Search for the lepton number violating process $J/\psi \to K^+K^+e^-e^- + c.c.$*

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Abstract: Based on $(10087\pm44)\times10^6$ J/ψ events collected with the BESIII detector, we search for the lepton number violating decay $J/\psi\to K^+K^+e^-e^-+c.c.$ for the first time. The upper limit on the branching fraction of this decay is set to 2.1×10^{-9} at the 90% confidence level with a frequentist method. This is the first search for J/ψ decays with a lepton number change by two, offering valuable insights into the underlying physical processes.

Keywords: Lepton number violation, matter anti-matter asymmetry, neutrinoless double beta decay

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I. INTRODUCTION

The absence of a right-handed neutrino component in the standard model (SM), coupled with the imperatives of $SU(2)_L$ gauge invariance and renormalizability, results in the prediction that neutrinos should be massless. However, experimental evidence from neutrino oscillation studies [1−4] compellingly demonstrates that neutrinos possess a non-zero, albeit minute, mass. This discrepancy hints at the existence of physics that extends beyond the current understanding provided by the SM.

In 1937, Majorana proposed that neutrinos might be their own antiparticles, a scenario in which the neutrino and antineutrino are indistinguishable [5]. This possibility raises an unresolved question: are neutrinos Dirac particles, distinct from their antiparticles, or Majorana particles, which are not? The "see-saw" mechanism [6−8] is a popular model for generating light neutrino masses, requiring a heavy Majorana neutrino with a mass ranging from a few hundred MeV/c^2 to a few GeV/c^2. If neutrino masses arise from this mechanism, there could be processes that violate the lepton number by two units ($\Delta L=2$), revealing the Majorana nature of neutrinos. Thus, a search for lepton number violation (LNV) is crucial to confirm whether neutrinos are Majorana particles. In 1939, based on Majorana's theory, Furry [9] studied the neutrinoless double beta ($0\nu2\beta$) decay [10], which is an LNV process. Since then, various theories concerning LNV processes have been proposed, and numerous experiments have been conducted to explore these processes.

In addition, the observed matter-antimatter asymmetry in the Universe presents a significant challenge to our understanding of nature. The Big Bang theory, which is the prevailing cosmological model for the Universe's evolution, predicts equal amounts of baryons and anti-baryons in the early Universe. However, the observed amount of baryons exceeds that of the anti-baryons by a factor currently estimated at 10^9-10^{10} [11]. To provide a reasonable interpretation of the baryon-antibaryon asymmetry, Sakharov proposed three principles [12], the first of which is that baryon number conservation must be violated. Several theories believe that, if there is baryon number violation, there will also be LNV [13]. Consequently, experimental searches for the LNV $\Delta L=2$ processes are of considerable interest.

Apart from the $0\nu2\beta$ decay experiments, which could search for Majorana neutrinos, several collider experiments have explored related processes. For example, the LHCb experiment investigated the $B^-\to\pi^+\mu^-\mu^-$ decays [14], the CMS experiment studied the $p\bar{p}\to e^+e^+X$ process [15], the BaBar experiment analyzed the $D_s^+\to\pi^+l^+l^+$ decays [16], and the ATLAS experiment searched for right-handed W bosons and heavy right-handed Majorana or Dirac neutrinos, using a final state containing a pair of charged leptons and two jets [17]. The GERDA experiment searched for the rare $0\nu2\beta$ decay process in ^{76}Ge [18]. Moreover, the CLEO experiment investigated the $D\to\pi(K)e^+e^+$ decays [19], and the FOCUS experiment searched for the decays of D^+ and D_s^+ containing the same-sign di-muons [20]. The BESIII experiment has recently searched for the LNV decays of charmed mesons, including $D\to K\pi e^+e^+$ [21], $D^0\to\bar{p}e^+(pe^-)$ [22], $D^+\to\bar{\Lambda}(\bar{\Sigma}^0e^+)$ [23], and $D^+(D^-)\to ne^+(\bar{n}e^-)$ [24]. In the above searches, no evidence has been found.

