were identified. It was found that the contribution from the LO term becomes negligibly small due to spin-isospin selection rules and the symmetry of the ${}^4He$ nucleus wave function. The NNLO terms result in a cross section by one order of magnitude smaller than the experimental one. More reliable calculations were performed [7] using realistic two- and three-nucleon interactions together with recent developments of microscopic four-body calculations [8]. That allowed to properly treat effects of deuteron-deuteron interaction in the initial state and to use a realistic ${}^4He$ bound-state wave function. This calculation confirmed that for s-wave the LO contribution is negligible and that NNLO the cross section is of the same order as the value determined experimentally. One of the most important issues was the identification of the large influence of initial-state interactions. It necessitates in new independent measurements providing information on pion-production reactions with the same initial state.

The presented overview of the existing data and the status of the theory demonstrate the necessity of new measurements that would allow to complete the program of the CSB studies for hadrons. Therefore with this motivation the experimental investigation of the $dd \to {}^3He n\pi^0$ reaction was performed at WASA-at-COSY. This reaction is a close relative to the $dd \to {}^4He\pi^0$ reaction, both having the same initial state. Therefore, the presented results should allow to fix initial-state interactions important in the analysis of CSB reaction and additionally will show how well the isospin conserving part of the four nucleon system is understood. Since there are no experimental data for the $dd \rightarrow {}^3Hen\pi^0$ reaction, already the information on the total cross section may contribute significantly to the understanding of the CSB sources in the forbidden reaction. The measurements of the full differential cross section for $dd \rightarrow {}^3Hen\pi^0$ reaction should even stronger constrain the theoretical analysis of the $dd \rightarrow {}^4He\pi^0$ reaction.

2. Experiment

The experiment was performed with the WASA-at-COSY detection system installed at the COSY synchrotron in Forschungszentrum Jülich. The beam of 1.2 GeV/c momentum with $6 \cdot 10^9$ stored deuterons was delivered by the COSY accelerator in combination with a deuteron pellet target. The average luminosity during the whole run was about 10^{30} cm^{-2} s^{-1}. The WASA detector consists of the Forward Detector covering polar angles in the range of $3^\circ - 18^\circ$ and Central Detector with a polar angle coverage of $20^\circ - 169^\circ$. The beam momentum of 1.2 GeV/c for $dd \rightarrow {}^3Hen\pi^0$ reaction corresponds to an excess energy of about 40 MeV. Therefore the outgoing ${}^3He$ has a maximum polar angle of about 17° and was detected in the Forward Detector only. The two photons from the π^0 decay were registered in the Scintillator Electromagnetic Calorimeter which is a part of the Central Detector. Photons were distinguished from charge particles reaching calorimeter using a Plastic Scintillator Barrel located inside of the calorimeter.

2.1 Selection of the dd $\rightarrow$ ^{3}Henπ^0 reaction

The $dd \rightarrow {}^3Hen\pi^0$ reaction has a very clean signature. It is the only reaction with a heavy particle and π^0 in the exit channel. The background due to $dd \rightarrow {}^4He\pi^0$ reaction is negligible since the cross section for this reaction is lower by 4 orders of magnitude. Therefore, already on the trigger level the $dd \rightarrow {}^3Hen\pi^0$ reaction can be selected requiring large energy deposit in the first layers of the Forward Detector and two neutral tracks in the Central Detector. The ${}^3He$ ions were finally identified via $\Delta E - \Delta E$ method. The very good separation of ${}^3He$ from lighter particles is shown in Fig. 1 (left) where the energy deposit in the second and third scintillator layer of the Forward Detector is shown. Applying the cut on ${}^3He$ the π^0 can be clearly identified in the invariant mass of two photons detected in Central Detector. As shown in Fig. 1 (right) the π^0 is clearly visible with almost no background.

2.2 Acceptance cuts

The energy of the outgoing ${}^3He$ is in the range of 64–214 MeV, therefore they are stopped already in the first three layers of the Forward Detector. In order to be identified, the ${}^3He$ must pass at least two scintillator layers. This requirement corresponds to a minimum kinetic energy of about 125 MeV for the identified ${}^3He$ ion which introduces an additional acceptance cut beside the geometrical cut on polar angles of the Forward and Central Detectors. Acceptance loss close to $\cos\theta_{cm} = 1$ is due to small polar angles cut (${}^3He$ at laboratory angles below 3° are not detected); acceptance loss for $\cos\theta_{cm} < 0$ is due condition on the minimum kinetic energy. The latter is of minor importance, since two identical particles in the entrance channel results in c.m. angular distribution symmetric around 90°. Therefore it is possible to recover unobserved part of the distributions.

