Measurement of Proton-Proton Bremsstrahlung Cross Sections at 42 MeV*

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We report the results of a proton-proton bremsstrahlung experiment. The cross sections were measured over wide angular ranges using a wire-chamber spectrometer. Where possible, comparisons are made with the theoretical predictions of the Hamada-Johnston potential.

In recent years there has been substantial interest in the proton-proton bremsstrahlung (PPB) process and its off-energy-shell effects. Many theoretical calculations and measurements of PPB cross sections have been done.[1] However, experimental counting rates have always been very low, i.e., only a few events/hour. In this paper we report the results of an experiment which differs greatly from those previously performed. The event rates were over 100 events/h and the PPB process was observed over a large part of phase space. It is hoped that the improved statistics and increased flexibility in interpretation of the data will stimulate new theoretical calculations.

The PPB measurements were performed at 42 MeV incident-proton energy using a two-arm wire-chamber spectrometer.[2] Each arm was composed of two wire chambers and a scintillation counter to determine particle trajectories and measure their energies. A carefully designed set of slits was used to allow detection of p-p elastic events together with PPB events. A 5-cm high by 2-mm wide beam and a 22-cm long H_2 gas target were used with typical proton currents of 3 nA. Angular resolutions measured were 0.53° and 1.20° in the spherical polar (θ) and the azimuthal (φ) angles, respectively, for 21-MeV protons scattered elastically from H_2 gas at $\theta = 45°$. The overall energy resolution (half width at half-maximum) of each spectrometer arm was measured to be $0.2\sqrt{E}$, where E is the proton energy in MeV. Proton trajectories were reconstructed on line by a model PDP-9 computer and tested for a common origin. Those events making a "good" vertex were transfered every few seconds to an IBM model 360/65 computer for a complete geometric and kinematic analysis and recording on magnetic tape;[3] all others were rejected. The number of random events was determined by using an additional coincidence circuit with one input delayed by one cyclotron rf period. The overall triggering rate was typically 50 events-sec with 10% making a good vertex (mainly p-p elastic events).

Each PPB event is once overdetermined. A goodness-of-fit parameter (essentially a first approximation to the usual χ^2 value) was defined and events were accepted if its value was less than 5.41 (corresponding to 98% probability). A total of 6563 prompt and 845 delayed events passed this criterion. Using $(p, 2p)$ data collected with the scattering chamber filled with air (~34 000 events), the overall contamination in the PPB data due to air impurities was estimated as (5 ± 1)%. The uncertainities in the overall spectrometer detection efficiency (typically ~80%) and system dead time were automatically corrected for by detecting p-p elastic and PPB events simultaneously.

The data were analyzed by defining eighteen polar-angle interval pairs, each 4° wide. For

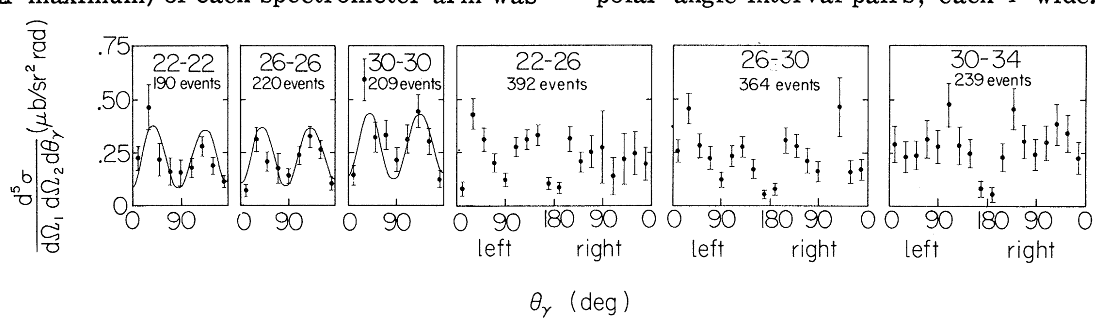

FIG. 1. Cross sections defined by Eq. (1) for the polar-angle combinations having the best statistics. The data were integrated over the φ_r range from 0 to 0.7. The theoretical curves were computed for $\varphi_D = 0$.

