Investigation of the $dd \rightarrow ^3\text{He}n\pi^0$ reaction with the FZ Jülich WASA-at-COSY facility

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An exclusive measurement of the $dd \rightarrow ^3\text{He}n\pi^0$ reaction was carried out at a beam momentum of $p_d = 1.2$ GeV/c using the WASA-at-COSY facility. Information on the total cross section as well as differential distributions was obtained. The data are described by a phenomenological approach based on a quasi-free model and a partial wave expansion for the three-body reaction was carried out at a beam momentum of $p_d = 1.2$ GeV/c using the WASA-at-COSY facility. Information on the total cross section as well as differential distributions was obtained. The data are described by a phenomenological approach based on a quasi-free model and a partial wave expansion for the three-body.
reaction. The total cross section is found to be $\sigma_{\text{tot}} = (2.89 \pm 0.01_{\text{stat}} \pm 0.06_{\text{syst}} \pm 0.29_{\text{norm}}) \mu \text{b}$.
The contribution of the quasi-free processes (with the beam or target neutron being a spectator) accounts for 38% of the total cross section and dominates the differential distributions in specific regions of phase space. The remaining part of the cross section can be described by a partial wave decomposition indicating the significance of $p$-wave contributions in the final state.

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INTRODUCTION

At the fundamental level of the Standard Model, isospin violation is due to quark mass differences as well as electromagnetic effects.\footnote{1,5,9}. Therefore, the observation of isospin violation is an experimental tool to study quark mass effects in hadronic processes. However, in general isospin violating observables are largely dominated by the pion mass differences, which are enhanced due to the small pion mass. An exception are charge symmetry breaking (CSB) observables. Charge symmetry is the invariance of a system under rotation by 180° around the second axis in isospin space that interchanges up and down quarks. It transforms a $\pi^+$ into a $\pi^-$ and, therefore, the pion mass difference does not contribute. Ref.\footnote{3} calls the investigation of CSB effects one of the most challenging subjects in hadron physics. On the basis of theoretical approaches with a direct connection to QCD, like lattice QCD or effective field theory, it is possible to study quark mass effects on the hadronic level, since the effects of virtual photons are under control — for a detailed discussion on this subject see Ref.\footnote{2}.

The first observation of the charge symmetry breaking $dd \to ^4\text{He}\pi^0$ reaction was reported for beam energies very close to the reaction threshold\footnote{3}. At the same time information on CSB in $np \to d\pi^0$ manifesting itself in a forward-backward asymmetry became available\footnote{3}. These data triggered advanced theoretical calculations within effective field theory, providing the opportunity to investigate the influence of the quark masses in nuclear physics.\footnote{8,9}. This is done using Chiral Perturbation Theory (ChPT) which has been extended to pion production reactions\footnote{10}. First steps towards a theoretical understanding of the $dd \to ^4\text{He}\pi^0$ reaction have been taken\footnote{11,12}. Soft photon exchange in the initial state could significantly enhance the cross section for $dd \to ^4\text{He}\pi^0$\footnote{13}. However, it was demonstrated in Ref.\footnote{14} that a simultaneous analysis of CSB in the two-nucleon sector and in $dd \to ^4\text{He}\pi^0$ strongly constrains the calculations.

The main problem in the calculation of $dd \to ^4\text{He}\pi^0$ is to get theoretical control over the isospin symmetric part of the initial state interactions, for here high accuracy wave functions are needed for $dd \to 4N$ in low partial waves at relatively high energies. These can be accessed by measurements of other, isospin conserving, $dd$ induced pion production reaction channels at a similar excess energy, such that the final state (and, thus, also the initial state) is constrained to small angular momenta. Then, the incoming system shares some of the partial waves in the initial state with the reaction $dd \to ^4\text{He}\pi^0$, while the transition operator is calculable with sufficient accuracy using ChPT. Such a reaction is $dd \to ^3\text{He}\pi^0$ and the corresponding measurement is presented here.

