On Electron-Positron Annihilation into Nucleon-Antinucleon Pairs

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Abstract

We discuss the puzzling experimental results on baryon-antibaryon production in e^+e^- annihilation close to the threshold, in particular the fact that $\sigma(e^+e^- \to \bar{n}n) \gtrsim \sigma(e^+e^- \to \bar{p}p)$. We discuss an interpretation in terms of a two-step process, via an intermediate coherent isovector state serving as an intermediary between e^+e^- and the baryon-antibaryon system. We provide evidence that the isovector channel dominates both $e^+e^- \to$ pions and from $\bar{N}N$ annihilation at rest, and show that the observed ratio of $\sigma(e^+e^- \to \bar{n}n)/\sigma(e^+e^- \to \bar{p}p)$ can be understood quantitatively in this picture.

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Experimental data from the FENICE collaboration [1] indicate that $\sigma(e^+e^- \to \bar{n}n)$ is relatively large close to threshold. Their data may be compared with earlier data on $e^+e^- \to \bar{p}p$ [2, 3] and also with data on the time-reversed reaction $\bar{p}p \to e^+e^-$, for which more precise data are available [4]. As seen in Fig. 1, the combined data indicate that $\sigma(e^+e^- \to \bar{n}n)/\sigma(e^+e^- \to \bar{p}p) \gtrsim 1$ when $E_{CM} \sim 2$ GeV. Averaging over the available data on both the direct and time-reversed reactions, which are very consistent, and ignoring any possible variation with energy, we find:

$$\frac{\sigma(e^+e^- \to \bar{p}p)}{\sigma(e^+e^- \to \bar{n}n)} = 0.66^{+0.16}_{-0.11} \tag{1}$$

The fact that this ratio is less than unity requires confirmation, but even equal cross sections for $e^+e^- \to \bar{p}p$ and $e^+e^- \to \bar{n}n$ would be quite surprising.

We recall that the ratio of the cross sections for the corresponding t-channel processes $ep(n) \to ep(n)$ should be infinite at zero momentum transfer, where the form factor simply measures the total proton and neutron charges, corresponding to a coherent sum over the electromagnetic charges of their constituent quarks. It is also believed that the ratio (1) should be large at high momentum transfers. In a naive perturbative description of e^+e^- annihilation into baryons, the virtual time-like photon first makes a 'primary' $\bar{q}q$ pair, which is then dressed by two additional quark-antiquark pairs that pop out of the vacuum. This dressing is thought to be a perturbative QCD process at high momentum transfers, which does not distinguish between the u and d quarks, since gluon couplings are flavor-blind. Thus, in this conventional perturbative picture, the only difference between the production rates of proton and neutron is through the different electric charges of the primary $\bar{q}q$ pairs. The total perturbative cross section is obtained by superposing the amplitudes with different primary $\bar{q}q$ pairs and squaring the result:

$$\sigma(e^+e^- \to \bar{N}N) \propto \left| \sum_{q \in N} Q_q a_q^N(s) \right|^2, \tag{2}$$

where $a_q^N(s)$ denotes the amplitude at $E_{CM}^2 = s$ for making the baryon N with a given primary flavor q, which is determined by the baryon wave functions.

