Angular distributions of pion-proton bremsstrahlung at 298 MeV*

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We report new measurements of $\pi^{\pm}p \to \pi^{\pm}p\gamma$ at 18 photon angles for 298-MeV incident pions. At all angles, the photon spectrum falls monotonically with increasing E_γ, and lacks the predicted structure due to the $\Delta(1232)$ resonance. The soft-photon approximation agrees with the data for $E_\gamma < 50$ MeV only. For higher E_γ, the simple external-emission-dominance calculation provides an acceptable but imperfect description of all results.

Hadron-hadron bremsstrahlung is a unique probe of strong interactions because the electromagnetic coupling of the photon is only a small perturbation to the hadronic interaction. Pion-nucleon bremsstrahlung is of particular interest because the π-N interaction exhibits strong resonances.

We report here a measurement of the photon angular distributions for $\pi^{\pm}p \to \pi^{\pm}p\gamma$ at an incident-pion energy of 298 MeV. In a previous experiment[1,2] we have measured these processes in a very limited detector geometry designed to optimize a possible determination of the magnetic dipole moment of the $\Delta^{++}(1232)$ in the manner first discussed by Kondratyuk and Ponomarev.[3] It was found that for both processes $d^5\sigma/d\Omega_\pi d\Omega_\gamma dE_\gamma$ decreases smoothly with increasing photon energy E_γ in contrast with theoretical calculations,[3,4] which predict a large bump around $E_\gamma \approx 70$ MeV, reflecting the formation of the $\Delta(1232)$ resonance (e.g., $\pi^+p \to \Delta^{++}\gamma \to \pi^+p\gamma$). For $E_\gamma < 50$ MeV, various calculations of the differential cross section agree approximately with the data.

A variety of models have been advanced to explain the results of Refs. 1 and 2. Musakhanov[5] recently published a new calculation of $\pi^+p \to \pi^+p\gamma$ which gives a value of $(3.6 \pm 2)\mu_p$ for the magnetic dipole moment of the $\Delta^{++}(1232)$ resonance when applied to the data of Ref. 1. An interesting aspect of Musakhanov's calculation is the use of partially conserved axial-vector current (PCAC) and current algebra,[6] and it incorporates the soft-pion limit of the $\pi^+p \to \pi^+p\gamma$ amplitude extracted from experiments on neutrino-induced pion production.[7,8] Piccioto[9] has analyzed $\pi^-p \to \pi^-p\gamma$ data to investigate off-mass-shell matrix elements. Beder[10] has made a critical analyses of the established $\pi^+p \to \pi^+p\gamma$ calculations,[3,4] and Thompson[11] and Bosco *et al.*,[12] have advanced static models which give a smoothly falling photon spectrum at the particular photon angles of Refs. 1 and 2.

The present experiment was designed to measure the differential $\pi^{\pm}p$ bremsstrahlung spectrum over an extended photon angular range, including the region around the scattered pion and recoil proton where the cross sections are large compared to the ones reported in Refs. 1 and 2. The new measurements allow a critical test of various models recently proposed to explain the $\pi^{\pm}p \to \pi^{\pm}p\gamma$ data of Refs. 1 and 2 and, in particular, Musakhanov's evaluation of the magnetic dipole moment of the Δ resonance.

Our experiment used a setup similar to that described in Ref. 2, except for the addition of nine new photon counters labeled $G_{11}-G_{19}$. The results for eight new photon counters will be reported here. The counter positions are given in Table I and are also indicated in Fig. 1; the position of the center of each counter is described by the horizontal projection angle α, measured clockwise from the beam line, and the angle of elevation β, measured upwards from the horizontal plane. The front face of counters $G_{11}-G_{15}$, G_{18}, and G_{19} is 63 cm away from the center of the hydrogen target, and for G_{17} it is 300 cm.

