BRIEF REPORTS

Brief Reports are short papers which report on completed research or are addenda to papers previously published in the **Physical Review**. *A Brief Report may be no longer than four printed pages and must be accompanied by an abstract.*

Differential cross section for proton-proton bremsstrahlung at 294 MeV

B. v. Przewoski, H. O. Meyer, H. Nann, P. V. Pancella, S. F. Pate, R. E. Pollock, T. Rinckel, M. A. Ross, and F. Sperisen

Department of Physics, Indiana University and Indiana University Cyclotron Facility, Bloomington, Indiana 47405

(Received 7 October 1991)

The differential cross section for $pp \to pp\gamma$ has been measured at an average bombarding energy of 294 MeV and for proton laboratory angles between 5° and 12°. The absolute normalization of the data is based on the concurrent measurement of pp elastic scattering. The experiment has been carried out with the Indiana University Cyclotron Facility Cooler Ring using an internal gas jet target in an electron-cooled beam. The data cover a region of the kinematic space where off-shell contributions of the NN interaction are expected to be enhanced. The shape of the measured cross sections as a function of the photon angle agrees fairly well with the expectation from phase space alone.

PACS number(s): 21.30.+y, 13.75.Cs, 25.10.+s

Nucleon-nucleon (NN) bremsstrahlung, in principle, is the least ambiguous source of information on the off-shell part of the NN interaction, since there are only two strongly interacting particles in the final state. Experiments on NN bremsstrahlung are summarized in a number of reviews (Refs. [1,2], and references therein). Generally, it has been found that the "soft-photon" approximation [3–5], where only *on-shell* information is used to calculate the matrix element, is able to reproduce most of the data. Departure from this behavior is expected when special kinematical conditions are chosen which emphasize a possible off-shell contribution. A criterion for such a choice is given by Fearing [6]; necessary conditions are a sufficiently high bombarding energy ($T_{\rm lab} > 200$ MeV), as well as large photon energies k^* in the NN center-of-mass system (in excess of about 100 MeV [7]). The latter condition requires the relative kinetic energy of the two nucleons to be low, or, the laboratory angles θ_1, θ_2 of *both* outgoing nucleons to be small.

Detecting reaction products at angles close to the beam axis is experimentally difficult. Thus, the measurement of $pp \to pp\gamma$ with two charged particles in the final state is favored for off-shell studies, even though at medium energy the cross section for $np \to np\gamma$ is 4–10 larger. Up to now, two $pp \to pp\gamma$ experiments, one at Lawrence Berkeley Laboratory [7] ($T_{\rm lab}=730$ MeV) and one at TRIUMF [8] ($T_{\rm lab}=280$ MeV, i.e., just below the pion production threshold), have reported data with a significant departure from a soft-photon calculation. In both experiments, the need for suppression of experimental background required that also the photon was detected in coincidence with the two protons. Both experiments were constrained to coplanar final states. In the TRIUMF experiment, which was carried out with a polarized beam, an off-shell signature has been seen in the analyzing power and, to a lesser extent, in the cross section, but only for the smallest proton angle pair measured ($\theta_1 = \theta_2 = 12.4° \pm 2.4°$). It is therefore desirable to cover even smaller proton angles.

In this paper we report first results on $pp \to pp\gamma$ obtained with a novel technique, making use of the recently constructed Indiana University Cooler Ring. In this experiment, a stored, electron-cooled beam passed through a windowless, internal hydrogen gas jet target of about 10^5 atoms/cm^2 thickness. Charged particles emerging in the forward direction at angles between 4° and 14° with respect to the beam direction were detected and their four-momenta determined. The detector system (as described in Ref. [9]) had cylindrical symmetry around the beam axis and consisted of a thin scintillator (F), two wire-chamber pairs for track reconstruction, and a 10.2-cm-thick (E) scintillator detector, followed by a veto counter (V). The latter was used to reject protons of more than 120 MeV that did not stop in the E detector. Protons with less than 20 MeV were below threshold and thus were not detected either. The experimental luminosity was measured by observing pp elastic scattering concurrently with the acquisition of inelastic data. Elastic scattering events were defined by requiring a coincidence between one forward-going proton and one recoil proton near 90°; the latter was detected in a 4.5-cm-long position-sensitive silicon detector, mounted along the beam axis at 11.5 cm distance from the beam. The detector system was optimized for an experiment to study the process $pp \to pp\pi^0$ close to threshold [9]. The $pp \to pp\gamma$ data presented here are a by-product of that experiment.

