PROTON-PROTON BREMSSTRAHLUNG AT 99 MeV

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Measurements of the proton-proton bremsstrahlung cross section $d\sigma/d\Omega_1 d\Omega_2$ at 99 MeV are reported. Cross sections of 3.77 ± 0.23, 5.14 ± 0.22, 9.01 ± 0.33, and 18.83 ± 1.15 $\mu b/sr^2$ were obtained at angles of 25°, 30°, 35°, and 40°, respectively. The angular distributions of the photons were determined kinematically. The results agree generally but not in detail with theoretical predictions.

Measurements of the proton-proton bremsstrahlung cross section[1] have been reported at various energies between 10 and 200 MeV. The essential features of the bremsstrahlung cross section have been explained[2,3] using elastic nucleon-nucleon amplitudes and a theorem of Low[4] which applies to such radiative processes. Other interpretations have been based on several different potential models of the nucleon-nucleon interaction.[5-9] As a test of these calculations we report measurements of the bremsstrahlung cross section at 99 MeV with an overall accuracy of about ±5%.

The external proton beam of the McGill synchrocyclotron was incident on a 2-cm liquid-hydrogen target. The two final-state protons were detected in coincidence by a pair of plastic scintillation counter telescopes at equal polar angles on opposite sides of the beam. Each telescope consisted of three thin defining counters followed by a total-energy counter. The final defining counter was 1 m from the target and subtended an angle of ±1° in both the scattering plane and the plane perpendicular to it. Recoil protons from elastic p-p events were detected in two conjugate veto counters.

The target consisted of a thin-walled (200-μg/cm^2 Al) flask containing liquid hydrogen. This was surrounded by a larger and stronger flask (10-mg/cm^2 H-film) containing gaseous hydrogen in equilibrium with the liquid hydrogen. Each telescope was arranged so that the solid angle of acceptance was uniform throughout the volume of the liquid hydrogen and decreased to zero at the walls of the outer flask.

Four methods were used to reject the background flux of elastically scattered protons in each telescope: a conjugate veto counter, time of flight between the first and third defining counters, differential energy loss in the second defining counter, and pulse height in the total-energy counter. With the elastic rate in each telescope thus reduced by a factor of 10^3, the ratio of real to chance coincidences was greater than 10 to 1. Real and chance (delayed) events were collected simultaneously in a two-dimensional analyzer and stored by a PDP-8 computer. The bremsstrahlung event rate was approximately 10/h and a total of about 4000 events was collected.

Our results are displayed in Table I. Real coincidences from $(p, 2p)$ reactions in the thin inner flask walls amounted to 8% of the total rate; a 2% contribution arose from the same process in the deuterium contamination of the hydrogen. Chance coincidences represented about 9% of the total rate. After subtracting these background events, corrections were made to allow for inefficiencies arising from the vetoing of real events and the low-energy cutoff (15 MeV) of the telescopes. Further corrections were necessary since noncoplanar events were accepted by the proton tele-

Table I. Data for proton-proton bremsstrahlung ($pp\gamma$) measurements at 99.0 ± 0.2 MeV incident proton energy and symmetric coplanar proton angles θ. Errors given with $pp\gamma$ cross sections are relative only. Additional normalization factor of 1.00 ± 0.02 to be applied.

Proton angle θ	Net $pp\gamma$ events	Efficiency and veto correction	Noncoplanar and multiple scattering correction	$d\sigma/d\Omega_1 d\Omega_2$ ($\mu b/sr^2$)
25°	792 ± 35	1.33 ± 0.05	1.00 ± 0.01	3.77 ± 0.23
30°	1025 ± 40	1.08 ± 0.01	1.04 ± 0.01	5.14 ± 0.22
35°	949 ± 37	1.07 ± 0.01	1.06 ± 0.01	9.01 ± 0.33
40°	459 ± 23	1.07 ± 0.01	1.19 ± 0.04	18.83 ± 1.15

scopes. The bremsstrahlung cross section decreases rapidly with increasing noncoplanarity[10]; the measured cross section is therefore smaller than the coplanar cross section. Another effect of the strong coplanar peaking of the cross section is a loss of real events due to multiple Coulomb scattering out of the solid angle of acceptance. Corrections for these effects were calculated using the theoretical out-of-plane cross sections of Drechsel and Maximon.[9] Correction factors for all these effects are shown in Table I.

The experimental errors in the cross sections are substantially smaller than those in previous measurements. The uncertainty in the effective solid angle was less than 1% on account of the double-walled target design. The bremsstrahlung cross sections were obtained by normalization to the accurate (±2%) elastic p-p cross sections of Wigan et al.[11] Statistical errors were small at all angles. Additional uncertainties were introduced at 25° because of the uncertainty in the correction for the low-energy cutoff and at 40° because of the strong azimuthal dependence of the cross section.

The variation of the bremsstrahlung cross section with proton angle is shown in Fig. 1. For comparison with these data, we have included one of several theoretical predictions[8] based on the Hamada-Johnston[12] potential. Other calculations using for example the Bryan-Scott[13] potential agree with this prediction to within 10% or less. Thus a discrimination between potentials is difficult. However, we can conclude that although the general agreement between experiment and theory is satisfactory at this energy, the data have less curvature than any of the theoretical calculations predicts.