In the τ-charm energy region, the huge dataset of charmonia (such as J/ψ) can be analyzed to search for various LNV processes, and it is feasible to search for $J/\psi\to K^+K^+e^-e^-$ (throughout this paper, charge conjugation is implied) and other LNV processes in the decay products of $\phi,\omega,K^0,\eta/\eta'$, etc. Figure 1 shows the Feynman diagram of $J/\psi\to K^+K^+e^-e^-+c.c$ through a possible high dimension operator [25]. A search for this process would provide hints for new physics, as they are expected to be suppressed owing to higher-order processes in the SM.

In this study, by analyzing $(10087\pm44)\times10^6$ J/ψ [26] events collected with the BESIII detector [27] operating at the BEPCII storage ring, we search for the LNV decay $J/\psi\to K^+K^+e^-e^-$ for the first time. Furthermore, we explore the upper limits on the branching fractions of this decay under different Majorana neutrino mass hypotheses. To avoid possible bias, a blind analysis technique is employed, where the data are analyzed only after the

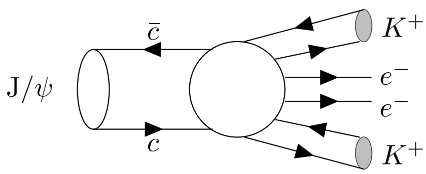

Fig. 1. Possible Feynman diagram of $J/\psi\to K^+K^+e^-e^-$

analysis procedure has been finalized and validated with Monte Carlo (MC) simulation.

II. BESIII DETECTOR AND MONTE CARLO SIMULATION

The BESIII detector is located at the south collision point of the BEPCII [28] storage ring, which operates at a center-of-mass energy range of $\sqrt{s}$ = 1.84 to 4.95 GeV, with a maximum luminosity of 1.1×10^{33} cm^{-2}s^{-1} at 3.773 GeV.

The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), plastic scintillator time-of-flight (TOF) system, and CsI(Tl) electromagnetic calorimeter (EMC). These components are enclosed within a superconducting solenoidal magnet that provides a magnetic field of 1.0 T (0.9 T in 2012). The solenoid is supported by an octagonal flux-return yoke, with resistive plate counter muon identifier modules interleaved with steel. The BESIII coordinate system is defined such that the z-axis aligns with the beam direction, the x-axis is horizontal and points outward from the interaction point, and the y-axis is vertical, forming a right-handed coordinate system.

At a momentum of 1 GeV/c, the charged particle momentum resolution is 0.5%, and the specific ionization energy loss (dE/dx) resolution is 6% for electrons from Bhabha scattering. The EMC has a photon energy 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, whereas in the end-cap region, it is 110 ps. In 2015, the end-cap TOF system was upgraded using multigap resistive plate chamber technology, improving the time resolution to 60 ps [29–31]. Approximately 87% of the data used in this analysis benefit from this upgrade.

Simulated samples produced with the GEANT4-based [32] MC program, which includes the geometric description [33, 34] of the BESIII detector and the detector response, are used to determine the detection efficiency and estimate the backgrounds. The simulation includes the beam energy spread and initial state radiation in the e^+e^- annihilations modeled with the generator KKMC [35]. The inclusive MC sample includes both the production of the J/ψ resonance and the continuum processes incorporated in KKMC [35]. All the particle decays are modeled with EVTGEN [36] using branching fractions either taken from the Particle Data Group [37], when available, or otherwise estimated with LUNDCHARM [38–40]. The final state radiation (FSR) from charged final state particles is incorporated using the PHOTOS package [41]. In this study, a sample of 100,000 phase space (PHSP) MC events is generated to study the detection efficiencies for the LNV decay, with equal contributions from each conjugate channel. For background analysis, 10 billion inclusive MC events are used. The continuum background is estimated using off-resonance data samples at $\sqrt{s} = 3.650$, 3.682, and 3.080 GeV [42], with integrated luminosities of 410 pb^{-1}, 404 pb^{-1}, and 167 pb^{-1}, respectively.

III. DATA ANALYSIS

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, defined with respect to the z-axis, which is the symmetry axis of the MDC. 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 transverse plane and z-axis, respectively. Events with at least four charged tracks with zero net charge are retained for further analysis.

