Search for an exotic $\mathbf{S = -2}$, $\mathbf{Q = -2}$ baryon resonance at a mass near 1862 MeV in quasi-real photoproduction

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A search for an exotic baryon resonance with $S = -2$, $Q = -2$ has been performed in quasi-real photoproduction on a deuterium target through the decay channel $\Xi^-\pi^- \to \Lambda\,\pi^-\pi^- \to p\pi^-\pi^-\pi^-$. No evidence for a previously reported $\Xi^{--}(1860)$ resonance is found in the $\Xi^-\pi^-$ invariant mass spectrum. An upper limit for the photoproduction cross section of 2.1 nb is found at the 90% confidence level. The photoproduction cross section for the $\Xi^0(1530)$ is found to be between 9 and 24 nb.

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The prediction for the existence of narrow exotic baryon resonances [1], based on the Chiral Soliton Model, has triggered an intensive search for the exotic members of an anti-decuplet with spin 1/2. In this anti-decuplet [1–3] all three vertices are manifestly exotic. The lightest exotic member of this anti-decuplet lying at its apex, named the Θ^+, was predicted [1] to have a mass of 1530 MeV and a narrow width. It corresponds to a $uudd\bar{s}$ configuration, and decays through the channels $\Theta^+ \to pK^0$ or $\Theta^+ \to nK^+$.

Experimental evidence for the Θ^+ first came from the observation of a narrow resonance at $1540\pm10(\mathrm{syst})$ MeV in the K^- missing mass spectrum for the $\gamma n \to K^+K^-n$ reaction on ^{12}C [4]. The decay mode corresponds to a S=+1 resonance and signals an exotic pentaquark state with quark content ($uudd\bar{s}$). Further evidence emerged from a series of experiments, with the observation of narrow peaks [5–15] in the nK^+ and pK^0_S invariant mass spectra near 1530 MeV, in most cases with a width that is limited by the experimental resolution. Some doubts have been raised recently, however, because of potential experimental artefacts [16] and the failure to observe a signal in other experiments [17–23].

Experimental evidence for a second exotic member of the anti-decuplet came from the reported observation of a S=−2, Q=−2 baryon resonance in proton-proton collisions at $\sqrt{s} = 17.2$ GeV at the CERN SPS [24]. A narrow peak at a mass of about 1862 MeV in the $\Xi^-\pi^-$ invariant mass spectrum is proposed as a candidate for the predicted exotic $\Xi^{--}_{3/2}$ baryon with S=−2, I=$\frac{3}{2}$ and a quark content of ($ddss\bar{u}$). At the same mass, a peak is observed that is a candidate for the $\Xi^0_{3/2}$ member of this isospin quartet. The corresponding anti-baryon spectra show enhancements at the same invariant mass. The observed mass of 1862 MeV falls below the prediction of Ref. [1] and above a prediction of Ref. [25], although closer to the latter. However, the result of Ref. [24] has been disputed [26]. In addition, this resonance has not been confirmed by other experimental searches [22, 27, 28]. Many further searches for the Ξ^{--} are presently underway [29] for which no final results are available yet.

This paper presents the results of a search for the Ξ^{--} in quasi-real photoproduction on deuterium. The data were obtained by the HERMES experiment with the 27.6 GeV positron beam of the HERA storage ring at DESY. Stored beam currents ranged from 9 to 45 mA. An integrated luminosity of 296 pb^{-1} was collected on a deuterium gas target. The target was either longitudinally polarized (223 pb^{-1}) or unpolarized (73 pb^{-1}). The yields were summed over two spin orientations when the target was polarized.

The HERMES spectrometer [30] consists of two identical halves located above and below the positron beam pipe, and has an angular acceptance of ±170 mrad horizontally, and ±(40 − 140) mrad vertically. The trigger was formed by either a coincidence between scintillator hodoscopes, a preshower detector and a lead-glass calorimeter, or a coincidence between three scintillator hodoscopes and two tracking planes, requiring that at least one charged track appears in each of the detector halves of the spectrometer.

The analysis searched for inclusive photoproduction of a Ξ^{--} followed by the decay $\Xi^{--} \to \Xi^-\pi^- \to \Lambda\,\pi^-\pi^- \to p\pi^-\pi^-\pi^-$ or a $\Xi^0 \to \Xi^-\pi^+ \to \Lambda\,\pi^-\pi^+ \to p\pi^-\pi^-\pi^+$. Events selected contained at least four tracks: three charged pions in coincidence with one proton. Identification of charged pions and protons was accomplished with a Ring-Imaging Čerenkov (RICH) detector [31] which provides separation of pions, kaons and protons over most of the kinematic acceptance of the spectrometer. The protons were restricted to a momentum range of 2–15 GeV/c and pions to a range of 0.25–15 GeV/c.