Since the wave functions of the baryon octet have a mixed symmetry, the amplitudes $a_q^N(s)$ tend to be highly asymmetric in specific models. For
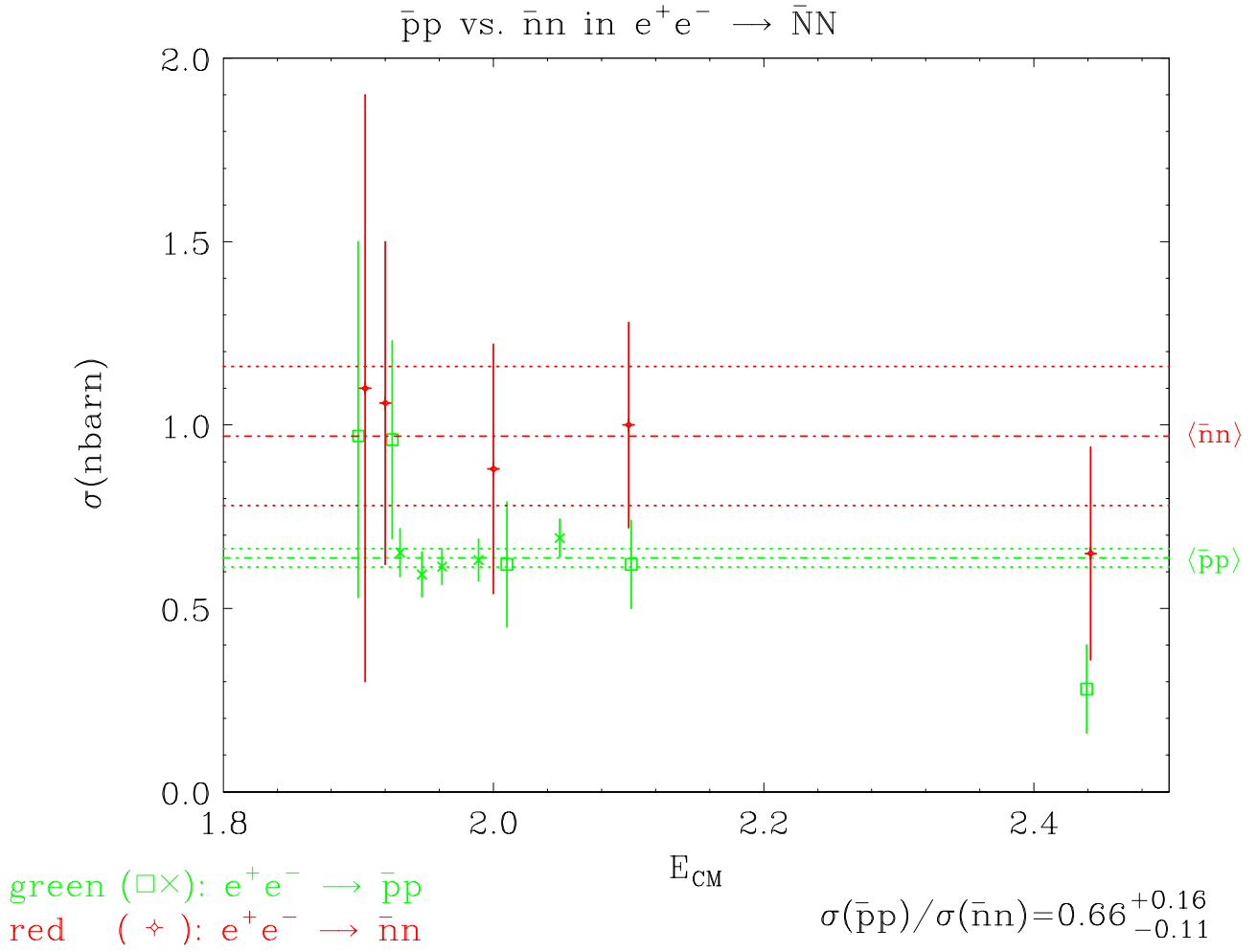
Figure 1: *Comparison of the cross sections for $e^+e^- \to \bar{n}n$ and $\bar{p}p$ in the threshold region $E_{CM} \sim 2$ GeV. In the case of $e^+e^- \to \bar{p}p$, the direct-channel data are combined with the data for the time-reversed reaction $\bar{p}p \to e^+e^-$ (marked by $\times$). The dash-dotted and dotted lines denote the average and 1-σ error bars, respectively, for the $\bar{p}p$ and $\bar{n}n$ data sets.*

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example, in the Chernyak-Zhitnitsky proton wave function [5], the u quark dominates, i.e., $a_u^p = \mathcal{O}(1)$, $a_d^p \ll 1$ and similarly $a_d^n = \mathcal{O}(1)$, $a_u^n \ll 1$. In such a limiting case we have

$$\frac{\sigma(e^+ e^- \to \bar{p}p)}{\sigma(e^+ e^- \to \bar{n}n)} \quad \longrightarrow \quad \frac{Q_u^2}{Q_d^2} = 4. \tag{3}$$

While this is an extreme case, on general grounds we expect that the u contribution dominates in the proton and the d in the neutron, so that $\sigma(e^+ e^- \to \bar{p}p)/\sigma(e^+ e^- \to \bar{n}n) \gg 1$ at large momentum transfers.

We find it puzzling that the experimental ratio (1) is apparently below unity when $E_{CM}^2 = s \sim 4\,\mathrm{GeV}^2$, whereas the ratio should be much larger than unity at both larger (timelike) and smaller (spacelike) momentum transfers. Clearly, the mechanism at work here is qualitatively different from those responsible for the above intuition.

The lack of a conventional theoretical explanation is part of the motivation for the proposed new asymmetrical $e^- e^+$ high-statistics collider at SLAC for the regime $1.4 < \sqrt{s} < 2.5$ GeV [6]. This machine will yield high-precision data on baryon production in $e^- e^+$ annihilation at threshold, providing a check on the FENICE data and an accurate benchmark for testing possible theoretical explanations.

