Exclusive Measurement of Coherent Proton-Deuteron Bremsstrahlung

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For the first time a high-precision proton-deuteron bremsstrahlung experiment has been performed in which all the different exit channels have been distinguished separately. High-precision cross sections and analyzing powers in one of the outgoing channels, namely, the coherent bremsstrahlung with a proton and a deuteron in the final state, are presented at 190 MeV incoming proton beam energy and are compared to calculations based on the low-energy theorem. The results of the calculations vary considerably calling for a fully microscopic calculation. However, using a recipe including the initial- and final-state interactions, the predictions come close to the data.

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Nucleon-nucleon bremsstrahlung is the most fundamental reaction used in studying effects beyond elastic scattering in the *NN* interaction. It involves only two strongly interacting particles in the final state and the electromagnetic interaction of a photon, which is well known from QED. The advent of high-precision detection systems and the success of modern potential-model calculations have recently boosted both the experimental and the theoretical efforts for the investigation of proton-proton bremsstrahlung [1–7]. The cross sections for nucleon-nucleon bremsstrahlung also serve as a basic input for calculations that deal with photon production in heavy-ion collisions. These calculations rely heavily on theoretical predictions of the nucleon-nucleon bremsstrahlung process. These predictions resort to soft-photon approximations which either involve only the leading order in the expansion of the amplitude in the photon momentum, or have a strong model dependence for terms beyond the second order [8,9]. In heavy-ion collisions, it is often assumed that the main contribution to the cross section comes from pn bremsstrahlung, which is at intermediate energies a factor 5 to 10 stronger than pp bremsstrahlung. Coherence effects, which are the result of very strong initial- and final-state interactions [10], are completely ignored in the calculations. The simplest reaction with which these effects can be studied is the $pd\gamma$ reaction which also forms the transition between the elementary *NN*-bremsstrahlung process and proton-nucleus bremsstrahlung.

All of the proton-deuteron bremsstrahlung experiments done in the past are inclusive in the sense that only the energy and angular distributions of the produced photons have been measured, implying an integration over all particles and reaction channels [11,12]. Comparison with theoretical estimates based on a meson-exchange potential model, in which only the pn bremsstrahlung has been considered and the pn bremsstrahlung probability was folded with the momentum distribution of the nucleon in the target nucleus, shows that the theory underestimates the data by up to $\approx 40\%$ depending on the photon emission angle [13]. This clearly demonstrates the need for more experimental and theoretical efforts. Very recently, the results of an experiment were published [14], in which all the outgoing particles were measured, albeit with a luminosity of about 3 orders of magnitude smaller than the present work and in a different kinematical regime.

We have performed an exclusive experiment in which the two-body final-state $\gamma\,^3$He (radiative capture), three-body final-state $pd\gamma$ (“coherent” bremsstrahlung) and the four-body final-state $ppn\gamma$ were identified separately [15]. In this Letter, we report on the cross sections and analyzing powers for the three-body final state, at an incident beam energy of 190 MeV, and show that the cross sections are of the same order of magnitude as the $pp\gamma$ cross sections. Results on the two-body final state can be found in Ref. [16]. Results for the four-body final state will be published in the near future.

A high-quality polarized-proton beam of 190 MeV delivered by the superconducting cyclotron AGOR at KVI was used to bombard a liquid-deuterium target which has the shape of a disk with a diameter of 20 mm and a thickness of 6 mm [17]. The bulging of the very thin foils increases the target thickness by about 25%. The protons and deuterons were detected using the small-angle large-acceptance detector (SALAD) specifically designed for bremsstrahlung measurements [18]. This detector has almost cylindrical symmetry with full azimuthal coverage between 6° and 20° and limited coverage for polar angles up to 26°. The large solid angle (about 400 msr) is mandated by the very small cross sections of the processes under study and the need to cover a large part of the phase space. The detector is equipped with two multiwire proportional chambers (MWPC) with a central hole [19] to allow free beam passage. With these MWPCs the positions of the outgoing hadrons were determined. Their energy is measured with a segmented layer of plastic scintillators that stop protons with energies of up to 135 MeV. Protons with higher energies entering SALAD result from elastic scattering. They will penetrate into a second layer of scintillators that acts as a veto counter thus allowing elastically scattered protons to be rejected. In order to accomplish this, a special trigger system was developed [20]. This trigger system reduced the trigger rate drastically by requiring that two energy detectors from the first layer were in coincidence with a photon of at least 15 MeV in energy and the second layer did not fire for these particles. This condition essentially rejects all events produced by elastically scattered protons.

