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The reaction $p(e, e' \pi^+) X^0$ was studied with two high-resolution magnetic spectrometers to search for narrow baryon resonances. A missing mass resolution of 2.0 MeV was achieved. A search for structures in the mass region of $0.97 < M_{X^0} < 1.06$ GeV yielded no significant signal. The yield ratio of $p(e, e' \pi^+) X^0 / p(e, e' \pi^+) n$ was determined to be $(-0.35 \pm 0.35) \times 10^{-3}$ at 1.004 GeV and $(0.34 \pm 0.42) \times 10^{-3}$ at 1.044 GeV. This measurement clearly demonstrated the potential of high-resolution missing mass searches in coincidence experiments.

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Since the discovery of the $\Delta(1232)$ resonance in the 1950s, many baryon resonances have been discovered with $m > m_\Delta$. These baryon states are interpreted as net three-quark color-singlet objects with angular and radial excitations [1]. The quark model explains the mass difference of $m_\Delta - m_N$ by quark spin-spin interactions [2]. Since all the low-lying quark-model states are accounted for, a baryon bound state with a mass between the nucleon and the Δ should not exist in the present theoretical framework. Indeed, there was no evidence for such a resonance prior to 1997, and several searches [3,4] for charge-2 resonances yielded null results. In 1997, however, possible evidence of neutral baryon states at 1.004, 1.044, and 1.094 GeV was reported in the $pp \rightarrow p \pi^+ X^0$ reaction [5]. The two lower-mass states are below pion threshold, and the only allowed decay channels are the radiative ones, which implies that their natural widths are of the order of a few keV, much narrower than the experimental resolution of a few MeV. The authors suggested a possible explanation of these resonance states in terms of interacting colored quark clusters.

These experimental results are most astounding when one considers the countless experiments carried out with many different probes over more than 50 years in which the claimed states were never observed. L'vov and Workman [6]

argued that the reported structures are “completely excluded” by the fact that no such structure was reported in the existing real Compton scattering data [7]. Furthermore, the existence of these states appears to be ruled out by their effects on the predicted composition of a neutron star which lead to a reduced maximal mass inconsistent with the observational limit [8]. As a counterargument, Kobushkin [9] suggested that the claimed states could be members of a total antisymmetric representation of a spin-flavor group such that the one-photon excitation or decay channels are forbidden and only the $2\gamma N$ channels are allowed. While there is no room for these new exotic baryon states within the many theoretical constituent quark models [10], a colorless diquark cluster model [11] mass formula closely reproduced the observed masses. Recently, a model based on the excitation of quark condensates [12] was suggested which interpreted the resonances as multiple production of a “genuine” Goldstone boson with a mass of 20 MeV.

The existence of baryon resonances below pion threshold, if established experimentally, could profoundly change our understanding of quark-quark interactions and strongly suggest new degrees of freedom in the quark model. However, the states claimed in Ref. [5] were of limited statistics amid a rather significant background. The signals of the $pp \rightarrow p \pi^+ X^0$ peaks were of the order of $\sim 10^{-3}$ compared to that of the $pp \rightarrow p \pi^+ n$ peak. Given the potential impact of these states, experimental verification in different reaction channels is highly desired. Recently, single-baryon states of 0.966, 0.987, and 1.003 GeV were reported in the missing

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FIG. 1. The Feynman diagrams of $p(e, e' \pi^+)n$ and $p(e, e' \pi^+)X^0$ reactions.

mass spectra of the $pd \rightarrow ppX^0$ reaction [13], but a similar search in the same reaction channel has reported no resonance structure [14]. This paper reports the first dedicated search in the $p(e, e' \pi^+)X^0$ channel in the mass region of $0.97 < M_{X^0} < 1.06$ GeV. As illustrated in Fig. 1, the X^0 states would be a product of strong interactions through an intermediate state N' of the nucleon, Δ , or N^* resonances.

The ratio of the coupling at the $\pi N' X$ vertex to that at the $\pi N' n$ vertex can be determined through the cross section ratio:

$$\left(\frac{g_{\pi N' X}}{g_{\pi N' n}} \right)^2 = \frac{\sigma_{p(e, e' \pi^+) X^0}}{\sigma_{p(e, e' \pi^+) n}} \equiv K_s. \quad (1)$$

According to Tatischeff *et al.* [5] the suppression factor K_s is expected to be in the order of $\sim 10^{-3}$, which falls close to an upper limit of 10^{-3} suggested by Azimov [15]. Therefore, a high-resolution, high-statistic, and low-background $(e, e' \pi^+)$ measurement could be used to reveal the resonance states as abnormal structures above the radiative tail of the $p(e, e' \pi^+)n$ reaction.

The measurement was conducted at the Thomas Jefferson National Accelerator Facility's experimental Hall A, taking advantage of the high-resolution spectrometer pair and the high-quality cw beam of the CEBAF accelerator. The data were collected during a 12 h period. An electron beam of energy 1.722 GeV and average current 33 μ A were scattered on a liquid hydrogen target. The target cell was an aluminum can 15 cm in length and 6.35 cm in diameter, and was oriented with its axis along the beam direction. Two magnetic spectrometers were used in coincidence. One spectrometer was set to a central momentum of 1.040 GeV/c to detect the scattered electrons at 19° on beam right; the other spectrometer was set to 41.6° on beam left to detect π^+ particles first at 0.621 GeV/c (kinematics A) corresponding to the missing neutron peak as a calibration and then at 0.543 GeV/c (kinematics B) for the resonance search. The four-momentum transfer square is 0.2 GeV², and the invariant mass of the $\pi^+ X^0$ system is $W \approx 1.44$ GeV.

