Polarized-Target Asymmetry in Pion-Proton Bremsstrahlung at 298 MeV

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Data are presented for the polarized-target asymmetry in $\pi^+ p \to \pi^+ p\gamma$ at incident pion energy of 298 MeV. The geometry was chosen to maximize the sensitivity to the radiation of the magnetic dipole moment μ_Δ of the Δ^{++}(1232 MeV). A fit of the asymmetry in the cross section as a function of the photon energy k to predictions from a recent isobar-model calculation yields $\mu_\Delta = 1.64(\pm 0.19$ expt, ± 0.14 theor) μ_p. Though this value agrees with bag-model corrections to the SU(6) prediction $\mu_\Delta = 2\mu_p$, further clarifications on the model dependence of the result are needed, particularly since the isobar model fails to describe both the cross section and the asymmetry at the highest photon energies.

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Baryon magnetic moments have traditionally played a central role in the development of quark models for hadronic states. However, because short lifetimes prevent the application of the spin-precession technique in a magnetic field, no data exist outside the ground state. In the case of the static moments of the $\Delta(1232)$, an alternative method using the reaction $\pi^+ p \to \pi^+ p\gamma$ was suggested quite some time ago.[1] Subsequent theoretical work[2] led to a first experiment for $\pi^\pm p \to \pi^\pm p\gamma$ at various energies around the Δ resonance,[3] which confirmed the radiation pattern predicted by the Low soft-photon theorem for hadronic processes and observed the destructive interference between external pion (π^+) and proton radiation in backward direction. However, it failed to observe the large enhancements in the cross section expected[1,2] in the kinematical window for the radiation from the magnetic dipole moment of the Δ (μ_Δ). The differential cross section followed a nearly k^{-1} (k is the photon energy) dependence. Only recently a dynamically consistent and gauge-invariant model for πN bremsstrahlung was developed,[4] which achieved a satisfactory representation of the existing, statistically limited data set from UCLA experiments[3] within the range $2.5 \le \mu_\Delta/\mu_p \le 3.5$. In this calculation, the πN dynamics entered via an isobar-model fit to the elastic-scattering phase shifts. Unfortunately, two alternative parametrizations were possible, which lead to bremsstrahlung cross sections differing by typically a factor of 2. It was argued by Moniz,[5] and shown in detail in the above model,[4] that the asymmetry in the cross section measured with a polarized target is not sensitive to these dynamical ambiguities, but still dependent on μ_Δ. This observation provided the main motivation for our experiment, which was designed to yield data for this hitherto unmeasured asymmetry. In a first step we measured the differential cross section for $\pi^+ p \to \pi^+ p\gamma$ with a liquid-hydrogen target at an incident pion momentum of 416 MeV/c.[6] These results confirmed the UCLA data,[3] where both data sets overlap, and agreed reasonably well with the theoretical predictions for μ_Δ in the range $2.3 \le \mu_\Delta/\mu_p \le 3.3$. They also showed the onset of discrepancies between theory and experiment at more backward pion angles. The experiment reached sufficient resolution in the kinematical quantities for $\pi^+ p\gamma$ events, that a measurement with a polarized target could also be attempted.

The experiment was performed at the 590-MeV proton cyclotron of the Paul Scherrer Institut. It made use of a 415-MeV/c pion beam providing 2.6×10^7 π^+/s within a 0.6% momentum bite. The setup is shown in Fig. 1 and some parameters are given in Table I. The target, consisting of 8-cm^3 frozen butanol beads, is dynamically polarized in a magnetic field of 2.5 T at a temperature of 0.5 K.[7] Either a positive or a negative polarization of the proton spins is achieved by applying microwaves of appropriate frequency without changing the direction or the magnitude of the magnetic field. The polarization P was measured by nuclear-magnetic-resonance methods using a fast-sweep Q meter calibrated against the natural (unenhanced) proton polarization at thermal equilibrium to an accuracy of 5%. The momentum of the scattered pion was measured in a magnetic spectrometer,[8] the proton energy and direction in a scintillator telescope equipped with a thin hodoscope for angular-resolution and energy-loss measurement and two total absorption counters. Photons were detected in an array of 64 NaI detectors ($6\times6\times40$ cm^3).[9] The general performance of these detector elements, their calibration, and the data-reduction techniques are described in our

