Observation of $\Xi(1620)^0$ and evidence for $\Xi(1690)^0$ in $\Xi^+ \to \pi^+\pi^+\pi^-$ decays

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We report the first observation of the doubly-strange baryon Ξ(1620)\(^0\) in its decay to Ξ\(^-\)π\(^+\)\π\(^+\) decays based on a 980 fb\(^{-1}\) data sample collected with the Belle detector at the KEKB asymmetric-energy \(e^+e^-\) collider. The mass and width are measured to be 1610.4 ± 6.0 (stat) +5.9 \(-3.5\) (syst) MeV/c\(^2\) and 59.9 ± 4.8 (stat) +3.0 \(-3.0\) (syst) MeV, respectively. We obtain 4.0σ evidence of the Ξ(1690)\(^0\) with the same data sample. These results shed light on the structure of hyperon resonances with strangeness \(S = -2\).

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The constituent quark model has been very successful in describing the ground state of the flavor SU(3) octet and decuplet baryons \([\bar{1}, \bar{5}]\). However, some observed excited states do not agree well with the theoretical prediction. It is thus important to study such unusual states, both to probe the limitation of the quark chromodynamics (QCD) description of the structure of the ground state of the flavor SU(3) and to spot unrevealed aspects of the quantum chromodynamics (QCD) description of the structure of hadron resonances. Intriguingly, the Ξ resonances with strangeness \(S = -2\) may provide important information on the latter aspect.

The quantum numbers of several nucleons and \(S = -1\) hyperon resonances have been measured. Recently, there has been significant progress in the experimental study of charmed baryons by the Belle, BaBar, and LHCb collaborations. In contrast, only a small number of Ξ states have been measured \([1]\). Neither the first radial excitation with the spin-parity of \(J^P = \frac{1}{2}^+\) nor a first orbital excitation with \(J^P = \frac{1}{2}^-\) has been identified. Determination of the mass of the first excited state is a vital test of our understanding of the structure of Ξ resonances. One candidate for the first excited state is the Ξ(1690), which has a three-star rating on a four-star scale \([1]\). Another candidate is the Ξ(1620), with a one-star rating \([1]\). If the \(\frac{1}{2}^-\) state is found, it will be the doubly-strange analogue to the Λ(1405) state, which has been postulated as a candidate meson-baryon molecular state or a pentaquark \([1]\).

Experimental evidence for the Ξ(1620) \(\rightarrow \Xi \pi\) decay was reported in \(K^-p\) interactions in the 1970’s \([5, 6]\). The mass and width measurements are consistent but have large statistical uncertainties. The most recent experiment, in 1981, has not seen this resonance \([5]\). There is a lingering theoretical controversy about the interpretation of the Ξ(1620) and Ξ(1690) states \([5, 10]\), extending from their assignment in the quark model to their existence. This would be addressed with new high-quality experimental results for the first excited state with \(S = -2\).

The hadronic decays of charmed baryons governed by the \(e \rightarrow s\) quark transition are a good laboratory to probe hyperon resonances.

In this Letter, we study the decay \(\Xi^+_c \rightarrow \Xi^{0} \pi^+, \Xi^0 \rightarrow \Xi^- \pi^+\) based on a data sample collected with the Belle detector at the KEKB asymmetric-energy \(e^+e^-\) collider \([17]\). The charge conjugate mode is included throughout this Letter. The sample corresponds to an integrated luminosity of 980 fb\(^{-1}\). The major part of the data was taken at the Υ(4S) resonance; in addition, smaller integrated luminosity samples were collected off resonance and at the Υ(1S), Υ(2S), Υ(3S), and Υ(5S). We use a Monte Carlo simulation (MC) sample to characterize the mass resolution, detector acceptance, and invariant mass distribution in the available phase space. The MC samples are generated with EVTGEN \([18]\), and the detector response is simulated with GEANT3 \([19]\).

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals; all these components are located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. The detector is described in detail elsewhere \([20]\). Two inner detector configurations were used. A 2.0 cm radius beampipe and a 3-layer SVD was used for the first sample of 156 fb\(^{-1}\), while a 1.5 cm radius beampipe, a 4-layer SVD and a small-cell inner CDC were used to record the remaining 824 fb\(^{-1}\) \([21]\).

