Possible study of the scalar $\epsilon(1300\text{–}1400)$ meson in the reaction $\pi^- p \to \eta\eta n \to 4\gamma n$

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The reaction $\pi^- p \to \eta\eta n$ may be a good choice for a final identification of the $\epsilon(1300\text{–}1400)$ resonance and for determining its nature.

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1. The experimental study of the scalar resonances ($J^P = 0^+$) is currently a central problem of hadron spectroscopy "down to the charm level." In the scalar sector, there have been theoretical predictions of a large (if not huge) number of two-quark, four-quark, and gluon states (see Refs. 1 and 2, for example).

The reactions primarily used for studying scalar mesons are the peripheral reactions of the type $\pi N \to \to \pi\pi N$, $\pi N \to K\bar{K}N$. In practice, it is a far from simple matter to obtain explicit experimental information about these states: The 0^+ mesons either are masked by high-spin resonances which have a high statistical weight $(2J+1)$ in the reaction cross section; or they are unusually broad, and difficult to distinguish from each other and from the background; or, finally, they lie at the thresholds of inelastic channels (as S^* and δ resonances do, for example) and feel the strong effects of these channels.[3] These phenomena are thus difficult to interpret theoretically. As a result, several possible solutions arise in a phase-shift analysis, some of which indicate a resonance behavior for the S wave and some of which do not.[4-6] This is precisely the situation which occurs in the case of the isosinglet 0^+ resonance $\epsilon(1300\text{-}1400)$ (its mass has not been reliably established), which has been the object of intense study in the reaction $\pi^{\pm}N\to K\bar{K}N$ since 1976 (Refs. 4,5, and 7-9).

2. In this letter we wish to call attention to the fact that the reaction $\pi^+\pi^-\to\eta\eta$ may yield a conclusive identification of the ϵ resonance and a determination of its nature. This reaction is free of essentially all of the difficulties listed above. We wish to emphasize that the results which have been obtained to date by various groups of investigators on the parameters of the ϵ resonance, obtained from $\pi^+\pi^-\to K\bar{K}$, $\pi\pi$ reactions, do not come close to a satisfactory agreement with each other.[4,5,7,8]

We are thus interested in a reaction with one-pion exchange in the t channel, of the type $\pi^-p\to\eta\eta n\to 4\gamma n$. The system of four γ rays might be detected with the spectrometer which was used on the Serpukhov accelerator to discover the h (2020) meson in the reaction[10] $\pi^-p\to\pi^0\pi^0 n\to 4\gamma n$. First attempts to study the $\eta\eta$ system in the 4γ channel have already been made with the help of a xenon bubble chamber in a study of the reaction $\pi^-n\to\pi^-n\eta\eta$ at 3.5 GeV/c (so far, the statistical base is very scanty).[11]

3. For some specific estimates, we note that the amplitude for the reaction $\pi^+\pi^-\to\eta\eta$ contains only even-parity partial waves. Over the range from the threshold, $2m_\eta = 1097.6$ MeV, up to 1600 MeV, this amplitude should be dominated by the two lowest-order (S and D) waves, as follows from an analysis of the reactions [4,5,7,8,12] $\pi^+\pi^-\to\pi\pi$, $K\bar{K}$. The D wave, as in the reactions $\pi^+\pi^-\to\pi\pi$, $K\bar{K}$, should be completely saturated by the known $f(1270)$ and $f'(1515)$ resonances. It is important to note that the contributions of the f and f' mesons to the reaction $\pi^+\pi^-\to\eta\eta$ are strongly suppressed with respect to the S-wave contribution, since the corresponding partial cross section is proportional to ρ_η^5 [$\rho_\eta = 2q_\eta/m = (1-4m_\eta^2/m)^{1/2}$, where q_η is the

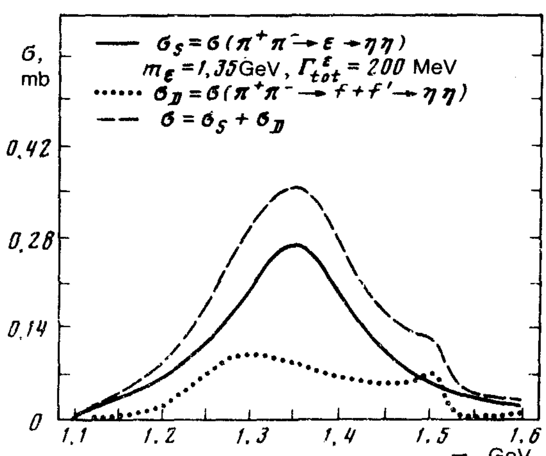

FIG. 1.

momentum of the η meson in the *c.m.* frame of the $\eta\eta$ system, and m is the invariant mass of this system]. The S-wave ϵ resonance may be dominant in the reaction $\pi^+\pi^-\to\eta\eta$; if so, this would be a unique situation.

