Search for $d^*$ Dibaryon by Double-radiative Capture on Pionic Deuterium

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Abstract

We report a search for $d^*$ dibaryon production by double-radiative capture on pionic deuterium. The experiment was conducted at the TRIUMF cyclotron using the RMC cylindrical pair spectrometer, and detected $\gamma$-ray coincidences following pion stops in liquid deuterium. We found no evidence for narrow dibaryons, and obtained a branching ratio upper limit, $BR < 1.5 \times 10^{-6}$ (90% C.L.), for narrow $d^*$ production in the mass range from 1920 to 1980 MeV.

Key words: dibaryon, double-radiative capture, pionic deuterium
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1 Introduction

At present the deuteron is the only established particle with a baryon number $B = 2$. However a large number of theoretical predictions for additional dibaryons have been published in the literature. The predictions have exploited both quark–gluon and hadron viewpoints, and include objects such as exotic multi–quark states and molecular–like baryonic states. Obviously the experimental discovery of another dibaryon would provide new insight into hadron and quark–gluon dynamics at the GeV scale.

A recent claim for dibaryon production has been published by the Di2\gamma collaboration at the JINR phasotron [1]. The collaboration measured the proton–proton double bremsstrahlung reaction $pp \rightarrow pp\gamma\gamma$ by directing 216 MeV

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protons onto a liquid hydrogen target and recording $\gamma$–ray coincidences in two CsI/NaI detector arrays. The authors observed an intriguing structure in the background–subtracted energy spectrum of the $\gamma$–ray coincidence data. It comprised a relatively narrow peak centered at about 24 MeV and a relatively broad peak centered at about 60 MeV. They attributed the structure to the $d^*$ dibaryon with mass $1956 \pm 6$ MeV and width $\leq 8$ MeV. They hypothesized that $d^*$ dibaryons were first produced via the two-body process $pp \rightarrow d^*\gamma$ and then decayed via the three-body process $d^* \rightarrow pp\gamma$, thus contributing to $pp$ double bremsstrahlung.

The $d^*$ dibaryon of Khrykin et al. would have an electric charge $Q = +2$, an isospin component $T_z = +1$, and therefore an isospin of $T \geq 1$. The narrow width of the claimed $d^*$ state implies that its quantum numbers either forbid or strongly suppress the $NN$ decay mode. Thus, if the $d^*$ is isovector ($T = 1$), it must have spin-parities $J^\pi = 1^+, 3^+, 5^+$ etc. Moreover Khrykin et al. have argued that $(J^\pi, T) = (1^+, 1)$ is the most natural choice for the $d^*$’s quantum numbers, being the lowest spin–isospin pp-decoupled state with zero orbital angular momentum.

Recently Gerasimov suggested that double-radiative capture on pionic deuterium

$$\pi^-d \rightarrow nn\gamma\gamma$$

is an excellent candidate for further investigations of the dibaryon’s existence. In Eqn. 1 the $d^* (T_z = -1)$ dibaryon is first produced via radiative capture $\pi^-d \rightarrow d^*\gamma$ and then disintegrates via radiative decay $d^* \rightarrow nn\gamma$. Using a simple model Gerasimov estimated that the branching ratio for the $d^*$–mediated process may be as large as 0.5%. This yield would exceed by 100 times the expected two–photon branching ratio for non–resonant double-radiative capture in pionic deuterium (see Beder and Tripathi et al.).

A number of $\gamma$–ray experiments on pionic deuterium have already been conducted, so is it possible for the signatures of the $d^*$ dibaryon to have been missed? Singles $\gamma$–ray data on pionic deuterium are available from the TRIUMF experiments of Highland et al. and Stanislaus et al. and the PSI experiment of Gabioud et al. Unfortunately, because of the large branching ratio $BR = 0.26$ for the single radiative capture reaction, which yields a $\sim 130$ MeV $\gamma$–ray peak with a large low–energy tail, a small contribution from dibaryon production with a branching ratio $\leq 10^{-2}$ is not excluded (the exact sensitivity of the singles $\gamma$–ray experiments is a strong function of the mass and the width of the dibaryon). Coincidence $\gamma$–ray data on pionic deuterium

\footnote{Gerasimov assumed a N$\Delta$ bound state for the $d^*$ dibaryon and a Kroll-Ruderman graph $\pi N \rightarrow \gamma\Delta$ for the production mechanism.}
are also available from the TRIUMF experiment of MacDonald et al. (8). However this experiment was designed for back–to–back photons originating from \( \pi^0 \to \gamma \gamma \) decay following \(^2\text{H}(\pi^-, \pi^0)\) charge exchange. Consequently their sensitivity to two-photon events from \( d^* \) dibaryon production in double-radiative capture was very low.

