Spin selectivity of $dd \rightarrow \alpha X$ reaction and its applications in hadron physics

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Abstract.
The $dd \rightarrow \alpha X$ reaction exhibits strong selectivity for the isospin, spin and parity of the $X$ system. The charge symmetry requires that the $X$ system should have isospin equal 0. The particle identity and conservations of the total angular momentum and parity impose very strong constraints on quantum numbers allowed in the reaction. This leads to very strong selectivity when $\alpha$ is emitted at 0° or 180°, as well as in the case of reactions at threshold. These features may be used to measure directly the individual partial wave contributions in the production reactions and to determine directly the spin and parity of the $X$ system. Such kind of applications will be discussed for the charge symmetry forbidden $dd \rightarrow \alpha \pi^0$ reaction, the investigations of the $\sigma$ meson in the $dd \rightarrow \alpha \sigma$ reaction and in studies of the $dd \rightarrow \alpha \gamma$ reaction.

1. Introduction
The $dd \rightarrow \alpha X$ is strongly selective due to features of the particles in the entrance channel and of the $\alpha$ particle. The total entrance channel isospin is equal to zero, as is also the isospin of the $\alpha$ particle. In such a case of the self coupled reaction, the charge symmetry requires the system $X$ to possess also isospin 0. This property may be used to select the isospin of the $X$ system. In case of the $dd \rightarrow \alpha X$ reaction in the entrance channel there are two identical bosons. This fact, together with conservations of the total angular momentum and parity permit only certain combinations of the initial spin and angular momentum for the exit channel with the system $X$ of given spin and parity. This leads to very strong spin selectivity of the $dd \rightarrow \alpha X$ reaction when $\alpha$ is emitted at 0° or 180°, as well as in the case of reactions at threshold (with only $S$ wave in the exit channel).

The spin and isospin selectivity of the $dd \rightarrow \alpha X$ reaction might be used to measure directly the individual partial wave contributions in the production reactions and to determine directly the spin and parity of the $X$ system. Those kinds of selectivity applications will be discussed in details for the charge symmetry forbidden $dd \rightarrow \alpha \pi^0$ reaction, the investigations of the $\sigma$ meson in the $dd \rightarrow \alpha \sigma$ reaction and in studies of the $dd \rightarrow \alpha \gamma$ reaction. In order to utilise the selectivity for these reactions, proper observables have to be selected. It will be shown that the spin selectivity of such kind of reactions is exhibited in certain analysing powers. The identification of the most interesting observables can be done easily by performing the partial wave expansion and expressing in those terms the cross section and analysing powers for the reactions. Then, the conditions under which the reaction is allowed or forbidden may be searched for, i.e. the best choice of the beam and/or target polarisation, which deliver the direct experimental, model independent information on the production and properties of the $X$ system.
The discussed selectivity was first utilised for the background subtraction in the $dd \rightarrow \alpha\eta$ reaction very close to threshold [1]. This reaction is allowed for the beam or target polarisation $P_{zz} = +1$, while it is forbidden for polarisation $P_{zz} = -2$. Subtraction of the data measured with these two polarisations delivers a very clean signal for the reaction of interest. Later on this reaction was investigated also at higher energies [2, 3], and with the use of polarised beam the magnitudes of several partial waves contributions were determined.

2. Partial wave expansion and spin selectivity

The partial wave expansion may be performed by using the invariant amplitude decomposition as shown in Ref. [2] for the $dd \rightarrow \alpha\eta$ reaction, where the formulae for polarisation observables for this reaction are presented. This method is equivalent to standard partial wave expansion, however, in case of limited experimental information, it allows to reduce the number of fitted parameters [3].