EXPERIMENT

The experiment was carried out at the Institute for Nuclear Physics of Forschungszentrum Jülich in Germany using the Cooler Synchrotron COSY\footnote{15} together with the WASA detection system. For the measurement of $dd \to ^3\text{He}\pi^0$ at an excess energy of $Q \approx 40$ MeV a deuteron beam with a momentum of 1.2 GeV/c was scattered on frozen deuterium pellets provided by an internal target. The reaction products $^3\text{He}$ and $\pi^0$ were detected by the Forward Detector and the Central Detector of the WASA facility, respectively, while the neutron remained undetected. The Forward Detector consists of several layers of plastic scintillators for particle identification and energy reconstruction and an array of straw tubes for precise tracking. The polar angular range between 3° and 18° fully covers the angular range of the outgoing $^3\text{He}$ with the exception of very small angles. At this beam momentum the $^3\text{He}$ ejectiles have kinetic energies in the range of 65 - 214 MeV and, thus, are already stopped in the first detector layers: in addition to the straw tube tracker only the two 3 mm thick layers of the Forward Window Counter and the first 5 mm thick layer of the Forward Trigger Hodoscope were used. The two photons from the $\pi^0$ decay were detected by the Scintillator Electromagnetic Calorimeter as part of the Central Detector. Photons were distinguished from charged particles using the Plastic Scintillator Barrel located inside the calorimeter. The experiment trigger was based on a coincidence between a high energy deposit in both layers of the Forward Window Counter together with a veto condition on the first layer of the Forward Range Hodoscope to select helium ejectiles and a low energy neutral cluster ($E > 20$ MeV) in the calorimeter to tag the decay of the pion. Further information on the WASA-at-COSY facility can be found in Ref.\footnote{16}.
dd → π\(^+\)π\(^-\) indicates the π cross section, dd by means of nature for this reaction. Helium isotopes are identified tral tracks forming a pion already provides a clean sig-
the identification of a forward going helium and two neu-
charge 2 particle and a neutral pion in final state. Thus,
clear separation between different particles types. The graph-
T rigger Hodoscope. The obtained energy pattern shows a
ical cut indicated in black represents the region used to sel ect
π selection corresponding to the
3
He has to pass at least the first
FWC2
2 layer of the F orward Window Counter and the first layer of the
going backward in the c.m. system. However, having two
Apart from the charge symmetry breaking reaction
dd → 3\text{He}π^0 with a four orders of magnitude smaller
cross section, dd → 3\text{He}nπ^0 is the only process with a charge 2 particle and a neutral pion in final state. Thus,
the identification of a forward going helium and two neu-
tral tracks forming a pion already provides a clean sign-
nature for this reaction. Helium isotopes are identified by means of \(\Delta E - \Delta E\) plots using the energy deposit in the Forward Window Counter and the first layer of the Forward Trigger Hodoscope (Fig. 1b).

The condition that the 3\text{He} has to pass at least the first
two scintillator layers introduces an additional acceptance cut of \(E_{\text{kin}} > 125\) MeV. This rejects most of the 3\text{He}
going backward in the c.m. system. However, having two

**DATA ANALYSIS**

FIG. 1. (Color online) (a) Energy loss in the Forward Window Counter versus energy loss in the first layer of the Forward Trigger Hodoscope. The obtained energy pattern shows a clear separation between different particles types. The graphical cut indicated in black represents the region used to select 3\text{He} candidates. (b) The two photon invariant mass distribution corresponding to the \(\pi^0 \rightarrow \gamma\gamma\) decay. The red dotted line indicates the \(\pi^0\) mass.