2 Experimental Setup

Herein we report a dedicated search for dibaryon production via double-radiative capture on pionic deuterium. The experiment was conducted on the M9A beamline at the TRIUMF cyclotron using the RMC pair spectrometer (see Fig. 1).

The beamline delivered a negative pion flux of \( 5 \times 10^5 \text{ s}^{-1} \) with a central momentum of 81.5 MeV/c and a momentum bite of about 10%. The beam was unseparated, having an \( e/\pi \) ratio of about 14/1 and a \( \mu/\pi \) ratio of about 1/1. The incoming pions were counted in a 4-element plastic scintillator telescope and stopped in a 2.5 liter liquid deuterium target.

The outgoing photons were detected by electron-positron pair production in a 1 mm cylindrical lead converter and \( e^+, e^- \) tracking in a cylindrical drift chambers. A 1.2 kG axial magnetic field was used for momentum analysis and concentric plastic scintillator rings were used for fast triggering. The trigger scintillator package consisted of 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 spectrometer see Wright et al. (9), note that in this experiment we moved the Pb converter from just inside the C-counter radius to just outside the A-counter radius.

The two–photon trigger was based upon the multiplicities and topologies of hits in the trigger scintillators and the drift chamber cells. The scintillator trigger required zero hits in the A-ring, two or more hits in the C-ring, three or more hits in the D-ring, and a C-D topology consistent with the conversion of two \( \gamma \)-rays. The drift chamber trigger imposed minimum values for number of the drift cell hits or the drift cell clusters in each drift chamber layer.

During a four week running period we accumulated \( \gamma \)-ray coincidence spectra from a total of about \( 3.8 \times 10^{11} \) pion stops in the deuterium target. We also collected data from \( \pi^- \) stops in liquid H\(_2\) for setup and calibration.

3 the RF separator was unavailable for the data taking
3 Data Reduction

The significant backgrounds involved (i) true coincidences from $\pi^0 \rightarrow \gamma \gamma$ decay following ($\pi^−$, $\pi^0$) charge exchange on $^1\text{H}$ contamination, (ii) accidental coincidences from two $\pi^−d \rightarrow nn\gamma$ events following two pion stops in one beam pulse (hereafter denoted $\pi$-$\pi$ events)\textsuperscript{4} and (iii) accidental coincidences between a delayed radiative $\mu$ decay $\gamma$-ray and a prompt radiative $\pi$ capture $\gamma$-ray (hereafter denoted $\mu$-$\pi$ events). The $\pi^0$ decay background yielded photon-pairs with opening angles of $\cos \theta_{12} \leq -0.76$ and summed energies of $E_{\text{sum}} = E_{\gamma 1} + E_{\gamma 2} \approx m_{\pi}$. The accidental coincidence backgrounds yielded photon-pairs with opening angles of $-1.0 \leq \cos \theta_{12} \leq +1.0$ and summed energies of up to $\sim 180$ MeV for $\mu$-$\pi$ accidentals and $\sim 260$ MeV for $\pi$-$\pi$ accidentals.