The first thing one must realize is that even though $q^2 \gtrsim 4m_N^2 \gg \Lambda_{QCD}^2$, the process is highly nonperturbative. This is because the 'extra' kinetic energy available to the quarks is very small.

Our approach [7] to this puzzle is based on thinking about the time-reversed processes: $\bar{N}N \to e^+ e^-$. These may be viewed as two-step processes, with a coherent meson state serving as an intermediate state. One possible motivation for this picture might be provided by the Skyrme model [8, 9], according to which baryons appear as solitons in a purely bosonic chiral Lagrangian. This model is formally justified as a low-energy approximation to large-N_c QCD [10, 11], and is known to provide a good description of many low-energy properties of baryons: see [12, 13] for reviews. Skyrmion-anti-Skyrmion annihilation provides [14]-[17] a fairly accurate description of low-energy baryon-antibaryon annihilation. Just after the Skyrmion and anti-Skyrmion touch, they 'unravel' each other, and a coherent classical pion wave emerges as a burst that takes away energy and baryon number as quickly as causality permits. A specific parametrization of the initial pion configu-

ration is [16]:

$$F(r, t = 0) = h \frac{r}{r^2 + a^2} e^{-r/a} , \tag{4}$$

where F is the profile of the chiral field, $U = \exp[\, i\, \tau \cdot \hat{r}\, F(r, t)\,]$, a is a range parameter, h is chosen so that the total energy is that of the $\bar{N}N$ pair, and the form of F guarantees that the pion configuration has zero net baryon number. This crude model has been shown [16] to reproduce satisfactorily the inclusive single-pion spectrum in $\bar{p}p$ annihilation at rest and the branching ratios for multi-pion final states.

The details of this specific configuration are unimportant for our purposes: what is important is that the data are not inconsistent with such a model. Indeed, although the Skyrme model provides some motivation for our approach, it is not even essential for our purpose. What is important is that a *single intermediate state should dominate* the two-step $\bar{N}N \to e^+ e^-$ process. This could, for example, equally well be a single intermediate $J^{PC} = 1^{--}$ resonant meson state.

To be more precise, since $\bar{N}N$ annihilation is a strong-interaction process, one must consider separately the $I = 1$ and $I = 0$ channels. Accurately stated, our key assumption is that both of these channels are dominated by single states. These might be some excited ρ^* and ω^* mesons, for example, just as well as coherent pion configurations (4) with $I = 1$ and $I = 0$.

With this picture in mind, we write the $I = 1, 0$ $\bar{N}N \to e^+ e^-$ annihilation amplitudes as $A_1, e^{i\alpha} A_0$, where the overall phase is irrelevant, A_1 and A_0 are relatively real, and α is the relative phase between the $I = 1$ and $I = 0$ amplitudes. We then have

$$f \equiv \frac{\sigma(e^+ e^- \to \bar{p}p)}{\sigma(e^+ e^- \to \bar{n}n)} = \left| \frac{A_1 + e^{i\alpha} A_0}{A_1 - e^{i\alpha} A_0} \right|^2 . \tag{5}$$

It is apparent from (5) that $\sigma(e^+ e^- \to \bar{n}n)/\sigma(e^+ e^- \to \bar{p}p) \sim 1$ if either $A_1 \gg A_0$ or *vice versa*.

Remarkably, *there is evidence from both $e^+ e^-$ and $\bar{N}N$ annihilations that $I = I$ final states dominate by large factors.*

The clearest evidence comes from $e^+ e^- \to n\pi$, where it is found by measuring final states with even and odd numbers of pions respectively that

$$\frac{\sigma(e^+ e^- \to (2m)\pi)}{\sigma(e^+ e^- \to (2m+1)\pi)} \sim 9 \ \text{ for } \ E_{CM} \sim 2 \text{ GeV}, \tag{6}$$
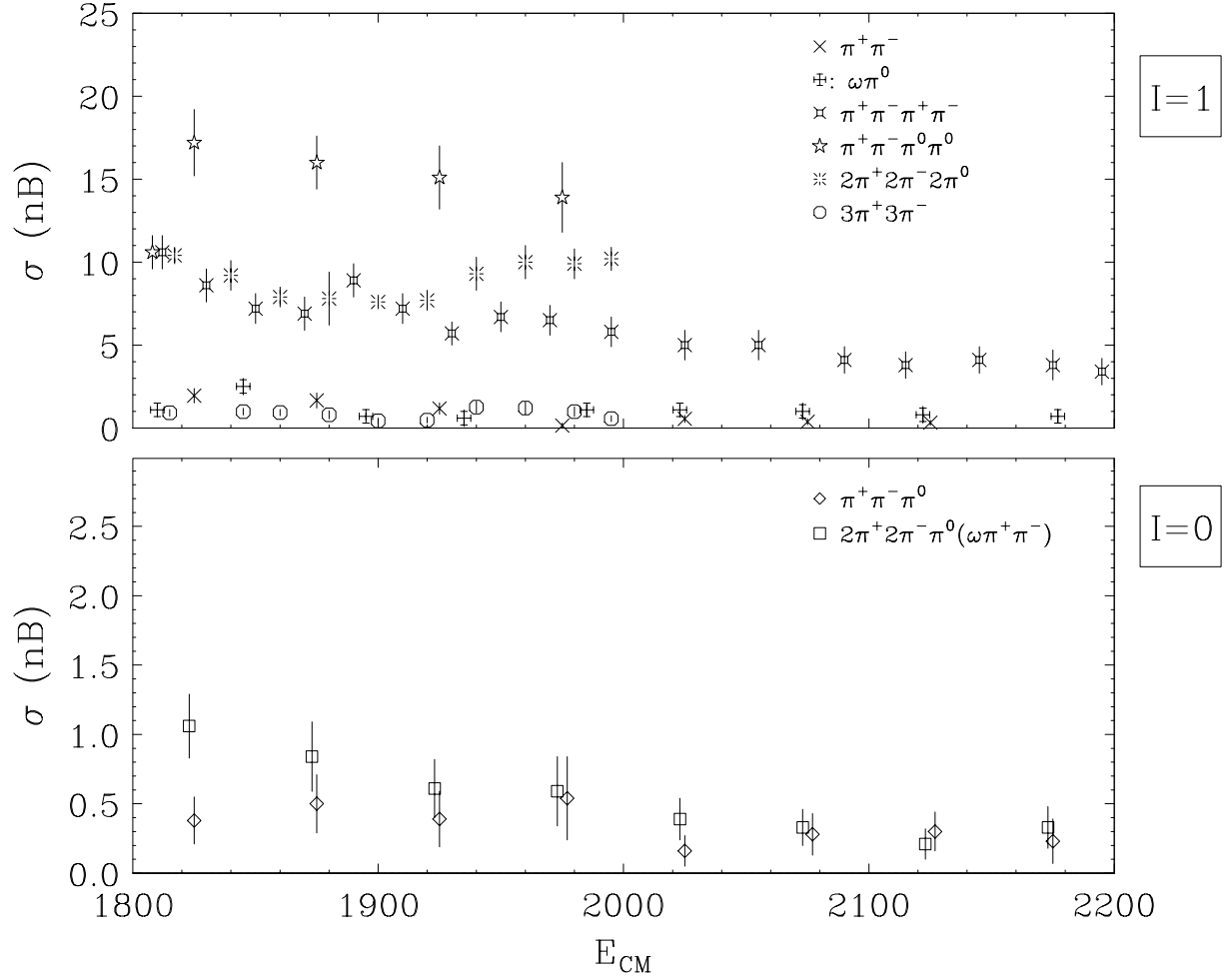
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Figure 2: *Cross sections for $e^+e^- \rightarrow$ multi-pion final states, for $E_{CM} \sim$ 2 GeV [19]. We note the dominance of $I = 1$ final states with even numbers of pions by about an order of magnitude over $I = 0$ states with an odd number of pions.*

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as seen in Fig. 2.[†] At these energies, we expect most final states created by $e^+e^- \to \bar{s}s$ to contain $K\bar{K}$ pairs, so that (6) corresponds to the non-$\bar{s}s$ initial states we expect to dominate in $\bar{N}N$ annihilation. The value (6) is similar to that found at lower energies, where $\Gamma(\rho \to e^+e^-) \sim 9 \times \Gamma(\omega \to e^+e^-)$, in agreement with naive quark models. The fact that the ratio $\sigma(I = 1)/\sigma(I = 0)$ continues to be large at higher energies is consistent with ideas of generalized vector meson dominance. The data from $\bar{N}N$ annihilations are less clear. Theoretically, there are various calculations and other suggestions that the cross sections for $\bar{N}N$ annihilations into $I = 1$ and $I = 0$ may be similar. Experimentally, several initial states contribute, including $^1S_0$, $^3S/D_1$ and various P waves, but we are interested only in the $J^{PC} = 1^{--}$ $^3S/D_1$ initial states. It is in principle possible to distinguish different initial states by comparing annihilations in gas and liquid, as has been done in the analysis of OZI-violating final states, but we are unaware of a comparable analysis of multi-pion final states. Because the initial state is a mixture with different $G = \pm 1$, it is not possible to separate $I = 1$ from $I = 0$ simply by counting pions, as was the case in e^+e^- annihilation.

The most convincing experimental information known to us comes from an analysis of $\bar{N}N \to \bar{K}K$. By comparing the rates for $\bar{p}p \to K^+K^-$ and $\bar{p}p \to K^0\overline{K}^0$, it has been possible to extract [18]

$$\left| \frac{A(^3S/D_1 \to \bar{K}K)_{I=1}}{A(^3S/D_1 \to \bar{K}K)_{I=0}} \right|^2 \sim 5 \text{ to } 10, \qquad (7)$$

which is comparable to the corresponding ratio (6) in e^+e^- annihilation. The fact that $I = 1$ dominates over $I = 0$ in the ratio (7) is consistent with the hypothesis that most of the $\bar{K}K$ final states are created by $\bar{u}u$ and $\bar{d}d$ pairs in the initial $\bar{N}N$ state, with a $\bar{s}s$ pair popping out of the vacuum. The ratio (7) would be small if primary $\bar{s}s$ pairs dominated.

We now use the experimental information on the dominance by the $I = 1$ channel in both e^+e^- (6) and $^3S/D_1$ annihilation (7) in a quantitative analysis of the $e^+e^- \to \bar{N}N$ production f ratio (5). Defining $\epsilon \equiv A_0/A_1$, we can rewrite (5) as

$$f = \left| \frac{1 + e^{i\alpha}\epsilon}{1 - e^{i\alpha}\epsilon} \right|^2. \qquad (8)$$

[†]The five-pion final state is predominantly $\omega\pi\pi$. The cross section in Fig. 2 corresponds to the final state $\omega\pi^+\pi^-$; for the total $\omega\pi\pi$ one should multiply it by 1.5 [19].

It is clear that the zero-momentum-transfer limit $\sigma(e^+e^- \to \bar{p}p) \gg (e^+e^- \to \bar{n}n)$ is obtained in the limit $\epsilon \to 1, \alpha \to 0$, and that the high-momentum-transfer limit $\sigma(e^+e^- \to \bar{p}p) \sim 4 \times (e^+e^- \to \bar{n}n)$ is obtained in the limit $\epsilon \to 1/3, \alpha \to 0$. In order to estimate $\epsilon = A_1/A_0$, our assumption of dominance in each isospin channel by a single state (either a coherent multi-pion state (4) or a generalized vector meson V^*) tells us that

$$\epsilon = \sqrt{\frac{\sigma(e^+e^- \to (I=0))}{\sigma(e^+e^- \to (I=1))}} \times \sqrt{\frac{\sigma(\bar{N}N \to (I=0))}{\sigma(\bar{N}N \to (I=1))}}. \tag{9}$$

Inserting the experimental indications (6,7) into (9), we estimate that

$$\frac{1}{10} \lesssim \epsilon \sim \frac{1}{3}. \tag{10}$$

The top end of this range seems to us quite conservative, whereas the lower end surely requires more justification from $\bar{N}N$ annihilation data. In the following numerical analysis, we keep ϵ general, but focus extra attention on the limits $\epsilon = 1/3$ and $1/10$.

It is apparent from (8) that $f \sim 1$ is possible for any value of ϵ, for a restricted range of the relative phase $\alpha \sim \pi/2$. However, the allowed range of α is extended if ϵ is small. It is easy to see that f lies in a narrow range Δf around unity if α falls within the following range:

$$\Delta\alpha \simeq \frac{\Delta f}{4\epsilon}. \tag{11}$$

It is apparent that $f \sim 1$ for all values of α if ϵ is small, as suggested (10) by the available data on e^+e^- and $\bar{N}N$ annihilation.

The quantitative behaviour of f as a function of $0 < \epsilon < 1/2$ and $-\pi < \alpha < \pi$ is shown in Fig. 3. Displayed explicitly is the region of the (ϵ, α) plane where f falls within the experimental range (1). We see that this range favours $|\alpha| > \pi/2$, whatever the value of ϵ. Fig. 4 displays projections of Fig. 3 for the two limiting values $\epsilon = 1/3$ and $1/10$. The allowed range (1) of f and the corresponding ranges of α are also shown.

We conclude that the *a priori* puzzling large experimental value of the ratio $\sigma(e^+e^- \to \bar{n}n)/\sigma(e^+e^- \to \bar{p}p)$ can be understood qualitatively. This is relatively easy if the $I=1$ amplitude dominates over the $I=0$ amplitude, as suggested by the available data on e^+e^- and $\bar{N}N$ annihilation and our
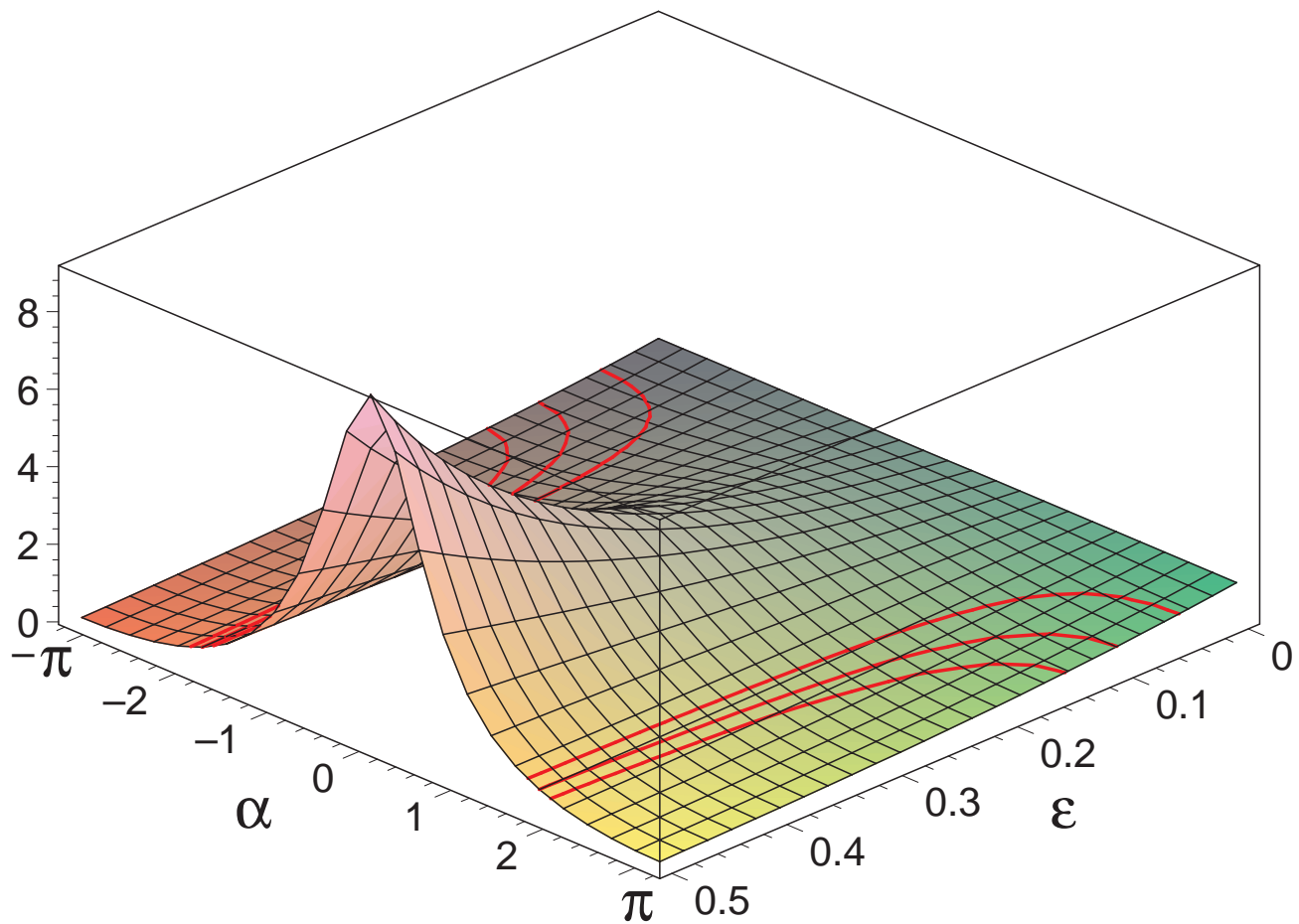
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Figure 3: *Three-dimensional plot of the cross-section