Study of the ABC enhancement in the \( \vec{d}d \rightarrow \alpha X^0 \) reaction

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Abstract: The \( \vec{d}d \rightarrow \alpha X^0 \) reaction at beam energies close to the \( \eta \) threshold shows very strong structure in the missing mass corresponding to the ABC enhancement. The deuteron tensor analysing power \( A_{yy} \), and the slope of the vector analysing power \( A_y \) with respect to angle, have been measured for this reaction around the forward direction. Both signals are small, and their variations with the \( \alpha \)-particle momentum are in broad agreement with a theoretical model in which each pair of nucleons in the projectile and target deuterons undergoes pion production through the \( NN \rightarrow d\pi \) reaction.
The discovery of a sharp enhancement in the missing mass spectrum of the $pd \rightarrow ^3\text{He}X^0$ reaction almost forty years ago \cite{1} excited great interest since it seemed to indicate either an enormous pion-pion scattering length (typically 3 fm \cite{2}) or a resonance in that system at only 30 MeV above the $2\pi$ threshold. The absence of any effect in the parallel $pd \rightarrow ^3\text{H}X^+$ case showed that the anomalous behaviour was associated with isospin-zero pion pairs and hence presumably $s$-wave. However, the weight of evidence is that the isoscalar scattering length is small \cite{3}, so that the ABC anomaly cannot be an intrinsic property of the two-pion system but must be associated with the presence of other particles.

The characteristics of the ABC phenomenon were independently confirmed in the $pd \rightarrow ^3\text{He}X^0$ reaction \cite{1} and exactly the same type of effect was observed in both $pn \rightarrow dX^0$ \cite{2} and $pp \rightarrow ppX^0$ at low $pp$ excitation energies \cite{3}. The most splendid ABC manifestation is in the $dd \rightarrow ^4\text{He}X^0$ reaction in the 1 GeV region, where it dominates a large fraction of the differential cross section, with sharp peaks associated with its production in the forward and backward c.m. hemispheres \cite{4,5}. Since the masses and widths of these peaks change somewhat with beam energy and production angle, this reinforces the idea that the ABC might be some kind of kinematic enhancement.

The simplest model for ABC production in $pn \rightarrow dX^0$ involves the excitation of both nucleons into $\Delta$-isobars through one pion exchange where, after the decay of the two $\Delta$’s, the final neutron-proton pair sticks together to produce the observed deuteron \cite{4,10}. A theoretical description actually looks simpler in the case of $dd \rightarrow ^4\text{He}X^0$, where double-pion production can be achieved by two pairs of beam and target nucleons undergoing a $pn \rightarrow d\pi^0$ reaction (or similarly for charged pion production), as illustrated in Fig. 1 \cite{11}.

Each of the single-pion-production amplitudes can be driven by virtual $\Delta$ excitation, and this allows the large momentum transfer to be shared evenly amongst all the nucleons. If the Fermi momenta in the initial deuterons are neglected, then the $dd$ c.m. system is also that in the $np$ channel, which means that the produced pions have the same energy. The dominantly $p$-wave nature
of the $pn \rightarrow d\pi^0$ amplitudes, combined with the form factor coming from the requirement that both deuterons stick to form an $\alpha$-particle, then leads naturally to enhancements when the two pion momenta are parallel. These correspond to the narrow ABC peaks with masses around 310 MeV and widths about 40 MeV. The model also predicts an enhancement when the pion momenta are antiparallel, though this is somewhat suppressed by the much smaller “sticking factor” when the two recoil deuterons are produced back to back [11]. The resultant broad central structure at the maximum missing mass of the reaction is a notable feature in all cases where the ABC is seen clearly [1, 5, 6, 8]. By taking the dominant $pn \rightarrow d\pi^0$ amplitudes into account in the calculation, a good description of the $dd \rightarrow ^4\text{He}X^0$ spectrum and its angular dependence could be obtained [11].

In order to provide extra tests on this and other theoretical models, we report here upon an experiment to measure the deuteron vector and tensor analysing powers in $d\bar{d} \rightarrow ^4\text{He}X^0$ in a small angular region around the forward direction.

The experiment was carried out at the SPESIII magnetic spectrometer at the Laboratoire National SATURNE (LNS) as a by-product of one to measure $\eta$ production in the $d\bar{d} \rightarrow ^4\text{He}\eta$ reaction near threshold. Data were therefore collected at several energies above the $\eta$-threshold at $T_d = 1121$ MeV, but also with one background run just below this energy. The experimental conditions were identical to those described in ref. [8] and so only the essential details are reported here. The SATURNE accelerator delivered four consecutive pulses of deuterons with different linear combinations of tensor and vector polarisations quantised in the vertical $(y)$ direction. These had maximum values of $\rho_{20} = 0.649 \pm 0.011$ and $\rho_{10} = -0.405 \pm 0.011$ respectively [12].