In analyzing the data a number of cuts were applied to select the two-photon events. A tracking cut imposed minimum values for the number of points in the tracks in the drift chamber and maximum values for the chi–squared of fits to the tracks. A photon cut required that the electron-positron pairs intersect at the lead converter and that the photon pairs originate from the deuterium target. The total number of photon pairs, i.e. events surviving the tracking cuts and photon cuts, was $2.3 \times 10^5$. These photon pairs (shown in Fig. 2) are dominated by the real $\gamma$-$\gamma$ coincidences from $\pi^0$ decays and accidental $\gamma$-$\gamma$ coincidences from $\pi$-$\pi$ events and $\mu$-$\pi$ events. The accidental $\gamma$-$\gamma$ background is clearly seen in the summed energy spectrum as events with $E > 150$ MeV. The $\pi^0$ decay background is clearly seen in the opening angle spectrum as events with $\cos \theta_{12} < -0.6$. In order to remove these backgrounds, a beam counter amplitude cut was applied to reject the $\pi$-$\pi$ accidentals and a C-counter timing cut to reject the $\mu$-$\pi$ accidentals. Finally an opening angle cut was used to reject the background from $\pi^0$ decay.

A total of 370 two-photon events were found to survive the beam counter amplitude cut, C-counter timing cut, and photon opening angle cut. Their photon opening angle and individual energy spectra are shown in Fig. 3. The opening-angle spectrum is a broad continuum and shows the opening angle cut of $\cos \theta_{12} > -0.2$ we employed to remove the events from $\pi^0$ decay. The individual energy spectrum is a broad continuum with a low–energy cut-off at about 25 MeV due to the acceptance of the spectrometer. The number and distribution of two-photon events in Fig. 3 is consistent with non-resonant pion double-radiative on deuterium capture (for details see Tripathi et al.\textsuperscript{4} and Zolnierczuk\textsuperscript{5}).

\textsuperscript{4} The pion beam had a micro–structure with a pulse width of 2–4 ns and a pulse separation of 43 ns. For an incident flux of $5 \times 10^5$ s$^{-1}$ the probability for more than one pion arriving in a single beam pulse was about 1.1%.

\textsuperscript{5} Actually a small contribution of $22 \pm 5$ $\pi^0$ decay background events and $24 \pm 2$
The expected signature of dibaryon events, a monoenergetic peak from the production process $\pi^-d \rightarrow d^*\gamma$ and a three-body continuum from the decay process $d^* \rightarrow nn\gamma$, is not seen.

4 Dibaryon Sensitivity

To determine the detection efficiency for dibaryon events we used a Monte Carlo computer program. The program incorporated the detailed geometry of the RMC detector and detailed interactions of the various particles. Our program was based on the CERN GEANT3 package (11) and is described in more detail in Ref. (12).

The simulation was tested by measurements of the detector response with a liquid $\text{H}_2$ target. Negative pion stops in hydrogen provide a well known source of photon pairs from (i) $\pi^-p \rightarrow \pi^0n$ charge exchange followed by $\pi^0 \rightarrow \gamma\gamma$ decay and (ii) accidental $\gamma-\gamma$ coincidences from multiple $\pi$ stops. We found the energy-angle distributions from experiment and simulation to be in good agreement. The absolute detection efficiencies from experiment and simulation differed by 4% (the run-to-run variation of the spectrometer acceptance was $< \pm 6\%$). This difference was attributed to detector inefficiencies that were present in the measurement but were absent in the simulation. A multiplicative correction factor $F = 0.96 \pm 0.06$ was therefore incorporated to account for this.

As described earlier, the $d^*$ signature is a monoenergetic $\gamma$-ray peak from dibaryon production, $\pi^-d \rightarrow d^*\gamma$, and a three-body continuum from dibaryon decay, $d^* \rightarrow nn\gamma$. The production $\gamma$-ray energy is approximately $E \sim M_{\pi^-d} - M_{d^*}$ and increases from $E \simeq 35$ MeV for $M_{d^*} = 1980$ MeV to $E \simeq 90$ MeV for $M_{d^*} = 1920$ MeV. The decay $\gamma$-ray spectrum is peaked near the end-point energy, $E \sim M_{d^*} - 2m_n$, as typically the two neutrons carry only a small fraction of the available energy. However the detailed shape of the three-body spectrum is dependent on the $nn$-final state interaction and consequently on the $d^*$ quantum numbers.

