Importance of d-wave contributions in the charge symmetry breaking reaction $dd \to {}^4\mathrm{He}\pi^0$

P. Adlarson,[1,*] W. Augustyniak,[2] W. Bardan,[3] M. Bashkanov,[4] F.S. Bergmann,[5] M. Berłowski,[6] A. Bondar,[7,8] M. Büscher,[9,10] H. Calén,[1] I. Ciepał,[11] H. Clement,[12,13] E. Czerwiński,[3] K. Demmich,[5] R. Engels,[14] A. Erven,[15] W. Erven,[15] W. Eyrich,[16] P. Fedorets,[14,17] K. Föhl,[18] K. Fransson,[1] F. Goldenbaum,[14] A. Goswami,[19,14] K. Grigoryev,[14,20] C.–O. Gullström,[1] C. Hanhart,[14,21] L. Heijkenskjöld,[1,*] V. Hejny,[14] N. Hüsken,[5] L. Jarczyk,[3] T. Johansson,[1] B. Kamys,[3] G. Kemmerling,[15,†] G. Khatri,[3,‡] A. Khoukaz,[5] O. Khreptak,[3] D.A. Kirillov,[22] S. Kistryn,[3] H. Kleines,[15,†] B. Kłos,[23] W. Krzemień,[6] P. Kulessa,[11] A. Kupść,[1,6] A. Kuzmin,[7,8] K. Lalwani,[24] D. Lersch,[14] B. Lorentz,[14] A. Magiera,[3] R. Maier,[14,25] P. Marciniewski,[1] B. Mariański,[2] H.–P. Morsch,[2] P. Moskal,[3] H. Ohm,[14] W. Parol,[11] E. Perez del Rio,[12,13,§] N.M. Piskunov,[22] D. Prasuhn,[14] D. Pszczel,[1,6] K. Pysz,[11] A. Pyszniak,[1,3] J. Ritman,[14,25,26] A. Roy,[19] Z. Rudy,[3] O. Rundel,[3] S. Sawant,[27] S. Schadmand,[14] I. Schätti–Ozerianska,[3] T. Sefzick,[14] V. Serdyuk,[14] B. Shwartz,[7,8] K. Sitterberg,[5] T. Skorodko,[12,13,28] M. Skurzok,[3] J. Smyrski,[3] V. Sopov,[17] R. Stassen,[14] J. Stepaniak,[6] E. Stephan,[23] G. Sterzenbach,[14] H. Stockhorst,[14] H. Ströher,[14,25] A. Szczurek,[11] A. Trzciński,[2] M. Wolke,[1] A. Wrońska,[3] P. Wüstner,[15] A. Yamamoto,[29] J. Zabierowski,[30] M.J. Zieliński,[3] J. Złomańczuk,[1] P. Żupranski,[2] and M. Żurek[14]

(WASA-at-COSY Collaboration)

