

Search for the baryon and lepton number violating decay $J/\psi \rightarrow pe^- + \text{c.c.}$

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Based on $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events collected by the BESIII detector operating at the BEPCII storage ring, we perform a search for the baryon- and lepton-number violating decay $J/\psi \rightarrow pe^- + \text{c.c.}$ via $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$. No significant signal is found. An upper limit on the branching fraction of $\mathcal{B}(J/\psi \rightarrow pe^- + \text{c.c.})$ is found to be 3.1×10^{-8} at 90% confidence level.

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I. INTRODUCTION

In the Standard Model, baryon number (BN) is strictly conserved. However, theoretical possibilities for baryon number violation (BNV) remain, despite the lack of experimental evidence. [1–3]. Unlike the stability of the electron, which is ensured by its status as the lightest charged particle, proton stability is tied to BN conservation, a symmetry that is not fundamental. If BN conservation is slightly broken, as suggested by various models [4–9], it could dramatically alter our understanding of the universe. BNV is crucial for explaining the current baryon-antibaryon asymmetry in the universe that began symmetrically from the big bang and is hence key to modern cosmology. Even a slight BNV would significantly impact the ultimate fate of the Universe.

Theoretical models suggest that BN might not be strictly conserved in nature. For instance, in grand unified theory (GUT), the proton could decay into various final states via intermediate particles like leptoquarks [1]. This could lead to BNV processes, such as $p \rightarrow e^+\pi^0$, which would break both baryon and lepton numbers while conserving their difference, $B - L$. Thus far, experimental constraints on proton decay have largely ruled out the simplest GUT models. Therefore, it is essential to explore other hadrons containing second-generation quarks, such as Λ_c and Ξ , in both theory and experiment. Several dimension-six operators lead to BNV processes [1,2,10]. Such operators could arise in models with R-parity-violating supersymmetric extensions of the Standard Model [11] or from heavy gauge bosons like leptoquarks. At BESIII, several BNV processes have been investigated [12], including $J/\psi \rightarrow \Lambda_c^+ e^-$ [13],

$\Lambda - \bar{\Lambda}$ oscillation [14], and various D decay channels [15–18]. No significant signal was found, and upper limits on the branching fractions were reported.

In this paper, we analyze $(2712.4 \pm 14.3) \times 10^6$ [19] $\psi(3686)$ events collected at $\sqrt{s} = 3.686$ GeV/ c^2 by the BESIII detector [20] at the BEPCII e^+e^- storage ring [21] during 2009, 2012, and 2021, and search for the baryon- and lepton-number violating decay $J/\psi \rightarrow pe^-$ (charge conjugation is implied throughout this paper) through the process $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector is located at the south collision point of the BEPCII storage ring, which operates at center-of-mass energies between 1.85 and 4.95 GeV/ c^2 , with a maximum luminosity 1.1×10^{33} cm⁻² s⁻¹.

The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), all enclosed in a superconducting solenoidal magnet that provides a 1.0 T magnetic field (The magnetic field intensity in the year 2012 was 0.9 T). The solenoid is supported by an octagonal flux-return yoke, with resistive plate counter muon identifier modules interleaved with steel.

The charged-particle momentum resolution at 1 GeV/ c is 0.5%, and the specific ionization energy loss (dE/dx) resolution is 6% for electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region. The time resolution in the TOF barrel region is 68 ps, while in the end cap region, it is 110 ps. The end cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps [22]. About 87% of the data used in this analysis benefit from the upgrade.

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Simulated samples produced with the Geant4-based [23] Monte Carlo (MC) program, which includes the geometric description [24,25] of the BESIII detector and the detector response, are used to determine the detection efficiency and estimate the background. The simulation incorporates the beam energy spread and initial state radiation in the e^+e^- annihilations modeled with the generator KKMC [26]. The known decay modes are modeled with EvtGen [27] using branching fractions taken from the Particle Data Group [3] and the remaining unknown decays from the charmonium states with Lundcharm [28]. Final state radiation from charged final-state particles is incorporated with Photos [29]. To study the detection efficiencies of the BNV decay, one million signal MC events are generated. For this analysis, 2748 million inclusive MC events including all the possible decays of the $\psi(3686)$ are used to study the background. The continuum background is estimated with the data samples at $\sqrt{s} = 3.650$ GeV and 3.682 GeV, corresponding to integrated luminosities of 410 pb $^{-1}$ and 404 pb $^{-1}$, respectively.

