Ratio of the real and imaginary parts of the $\bar{p}p$ scattering amplitude near the $\bar{n}n$ threshold

O. D. Dal'karov and K. V. Protasov
P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow

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The appearance of a maximum in the observed momentum dependence of the ratio of the real and imaginary parts of the amplitude for forward $\bar{p}p$ scattering in the range 0–200 MeV/c of the momentum of the incident antiproton is explained. It results from the opening of the $\bar{n}n$ channel and the rapid growth of, and the relatively large magnitude of, the P-wave component of low-energy $\bar{N}N$ scattering.

The ratio of the real and imaginary parts of the amplitude for forward $\bar{p}p$ scattering $[\epsilon = \mathrm{Re} f_{\bar{p}p}(\theta = 0)/\mathrm{Im} f_{\bar{p}p}(\theta = 0)]$ at previously unattainable momenta of the incident antiproton, $p \approxeq 180$–300 MeV/c, has been measured in recent experiments at the LEAR antiproton storage ring at CERN (the LEAR data are shown in Fig. 1).[1,2] It follows from these results that the value of ϵ changes sign at ~ 230 MeV/c, again becoming positive. The same quantity is known at vanishing energies from atomic data[3] ($\epsilon = 2\Delta E/\Gamma = -1.7 \pm 0.5$, where ΔE is the shift of the $1S$ level of the $\bar{p}p$ atom, and Γ is the width of the K_α line). We conclude that this result means that ϵ should change sign at least one more time in the momentum range 0–200 MeV/c.

In this letter we wish to call attention to a possible explanation for this very unusual behavior of ϵ on the basis of the proximity of the threshold for the inelastic channel $\bar{p}p \to \bar{n}n$ [the difference between the masses of the $\bar{n}n$ and $\bar{p}p$ channels is $\Delta M = 2(m_n - m_p) = 2.6$ MeV; this value corresponds to a momentum $p = 98.8$ MeV/c of the incident antiproton] and the comparatively large P-wave component of the $\bar{N}N$ scattering at very low energies. We begin by seeking the qualitative reason why, despite the comparatively small component (the charge-exchange cross section σ^{ch} is no more than about 20% of the elastic cross sections σ^{el} in the momentum range of interest here), the opening of the $\bar{p}p \to \bar{n}n$ channel might have a strong effect on the behavior of ϵ. What is involved here is that the value of ϵ at the momenta p with which we are concerned is small: Specifically, ϵ ranges from -0.1 to $+0.1$ over the momentum range 200 MeV/$c \leqslant p \leqslant 400$ MeV/c. At these momenta, according to data from phase-shift analysis,[7] the S- and P-wave components of elastic $\bar{p}p$ scattering are roughly the same (the behavior of the partial amplitudes for low-energy $\bar{p}p$ scattering is discussed in detail in Ref. 8). We rewrite ϵ as $\epsilon = (\mathrm{Re}^S + \mathrm{Re}^P/\mathrm{Im}^{S+P})$, where superscripts S and P mean the S- and P-wave partial amplitudes $[\mathrm{Re}^{S,P} \approxeq \mathrm{Re} f^{S,P}_{\bar{p}p}(\theta = 0)$, $\mathrm{Im}^{S+P} = \mathrm{Im}^S_{\bar{p}p}(\theta = 0) + \mathrm{Im} f^P_{\bar{p}p}(\theta = 0)]$. We then have two ways to explain the small value of ϵ: (a) $|\mathrm{Re}^S/\mathrm{Im}^{S+P}| \ll 1$ and $|\mathrm{Re}^P/\mathrm{Im}^{S+P}| \ll 1$; (b) $|\mathrm{Re}^S/\mathrm{Im}^{S+P}| \sim |\mathrm{Re}^P/\mathrm{Im}^{S+P}|$. These ratios are not small, but the signs of Re^S and Re^P are opposite. Possibility (b) appears to be the stronger candidate from the physical standpoint since (first) different signs for Re^S and Re^P follow from the data of phase-shift analysis and (second) the ratio $\mathrm{Re}^S/\mathrm{Im}^S$ at vanishing momenta (atom-

