Pentaquark Θ^+ search at HERMES

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The earlier search at HERMES for narrow baryon states excited in quasi-real photoproduction, decaying through the channel $pK^0_S \to p\pi^+\pi^-$, has been extended with improved decay-particle reconstruction, more advanced particle identification, and increased event samples. The structure observed earlier at an invariant mass of 1528 MeV shifts to 1522 MeV and the statistical significance drops to about 2σ for data taken with a deuterium target. The number of events above background is $68^{+98}_{-31}(\text{stat}) \pm 13(\text{sys})$. No such structure is observed in the hydrogen data set.

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I. INTRODUCTION

Exotic hadrons consisting of five quarks were proposed on the basis of quark and bag models [1–3] in the early days of QCD. Predictions based on the Skyrme model [4–7] generated renewed interest in the possible existence of such manifestly exotic baryon states, and chiral-soliton calculations suggested a narrow resonance at $\sim 1530\,\mathrm{MeV}$ [8], named Θ^+. Possible experimental evidence for this state came from the observation of a narrow peak at 1.54 ± 0.01 GeV in both the K^- and K^+ missing-mass spectrum for the $\gamma n \to K^+K^-n$ reaction on ^{12}C [9]. This observation provoked a series of reports of experimental sightings and theoretical predictions for such states. Increased experimental scrutiny failed to confirm most of these initial reports, and it is now generally accepted that there is no substantial evidence for the existence of the Θ^+ state [10, 11].

Motivated by the early reports of its existence, the HERMES Collaboration undertook a search for the Θ^+ in quasi-real photoproduction off a deuterium target. The reaction searched for was inclusive photoproduction of the Θ^+ followed by the decay $\Theta^+ \to pK^0_S \to p\pi^+\pi^-$. A narrow structure was observed at 1528 MeV with a significance of $3.7\,\sigma$ [12]. Consequently, in spite of the demise of the Θ^+, it remained of interest to improve the sensitivity of the HERMES data to explore the possibility that the observed structure signals a hitherto unobserved baryon resonance.

This paper presents results of a more precise study of the pK^0_S mass region near 1528 MeV where a narrow structure in the $M(pK^0_S)$ distribution was observed in the earlier HERMES search. In addition to an increased number of events analyzed, the new analysis employed a better track reconstruction algorithm and an improved particle identification technique to extract a much cleaner sample of K^0_S's. In addition, data obtained on a hydrogen target have been analysed.

II. THE EXPERIMENT

HERMES was a fixed-internal-target experiment in which the target, a storage cell, was traversed by the circulating beam of the HERA lepton storage ring [13]. The target consisted of an open-ended elliptical storage cell that was aligned coaxially to the lepton beam. The cell was fed by polarized or unpolarized gas. The polarized target used an atomic beam source [14], which could produce luminosities of the order of 10^{31} to 10^{32} cm^2/s. Unpolarized data were obtained using an unpolarized gas feed system, operating with up to three orders of magnitude higher luminosities. An integrated luminosity of $\sim 500\,\mathrm{pb}^{-1}$, corresponding to 28.4 million deep-inelastic scattering (DIS) events, was collected on a longitudinally polarized (unpolarized) deuterium target over the years 1998-2000 (2006-2007). With the hydrogen target approximately twice the luminosity was collected, corresponding to 54.9 million DIS events accumulated over the years 2002-2005 (2006-2007) on a transversely polarized (unpolarized) target. Polarized data were summed over the spin orientations.

For an overview of the configuration of the experiment the reader is referred to the earlier HERMES paper [12]. Advances in several aspects of the techniques of the experiment reported there increase the sensitivity in the search for new baryon resonances. In the original measurement, particle identification was accomplished with reconstruction of the event response of the HERMES ring-imaging Cherenkov detector (RICH) [15] on a track-by-track basis. This approach was dictated by the limited computing capability available at that time. However, this technique does not account for complications in particle identification caused by overlapping Cherenkov rings from two or more tracks in the same detector half. By its nature, the search reported here focuses on events with at least three tracks. In the analysis presented, the defect is remedied by the implementation of a more advanced method of particle identification, in which the response pattern in the RICH is reconstructed with simultaneous generation of the response to all the tracks present in an event [16]. In this way, possible track-to-track cross talk is accounted for and the efficiency and purity of the RICH particle identification is improved.

