New Results of a Proton-Proton Bremsstrahlung Experiment at 42 MeV*

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We report the results of new measurements and analysis of 42-MeV proton-proton bremsstrahlung cross sections. Comparison with the predictions of the Hamada-Johnston potential over proton polar-angle ranges from 16° to 40° is made and significant disagreement is observed.

In a previous publication,[1] the basic experimental information and the preliminary results of a proton-proton bremsstrahlung (PPB) experiment were reported. The experiment was done with use of a wide-angle, two-arm wire-chamber spectrometer which has been described in detail elsewhere.[2] In this paper, results of a second experiment, as well as reanalyzed results of the earlier data, are presented and compared with a specific theoretical calculation. A report containing all numerical details is available on request.[3] Full experimental details will be published later.[4]

A total of 13 066 net PPB events[5] were collected. Most of these were obtained during the second experiment in which the energy thresholds of the scintillation counters were also lowered, thereby increasing the fraction of the data which was furthest off-energy-shell.

The comprehensive comparison of experiment with theory and the refined analysis procedures required an extensive set of cross sections to be computed. A total of 6850 $d^5\sigma/d^2\Omega_1 d^2\Omega_2 d\psi_\gamma$ differential cross sections[3] were calculated for polar-angle pairs (θ_1, θ_2) from (14°, 14°) to (46°, 42°). The Harvard photon angle, ψ_γ, was varied in 10° increments and five values of the relative noncoplanarity,[1] φ_r, were used. The calculations were performed[6] in the laboratory system with use of the Hamada-Johnston (HJ) potential and included internal rescattering terms and relativistic spin corrections but did not include Coulomb effects[7] and exchange terms. Some results from this code have been compared elsewhere[8] to an independent calculation and good agreement was found.

Geometric and energy-dependent biases were corrected for by Monte Carlo techniques. The experiment was simulated with a set of about 400 000 PPB events generated uniformly in both phase space and reaction volume. The protons from each event were then traced through the spectrometer taking into account the effects of energy loss and multiple scattering. Finally, for each event a weight proportional to the $d^5\sigma/d^2\Omega_1 d^2\Omega_2 d\psi_\gamma$ cross section divided by the invariant phase space was computed. The overall accuracy of the Monte Carlo calculation was established by comparing various theory-independent distributions (e.g., the distributions in vertex errors and position) with similar distributions formed from the data.

The experimental cross sections were obtained by use of the same formulas as in Ref. 1 [Eqs. (1)–(3)] except that the photon polar angle, θ_γ, used in Eq. (1) was replaced by the Harvard angle, ψ_γ, and the correction factors, α and α', were computed with use of the weighted and randomized Monte Carlo events.

Three sets of experimental cross sections were calculated: $d^5\sigma/d^2\Omega_1 d^2\Omega_2 d\psi_\gamma$, $d^4\sigma/d^2\Omega_1 d^2\Omega_2$, and $d^2\sigma/d\theta_1 d\theta_2$. The first two sets are presented in both graphical and numerical form elsewhere[3] and are not included here. All cross sections have been corrected for all spectrometer efficiencies but the angular and energy resolutions of the spectrometer have not been unfolded. To make a fair comparison with theory, the theoretical cross sections were averaged over the experimental bin sizes and the spectrometer resolutions were folded in. These calculations were done by use of Monte Carlo techniques.[4]

The most significant results of the experiment are presented in Fig. 1 where the ratios of the experimental and theoretically simulated $d^2\sigma/d\theta_1 d\theta_2$ cross sections are shown as a function of $\theta_s = \theta_1 + \theta_2$ for different values of $\theta_d = |\theta_1 - \theta_2|$. The data from the two experiments[11] are shown separately to illustrate the extent of agreement between them. Also included in Fig. 1 are the results from other experiments.[9, 10] Note that these are not fully integrated $d^2\sigma/d\theta_1 d\theta_2$ cross sections, but $d^4\sigma/d^2\Omega_1 d^2\Omega_2$ cross sections integrated over a sizable fraction of the kinematically allowed φ_r range.

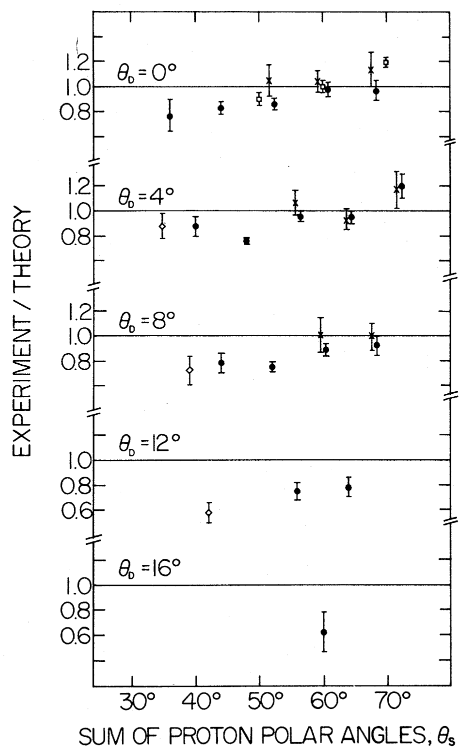

FIG. 1. Ratio of the experimental to theoretical $d^2\sigma/d\theta_1 d\theta_2$ cross sections as a function of $\theta_s = \theta_1 + \theta_2$ for different values of $\theta_d = |\theta_1 - \theta_2|$. The theoretical cross sections were based on the HJ potential and all experimental resolutions were folded in before the ratios were taken. The points × and ● are due to the first and second experiments, respectively. There is an error of 6% in the overall normalization which has not been included in the error bars. The results of Refs. 9 and 10 are also shown (denoted by □ and ◇, respectively) in a form suitable for comparison to data from this experiment.