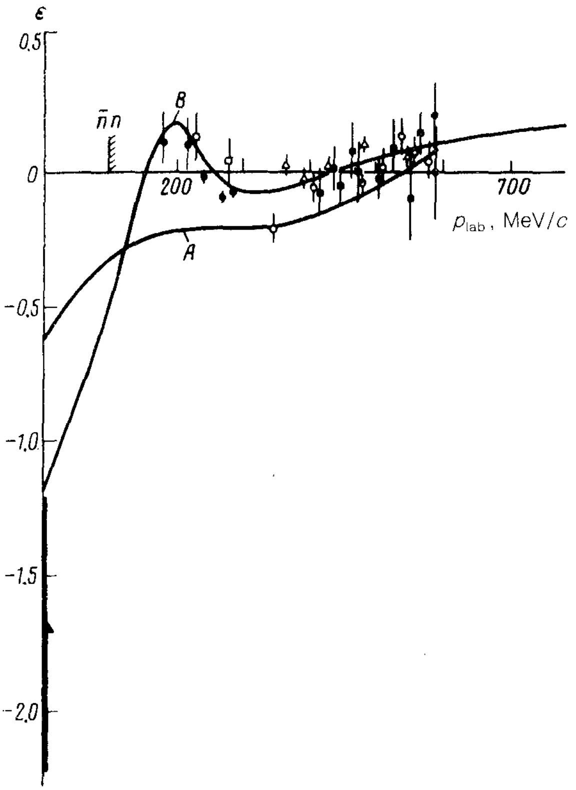

FIG. 1. The ratio $\epsilon = \mathrm{Re} f_{\bar{p}p}(\theta = 0) : \mathrm{Im} f_{\bar{p}p}(\theta = 0)$ as a function of the momentum of the incident antiproton. The points are experimental data. ●—From Ref. 1; □—Ref. 2; ▲—Ref. 3; ■—Ref. 4; ○—Ref. 5; △—Ref. 6. The curves are calculated. *A*—Coupled-channel model[9]; *B*—model with total-absorption boundary condition.[10]

ic data) is negative and comparatively large in absolute value. In this sense, the small value of ϵ would be explained as a consequence of a cancellation of quantities that are not small, $\mathrm{Re}^S/\mathrm{Im}^{S+P}$ and $\mathrm{Re}^P/\mathrm{Im}^{S+P}$, so that any small perturbation in one of the waves (S or P) might lead to a pronounced change in ϵ. Let us denote by α a small admixture in Re^S and by β a small admixture in Im^S. We then have the new value $\tilde{\epsilon} = \tilde{\mathrm{Re}}/\tilde{\mathrm{Im}} = (\mathrm{Re}^S + \alpha \mathrm{Re}^S + \mathrm{Re}^P/\mathrm{Im}^{S+P} + \beta \mathrm{Im}^S) \simeq \epsilon + \alpha(\mathrm{Re}^S/\mathrm{Im}^{S+P})$. If $\alpha \sim \epsilon$ and $|\mathrm{Re}^S/\mathrm{Im}^{S+P}| \sim 1$ [possibility (b)], then we have $|\epsilon - \tilde{\epsilon}| \sim \epsilon$. In the models which we will discuss below, we have $|\mathrm{Re}^S/\mathrm{Im}^{S+P}| \lesssim 1$ (the coupled-channel model[9]) and $|\mathrm{Re}^S/\mathrm{Im}^{S+P}| \sim 2$ (the boundary-condition model[10]). In this situation, the opening of the $\bar{n}n$ channel, which is manifested in the momentum range $p \simeq 100$–200 MeV/c only in the behavior of the S-wave component of elastic $\bar{p}p$ scattering, can therefore have a significant effect on the behavior of ϵ. An accurate calculation of ϵ in the momentum range of interest would require solving either the coupled-channel problem ($\bar{p}p$, $\bar{n}n$, and $n\pi$) or, e.g., the two-channel problem $\bar{p}p$ or $\bar{n}n$ with a boundary condition. Although these problems are quite complicated, they are solvable in principle. To evaluate the effect here, we use approximate expressions which are valid at $k_0 R \ll 1$, where k_0 is the relative momentum in the $\bar{n}n$ channel, and R is a quantity ~ 1 fm.

In this case, the S-matrix element, which corresponds to elastic $\bar{p}p$ scattering near the $\bar{n}n$ threshold, can be written[11]

$$S^{S,P} = e^{2i\delta_{S,P}}(1 - \gamma_{S,P}),$$

where δ_S and δ_P are the phase shifts of $\bar{p}p$ scattering in the S- and P-waves without allowance for the $\bar{n}n$ channel (these phase shifts are different for states with definite values of the total angular momentum, the spin, and the isospin of the channel), and the factor γ_S is expressed in terms of the cross section for charge exchange in the S-wave: $\gamma_S = (k/2\pi)\sigma_S^{\rm ch}$ (here $\sigma_S^{\rm ch}$ is proportional to k_0). Near the $\bar{n}n$ threshold, the factor $\gamma_P \cong \gamma_S (k_0 R)^2$ is very small, so that the opening of the $\bar{p}p \to \bar{n}n$ channel is important only in the S-wave. The effect of the threshold in the P-wave comes into play at larger momenta and results in a restoration of the cancellation of Re^S and Re^P.

Two realistic models have been used in the specific calculations: the coupled-channel model[9] and the model with a total-absorption boundary condition.[10] The results of these calculations are shown in Fig. 1, by curves A and B, respectively. We see that ϵ has a maximum at momenta $p \cong 200$ MeV/c and that the magnitude of this maximum depends very strongly on the model adopted for the $\bar{N}N$ interaction. The appearance of the maximum is a consequence of the opening of the $\bar{n}n$ channel and the exceedingly rapid growth of the P-wave component ($|\mathrm{Re}^P| \sim |\mathrm{Re}^S|$ in the region with $kR \ll 1$). We interpret these results as meaning that P-wave states of a quasinuclear type[12] exist near the threshold in the $\bar{N}N$ system.

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