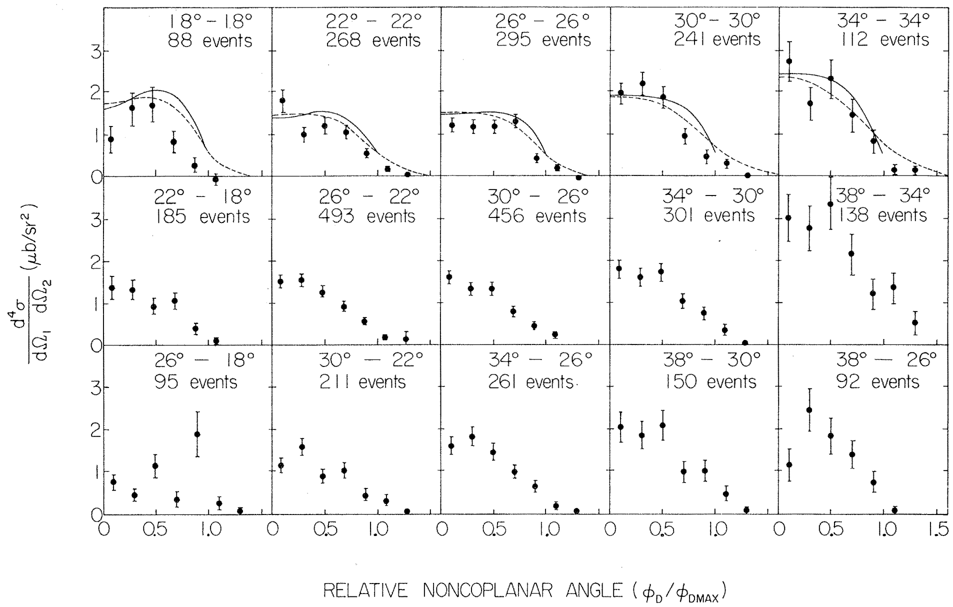

FIG. 2. Cross sections defined by Eq. (2) for various polar-angle combinations, as a function of φ_r. The dashed curve represents theoretical cross sections after the experimental angular resolution (always equal to about ±0.2 in φ_r) has been folded in.

each pair, a vertex position range in the reaction volume was chosen such that the detection efficiency was independent of the event origin within that range. These eighteen angular intervals contained 65% of all PPB events detected. The cross sections obtained are shown in Figs. 1, 2, and 3. A spherical polar coordinate system is used throughout. Heavy lines show the results of a theoretical calculation by Liou[5] using the Hamada-Johnston potential. Vertical bars represent statistical errors.

Systematic error in the overall normalization factor K in Eq. (1) is estimated to be ±10% and is not shown in the figures. It is common to all data points.

The cross sections shown in Figs. 1, 2, and 3(a) were computed using the formulas

$$\frac{d^5\sigma(\theta_\gamma)}{dx_1 d\varphi_1 dx_2 d\varphi_2 \theta_\gamma} = \frac{K(\alpha N/lN_e)}{\Delta x_L \Delta\varphi_L \Delta x_R 2\Delta\varphi_D \Delta\theta_\gamma}, \tag{1}$$

$$\frac{d^4\sigma(\varphi_r)}{dx_1 d\varphi_1 dx_2 d\varphi_2} = \frac{K(\alpha' N'/lN_e)}{\Delta x_L \Delta\varphi_L \Delta x_R 2\Delta\varphi_D}, \tag{2}$$

and

$$\frac{d^2\sigma(\theta_S, \theta_D)}{d\theta_1 d\theta_2} = y_L y_R \frac{\pi^2 \varphi_{DM}}{450} \sum \frac{d^4\sigma}{dx_1 d\varphi_1 dx_2 d\varphi_2}, \tag{3}$$

where $x = \cos\theta$ and $y = \sin\theta$; subscripts L and R refer to the left and right hodoscopes; θ_γ is the polar angle of the photon; $\varphi_D = \varphi_R - \varphi_L - \pi$ is the "noncoplanarity" angle; φ_{DM} is the maximum φ_D allowed by kinematics; $\varphi_r = \varphi_D/\varphi_{DM}$; $\theta_S = \theta_1 + \theta_2$ and $\theta_D = \theta_2 - \theta_1$; N and N' are net numbers of PPB events; l is the length of reaction volume as de-

