Measurement of Proton-Proton Bremsstrahlung at 389 MeV

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Proton-proton bremsstrahlung cross sections have been measured at 389 MeV incident energy. A two-arm spectrometer and a liquid hydrogen target system have been used to measure the proton-proton bremsstrahlung events with small background. At the present kinematical conditions, an enhancement of the cross sections due to the Δ current contribution is predicted. The measured cross sections are larger than the theoretical predictions including the Δ current contribution. [S0031-9007(99)09352-7]

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Proton-proton bremsstrahlung ($pp\gamma$) is one of the most fundamental nucleon-nucleon (*NN*) inelastic scattering reactions. It has been investigated to study the off-shell behavior of the *NN* interaction and differentiate between the various models for many years [1,2]. A recent theoretical study, however, pointed out that the information that can be obtained in determining the off-shell effect is less clear than previously thought [3]. In some theoretical studies on the $pp\gamma$ reaction at the intermediate energy, it is predicted that the influence of more elaborate mechanisms on the $pp\gamma$ reaction should be included, such as meson-exchange currents, negative energy states, and the Δ current [4–7]. Some of these calculations predict that the Δ current contribution may increase the cross section about 100% even at about 400 MeV incident proton energy, which is far below the Δ resonance region [5–7]. The contribution of the Δ current to the differential cross section is predicted to be maximum at the proton angles $\theta_1 = \theta_2 \sim 20°$ and $\theta_\gamma \sim 70°$ [5,6]. There were several measurements of $pp\gamma$ reaction around and above the pion production threshold energy at TRIUMF [8] ($T_{\rm lab} = 280$ MeV), IUCF [9] ($T_{\rm lab} = 294$ MeV), COSY [10] ($T_{\rm lab} = 293$ MeV), and LBL [11] ($T_{\rm lab} = 730$ MeV). Recently, the virtual bremsstrahlung in proton-proton scattering ($pp \rightarrow ppe^+e^-$) was also measured at below the pion production threshold [12]. In the TRIUMF, IUCF, and COSY experiments, incident energies were not high enough to be sensitive to the effect of the Δ current. In the TRIUMF and IUCF experiments, they aimed mainly at the off-shell effects of the *NN* interaction and measured both protons at small angle. Therefore their setups were not suitable for investigating the Δ current contribution to the $pp\gamma$ process. In the LBL experiment, their experimental setup did not cover the kinematical region where the Δ effect is expected to be large. The measurement of the virtual bremsstrahlung aimed at obtaining new aspects for the bremsstrahlung process.

In this paper we report the measurement of the $pp\gamma$ reaction at a proton incident energy of 389 MeV. We measured the two outgoing protons with two magnetic spectrometers. The spectrometers were placed at the most forward angles, which were 26°, on each side of the beam so as to be close to the kinematical condition that gives maximum Δ contribution. In this kinematical condition, the Δ current contribution is predicted to be large, especially at forward photon emission angles [5,7]. The phase space is almost constant as a function of the photon emission angle, and the angular dependence of the cross sections is sensitive to that of the matrix elements of the $pp\gamma$ reaction.

The experiment was performed at the Research Center for Nuclear Physics (RCNP), Osaka University. A 389 MeV proton beam from the RCNP ring cyclotron was delivered to a liquid hydrogen target, which was developed by the Kyushu University group [13]. The target thickness was about 9 mm and the container windows were made of 12.5 μm thick aramid foil. Two outgoing protons were detected with the two-arm spectrometer, Grand Raiden (GR) [14] and Large Acceptance Spectrometer (LAS) [15], both at 26.0°. A schematic view of the two-arm spectrometer is shown in Fig. 1. The counter system for both spectrometers consisted of two pairs of multiwire vertical drift chambers (MWDC) for track reconstruction and trigger scintillators, which are set on the focal plane of the spectrometers. The event was triggered by hits at both the GR and LAS trigger scintillators. The position and direction, x, x', y, and y' on the focal plane of the spectrometer, were measured by a pair of MWDC. Since particles cross the MWDC at an inclination of 45° (36°) for the GR (LAS), several sense wires along a particle trajectory put out signals and a relatively large efficiency of the MWDC is obtained. The detection efficiency of each MWDC was more than 99%, and the track-finding efficiencies were about 98% for the GR and