The K^0_S spectrum is reconstructed with improved resolution and background rejection. This results from the use of constraints on the track geometry instead of pion identification with the RICH, and of data reprocessing with a tracking code involving event-level fitting based on a Kalman-filter algorithm [17], which corrects the tracking parameters for the effects from magnetic fields and accounts for all detector materials and known misalignments. In this case, imposition of collinearity and track-vertex reconstruction generates spectra of K^0_S of purity superior to that from the earlier measurements.

III. EVENT SELECTION

In the present analysis, the search for the Θ^+ is based on the observation of events in the decay channel $\Theta^+ \to pK^0_S \to p\,\pi^+\pi^-$. Hadron tracks are identified with an efficiency greater than 99% and a lepton contamination of <1% [18] through the combined response of a transition-radiation detector, a scintillator hodoscope preceded by two radiation lengths of lead (the pre-shower detector), a lead-glass calorimeter and the RICH. Only tracks that are within the spatial volume of fiducial limits corresponding to the acceptance of the HERMES spectrometer and within the momentum range $1-15$ GeV are accepted. Events selected must have at least three tracks: one track identified as a proton by the RICH with momentum in the region $4-15$ GeV, in which the RICH is able to identify protons, and at least two oppositely charged tracks not identified as protons. In the subsequent event reconstruction these tracks are assumed to be pions, i.e., for tracks between $1-4$ GeV the pion hypothesis is always applied while it is done so in the region of $4-15$ GeV when the RICH does not identify the particle as a proton.

The first step of the event reconstruction is the selection of the K^0_S through the invariant-mass spectrum of the two oppositely charged particles, which are assumed to be pions. The reconstructed trajectory of the K^0_S candidate is then combined with the proton track to reconstruct the Θ^+ candidate. The geometry assumed in the search for the decay of the Θ^+ is shown in Fig. 1. The momentum of the Θ^+ candidate is inferred from the momenta of the decay pions at their crossing point together with that of the proton. The Θ^+ decay vertex is taken as the intersection of the proton track with the beam. The distance between the K^0_S decay point along the beam direction and the crossing point, $V_p^{\rm Beam}$, between proton and beam trajectories must be greater than 4 cm. The direction of the momentum of the K^0_S candidate, as determined by the summed momenta of the decay pions, is required to agree within one degree with the direction of the vector connecting $V_p^{\rm Beam}$, assumed to be the production point of the Θ^+ candidate, and the point of decay of the K^0_S ($\alpha < 1^\circ$ as shown in Fig. 1). The decay vertex of the Θ^+ candidate is required to be in the target-cell region, i.e., along the beam direction within $(-20, +20)$ cm for the long cell used in 1998-2005 and within $(+2, +22)$ cm for the short cell used in 2006-2007.

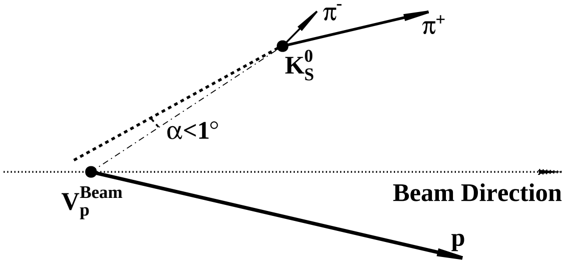

FIG. 1. Diagram of the kinematic reconstruction of the decay of a Θ^+. The angle α is the difference in the direction of the K^0_S momentum (dotted line), as given by the pion momenta, and by the vector connecting the event origin, $V_p^{\rm Beam}$, with the decay of the K^0_S (dash-dotted line).

The invariant-mass distribution, $M(\pi^+\pi^-)$, of the pion pairs obtained after applying all selection criteria is shown in Fig. 2. A Gaussian function for the peak together with a third-order Chebychev function for the background is fitted to the spectrum. Compared to HERMES data published in 2004 [12], the resolution of the K^0_S peak has been improved from 6.2 ± 0.2 MeV to 5.24 ± 0.09 MeV. The peak position value agrees within ± 0.2 MeV with the PDG-value 497.614 ± 0.024 MeV [10]. The K^0_S peak is also much cleaner than that of the data in Ref. [12]. The fit as shown in Fig. 2 results in the number of K^0_S of 3311 ± 60 (within $\pm 2\sigma$) with 87 ± 11 background events in the new analysis, compared with 963 ± 38 K^0_S contaminated by 180 ± 15 background events for the previously published $M(\pi^+\pi^-)$ spectrum.

In order to search for the Θ^+, events were selected with a $M(\pi^+\pi^-)$ invariant mass within $\pm 2\,\sigma$ about the centroid of the K^0_S peak.