The absolute normalization was done relative to the
\(dd \rightarrow 3\text{He}n\) reaction. Corresponding data were taken in parallel during the first part of the run using a dedicated trigger. Due to the correlation between kinetic energy and scattering angle for the binary reaction, quasi mono-
energetic particles form a distinct and clean peak in the
\(\Delta E - \Delta E\) plots. For the selected events the 3\text{He} missing mass distribution reveals a background free peak at the mass of the neutron (Fig. 2a). In order to determine the integrated luminosity the data presented in Ref. 17 were used. The authors measured the reaction \(dd \rightarrow 3\text{He}\) for beam momenta between 1.09 GeV/c - 1.78 GeV/c and
\(dd \rightarrow 3\text{He}\) for beam momenta in the range of 1.65 GeV/c - 2.5 GeV/c. Moreover, they showed that the differential cross sections for both channels at 1.65 GeV/c are identical within the presented errors. Based on these results we used the measured cross sections for \(dd \rightarrow 3\text{He}\) to
calculate the cross sections for $dd \rightarrow ^3\text{He}n$ at 1.2 GeV/c. For this the angular distributions for the beam momenta of 1.109 GeV/c, 1.387 GeV/c and 1.493 GeV/c were parametrized. Then, for selected polar angles the dependence of the differential cross section on the beam momentum of 1.2 GeV/c. The resulting distribution was used as an input for the simulation of $dd \rightarrow ^3\text{He}n$. The angular distribution of $^3\text{He}n$ in data and the Monte-Carlo filtered event generator. The extracted integrated luminosity is determined to be $L_{\text{int}} = (877 \pm 2_{\text{stat}} \pm 6_{\text{sys}} \pm 6_{\text{norm}}) \text{nb}^{-1}$, where the superscript 1 refers to the first part of the run. The systematic uncertainty reflects different parametrizations of the reference data. In addition, the uncertainty of 7% in the absolute normalization of the reference data is also included. The result for the total cross section given below is based only on this first part of the run. The second part was optimized for high luminosities and also served as a pilot run for a measurement of $dd \rightarrow ^4\text{He}n\pi^0$. It provided data to extract high statistics differential distributions for $dd \rightarrow ^3\text{He}n\pi^0$. These have been absolutely normalized relative to the first part of the run using the rates of the $dd \rightarrow ^3\text{He}n\pi^0$ reaction. The integrated luminosity obtained for the second part of the run amounts to $L_{\text{int}}^2 = (4909 \pm 13_{\text{stat}} \pm 350_{\text{sys}} \pm 350_{\text{norm}}) \text{nb}^{-1}$.

The uncertainty on the integrated luminosity (in total 10% if all contributions are added quadratically) is the dominant source for the systematic error on the absolute normalization. Another source is associated with the cut on the cumulated probability distribution of the kinematic fit. In order to quantify the influence of this cut, the analysis was repeated for different regions in the probability distribution. For the total cross section the maximum deviation from the average value was taken as error. Changes in the shape of the differential distributions were extracted similarly, however excluding the variation in the absolute scale. For all other analysis conditions according to the criteria discussed in Ref. [18] no significant systematic effect was observed.

PHENOMENOLOGICAL MODELS

Presently, no theoretical calculation exists for a microscopic description of the investigated reaction. However, in order to have a sufficiently precise acceptance correction a model which reproduces the experimental data reasonably well is required. The ansatz used here is the incoherent sum of a quasi-free reaction mechanism based on $dp \rightarrow ^3\text{He}n\pi^0$ and a partial-wave expansion for the 3-body reaction. While the latter is limited to $s$- and $p$-waves, the large relative momenta between the spectator nucleon and the rest system in the quasi-free model corresponding to higher partial waves motivate the incoherent sum and the neglect of interference terms.