Charged particles were identified as protons by a condition on the relation between the time of flight from the F to the E detector, and the energy deposited in the E detector. From the measured four-momenta of the two protons, the squared missing mass m_3^2 and the laboratory angle θ_3 of the third, unobserved particle were reconstructed in order to select $pp \to pp\gamma$ events. In Fig. 1 the m_3^2 spectrum is shown for the subset of the data which is discussed below. Bremsstrahlung events were defined by the condition that the squared missing mass m_3^2 had to fall between $-(141\ \text{MeV}/c^2)^2$ and $+(85\ \text{MeV}/c^2)^2$ (gate "b" in Fig. 1). Since this experiment was carried out above the π^0 production threshold, there is a background contribution to the contents of gate b from $pp \to pp\pi^0$ events, misplaced due to reaction losses in the scintillators and due to the finite angular resolution of the detector system. A Monte Carlo simulation of the experimental setup was used to study this background. The simulation assumed phase-space distribution of the three-body final states and incorporated the effects of multiple scattering, reaction losses in the scintillators, and the performance characteristics of the wire chambers. In Fig. 1, simulated missing mass distributions are shown as dotted lines for $m_3 = m_\gamma = 0$ as well as $m_3 = m_\pi$. As can be seen, the two reaction channels completely account for the missing mass spectrum, and gate "b" provides a good separation between $pp \to pp\gamma$ and $pp \to pp\pi^0$. To further illustrate the separation between $pp\gamma$ and $pp\pi^0$ events, distributions with respect to the energies of the two detected protons are shown in Fig. 2. The panels on the left contain a sample of our data, while the distributions on the right are obtained with the Monte Carlo simulation described earlier. The upper two panels correspond to events within the mass gate "b" of Fig. 1 ($pp\gamma$ events), while the lower panels contain events which are excluded by this gate ($pp\pi^0$ events). The solid lines are kinematic loci for the $pp \to pp\gamma$ reaction. These have been calculated for the smallest allowed azimuthal angle between the protons and for a bombarding energy and proton angle (within the range included in the sample) which gives the locus closest to the $pp\pi^0$ peak. An uncertainty of the number of accepted $pp \to pp\gamma$ events was derived from varying the m_3^2 cut within reasonable limits (gates "a" and "c" in Fig. 1).

In presenting the results from this experiment, we have arbitrarily selected the following subset of the obtained $pp\gamma$ data. Accepted $pp\gamma$ events have been sorted with respect to the measured proton polar angles θ_1 and θ_2 into 2.4° wide bins, covering the range from 4.8° to 12.0°. Only symmetric events, with θ_1 and θ_2 in the same bin, were selected. The events in each bin were sorted with respect to the reconstructed photon laboratory angle θ_γ. The experimental angular FWHM resolution was determined using the detector simulation mentioned above. For θ_1, θ_2 it was about 2°, and for the reconstructed θ_γ a resolution of about 10° was estimated. The number of $pp\gamma$ events for which both protons fall into the same angle bin ($\theta_{\text{low}} < \theta_1, \theta_2 < \theta_{\text{high}}, 0 < \phi_1, \phi_2 < 2\pi$) was multiplied by angle-independent correction factors due to multiple wire-chamber hits (1.06 ± 0.02) and scintillator efficiency (1.025 ± 0.010), and divided by the solid angle factor $d\Omega^2 = [2\pi(\cos\theta_{\text{high}} - \cos\theta_{\text{low}})]^2$. The result was then converted to an absolute cross section by comparing to pp elastic scattering which was observed concurrently, as mentioned earlier. This normalization procedure is analogous to the treatment of $pp \to pp\pi^0$, and is described in more detail in Ref. [9]. The resulting cross sections as

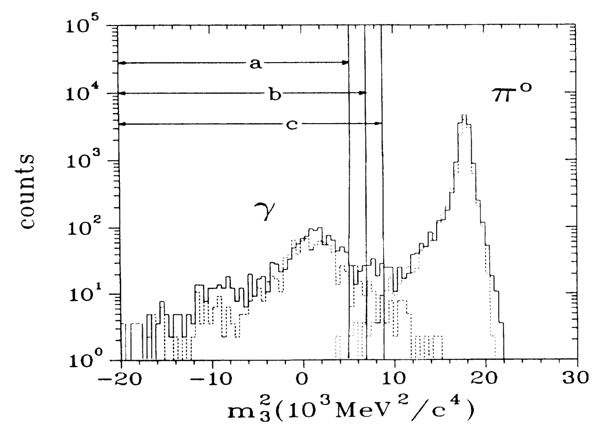

FIG. 1. Squared missing mass m_3^2 reconstructed from the two observed protons. Shown is the subset corresponding to proton angles $\theta_1 = \theta_2 = 10.8° \pm 1.2°$. Also indicated is the simulated response of the detector system to events with $m_3 = 0$ and $m_3 = m_\pi$, respectively. The gates $a-c$ are explained in the text.