We reconstruct the \(\Xi^+_c\) via the \(\Xi^+_c \rightarrow \Xi^- \pi^+ \pi^+, \Xi^- \rightarrow \Lambda \pi\), \(\Lambda \rightarrow p \pi^-\) decay channel. Final-state charged particles, \(p\) and \(\pi^\pm\), are identified using the information from the tracking (SVD, CDC) and charged-hadron identification (CDC, ACC, TOF) systems combined into likelihood ratios \(L(i : j) = L_i/(L_i + L_j)\), where \(i, j \in \{p, K, \pi\}\). The \(\pi^\pm\) particles are selected by requiring the likelihood ratios \(L(\pi : K) > 0.6\); this has about 90% efficiency. The likelihood ratios \(L(p : \pi) > 0.6\) and \(L(p : K) > 0.6\) are required for proton candidates from the Λ. The Λ particles are reconstructed from \(p\pi^-\) pairs with about 98% efficiency. The three-momentum of the Λ is combined with that of a \(\pi^-\) track to reconstruct the helix trajectory of the Ξ\(^-\) candidate; this helix is extrapo-
lated back toward the IP. A vertex fit is applied to the \( \Xi^- \rightarrow \Lambda \pi^- \) decay and the \( \chi^2 \) is required to be less than 50. We retain \( \Xi^- \) candidates whose mass is within \( \pm 3.0 \text{ MeV}/c^2 \) of the nominal \( \Xi^- \) mass. Then, we combine the \( \Xi^- \) with two \( \pi^+ \) candidates, where the pion with the lower (higher) momentum is labeled \( \pi^+_1 \) (\( \pi^+_2 \)).

The closest distance between the \( \pi^+ \) track and the nominal \( e^+e^- \) interaction point must satisfy \( |dz| < 1.3 \text{ cm} \) along the beam direction, and \( |dr| < 0.16 \) (0.13) cm in the transverse plane for \( \pi^+_1 \) (\( \pi^+_2 \)) for both \( \pi^+_1 \) and \( \pi^+_2 \). A vertex fit is applied to the \( \Xi^+ \rightarrow \Xi^- \pi^+ \pi^+ \) decay. The \( \chi^2 \) is required to be less than 50. To purify the \( \Xi^+_1 \) samples, the scaled momentum \( x_p = p_{CM}/\sqrt{1/2 - m(\Xi^+_1)^2} \) is required to exceed 0.5, where \( p_{CM} \) is the momentum of \( \Xi^+_1 \) in the \( e^+e^- \) center-of-mass system, \( s \) is the squared total center-of-mass energy, and \( m(\Xi^+_1) \) is the \( \Xi^+_1 \) nominal mass. We retain \( \Xi^+_2 \) candidates that satisfy \( |M(\Xi^- \pi^- \pi^+) - m(\Xi^+_2)| < 12.7 \text{ MeV}/c^2 \). The region 30.0 \text{ MeV}/c^2 < \( |M(\Xi^- \pi^- \pi^+) - m(\Xi^+_2)| < 55.4 \text{ MeV}/c^2 \) defines the sideband for estimation of the combinatorial background.

The \( M(\Xi^- \pi^+_1) \) and \( M(\Xi^- \pi^+_2) \) distributions of the final sample are shown in Fig. 1(a). Peaks corresponding to \( \Xi(1530)^0 \), \( \Xi(1620)^0 \), and \( \Xi(1690)^0 \) are observed in the \( M(\Xi^- \pi^+_1) \) distribution. A reflection due to \( \Xi(1530)^0 \) decays is seen around 2.2 \text{ GeV}/c^2 in \( M(\Xi^- \pi^+_1) \). The hatched histograms are the distributions of the \( \Xi^+_1 \) sideband events, where only the \( \Xi(1530)^0 \) is observed. The Dalitz plot of \( M^2(\Xi^- \pi^+_1) \) vs. \( M^2(\Xi^- \pi^+_2) \) is shown in Fig. 1(b). The cluster of events due to the \( \Xi(1530)^0 \) is observed in the \( \Xi(1620)^0 \) and \( \Xi(1690)^0 \) signals. There are currently no known particles with a mass in the range of 2.1 - 2.3 \text{ GeV}/c^2 that would decay into \( \Xi \pi \). Such massive particles would decay predominantly into three-particle final state such as \( \Xi \pi \pi \). The peaks around 1.60 and 1.69 \text{ GeV}/c^2 in \( M(\Xi^- \pi^+_1) \) are interpreted as the \( \Xi(1620)^0 \) and \( \Xi(1690)^0 \) resonances. We see an unknown structure in the range 1.8 - 2.1 \text{ GeV}/c^2 in \( M(\Xi^- \pi^+) \). These events are expected to be due to resonances such as \( \Xi(1820)^0 \), \( \Xi(1950)^0 \), and \( \Xi(2030)^0 \).

