Search for exotic baryons in double radiative capture on pionic hydrogen.

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Abstract

We report a search for low-lying exotic baryons via double radiative capture on pionic hydrogen. The data were collected at the TRIUMF cyclotron using the RMC spectrometer by detecting gamma-ray pairs from pion stops in liquid hydrogen. No evidence was found to support an earlier claim for exotic baryons of masses 1004 and 1044 MeV/c\(^2\). We obtain upper limits on the branching ratios for double radiative capture via these exotic states of \(< 3 \times 10^{-6}\) and \(< 4 \times 10^{-6}\) respectively.

Key words:

1 Introduction

Until recently all hadrons were classified as either three quark or quark-antiquark states. The mounting evidence [1,2,3,4,5,6] for an exotic baryon – the \(\theta^+(1540)\) – has likely begun a new chapter in hadron spectroscopy. The \(\theta^+(1540)\) has baryon number \(B = +1\) and strangeness \(S = +1\), which implies a minimally exotic pentaquark substructure \(uudd\bar{s}\). Such exotics would provide a new venue for exploring the rich dynamics of QCD and testing the multifarious models of hadrons.

In this light the recent claim by Tatischeff \textit{et al.} [7,8] of evidence for low-lying exotic baryons between the nucleon and the \(\Delta\) resonance is quite intriguing. Tatischeff \textit{et al.} investigated the \(pp \rightarrow p\pi^+X\) reaction using the SPES3 spectrometer at the Saturne Synchrotron by detecting the forward-going \(\pi^+/p\)

Preprint submitted to Elsevier Science
pairs from $p-p$ collisions at energies of 1520-2100 MeV. From the $\pi^+/p$ momenta they reconstructed the missing mass $M_X$ for $pp \to p\pi^+X$ events and found several small peaks. The observed intensities of the peaks were about $10^3$ times smaller than the intensity of the neutron peak from the $pp \to p\pi^+n$ reaction. They observed two peaks below the $\pi N$ threshold corresponding to masses of 1004 MeV/$c^2$ and 1044 MeV/$c^2$, with widths of $< 15$ MeV/$c^2$. The authors have claimed these structures as evidence of low-lying exotic baryons.

Their claim has rekindled an old suggestion by Azimov of a low-lying exotic baryon octet [9,10]. The catalyst for the original work was the difficulty of the multiplet assignment for the $\Sigma(1480)$. Azimov suggested identifying the strangeness $S = -1 \Sigma(1480)$ [11,12], the strangeness $S = -1 \Lambda(1330)$ [13,14], and strangeness $S = -2 \Xi(1620)$ [15], as three members of a new low-lying exotic baryon octet. 1 Azimov then used the Gell-Mann-Okubo mass formula to estimate the mass of the lowest-lying non-strange member of the multiplet to be roughly 1100 MeV/$c^2$. We shall follow the convention adopted in Refs. [9,10] and denote this isodoublet by $n'$. More recently in Ref. [10] the authors have considered the possibility of a pentaquark substructure for this exotic octet, and discussed the relation between the octet containing the $n'$ and the anti-decuplet containing the $\theta^+(1540)$. They argue that $J^\pi = 1/2^-$ is the most likely spin-parity for the $n'$ state.

Other attempts to explain the baryon candidates of Tatischeff et al. are also available. These include such ideas as a fully antisymmetric $q^3$ spin-flavor state [17], colored $q\bar{q} - q^3$ and $qq - q$ quark clusters [8,18], and the collective excitations of the $q\bar{q}$ condensate [19]. We refer the reader to Ref. [8] for a fuller discussion of these ideas.

