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Unconventional Analysis of the Data from the 42-MeV *p-p* Bremsstrahlung Experiment*

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By use of an unconventional method of analysis, the data from the 42-MeV *p-p* bremsstrahlung experiment are reanalyzed and compared in the laboratory and c.m. systems with a theoretical calculation based on the Hamada-Johnston potential. Large disagreements, which were not seen previously, are observed.

In previous papers[1-3] results from two proton-proton bremsstrahlung (ppB) experiments were reported and compared with a theoretical calculation based on the Hamada-Johnston potential. A significant disagreement between the experiment and theory was observed. These results were presented in a "conventional" manner, that is, the cross sections having been calculated in terms of a standard set of variables according to conventional formulas.[1] This method of analysis has a number of shortcomings that are discussed briefly elsewhere.[4] The purpose of this paper is to present some results of a reanalysis of the data from the second experiment[2] in an "unconventional" manner.

The method to be used here[4] is, in principle, an old method of comparing data with theoretical calculations. It has been used in other branches of physics whenever the efficiency and the response function of the experimental equipment were very complicated.[5] Here, this method has been extended and applied to reactions with three-body final states. A brief discussion of this method and of its chief advantages and disadvantages is presented elsewhere.[4] It suffices to say here that the experimental data were compared with a set of weighted events[2] which was generated by Monte Carlo techniques. All experimental resolutions and efficiencies were folded into these simulated events in such a manner as to duplicate the effects of all experimental conditions. The numerical calculation of the ppB cross sections used to generate the appropriate weight for each event and the Monte Carlo simulation procedure have been previously described.[2,3] The comparison between experiment and theory was made by forming event frequency distributions from the experimental data as a function of a given variable, and then, comparing them with the corresponding distributions formed from the simulated set of events. This method of comparing experiment to theory is quite flexible and free from the approximations which are inherent in the conventional analysis.

The reliability of the simulation procedure, as well as the major systematic errors in the experiment, was briefly discussed in Ref. 2 (P2) and will be described in detail elsewhere.[6] The chief systematic error is due to the uncertainties in the energy calibration of the scintillation counters, particularly at low proton energies. The effects of these uncertainties were investigated in detail and it will be shown[6] that the conclusions presented in this paper are independent of these, as well as other systematic errors.

The behavior of the data as a function of many different variables in both the laboratory and center-of-mass systems was studied.[7] In this paper, the most interesting of the results are shown. In the figures where the ratios of the experimental and simulated ("theoretical") distributions are shown, the heavy error bars are due to statistical errors only. The extended light bars show possible systematic effects due to the uncertainties in the energy calibration of the scintillation counters. The effects of other systematic errors were estimated to be smaller.

In Figs. 1(a) and 1(c), the experimental and simulated event distributions are shown as a function of the sum of the proton polar angles subject to the constraints explained in the figure caption. In Figs. 1(b) and 1(d), the experimental-to-theoretical ratios of these distributions are plotted. The four points indicated by joined arrows in Fig. 1(a) were used to normalize the simulated data to the experimental data. These

