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Charge Symmetry Breaking In The $\mathrm{dd} \rightarrow {}^4\mathrm{He}\pi^0$ Reaction With WASA-at-COSY

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The presented study concentrates on the charge symmetry breaking reaction $dd \rightarrow {}^4\mathrm{He}\pi^0$. The aim is to provide experimental results for comparison with predictions from chiral perturbation theory (ChPT) to study effects induced by quark masses on the hadronic level, e.g., the proton-neutron mass difference. First calculations showed that more data are required, in addition to the existing high-precision measurements from TRIUMF and IUCF, for a precise determination of the parameters of ChPT. These new data should comprise the measurement of the charge symmetry forbidden $dd \rightarrow {}^4\mathrm{He}\pi^0$ reaction at sufficiently high energy to get access to the higher partial waves contributions, especially p-wave. A first result from the WASA-at-COSY experiment at an excess energy of $Q = 60$ MeV did not allow for a decisive interpretation because of limited statistics. In this paper the second measurement of the $dd \rightarrow {}^4\mathrm{He}\pi^0$ 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 $\sigma^{\mathrm{tot}}_{\mathrm{prel}} = \left(79.1 \pm 7.3(\mathrm{stat.})^{+1.2}_{-10.5}(\mathrm{syst.}) \pm 8.1(\mathrm{norm.}) \pm 2.0(\mathrm{lumi.\ syst.})\right)$ 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 $a_{\mathrm{prel}} = \left(1.75 \pm 0.46(\mathrm{stat.})^{+0.31}_{-0.8}(\mathrm{syst.})\right)$ pb/sr and $b_{\mathrm{prel}} = \left(13.6 \pm 2.2(\mathrm{stat.})^{+0.9}_{-2.7}(\mathrm{syst.})\right)$ pb/sr.

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1. Introduction

If protons and neutrons were treated equally by all types of interactions, isospin symmetry would be conserved. Since up and down quarks, which are the constituent quarks of the proton and the neutron, have different charges and masses, isospin symmetry is not an exact one. Within the Standard Model it is broken both by electromagnetic and strong interactions. The isospin symmetry breaking on the hadronic level manifests itself in several static observables. One important observable is the proton-neutron mass difference ΔM_{pn}. If isospin symmetry was broken only because of the different charges of the lightest quarks, ΔM_{pn} would be a purely electromagnetic effect, with the result that the proton would be heavier then the neutron. Nature shows that this is not the case and that the proton as a stable particle is lighter then the neutron [1, 2].

Probing elementary symmetries and symmetry breaking tests our understanding of Quantum Chromodynamics (QCD). The effective field theory for low energy QCD is chiral perturbation theory (ChPT). It maps all symmetries of the underlying theory into hadronic operators. Their strength has to be fixed from experiment or lattice calculations. Chiral perturbation theory provides a link between the static isospin symmetry breaking observable which is the proton-neutron mass difference induced by the u and d quark difference ΔM_{pn}^{strong} and the dynamic isospin-violating terms in NN-induced pion-production reactions.

In low energy hadron physics it is difficult to get access to quark mass effects, since the pion mass difference $\Delta\pi = M_{\pi^\pm} - M_{\pi^0}$, which is of electromagnetic origin, is the by far dominant term. Therefore, it is favorable to investigate charge rather than isospin symmetry breaking (CSB) observables where the relative pion mass difference does not contribute. Weinberg predicted a huge effect of CSB in $\pi^0 N$ scattering. He has shown that the difference in the scattering lengths for $n\pi^0$ and $p\pi^0$ should be up to 30% [1]. However, the direct measurement of $f(\pi^0 p) - f(\pi^0 n)$ in πN scattering is impossible, because of the lack of π^0 beams. Thus, as an alternative access to CSB pion-nucleon scattering, NN-induced pion production has been suggested [3, 4].

The corresponding CSB observables, namely the forward-backward asymmetry A_{fb} in the $np \to d\pi^0$ reaction [5] and the total cross section of the reaction $dd \to {}^4\text{He}\pi^0$ close to the threshold [6] have been measured. The first theoretical results for $dd \to {}^4\text{He}\pi^0$ [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 πN re-scattering term, which is formally leading for both of these reactions, is suppressed in $dd \to {}^4\text{He}\pi^0$ due to selection rules in spin and isospin space.