Unfortunately the claims for exotic baryons by Tatischeff et al. [7,8] were not corroborated in two subsequent electro-production experiments. Jiang et al. [20] employed the two high resolution spectrometers in Hall A at JLab to search for evidence of narrow baryon resonances in the $ep \to e\pi^+X$ reaction at an incident energy of 1.7 GeV. They found no evidence of peaks in the $ep \to e\pi^+X$ missing-mass spectrum, and set upper limits of $7 \times 10^{-4}$ for the 1004 MeV/$c^2$ state and $8 \times 10^{-4}$ for the 1044 MeV/$c^2$ state, with respect to neutrons from $ep \to e\pi^+n$. Likewise Kohl et al. [21], who employed the three-spectrometer facility at MAMI to study the $ep \to e\pi^+X$ reaction at 855 MeV, found no evidence for any peaks in the $ep \to e\pi^+X$ missing-mass spectrum in the mass range 970-1060 MeV/$c^2$. They established an upper limit on electro-production of exotic baryons of about $10^{-4}$ the yield of the neutrons from the $ep \to e\pi^+n$ reaction.

The null results from the electro-production experiments do not necessar-

1 We caution the reader that the $\Lambda(1330)$ is not listed, and the $\Sigma(1480)$ and $\Xi(1620)$ have only one-star status, in the Particle Data Group listings [16].
ily conflict with the hadro-production experiment since a hadro-production channel for exotic baryons may be absent in the electro-production case [20]. Further, the different reactions and the different kinematics may have unique sensitivities to such exotic baryons, thus preventing the direct comparison of hadro-production yields and electro-production limits.

Another concern, first raised by L’vov and Workman [22] and later discussed by Azimov et al. [10], is that low-lying exotic baryons would contribute to Compton scattering on protons and neutrons. More specifically, the 1004 MeV/c² state would produce a peak at 68 MeV and the 1044 MeV/c² state would produce a peak at 112 MeV in nucleon Compton scattering. However the cross section is proportional to the radiative width of the $n' \rightarrow n \gamma$ transition, thus ultra-narrow baryons could escape detection in Compton scattering. Indeed, using the available Compton scattering data, the authors of Refs. [10,22] have set limits of roughly 1-10 eV on the radiative widths of the exotic baryon candidates from the Tatischeff et al. experiment.

In Refs. [9,10] the authors have further observed that exotic baryons below the pion-nucleon threshold could additionally contribute to double radiative capture on pionic hydrogen atoms, i.e. $\pi^- p \rightarrow \gamma \gamma n$. Specifically, the $n'$ could contribute through a two-step sequence involving $n'$ production and subsequent radiative decay

$$\pi^- p \rightarrow n' \gamma \quad \leftrightarrow \quad n \gamma.$$  \hspace{1cm} (1)

Indeed Azimov et al. have used the measured branching ratios for single and double radiative capture to set a conservative upper limit on $n'$ production of $\text{B.R.}(\pi^- p \rightarrow n' \gamma)/\text{B.R.}(\pi^- p \rightarrow n \gamma) < 8 \times 10^{-5}$ [10].

The energetics of double radiative capture via $n'$ production are shown in Fig. 1. The production mechanism yields a mono-energetic gamma-ray and the $n'$ decay produces a Doppler broadened gamma-ray. The gamma-rays energies are therefore determined by the $n'$ mass, with $E_{\gamma 1} = 71$ MeV and $E_{\gamma 2} \simeq 66$ MeV for a 1004 MeV/c² $n'$ state, and $E_{\gamma 1} = 33$ MeV and $E_{\gamma 2} \simeq 99$ MeV for a 1044 MeV/c² $n'$ state. The Doppler width $2E_{\gamma 2}(v/c)$ of the decay $\gamma$-ray is about 9.3 MeV for $M = 1004$ MeV/c², and about 6.3 MeV for $M = 1044$ MeV/c². Additionally, assuming the $n'$ baryon has spin-parity $J^P = 1/2^-$ [10], the two-step process in Fig. 1 involves a spin-parity sequence of $1/2^- \rightarrow 1/2^- \rightarrow 1/2^+$ and yields an isotropic angular correlation between the production and decay gamma-rays.

In this article we report a search for evidence of exotic baryons with masses below the $\pi N$ threshold via double radiative capture on pionic hydrogen. The experimental data were originally collected to study the direct two-photon
process of double radiative capture, and are reported in Tripathi et al. [23]. Herein we have re-analyzed the data to search for evidence of any exotic baryons in the mass range 970-1050 MeV/c². In Secs. 2 and 3 we briefly describe the experimental setup and background sources for the measurement. In Sec. 4 we discuss our approach in searching for any \( n' \)-mediated events and in Sec. 5 we discuss our method for setting limits on \( n' \)-mediated capture. We summarize in Sec. 6.

