Remark concerning the $f_0(1370)$ and $f_0(1520)$ scalar resonances observed in $\bar{N}N$ annihilation reactions at rest

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It is shown that 1) to describe the $(4\pi)^0$ mass spectra in the reactions $\bar{N}N\to(4\pi)^0\pi$ taking into account the energy dependence of the total width f_0 of the resonance, the mass of the resonance cannot be equal to 1370 MeV but rather it must lie above 1500 MeV; 2) these spectra are found to be virtually insensitive to high values of the mass of the f_0 resonance; and 3) the spectra also admit a nonresonance interpretation. Attention is focused on the possible relation between the heavy f_0 resonance, which predominates in the $(4\pi)^0$ channel, and the $f_0(1520)$ state observed in the reactions $\bar{N}N\to3\pi$ and $\bar{N}N\to2\eta\pi$. The results obtained show that the existing analyses of the data on the reactions $\bar{N}N\to(4\pi)^0\pi$ must be reexamined. © *1995 American Institute of Physics.*

In the last few years new resonance structures, not yet observed in other reactions, have been detected and investigated in the two- and four-particle mass spectra of the nucleon-antinucleon annihilation reactions at rest[1-14] $\bar{N}N\to3\pi$, $5\pi,\eta\eta\pi,\eta\pi\pi$, and $\eta\eta'\pi$. The history of some of them turned out to be very dramatic.[8-13] For example, the first resonances $AX(1565, I^GJ^P=0^+2^+)\to\pi\pi$ (Refs. 1 and 2) and $\zeta(1480, I^GJ^P=0^+2^+)\to\rho\rho$ (Ref. 4) gradually transformed from tensor into scalar resonances.[8-13] Today the situation can be briefly summarized as follows. In the reactions $\bar{p}n\to3\pi^-2\pi^+$ (Ref. 8), $\bar{n}p\to3\pi^+2\pi^-$ (Ref. 9), and $\bar{p}p\to\pi^+\pi^-3\pi^0$ (Ref. 10) the production of the intermediate state X with $I^GJ^P=0^+0^+$, mass in the range 1330–1400 MeV, and width 300–400 MeV predominates:[11] $\bar{N}N\to X\pi\to(4\pi)^0\pi$. The decay $X\to4\pi$ is the main reaction (>80%) which proceeds according to the scheme[8-13] $X\to\rho\rho+\sigma\sigma\to4\pi$. Following Ref. 12 , we shall call this state $f_0(1370)$. It is believed that the rare decays of this resonance $f_0(1370)\to\pi^0\pi^0$ and $f_0(1370)\to\eta\eta$ are observed in the region 1400 MeV in the reactions[11-13] $\bar{p}p\to\pi^0\pi^0\pi^0$ and $\bar{p}p\to\eta\eta\pi^0$. Moreover, one other state is observed in the reactions $\bar{p}p\to\pi^0\pi^0\pi^0$, $\bar{p}p\to\eta\eta\pi^0$, and $\bar{p}p\to\eta\eta'\pi^0$: $f_0(1520)\to\pi^0\pi^0$, $\eta\eta$, $\eta\eta'$ with $I^GJ^P=0^+0^+$ and width 100–250 MeV.[6,7,11-14] The ratios of the probabilities for the decays in different channels for the resonances $f_0(1370)$ and $f_0(1520)$ have still not been determined very accurately: For $f_0(1370)$ $4\pi(\rho\rho+\sigma\sigma)/\pi\pi/\eta\eta/K\bar{K}\approx10/1/1/?$ from Ref. 12, $4\pi/\pi\pi\approx5/1$ from Ref. 13. For $f_0(1520)$ $\pi^0\pi^0/\eta\eta/\eta\eta'\approx1/0.72/1.05$ (±0.25) from Ref. 12, $\pi\pi/\eta\eta\approx5/1$ from Ref. 13, $\eta\eta'/\eta\eta<0.29$ from Ref. 7 . In order for $f_0(1520)$ to be unobservable in the elastic $\pi\pi$ scattering,[13] it must decay with a high probability in some other channels [i.e., it must be strongly inelastic, just as[12,13] $f_0(1370)$]. If this channel were 4π, then $f_0(1520)$ would be seen in the reactions $\bar{N}N\rightarrow f_0(1520)\pi\rightarrow(4\pi)^0\pi$. It is now assumed, however, that such a signal is not present in the existing data.[8-12]

