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THE ($\pi^-, \gamma\gamma$) PROGRAM AT TRIUMF *

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We report the first observation of the doubly-radiative decay mode of pionic hydrogen ($\pi^- p \to \gamma\gamma n$) and deuterium ($\pi^- d \to \gamma\gamma X$) using the RMC pair spectrometer at TRIUMF [1]. The process is interesting in the context of the π-Compton scattering [2] and the χPT predictions of the pion polarizability [3]. We present our preliminary values for the $\mathrm{BR}_{[\pi^- p \to \gamma\gamma\, n]} = 3.8 \times 10^{-5}$ and $\mathrm{BR}_{[\pi^- d \to \gamma\gamma X]} = 1.6 \times 10^{-5}$. Our $\pi^- p$ data indicates the dominance of $\pi\pi \to \gamma\gamma$ mechanism. The $\pi^- d$ data shows no evidence for the d_1^* dibaryon.

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1. Motivation

The double radiative decay of pionic atoms $\pi^- A \to \gamma\gamma X$ was investigated theoretically by Ericson and Wilkin [4] a quarter of a century ago. They predicted that the dominating reaction mechanism was the annihilation of the stopped, real π^- with a soft, virtual π^+, *i.e.* $\pi\pi \to \gamma\gamma$. As they advertised, the annihilation mechanism affords a selective coupling to soft pions, and special sensitivity to renormalization effects in nuclear matter.

In order to understand the $\gamma\gamma$ decay mode of a pionic atom, it is necessary to understand the elementary process of $\pi^- p \to \gamma\gamma\, n$. Several authors have made tree-level calculations of the $\gamma\gamma\, n$ capture mode of pionic hydrogen. The most recent published calculations are due to Beder [5], who obtained 5.1×10^{-5} for the $\gamma\gamma\, n$ branching ratio. Beder also pointed out the importance of the pion annihilation diagram, especially at small photon opening angles (see Fig. 1(a)).

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The first attempt to observe the two photon emission in hydrogen pion capture was made by Vasilevsky *et al.* [6] at JINR Dubna. They obtained an upper limit of the $\gamma\gamma n$ branching ratio, B.R. $\leq 5.5 \times 10^{-4}$, *i.e.* a value ten times larger than the theoretical prediction of Ref. [5].

The predicted dominance of the $\pi\pi \to \gamma\gamma$ annihilation amplitude in $\pi^- p \to \gamma\gamma n$ allows to study pion Compton scattering [2]. The Feynman diagram in Fig. 1(b) can be viewed as the annihilation of a real pion with a virtual pion $\pi^-\pi^+ \to \gamma\gamma$ or, via crossing symmetry, as the transition of a real pion to a virtual pion via Compton scattering $\gamma\pi \to \gamma\pi$ (Fig. 1(c)).

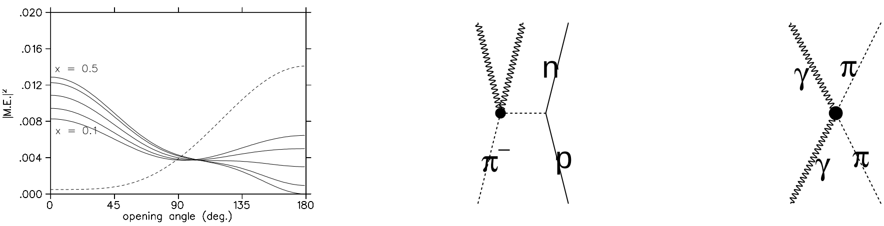

Fig. 1. (a) Beder predictions for $\pi^- p \to \gamma\gamma n$ amplitude. Solid lines represent the contribution from the annihilation graph for various photon energy sharing parameters $x = E_1/(E_1 + E_2)$. The dashed one is the bremsstrahlung contribution, (b) $\pi^- p \to \gamma\gamma n$ annihilation graph, (c) pion Compton scattering graph.

Pion Compton scattering is a probe of the pion polarizability $\alpha_{\rm E}^{\pi^\pm}$ (see *e.g.* [3]). A summary of the current determinations of the pion polarizability is shown in Table I. The extracted pion polarizabilities have large

TABLE I

Experimental determinations of pion electric polarizability $\alpha_{\rm E}^{\pi^\pm}$.

Reaction	$\alpha_{\rm E}^{\pi^\pm}$ ($\times 10^{-4}$ fm^3)	Experiment	Reference
$\pi A \to \gamma\pi A$	$6.8 \pm 1.4 \pm 1.2$	Serpukhov	[7]
$\pi p \to \gamma\pi p$	20 ± 12	Lebedev	[8]
$\gamma\gamma \to \pi\pi$	$19.1 \pm 4.9 \pm 5.6$	PLUTO	[9]
$\gamma\gamma \to \pi\pi$	2.2 ± 1.6	MARK II	[9]

uncertainties and are (except MARK II) substantially larger than the χPT prediction [3], $\alpha_{\rm E}^{\pi^\pm} = (2.7 \pm 0.4) \times 10^{-4}$ fm^3, which is based on a robust relationship between radiative pion decay $\pi \to e\nu\gamma$ and pion Compton scattering $\gamma\pi \to \gamma\pi$. This discrepancy between theory and experiment obviously calls for more experimental attention.

