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QUANTUM NUMBERS AND TOTAL AND PARTIAL WIDTHS OF THE RESONANCE $N\bar{N}(1970)$

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We have previously considered [1] the resonant states in the nucleon-antinucleon system. A characteristic feature of these resonances is the large partial width of the decay through the nucleon-antinucleon channel. Calculations show that for resonances consisting of a nucleon and an antinucleon, the partial width $\Gamma_{N\bar{N}}$ is of the same order of magnitude as the total width Γ [1]. For mesons of a different nature, in the same mass region, the $N\bar{N}$ channel is not singled out in any way, and estimates based on the statistical theory yield $\Gamma_{N\bar{N}}/\Gamma \sim 0.1 - 1\%$.

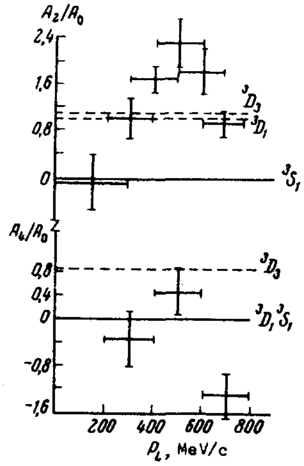
In the present paper, on the basis of experimental data, we estimate the ratio $\Gamma_{N\bar{N}}/\Gamma$ for the meson $N\bar{N}(1970)$. This meson was observed in two independent experiments: in the reaction

$$\bar{p}p \to K_S^0 K_L^0 \tag{1}$$

and in elastic backward $\bar{p}p$ scattering [2, 3]. In [2] they investigated the cross section of reaction (1) and the angular distribution of $K_S^0K_L^0$ at an incident-antiproton momentum lower than 800 MeV/c. The final state of $K_S^0K_L^0$ has negative C-parity (accurate to CP-violation, which is immaterial here). In the investigated region of incident antiproton momenta, the main contribution to the cross section of process (1) is made by the initial states of the $\bar{p}p$ system with orbital angular momentum ℓ not larger than two [4]. From C- and P-parity conservation it follows that at $\ell \leq 2$ only the $^3S_1$, $^3D_1$, and $^3D_3$ states of the $\bar{p}p$ system can participate in the reaction (1).

As was established in [2], the cross section of the process (1) has a clearly pronounced resonant character with a maximum in the 600 MeV/c region, corresponding to a resonance mass equal to 1970 MeV. The maximum value of the cross section in the resonant region exceeds by 3 - 4 times the background level. Therefore the cross section σ of reaction (1) can be represented in the form of an incoherent superposition of the smooth background σ^0 and the Briet-Wigner resonance. At resonance we obtain the following expression for the sought ratio $\Gamma_{N\bar{N}}/\Gamma$:

$$\frac{\Gamma_{N\bar{N}}}{\Gamma} = \left(\frac{\Gamma}{\Gamma_{K_S K_L}}\right)\frac{(\sigma - \sigma_0)p^2}{\pi(2l + 1)} , \tag{2}$$



Coefficient ratios A_2/A_0 and A_4/A_0 obtained from an analysis of the angular distributions of $K_S^0K_L^0$ in the reaction (1). The dashed lines correspond to pure $^3S_1$, $^3D_1$, and $^3D_3$ states of the $\bar{p}p$ system.

where I is the spin of the resonance.

The experimental value of $(\sigma - \sigma_0)$ is 75 ± 20 μV. The ratio $\Gamma_{K_SK_L}/\Gamma$ at the energy of interest to us is unknown. However, for antiprotons "at rest" this ratio has been measured and amounts to $(0.61 \pm 0.09) \times 10^{-3}$ [5]. From this we find in accordance with formula (2) that $\Gamma_{N\bar{N}}/\Gamma = 1.2 \pm 0.4$ for the $^3D_3$ state and $\Gamma_{N\bar{N}}/\Gamma = 2.7 \pm 0.8$ for the $^3D_1$ and $^3S_1$ states. We note that the same ratio of $\Gamma_{K_SK_L}/\Gamma$ is obtained from the following considerations: It is known [6] that in a wide energy interval the cross section of the annihilation $\bar{p}p \to \pi^+\pi^-$ is approximately three times larger than the cross section of the annihilation $\bar{p}p \to \bar{K}K$. At an antiproton momentum 600 MeV/c, the cross section of annihilation into $\pi^+\pi^-$ amounts to 300 μV [7], and the total cross section of the $\bar{p}p$ interaction is σ_{tot} = 150 μV [8]. Thus, for $\Gamma_{K_SK_L}/\Gamma$ we obtain an estimate that coincides with the one given above. Finally, we can estimate $\Gamma_{K_SK_L}/\Gamma$ also directly from the data of the discussed experiment, if we assume beforehand that the process proceeds via formation of a resonant state in the nucleon-antinucleon system. The decay width of such a resonance via the $K_S^0K_L^0$ channel can be estimated from the formula [1]:

