Observation of Double Radiative Capture on Pionic Hydrogen

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(Received 25 April 2002; revised manuscript received 3 September 2002; published 4 December 2002)

We report the first observation of double radiative capture on pionic hydrogen. The experiment was conducted at the TRIUMF cyclotron using the RMC spectrometer and detected γ-ray coincidences following π^- stops in liquid hydrogen. We found the branching ratio for double radiative capture to be $[3.05 \pm 0.27(\text{stat}) \pm 0.31(\text{syst})] \times 10^{-5}$. The measured branching ratio and angle-energy distributions support the theoretical prediction of a dominant contribution from the $\pi\pi \rightarrow \gamma\gamma$ annihilation mechanism.

DOI: 10.1103/PhysRevLett.89.252501 PACS numbers: 25.80.Hp, 13.60.–r, 36.10.Gv

Negative pions stopped in hydrogen form pionic hydrogen atoms. These atoms can disintegrate via several modes that include the well-known processes of charge exchange $\pi^- p \rightarrow \pi^0 n$ [1], radiative capture $\pi^- p \rightarrow \gamma n$ [1], and pair production $\pi^- p \rightarrow e^+ e^- n$ [2,3].

However, for pionic hydrogen, an additional mode of capture is predicted by theory,

$$\pi^- p \rightarrow \gamma\gamma n. \qquad (1)$$

This double radiative process has been investigated theoretically by several authors, including Ericson and Wilkin [4], Christillin and Ericson [5], Gil and Oset [6], and Beder [7]. The predicted branching ratio is 5.1×10^{-5} [7], with a mechanism that is dominated by the annihilation of the stopped, real π^- on a soft, virtual π^+, i.e., $\pi\pi \rightarrow \gamma\gamma$. Beder also predicted different photon energy-angle distributions for the contributing annihilation and bremsstrahlung mechanisms.

The underlying dynamics of $\pi\pi$ annihilation in double radiative capture is rather intriguing. For example, it led Ericson and Wilkin [4] and Nyman and Rho [8] to suggest the reaction as a probe of the pion field in the nucleus and Gil and Oset [6] to suggest the reaction as a novel window on the $\pi\pi \rightarrow \gamma\gamma$ vertex. Also, the related $\gamma p \rightarrow \gamma\pi n$ reaction was considered by Wolfe *et al.* [9] and Drechsel and Fil'kov [10] as a possible probe of the pion polarizability.

The only experimental search for double radiative capture on pionic hydrogen was conducted by Vasilevsky *et al.* [11] at Joint Institute for Nuclear Research. They used a large-acceptance photon-pair spectrometer and obtained a branching ratio upper limit of 5.5×10^{-4}. However, double radiative capture on beryllium and carbon has been observed in experiments by Deutsch *et al.* [12] at CERN and Mazzucato *et al.* [13] at TRIUMF. Unfortunately, these data are difficult to interpret due to (i) nuclear structure effects and (ii) capture occurring from both the s and p states of the πBe and πC atoms.

Our experiment was performed at the TRIUMF cyclotron using the RMC spectrometer [14]. The incident beam had a pion flux of 7×10^5 s^{-1}, a central momentum of 81.5 MeV/c, and electron and muon contamination of 18% and 9%, respectively. The incoming pions were counted in a 4-element plastic scintillator telescope and stopped in a 2.7 liter liquid hydrogen target of length 15 cm, diameter 16 cm, and wall thickness 254 μm [14]. The outgoing photons were detected by pair production in a 1 mm thick cylindrical Pb converter and electron-positron tracking in cylindrical multiwire and drift chambers. A 1.2 kG axial magnetic field was used for momentum analysis and concentric rings of segmented scintillators were used for fast triggering. The trigger scintillators comprised the A ring (just inside the Pb converter radius), the C ring (just inside the multiwire chamber radius), and the D ring (just outside the drift chamber radius). For more information on the RMC spectrometer, see Wright *et al.* [14]. Note that in this experiment we moved the Pb converter from just inside the C-counter radius to just outside the A-counter radius.