Particle identification (PID) for charged tracks combines the measurements of the energy deposited in the MDC (dE/dx), the flight time in the TOF, and the energy and shape of clusters in the EMC to calculate the confidence level (CL) for electron, pion, and kaon hypotheses (CL$_e$, CL$_\pi$, CL$_K$). Electron candidates must have a CL$_e$ greater than 0.001, and the ratio of CL$_e$ to the sum of CLs for electrons, kaons, and pions (CL$_e$ + CL$_K$ + CL$_\pi$) should be greater than 0.8. Furthermore, the ratio of the energy deposited in the EMC(E) to the momentum measured in the MDC(p) must lie between 0.8c and 1.2c. For kaon candidates, the criteria include CL$_K > 0$ and CL$_K >$ CL$_\pi$. To further reduce the misidentification (mis-PID) between electrons and kaons, an additional requirement of E/p less than 0.8c is applied [43]. The charges of the two selected kaons must be identical and opposite to the charges of the two selected electrons, which also must be the same. The minimum numbers of kaons and electrons are two. If there are multiple candidates in an event, the combination with the smallest χ^2_{4C} is retained for further analysis, where χ^2_{4C} is obtained from a kinematic fit [44] enforcing four-momentum conservation (4C).

To suppress potential contamination from mis-PID in processes with the same charged multiplicity, we perform an additional 4C kinematic fit with the hypotheses of $e^+e^- \to K^+K^-\pi^+\pi^-$, $K^+K^-K^+K^-$, and $\pi^+\pi^-\pi^+\pi^-$. By requiring that the χ^2_{4C} of the $K^+K^+e^-e^-$ mass assignment be the smallest among all possible assignments, such backgrounds can be effectively suppressed and only events with $\chi^2_{K^+K^+e^-e^-,4C} < 20$ are retained for further analysis. This requirement has been optimized with the Punzi significance [45] using the formula $\frac{\varepsilon}{1.5+\sqrt{b}}$, where ε is the detection efficiency from the signal MC simulation, and b is the number of background events from the inclusive MC sample. Furthermore, the selected $K^+K^-e^+e^-$ and $\pi^+\pi^-e^+e^-$ combinations will be rejected if the e^+e^- pair originates from gamma conversions in the beam pipe.

The J/ψ signal region is defined as [3.07, 3.12] GeV/c^2, which corresponds to a range of three times of the mass resolution around the J/ψ mass [37]. The detection efficiency is determined to be 15.68% based on the simulated $J/\psi \to K^+K^+e^-e^-$ events.

With the above selections applied, only one event from the data is left in the signal region as shown in Fig. 2, whereas no event survives from the inclusive MC sample. To investigate the potential contamination from continuum processes, we analyze the off-resonance data samples taken at $\sqrt{s} = 3.650$ GeV, 3.682 GeV, and 3.080 GeV [42]. After considering the differences in integrated luminosities, cross sections, particle momenta, and center-of-mass energies, no event survives in the signal region, $N^{\rm continuum} = 0$. Thus, the total number of background events is calculated as $N^{\rm bkg} = N^{\rm inc} + N^{\rm continuum} = 0$.

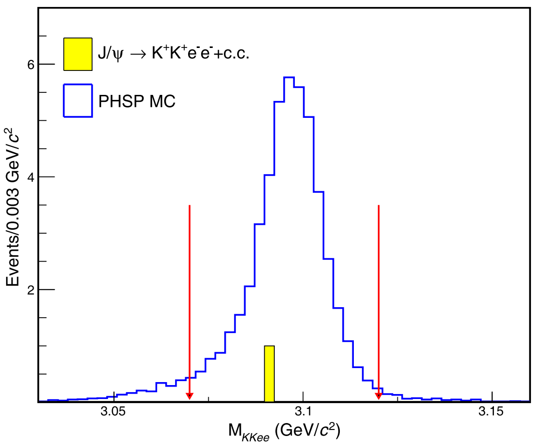

Fig. 2. (color online) Distribution of $M_{K^+K^+e^-e^-+c.c.}$, where the blue histogram represents the simulated shape of the signal, the yellow filled histogram represents data, and the red arrows indicate the signal region.

IV. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties in the measurement arise from the total number of J/ψ events, tracking, PID, kinematic fit, MC modeling, and signal region.

• The uncertainty in the total number of J/ψ events, determined using inclusive hadronic events, is 0.5% [26].

