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# STUDIES OF CHARGE SYMMETRY BREAKING REACTIONS AT COSY

*A. Magiera*
Institute of Physics
Jagiellonian University
Reymonta 4, 30-059 Cracow, Poland

**Abstract**

Investigations of the charge symmetry breaking become the most important topic for WASA detector at COSY. The planned studies concentrate on charge symmetry forbidden reaction $d + d \rightarrow \alpha + \pi^0$ and decays of $\eta'$ meson. The experimental results will be compared with Chiral Perturbation Theory ($\chi$PT) predictions, providing information on up and down quarks mass difference. For $d + d \rightarrow \alpha + \pi^0$ reaction various mechanisms within $\chi$PT were considered and it was found that the leading process is suppressed due to the selection rules. It is shown that another (not yet investigated) charge symmetry forbidden reaction, $d+d \rightarrow d+d+\pi^0$, may deliver new information on such leading process. In this case the use of tensor polarized deuteron beam will be especially important, allowing extraction of contributing amplitudes. The physical issues of charge symmetry breaking in $\vec{d} + d \rightarrow d + p + n$ reaction, which may be measured simultaneously, are presented. Feasibility to perform measurements of these reactions with WASA at COSY is discussed.

## 1 Introduction

The observed experimentally similarities in proton and neutron masses and interactions led Heisenberg to introduce isospin, which allows treating both these particles as two states of the nucleon. This concept gave way to a more general preposition on isospin and charge symmetry, described as the invariance of the hadron system under rotations in the isospin space. After discovery of various hadrons this idea was followed by introducing the SU3 symmetry, allowing to group them into multiplets. A direct consequence of this observation was the concept of quarks - elementary particles building all hadrons.

Since the masses and interactions of different hadrons belonging to the same SU3 multiplet are not the same, the charge and isospin symmetries are not exact. Therefore, until discovery of quarks, these symmetries were considered as accidental. Presently the appearance of these symmetries may be explained by the up and down quark mass difference and by their different electromagnetic interaction. Therefore, the observation of isospin or/and charge symmetry violation for hadrons opens a unique window to study the quark mass term of the QCD.

Despite that the isospin and charge symmetries are approximate, they were widely applied in various nuclear and particle physics investigations. Consequently, the searches for charge symmetry breaking (CSB) and isospin symmetry breaking (ISB) were performed very intensively (see ref. [1] for a review). However, it was not possible to relate the observed CSB and ISB to the elemental level of the QCD. Recently CSB was discovered by observation of the charge symmetry forbidden reaction $d + d \rightarrow \alpha + \pi^0$ [2] and of forward-backward asymmetry in the $p + n \rightarrow d + \pi^0$ reaction [3]. This triggered intensive theoretical calculations in the frame of Chiral Perturbation Theory (ChPT) [4–6]. Significant progress has been obtained in the theoretical analysis (see [7] for a review), however, still more experimental data are necessary.

# 2 Existing data and its implications

Major effect of ISB have the origin in the static symmetry breaking due to hadron mass differences. In the case of pions the origin of the mass difference is predominantly due to electromagnetic quark interaction. In order to have access to the dynamical symmetry breaking it is more favorable to study effect of CSB, where the pion mass difference does not contribute. However, the observation of CSB is difficult since these effects are very small. Therefore the best choice for studying the CSB are processes forbidden by charge symmetry invariance. This is the case for $d + d \rightarrow \alpha + \pi^0$ reaction, recently observed at the beam energies close to the kinematical threshold [2]. The total cross section values measured for two beam energies ($\sigma = 12.7 \pm 2.2$ pb at $T_d = 228.5$ MeV and $15.1 \pm 3.1$ pb at 231.8 MeV) are in agreement with the $S$-wave production. The difficulties in observation of CSB in allowed reactions is demonstrated in studies of the forward-backward asymmetry in the $p + n \rightarrow d + \pi^0$ reaction [3]. The final result $A_{fb} = [17.2 \pm 8(stat) \pm 5.5(sys)] \cdot 10^{-4}$ due to large uncertainties is a less convincing demonstration of CSB effects. Both recent experiments on CSB are under analysis using the ChPT [7]. A theory collaboration group, aiming at calculating the CSB effects in $\pi^0$ production reactions, has been formed [8] and the work on the theoretical frontier is in progress.

