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Nucleon polarization in the process $e^+e^- \to N\bar{N}$ near threshold

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ABSTRACT

The process $e^+e^- \to N\bar{N}$ is studied nearby a threshold with account for polarizations of all initial and final particles. The nucleon polarization ζ^N reveals a strong energy dependence due to that of the nucleon electromagnetic form factors $G_E(Q^2)$ and $G_M(Q^2)$ caused by the final-state interaction of nucleons. It is shown that the modulus of the ratio of these form factors and their relative phase can be determined by measuring ζ^N along with the differential cross section. The polarization degree is analyzed using Paris $N\bar{N}$ optical potential for calculation of the form factors. It turns out that $|\zeta^N|$ is high enough in a rather wide energy range above the threshold. Being especially high for longitudinally polarized beams, $|\zeta^N|$ is noticeable even if both e^+e^- beams are unpolarized.

1. Introduction

Experiments with polarized antinucleons may substantially add to our knowledge of the nucleon–antinucleon ($N\bar{N}$) interaction. However, generating of polarized $\bar{N}$ is a complex task. Very recently it was proposed in Ref. [1] to produce polarized $\bar{N}$ at e^+e^- colliders in the reaction $e^+e^- \to N\bar{N}$. For longitudinal polarization of e^+e^- beams considered in Ref. [1], helicity conservation in the annihilation along with the fact that $N\bar{N}$ pair is produced near the threshold mainly with zero angular momentum provide high polarization degree of nucleon and antinucleon. Estimates done in Ref. [1] with parameters of $c\tau$-factory reported in Ref. [2] show that it is possible to probe a spin-dependent part of the $N\bar{N}$ inelastic scattering cross section using appropriate polarized targets. The spin-dependent part of the proton–antiproton, $p\bar{p}$, cross section is important at calculations of the polarization buildup rate in the $\bar{p}$ beam interacting with a polarized target in a storage ring (see, e.g., Ref. [3] and references therein).

A recent renewal of interest in low-energy $N\bar{N}$ physics has been stimulated, in particular, by experimental investigation of the proton (antiproton) electric, $G_E(Q^2)$, and magnetic, $G_M(Q^2)$, form factors in the process $e^+e^- \to p\bar{p}$ [4–6]. Namely, it was found that the ratio $r = |G_E(Q^2)/G_M(Q^2)|$ strongly depends on $Q^2 = 4E^2$ (E is the energy in the center-of-mass frame) nearby the reaction threshold at $E = M$. The most natural explanation of this phenomenon is final state interaction of the proton and antiproton, since a strong dependence at small $(E-M)/M$ addresses the interaction at distances much larger than $1/M$. Therefore, it is possible to use some phenomenological $N\bar{N}$ optical potentials for theoretical description of the process $e^+e^- \to N\bar{N}$, Refs. [7,8], as well as of other processes at low energy (see recent reviews [9,10]). Such potentials have many parameters which are determined by fitting existing experimental data. The imaginary part of these potentials is known worst of all. Therefore, new data on $N\bar{N}$ annihilation, especially the spin data, may essentially upgrade quality of theoretical predictions.

In the present Letter, the Paris $N\bar{N}$ optical potential suggested in Ref. [11] and then upgraded in [12–14] is applied to calculate $G_E(Q^2)$ and $G_M(Q^2)$ by the method used in [8]. We use the latest version of the Paris $N\bar{N}$ optical potential presented in Ref. [14]. Having the form factors at disposal, we analyze the hadron polarization ζ^N arising in the reaction $e^+e^- \to N\bar{N}$ for arbitrarily polarized e^+e^- beams. It is shown that both the ratio $r = |G_E(Q^2)/G_M(Q^2)|$ and the relative phase of the form factors χ can be extracted from data on ζ^N and the differential cross section. In a wide energy range above the threshold, the polarization degree is rather high for transversally and especially for longitudinally polarized beams. It turns out that the polarization is not too small even if both e^+ and e^- beams are unpolarized.