The bremsstrahlung photons were detected using the Two-Arm Photon Spectrometer, TAPS [21]. TAPS, in the present experiment, consisted of approximately 400 BaF_2 crystals and was used in two different geometries. In the first geometry, called the ''supercluster'' geometry, the crystals were mounted in a large hexagon around the beam pipe, covering a polar angular range of 125°–170°. This setup has a cylindrical symmetry that allows for an integration of the data over the full azimuthal range to obtain higher statistical accuracy. In the second geometry, called the ''block'' geometry, the crystals were mounted in six rectangular frames of 64 crystals each, positioned around the target and covering a polar angular range of 60°–170°. In both geometries, TAPS had an angular resolution of about 6° and covered more than 20% of the full 4π solid angle. It should be noted, however, that due to energy thresholds set by the detection system for protons (about 20 MeV) and deuterons (about 28 MeV), and the kinematics of the reaction, the accessible range of angles is limited considerably for the $pd\gamma$ channel.

An average beam current of 1 nA resulted in a trigger rate of 1 kHz, about 99% of which is originating from events which have been caused by accidental coincidences of elastically scattered particles that have undergone hadronic interactions thereby losing energy and thus not punching through to the veto detector. Typical singles rates were about 3 MHz for SALAD and 20 kHz for TAPS. The collected data were analyzed offline to identify the $pd\gamma$ events. The photons detected in TAPS were discriminated from massive particles using time-of-flight and pulse-shape analysis. The $pd\gamma$ final state is characterized by nine independent parameters, all of which are measured. Because of energy and momentum conservation only five kinematical variables are needed to completely identify an event, resulting in four redundant variables. Using the polar and azimuthal angles of the proton and the deuteron and the polar angle of the photon, the energies of all three particles and the azimuthal angle of the photon can be reconstructed and compared to the measured ones on an event-by-event basis. The overdetermined kinematics provides a very good tool for reducing the background since the reconstruction of background events will, in general, result in forbidden momenta. Since SALAD does not provide particle identification, protons and deuterons can *a priori* not be distinguished and both permutations have to be checked. Because of the large mass difference between the proton and deuteron the correct and the wrong solutions can easily be disentangled. After choosing the events which had a good agreement between their measured and reconstructed hadron energies, the background level dropped to 2% and 5% for the supercluster and block geometries, respectively. This background has been appropriately subtracted using one of the redundant variables, namely ϕ_γ. The final data set consists of about 0.8×10^6 good $pd\gamma$ events for each geometry.

In order to obtain absolute cross sections various corrections to the data have to be applied. The effects of the cuts made to select the good events and the acceptance of the detection system were investigated using Monte Carlo techniques [22]. The efficiency of the MWPCs was determined from the data [19] and was typically between 91% to 98%. The trigger efficiency for $pd\gamma$ events was determined [20] and found to be typically between 75% and 95% depending on the angle of the photon detector. For the present measurement, it was decided to use the simultaneously recorded elastic-scattering data for the monitoring of the luminosity and beam polarization. The cross sections, so obtained, were compared to the results of a recent measurement also performed at KVI with a solid target and a different setup [23], where the absolute cross sections for proton-deuteron elastic scattering were accurately determined. This comparison resulted in a normalization factor for the absolute bremsstrahlung cross sections which was not very different from the nominal luminosity values. The beam polarization was measured using the KVI in-beam polarimeter (IBP) [24], with an accuracy of 2% during the SALAD measurements. The left-right asymmetry in SALAD was calibrated to this IBP measurement and used further in the experiment to monitor the beam polarization. The cross section and analyzing-power data are shown for different combinations of proton, deuteron, and photon angles in Figs. 1 and 2.