In the case of CSB in the $p+n \to d+\pi^0$ reaction the calculations within meson exchange coupled channel model [9] showed that the CSB effects are induced by $\pi^0-\eta$ mixing. However, this results in negative $A_{fb}$ value in disagreement with the experimental observation. The calculations performed using ChPT [4] lead to positive values of forward-backward asymmetry, as observed experimentally. In this case the CSB is driven by charge symmetry violation in $\pi^0$-nucleon interaction. The predicted effect is much larger than observed experimentally. Therefore further theoretical analysis is required and more precise data on CSB in this reaction are necessary.

The first calculations using ChPT were performed for the $d+d \to \alpha+\pi^0$ reaction [5]. It was found that at the leading order (LO) only charge symmetry violation in pion rescattering contributes. There is no NLO order contribution and some NNLO contributions were identified. Calculations of the cross section were performed using plane wave approximation in the entrance channel and simplified $\alpha$ particle wave function. It was found that the contribution from the LO term becomes negligibly small due to spin-isospin selection rules and the symmetry of $\alpha$ wave function. The NNLO terms result in the cross section by a factor of two larger than the experimentally observed. It necessitates, however, in surprisingly large value of the graph used to estimate the influence of the short range physics. Without this graph the cross section will be reduced to a value by one order of magnitude smaller than the experimental one. More reliable calculations were performed using realistic four body wave functions in the entrance and exit channels [6]. It was confirmed that the LO contribution is negligible and that at NNLO the first non vanishing contribution gives the cross section of the same order of magnitude as the observed experimentally. At NNLO new terms with unknown strength contribute to $s$-wave pion production in the $d+d \to \alpha+\pi^0$ reaction. In order to fix the strength of the isospin violating $\pi NN$ constant a new measurement for $p$-wave production is planned at COSY [10]. A dramatic influence of the initial state interaction was identified. Therefore new experimental constraints for deuteron-deuteron interaction becomes of great importance. This will be delivered by new measurements performed at COSY for charge symmetry conserving reactions $d+d \to {}^3A+N+\pi$ at threshold [11] and substantially above the threshold [10].

Advanced analysis of CSB effect using ChPT will profit also from data for other CSB reactions that may be studied at COSY. These other possible measurements comprise investigations of charge symmetry forbidden reaction $d+d \to d+d+\pi^0$ and polarization observables in deuteron break-up $d+d \to d+p+n$. The $d+d \to d+d+\pi^0$ reaction was never observed and it may deliver direct information on the LO term not accessible in the $d+d \to \alpha+\pi^0$ reaction. The use of polarized deuteron beam will enable to evaluate the contributions from various transition amplitudes directly from the experimental data, without any theoretical assumptions. Comparison of the polarization observables for the $d-p$ and $d-n$ coincidences as well as data on $p-n$ coincidences in deuteron break-up may deliver information on CSB in the entrance channel. This may be crucial in understanding of the CSB effect in pion production reactions.

# 3 Partial wave expansion

The use of polarization observables allows to measure directly the transition amplitudes for the $d+d \to \alpha + \pi^0$ and $d+d \to d+d+\pi^0$ reactions. This unique feature is due to the identical bosons in the entrance channel and the spin zero particles in the exit channel.

The identical bosons in the entrance channel require that their wave function has to be symmetric. The entrance channel spin $s_i$ (parity $\pi_s$) and angular momentum $l_i$ (parity $\pi_l$) couple to total angular momentum $J$ (parity $\pi$). For particles with spin-parity $1^+$ only certain combinations $(s_i^{\pi}, l_i^{\pi_l}) \to J^{\pi}$ are allowed: $(0^+, 0^+) \to 0^+$, $(0^+, 2^+) \to 2^+$, $(1^+, 1^-) \to 0^- - 2^-$, $(2^+, 0^+) \to 2^+$, $(2^+, 2^+) \to 0^+ - 4^+$.