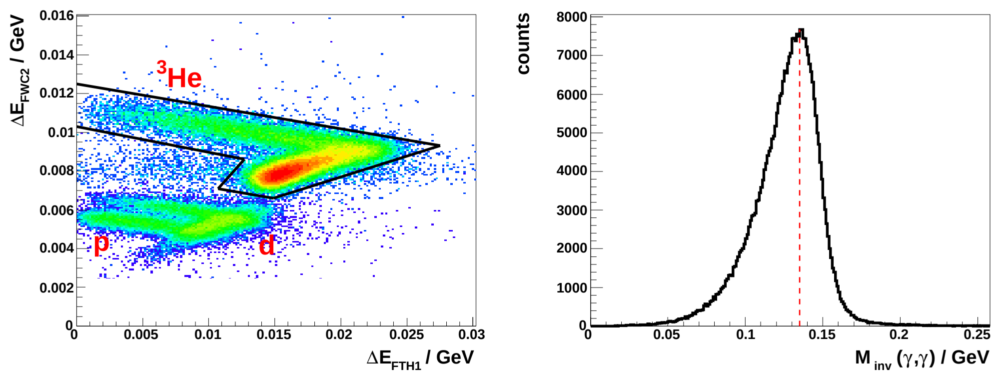

Figure 1: Left: energy deposit in the second and third scintillator layer of the Forward Detector with the requirement of two neutral tracks in the Central Detector. The cut on ^3He is shown as a black contour. Right: the invariant mass of two photons detected in the Central Detector with the applied ^3He cut. The red dashed line mark the π^0 mass.

2.3 Luminosity determination

For the luminosity determination the reaction $dd \rightarrow {}^3Hen$ was used. It was measured simultaneously with a different prescaled trigger. Therefore, it was possible to extract the angular distribution for outgoing ^3He integrated over the whole run. Data for $dd \rightarrow {}^3Hen$ and $dd \rightarrow {}^3Hp$ are available for similar beam momenta as used in present experiment [9]. It was further assumed that the cross section for those two reactions are equal, as it was shown by the authors of [9] for the beam momentum of 1.65 GeV/c. The angular distributions for $dd \rightarrow {}^3Hp$ for beam momenta of 1.109 GeV/c, 1.387 GeV/c and 1.493 GeV/c were parametrized. Than, for each polar angle, the differential cross section was calculated according to this parametrization for every beam momentum. The dependence of the differential cross section on the beam momentum was fitted and then extrapolated to the present beam momentum of 1.2 GeV/c. The resulting distributions were used in the simulations of $dd \rightarrow {}^3Hen$ and the results were compared with the present experimental data. The whole procedure allowed to determine integrated luminosity to be $L_{int} = (350.1 \pm 1.8_{stat.} \pm 24.8_{sys.})$ nb^{-1}. The systematic uncertainty was estimated from various parametrizations of the reference cross sections. Additionally, an uncertainty of 7% in the absolute normalization of the reference data from Ref. [9] has to be added.

3. Phenomenological model

Presently there are no theoretical models existing for the investigated reaction. However, such a model description of the data is necessary in order to perform precise acceptance corrections. In presented analysis two phenomenological approaches were used.