The experiment was performed at the Lawrence Berkeley Laboratory 184-in. cyclotron. A π^+ or π^- beam was incident on a liquid hydrogen target, and all three final-state particles were detected. The scattered pion was momentum-analyzed in a magnetic spectrometer centered on an angle of 50.5° to the beam line. The recoil proton was detected in a set of wire spark chambers and a scintillator range telescope. The photon direction was measured by one of 19 lead-glass Cherenkov counters,[13] 10.2 cm square and five radiation lengths thick. The photon energy was reconstructed in a two-constraint kinematic fit to the measured variables. The most serious background, $\pi^{\pm}p \to \pi^{\pm}p\pi^0$, was easily rejected by the additional proton-range information as well as by a cut on χ^2. Full experimental details are given in Ref. 2.

Our results are presented in Tables I and II. Counters G_1-G_{10} have been combined, as their distribution has already been reported[2]. The

TABLE I. Differential cross section $d^5\sigma/d\Omega_\pi d\Omega_\gamma dE_\gamma$ in nb/sr^2 MeV in the laboratory for $\pi^+p\to\pi^+p\gamma$ at 298 MeV incident π^+ for different photon counters and photon energy intervals. G = photon counter. α is the horizontal projection angle measured clockwise from the beam line. β = angle of elevation measured upwards from the horizontal plane. The location of G_1–G_{10} is given in Ref. 2.

G	α	β \ E_γ	15–30 MeV	30–50 MeV	50–70 MeV	70–90 MeV	90–110 MeV	110–130 MeV	130–150 MeV
1–10			1.93 ± 0.29	1.10 ± 0.17	1.03 ± 0.15	0.76 ± 0.13	0.44 ± 0.09	0.44 ± 0.12	
11	160°	0	4.9 ± 1.3	3.0 ± 0.8	1.53 ± 0.56	0.96 ± 0.43	0.41 ± 0.29	0 ± 0.3	
12	140°	0	12.4 ± 2.3	5.2 ± 1.1	3.1 ± 0.8	2.1 ± 0.7	0.21 ± 0.21	0 ± 0.3	0 ± 0.5
13	120°	0	24.7 ± 3.8	16.1 ± 2.3	9.0 ± 1.5	7.9 ± 1.4	2.4 ± 0.7	1.09 ± 0.50	0 ± 0.3
14	103°	0	42.3 ± 5.6	24.9 ± 3.2	13.5 ± 1.9	8.5 ± 1.4	7.3 ± 1.3	1.34 ± 0.55	1.1 ± 0.5
15	103°	−20°	40.3 ± 5.5	21.7 ± 2.9	11.0 ± 1.7	8.9 ± 1.5	6.6 ± 1.3	3.3 ± 0.9	0.3 ± 0.3
17	50°	4°		133 ± 78	44 ± 44	108 ± 65	108 ± 49	87 ± 44	44 ± 31
18	320°	−56°	30.6 ± 4.7	23.5 ± 3.2	21.8 ± 3.2	15.6 ± 2.9	13.2 ± 3.0	12.2 ± 3.2	7 ± 3
19	0	−59°	69.8 ± 8.6	42.0 ± 5.0	31.0 ± 3.6	27.2 ± 3.6	19.3 ± 3.0	11.2 ± 2.3	9.2 ± 2.2

agreement with the previous work is good. The errors quoted for the results of counter G_{17} are larger than those of other counters for two reasons. G_{17} is located far away behind the pion spectrometer magnet and subtends only $\frac{1}{20}$ of the solid angle of other photon counters. Scattered pions that interact in the pion counters and in the shielding blocks give rise to a large background which is hard to discriminate against.

