A Possible Resolution of the $e^+e^- \to \bar{N}N$ Puzzle

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We sketch some recent ideas proposed as the mechanism behind the puzzling experimental results on baryon-antibaryon production in e^+e^- annihilation close to threshold. The essential new point in the proposed mechanism is that it is a two-stage process, with a coherent state of pions serving as an intermediary between e^+e^- and the baryon-antibaryon system. Skyrmion-antiskyrmion annihilation is proposed as a concrete computational framework for a quantitative description of the baryon-antibaryon annihilation. We also point out the possible connection to similarly puzzling data on baryon-antibaryon production in photon-photon collision.

1. INTRODUCTION—THE PUZZLE

The FENICE data [1], on the reaction $e^+e^- \to \bar{n}n$ close to threshold, together with earlier analogous measurements for the proton [2]-[4] indicate that at threshold $\sigma(e^+e^- \to \bar{p}p)/\sigma(e^+e^- \to \bar{n}n) \approx 1$. In other words, the timelike form factors of the neutron and the proton are approximately equal at $q^2 \gtrsim M_N^2$.

This is a very surprizing and puzzling result and it is hard to understand in the conventional perturbative picture of baryon-antibaryon production in e^+e^- annihilation, as shown in Figure 1.

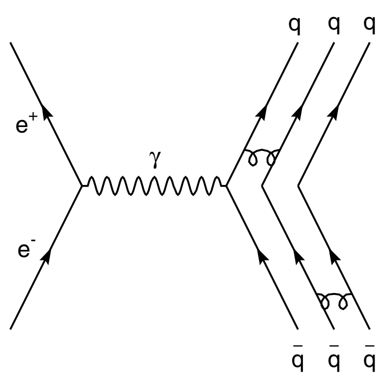

Figure 1: Feynman diagram corresponding to the naive perturbative description for $e^+e^- \to \bar{N}N$.

1.1. The perturbative picture

In the naive perturbative description of the e^+e^- annihilation into baryons, the virtual timelike photon first makes a "primary" $\bar{q}q$ pair, which then "dresses up" with two additional quark-antiquark pairs which pop up from the vacuum. The "dressing up" is a QCD process, which does not distinguish between u and d quarks, since gluon couplings are flavor-blind. Thus in the conventional picture the only difference between proton and neutron is through the different electric charge of the primary $\bar{q}q$ pair. The total perturbative cross-section $\sigma_{\rm PT}$ at a given CM energy is obtained by superposing the amplitudes with different flavors q in the primary $\bar{q}q$ pair and squaring the result,

$$\sigma_{\rm PT}(e^+e^- \to \bar{N}N) \propto \left| \sum_{q\in N} Q_q a_q^N(s) \right|^2 \qquad (1)$$

where $a_q^N(s)$ denotes the amplitude at $E_{CM}^2 = s$ for making the baryon N with a given the primary flavor q. These amplitudes are determined by the baryon wavefunctions.

Since the wave functions of the baryon octet have a mixed symmetry, the amplitudes $a_q^N(s)$ tend to be highly asymmetric. Thus for example in the Chernyak-Zhitnitsky proton wave function [5] the u quark dominates, that is, $a_u^p \approx 1$, $a_d^p \ll 1$ and similarly $a_d^n \approx 1$, $a_u^n \ll 1$. In such a limiting case we have

$$\frac{\sigma_{\rm PT}(e^+e^- \to \bar{p}p)}{\sigma_{\rm PT}(e^+e^- \to \bar{n}n)} \quad \longrightarrow \quad \frac{Q_u^2}{Q_d^2} = 4. \qquad (2)$$

While this is an extreme case, on general grounds we expect that u dominates in the proton and d in the neutron, so $\sigma_{\rm PT}(\bar{p}p)/\sigma_{\rm PT}(\bar{n}n) \gg 1$. Intuitively one can understand this perturbative result directly from Figure 1, by recalling that the average charge squared of quarks in the proton is higher than in the neutron. Thus the naive perturbation theory clearly disagrees with the experimental result [1].