• The uncertainty in the MDC tracking is estimated by comparing the efficiency between the data and MC control samples of $J/\psi \to e^+e^-(\gamma_{\rm FSR})$ and $J/\psi \to \pi^0K^+K^-$. The resulting uncertainties are 0.7% per electron and 0.3% per kaon. Consequently, the total systematic uncertainty in the MDC tracking is 2.0%.

• The uncertainty in the PID is evaluated using the same high-purity control samples of electrons and kaons as mentioned above. The uncertainties are determined to be 0.5% per electron and 0.6% per kaon, resulting in a total PID uncertainty of 2.2%.

• The systematic uncertainty from the 4C kinematic fit and the $\chi^2_{4C} < 20$ requirement is studied using a control sample of $J/\psi \to p\bar{p}\pi^+\pi^-$. The relative difference in efficiencies between the data and MC simulation is determined to be 6.2%, which is taken as the systematic uncertainty from this source.

• The systematic uncertainty associated with the signal region is also calculated using the control sample of $J/\psi \to p\bar{p}\pi^+\pi^-$. The relative difference in efficiencies, 0.4%, is taken as the uncertainty.

• The uncertainty owing to the signal MC sample size is 0.9%.

• To obtain the systematic uncertainty from the MC modeling, we compare the difference in the detection efficiency between the PHSP generator and two alternative MC models, *i.e.*, $J/\psi \to \nu_M K^+e^- \to (K^+e^-)K^+e^-$ and $J/\psi \to \nu_M\nu_M \to (K^+e^-)(K^+e^-)$, where the Majorana neutrino ν_M decays into K^+e^- with different Majorana masses and corresponding detection efficiencies. The possible Feynman diagrams are shown in Fig. 3. The Majorana neutrino mass is varied from the Ke mass threshold to the maximum phase space allowed by the J/ψ decay, approximately from 0.575 GeV/c^2 to 1.525 GeV/c^2, with an interval of 0.025 GeV/c^2. The largest efficiency difference, 1.0%, is taken as the systematic uncertainty.

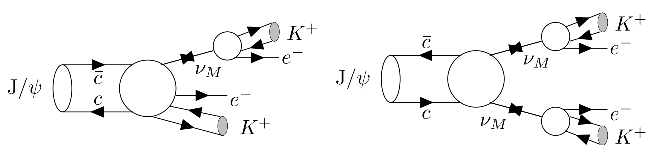

Fig. 3. Possible Feynman diagrams for the decay process of $J/\psi \to \nu_M\nu_M \to (K^+e^-)(K^+e^-)$(left), and for the decay process of $J/\psi \to \nu_M K^+e^- \to (K^+e^-)K^+e^-$(right).

All the uncertainties are summarized in Table 1, and the total systematic uncertainty ($\Delta^{\rm sys}$) is obtained by adding the individual effects in quadrature.

V. RESULTS

A. Upper limit on $J/\psi \to K^+K^+e^-e^-$

A candidate event ($N^{\rm obs}$) is observed in the signal region, whereas a zero background event ($N^{\rm bkg}$) is expected. The efficiency-corrected upper limit (UL) on the sig-

Table 1. Summary of the systematic uncertainties.

Source	Uncertainty (%)
$N_{J/\psi}$	0.5
MDC tracking	2.0
PID	2.2
4C kinematic fit and χ^2 cut	6.2
signal region	0.4
MC statistics	0.9
MC modeling	1.0
Total $\Delta^{\rm sys}$	7.0

nal yield $N^{\rm up}_{K^+K^+e^-e^-}$ is estimated to be 23.2 at the 90% CL using a frequentist method [46]. This estimation employs an unbounded profile likelihood approach to account for systematic uncertainties ($\Delta^{sys} = 7.0\%$), where both observed events ($N^{\rm obs} = 1$) and background events ($N^{bkg} = 0$) are modeled by a Poisson distribution, the detection efficiency ($\varepsilon_{K^+K^+e^-e^-} = 15.83\%$) follows a Gaussian distribution, and the systematic uncertainty is taken as its standard deviation. The UL of the branching fraction (BF) of $J/\psi \to K^+K^+e^-e^-$ at the 90% CL is determined by

$$\mathcal{B}(J/\psi \to K^+K^+e^-e^-) < \mathcal{B}^{\rm UL}(J/\psi \to K^+K^+e^-e^-) = \frac{N^{\rm up}_{K^+K^+e^-e^-}}{N^{\rm tot}_{J/\psi}} = 2.1\times10^{-9}, \quad (1)$$

where $N^{\rm tot}_{J/\psi} = (10087 \pm 44)\times10^6$ is the total number of J/ψ events in the data.