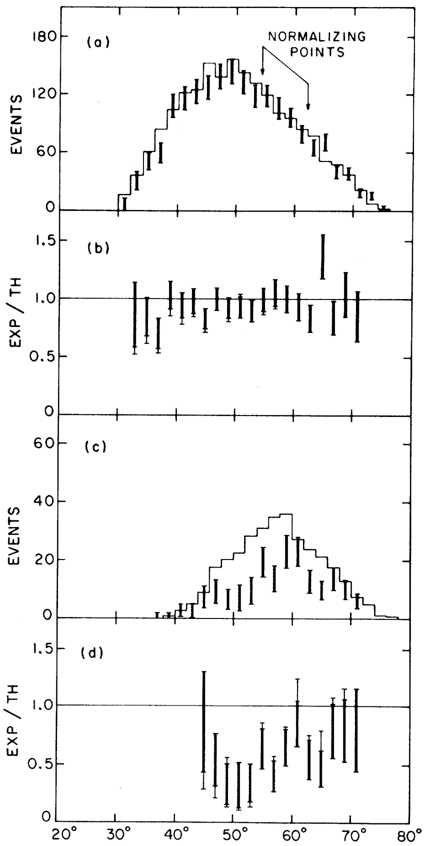

FIG. 1. (a) Distribution of events for experimental (points with error bars) and simulated data (histogram) as a function of the sum of proton polar angles ($\theta_s = \theta_1 + \theta_2$) for all "symmetric" ($|\theta_D| = |\theta_1 - \theta_2| < 2°$) events. (b) Ratio of experimental to simulated data as obtained from the distributions in (a). (c) Distribution of events for experimental and simulated data as in (a) but for "asymmetric" ($|\theta_D| > 9°$) and "noncoplanar" ($|\phi_r| > 0.7$) events. (d) The ratio of experimental to simulated data as obtained from (c).

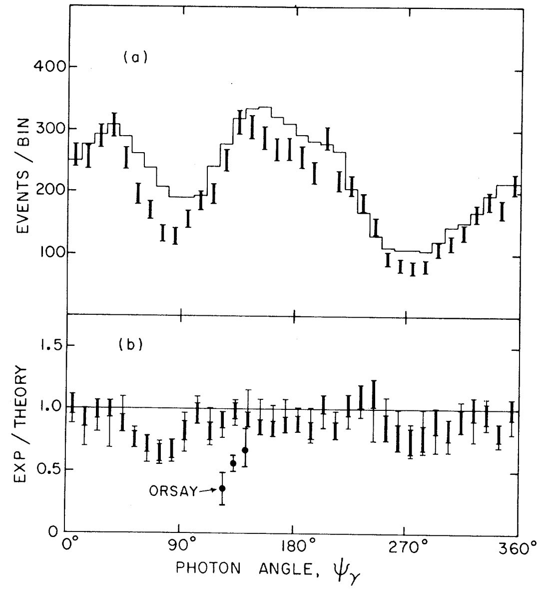

FIG. 2. (a) Distribution of all detected events for experimental (points with error bars) and corresponding simulated data (histogram) as a function of the Harvard photon angle, ψ_γ. (b) The ratio of experimental to simulated data as obtained from the distributions in (a).

points were chosen because the results of the conventional analysis[2,3] showed that in this particular angular range the experiment and theory were in good agreement. The normalization factor so obtained was then used to normalize all the results reported here and elsewhere.[7] This procedure thus emphasizes disagreements in the shapes of the various distributions.

Figure 1(b) shows good agreement with the results shown in the top line of Fig. 1 in P2. This demonstrates the consistency of the present method of analysis and the one used in P2.[8] The data shown in Figs. 1(c) and 1(d) represent, to a large extent, a subset of the events used in computing the cross sections for the $\theta_D = 12°$ and $\theta_D = 16°$ lines of Fig. 1 in P2. It is interesting to note that the ratio of the integrals of the two distributions in Fig. 1(c) is 0.55 ± 0.05 (± 0.08) where the error quoted in parentheses was obtained by adding the systematic and statistical errors.

In Fig. 2(a), the experimental and simulated event distributions are shown as a function of the Harvard photon angle,[2] ψ_γ, and in Fig. 2(b), their ratios are plotted. The three points indicated by circles are results from the Orsay experiment[9] which were compared with calculations performed by Brown.[10,11]

In Fig. 3, some results in the c.m. system are presented. The following four c.m. variables were somewhat arbitrarily chosen in this particular investigation: the photon energy, E_γ^*; θ_p^*, the smallest of the four polar angles that either proton makes with the positive or negative z axis; the angle, δ^*, that the photon makes with the proton having the polar angle θ_p^*; and, $\beta^* = |\alpha^* - 90°|$, where α^* is the angle that the normal to the final-state reaction plane makes with either the positive or negative z axis.

Besides confirming the conclusions stated in P2, the results of the present analysis lead to the following additional conclusions.