ratio* $f \equiv \sigma(e^+e^- \to \bar{p}p)/\sigma(e^+e^- \to \bar{n}n)$ *as a function of* ϵ *and* α, *indicating the region where* f *falls within the range (1).*
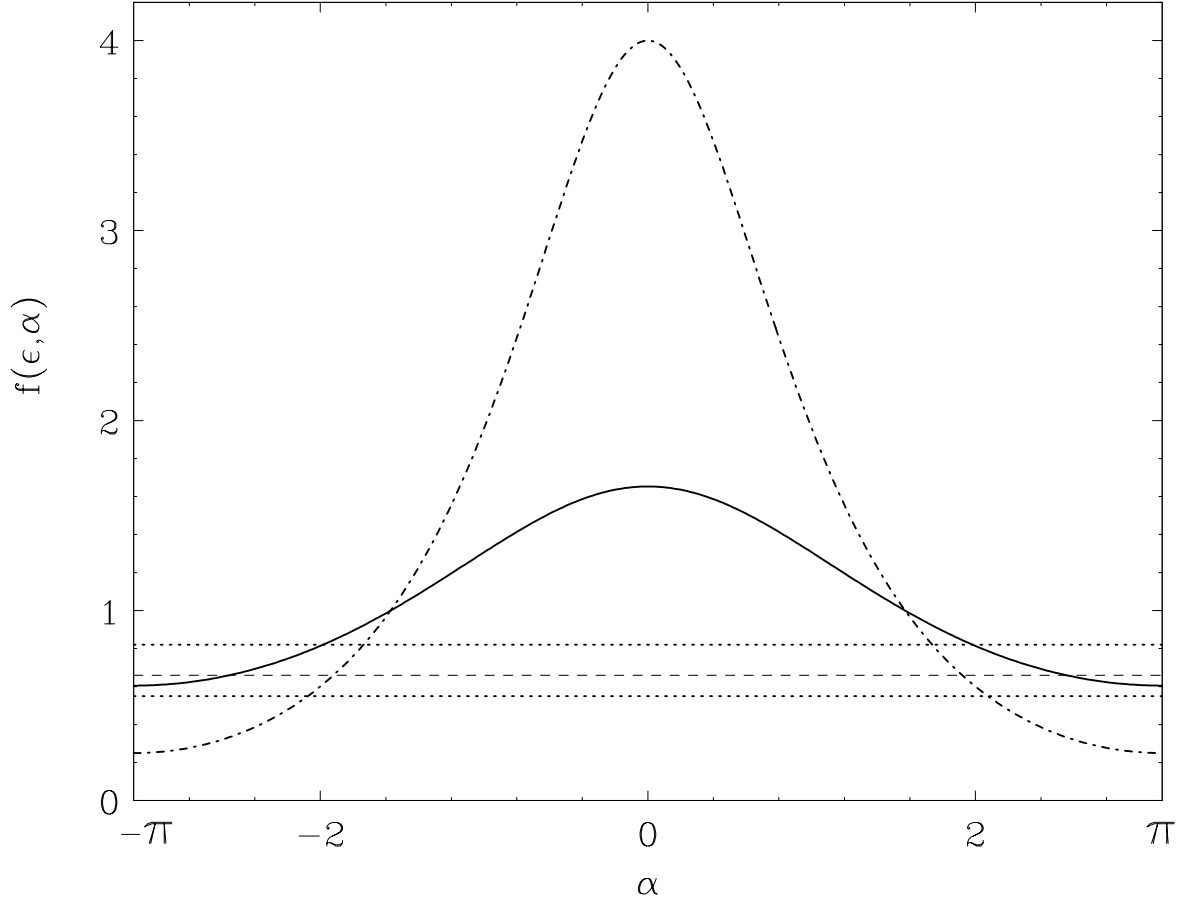
Figure 4: *Two-dimensional plot of the cross-section ratio $f \equiv \sigma(e^+e^- \to \bar{p}p)/\sigma(e^+e^- \to \bar{n}n)$ as a function of α for $\epsilon = 1/3$ (dot-dash curve) and $\epsilon = 1/10$ (continuos curve), indicating the ranges where f falls within (1).*