In all the evaluations of data on the $\bar{N}N\rightarrow f_0(1370)\pi\rightarrow(4\pi)^0\pi$ reactions known to us,[8-10] it was assumed that the total width of the f_0 resonance appearing in the denominator of its Breit–Wigner propagator does not depend on the energy. Ignoring the complications arising when the identity of the pions in the final state is taken into account, the formula which was actually employed in Refs. 8 –10 to describe the resonance four-pion mass spectra in the reactions $\bar{N}N\rightarrow f_0\pi\rightarrow(4\pi)^0\pi$ can be written in the form

$$\frac{dN_{4\pi}}{dm}=C\rho(\sqrt{s},m,m_\pi)\frac{2m}{\pi}\left(\frac{m\Gamma_{f_0\rightarrow4\pi}(m)}{(m_{f_0}^2-m^2)^2+(m_{f_0}\Gamma_{f_0}^{\rm tot})^2}\right), \tag{1}$$

where $m=m_{4\pi}$, $\rho(\sqrt{s},\ m,\ m_\pi)=[(1-((m-m_\pi)/\sqrt{s})^2)(1-((m+m_\pi)/\sqrt{s})^2]^{1/2}$, $s=4m_N^2$, and $\Gamma_{f_0}^{\rm tot}$ is the total width of the f_0 resonance. In Refs. 8 –10 models with intermediate states $\rho\rho$ and $\sigma\sigma$ were constructed for the width of the decay $f_0\rightarrow4\pi$. The function $m\Gamma_{f_0\rightarrow4\pi}(m)$ in the numerator of Eq. (1) was found to increase by a factor of 10 as m changed from 1200 to 1740 MeV. In the annihilation processes $\bar{N}N\rightarrow(4\pi)^0\pi$ at rest the resonance enhancement under discussion in the $(4\pi)^0$ mass spectra has a visible maximum at $m\approx1500$ MeV and is concentrated nearly completely in the interval[8-10] $1200<m<1740$ MeV. An appreciable shift of the maximum of the Breit–Wigner distribution from the point $m=m_{f_0}$ in the region of large masses occurs because of the strong growth of $m\Gamma_{f_0\rightarrow4\pi}(m)$ in Eq. (1). Expression (1) therefore reproduces well the experimentally observed spectra with m_{f_0} in the region[8-10] 1330–1400 MeV. Despite the good description of the data, however, expression (1) with a constant total width $\Gamma_{f_0}^{\rm tot}$ and the value obtained for m_{f_0} using it do not seem to us to be adequately justified. Since the decay $f_0\rightarrow4\pi$ is the main process,[8-13] the total width of the f_0 resonance, in accordance with the unitarity condition, must depend on the energy virtually in the same manner as $\Gamma_{f_0\rightarrow4\pi}(m)$. In Eq. (1) we replace $m_{f_0}\Gamma_{f_0}^{\rm tot}$ by $m\Gamma_{f_0}^{\rm tot}(m)=m\Gamma_{f_0\rightarrow4\pi}(m)+m_{f_0}\Gamma_{f_0\rightarrow\rm others}$, where $\Gamma_{f_0\rightarrow\rm others}$ is the width of the decay f_0 into $\pi\pi,\eta\eta$, etc., i.e., into all other channels except for the main four-pion channel. The width $\Gamma_{f_0\rightarrow\rm others}$ can be regarded as constant against the background of the large and rapidly varying contribution from $\Gamma_{f_0\rightarrow4\pi}(m)$. To estimate it, we assume that the ratio $N_{4\pi}/N_{\rm others}\approx5/1$ [where $N_{4\pi}$ and $N_{\rm others}$ are the numbers of events in the reactions $\bar{N}N\rightarrow f_0\pi\rightarrow(4\pi)^0\pi$ and $\bar{N}N\rightarrow f_0\pi\rightarrow(\text{others})^0\pi$]. For the energy dependence of the width of the decay $f_0\rightarrow4\pi$ we shall consider the two limiting cases