In case of the $dd \rightarrow \alpha X$ reaction, in the entrance channel there are two identical bosons. Therefore the entrance channel wave function must be symmetric and only some specific combinations of the initial spin $s_i$ and angular momentum $l_i$ are allowed. The total angular momentum $J$ and parity conservations imply that only certain combinations of $(s_i, l_i)$ lead to the exit channel with total spin and angular momentum $(s_f, l_f)$ and defined parity. Due to the parity conservation there is additional limitation for the discussed reaction for the particle emission angles of $0^\circ$ or $180^\circ$. Then, out of possible transitions only those with even total angular momentum with 3-rd component $J_z = 0$ are allowed. That corresponds to the initial states with total spin equal to 1, with the 3-rd component equal to 0.

The partial wave expansion under the discussed limitations allows to identify when the reaction is allowed or forbidden. The results for the beam $P_{zz}^b$ and/or target $P_{zz}^t$ polarisations are summarised in table 1 for the selected spin and parity of $X$ particle. It can be seen that for pseudoscalar particles produced in the $dd \rightarrow \alpha X$ reaction it is sufficient to use polarised beam. By changing the beam tensor polarisation it is possible to turn on or off the pseudoscalar particle production. For scalar particles it is necessary to use tensor polarised beam and target. With a proper choice of polarisations one may turn on and off the scalar particle production. For

### Table 1. Identified beam and/or target polarisations for cases when the $dd \rightarrow \alpha X$ reaction is allowed or forbidden for selected mesons as $X$ particle. Beam and target polarisations may be exchanged. Additional selectivity is due to isospin – reactions with particle $X$ having isospin 1 are forbidden by charge symmetry.

| meson | isospin | spin and parity | beam and target polarisation |
|-------|---------|----------------|-----------------------------|
|       |         |                | allowed                     | forbidden                           |
| $\pi^0$ | 1       | 0^-            | $P_{zz}^b = +1, P_{zz}^t = 0$ | $P_{zz}^b = -2, P_{zz}^t = 0$ |
| $\eta$  | 0       |                | $P_{zz}^b = +1$              | $P_{zz}^t = -2$                      |
| $\eta'$ | 0       |                | $P_{zz}^b = -2, P_{zz}^t = -2$ |                                       |
| $\sigma$ | 0       | 0^+            | $P_{zz}^b = -2, P_{zz}^t = -2$ |                                       |
| $f_0$  | 0       | 0^-            | $P_{zz}^b = +1$              | $P_{zz}^t = -2$                      |
| $a_0$  | 1       |                | $P_{zz}^b = -2, P_{zz}^t = -2$ |                                       |
| $\rho$ | 1       |                | $P_{zz}^b = -2, P_{zz}^t = +1$ |                                       |
| $\omega$ | 0      | 1^-            | $P_{zz}^b = -2, P_{zz}^t = -2$ | $P_{zz}^b = -2, P_{zz}^t = -2$    |
| $\phi$ | 0       |                | $P_{zz}^b = -2, P_{zz}^t = -2$ | $P_{zz}^b = -2, P_{zz}^t = -2$    |
vector particles it is also necessary to use tensor polarised beam and target but the selectivity for the vector particle production appears only at threshold. Additional selectivity due to charge symmetry is present for particles with isospin equal to 1 ($\pi^0$, $a_0$ and $\rho$).

3. $dd \rightarrow \alpha\pi^0$ reaction

Study of CSB in the $dd \rightarrow \alpha\pi^0$ reaction presents an opportunity to investigate the influence of quark masses in nuclear physics [4]. This became possible only recently with the use of chiral perturbation theory [5, 6], which has been extended to pion production reactions [7]. The $dd \rightarrow \alpha\pi^0$ reaction was first observed experimentally only recently for beam energies very close to the reaction threshold [8]. Due to very small energy available in the exit channel, only $S$ wave contribution is possible at the investigated energies. The first steps towards the theoretical understanding of this reaction have been taken [9]. It was found that the LO production mechanism is suppressed by symmetries in the $\alpha$ particle wave function, the NLO terms do not contribute and NNLO diagrams are too small to account for the observed cross section. However, the inclusion of initial and final state interactions enhances the contributions of these terms. In order to investigate this problem in details new data on the charge symmetry conserving $dd \rightarrow 3H/HeN\pi$ reactions and the charge symmetry breaking $dd \rightarrow \alpha\pi^0$ reaction are necessary. The first reaction will put important constraints for the initial state interaction and it will demonstrate how well the isospin conserving part of the 4 nucleon system is controlled by the theory. The second reaction should be investigated at beam energies higher than in Ref. [8].