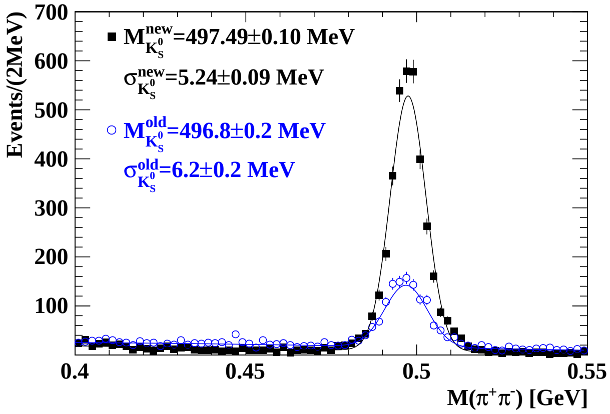

FIG. 2. Invariant-mass spectra of two oppositely charged pions showing a clear K^0_S signal peak. The filled circles denote this analysis with data from 1998-2000 and 2006-2007 while the crosses are the previously published analysis of the 1998-2000 data. For comparison, the standard deviations and mean values of a single Gaussian function fit to the data together with a third-order Chebychev function for the background are given. The new analysis has a much improved mass resolution and signal-to-noise ratio compared to that of the previous HERMES analysis.

IV. RESULTS

The invariant-mass distributions of the pK^0_S system, $M(pK^0_S)$, for data taken with deuterium targets are shown in Fig. 3. It includes the previously published spectrum (open circles), a spectrum of that data reanalyzed (filled circles), a spectrum for data taken in the years 2006-2007 (filled stars), and the spectrum resulting from summing the data from both these periods of HERMES running (filled squares). Only weak suggestions of resonance structure are observed in the newly analyzed spectra.

The presence of significant resonance strength can only be established by a careful analysis. In order to put a limit on the presence of a resonance in the region near 1528 MeV reported in the earlier HERMES paper, the summed data were used in a fit of a peak near that energy accompanied by smooth backgrounds. In order to explore the influence of the background shape on the strength of the fitted peak, several different fitting intervals were used. The background shape has been described with the D^*-D^0 mass-difference function (RooDstD0BG function in RooFit package [19] of ROOT) and also with a third-order Chebychev shape (RooChebychev function in the RooFit package). The peak function is a Breit–Wigner function convoluted with a Gaussian function (RooVoigtian function in RooFit). The σ of the Gaussian function is fixed at 6 MeV as determined from a Monte Carlo study of the spectrometer resolution. Fitting the data in different regions yields an average number of signal events $N = 68^{+98}_{-31}({\rm stat}) \pm 13({\rm sys})$. Here, the systematic uncertainty includes the effects of using

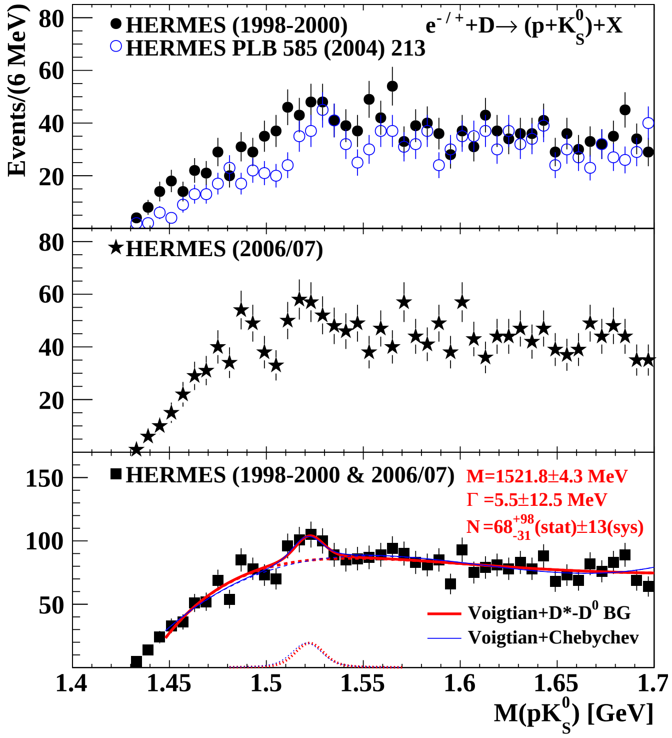

FIG. 3. The various $M(pK^0_S)$ spectra for deuterium data taken at the HERMES experiment in the years 1998-2000 (top), 2006-2007 (middle), and for both periods combined (bottom). Also shown in the top panel is the previously published spectrum [12] from 1998-2000 of data that has been reanalyzed here. A Voigtian (using a Gaussian with a width fixed to 6 MeV) together with two different background hypotheses was fitted to the summed spectrum in the bottom panel. The resulting curves are shown separated into signal and background contribution and also combined. The width Γ of the Breit–Wigner function, the peak position M, and the number of signal events obtained from the fits are given in the panel.