[1] *Division of Nuclear Physics, Department of Physics and Astronomy, Uppsala University, Box 516, 75120 Uppsala, Sweden*
[2] *Department of Nuclear Physics, National Centre for Nuclear Research, ul. Hoza 69, 00-681, Warsaw, Poland*
[3] *Institute of Physics, Jagiellonian University, prof. Stanisława Łojasiewicza 11, 30-348 Kraków, Poland*
[4] *School of Physics and Astronomy, University of Edinburgh, James Clerk Maxwell Building, Peter Guthrie Tait Road, Edinburgh EH9 3FD, Great Britain*
[5] *Institut für Kernphysik, Westfälische Wilhelms–Universität Münster, Wilhelm–Klemm–Str. 9, 48149 Münster, Germany*
[6] *High Energy Physics Department, National Centre for Nuclear Research, ul. Hoza 69, 00-681, Warsaw, Poland*
[7] *Budker Institute of Nuclear Physics of SB RAS, 11 akademika Lavrentieva prospect, Novosibirsk, 630090, Russia*
[8] *Novosibirsk State University, 2 Pirogova Str., Novosibirsk, 630090, Russia*
[9] *Peter Grünberg Institut, Forschungszentrum Jülich, 52425 Jülich, Germany*
[10] *Institut für Laser– und Plasmaphysik, Heinrich–Heine Universität Düsseldorf, Universitätsstr. 1, 40225 Düsseldorf, Germany*
[11] *The Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, 31–342 Kraków, Poland*
[12] *Physikalisches Institut, Eberhard–Karls–Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany*
[13] *Kepler Center für Astro– und Teilchenphysik, Physikalisches Institut der Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany*
[14] *Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[15] *Zentralinstitut für Engineering, Elektronik und Analytik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[16] *Physikalisches Institut, Friedrich–Alexander–Universität Erlangen–Nürnberg, Erwin–Rommel-Str. 1, 91058 Erlangen, Germany*
[17] *Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre "Kurchatov Institute", 25 Bolshaya Cheremushkinskaya, Moscow, 117218, Russia*
[18] *II. Physikalisches Institut, Justus–Liebig–Universität Gießen, Heinrich–Buff–Ring 16, 35392 Giessen, Germany*
[19] *Department of Physics, Indian Institute of Technology Indore, Khandwa Road, Simrol, Indore–453552, Madhya Pradesh, India*
[20] *High Energy Physics Division, Petersburg Nuclear Physics Institute named by B.P. Konstantinov of National Research Centre "Kurchatov Institute", 1 mkr. Orlova roshcha, Leningradskaya Oblast, Gatchina, 188300, Russia*
[21] *Institute for Advanced Simulation, Forschungszentrum Jülich, 52425 Jülich, Germany*
[22] *Veksler and Baldin Laboratory of High Energiy Physics, Joint Institute for Nuclear Physics, 6 Joliot–Curie, Dubna, 141980, Russia*
[23] *August Chełkowski Institute of Physics, University of Silesia, Uniwersytecka 4, 40–007, Katowice, Poland*
[24] *Department of Physics, Malaviya National Institute of Technology Jaipur, JLN Marg Jaipur - 302017, Rajasthan, India*
[25] *JARA–FAME, Jülich Aachen Research Alliance, Forschungszentrum Jülich, 52425 Jülich, and RWTH Aachen, 52056 Aachen, Germany*
[26] *Institut für Experimentalphysik I, Ruhr–Universität Bochum, Universitätsstr. 150, 44780 Bochum, Germany*
[27] *Department of Physics, Indian Institute of Technology Bombay, Powai, Mumbai–400076, Maharashtra, India*
[28] *Department of Physics, Tomsk State University, 36 Lenina Avenue, Tomsk, 634050, Russia*
[29] *High Energy Accelerator Research Organisation KEK, Tsukuba, Ibaraki 305–0801, Japan*
[30] *Department of Astrophysics, National Centre for Nuclear Research, 90–950 Łódź, Poland*

(Dated: September 20, 2017)

This letter reports the first measurement of the contribution of higher partial waves in the charge symmetry breaking reaction $dd \to {}^4\mathrm{He}\pi^0$ using the WASA-at-COSY detector setup at an excess energy of $Q = 60\,\mathrm{MeV}$. The determined differential cross section can be parametrized as

$d\sigma/d\Omega = a + b\cos^2\theta^*$, where θ^* is the production angle of the pion in the center-of-mass coordinate system, and the results for the parameters are $a = \left(1.55 \pm 0.46(\text{stat})^{+0.32}_{-0.8}(\text{syst})\right)$ pb/sr and $b = \left(13.1 \pm 2.1(\text{stat})^{+1.0}_{-2.7}(\text{syst})\right)$ pb/sr. The data are compatible with vanishing p-waves and a sizable d-wave contribution. This finding should strongly constrain the contribution of the Δ isobar to the $dd \to {}^4\text{He}\pi^0$ reaction and is therefore crucial for a quantitative understanding of quark mass effects in nuclear production reactions.

PACS numbers: 24.80.+y, 24.85.+p, 13.75.Cs, 25.45.-z, 25.10.+s, 11.30.Hv

Within the Standard Model of elementary particles isospin symmetry is violated via quark mass differences as well as electromagnetic effects [1–3]. On the hadronic level this is reflected, for example, by the proton-neutron mass difference. It is due to quark-mass effects that the proton is lighter than the neutron and, therefore, stable. The observation of isospin violation (IV) in hadronic reactions in principle allows one to study the effects of quark masses. However, most experimental signatures of IV are dominated by the pion mass difference $m_{\pi^0} - m_{\pi^\pm}$, which is to a very good approximation of purely electromagnetic origin. An exception are observables that are charge symmetry breaking (CSB). Charge symmetry, a subgroup of isospin symmetry, is the invariance of the Hamiltonian under rotation by 180° around the second axis in isospin space that interchanges up and down quarks. The charge symmetry operator does not interchange charged and neutral pion states, and the pion mass difference does not enter (see, e.g., [4]). On the basis of theoretical approaches with a direct connection to QCD, like lattice QCD and chiral perturbation theory (ChPT), it is therefore possible to link quark-mass effects to hadronic observables.