assumption of dominance by a single coherent state in each isospin channel. The specific range (1) can be understood quantitatively if the $I = 1$ and $I = 0$ amplitude have a large relative phase α. We are not in a position to judge the plausibility of such a large value of α, from either an experimental or a theoretical point of view. It would be interesting to make tests of this possibility.

We comment finally on the surprisingly large value of the ratio $\sigma(\gamma\gamma \to \bar{\Lambda}\Lambda)/\sigma(\gamma\gamma \to \bar{p}p)$ observed by the CLEO Collaboration [20] (see also [21]-[23] for related experimental work). CLEO find that $\sigma(\gamma\gamma \to p\overline{p}) \approx \sigma(\gamma\gamma \to \Lambda\overline{\Lambda})$ close to threshold, which seems analogous to FENICE result for the $\bar{n}n/\bar{p}p$ ratio. For a given quark flavor, the perturbative amplitude for baryon-antibaryon production in the photon-photon reaction scales like the quark charge squared, compared with the linear dependence of the amplitudes on the quark charge in the e^+e^- case discussed earlier. Thus one might naively expect the ratio $\sigma(\overline{\Lambda}\Lambda)/\sigma(\bar{p}p)$ to be even smaller than the corresponding perturbative prediction for $\sigma(\bar{n}n)/\sigma(\overline{p}p)$ in e^+e^-. It would be interesting to approach this puzzle from a point of view similar to that adopted in this paper. However, the situation in $\gamma\gamma$ collisions is more complicated, because of the wider range of possible spin and isospin states. Also, the information available on the isospin and spin decomposition is sparse compared with that in e^+e^- annihilation, which we used above. Data for $\gamma\gamma \to \overline{n}n$ close to threshold might cast light on the $\sigma(\gamma\gamma \to \bar{\Lambda}\Lambda)/\sigma(\gamma\gamma \to \bar{p}p)$ puzzle, but are not yet available.

We have proposed in this paper a simple model that is able to accommodate the suprisingly large observed value of the ratio $\sigma(e^+e^- \to \bar{n}n)/\sigma(e^+e^- \to \bar{p}p)$. Our suggestion is based on a simple two-step approach, in which a single intermediate state with $I = 1$ dominates over $I = 0$. This dominant intermediate state could be motivated by a Skyrmion-anti-Skyrmion picture, or could be some excited ρ^* resonance. Our model could be tested by further measurements of the ratios of different isospin amplitudes in e^+e^- and $\bar{N}N$ annihilation, and suggests a relatively large phase difference between $I = 1$ and $I = 0$ amplitudes. We look forward to more experimental data bearing on these issues, for example from a new low-energy e^+e^- collider [6].

Acknowledgments

References

[1] A. Antonelli *et al.*, Nucl. Phys. B **517**, 3 (1998).

[2] A. Antonelli *et al.*, Phys. Lett. B **334**, 431 (1994).

[3] D. Bisello *et al.* [DM2 Collaboration], Z. Phys. C **48**, 23 (1990).

[4] G. Bardin *et al.*, Nucl. Phys. B **411**, 3 (1994).

[5] V. L. Chernyak and A. R. Zhitnitsky, Phys. Rept. **112**, 173 (1984).

[6] *Letter of intent for a new asymmetrical e^-e^+ collider for the regime* $1.4 < \sqrt{s} < 2.5$ *GeV*,
http://www.slac.stanford.edu/grp/rd/epac/LOI/ .
See also
http://www-project.slac.stanford.edu/pep-n/Default.htm .

[7] M. Karliner, *"A possible resolution of the $e^+e^- \to \bar{N}N$ puzzle"*, hep-ph/0108106, invited talk at e^+e^- *Physics at Intermediate Energies*, SLAC, 30 Apr – 2 May 2001.

[8] T. H. Skyrme, Proc. Roy. Soc. Lond. A **260** (1961) 127.

[9] T. H. Skyrme, Nucl. Phys. **31** (1962) 556.

[10] E. Witten, Nucl. Phys. B **160**, 57 (1979).

[11] G. S. Adkins, C. R. Nappi and E. Witten, Nucl. Phys. B **228**, 552 (1983).

[12] I. Zahed and G. E. Brown, Phys. Rept. **142**, 1 (1986).

[13] J. Schechter and H. Weigel, hep-ph/9907554.

[14] J. J. Verbaarschot, T. S. Walhout, J. Wambach and H. W. Wyld, Nucl. Phys. A **461**, 603 (1987).

[15] H. M. Sommermann, R. Seki, S. Larson and S. E. Koonin, Phys. Rev. D **45**, 4303 (1992).

[16] Y. Lu and R. D. Amado, Phys. Rev. C **52**, 2158 (1995) [nucl-th/9505021], M. A. Halasz and R. D. Amado, Phys. Rev. D **63**, 054020 (2001) [hep-ph/0009260] and references therein.

[17] R. D. Amado, private communication.

[18] C. B. Dover, T. Gutsche, M. Maruyama and A. Faessler, Prog. Part. Nucl. Phys. **29**, 87 (1992).

[19] S. Eidelman, private communication.

[20] S. Anderson *et al.* [CLEO Collaboration], Phys. Rev. D **56**, 2485 (1997) [hep-ex/9701013].

[21] M. Artuso *et al.* [CLEO Collaboration], Phys. Rev. D **50**, 5484 (1994).

[22] L3 Collaboration, Note 2566, $\Lambda\bar{\Lambda}$ *Formation in Two-Photon Collisions at LEP*, June 2000, submitted to ICHEP-2000 in Osaka.

[23] H. Hamasaki *et al.* [VENUS Collaboration], Phys. Lett. B **407**, 185 (1997).