New vector state near the $\bar{N}N$ threshold

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The coupled-channel model is used to describe experimental data which confirm the earlier prediction that a minimum could appear on the cross section for multipion e^+e^- annihilation near the $\bar{N}N$ threshold. Analysis of an irregularity which is observed points to the existence of a narrow vector state which corresponds to the $2^{33}S_1$ state in a system with a mass of about 1800 MeV and a width on the order of 15 MeV.

Experimental data recently obtained on the e^+e^- interaction in the mass region 1.5–2 GeV indicate that there is structure in the cross section for multipion e^+e^- annihilation near the $\bar{N}N$ threshold.[1] The well-expressed minimum seen experimentally in the cross section for the reaction $e^+e^- \to 2\pi^+2\pi^-2\pi^0$(Fig. 1) coincides approximately with the mass of two nucleons. The possible existence of such a structure, due to the proximity of the $\bar{N}N$ channel, had been predicted previously.[2] In the present letter we work from some very general considerations regarding the strong attraction between $\bar{N}$ and N, combined with the short-range nature of the annihilation, to show that the energy dependence of the cross section for the process $e^+e^- \to$ hadrons may be nonmonotonic. The predicted effect should be observable in multipion modes corresponding to the primary channels for $\bar{N}N$ annihilation.

The annihilation $e^+e^- \to$ hadrons near the $\bar{N}N$ threshold was studied in Ref. 2 as a coupled-channel problem: e^+e^-,$\bar{N}N$, and $n\pi$. This process can be represented graphically by the Feynman diagram in Fig. 2. The reaction amplitude corresponding to diagram a is proportional to the transition amplitude

$$M \sim \langle T_0 \mid G_{\bar{N}N} \mid V_{Nh} \rangle, \tag{1}$$

where $G_{\bar{N}N}$ is the complete Green's function of the $\bar{N}N$ system (the hatched rectangle in Fig. 2a), T_0 is the amplitude for the annihilation $e^+e^- \to \bar{N}N$ (without consideration of the $\bar{N}N$ interaction in the final state), and V_{Nh} is a short-range potential which couples the $\bar{N}N$ and $n\pi$ channels. The diagram in Fig. 2b incorporates a nonpotential contribution to the annihilation $e^+e^- \to n\pi$ and is a background process. Making use of the short-range nature of T_0 and V_{Nh}, we can rewrite (1) expression (1) for the amplitude M as

$$M \sim -\frac{|\varphi(0)|^2}{|\epsilon_b| + \epsilon + i\eta} + \int \frac{dk\,|\varphi_k(0)|^2}{(k^2/m) - \epsilon - i\eta}, \tag{2}$$

where $\varphi_k(r)$ and $\varphi(r)$ are the wave functions of the continuous and discrete spectra of the potential $V_{\bar{N}N}$ ϵ_b is the binding energy of the $\bar{N}N$ level which arises from the strong attraction between $\bar{N}$ and N (the potential $V_{\bar{N}N}$ is deep enough for the appearance of a

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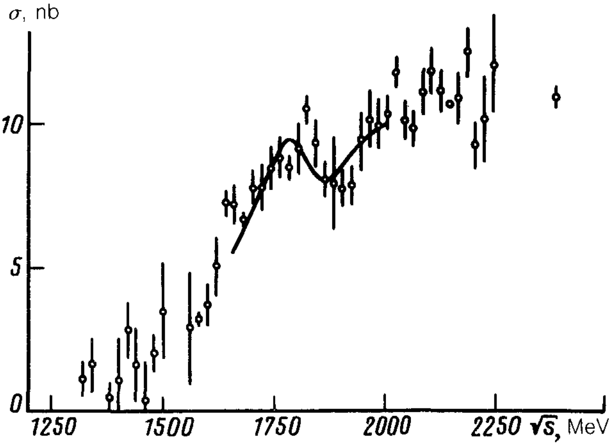

FIG. 1. The annihilation $e^+e^- \to 2\pi^+2\pi^-2\pi^0$ in the mass region 1.4–2 GeV. The experimental data are from Ref. 1; the solid curve is theoretical.

bound state), and $\epsilon = \sqrt{s'} - 2m$ is the $\overline{N}N$ kinetic energy in the c.m. frame. It is not difficult to see that the integral over the continuous spectrum in (2) is positive if $\epsilon < 0$, while the contribution of the pole corresponding to the bound state changes sign at the point $\epsilon = -|\epsilon_b|$. At a certain point in the region $-|\epsilon_b| < \epsilon < 0$ there can thus be an exact cancellation of these terms, i.e., the appearance of a zero in the Green's function in the corresponding brackets. The effect will be a vanishing of the amplitude for the annihilation $e^+e^- \to n\pi$ without the background (the exact position of the zero obviously depends on the relative importance of the pole term and of the integral over the continuous spectrum). In the region $\epsilon < -|\epsilon_b|$ we can expect the annihilation cross section to grow as a result of a constructive interference of the two terms in (2). Model calculations carried out in Ref. 2 have confirmed these qualitative arguments and have furthermore shown that the actual behavior of the cross section for $e^+e^- \to$ hadrons depends on the relative phase of the background amplitude.