3.1 Independent variables

For a three-body reaction $a + b \rightarrow 1 + 2 + 3$ there are four independent variables fully describe the final state. In the present analysis the choice of those independent variables is based on the Jacobi momenta commonly used for the description of three-body reactions. In the global c.m.

system only two nontrivial Jacobi momenta denoted by $\vec{p}$ and $\vec{q}$ remain. Momentum $\vec{q}$ corresponds to the momentum of particle 1 in global c.m. system and momentum $\vec{p}$ corresponds to the momentum of particle 2 in the c.m. frame of subsystem of particles 2 and 3. Using these Jacobi momenta the following independent variables are defined: M_{23} – invariant mass of the 2-3 subsystem, $\cos\theta_q$ – cosine of the angle between momentum vector $\vec{q}$ and beam momentum (versor $\hat{z}$) in global c.m., $\cos\theta_p$ – cosine of angle between momentum vector $\vec{p}$ and beam momentum in global c.m. and φ – relative angle between planes spanned by $\vec{q}$ and versor $\hat{z}$ and by $\vec{p}$ and versor $\hat{z}$. The assignment of outgoing particles to reaction denoted by $a+b \to 1+2+3$ is completely free. In present analysis the following assignment was used: $1-n$, $2-\pi^0$ and $3-{}^3He$.

3.2 Quasi-free reaction model

High momentum transfer reactions involving a deuteron can proceed via the interaction with a single nucleon of the deuteron (participant), while the second nucleon is a spectator. In this case the spectator nucleon has a momentum equal to its internal momentum in the deuteron. In the present analysis the quasi-free reaction model was considered as the two-body reaction $dp \to {}^3He\pi^0$ with spectator neutron. Since in the investigated reaction two deuterons are involved the reaction may proceed with a projectile as well as a target neutron spectator.

The quasi-free contribution to $dd \to {}^3Hen\pi^0$ reaction was determined using the cross section for $dp \to {}^3He\pi^0$ convoluted with the momentum distribution of the proton in the deuteron obtained from the deuteron wave function based on the Paris potential [10]. The parametrized experimental differential cross section for the $dp \to {}^3He\pi^0$ reaction was used for energies from threshold up to an excess energy of 10 MeV [11] and for excess energies of 40, 60 and 80 MeV [12]. The use of experimental cross sections results in an absolutely normalized quasi-free contribution to $dd \to {}^3Hen\pi^0$ reaction.

3.3 Partial wave decomposition

In order to extract information on the contributions of various partial waves from the measured distributions for $dd \to {}^3Hen\pi^0$ a partial wave decomposition was applied. For a three-body reaction the following quantum numbers labeling the partial wave amplitudes were used: s_i – entrance channel spin, L_i – entrance channel orbital angular momentum, s_{23} – spin in subsystem of particles 2 and 3, L_{23} – orbital angular momentum in subsystem of particles 2 and 3, j_{23} – total angular momentum in subsystem of particles 2 and 3, L_1 – orbital angular momentum of particle 1, j_1 – total angular momentum of particle 1 and J – total angular momentum of the three particle system. Limiting to orbital angular momentum in the exit channel not greater than 1, 18 partial wave amplitudes labeled with those quantum numbers remained. These are still too many for an unambiguous partial wave decomposition. Therefore, a simpler formula for the transition amplitude was constructed by grouping the derived partial wave amplitudes. Additionally, the momentum dependence of the partial wave amplitudes was introduced explicitly. In the approximation that the wave functions may be considered as plane waves, which asymptotically are expressed by the Bessel functions the transition amplitude for defined momentum P and angular momentum L is proportional to P^L. With this approximation it was found that the differential cross section within a partial wave decomposition may be expressed in the compact form:

$$\frac{d^4\sigma}{2\pi\, dM_{23}\, d\cos\theta_p\, d\cos\theta_q\, d\varphi} = \frac{pq}{32(2\pi)^5 s p_a^*(2s_a+1)(2s_b+1)} \Big[A_0 + A_1 q^2 + A_3 p^2 + \frac{1}{4} A_2 q^2 (1 + 3\cos 2\theta_q) + \frac{1}{4} A_4 p^2 (1 + 3\cos 2\theta_p) + A_5 pq\cos\theta_p \cos\theta_q + A_6 pq \sin\theta_p \sin\theta_q \cos\varphi \Big] , \tag{3.1}$$

where s_a and s_b denote the spin of beam and target and p_a^* is the c.m. beam momentum. In this expression the term with A_0 corresponds to $L_1 = 0$ and $L_{23} = 0$ (*sS* partial waves), the terms with A_1 and A_2 correspond to $L_1 = 1$ and $L_{23} = 0$ (*pS* partial waves), the terms with A_3 and A_4 correspond to $L_1 = 0$ and $L_{23} = 1$ (*sP* partial waves) and terms with A_5 and A_6 correspond to an interference between *pS* and *sP* waves.