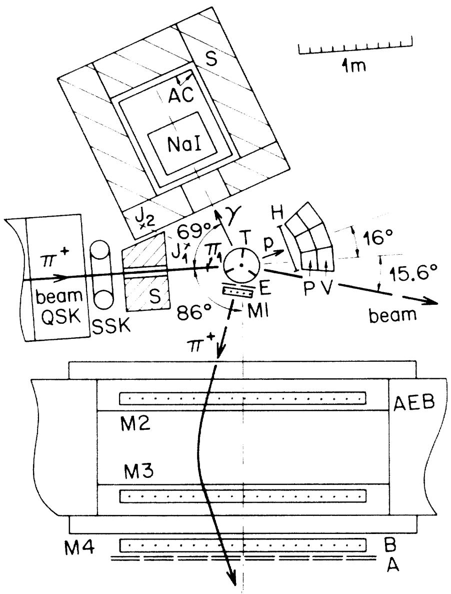

FIG. 1. Experimental setup. AEB, pion spectrometer magnet; QSK, quadrupole triplet; SSK, horizontal steering magnet; S, shielding; J_1,J_2, beam-monitor telescope (above beam plane); $M1$–$M4$, multiwire proportional chambers; T, polarized target; A,B,E, trigger-counter banks in pion spectrometer; H,P,V, proton hodoscope, total absorption, and veto counters; NaI, 64-fold photon-detector matrix; AC, cosmic-ray and charged-particle veto counters.

previous article[6] in more detail.

Starting from 2.2×10^6 triggers on tape we first selected those events with a pion and a proton in the correct detector arms using a combination of energy loss and time of flight for particle identification. The surviving events [Fig. 2(a)] were in the majority of cases πp elastic-scattering events on bound or free protons in coincidence with a random photon. To eliminate these, we required the pion momentum to be less than the momentum of an elastically scattered pion at the observed angle by at least 6 MeV/c [Fig. 2(a)]. After this cut the reconstructed-target-mass distribution [Fig. 2(b)] already showed a clear signal near m_p superimposed on a broad background. Random photons [time window B in Fig. 2(d)] had three main sources: (i) neutrons or (ii) photons from charge exchange or quasielastic scattering on bound neutrons induced by a second pion in the same beam burst (time correlated), and (iii) positrons from the decay of scattered π^+ inside the NaI (time uncorrelated). Only near the threshold of 20 MeV, a small chance existed that the energy of a random photon could balance the missing energy and momentum of the πp system. Consequently, the 5% random background events which survived the kinematical fit were nearly all found in the lowest-energy bin. Finally, we performed a four-constraint kinematical fit by the $\pi^+p\to\pi^+p\gamma$ hypothesis using the measured momenta and directions of the initial- and all three final-state particles as input.

TABLE I. Experimental parameters (laboratory system). The resolution is given for the center of the range and includes contributions from the target (e.g., energy loss or deflection in the polarizing field).

Quantity (typical range)	Resolution (FWHM)
Target mass	12 MeV/c^2
Beam momentum (415 MeV/c)	3.3 MeV/c
Beam angle horizontal (vertical)	1.7° (1.0°)
Pion momentum (170–320 MeV/c)	7.1 MeV/c
Pion angle (69°–110°) horizontal (vertical)	2.5° (0.4°)
Photon energy (20–125 MeV)	9.5 MeV
Photon angle (249° ± 10°) horizontal (vertical)	2.4° (2.4°)
Proton momentum (380–550 MeV/c)	16.5 MeV/c
Proton angle (31.6° ± 25.4°) horizontal (vertical)	4.0° (3.9°)
Polarization $\langle P\uparrow(\downarrow)\rangle=0.58\ (-0.47)$	±0.05[a]

[a]Relative error of the calibration; see Ref. 7.

The standard-deviation errors which entered this fit are given in Table I; the corresponding confidence-level distribution is shown in Fig. 2(e). The pion and proton parameters were checked using elastic-scattering data with a random photon, while the photon values stemmed from a separate $\pi^-p\to n\gamma$ calibration run with pions at rest. These calibration procedures also furnished elastic-scattering asymmetry data [Fig. 3(a)]. The bremsstrahlung asymmetry shown in Fig. 3(b) was calculated from those events which survived a cut at 20% confidence level. After the cut only 74 ($k\geq 20$ MeV: 32) random background events remained within the 1373 (1147) events of the final data sample. The reconstructed mass for these events is shown in Fig. 2(c). For a carbon dummy target the number of in-time events after random subtraction was consistent with zero (12 ± 15). At higher energies the statistical errors increase, because both the cross section and the acceptance decrease. The latter decreases because at smaller momenta fewer pions are accepted by the spectrometer and more decay, and because above $k=108$ MeV the protons begin to miss the proton detector in the forward direction.

