Search for baryon and lepton number violation in $J/\psi \to \Lambda_c^+ e^- + \mathrm{c.c.}$

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Using 1.31×10^9 J/ψ events collected by the BESIII detector at the Beijing Electron Positron Collider, we search for the process $J/\psi \to \Lambda_c^+ e^- + \text{c.c.}$ for the first time. In this process, both baryon and lepton number conservation is violated. No signal is found and the upper limit on the branching fraction $\mathcal{B}(J/\psi \to \Lambda_c^+ e^- + \text{c.c.})$ is set to be 6.9×10^{-8} at the 90% confidence level.

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I. INTRODUCTION

The observed matter–antimatter asymmetry in the universe composes a serious challenge to our understanding of nature. The big bang theory, the prevailing cosmological model for the evolution of the universe, predicts exactly equal numbers of baryons and antibaryons in the dawn epoch. However, the observed baryon number (BN) exceeds the number of antibaryons by a very large ratio, currently estimated at 10^9–10^{10} [1]. To give a reasonable interpretation of the baryon-antibaryon asymmetry, Sakharov proposed three principles [2], the first of which is that BN conservation must be violated. Many proposals predict BN violation within the extended Standard Model (SM) and beyond. Among them, proposals that evoke the spontaneous breaking of a large gauge group are especially appealing. In these models, several heavy gauge bosons emerge whose couplings to matter explicitly violate both baryon and lepton number conservation simultaneously. Although some of the theories, e.g., the SU(5) grand unification theory (GUT) [3], are excluded by the proton decay experiment [4], this does not rule out the need to search for GUTs that allow for BN violation. For example, the SO(10), the E6 and the flipped SU(5) models all predict a longer proton lifetime that is not in conflict with the present data.

Searches for physics beyond the SM ("new physics") with collider experiments are complementary to searches with specifically designed precision detection experiments. For example, the existence of dark matter is strongly suggested by cosmological observations [5], and searches for particle candidates of the dark sector are carried out both at e^+e^- [6] and pp [7] collider experiments and in dedicated direct detection experiments [8]. Similarly, searches for Majorana neutrinos at flavor factory [9] and high energy frontier [10] supplement the neutrino-less double beta decay experiments [11]. The two independent ways of searching for new physics are fruitfully supporting each other. Therefore, although there are some searches for BN violation processes in charm or bottom baryons decay [12] at the collider experiments, which might provide different and complementary information from the proton decay experiments [13], searching for the processes in quarkonium decay opens a new avenue to study the BN violation.

In any case, the matter–antimatter asymmetry in the universe is an observable fact. The absence so far of an

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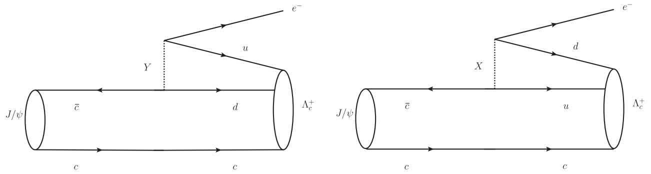

FIG. 1. Decay diagrams for $J/\psi \to \Lambda_c^+ e^-$, where X and Y are leptoquarks, which carry color charge, fractional electric charge, and both lepton and baryon quantum numbers [14].

experimental observation of proton decay, which is predicted by GUT, does not imply by any means that BN is absolutely conserved. Therefore, an alternative approach to test the GUT scheme at collider experiments has been devised. The CLEO Collaboration searched for very rare processes which violate BN conservation in decays of heavy-flavor mesons. In particular, they suggested to look for the process $D^0 \to \bar{p}e^+$, whose branching fraction upper limit is set at 10^{-5} at 90% confidence level (CL). Based on the huge data sample of 1.3106×10^9 J/ψ decays produced at the BESIII experiment, we are able to study the analogous process $J/\psi \to \Lambda_c^+ e^-$, as shown in Fig. 1, and expect the first constraint of BN violation from charmonium decay.