The wire chambers placed close to the focal plane of the spectrometer measured the production angle of $\alpha$-particles in the horizontal $(x)$ plane up to $\theta_x = \pm 50$ mrad about the forward direction, but the only information on the $y$-coordinate of the track was provided by collimators. In most of the runs these subtended angles $\theta_y = \pm 20$ mrad and so the data were integrated over this vertical angular domain.
In Fig. 2 is shown a scatter plot of the momentum per unit charge \( p/Z \) and horizontal production angle \( \theta_x \) of identified \( \alpha \)-particles arising from the interactions of unpolarised deuterons just below the \( \eta \) threshold. The vertical bands close to the kinematic limits, and the less intense one in the middle of the plot, are clear indications of the ABC peaks and central bump respectively. Equally clear are the signs of the granularity and inefficiencies in the detector system. It is important to note that these are geometric in nature and rest unchanged for different polarisation states of the incident beam. Summing this spectrum over \( \theta_x \), the experimental counting rate for the \( dd \to ^4\text{He} X^0 \) reaction is shown in Fig. 3a, from which it is easier to identify the ABC peaks and central bump.

Although the vector analysing power \( A_y \) has to vanish at \( \theta_x = 0 \), the experiment shows a clear left-right asymmetry over the horizontal opening angle of \( \pm 50 \) mrad which is associated with the state of vector polarisation of the beam. In the regions of the ABC peaks, where the statistics are very good, it is possible to fit this directly with the form \( A_y = c \theta_x \), allowing us to deduce the slope \( c \) of the analysing power near the forward direction. However, since the typical \( A_y \) signal is 0.05 or less, we attempt to compensate for this and the inefficiencies of the system by defining an average slope through

\[
\overline{A_y} = \frac{dA_y}{d\theta} = \int d\Omega \ \theta_x A_y \left( \frac{d^2\sigma}{d\Omega dp} \right) \left/ \int d\Omega (\theta_x)^2 \left( \frac{d^2\sigma}{d\Omega dp} \right) \right.
\]

(1)

The identification of this quantity with the slope of the analysing power at \( \theta = 0 \) is valid provided the angular integration domain is small, such that \( A_y \) varies linearly with \( \theta_x \) and the differential cross section is essentially constant at its value in the forward direction. To first order in \( (\theta_x, \theta_y) \) the form is not disturbed by the non-measurement of \( y \)-component of the \( \alpha \)-particle production angle in SPESIII. This is a reasonable assumption in the region of the ABC peaks, where the maximum horizontal and vertical c.m. angles are about 17.5\(^\circ\) and 6\(^\circ\) respectively. However in the central bump, where the c.m. momenta are quite small, the integration in Eq. (1) is over most of the available phase space and this has to be borne in mind in any subsequent interpretation.
By replacing the integrals in Eq. (1) by sums over the experimental events, using the polarised and non-polarised data respectively, the experimental value of $A_y'$ is deduced and shown in Fig. 3b. The data set taken just below the $\eta$ threshold contained less than 10% of the total available counts and, in order to increase the statistical significance, results at six different energies above and below the $\eta$ threshold ($1116.7 \leq T_d \leq 1127$ MeV) were summed in Fig. 3b. As a consequence the experimental points in the middle of the central bump, $2000 \leq p \leq 2100$ MeV/c, include some $\eta$-production.

Only statistical errors in $A_y'$ are shown in Fig. 3b. The results depend weakly upon a possible off-set in the angular reading of 4 mrad and, apart from a reduction in statistics, are not changed significantly by cutting the range in $\theta_x$ from $\pm 50$ mrad to $\pm 30$ mrad. The influence of potential systematic effects, arising from detector inefficiencies or angular offset, could be tested by applying the same angular average as in Eq. (1) to evaluate the slope of the tensor analysing power $dA_{yy}/d\theta$, which should vanish in the forward direction. Within statistical errors this was found to be consistent with zero for all values of $p$ with a mean value of $\langle A_{yy} \rangle = (-0.05 \pm 0.10)\text{ rad}^{-1}$. The overall systematic error on $A_y'$ is hard to quantify but could be rather larger than this due to the smallness of the signal.

