Search for the Charge-Symmetry–Breaking Reaction $d+d \rightarrow {}^4\mathrm{He}+\pi^0$ at 0.8 GeV

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For the charge-symmetry–breaking reaction $d+d \rightarrow {}^4\mathrm{He}+\pi^0$ at $T_d=0.8$ GeV around 100° c.m., an upper limit on the production cross section of ≈ 0.8 pb/sr is obtained. This represents about a factor of 20 improvement on previous measurements, but is still a factor of 5 above expected violations.

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The reaction $d+d \rightarrow {}^4\mathrm{He}+\pi^0$, after the pioneering work of Lapidus in 1956,[1] has become a classic test of charge-symmetry breaking (CSB).[2–8] On the basis of CSB Δ-excitation diagrams, Cheung[9] has calculated that the reaction $d+d \rightarrow {}^4\mathrm{He}+\pi^0$ should display a cross section of 0.1–0.01 pb/sr in the Δ energy region, i.e., around $T_d \approx 0.6$ GeV, and then fade away. This CSB Δ excitation may proceed via electromagnetic photon exchange; but the strong interaction can also contribute via $\Delta I=1$ meson exchanges such as the π-η mixing diagram of Fig. 1(a) which would indeed afford the major contribution to $d+d \rightarrow {}^4\mathrm{He}+\pi^0$. It is also expected to be dominant in a CSB forward-backward asymmetry, yet unobserved, in the c.m. of the reaction $n+p \rightarrow d+\pi^0$,[10,11] while the *np* scattering asymmetry,[12–14] recently measured at TRIUMF,[14] is mostly attributed to π exchange, via the CSB component induced by the *n*-*p* mass difference.[13]

On the basis of the (first) observation[15] of the reaction $d+d \rightarrow {}^4\mathrm{He}+\eta$, Coon and Preedom[16] have estimated the corresponding yield of $d+d \rightarrow {}^4\mathrm{He}+\pi^0$ production, through the final-state $\eta \rightarrow \pi^0$ transition (via π-η mixing), according to Fig. 1(b). From our (0.25 ± 0.10)-nb/sr measurement of $d+d \rightarrow {}^4\mathrm{He}+\eta$, at $T_d=1.95$ GeV, they derived a cross section of 0.12 ± 0.05 pb/sr for $d+d \rightarrow {}^4\mathrm{He}+\pi^0$ at that energy, which is about as large

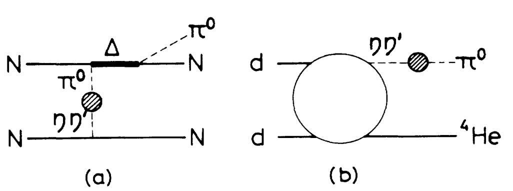

FIG. 1. (a) Δ-excitation diagram via $\Delta I=1$ π-η exchange; (b) $d+d \rightarrow {}^4\mathrm{He}+\pi^0/\eta$ through the final-state $\eta \rightarrow \pi^0$ transition.

as the most optimistic evaluation of Cheung for $T_d \approx 0.6$ GeV. This brings out the possibility that, at least for energies above the Δ, the final-state $\eta \rightarrow \pi^0$ transition may be the dominant contribution to $d+d \rightarrow {}^4\mathrm{He}+\pi^0$ production. If so, this "may provide the cleanest method yet of measuring the matrix elements $\langle \eta | H_{\mathrm{em}} | \pi^0 \rangle$ and $\langle \eta' | H_{\mathrm{em}} | \pi^0 \rangle$ and the semistrong mixing angle ϕ."[16]

The π-η mixing, although it might fully account for the large *G*-parity–nonconserving $\eta \rightarrow 3\pi^0$ decay, does not rely on direct experimental evidence (unlike the ρ-ω mixing); it remains to some extent an open question[17–22] which is of relevance to the problem of the chiral symmetry in QCD[23,24] [the "U1 problem"].