The state-of-the-art calculations for the three-nucleon system should be done in the framework of Faddeev formalism. These calculations include modern *NN* potentials and can even take higher-order effects, such as the

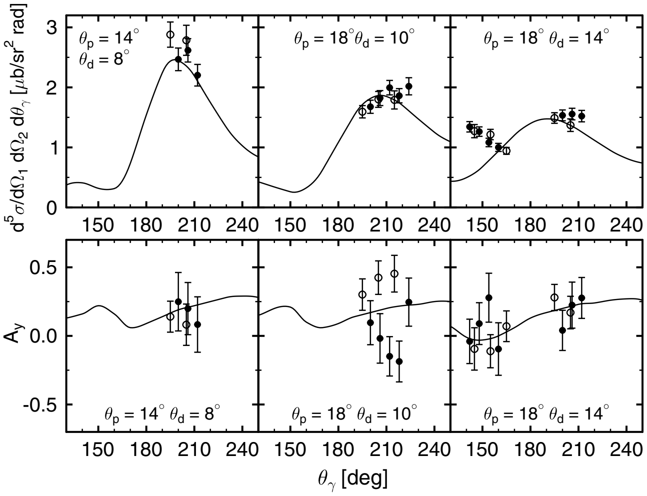

FIG. 1. Cross sections and analyzing powers for the coplanar geometry for three different combinations of proton and deuteron scattering angles as a function of the photon polar angle. Solid (open) dots represent data from the supercluster (block) geometry measurements. Only statistical uncertainties are shown. The systematic uncertainties of about 10% in the cross sections are not shown. The SPM predictions (solid curve) are discussed in the text.

effects of the three-body force, into account. Since such a calculation for the bremsstrahlung channel is beyond the present capability, one reverts to soft-photon models (SPM). The leading terms in a soft-photon description are formed by diagrams corresponding to radiation off external legs, supplemented with contact terms. In an SPM, these diagrams are calculated by using the on-shell T-matrix for the hadronic scattering process. The on-shell T-matrix can, in principle, be extracted from observables for elastic scattering. The construction of the contact terms is largely phenomenological and mimics processes not explicitly considered such as certain rescattering processes and meson-exchange processes. The contact terms are strongly restricted by the constraints of gauge-invariance (current conservation) and the condition that the contact term is free from pole structures in the limit of vanishing photon energy. Obeying the low-energy theorem warrants that in an expansion of the amplitude for the process in powers of the photon momentum, the leading two terms (which are model independent) are reproduced correctly. Because of the model dependence of the contact term, several soft-photon amplitudes can be constructed for any particular process, but only one will be presented here.

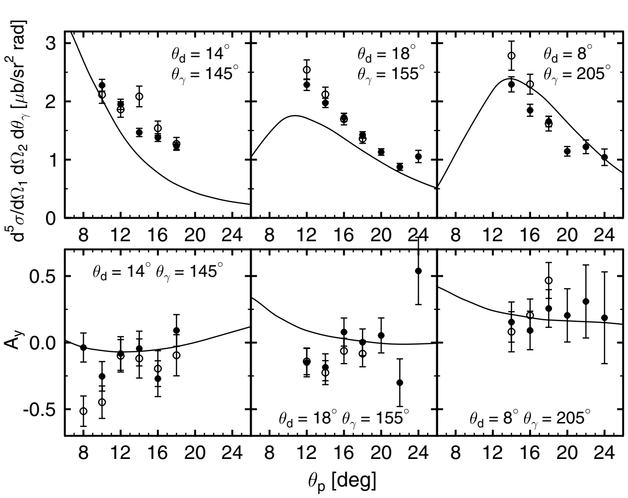

FIG. 2. Cross sections and analyzing powers for coplanar geometry as a function of proton angle for a number of fixed deuteron and photon angles. The meaning of the symbols and curves is the same as in Fig. 1.

