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Proton–proton bremsstrahlung towards the elastic limit at 190 MeV incident beam energy

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Abstract

A series of nucleon–nucleon bremsstrahlung ($NN\gamma$) experiments at 190 MeV incident beam energy have been performed at KVI in order to gain more insight into the dynamics governing the bremsstrahlung reaction. After initial measurements wherein the bremsstrahlung process was studied far away from the elastic limit, a new study was used to probe the process nearer to the elastic limit by measuring at lower photon energies. Measured cross sections and analyzing powers are compared with the predictions of a microscopic model and those of two soft-photon models. The theoretical calculations overestimate the data by up to ≈ 30%, for some kinematics.

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The nucleon–nucleon (NN) interaction is the corner-stone of any model dealing with nuclear systems. It is, therefore, vital to have a good understanding of the NN potential before searching for smaller effects such as the three nucleon force. The NN potential can be addressed by studying the deuteron as the simplest bound state, or by investigating observables of NN scattering. As the result of NN-elastic scattering experiments performed in the last decades, a very extensive data set has emerged. On the theoretical side, modern potentials [1–3] have been constructed which fit the data with a χ^2 close to unity. Since the predictions of different realistic potential models are nearly the same for elastic NN scattering, they are said to be "data-equivalent". It has been a long-standing hope to distinguish among these models by using the observables of proton–proton bremsstrahlung (hereafter $pp\gamma$) [4–6], which involves a photon in addition to two nucleons in the final state. However, due to the fact that the predictions of bremsstrahlung models using various potentials are very similar [7], and the differences between them are smaller than their differences with the data, the experimental $pp\gamma$ data can be used to understand the underlying physics of the nucleon–nucleon bremsstrahlung process.

In 1996, a series of measurements were performed at KVI to study $pp\gamma$ at 190 MeV incident beam energy. The first data at small proton opening angles, corresponding to large photon energies, typically 65 MeV, were published subsequently [8–11]. In continuation of that work and in order to cover a much larger area of the available phase space, a new experiment using a new setup was performed. This setup was designed in a way

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to be able to measure larger proton opening angles or equivalently smaller photon energies, typically 45 MeV, thus moving towards the elastic limit. At the elastic limit all gauge-invariant microscopic models should yield predictions that converge to the results of the calculations based on the soft-photon theorem as these calculations are by construction in agreement with the results of elastic scattering. In this Letter, the results of this experiment, closer to the elastic limit, are compared to microscopic [12–15] and soft-photon model (SPM) calculations [16,17].

In the present experiment, a proton beam with average intensity and polarization of 1.5 nA and 0.6, respectively, was delivered by the AGOR cyclotron. The beam was impinged on a liquid hydrogen target with a nominal thickness of 6 mm [18]. SALAD (small-angle large-acceptance detector) [19] was employed to detect protons at forward angles, and to measure their energies and coordinates. It consists of a MWPC placed 30 cm away from the target (as opposed to 50 cm in the previous measurements [8–11]) and two arrays of plastic scintillators. The MWPC is capable of determining the angular coordinates of protons with a resolution of 0.7°. The first array of scintillators, called energy scintillators, consists of 24 scintillator elements. These scintillators are made thick enough to stop all protons originating from the bremsstrahlung reaction, thereby measuring their energies. However, most of the elastically-scattered protons punch through the energy layer and reach the second array of scintillators, the Veto scintillators. The Veto scintillators, consisting of 26 scintillators, are deployed to identify elastically-scattered protons. This identification is used to reject events, which are not $pp\gamma$ events, at the first trigger level. In the chosen geometry, SALAD is capable of detecting protons with polar angles between 10° and 36° with a high efficiency. However, the azimuthal-angle coverage of the detector is not 100% for polar angles larger than 28° and goes to zero at polar angle of $\sim 40°$. The backward hemisphere of plastic ball [20], consisting of 340 phoswich detector modules, was used to detect photons scattered to angles larger than 90°. The opening angle of each module is 10°, providing a good enough resolution in the determination of the coordinates of the photons for the kinematical reconstruction. The photon detector covered a polar angular range of 90° to 160° with a full azimuthal coverage. With this setup all the outgoing particles of the bremsstrahlung process were detected.

