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# First Observation of $\Xi_c^+ \to \Xi^0 e^+ \nu_e$ and an Estimate of the $\Xi_c^+/\Xi_c^0$ Lifetime Ratio

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## Abstract

Using the CLEO II detector at CESR we have observed the decay modes $\Xi_c^+ \to \Xi^0 e^+ \nu_e$ and $\Xi_c^0 \to \Xi^- e^+ \nu_e$ by the detection of a $\Xi$–positron pair of appropriate invariant mass. We find $\mathcal{B}(\Xi_c^+ \to \Xi^0 e^+ \nu_e) \cdot \sigma(e^+e^- \to \Xi_c^+ X) = (1.55 \pm 0.33 \pm 0.25)$pb, $\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) \cdot \sigma(e^+e^- \to \Xi_c^0 X) = (0.63 \pm 0.12 \pm 0.10)$pb, $\frac{\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)}{\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)} = 0.32 \pm 0.10^{+0.05}_{-0.03}$ and $\frac{\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)}{\mathcal{B}(\Xi_c^+ \to \Xi^0 e^+ \nu_e)} = 0.44 \pm 0.11^{+0.11}_{-0.06}$. Assuming the $\Xi_c^+$ and $\Xi_c^0$ are equally produced in $e^+e^-$ annihilation events at 10 GeV, the lifetime ratio of $\Xi_c^+/\Xi_c^0$ is measured to be $2.46 \pm 0.70^{+0.33}_{-0.23}$.

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The naive spectator model of heavy quark decay predicts that the lifetimes of the charmed hadrons are equal. Experimentally this is not the case, as $\frac{\tau(D^+)}{\tau(D^0)} = 2.55 \pm 0.04$ [1]. However, isospin symmetry requires equal transition rates for the Cabibbo favored semileptonic decays of the $D^+$ and $D^0$ which dominate the semileptonic width [2], therefore the source of the lifetime difference is the hadronic width. It is believed that destructive interference between the internal and external Cabibbo allowed spectator graphs is sufficient to decrease the hadronic width of the $D^+$ relative to the $D^0$ by about the amount required to explain the lifetime ratio [3].

In the charmed baryon sector, destructive interference between the external and internal spectator graphs can occur when a spectator is a $u$ quark. In addition, when a spectator quark is an $s$, constructive interference between two internal spectator graphs can occur. Finally, the W-exchange diagram is not helicity nor color suppressed for baryons. By considering the relative importance of these three effects a hierarchy of lifetimes for charm baryons can be predicted. Guberina *et al.* [4] predict $\tau(\Omega_c) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$ while Voloshin and Shifmann [5] give a different hierarchy: $\tau(\Omega_c) < \tau(\Xi_c^0) < \tau(\Xi_c^+) \approx \tau(\Lambda_c^+)$. Although $\tau(\Lambda_c^+)$ is known to 5% [1], neither of the charm cascade lifetimes is known very well and the lifetime of the $\Omega_c$ is completely unknown. New measurements are needed to test the lifetime hierarchies.

In this paper we report a measurement of $\mathcal{B}(\Xi_c^+ \to \Xi^0 e^+ \nu_e) \cdot \sigma(e^+e^- \to \Xi_c^+ X)$ and $\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e) \cdot \sigma(e^+e^- \to \Xi_c^0 X)$ and estimate the lifetime ratio $\tau_{\Xi_c^+}/\tau_{\Xi_c^0}$. Combining with the charm semileptonic width and the lifetime of the $\Xi_c$, reliable upper bounds for the absolute branching ratios $\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$ and $\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$ are also obtained. The data sample used in this study contains about 3 million $e^+e^- \to c\,\overline{c}$ events corresponding to an integrated luminosity of 2.3 $fb^{-1}$ collected with the CLEO II detector at the Cornell Electron Storage Ring (CESR) at and below the $\Upsilon(4S)$. The CLEO II detector is described in detail elsewhere [6].

We search for the decays $\Xi_c \to \Xi e^+ \nu_e$ by detecting a $\Xi e^+$ (right sign) pair with invariant mass in the range $m_\Xi < m_{\Xi e^+} < m_{\Xi_c}$ [7]. Positrons are required to have a momentum greater than 0.5 GeV/c and to satisfy $|\cos\theta| < 0.71$, where $\theta$ is the angle between the positron momentum and the beamline. Photon candidates are required to have a minimum energy of 40 MeV and neutral pion candidates are selected from pairs of photons. Due to their low detection efficiency in the momentum range of interest, muons are not used in this analysis. To reduce the background from B decay we require the ratio of Fox-Wolfram moments $H_2/H_0 > 0.2$ [8].