1.2. Where do we go from here?

As the first step, one has to realize that we are dealing with a highly nonperturbative process. Even though the form factors are measured at a momentum transfer which is much higher than Λ_{QCD}, $q^2 \gtrsim 4M_N^2 \sim 4\ {\rm GeV}^2$, we are very far from the

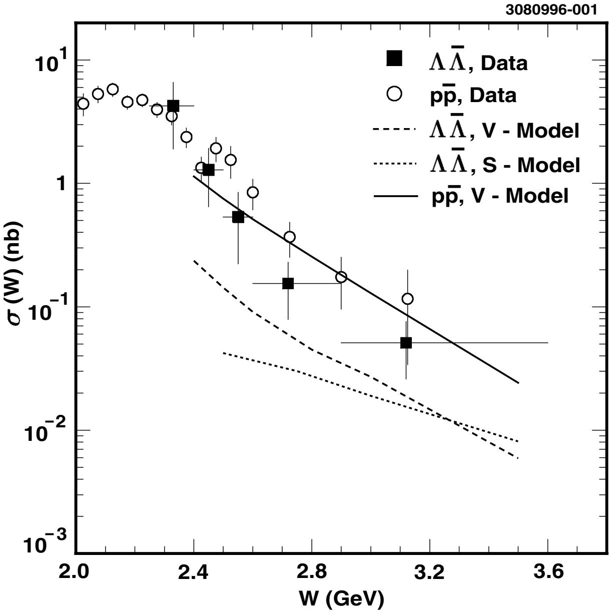

Figure 2: CLEO data [6] for $\sigma_{\gamma\gamma \to \Lambda\overline{\Lambda}}(W)$, $\sigma_{\gamma\gamma \to p\overline{p}}(W)$ for $|\cos\theta^*| < 0.6$. Vertical error-bars include systematic uncertainties. Horizontal markings indicate bin width. S-model: scalar quark-diquark model; V-model: vector quark-diquark model.

perturbative regime. The reason is that all the available energy is very quickly divided among the quarks and antiquarks in the $\bar{N}N$ system. Since the total available energy is very close to the rest mass of the $\bar{N}N$ system, none of the quarks has any "spare" momentum.

There have been several attempts to explain the FENICE data by various theoretical proposals utilizing specific nonperturbative mechanisms (for a recent report on some of this work see [7]), but to the best of my knowledge, so far there is no satisfactory explanation in terms of conventional mechanisms or their straightforward extensions.

The lack of such 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 [8]. 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.

In this context it is amusing to note the perturbation theory predictions for the Δ baryon resonance multiplet production in e^+e^- near threshold. Since the Δ has a totally symmetric wave function, the corresponding amplitudes are equal, $a_u^\Delta = a_d^\Delta \equiv a^\Delta$, for all four members of the multiplet, $\{\Delta^{++}, \Delta^+, \Delta^0, \Delta^-\}$. Thus perturbation theory makes a striking prediction for the neutral member of the multiplet,

$$\sigma_{\rm PT}(e^+e^- \to \bar{\Delta}^0\Delta^0) \propto \left| a^\Delta \left(\frac{2}{3} - \frac{1}{3} - \frac{1}{3} \right) \right|^2 = 0. \quad (3)$$

More generally, the relative yields predicted by perturbation theory are

$$\Delta^{++} : \Delta^+ : \Delta^0 : \Delta^- = 4 : 1 : 0 : 1. \quad (4)$$

2. $\gamma\gamma \to \bar{N}N$: A RELATED PUZZLE?

The FENICE puzzle is reinforced by the CLEO data on baryon-antibaryon production in photon-photon collisions [9], as shown in Figure 2 (see also [10] and [11] for related experimental work).