The $dd \to {}^4\text{He}\pi^0$ reaction near threshold can be used together with the forward-backward asymmetry in $np \to d\pi^0$ to fix all the parameters to NNLO in the ChPT calculations of $dd \to {}^4\text{He}\pi^0$ [9]. Once the parameters are fixed, the p-wave contribution can be predicted parameter-free to leading and next-to-leading order, which will provide an important cross-check for the χ_{PT} predictions. Therefore, the measurement of higher partial waves in $dd \to {}^4\text{He}\pi^0$ provides a non-trivial test of the understanding of isospin violation on the hadronic level [12].

In June 2008 an initial two-week long high-luminosity run dedicated to the measurement of the $dd \to {}^4\text{He}\pi^0$ reaction took place. The main goal of this experiment was to obtain the total cross section at excess energy $Q = 60$ MeV [12]. 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

In February 2014, a dedicated eight-week long experiment for the $dd \rightarrow {}^4\mathrm{He}\pi^0$ reaction measurement at $Q = 60$ MeV was performed at the Institute for Nuclear Physics at the Forschungszentrum Jülich in Germany. A deuteron beam with a momentum of $p_d = 1.2$ GeV/c was provided by the Cooler Synchrotron COSY [11]. The particles produced in the collisions of the beam with deuteron pellets were detected in the modified WASA facility [10] presented.

The WASA detector consists of the Forward and Central Detector, where the ^{4}He ejectiles and the photons from the π^0 decay were detected, respectively. Compared to the original version of WASA (Fig. 1), the detector setup was optimized based on the experience gained during the first measurement (Fig. 2). The main goal was to get access to the time-of-flight information of forward going particles. Therefore, all the detectors between the Forward Proportional Chamber and the Forward Veto Hodoscope were removed (see the comparison between Fig. 1 and Fig. 2). This detector configuration allows the slow ^{4}He from the $dd \rightarrow {}^4\mathrm{He}\pi^0$ reaction to reach the last layer of the Forward Veto Hodoscope instead of being stopped in the first scintillator layer after the Forward Proportional Chamber. The main advantages of using the time-of-flight information are an independent method for detector calibration (in the previous measurement the calibration of the energy deposit in the thin plastic scintillators was based only on the correlation of the energy loss in the different layers), and a better separation between the signal $dd \rightarrow {}^4\mathrm{He}\pi^0$ and the main background $dd \rightarrow {}^3\mathrm{He}n\pi^0$ reaction.

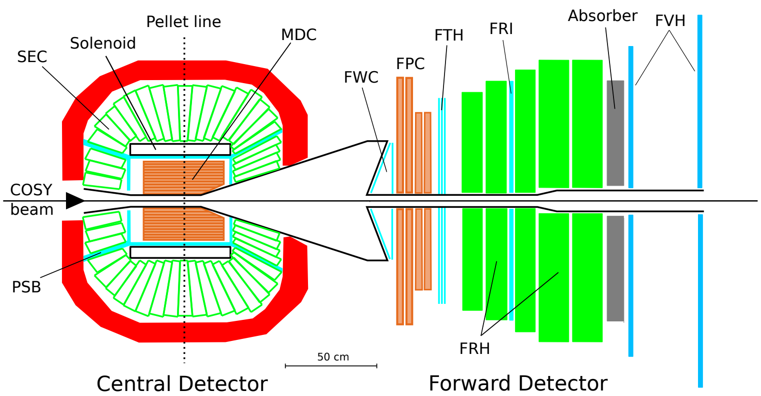

Figure 1: WASA detector setup as described in [10] and used in the measurements in [12] and [14]. The Forward Detector consists of two layers of the Forward Window Counter (FWC), four planes of the Forward Proportional Chamber (FPC), three layers of the Forward Trigger Hodoscope (FTH), five layers of the Forward Range Hodoscope (FRH), one layer of the Forward Range Intermediate Hodoscope (FRI), one layer of the absorber, and two layers 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 [10].

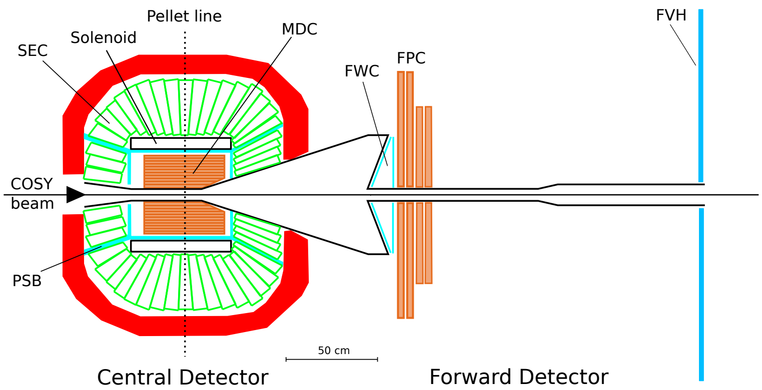

Figure 2: Schematic side view of the WASA detector setup. All the detectors between the Forward Proportional Chamber and the Forward Veto Hodoscope were removed during the modification in 2013. Adapted from [10].