Based on the intrinsic tracking resolution, the required event topology included a minimum distance of approach between a proton and a negative pion track less than 1.5 cm (the midpoint of which is defined as the Λ decay vertex), a minimum distance of approach between a second negative pion and the reconstructed Λ track less than 1.0 cm (the midpoint of which is defined as the Ξ^- decay vertex), a minimum distance of approach between a third pion and the reconstructed Ξ^- track less than 2.5 cm (the midpoint of which is defined as the production vertex), a radial distance of the production vertex from the positron beam axis less than 6 mm, a z coordinate of the production vertex in the ±20 cm long target cell within $-18\,\mathrm{cm} < z < +18\,\mathrm{cm}$ along the beam direction, a Λ decay length (separation of Ξ^- and Λ decay vertices) greater than 7 cm, and a Ξ^- decay length (separation of production and Ξ^- decay vertices) greater than 10 cm. Both possible $\pi^+\pi^-$ combinations were examined for a K^0_S peak in the $M_{\pi^+\pi^-}$ mass spectrum, and none were found.

The first step in the analysis was to search for Λ candidates. The resulting invariant $M_{p\pi^-}$ spectrum is shown in Fig. 1a. The position of the observed Λ peak at $1115.73 \pm 0.01(\text{stat})$ MeV is in good agreement with the nominal value [32]. Events were selected with a $M_{p\pi^-}$ invariant mass within $\pm 3\,\sigma$ of the centroid of the Λ peak. They were then combined with a π^- to form the Ξ^- candidates. The resulting invariant $M_{\Lambda\pi^-}$ spectrum, shown in Fig. 1b, yields a Ξ^- peak at $1321.8 \pm 0.3(\text{stat})$ MeV, which is in good agreement with the expected value of 1321.3 MeV [32].

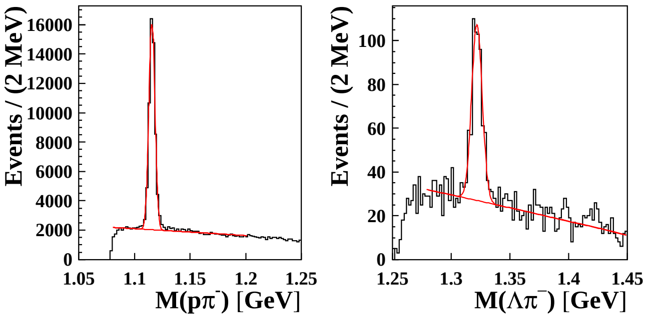

FIG. 1: (a) Invariant mass distribution of the $p\pi^-$ system. (b) Invariant mass distribution of the $p\pi^-\pi^-$ system. Both invariant mass distributions contain also the charge conjugate (c.c.) modes ($\overline{p}\pi^+$, $\overline{p}\pi^+\pi^+$), and are subject to the constraints in event topology discussed in the text.

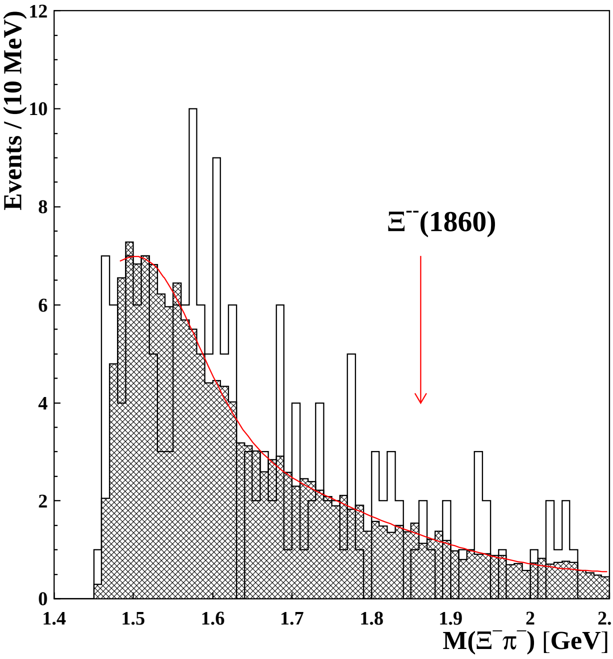

FIG. 2: Invariant mass distribution of the $p\pi^-\pi^-\pi^-$ system, subject to the constraints in event topology discussed in the text. The mixed-event background is represented by the gray shaded histogram, which is normalized to the background component of the fitted curve described in the text. The arrow shows the hypothetical $\Xi^{--}_{3/2}$ mass.