At higher energy $P$ waves will be relevant, allowing to extract some parameters of the chiral perturbation theory at NNLO. This result will be used not only for theoretical analysis of the $dd \rightarrow \alpha\pi^0$ reaction but it may be also compared directly to the results of the analysis of the forward-backward asymmetries in $pn \rightarrow d\pi^0$ [10, 11].

The direct access to $P$ waves in the $dd \rightarrow \alpha\pi^0$ reaction is provided by the measurement of the analysing power. Due to large selectivity of this reaction (see table 1) the measurements of cross section and tensor analysing powers allow to extract $S$ and $P$ contributions and their relative phase in a model independent way, directly from the experimental data. The first measurement at beam momentum of 1.2 GeV/c with unpolarised beam was already performed at COSY and further measurements with vector and tensor polarised deuteron beam are planned.

4. $dd \rightarrow \alpha\sigma$ reaction

Usually the $\sigma$ pole properties are obtained from the analysis of $\pi\pi$ scattering derived from the $K_{e4}$ decay and $\pi N \rightarrow \pi\pi N$ reactions. Recent evaluation [12, 13] the sigma pole properties were determined to a high accuracy from Roy equation studies. As a broad structure, the $\sigma$ was observed only recently in decay data of some heavy mesons. The Dalitz plot analysis of the $D^+ \rightarrow \pi^-\pi^+\pi^+$ decay was performed using various models [14, 15]. It was shown that within isobar model the large $\sigma\pi^+$ component is required in order to describe the data. The $\sigma$ bump was also seen in the decays $J/\psi \rightarrow \omega\pi^+\pi^-$ [16] and $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$ [17]. Partial wave analysis performed using various $\sigma$ parametrisations resulted in different mass and width values. All those analysis required many parameters describing heavy meson decay channels.

The $dd \rightarrow \alpha\sigma$ reaction, because of large selectivity for states with quantum numbers $I = 0$ and $J^z = 0^+$, offers good possibility to observe the $\sigma$ meson in the production reaction. Due to charge symmetry, only isospin equal to 0 is allowed, and the spin selectivity is seen in the table 1. With tensor polarised beam of $P_{zz} = -2$ and tensor polarised target of $P_{zz} = -2$ only states with $J^z = 0^+$ are allowed. With beam or target polarisation changed to $P_{zz} = +1$ such states are forbidden. This should allow to disentangle the non-resonant background with $J^z \neq 0^+$, obtaining clear signal from the resonant $J^z = 0^+$ $\sigma$ state. The discussed spin selectivity appears for the reaction at its threshold, and for any beam energy when the $\alpha$ particle is detected at $0^\circ$. Therefore two experimental scenarios are possible. Using the selectivity at threshold, the
beam energy should be varied from 0.53 GeV up to 2.25 GeV and the α particle with the energy corresponding to the reaction threshold value should be detected at 0°. With this beam energy range the two pion invariant mass from $2m_π = 0.28$ GeV up to 1 GeV may be covered, what is sufficient for the observation of broad σ meson. The second possibility is to fix the beam energy at 2.25 GeV and detect the α particle at 0° only. Both scenarios may be combined, delivering complementary results.