3. Analysis

The signature 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 $dd \to {}^3\text{He}n\pi^0$ and $dd \to {}^4\text{He}\gamma\gamma$ reactions. The suppression of the $dd \to {}^3\text{He}n\pi^0$ reaction is challenging since ^{3}He and ^{4}He have similar energy losses in the Forward Window Counters and similar time-of-flight. In addition, the cross section of this reaction is about five orders of magnitude larger than the signal cross section. The double radiative capture $dd \to {}^4\text{He}\gamma\gamma$ is an irreducible physics background.

As the first step of the analysis, the raw signals from the detectors have been calibrated largely based on Monte Carlo simulations. The calibrated energy loss in the Forward Windows Counters and time-of-flight have been used to reconstruct the kinetic energy of the outgoing ^{3}He and ^{4}He particles by matching their patterns to Monte Carlo simulations. The full four-vectors of the outgoing helium isotopes have been obtained using in addition the azimuthal and horizontal angles reconstructed by the Forward Proportional Chamber. In the Forward Detector at least one track has been required. Furthermore, at least two well reconstructed clusters of crystals with energy deposited by neutral particles have been required in the Central Detector.

The $dd \to {}^4\text{He}\pi^0$ candidates have been selected using a kinematic fit. The purpose of the kinematic fit was to improve the precision of the measured kinematic variables (i.e., the kinetic energy, polar and azimuthal angles) and to serve as a selection criterion for background reduction. The idea is to vary the measured variables within the experimental uncertainty until certain kinematic constraints are fulfilled. The main constraint is the overall momentum and energy conservation. For every event the $dd \to {}^4\text{He}\gamma\gamma$ hypothesis has been fitted. No additional constraint on the invariant 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 $dd \to {}^3\text{He}n\gamma\gamma$ hypothesis has been also fitted.

A significant reduction of the $dd \to {}^3\text{He}n\pi^0$ background is only possible using a cut on the two-dimensional complementary cumulative distribution (p-value) from the kinematic fits. In Fig. 3

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 data and simulation of the $dd \to {}^4\mathrm{He}\pi^0$ and $dd \to {}^3\mathrm{He}n\pi^0$ reactions. The $dd \to {}^4\mathrm{He}\pi^0$ events form a uniform distribution for the $dd \to {}^4\mathrm{He}\gamma\gamma$ hypothesis are located in the low p-value region for the $dd \to {}^3\mathrm{He}n\gamma\gamma$ hypothesis. The events from the $dd \to {}^4\mathrm{He}\gamma\gamma$ reaction have the same signature. The situation is opposite for the $dd \to {}^3\mathrm{He}n\pi^0$ reaction. The final cut based on Monte Carlo simulations is indicated with a red line. It has been optimized to maximize the statistical significance of the π^0 signal in final missing mass plot. The cut variations in the horizontal and vertical directions used in the studies of systematic effects and the cut optimization are marked with blue lines. In addition to the p-value cut, the polar angle θ of outgoing ^{4}He candidates has been required to be smaller then 9°. This covers fully the angular range of the $dd \to {}^4\mathrm{He}\pi^0$ reaction, when the maximal θ of ^{3}He from the $dd \to {}^3\mathrm{He}n\pi^0$ reaction is about 16°.

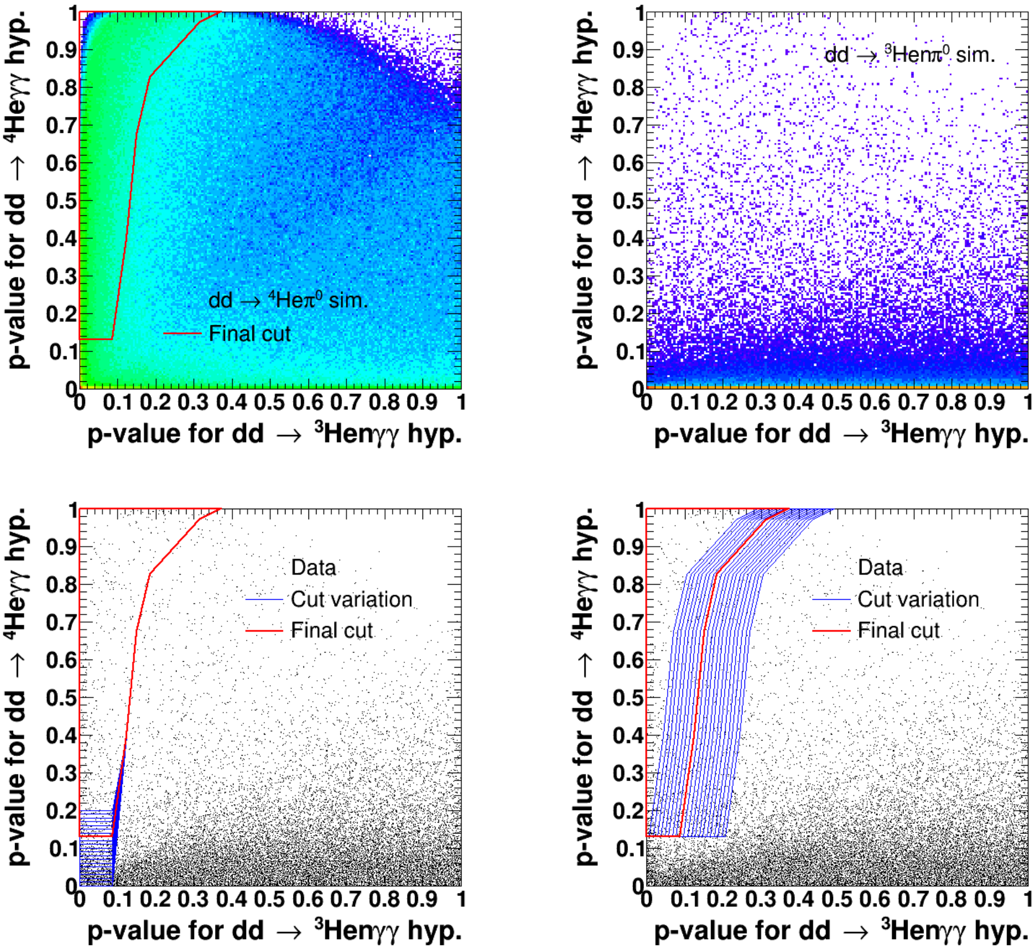

Figure 3: Two-dimensional distributions of the p-value from the kinematic fits of the $dd \to {}^4\mathrm{He}\gamma\gamma$ hypothesis and the $dd \to {}^3\mathrm{He}n\gamma\gamma$ hypothesis. In the upper row, the distributions for the $dd \to {}^4\mathrm{He}\pi^0$ and $dd \to {}^3\mathrm{He}n\pi^0$ simulations are presented. In the bottom row, the distributions for data are plotted. The final two-dimensional cut applied in the analysis is presented with a red line. The cut variations in the horizontal and vertical directions used in the studies of systematic effects are marked with blue lines. Source: [13].

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 neutral pion mass. In Fig. 4 the missing mass spectra for the whole data sample is shown. On a flat broad background, coming from double radiative capture $dd \to {}^4\mathrm{He}\gamma\gamma$, two significant peaks are visible. The first, coming from the signal reaction $dd \to {}^4\mathrm{He}\pi^0$, is located at about 135 MeV. The second one corresponds to misidentified events from the background reaction $dd \to {}^3\mathrm{He}n\pi^0$ and is shifted because of the ${}^3\mathrm{He}-n$ binding energy. The missing mass spectra have been fitted with Monte Carlo templates to obtain the number of registered signal events. 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 [14] 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 spectra have been fitted with a linear combination of the simulated signal reaction and background contributions. Compared to the previous experiment the number of events in the final missing mass plot increased roughly by a factor of 4.

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 into four angular bins within the detector acceptance ($-0.9 \leq \cos\theta^* \leq 0.4$), and for each bin the number of signal candidates has been extracted. 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 [14].

