First Observation of the Semileptonic Decay $A^+ \to pK^e\bar{\nu}_e$
The study of $\Lambda^+_c$ semileptonic (SL) decays provides valuable information about weak and strong interactions in baryons containing a heavy quark. (Throughout this Letter, charge-conjugate modes are implied unless explicitly noted.) Its decay rate depends on the weak quark mixing Cabibbo-Kobayashi-Maskawa (CKM) matrix [1] element $|V_{cs}|$ and strong interaction effects parameterized by form factors describing the hadronic transition between the initial and the final baryons. In comparison to experimental studies of SL decays in the charmed meson sector [2], rather few measurements exist of $\Lambda^+_c$ SL decays. No other exclusive SL decay except $\Lambda^+_c \rightarrow \Lambda \ell^+ \nu_\ell$ ($\ell = e, \mu$) has been reported to date [3, 4]. In addition, comparison of the branching fractions (BFs) for the exclusive decay $\Lambda^+_c \rightarrow \Lambda \ell^+ \nu_\ell$ and inclusive decay $\Lambda^+_c \rightarrow X \ell^+ \nu_\ell$ shows that the ratio of relative BF is close to one [5], which exhibits a different pattern compared with heavy bottom or charm meson [2, 6]. Searching for unknown exclusive SL $\Lambda^+_c$ decay can provide important information to validate and understand this pattern. The decay of $\Lambda^+_c \rightarrow pK^- e^+ \nu_e$ is one of the best suited channels to be searched for [7–12], as the final state of the decay is simple with a high detection efficiency, in comparison to decays such as $\Lambda^+_c \rightarrow \Sigma \pi e^+ \nu_e$ etc.

Because of the $ud$-diquark in $\Lambda^+_c$ is the spectator, the SL $\Lambda^+_c \rightarrow pK^- e^+ \nu_e$ decay provides a perfect filter of isospin $I = 0$ meson-baryon states with almost no contamination from the $\Sigma^*$ and $I = 1$ amplitude [8, 13]. This provides an ideal platform to study the internal structure of exotic $\Lambda^*$ states. Among these states, particular interest is concentrated on the $\Lambda(1405)$, in which the high-mass pole strongly couples to $KN$ final-state [2]. The $\Lambda(1405)$ is considered as the most striking state in understanding the spectrum of baryons with strangeness and has been continuously studied for more than 60 years since its theoretical prediction [14, 15]. However, the nature of $\Lambda(1405)$ is still mysterious [16, 17]. It is suggested as a dynamically generated meson-baryon molecular state [8, 15, 18] or a three-quark $uds$ bound state [7, 9]. The decay of $\Lambda^+_c \rightarrow \Lambda(1405)e^+ \nu_e$ is expected to be a promising

\[ B(\Lambda^+_c \rightarrow \Lambda(1405)e^+ \nu_e) = (2.1 \pm 0.4_{\text{stat}} \pm 0.2_{\text{syst}}) \% \]
process to distinguish its structure because the predicted BF of the decay in two suggestions differs roughly 100 times [7–9], as shown in Table I discussed later.

Furthermore, in heavy-baryon SL decays, most previous LQCD calculations are concentrated on the transition of \( J^P = 1/2^+ \rightarrow J^P = 1/2^+ \) [19–28], while the calculations regarding the transitions of \( J^P = 1/2^+ \rightarrow J^P = 3/2^+ \) are still very limited [29, 30]. That is because the LQCD calculations in \( 1/2^+ \rightarrow 3/2^+ \) are substantially more challenging due to the fact that the correlation functions for negative-parity baryons have more statistical noise than those for the lightest positive-parity baryons [31]. On the other hand, no experimental data is available to calibrate the calculations in \( 1/2^+ \rightarrow 3/2^+ \) transitions [2]. Recently, the LQCD extended the prediction on negative-parity baryons by performing the first calculation in \( \Lambda^+_c \rightarrow \Lambda(1520)\ell^+\nu_\ell \) [11, 12] decays, under the approximation that the \( \Lambda(1520) \) is a stable particle in the strong interactions because of its narrow width. An experimental measurement on \( \Lambda^+_c \rightarrow \Lambda(1520)e^+\nu_e \) will certainly provide a valuable check of the methodology applied in LQCD calculation, which is largely shared also with the calculations in \( \Lambda_c \) decays [12, 29, 30]. Comparison of \( \Lambda^+_c \rightarrow \Lambda(1520)/\Lambda(1405)e^+\nu_e \) decay rate between measurement and theoretical predictions provides necessary check on calculations from nonrelativistic quark model [9] and Constituent quark model [7].