In this paper, we analyze the J/ψ data sample collected with the BESIII [15] detector operating at the BEPCII storage ring [16] to search for the SM forbidden baryon-lepton number violating decay $J/\psi \to \Lambda_c^+ e^-$ (charge conjugation is implied throughout this paper). Based on this analysis, we set an upper bound on the rate of $J/\psi \to \Lambda_c^+ e^-$.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector has a geometric acceptance covering 93% of the 4π solid angle and consists of the following main components. (1) A small-celled main drift chamber (MDC) with 43 layers is used to track charged particles. The average single-wire resolution is 135 μm, the momentum resolution for 1 GeV$/c$ charged particles in a 1 T magnetic field is 0.5%, and the specific energy loss (dE/dx) resolution is better than 6%. (2) An electromagnetic calorimeter (EMC) is used to measure photon energies. The EMC is made of 6240 CsI(Tl) crystals arranged in a cylindrical shape (barrel) plus two endcaps. For 1.0 GeV photons, the energy resolution is 2.5% in the barrel and 5% in the endcaps, and the position resolution is 6 mm for the barrel and 9 mm for the endcaps. (3) A time-of-flight (TOF) system is used for particle identification (PID). It is composed of a barrel made of two layers, each consisting of 88 pieces of 5 cm thick and 2.4 m long plastic scintillators, as well as two endcaps each with 96 fan-shaped 5 cm thick plastic scintillators. The time resolution is 80 ps in the barrel and 110 ps in the endcaps, providing a K/π separation of more than 2σ for momenta up to about 1.0 GeV$/c$. (4) A muon chamber system for muon detection is made of resistive plate chambers arranged in 9 layers in the barrel and 8 layers in the endcaps and is incorporated into the return iron yoke of the superconducting magnet.

Optimization of the event selection criteria and estimation of physics backgrounds are performed through Monte Carlo (MC) simulations of background and signal samples. The GEANT4-based [17] simulation software BOOST [18] includes the geometric and material description of the BESIII detector, the detector response and digitization models, and also keeps track of the detector running conditions and performance. The analysis is performed in the framework of the BESIII Offline Software System (BOSS) [19] which takes care of the detector calibration, event reconstruction and data storage. Inclusive MC events of J/ψ decays are generated by the KKMC [20] generator around $\sqrt{s} = 3.097$ GeV, in which the beam energy and spread are set to the values measured at BEPCII, and initial state radiation (ISR) is considered. The known J/ψ decays are generated by BesEvtGen [21,22] with branching fractions set to the world average values according to the Particle Data Group (PDG) [23], and the remaining unknown decays are modeled by Lundcharm [21].

III. DATA ANALYSIS

We search for the decay $J/\psi \to \Lambda_c^+ e^-$, where the Λ_c^+ is reconstructed through the decay $\Lambda_c^+ \to pK^-\pi^+$. In each event, at least four charged tracks are required. All charged tracks are required to satisfy a geometrical acceptance of $|\cos\theta| < 0.93$, where θ is the polar angle of the charged track. Each track must originate from the interaction region, defined as $R_{xy} < 1.0$ cm and $|R_z| < 10.0$ cm, where R_{xy} and R_z are the distances of the closest approach to the interaction point of the track in the xy-plane and z-direction, respectively. Events with exactly four selected charged tracks with zero net charge are retained for further analysis.

For charged particle identification, we use a combination of the energy loss dE/dx in the MDC, time of flight in the TOF, and the energy and shape of clusters in the EMC to calculate the CL for the electron, pion, kaon, and proton hypotheses (CL_e, CL_π, CL_K and CL_p). The electron and positron candidates are required to satisfy $CL_e > 0.001$ and $CL_e/(CL_e + CL_K + LC_\pi) > 0.8$. Other charged tracks will be considered a pion, kaon or proton, according to the highest CL of the corresponding hypothesis.