In the data analysis, both elastic and inelastic (bremsstrahlung) channels were analyzed. Asymmetries were also obtained from the data. By fitting the asymmetries for elastic scattering to the predictions of a global data analysis such as PWA93 [21], the beam polarization is determined with high accuracy. In this way, the systematic uncertainty in the beam polarization was kept below 0.005. The elastic-scattering data were also used as a monitor of the system.

The main trigger, called $pp\gamma$ trigger, is made when within a time window of 100 ns, the number of hits detected by energy scintillators minus that detected by the Vetos is equal or larger than two, along with at least one hit on the plastic ball. Using this trigger the background originating from the elastically-scattered protons was considerably suppressed. Yet, only 1.5% of the events read-out through this trigger are real $pp\gamma$ events; the rest are background events originating primarily from elastic scattering. As the first step in $pp\gamma$ event selection, a gate is set on the TDC spectra of SALAD scintillators, selecting the prompt coincidences. This way the protons with the right arrival-time difference are selected. On the plastic-ball side, the charged particles are identified by pulse-shape analysis and eliminated.

The kinematics of proton–proton bremsstrahlung involves three particles, resulting in nine kinematic variables, polar and azimuthal angles of the protons and the photon which are denoted as, θ_1, θ_2, θ_γ, ϕ_1, ϕ_2, and ϕ_γ respectively. However, it is more conventional to use two other variables, namely noncoplanarity angle (ϕ_{nonco}) and the azimuthal angle of the event (ϕ_{event}), instead of ϕ_1 and ϕ_2. ϕ_{nonco} is the angle between the projected momentum of each proton onto the x–y plane and a plane containing the incoming beam but rotated so much to make the same angle with both protons. This plane is called the coplanar plane. ϕ_{event} is the angle between a vector normal to the coplanar plane and y-axis. The normal vector is on the same side of the coplanar plane as the protons are. Due to energy and momentum conservation, only five of these variables are needed to kinematically reconstruct an event. In this experiment, all nine variables were measured, providing four over-determined variables. The angular coordinates of the protons and the polar angle of the photon were used as input for the event reconstruction as they were measured with relatively better resolution than other variables. The reconstruction leads to two physically acceptable solutions. There is a unique way to label and distinguish the solutions. Labeling the solutions give rise to the labeling of the protons (see Ref. [11] for more details). When moving towards the elastic limit, one can see that the non-coplanarity angle approaches zero. For this limit, the definition of proton 1 and proton 2 is rather trivial. The proton which is on the same side as the photon with respect to the beam direction is proton 1 and the other one is proton 2. Subsequently, by plotting the difference between the reconstructed and measured energies of proton 1 versus the same quantity for proton 2 a pattern emerges, highlighting the most probable proton–proton bremsstrahlung events as shown in Fig. 1. These events are selected by applying the graphical cut indicated in the figure. Further background rejection is done by requiring the measured energy of the photon to be above 25 MeV, as a study of the background revealed that the background on the plastic-ball side mainly stems from low-energy photons. The effect of this cut was corrected for by Monte Carlo simulations. The last over-determined variable, the azimuthal angle of the photon was used to estimate the remaining background. After applying all cuts, the remaining background is estimated to be generally less than 0.5%.

In this experiment there were four types of inefficiencies, namely, data-acquisition dead-time, MWPC inefficiency, trigger inefficiency, and photon detection inefficiency. The dead-time and the MWPC inefficiency were typically 50% and 5%, respectively. Trigger inefficiency is the fraction of the $pp\gamma$ events which are lost at the level of defining the main event trigger, and was estimated to be around 4%. Finally, the photon