The calculation of the asymmetry is, however, independent of the solid-angle effects. The asymmetry $A\equiv[\sigma(\uparrow)-\sigma(\downarrow)]/[\sigma(\uparrow)+\sigma(\downarrow)]$ was calculated from the event numbers $N_\pm$, the background $B_\pm$, and the average target polarization $P_\pm$,

$$A=\frac{N_+-qN_-}{qN_-P_+-N_+P_--(P_+-P_-)q(B_++B_-)/(q+1)}\,.$$

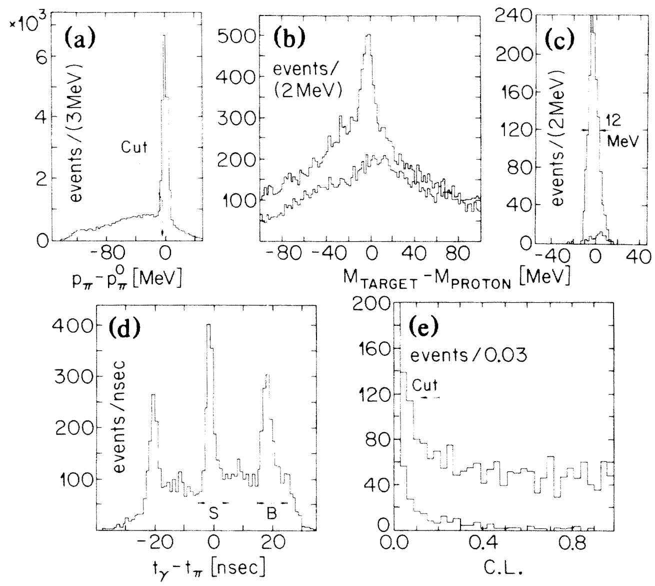

FIG. 2. Typical spectra illustrating the data-reduction method for events with a bremsstrahlung trigger. (a) Pion momentum relative to π^+p elastic-scattering momentum at the same angle. (b),(c) Reconstructed target mass for events to the left of the cut in (a), lower (upper) histogram for background (signal) time window in (d) for all runs. (c) Only events with a confidence level > 20% (final data sample). (d) Photon-pion relative-time spectrum for a single run. The center peak (S) contains true coincidences, the two side peaks (B) are from neighboring beam bursts (50-MHz accelerator radio frequency). (e) Confidence-level distribution for all events submitted to the kinematical fit (see text), upper (lower) histogram as in (b).

Here $P_\pm = P(\uparrow\downarrow)$ refers to the normal to the scattering plane $\hat{\mathbf{n}} = (\mathbf{p}_\pi^{\rm in} \times \mathbf{p}_\pi^{\rm out})/|\mathbf{p}_\pi^{\rm in} \times \mathbf{p}_\pi^{\rm out}|$, $q = N_+^\pi/N_-^\pi$ $(=B_+/B_-$ for polarization-independent background as found here), $N_\pm^\pi$ is the number of pions for each polarization direction taken from the beam-monitor telescope, and $P_\pm = (\sum_i N_{i\pm}^\pi P_{i\pm})/N_\pm^\pi$. The summation was taken over individual runs, and corrections were made for small-run-dependent, but polarization-independent variations in chamber efficiencies.

The asymmetries shown in Fig. 3 include the systematic error from the measurement of the polarization added linearly. The elastic-scattering data agree very well with previous data at approximately the same momenta[10] as well as recent phase-shift analysis,[11] which may be taken as evidence for the correctness of normalization and calibration procedures.

To extract μ_Δ, we computed the cross section and the asymmetry averaged over the experimental acceptance for the MIT model[4] in the range $0.1 \le \mu_\Delta/\mu_p \le 3.0$ in typically $0.3\mu_p$ steps, except near the best-fit value, where a finer step size $(0.1\mu_p)$ was chosen [see Fig. 3(b)]. Both parametrizations for the $\pi N\Delta$ vertex function $f_{\pi N\Delta}H(q^2) = m_\pi g/(1+q^2/\alpha^2)^n$ and the Δ propagator $G_\Delta = (E - M_\Delta - \Sigma_\Delta)^{-1}$ were used: (i) $\alpha = 1.2$ fm^{-1}, $g = 2.12 m_\pi^{-3/2}$, $M_\Delta = 1445$ MeV, $n=1$ and (ii) $\alpha = 2.2$ fm^{-1}, $g = 1.79 m_\pi^{-3/2}$, $M_\Delta = 1322$ MeV, $n=2$. The first set gave better fits[4,6] to the cross-section data at various energies,[3,6] but for the asymmetry the difference is small, and the second set is used mainly to assess the systematic error. For the preferred model (i) we obtained $\mu_\Delta/\mu_p = 1.64 \pm 0.19$ for $k \le 95$ MeV (number of data points $n_D = 5$, $\chi^2 = 2.0$). When the fit was extended to the maximum energy or restricted to $k \le 80$ MeV, we found $\mu_\Delta/\mu_p = 1.59 \pm 0.17$ $(n_D = 7, \chi^2 = 7.2)$ or 1.71 ± 0.20 $(n_D = 4, \chi^2 = 1.2)$, respectively, while model (ii) yielded 1.50 ± 0.21 $(n_D = 5, \chi^2 = 2.1)$.