In order to improve the mass resolution, a kinematic fit enforcing energy-momentum conservation is performed. To suppress contamination from other decay modes with four charged tracks, six different combinations of mass assignments are considered: $pK^-\pi^+e^-$, $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-K^+K^-$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-p\bar{p}$ and $K^+K^-p\bar{p}$. If the kinematic fit procedure for the $pK^-\pi^+e^-$ mass assignment is successful and the goodness of fit for this hypothesis is the best among these six assignments, then the event is accepted for further analysis.

Based on a fit to the simulated $M_{pK\pi}$ spectrum, with a double Gaussian function and a Chebychev polynomial to model the signal and background shape, respectively, the Λ_c^+ signal window is defined to be $(2.27, 2.30)$ GeV$/c^2$ in the $pK^-\pi^+$ invariant mass distribution. This corresponds to a range of ± 4 times the mass resolution around the Λ_c^+ nominal mass. The detection efficiency is determined to be $(35.43 \pm 0.02)\%$ based on simulated $J/\psi \to \Lambda_c^+ e^- \to pK^-\pi^+ e^-$ events, where the Λ_c^+ decay is modeled by a dedicated generator according to the result of a partial wave analysis of the decay $\Lambda_c^+ \to pK^-\pi^+$ [24]. Besides the nonresonant 3-body decay process, processes with intermediate states (such as Δ^{++}, $\Delta(1600)^{++}$, excited Λ states, excited Σ states), as well as the corresponding interferences, are also included in the helicity amplitudes. Parity conservation is not required since this is a weak decay. The data and MC simulation for the decay $\Lambda_c^+ \to pK^-\pi^+$ are compared and found to be in good agreement, based on 567 pb^{-1} of experimental data taken at $\sqrt{s} = 4.599$ GeV, just above the threshold for Λ_c pair production [24]. This consistency leads to a negligible systematic uncertainty due to the generator.

The background from J/ψ decays is investigated using an inclusive MC sample which has the same size as the J/ψ data sample. No background events are found in the signal window. The background from QED processes is studied with other simulated MC samples of $e^+e^- \to q\bar{q}$, $e^+e^- \to (\gamma)e^+e^-$ and $e^+e^- \to (\gamma)\mu^+\mu^-$ which correspond to 40, 1.5 and 30 times the J/ψ data, respectively. Most of these backgrounds are rejected by the PID requirements and the kinematic fit. The normalized number of surviving background events is 0.03, which is from wrong PID in the process $e^+e^- \to K^+K^-\pi^+\pi^-$. The background from QED processes is also verified by using experimental data samples taken away from the J/ψ and $\psi(3686)$ mass regions, including data taken at 3.08 GeV, 3.65 GeV, and scan data sets covering the energy range from 2.23 to 4.59 GeV. No events are found in the signal window after taking into account the differences in the integrated luminosities, the cross sections, the particle momenta, and the beam energies [25].

The candidate events of $J/\psi \to \Lambda_c^+ e^-$ are studied by examining the invariant mass of the $pK^-\pi^+$ system, $M_{pK^-\pi^+}$, as shown in Fig. 2.

IV. RESULT

Since no events are observed in the signal window, the upper limit on the number of signal events s_{90} for $J/\psi \to \Lambda_c^+ e^-$ is estimated to be 5.7 at the 90% CL by utilizing a frequentist method [26] with unbounded profile likelihood treatment of systematic uncertainties, where the number of the signal and background events are assumed to follow a Poisson distribution, the detection efficiency is assumed to follow a Gaussian distribution, and the systematic uncertainty, which will be discussed below, is considered as the standard deviation of the efficiency. The upper limit on the branching fraction of $J/\psi \to \Lambda_c^+ e^-$ is determined by