The next step was to search for $\Xi^{--}_{3/2}$ ($\Xi^0_{3/2}$) candidates in the $M_{\Xi^-\pi^-}$ ($M_{\Xi^-\pi^+}$) spectra. Events were selected with a $M_{\Lambda\pi^-}$ invariant mass within $\pm 3\,\sigma$ of the centroid of the Ξ^- peak. The resulting spectrum of the invariant mass of the $p\pi^-\pi^-\pi^-$ system is displayed in Fig. 2. No peak structure is observed near 1862 MeV. Fig. 3 shows the resulting spectrum of the invariant mass of the $p\pi^-\pi^-\pi^+$ system. While no peak structure is observed near 1862 MeV, one appears at the mass of the known $\Xi^0(1530)$.

The shape of the background in Fig. 2 (Fig. 3) was determined from randomly mixing Ξ^- events with π^- (π^+) tracks from other events. Each resulting distribution was fit with a broad Gaussian shape plus a polynomial. The $M_{\Xi^-\pi^-}$ distribution shown in Fig. 2 was fit (smooth curve) with this background form with a free normalization, together with a Gaussian shape whose position was fixed at 1862 MeV and whose width was fixed to the instrumental resolution of $\sigma = 10.2$ MeV, derived from a simulation of the spectrometer described below. The upper limit at the 90% confidence level (C.L.) for the hypothetical $\Xi^{--}_{3/2}$ peak is found to be 3.9 events. The $M_{\Xi^-\pi^+}$ distribution was fit (curve in Fig. 3) using two peak shapes plus the functional form that represents the mixed-event background. One peak shape was Gaussian with a position fixed at 1862 MeV and a fixed width of $\sigma = 10.2$ MeV, while the other was a convolution of Gaussian and Breit-Wigner shapes that was allowed to vary freely near the position of the well established $\Xi^0(1530)$. This Gaussian contribution had a width fixed at 7.2 MeV, while the Breit-Wigner shape had the width fixed at the known $\Gamma = 9.1$ MeV for the $\Xi^0(1530)$ [32]. The position of the $\Xi^0(1530)$ at $1536.5 \pm 3.6(\text{stat})$ MeV is consistent with the expected value of 1531.8 MeV. The values for both Gaussian widths correspond to the simulated instrumental resolutions. The area of the $\Xi^0(1530)$ peak is found to be 35±11 events. For the hypothetical $\Xi^0_{3/2}$ peak at 1862 MeV, the 90% C.L. upper limit is found to be 4.6 events. All of these results are from unbinned maximum likelihood fits [33] to the original event distributions.

In order to derive cross sections, the detector acceptance was simulated using two alternative models for the unknown production kinematics. In the first ansatz, the unknown kinematic distribution of the parent was described by functional forms resembling the transverse and longitudinal momentum distributions of Λ hyperons observed at HERMES. For the second model, the kinematic distributions of the parent were taken to be those of the $\Xi^0(1530)$ as predicted by the PYTHIA6 Monte Carlo code [34]. Both models were isotropic in the decay angle distribution.