The photon angular distributions shown in Fig. 2 were determined kinematically from the momenta of the final-state protons. The distributions have been corrected for inefficiencies in the counter telescopes. These inefficiencies occurred mainly in the region of forward photon emission at proton angles of 25° where the final-state proton energies were low. The experimental distributions have a quadrupole shape and indicate a tendency toward backward emission of the photon as predicted by the calculations of Drechsel and Maximon.[9]

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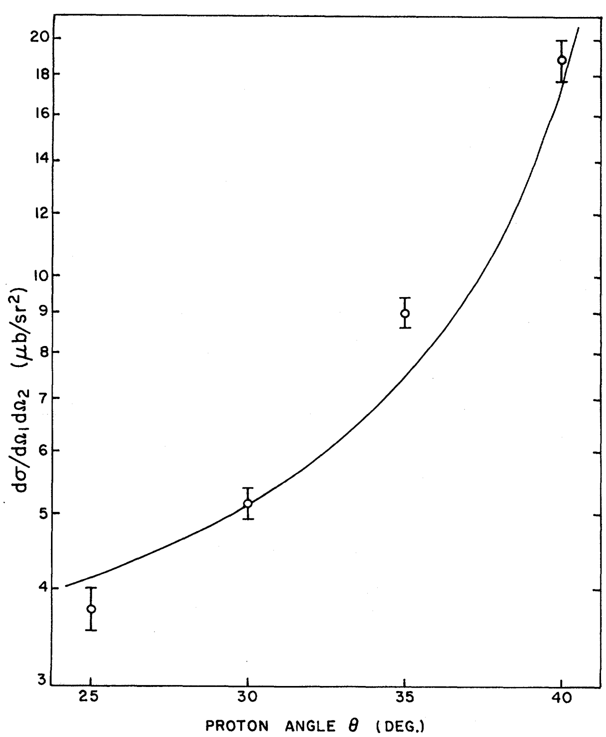

FIG. 1. The cross section $d\sigma/d\Omega_1 d\Omega_2$ at 99 MeV as a function of proton angle. The curve was calculated by Brown (Ref. 8) using the Hamada-Johnston potential.

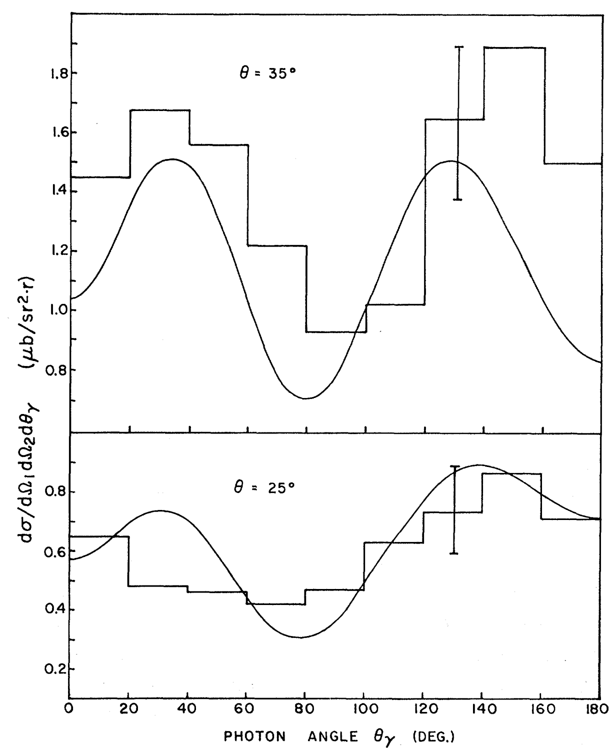

FIG. 2. The kinematically determined photon distributions (histograms) at proton angles of 25° and 35°. The bin size of 20° corresponds to the resolution in the photon angle. The curves were calculated by Drechsel and Maximon (Ref. 9) using the Hamada-Johnston potential.

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POLARIZATION-ASYMMETRY TEST OF TIME-REVERSAL INVARIANCE*

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Time-reversal invariance for strong interactions, in particular for that part of the force which flips the spin of the proton, has been tested by comparing the polarization and asymmetry in the elastic scattering of 32.9-MeV protons from ^{13}C at 60°. By making the measurements for ^{13}C relative to ^{12}C, where spin flip is forbidden except in case of parity nonconservation, we avoid the need to measure either an absolute beam polarization or absolute analyzing power. Our first result is that the polarization and asymmetry are equal to ±2.5%; consequently, we observe no violation of time-reversal invariance.

The discovery of the violation of charge conjugation and space inversion (CP) invariance in the decay of the K_2^0 meson by Christenson et al.[1] has stimulated a whole host of experiments in search of violation under time reversal of the weak, electromagnetic, and strong interactions. The search for time-reversal violation in nuclear reactions has centered on tests of detailed balance by the comparison of cross sections in inverse reactions. Very accurate measurements[2] have been made which have reduced the uncertainty in the cross-section comparisons to about ±0.3%. Handler et al.[3] have tested time-reversal invariance in p-p scattering at 430 MeV by comparing selected triple-scattering parameters.

Another time-reversal test in nuclear reactions is the comparison of polarization and asymmetry in elastic scattering. For particles of spin $\frac{1}{2}$, the polarization P is defined as the scattered-beam polarization when an unpolarized target is bombarded by an unpolarized beam, and the asymmetry A is defined as the experimentally measured left-right asymmetry ϵ when a beam of 100% polarization is scattered by an unpolarized target. All scatterings are at the same angle θ. In the case of a beam which is not 100% polarized, A is related to ϵ by

$$\epsilon = P_0 A = \frac{\text{No. scattered left}}{\text{No. scattered left and right}} - \frac{\text{No. scattered right}}{\text{No. scattered left and right}} \equiv P_0(L-R),$$

where P_0 is the fractional polarization of the incident beam. In order to indicate why a polarization-asymmetry comparison is sensitive to time-reversal invariance, we follow Squires[4] and con-