In this Letter, we perform the first study of \( \Lambda^+_c \) SL decay \( \Lambda^+_c \rightarrow pK^-e^+\nu_e \). We further search for SL decays of \( \Lambda^+_c \rightarrow \Lambda(1405)e^+\nu_e \) and \( \Lambda^+_c \rightarrow \Lambda(1520)e^+\nu_e \), which are expected to contribute the dominant components in \( \Lambda^+_c \rightarrow \Lambda^*e^+\nu_e \) decays [7, 9], by investigating the \( pK^- \) invariant-mass spectrum in \( \Lambda^+_c \rightarrow pK^-e^+\nu_e \) data. The analysis is performed using data sets collected at BESIII with center-of-mass energies of \( \sqrt{s} = 4.600, 4.612, 4.628, 4.641, 4.661, 4.682, 4.699 \text{ GeV} \). The total integrated luminosity for these data sets is 4.5 fb\(^{-1} \) [32, 33]. This is the largest data sample collected in \( e^+e^- \) collisions near the \( \Lambda^+_c \Lambda^- \) pair production threshold.

The construction and performance of the BESIII detector are described in detail in Ref. [34]. A GEANT4-based [35] Monte Carlo (MC) simulation package, which includes the geometric description of the detector and the detector response, is used to determine signal detection efficiencies and to estimate potential background contributions. Signal MC samples of \( e^+e^- \rightarrow \Lambda^+_c\bar{\Lambda}^- \) with a \( \Lambda^+_c \) baryon decaying to \( pK^-e^+\nu_e \) or \( \Lambda(1520)/\Lambda(1405)e^+\nu_e \) together with a \( \Lambda^- \) decaying to the analyzed hadronic decay mode described below are generated by KKMC [36] with EVTGEN [37], with initial-state radiation (ISR) [38] and final-state radiation (FSR) [39] effects included. The simulation of the SL decays \( \Lambda^+_c \rightarrow pK^-e^+\nu_e \) or \( \Lambda^+_c \rightarrow \Lambda(1405)/\Lambda(1520)e^+\nu_e \) is modeled with a phase-space generator. To study the possible peaking and combinatoral background contributions, inclusive MC samples consisting of open-charm states, radiative return to charmtonium(like) \( \psi \) states at lower masses and continuum processes of \( q\bar{q} \) (where \( q = u, d, s \), along with Bhabha scattering, \( \mu^+\mu^- \), \( \tau^+\tau^- \) and \( \gamma\gamma \) events are generated.

The first step of the analysis is the selection of “single-tag” (ST) events with a fully reconstructed \( \Lambda^- \) candidate. The \( \Lambda^- \) hadronic decay modes used in this analysis are: \( \bar{\Lambda}^- \rightarrow \bar{p}K^0_S, \bar{p}K^+\pi^- \), \( \bar{p}K^0_S\pi^0 \), \( \bar{p}K^+\pi^-\pi^0 \), \( \Lambda^-\), \( \Lambda^-\pi^-\pi^0 \), \( \Lambda^-\pi^-\pi^0 \), \( \Sigma^0\pi^-\pi^0 \), \( \Sigma^0\pi^-\pi^0 \), \( \Sigma^0\pi^-\pi^0 \), \( \Sigma^0\pi^-\pi^0 \), \( \Sigma^0\pi^-\pi^0 \). The intermediate particles \( K^0_{S,L}, \Sigma^0, \Sigma^- \), and \( \pi^0 \) are reconstructed via their decays: \( K^0_{S,L} \rightarrow \pi^+\pi^- \), \( \Lambda^- \rightarrow \bar{p}n^+ \), \( \Sigma^- \rightarrow \bar{p}n^0 \), \( \pi^0 \rightarrow \gamma\gamma \). Within this ST sample a search is then performed for \( \Lambda^+_c \rightarrow pK^-e^+\nu_e \) decay. The events passing this selection are referred to as the double-tag (DT) sample. For a specific tag mode \( i \), the ST and DT event yields can be written as

\[
N_{ST}^i = 2N_{\Lambda_c\Lambda_c}B_{ST}^i\epsilon_{ST}^i \quad \text{and} \quad N_{DT}^i = 2N_{\Lambda_c\Lambda_c}B_{ST}^iB_{SL}^i\epsilon_{SL}^i,
\]

