Physics

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1965

SovietRxiv

Abstract

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Leptonic Annihilation of Proton–Antiproton Pairs with Account of Form Factors and Polarization Correlations

(Presented by Academician N. N. Bogolyubov on 13 XI 1964)

Recent experiments ([1]), carried out at CERN with the aim of studying the electromagnetic structure of the proton in the region of timelike values of the transferred momentum ($q^2 = -6.8\,(\mathrm{BeV}/c)^2$), show that the cross section of the process $\tilde{p} + p \to \mu^+ + \mu^-$ has an upper limit $\sigma \leqslant 10 \cdot 10^{-33}$ cm^2, whereas in the case of a point proton, theoretical calculations for the cross section give the value $\sigma \simeq 247 \cdot 10^{-33}$ cm^2. The results of these experiments indicate the existence of structural form factors of the proton for timelike momentum transfers.

In a number of works ([2–4]), the cross sections of the processes $p + \tilde{p} \to e^+ + e^-$, $\tilde{p} + p \to \mu^+ + \mu^-$ were calculated with account of the proton form factors. In ([3,4]) the influence of the polarization of only one of the initial particles on the indicated processes was also investigated. The influence of polarization states and particle form factors on the annihilation process $e^- + e^+ \to p + \tilde{p}$ was considered in ([5]). It was shown that the study of polarization correlations of particles can provide additional information on the electromagnetic form factors of the proton for timelike values of momentum transfer.

In the present work the annihilation process is investigated

$$\tilde{p} + p \to \tilde{l} + l \tag{1}$$

($l = e^-$ or μ^-; $\tilde{l} = e^+$ or μ^+), with simultaneous account of the form factors of the proton and of the polarization correlations between all particles participating in the process.

In the one-photon approximation the matrix element of process (1), with account of the proton form factors, is represented in the form ($\hbar = c = 1$)

$$M = \frac{e^2}{q^2}\left[\bar{v}_{\tilde{p}}\left(F_1(q^2)\gamma_\mu + \frac{\varkappa_a}{2M_p}F_2(q^2)\sigma_{\mu\nu}q_\nu\right)v_p\right](\bar{u}_l\gamma_\mu u_{\tilde{l}}). \tag{2}$$

Here $\sigma_{\mu\nu} = \dfrac{i}{2}(\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu)$; $q_\nu = P_\nu^{\tilde{p}} + P_\nu^{p} = p_\nu^{\tilde{l}} + p_\nu^{l}$ is the four-dimensional transferred momentum; $F_1(q^2)$ and $F_2(q^2)$ are the Dirac and Pauli form factors of the proton; M_p and $\varkappa_a$ are the mass and anomalous magnetic moment of the proton.

The differential cross section of process (1), with account of the form factors and polarization states of both initial and final particles in the center-of-inertia system, is given by the formula

$$d\sigma_{s_p s_{\tilde{p}}}(E, \theta, s_l, s_{\tilde{l}}) = \frac{\pi\alpha^2}{32M_p^2}\frac{\beta_l}{\beta\gamma^2}\left\{\Phi_0(\theta) + s_l s_{\tilde{l}}\Phi_1(\theta) + s_p s_{\tilde{p}}\Phi_2(\theta) + \right.$$

$$\left. +(s_l - s_{\tilde{l}})(s_p - s_{\tilde{p}})\Phi_3(\theta) + s_l s_{\tilde{l}} s_p s_{\tilde{p}}\Phi_4(\theta)\right\} d(\cos\theta), \qquad (3)$$

where

$$\Phi_0(\theta) = \frac{1}{\gamma^2}|F_1|^2\varphi_0 + \chi_a^2|F_2|^2\varphi_0' - \chi_a(3 - \beta_l^2)(F_1F_2^* + F_1^*F_2),$$

$$\Phi_1(\theta) = \frac{1}{\gamma^2}|F_1|^2(\varphi_0 - 2\xi_0) + \chi_a^2|F_2|^2(\varphi_0' - 2\xi_0') + \chi_a(1 + \beta_l^2)(F_1F_2^* + F_1^*F_2),$$

$$\Phi_2(\theta) = \frac{1}{\gamma^2}|F_1|^2\varphi_1 + \chi_a^2|F_2|^2\varphi_1' - \chi_a\left[(1 - \beta_l^2) - 2(1 - \beta_l^2\sin^2\theta)\right]\times$$

$$\times(F_1F_2^* + F_1^*F_2),$$

$$\Phi_3(\theta) = 2\cos\theta\left[|F_1|^2 + \chi_a^2|F_2|^2 - \chi_a(F_1^*F_2 + F_1F_2^*)\right],$$

$$\Phi_4(\theta) = \frac{1}{\gamma^2}|F_1|^2(\varphi_1 - 2\xi_1) + \chi_a^2|F_2|^2(\varphi_1' - 2\xi_1') - \chi_a\left[1 + \beta_l^2 - 4\sin^2\theta + \right.$$

$$\left. +2(1 - \beta_l^2\cos^2\theta)\right](F_1F_2^* + F_1^*F_2),$$

$$\varphi_{0,1} = 1 - \beta_l^2\cos^2\theta \mp \gamma^2(2 - \beta_l^2\sin^2\theta),$$

$$\varphi_{0,1}' = \gamma^2(1 - \beta_l^2\cos^2\theta) \mp (2 - \beta_l^2\sin^2\theta),$$