III. DATA ANALYSIS

To avoid possible bias, a blind analysis technique is employed, where the data is analyzed only after the analysis procedure has been finalized and validated with MC simulation. The signal channel is $J/\psi \rightarrow pe^-$, via $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$. All tracks must satisfy $|\cos\theta| < 0.93$, where θ is defined with respect to the symmetry axis of the MDC, referred to as the z -axis. 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 at least four selected charged tracks and zero net charge are retained for further analysis.

Charged tracks with momentum less than 0.45 GeV/ c are assigned as pions. This strategy has been studied in detail in an identical channel $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$ in Ref. [30]. For particle identification (PID) of electrons and protons, the dE/dx , TOF, and EMC information are combined to calculate the confidence levels (CL) for electron, pion, kaon, and proton hypotheses: CL_e , CL_π , CL_K , and CL_p . The electron candidates are required to satisfy $CL_e > 0.001$, $CL_e/(CL_e + CL_K + CL_\pi) > 0.8$ and $0.8 < E/p < 1.2$, where E is the energy deposited by the electron in the EMC, and p is the momentum in the MDC. The proton candidates are required to satisfy $CL_p > 0.001$, $CL_p > CL_K$, $CL_p > CL_\pi$, and $CL_p > CL_e$.

In order to improve the mass resolution, a kinematic fit [31] enforcing four-momentum conservation (4C) for four charged tracks is performed on the selected $\pi^+\pi^-pe^-$ combination. If there are multiple combinations, only the one with minimum $\chi^2_{\pi^+\pi^-pe^-,4C}$ is retained. To suppress potential backgrounds, events with $\chi^2_{\pi^+\pi^-pe^-,4C} < 10$ are

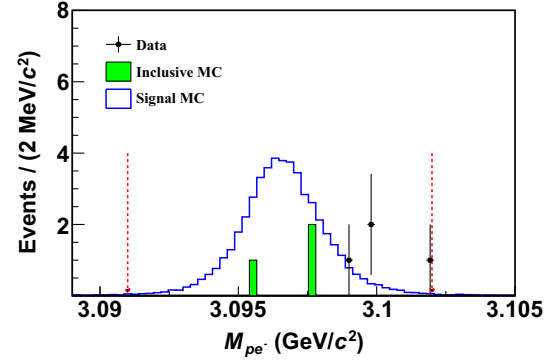


FIG. 1. The M_{pe^-} distribution shows data points with error bars, the background as a green histogram, the signal MC as a blue histogram, and the signal region is marked by red dashed arrows.

kept for further analysis. MC studies show that this requirement can veto 94% of the background while preserving 50% of the signal events. This requirement has been optimized using the Punzi significance method [32] with the formula $\varepsilon/(1.5 + \sqrt{b})$, where ε is the detection efficiency from the signal MC simulation and b is the number of background events from the inclusive MC sample.