where \( N_{\Lambda_c\Lambda_c} \) is the number of \( \Lambda_c\Lambda_c \) pairs; \( B_{ST}^i \) and \( B_{SL}^i \) are the BFs of the \( \Lambda^- \) tag mode and the \( \Lambda^+_c \) SL decay mode, respectively; \( \epsilon_{ST}^i \) is the efficiency for finding the tag candidate; and \( \epsilon_{DT}^i \) is the efficiency for simultaneously finding the tag \( \Lambda^- \) and the SL decay. The BF of the SL decay can be expressed as:

\[
B_{SL} = \frac{N_{DT}^i}{\sum N_{ST}^i \times \epsilon_{DT}^i/\epsilon_{ST}^i} = \frac{N_{DT}^i}{N_{ST}^i \times \epsilon_{SL}^i} \tag{1}
\]

where \( N_{DT} \) is the total yield of DT events, \( N_{ST} \) is the total ST yield, and \( \epsilon_{SL} = \sum N_{ST}^i \times \epsilon_{DT}^i/\epsilon_{ST}^i \) is the average efficiency for finding a SL decay weighted by the relative yields of tag modes in data.

Selection criteria for \( \gamma, \pi^\pm, K^\pm, p(\bar{p}) \) as well as the reconstruction of \( \pi^0 \) and \( K^0_S \) candidates are the same as those used in Refs. [3, 4]. The invariant masses \( M_{p\bar{p}e^+\nu_e}, M_{\Lambda^-\pi^-\pi^0} \), and \( M_{p\pi^0\pi^0} \) are required to be within \((1.110, 1.121) \text{ GeV/c}^2 \), \((1.179, 1.205) \text{ GeV/c}^2 \), and \((1.171, 1.204) \text{ GeV/c}^2 \) to form candidates of \( \Lambda^- \), \( \Sigma^0 \), and \( \Sigma^- \), respectively.

The ST \( \Lambda^- \) signals are identified using the beam-constrained mass:

\[
M_{BC} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}_{\Lambda^-}|^2/c^2}, \tag{2}
\]

where \( \vec{p}_{\Lambda^-} \) is the measured momentum of the ST \( \Lambda^- \). The energy difference \( \Delta E = \sqrt{s}/2 - E_{\Lambda^-} \) is defined to improve the signal significance for ST \( \Lambda^- \) baryons, where \( E_{\Lambda^-} \) is the measured energy. If more than one \( \Lambda^- \) tag is reconstructed in the event, only the tag with the minimum \( |\Delta E| \) is kept to avoid double counting of STs with the same final state. The \( M_{BC} \) distributions at \( \sqrt{s} = 4.682 \text{ GeV} \) for the fourteen ST modes are shown in Fig. 1. An unbinned maximum-likelihood fit is performed to the spectra, using the MC-simulated signal shape convolved with a Gaussian function to describe the signal and an ARGUS function [40] to describe the background. The signal yield is determined in the mass region \((2.28, 2.30) \text{ GeV/c}^2 \), which is regarded as the signal region. The \( \Delta E \) requirements, \( M_{BC} \) distributions for other data sets and their ST yields are documented in the supplementary materials [41]. The total ST yield reconstructed in all data samples is \( N_{ST} = 122268 \pm 474 \), where only the statistical uncertainty is reported.

Candidates for \( \Lambda^+_c \rightarrow pK^-e^+\nu_e \) are selected from the remaining tracks recoiling against the ST \( \Lambda^- \) candidates and the
FIG. 1. Fits to the $M_{BC}$ distributions for different ST modes at $\sqrt{s} = 4.682$ GeV. The points with error bars are data, the (red) solid curves show the total fits and the (blue) dashed curves are the fitted backgrounds.

FIG. 2. (Left) Fit to the $U_{\text{miss}}$ distribution for $\Lambda_c^+ \rightarrow pK^−e^+\nu_\epsilon$ in data. (Right) The distribution of $U_{\text{miss}}$ vs. $M_{pK^-}$ for $\Lambda_c^+ \rightarrow pK^−e^+\nu_\epsilon$ candidates.