$$m\Gamma_{f_0\rightarrow4\pi}(m)=\frac{G^2}{16\pi}R(m)$$

$$=\frac{G^2}{16\pi}\int_{4m_\pi^2}^{(m-2m_\pi)^2}dm_1^2\int_{4m_\pi^2}^{(m-m_1)^2}dm_2^2F(m_1)F(m_2)\rho(m,m_1,m_2),$$

where $\rho(m, m_1, m_2)=[(1-((m_1-m_2)/m)^2)(1-((m_1+m_2)/m)^2]^{1/2}$, and the functions $F(m_1)$ and $F(m_2)$ describe, respectively, the mass spectra of the systems $(2\pi)_1$ and $(2\pi)_2$ in the decay $f_0 \to (2\pi)_1(2\pi)_2$. In case I (model of a $\rho\rho$ intermediate state, $f_0 \to \rho\rho \to 4\pi$) we have $G=g_{f_0\rho\rho}$, $F(m_i)=(m_i\Gamma_\rho(m_i)/\pi)/[(m_\rho^2-m_i^2)^2+(m_i\Gamma_\rho(m_i))^2]$, where

$$\Gamma_\rho(m_i)=\Gamma_\rho(m_\rho)\frac{m_\rho}{m_i}\left(\frac{q(m_i)}{q(m_\rho)}\right)^3 \frac{2q^2(m_\rho)}{q^2(m_\rho)+q^2(m_i)}, \quad q(m_i)=\frac{1}{2}\sqrt{m_i^2-4m_\pi^2},$$

$i=1,2$. The function $m\Gamma_{f_0\to 4\pi}(m)$ in the interval $1200<m<1740$ MeV increases by two orders of magnitude as m increases. In case II (model of point decay $f_0 \to 4\pi$) we have $G=\tilde{g}_{f_0 4\pi}$, $F(m_i)=\sqrt{\pi^3/8}\times\sqrt{1-4m_\pi^2/m_i^2}$ and the function $m\Gamma_{f_0\to 4\pi}(m)$ in the interval $1200<m<1740$ MeV increases by a factor of 8 as m increases. All models of the decay $f_0 \to 4\pi$ through the $\rho\rho+\sigma\sigma$ intermediate state, which were studied in Refs. 8 –10 , lead to m dependences of $m\Gamma_{f_0\to 4\pi}(m)$ which fall between the limiting cases indicated above. For the mass spectrum $dN_{4\pi}/dm$ we shall therefore analyze an expression with an energy-dependent total width

$$\frac{dN_{4\pi}}{dm}=C\rho(\sqrt{s},m,m_\pi)\frac{2m}{\pi}\left(\frac{m\Gamma_{f_0\to 4\pi}(m)}{(m_{f_0}^2-m^2)^2+(m\Gamma_{f_0}^{\mathrm{tot}}(m))^2}\right). \tag{2}$$

The difference in Eqs. (1) and (2) is that additional suppression of the right-hand wing of the Breit–Wigner distribution appears in the case where $m\Gamma_{f_0}^{\mathrm{tot}}(m)$ in Eq. (2) increases appreciably. This makes it impossible to obtain a peak in the region of 1500 MeV at $m_{f_0} \approx 1370$ MeV, as was the case in Refs. 8–10 using expression (1) with a constant $\Gamma_{f_0}^{\mathrm{tot}}$. An enhancement concentrated in the interval 1200–1740 MeV with a peak near 1500 MeV can be obtained in $dN_{4\pi}/dm$ with the help of expression (2) by shifting the mass of the f_0 resonance into the region above 1500 MeV. The results of our calculations are shown in Figs. 1 and 2. Figure 1 shows the normalized mass spectra $(dN_{4\pi}/dm)/N_{4\pi}$ in the reaction $\bar{N}N \to f_0\pi \to (4\pi)^0\pi$ for the f_0 resonance with mass 1370 MeV, which correspond to case I. Curve *1* corresponds to Eq. (1) with a constant total width $\Gamma_{f_0}^{\mathrm{tot}}=300$ MeV. It was noted that such a parameterization leads to a completely satisfactory description of the data (see also Fig. 2). Curves *2–4* obtained from Eq. (2) with $g_{f_0\rho\rho}^2/16\pi=5$, 10, and 20 GeV^2 (and $\Gamma_{f_0\to \mathrm{others}} \approx 12.5$, 21, and 30 MeV), respectively, differ markedly from curve *1*. For $g_{f_0\rho\rho}^2/16\pi<5$ GeV^2 the resonance peak becomes even narrower than curve *2*, and for $g_{f_0\rho\rho}^2/16\pi>20$ GeV^2 it becomes even wider and shifts farther to the left than curve *4*. Consequently, the resonance with mass 1370 MeV and energy-dependent total width cannot describe, for any value of the coupling constant $g_{f_0\rho\rho}^2/16\pi$, the data obtained in Refs. 8–10. A completely analogous situation also occurs for the second limiting case of the m dependence of the function $m\Gamma_{f_0\to 4\pi}(m)$.