Conservation of total angular momentum $J$ and parity leads to a limited number of partial wave amplitudes allowed for the given angular momentum $l_f$ and the total spin $s_f$ in the exit channel. For the $d+d \to \alpha+\pi^0$ reaction the exit channel spin is $s_f = 0^-$ and the only allowed amplitudes are: for $s$-wave - $a_{11000}$ and for $p$-wave - $a_{22110}$ (subscripts denote values $l_i$, $s_i$, $J$, $l_f$ and $s_f$). In the case of the $d+d \to d+d+\pi^0$ reaction one has to take into account the identity of the two deuterons in the exit channel. Then, considering only $s$-wave in the exit channel, the total spin is limited to $s_f = 0$ and $s_f = 2$. Therefore for this reaction in $s$-wave there are three transition amplitudes: $b_{11000}$, $b_{11202}$ and $b_{31202}$.

The unpolarized cross section $d\sigma_0$ and the analyzing powers $T_{11}$, $T_{20}$ and $T_{22}$ may be written in terms of derived allowed transition amplitudes (the common factor is $4\pi(2s_a+1)(2s_b+1)$, where $s_a = 1$ and $s_b = 1$ are spins of particles in the entrance channel). For the $d+d \to \alpha+\pi^0$ reaction in $s$ and $p$ waves one obtains the expressions:

$$
\begin{aligned}
36\pi\sigma_0 &= \tfrac{1}{3}\ a^2_{11000} + \tfrac{9}{10}\ a^2_{22110}\sin^2\theta \\
36\pi\sigma_0 iT_{11} &= \tfrac{3}{2\sqrt{10}}\ \Im\left(a_{11000}a^*_{22110}\right)\sin\theta \\
36\pi\sigma_0 T_{20} &= \tfrac{1}{3\sqrt{2}}\ a^2_{11000} - \tfrac{9}{20\sqrt{2}}\ a^2_{22110}\sin^2\theta \\
36\pi\sigma_0 T_{22} &= \tfrac{9\sqrt{3}}{40}\ a^2_{22110}\sin^2\theta
\end{aligned}
\tag{1}
$$

By measuring angular distributions of unpolarized cross section $\sigma_0$ and analyzing powers $T_{11}$, $T_{20}$ and $T_{22}$ it is possible to unambiguously determine two complex amplitudes. Since amplitude $a_{11000}$ is strongly suppressed at LO, the observables $\sigma_0$, $T_{20}$ and $T_{22}$ may be dominated by $p$-wave amplitude $a_{22110}$. However, the measurement of interference term in $T_{11}$ should deliver information on the $a_{11000}$ amplitude.

For the $d+d \rightarrow d+d+\pi^0$ reaction in just $s$ wave the cross section and analyzing powers are:

$$
\begin{aligned}
36\pi\sigma_0 &= \tfrac{1}{3}\ b^2_{11000} + \tfrac{5}{3}\ b^2_{11202} + \tfrac{5}{7}\ b^2_{31202} - \tfrac{2\sqrt{2}}{3}\ \Re\left(b_{11000}b^*_{11202}\right) + \\
&\qquad + \tfrac{2}{\sqrt{7}}\ \Re\left(b_{11000}b^*_{31202}\right) \\
36\pi\sigma_0 T_{20} &= \tfrac{1}{3\sqrt{2}}\ b^2_{11000} + \tfrac{1}{6\sqrt{2}}\ b^2_{11202} + \tfrac{2}{7\sqrt{2}}\ b^2_{31202} - \tfrac{2}{3}\ \Re\left(b_{11000}b^*_{11202}\right) + \\
&\qquad + \tfrac{\sqrt{2}}{7}\ \Re\left(b_{11000}b^*_{31202}\right) - \tfrac{3}{\sqrt{7}}\ \Re\left(b_{11202}b^*_{31202}\right)
\end{aligned}
\tag{2}
$$

The amplitude $b_{11000}$ is strongly suppressed at LO (similarly as $a_{11000}$ due to the same spin structure). Therefore the measurement of the unpolarized cross section and analyzing power $T_{20}$ for the $d+d \rightarrow d+d+\pi^0$ reaction will deliver information on the LO allowed amplitudes $b_{11202}$ and $b_{31202}$.