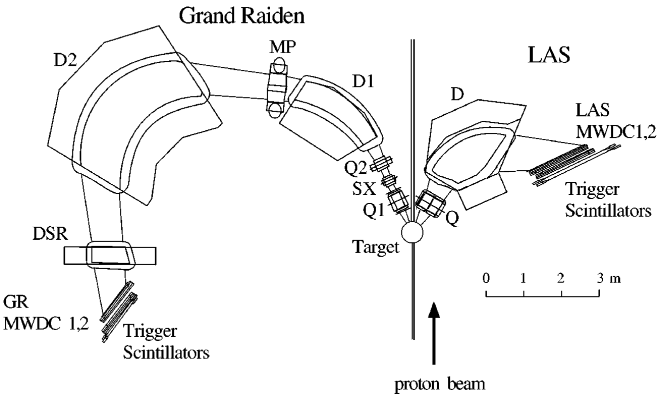

FIG. 1. Schematic view of the two-arm spectrometer system, the Grand Raiden (GR) and the Large Acceptance Spectrometer (LAS). D, Q, SX, and MP denote dipole, quadrupole, sextupole, and multipole magnets, respectively.

95%−98% for the LAS. From the x, x', y, and y' at the focal plane, the momentum vector of the outgoing particle was traced back. The momentum resolutions of the GR and LAS were 420 keV$/c$ and 560 keV$/c$ (FWHM), respectively, for the 928 MeV$/c$ proton, which were obtained by the measurement of the p-C elastic scattering and including the beam energy spread. Live times of the DAQ system were 86%−99% by using a fast DAQ system for the spectrometer system at RCNP [16]. The four-momentum and invariant mass of the third outgoing particle were calculated with the measured proton momenta. In order to reduce the background caused by the beam halo, a beam halo monitor system which consisted of four plastic scintillators was set at about 100 cm upstream from the target. The beam was tuned to minimize the counting rate of these plastic scintillators. The beam intensity was monitored with a beam line polarimeter placed upstream of the target, which counted the pp elastic scattering events from an aramid foil target. The beam intensity was about 15 nA. The luminosity was measured by observing the pp elastic scattering on the liquid hydrogen target. These protons were detected by the luminosity monitor, which consisted of plastic scintillators mounted vertically at the angle of 42.2°, at a distance of 33.8 cm from the target.

At noncoplanar geometries, the dynamic range of the photon emission angle is suppressed by the momentum conservation and the phase space changes largely near the kinematical limit. In order to avoid such a large change, coplanar geometries are desirable [4]. Moreover, most of the theoretical calculations are performed at coplanar geometries. In order to select the coplanar $pp\gamma$ events, we put slits in front of the magnets of the two-arm spectrometer and limited the out-of-plane angles to ± 30 mrad. The in-plane angular ranges were ± 15 mrad for the GR and ± 60 mrad for the LAS. The solid angles of the GR and LAS were 1.8 and 7.2 msr, respectively, with these slits. The solid angles were checked by the measurement of the pp elastic scattering with a CH_2 target. The difference of the phase space between the coplanar case and the present geometrical setting is less than 2%, and it was corrected.

The momentum acceptances of the GR and LAS were limited to 4% and 20%, respectively, by a software cut. The $pp\gamma$ events cannot be covered by one magnetic field setting, so that we have chosen 11 settings of the two-arm spectrometer in order to measure the angular distribution of the photon emission between 30° and 180°. Figure 2 shows the $pp\gamma$ phase space corresponding to the momenta of the two protons, with the geometrical acceptances of the two-arm spectrometer taken into account. The boxes $A-K$ in this figure correspond to the 11 magnetic field settings. For example, the settings A, B, and C correspond to $\theta_\gamma = 30°$ and the settings H, I, and K to $\theta_\gamma = 150°-180°$. The photon is emitted to the same side of the LAS. The limited momentum acceptance of the spectrometer reduces the phase space of the $pp\gamma$ events. This reduction was corrected with a phase space calculation.

At an incident energy of 389 MeV, there are large possible sources of background. One of them is the $pp \to pp\pi^0$ process, which at this energy has a rather large cross section of 48 μb [17]. Protons from the pp elastic scattering from the target hydrogen and inelastic scattering from nuclei of the target container foils also cause large backgrounds. Using the two-arm spectrometer and the liquid hydrogen target, we suppressed these backgrounds and obtained the $pp\gamma$ events with a good signal-to-noise ratio [18]. The spectrometer has been set to detect protons from the $pp\gamma$ reactions, therefore the protons from the $pp\pi^0$ process do not hit the trigger scintillators because