Figure 1 shows the cross sections for our "coplanar" ($\beta = 0^0$) photon counters G_1, G_4, G_7, and G_{11}–G_{14} in the interval $15 < E_\gamma < 30$ MeV, plotted vs the horizontal projection angle α. The dashed curve represents the prediction of the soft-photon approximation (SPA)[2] for a photon energy of 22.5 MeV averaged over the experimental acceptance by a Monte Carlo calculation. The SPA is based on Low's prescription[14] for calculating the first two terms of an expansion in E_γ of the bremsstrahlung matrix element. The solid curve is the prediction of a simple calculation containing essentially the leading term of a Low-type expansion. We have named this calculation the "external-emission dominance" (EED), and have shown that it gives a reasonable description of our preliminary experimental results.[15] In the intervals $15 < E_\gamma < 30$ MeV and $30 < E_\gamma < 50$ MeV, SPA and EED both give a good account of the absolute magnitude and the strong angular variation of the cross section for π^+ and π^- bremsstrahlung. Only in these two intervals do our π^+ results agree better with SPA than EED. There are no adjustable parameters in the SPA and EED calculations. They depend only on the pion-nucleon interaction through the elastic-scattering amplitudes; in fact, the EED cross section is proportional to the measured elastic cross section.

The substantial difference between π^+ and π^- bremsstrahlung, apparent in Fig. 1, is due primarily to the interference of radiation from the

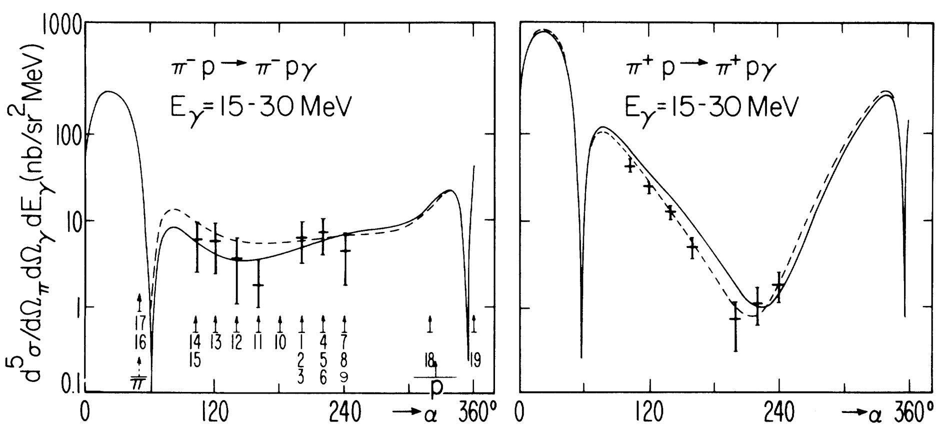

FIG. 1. Coplanar angular distribution ($\beta = 0$) of $d^5\sigma/d\Omega_\pi d\Omega_\gamma dE_\gamma$. ----: soft-photon approximation (Refs. 2 and 14) for $E_\gamma = 22.5$ MeV. ——: external emission dominance (Ref. 15) for $E_\gamma = 22.5$ MeV. Solid vertical arrow: position of photon counter. Dashed vertical arrow: scattered pion angle. Arrow above p: recoil proton angle. Crosses: data points for coplanar counters G_1, G_4, G_7, and G_{11}–G_{14}.

TABLE II. Differential cross section $d^5\sigma/d\Omega_\pi d\Omega_\gamma dE_\gamma$ in nb/sr^2 MeV for $\pi^- p \rightarrow \pi^- p\gamma$. See caption of Table I.

