MEASUREMENT OF THE PROTON ELECTROMAGNETIC FORM FACTORS AT BABAR

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Abstract

The process $e^+ e^- \rightarrow p\bar{p}$ has been studied in the $p\bar{p}$ mass range from threshold to 6.5 GeV/$c^2$ using the initial-state-radiation technique with both detected and undetected photon. The analysis is based on 469 fb$^{-1}$ of integrated luminosity collected with the BABAR detector at the PEP-II collider at $e^+ e^-$ center-of-mass energies near 10.6 GeV.

1 Introduction

The energy dependence of the $e^+ e^- \rightarrow p\bar{p}$ cross section is given by

$$\sigma_{pp}(M_{pp}) = \frac{4\pi\alpha^2\beta C}{3M_{pp}^2} \left[ |G_M(M_{pp})|^2 + \frac{\tau}{2} |G_E(M_{pp})|^2 \right], \quad (1)$$

where $M_{pp}$ is the $p\bar{p}$ invariant mass, $\tau = 4m_p^2/M_{pp}^2$, $\beta = \sqrt{1-\tau}$, $C = y/(1-e^{-y})$ is the Coulomb correction factor [1], and $y = \pi\alpha(1+\beta^2)/\beta$. The cross section depends on two form factors, electric $G_E$ and magnetic $G_M$. From measurement of the cross section we determine the effective form factor

$$F_p(M_{pp})^2 = (|G_M(M_{pp})|^2 + \frac{\tau}{2}|G_E(M_{pp})|^2)/(1+\frac{\tau}{2}). \quad (2)$$

It should be noted that such a definition was used in all previous measurements made with assumption that $G_E$ is equal to $G_M$.

The $G_M$ and $G_E$ terms in the differential cross section have different angular dependencies, $1 + \cos^2 \theta$ and $\sin^2 \theta$, respectively. The ratio of the form factors can be extracted from the analysis of the proton angular distribution. At threshold $G_E = G_M$, and the angular distribution is uniform.

The process $e^+ e^- \rightarrow p\bar{p}$ is studied during 40 years [2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. However, all data before recent BABAR [8, 10, 11] and CLEO measurements [7, 9] had an accuracy of 20-30%. The statistics was not sufficient to determine $G_E/G_M$ ratio from angular analysis.
More precise results were obtained in the inverse reaction $p\bar{p} \rightarrow e^+e^-$ \cite{12, 13, 14}. In PS170 experiment \cite{12} at LEAR the proton form factor was measured near threshold. A steep near-threshold mass-dependence was observed. The $G_E$ to $G_M$ ratio was measured with about 30% accuracy and was found to be compatible with unity. Above 3 GeV/$c^2$ measurements were performed at Fermilab \cite{13, 14}. The strong decrease of the form factor was observed which agrees with the dependence $M_{p\bar{p}}^{-4}$ predicted by QCD for asymptotic proton form factor. Recently, very precise measurement of the form factor was performed on about 1.4 fb$^{-1}$ data collected by CLEO at 3.77 and 4.17 GeV \cite{9}.

2 Initial state radiation technique

The initial-state-radiation (ISR) method is used at BABAR to measure the $e^+e^- \rightarrow p\bar{p}$ cross section. In the ISR reaction $e^+e^- \rightarrow p\bar{p}\gamma$ the photon is emitted by the initial electron or positron. The mass spectrum of the $p\bar{p}$ pair is related to the cross section of the nonradiative process $e^+e^- \rightarrow p\bar{p}$.

The ISR photons are emitted predominantly along beam axis. There are two approaches in ISR measurements: tagged or large-angle (LA) ISR, when the ISR photon is required to be detected, and mainly small-angle (SA) untagged ISR. Only about 10% of the ISR photons can be detected at BABAR calorimeter. The produced $p\bar{p}$ system is boosted against the ISR photon. Due to limited detector acceptance, the $M_{p\bar{p}}$ region below 3 GeV/$c^2$ can be studied only with detected photon. Above 3 GeV/$c^2$ statistics can be significantly increased with the use of SA ISR.

The advantage of the ISR method over conventional $e^+e^-$ and $p\bar{p}$ experiments is that a wide mass region is studied in a single experiment. The large-angle ISR has additional advantages. The first of them is a low dependence of the detection efficiency on the $p\bar{p}$ invariant mass. Measurement near and above threshold can be done with the same selection criteria. The second is a low dependence of the detection efficiency on hadron angular distributions (in the hadron rest frame). For protons this significantly increases sensitivity for measurements of the $G_E/G_M$ ratio and decreases model uncertainty in the cross section measurement.

Here we present BABAR results based on analysis of 469 fb$^{-1}$ data collected at $e^+e^-$ c.m. energy near 10.6 GeV. Both LA ISR events \cite{10} and SA ISR events \cite{11} have been used for analysis.

The selection of $e^+e^- \rightarrow p\bar{p}\gamma$ candidates requires detection of two charged tracks of opposite charge originating from the interaction region and identified as protons. In LA ISR events a photon with the energy higher than 3 GeV is additionally required. For each LA ISR candidate a kinematic fit with requirement of total energy and momentum conservation is performed. The final selection is based on a condition on $\chi^2$ of the kinematic fit. For SA ISR candidate the selection is based on two parameters: the transverse momentum of the $p\bar{p}$ pair, and the invariant mass of the system recoiling against $p\bar{p}$. Both parameters should be close to zero.