The correction of the event-reconstruction efficiency is applied to the mass spectrum. To calculate this efficiency, we generate MC events for the non-resonant three-body decay \( \Xi^+_1 \rightarrow \Xi^- \pi^+ \pi^+ \) with a uniform distribution in phase space. The efficiency is the number of events surviving the selections divided by the total number of generated events, and is measured as a function of \( M(\Xi^- \pi^+_1) \); the resulting efficiency is from 0.082 to 0.097 and shows a nearly flat distribution in \( M(\Xi^- \pi^+_1) \). The mass distribution is divided by this efficiency and is normalized by the total number of events.

We perform a binned maximum-likelihood fit to the efficiency-corrected \( M(\Xi^- \pi^+_1) \) distribution. The fit is applied for the data samples in the signal region and the sideband region simultaneously. The fitting range is restricted to \( (1.46, 1.76) \text{ GeV}/c^2 \) to avoid inclusion of the unknown structure between 1.8 and 2.1 \text{ GeV}/c^2. The fitting function for the mass spectrum in the signal region includes resonances due to the \( \Xi(1530)^0 \), \( \Xi(1620)^0 \), and \( \Xi(1690)^0 \), a non-resonant contribution, and the combinatorial background. The fitting function for the mass spectrum in the sideband region includes the \( \Xi(1530)^0 \) signal and the combinatorial background. The shape of the fitting function for the combinatorial backgrounds is common for the mass spectra in the signal region and the sideband region, and is made by a function with a threshold: \( u^a \exp(u b) + c u \), where \( u = 1 - [(2 - M)/(2 - d)]^2 \) and \( M = M(\Xi^- \pi^+_1) \); \( a, b, c, \) and \( d \) are free parameters. We assume an S-wave non-resonant contribution, and generate the distribution from the MC simulation of \( \Xi^+_1 \rightarrow \Xi^- \pi^+ \pi^+ \) decays with a uniform distribution in phase space. The \( \Xi(1620)^0 \) signal is modeled with the S-wave relativistic Breit-Wigner function. The interference between \( \Xi(1620)^0 \) and the S-wave non-resonant process is taken into account, and these are coherently added. The \( \Xi(1530)^0 \) and \( \Xi(1690)^0 \) signals are modeled with P- and S-wave relativistic Breit-Wigner functions convolved with a fixed Gaussian resolution function of width 1.38 \text{ MeV}/c^2 and 2.04 \text{ MeV}/c^2, respectively, as determined from the MC simulation. The width and mass of \( \Xi(1530)^0 \) and \( \Xi(1690)^0 \) particles are floated in the fit. The mass and width of the \( \Xi(1690)^0 \) are fixed in the fit to the values (1686 \text{ MeV}/c^2 and 10 \text{ MeV}, respectively) measured by the WA89 Collaboration. Figure 1(a) shows the \( \Xi^- \pi^+_1 \) mass spectrum with the fitting result. The \( \chi^2/\text{ndf} \) (where \( \text{ndf} \) is the number of degrees of freedom) is 66/86. For the \( \Xi(1690)^0 \) resonance, the fit is repeated by fixing the yield to zero; the resulting difference in log-likelihood with respect the nominal fit and the change of the number of degrees of freedom are used to obtain the signal significance. The statistical significance of the \( \Xi(1690)^0 \) is 4.5\( \sigma \). To check the stability of

![FIG. 1: (a) The \( \Xi^- \pi^+_1 \) (solid) and \( \Xi^- \pi^+_1 \) (dashed) invariant mass distributions in the \( \Xi^+_1 \) signal region, as well as the corresponding distributions (hatched) in \( \Xi^+_1 \) sideband region. (b) The Dalitz distribution for \( \Xi^+_1 \rightarrow \Xi^- \pi^+ \pi^+ \). (color online)"

\[ M(\Xi^- \pi^+_1) \]
the significance of the $\Xi(1690)^0$, various fit conditions are tried. When the P-wave-only relativistic Breit-Wigner with fixed mass and width is used as the fitting function, the significance is 4.0σ. When the S-wave-only relativistic Breit-Wigner with the floated mass and width is used, the significance is 4.6σ. We take the minimum value of 4.0σ as the significance including the systematic uncertainty. The measured mass and width of $\Xi(1530)^0$ are 1533.4 ± 0.35 MeV/c² and 11.2 ± 1.5 MeV, respectively. The measured mass and width of $\Xi(1620)^0$ are 1610.4 ± 6.0 MeV/c² and 60.0 ± 4.8 MeV, respectively. The mass resolution ($\sigma$) at 1600 MeV/c² is 1.6 MeV/c² as determined from the MC simulation. The width of the $\Xi(1620)^0$ is 59.9 MeV after incorporating this mass resolution.