The most recent data[8] on the reaction $d+d \rightarrow {}^4\mathrm{He}+\pi^0$ gave an upper limit of 19 pb/sr [68% confidence level (C.L.)]. We report here an upper limit improved by a factor ≈ 20, obtained with a setup including a photon detector. Data were taken mostly with incident deuterons of $T_d=0.8$ GeV, for large ($\approx 100°$) c.m. angles. A short run was made at 1.35 GeV for $\approx 80°$ c.m.

In the $T_d=0.8$ GeV energy region, the ^{4}He ions, whether they are produced by $d+d \rightarrow {}^4\mathrm{He}+\pi^0$ or $d+d \rightarrow {}^4\mathrm{He}+\gamma$, still have distinct kinematic domains. The ^{4}He were detected in the SPES-4 spectrometer.[25] Five scintillator hodoscopes were used for measurements of ionization and time of flight over the 16 m between the intermediate and the final focal planes. The 44-counter hodoscope at the final focus delimits momentum bites of $\Delta p/p \approx 2 \times 10^{-3}$.

An array of lead-glass Cherenkov counters to detect the photons from π^0 decay has been installed near the target, at ≈ 0.75 m. It consists of twelve PEMG2 lead-glass cubes, each 15 cm on a side, closely packed in a 3×4 array. Each cube was equipped with a 12.5-cm-diam fast photomultiplier tube, glued directly onto one face.

Because of the intense flux of charged particles from the target, no veto scintillators were put in front of this detector. However, a powerful background rejection is afforded by our imposing a 2-ns window (see Fig. 2) on the time difference between the ^{4}He detection by the SPES-4 and the detection of the photon by the Cherenkov counter. In particular, the background from the 30-μm titanium target windows is reduced by $\approx 10^{-3}$ (down to ≈ 0.2 pb/sr) as estimated from a run with a 2-mm-thick titanium target.

The choice of the angular region, at $T_d = 0.8$ GeV, is based on the Jacobian-peak method (already used by Poirier and Pripstein[7] in 1961 for the study of the same reaction). By selecting ^{4}He around the maximum laboratory angle allowed by the kinematics, in a $\Delta\theta = \pm 0.20°$ interval (and 0.31×10^{-3}-sr solid angle), we have access to a large c.m. angular range of $\Delta\theta_{\text{c.m.}} \approx 15°$, mostly limited by the $\Delta p/p \approx 6\%$ momentum acceptance of the setup. Beyond the maximum laboratory angle, the ^{4}He yield must vanish; it should also vanish at smaller angles because the ^{4}He momentum is then either too high or too small to fall within the 6% momentum acceptance. Data were taken at four angular settings of the SPES-4 spectrometer: at the optimal angles for π_0 and γ productions, and at "off-kinematics" settings, one below and one above these.

The Cherenkov responses E_C for each of these four settings are displayed in Figs. 3(a)–3(d). The E_C signals, here expressed in megaelectronvolts, have been scaled in such a way that the continuous E_C spectra induced by photons of given E_γ energies have their end points at $E_C = E_\gamma$. Shower simulations in the lead-glass blocks, with the use of the EGS-3 code,[26] have resulted in distributions such as the one shown by the dashed curve in Fig. 3(c) for the quasimonoenergetic photons from $d+d \rightarrow {}^4\text{He}+\gamma$. A rather similar curve has been derived for the photons from $d+d \rightarrow {}^4\text{He}+\pi^0$ [see Fig. 3(b)]. The signals for each Cherenkov block were calibrated, within $\approx 10\%$ (for the same E_C scale), by the use of cosmic rays, and of $d+d \rightarrow {}^4\text{He}+\gamma/\pi^0$ and $N+N \rightarrow d+\pi^0$ events.

The accumulations observed at low energy in Figs. 3(a)–3(d) most probably originate from the reaction $d+d \rightarrow {}^4\text{He}+\pi^0+\pi^0$ which is enhanced near threshold; this is known as the ABC effect.[27] The ^{4}He is normally not in the angular acceptance, but the incoming deuteron might first undergo a scattering within the target, and then produce the two π^0's on a second encounter with a target deuteron. For the smaller angular setting, the corresponding expected E_C distribution fits the data rather well, as shown in Fig. 3(a). At larger angles, this background should shrink, both in magnitude and in energy, as indeed observed in Figs. 3(b)–3(d).

The c.m. cross section is given, in pb/sr and for a 40-

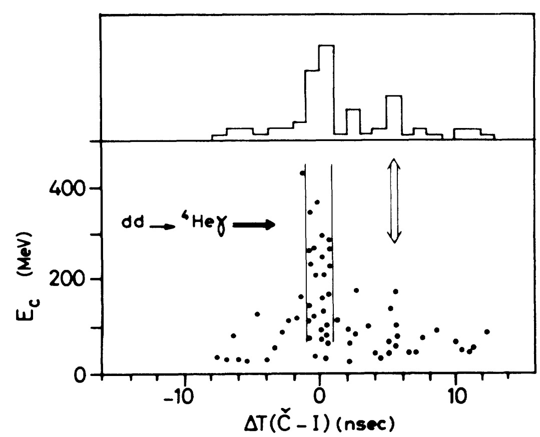

FIG. 2. Photon energies vs the ^{4}He-to-γ detection-time difference (corrected for the ^{4}He momentum and path-length dependence, and for amplitude slewing effects). The events are those for the central Cherenkov block with the spectrometer set for $d+d \rightarrow {}^4\text{He}+\gamma$ [see also Fig. 3(c)]. The accumulation of a few events with a 6-ns delay (arrow), which we also observed for a H_2 instead of a D_2 target, can be attributed to ^{4}He+γ production on the collimator by deuterons previously scattered in the target; this effect has certainly contributed to the background in the previous experiments without Cherenkov detectors.

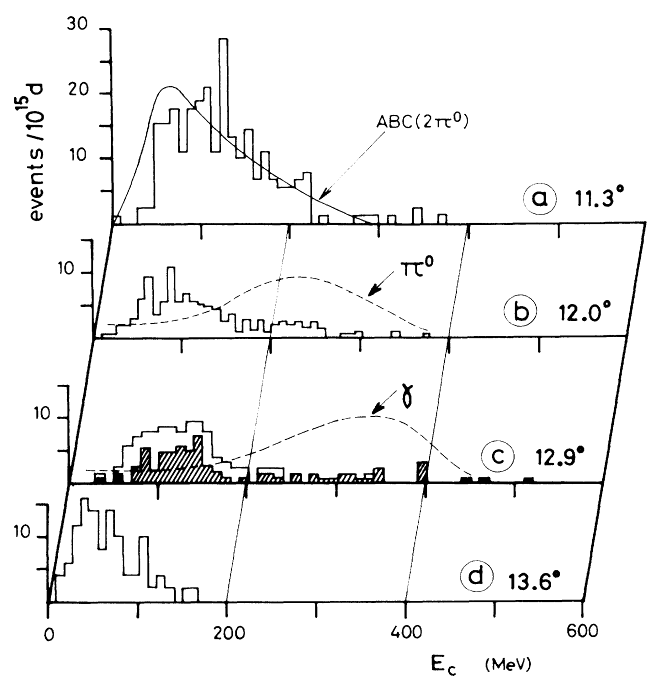

FIG. 3. Photon energy distributions for each of the four SPES-4 angular settings. The hatched events in (c) are those lying in the three Cherenkov blocks which are in the acceptance of the $d+d \rightarrow {}^4\text{He}+\gamma$ kinematics. The dashed curves are obtained from Monte Carlo simulations (Ref. 26). A trigger cutoff has depressed the counting rate below $E_C \approx 50$ MeV in (a)–(c).

mm-thick liquid-deuterium target, by

$$\frac{d\sigma}{d\Omega_{\text{c.m.}}} = \frac{5.05\times 10^{12}}{N_d \epsilon_G \Delta\Omega_{\text{c.m.}}} \frac{n_{\text{evt}}}{\epsilon_C}, \tag{1}$$

where ϵ_G is an attenuation factor related to the collimator and Cherenkov acceptances; $\Delta\Omega_{\text{c.m.}} = \langle \Delta\phi_{\text{c.m.}} \times \Delta\cos\theta_{\text{c.m.}} \rangle$ is the c.m. solid angle, obtained by a Monte Carlo integration, with limits on $\phi_{\text{c.m.}} (=\phi_{\text{lab}})$ given by the collimator, and limits on $\cos\theta_{\text{c.m.}}$ mostly defined by the spectrometer momentum acceptance; n_{evt} and ϵ_C are, above a given E_C, the observed number of events and the expected percentage as deduced from the computed E_C distributions [the dashed curves in Figs. 3(b) and 3(c)].

For $d+d \rightarrow {}^4\text{He}+\gamma$, if we choose a cutoff at $E_C > 260$ MeV, 21 events survive, all of which but one are concentrated on the expected three Cherenkov blocks [the hatched region in Fig. 3(c)]. About half of them, as expected from kinematics, are concentrated in a single block; they are indeed visible in Fig. 2, which shows for this block the scatter plot of E_C versus time. The single event lying outside of the three relevant blocks indicates that the level of the $2\pi^0$ background discussed above is here quite low. From relation (1), with $n_{\text{evt}}=20 \pm 4.5(\text{stat})$ and $\epsilon_C \approx 0.57 \pm 0.06$, and with $N_d = (1.28 \pm 0.13)\times 10^{15}$, $\epsilon_G \approx 0.56 \pm 0.06$, and $\Delta\Omega_{\text{c.m.}} \approx (54 \pm 3) \times 10^{-3}$ sr, the $d+d \rightarrow {}^4\text{He}+\gamma$ cross section is $d\sigma/d\Omega_{\text{c.m.}} \approx 4.7 \pm 1.1(\text{stat}) \pm 0.9(\text{syst})$ pb/sr, in agreement with the data of Arends *et al.*[28] on the reversed reaction.

For the sake of $d+d \rightarrow {}^4\text{He}+\pi^0$ evaluation, the background behavior has been studied as a function of the ${}^4\text{He}$ angle. In Fig. 4, the data for $E_C > 200$ MeV are well described by an exponential law, and, for $E_C > 260$ MeV, the same law also applies when scaled down by a factor ≈ 2.5. In either plot, no excess events are evidenced for the 12° ${}^4\text{He}$ angle. Taking into account the statistical uncertainties on n_{evt} and on the background subtraction, we are left with 0.0 ± 3.9 events. From relation (1), with $n_{\text{evt}} < 3.9(\text{stat})$ and $\epsilon_C \approx 0.34 \pm 0.08$, and with $N_d = (2.53 \pm 0.25)\times 10^{15}$, $\epsilon_G \approx 0.67 \pm 0.08$, and $\Delta\Omega_{\text{c.m.}} \approx (61 \pm 4)\times 10^{-3}$ sr, the $d+d \rightarrow {}^4\text{He}+\pi^0$ cross-section upper limit, to 68% C.L., is $d\sigma/d\Omega_{\text{c.m.}} < 0.8$ pb/sr.

At 1.35 GeV, from 0.7×10^{15} incident deuterons (in a 5-h run), we obtained a $dd \rightarrow {}^4\text{He}+\pi^0$ c.m. cross-section upper limit of ≈ 5 pb/sr with 68% C.L. and a $d+d \rightarrow {}^4\text{He}+\gamma$ cross section of $\approx 3.5^{+2.8}_{-1.4}$ pb/sr. These two results are in qualitative agreement with those at 0.8 GeV.

The use of a lead-glass array, by allowing a coincidence between the ${}^4\text{He}$ and γ, together with the γ-energy measurement, has proven to be quite valuable for the study of $d+d \rightarrow {}^4\text{He}+\pi^0$. A good check on the method was afforded by the observation of the reaction $d+d \rightarrow {}^4\text{He}+\gamma$.

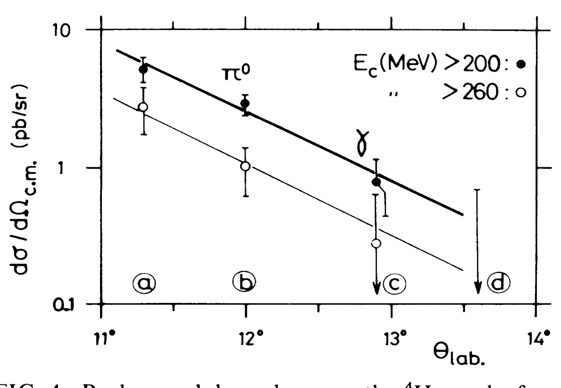

FIG. 4. Background dependence on the ${}^4\text{He}$ angle, from the data of Figs. 3(a) to 3(d) after cuts at $E_C > 200$ and 260 MeV. Genuine direct γ production is suppressed by removal of the coincidences which involve any one of the three relevant Cherenkov blocks. The vertical scale is expressed in terms of the equivalent π^0 production cross section (with the assumption of the same ϵ_C coefficient at all angles).

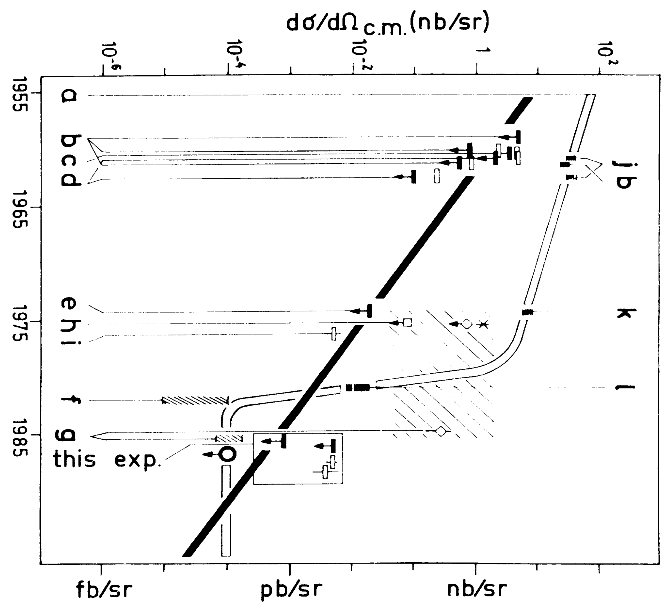

FIG. 5. Historical synopsis of the experimental and theoretical determinations for $d+d \rightarrow {}^4\text{He}+\pi^0/\gamma$ (closed rectangles/open rectangles). The letters a–l appearing on the figure have the following correspondences with the text references: a, Ref. 1; b, Ref. 4; c, Ref. 6; d, Ref. 7; e, Ref. 8; f, Ref. 9; g, Refs. 15 and 16; h, Ref. 27; i and j, Ref. 5; k, Refs. 5 and 7; and l, Ref. 5. The hatched region contains the $I=0$ meson allowed production in $d+d \rightarrow {}^4\text{He}+X$, the asterisk, lozenge, and square corresponding to ω, η, and η', respectively. The upper limits have been reevaluated so that all are expressed in terms of the same 68% C.L. The sensitivity aimed at by the experiment under preparation is shown by the open circle. The historical progress displays an exponential trend, at least for the experimental achievement. The theoretical predictions lie on a curve which shows a fast "transition" corresponding to the onset of meson mixing in this context.

The search for $d+d \rightarrow {}^4\mathrm{He}+\pi^0$ (upper limits only so far) has continued to improve in sensitivity over several decades, as illustrated on the historical synopsis of Fig. 5. Theoretical computations also have changed over this period of time. An extension of this experiment now under way is aimed at the sensitivity level of the present expectations.

In conjunction with an improved measurement of the reaction $d+d \rightarrow {}^4\mathrm{He}+\eta$ reaction, and hopefully with the measurement of $d+d \rightarrow {}^4\mathrm{He}+\eta'$, the observation of $d+d \rightarrow {}^4\mathrm{He}+\pi^0$ should afford valuable information on π-η-η' mixing.

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