nents from $\Lambda_c^+ \rightarrow pK^−\pi^+\pi^0$ and $\Lambda_c^+ \rightarrow pK^−\mu^+\nu_\mu$, and an MC-derived non-resonant shape describing the combinatorial backgrounds. The yield of the $\Lambda_c^+ \rightarrow pK^−\mu^+\nu_\mu$ component, $N_{\text{DT}}^{pK^-\mu^+\nu_\mu}$, is related to $N_{\text{DT}}^{pK^-e^+\nu_\epsilon}$, which is the yield of $\Lambda_c^+ \rightarrow pK^−e^+\nu_\epsilon$ decay, by:

$$N_{\text{DT}}^{pK^-\mu^+\nu_\mu} = N_{\text{DT}}^{pK^-e^+\nu_\epsilon} \times R_\epsilon \times R_B,$$

where $R_B = \frac{B(\Lambda_c^+ \rightarrow pK^−\mu^+\nu_\mu)}{B(\Lambda_c^+ \rightarrow pK^−e^+\nu_\epsilon)} = 0.88 \pm 0.05$ [9]. The uncertainty on $R_B$ is evaluated by comparing the difference of the BF's of $\Lambda^*$ resonances decaying into $NK e^+\nu_\epsilon$ final states. The parameter $R_\epsilon$, defined as the relative detection efficiency between $\Lambda_c^+ \rightarrow pK^−\mu^+\nu_\mu$ and $\Lambda_c^+ \rightarrow pK^−e^+\nu_\epsilon$, is evaluated to be 0.15 with MC simulation. The event yield for $\Lambda_c^+ \rightarrow pK^−e^+\nu_\epsilon$, as determined from the fit to the $U_{\text{miss}}$ distribution, is $N_{\text{DT}}^{pK^-e^+\nu_\epsilon} = 33.5 \pm 6.3$, where the uncertainty is statistical. The statistical significance of the $\Lambda_c^+ \rightarrow pK^−e^+\nu_\epsilon$ signal is determined to be $8.9 \sigma$, calculated via $\sqrt{-2 \times \Delta \ln L}$, where $\Delta \ln L$ is the variation in $\ln L$ of the likelihood fit with and without the signal component included.

To search for $\Lambda_c^+ \rightarrow \Lambda(1520)/\Lambda(1405)e^+\nu_\epsilon$, the distribution of $U_{\text{miss}}$ vs. $M_{pK^-}$ is studied, as shown in Fig. 2 (Right). An accumulation of events around the intersection of the $\Lambda(1520)/\Lambda(1405)$ and $pK^-e^+\nu_\epsilon$ signal regions is observed. To extract the yield of $\Lambda_c^+ \rightarrow \Lambda(1520)/\Lambda(1405)e^+\nu_\epsilon$, a two-dimensional (2D) likelihood fit is performed to the $M_{pK^-}$ and $U_{\text{miss}}$ distributions. The $M_{pK^-}$ and $U_{\text{miss}}$ distributions are modeled with a product of two one-dimensional probability density functions (PDFs), one for each dimension. The signal functions in the $M_{pK^-}$ distribution for $\Lambda(1520)$ and $\Lambda(1405)$ are described by a Breit-Wigner (BW) function and a Flatté-parameterization [43], respectively. The masses and widths for $\Lambda(1520)$ and $\Lambda(1405)$ are fixed to the PDG values [2]. The $M_{pK^-}$ distributions of the non-resonant (NR) components of $\Lambda_c^+ \rightarrow (pK^-)_{\text{NR}}e^+\nu_\epsilon$ and $\Lambda_c^+ \rightarrow pK^−\mu^+\nu_\mu$ are described with phase-space models, while for the components from $\Lambda_c^+ \rightarrow pK^−\pi^+\pi^0$ and the other background sources, the MC-derived shapes are used to describe the $M_{pK^-}$ distributions. The $U_{\text{miss}}$ distributions from $\Lambda_c^+ \rightarrow \Lambda(1520)e^+\nu_\epsilon$ and $\Lambda_c^+ \rightarrow (pK^-)_{\text{NR}}-\Lambda(1520)e^+\nu_\epsilon$ decays are both described by the function $f$ with parameters taken from MC simula-

number of the remaining charged tracks must be exactly three. To select protons and kaons, the same criteria as those used in the ST selection are used. The proton and kaon charges must be opposite in sign. Detection and reconstruction of the positron follow the procedures in Ref. [3]. Background from $\Lambda_c^+ \rightarrow pK^−\pi^+\pi^0$ decay reconstructed as $\Lambda_c^+ \rightarrow pK^−e^+\nu_\epsilon$ is rejected by requiring the $pK^-e^+$ invariant mass ($M_{pK^-e^+}$) to be less than 2.15 GeV/$c^2$. To suppress contamination from $\Lambda_c^+ \rightarrow pK^−\pi^+\pi^0$ decays, a search is made for an additional $\pi^0$ in the recoiling system of the $\Lambda_c^+$ baryon. If found, then a candidate $\Lambda_c^+ \rightarrow pK^−\pi^+\pi^0$ decay is reconstructed, where the positron is now assigned a pion hypothesis. For the event to be retained, it is required that the beam-constrained mass of this candidate falls outside the signal region. As the neutrino is not detected, we employ the kinematic variable $U_{\text{miss}} = E_{\text{miss}} - c|p_{\text{miss}}|$ to obtain information on the neutrino, where $E_{\text{miss}}$ and $p_{\text{miss}}$ are the missing energy and momentum carried by the neutrino, respectively, and are defined similarly as in Ref. [3].

