Has Charge Symmetry Breaking Been Observed in the $dd \to \alpha\pi^0$ Reaction?

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(Received 26 May 1999)

Estimates are made of the $dd \to \alpha\gamma\gamma$ production cross sections in a model where each neutron-proton pair in the beam and target initiates an $np \to d\gamma$ reaction. This approach, which successfully reproduces observables in two-pion production at intermediate energies, suggests that direct two-photon production could provide a very significant background to the measurement of the charge-symmetry-breaking (CSB) reaction $dd \to \alpha\pi^0$. A nonvanishing CSB cross section has been reported which might be confused with such two-photon production under the given experimental conditions.

PACS numbers: 25.45.–z, 11.30.Hv, 25.10.+s

In quark language, the charge symmetry operator interchanges the d and u quarks and this almost leaves the system invariant because of the small mass differences between the current quarks [1]. These mass terms would, for example, mix different isospin states such as the π^0 and η mesons. The most convincing proof of charge symmetry breaking (CSB) in nuclear reactions would be the observation of a nonvanishing rate for the $dd \to \alpha\pi^0$ reaction [2], because this would be proportional to the square of a CSB amplitude, with no contribution from interference terms [3]. Moreover, a single unambiguous measurement of this single reaction at one set of kinematic conditions could be sufficient to detect a violation.

In a series of steadily more refined experiments [4–6], a Saturne group first deduced upper bounds on the c.m. differential cross section, most notably $d\sigma/d\Omega \leq 0.8$ pb/sr at a beam energy of $T_d = 800$ MeV [5] and a production angle of $\theta_\alpha^{\mathrm{lab}} = 12°$, corresponding to the peak of the Jacobian transformation from the c.m. to laboratory systems. The final experiment was carried out at the higher energy of $T_d = 1100$ MeV, also at $\theta_\alpha^{\mathrm{lab}} = 12°$ ($\theta_\alpha^{\mathrm{c.m.}} = 73°$). This is no longer the Jacobian peak, but was chosen to fit best the photon and α-particle acceptances. The beam energy was taken close to the threshold for η production in the analogous $dd \to \alpha\eta$ reaction (1121 MeV), with the hope that some η's produced virtually might mix, through a CSB interaction, and emerge as π^0's. A pion signal was claimed [6] with a c.m. cross section of

$$\frac{d\sigma}{d\Omega}(dd \to \alpha\pi^0) = (1.0 \pm 0.20 \pm 0.25)\ \mathrm{pb/sr}\,, \quad (1)$$

where the first error is statistical and the second systematic. It should be noted that this represents only about 10^{-10} of the deuteron-deuteron total cross section. Within a simple model [7], which compares the reaction to the measured $dd \to \alpha\,\eta$ reaction near threshold [8,9], a cross section of around 1 pb/sr is consistent with other determinations of the π^0/η mixing angle, although systematic uncertainties are difficult to quantify.

The validity of the conclusions of Ref. [6] was questioned at the time by some of the experimentalists involved [10] and, to understand the problem, a description of the experiment is necessary. Well-identified α particles were detected in the SPESIV magnetic spectrometer [11]. The scintillator hodoscope momentum binning of $\Delta p/p = 0.2\%$ [5] was degraded to a FWHM of 2% through the opening of the collimator to increase the counting rate. A Čerenkov photon detector of 32 lead-glass blocks had a good acceptance for the two photons from π^0 decays. Each detected γ was viewed by up to three neighboring blocks and its energy evaluated with a precision of ≈30% and its direction to within ≈3°. The photon energy and angular information could be correlated with the α-particle momentum on an event-by-event basis so that, apart from a possible e/γ ambiguity, the three final-state four-momenta of $\alpha\gamma\gamma$ events could be determined.

The experiment resulted in 230 candidates with a detected $\alpha\gamma\gamma$ topology and 565 where only one photon was seen (although another photon could have escaped detection). By applying a series of severe cuts in the off-line analysis, the authors of Ref. [6] were left with 15 $dd \to \alpha\gamma\gamma$ events which were spread in effective mass over the range $95 \leq m_{\gamma\gamma} \leq 175\ \mathrm{MeV}/c^2$. Monte Carlo simulations indicate that such a wide spread in $m_{\gamma\gamma}$ is consistent with single π^0 production and decay measured with a 2% momentum resolution [6]. These 15 events correspond to a cross section of $(1.1 \pm 0.30 \pm 0.20)$ pb/sr. A slightly smaller figure came from analyzing a selection of the single-photon events, where one photon was presumed lost.