# 4 Break-up reaction $d+d \rightarrow d+p+n$

The break-up reaction $d+d \rightarrow d+p+n$ conserves charge symmetry since it cannot be distinguished from the process with all protons exchanged to neutrons and vice versa. Studies of this reaction offer many advantages over other processes in which CSB may be investigated [13]. One of the important topics is systematic investigation of the CSB induced by the Coulomb effects. Therefore a deconvolution of these effects from CSB induced by strong interaction might be possible. This will be of great importance for the analysis of CSB in the $d+d \rightarrow \alpha+\pi^0$ and $d+d \rightarrow d+d+\pi^0$ reactions. Using simplified model it was shown [14] that the entrance channel Coulomb interaction in the $d + d \to \alpha + \pi^0$ reaction may lead to CSB comparable in magnitude to the contributions from other effects.

Up to now the charge symmetry breaking in this reaction was studied only at very low energy [13]. The measurement for beam energy of 12 MeV was performed for very limited range of angular configurations of the coinciding particles (only in the region close to quasi-free scattering). With quite low statistic it was not possible to derive final conclusion on observation of CSB effects.

If charge symmetry holds, all observables should demonstrate proper symmetries under exchange of all protons to neutrons and vice versa. However, a precise comparison of the cross sections is not possible, since they are affected by efficiency of the detection system, introducing large systematic uncertainty. Therefore the best observables to search CSB are analyzing powers. They are measured always relatively, therefore most of the systematic uncertainties cancel and high precision data may be obtained. If charge symmetry holds, all analyzing powers $T_{ij}$ for $d-p$ and $d-n$ coincidences should be equal along the kinematical curve (described by the arc length $S$) for given polar and azimuthal angles $\theta_d$ for deuterons and $\theta_p$, $\phi_p$ and $\theta_n$, $\phi_n$ for protons and neutrons:

$$T_{ij}(\theta_d, \theta_p = \theta, \phi_p = \phi, S) = T_{ij}(\theta_d, \theta_n = \theta, \phi_n = \phi, S). \tag{3}$$

In the case of $p-n$ coincidences the tensor analyzing powers should be symmetric while the vector analyzing power should be antisymmetric about the point where proton and neutron energies $E_p$ and $E_n$ are equal:

$$\begin{aligned} T_{ij}(\theta_p = \theta, \theta_n = -\theta, E_p = E_1, E_n = E_2) = \\ = (-1)^i T_{ij}(\theta_p = \theta, \theta_n = -\theta, E_p = E_2, E_n = E_1). \end{aligned} \tag{4}$$

# 5 Measurements with WASA at COSY

## 5.1 $d + d \to \alpha + \pi^0$ reaction

A possibility to perform measurements of the $d + d \to \alpha + \pi^0$ reaction at WASA at COSY was studied very intensively [15]. The WASA detection system allows to measure both outgoing particles, registering $\alpha$ particles and two $\gamma$ quants from $\pi^0$ decay. This kinematically over-constrained measurement put strong requirements for the analysis of the reaction of interest. However, due to the small cross section of few picobarn for the goal reaction, the background conditions are of great importance. The major background problem arises from particle misidentification for $\alpha$ from the investigated reaction and $^3He$ produced with a large cross section in the $d{+}d \rightarrow {}^3He{+}n{+}\pi^0$ reaction. It was shown [15] that this background may be efficiently reduced by applying all possible cuts and using kinematical constraints. This leads to the background contribution of only 3% in the observables identifying the $d + d \rightarrow \alpha + \pi^0$ reaction.