Systematic effects have been studied extensively and will be treated in detail elsewhere.[4] Three sources of systematic errors were found to have a significant effect on the data. The uncertainty in the normalizing constant, K [see Eqs. (1)–(3) in Ref. 1], was ±6%. This has not been included in the errors shown in Fig. 1. Errors in the pulse-height–energy calibration are reflected primarily in the positions of the low-energy cutoffs, thereby influencing mostly the data at small and asymmetric angles. Systematic errors in the prompt-background subtraction were difficult to estimate, but the amount of prompt background was always less than 20%. In some cases, where systematic errors could only be approximately estimated, the errors quoted with the data have been increased to allow for this.

Figure 1 exhibits a significant discrepancy between the experimental results and one particular theoretical calculation based on the HJ potential. In general, the agreement is good for large values of θ_s and small values of θ_d, but, as θ_s decreases and/or θ_d increases, the experimental results become significantly lower than theory. As seen from Fig. 1, this trend is rather uniform. It is of interest to note that the data of Ref. 10 show the same trend of discrepancy, increasing with increasing θ_d in spite of θ_s also increasing, and that the data of Ref. 9 show the same trend for $\theta_d = 0°$. The data of both Refs. 9 and 10 were compared with similar, although not identical, theoretical calculations based on the HJ potential.

For reasons discussed earlier, and because the results from the three experiments are compared with entirely independent theoretical calculations, it is very unlikely that the discrepancy is due to errors in these calculations. On the other hand, none of the theoretical calculations includes all known corrections. At present, indications are that the combined effect of all these corrections will not bring the theory into agreement with experiment, but clearly, this cannot be ruled out until these calculations are performed.

The possibility that a common systematic error in all three experiments gives rise to the discrepancy can be completely ruled out since different techniques were used in each experiment. Since most of the evidence for disagreement comes from this experiment, some further comments about systematic errors are in order. Possible errors in the energy calibration of the scintillation counters constitute the major source of uncertainty in the experiment. This influences the data primarily at the smallest and most asymmetric polar angles. Although the observed discrepancy is largest in these regions, significant disagreement is also observed in the middle of the acceptance range of the spectrometer. These points generally have the best statistics and are only weakly influenced by possible errors in the energy calibration. Hence, they are considered quite reliable. As an additional check on the reliability of the results presented, the sensitivity of all cross sections to known systematic errors has been studied by artificially introducing certain biases into the data. With any reasonable assumption about the magnitude of the systematic errors, no shift in the experimental data large enough to bring experiment into agreement with theory could be produced.

In the past, there has been a certain reluctance to interpret the results of Ref. 10 as being inconsistent with theory.[12] However, when compared with the data presented here, these results provide a strong independent corroboration of the disagreement with the HJ-model predictions observed in this experiment. The implications of this are very significant, for if both the experimental data and the theoretical calculations are correct, then it must be concluded that the HJ potential model is unable to describe off-energy-shell effects. Furthermore, according to a recent calculation,[13] significant differences in the predictions of phase-equivalent potential models are not possible at 42 MeV. This raises the distinct possibility that the entire class of potential models which were so successful in describing elastic nucleon-nucleon scattering are inadequate in describing the off-energy-shell effects of the nucleon-nucleon interaction.

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[1]J. V. Jovanovich *et al.*, Phys. Rev. Lett. 26, 277 (1971). Some of the theoretical cross sections presented in this paper were incorrect. They are correctly given by L. G. Greeniaus *et al.*, Cyclotron Laboratory, University of Manitoba, Report No. 75-11 (unpublished).

[2]J. McKeown *et al.*, Nucl. Instrum. Methods 104, 413 (1972).

[3]Greeniaus *et al.*, Ref. 1.

[4]C. A. Smith *et al.*, "Proton-Proton Bremsstrahlung Experiment at 42 MeV" (to be published).

[5]The total number of all events (in both experiments) passing PPB constraints was 15 792. Of these, 1481 were classified as being due to random background and 1245 as being due to prompt background arising from impurities in the hydrogen gas.

[6]M. K. Liou and K. S. Cho, Nucl. Phys. A160, 417 (1971).

[7]L. Heller and M. Rich have shown [Phys. Rev. C 10, 479 (1974)] that Coulomb effects lower all the cross sections by 7 to 10% in the energy and angular ranges involved in this experiment.

[8]M. K. Liou and M. I. Sobel, Ann. Phys. (N.Y.) 72, 323 (1972).

[9]F. Sannes *et al.*, Nucl. Phys. A146, 438 (1970).

[10]A. Willis *et al.*, Phys. Rev. Lett. 28, 1063 (1972). Experiment-to-theory ratios shown in Fig. 1 were obtained by use of a calculation done by L. S. Celenza *et al.*, Phys. Rev. C 8, 838 (1973), and joining the first two points together.

[11]The number of points in Fig. 1 from the first experiment is smaller than in Ref. 1. This is the result of more stringent selection criteria used in the new analysis procedures.

[12]M. K. Liou, in Proceedings of the International Conference on Few Body Problems in Nuclear and Particle Physics, Quebec, Canada, 27–31 August 1974 (to be published).

[13]L. Heller, Bull. Am. Phys. Soc. 17, 480 (1972). See also P. Signell, in *Proceedings of the International Conference on Few Particle Problems in the Nuclear Interaction, Los Angeles, California, 1972,* edited by I. Šlaus *et al.* (North-Holland, Amsterdam, 1973), pp. 1–25.