For $\pi^- p \rightarrow \gamma\gamma n$ data-taking, we employed a two-photon trigger based on the hit multiplicities and the hit topologies in the trigger scintillator rings and the drift chamber cells. A typical $\pi^- p \rightarrow \gamma\gamma n$ event that fulfilled the trigger is shown in Fig. 1. It has zero hits in the A-counter ring, two hits in the C-counter ring, and four hits in the D-counter ring. To reduce the high rate of back-to-back photons from $\pi^0 \rightarrow \gamma\gamma$ decay, we rejected photon pairs reconstructed with drift cell hits or trigger scintillator hits separated by large azimuthal angles.

During a four week running period, we collected $\pi^- p \rightarrow \gamma\gamma n$ data from a total of 3.1×10^{11} pion stops in liquid hydrogen. Calibration data with a dedicated $\pi^0 \rightarrow \gamma\gamma$ trigger were also taken periodically.

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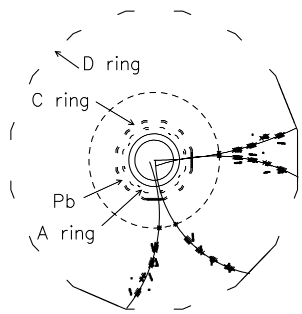

FIG. 1. A typical $\pi^- p \to \gamma\gamma n$ event. The plot shows the fit in the plane perpendicular to the beam axis. The electron-positron pairs converge at the lead converter and the reconstructed photon pairs originate from the hydrogen target located at the center. The trigger pattern of zero hits in the A-counter ring, two hits in the C-counter ring, and four hits in the D-counter ring is also displayed. For scale, the radius of the D ring is about 60 cm.

One source of background was real γ-γ coincidences arising from $\pi^0 \to \gamma\gamma$ decay. The π^0's were produced by either at-rest or in-flight pion charge exchange. The at-rest source yields π^0's with energy $T = 2.8$ MeV and decay photons with opening angles $\cos\theta < -0.91$, while the in-flight source yields π^0's with $T \leq 15$ MeV and photons with $\cos\theta < -0.76$. The at-rest background was roughly 1600× the double radiative capture signal, and the in-flight background was roughly 10× the double radiative capture signal. Consequently, for $\pi^- p \to \gamma\gamma n$, the $\cos\theta < -0.76$ region was overwhelmed by π^0 background, and, due to the finite resolution of the photon-pair spectrometer, the π^0 background was a potential problem for opening angles with $\cos\theta > -0.76$.

Another source of background was accidental γ-γ coincidences arising from simultaneous multiple π^- stops. The pion beam had a microstructure with a pulse width of 2–4 ns and a pulse separation of 43 ns. With an incident flux of 7×10^5 s^{-1} the probability for more than one pion arriving in a single beam pulse is 1.5%. Multiple pion stops in one beam pulse can yield a γ-ray pair by the accidental coincidence of one photon from each pion. This background was roughly 900× our signal. It yields photon pairs with opening angles 0°–180° and summed energies 106–258 MeV. Note that the summed energy from random background events can exceed the m_π limit for single π capture.

In analyzing the data, a number of cuts were applied to identify photon pairs and reject background sources. A tracking cut imposed minimum values for the number of points in the tracks and maximum values for the chi-squared of fits to the tracks. A photon cut required that the electron-positron pairs intersect at the Pb converter and that the reconstructed photon pairs originate from the H_2 target. To reject the multi-π background, we imposed a C-counter timing cut and a beam telescope amplitude cut. The telescope amplitude cut was imposed on the normalized sum of the light output from the eight photomultiplier tubes viewing the four individual beam scintillators. The ± 4 ns C-counter timing cut was imposed on the time difference between the two C counters intersecting the two emerging e^+e^- pairs. The remaining inefficiency in rejecting the accidental coincidences was 1.3×10^{-4}. To reject the π^0 background, we imposed a photon opening angle cut of $\cos\theta > -0.1$.