Figure 2 shows data for $(dN_{4\pi}/dm)/N_{4\pi}$ from Ref. 9 . We note that in Ref. 9 the reaction $\bar{n}p \to 3\pi^+2\pi^-$ was investigated and a mass spectrum was constructed for the $(4\pi)^0$ system such that to a first approximation it is free from the combinatorial back-

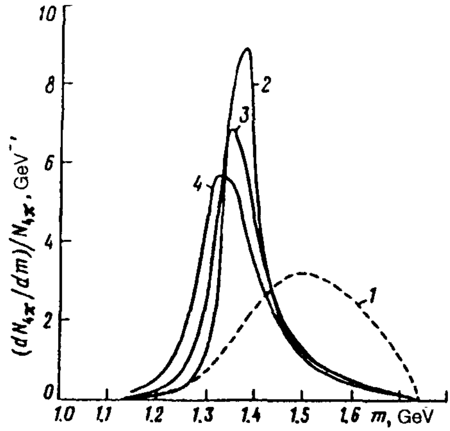

FIG. 1. Normalized mass spectra $(dN_{4\pi}/dm)/N_{4\pi}$ in the reaction $\bar{N}N \to f_0\pi \to (4\pi)^0\pi$ for the f_0 resonance with mass 1370 MeV in the case of the $f_0 \to \rho\rho \to 4\pi$ decay mechanism.

ground, i.e., free from effects associated with identical pions. The curves *1* and *2* in Fig. 2 illustrate the possibility of describing this spectrum on the basis of the resonance interpretation with the help of expression (2). Curve *1* for case I corresponds to $m_{f_0} = 1700$ MeV, $g^2_{f_0\rho\rho}/16\pi = 10$ GeV^2, $\Gamma_{f_0 \to \text{others}} \approx 60$ MeV, and $\Gamma^{\text{tot}}_{f_0}(m_{f_0}) \approx 1440$ MeV. Curve *2* for case II corresponds to $m_{f_0} = 1550$ MeV, $\tilde{g}^2_{f_0 4\pi}/16\pi = 0.5$ GeV^{-2}, $\Gamma_{f_0 \to \text{others}} \approx 35$ MeV, and $\Gamma^{\text{tot}}_{f_0}(m_{f_0}) \approx 290$ MeV. By combining for the f_0 resonance the

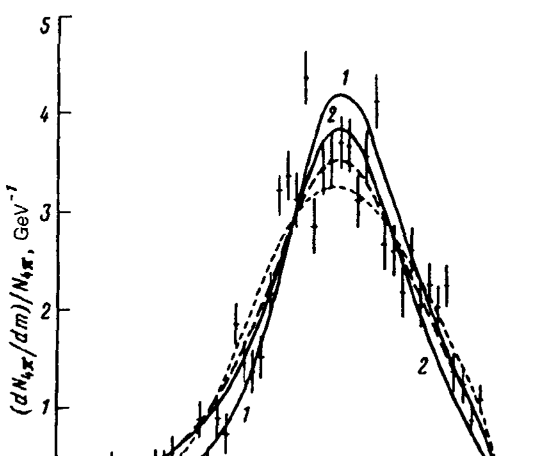

FIG. 2. Description of the data of Ref. 9 for the normalized mass spectrum of the $(4\pi)^0$ system in the reaction $\bar{n}p \to 3\pi^+ 2\pi^-$.

model for the decay via the $\rho\rho$ intermediate state with the model for a point four-pion decay or with the model for the decay via the $\sigma\sigma$ intermediate state[8-10] it is possible to obtain an acceptable description of the data for any value of m_{f_0} in the range from 1550 to 1700 MeV.