$$\xi_{0,1} = \sin^2\theta \mp \gamma^2(1+\cos^2\theta),$$

$$\xi'_{0,1} = \gamma^2\sin^2\theta \mp (1+\cos^2\theta),$$

$$\gamma = \frac{E}{M_p}, \qquad \gamma_0 = \frac{E}{m_l}, \qquad \beta = \frac{\sqrt{\gamma^2-1}}{\gamma}, \qquad \beta_l = \frac{\sqrt{\gamma_0^2-1}}{\gamma_0},$$

$$\alpha = \frac{e^2}{4\pi} = \frac{1}{137}.$$

Here the upper sign refers to functions with index 0, and the lower sign to those with index 1; E and θ are the total energy of the proton and the lepton emission angle in the center-of-inertia system; m_l is the lepton mass; the quantities $s_a = \pm 1$ $(a = p, \tilde{p}, l, \tilde{l})$ determine the projection of the doubled spin $\vec{\sigma}$ along and opposite to the direction of the fermion momentum (see ([6])).

Integrating (3) over the angle θ, we obtain, for the total cross section of leptonic annihilation of polarized protons and polarized antiprotons, the following expressions:

$$\sigma_{s_p s_{\tilde{p}}}(E, s_l, s_{\tilde{l}}) = \frac{\pi\alpha^2}{48M_p^2}\frac{\beta_l}{\beta\gamma^2}\Big\{(3-\beta_l^2) - (1+\beta_l^2)s_l s_{\tilde{l}}\Big\}\left[\frac{1+2\gamma^2}{\gamma^2}|F_1|^2 + \right.$$

$$\left. + \chi_a^2(2+\gamma^2)|F_2|^2 - 3\chi_a(F_1F_2^* + F_1^*F_2)\right] +$$

$$+ s_p s_{\tilde{p}}\left[\frac{1-2\gamma^2}{\gamma^2}|F_1|^2 - \chi_a^2(2-\gamma^2)|F_2|^2 + \chi_a(F_1F_2^* + F_1^*F_2)\right]\Big\}. \qquad (4)$$

In contrast to the differential cross section, the total cross section does not contain pair proton–lepton polarization correlations. Formulas (3), (4) determine the influence of the form factors and spin states of the proton, antiproton, and of the produced lepton and antilepton (correlation terms $\sim s_l s_{\tilde{l}}$, $s_p s_{\tilde{p}}$, $s_l s_p$, etc.) on the angular and energy distributions of the pairs. It follows from (4) that, for fixed longitudinal polarizations of both initial particles ($s_p s_{\tilde{p}} = 1$ or -1), the lepton and antilepton of the produced pair may have longitudinal polarization of the same ($s_l s_{\tilde{l}} = 1;\ s_l = s_{\tilde{l}}$) and opposite ($s_l s_{\tilde{l}} = -1;\ s_l = -s_{\tilde{l}}$) directions.

Averaging (4) over the spin states of the proton and antiproton, we obtain for the total cross section for the production of longitudinally polarized lepton-antilepton pairs in the annihilation of unpolarized protons and anti-

protons:

$$\sigma(E, s_l, s_{\tilde{l}}) = \frac{\pi\alpha^2}{48M_p^2}\,\frac{\beta_l}{\beta\gamma^2}\,(3-\beta_l^2-(1+\beta_l^2)s_l s_{\tilde{l}})\left\{\frac{1+2\gamma^2}{\gamma^2}|F_1|^2+\right.$$

$$\left.+\varkappa_a^2(2+\gamma^2)|F_2|^2-3\varkappa_a(F_1F_2^*+F_1^*F_2)\right\}. \tag{5}$$

If one is not interested in the polarization of the lepton pairs produced, then formula (5) should be summed over the spin states of the lepton (s_l) and antilepton ($s_{\tilde{l}}$). Then the term $\sim s_l s_{\tilde{l}}$ disappears, while the term independent of $s_l s_{\tilde{l}}$ is multiplied by 4. In the region of timelike momentum transfers, for the proton form factors we shall use the following approximate expressions ([7]):

$$F_1(q^2) = 1 - \frac{1.18\,q^2}{q^2+30\mu^2},$$

$$F_2(q^2) = 1 - \frac{1.59\,q^2}{q^2+30\mu^2}. \tag{6}$$

Here μ is the pion mass. Choosing the proton form factors in the form (6), and for $q^2 = -6.8$ $(\mathrm{BeV}/c)^2$ and $s_\mu s_{\tilde{\mu}} = -1$, from formula (5) we obtain for the annihilation cross section $\tilde{p}+p\to\mu^++\mu^-$ the value $\sigma_{\tilde{p}p\to\mu^+\mu^-}\cong 16\cdot 10^{-33}$ cm^2, which is in agreement with the results ([1]).

Fig. 1. Dependence of the total annihilation cross section $\tilde{p}+p\to\mu^++\mu^-$ on the proton energy.

Figure 1 presents the dependence of σ, calculated from (5) and (6), on the proton energy $\gamma = E/M_p$ for $s_\mu s_{\tilde{\mu}} = -1$ (curve 2) and $s_\mu s_{\tilde{\mu}} = 1$ (curve 3). Also shown is the energy dependence of the cross section σ_0, summed over the spin states of the lepton and antilepton (curve 1). From formula (5) and the figure it is evident that the energy dependence of the cross section of annihilation process (1) is very sensitive both to the proton form factors and to the polarization correlations of the lepton–antilepton pair produced. Taking account of the proton form factors and the spin states of the leptons leads to a noticeable decrease of the total cross section in comparison with the cross section for a point proton, as indicated by recent experiments ([1]).

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Received
3 XI 1964

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Note: Figure translations are in progress. See original paper for figures.