The dominant source of background in the LA case arises from $e^+e^- \rightarrow p\bar{p}\pi^0$ events with an undetected low-energy photon, or with merged photons from the $\pi^0$ decay. This background is estimated using a control sample of $e^+e^- \rightarrow p\bar{p}\pi^0$ events. Its level is found to
change from 5% near threshold to 50% at 4 GeV/c$^2$. All observed $p\bar{p}\gamma$ candidates with the mass greater than 4.5 GeV/c$^2$ are consistent with $p\bar{p}\pi^0$ background. The contribution of other background processes is estimated to be about 1% of selected data events. The dominant background sources in the SA ISR case are the ISR process $e^+e^-\rightarrow p\bar{p}\pi^0\gamma$ and two-photon $p\bar{p}$ production. The background level is estimated to be about 5% and subtracted.

3 Results

From the measured $p\bar{p}$ mass spectrum we obtain the $e^+e^-\rightarrow p\bar{p}$ cross section and the proton effective form factor. In the mass region under study, the cross section changes by 6 orders of magnitude, from about 1 nb at the $pp$ threshold to about 1 fb at 6 GeV/c$^2$. The measured effective form factor is shown in Fig. 1 in comparison with existing $e^+e^-$ and $p\bar{p}$ data. Our data are in reasonable agreement with previous measurements everywhere except near-threshold region, where the BABAR results are systematically larger than the PS170 data [12].

The measured mass dependence of the ratio $|G_E/G_M|$ is shown in Fig. 2. To measure
the ratio the distribution of \( \cos \theta_p \) is analyzed, where \( \theta_p \) is the angle between the proton momentum in the \( pp \) rest frame and the momentum of the \( pp \) system in the \( e^+e^- \) c.m. frame. The measured ratio is higher than unity at masses below 2.2 GeV/\( c^2 \). Our results disagree with the previous PS170 measurement [12].

We have also searched for an asymmetry in the proton angular distribution. An asymmetry is absent in the lowest order (one-photon \( pp \) production). It arises from higher-order contributions (soft extra ISR and FSR interference, two-photon exchange). The integral asymmetry for events with \( pp \) mass below 3 GeV/\( c^2 \) is found to be consistent with zero:

\[
A_{\cos \theta_p} = \frac{\sigma(\cos \theta_p > 0) - \sigma(\cos \theta_p < 0)}{\sigma(\cos \theta_p > 0) + \sigma(\cos \theta_p < 0)} = -0.025 \pm 0.014 \pm 0.003. \tag{3}
\]

The measured form factor has a complex mass dependence. The growth of the form factor near threshold as well as the deviation of the ratio \( |G_E/G_M| \) from unity may be due to final-state interaction between the proton and antiproton [15]. At higher energies the form factor and cross section display a steplike mass dependence with three steps near 2.2, 2.5, and 3 GeV/\( c^2 \). Such a dependence is not described by existing models for the form factors (see, for example, Refs. [16, 17, 18, 19]). The \( e^+e^- \rightarrow pp \) cross section in the mass regions of the steps is shown in Fig. 3.

Figure 4 depicts the existing form-factor data above 3 GeV/\( c^2 \) in log scale. To compensate the main mass dependence of the form factor \( (1/m^4) \) we also show the scaled (multiplied by \( M_{pp}^4 \)) form factor. The dashed curve in Fig. 4 corresponds to a fit of the asymptotic QCD dependence of the proton form factor, \( m^4 F_p \sim \alpha_s^2(m) \) [20], to the form factor data. All the data above 3 GeV/\( c^2 \) except the two points marked “NU” [9] are well described by this function. Adding the “NU” points changes the fit \( \chi^2/\nu \) from 17/24 to 54/26. Our data shows that the form factor decreases in agreement with the asymptotic QCD prediction. The decrease may be even faster above 4.5 GeV/\( c^2 \). The local deviations of the “NU” points from the global fit may be result of the \( \psi(3770) \) and \( \psi(4160) \) resonance contributions.

The points marked “SLAC 1993” represent data on the space-like magnetic form factor measured in \( ep \) scattering [21]. The asymptotic values of the space- and time-like form factors are expected to be the same. In the mass region from 3 to 4.5 GeV/\( c^2 \) the time-like...
form factor is about two-three times larger than the space-like one. The new BABAR data at high masses give an indication that the difference between the time- and space-like form factors decreases with mass increase.

4 Summary

The $e^+e^- \rightarrow pp$ cross section and the proton effective form factor have been measured from threshold up to 6.5 GeV/$c^2$ using the full BABAR data sample.

The form factor has complex mass dependence. There are a near-threshold steep falloff and a step-like behavior at higher masses. At masses above 3 GeV/$c^2$ the observed decrease of the form factor agrees with the asymptotic dependence predicted by QCD or is even faster.

The $|G_E/G_M|$ ratio has been measured from threshold to 3 GeV/$c^2$. A large deviation of this ratio from unity is observed below 2.2 GeV/$c^2$. The asymmetry in the proton angular distribution has also been measured.

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