The first observation of the CSB reaction $dd \to {}^4\text{He}\pi^0$ was reported for beam energies very close to the reaction threshold in 2003 [5]. At the same time, CSB was observed via a non-vanishing forward-backward asymmetry in $np \to d\pi^0$ [6]. The signal of the latter measurement was shown to be proportional to the quark-mass-induced part of the proton-neutron mass difference up to next-to-leading order in ChPT [7, 8]. This was extended to pion production reactions in Ref. [9] and has been pushed recently to next-to-next-to-leading order for s-waves [10, 11]. The contribution of p-waves has been investigated in Ref. [12]. For a recent review see Ref. [13].

First steps towards a theoretical understanding of the $dd \to {}^4\text{He}\pi^0$ reaction were taken in Refs. [14, 15]. Additional CSB effects from soft photons in the initial state have been studied in Refs. [16, 17]. The focus has been on s-waves in the final state, since no experimental information on higher partial waves was available until now. However, such information is important, since it will allow one to constrain the contribution from the Δ resonance that is known to provide the bulk of the p-wave contributions in the isospin conserving $pp \to d\pi^+$ reaction [18–20] — without this, a quantitative control of higher order operators for the reaction at hand appears impossible. A first measurement with WASA was inconclusive due to limited statistics [21]. In this paper for the first time data are presented that quantify the contribution of higher partial waves to the reaction $dd \to {}^4\text{He}\pi^0$.

The ten-week-long experiment was performed at the Cooler Synchrotron COSY [22] of the Institute for Nuclear Physics at the Forschungszentrum Jülich in Germany. The particles produced in the collisions of a deuteron beam with a momentum of $p_d = 1.2\,\text{GeV}/c$ ($Q = 60\,\text{MeV}$) with frozen deuteron pellets were detected in the modified WASA facility [23]. The setup consisted of forward and central detectors, where the ^{4}He ejectiles and the photons from the π^0 decay were detected, respectively. For this experiment the forward detector was optimized for a time-of-flight (TOF) measurement. Several layers of the original detector were removed to introduce a free flight path of more than 1.5 m. The new setup consisted of an array of straw tubes for precise tracking and three layers of plastic scintillators for energy reconstruction and particle identification: two 3 mm thick layers of the forward window counter, used as start detectors, and the 20 mm thick layer of the forward veto hodoscope, used as a stop detector. Photons from the π^0 decay were detected in the central electromagnetic calorimeter and discriminated from charged particles by means of a veto signal from the plastic scintillator barrel located inside the calorimeter.

The main trigger required a high energy deposit in at least one element of the first and the second layer of the forward window counter and at least one cluster originating from a neutral particle in the central detector.

The signature of the $dd \to {}^4\text{He}\pi^0$ reaction is a forward-going ^{4}He particle and two photons from the decay of the π^0. The only other channel with ^{4}He and two photons in the final state is the double radiative capture reaction $dd \to {}^4\text{He}\gamma\gamma$ as an irreducible physics background. A further source of background is the isospin symmetry conserving $dd \to {}^3\text{He}n\pi^0$ reaction with a more than four orders of magnitude higher cross section [24]. The suppression of this reaction is challenging since ^{3}He and ^{4}He have similar energy losses in the forward window counters with respect to detector resolution. Compared to $dd \to {}^3\text{He}n\pi^0$, the direct two photon production in $dd \to {}^3\text{He}n\gamma\gamma$ is suppressed by a factor of α^2 (with α being the fine-structure constant) and can be neglected.

The energy loss in the forward window counters and TOF 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 have been obtained using in addition the azimuthal and polar angles reconstructed by the forward tracking detector. For the further analysis at least one track in the forward detector and at least two reconstructed clusters of crystals with energy deposited by neutral particles in the central detector have been required.