Figure 1 shows a possible manifestation of the ϵ resonance in the cross section for the reaction $\pi^+\pi^-\to\eta\eta$. Table I lists the parameters of the f, f', and ϵ resonances which we used in estimating the corresponding contributions. The relations between the coupling constants were found from the simplest version of the quark model; the $\eta-\eta'$ mixing angle is $\theta_{\eta\eta'}\approx-10°$. We see that the ϵ resonance does in fact dominate the D-wave contribution. In the $\pi^+\pi^-\to K^+K^-$ reaction, in the interval between m_f and the $m_{f'}$, there is a constructive interference of the f and f' contributions.[4,5,8] The same picture should be observed in the reaction under consideration, here according to the quark model. We used the ordinary Breit–Wigner equations [4,5] for the ϵ, f, and f' resonances in deriving the cross sections $\sigma_S=\sigma(\pi^+\pi^-\to\epsilon\to\eta\eta)$ and $\sigma_D=\sigma(\pi^+\pi^-\to f+f'\to\eta\eta)$.

For the ϵ meson, the ratio $g^2_{\epsilon\eta\eta}/g^2_{\epsilon\pi^+\pi^-}\approx1/8$ does not depend on whether this meson has a two-quark structure, $\epsilon=(u\bar{u}+dd)/\sqrt{2}$, or a four-quark structure, $\epsilon=u\bar{u}d\bar{d}$ (Ref. 1). If this is a four-quark entity, it might be identified as the lightest representative of the second (heavy) nonet of 0^+ mesons predicted by Jaffe on the basis of the MIT bag model.[1] It may happen that there are two resonances, rather than a single resonance, in the interval 1300–1400 MeV; this point would have to be resolved experimentally.

Finally, we can estimate the cross section for the reaction $\pi^-p\to\epsilon n\to\eta\eta n\to4\gamma n$, which is proportional to $\sigma(\pi^+\pi^-\to\epsilon\to\eta\eta)$. A simple approach here is to use the equations for one-pion exchange in the t channel (see Refs. 4, 5, and 12, for example). In the interval $'|t|_{min}\leqslant|t|\leqslant0\alpha,1$ (GeV/c)^2 and for $2m_\eta\leqslant m\leqslant1,6$ GeV, we have

$$\sigma\,(\pi^-p\to\epsilon n\to\eta\eta n\to4\gamma n)\approx\left(\frac{1\ \mathrm{GeV}^2}{S}\right)^2 0.175\ \mathrm{mb}\approx1{,}2;\quad0{,}11;\quad0.027\ \mu\mathrm{b}\ ,$$

respectively, for $q_{\rm lab}=6$, 20, and 40 GeV/c; $[BR_\eta(\gamma\gamma)]^2=0.38^2=0.144$. These values are completely feasible for experimental study, for example, with the apparatus at Serpukhov designed for detecting neutral decay modes of resonances.[10] By way of comparison, we note that the cross section for the production of the h meson ($J^P=4^+$) in the reaction $\pi^-p\to hn\to\pi^0\pi^0n\to4\gamma n$ is of the same order of magnitude.[10]

TABLE I.

Resonance	Characteristics
$f(1270)$ [9]	$\Gamma^f_{tot}=180$ MeV, $BR_f(\pi\pi)=83\%$, $BR_f(K\bar{K})=2.8\%$ $g^2_{f\eta\eta}/g^2_{f\pi^+\pi^-}\approx1/8$, $BR_f(\eta\eta)\approx0.26\%$
$f'(1515)$ [4,5,7–9]	$\Gamma^{f'}_{tot}\doteq70$ MeV, $BR_{f'}(K\bar{K})=70\%$, $BR_{f'}(\pi\pi)=2\%$, $g^2_{f'\eta\eta}/g^2_{f'K^+K^-}\approx1/2$, $BR_{f'}(\eta\eta)\approx11\%$
ϵ (1300 – 1400) [4, 5, 7 – 9]	$\Gamma^\epsilon_{tot}=\Gamma^\epsilon_{\pi\pi}+\Gamma^\epsilon_{K\bar{K}}+\Gamma^\epsilon_{\eta\eta}\approx(160-300)$ MeV, $BR_\epsilon(K\bar{K})\approx(7-15$ $g^2_{\epsilon\eta\eta}/g^2_{\epsilon\pi^+\pi^-}\approx1/8$, $BR_\epsilon(\eta\eta)\approx4\%$

In principle, there could be contributions ("tails") from lighter or heavier S-wave resonances in the $\epsilon(1300\text{-}1400)$ region. For example, there could be a contribution from the $S^*(980)$ resonance, which lies below the threshold for the reaction under discussion here; this resonance should be strongly coupled with the $\eta\eta$ channel.[3] We believe that a detailed analysis of the $\epsilon + S^* + \cdots$ resonance complex (an analysis of possible interference patterns) will be justified after experimental data become available on the reaction $\pi^+\pi^- \to \eta\eta$ in the region $2m_\eta \leqslant m \leqslant 1.5$ GeV.

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