The alternative interpretation [10] is that the 15 events belong to a continuum of $\alpha\gamma\gamma$ or $\alpha\gamma\gamma\gamma$ reactions, that have been artificially selected by the experimental cuts. The population of events compatible with the $\alpha\pi^0$ hypothesis does not show any obvious accumulation in the plot of the α-particle momentum *versus* the $\gamma\gamma$ opening angle. This suggests that $\alpha\pi^0$ production is not the dominant process and, if it exists, is not separated in the data from the multiphoton continuum.

We have recently made estimates of two-pion production in the $dd \rightarrow \alpha\pi^0\pi^0$ reaction in a model where both neutron-proton pairs undergo independent $np \rightarrow d\pi^0$ reactions, as indicated in Fig. 1 [12,13]. The predicted $2\pi^0$ cross section is roughly proportional to the square of that for single π^0 production times a form factor representing the probability for the two final deuterons sticking to form an α particle. This overlap is very favorable because the c.m. frames in the np and dd systems largely coincide. After inserting phenomenological $np \rightarrow d\pi^0$ amplitudes, and including also the charged pion contribution, the model reproduces well the observed differential cross section for $dd \rightarrow \alpha X$ as a function of the missing mass m_X and α-particle angle [13], as well as the measured deuteron vector and tensor analyzing powers [14]. The absolute normalization is reproduced to within a factor of 1.5 throughout the 900 to 1300 MeV range of beam energies, where single-pion (or -photon) production is copious in nucleon-nucleon collisions because of the Δ isobar. The predicted $2\pi^0$ cross section is shown in Fig. 2 under the conditions corresponding to the CSB experiment [6]. This spectrum displays a sharp ABC structure close to the 2π threshold [15], as well as a broader peak near the maximum missing mass. These features, which are equally prominent in data [16], arise in our model from the shape of the $np \rightarrow d\pi^0$ cross section which is forward/backward peaked. The two-pion cross section is then large when the two pions emerge parallel (the ABC peak) or antiparallel (the central bump). We wish to use the same model to estimate the background to the CSB experiment, replacing the π^0's in Fig. 1 by photons.

The formalism follows very closely that developed for two-pion production [13], to which the reader is referred for further details. The effective mass distributions in the $\alpha\gamma\gamma$, or $\alpha\pi^0\pi^0$, channels are expressed in terms of the matrix element $\mathcal{M}$ through

$$\frac{d^2\sigma}{d\Omega\, dm_X}(dd \rightarrow \alpha X) = \frac{1}{64(2\pi)^5}\,\frac{k_\alpha^{\mathrm{c.m.}}k^*}{p_d^{\mathrm{c.m.}}s} \times \frac{1}{9}\int d\Omega^* \sum_{\mathrm{ext\,pol}} |\mathcal{M}^*|^2, \quad (2)$$

where $\sqrt{s}$ is the total c.m. energy, k is the relative $\gamma\gamma$ or $\pi^0\pi^0$ momentum, and the sum is over external spin projections. Quantities denoted by an asterisk ($*$) are evaluated in the 2γ or 2π rest frame.

In evaluating the amplitudes corresponding to Fig. 1, we neglect the deuteron D state and the influence of the Fermi motion on the spin couplings. The matrix element then factorizes into a kernel $\mathcal{K}$, that contains the spin couplings, and a form factor $\mathcal{W}$; $\mathcal{M} = -i(m_\alpha/v_d)\,\mathcal{K}\mathcal{W}$, where v_d is the deuteron speed. In this approximation the form of $\mathcal{W}$ is the same as that for two-pion production, which is successfully described by this approach [13].