(1) In some parts of phase space observed in this experiment, the agreement with theory is excellent. In others, the discrepancy is very

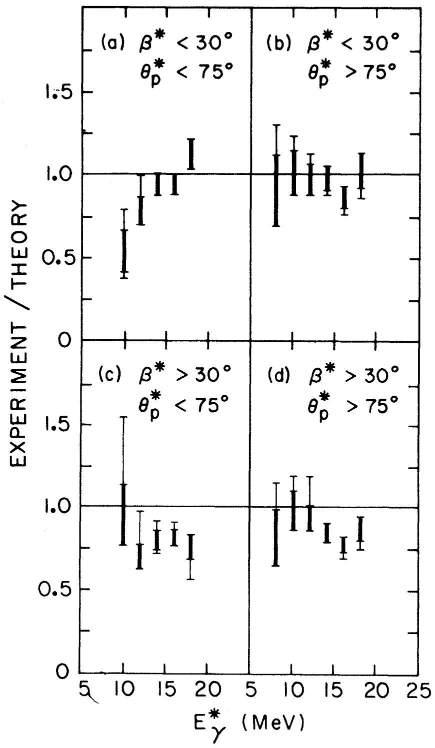

FIG. 3. Ratios of experimental to simulated distributions as a function of photon energy, $E_\gamma{}^*$, in the c.m. system for events having $\delta^* < 110°$. Additional constraints are imposed as indicated.

large, at times more than a factor of 2. In a certain part of phase space [see Fig. 3(a)], the discrepancy increases with *decreasing* photon energy.[12]

(2) The method used here has proved to be a very general and useful one. Should a need arise it would be relatively straightforward to compare results of this experiment with theory in terms of any dynamic variable, a task that cannot be done by analyzing the data in a conventional manner. This fact should give incentive to theorists to search for new interesting variables that might reveal certain dynamic properties of the off-energy-shell interaction which are hidden otherwise.

(3) It was pointed out in P2 that the results of this experiment raise serious questions concerning the validity of the commonly used potential models off energy shell. The present analysis accurately pinpoints regions of very large discrepancy between experiment and theory. The results presented here also illustrate the great richness of the bremsstrahlung process and demonstrate that more extensive experiments and calculations will have to be done before any definite conclusions about the validity of potential models off energy shell can be made.

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[4]J. V. Jovanovich, in *Proceedings of the International Conference on Few Body Problems in Nuclear and Particle Physics, Laval University, Quebec City, Canada, 1974*, edited by R. J. Slobodrian, B. Cujec, and K. Ramavataram (Les Presses de l'Université Laval, Quebec City, Canada, 1974), p. 218–227; see also Cyclotron Laboratory, University of Manitoba, Report No. 74-755A (unpublished).

[5]This method has been used in high energy physics as illustrated, for instance, in Fig. 3(a), B. Knapp *et al.*, Phys. Rev. Lett. 34, 1044 (1975).

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

[7]C. A. Smith and J. V. Jovanovich, Cyclotron Laboratory, University of Manitoba, Report No. 76-4 (unpublished).

[8]Careful examination of the constraints and bin sizes used in the selection of events for Fig. 1(c) and the top part of Fig. 1 in P2 reveal that there exists only a partial overlap of events used. Furthermore, some systematic corrections were handled here in a different manner than in P2; therefore exact agreement between the two figures should not be expected.

[9]A. Willis *et al.*, Phys. Rev. Lett. 28, 1063 (1972).

[10]V. R. Brown, Phys. Rev. C 6, 1110 (1972).

[11]The relationship $\psi_\gamma = -\theta_\gamma$ for θ_γ negative and $\psi_\gamma = 2\pi - \theta_\gamma$ for θ_γ positive between θ_γ from Ref. 10 and ψ_γ from Fig. 2 exists for coplanar events, thus making it possible to compare these results qualitatively.

[12]Note that this result does not contradict Low's low-energy theorem since the photon energy is not sufficiently small in this region to insure the validity of Low's theorem. It does, however, indicate that the off-energy-shell effects do not increase monotonically with photon energy, a result which is often inferred from Low's theorem.