Representative simulations of dibaryon signatures for $M_{d^*} = 1920$ and 1956 MeV, assuming a 3-body phase space distribution for $d^* \rightarrow nn\gamma$ decay, are shown in Fig. 4. Note that for $M_{d^*} = 1920$ MeV the production and decay $\gamma$-ray spectra are separated whereas for $M_{d^*} = 1956$ MeV the production and accidental coincidence background events is present in Fig. 3. The residual $\pi^0$ decay background was estimated using the number of $\pi^0$ events with $\cos \theta_{12} < -0.45$ and the residual accidental coincidence background was estimated using the number of $\pi^-\pi/\mu-\pi$ events with $E_{\text{sum}} > 150$ MeV.
decay $\gamma$-ray spectra overlap. Because the exact line shape of the decay $\gamma$-ray is not known, we obtained our limits on $d^*$ production by determining limits on the production $\gamma$-ray yield. Specifically we fit the sum of a polynomial function, parameterizing the non-resonant background, and a Gaussian peak, accounting for $d^*$ production, to the $\gamma-\gamma$ coincidence energy spectrum in Fig. 4.

The Gaussian peak centroid was stepped from $E = 35$ to 90 MeV and the Gaussian peak width was fixed at the instrumental resolution of the RMC detector (i.e. $\sigma =$4-5 MeV for $E =$40-80 MeV). This procedure yielded a limit on the number of dibaryon events as a function of dibaryon mass. We then converted the event limit on dibaryon production to a branching ratio limit on dibaryon production via

$$B.R. = \frac{N_{d^*}}{N_{\pi^-} \cdot \epsilon \Omega \cdot F \cdot C}$$

where $N_{d^*}$ is the limit on the dibaryon events, $N_{\pi^-}$ is the number of live-time corrected pion stops, and $\epsilon \Omega \cdot F$ is the detector acceptance. The appropriate acceptance was obtained using the Monte Carlo for dibaryon production and assuming a three-body phase space distribution for $d^* \rightarrow nn\gamma$ decay. As discussed earlier the factor $F$ accounts for detector inefficiencies which are present in the experiment but are absent in the simulation. The factor $C = 0.85 \pm 0.01$ accounts for the fraction of incident pions that stopped in deuterium (see Wright et al. (12) for details).

The resulting branching ratio upper limit on $d^*$ production in $\pi^-d$ capture was found to be $B.R < 1.5 \times 10^{-6}$ (90% C.L.) for $d^*$’s in the mass range of 1920 to 1980 MeV and width of < 10 MeV. In particular, we observed no evidence for a narrow dibaryon of mass $M = 1956$ MeV as claimed by Khrykin et al. (1). However above and below this mass range, our experimental sensitivity rapidly deteriorates due to the energy cut-off in the spectrometer acceptance.

5 Summary

In summary we have found no evidence for narrow dibaryon production in $\pi^-d$ capture. Our upper limit on dibaryon production, $B.R < 1.5 \times 10^{-6}$ (90% C.L.), is several orders of magnitude below the yield estimate of Gerasimov (2). Our null result is consistent with the null result of Calén et al. (13) obtained from $pp$ bremsstrahlung measurements using the WASA detector at the CELSIUS storage ring.

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Fig. 1. The RMC spectrometer showing the deuterium target, lead converter, cylindrical drift chamber, trigger scintillators and spectrometer magnet.

Fig. 2. The photon opening angle $\cos \theta_{12}$ (top) and summed photon energy spectra (bottom) for events passing the tracking cuts and photon cuts. The events are mainly real $\gamma\gamma$ coincidences from $\pi^0$ decay and accidental $\gamma\gamma$ coincidences from $\pi\pi$ and $\mu\pi$ events.
Fig. 3. The photon opening angle $\cos \theta_{12}$ (top) and individual photon energy spectra (bottom) for events passing all cuts. The spectra are dominated by non-resonant pion double-radiative capture on deuterium. Note that the distributions are folded with the acceptance of the detector.

Fig. 4. Examples of the individual $\gamma$-ray energy spectra for dibaryons with $M = 1956$ MeV (solid line) and $M = 1920$ MeV (dashed line). We assumed a three-body phase space distribution for the $d^* \rightarrow \gamma nn$ decay $\gamma$-ray spectrum.