We reconstruct the $\Xi^0$ and the $\Xi^-$ through their decay modes $\Lambda\pi^0$ and $\Lambda\pi^-$ respectively. The $\Lambda$ is reconstructed through its decay to $p\pi$. The measured dE/dx of the proton is required to be consistent with the expected value. We reject combinations that can be interpreted as a $K_s^0$. The $\Xi$ candidates are formed by combining each $\Lambda$ candidate either with a negatively charged track which has a combined dE/dx and time of flight probability consistent with a pion hypothesis, or with a $\pi^0$ in the event. A tertiary vertex is formed from the intersection of the $\Lambda$ momentum vector and the negatively charged track or $\pi^0$ momentum [9]. This vertex is required to be closer to the event vertex than the $\Lambda$ decay vertex. For the $\Xi^0$, the momenta of the two photons are recalculated from the vertex constraint. Photon pairs with recalculated invariant mass within 2.5 $\sigma$ of the known $\pi^0$ mass are selected as $\pi^0$ candidates.

The $\Xi$ candidates are then combined with positrons. The invariant mass of the $\Xi e^+$ pair is required to satisfy $1.33 < m_{\Xi e^+} < 2.47$ GeV/$c^2$ and the pair is required to have a momentum greater than 1.4 GeV/c to reduce background. To determine the number of events passing our cuts we fit the $(p\pi)\pi$ invariant mass distributions for these events, shown in Figure 1(a) and Figure 1(c), with a function consisting of a Gaussian, with width determined by a Monte Carlo (MC) simulation of the signal, and a polynomial background. The values returned by the fits are given in Table I.

We now consider sources of background to the signal. We have searched for decays of the type $\Xi_c \to \Xi X e^+ \nu_e$ where $X$ represents additional decay products, for example $\Xi_c \to \Xi^* e^+ \nu_e$ with $\Xi^* \to \Xi\pi$. The best understood resonance in this family is the $\Xi(1530)$ [10]. We reconstruct the resonance in the mode $\Xi^0(1530) \to \Xi^- \pi^+$. We fit to the $\Xi^-\pi^+$ invariant mass distribution and find 218$\pm$34 events. Only $0.4 \pm 3.3$ of these events include a suitable positron. Other $\Xi(1530)$ decay modes have at least one $\pi^0$ in the final state and therefore have smaller efficiencies and poor signal to noise. No $\Xi(1530)$ signals are found in decay modes including $\pi^0$s. As the $\Xi(1530)$ background is consistent with zero we do not subtract it but incorporate it into the systematic error. We have not searched for the non-resonant decays $\Xi_c \to \Xi(n)\pi e^+ \nu_e$ due to their low efficiency and large backgrounds.

Other background sources of $\Xi e^+$ pairs are: real positrons with fake $\Xi$'s, fake positron-real $\Xi$ combinations, the continuum production of random $\Xi e^+$ pairs where the $\Xi$ is not associated with charm baryons, and B decays at the $\Upsilon(4S)$. Fake $\Xi$'s are excluded by fitting to the $\Xi$ mass to determine the yield. For the other backgrounds approximately equal numbers of $\Xi e^+$ (right sign) pairs and $\Xi e^-$ (wrong sign) pairs are expected to be produced. We therefore use the number of $\Xi e^-$ pairs in the data to estimate these backgrounds.

We repeat the analysis for wrong sign pairs. The fits to the $(p\pi)\pi$ invariant mass distributions are shown in Figure 1(b) and Figure 1(d). The fit results are given in Table I. As an independent check that the wrong sign pairs correctly estimate the right sign background we determine the number of fake positron-real $\Xi$ pairs. The fake positron background is estimated by combining a $\Xi$ with all tracks which are not positively identified as lepton tracks, and multiplying by the fake probabilities weighted by the particle population of continuum events containing a strange baryon [11]. We fit the $(p\pi)\pi$ invariant mass distribution to determine the number of fake positrons–real $\Xi$ combinations. This procedure is repeated for electrons to obtain the number of wrong sign fakes. The results are given in Table I. The equality of the right and wrong sign fakes, which are the largest component of the background, justifies our use of wrong sign events to estimate the right sign background.