Figure 2 (Left) shows the $U_{\text{miss}}$ distribution of the reconstructed candidates for $\Lambda_c^+ \rightarrow pK^−e^+\nu_\epsilon$ in data. To obtain the signal yield, the $U_{\text{miss}}$ distribution is described with four components: a signal function $f$ which consists of a Gaussian to describe the core of the $U_{\text{miss}}$ distribution and two power-law tails to account for initial- and final-state radiation [3, 42], two MC-derived shapes describing compo-
For the other components, the shapes obtained from MC simulation are used. The projection of the 2D fit on the $M_{pK^{-}}$ axis is shown in Fig. 3. The fitted DT yields for $\Lambda_{c}^{+} \rightarrow \Lambda (1520) e^{+} \nu_{e}$ and $\Lambda_{c}^{+} \rightarrow \Lambda (1405) e^{+} \nu_{e}$ are 8.4 ± 4.3 and 14.8 ± 6.7, respectively, where the uncertainties are statistical only. The statistical significance of $\Lambda_{c}^{+} \rightarrow \Lambda (1520) e^{+} \nu_{e}$ and $\Lambda_{c}^{+} \rightarrow \Lambda (1405) e^{+} \nu_{e}$ is determined to be 4.5σ, with respect to the hypothesis that neither of the two states is included. The hypothesis of including only one $\Lambda (1520)$ or $\Lambda (1405)$ state is also studied, and the statistical significance of either one is evaluated to be 3.8σ. It suggests that the two resonances contribute equally and neither of them can be neglected.

The averaged efficiencies for detecting the $\Lambda_{c}^{+} \rightarrow pK^{-} e^{+} \nu_{e}$, $\Lambda_{c}^{+} \rightarrow \Lambda (1520) e^{+} \nu_{e}$ and $\Lambda_{c}^{+} \rightarrow \Lambda (1405) e^{+} \nu_{e}$ decays are determined to be $\varepsilon_{pK^{-} e^{+} \nu_{e}} = 0.3101$, $\varepsilon_{\Lambda (1520) e^{+} \nu_{e}} = 0.0691$ and $\varepsilon_{\Lambda (1405) e^{+} \nu_{e}} = 0.0716$ [44], respectively. Inserting the values of their DT yields, averaged efficiencies and $N_{\text{ST}}$ into Eq. (1), results in $B(\Lambda_{c}^{+} \rightarrow pK^{-} e^{+} \nu_{e}) = (0.88 \pm 0.17 \pm 0.07) \times 10^{-3}$, $B(\Lambda_{c}^{+} \rightarrow \Lambda (1520) e^{+} \nu_{e}) = (0.99 \pm 0.51 \pm 0.10) \times 10^{-3}$ and $B(\Lambda_{c}^{+} \rightarrow \Lambda (1405) e^{+} \nu_{e}) = (1.69 \pm 0.76 \pm 0.16) \times 10^{-3}$, where the first uncertainties are statistical and the second are systematic.

