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Proton-Proton Bremsstrahlung at 730 MeV*

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We have measured the differential cross section for proton-proton bremsstrahlung at sixteen photon angles for 730-MeV incident protons. At all angles, the photon spectra fall smoothly with increasing photon energy up to $E_\gamma \sim 80$ MeV and are in quantitative agreement with the prediction of external-emission dominance (EED). Above $E_\gamma \sim 80$ MeV the spectra are consistently above the EED calculations.

We report on new measurements of proton-proton bremsstrahlung (PPB) at an incident energy of 730 MeV. This energy is substantially higher than that of previous PPB measurements,[1] making our experiment different from earlier ones in some important ways. First, the maximum photon energy at many angles is so large that the photon wavelength is smaller than the hadronic interaction radius. At such photon energies, PPB can be sensitive to the internal structure of the nucleon-nucleon interaction. Second, the incident proton energy is well above the pion production threshold and approximately half of the pp total cross section at 730 MeV is inelastic. All previous PPB experiments have been below pion production threshold. There is no potential model which describes the elastic scattering at 730 MeV and there are no theoretical calculations of PPB in the inelastic region. Even the soft-photon approximation (SPA), which is based on the theorem of Low[2] and is expected to be valid for low-energy photons, cannot be evaluated at our energy. Although the SPA for PPB have been worked out explicitly by Nyman[3] and Fearing,[4] it requires the decomposition of the pp elastic scattering amplitude into five invariant functions $F_\alpha(\nu, \Delta)$ which are not known in this energy region. The one feasible calculation for PPB at our energy is external-emission dominance (EED),[5] which is based on the leading term of the SPA calculation, and has been successful in describing the results of experiments on $\pi^\pm p \to \pi^\pm p\gamma$.

Interest in PPB in the inelastic region has been greatly stimulated recently by the discovery of an unexpectedly large lepton-to-pion ratio in the final states of pp interactions at high energy. It has been proposed that this anomaly is entirely[6] or partly[7,8] of electromagnetic origin. These proposals can be tested in PPB at a high incident beam energy.

The presence of inelastic channels (especially π^0 production) also introduces experimental complications. An overconstrained detection arrangement must be used in order to separate PPB events from backgrounds.

The experiment was performed at the Lawrence Berkeley Laboratory 184-in. cyclotron, and used a modification of the apparatus employed by the University of California at Los Angeles group in $\pi p \to \pi p\gamma$ experiments.[9-11] A new proton beam was constructed to transport the highest proton energy available at the cyclotron. The geometry of the experiment is shown in Fig. 1. Protons scattered at $\theta_p \sim 50.5°$ are detected by a large-aperture magnetic spectrometer bending vertically, with two sets of three wire spark chambers for measurement of the momentum and scattering angle. The direction of the recoil proton is measured by a set of three wire spark

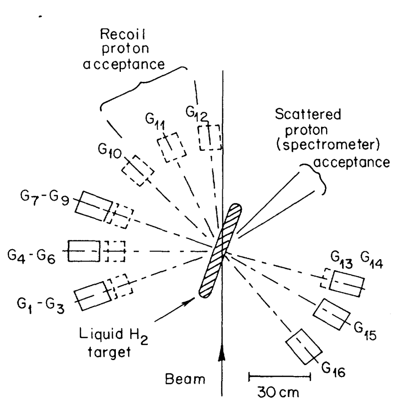

FIG. 1. Plan view of detector system. G_n is photon counter. The dashed-line rectangles indicate photon counters located below the horizontal plane.

chambers and counters on the opposite side of the beam line. Sixteen lead-glass Cherenkov counters are used to measure the photon direction and to provide good timing information. The location of the counters is given in Table I. Each photon counter subtends an angular width of approximately $\pm 5°$ horizontally and vertically. The efficiency of the photon counters as a function of photon energy has been accurately determined.[12] The acceptances of the two proton detectors are given in the caption of Table I.

The setup allows us to make a two-constraint fit of every recorded event to the $pp \to pp\gamma$ hypothesis with the photon energy calculated from the fit. After a preliminary geometric cut, the χ^2 of the fit is used to separate good PPB events from the substantial background in the experiment, which is predominantly $pp \to pp\pi^0$. The background discrimination is excellent. Small subtractions based on the χ^2 and photon time-of-flight distributions were used to remove the remaining background of π^0 and random events. Furthermore, a small correction was applied for accidental anticoincidences. The proton and photon solid-angle acceptances have been obtained from Monte Carlo calculations, and the photon counter efficiency determined as in Ref. 12.