Quasi-free reaction model

High momentum transfer reactions involving a deuteron can proceed via the interaction with a single nucleon of the deuteron and with the second nucleon being regarded as a spectator. Naturally, this mechanism is most significant in regions of the phase space where the momentum of one nucleon in final state matches the typical Fermi momenta in the deuteron. In the present experiment two deuterons are involved and, thus, the reaction may proceed with a projectile or target neutron spectator. For the parametrization of the quasi-free sub reaction $dp \rightarrow ^3\text{He}n\pi^0$, the empirical angular distributions and the energy dependent cross section in the energy regime from threshold up to an excess energy of 10 MeV [19] and for excess energies of 40, 60 and 80 MeV [20] have been used. They have been convoluted with the momentum distribution of the proton in the

![FIG. 2.](Color online) Measurement of the $dd \rightarrow ^3\text{He}n$ reaction. (a) $^3\text{He}$ missing mass distribution, the vertical red dotted line indicates the neutron mass. (b) Measured angular distribution in comparison with a Monte Carlo simulation based on a parametrized cross section (see text).
deuteron using an analytical form of the deuteron wave function based on the Paris potential \[21\]. As a result one gets absolutely normalized differential cross sections for the quasi-free contribution to \(dd \rightarrow ^3\text{He} \pi^0\), which can be directly compared to the measured data. Figure 3a shows the momentum distribution of the neutron for data smaller than 90 MeV/c (indicated by the vertical red dotted line in the upper plot). Data are not corrected for acceptance.

Partial wave decomposition

For the remaining part of the data which cannot be described with the quasi-free process a 3-body model based on a partial wave decomposition has been developed. The relative angular momenta were defined according to the coordinates introduced earlier: one in the \(\pi^0\) - \(^3\text{He}\) system and one in the \(^3\text{He} - n\) subsystem (denoted by \(l\) and \(L\), respectively). For the partial wave decomposition the angular momenta have been limited to \(l + L \leq 1\), \(i.e.\) to at most one \(p\)-wave in the system. For the momentum dependence the standard approximation \(|M|^2 \propto q^2 p^{2L}\) was used. Taking into account all possible spin configurations this results in 18 possible amplitudes. After combining the amplitudes with the same signature in final state, four possible contributions can be identified: \(s\)-wave in both systems \((sS)\), one \(p\)-wave in either system \((sP\) and \(pS\)) and a \(sP - pS\) interference term. They can be described by seven real coefficients (four complex amplitudes minus one overall phase). With this the four-fold differential cross section can be written as:

\[
\frac{d^4 \sigma}{2\pi \, dM_{^{3}\text{He}n} \, d \cos \theta_p \, d \cos \theta_q \, d \varphi} = C \, p_q \, [A_0 + A_1 q^2 + A_3 p^2 + \frac{1}{4} A_2 q^2 (1 + 3 \cos 2 \theta_q) + \frac{1}{4} A_4 p^2 (1 + 3 \cos 2 \theta_p) + A_5 p q \cos \theta_p \cos \theta_q + A_6 p q \sin \theta_p \sin \theta_q \cos \varphi] \tag{1}
\]

with

\[
C = \frac{1}{32(2\pi)^3 s_p (2s_a + 1)(2s_b + 1)} \tag{2}
\]

where \(s_a\) and \(s_b\) denote the spin of beam and target and \(s\) and \(p^*_p\) the total energy squared and the beam momen-
Integration of Eq. [1] results in a set of equations for the description of the single differential cross sections:

\[
\frac{d\sigma}{dM^2_{\text{3He}}} = 16\pi^2 Cpq \left[ A_0 + A_1 q^2 + A_3 p^2 \right] \tag{3a}
\]
\[
\frac{d\sigma}{2\pi d\cos\theta_q} = 4\pi C \left[ B + \frac{1}{2} A_2 (1 + 3 \cos 2\theta_q) I_{pS} \right] \tag{3b}
\]
\[
\frac{d\sigma}{2\pi d\cos\theta_p} = 4\pi C \left[ B + \frac{1}{4} A_4 (1 + 3 \cos 2\theta_p) I_{sP} \right] \tag{3c}
\]
\[
\frac{d\sigma}{d\varphi} = 8\pi C \left[ B + \frac{\pi^2}{16} A_6 I_{pS+sP} \cos \varphi \right] \tag{3d}
\]

with the new coefficient

\[
B = A_0 I_{sS} + A_1 I_{pS} + A_3 I_{sP}. \tag{4}
\]