A total of 2.3×10^6 photon pairs passed both the tracking cuts and photon cuts. These photon pairs are shown in Fig. 2 and are dominated by the backgrounds from π^0 decays and multi-π stops. The multi-π background is clearly seen in the summed energy spectrum as events with $E_{sum} > 150$ MeV, and the π^0 background is clearly seen in the opening angle spectrum as events with $\cos\theta < -0.76$. The beam telescope amplitude cut removed about 0.8×10^6 accidental γ-γ coincidences from multi-π stops, and the photon opening angle cut removed about 1.4×10^6 real γ-γ coincidences from π^0 decays. A total of 635 events with $E_{sum} > 80$ MeV and $\cos\theta > -0.1$ were found to survive all cuts (see Fig. 3).

A small quantity of two-photon background from π^0 decays and from multi-π stops does, however, survive the applied cuts. The remaining π^0 contamination was subtracted using (i) the observed number of π^0 events with $\cos\theta < -0.76$ and (ii) the known angular response of the photon-pair spectrometer. The remaining multi-π

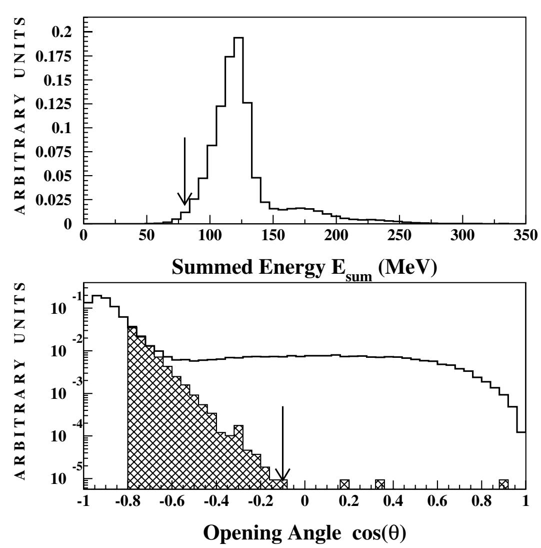

FIG. 2. The summed energy spectrum (top) and opening angle spectrum (bottom) for reconstructed photon pairs, i.e., the events passing the tracking and photon cuts. Note that the multi-π background can produce events with $E_{sum} > 150$ MeV (see top plot) and the π^0 background will produce events with $\cos\theta < -0.76$ (see bottom plot). The Monte Carlo generated π^0 background is shown overlaid as the shaded histogram in the bottom plot. The arrow in the upper plot indicates the $E_{sum} >$ 80 MeV cut and the arrow in the lower plot indicates the $\cos\theta > -0.1$ cut.

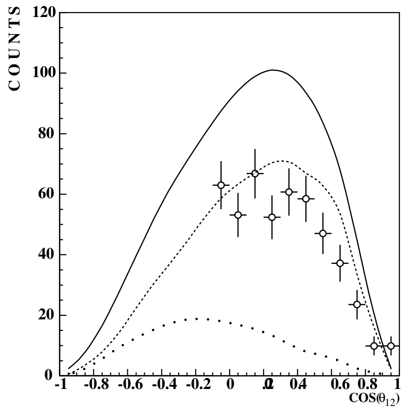

FIG. 3. Comparison of the opening angle distributions from the background subtracted experimental data (open circles) and the theoretical calculation (curves). The dashed curve is the $\pi\pi$ annihilation process, the dotted curve is the NN bremsstrahlung process, and the solid curve is the full calculation. These curves are convoluted with the response function of the RMC spectrometer.

contamination was subtracted using (i) the observed number of 2π events with $E_{\rm sum} > 170$ MeV and (ii) the measured sum energy spectrum for the multi-π background. These procedures indicated 53 ± 30 π^0 background events, or $(8.3 \pm 4.8)\%$, and 100 ± 16 multi-π background events, or $(15.7 \pm 2.5)\%$, with $E_{\rm sum} >$ 80 MeV and $\cos\theta > -0.1$. After subtraction this yielded a total of 482 ± 42 $\pi^- p \to \gamma\gamma n$ events with $E_{\rm sum} >$ 80 MeV and $\cos\theta > -0.1$. Using the data from Refs. [12,13], we further estimated the backgrounds originating from the nuclear $(\pi, 2\gamma)$ reaction on the target walls, etc., to be $\leq 1\%$.