5. $dd \to αγ$ reaction

Studies of the $dd \to αγ$ reaction are complementary to pion production reaction. Comparison of photon and pion production at the same beam momentum, with the same entrance channel and almost identical momentum transfer, should allow for direct tests of the most important theoretical ingredients used for the description of charge symmetry breaking in the $dd \to ασ^0$ reaction. Precise data for the $dd \to αγ$ reaction may contribute to understanding of the isospin symmetry breaking as predicted by simple long wave approximation. The studies of this reaction may allow to investigate the few-body forces. One may expect that three-body forces can be relatively more important in the four-nucleon system, where there are four triplet pairs and the nucleon density in α particle is quite large. All these effects together may enhance the contribution of three-nucleon forces in the four-nucleon system with respect to their action in the three-nucleon environment.

The $dd \to αγ$ has been measured in a broad energy range (also as the inverse $γα \to dd$ reaction). It seems that there is a general understanding of the existing data in the low energy region up to 50 MeV γ energy. There the data are internally consistent, the measured angular distributions are in agreement with the shape of the first allowed $E_2$ transition. At the higher energy region only few data sets are available [18–23]. Almost two orders of magnitude discrepancies are observed in the total cross section, and there are strong discrepancies in the shape of the angular distributions. The angular distribution in Refs. [20–22] do not show the shape expected for presumably dominating $E_2$ transition but rather that of the presumably strongly suppressed $E_1$ transition, while the shape of the angular distribution in Ref. [23] is consistent with a pure $E_2$ transition.

In the long wave approximation the multipole expansion limited to the lowest allowed multipole transition is the common method used for description of the radiative capture or photo-disintegration reactions. In case of the $dd \to αγ$ reaction selection rules strongly reduce the number of allowed transitions. Spin and parity restrictions allow $E_1$ and $M_1$ transitions, for which the shape of the angular distribution should be given by $1 + \cos^2 θ$. However, for a self-conjugate system (as is the case for $dd$ and α), the isospin symmetry requires that no $E_1$ transition takes place between states of equal isospin. The same selection rule implies also a strong reduction of $M_1$ transition, by a factor of about 100. Therefore the first allowed transition is $E_2$. There are four such $E_2$ transitions, three of them with initial spin equal to 2 (with deuteron spin flip suppressed by a factor of 1000), and one (dominant) with the entrance channel spin equal to 0. From the multipole expansion it is known that for such transition the angular distribution should behave like $\sin^2 θ$. The analysing power $T_{20}$ may deliver very valuable information on the admixture of $E_1$ transition to the dominating $E_2$ transition. For transitions $E_1$ and $M_1$ the analysing power $T_{20}$ is non-zero and exhibits angular dependence. For the dominating $E_2$ transition the analysing power $T_{20}$ is equal to zero due to the strong selection rules for the $dd \to αγ$ reaction. For other $E_2$ transitions the analysing power $T_{20}$ is constant. Therefore any angular dependence of the analysing power $T_{20}$ would indicate an existence of contribution of isospin forbidden (or strongly suppressed) lower order multipoles.

The multipole expansion may be questionable since it is a long wave approximation. Only microscopic calculations may deliver more detailed information on the possible isospin symmetry breaking in the $dd \to αγ$ reaction. They would enable to study also few-body interactions and
may be combined with the calculations of the charge symmetry forbidden $dd \rightarrow \alpha \pi^0$ reaction. Microscopic calculations for the $dd \rightarrow \alpha \gamma$ reaction are already possible with the use of realistic nuclear potentials [24, 25] or within the chiral effective field theory [26].

6. Summary

It has been shown that the $dd \rightarrow \alpha X$ reaction is very selective for isospin and spin observables. The isospin selectivity allows to study the charge symmetry breaking processes (e.g. in the $dd \rightarrow \alpha \pi^0$ reaction). The isospin selectivity combined with the spin selectivity allow to access single parameters of the chiral perturbation theory that are of importance in description of processes where the pion couplings enter, and in turn the influence of the light quark masses to nuclear physics processes becomes accessible. The spin selectivity of the $dd \rightarrow \alpha \sigma$ reaction should enable to extract in a model independent way parameters of the $\sigma$ meson, which up to now was observed only in heavy mesons decays. The isospin and spin selectivity of the $dd \rightarrow \alpha \gamma$ reaction allow to access the isospin forbidden transitions and clarify the ambiguous experimental data for this reaction. The data for polarisation observables combined with microscopic calculations would enable to access also the few-body interactions.

The measurements utilising selectivity of the $dd \rightarrow \alpha X$ reaction are possible at COSY using the WASA-at-COSY and ANKE detection systems. The COSY accelerator delivers vector and tensor polarised deuteron beam with momentum up to 3.7 GeV/c. The WASA-at-COSY detection system [27] allows to detect $\alpha$ particles in the forward direction and the neutral particles in almost full angular range. Therefore it is suitable for investigations of e.g. $d\bar{d} \rightarrow \alpha \pi^0$ and $d\bar{d} \rightarrow \alpha \gamma$ reactions. The ANKE detection system [28] is equipped with a polarised internal target [29] and allows detection of $\alpha$ particles close to $0^\circ$. Therefore it is well suited for detailed investigations of $\sigma$ meson properties via $d\bar{d} \rightarrow \alpha \sigma$ reaction.

Acknowledgments

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References

[1] Willis N et al. 1997 Phys. Lett. B 406 14
[2] Wrońska A et al. 2005 Eur. Phys. J. A 26 421
[3] Budzanowski A et al. 2009 Nucl. Phys. A 821 193
[4] Miller G A, Opper A K and Stephenson E J 2006 Ann. Rev. Nucl. Part. Sci. 56 253
[5] Bedaque P F and van Kolck U 2002 Ann. Rev. Nucl. Part. Sci. 52 339
[6] Epelbaum E, Hammer H W and Meissner U G 2009 Rev. Mod. Phys. 81 1773
[7] Hanhart C 2004 Phys. Rep. 397 155
[8] Stephenson E J et al. 2003 Phys. Rev. Lett. 91 142302
[9] Nogga A et al. 2006 Phys. Lett. B 639 465
[10] Bolton D R and Miller G A 2010 Phys. Rev. C 81 014001
[11] Filin A et al. 2009 Phys. Lett. B 681 (2009) 423
[12] Caprini I, Colangelo G and Leutwyler H 2006 Phys. Rev. Lett. 96 132001
[13] Martin R G, Kaminski R, Pelaez J R, de Elvira J R and Yndurain F J 2011 Preprint arXiv:1102.2183
[14] Aitala E M 2001 Phys. Rev. Lett 86 770
[15] Bonvicini G et al. 2007 Phys. Rev. D 76 012001
[16] Ablikim M et al. 2004 Phys. Lett. B 598 149
[17] Ablikim M et al. 2007 Phys. Lett. B 645 19
[18] Akimov Yu K et al. 1962 Sov. Phys. JETP 14 512
[19] Asbury J G and Loeffler H J 1965 Phys. Rev. 137 B1214
[20] Arends J et al. 1976 Phys. Lett. B 62 411
[21] Silverman B H et al. 1984 Phys. Rev. C 29 35
[22] Rice B J et al. 2000 Phys. Rev. C 61 064612
[23] Berman B L 2007 Nucl. Phys. A 790 167c
[24] Gazit D et al. 2006 Phys. Rev. Lett. 96 112301
[25] Bacca S 2007 Phys. Rev. C 75 044001
[26] Quaglioni S and Navrátil P 2007 Phys. Lett. B 652 370
[27] Adam H H et al. (WASA-at-COSY Collaboration) 2004 arXiv:nucl-ex/0411038
[28] Barsov S et al. 2001 Nucl. Inst. Meth. A 462 364
[29] Rathmann F et al. 2003 AIP Conf. Proc. 675 924