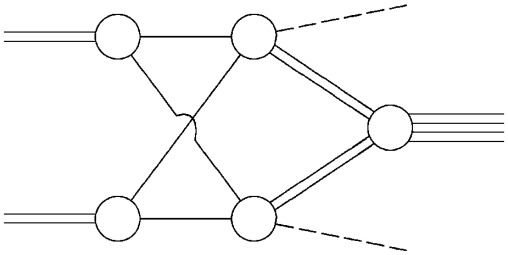

FIG. 1. Feynman diagram for the $dd \rightarrow \alpha\gamma\gamma$ and $dd \rightarrow \alpha\pi^0\pi^0$ reactions, where the dashed lines denote either pions or photons.

Rather than averaging the c.m. energies of the subprocesses over the Fermi momenta, these are fixed by assuming that the two production reactions share the total c.m. energy equally. For two-photon production this assumption means that the photon laboratory energy in the inverse $\gamma d \rightarrow np$ reaction is given by $E_\gamma^{\mathrm{lab}} = T_d/4$.

The input $np \rightarrow d\gamma/\pi^0$ vertices are parametrized in terms of experimentally determined partial-wave amplitudes, with those for pion production being discussed in our earlier work [13]. The photon amplitudes were obtained from the phenomenological multipoles of

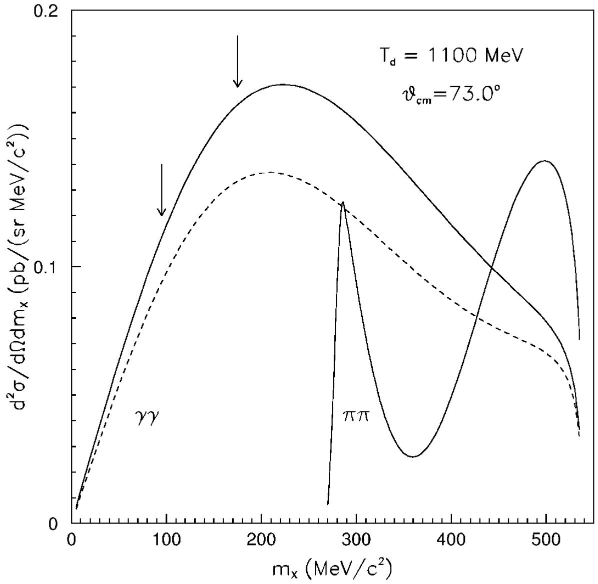

FIG. 2. Predicted missing mass distributions at $T_d = 1100$ MeV and $\theta_\alpha^{\mathrm{c.m.}} = 73°$ for the $dd \rightarrow \alpha\gamma\gamma$ and $dd \rightarrow \alpha\pi^0\pi^0$ reactions, the latter being reduced by a factor of 10^4. Solid lines in the photon case correspond to the full calculation, incorporating all $L \leq 2$ amplitudes, while the dashed lines are derived purely from the $M1(^1D_2)$ and $E1(^3F_2)$ amplitudes. The limits of the experimental acceptance (95 to 175 MeV/c^2) are indicated.

Arenhövel [17] using

$$AL(^{2s+1}l_j) = \sqrt{\frac{2l+1}{4\pi(2j+1)}} \sum_{m_s,m_d} \langle 1 m_d L m_s - m_d | j m_s \rangle \times \langle l 0 s m_s | j m_s \rangle \langle s m_s | A^{(L)} | m_d \rangle , \qquad (3)$$

where $\langle s m_s | A^{(L)} | m_d \rangle$ is a spin-projected multipole. In this notation (L, j) are the total angular momenta of the photon and the whole process, (s, l) are the spin and orbital angular momentum of the np system, and A denotes either electric (E) or magnetic (M). At $E_\gamma^{\mathrm{lab}} = T_d/4 = 275$ MeV the $np \to \gamma d$ cross section is dominated by $M1(^1D_2)$ and $E1(^3F_2)$ partial waves [18], that have angular distributions $(3\sin^2\theta + 2)$ and $(\sin^2\theta + 1)$, respectively, and which are both maximal at 90°. Together, these amplitudes reproduce most of the observed $(a\sin^2\theta + 1)$ behavior, with $a > 1$. This variation is to be contrasted with the $(3\cos^2\theta + 1)$ dependence, typical for $np \to \pi^0 d$ at these energies, which is sharply peaked towards $\theta = 0°$ and 180°.