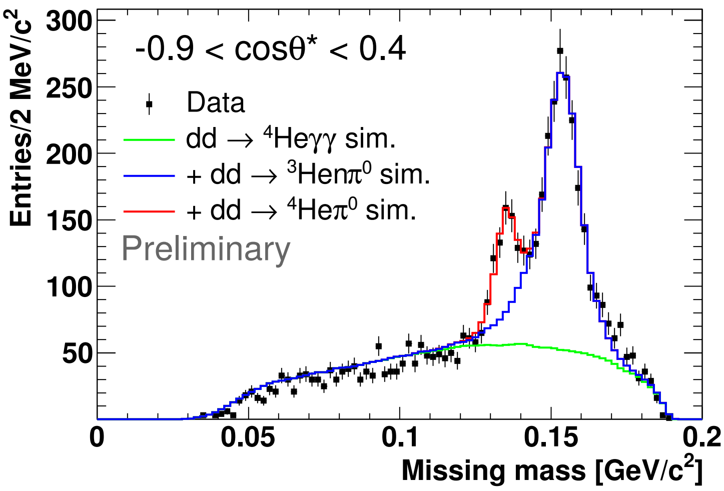

Figure 4: Missing mass for the $dd \to {}^4\mathrm{He}X$ reaction for $-0.9 \leq \cos\theta^* \leq 0.4$. The spectrum is fitted with a linear combination of the simulated signal and background reactions: $dd \to {}^4\mathrm{He}\gamma\gamma$ (green line), plus $dd \to {}^3\mathrm{He}n\pi^0$ (blue line), plus $dd \to {}^4\mathrm{He}\pi^0$ (red line). Source: [13].

4. Results and Discussion

The total and differential cross sections for the $dd \to {}^4\mathrm{He}\pi^0$ reaction at $Q = 60$ MeV have been determined. Considering only terms up to second order in pion momentum, in final state only s-wave, p-wave and $s-d$ interference terms contribute and the shape of the differential cross section can be described with the function $\mathrm{d}\sigma/\mathrm{d}\Omega = a + b\cos^2\theta^*$, as it has been shown in [15]. 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 $\cos\theta^* = 0$. In Fig. 5 the angular distribution is presented. The obtained preliminary parameters of the fit of the angular distribution are:

$$a_{\text{prel}} = \left(1.75 \pm 0.46(\text{stat.})^{+0.31}_{-0.8}(\text{syst.})\right)\text{pb/sr}, \tag{4.1a}$$

$$b_{\text{prel}} = \left(13.6 \pm 2.2(\text{stat.})^{+0.9}_{-2.7}(\text{syst.})\right)\text{pb/sr}. \tag{4.1b}$$

Both parameters have common systematic uncertainties of about 10% from external normalization and about 2% from luminosity determination. The non-zero value for b is an indication of the importance of higher partial waves. The preliminary total cross section has been obtained as the integral over $\cos\theta^*$ from the fit of the angular distribution:

$$\sigma^{\text{tot}}_{\text{prel}} = \left(79.1 \pm 7.3(\text{stat.})^{+1.2}_{-10.5}(\text{syst.}) \pm 8.1(\text{norm.}) \pm 2.0(\text{lumi. syst.})\right)\text{pb}. \tag{4.2}$$

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 total cross section is smaller than the previous result, but still consistent within the errors.

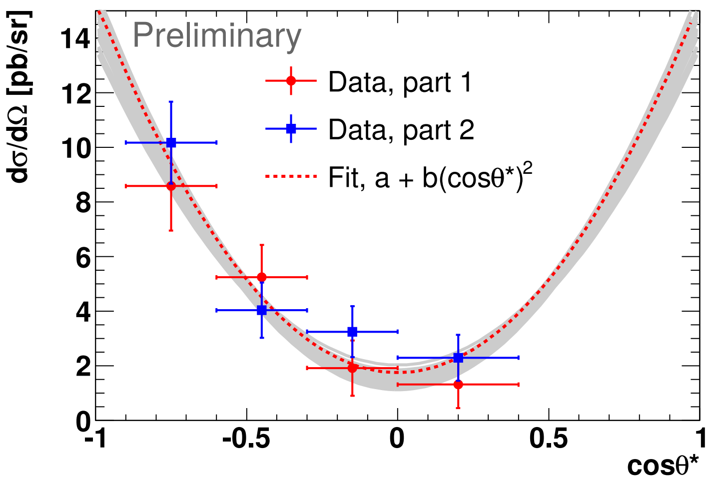

Figure 5: Preliminary angular distribution of the $dd \to {}^4\text{He}\pi^0$ reaction. Data from the first and the second half of the beam time are shown separately (red and blue points). The result of the simultaneous fit up to second order in $\cos\theta^*$ is shown with a red dashed curve. The systematic errors are presented as a gray band. Source: [13].

5. 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 higher partial waves.

6. Acknowledgements

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