The possibility of extracting the electromagnetic proton form factor from deuteron reactions in the nonphysical region

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It is shown that the electromagnetic proton form factor (EPF), obtained from experimental data for the reaction $\bar{p}d \to e^+ e^- + n_s$, is effectively in full accord with the annihilation of an antiproton by a free proton. The mechanism for this effect is examined, and the kinematic region, in which this effect occurs, is determined.

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A theoretical study of the physics of $N\bar{N}$ interaction has led to the prediction of the existence of "baryonium" and many physical effects attributable to the existence of quasi-nuclear systems.[1-4] In particular, it was found to be possible to predict the behavior of electromagnetic proton form factor (EPF) in the timelike region of momentum transfer up to the $p\bar{p}$ threshold.[3] In order to obtain information about the EPF in the non-physical region of transferred momenta, it was reasonable to use the annihilation reaction of an antiproton by a proton of the nucleus, for example, the $\bar{p}d \to e^+ e^- + n_s$ reaction. In this paper we show that in view of the specific properties of the nuclear system (a deuteron), the amplitude of the annihilation $pp \to e^+ e^-$ should be included in the diagrams of the process $\bar{p}d \to e^+ e^- + n_s$ at the energy corresponding to the annihilation of an antiproton by a free proton.

In order to prove this assertion, we must choose a model for the amplitude Γ_u of the $\bar{p}p \to e^+ e^-$ process. In this paper we shall assume that the annihilation $\bar{p}p \to e^+ e^-$ is described by the dynamic-enhancement mechanism,[3] which in our opinion, is responsible for this phenomenon.

The diagram in Fig. 1 correspond to the dynamic-enhancement mechanism of the $\bar{p}p \to e^+ e^-$ process (in first order with respect to α). In Fig. 1 $t_{\bar{p}p}$ is the amplitude of $\bar{p}p$ elastic scattering, which contains no elastic scattering via the annihilation channels, and Γ_0 is the amplitude of the $\bar{p}p$ transition to a photon, which includes all the annihilation channels. Using the symbols of operator algebra,[5] we can write the annihilation amplitude of $\bar{p}p \to e^+ e^-$ (Fig. 1) in the form

$$\Gamma_u(q) = \Gamma_0(q, u) - \hat{t}\, g_u^{(0)} \Gamma_0 \, . \tag{1}$$

where q is the relative momentum of proton and antiproton, u is their kinetic energy in c.m.s., and $g_u^{(0)}$ is the Green's function of free motion. For simplicity, we assume that Γ_0 does not depend on u (Γ_0 is strongly dependent on u only in the energy region near the "baryonium" binding energies ϵ).[4]

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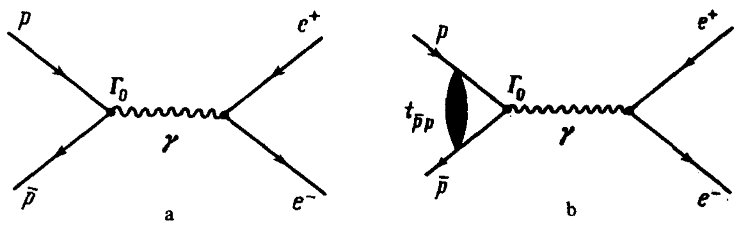

FIG. 1. Feyman diagrams for the $p\bar{p}\to e^+e^-$ annihilation.

The amplitude of the annihilation $\bar{p}d\to e^+e^- + n_s$ in the polar approximation (Fig. 2) has the form

$$M_a = \phi_d(p_s)\Gamma_u\left(\frac{k+p_s}{2}\right) \qquad (2)$$

$\phi_d(p_s)$ is the deuteron wave function, p_s is the spectator neutron momentum, and k is the momentum of the incident antiproton. The value of u is

$$u = \frac{(k+p_s)^2}{4m} - \frac{p_s^2}{m} - \epsilon_d = v - \frac{p_s^2}{m} - \epsilon_d, \qquad (3)$$

where $v=(k+p_s)^2/4m$ is the kinetic energy in c.m.s. of the free p and $\bar{p}$ with momenta p_s and k, respectively.

To demonstrate the mathematical aspect of the problem as well as the physical consequences, we shall assume that the $n\bar{p}$ interaction is missing. Thus, we have an infinite number of diagrams (Fig. 2), in which the proton of the deuteron interacts with a neutron between two successive $p\bar{p}$ interactions. Allowance for other diagrams with the np interaction does not alter our result. (The role of diagrams with np rescatterings and their calculation methods were analyzed in Refs. 6–8.)

A method based on the relationship between the amplitude of the np scattering and the Green's function was used to calculate the diagrams (Fig. 2).[7,8] By using this method, we can obtain the following expression for the diagram in Fig. 2b:

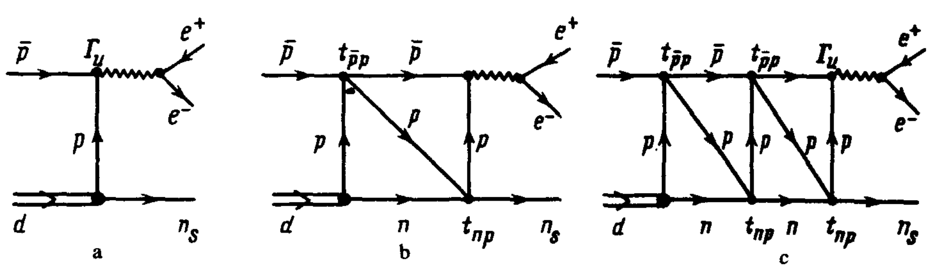

FIG. 2. Feyman diagrams for the reaction $\bar{p}d\to e^+e^- + n_s$ in the absence of $n\bar{p}$ interaction.

