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On the strong energy dependence of the $e^+e^- \leftrightarrow p\bar{p}$ amplitude near threshold

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Abstract

We study the energy dependence of the $e^+e^- \to p\bar{p}$ cross section close to the two-nucleon threshold, recently reported by the BaBar Collaboration. Our analysis also includes the $\bar{p}p \to e^+e^-$ data collected by PS170 Collaboration and the $e^+e^- \to N\bar{N}$ data from the FENICE Collaboration. We show that the near-threshold enhancement in the $e^+e^- \to p\bar{p}$ cross section can be explained by the final-state interaction between proton and antiproton in the $^3S_1$ partial wave, utilizing the Jülich nucleon–antinucleon model. As a consequence, the strong dependence of the proton electromagnetic form factors on the momentum transfer close to the two-nucleon threshold is then likewise driven by this final-state interaction effect. This result is in line with our previous studies of the near-threshold enhancement of the $p\bar{p}$ invariant mass spectrum seen in the $J/\Psi \to \gamma p\bar{p}$ decay by the BES Collaboration and in the $B^+ \to p\bar{p}K^+$ decay by the BaBar Collaboration.

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The observation of a steep energy dependence of the proton electromagnetic form factors (EMFF) in the time-like region at momentum transfers $q^2 \approx (2m_p)^2$, where m_p is the proton mass, was first reported by the PS170 Collaboration [1], based on a measurement of the $\bar{p}p \to e^+e^-$ reaction cross section close to the $p\bar{p}$ threshold at LEAR. Later the FENICE Collaboration at Frascati measured the cross section for the time-reversed process $e^+e^- \to p\bar{p}$ [2,3]. However, their data were taken at energies not close enough to the threshold in order to confirm this strong energy dependence and, furthermore, had very large uncertainties. The FENICE Collaboration also made the first and only measurement of the $e^+e^- \to n\bar{n}$ cross section [3] which turned out, within the large experimental errors, to be close to the $e^+e^- \to p\bar{p}$ one. Only recently the BaBar Collaboration reported very precise data on the $e^+e^- \to p\bar{p}$ cross section down to energies very close to the $p\bar{p}$ threshold [4]. The form factor deduced from those data substantiates the finding of the PS170 Collaboration.

A steep dependence of the proton EMFF on the momentum transfer simply reflects the fact that the underlying (measured) $e^+e^- \to p\bar{p}$ cross section shows a significant enhancement near the $p\bar{p}$ threshold. It is interesting that a near-threshold enhancement was also reported recently in an entirely different reaction involving the $p\bar{p}$ system, namely the radiative decay $J/\Psi \to \gamma p\bar{p}$ [5]. For the latter case several explanations have been put forth, including scenarios that invoke $N\bar{N}$ bound states or so far unobserved meson resonances. However, it was also shown that a rather conventional but plausible interpretation of the data can be given in terms of the final-state interaction (FSI) between the produced proton and antiproton [6–10]. Specifically, in the calculation of our group [6] utilizing the Jülich $N\bar{N}$ model [11,12], the mass dependence of the $p\bar{p}$ spectrum close to the threshold could be nicely reproduced by the S-wave $p\bar{p}$ FSI in the isospin $I = 1$ state within the Watson–Migdal [13] approach.

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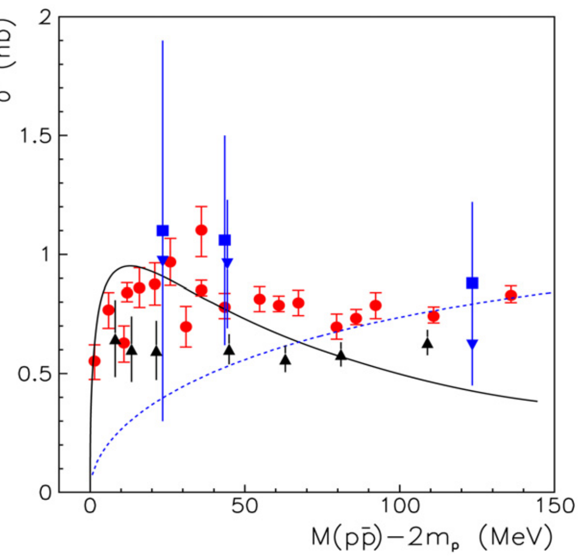

Fig. 1. Cross section of the $e^+e^- \to p\bar{p}$ and $e^+e^- \to n\bar{n}$ reactions as a function of the excess energy. The data are from the FENICE [3] (inverse triangles and squares) and BaBar [4] (circles) collaborations. Triangles represent results obtained by applying detailed balance to the $\bar{p}p \to e^+e^-$ cross section measured by the PS170 Collaboration [1]. The dashed line indicates the energy dependence of the two-body phase space. The solid line is the scattering amplitude squared predicted by the Jülich $N\bar{N}$ model A(OBE) [11] for the ${}^3S_1$ partial wave, multiplied by appropriate phase-space factors.