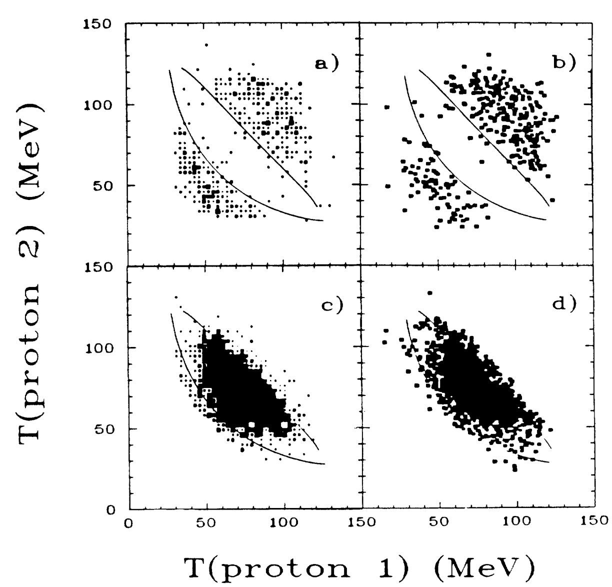

FIG. 2. Distribution of events with respect to the energies of the two detected protons. The data subset with $\theta_1 = \theta_2 = 8.4° \pm 1.2°$ is shown in (a) and (c) and may be compared to the corresponding distributions in (b) and (d) as obtained with the Monte Carlo simulation described in the text. The upper two panels correspond to events within the mass gate "b" of Fig. 1 ($pp\gamma$ events), while the lower panels contain events which are excluded by this gate ($pp\pi^0$ events). The solid lines indicate the kinematic loci for the $pp \to pp\gamma$ reaction calculation for the bombarding energy and proton angles which gives the locus closest to the $pp\pi^0$ peak; they are the same for all four panels.

a function of the reconstructed photon laboratory angle θ_γ are shown in Fig. 3. The average photon energy k^*, corresponding to the three angle bins, is 128, 126, and 124 MeV, respectively. The errors given contain a statistical error (15–20 %), an error due to a $pp\pi^0$ background contribution (10–20 % for $\theta_1=\theta_2=6.0°\pm1.2°$ and 5–10 % for $\theta_1=\theta_2=10.8°\pm1.2°$), and an error due to the corrections mentioned above (2%). The uncertainty due to the $pp\pi^0$ background is largest at small photon angles, since the θ_π distribution for $pp\pi^0$ events is forward peaked. Not included in the errors shown is an overall normalization error of 5% which arises from the uncertainty of the pp elastic scattering cross section. Note that for the data presented here no experimental restriction applies on the azimuthal angles of the two protons, nor on the energy of the photon, but the laboratory kinetic energies of the protons are constrained to the range from 20 to 120 MeV.

In the experiment described here, a total integrated luminosity of about 158 nb^{-1} was accumulated during about 45 h of production running. During this time, a total of 1.83×10^4 $pp\gamma$ events were acquired, while the subset of our data, which is displayed in Fig. 3, contains 2.22×10^3 $pp\gamma$ events. Runs at 31 different bombarding energies between 278 and 325 MeV were carried out.