## 5.2 $d + d \rightarrow d + d + \pi^0$ reaction

Similar studies were performed for the $d{+}d \rightarrow d{+}d{+}\pi^0$ reaction. In this case the reaction will be identified by detecting two deuterons and two $\gamma$ quants from $\pi^0$ decay. Also in this case the major background originate from the particles misidentification between deuterons and protons or tritons produced in the charge symmetry allowed $d + d \rightarrow t + p + \pi^0$, $d + d \rightarrow d + p + n + \pi^0$ and $d + d \rightarrow p + p + n + n + \pi^0$ reactions. Since the measurement of the $d{+}d \rightarrow d{+}d{+}\pi^0$ reaction is planned close to the threshold, a careful choice of the incident deuteron momentum may substantially reduce this background. The threshold beam momentum for the reaction of interest is 1.052 GeV/c and for the background reactions are: 1.035 GeV/c for the $d{+}d \rightarrow t{+}p{+}\pi^0$, 1.061 GeV/c for the $d + d \rightarrow d + p + n + \pi^0$ and 1.071 GeV/c for the $d + d \rightarrow p + p + n + n + \pi^0$ reactions. Therefore for the beam momentum of 1.061 GeV/c the only allowed background reaction is $d{+}d \rightarrow t{+}p{+}\pi^0$. At this beam momentum the available energy for the investigated reaction is $Q$=2.2 MeV, while for the background reaction $Q$=6.2 MeV. Than the expected ratio of the cross sections is $\sigma(tp\pi^0)/\sigma(dd\pi^0) = 10^5$. The background may be produced only when both deuterons are misidentified, one with triton and second with proton. This requirement leads to background reduction by a factor of $10^4$. Further reduction is obtained by proper cuts on the energy of the detected particles. It is shown in Fig. 1 that the $d{+}d \rightarrow d{+}d{+}\pi^0$ reaction may be clearly distinguished from background by accepting deuterons with the energies within the interval where particles from the background reaction are not allowed. Such requirement eliminates the background completely and limits the acceptance for the investigated reaction only to about 50%.

## 5.3 $d + d \rightarrow d + p + n$ reaction

This reaction will be measured by detecting deuteron and proton in coincidence. Comparison of the analyzing powers for $d - p$ and $d - n$ coincidences will be performed for many angular configurations. Also tests of the symmetry of the tensor analyzing powers and antisymmetry of the vector analyzing

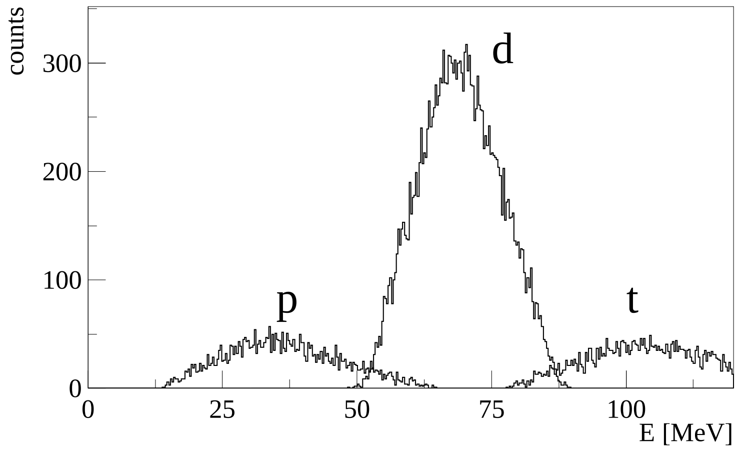


Figure 1: Energy of deuterons from the $d + d \rightarrow d + d + \pi^0$ reaction and energies of tritons and protons from the $d + d \rightarrow t + p + \pi^0$ background reaction. Cuts on particle identification and kinematical constraints were applied.

power will be performed for $p - n$ coincidences. The energy and angles of the not detected neutron for $d - n$ and $p - n$ coincidences will be deduced from the registered proton and deuteron, respectively. The limited angular acceptance and threshold for deuteron and proton detection lead to an inhomogeneous acceptance. However, as seen in Fig. 2, almost the whole allowed region on the Dalitz plot is covered. Therefore the investigation of CSB in the whole kinematical region by comparison of $d - p$ and $d - n$ coincidences as well as for $p - n$ coincidences is possible.