CLEO has compared the $\gamma\gamma$ cross-sections for $\Lambda\overline{\Lambda}$ and $\bar{p}p$ production and they find that close to threshold $\sigma(\gamma\gamma \to p\overline{p}) \approx \sigma(\gamma\gamma \to \Lambda\overline{\Lambda})$. This is quite similar to the FENICE puzzle for the $\bar{p}p/\bar{n}n$ ratio. The naive perturbative description of the baryon-production in the photon-photon reaction is given by the Feynman diagram in Figure 3. Since there are two photons here, instead of one in Figure 1, for each flavor of the primary $\bar{q}q$ pair the corresponding amplitude scales like the quark charge squared, to be compared with linear dependence of the amplitudes on the quark charge in the e^+e^- case. Thus one would naively expect the ratio $\sigma(\bar{p}p)/\sigma(\overline{\Lambda}\Lambda)$ to be even larger than the corresponding perturbative prediction for $\sigma(\bar{p}p)/\sigma(\overline{n}n)$ in e^+e^-.

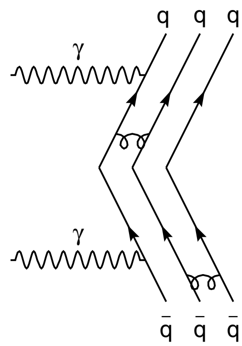

Figure 3: Feynman diagram corresponding to the naive perturbative description for $\gamma\gamma \to \bar{N}N$.

The disagreement between the naive theoretical prediction and experiment is striking again.

Just like in the FENICE case, despite several attempts, there is no satisfactory theoretical explanation for this CLEO data (for example, see [12] for a recent theoretical analysis of $\gamma\gamma \to$ baryons in terms of di-quarks).

It would be highly interesting to see the data for $\gamma\gamma \to \overline{n}n$ close to threshold, but such analysis has not yet been done due to some technical difficulties [13]. As will be clear from the following discussion, close to threshold we expect the $\gamma\gamma \to \overline{n}n$ cross-section be the same as $\gamma\gamma \to \overline{p}p$. We urge our experimental colleagues to carry out such an analysis.

The perturbative ratios are even more dramatic for the rates for $\gamma\gamma \to \bar{\Delta}\Delta$, which are proportional to the fourth power of the Δ electric charge, if one has symmetric wavefunctions. Thus for $\sigma_{\rm PT}(\gamma\gamma \to \bar{\Delta}\Delta)$ near threshold, the analogue of Eq. 4 is

$$\Delta^{++} : \Delta^+ : \Delta^0 : \Delta^- = 16 : 1 : 0 : 1. \quad (5)$$

As we shall discuss in more detail in the following section, the mechanism we propose for this type of reactions predicts a completely different result.

3. THE PROPOSED RESOLUTION

In view of these FENICE and CLEO puzzles, we have proposed [14] a novel mechanism which might explain the data. The essential new point in the proposed mechanism is that it is a two-stage process, with a coherent state of pions serving as an intermediary between e^+e^- and the baryon-antibaryon system, as shown schematically in Figure 4.

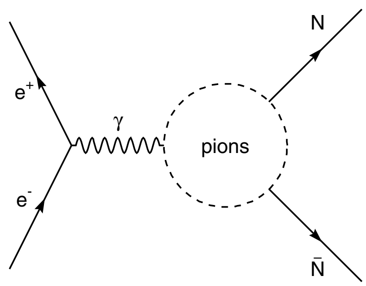

Figure 4: $\bar{N}N \to e^+e^-$ as a two-stage process, where e^+e^- annihilate into a timelike photon which first couples to an intermediate pion state, which then produces the $\bar{N}N$ pair.

3.1. $\bar{N}N$ annihilation into pions

We propose to use the Skyrme model as a concrete computational framework for a quantitative description of the baryon-antibaryon dynamics. In the Skyrme model [15, 16] baryons appear as solitons in a purely bosonic chiral Lagrangian. The model is formally justified as a low-energy approximation to large-N_c QCD [17, 18]. It is known to provide a good description of many low-energy properties of baryons (see [19] and [20] for a review).