G \ E_γ	15–30 MeV	30–50 MeV	50–70 MeV	70–90 MeV	90–110 MeV	110–130 MeV	130–150 MeV
1–10	5.7 ± 1.1	4.7 ± 0.9	2.2 ± 0.5	2.6 ± 0.6	0.94 ± 0.34	0.61 ± 0.31	
11	1.8 ± 1.8	1.3 ± 1.3	0 ± 1.3	0 ± 1.3	0 ± 1.4	0 ± 1.6	
12	3.7 ± 2.6	3.9 ± 2.3	3.9 ± 2.3	0 ± 1.3	0 ± 1.4	0 ± 1.6	
13	5.9 ± 3.5	7.9 ± 3.3	7.9 ± 3.3	1.3 ± 1.3	0 ± 1.4	0 ± 1.5	0 ± 2.3
14	6.1 ± 3.6	5.4 ± 2.8	1.3 ± 1.3	4.0 ± 2.3	2.9 ± 2.0	1.5 ± 1.5	0 ± 1.8
15	14.0 ± 5.5	5.4 ± 2.8	1.3 ± 1.3	2.7 ± 1.9	1.4 ± 1.4	3.1 ± 2.2	0 ± 1.8
17	93 ± 93	0 ± 64	0 ± 63	62 ± 63	0 ± 63	0 ± 63	0 ± 65
18	16.5 ± 6.1	5.8 ± 2.9	11.4 ± 4.5	14.0 ± 5.6	12.7 ± 6.0	10.3 ± 6.2	4.7 ± 4.7
19	26.3 ± 7.8	15.4 ± 4.9	9.9 ± 3.8	4.6 ± 2.7	5.2 ± 3.1	4.1 ± 2.9	8.2 ± 4.8