The final candidate events have been selected by means of a kinematic fit. The purpose of the fit was to improve the precision of the measured kinematic variables and to serve as a selection criterion for background reduction. For the assumed reaction hypothesis the measured variables were varied within the experimental uncertainties until certain kinematic constraints were fulfilled, here the overall momentum and energy conservation. For every event the $dd \to {}^3\mathrm{He}n\gamma\gamma$ and $dd \to {}^4\mathrm{He}\gamma\gamma$ hypotheses have been tested separately. No additional constraint on the invariant mass of the two photons has been imposed, in order not to produce an artificial π^0 signal. In case of more than one track in the forward detector or more than two neutral clusters in the central detector (caused by event pileup or low energy satellites of the main photon clusters) the combination with the smallest χ^2 from the fit has been chosen.

The main reduction of the $dd \to {}^3\mathrm{He}n\pi^0$ background by four orders of magnitude has been achieved using a cut on the two-dimensional cumulative probability distribution from the kinematic fits, analogously as in Ref. [21]. The cut has been optimized by maximizing the statistical significance of the π^0 signal in the final missing mass plot.

The four-momenta obtained from the kinematic fit of the $dd \to {}^4\mathrm{He}\gamma\gamma$ hypothesis have been used to calculate the missing mass m_X for the reaction $dd \to {}^4\mathrm{He}X$ as a function of the center-of-mass production angle θ^* of the π^0. In Fig. 1 the missing mass spectra for the four angular bins within the detector acceptance ($-0.9 \leq \cos\theta^* \leq 0.4$) are presented. On a smooth background from double radiative capture $dd \to {}^4\mathrm{He}\gamma\gamma$ two significant peaks are visible. One, originating from the signal reaction $dd \to {}^4\mathrm{He}\pi^0$, is located at the π^0 mass. The other corresponds to misidentified events from the background reaction $dd \to {}^3\mathrm{He}n\pi^0$ and is shifted by the $^3\mathrm{He} - n$ binding energy. The missing mass spectra have been fitted with a linear combination of the following high-statistics Monte-Carlo templates: (i) $dd \to {}^4\mathrm{He}\gamma\gamma$ assuming a 3-body phase-space distribution, (ii) $dd \to {}^3\mathrm{He}n\pi^0$ using the model from [24], and (iii) the two-body reaction $dd \to {}^4\mathrm{He}\pi^0$. For each $\cos\theta^*$ bin, a fit of the Monte-Carlo templates to the data has been performed with the constraint that the sum of the fitted templates has to fit the overall missing mass spectrum. As result, the π^0 peak from the $dd \to {}^4\mathrm{He}\pi^0$ reaction contains 336 ± 43 events in total.

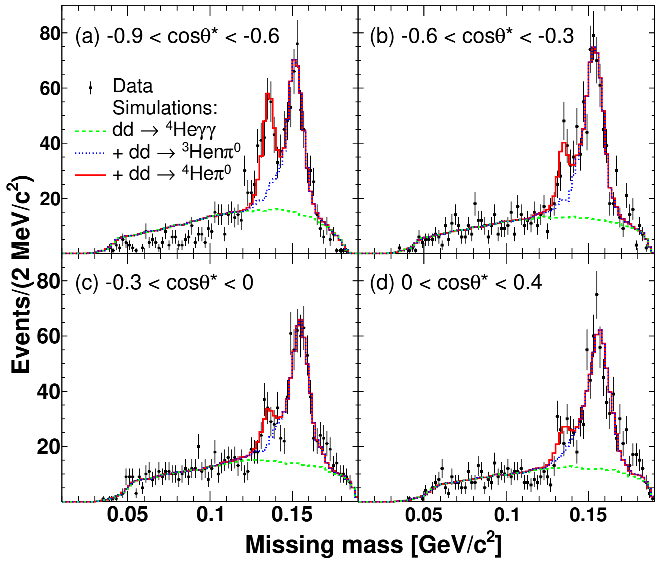

FIG. 1. Missing mass for the $dd \to {}^4\mathrm{He}X$ reaction for the four angular bins of the production angle of the pion in the center-of-mass system. The spectrum is fitted with a linear combination of the simulated signal and background reactions: double radiative capture $dd \to {}^4\mathrm{He}\gamma\gamma$ (green dashed line), plus $dd \to {}^3\mathrm{He}n\pi^0$ (blue dotted line), plus $dd \to {}^4\mathrm{He}\pi^0$ (red solid line). The fit excludes the missing mass region below $0.11\,\mathrm{GeV}/c^2$.