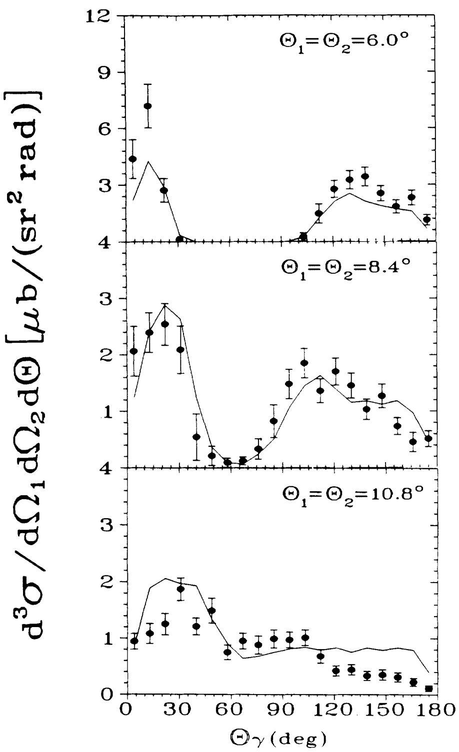

FIG. 3. Differential cross section for $pp\to pp\gamma$ in the laboratory system. The data shown here are for three choices of symmetric proton angle bins, 2.4° wide, centered at $\theta_1=\theta_2$. The kinetic energy of observed protons is constrained to the range between 20 and 120 MeV; no restriction applies to their azimuthal angle. The absence of counts between 30° and 90° is due to the kinematic constraints of this experiment. The curves correspond to a phase-space distribution, arbitrarily normalized. The normalization is the same for all three distributions.

Since over this limited energy range no energy dependence of the $pp\gamma$ cross section was found, the $pp\gamma$ data were summed over all runs. The luminosity-weighted average energy was 294 MeV.

Calculations for $pp\to pp\gamma$ at 280 MeV have been reported by Workman and Fearing [10,11] (WF), and Herrmann and Nakayama [12,13] (HN). Both groups explain the analyzing power and find clear evidence for off-shell contributions in the TRIUMF analyzing powers [8] at the most forward angles, where the soft-photon approximation is not sufficient to reproduce the data. Also, both calculations find little sensitivity to the *NN* potential used. This is expected since it is known [14] that realistic *NN* potentials with very different momentum-space behavior still yield similar off-shell amplitudes at low and medium energy (50 to 350 MeV). Thus, there is little hope that bremsstrahlung experiments will distinguish between different realistic *NN* potential representations. After inclusion of relativistic spin corrections by HN (resulting in a lower cross section), the two calculations (WF, HN) give similar cross sections with much smaller off-shell effects than in the analyzing power. Agreement with the TRIUMF cross sections is obtained when the data are multiplied by a factor of $\frac{2}{3}$ which, unfortunately, seems to be within the normalization uncertainty of the experiment [8]. Even though the normalization of the data reported here is well known, a direct comparison with the TRIUMF cross sections [8] is unreliable because the kinematical constraints of the two experiments are quite different. It would, of course, be possible to test the $pp\gamma$ models [10–13] against the present data by calculating cross sections corresponding to the phase space which is covered by this experiment; however, it seems that such calculations have to wait for the solution of technical difficulties [15,16]. A third calculation performed recently by Brown *et al.* [17] includes rescattering effects but no relativistic spin correlations and agrees with the TRIUMF cross sections before renormalization by $\frac{2}{3}$. The agreement with the analyzing power is worse than for the previous calculations [10–13].

Since in calculating a cross section, the matrix element is usually separated from a phase-space factor which represents the "trivial" dependence on kinematic variables, it is interesting to investigate to what extent the observed angular distributions can be accounted for by this phase-space factor alone. To this aim, we have randomly generated phase-space-distributed $pp\gamma$ events in the center-of-mass system. The orientation with respect to the incident momentum was chosen such that the photon polar angle θ_γ^* was distributed as $\frac{1}{3}+\cos^2\theta_\gamma^*$, in order to account for the quadrupole character of the radiation. The events were then transformed to the laboratory frame, modified to take into account the experimental angle and energy resolution, and histogrammed according to their phase-space weight. The result for 294 MeV incident energy is shown as solid curves in Fig. 3. The normalization of the curves is arbitrary, but it is the same for all three angular distributions. The agreement between this pure phase-space distribution and the shape of the data in Fig. 3 is fairly good, even though we are exploring $pp\to pp\gamma$ far off the energy shell. We also note that a common normalization gives a fair representation of all three angular distributions, corresponding to different proton angles and thus to different average photon energies. Thus, it seems that off-shell effects in the differential cross section, even for kinematic situations where they should be enhanced, are subtle.

In summary, we have measured the differential cross section for $pp \rightarrow pp\gamma$ at an average incident energy of 294 MeV. The outgoing protons were constrained to angles from 4.8° to 12.0° and kinetic energies between 20 and 120 MeV. A differential cross section has been extracted for three symmetric pairs of proton angles, $\theta_1 = \theta_2 = 6.0°$, 8.4°, and 10.8°. The absolute normalization of the data is based on the concurrent measurement of pp elastic scattering and is known to $\pm 5\%$.