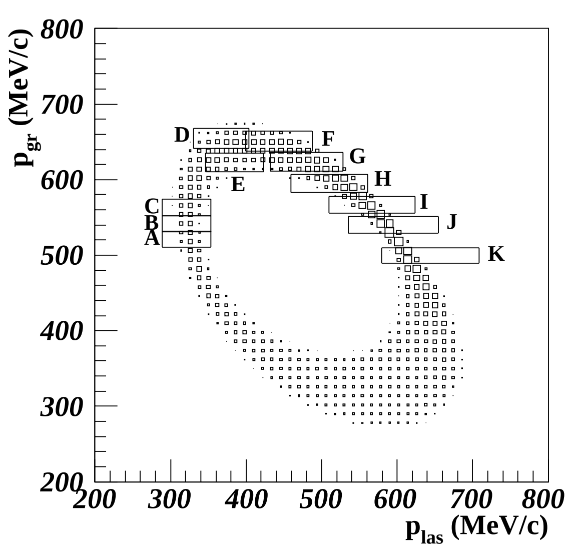

FIG. 2. The $pp\gamma$ phase space as a function of the momenta of the two protons at our experimental setting. The boxes in this figure are the momentum acceptances for each magnetic field setting. This is obtained with a phase space calculation.

they have very different momenta from those of the $pp\gamma$ process. The pp elastic scattering events are not detected either, unless one of the protons is scattered from the wall and loses energy in the spectrometer. The protons from the $A(p,p')$ reactions also cause triggers. Two independently scattered protons may enter the spectrometer in an accidental coincidence. We estimated the number of these events from coincidences coming from two different beam bunches and it is subtracted. The $A(p,2p)$ quasielastic events from nuclei of the target container foils also contributed to the background. The magnitude of this contribution was estimated from the "empty target" runs, which were hydrogen gas target runs. Because of the low temperature of the liquid hydrogen target, the residual gas in the scattering chamber was frozen on the target foils and this also caused background. In order to estimate the contribution from the frozen gas correctly, we performed the empty target runs at a temperature of about 25 K, where nitrogen and oxygen molecules are still frozen.

The squared missing mass spectra reconstructed from the detected two protons are shown in Fig. 3. These are obtained from the D and F magnetic field settings which correspond to about 70° and 120° photon emission angles, respectively. A clear peak about 0 MeV^2 which corresponds to the $pp\gamma$ process is obtained. The background events due to the accidental coincidence and from the empty target run are also shown in the top figures. The yield of the empty target run are normalized to that of the liquid hydrogen target run using the beam current. The difference spectra, given by open circles with statistical errors, are shown in the bottom figures. The figures show that the background has been estimated correctly and has been subtracted from the data. The experimental data are compared to the result of a Monte Carlo simulation. In this simulation, the events were generated with the phase space distribution, and the energy straggling and multiple scattering in the target and the momentum and angular resolutions of the spectrometer were taken into account. It is clear that the missing mass spectra were well accounted by the simulation.

Figure 4 shows the coplanar $pp\gamma$ differential cross sections as a function of the reconstructed photon emission angle θ_γ in the laboratory system. The error bars in this figure include statistical errors and include the error in the magnetic field setting of the spectrometer. If a change in the magnetic field of the spectrometer occurs, the $pp\gamma$ phase space changes and it causes error in the phase space correction. This change of the magnetic field setting was less than 0.1%, and the error for the phase space correction is less than 15%. It was estimated using a phase space calculation. In order to verify the accuracy of the absolute normalization factor, we measured the pp elastic scattering cross section with a CH_2 target of 2.37 mg/cm^2 thickness. The measurements were done in three ways: the GR single-arm measurement, the LAS single-arm measurement, and the GR and LAS two-arm coincidence measurement. In addition, the liquid hydrogen target was also used to measure the pp elastic scattering with the GR and the luminosity monitor. As shown in Fig. 5 the measured pp elastic scattering cross sections

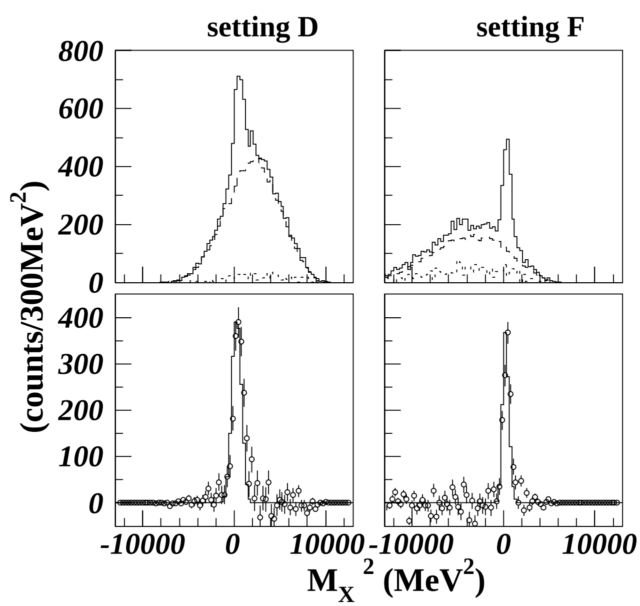

FIG. 3. The squared missing mass (M_X^2) spectra reconstructed from the two observed proton momenta. The results for the D and F magnetic field settings are shown. Top: The spectra as taken with the liquid hydrogen target runs (solid), contribution from the accidental coincidence events (dashed), and the "empty target" runs (dotted). Bottom: The missing mass spectra after subtracting the accidental coincidence and the background events (open circles with error bars). The solid lines show the result of a Monte Carlo simulation.