For the final acceptance correction, the $dd \to {}^4\mathrm{He}\pi^0$ generator with the angular distribution obtained in this analysis has been used. The integrated luminosity has been calculated using the $dd \to {}^3\mathrm{He}n\pi^0$ reaction, based on the previous measurement with WASA at $p_d = 1.2\,\mathrm{GeV}/c$ [24].

In the course of the analysis several systematic effects have been investigated. In the missing mass spectra, the background originating from misidentified $dd \to {}^3\mathrm{He}n\pi^0$ events is slightly shifted in comparison to the simulation. The largest effect is visible for forward angles. This shift can be attributed to systematic differences in the simulated detector response for ^{4}He and ^{3}He. The limited statistics after all cuts prevents studying this effect in detail. Therefore, this mismatch has been compensated by introducing an angle-dependent scaling factor in the missing mass m_X for the $dd \to {}^3\mathrm{He}n\pi^0$ background as a free parameter. The obtained factors (from backward to forward angles) are within the range of 1.005–0.972. No additional systematic uncertainty has been assigned to this effect, since the resulting fit describes the shape of the background in the region of the π^0 mass peak.

Another systematic effect is linked to a mismatch in the missing mass spectra below $0.11\,\mathrm{GeV}/c^2$ in the most backward angular bin. The fit shows that this region is dominated by the $dd \to {}^4\mathrm{He}\gamma\gamma$ reaction which has been simulated using 3-body phase space. This model does not provide a good description in that region. However,

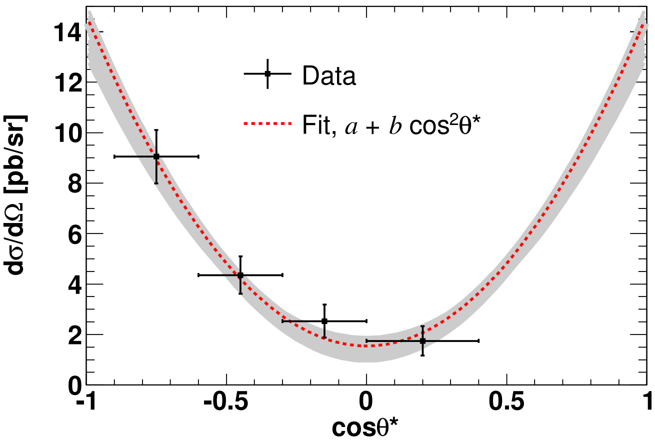

FIG. 2. Angular distribution of the $dd \to {}^4\mathrm{He}\pi^0$ reaction at $Q = 60\,\mathrm{MeV}$. The result of the fit up to second order in $\cos\theta^*$ is shown with a dotted curve. The systematic errors of the fit are presented as a gray band. The horizontal error bars indicate the bin width.

the dominating background from the $dd \to {}^3\mathrm{He}n\pi^0$ reaction at higher missing masses prevents describing all contributions precisely enough to verify more advanced models. The final fit therefore excludes the missing mass range below $0.11\,\mathrm{GeV}/c^2$ in all angular bins.

In addition, the stability of the results has been tested against variations of the selection cuts, according to the method described in Ref. [25]. The only statistically significant effect has been observed with the variation of the cumulative probability distribution cut.

Figure 2 presents the obtained differential cross section. Since identical particles in the initial state require a forward-backward symmetric cross section, it has been fitted using the function $\mathrm{d}\sigma/\mathrm{d}\Omega = a + b\cos^2\theta^*$ resulting in:

$$a = \left(1.55 \pm 0.46(\mathrm{stat})^{+0.32}_{-0.8}(\mathrm{syst})\right)\,\mathrm{pb/sr}, \quad (1a)$$

$$b = \left(13.1 \pm 2.1(\mathrm{stat})^{+1.0}_{-2.7}(\mathrm{syst})\right)\,\mathrm{pb/sr}. \quad (1b)$$

Both parameters have in addition a common systematic uncertainty of about 10% from normalization.