We obtain the yield given in Table I by subtracting the number of wrong sign events from the number of right sign events. The statistical error in the yield is calculated from the error in the number of right sign and wrong sign events added in quadrature. The efficiencies given in Table I are obtained by MC simulation and include $B(\Lambda \to p\pi)$. The MC model used for the signal is the HQET inspired Körner–Krämer (KK) model [12] which has previously been used to describe the data [13]. To compare the data to the model, in Figure 2 we plot the $\Xi e^+$ invariant mass distribution after subtraction of the $\Xi$ sideband. Agreement between the data and the model is good. The efficiency-corrected yield and integrated luminosity $\mathcal{L}$ are used to obtain the $\mathcal{B} \cdot \sigma$ given in Table I.

The largest experimental source of the systematic error in $\mathcal{B} \cdot \sigma$ for the $\Xi_c^0$ and $\Xi_c^+$ is the contribution from $\Xi(1530)$ feeddown (13%, 5%). We have investigated the model dependence by varying the fragmentation function (10% for both) and by taking the difference in calculated efficiencies from the HQET KK model [12] and a semileptonic decay model producing $\Xi$'s with no net polarization (10%, 8%). An additional source of systematic error is background from the decay $\Omega_c \to \Omega e^+\nu_e$, with $\Omega \to \Xi\pi$. The $e^+e^-$ production cross section for the $\Omega_c$ is unknown. The $e^+e^-$ production cross sections of the $\Xi_c$ and the $\Lambda_c$ are in the approximate ratio 1:4 [14]. We expect a similar ratio of production cross sections for the $\Omega_c$ and the $\Xi_c$. By MC simulation, we find that for the selection criteria used in this analysis the efficiency of reconstructing $\Omega_c$ semileptonic decay background is about 70% of that for $\Xi_c \to \Xi e^+\nu_e$. Using the relative efficiency, the known branching ratios, and our estimate of the $\Omega_c$ cross section we obtain a systematic error of (1%, 3%).

The final source of systematic error is due to using $\Xi e^-$ pairs to estimate the background from the continuum and $\Upsilon(4S)$. On the continuum, there are two sources that only produce $\Xi e^-$ pairs. They are $e^+e^- \to Y_c\overline{Y}_c$, where $Y_c$ is a charmed baryon which decays to a $\Xi$ and $\overline{Y_c}$ decays semielectronically, and $e^+e^- \to Y_c\overline{M}_c\overline{N}$, where $\overline{M_c}$ is a charm meson that decays semielectronically. In both cases the $\Xi e^-$ invariant mass normally satisfies $m_{\Xi e^-} > m_{\Xi_c}$ and is rejected. However, there is a small probability that wrong sign pairs from these sources will satisfy our selection criteria and lead to an overestimate of the right sign background. The systematic error due to this effect is (7% , 6%).

Our results are : $\mathcal{B}(\Xi_c^+ \to \Xi^0 e^+\nu_e) \cdot \sigma(e^+e^- \to \Xi_c^+ X) = (1.55 \pm 0.33 \pm 0.25)$pb and $\mathcal{B}(\Xi_c^0 \to \Xi^- e^+\nu_e) \cdot \sigma(e^+e^- \to \Xi_c^0 X) = (0.63 \pm 0.12 \pm 0.10)$pb. This is the first observation of $\Xi_c^+ \to \Xi^0 e^+\nu_e$. Our cross section for $\Xi_c^0 \to \Xi^- e^+\nu_e$ is in agreement with the previous measurement [14].

At present, there is no reliable normalization of the $\Xi_c$ branching ratios. Under the assumption that the semileptonic widths of all charmed particles are equal [15] we estimate the inclusive semileptonic branching ratio of the $\Xi_c$, $\mathcal{B}_{\ell X}$, from the weighted average of the inclusive semileptonic widths of the $D^0$ and $D^+$ ($\langle\Gamma_{SL}\rangle$) [1] and the $\Xi_c$ lifetime: $\mathcal{B}_{\ell X} = \mathcal{B}(\Xi_c \to \ell^+ X) = \langle\Gamma_{SL}\rangle\tau_{\Xi_c}$. Then the ratio of our $\mathcal{B} \cdot \sigma$ to $\mathcal{B} \cdot \sigma$ for a hadronic mode places a reliable model independent upper bound on the absolute branching ratio of the hadronic mode. This technique was recently applied to the $\Lambda_c$ to derive an upper limit for $B(\Lambda_c \to pK\pi)$ [13].