In the spin-amplitude formalism [13], the spin structure of the dominant partial waves is given by

$$M1(^1D_2) \leftrightarrow -\frac{i\sqrt{3}}{2} \Big\{ (\hat{\boldsymbol{p}} \cdot \boldsymbol{\epsilon}_d^\dagger) \hat{\boldsymbol{p}} \cdot (\hat{\boldsymbol{k}} \times \boldsymbol{\epsilon}_\gamma^\dagger) - \frac{1}{3} \boldsymbol{\epsilon}_d^\dagger \cdot (\hat{\boldsymbol{k}} \times \boldsymbol{\epsilon}_\gamma^\dagger) \Big\} , \qquad (4)$$

$$E1(^3F_2) \leftrightarrow -\frac{\sqrt{5}}{2} \Big\{ \boldsymbol{\sigma} \cdot \hat{\boldsymbol{p}} \Big[(\hat{\boldsymbol{p}} \cdot \boldsymbol{\epsilon}_d^\dagger)(\hat{\boldsymbol{p}} \cdot \boldsymbol{\epsilon}_\gamma^\dagger) - \frac{1}{5} \boldsymbol{\epsilon}_d^\dagger \cdot \boldsymbol{\epsilon}_\gamma^\dagger \Big] - \frac{1}{5} [(\boldsymbol{\sigma} \cdot \boldsymbol{\epsilon}_d^\dagger)(\hat{\boldsymbol{p}} \cdot \boldsymbol{\epsilon}_\gamma^\dagger) + (\sigma \cdot \boldsymbol{\epsilon}_\gamma^\dagger)(\hat{\boldsymbol{p}} \cdot \boldsymbol{\epsilon}_d^\dagger)] \Big\} , \qquad (5)$$

where $(\boldsymbol{p}, \boldsymbol{k})$ are the proton and photon momenta, $(\boldsymbol{\epsilon}_d^\dagger, \boldsymbol{\epsilon}_\gamma^\dagger)$ the deuteron and photon polarization vectors, and $\boldsymbol{\sigma}$ the Pauli spin matrices. These expressions are to be multiplied by the corresponding complex amplitude determined using the spin structure of Eq. (3).

In a first approach, only the two $E1$ and $M1$ photodisintegration amplitudes were retained. The predictions for the $\alpha\gamma\gamma$ and $\alpha\pi^0\pi^0$ channels are given in Fig. 2. The magnitude of the two-photon cross section is sensitive to both the relative strength and phase of the two-photon-producing amplitudes, with values ranging from 0.4 to 1.3 times the predicted curves being possible with reasonable variation of these two parameters.

The solid curves in Fig. 2 represent the result of a calculation using all the $np \to d\gamma$ amplitudes with $L \le 2$, as determined by Arenhövel [18]. These amplitudes predict a $\gamma d \to np$ total cross section about a factor of 1.2 larger than that suggested by the available data [19] and so the input was reduced by this amount. The similarity of the two calculations illustrated in Fig. 2 indicates that the small $np \to d\gamma$ amplitudes are not crucial in our estimates. The complete lack of structure in the 2γ effective mass distributions is in stark contrast to the ABC peaks in the 2π spectrum. This is a direct consequence of the very different angular dependences of the subprocesses and, in particular, the tendency for the photons to emerge at large c.m. angles. There is, however, a strong angular dependence in the $\gamma\gamma$ form factor. For α-particle momenta $k_\alpha^{\mathrm{c.m.}} > 420$ MeV/c, corresponding to $m_X < 300$ MeV/c^2, photon emission parallel to the α particle is expected to be orders of magnitude smaller than perpendicular emission.