2 Experimental setup

The experiment was conducted at the TRIUMF cyclotron using the RMC spectrometer. Incoming pions of flux \( 7 \times 10^5 \) s⁻¹ and momentum 81.5 MeV/c were counted in a 4-element plastic scintillator telescope and stopped in a 3 liter liquid hydrogen target. Outgoing photons were detected by pair production in a 1 mm thick cylindrical lead converter and e⁺e⁻ tracking in cylindrical multi-wire 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: an A-ring located inside the lead converter, a C-ring located between the lead converter and the tracking chambers, and a D-ring located outside the drift chamber. For more details on the RMC spectrometer see Wright et al. [25].

We employed a two–photon trigger that was based on the multiplicities and the topologies of the hits in the trigger scintillators and the drift chamber cells. The A-ring scintillators were used to reject events that had charged particles originating from the target region. The pattern of C and D-ring scintillators hits and drift cells hits were used to select events with topologies resembling...
the two $e^+e^-$ pairs from two-photon events [23].

During a four week running period we recorded $\pi^-p \rightarrow \gamma\gamma n$ data from $4.0 \times 10^{11}$ pion stops in liquid hydrogen. Calibration data with a dedicated $\pi^o \rightarrow \gamma\gamma$ trigger were also collected.

3 Background sources

The signature of $n'$ production in double radiative capture is a coincident $\gamma\gamma$ pair with one mono-energetic gamma-ray and one nearly mono-energetic gamma-ray with an energy sum $E_{\gamma1} + E_{\gamma2} \simeq m_\pi$ (ignoring the $n'$ recoil energy and the neutron-proton mass difference).

The $n'$ mechanism will compete with direct two-photon production from double radiative capture on pionic hydrogen. The later process yields a photon pair with individual energies $E_{\gamma1}$, $E_{\gamma2}$ and summed energy $E_{\gamma1} + E_{\gamma2}$ that span that full $\pi^-p \rightarrow \gamma\gamma n$ three-body phase space. The branching ratio for double radiative capture on pionic hydrogen has been measured by Tripathi et al. [23] and calculated by Joseph [26], Lapidus and Musakhanov [27], and Beder [28]. The measurement by Tripathi et al. yielded $B.R. = (3.09 \pm 0.44) \times 10^{-5}$ and the tree-level calculation by Beder yielded $B.R. = 5.1 \times 10^{-5}$, in fair agreement. The photon energy and angle distributions from experiment and theory are in good agreement. Thus, together the small branching ratio of the direct two-photon process and distinctive kinematics of the $n'$ mediated process are sufficient to separate these two sources of photon pairs.

One source of two-photon background is real $\gamma\gamma$ coincidences from $\pi^o \rightarrow \gamma\gamma$ decay. The $\pi^o$'s were produced by pion charge exchange $\pi^-p \rightarrow \pi^0 n$, both at-rest and in-flight. The branching ratio for at-rest charge exchange is $B.R. = 0.6$ and yields $\pi^o$'s with energies $T = 2.8$ MeV and photon pairs with opening angles $\cos \theta < -0.91$. The much smaller contribution from in-flight charge exchange yields $\pi^o$'s with energies $T < 15$ MeV and photon pairs with opening angles $\cos \theta < -0.76$. Consequently the $\pi^o$ background overwhelms other two-photon signals at large opening angles. Thus the direct two-photon process and the $n'$ mediated process are only detectable at smaller angles.

Another source of background was accidental $\gamma\gamma$ coincidences arising from multiple $\pi^-$ stops. The pion beam had a micro-structure with a pulse width of 2–4 ns, and a pulse separation of 43 ns. With an incident flux of $7 \times 10^5$ s$^{-1}$, the probability for more than one pion arriving in a single beam pulse is about 1.5%. Multiple pion stops in one beam pulse can yield a $\gamma\gamma$ pair by the accidental coincidence of one photon from the first pion and another photon from the second pion. These accidental $\gamma\gamma$ coincidences yield photon-pairs
with opening angles $-1.0 < \cos \theta < +1.0$ and summed energies 106-258 MeV.