A combination of a threshold gas Cherenkov counter and a lead-glass calorimeter array at the focal plane provided clean e/π^- separation in the electron arm. In the hadron arm, the π^+/p separation was achieved by an Aerogel Cherenkov detector combined with the particle's velocity and energy loss measured by the trigger scintillators. The resolution of the reconstructed two-arm vertex was $\sigma_z = 0.6$ cm along the beam direction and was mainly limited by the multiple scattering through the window material at the target chamber

FIG. 2. The time-of-flight spectrum in kinematics B. The 2.0 ns beam structure is clearly visible in the accidental events. Particle identification cuts and vertex cuts have been applied.

and the spectrometer entrance. The path length corrected coincidence time had a resolution of 2.0 ns which is dominated by the rise time of the photomultiplier tubes attached to the scintillators. After particle identification cuts and a two-arm vertex cut of $|\Delta z| < 1.0$ cm, the ratio of real-to-random coincidences was about 1:1 in kinematics B as shown in Fig. 2.

Yields were corrected for event-reconstruction efficiencies ($\sim 90\%$) and data-acquisition dead times ($\sim 10\%$). The effect of pion decay was accounted for by weighting each event with a survival factor which was calculated based on the pion's momentum and path length (~ 23.5 m). A window of 3.4 ns centered around the timing peak was used to select the $(e, e' \pi^+)$ events, and accidental events were sampled from a 34 ns time window on each side of the timing peak. No noticeable fine structure was observed in any spectrum of accidental events. The phase space volumes were calculated through a Monte Carlo simulation which started by sampling a missing mass range uniformly. Spectrometer models, reconstruction resolutions, and target material effects were considered in the simulation. The charge-normalized $(e, e' \pi^+)$ yields were obtained by subtracting the accidental events from the coincident events and dividing the result by the phase space volume.

The normalized yield, as a function of missing mass, is plotted in Fig. 3(a) in 1.0 MeV bins in arbitrary units. The missing mass resolution is 2.0 MeV, as demonstrated in kinematics A, and is mainly due to the energy loss in the target material. As a result of the large size of the target cell, the incident electron, the scattered electron, and the outgoing pion passed through averaged material thickness of 0.5, 0.6, and 0.4 g/cm², respectively. The yield of kinematics B, which is the Bethe-Heitler radiation tail of the $p(e, e' \pi^+)n$ reaction, has been amplified 50 times in Fig. 3(a). A third-order polynomial was fit to the kinematics B yield with a reduced χ^2 of 1.2 for 90 data points. The signature of an X^0 resonance would be an excess of yield above the smooth shape of the radiation tail. A line shape corresponding to such a signal with the strength of $K_s = 1.0 \times 10^{-3}$ at 1.004 and 1.044 GeV is illustrated in Fig. 3(a) by the curve shifted from the data. The deviations of the data from the polynomial fit are divided by the $p(e, e' \pi^+)n$ peak height and plot-

FIG. 3. Normalized $(e, e' \pi^+)$ yields in arbitrary units are plotted in 1.0 MeV missing mass bins in (a). A third-power polynomial fits the data, the fit residues divided by the $p(e, e' \pi^+)n$ peak height are plotted in (b). Error bars are statistical only.

ted in Fig. 3(b). To the level of $K_s \approx 1.0 \times 10^{-3}$, no resonance signal can be identified in the mass region of $0.97 < M_{X^0} < 1.06$ GeV. Fitting these fluctuations with a Gaussian of FWHM = 2.0 MeV, the experimental resolution, leads to $K_s = (-0.35 \pm 0.35) \times 10^{-3}$ at 1.004 GeV and $K_s = (0.34 \pm 0.42) \times 10^{-3}$ at 1.044 GeV. For the reported states at 0.975 GeV and 0.986 GeV of Ref. [13], we found $K_s = (1.12 \pm 0.73) \times 10^{-3}$ and $K_s = (-0.94 \pm 0.44) \times 10^{-3}$, respectively. The 0.966 GeV state of Ref. [13] was covered in

kinematics A with limited statistics and we found $K_s \approx (3 \pm 5) \times 10^{-3}$. The state at 1.094 GeV of Ref. [5] was not covered in this measurement.

The null result of this experiment does not necessarily contradict the claim of Ref. [5]. First, the hadronic reaction could have allowed more exotic channels for the production of X^0 , for example, through a reaction with a dibaryon type intermediate state. Second, as a result of the limited beam time and the unfavorable target geometry, the sensitivity of this measurement was not much improved compared to Ref. [5]. However, this measurement clearly demonstrated the potential of high-resolution missing mass searches in coincidence experiments. Further improvements of the experimental apparatus underway are expected to reduce the timing resolution to 0.5 ns and the missing mass resolution to 0.5 MeV. A dedicated search [16] can set a tighter limit of $K_s \leq 1.0 \times 10^{-4}$. With the new generation of high-resolution spectrometers and the high-intensity cw electron beam of Jefferson Lab, a carefully planned experiment could set a much tighter limit on or even discover narrow baryon structures which might not have been visible in earlier lower-resolution experiments.

In conclusion, a high-resolution missing mass search in the $p(e, e' \pi^+)X^0$ reaction yielded no significant signal in the mass region of $0.97 < M_{X^0} < 1.06$ GeV. The yield ratio of $p(e, e' \pi^+)X^0/p(e, e' \pi^+)n$ was determined to be $(-0.35 \pm 0.35) \times 10^{-3}$ at 1.004 GeV and $(0.34 \pm 0.42) \times 10^{-3}$ at 1.044 GeV, consistent with a null signal.

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