We itemize the systematic uncertainties on the mass and width of the $\Xi(1620)^0$ resonance in Table I. The mass scale and width are checked by comparing the reconstructed mass of the $\Xi(1530)^0$ in the $\Xi^-\pi^+$ channel with the nominal mass. The differences of the mass and width are −1.5 MeV/c² and −2.7 MeV, respectively. We then generate and simulate $\Xi^+_c \rightarrow \Xi^0\pi^+$, $\Xi^+ \rightarrow \Xi^-\pi^+$ events and analyze these events by the same program as for the real data; the mass scale is checked by comparing the reconstructed mass of $\Xi^+$ with the generated mass. Here, the difference of the mass is −0.2 MeV/c² and the difference of the width is less than the statistical error. The systematic uncertainty due to the mass shape of the $\Xi(1620)^0$ is obtained by applying the fit with the P-wave relativistic Breit-Wigner function instead of the S-wave function. The systematic error due to the mass shape of the $\Xi(1690)^0$ is obtained by applying the fit with the P-wave relativistic Breit-Wigner function instead of the S-wave function, with floated mass and width. The nominal bin width of the mass spectrum is 3.0 MeV/c². We determine its systematic uncertainty by changing the bin size from 2.5 to 3.5 MeV/c² and refitting.

All of the above sources are uncorrelated, so the total systematic uncertainty is calculated by summing them in quadrature.

We refit the data using a function that excludes the interference between $\Xi(1620)^0$ and the S-wave non-resonant process. Figure 2(b) shows the $\Xi^-\pi^+$ mass spectrum with this hypothesis. The $\chi^2$/ndf is 80/87, which is worse than for the nominal fit. Here, the measured mass and width of the $\Xi(1620)^0$ are 1601.2 ± 1.5 MeV/c² and 63.6 ± 8.7 MeV, respectively.

For the first time, the $\Xi(1620)^0$ particle is observed in its decay to $\Xi^-\pi^+$ via $\Xi^+_c \rightarrow \Xi^-\pi^+\pi^+$ decays. The number of $\Xi(1620)^0$ events is two orders of magnitude larger than in previous experiments. The measured mass and width of the $\Xi(1620)^0$ are consistent with the results of previous measurements within the large uncertainties of the latter and are much more precise. The width of the $\Xi(1620)^0$ is somewhat larger than that of the other $\Xi^+$ particles [1].

The constituent quark models have predicted the first excited states of $\Xi$ around 1800 MeV/c² [2]; therefore, it is difficult to explain the structure of the $\Xi(1620)^0$ and $\Xi(1690)^0$ in this context. Instead, it implies that these states are candidates of a new class of exotic hadrons. We observe in the low-mass region two states with a mass difference of about 80 MeV/c²: the $\Xi(1620)^0$ is strongly coupled to $\Xi\pi$ and the $\Xi(1690)^0$ to $\Sigma K$. The situation is similar to the two poles of the $\Lambda(1405)$ [3] and suggests the possibility of two poles in the $S = -2$ sector. Studying these states may explain the riddle about the $\Lambda(1405)$; consequently, the interplay between the $S = -1$ and $S = -2$ states can help resolve this longstanding problem of hadron physics.

The $\Xi(1620)^0$ and $\Xi(1690)^0$ particles are found in the decay of $\Xi^+_c$ while their signals are not seen in the sideband events of Fig 2(a). These results offer a clue for

| Source          | Mass (MeV/c²) | Width (MeV) |
|-----------------|--------------|-------------|
| Mass scale      | −1.5         | −2.7        |
| Mass shape of $\Xi(1620)$ | +4.5   | +1.8        |
| Mass shape of $\Xi(1690)$ | +2.3   | +1.7        |
| Bin size        | ±3.1         | ±1.3        |
| Total           | ±3.5         | ±1.2        |
understanding the quark structure of these exotic states. The result indicates that the hadronic decays of charmed baryons via charm-to-strange quark transitions are potentially a promising system for further studies of strange baryons [16].

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