In the present letter we analyze the $e^+e^- \to n\pi$ annihilation near the $\overline{N}N$ threshold in the realistic coupled-channel model which has been used previously[3] to describe the existing data on the near-threshold $\overline{N}N$ interaction and which agrees within 10–15% with experimental data. The coupling of the $\overline{N}N$ and e^+e^- channels is achieved by means of the δ-function potential $V_0\delta(r)$; there is no direct coupling of the e^+e^- and $n\pi$ channels; i.e., the e^+e^- channels and annihilation channel $n\pi$ are coupled with each other only through the $\overline{N}N$ channel (see the diagram in Fig. 2a). We assigned V_0

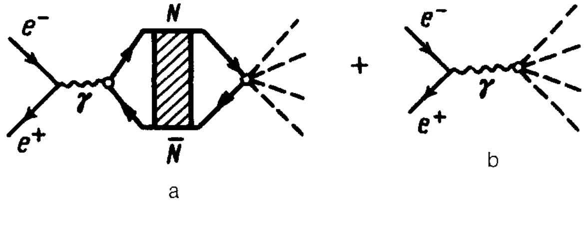

FIG. 2. Feynman diagrams for the annihilation $e^+e^- \to n\pi$.

the same value as in the calculation of the electromagnetic form factor of the nucleon near the $\overline{N}N$ threshold in this model[4] (the magnitude and behavior of the electromagnetic form factor of the proton, which were found in Ref. 4, agree well with the data of Ref. 5). The amplitude for the process $e^+e^- \to 2\pi^+2\pi^-2\pi^0$ is written in the form

$$M(e^+e^- \to n\pi) = M + M_b, \tag{3}$$

where M is the amplitude calculated in the coupled-channel model, and M_b is the background amplitude, which corresponds to the direct annihilation $e^+e^- \to 2\pi^+2\pi^-2\pi^0$ (the diagram in Fig. 2b). The background amplitude was approximated by a smooth polynominal function and was normalized at the point $\sqrt{S} = 2$ GeV, where the contribution of M is small. We introduced a factor of $(s/4m^2)^2$ in the calculated amplitude M in order to allow for the dependence of the probability for the six-pion annihilation on the mass of the annihilating $\overline{N}N$ system. We chose the relative phase of the amplitudes by fitting the experimental data; we found $\varphi = -\pi/4$.

The results of the calculations are shown in Fig. 1 (the solid curve). We see that the exact calculation in the realistic model confirms the basic qualitative behavior which we mentioned above. The annihilation $e^+e^- \to 2\pi^+2\pi^-2\pi^0$ can go only through the $^{33}S_1$ states of the $\overline{N}N$ system (with a spin and isospin of 1). This conclusion follows from the definite G-parity ($G = +1$) and the restriction to the S-wave (by virtue of the short-range nature of the δ-function potential for $e^+e^- \to \overline{N}N$). A study of the spectrum in the $^{33}S_1$ state showed that in this wave there is indeed a level with a binding energy $|\epsilon_b| \approx 90$ MeV and a width of 15 MeV, which corresponds to a node state $2^{33}S_1$ in the $\overline{N}N$ system. Such a level should be manifested as a rather narrow vector meson ($J^{PC} = 1^{--}$) with a mass of 1790 MeV. We should stress that because of the particular nature (the zero of the Green's function) of the structure observed in $e^+e^- \to 2\pi^+2\pi^-2\pi^0$, the existence of such a narrow level causes the appearance of a wide anomaly, which would simulate a resonant behavior.

The narrow vector meson which has been predicted can be observed directly in experiments on the annihilation $\bar{p}d \to N_S + 2\pi^+2\pi^-2\pi$, where N_S is a spectator nucleon. Gary *et al.*[6] found an indication of the existence of a meson state with a mass of 1794 MeV and a width < 15 MeV in the six-pion annihilation mode in $\bar{p}d$ annihilation (see also Ref. 7). Another approach to an experimental observation might be to study the γ spectrum in $\bar{p}p$ annihilation at rest in experiments with a gaseous hydrogen target. In this case the $\bar{p}p$ annihilation (due to the suppression of the Stark effect) occurs from P-states of protonium, and the branching ratio for the $E1$ transition from the $2P$ state of the $\bar{p}p$ atom to the predicted $2^{33}S_1$ nuclear state of the $\overline{N}N$ system would be on the order of 10^{-2}–10^{-3}—completely accessible in the experiments planned for the LEAR antiproton storage ring.

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