The constants \( I_{sS}, I_{pS}, I_{sP} \) and \( I_{pS+sP} \) are the results of the integration over \( M^2_{\text{3He}} \):

\[
I_{sS} = \int (\sqrt{\tau} - M^2) dq dM^2_{\text{3He}} \tag{5a}
\]
\[
I_{pS} = \int (\sqrt{\tau} - M^2)^2 dq dM^2_{\text{3He}} \tag{5b}
\]
\[
I_{sP} = \int (\sqrt{\tau} - M^2)^2 dq^3 dM^2_{\text{3He}} \tag{5c}
\]
\[
I_{pS+sP} = \int (\sqrt{\tau} - M^2)^2 dq^2 q dM^2_{\text{3He}} \tag{5d}
\]

Equations [3] do not contain the coefficient \( A_5 \) as the corresponding term vanishes with the integration over \( \cos \theta_q \) and \( \cos \theta_p \). In order to extract this coefficient Eq. [4] has to be multiplied by \( \cos \theta_q \cos \theta_p \) before integration. This results in the following formula to determine \( A_5 \):

\[
\frac{d\sigma'}{d\varphi} = 8\pi C A_5 I_{pS+sP} \tag{6}
\]

with \( \sigma'(q,p) = \sigma(q,p) \cdot \cos \theta_q \cos \theta_p \).

It has to be noted that the coefficients \( A_0, A_1 \) and \( A_3 \) cannot be extracted unambiguously from the differential distribution \( d\sigma/dM^2_{\text{3He}} \). In the non-relativistic limit \( q^2 \) and \( p^2 \) are both linear in \( M^2_{\text{3He}} \) introducing a correlation of all three coefficients. For the measurement of \( dd \rightarrow ^3\text{He}_p \pi^0 \) at an excess energy of \( Q \approx 40 \text{ MeV} \) a non-relativistic treatment is still a good approximation. Thus, only a value for \( B \) can be extracted from the data. Any values for \( A_0, A_1 \) and \( A_3 \) fulfilling Eq. [4] and the fit to \( d\sigma/dM^2_{\text{3He}} \) will lead to the same model description. However, in order to provide a complete set of coefficients the parameter \( A_1 \) has been fixed manually.

RESULTS

In a first step a sum of Monte-Carlo filtered distributions for each contribution from the partial wave decomposition (coefficients \( A_0 \) to \( A_6 \)) and from the quasi-free model (coefficient \( A_7 \)) was fitted to the uncorrected, single differential spectra. The result served as input for the Monte-Carlo simulation finally used to determine the acceptance correction.

The final distributions after acceptance correction are presented in Fig. 4. Contributions from the quasi-free model, the partial wave decomposition and the full model are shown in blue, green and red, respectively. These spectra were refitted using the analytical formulas given in the previous section. The result is consistent with the initial fit. Although the partial wave expansion was limited to at most one \( p \)-wave in the final state it provides a reasonable overall description of the data: both angular distributions show a significant contribution of \( p \)-waves of similar size, the \( pS-sP \) interference term is visualized by the non-isotropic distribution of \( d\sigma/d\varphi \). The quasi-free contribution is about 1.11 \( \mu \)b and, thus, is in agreement with the prediction of the quasi-free model (1.19 \( \mu \)b) within the normalization error of about 10% given in Ref. [19]. The result of the fit using Eq. [6] and the quasi-free model is presented in Fig. 5. The values for the extracted coefficients from the global fit are summarized in Table 1.