Since the complete set of partial-wave amplitudes has not been determined experimentally for the pd (a spin-1/2, spin-3/2) system, we used the results of the calculations by the Bochum-Cracow group [25] for constructing the (on-shell) T-matrix. To arrive at a covariant description, the amplitude for the elastic process is cast in the form of a sum of 12 Lorentz tensors which reduce in the nonrelativistic limit to those defined by Seyler [26], similar to that used in Ref. [27] for the NN T-matrix. The SPM calculation shown in Figs. 1 and 2 is an adapted version of the 2S2T model of Ref. [28]. The on-shell T-matrix is evaluated at energies appropriate for the incoming and the outgoing proton-deuteron system. The momentum transfer which, in conjunction with the energy, determines the kinematics of the on-shell point is reconstructed, for each diagram, from a symmetric combination of Mandelstam t and u variables. This particular recipe for constructing the bremsstrahlung amplitudes attempts, thus, to account for the initial- and final-state interactions of the pd system.

In this Letter, we present only coplanar data, i.e., events where the momentum vectors of the outgoing proton and deuteron lie in the same plane as the momentum vector of the incoming beam. For coplanar data, only one analyzing power, namely A_y (or $A_\gamma^\perp$, depending on the frame), can exist and the other two possible analyzing powers go to zero due to parity arguments. The possible false asymmetries in the system have been corrected for by using a beam of unpolarized protons. In Fig. 1, the fivefold differential $p + d \rightarrow p + d + \gamma$ cross sections and the analyzing powers are plotted as a function of θ_γ for three different combinations of proton and deuteron scattering angles, and for a maximum noncoplanarity of 5°. The bin size for the polar angle of protons and deuterons is 2°. The photon polar angle is measured from the same side as for the protons and runs from 0 to 2π. The presented absolute cross sections for both geometries have a systematic uncertainty of about 10%, which is determined mainly by the uncertainty in the target thickness and the detector acceptance which has been evaluated with Monte Carlo simulations. Figure 2 shows the cross sections and analyzing powers for fixed deuteron and photon angles, as a function of the outgoing proton angle. The data sets from the two geometries are in good agreement. The inelasticity of the measurements can be judged best by the photon energy which is about 80 MeV for photons emitted at the most backward angles measured in the present experiment.

As can be seen from the figures, the results of the SPM calculations are close to the data at various kinematics. However, the results of different approaches (within the soft-photon approximation) differ considerably (not shown here). This might be due to the fact that an SPM calculation is based on the on-shell T-matrix which varies strongly as a function of its kinematic variables. For example, the *pd* elastic cross section varies by almost 2 orders of magnitude across the range of scattering angles (as opposed to the rather flat distribution for the *pp* system). As a general rule, one can expect an SPM to give reliable predictions as long as the T-matrix does not vary very much over the range of kinematical variables. The precise recipe for constructing the amplitudes is, then, rather sensitive to these variations and the results of this type of calculations should be looked at with great care for the system under study. The reason that the chosen SPM does quite well compared to others is due to the fact that the approach taken in this calculation attempts to account for initial- and final-state interactions through the appropriate energy dependence of the T-matrix. It should then be concluded that the *pd* system is a nontrivial one and forms a sensitive testing ground for the dynamics which should be treated in the framework of a microscopic calculation such as a Faddeev calculation.

In summary, a high-precision exclusive measurement of the cross section of one of the three channels in proton-deuteron scattering involving a photon, namely, the coherent three-body final state has been performed for the first time and presented. The results of the two measurements performed at different times with different geometries are in good agreement. The data have been compared with the predictions of an SPM and show a general agreement. There is, however, a large degree of model dependence in constructing these amplitudes in the SPM, indicating the sensitivity of the process to the underlying dynamics and a microscopic calculation is called for. In addition, as was mentioned in the introduction, the magnitude of the cross sections measured shows that the coherent process is as important as the proton-proton bremsstrahlung channel [1] and should not be simply ignored in the heavy-ion collisions involving photons.

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