The cross sections are systematically smaller than the result from Ref. [21], however, consistent within errors. This difference might be related to the implementation of low-energy nuclear interactions of ^{3}He in the Monte-Carlo simulation, which has been used for normalization. While a corresponding uncertainty has not been taken into account for the previous measurement, the simulation code has been updated accordingly for the current measurement. In addition, the TOF cut in the current analysis is less sensitive to this effect than the previously used energy-loss correlations.

For a further analysis of the differential cross section in terms of partial waves in the final state, the formalism from Ref. [26] has been used. Considering only s- and p-waves the parameter b can be written as:

$$b = -\frac{p_{\pi^0}}{p}\frac{2}{3}|C|^2 p_{\pi^0}^2, \quad (2)$$

where C is the p-wave amplitude, p_{π^0} is the momentum of the pion, and p is the incident deuteron momentum, both in the center-of-mass system. Up to this order, p-waves contribute with a negative sign corresponding to a maximum at $\theta^* = 90^\circ$ in the angular distribution. The observed minimum can only be explained extending the formalism to d-waves in the final state. Therefore, these data establish for the first time the presence of sizable contribution of d-waves to the $dd \to {}^4\mathrm{He}\pi^0$ reaction, which have so far not been considered in the theoretical calculations.

A consistent description that includes d-waves has to consider terms up to fourth order in pion momentum. Following Ref. [26] the differential cross section can be written as:

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{p_{\pi^0}}{p}\frac{2}{3}\Big(&|A_0|^2 + 2\,\mathrm{Re}(A_0^*A_2)P_2(\cos\theta^*)p_{\pi^0}^2 \\ &+ |A_2|^2 P_2^2(\cos\theta^*)p_{\pi^0}^4 + |C|^2\sin^2\theta^* p_{\pi^0}^2 \\ &+ |B|^2\sin^2\theta^*\cos^2\theta^* p_{\pi^0}^4\Big).\end{aligned} \quad (3)$$

Here, A_0 is the s-wave amplitude, A_2 and B are the d-wave amplitudes, and P_2 is the second order Legendre polynomial. Note that the symmetry of the initial state requires that only partial waves of the same parity interfere. The corresponding expression for the total cross section reads:

$$\begin{aligned}\sigma_{\mathrm{tot}} = \frac{p_{\pi^0}}{p}\frac{8\pi}{3}\Big(&|A_0|^2 + \frac{2}{3}|C|^2 p_{\pi^0}^2 \\ &+ \frac{1}{5}|A_2|^2 p_{\pi^0}^4 + \frac{2}{15}|B|^2 p_{\pi^0}^4\Big).\end{aligned} \quad (4)$$

Since a full fit with four independent amplitudes and one relative phase is beyond the means of the presented data, quantitative results can only be obtained using additional constraints. For example, one may assume that the amplitudes A_0, A_2, B and C do not carry any momentum dependence. Then the angular distribution can be fitted simultaneously together with the momentum dependence from Eq. (4) by including the data from Ref. [5]. In addition, the results have been systematically studied by fixing the different amplitudes in the fit, restricting the fit function to terms up to $p_{\pi_0}^2$, and limiting the fit to the angular distribution only. This has shown that the data are not sensitive to $|B|$, which has comparatively large errors and is always consistent with zero. There is also no indication of a sizable p-wave contribution. All other parameters are stable within the uncertainties of the fit. This also applies for the values of $|A_0|$ from the combined fit and the fit to the angular distribution only. This supports the assumption of a momentum independent s-wave amplitude: for the simultaneous fit the value of $|A_0|$ is mostly constrained by the two points close to threshold from Ref. [5] where s-wave is dominating. The relative phase δ between A_0 and A_2 (i.e., $\Re\{A_0^* A_2\} = |A_0||A_2|\cos\delta$) has been determined to be equal to zero with a statistical uncertainty in the range of $\pm(1.0$–$1.6)$ rad.