4. Results

The quasi-free reaction model delivered an absolutely normalized prediction for the investigated reaction. Therefore, this model was first compared to the data in order to check its contribution. The results of this comparison are shown in Fig. 2. In the left panel of Fig. 2 it is seen that up to a neutron momentum of 90 MeV/c the data can be described by only using the quasi-free reaction model. In order to confirm this agreement the angular distribution of the pion in the c.m. of subsystem ${}^3He - \pi^0$ is also compared (right panel of Fig. 2) limiting the neutron momenta to less than 90 MeV/c.

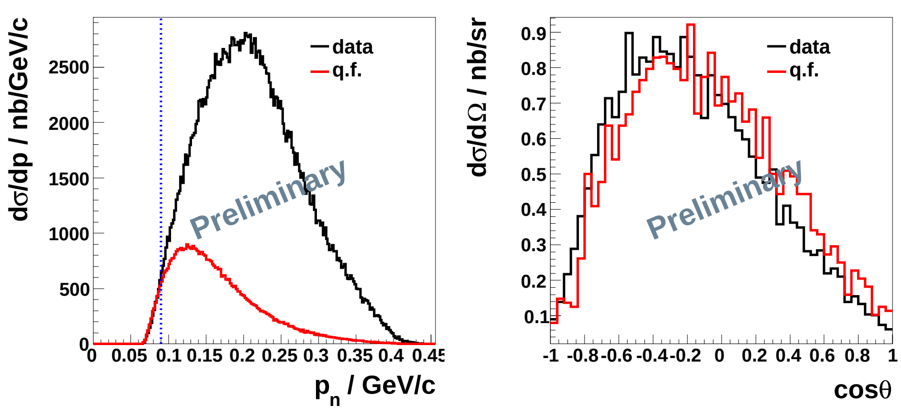

Figure 2: Left: comparison of the momentum distribution of the neutron from $dd \to {}^3He n\pi^0$ reaction for data (black line) and the quasi-free model (red line). Right: the scattering angle of pion in the c.m. of subsystem ${}^3He - \pi^0$. This distribution contains only events for which the neutron momentum is smaller than 90 MeV/c (this cut is indicated by blue dashed line in the left panel). The data are not corrected for acceptance, but the model calculations were filtered with the detection system response instead.

In order to describe the remaining part of the experimental cross section the partial wave decomposition was performed. To the one dimensional distributions in independent variables $\cos\theta_p$, $\cos\theta_q$, φ, M_{23} and $\cos\theta_q \pm \cos\theta_p$ the partial amplitudes $A_0 - A_6$ in expressions derived from Eq.

3.1 were fitted to the data. The fixed contribution from the quasi-free reaction was added incoherently to the model. The resulting values of partial amplitudes and the quasi-free reaction predictions were than used for the acceptance correction. The final distributions are shown in Fig. 3.