Recently Gerasimov [10], pointed out, that the double radiative decay of the pionic deuterium ($\pi^- d \to \gamma\gamma X$) can be used as a means to investigate the existence of the $d_1^*(1920)$ dibaryon ($\Gamma \sim 10$ keV) that was claimed by the DIB-2gamma collaboration [11]. As pointed out by Gerasimov if the $d_1^*(1920)$ does indeed exist, one should be able to detect it via the following chain:

$$\pi^- d \to d_1^*(1920)\gamma, \quad d_1^*(1920) \to \gamma\, nn\,.$$

Based on a toy model, Gerasimov estimated that the resonant decay of pionic deuterium via $d_1^*(1920)$ should occur roughly 100 times more frequently than non-resonant decay of $\pi^- p \to \gamma\gamma\, nn$. Additionally, a clear signature of the hypothetical d_1^* would be the photon spectrum with two lines: one at ~ 90 MeV ($\pi^- d \to d_1^*\gamma$) and the other at ~ 40 ($d_1^* \to \gamma\, nn$).

2. TRIUMF $(\pi^-, \gamma\gamma)$ experiments and preliminary results

The experiments presented here were performed at TRIUMF Laboratory using the RMC pair spectrometer [1] on the M9A beam line. The pionic hydrogen data (E838) were taken in December 1998 and April-May 1999 and the pionic deuterium data (E864) were taken in April 2000.

An 82 MeV/c pion beam was stopped in a liquid hydrogen (deuterium) target (approximate dimensions: length 15 cm, $\varphi = 16$cm). The photons were converted into e^+e^- pairs in a 1mm thick Pb cylinder. The e^+/e^- trajectories were then measured in a set of cylindrical wire and drift chambers, and the magnetic field provided momentum analysis. Trigger scintillators hit patterns were used to identify events.

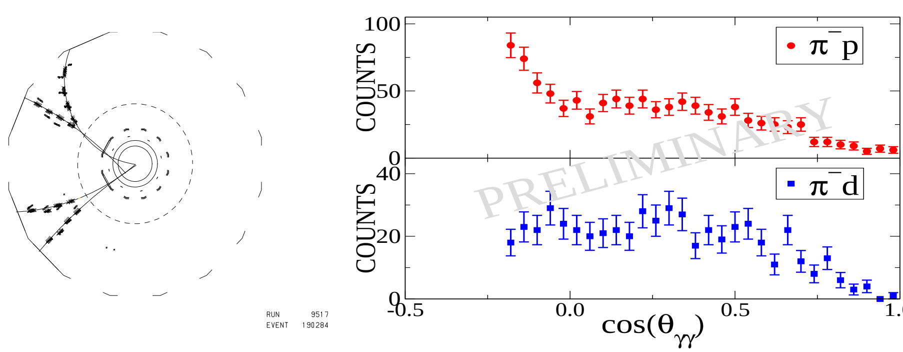

Fig. 2. A typical $\gamma\gamma$ event and opening angle distributions for pionic hydrogen (circles) and deuterium (squares).

We collected approximately 1000 $\pi^- p \to \gamma\gamma\, n$ events and 500 $\pi^- d \to \gamma\gamma X$ events. A cut on the $\gamma\gamma$ opening angle was used to remove $\pi^0 \to \gamma\gamma$ events and a cut on the beam/trigger scintillators was used to remove accidental $\gamma\gamma$ events.

Fig. 2 shows a typical event and the preliminary opening angle distributions for the pionic hydrogen and deuterium. Our preliminary branching ratios are $\mathrm{BR}_{[\pi^- p \to \gamma\gamma\, n]} = 3.8 \times 10^{-5}$ and $\mathrm{BR}_{[\pi^- d \to \gamma\gamma X]} = 1.6 \times 10^{-5}$. The pionic hydrogen BR is in approximate agreement with Beder calculations [5] and the yield at small opening angles demonstrates the dominance of the pion annihilation graph. We see no evidence for the the $d_1^*(1920)$ in our deuterium data.

In order to compare our results to the existing carbon data [12] we quote the relative branching ratios: $\mathrm{BR}_{\gamma\gamma/\gamma} = 1.0 \times 10^{-4}$ for the pionic hydrogen and $\mathrm{BR}_{\gamma\gamma/\gamma} = 0.6 \times 10^{-4}$ for the pionic deuterium.

3. Summary

Our preliminary results indicate that the the $\pi\pi \to \gamma\gamma$ graph is indeed dominant in the $\pi^- p \to \gamma\gamma\, n$ reaction hence this reaction is a potential probe for pion polarizability. We have found no evidence for the $d_1^*(1920)$ in the decay of pionic deuterium. We plan to extend our studies to nuclear targets.

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