Therefore we have measured the ratios $R_0 = \frac{\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+)}{\mathcal{B}(\Xi_c^0 \to \Xi^- e^+\nu_e)}$ and $R_+ = \frac{\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+)}{\mathcal{B}(\Xi_c^+ \to \Xi^0 e^+\nu_e)}$. For $R_+$ the obvious choice of numerator is $\Xi_c^+ \to \Xi^0\pi^+$, but a search for this mode yields very few events. In order to present a ratio with a smaller statistical error we choose the copious $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ mode instead. For the modes $\Xi_c^0 \to \Xi^-\pi^+$ and $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ $35 \pm 8$ events and $137 \pm 16$ events are found respectively. In each case the error is that returned by the fit. For $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ three body phase space is assumed. If instead the decay proceeds via $\Xi_c^+ \to \Xi^0(1530)\pi^+$ with $\Xi^0(1530) \to \Xi^-\pi^+$ the efficiency decreases by a factor of two. The average of the two efficiencies is used for the final result while the difference between them is taken as a measure of the systematic error from this source. After correcting the yields for the efficiency we compute: $R_0 = 0.32 \pm 0.10^{+0.05}_{-0.03}$ and $R_+ = 0.44 \pm 0.11^{+0.11}_{-0.06}$. Many of the systematic errors cancel in forming the ratios. The largest remaining sources of systematic error are the $\Upsilon(4S)$ and continuum backgrounds in the denominator and the selection criteria in the numerator. No theoretical predictions exist for either ratio.

Using the world average of the individual $\Xi_c$ lifetime measurements [1] we compute $\mathcal{B}^+_{\ell X} = \mathcal{B}(\Xi_c^+ \to \ell^+ X) = (3.2^{+1.0}_{-0.6})\%$ and $\mathcal{B}^0_{\ell X} = \mathcal{B}(\Xi_c^0 \to \ell^+ X) = (1.4^{+0.3}_{-0.2})\%$. There exists no theoretical relationship between $\mathcal{B}(\Xi_c \to \Xi \ell^+ \nu_l)$ and $\mathcal{B}_{\ell X}$, however by definition $f_{\Xi_c} \equiv \mathcal{B}(\Xi_c \to \Xi \ell^+ \nu_l)/\mathcal{B}_{\ell X} \leq 1$. Therefore $\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+) = f_{\Xi_c} R_+ \mathcal{B}^+_{\ell X} = f_{\Xi_c}(1.4 \pm 0.3^{+0.5}_{-0.4}) \times 10^{-2}$ and $\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+) = f_{\Xi_c} R_0 \mathcal{B}^0_{\ell X} = f_{\Xi_c}(4.3 \pm 1.3^{+0.5}_{-0.4}) \times 10^{-3}$ where the first error is from the determination of $R$ and the second error is from our estimate of $\mathcal{B}_{\ell X}$. Unfortunately the value of $f_{\Xi_c}$ is unknown and no theoretical estimates presently exist, nevertheless these results place reliable upper bounds on the charmed cascade absolute branching ratios for the first time.

Since we measure both charged and neutral $\Xi_c$ semileptonic decays using similar cuts in one experiment, the lifetime ratio $R = \tau_{\Xi_c^+}/\tau_{\Xi_c^0}$ can be extracted from the ratio of our measurements under the following assumptions. We assume that semileptonic decay width of $\Xi_c^+$ and $\Xi_c^0$ are equal and that $\Gamma(\Xi_c^+ \to \Xi^0 e^+ \nu_e) = \Gamma(\Xi_c^0 \to \Xi^- e^+ \nu_e)$. Both of these assumptions follow from isospin invariance. We also assume that the $\Xi_c^+$ and $\Xi_c^0$ are equally produced from $e^+e^-$ annihilations at 10 GeV. This is reasonable because the $\Xi_c^*$'s are expected to decay to the ground state via pion emission, and to be sufficiently heavy that no channel related by isospin is excluded by phase space [16], and the $\Xi_c'$ decays electromagnetically to a $\Xi_c$ [17]. The lifetime ratio is then related to the ratio of branching ratios:

$$R = \frac{\mathcal{B}(\Xi_c^+ \to \Xi^0 e^+ \nu_e)}{\mathcal{B}(\Xi_c^0 \to \Xi^- e^+ \nu_e)} = \frac{\Gamma_{sl}(\Xi_c^+) \cdot \tau(\Xi_c^+)}{\Gamma_{sl}(\Xi_c^0) \cdot \tau(\Xi_c^0)} = \frac{\tau(\Xi_c^+)}{\tau(\Xi_c^0)}$$

where $\Gamma_{sl}$ is the semileptonic decay width of $\Xi_c^+$ and $\Xi_c^0$, and $\tau$ is the appropriate lifetime. Combining our measurements, the lifetime ratio is found to be $R = \frac{\tau(\Xi_c^+)}{\tau(\Xi_c^0)} = 2.46 \pm 0.70^{+0.33}_{-0.23}$.