To suppress residual background from processes with four tracks due to particle misidentification, such as $e^+e^- \rightarrow \pi^+\pi^-e^+e^-$, $\pi^+\pi^-\mu^+\mu^-$, $\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-K^+K^-$ or $\pi^+\pi^-p\bar{p}$ processes, we reassign the masses of the third and fourth tracks in the $\pi^+\pi^-pe^-$ candidate according to the above hypotheses and perform the 4C kinematic fit again. To suppress these backgrounds, the χ^2_{4C} of each hypothesis is required to be larger than $\chi^2_{\pi^+\pi^-pe^-,4C}$. After the above selection, the number of estimated background events based on the generic $\psi(3686)$ inclusive MC sample is found to be $N^{\text{inc}} = 3$, as shown in Fig. 1. These remaining events consist of two $\psi(3686) \rightarrow \pi^+\pi^-J/\psi, J/\psi \rightarrow e^+e^-\gamma^f\gamma^f$ processes and one $\psi(3686) \rightarrow \pi^+\pi^-J/\psi, J/\psi \rightarrow e^+e^-\gamma^f$ process, where an f superscript denotes final-state radiation. Additionally, the continuum background, $N_{\text{bkg}}^{\text{cont}}$, is estimated by analyzing data samples collected at $\sqrt{s} = 3.650$ and 3.682 GeV [33]. Using the same analytical procedure, no events were found within the J/ψ signal window after normalization, accounting for differences in integrated luminosities and the energy-dependent cross sections as follows [34],

$$N_{\text{bkg}}^{\text{cont}} = N_{\text{cont}} \frac{\mathcal{L}_{3.686}}{\mathcal{L}_{\text{cont}}} \left(\frac{E_{\text{cont}}}{3.686} \right)^2, \quad (1)$$

where N_{cont} represents the number of background events from the continuum process, $\mathcal{L}_{\text{cont}}$ and $\mathcal{L}_{3.686}$ are the integrated luminosities for continuum and $\psi(3686)$ data, respectively, and E_{cont} is the center-of-mass energy for the continuum. The number of continuum background events

is estimated to be $N_{\text{bkg}}^{\text{cont}} = 0$ as $N_{\text{cont}} = 0$. Combining contributions, the total background yield is estimated to be $N^{\text{bkg}} = N^{\text{inc}} + N_{\text{bkg}}^{\text{cont}} = 3$. Based on the fit to the distribution of the pe^- invariant mass, M_{pe^-} , from the signal MC simulation, using a double Gaussian function and a first-order polynomial to model the signal and background shapes, respectively, the J/ψ signal window in M_{pe^-} is set as $[3.091, 3.102]$ GeV/ c^2 , corresponding to three standard deviations. The detection efficiency is determined to be $(19.94 \pm 0.07)\%$ based on simulated $\psi(3686) \rightarrow \pi^+\pi^-J/\psi, J/\psi \rightarrow pe^-$ events, where $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$ is generated according to the results in Ref. [35], which takes into account the small dipion D-wave contribution in addition to the dominant S-wave component.

IV. SYSTEMATIC UNCERTAINTY

Systematic uncertainties in the measurement of the branching fraction can be classified into additive and multiplicative categories. The uncertainty due to the choice of signal window is considered additive, while the sources of multiplicative uncertainties, that are combined in quadrature, include the total number of $\psi(3686)$ events, the MDC tracking and PID efficiencies, the 4C kinematic fit, MC signal modeling, and the branching fraction for $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$. The uncertainty in the total number of $\psi(3686)$ events, determined from inclusive hadronic final states, is 0.5% [19]. The uncertainty in tracking charged particles is assigned as the tracking efficiency difference between data and MC simulation, evaluated using control samples of $J/\psi \rightarrow \pi^+\pi^-\pi^0, J/\psi \rightarrow e^+e^-(\gamma^f)$, and $J/\psi \rightarrow \pi^+\pi^-p\bar{p}$. The uncertainties are assigned as 1.0% per pion, 1.0% per electron, and 1.0% per proton [18,36]. Consequently, the total systematic uncertainty in MDC tracking is 4.0%. The uncertainties in PID efficiencies are estimated using high-purity control samples of electrons and protons. The resulting uncertainties are 1.1% per electron and 2.8% per proton [18,36]. No PID is required for the pions, so the total systematic uncertainty in PID efficiency, conservatively allowing for full correlation, is 3.9%. The systematic uncertainty in 4C kinematic fit is assessed by comparing the efficiency differences before (nominal analysis) and after a tracking helix correction [37]. The relative difference in efficiencies, measured as 9.0%, is taken as the uncertainty. The uncertainty in the MC modeling arises from variations in the parameters of angular distribution, described by the formula $\frac{dN}{d\cos\theta} \propto 1 + \alpha \cos^2\theta$, where θ is the polar angle between the beam direction and the outgoing baryon. In this work, the $J/\psi \rightarrow pe^-$ process is generated with $\alpha = 0$, resulting in a flat angular distribution. To account for the systematic uncertainty due to MC modeling, alternative signal MC events are generated with α values set to be 0.68 and 1.0, respectively. The resulting standard deviation of efficiency, 0.8%, is taken as the uncertainty.