$$M_b = \phi_d(p_s)[\hat{t}_{\bar{p}p}(\hat{g}_u^{(o)} - \hat{g}_E)\hat{\Gamma}_u] + M'. \tag{4}$$

It can be shown that the quantity M' amounts to about 0.1 —0.2 of the value of M_b for $p_s R \lesssim 1$ (R is the deuteron radius) and, therefore, it can be dropped. The value of g_E is approximately equal to the free Green's function $g_v^{(0)}$ (within 30% accuracy) with energy v in the c.m.s. corresponding to free p and $\bar{p}$. Expressions for the other terms of the series in Fig. 2 can be obtained in an analogous manner. The sum of all the diagrams with np rescattering has the following form:

$$M_b + M_c + \ldots = \phi_d(p_s)\{\Gamma_o - \Gamma_u - (\hat{t}_u + \hat{t}_u(\hat{g}_u^{(o)} - \hat{g}_v^{(o)})\hat{t}_u + \ldots)g_v^{(o)}\Gamma_o\}. \tag{5}$$

Using the relation between the amplitude $t_{\bar{p}p}$ at the energy surface and outside the energy surface[6-8]

$$t_v = t_u + \hat{t}_u(\hat{g}_u^{(o)} - \hat{g}_v^{(o)})\hat{t}_u + \ldots \tag{6}$$

and the relation (1), we obtain

$$M_b + M_c + \ldots = \phi_d(p_s)(\Gamma_v - \Gamma_u). \tag{7}$$

Thus, the sum of all diagrams of the series (Fig. 2) is

$$M = M_a + M_b + M_c + \ldots = \phi_d(p_s)\Gamma_v. \tag{8}$$

Equation (8) is satisfied within the accuracy of terms of the order of $m(\Gamma_u - \Gamma_v)/2m(1 + m/2m) = \frac{1}{3}(\Gamma_u - \Gamma_v)$. The terms $\frac{1}{3}(\Gamma_u - \Gamma_v)$, attributable to the replacement of g_F by $-g_v^{(0)}$, lead to the fact that at energies close to the resonance binding energy ϵ_x, this resonance will appear if $\frac{1}{3}(\Gamma_u - \Gamma_v) \gg \Gamma_v$. Note that in our model the narrow resonance above the $p\bar{p}$ threshold also appears below it. We emphasize, however, that the analyzed amplitude renormalization of the annihilation $\bar{p}p \to e^+e^-$ occurs within a comparatively narrow range of spectator momenta that satisfy the condition $p_s \lesssim R^{-1} \lesssim 100$ MeV/c.

Figure 3 shows the behavior of the quantity $\tilde{G} = \alpha^{-1}|M/\phi_d| = |\Gamma_v|$ for different experimental arrangements. Let us assume, for example, that $p_s = 0$. Thus, the value of $v \to 0$ as $k \to 0$, and the amplitude Γ_v increases according to the prediction of the dynamic-enhancement model[3] and reaches a maximum at $v = 0$ at the point $u = -\epsilon_d$. We shall now decrease u for $k = 0$ by increasing p_s. Although the value of u decreases [see Eq. (3)], the value of v increases as $p_s^2/4m$. Therefore, $\tilde{G}$ decreases. Thus, we should observe a peak at $u = -\epsilon_d$, which may vanish for other kinematic conditions of the experiment.

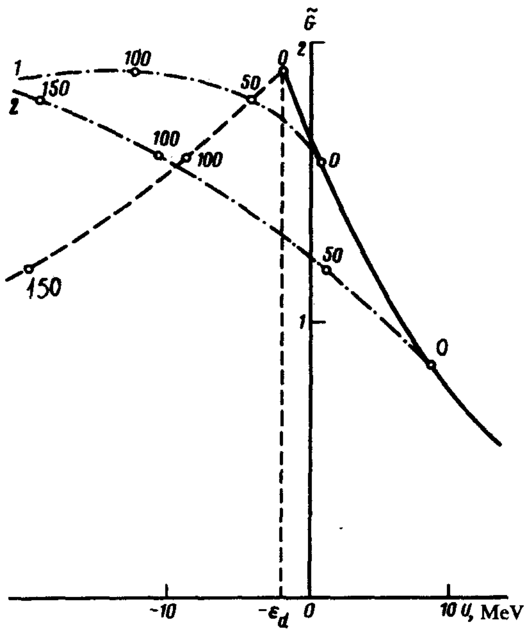

FIG. 3. Behavior of the quantity $\tilde{G} = \alpha^{-1}|M/\phi_d|$ as a function of the invariant variable $u = \sqrt{s} - 2m$, where $\sqrt{s}$ is the effective mass of the e^+e^- system. The solid curve corresponds to annihilation by a quasi-free proton, i.e., when the momentum of the spectator neutron is $p_s = 0$. The dashed curve corresponds to annihilation of stopped antiprotons ($k_{\bar{p}} = 0$). The numbers on the curves denote the corresponding momenta of the spectator neutron momentum. The dot-dash curves 1 and 2 correspond to escape of the spectator neutron at a 180° angle with respect to the direction of the momentum of the incident $\bar{p}$ momenta are $\bar{k}_p = 100$ MeV/c and 200 MeV/c for curves 1 and 2, respectively).

Thus, it follows from the foregoing discussion that the extraction of the EPF from the deuteron reaction requires a careful evaluation of the obtained information, because of renormalization of the amplitude of the annihiliation $\Gamma_u(p\bar{p}\to e^+e^-)$. Experimental studies of the reaction $\bar{p}d\to e^+e^- + n_s$ in a wider range of variation of the kinematic variables must be performed to verify the predicted effected.

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