This type of experiment is ideally suited for the Indiana University Cyclotron Facility (IUCF) Cooler Ring and benefits in several ways from the novel experimental environment of an internal target in an electron-cooled beam. Most importantly, it allows to access the kinematic region of small proton angles which is particularly sensitive to the off-shell portion of the nuclear matrix element. Further, the photon does not need to be observed in coincidence, as was the case with earlier experiments [7,8], since $pp\gamma$ events are cleanly defined by the missing mass calculated from the two protons. Previous experiments also were constrained to coplanitary in the laboratory, while no such restriction applies in our case.

The present data cover a region of the phase space where off-shell contributions of the NN interaction are expected to be enhanced. Since more sophisticated calculations are not yet available for the covered kinematic region, we have compared the measured angular distributions with the expectation from phase space alone and found fair agreement, suggesting that a possible off-shell contribution manifests itself, at best, in the overall value of the cross section.

In a possible future follow-up experiment it would be fairly straight forward to remove the constraint of the present data to proton energies below 120 MeV. In an experiment below the $pp \rightarrow pp\pi^0$ threshold, the contribution to the background from this reaction could be eliminated. Polarized proton beams are available in the IUCF Cooler Ring. It thus would be possible, albeit with lower luminosity, to study various analyzing powers of the three-body final state. Finally, work is currently in progress to develop an internal polarized hydrogen target. Making use of a polarized atomic beam source and a storage cell [18] (such a target is carrier free and windowless) offers the future possibility to cleanly measure spin-correlation coefficients, if a strong theoretical motivation should arise.

The authors would like to thank H. W. Fearing, K. Nakayama, and V. Herrmann for useful discussions and P. Schwandt for his contribution to the design of experimental hardware. This work has been supported by the U.S. National Science Foundation under Grant No. NSF PHY 87-14406 and one of us (B.v.P.) has been supported by the Deutscher Akademischer Austauschdienst.

[1] M. L. Halbert, in *Proceedings of the Symposium on the Two-Body Force in Nuclei (Gull Lake, Michigan, 1971)*, edited by S. M. Austin and G. M. Crawley (Plenum, New York, 1972), p. 53.
[2] J. V. Jovanovich, in *Procedings of the Second International Conference on Nucleon-Nucleon Interactions (Vancouver, 1977)*, edited by D. F. Measday, H. W. Fearing, and A. Strathdee, AIP Conf. Proc. No. 41 (AIP, New York, 1978), p. 451.
[3] F. E. Low, Phys. Rev. **110**, 974 (1958).
[4] E. M. Nyman, Phys. Rev. **170**, 1628 (1969).
[5] H. W. Fearing, Phys. Rev. C **6**, 1136 (1972).
[6] H. W. Fearing, Phys. Rev. Lett. **42**, 1394 (1979).
[7] B. M. K. Nefkens, O. R. Sander, D. I. Sober, and H. W. Fearing, Phys. Rev. C **19**, 877 (1979).
[8] K. Michaelian, P. Kitching, D. A. Hutcheon, R. Abegg, G. H. Coombes, W. K. Dawson, H. W. Fearing, H. Fielding, G. Gaillard, P. Green, L. G. Greeniaus, M. Hugi, C. A. Miller, G. C. Neilson, W. C. Olsen, J. Soukup, N. R. Stephenson, J. Wesick, and R. L. Workman, Phys. Rev. D **41**, 2689 (1990).
[9] H. O. Meyer, C. Horowitz, H. Nann, P. V. Pancella, S. F. Pate, R. E. Pollock, B. v. Przewoski, T. Rinckel, M. A. Ross, and F. Sperisen, Nucl. Phys. A (in press).
[10] R. L. Workman and H. W. Fearing, Phys. Rev. C **34**, 780 (1986).
[11] H. W. Fearing, Nucl. Phys. **A463**, 95c (1987).
[12] V. Herrmann and K. Nakayama, Phys. Lett. B **251**, 6 (1990).
[13] V. Herrmann, J. Speth, and K. Nakayama, Phys. Rev. C **43**, 394 (1991).
[14] E. F. Redish and K. Stricker-Bauer, Phys. Rev. C **36**, 513 (1987).
[15] V. Herrmann, KFA Juelich, private communication.
[16] H. W. Fearing, TRIUMF, private communication.
[17] V. R. Brown, P. L. Anthony, and J. Franklin, Phys. Rev. C **44**, 1296 (1991).
[18] W. Haeberli, Proceedings of the International Workshop on Polarized Sources and Targets [Helv. Phys. Acta **59**, 597 (1986)].