Consequently, the resonance interpretation of the $(4\pi)^0$ mass spectra in the reactions $\bar{N}N\to(4\pi)^0\pi$, taking into account the energy dependence of the total width of the resonance, leads to an interesting result: The $(4\pi)^0$ spectra are virtually insensitive to the mass of the resonance lying above the nominal $\rho\rho$ threshold. This observation and the possibility of describing the data satisfactorily with the help of a resonance with a constant, large (300 MeV) total width (see the short-dashed curve in Fig. 2) indicate that the resonance interpretation of the $(4\pi)^0$ mass spectra is not necessary at all. Let us now consider, for example, the parameterization of the spectra in an approximation similar to the approximation of the scattering length in the one-channel case: $dN_{4\pi}/dm = C\rho(\sqrt{s}, m, m_\pi)R(m)/|1-iaR(m)|^2$, where $R(m)$ is the phase volume of the S-wave system of two unstable ρ mesons. The long-dashed curve with $a=11.1$ in Fig. 2 confirms our "description," i.e., it agrees well with the data.

As our analysis shows, the assertion made in Refs. 8 –10 about the existence of a scalar resonance with mass 1370 MeV in the $(4\pi)^0$ channel are therefore very doubtful. In any case, the data in Refs. 8–10 must be reexamined. Analysis of data from new experiments must take into account the energy dependence of the total width of the resonance.

If there is no $f_0(1370)$ state in the main four-pion channel, then it cannot be associated even with the enhancements in the region 1300–1400 MeV which are observed in the $\pi\pi$ and $\eta\eta$ mass spectra in $\bar{N}N\to3\pi$ and $\bar{N}N\to2\eta\pi$, although thus far such a connection has been regarded as completely logical.[11,12] Let us now consider how the heavy f_0 resonance with $m_{f_0}>1500$ MeV, if it exists in the $(4\pi)^0$ channel, looks in the other ($\pi\pi$, $\eta\eta$, ...) decay channels. The corresponding expression for the mass spectra in the reactions $\bar{N}N\to f_0\pi\to(\text{others})^0\pi$ has the form

$$\frac{dN_{\text{others}}}{dm} = C\rho(\sqrt{s},m,m_\pi)\frac{2m}{\pi}\left(\frac{m_{f_0}\Gamma_{f_0\to\text{others}}}{(m_{f_0}^2-m^2)^2+(m\Gamma_{f_0}^{\text{tot}}(m))^2}\right), \tag{3}$$

where $m=m_{\text{others}}$. As a result of the strong growth of $m\Gamma_{f_0}^{\text{tot}}(m)$, the resonance with mass 1700 MeV in case I and 1550 MeV in case II appears in other channels as a peak with a maximum at 1425 MeV and 1480 MeV, respectively. One should keep in mind the fact that in the $\pi\pi$ and $\eta\eta$ channels this picture can be strongly distorted because of interference with other existing contributions. For example, the peak from the heavy f_0 resonance can be displaced to lower or higher masses. If, as a result of interference, it is displaced in the $\pi\pi$ and $\eta\eta$ channels slightly below 1400 MeV, then the enhancement of $f_0(1370)$ in these channels can be attributed to this peak at least partially. Another interesting scenario arises if, as a result of interference, the peak from the heavy f_0 resonance is displaced in the $\pi\pi$ and $\eta\eta$ channels slightly above 1500 MeV. Then it can be attributed to the gain of $f_0(1520)$ found in these channels. As mentioned above, the $f_0(1520)$ state requires strong coupling with some unknown decay channel. It is now completely obvious that the four-pion decay channel can be such a channel. The heavy

f_0 resonance, which predominates in the $(4\pi)^0$ mass spectra in the reactions $\bar{N}N \rightarrow (4\pi)^0\pi$ and which in this sense replaces the previous resonance $f_0(1370)$, can thus be directly related to the appearance of $f_0(1520)$ which is associated with the reactions $\bar{N}N \rightarrow 3\pi$ and $\bar{N}N \rightarrow 2\eta\pi$. Of course, as follows from the discussion presented above, there remains the problem of obtaining directly the observed peak near 1520 MeV in the $\pi\pi$ and $\eta\eta$ channels by the interference mechanism (or some other method).

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