In subsequent discussions we shall denote the real $\gamma-\gamma$ coincidences from $\pi^0$ decay the “$\pi^0$ background”, and the accidental $\gamma-\gamma$ coincidences from multiple pion stops the “$2\pi$ background”.

4 Event selection

The data analysis was a three step process. In step one we applied cuts to identify photon pairs that originated from the target. In step two we applied cuts to reject the contributions from the $\pi^0$ background and the $2\pi$ background and select the events from either double radiative capture or $n'$ mediated capture. In step three we used the distinctive photon energy distributions of double radiative capture and $n'$ mediated capture to search for evidence of the later process.

To identify photon pairs we applied both a tracking cut and a photon cut. The tracking cut imposed minimum values for the number of points in the drift chamber tracks, and maximum values for the chi–squared of the fits. The photon cut required that the electron-positron pairs intersect at the lead converter and that the reconstructed photon pairs originate from the hydrogen target. A total of $2.3 \times 10^6$ photon pairs were found to survive these cuts. These events were dominated by the $\pi^0$ and $2\pi$ backgrounds.

To reject the $\pi^0$ and $2\pi$ backgrounds we applied a beam counter amplitude cut, a C-counter timing cut, and a two-photon opening angle cut. The beam counter amplitude cut rejected events with large energy deposition in the beam scintillators, thus indicating the arrival of multiple pions in one beam pulse. The C-counter timing cut rejected events with large time differences between the C-counter hits, thus indicating the two photons to have originated from two neighboring beam pulses. The opening angle cut eliminated events with $\cos \theta < -0.1$, rejecting the background from $\pi^0 \rightarrow \gamma\gamma$ decay. A total of 635 events with summed energies $> 80$ MeV was found to survive all cuts.

The individual energy, summed energy, and opening angle spectra for the 635 events that survived all cuts are shown in Fig. 2. The summed energy spectrum shows a peak at $E \sim m_\pi$. The individual energy spectrum shows a broad continuum with a low energy cut-off at about 20 MeV and a high energy cut-off at about 100 MeV due to the acceptance of the spectrometer. The opening-angle spectrum shows the minimum two-photon opening angle.

\footnote{The peak’s centroid is shifted downward due to energy loss of the $e^+e^-$ pairs in traversing the lead converter, trigger scintillators, etc.}
Fig. 2. The individual photon energy spectrum (top), summed photon energy spectrum (center), and two-photon opening angle spectrum (bottom), for the 635 events that passed all cuts. Note the individual energy spectrum contains $2 \times 635$ photons.

at $\cos \theta = -0.1$.

Note that the spectra in Fig. 2 contain a small residual contribution from the $\pi^0$ background and the $2\pi$ background. These contaminations were estimated in Ref. [23] at $(8.3 \pm 1.1)\%$ and $(6.0 \pm 0.9)\%$, respectively.

5 Baryon sensitivity

A maximum likelihood procedure [31] was employed to search for evidence of any $n'$-mediated events. Specifically, we fit the individual photon energy spectrum in Fig. 2 to the function

$$f(E_\gamma) = N_{n'} f_{n'}(E_\gamma) + N_d f_d(E_\gamma)$$

where $f_{n'}(E_\gamma)$ and $f_d(E_\gamma)$ are distributions that describe the expected energy spectra of $n'$-mediated capture and direct two-photon capture, and $N_{n'}$ and $N_d$ are the corresponding amplitudes of the two processes.
To obtain the distributions $f_{n'}(E_\gamma)$ and $f_d(E_\gamma)$, which involve a convolution of their true energy distributions with the detector response function, we used a Monte Carlo simulation. The Monte Carlo was based on the CERN GEANT3 package [30] and incorporated both the detailed geometry of the RMC detector and the detailed interactions of the various particles. The simulation was tested by comparison to photon spectra from at-rest pion radiative capture $\pi^- p \to \gamma n$ and at-rest pion charge exchange $\pi^- p \to \pi^n n$. For further details see Refs. [23,24].