It turns out that it is also possible to obtain a fairly accurate description of low-energy baryon-antibaryon annihilation in terms of Skyrmion-antiskyrmion annihilation [21–24].

Instead of asking how a $\bar{p}p$ or $\bar{n}n$ configuration is formed by a virtual timelike photon, or by two photons, it is conceptually easier to consider the reverse processes, that is, $\bar{p}p \to \gamma \to e^+e^-$ or $\bar{n}n \to \gamma \to e^+e^-$, as shown schematically in Figure 5, and the analogous processes for two photons.

It is interesting to note that it has been argued [25] that in perturbation theory the production of extended objects, such as a soliton-antisoliton configuration, by pointlike particles, such as in e^+e^- annihilation, is suppressed by a large exponential factor $\sim \exp(-4/\alpha_s)$. Thus the fact that the reaction $e^+e^- \to \bar{N}N$ has been measured with a small, but finite cross-section is yet another indication of the nonperturbative nature of the process.

Following the pioneering numerical work of [21] and [22], we now have the following picture of the $N\bar{N}$ annihilation at rest as a Skyrmion anti-Skyrmion annihilation: just after the Skyrmion and anti-Skyrmion touch, they "unravel" each other, and a classical pion wave emerges as a coherent burst and

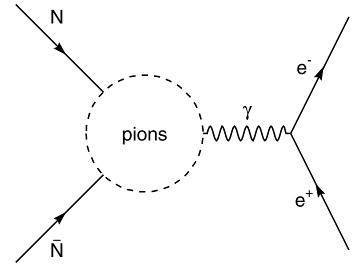

Figure 5: Time-reversed process of Figure 4, that is, $\bar{N}N \to e^+e^-$ as a two-stage process, where the nucleons first annihilate into pions, which then couple to a timelike photon to produce the e^+e^- pair.

takes away energy and baryon number as quickly as causality permits.

This observation led the authors of [23] to suggest the following simplified version of $N\bar{N}$ annihilation at rest. After a very fast annihilation a spherically symmetric "blob" of pionic matter of size $\sim$ 1 Fm, baryon number zero and the total energy twice the nucleon rest mass is formed. The further evolution of the system and the branching rates of various channels are completely determined by the parameters of this "blob."

For a very crude toy model of what is going on, let's assume that $\bar{p}p$ annihilate into two pions which then go to e^+e^- via a timelike photon,

$$\bar{p}p \to \pi^+\pi^- \to \gamma \to e^+e^- \tag{6}$$

Clearly, the real process involves an intermediate state with a much larger number of pions on the average, but two pions are sufficient to understand why within this physical picture we expect the $\bar{n}n \to e^+e^-$ rate to be the same as the $\bar{p}p \to e^+e^-$ rate. The basic argument is that since we have a two-stage process, the crucial issue is the rate $\bar{p}p \to \pi^+\pi^-$ versus the rate $\bar{n}n \to \pi^+\pi^-$. Since this is a purely strong interaction process, we expect the two rates to be equal. The next step is $\pi^+\pi^- \to \gamma \to e^+e^-$ which does not care whether the pions were produced by $\bar{p}p$ or $\bar{n}n$ annihilation. Clearly if $\bar{p}p \to e^+e^-$ has the same cross-section as $\bar{n}n \to e^+e^-$, the same will apply to the reverse processes.

It is tempting to assume that a similar argument can be made for $\gamma\gamma \to \bar{\Lambda}\Lambda$ versus $\gamma\gamma \to \bar{p}p$, although one expects the corresponding analysis to be more difficult, as one will have K^+K^- in the intermediate state.

We should stress that the two pion intermediate state is used here only as an illustration. In practice the two pion channel is very small and most difficult to treat within the approach of [23], since the semiclassical approximation is best suited for coherent states. A similar comment applies to a possible calculation of $\bar{N}N$ annihilation into two photons [24].