In the case of the $\Xi^0(1530)$, the acceptance times effi-

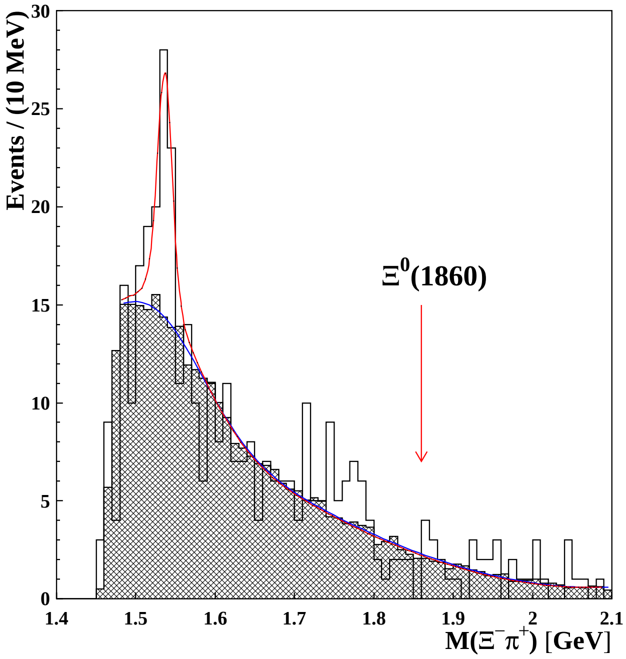

FIG. 3: Invariant mass distribution of the $p\pi^-\pi^-\pi^+$ (plus c.c.) system, subject to the constraints in event topology discussed in the text. The mixed-event background is represented by the gray shaded histogram, which is normalized to the background component of the fitted curve described in the text. The arrow shows the hypothetical $\Xi^0_{3/2}$ mass. The excess near 1.77 GeV has a statistical significance of only $1.8\,\sigma$.

ciency from these two approaches are 0.036%[1] and 0.10%, respectively. This range in acceptance values due to the unknown production mechanism was carried forward into the cross section calculations. The photoproduction cross sections were evaluated using the Weizsäcker-Williams flux factor calculated over the range $3.6\,\mathrm{GeV} < \nu < 24.6\,\mathrm{GeV}$. If the branching ratio of $\Xi^0(1530) \rightarrow \Xi^-\pi^+$ decay is taken to be 2/3 [35], its photoproduction cross section is found to be between 8.8 and 24 nb. This experimental result is considerably higher than the PYTHIA6 model prediction [34] in 4π acceptance of 0.92 nb for production of $\Xi^0(1530)$ plus $\overline{\Xi}^0(1530)$. However, the cross section ratio of $\overline{\Xi}^0(1530)$ to $\Xi^0(1530)$ production predicted by PYTHIA6 is 1:4, which is consistent with the present data.

To simulate the detector response for the hypothetical $\Xi^{--}_{3/2}$ and $\Xi^0_{3/2}$ resonances, the particles were generated with a mass of 1862 MeV and an intrinsic width of $\Gamma = 2\,\mathrm{MeV}$, at vertices distributed according to the HERMES target gas profile. For the initial kinematic distributions, the same two models as for the $\Xi^0(1530)$ were employed. The instrumental resolution derived from this simulation was $\sigma = 10.2\,\mathrm{MeV}$ in the $M_{\Xi^-\pi^-}$ and $M_{\Xi^-\pi^+}$ mass spectra near 1860 MeV.

Estimates of the spectrometer acceptance times efficiency from the simulation were used to estimate an upper limit for the cross section for production of the Ξ^{--} and Ξ^0. Employing the two models described above for the initial kinematic distributions, the acceptances for these particles were estimated to be 0.031% and 0.065%, respectively. Using the fit results described above, the corresponding results for the upper limit for the Ξ^{--} (Ξ^0) photoproduction cross section times branching fraction is found to be 1.0 to 2.1 nb (1.2 to 2.5 nb) at the 90% confidence level (C.L.). Based on the cross section ranges for the $\Xi^0(1530)$ and Ξ^{--} reported here, a 90% C.L. upper limit on the cross section ratio of $\Xi^{--} \rightarrow \Xi^-\pi^-$ to $\Xi^0(1530)$ between 0.06 and 0.15 has been derived. The values were obtained by assuming a central value for each cross section range, assigning the uncertainty to be half of the range, and performing error propagation on the ratio.

In summary, a search for the exotic Ξ^{--} baryon resonance has been performed in quasi-real photoproduction on a deuterium target through the decay channel $\Xi^-\pi^- \rightarrow \Lambda\,\pi^-\pi^- \rightarrow p\pi^-\pi^-\pi^-$. The upper limit for the Ξ^{--} photoproduction cross section is 2.1 nb (90% C.L.). In addition, the well established $\Xi^0(1530)$ is clearly identified in this experiment, and its photoproduction cross section is found to be between 8.8 and 24 nb, the range being due the effect of the uncertainty in the production kinematics on the acceptance correction.

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[1] The acceptance for the 4-track decay of the $\Xi^0(1530)$ resonance is comparable to that for the 3-track decay of the Θ^+ [10] due to the inclusion of short tracks. These are tracks that make it through the spectrometer magnet, but not all the way to the RICH detector.

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