As a check on the acceptance and normalization of our experiment, we have measured the pp elastic scattering cross section averaged over our spectrometer acceptance. The result (in the center-of-mass system) is $d\sigma/d\Omega^* = 1.9 \pm 0.2$ mb/sr at an average scattering angle of $\theta^* = 112°$ with an acceptance of $\pm 10°$. The predicted value is $d\sigma/d\Omega^* = 1.9 \pm 0.2$ mb/sr based on averaging the fits of Ryan *et al.*[13] over our acceptance. We have assumed that the polarization of the incident protons is negligible.[14]

The results of our experiment are expressed in terms of the laboratory differential cross section $d^5\sigma/d\Omega_{p_s} d\Omega_\gamma dE$, averaged over the system acceptance for each photon counter and 20-MeV-wide bins in photon energy. The $d\Omega_{p_s}$ refers to the solid angle of the proton that scatters into the spectrometer. The preliminary results of our experiment for all sixteen photon counters are listed in Table I. The maximum photon energy observable is limited by kinematics and varies considerably with photon-counter position. The photon energy resolution (rms) is better than 4 MeV for all counters except G_{10}, G_{11}, and G_{12} for which it is 6, 8, and 8 MeV, respectively. The quoted resolution has been obtained from the analysis of a sample of $pp \to pp$ events that were

TABLE I. Differential cross section $d^5\sigma/d\Omega_{p_s}\, d\Omega_\gamma dE_\gamma$ in nb/sr^2 MeV in the laboratory for $pp \to pp\gamma$ at 730-MeV incident protons for different photon energy intervals, for all photon counters. G_n is the proton counter number. α is the horizontal projection angle measured clockwise from the beam line. β is the angle of elevation measured upwards from the horizontal plane. d is distance in inches from center of target to front of photon counter. The solid angle of the proton spectrometer is given by $\alpha = 50.5 \pm 7.0°$ and $\beta = 0°{}^{+24°}_{-10°}$. The recoil-proton detector covers a solid angle given by $\alpha = 325 \pm 25°$ and $\beta = 0 \pm 26°$.

				E_γ (MeV)						
G	α	β	d	20 - 40	40 - 60	60 - 80	80 - 100	100 - 120	120 - 140	140 - 160
1	254°	-1°	23.2	5.7 ± 1.0	3.6 ± 0.9	3.0 ± 1.2				
2	250°	-19°	23.3	5.7 ± 1.1	2.3 ± 0.8	2.5 ± 1.2				
3	250°	-37°	23.5	3.2 ± 0.8	3.2 ± 0.7	2.4 ± 1.0				
4	270°	-2°	23.2	8.6 ± 1.3	3.8 ± 0.8	3.7 ± 0.8	3.3 ± 1.4			
5	269°	-19°	23.3	8.6 ± 1.2	5.8 ± 1.0	4.9 ± 1.0	1.6 ± 1.0			
6	270°	-37°	23.4	6.6 ± 1.1	4.0 ± 0.9	2.6 ± 0.8	3.4 ± 1.2			
7	293°	-1°	23.5	6.5 ± 1.1	4.1 ± 0.9	3.4 ± 0.8	4.2 ± 0.9	4.8 ± 1.1	5.9 ± 1.8	
8	293°	-19°	23.3	7.7 ± 1.2	4.5 ± 0.9	4.1 ± 0.8	3.0 ± 0.8	4.0 ± 1.0	5.4 ± 2.1	
9	292°	-36°	23.6	6.6 ± 1.0	3.3 ± 0.7	4.0 ± 0.8	3.6 ± 0.8	3.6 ± 1.3		
10	318°	-38°	27.1	4.1 ± 1.0	2.3 ± 0.8	1.7 ± 0.6	2.1 ± 0.7	3.0 ± 0.8	3.0 ± 1.1	4.5 ± 1.5
11	335°	-38°	27.1	4.1 ± 1.8[a]	5.9 ± 1.3	4.5 ± 1.1	3.1 ± 1.1	4.3 ± 1.1	6.2 ± 1.3	5.3 ± 1.3
12	355°	-39°	27.1	6.7 ± 1.6[a]	4.8 ± 1.0	4.5 ± 1.0	2.6 ± 0.7	3.4 ± 0.8	3.8 ± 1.1	3.9 ± 1.0
13	104°	1°	22.2	6.7 ± 1.0	2.4 ± 0.8					
14	105°	-22°	22.0	5.4 ± 1.0	3.6 ± 0.9					
15	122°	1°	22.3	8.0 ± 1.3	2.7 ± 1.1					
16	142°	0°	22.3	5.2 ± 1.1						

[a]Photon energy interval limited to 30–40 MeV.

handled as $pp \to pp\gamma$ events. In view of the limited photon-energy resolution of counters G_{11} and G_{12} (which leads to a poor discrimination against elastic scattering events), we report only results for $E_\gamma \geq 30$ MeV for these two counters.

The angular distribution of the laboratory differential cross section for the photon interval $20 \leq E_\gamma < 40$ MeV ($30 \leq E_\gamma < 40$ MeV for G_{11} and G_{12}) is shown in Fig. 2. The EED predictions (based on Ref. 5) are indicated by the open rectangles. In the calculation we have taken the pp elastic cross sections from the measurement of Ryan *et al.*[13] There is an uncertainty of about 11% in these cross sections, which results in a corresponding uncertainty in the EED predictions. This is indicated in Fig. 2 by the height of the rectangles. In addition, we have used two different prescriptions for the choice of kinematic variables at which the elastic cross section is evaluated in EED calculation. In the calculation called EED($\bar{s},\bar{t}$) (solid-lined rectangle in Fig. 2), we have used the average over the kinematics of the incident and outgoing protons. EED(s_0,t_0) (dashed-lined rectangle) employed kinematic variables that are evaluated at the zero-photon-energy limit. In the notation of Ref. 5, $\bar{s} = \frac{1}{2}[(P_1 + P_2)^2 + (P_3 + P_4)^2]$ and $\bar{t} = \frac{1}{2}[(P_1 - P_3)^2 + (P_2 - P_4)^2]$

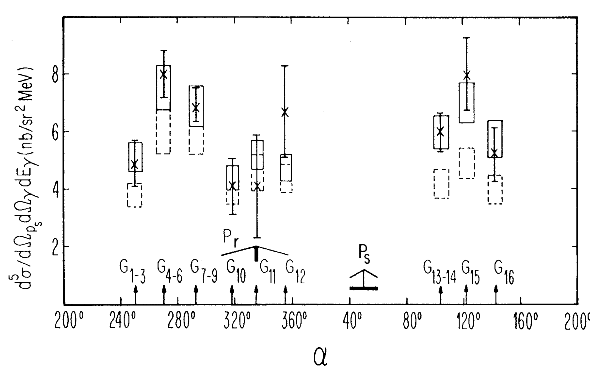

FIG. 2. Differential cross section for $pp \to pp\gamma$ in the photon energy interval $20 \leq E_\gamma < 40$ MeV ($30 \leq E_\gamma < 40$ MeV for G_{11} and G_{12}). α is the horizontal projection angle of the photon counters. The rectangles give the EED prediction (see text): solid line for EED($\bar{s},\bar{t}$) and dashed line for EED(s_0,t_0). The vertical arrows on the abscissa show the position of the photon counters. P_s indicates the angular acceptance for the scattered proton (into spectrometer) and P_r indicates the angular acceptance for the recoil proton.

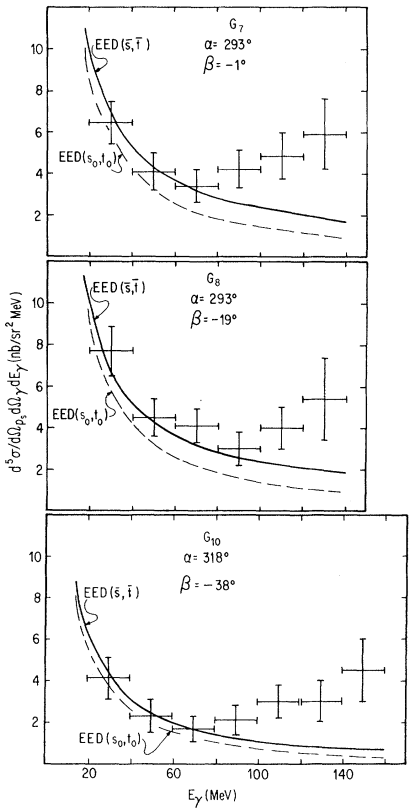

FIG. 3. $pp \to pp\gamma$ laboratory differential cross section for three photon counters. EED is the external-emission-dominance calculation (see text).

while $s_0 = (P_1 + P_2)^2$ and $t_0 = (P_5 - P_1)^2$, where P_1, $\ldots$, P_4 are the four-momenta of the incident, target, scattered, and recoil proton, respectively. The scattered proton is the one that goes into the spectrometer at $\theta_{1\mathrm{ab}} \sim 50°$ and P_5 is the four-momentum of a proton elastically scattered at $\theta_{1\mathrm{ab}} = 50°$.

The photon spectra for counters G_7, G_8, and G_{10} are shown in Fig. 3. The solid and dashed line in this figure represent the predictions of the EED($\bar{s}, \bar{t}$) and EED(s_0, t_0), respectively. We reiterate that there is an 11% uncertainty in our EED predictions as a result of the 11% uncertainty in the proton-proton elastic scattering cross section.

The calculated cross section has been averaged over the experimental acceptance by means of a Monte Carlo computer program. In this way, the effects of noncoplanar geometry are accounted for in a natural and accurate way. Note that the acceptance geometry for photon counters centered on $\beta_\gamma \simeq 0°$ (Table I) includes many noncoplanar events because of the finite vertical acceptance of the spectrometer but is, on the average, nearly coplanar. The effect of the acceptance averaging on the cross section is small (± 10% for most counters). For the out-of-plane counters with $\beta_\gamma \neq 0$, the cross section may differ substantially from the value for $\beta_\gamma = 0$ at the same α_γ, especially near $\alpha_\gamma \simeq 0$.

Most of the measured cross sections agree very well with the EED predictions up to $E_\gamma \sim 80$ MeV, although the data for counters G_{11} and G_{12} are somewhat above EED in this region. The EED($\bar{s}, \bar{t}$) prescription fits the data slightly better than EED(s_0, t_0), similar to the case of $\pi p \to \pi p \gamma$.[5] For photon energies above $E_\gamma \sim 80$ MeV, the experimental spectra either rise or remain flat, in disagreement with EED. This is in marked contrast to the $\pi p \to \pi p \gamma$ results obtained at an incident energy of 269 and 298 MeV[9-11] which show a monotonically decreasing differential cross section with increasing photon energy up to the highest photon energy of 120 MeV. The rising photon spectrum could be associated with the onset of a vector-meson-dominance contribution,[15] although the theoretical foundations of the EED calculation are so slim that any speculation about its failure must be treated as pure conjecture.

Our PPB results lend support to the Rückl model[7] in which the low-energy direct leptons observed in high-energy pp interactions are of electromagnetic origin. Rückl's soft-photon approximation is essentially the same as our EED (s_0, t_0). Since our measured photon yield is slightly above the EED prediction, the number of low-energy leptons of electromagnetic origin is expected to be above the number calculated by the Rückl model.[16]

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Inclusive Hadron Scattering from 50 to 175 GeV/c*†

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This Letter reports measurements for the processes $a+p\to a+X$ where a is $\pi^\pm, K^\pm$, or $p^\pm$ over range of the Feynman x from 0.7 to 0.975 at Fermilab energies. The data for all reactions are well represented by a simple parametrization. The cross sections show significant energy dependence in the high-x region. While the data are consistent with factorization in the high-x region and small t, the proton data are inconsistent with factorization for $x \lesssim 0.9$.

We report here measurements of the inclusive reactions $a+p\to a+X$, where X is an undetected missing mass, and a is one of the six particles $\pi^\pm$, $K^\pm$, p, or $\bar{p}$. Previous high-statistics experiments have been limited to incident protons, and this is the first systematic study of all six processes. The measurements were performed at Fermilab, using the single arm spectrometer facility at beam momenta of 50, 70, 100, 140, and 175 GeV/c. They cover a range in four-momentum transfer squared $-t$ of approximately 0.03 to 0.7 GeV^2 and a range in x from 1.0, the elastic peak, down to approximately 0.7. In the context of a triple Regge formalism, this region is of particular interest because it is expected to be influenced by both Reggeon and Pomeron exchanges. To a good approximation, x is equal in our kinematic region to the Feynman variable and is defined here as

$$x = p_s/p_b \sim 1-(M_x^{\,2}-m_p^{\,2})/s, \tag{1}$$

where p_b and p_s are the beam and spectrometer momenta respectively. The quantities M_x, m_p, and s are the missing mass, proton mass, and