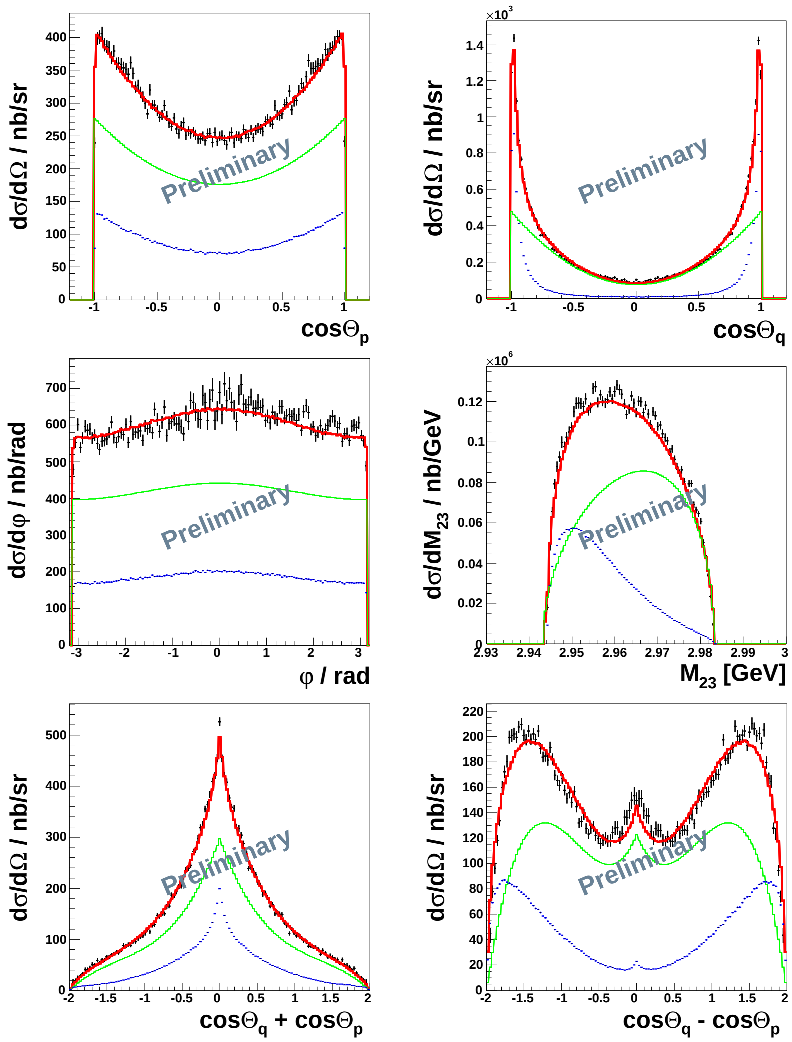

Figure 3: The experimental distributions (black points) corrected for acceptance are compared to theoretical predictions (red line) which is a sum of quasi-free reaction (blue line) and partial wave model (green line).

It is seen that the data are very well reproduced by the applied models. The contribution of the quasi-free reaction is of about 30% of the observed cross section. It dominates the $\cos\theta_q$ distribution for the most forward and backward angles. The important contribution of $p-$waves is clearly visible in $\cos\theta_p$ and $\cos\theta_q$ distributions. The significance of sP and pS interference is seen in φ distribution, which should be isotropic without such interference. From the presented analysis it was impossible to extract absolute contributions of sS, sP and pS partial waves since the corresponding parameters A_0, A_1 and A_3 were found to be strongly correlated in the performed fit. The extracted preliminary total cross section for $dd \to {}^{3}Hen\pi^{0}$ reaction equals to $\sigma_{tot} = (3.81 \pm 0.01_{stat.} \pm 0.42_{sys.})\ \mu b$.

5. Outlook

The investigated charge symmetry conserving reaction $dd \rightarrow {}^3He n\pi^0$ is a part of a broader research program of CSB studies at WASA-at-COSY. The presented results are the first step towards a detailed theoretical analysis of CSB $dd \rightarrow {}^4He\pi^0$ reaction within a χPT calculation. While the χPT terms for the charge symmetry conserving reaction are known, the analysis of $dd \rightarrow {}^3He n\pi^0$ would allow to fix the initial state parameters, which strongly influence the theoretical results for $dd \rightarrow {}^4He\pi^0$ reaction.

The studies of CSB at WASA-at-COSY will be continued by the measurement of $dd \rightarrow {}^4He\pi^0$ reaction at excess energies larger than the presently existing data. That would allow to find the $p-$wave contribution and determine the β_1 parameter of χPT. A first attempt to measure this reaction was already undertaken and the data analysis is in progress [13]. While the signal of $dd \rightarrow {}^4He\pi^0$ reaction is visible and the measurement is feasible, the bad separation of ${}^3He$ and ${}^4He$ ions results in large background. Therefore some modification of the WASA-at-COSY setup seems to be necessary. Then in a first step the angular distribution for $dd \rightarrow {}^4He\pi^0$ reaction will be measured at excess energy of about 60 MeV. Any anisotropy will be a signature of $p-$wave or higher partial waves contribution. In order to clearly extract $p-$wave contribution further measurements with polarized deuteron beam will be performed.

The extension of the studies of CSB at WASA-at-COSY by measurements of $dd \rightarrow dd\pi^0$ reaction is considered. While this reaction was never investigated, it may deliver complementary information to $dd \rightarrow {}^4He\pi^0$ reaction with access to dd $p-$waves.

Acknowledgments

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