| Parameter | Fit result |
|-----------|------------|
| \( B \)   | (1.840 ± 0.003) \( \mu \)b |
| \( A_0 \) | (0.41 ± 0.01) \( \times 10^4 \) \( \mu \)b/GeV^3 |
| \( A_1 \) | 8.4 \( \times 10^4 \) \( \mu \)b/GeV^3 |
| \( A_2 \) | (18.3 ± 0.3) \( \times 10^4 \) \( \mu \)b/GeV^3 |
| \( A_3 \) | (1.08 ± 0.05) \( \times 10^4 \) \( \mu \)b/GeV^3 |
| \( A_4 \) | (18.04 ± 0.07) \( \times 10^4 \) \( \mu \)b/GeV^3 |
| \( A_5 \) | (−45.4 ± 0.3) \( \times 10^4 \) \( \mu \)b/GeV^3 |
| \( A_6 \) | (−15.0 ± 0.2) \( \times 10^4 \) \( \mu \)b/GeV^3 |
| \( \sigma_{qf} \cdot A_7 \) | (1.108 ± 0.003) \( \mu \)b |

TABLE 1. Collection of the extracted fit parameters. The amplitudes are given in units of \( (4\pi)^2 C \). The parameters \( A_0, A_1 \) and \( A_3 \) are correlated and could not be extracted unambiguously: the given numbers represent one possible solution with \( A_1 \) being fixed (see text).
FIG. 4. (Color online) Acceptance corrected data (black points) presented as functions of (a) $\cos \theta_q$, (b) $\cos \theta_p$, (c) $\varphi$ and (d) $M_{^3\text{He}n}$. The curves represent the fit to the model: full model (red solid), quasi-free contribution (blue dotted) and the partial wave decomposition (green long dashed). The hatched areas indicate the systematic uncertainties on the shape of the differential distributions. Uncertainties on the absolute normalization are not included.

larger for low excess energies in the $^3\text{He}n$ system (corresponding to low relative momenta). One possible reason for this might be excited states with isospin $I = 1$ in the $^3\text{He}n$ system at low excess energies as reported in Ref. [22] (the production of an $I = 0$ state would be charge symmetry breaking).

Figure 7 shows the acceptance corrected Dalitz plot for $M_{\pi\pi}^2$ versus $M_{^3\text{He}n}^2$. It should be noted that the Dalitz plot is fully covered except for a small region for large $\pi^0 - n$ invariant masses due to the acceptance hole for $\theta_{^3\text{He}} < 3^\circ$. The quasi-free reaction process mainly populates the region for small $\pi^0 - n$ invariant masses and large $^3\text{He} - n$ invariant masses. The observation of an increasing $p$-wave contribution for small excess energies in the $^3\text{He} - n$ system possibly caused by an excited $I = 0$ state comes with an enhancement in the Dalitz plot for small $^3\text{He} - n$ invariant masses.

Integrating over the differential distributions we obtain
for the total cross section of the \(dd \rightarrow ^3\text{He}n\pi^0\) reaction:

\[
\sigma_{tot} = (2.89 \pm 0.01_{\text{stat}} \pm 0.06_{\text{sys}} \pm 0.29_{\text{norm}}) \mu\text{b} \quad (7)
\]

**SUMMARY**

For the first time an exclusive measurement of the \(dd \rightarrow ^3\text{He}n\pi^0\) reaction has been performed. A total cross section of \(\sigma_{tot} = 2.89 \mu\text{b}\) with an accuracy of about 11\% has been extracted. Differential distributions have been compared to the incoherent sum of a quasi-free reaction model and a partial-wave expansion limited to at most one \(p\)-wave in the final state. The contribution of the quasi-free processes accounts for about 1.11 \(\mu\text{b}\) of the total cross section matching the prediction of the quasi-free reaction model. The partial wave decomposition reveals the importance of \(p\)-wave contributions in the final state. The applied model shows a reasonable agreement for all differential distribution. Thus, based on this comparison no indication for significant contributions of higher partial waves can be deduced.

The whole data set amounts to about \(3.4 \times 10^6\) fully reconstructed and background-free events. The presented differential distributions are only one possible representation of the results. One goal of the measurement was to provide data for studying \(dd\) initial state interaction for small angular momenta, which is one missing information in the microscopic description of the charge symmetry breaking reaction \(dd \rightarrow ^4\text{He}\pi^0\) within the framework of Chiral Perturbation Theory. Once the important observables have been identified the corresponding experimental distributions can be provided.

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