In order to compare the experiment with theory, we performed both measurements and simulations of the two-photon response function of the RMC spectrometer. To measure the response, we employed the multi-π accidentals. Specifically, by counting the numbers of incoming multi-π stops and outgoing γ-γ accidentals, we mapped the detector's response versus energy and angle. [A minor complication is that the two photons from the multi-π stops may have time differences of up to 4 ns (i.e., the pion beam pulse width). This time difference slightly decreases both the track reconstruction efficiency and the two-photon acceptance. From simulations we found the loss in acceptance to be 6%.] Note that the calibration data and $\pi^- p \to \gamma\gamma n$ data were collected simultaneously and passed through the same cuts (with the exception of the beam telescope cut). Conveniently, the energy range and angular range for multi-π accidentals covers the kinematical range for $\pi^- p \to \gamma\gamma n$ events.

To simulate the detector response function, we used a Monte Carlo program. The program incorporated both the detailed geometry of the RMC detector and the detailed interactions of the relevant particles. Our program was based on the CERN GEANT3 package [15] and is described in Wright *et al.* [14]. We tested the simulation by comparison to the response function measurements with the multi-π accidentals. We found the energy-angle distributions from experiment and simulation to be in very good agreement. However, the absolute detection efficiencies from experiment and simulation were found to differ on average by 10%. Moreover, the measured acceptance was found to vary by $\pm 4\%$ from run to run and decreased by 10% between the early runs and the late runs. We attributed these variations to changes in the chamber efficiencies and fluctuations in the chamber noise, neither of which were incorporated in the simulation of the acceptance. To account for these differences between the measured and the simulated acceptance, we employed a multiplicative correction factor of $F = 0.90 \pm 0.09$. The quoted uncertainty is very conservative and embodies the entire variation of the measured acceptance over the running period.

In addition, we compared the results of measurements and simulations of photon pairs from at-rest charge exchange $\pi^- p \to \pi^0 n$ followed by neutral pion decay $\pi^0 \to \gamma\gamma$. Here we used dedicated "π^0 runs" with a modified trigger arrangement for these back-to-back photon pairs. We found excellent agreement between the simulation and the measurements using the factor $F = 0.90$.

The branching ratio for double radiative capture on pionic hydrogen was obtained via

$$B = \frac{N_{\gamma\gamma}}{N_{\pi^-} \epsilon \Omega F c_{\rm bm} c_{\rm stop}} \qquad (2)$$

where N_{π^-} is the number of livetime-corrected pion stops, $N_{\gamma\gamma}$ is the number of background-subtracted $\pi^- p \to \gamma\gamma n$ events, and $\epsilon\Omega \cdot F$ is the detector acceptance. Note that the appropriate acceptance was obtained using Monte Carlo [16] with the $\pi^- p \to \gamma\gamma n$ kinematical distributions taken from Beder [7]. The factor $c_{\rm stop} = 0.85 \pm 0.01$ accounts for the fraction of incident pions that stopped in hydrogen (see Wright *et al.* [16] for details) and the factor $c_{\rm bm} = 0.99$ accounts for the efficiency of $\pi^- p \to \gamma\gamma n$ events passing the beam telescope cut. Using Eq. (2) we obtained a branching ratio of $[3.05 \pm 0.27({\rm stat}) \pm 0.31({\rm syst})] \times 10^{-5}$. Note that the quoted uncertainty contains a statistical error of $\pm 8\%$ from $N_{\gamma\gamma}$ and a systematic error of $\pm 10\%$ in total. The systematic error is completely dominated by the $\pm 10\%$ uncertainty in the determination of the acceptance $\epsilon\Omega \cdot F$. The uncertainties in N_{π^-}, $c_{\rm stop}$, and $c_{\rm bm}$ were each $\leq 2\%$ and entirely negligible. We stress that the result we quote is the total $\pi^- p \to \gamma\gamma n$ branching ratio for all photon energies ($0 < E_\gamma < m_\pi$) and all opening angles ($-1.0 < \cos\theta < +1.0$).