At the highest photon energies the agreement with the predictions is poorer, but the dependence on μ_Δ is weak and hence the shift in the results with the energy-range limits small. This is not the case for the cross-section data.[6] We repeated the fits to the latter data for the lim-

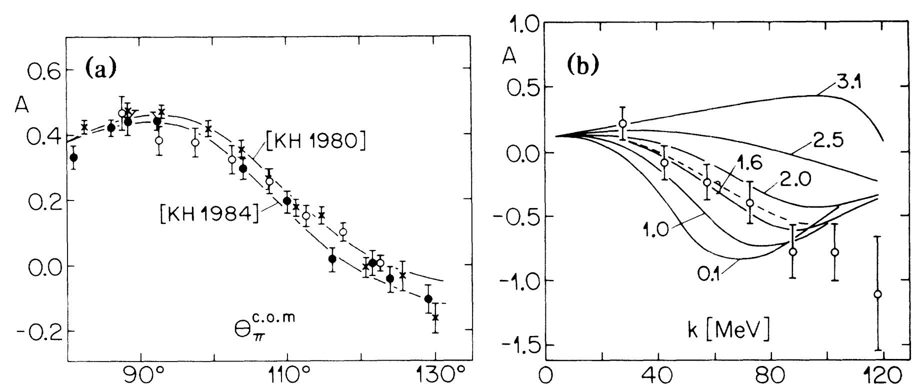

FIG. 3. Polarized-target asymmetry in π^+p elastic scattering vs pion angle (○) in this experiment compared to the Karlsruhe-Helsinki (KH 1980/84) phase-shift analysis (Ref. 11) and previous data (●,×) (Ref. 10). (b) Asymmetry for bremsstrahlung events vs photon energy averaged over all pion angles. The solid curves are theoretical predictions (Ref. 4) computed with our angular acceptance for various values of μ_Δ/μ_p. The dashed curve shows the influence of the alternative parametrization for the Δ vertex function (see text for details).

ited energy region with $k \leq 80$ MeV and the angular region $75° \leq \Theta_\pi \leq 95°$ (backward data sample to overlap with the present sample) and obtained $\mu_\Delta/\mu_p = 1.9 \pm 0.3$ [(i) $n_D = 4$, $\chi^2 = 6.0$] and 1.8 ± 0.3 [(ii) $\chi^2 = 30$], consistent with our present results, but to be contrasted with the value from the complete data set $\mu_\Delta/\mu_p = 2.80 \times (\pm 0.25$ expt, ± 0.25 theor). With smaller values of μ_Δ, the predicted cross section considerably exceeds the measured one for the highest energies (see Ref. 6). This comparison demonstrates the advantage of the asymmetry measurement and shows that the theoretical uncertainty from the choice of the input parameters for the isobar dynamics as well as the energy range used in the fit is limited to $|\delta\mu_\Delta| \leq 0.14\mu_p$. The isobar model is expected[4] to be less reliable at higher energies ($k \approx \Gamma_\Delta = 116$ MeV), where one is farthest off the mass shell, free from the bounds set by Low's theorem at low k and beyond the point, where the invariant mass of the final $\pi^+ p$ system is equal to the physical Δ mass ($k = 60$ MeV in our kinematics) and where the sensitivity to μ_Δ is maximal.

In the simple SU(6) model one expects $\mu_\Delta/\mu_p = e_\Delta/e_p = 2$, i.e., the ratio of the charges e.[12,13] Pion-cloud contributions will lead to a downward correction of the nonstrange quark moments, and it was estimated[14] that the Δ^{++} magnetic moment will be renormalized by 17% to 21%. These bag-model results are supported by our experiment. Despite this encouraging fact, we feel that further asymmetry and cross-section measurements are needed as well as variants of the theoretical model used to examine more closely the model dependence of our result. Various extensions of the soft-photon results to higher energies exist in the literature and are cited in Ref. 4, but predictions for the comparison with our data are missing.

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