In addition to the $e^+e^- \to, \bar{N}N$, one can also carry out an analogous analysis for $e^+e^- \to \bar{\Delta}\Delta$. The relative yields of Δ^{++}, Δ^+, Δ^0 and Δ^- will be determined by the relevant Clebsch-Gordan coefficients [26] and by the corresponding reduced matrix elements for isospin 1 and 0. We do not know the precise values of these reduced matrix elements, but even without this information, from the Clebsch-Gordan decomposition we expect

$$BR(\Delta^{++}) = BR(\Delta^-)$$

and

$$BR(\Delta^+) = BR(\Delta^0) \tag{7}$$

as opposed to the perturbative prediction (4).

Eqs. (7) hold also for $\gamma\gamma \to \bar{\Delta}\Delta$, since $|{I_3}^{\Delta^{++}}| = |{I_3}^{\Delta^-}|$, etc., to be contrasted with the perturbative prediction (5). It would be very interesting to put this to an experimental test!

3.2. Time scales of strong versus EM interactions

It is not enough to propose a mechanism which can explain the equality of the observed $\bar{p}p$ and $\bar{n}n$ rates. We also have to explain why the proposed mechanism dominates over the standard one. After all, the reaction can in principle still proceed via the usual naive perturbative mechanism, where quarks couple directly to the virtual photon, like in Figure 1, and where the $\sigma(\bar{p}p)/\sigma(\bar{n}n) = 3/2$. Thus a crucial question is why $\bar{p}p \to e^+e^-$ or $\bar{p}p \to e^+e^-$ proceed via intermediate hadronic states, rather than via direct EM annihilation. In order to answer this question, it is helpful to consider the relevant time scales.

Consider $\bar{p}p$ on top of each other at rest. The QCD annihilation occurs at a typical time scale of strong interactions, that is, $\sim 10^{-24}$ sec. This is much shorter than a typical time scale for EM interactions, so that the "direct" QED process, where $\bar{q}q$ in the $\bar{p}p$ annihilate into a virtual photon simply has no chance of occurring: QED here is a "Johnny come lately" who cannot compete with the QCD rate.

QED enters only at the second stage, where the mesonic "soup" has a (small) chance of going into a virtual photon. But here we are concerned with the *relative* rate of $\bar{p}p$ versus $\bar{n}n$, so the overall smallness of the QED process pions $\to e^+e^-$ is not a priori a problem.

3.3. A more realistic intermediate state

The two-pion intermediate state is of course only a toy model which is helpful in understanding the qualitative features of the reaction. In order to obtain a more realistic description, we need to put in a more realistic intermediate state. The first improvement would be to include intermediate states with n pions, where n goes over all allowed values,

$$\sigma(\bar{p}p \to e^+e^-) \sim \left| \sum_n \langle \bar{p}p|n\pi\rangle\langle n\pi|e^+e^-\rangle. \right|^2 \tag{8}$$

In principle one could compute the $\bar{p}p \to n\pi$ rates using the methods of [23]. It is not clear how to obtain the relative phases for different values of n, but if one of the intermediate states dominates, this problem will not be of practical significance.

A more sophisticated treatment will involve summing over all allowed intermediate states, not just the $n-\pi$ states. In principle this could be done by combining the low-energy $e^+e^- \to$ hadrons data with the corresponding data for $\bar{N}N$ annihilation at rest. One would then sum them channel by channel. There are very precise data from LEAR for $\bar{N}N$ annihilation at rest and there are also good data for $e^+e^- \to$ hadrons. Recently the VEPP-2M collider at Novosibirsk provided highly accurate e^+e^- data for $E_CM < 1.4$ GeV [27], with excellent finite state resolution, as shown in Figure 6.

This energy range is below what we need, but it shows the expected richness of the data. If similar data can be obtained for $E_{CM} \gtrsim 2$ GeV, they could be combined with the LEAR data to provide an estimate of the $\bar{p}p \to e^+e^-$ rate through our mechanism.