2. Form factors and nucleon polarization

Using a standard definition [15] of the electromagnetic hadronic current, one easily obtains the differential cross section of $e^+e^- \to N\bar{N}$ annihilation in the center-of-mass frame

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta S}{2Q^2} \left|G_M(Q^2)\right|^2, \tag{1}$$

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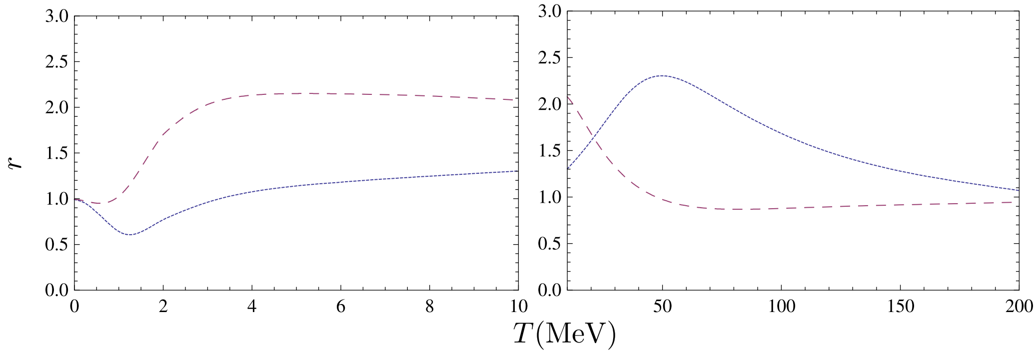

Fig. 1. Dependence of $r = |G_E(Q^2)/G_M(Q^2)|$ on kinetic energy $T = E - M$, $Q^2 = 4E^2$, for proton (solid line) and neutron (dashed line).

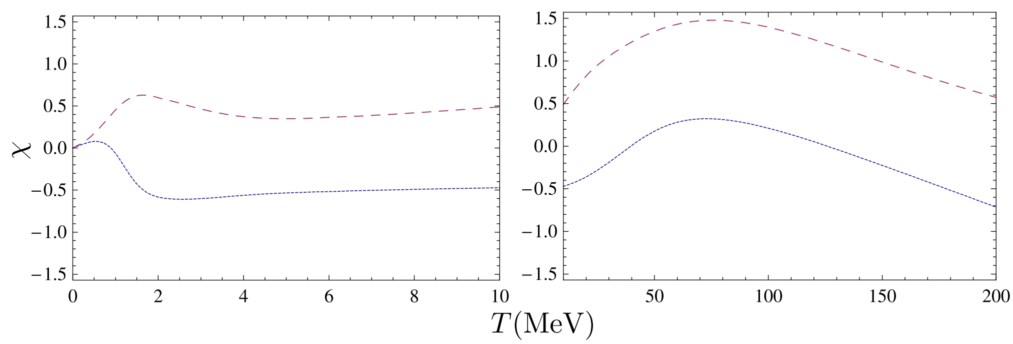

Fig. 2. Dependence of the phase $\chi = \arg(G_E(Q^2)/G_M(Q^2))$ on kinetic energy $T = E - M$, $Q^2 = 4E^2$, for proton (solid line) and neutron (dashed line).

where $\beta = \sqrt{1 - M^2/E^2}$ is the nucleon velocity, $Q^2 = 4E^2$, and

$$S = 1 + (\boldsymbol{\nu} \cdot \boldsymbol{\zeta}^-)(\boldsymbol{\nu} \cdot \boldsymbol{\zeta}^+) + (R^2 - 1)\left[\frac{1}{2}(1 + \boldsymbol{\zeta}^- \cdot \boldsymbol{\zeta}^+)\boldsymbol{n}_\perp^2 - (\boldsymbol{\zeta}^- \cdot \boldsymbol{n}_\perp)(\boldsymbol{\zeta}^+ \cdot \boldsymbol{n}_\perp)\right]. \quad (2)$$

Here $R = M|G_E(Q^2)|/(E|G_M(Q^2)|) \equiv rM/E$, $\boldsymbol{n} = \boldsymbol{p}/p$, $\boldsymbol{p}$ is the nucleon momentum, $\boldsymbol{n}_\perp = \boldsymbol{n} - \boldsymbol{\nu}(\boldsymbol{\nu} \cdot \boldsymbol{n})$, $\boldsymbol{\nu}$ is the unit vector parallel to the collision axis; $\boldsymbol{\zeta}^-$ and $\boldsymbol{\zeta}^+$ are polarizations of the e^- and e^+ beam, respectively. The cross section (1) is independent of the phase $\chi = \arg(G_E(Q^2)/G_M(Q^2))$. Small terms of the order of $(m_e/E)^2$ (m_e is the electron mass) were neglected in obtaining (1). As a result, the quantity S defined by Eq. (2) vanishes along with the cross section if both $\boldsymbol{\zeta}^+$ and $\boldsymbol{\zeta}^-$ are collinear with $\boldsymbol{\nu}$ and $\boldsymbol{\zeta}^- \cdot \boldsymbol{\zeta}^+ = -1$. So the expression (2) for S is valid if $1 + (\boldsymbol{\nu} \cdot \boldsymbol{\zeta}^+)(\boldsymbol{\nu} \cdot \boldsymbol{\zeta}^-) \gg (m_e/E)^2$.