For the $n'$-mediated process the photon energy spectrum has a double-peak structure with the production gamma-ray centered at approximately $E_{\gamma1} \simeq (M_{\pi p} - M_{n'}) = (1078 - M_{n'})$ MeV and the decay gamma-ray centered at approximately $E_{\gamma2} \simeq (M_{n'} - M_n) = (M_{n'} - 940)$ MeV. However, in the mass region $1000$ MeV/c$^2 < M_{n'} < 1020$ MeV/c$^2$, these two peaks are overlapping because of the finite resolution of the pair spectrometer and the Doppler broadening of the decay gamma-ray. In addition, for either $M_{n'} < 970$ MeV/c$^2$ or $M_{n'} > 1050$ MeV/c$^2$, the photon pairs becomes unobservable because of the low energy cut-off of the pair spectrometer.

For the direct two-photon process the photon energy spectrum is a three-body continuum. The spectrum was calculated by Beder in Ref. [28] and measured by Tripathi et al. in Ref. [23]. Given the agreement between the calculation and the measurement, we employed the Beder calculation of the $\gamma$-energy spectrum shape for simulating the direct two-photon process. The resulting energy spectrum, after the convolution with the response function of the pair spectrometer, is a broad continuum with a low energy cut-off at about 20 MeV, a high energy cut-off at about 100 MeV, and a maximum at about 60 MeV.

The resulting distributions for describing the direct two-photon process and $n'$-mediated process are shown in Fig. 3. For $f_{n'}(E_\gamma)$ we plot the distributions for both $M_{n'} = 1004$ MeV/c$^2$ and $M_{n'} = 1044$ MeV/c$^2$. In the latter case the production gamma-ray and decay gamma-ray are well separated and the double-peaked $f_{n'}(E_\gamma)$ and broad continuum $f_d(E_\gamma)$ are easily distinguished. However in the former case the production gamma-ray and decay gamma-ray are overlapping, and the discrimination between the line-shapes is reliant on the different widths of the two distributions (the full width half maximum is about 25 MeV for the $n'$-mediated process, and about 50 MeV for the direct two-photon process). Consequently, our sensitivity to $n'$ production is dependent on the mass of the $n'$ state.

In the maximum likelihood procedure we stepped the value of $M_{n'}$ from 970 MeV/c$^2$ to 1050 MeV/c$^2$ in increments of 10 MeV/c$^2$ and varied the ratio of $n'$ mediated events to direct two-photon events, i.e. $N_{n'}/N_d$. Note that (i) the fit was restricted to $20 < E_\gamma < 100$ MeV in order to avoid the $2\pi$ background events at energies above 100 MeV, and (ii) we forced the sum.
Fig. 3. The functions $f_d(E_{\gamma})$ (top), $f_{n'}(E_{\gamma})$ with $M_{n'} = 1004$ MeV/c$^2$ (center), and $f_{n''}(E_{\gamma})$ with $M_{n''} = 1044$ MeV/c$^2$ (bottom), that were utilized in the fitting procedure. The functions were obtained by Monte Carlo simulation in order to convolute the detector response function and theoretical line-shape.

$N_{n'} + N_d$ to equal the total number of photon pairs observed in the region of the fit. The procedure yielded values of $N_{n'}/N_d$ that were consistent with zero for all values of $M_{n'}$. Thus no evidence for $n'$-mediated capture was found for $970 < M_{n'} < 1050$ MeV/c$^2$, the measured spectrum being completely consistent with direct two-photon capture only.