Again, one remaining difficulty is the issue of relative phases, but as already mentioned, if the intermediate state is dominated by one particular channel, the phase issue will not be of practical significance.

3.4. A caveat

Clearly, what is presented here is merely a sketch of the proposed calculation, and in order to convince oneself that it correctly describes the physics, one should actually put in the rates for the relevant intermediate processes, in order to provide a theoretical estimate which can be compared with the measured rate for $e^+e^- \to \bar{p}p$ or $e^+e^- \to \bar{n}n$.

4. ACKNOWLEDGEMENTS

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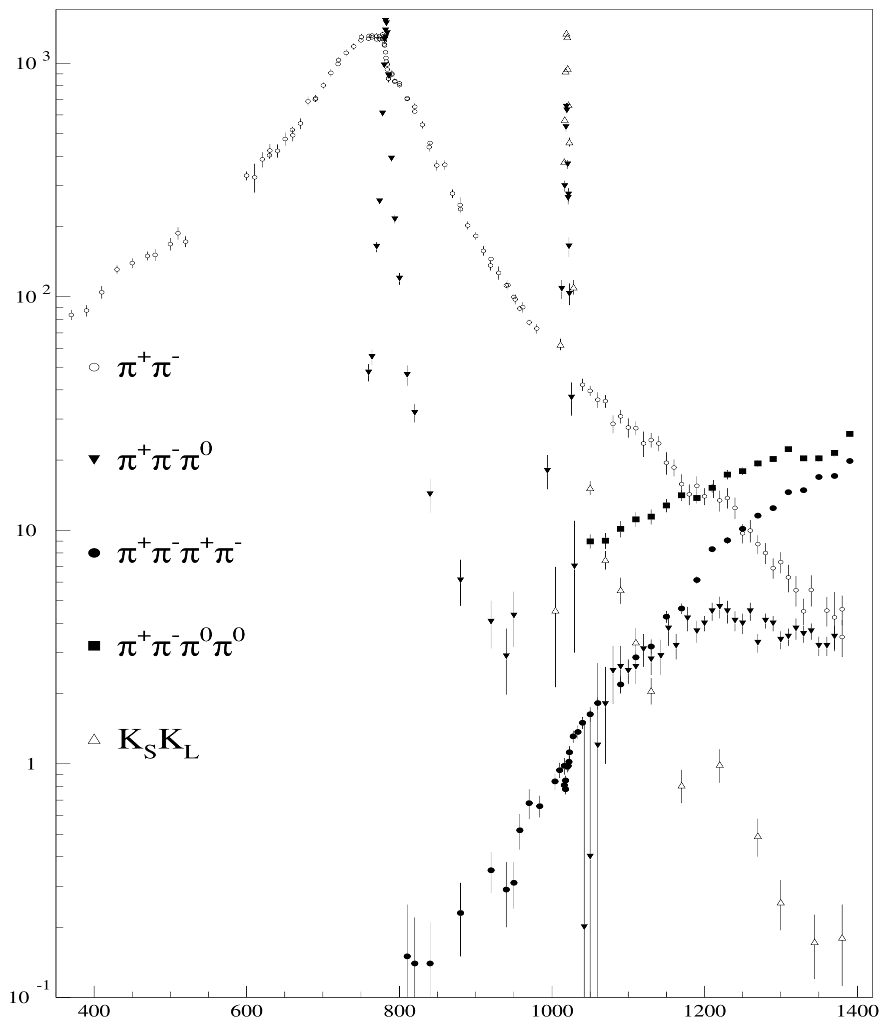

Figure 6: $e^+e^- \to$ hadrons for $E_{CM} < 1400$ MeV; recent data from Novosibirsk VEPP-2M collider [27].

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[27] A. Bondar, private communication; see also scanned transparencies from a talk by A. Bondar at ICHEP-2000 in Osaka, `http://ichep2000.hep.sci.osaka-u.ac.jp/scan/0728/pa01/bondar/index.html`