The DT technique means that the measured BFs are insensitive to any systematic uncertainties in the ST selection. Sources of systematic uncertainty are, instead, related to the tracking and PID efficiencies of the $e^{+}$ (0.4% and 0.5%, respectively), $p$ (1% and 1%), and $K^{-}$ (1% and 1%), evaluated with control samples of radiative Bhabha scattering, $J/\psi \rightarrow p\overline{p} \pi^{+}\pi^{-}$ and $J/\psi \rightarrow K_{S}^{0} K^{+}\pi^{-}$, respectively. The uncertainties arising from the fit are determined by using alternative line shapes to parameterize the signal and background contributions. For $\Lambda_{c}^{+} \rightarrow pK^{-} e^{+} \nu_{e}$, the alternative fit uses the shape from MC simulation for the signal, with a constant to describe the combinatorial background, which results in an uncertainty of 3.8%. For $\Lambda_{c}^{+} \rightarrow \Lambda (1520)/\Lambda (1405) e^{+} \nu_{e}$, the masses and widths of the signal function are varied by ±1σ, and the data-driven $M_{pK^{-}}$ shape is used to describe the $\Lambda_{c}^{+} \rightarrow pK^{-} \pi^{+} \pi^{0}$ background, which results in an uncertainty of 4.6/3.9%. The uncertainties due to the knowledge of $R_{B}$ on the three BFs are estimated to be 3.6%, 1.7% and 1.7% by varying the nominal value of $R_{B}$ by ±0.05 in the fits. The uncertainty arising from the MC model of $\Lambda_{c}^{+} \rightarrow pK^{-} e^{+} \nu_{e}$ is assigned by varying the fraction of the mixed components between $\Lambda_{c}^{+} \rightarrow (pK^{-})_{\text{NR}} e^{+} \nu_{e}$ and $\Lambda_{c}^{+} \rightarrow \Lambda (1520)/\Lambda (1405) e^{+} \nu_{e}$ by ±1σ in the MC generation. In the case of $\Lambda_{c}^{+} \rightarrow \Lambda (1520)/\Lambda (1405) e^{+} \nu_{e}$, a new MC model based on leading-order heavy-quark effective theory is introduced [9]. These alternative models lead to a relative difference of 3.7% and 2.7/3.6% in the efficiencies of $\Lambda_{c}^{+} \rightarrow pK^{-} e^{+} \nu_{e}$ and $\Lambda_{c}^{+} \rightarrow \Lambda (1520)/\Lambda (1405) e^{+} \nu_{e}$, respectively, which is assigned as the corresponding uncertainty. To account for the neglect of the possible interference effects in measuring the BF of $\Lambda_{c}^{+} \rightarrow \Lambda (1520)/\Lambda (1405) e^{+} \nu_{e}$, an additional 6.1% uncertainty is assigned based on studies of the inclusive $K \pi$ system in $D$ SL decays [45, 46]. In addition the uncertainties of the quoted BF for $\Lambda (1520) \rightarrow pK^{-} e^{+} \nu_{e}$ (4.3%), requirements of $M_{B_{S}}$ (2.1%) and $M_{pK^{-}}$ (3.1%), the $\text{N}_{\text{ST}}$ (1.0%) as well as the MC sample size (1.0%) are considered. Adding these contributions in quadrature gives total systematic uncertainties of 7.8% for $B(\Lambda_{c}^{+} \rightarrow pK^{-} e^{+} \nu_{e})$, 10.4% for $B(\Lambda_{c}^{+} \rightarrow \Lambda (1520) e^{+} \nu_{e})$ and 9.4% for $B(\Lambda_{c}^{+} \rightarrow \Lambda (1405) e^{+} \nu_{e})$. When considering each of these systematic contributions in turn, the minimum signal significances for $\Lambda_{c}^{+} \rightarrow pK^{-} e^{+} \nu_{e}$, $\Lambda_{c}^{+} \rightarrow \Lambda (1520) e^{+} \nu_{e}$ and $\Lambda_{c}^{+} \rightarrow \Lambda (1405) e^{+} \nu_{e}$ are determined to be 8.2σ and 4.0σ, respectively.

In summary, using 4.5 fb$^{-1}$ of data collected at centre-of-mass energies from 4.600 GeV to 4.699 GeV, the SL decays $\Lambda_{c}^{+} \rightarrow pK^{-} e^{+} \nu_{e}$ is observed with 8.2σ significance. We also find an evidence for $\Lambda_{c}^{+} \rightarrow \Lambda (1520) e^{+} \nu_{e}$ and $\Lambda_{c}^{+} \rightarrow \Lambda (1405) e^{+} \nu_{e}$ with a significance of 4.0σ. The measured BFs are $B(\Lambda_{c}^{+} \rightarrow pK^{-} e^{+} \nu_{e}) = (0.88 \pm 0.17 \pm 0.07) \times 10^{-3}$, $B(\Lambda_{c}^{+} \rightarrow \Lambda (1520) e^{+} \nu_{e}) = (0.99 \pm 0.51 \pm 0.10) \times 10^{-3}$ and $B(\Lambda_{c}^{+} \rightarrow \Lambda (1405) e^{+} \nu_{e}) = (1.69 \pm 0.76 \pm 0.16) \times 10^{-3}$.