The features of the WASA at COSY offer very good conditions for CSB studies in deuteron break-up on deuteron target. The measurement may be performed simultaneously for all possible kinematical configurations. The CSB effect will be traced by comparison of the analyzing powers for various coincidences. The measurement will be relative, therefore knowledge of the beam intensity and polarization is not required and all systematic uncertainties cancel. Cross section for the break-up reaction is of the order of a milibarn, therefore large statistic may be reached. At beam energies close to the pion production threshold this break-up reaction is the only dominant process, therefore there will be virtually no background. Considering all these arguments implies that high precision may be reached, allowing to study CSB with exceptional precision.

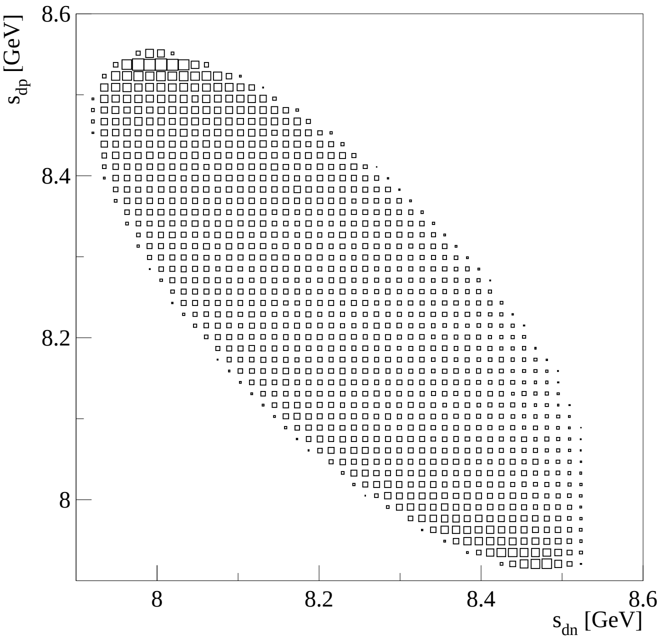


Figure 2: Dalitz plot for $s_{dp}$ versus $s_{dn}$ for the $d + d \to d + p + n$ reaction. All cuts on angular acceptance and detection threshold were applied.

# 6 Summary

The experiments searching for charge symmetry breaking with WASA at COSY are discussed. The existing data on CSB and the theoretical analysis performed up to now show that new data on charge symmetry allowed reactions and on CSB reactions for the $d + d$ system at higher beam momenta than available are badly needed. This defines the experimental strategy for CSB searches at COSY. The data for the charge symmetry allowed $d + d \to {}^3A + N + \pi$ reaction, measured close to threshold, will be soon analyzed. The new measurement of this reactions, substantially above threshold, will be performed. In the next step, the charge symmetry forbidden reactions $d + d \to \alpha + \pi^0$ and $d + d \to d + d + \pi^0$ will be investigated. The vector and tensor polarized beam will be used, what enables a model independent extraction of the partial wave amplitudes for these reactions. Simultaneously, the analyzing powers for the break-up $d + d \to d + p + n$ reaction in the whole kinematical region will be measured. It is demonstrated that WASA at COSY is an unique detection system that may deliver high quality data for all these reactions. By completing this investigation program, an extensive set of experimental data for reactions initiated from the $d + d$ entrance channel will be provided. These data, together with a proper analysis within the chiral perturbation theory, will enable to understand the charge symmetry breaking effects on the quark level.

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