TABLE I. Multiplicative systematic uncertainties in the branching fraction measurements.

Source	Uncertainty (%)
$N_{\psi(3686)}^{\text{tot}}$	0.5
Tracking	4.0
PID	3.9
4C kinematic fit	9.0
MC modeling	0.8
$\mathcal{B}(\psi(3686) \rightarrow \pi^+\pi^-J/\psi)$	1.0
Total	10.7

The uncertainty in the quoted branching fraction $\mathcal{B}(\psi(3686) \rightarrow \pi^+\pi^-J/\psi) = (34.69 \pm 0.34)\%$ is 1.0% [3]. All multiplicative systematic uncertainties discussed above are summarized in Table I. By combining all sources in quadrature, the total systematic uncertainty is determined to be 10.7%.

The uncertainty in the signal window is estimated using various ranges, from $\mu \pm 1\sigma$ to $\mu \pm 5\sigma$. Among these variations, the largest upper limit on the branching fraction of $J/\psi \rightarrow pe^-$ is chosen as our final result. The resulting efficiency-corrected upper limit on the yield is $N^{\text{up}} = 29.7$, obtained using a frequentist method [38]. This estimation employs an unbounded profile likelihood approach to account for systematic uncertainties, with both signal and background events modeled by a Poisson distribution. The detection efficiency is assumed to follow a Gaussian distribution, with the systematic uncertainty treated as the standard deviation of the efficiency. Consequently, the upper limit of $\mathcal{B}(J/\psi \rightarrow pe^-)$ at 90% CL is determined by

$$\mathcal{B}(J/\psi \rightarrow pe^-) < \frac{N^{\text{up}}}{\mathcal{B}_{\psi} N_{\psi(3686)}^{\text{tot}}} = 3.1 \times 10^{-8}, \quad (2)$$

where $N_{\psi(3686)}^{\text{tot}} = 2712.4 \times 10^6$ is the total number of $\psi(3686)$ events, and $\mathcal{B}_{\psi} = \mathcal{B}(\psi(3686) \rightarrow \pi^+\pi^-J/\psi) = 34.69\%$ is the branching fraction for the decay $\psi(3686) \rightarrow \pi^+\pi^-J/\psi$.

V. RESULT

As shown in Fig. 1, the number of observed events in the data is $N_{\text{obs}} = 4$ which is consistent with the estimated background yield of $N_{\text{bkg}} = 3$. Therefore, the upper limit on the number of signal events for $J/\psi \rightarrow pe^-$ at the 90% CL, N^{up} is estimated to be 29.7. Based on Eq. (2), the upper limit on the branching fraction of $J/\psi \rightarrow pe^-$ is calculated to be 3.1×10^{-8} at 90% CL.

VI. SUMMARY

Using $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events collected by the BESIII detector at the BEPCII collider, we search for

the baryon- and lepton-number violating decay $J/\psi \rightarrow pe^- + \text{c.c.}$ for the first time. The number of observed events is consistent with the estimated background level. No obvious signals have been observed. The upper limit on the branching fraction of $J/\psi \rightarrow pe^- + \text{c.c.}$ is found to be 3.1×10^{-8} at 90% CL, which provides stronger experimental constraints compared to similar scenarios, such as $D^0 \rightarrow \bar{p}e^+ + \text{c.c.}$ [18] and $J/\psi \rightarrow \Lambda_c^+ e^- + \text{c.c.}$ [13]. Our result can stimulate possible new BNV models concerning second generation quarks. This result is expected to be improved by a factor of a thousand at the next-generation super τ -charm factory [39].

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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