Agreement among the existing lifetime ratio measurements, $4.06 \pm 1.26$ (E687) [18], $2.44 \pm 1.68$ (NA32) [19], and this result, is good. As our result is not a direct measurement of the lifetimes, it has entirely different systematic errors than E687 and NA32 and therefore serves as independent confirmation of the fixed target results.

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## TABLES

TABLE I. Signals and backgrounds

| mode | $\Xi_c^+ \to \Xi^0 e^+ \nu_e$ | $\Xi_c^0 \to \Xi^- e^+ \nu_e$ |
|---|---|---|
| $N_{\Xi e^+}$ (right sign) | $47 \pm 8$ | $62 \pm 9$ |
| $N_{\Xi e^-}$ (wrong sign) | $6 \pm 3$ | $8 \pm 4$ |
| corrected yield | $41 \pm 9$ | $54 \pm 10$ |
| efficiency (%) | $1.17 \pm 0.02$ | $3.80 \pm 0.05$ |
| $\sigma \cdot \mathcal{B}$ (pb) | $1.55 \pm 0.33 \pm 0.25$ | $0.63 \pm 0.12 \pm 0.10$ |
| fakes (right sign) | $4 \pm 2$ | $7 \pm 2$ |
| fakes (wrong sign) | $4 \pm 2$ | $5 \pm 2$ |