### Table I. Comparison of $B(\Lambda_{c}^{+} \rightarrow \Lambda (1520)/\Lambda (1405) e^{+} \nu_{e})$ [in $\times 10^{-3}$] between theoretical calculations and this measurement.

| Model                | $B(\Lambda_{c}^{+} \rightarrow \Lambda (1520) e^{+} \nu_{e})$ | $B(\Lambda_{c}^{+} \rightarrow \Lambda (1405) e^{+} \nu_{e})$ |
|----------------------|-------------------------------------------------------------|-------------------------------------------------------------|
| Constituent quark model [7] | 1.001                                                       | 1.034                                                       |
| Molecular state [8]   | --                                                          | 0.02                                                        |
| Nonrelativistic quark model [9] | 0.60                                                    | 2.43                                                        |
| Lattice QCD [11, 12]  | 0.512 ± 0.082                                               | 2.43                                                        |
| Measurement          | 0.99 ± 0.51 ± 0.10                                          | 1.69 ± 0.76 ± 0.10                                          |
which hints that the $\Lambda(1405)$ is not a pure meson-baryon molecular state, based on calculations in Refs. [7–9]. In addition, the measured $B(\Lambda^+_c \to \Lambda(1520)e^+\nu_e)$ is consistent with LQCD calculation [11, 12] within one standard deviation. The validation of the predicted $B(\Lambda^+_c \to \Lambda(1520)e^+\nu_e)$ from LQCD can provide useful information in extending the LQCD calculations on $\Lambda_b \to \Lambda(1520)\ell^+\ell^-$ [12, 29] and $\Lambda_b \to \Lambda_c(2595)/\Lambda_c(2625)\ell^+\bar{\nu}$ [12, 30] to the high-recoil region [47, 48]. This will be crucial for future LHCb analysis of $\Lambda_b \to \Lambda(1520)\ell^+\ell^-$ decays [49, 50]. The measured BF of $\Lambda^+_c \to \Lambda(1405)e^+\nu_e$ will provide important data in intriguing the extension of the LQCD calculations on baryonic SL decays involving $\Lambda(1405)$ state, which will be valuable in understanding the nature of $\Lambda(1405)$.

Combing the BF of $\Lambda^+_c \to \Lambda(1520)e^+\nu_e$ measured in this work, $\tau_{\Lambda_c}$, and the $q^2$-integrated rate predicted by LQCD [11, 12], we determine $|V_{c}\bar{\Lambda}| = 1.3 \pm 0.3_{\text{stat}} \pm 0.1_{\text{LQCD}}$, which is in consistency with $|V_{c}\bar{\Lambda}| = 0.97401(11)$ obtained from CKM unitarity [2] within one standard deviation. This is the first determination of $|V_{c}\bar{\Lambda}|$ using data of baryonic SL decays into excited $\Lambda$ state. Our results presented in this Letter are valuable in extending the understanding of $\Lambda^+_c$ SL decays beyond the mode $\Lambda^+_c \to \Lambda\ell^+\nu$, and represent a significant advance in knowledge since the discovery of the $\Lambda^+_c$ more than 40 years ago. The observation of $\Lambda^+_c \to pK^-e^+\nu_e$ is that of the first $\Lambda_c$ decay mode that does not contain a $\Lambda$ baryon in the final state [7, 10]. In addition, the observed $pK^-$ invariant-mass spectrum in this work can provide new insights into internal structure of excited $\Lambda$ states as well as in the study of hyperon spectroscopy [8, 13, 16, 51, 52], complementary with that measured in the pentaquark searches using $\Lambda_b \to pK^-J/\psi$ [43]. With the larger samples that BESIII expects to collect [53], an amplitude analysis of the $pK^-$ mass spectrum will be performed to understand the internal structure of the contributing $\Lambda^*$ states.