The model does indeed predict the production of a significant 2γ continuum. Its gross contribution in the π^0 region may be estimated by integrating the missing mass distribution in Fig. 2 over the experimental acceptance interval $95 < m_X < 175$ MeV/c^2 [6]. This leads to a c.m. cross section of $d\sigma(\alpha\gamma\gamma)/d\Omega \approx 11.3$ pb/sr at $\theta_\alpha^{\mathrm{c.m.}} = 73°$. Though this is larger than the π^0 signal reported [6], the reduction resulting from the experimental cuts imposed is hard to quantify. If the 2γ distribution were uniform, simple cuts would reduce the signal by a factor of 3 or more [10], though this might be modified by any strong photon angular distribution. The naive initial flux damping factor introduced in Ref. [13], could also diminish the cross section by ≈10%–15%. After taking such reductions into account, the similarity between our estimate and the claimed π^0 signal [6] gives cause for concern, especially since there is a theoretical uncertainty of at least a factor of 2, due in part to errors in the photoproduction input. Unless the influence of the predicted $\gamma\gamma$ continuum can be reduced, the significance of the CSB measurement must be questioned.

Estimates at $T_d = 800$ MeV give a similar value for the double-differential cross section of $d^2\sigma(\alpha\gamma\gamma)/d\Omega\, dm_{\gamma\gamma} \approx 0.14$ pb/(sr MeV/c^2). The early experiment [5] quoted only an upper bound for π^0 production because of an unidentified but significant background that varied smoothly with angle. Taking into account the effect of the cut imposed on the basis of the Čerenkov information, the background cross section at $\theta_{\mathrm{lab}} = 12°$ was (5 ± 2) pb/sr. Integrating over an experimental acceptance of ≈40 MeV/c^2 yields a 2γ estimate of almost exactly this figure, suggesting that the background is indeed due to two-photon production as discussed here.

Another possible background to the CSB experiment might arise from a $\pi^0\gamma$ final state with one very soft (and undetected) photon. One could try to estimate this cross section in a similar model to that of Fig. 1, replacing just one of the pions by a soft photon. However, in this kinematic limit the momentum sharing is destroyed and the form factor $\mathcal{W}$ becomes very small and model dependent. Within our approach the $\pi^0\gamma$ background is likely to be far less serious than the 2γ one studied here.

Our calculations suggest that the evidence for charge symmetry violation in the $dd \to \alpha\pi^0$ reaction [6] must be treated with great caution. We have shown that direct two-photon production is important for both this and the earlier experiment [5]. Experiments are needed with a better π^0 mass resolution and, though the signal might be weaker, this is most easily achieved near the $\alpha\pi^0$ threshold ($T_d = 226$ MeV). At, for example, 10 MeV above threshold in the c.m., the dominant photodisintegration amplitudes are $E1(^3P_1)$ and $E1(^3P_2)$ [18] and we predict an integrated cross section of $d\sigma(\alpha\gamma\gamma)/dm_{\gamma\gamma} = 3.6$ pb /(MeV/c^2). At the IUCF storage ring the experiment could be carried out with tensor polarized deuterons [20]. Because of conservation laws, η production in $dd \rightarrow \alpha\ \eta$ at threshold has an analyzing power of $t_{20} = 1/\sqrt{2}$, and this allows a signal to be cleanly picked out against a strong background [9]. The same technique can be used for pion production since our prediction for two-photon production gives a value of t_{20} which is consistent with zero. Alternatively, a new experiment might take advantage of the distribution in the angle $\theta_{\gamma\gamma}$ of the two photons in their rest frame, which must be isotropic for true π^0 production. Because of the preferential photon emission at 90° in the $np \rightarrow d\gamma$ reaction at low energies, our model suggests that, near threshold and in the forward α-particle direction, $d\sigma/d\Omega_{\gamma\gamma} \propto (1 + b\sin^2\theta_{\gamma\gamma})^2$, where $b \approx 2$. This could be investigated with the WASA $4\pi\ \gamma$ detector at the CELSIUS ring [21].

One of the authors (C. W.) gratefully acknowledges many detailed discussions over 15 years with L. Goldzahl regarding the CSB experiments described here. The crucial importance of direct 2γ production, possibly from the decay of two Δ's, was pointed out to us by P. Fleury and F. Plouin. H. Arenhövel has been very helpful in providing the necessary photodisintegration amplitudes. This work has benefited from the continued financial support of the Swedish Royal Academy and the Swedish Research Council. Two of the authors (D. D. and C. W.) wish to thank The Svedberg Laboratory for its generous hospitality.

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