In Fig. 3c are shown the values of the tensor analysing power $A_{yy}$ integrated over the whole horizontal and vertical aperture of SPESIII. Since a slope determination is not required, the statistics from the single run at $T_d = 1116.7$ MeV, i.e. below the $\eta$ threshold, are here sufficient. In addition to the statistical error bars, there is a systematic uncertainty of only $\pm 2\%$ arising from the polarisation of the beam [12]; it should be noted that the value deduced for $A_{yy}$ for $\eta$ production in this experiment is in agreement with the threshold theorem to this accuracy [8]. Detector inefficiencies in the ABC peaks could however lead to slightly larger uncertainties. In this context it should be noted that at strictly $0^\circ$ the values of $A_{yy}$ for the production of a $0^+$ state, such as the ABC, should be identical in the forward and backward peaks. The difference in the peaks of Fig. 3c of $0.05 \pm 0.02$
could in part arise from integration over the finite SPESIII angular acceptance.

The analysing power signals are small and fluctuate with a similar frequency to the counting rate shown in Fig. 3a. The shape of the latter is well reproduced by the double-Δ model of ref. [11] where the theoretical calculation has been integrated over $|\theta_x| \leq 50$ mrad, $|\theta_y| \leq 20$ mrad. The predictions in the central bump are the most uncertain since, in this region, the $dd \rightarrow \alpha$ “sticking” factor is required for high relative momenta. Furthermore, as noted in the top scale, the missing mass is well above the three-pion threshold and extra pions could be produced.

In the original double-Δ calculation of ref. [11], only the dominant $NN \rightarrow d\pi$ partial wave amplitude was considered and this gives zero for both the vector and tensor analysing powers. By including all the significant amplitudes of the C500 solution of ref. [13], the very encouraging estimates shown in Figs 3b, 3c at 1122 MeV could be achieved, where the results have been averaged over the experimental acceptance [14]. The refined model reproduces all the main features of both $A_{yy}$ and $A'_{y}$, the frequency of their fluctuations and their strengths. The only gross discrepancy is an overall displacement of $A'_{y}$ by about 2 rad$^{-1}$, but this quantity is very sensitive to any small extra terms in the theoretical model.

Our results on the vector and tensor analysing powers in $\bar{d}d \rightarrow ^4\text{He} X^0$ give strong quantitative support to the idea that $2\pi^0$ production in this reaction is the result of single pion production occurring twice through the $pn \rightarrow d\pi^0$ reaction being repeated, or similarly for charged pions. Whether this remains true closer to threshold, where the ABC peaks are not seen [13], would require the measurement of analysing powers over a greater range in energy. This is no longer possible at Saturne following its final closure on December 2$^{nd}$ 1997.

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**Figure Captions**

**Fig. 1** : Double $NN \rightarrow d\pi$ model for the $d d \rightarrow ^4He X^0$ reaction

**Fig. 2** : Two-dimensional scatter plot of the momentum per unit charge $p/Z$ and horizontal production angle $\theta_x$ of identified $\alpha$-particles arising from the unpolarised $d d \rightarrow ^4He X^0$ reaction just below the $\eta$ threshold at $T_d = 1116.7$ MeV.

**Fig. 3** :
(a) Raw counting rate for the unpolarised $d d \rightarrow ^4He X^0$ reaction at $T_d = 1116.7$ MeV, integrated over $\pm 20$ mrad in the vertical and $\pm 50$ mrad in the horizontal directions, as a function of the $\alpha$-particle momentum. The curve is the unnormalised prediction of the double-$\Delta$ model [11, 14], integrated over the experimental acceptance. The top scale shows the values of the missing mass $M_X$.

(b) Average slope $A'_y$ of the deuteron vector analysing power of the $\vec{d}d \rightarrow ^4He X^0$ reaction defined as in Eq. (1). The experimental data are an average over six beam energies with $1116.7 \leq T_d \leq 1127$ MeV, whereas the solid curve is the prediction of the double-$\Delta$ model [11, 14] at $T_d = 1122$ MeV. An arbitrary displacement of the predictions by $2 \text{ rad}^{-1}$ gives the dashed curve, which is a much better representation of the data.

(c) Deuteron tensor analysing power $A_{yy}$ of the $\vec{d}d \rightarrow ^4He X^0$ reaction at $T_d = 1116.7$ MeV, averaged over the aperture of SPESIII. The theoretical curve is the prediction of the double-$\Delta$ model [11, 14].
Figure 1:

Figure 2:
Figure 3: