Polarized Proton-Proton Bremsstrahlung

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The analyzing power for proton-proton bremsstrahlung has been measured at TRIUMF with 280-MeV polarized protons. All three outgoing particles were detected in coincidence. After appropriate cuts were applied, over 160000 $pp\gamma$ events remained, an order of magnitude more than in previous $pp\gamma$ experiments. The analyzing-power measurements are in good agreement with calculations based on modern potential models of the *NN* interaction, but disagree with the predictions of the soft-photon approximation.

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The most direct and unambiguous way of investigating the off-energy-shell behavior of the *NN* interaction is by measurements of nucleon-nucleon bremsstrahlung. In spite of this, bremsstrahlung experiments have hitherto shown no evidence of off-shell effects, even in kinematic situations where one would expect sensitivity to them. For example, an earlier experiment[1] at TRIUMF gave results for the proton-proton bremsstrahlung ($pp\gamma$) cross section at 200 MeV which were in better accord with the soft-photon approximation (SPA) than with the predictions of modern potential models of the *NN* interaction. This is surprising since the SPA contains only on-shell information, potential models should certainly be valid at 200 MeV, and the precision attained in the measurements was apparently sufficient to distinguish between the two approaches. We have therefore measured both the analyzing power (which has not previously been measured) and cross section for $pp\gamma$ in a variety of kinematic situations, in some of which off-shell effects should be negligible and in others of which they should be easily observable. Only the analyzing-power results are reported here.

The measurements were carried out at TRIUMF with a proton beam of energy 280 MeV and polarization typically 75%–80% impinging on a 5-mm-thick liquid-hydrogen target. The liquid hydrogen was enclosed between thin (7.5 μm) Mylar walls supported by cold hydrogen gas at atmospheric pressure in a 1-m-long container. Shielding prevented the detectors from viewing directly the 0.127-mm-thick stainless-steel end windows of the gas container. With this arrangement the background contribution from the target walls was reduced to less than 5%.

All three outgoing particles from the $pp\gamma$ reaction were detected in a coplanar geometry with the apparatus shown in Fig. 1. The momentum and production angle of the higher-energy proton were measured in a spectrometer consisting of a dipole magnet and vertical drift chambers. The drift cell design allowed measurement of track position, angle, and time, giving enough information that extraneous tracks could be eliminated from many of the ($pp\gamma$) events. Operation at low gas gain ($\lesssim 10^4$) and independent time digitization for each wire were necessary to cope with the high elastic-scattering flux. Before the magnet two of the drift chambers mea-

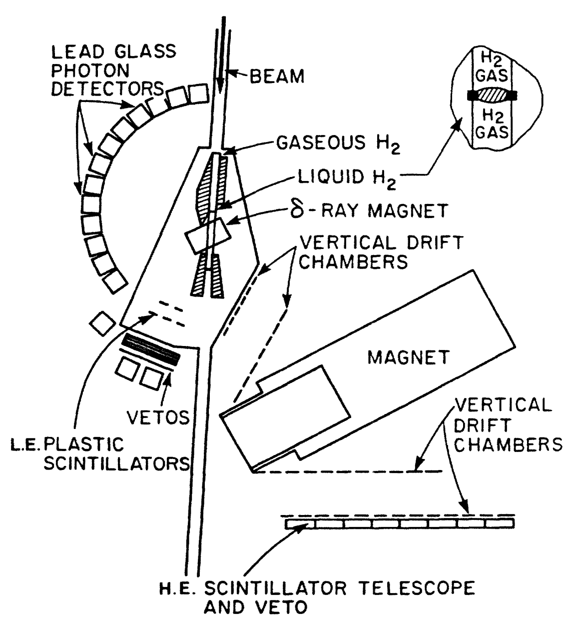

FIG. 1. Schematic representation of experimental apparatus.

sured the displacement of the trajectory in the horizontal plane, enabling the point of origin in the target to be determined. A third drift-chamber plane just in front of the entrance to the magnet recorded the vertical displacement of the trajectory. The two chambers after the magnet, used in combination with the front chambers to determine the momentum of the proton, were followed by a hodoscope of eight plastic scintillation counters (HE counters). The hodoscope was put in coincidence with two large plastic scintillators covering the same area and in anticoincidence with eight more plastic scintillators placed behind copper degraders whose thickness was chosen to stop protons from the $pp\gamma$ reaction, but not to stop protons from elastic scattering. This arrangement enabled most of the elastically scattered protons to be vetoed. The angular acceptance of the spectrometer was 10° horizontally by 3° vertically. The kinematics of the $pp\gamma$ reaction is such that in some situations the second proton is produced with an energy as low as 10 MeV, so that it had only a few megaelectronvolts emerging from the hydrogen target. This proton was therefore detected in one of five plastic scintillators (LE counters) mounted inside the vacuum vessel and each subtending 4° horizontally by 3° vertically at the target. The angular range spanned by the LE detectors was from 10° to 30°. Elastically scattered protons were vetoed by another five plastic scintillators behind a degrader made of polyethylene, which was chosen so that absorption of photons was minimized.

The photons from the $pp\gamma$ reaction were detected by 16 lead-glass Cherenkov counters, of which 8 were 150-mm cubes of lead glass while the other 8 (which had been built for an earlier experiment) were cylinders 125 mm in diameter and 178 mm long. The counters were located at 10° intervals and each was preceded by a thin plastic scintillator to veto charged particles. The efficiency of the counters was calculated with the EGS[2] code and checked with 70-MeV electrons at TRIUMF.

A valid trigger consisted of a triple coincidence between a particle passing through the spectrometer (but not through the veto counter), another particle passing through one of the LE counters (but not through its veto), and a count in one of the lead-glass Cherenkov detectors (but not its veto). The beam intensity (typically 15 nA) was measured throughout the experiment by means of a secondary-emission monitor (SEM) downstream of the target and also with a polarimeter which utilized pp elastic scattering from a polyethylene foil to monitor both intensity and polarization. In addition, a fraction of the elastically scattered protons going through the spectrometer was recorded to give an independent measure of the effective thickness of the liquid-hydrogen target and of the polarization of the incident proton beam. The dead time of the system was continuously monitored by triggering light-emitting diodes on the scintillators with a known number of pulser triggers, and counting how many were recorded on tape.

Data were taken in two runs with the spectrometer subtending angles at the center of the target of 30° to 20° and then 20° to 10°. The arrival times of pulses in the HE, LE, and Cherenkov counters were recorded, including the time relative to the beam microstructure. Pulse heights of signals in the LE and Cherenkov counters were also recorded.

During data reduction, events were accepted only if all of the recorded parameters, including drift-chamber coordinates, were consistent with $pp\gamma$ kinematics with the event originating in the liquid-hydrogen target volume. Typical plots of high-energy–proton bend angle versus photon production angle and low-energy–proton energy versus photon production angle are shown in Fig. 2. The kinematic loci of the $pp\gamma$ events can clearly be seen. The number of accidental background events, estimated by application of the same cuts to events in which detected particles came from different beam bursts, averaged 1–2% of the real $pp\gamma$ events from which they were subtracted.

The analyzing power was obtained from the numbers

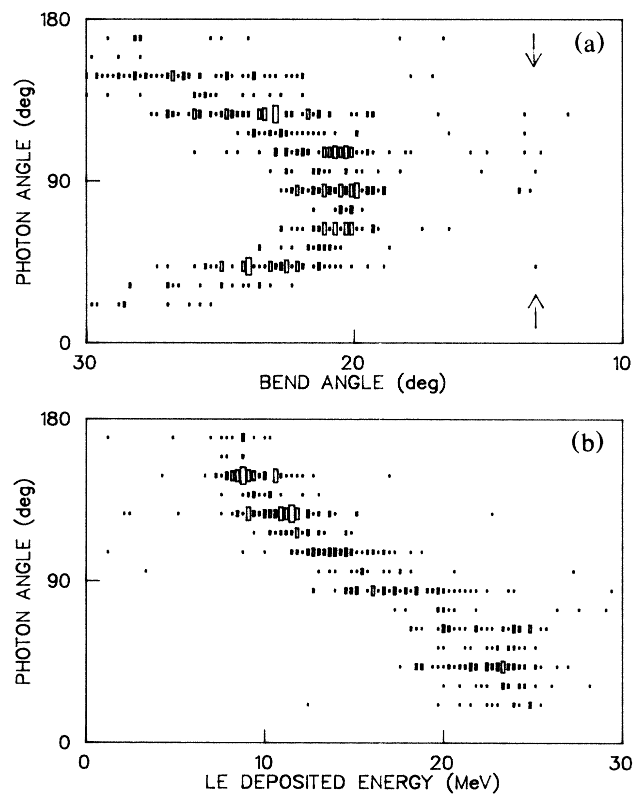

FIG. 2. Photon detector number vs (a) bend angle through spectrometer, and (b) energy deposited in LE detector for events assumed to be from $pp\gamma$ process. The area of each rectangle is proportional to the number of counts in each bin. The differences in intensity between adjacent photon detectors are caused by differences in the size of the detector and its distance from the target. The arrows indicate where elastically scattered protons would appear.

of spin-up and spin-down events separately corrected for the polarization and flux of the incident particles and the dead time of the system determined from pulser events. The final data were divided into five bins 4° wide in low-energy–proton production angle, four bins 5° wide in high-energy–proton angle, and sixteen photon-production-angle bins (one for each Cherenkov counter), which gives a total of 320 values of $pp\gamma$ analyzing power.

The experimental results were compared with theoretical calculations of two different types, namely the soft-photon approximation[3] (SPA) and potential-model[4] calculations. In the soft-photon approximation the cross section for the $pp\gamma$ process may be written as

$$d^3\sigma/d\Omega_3 d\Omega_4 d\theta_\gamma = A^2/k + 2\mathrm{Re}AB^* + (B^2 + 2\mathrm{Re}AC^*)k + O(k^2),$$

where k is the photon momentum and A, B, and C are coefficients arising from the expansion of the $pp\gamma$ amplitude about the on-shell ($k=0$) point. The coefficients A and B contain kinematic factors and purely on-shell (elastic) information, while C and the higher-order coefficients contain off-shell information as well as higher-order on-shell contributions. The soft-phonon approximation, as used here, assumes that C and $O(k^2)$ terms are negligible but includes the B^2 term of $O(k)$.

New potential-model calculations[4] were carried out with the Paris and Bonn potentials, which are generally believed to be the best available at the present time. For each case the Lippmann-Schwinger equation was solved in momentum space to obtain half-off-shell nucleon-nucleon amplitudes, which were then combined with propagator and electromagnetic vertex factors to get the bremsstrahlung amplitude. One-pion–exchange amplitudes were used for the partial waves with $J \geq 6$, some Coulomb corrections were included, and the calculation was done so that gauge invariance was respected. Several different relativistic corrections were included, the most important being v/c corrections at the photon-nucleon vertex. Relativistic kinematics and proper transformations between frames were also used. Thus, leading relativistic effects have been included, though, since the calculation is based on a potential, certain aspects remain inherently nonrelativistic. Under the kinematic conditions applicable to this experiment, results obtained with Paris and Bonn potentials differed very little, the differences in the calculated analyzing power, for instance, being always less than 0.07. Theoretical calculations were averaged over four coplanar points, weighted by the cross section, within each bin. Comparison of A_y calculated by averaging over sixteen coplanar and noncoplanar points showed that averaging over only four points gave rise to an error generally less than 1% and always less than 5% of A_y.

When these calculations are compared with the measured values of the analyzing power the following conclusions may be drawn: (1) At the larger proton opening angles where the photon energy is small and the NN amplitude is nearly on shell, the measured analyzing powers are consistent with zero and in agreement with the (small) predicted analyzing powers, whether calculated in the SPA or in either potential model. (2) At the smaller proton opening angles, the measured analyzing powers are in strong disagreement with the SPA predictions, but in good agreement with both the Bonn and Paris potential models. Overall, the value of χ^2 per degree of freedom is ~ 1.5 for both Paris and Bonn potentials and is ~ 5.5 for the SPA. Figure 3 shows the angular distribution of the analyzing power for the smallest two of the twenty angle pairs at which data were obtained in the experiment.

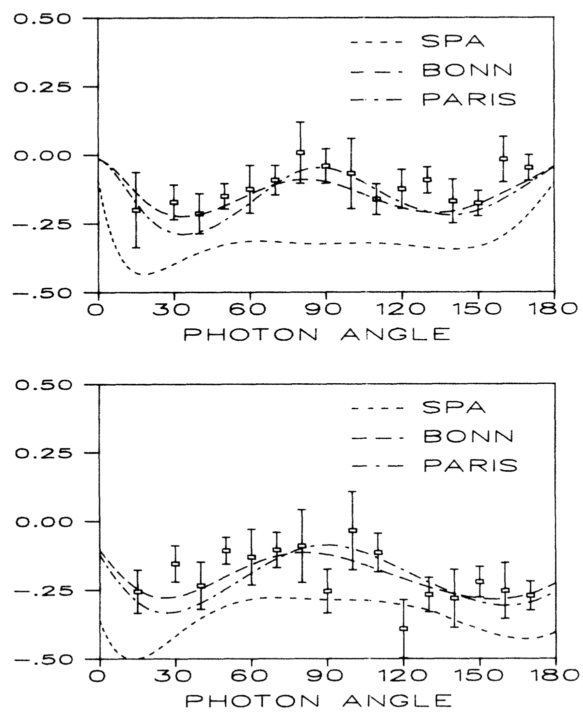

FIG. 3. Analyzing powers compared with theoretical calculations based on the soft-phonon approximation (SPA) and the Bonn and Paris potentials. Data for two LE detectors were added for better statistics. Theoretical calculations were also averaged over the angle range of two LE detectors. Results are shown for angle of high-energy proton $=(12.36 \pm 2.5)°$ and (a) angle of low-energy proton $=(14 \pm 4)°$, (b) angle of low-energy proton $=(22 \pm 4)°$.

Thus, in contrast to earlier $pp\gamma$ experiments the measurements reported here are in strong disagreement with the predictions of the soft-photon approximation, which incorporates only on-shell amplitudes. The data are in good agreement with potential models using either the Bonn or Paris potentials, which differ little in their predictions for the kinematics of interest here.

This conclusion may be interpreted to mean that the Bonn and Paris potentials differ little in their behavior for off-shell momenta probed by this experiment, estimated from the kinematics to be $\sim 1-2.5\ \text{fm}^{-1}$. This statement should be qualified by noting that at 280 MeV the experiment is more sensitive to the *P*-wave amplitude, whereas calculations show that the Bonn and Paris potentials differ most in the *S*-wave off-shell behavior. However, at lower energies, where the *S* wave would be more important, off-shell effects will in general be smaller.

In any case the experiment is the first direct measurement of the off-shell behavior of the *NN* force, and the fact that it is in agreement with modern potential models of the *NN* force increases our confidence in the essential validity of these models.

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