$$\Gamma_{K_SK_L} = (v\sigma_{K_SK_L})\overline{|\psi(0)|^2}, \tag{3}$$

where v is the relative velocity of the proton and the antiproton, $\sigma_{K_SK_L}$ is the cross section of the annihilation $\bar{p}p \to K_S^0K_L^0$, and $|\psi(0)|^2$ is the average particle density in the annihilation region. In such a model it is necessary to take $\sigma_{K_SK_L}$ in the form of the nonresonant background part of the cross section, equal to 25 ± 10 μV. The total width is determined by an analogous formula:

$$\Gamma = (v\sigma_{tot})\overline{|\psi(0)|^2}, \tag{4}$$

where σ_{tot} is the total cross section of the $\bar{p}p$ interaction in a state with quantum numbers corresponding to the given resonance. There is no phase shift analysis of the $\bar{p}p$ interaction, and only the total cross section σ_{tot} = 150 ± 5 mV is known [8] for the states with all possible quantum numbers. Using this value, we obtain from formulas (3) and (4) an estimate, known to be high, viz., $\Gamma_{N\bar{N}}/\Gamma = 4 \pm 2$ for the $^3D_3$ state and $\Gamma_{N\bar{N}}/\Gamma = 10 \pm 4$ for $^3D_1$ and $^3S_1$.

Benvenuti et al. [2] assign to the observed resonance the quantum numbers $I^{PC} = 1^{--}$, assuming it to be a resonance of the $^3S_1$ and $^3D_1$ states. The estimates given above give more weighty reasons for assuming this resonance to be a $^3D_3$ state with quantum numbers $I^{PC} = 3^{--}$. This conclusion is arrived also from an analysis of the $K_S^0K_L^0$ angular distribution. The figure shows the coefficient ratios A_2/A_0 and A_4/A_0 in the Legendre-polynomial expansion of the differential cross section as a function of the incoming-antiproton momentum. The horizontal lines correspond to the pure initial states $^3S_1$, $^3D_1$, and $^3D_3$. For the $^3S_1$ state we have $A_2 = A_4 = 0$, for $^3D_1$ we have $A_2/A_0 = 1$ and $A_4/A_0 = 0$, and for $^3D_3$ we have $A_2/A_0 = 8/7$ and $A_4/A_0 = 6/7$. The coefficient A_6 is equal to zero both in experiment and for all three states $^3S_1$, $^3D_1$, and $^3D_3$. Owing to the large experimental errors, and also because of the impossibility of taking the superposition effects into account, it is difficult to make a unique choice between the states $^3S_1$, $^3D_1$, and $^3D_3$. However, preference must be given to the state $^3D_3$, especially if it is recognized that the estimates obtained for $\Gamma_{N\bar{N}}/\Gamma$ of this state are more reasonable.

The resonance $N\bar{N}(1970)$ appears also in backward $\bar{p}p$ elastic scattering [3]. In [3] is given, in particular, the cross section of $\bar{p}p$ scattering in the angle interval $-1 < \cos\theta < -0.8$, where θ is the scattering angle in the c.m.s. The cross section reveals several peaks, one of which corresponds to 1970 MeV. If it is assumed that the cross section is pure Breit-Wigner, then we get for the $\Gamma_{N\bar{N}}/\Gamma$ ratio

$$\frac{\Gamma_{N\bar{N}}}{\Gamma} = \sqrt{\frac{p^2 \sigma_{N\bar{N}}}{\pi(2l+1)}} \ . \tag{5}$$

The total cross section $\sigma_{N\bar{N}}$ can be determined from the experimental value of the cross section $\Delta\sigma_{N\bar{N}}$ in the angle interval $-1 < \cos\theta < -0.8$, in the following manner. The quantity $\Delta\sigma_{N\bar{N}}$ is connected with the differential cross section by the formula

$$\Delta\sigma_{N\bar{N}} = \int_{\Delta\Omega} \frac{d\sigma_{N\bar{N}}}{d\Omega} d\Omega = 2\pi \int_{-1}^{-0.8} \frac{d\sigma_{N\bar{N}}}{dx} dx, \tag{6}$$

where $x = \cos\theta$. On the other hand, $d\sigma_{N\bar{N}}/dx$ can be represented in the form

$$\frac{d\sigma_{N\bar{N}}}{dx} = \sum_L A_L \mathcal{P}_L(x) = A_0 \left\{ 1 + \sum_{L>0} \frac{A_L}{A_0} \mathcal{P}_L(x) \right\} \ . \tag{7}$$