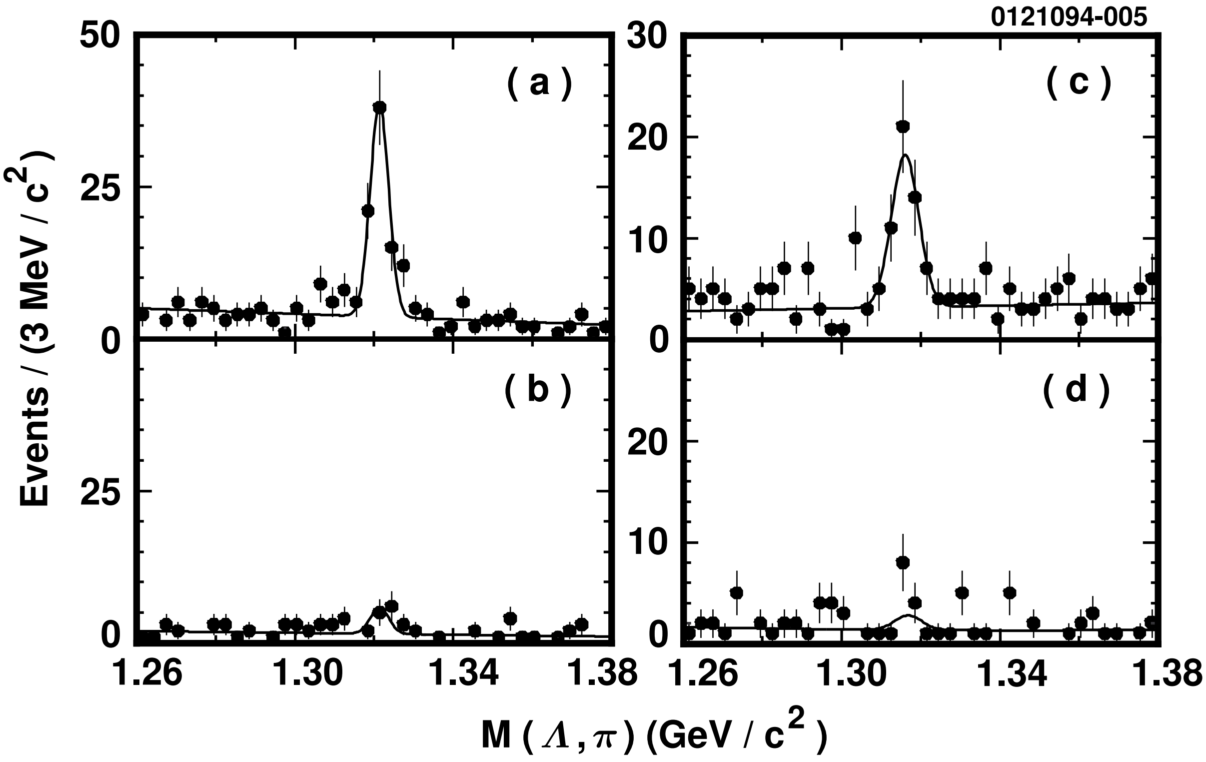


FIG. 1. The $(p\pi)\pi$ invariant mass for right sign and wrong sign $\Xi e$ combinations satisfying the cuts described in the text; (a)$(p\pi)\pi^-$ right sign, (b)$(p\pi)\pi^-$ wrong sign; (c)$(p\pi)\pi^0$ right sign, (d)$(p\pi)\pi^0$ wrong sign.

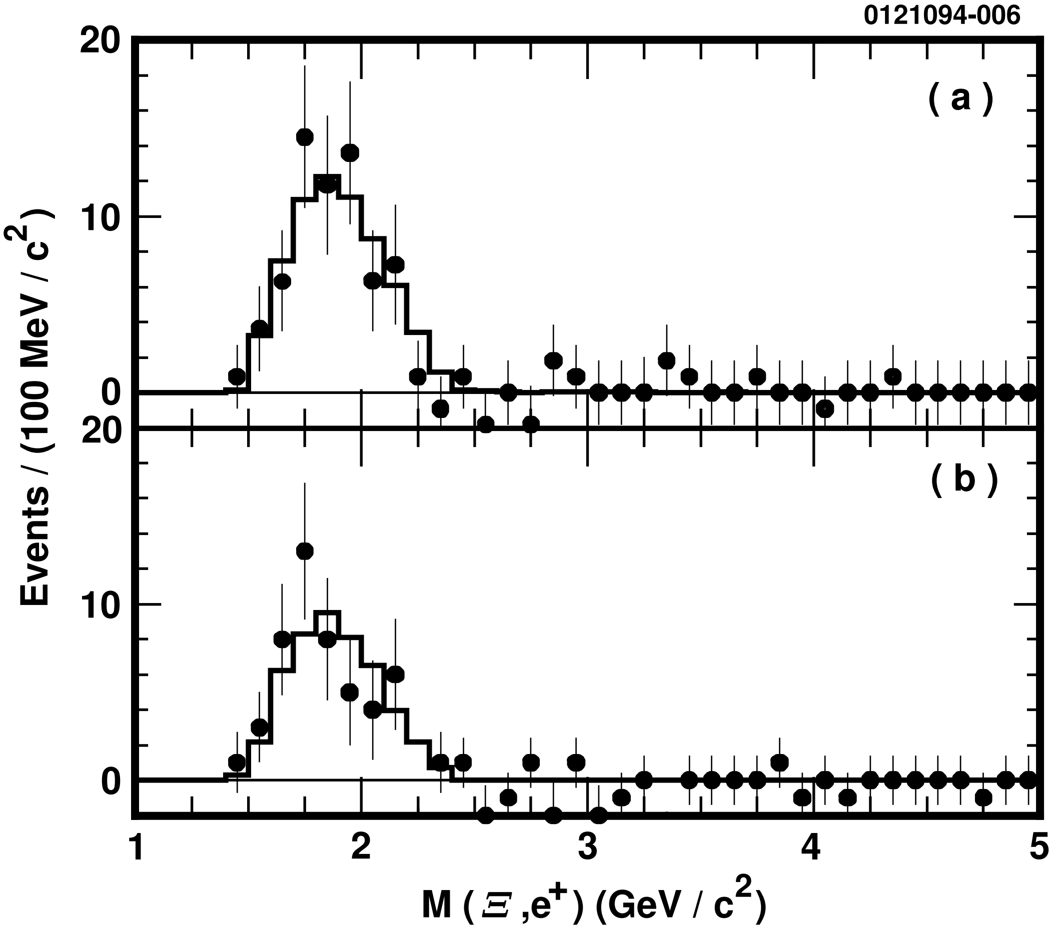


FIG. 2. The $\Xi e^+$ invariant mass for right sign combinations (a) $\Xi^- e^+$, (b)$\Xi^0 e^+$. The points with error bars are data after the subtraction of wrong sign events and fake cascades estimated using the $(p\pi)\pi$ invariant mass sidebands. The solid line is a Monte Carlo simulation of $\Xi_c \to \Xi e \nu_e$ signal using the KK model.