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### Table II

| $\Lambda_c^+ \rightarrow$ | $\Delta E$ (GeV) | $N_{ST}^{\text{min}}$ | $N_{ST}^{\text{max}}$ | $N_{ST}^{\text{mean}}$ | $N_{ST}^{\text{stdev}}$ | $N_{ST}^{\text{max2}}$ | $N_{ST}^{\text{stdev2}}$ | $N_{ST}^{\text{max3}}$ |
|--------------------------|------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
| $\bar{p}K^+ \pi^-$      | $[-0.031, 0.033]$| 1144 ± 38              | 230 ± 17               | 837 ± 34               | 948 ± 35               | 922 ± 34               | 2816 ± 59              | 791 ± 31               |
| $\bar{p}K^+ \pi^- \pi^0$| $[-0.030, 0.039]$| 6692 ± 90              | 1123 ± 37              | 5174 ± 81              | 5935 ± 86              | 5572 ± 82              | 16512 ± 139            | 4834 ± 75              |
| $\bar{p}K^0 \pi^+ \pi^-$| $[-0.049, 0.052]$| 622 ± 42               | 103 ± 15               | 545 ± 40               | 550 ± 41               | 568 ± 40               | 1649 ± 62              | 411 ± 34               |
| $\bar{p}K^0 \pi^+ \pi^- \pi^0$| $[-0.048, 0.049]$| 729 ± 41               | 145 ± 18               | 566 ± 36               | 644 ± 40               | 585 ± 38               | 1738 ± 66              | 555 ± 38               |
| $\bar{p}K^+ \pi^- \pi^- \pi^0$| $[-0.043, 0.051]$| 1598 ± 62              | 275 ± 24               | 1163 ± 54              | 1319 ± 62              | 1295 ± 55              | 3943 ± 97              | 1077 ± 50              |
| $\Lambda \pi^-$         | $[-0.031, 0.034]$| 878 ± 30               | 143 ± 12               | 712 ± 30               | 792 ± 29               | 730 ± 29               | 2254 ± 50              | 580 ± 26               |
| $\Lambda \pi^- \pi^0$   | $[-0.044, 0.057]$| 1803 ± 56              | 279 ± 22               | 1339 ± 48              | 1600 ± 52              | 1443 ± 49              | 4211 ± 85              | 1258 ± 47              |
| $\Lambda \pi^- \pi^+ \pi^-$| $[-0.043, 0.045]$| 1023 ± 44              | 199 ± 18               | 737 ± 39               | 960 ± 44               | 935 ± 43               | 2599 ± 77              | 710 ± 39               |
| $\Sigma^0 \pi^-$        | $[-0.032, 0.040]$| 577 ± 28               | 105 ± 11               | 424 ± 24               | 467 ± 25               | 503 ± 24               | 1423 ± 41              | 384 ± 21               |
| $\Sigma^- \pi^0$        | $[-0.050, 0.060]$| 310 ± 25               | 70 ± 11                | 264 ± 23               | 282 ± 26               | 314 ± 26               | 827 ± 42               | 222 ± 23               |
| $\Sigma^- \pi^+ \pi^-$  | $[-0.043, 0.052]$| 1234 ± 62              | 224 ± 24               | 942 ± 51               | 1069 ± 64              | 938 ± 53               | 2941 ± 96              | 858 ± 54               |
| $\Omega^- \pi^- \pi^-$  | $[-0.040, 0.040]$| 603 ± 48               | 128 ± 21               | 454 ± 45               | 490 ± 48               | 528 ± 49               | 1553 ± 86              | 443 ± 50               |
| $\Xi^0 \pi^- \pi^- \pi^-$| $[-0.030, 0.030]$| 224 ± 18               | 34 ± 10                | 150 ± 22               | 185 ± 24               | 144 ± 23               | 420 ± 40               | 133 ± 25               |
| $\Xi^0 \pi^- \pi^- \pi^-$| $[-0.030, 0.032]$| 541 ± 36               | 102 ± 15               | 392 ± 30               | 470 ± 32               | 418 ± 31               | 1246 ± 53              | 437 ± 30               |

Figures 4, 5 and 6 show the $M_{BC}$ distributions obtained at $\sqrt{s} = 4.600$ GeV and $4.612$ GeV, respectively. The ST yields for each of the ST modes collected at different energy points are given in Table II.

**Fig. 4.** Fits to $M_{BC}$ distributions for different ST modes at (left) $\sqrt{s} = 4.600$ GeV and (right) $\sqrt{s} = 4.612$ GeV. The points with error bars are data, the (red) solid curves show the total fits and the (blue) dashed curves are the background shapes.
FIG. 5. Fits to $M_{BC}$ distributions for different ST modes at (left) $\sqrt{s} = 4.628$ GeV and (right) $\sqrt{s} = 4.641$ GeV. The points with error bars are data, the (red) solid curves show the total fits and the (blue) dashed curves are the background shapes.

FIG. 6. Fits to $M_{BC}$ distributions for different ST modes at (left) $\sqrt{s} = 4.661$ GeV and (right) $\sqrt{s} = 4.699$ GeV. The points with error bars are data, the (red) solid curves show the total fits and the (blue) dashed curves are the background shapes.