For the state $^3S_1$, only the coefficient A_0 differs from zero; $A_2/A_0 = 1/2$ for $^3D_1$ and $A_2/A_0 = 48/49$ and $A_4/A_0 = 22/49$ for $^3D_3$. The common coefficient A_0 is obtained by substituting (7) in (6). The total cross section $\sigma_{N\bar{N}}$ is equal to $4\pi A_0$. For $^3S_1$ we have $\sigma_{N\bar{N}} = 8 \pm 2$ mV and $\Gamma_{N\bar{N}}/\Gamma = 0.8 \pm 0.1$; for $^3D_1$ we have $\sigma_{N\bar{N}} = 6 \pm 2$ mV and $\Gamma_{N\bar{N}}/\Gamma = 0.4 \pm 0.1$; for $^3D_3$ we have $\sigma_{N\bar{N}} = 4.4 \pm 1$ mV and $\Gamma_{N\bar{N}}/\Gamma = 0.22 \pm 0.05$. The cross sections $\sigma_{N\bar{N}}$ corresponding to the resonance have the same order of magnitude (5 - 10 mV) as the errors in the determination of the total cross section of the $\bar{p}p$ interaction [8]. Therefore this resonance is not observed in the total cross section. In [3] there is given also the cross section for scattering in the angle interval $-0.2 < \cos\theta < 0$. It follows from experiment that the cross section ratio in the intervals $-1 < \cos\theta < -0.8$ and $-0.2 < \cos\theta < 0$ amounts to 2 ± 1. When this ratio is determined by the method described above, the result is unity for the $^3S_1$ state, 1.8 for $^3D_1$, and 2.7 for $^3D_3$.

The foregoing estimates of $\Gamma_{N\bar{N}}/\Gamma$, which turns out to be close to unity in order of magnitude, allow us to conclude that the $N\bar{N}(1970)$ meson is a resonant state in the nucleon-antinucleon system.

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INTERPRETATION OF EXPERIMENTS ON THE SEARCHES FOR THE $K_S \to 2\mu$ DECAY

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In connection with the contradiction between the results of experiments on the decays $K_L \to 2\mu$ [1] and $K_L \to 2\gamma$ [2], a hypothesis was advanced [3, 4], according to which the suppression of the $K_L \to 2\mu$ decay is due to destructive interference of the $K_2 \to 2\mu$ and $K_1 \to 2\mu$ transitions. The width of the $K_S \to 2\mu$ decay should in this case be relatively large [4]. $\Gamma_S^\mu \geq 1.7 \times 10^{-7}\Gamma_S$. As is implied in [4] and discussed explicitly in [5], this lower limit is attainable only in the presence of a strong $2\pi - 2\mu$ interaction. We shall discuss below the possibility that this interaction is CP-noninvariant and analyze the limitations imposed on the width of the $K_S \to 2\mu$ decay under different hypotheses concerning the anomalous interactions of muons, photons, and pions.

We assume in accordance with the experiments of [1, 2] and with the definitions of Γ and T [3, 4] that

$$\Gamma_L^\mu = |T_2^{\mu+} + \epsilon T_S^{\mu+}|^2 + |T_2^{\mu-} + \epsilon T_S^{\mu-}|^2 \leqslant \bar{\Gamma}_L^\mu = 1.8 \cdot 10^{-9}\Gamma_L, \quad (1)$$

$$\Gamma_L^\gamma = |T_2^{\gamma+} + \epsilon T_S^{\gamma+}|^2 + |T_2^{\gamma-} + \epsilon T_S^{\gamma-}|^2 = 5 \cdot 10^{-4}\Gamma_L. \quad (2)$$

The indices L and S pertain to K_L and K_S, the indices 1 and 2 to K_1 and K_2, and the indices μ and γ to the states 2μ and 2γ, while ± stands for CP = +1 and -1, respectively:

$$K_{L,S} = K_{2,1} + \epsilon K_{1,2},$$
$$\epsilon = |\epsilon| e^{i\phi_\epsilon} \approx 2 \cdot 10^{-3} e^{i45^\circ}.$$

Let us consider a few possibilities.

1) Let the $K_L \to 2\gamma$ decay be CP-invariant: $T_2^{\gamma+} = T_2^{\mu+} = 0$. Then $|\mathrm{Im}\, T_2|^2 = 1.2 \times 10^{-5}\Gamma_L^\gamma = 6 \times 10^{-9}\Gamma_L$ [4], and it follows from (1) that [3, 4]

$$\Gamma_S^\mu \geqslant |T_S^{\mu-}|^2 \geqslant (\sqrt{1.2 \cdot 10^{-5}\Gamma_L^\gamma} - \sqrt{\bar{\Gamma}_L^\mu})^2 / |\epsilon|^2 \cos^2(\phi_\epsilon + \phi_S^{\mu-}), \quad (3)$$