If a polarization of only one of the created particles (nucleon or antinucleon) is measured, the polarization vector $\boldsymbol{\zeta}^N$ reads

$$\boldsymbol{\zeta}^N = \frac{1}{S}(\boldsymbol{\nu} \cdot \boldsymbol{\zeta}^- + \boldsymbol{\nu} \cdot \boldsymbol{\zeta}^+)\{\boldsymbol{n}(\boldsymbol{\nu} \cdot \boldsymbol{n}) + (\boldsymbol{\nu} - \boldsymbol{n}(\boldsymbol{\nu} \cdot \boldsymbol{n}))R\cos\chi\} + \frac{R}{S}\sin\chi\{[\boldsymbol{n} \times \boldsymbol{\nu}](\boldsymbol{\nu} \cdot \boldsymbol{n})(1 + \boldsymbol{\zeta}^- \cdot \boldsymbol{\zeta}^+) + [\boldsymbol{n} \times \boldsymbol{\zeta}_\perp^+](\boldsymbol{\zeta}^- \cdot \boldsymbol{n}_\perp) + [\boldsymbol{n} \times \boldsymbol{\zeta}_\perp^-](\boldsymbol{\zeta}^+ \cdot \boldsymbol{n}_\perp)\}, \quad (3)$$

where $\boldsymbol{\zeta}_\perp = \boldsymbol{\zeta} - \boldsymbol{\nu}(\boldsymbol{\nu} \cdot \boldsymbol{\zeta})$. Since $\boldsymbol{\zeta}^N$ depends on the phase χ, measurement of the nucleon polarization along with the differential cross section allows one to pin down the complex function $G_E(Q^2)/G_M(Q^2)$, that is to measure both $r(Q^2)$ and $\chi(Q^2)$.

To find the polarization $\boldsymbol{\zeta}^N$ from Eq. (3), one should first estimate the quantities $r(Q^2)$ and $\chi(Q^2)$. Here they are estimated using an approach described in detail in Ref. [8], where the Dirac form factors $F_1(Q^2)$ and $F_2(Q^2)$ were considered. The form factors $G_E(Q^2)$ and $G_M(Q^2)$ are expressed via Dirac form factors by (see, e.g., [15]) relations: $G_E = F_1 + \frac{Q^2}{4M^2}F_2$, $G_M = F_1 + F_2$. From these relations we have at the threshold $r(Q^2 = 4M^2) = 1$ and $\chi(Q^2 = 4M^2) = 0$. The scheme of calculations is as follows. The bare form factors $\tilde{F}_1$ and $\tilde{F}_2$ are introduced which address a short-range interaction. They weakly depend on Q^2 and can be considered as phenomenological constants in the vicinity of the threshold. These form factors are used if the interaction between the created particles at large distances $l \gg 1/M$ is neglected. The final state interaction described by an optical potential essentially modifies the wave functions at the distances $l \ll 1/(\beta M)$ where the hadronic state is formed. The wave functions at small distances are obtained by solving the Schrödinger equation for the wave function of the $N\bar{N}$ system with the total spin one and isospin one or zero. As a result, additional factors appear which are equivalent to turn from the bare form factors $\tilde{F}_{1,2}$ to the dressed form factors $F_{1,2}(Q^2)$. This renormalization is similar to that in quantum electrodynamics (QED) where the well-known Coulomb distortion factor (Sommerfeld–Schwinger–Sakharov rescattering factor [15]) appears in the reaction $e^+e^- \to \mu^+\mu^-$ close to the threshold of $\mu^+\mu^-$ pair production. It is important that, due to the tensor part of the potential of a strong $N\bar{N}$ interaction, the renormalization of $\tilde{F}_1$ differs from $\tilde{F}_2$ unlike the case of QED. The final set of constants $\tilde{F}_1$ and $\tilde{F}_2$ is that which provides the best fit to experimental data for these cross sections. Using this scheme and the latest version of the Paris optical potential [14], we obtain a dependence of the ratio r and the phase χ on kinetic energy $T = E - M$ shown in Figs. 1 and 2 for proton and neutron. In order to stress the strong dependence of these quantities on T in the region close to the threshold, we plot this region on a separate figure. It turns out that the main uncertainty of our predictions comes from rather big errors in available $n\bar{n}$ data. Therefore, more accurate measurement of $e^+e^- \to n\bar{n}$ cross section would essentially increase the accuracy of theoretical estimates of the form factors.