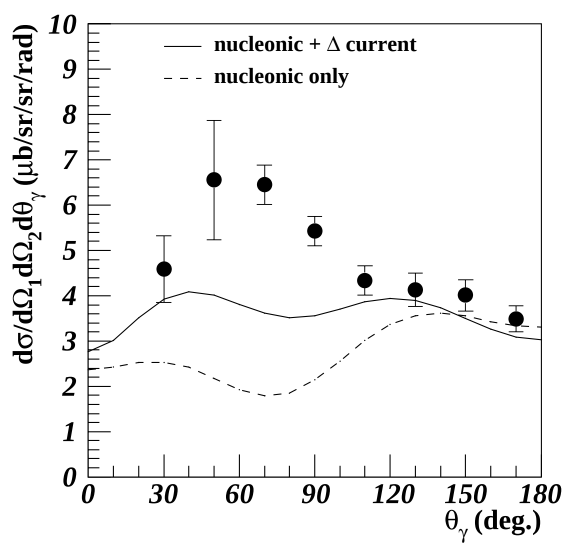

FIG. 4. The differential cross sections for the $pp \rightarrow pp\gamma$ in the laboratory system. The lines indicate the results of the theoretical calculations including the Δ current (solid) and only the nucleonic current (dashed).

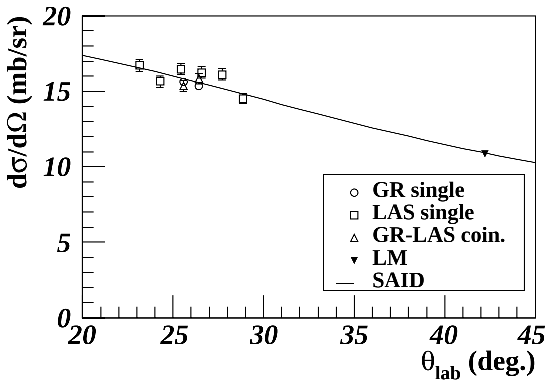

FIG. 5. The differential cross sections for the pp elastic scattering in the laboratory system. The results of the GR single-arm measurement (open circles), the LAS single-arm measurement (open squares), the GR and LAS coincidence measurement (open triangles), and the measurement with the luminosity monitor (closed triangle) are shown. The line is the result of the SAID.

agree with the values obtained by the SAID program [19] within 4%.

The $pp\gamma$ differential cross sections of the present work were compared to the theoretical calculations of de Jong *et al.* [5]. In Fig. 4, the solid line corresponds to the calculation including the contribution from the Δ current, and the dashed line is the result of the calculation that incorporates only the nucleonic current contribution. These calculations predict that the Δ effect is seen at forward photon emission angles and the differential cross section increases by a factor of 2 at about $\theta_\gamma = 70°$. The present data favor the calculations including the Δ current, but especially at about $\theta_\gamma = 70°$, where the effect of the Δ current seems to be large, the present result is about 70% larger than the theoretical prediction including the contribution of the Δ current. On the other hand, the present result is not much different from the theoretical predictions at the backward angles. Another result of the calculation including the meson-exchange currents and the Δ current at our kinematical conditions [7] also predicts a smaller differential cross section than that of the present data. This suggests that there might be contributions of some other mechanisms to the $pp\gamma$ cross section, and a further theoretical study is desired.

In summary, we have measured the differential cross sections for the $pp \rightarrow pp\gamma$ at 389 MeV incident energy. The two outgoing protons were detected with the two-arm magnetic spectrometer both at the scattering angles of 26.0°. Using the magnetic spectrometer and the liquid hydrogen target, we have succeeded in measuring $pp \rightarrow pp\gamma$ events with a small background. The accuracy of the absolute normalization factor is verified by the measurement of the pp elastic scattering. The measured pp elastic scattering cross sections agree with the values obtained by the SAID program within 4%. The obtained $pp\gamma$ cross sections are larger than the theoretical predictions including the Δ current contribution at about $\theta_\gamma = 70°$. A further theoretical study is needed to pin down the origin of this discrepancy.

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