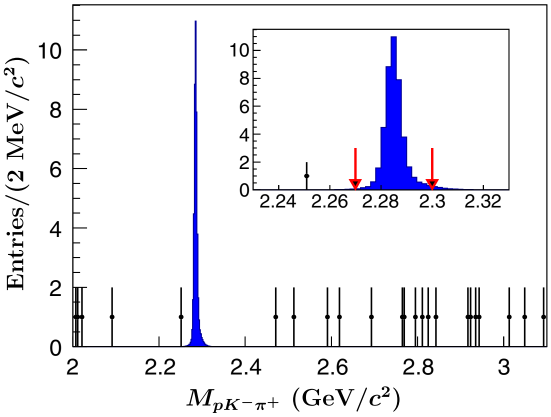

FIG. 2. Distributions of $M_{pK^-\pi^+}$ for the $J/\psi \to \Lambda_c^+ e^-$ candidate events for signal MC simulation (shaded histogram) and data (dots with error bars), where the signal MC sample is normalized arbitrarily. The inset plot shows a narrow mass range within $(2.23, 2.33)$ GeV$/c^2$, where the arrows represent the signal mass window.

$$\mathcal{B}(J/\psi \to \Lambda_c^+ e^-) < \frac{s_{90}}{N_{J/\psi}^{\mathrm{tot}} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)},$$

where $N_{J/\psi}^{\mathrm{tot}} = (1310.6 \pm 7.0) \times 10^6$ is the total number of J/ψ decays [27], and $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.35 \pm 0.33)\%$ is the decay branching fraction taken from Ref. [12]. Inserting the numbers of s_{90}, $N_{J/\psi}^{\mathrm{tot}}$ and $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ into the above equation, the upper limit on the branching fraction of $J/\psi \to \Lambda_c^+ e^-$ is determined to be

$$\mathcal{B}(J/\psi \to \Lambda_c^+ e^-) < 6.9 \times 10^{-8}.$$

V. SYSTEMATIC UNCERTAINTY

Systematic uncertainties in the measurement of $\mathcal{B}(J/\psi \to \Lambda_c^+ e^-)$ mainly originate from the total number of J/ψ events, the tracking efficiency, the PID efficiency, the kinematic fit, the MC modeling, and the quoted branching fraction for $\Lambda_c^+ \to pK^-\pi^+$. The uncertainty in the total number of J/ψ, determined via inclusive hadronic events, is 0.5% [27]. The uncertainty due to tracking efficiency is 1.0% for each track, as determined from a study of the control samples $J/\psi \to pK^-\bar{\Lambda}$ and $\psi(3686) \to \pi^+\pi^- J/\psi$ [28]. The uncertainties arising from the differences of PID efficiencies between data and MC simulation for electron, pion, kaon, and proton are determined with the control samples $e^+e^- \to \gamma e^+e^-$ (at 3.097 GeV), $J/\psi \to K^+K^-\pi^0$, $J/\psi \to \pi^+\pi^-\pi^0$ and $J/\psi \to \pi^+\pi^- p\bar{p}$, respectively. They are 0.3%, 1.0%, 0.5% and 0.6% for electron, pion, kaon and proton, respectively. The uncertainty of the kinematic fit is estimated using a control sample of $J/\psi \to \pi^+\pi^- p\bar{p}$, where a selection efficiency is defined by counting the number of events with and without the kinematic fit requirement. The difference of the selection efficiencies between data and MC simulation, 0.2%, is assigned as the corresponding systematic uncertainty. The uncertainty due to MC modeling is negligible [24]. In the calculation of the upper limit, the branching fraction $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.35 \pm 0.33)\%$ is quoted from Ref. [12], yielding a systematic uncertainty of 5.2%. The total systematic uncertainty is 7.0%, obtained by adding all of the above uncertainties in quadrature.

VI. SUMMARY

In summary, by analyzing 1.3106×10^9 J/ψ events collected at $\sqrt{s} = 3.097$ GeV with the BESIII detector at the BEPCII collider, the decay of $J/\psi \to \Lambda_c^+ e^- + \text{c.c.}$ has been investigated for the first time. No signal events have been observed and thus the upper limit on the branching fraction is set to be 6.9×10^{-8} at the 90% CL, which is more than two orders of magnitude more strict than that of CLEO's measurement in the analogous process [29]. The result is one of the best constraints from meson decays [30,31] and is consistent with the conclusion drawn from the proton decay experiment [13].

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