As final result the fit has been chosen where B was omitted, the relative phase between A_0 and A_2 was fixed to zero, and the momentum dependence of the total cross section was included. The extracted amplitudes are:

$$|A_0| = \big(5.77 \pm 0.35(\text{stat})^{+0.08}_{-0.33}(\text{syst}) \\ {}^{+0.01}_{-0.19}(\text{norm})\big)\,(\text{pb/sr})^{1/2}, \quad (5a)$$

$$|A_2| = \big(255 \pm 59(\text{stat})^{+48}_{-38}(\text{syst}) \\ {}^{+37}_{-12}(\text{norm})\big)\,\frac{(\text{pb/sr})^{1/2}}{(\text{GeV}/c)^2}, \quad (5b)$$

$$|C| = \big(4 \pm 38(\text{stat})^{+9}_{-10}(\text{syst}) \\ {}^{+10}_{-5}(\text{norm})\big)\,\frac{(\text{pb/sr})^{1/2}}{\text{GeV}/c}. \quad (5c)$$

The systematic uncertainties also include the systematic effects associated with the results from [5]. The given errors are not independent but highly correlated. The total cross section obtained as the integral of the function fitted to the angular distribution amounts to:

$$\sigma_{\text{tot}} = (76.9 \pm 7.8(\text{stat})^{+1.9}_{-8.8}(\text{syst})^{+8.3}_{-5.7}(\text{norm}))\,\text{pb}. \quad (6)$$

The resulting momentum dependence of the reaction amplitude squared $(p/p_{\pi^0})\sigma_{\text{tot}}$ is shown in Fig. 3 as dotted curve.

In summary, this letter reports for the first time a successful measurement of higher partial waves in the differential cross section of the charge symmetry violating reaction $dd \to {}^4\text{He}\pi^0$. The data with a minimum at $\theta^* = 90°$ can be understood only by the presence of a significant d-wave contribution in the final state. At the same time they are consistent with a vanishing p-wave.

It is well known from phenomenology as well as studies using effective field theory that the Δ isobar plays a crucial role in pion production reactions, especially for partial waves higher than s-wave [18–20]. Since isospin conservation does not allow for the excitation of a single Δ in the dd state, the appearance of prominent higher partial waves in $dd \to {}^4\text{He}\pi^0$ might point at an isospin violating excitation of the Δ isobar. This indicates that a theoretical analysis of the data presented in the letter should allow for deep insights not only into the dynamics of the nucleon-nucleon interaction but also into the role of quark masses in hadron dynamics.

We would like to thank the technical staff of the COoler SYnchrotron COSY. We thank C. Wilkin for valuable discussions. This work was supported in part by the EU Integrated Infrastructure Initiative Hadron Physics Project under contract number RII3-CT-2004-506078; by the European Commission under the 7th Framework Programme through the Research Infrastructures action of the Capacities Programme, Call: FP7-INFRASTRUCTURES-2008-1, Grant Agreement No. 227431; by the Polish National Science Centre through the grants 2016/23/B/ST2/00784, 2014/15/N/ST2/03179, DEC-2013/11/N/ST2/04152, and the Foundation for Polish Science (MPD), co–financed by the European Union within the European Regional Development Fund. We acknowledge the support given by the Swedish Research Council, the Knut and Alice Wallenberg Foundation, and the Forschungszentrum Jülich FFE Funding Program. This work is based on the PhD thesis of Maria Żurek.

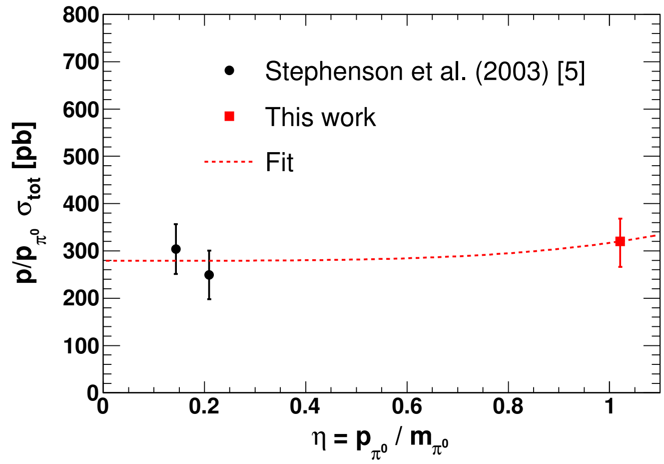

FIG. 3. The $dd \to {}^4\text{He}\pi^0$ reaction amplitude squared $(p/p_{\pi^0})\sigma_{\text{tot}}$ as a function of $\eta = p_{\pi^0}/m_{\pi^0}$. The circles represent the results from [5], the square corresponds to the final result for the total cross section from Eq. (6). The error bars show the combined statistical and systematic uncertainties. The dotted curve indicates the momentum dependence with the amplitudes from Eq. (5).