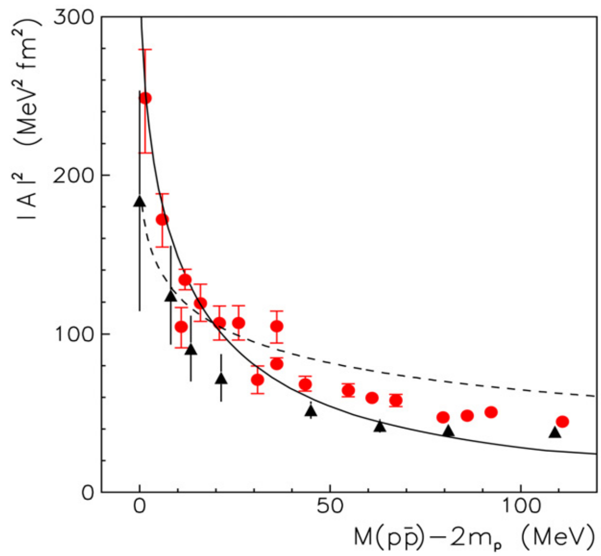

Fig. 2. The Lorentz invariant amplitude squared for the $e^+e^- \to p\bar{p}$ (circles) and $\bar{p}p \to e^+e^-$ (triangles) reactions extracted from the data [1,4] by Eq. (2) shown as a function of the excess energy. The dashed line is the result based on Eq. (3) with N fixed to the threshold data, while the solid line is the scattering amplitude squared predicted by the Jülich $N\bar{N}$ model A(OBE) [11] for the ${}^3S_1$ partial wave.

The success of those investigations suggests that the same effects, namely the FSI between proton and antiproton, could be also responsible for the near-threshold enhancement in the $e^+e^- \to p\bar{p}$ cross section and, accordingly, for the strong momentum-transfer dependence of the proton EMFF in the time-like region near $q^2 \approx (2m_p)^2$. In the present Letter, we report results of a corresponding calculation, utilizing again the scattering amplitudes of the Jülich $N\bar{N}$ model and applying the Watson–Migdal approach.

Fig. 1 shows the $e^+e^- \to p\bar{p}$ and $e^+e^- \to n\bar{n}$ cross sections measured by the FENICE [3] and BaBar [4] Collaborations as a function of the excess energy, $M(p\bar{p}) - 2m_p$, with $M(p\bar{p}) = \sqrt{s}$ the invariant energy of the $p\bar{p}$ system. In order to compare the $\bar{p}p \to e^+e^-$ data (also shown in the figure) with the $e^+e^- \to p\bar{p}$ results, we apply detailed balance assuming time-reversal invariance, i.e.

$$\sigma\left(e^+e^- \to p\bar{p}\right) \simeq \left[1 - \frac{4m_p^2}{M^2(p\bar{p})}\right]\sigma\left(\bar{p}p \to e^+e^-\right), \tag{1}$$

where we neglect the electron mass. Although there seems to be a systematical difference between the $e^+e^- \to p\bar{p}$ and $\bar{p}p \to e^+e^-$ cross section data, the latter are by a factor of about 1.3 smaller, their energy dependence is very similar. The dashed line in Fig. 1 shows the energy dependence due to the two-body phase space given by

$$\sigma\left(e^+e^- \to p\bar{p}\right) = \frac{|A|^2}{16\pi M^2(p\bar{p})}\left[1 - \frac{4m_p^2}{M^2(p\bar{p})}\right]^{1/2}, \tag{2}$$

where the constant Lorenz invariant amplitude A was normalized to the data at the excess energy of 136 MeV, $|A|^2 = 46\ \mathrm{MeV}^2\,\mathrm{fm}^2$. The experimental results clearly exhibit an energy dependence that differs from the phase space especially at excess energies below 50 MeV. This implies that the transition amplitude A must vary substantially for energies close to the $p\bar{p}$ threshold.

To illustrate this conjecture more transparently we extract the squared invariant amplitude $|A|^2$ from the near-threshold data [1,4] by dividing out the phase space factor according to Eq. (2). The corresponding results are shown in Fig. 2. They clearly indicate that the squared transition amplitude depends rather strongly on the energy within the range $M(p\bar{p}) - 2m_p \leqslant 50$ MeV, say.

Since the $e^+e^- \to p\bar{p}$ and $\bar{p}p \to e^+e^-$ data are used for the extraction [14] of the proton EMFF, the strong energy dependence of the transition amplitude is reflected in the behaviour of the EMFF in the time-like region close to threshold. Phenomenological models such as vector dominance model (VDM), which assumes that the photon couples to hadrons through intermediate vector mesons [15,16], fail to describe that steep energy dependence. To resolve this discrepancy the VDM was extended to include also heavier vector mesons [16,17] besides the light ρ, ω and ϕ mesons. Taking the couplings of the heavy vector mesons to the proton as free parameters it was possible to reproduce the steep dependence of the $\bar{p}p \to e^+e^-$ cross section close to $p\bar{p}$ threshold. For a discussion of this issue in the context of dispersion relations, see [18,19].

On the other hand, the success of $p\bar{p}$ FSI effects in explaining the near-threshold enhancement in the $p\bar{p}$ mass spectrum of $J/\Psi \to \gamma p\bar{p}$ suggests that the same mechanisms could be also responsible for the behaviour of the EMFF. Indeed FSI effects have been already considered before [20,21] to describe the near-threshold energy dependence of the $\bar{p}p \to e^+e^-$ reaction by the $p\bar{p}$ initial-state-interaction, though at a time when