different background functions and different fit ranges. It also includes the bias determined by repeating many times a Monte Carlo simulation, in which the same statistics as in the real-data spectrum were generated using a fitted shape of the real data. The number of counts under the peak was fitted, and input and output numbers were compared. The average peak position found is 1521.8 ± 4.3 MeV with a width of the Breit–Wigner function 5.5 ± 12.5 MeV. A significance of this peak of $1.9\,\sigma$ is obtained from the difference between maximum-likelihood values from un-binned fits [19] with and without the peak function accompanying a smooth background shape. A value of $2.2\,\sigma$ is obtained when it is estimated from many trials using a Monte Carlo simulation with an event generator giving a smooth shape and each trial fitted with a peak plus background shape, in order to determine the probability to produce a fake peak with a strength equal to or larger than 68, the number of signal events resulting from the fit. Taken together, all these methods show that the significance of a signal for a potential resonant structure at 1521.8 MeV is about $2\,\sigma$ for the HERMES deuterium data.

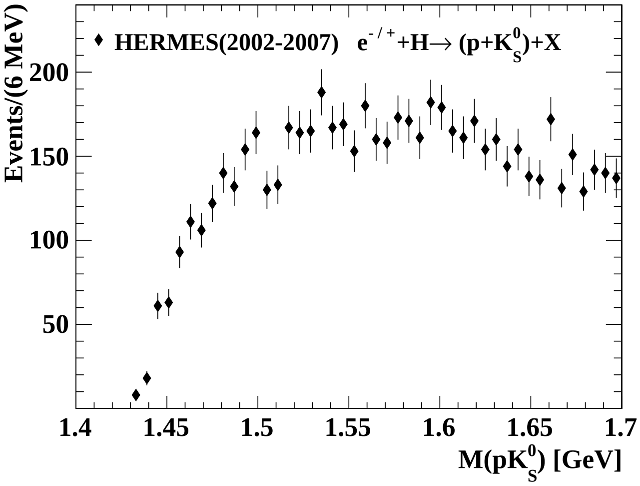

FIG. 4. $M(pK^0_S)$ spectrum from the hydrogen target.

For the HERMES hydrogen data there is no evidence for a resonance structure in the $M(pK^0_S)$ invariant-mass spectrum, as shown in Fig. 4.

These results are confirmed by two independent analysis methods [20] based on slightly different event selection criteria. In one case the events were selected based on a multi-parameter scan in an optimization of the figure of merit $Z = S/\sqrt{S+B}$, where S and B refer to the K^0_S signal and background yields, respectively, in the K^0_S reconstruction and proton identification. In the other, the additional requirement of a constrained purity $P = S/(S + B)$ along the 97% contour in the parameter space was applied. The results for the $M(pK^0_S)$ analysis of all three methods are in statistical agreement with one another for both targets, hydrogen and deuterium.

V. SUMMARY

In summary, the HERMES Collaboration has revisited the earlier reported search [12] for a possible Θ^+ excitation in quasi-real photoproduction on a deuterium target with improved tracking and more advanced particle identification. The original data set taken in the years 1998-2000 has been combined with an additional data set taken in the years 2006-2007, resulting in nearly twice as many events as in the original measurement. As a result of the improved tracking and kinematic reconstruction methods, the invariant-mass spectrum of K^0_S is obtained with significantly less background and better mass resolution. The significance of the potential resonance structure in the $M(pK^0_S)$ spectrum of the deuterium data near the 1522 MeV region is about $2\,\sigma$, compared to the previously published significance of $3.7\,\sigma$ [12]. The position of the structure is 6 MeV lower in mass than the previously reported 1528 MeV, consistent with the accuracies of the old and present analyses.

The observed drop in significance from $3.7\,\sigma$ to about $2\,\sigma$, in spite of twice the number of events for the data from a deuterium target, does not support the presence of a positive Θ^+ signal at HERMES kinematics. For the hydrogen data there is no indication of the existence of an enhancement in the region of interest. The limited statistics of the HERMES measurement preclude a firm conclusion regarding the existence of five-quark exotic baryons.

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