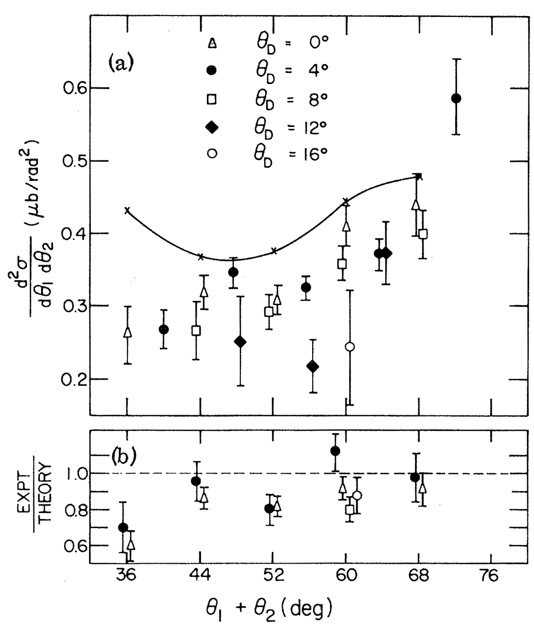

FIG. 3. (a) Cross sections defined by Eq. (3) as a function of θ_S and θ_D. (b) The ratios of experimental to theoretical cross sections for symmetric polar angles. Closed circles represent coplanar cross sections, and triangles double differential cross sections. Recent Oak Ridge results (Ref. 4) are shown as an open circle and square, respectively.

fined for a particular combination of polar angles; and N_e is the number of calibration p-p elastic events. The normalization factor K depends on the p-p elastic-scattering cross section and a few other quantities that we have measured in auxiliary experiments. The factors α and α' correct the data for the dependence of spectrometer efficiency on φ_D and for the existence of energy-detection cutoffs (~10 MeV) for protons. The summation in Eq. (3) is carried out over the appropriate points in Fig. 2 with errors compounded in the usual manner.

Due to poor statistics and the relatively large range of φ_D taken, only qualitative conclusions about the comparison with Liou's calculation can be made from Fig. 1. Data in Fig. 2 seem to indicate that the experimental points are somewhat low. In Fig. 3(a) the discrepancy is outside statistics although no calculations exist yet for asymmetric angles. In interpreting these data it should be borne in mind, first, that the systematic error of ±10% is not shown on these graphs; and second, that the correction factors α and α' were computed by a Monte Carlo calculation assuming phase-space dependence of cross sections, as comprehensive theoretical calculations were not available. Such a procedure is insufficiently accurate and affects mostly the data with smaller polar angles.

In Fig. 3(b) the experimental-to-theoretical ratios for the symmetric coplanar $[d^4\sigma(\varphi_r=0)/dx_1d\varphi_1dx_2d\varphi_2]$ and double differential $(d^2\sigma/d\theta_1d\theta_2)$ cross sections are plotted. Recent data from Oak Ridge[4] taken at 64.4 MeV are also shown and they seem to be in general agreement with our measurements. It is interesting to notice that the coplanar ratios are almost always larger than the double differential ratios, although the statistical significance of this difference is small.

In order to use all of our data and avoid their "fragmentation" into many angular bins we are trying to interpret them by using a Monte Carlo method. Only a phase-space dependence of cross sections has been used so far and the conclusions are not very informative. We plan to extend these Monte Carlo calculations as comprehensive theoretical results become available as well as to repeat the experiment with significantly improved accuracy.

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[1]For an extensive list of references see D. Marker and P. Signell, Phys. Rev. 185, 1286 (1969); or M. K. Liou and K. S. Cho, to be published.

[2]L. G. Greeniaus, J. V. Jovanovich, J. McKeown, T. Millar, D. G. Peterson, J. C. Thompson, and D. R. Reimer, in *Proceedings of the International Symposium on Nuclear Electronics, Versailles, France, 1968* (Documentation Francaise, Paris, 1968), Vol. III, p. 53-1. See also University of Manitoba Cyclotron Reports No. 70-2, No. 70-4, No. 70-5, and No. 70-6, 1970 (unpublished).

[3]D. Reimer, J. V. Jovanovich, J. McKeown, and J. C. Thompson, in *Proceedings of the Spring Symposium of the Digital Equipment Computer Users Society, 1968* (Digital Equipment Corp., Maynard, Mass., 1968), p. 17.

[4]D. O. Galde, M. L. Halbert, C. A. Ludemann, and A. van der Woude, Phys. Rev. Lett. 25, 1581 (1970).

[5]M. K. Liou, private communication.