Our quoted branching ratio was extracted assuming the energy-angle distributions calculated by Beder [7], although we actually observed only the region with $\cos\theta >$ -0.1 and $E_\gamma > 25$ MeV. Tests of the sensitivity of the extracted branching ratio to the energy-angle cuts revealed only a $\pm 2.9\%$ variation for $-0.2 < \cos\theta < 0.0$ and a $\pm 2.8\%$ variation for analyses with different sum energy cuts. Also, when using a phase space energy-angle distribution rather than Beder's energy-angle distribution [7], the extracted branching ratio changed by only -7%.

In Beder's calculation [7] of double radiative capture, the main contributions originate from $\pi\pi$ annihilation graphs, NN bremsstrahlung graphs, and their interference. The $\pi\pi$ annihilation graphs alone account for 64% of the total branching ratio and yield a distribution that is peaked at small opening angles. The NN bremsstrahlung graphs alone account for 20% of the total branching ratio and yield a distribution that is peaked at large opening angles. At threshold, the pion bremsstrahlung contributions vanish, and effects of vector meson exchange and delta resonance excitation are calculated to be very small.

In Fig. 3 we compare our measured data with Beder's calculation [7]. The background contributions of $(8.3 \pm 4.8)\%$ from π^0 decay events and $(15.7 \pm 2.5)\%$ from multi-π stop events have been subtracted from the measured data, and the resulting 482 events are plotted as open circles. The theoretical curves have been convoluted with the response function of the RMC spectrometer. The plot shows that the $\pi^- p \rightarrow \gamma\gamma n$ branching ratio and opening angle distributions from experiment and theory are in reasonable agreement. The overall consistency of experiment and theory supports the theoretical prediction of a dominant $\pi\pi$ annihilation mechanism. As seen in Fig. 3, the bremsstrahlung graphs alone underpredict the data by about a factor of 5.

However, our measured branching ratio is somewhat smaller than the theoretical branching ratio. We note that Beder's calculation was performed at tree level and neglects contributions from pion loops, etc. We therefore speculate that higher-order terms might explain the difference between the experimental and the predicted branching ratio. A new calculation of double radiative capture on pionic hydrogen using chiral perturbation theory is currently underway [17].

We remind the reader of the results from the previous nuclear $(\pi, 2\gamma)$ measurements. For ^{12}C, Deutsch *et al.* [12] obtained a partial branching ratio of $(1.4 \pm 0.2) \times 10^{-5}$, for $E_\gamma > 25$ MeV and $\cos\theta < 0.71$, and Mazzucato *et al.* [13] obtained a partial branching ratio of $(1.2 \pm 0.2) \times 10^{-5}$, for $E_\gamma > 17$ MeV and $\cos\theta < 0.71$. Unfortunately, the comparison of the earlier nuclear data with our hydrogen data is difficult as (i) π capture is predominantly from the $1S$ state in ^{1}H and the $2P$ state in ^{12}C, and (ii) the nuclear data were mainly taken at large two-photon opening angles and our hydrogen data were mainly taken at small opening angles.

In summary, we have made the first measurement of double radiative capture on pionic hydrogen by recording γ-ray coincidences from π^- stops in liquid H_2. We found the branching ratio to be $[3.05 \pm 0.27(\text{stat}) \pm 0.31(\text{syst})] \times 10^{-5}$ by assuming the kinematical distributions from Beder [7]. Moreover, the measured branching ratio and opening angle distribution support the theoretical hypothesis of a $\pi\pi$ annihilation mechanism. We hope this work will stimulate further studies into using double radiative capture as a novel probe of the proton's pion cloud and the $\pi\pi \rightarrow \gamma\gamma$ vertex.

We wish to thank the staff of the TRIUMF laboratory for their support of this work. In particular, we acknowledge the help of Renée Poutissou on the data acquisition and Dennis Healey on the hydrogen target. In addition, we thank Douglas Beder and Harold Fearing for helpful discussions and the National Science Foundation (United States), the Natural Sciences and Engineering Research Council (Canada), the Henry Luce Foundation (JHDC), and the Jeffress Memorial Trust (DSA) for financial support.

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