In the absence of any $n'$ signal, we employed the above procedure to establish the 90% confidence limit on the $N_{n'}$ counts as a function of the mass $M_{n'}$. To convert the upper limit on the counts to an upper limit on the branching ratio for the $n'$-mechanism we used

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

where $N_{\pi^-}$ is the number of live-time corrected pion stops, and $\epsilon \Omega \cdot F$ is the detector acceptance. The acceptance was obtained using the Monte Carlo for $n'$ production. The factor $F = 0.90 \pm 0.09$ [23] accounts for detector inefficiencies which are present in the experiment but are absent in the simulation. The factor $C = 0.85 \pm 0.01$ [29] accounts for the fraction of the incoming pions that stop in the hydrogen target.
The resulting branching ratio limit for \( n' \) production in \( \pi^- p \) capture is shown in Fig. 4. The double-well shape of the branching ratio limit is a consequence of two factors. Firstly, for either low or high masses, the \( n' \) detection efficiency decreases sharply and hence the \( n' \) branching ratio limit increases sharply. Secondly, for masses from 1000 to 1020 MeV/c\(^2\), the overlapping production and decay gamma-rays make discrimination between the direct two-photon and \( n' \)-mediated capture more troublesome and hence the \( n' \) branching ratio limit also rises. For \( M_{n'} = 1004 \) MeV/c\(^2\) we obtained the 90% C.L. limit \( BR < 3 \times 10^{-6} \) and for \( M_{n'} = 1044 \) MeV/c\(^2\) we obtained \( BR < 4 \times 10^{-6} \).

In Ref. [10] the authors have employed the \( n' \) mechanism in double radiative capture to establish a limit on the \( n' \rightarrow n \gamma \) radiative width \( \Gamma_\gamma(n') \). Their scheme for estimating \( \Gamma_\gamma(n') \) was based on the suppression between the radiative capture to the \( n' \) state, \( i.e. \pi^- p \rightarrow \gamma n' \), and the neutron state, \( i.e. \pi^- p \rightarrow \gamma n \). The authors of Ref. [10] have used this suppression factor to estimate the \( n' \) radiative width from the \( \Delta \) radiative width by assuming the same factor also relates the \( n' \rightarrow n \gamma \) decay and \( \Delta \rightarrow n \gamma \) decay. Of course this method is rough and ready - for example, in neglecting the different multipolarities for the radiative decays of the \( n' \) state (1/2\(^{-}\) → 1/2\(^{+}\)) and the

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\(^3\) These limits assume an isotropic two-photon angular distribution for the \( n' \) contribution to the double radiative capture reaction.
Δ resonance \( (3/2^+ \to 1/2^+) \). However, while noting this reservation, by applying the method of Ref. [10] we obtained limits for \( n' \) radiative decay of 
\[ \Gamma_\gamma(n') < 0.05 \text{ eV} \]
for the \( M_{n'} = 1004 \text{ MeV}/c^2 \) candidate and 
\[ \Gamma_\gamma(n') < 0.3 \text{ eV} \]
for the \( M_{n'} = 1044 \text{ MeV}/c^2 \) candidate. For comparison, the limits from Compton scattering are 
\[ \Gamma_\gamma(n') < 0.2 \text{ eV} \]
and 
\[ \Gamma_\gamma(n') < 1.6 \text{ eV} \]
respectively [22].

6 Summary

Using the RMC spectrometer at the TRIUMF cyclotron we have searched for contributions of low-lying exotic baryons to double radiative capture on pionic hydrogen. We found no evidence for exotic baryons of masses 1004 and 1044 MeV/c\(^2\) as claimed by Tatischeff et al. [7,8], and set upper limits on the branching ratios of double radiative capture via these exotic states of < 3 \times 10^{-6} \) and < 4 \times 10^{-6} \) respectively. Our result, together with null results from pion electro-production [20,21] and nucleon Compton scattering [10,22], are important constraints on any models of such baryons. Moreover the absence of confirmation of Tatischeff’s claims in subsequent experiments now casts some doubt on the existence of such low-lying states. A further hadro-production experiment is required to settle the issue.

The authors are indebted to Profs. Yakov Azimov and Igor Strakovsky for prompting our efforts and many valuable discussions. We wish to thank the staff of the TRIUMF laboratory for their support of this work. In particular we acknowledge the help of Dr. Renée Poutissou on the data acquisition, and Dr. Dennis Healey on the hydrogen target. In addition we thank the National Science Foundation (United States), the Natural Sciences and Engineering Research Council (Canada), the Clare Boothe Luce Foundation (JHDC), and the Jeffress Memorial Trust (DSA), for financial support.

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