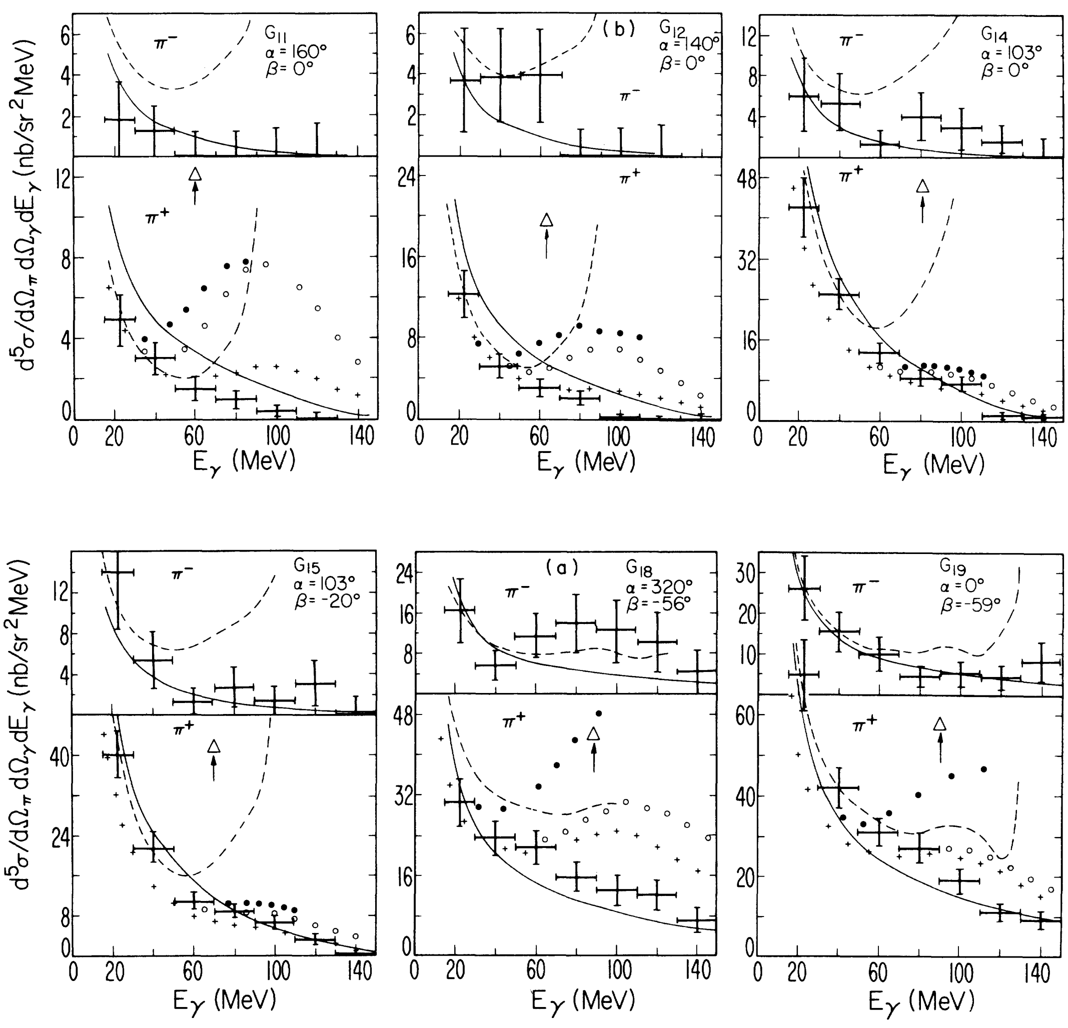

FIG. 2. Laboratory differential cross section for different photon counters. ----: soft-photon approximation (Refs. 2 and 14). ——: external-emission dominance (Ref. 15). ++++: Kondratyuk and Ponomarev (Refs. 3 and 16) for $\mu(\Delta^{++}) = 2\mu_p$. ○○○○: Kondratyuk and Ponomarev (Refs. 3 and 16) for $\mu(\Delta^{++}) = 0$. ●●●●: Fischer and Minkowski (Ref. 4) for $\mu(\Delta^{++}) = 2\mu_p$. Δ with vertical arrow: peak of Δ(1232) resonance. Crosses: data points from this experiment.

proton and the pion. For photon angles near $\alpha \approx 220°$ this interference is destructive for π^+ and constructive for π^-. The consequent deep minimum in the π^+ bremsstrahlung cross section gives the most favorable condition for probing internal structure effects, as suggested in Ref. 3.

The cross sections as a function of photon energy are shown in Fig. 2 together with the predictions of SPA and EED for six representative photon counters. Kondratyuk and Ponomarev[3] (KP) have made an isobar calculation of $\pi^+ p \to \pi^+ p\gamma$ that incorporates the contribution of the magnetic dipole moment of the $\Delta^{++}(1232)$. The KP prediction, as modified slightly by Vanzha and Musakhanov[16] and evaluated for the acceptance of our detectors, is shown in Fig. 2 for two cases: $\mu(\Delta^{++}) = 2\mu_p$ (the SU(6) prediction) and $\mu(\Delta^{++}) = 0$. Also shown is the prediction by Fischer and Minkowski[4] (FM), based on an extension of the soft-photon formalism of Low, for the case $\mu(\Delta^{++}) = 2\mu_p$.

Inspection of Fig. 2 shows that SPA is good up to $E_\gamma \approx 50$ MeV. Above this energy the SPA calculations appear to "blow up" because of a combination of effects: a resonant rise in the proton-magnetic-moment contribution, breakdown of the linear approximation, large values of the derivative of the amplitude, and rapid variation in the effective elastic-scattering angle. These matters will be treated in a subsequent publication.

The various bremsstrahlung calculations are expected to converge to the well-known limit of $1/E_\gamma$ at low E_γ. The KP isobar-model calculation (Fig. 2) does not quite do so because it omits the s_{31} and p_{31} partial waves in the πp interaction; the other calculations use a complete set of partial waves.

Figure 2 shows that our π^+ data do not agree with the KP and FM calculations. The disagreement at the new photon angles is not as extreme as for the backward angles reported previously.[2] In general, the discrepancy is greatest where the cross section is smallest.

A satisfactory, though not perfect, description of our experimental results at all angles for both π^+ and π^- and up to the highest photon energy of 140 MeV is given by EED.[15] The EED calculation contains only the external-charge-radiation contribution, and neglects the proton's magnetic dipole moment as well as all off-mass-shell and strong-interaction-related contributions. The reason why this exceedingly simple, parameter-free calculation appears valid here remains a mystery.

The most conspicuous feature of our data as shown in Fig. 2 is the monotonic decrease of the cross section with increasing photon energy and the absence of any obvious bump or structure related to the presence of the $\Delta(1232)$ in the final state.

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