* present address: Institut für Kernphysik, Johannes Gutenberg–Universität Mainz, Johann–Joachim–Becher Weg 45, 55128 Mainz, Germany
† present address: Jülich Centre for Neutron Science JCNS, Forschungszentrum Jülich, 52425 Jülich, Germany
‡ present address: Department of Physics, Harvard University, 17 Oxford St., Cambridge, MA 02138, USA
§ present address: INFN, Laboratori Nazionali di Frascati, Via E. Fermi, 40, 00044 Frascati (Roma), Italy

[1] S. Weinberg, Trans. New York Acad. Sci. **38**, 185 (1977).
[2] J. Gasser and H. Leutwyler, Phys. Rept. **87**, 77 (1982).
[3] H. Leutwyler, Phys. Lett. **B378**, 313 (1996).
[4] G. A. Miller, B. M. K. Nefkens, and I. Šlaus, Phys. Rept. **194**, 1 (1990).

[5] E. J. Stephenson *et al.*, Phys. Rev. Lett. **91**, 142302 (2003).
[6] A. K. Opper *et al.*, Phys. Rev. Lett. **91**, 212302 (2003).
[7] G. A. Miller, A. K. Opper, and E. J. Stephenson, Ann. Rev. Nucl. Part. Sci. **56**, 253 (2006).
[8] A. A. Filin, V. Baru, E. Epelbaum, J. Haidenbauer, C. Hanhart, A. E. Kudryavtsev, and U.-G. Meißner, Phys. Lett. **B681**, 423 (2009).
[9] C. Hanhart, Physics Reports **397**, 155 (2004).
[10] A. A. Filin, V. Baru, E. Epelbaum, H. Krebs, C. Hanhart, and F. Myhrer, Phys. Rev. **C88**, 064003 (2013).
[11] V. Baru, E. Epelbaum, A. A. Filin, C. Hanhart, H. Krebs, and F. Myhrer, Eur. Phys. J. **A52**, 146 (2016).
[12] V. Baru, E. Epelbaum, J. Haidenbauer, C. Hanhart, A. E. Kudryavtsev, V. Lensky, and U.-G. Meißner, Phys. Rev. **C80**, 044003 (2009).
[13] V. Baru, C. Hanhart, and F. Myhrer, Int. J. Mod. Phys. **E23**, 1430004 (2014).
[14] A. Gårdestig, C. J. Horowitz, A. Nogga, A. C. Fonseca, C. Hanhart, G. A. Miller, J. A. Niskanen, and U. van Kolck, Phys. Rev. **C69**, 044606 (2004).
[15] A. Nogga, A. C. Fonseca, A. Gårdestig, C. Hanhart, C. J. Horowitz, G. A. Miller, J. A. Niskanen, and U. van Kolck, Phys. Lett. **B639**, 465 (2006).
[16] T. A. Lahde and G. A. Miller, Phys. Rev. **C75**, 055204 (2007).
[17] A. C. Fonseca, R. Machleidt, and G. A. Miller, Phys. Rev. **C80**, 027001 (2009).
[18] J. A. Niskanen, Nucl. Phys. **A298**, 417 (1978).
[19] J. A. Niskanen, Phys. Rev. **C53**, 526 (1996).
[20] C. Hanhart, J. Haidenbauer, O. Krehl, and J. Speth, Phys. Lett. **B444**, 25 (1998).
[21] P. Adlarson *et al.* (WASA-at-COSY), Phys. Lett. **B739**, 44 (2014).
[22] R. Maier, Nucl. Instrum. Meth. **A390**, 1 (1997).
[23] H.-H. Adam *et al.* (WASA-at-COSY), (2004), arXiv:0411038 [nucl-ex].
[24] P. Adlarson *et al.* (WASA-at-COSY), Phys. Rev. **C88**, 014004 (2013).
[25] R. Barlow, (2002), arXiv:0207026 [hep-ex].
[26] A. Wrońska *et al.*, Eur. Phys. J. **A26**, 421 (2005).