B. Majorana mass dependent upper limits

In addition to the overall UL, assuming the LNV signal from a Majorana neutrino, we investigate the ULs on the BFs of $J/\psi \to 2\nu_M \to (K^+e^-)(K^+e^-)$ with different Majorana masses. The full kinematic range of the Ke invariant mass (m_{Ke}) from the threshold to the largest phase space allowed in the J/ψ decay,

$$m_K + m_e \leq m_{\nu_M} \leq \frac{m_{J/\psi}}{2}, \quad (2)$$

is considered. We consider the Majorana neutrino mass m_{ν_M} from 0.575 GeV/c^2 to 1.500 GeV/c^2 and divide this mass range into uniform intervals, with a width of 0.025 GeV/c^2. In each interval, the Majorana mass is taken as the center value. Owing to an extremely small phase space, the first three (0.500 GeV/c^2, 0.525GeV/c^2, and 0.550 GeV/c^2) are not selected as mass possibilities.

The values of the mass dependent detection efficiencies, signal event counts, background event counts, total systematic uncertainties, and the ULs on the BFs at the 90% CL are reported in Table 2, for each m_{Ke} bin. The mass dependent ULs are calculated to be [2.04, 0.92]$\times10^{-9}$ with the same method, and the results are shown in Fig. 4.

Table 2. Mass dependent detection efficiencies (ϵ_i), signal event counts ($N_i^{\rm sig}$), background event counts ($N_i^{\rm bkg}$), total systematic uncertainties ($\Delta_i^{\rm sys}$), and the ULs on the BFs at the 90% CL($\mathcal{B}^{\rm UL}$) for different Majorana mass hypotheses from 0.575 GeV/c^2 to 1.525 GeV/c^2 with an interval of 0.025 GeV/c^2.

m_{ν_M}/(GeV/c^2)	$\varepsilon_{2\nu_M}$ (%)	$N_i^{\rm sig}$	$N_i^{\rm bkg}$	$\Delta_i^{\rm sys}$ (%)	$\mathcal{B}^{\rm UL}$ (10^{-9})
0.575	8.97	0	0	26.8	2.04
0.600	12.34	0	0	25.8	1.48
0.625	13.69	0	0	26.4	1.34
0.650	13.60	0	0	22.9	1.35
0.675	13.79	0	0	19.3	1.33
0.700	14.15	0	0	16.9	1.29
0.725	14.56	0	0	15.5	1.26
0.750	15.32	0	0	14.1	1.19
0.775	15.87	0	0	12.1	1.15
0.800	16.14	0	0	11.3	1.13
0.825	16.18	0	0	8.4	1.13
0.850	16.67	0	0	11.2	1.10
0.875	16.57	0	0	9.0	1.11
0.900	16.26	0	0	7.0	1.11

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Table 2-continued from previous page

m_{ν_M}/(GeV/c^2)	$\varepsilon_{2\nu_M}$ (%)	$N_i^{\rm sig}$	$N_i^{\rm bkg}$	$\Delta_i^{\rm sys}$ (%)	$\mathcal{B}^{\rm UL}$ (10^{-9})
0.925	16.55	0	0	7.0	1.11
0.950	16.55	0	0	7.0	1.09
0.975	16.72	0	0	7.0	1.09
1.000	16.74	0	0	7.0	1.08
1.025	16.94	0	0	7.1	1.08
1.050	16.96	0	0	7.0	1.07
1.075	17.16	0	0	7.2	1.08
1.100	16.96	0	0	7.5	1.08
1.125	17.01	0	0	7.8	1.06
1.150	17.28	0	0	7.0	1.05
1.175	17.36	0	0	7.4	1.05
1.200	17.47	1	0	7.2	1.93
1.225	17.94	0	0	7.0	1.02
1.250	17.16	0	0	7.0	1.01
1.275	18.30	0	0	7.5	1.00
1.300	18.55	0	0	7.3	0.99
1.325	18.51	0	0	7.6	0.99
1.350	18.75	0	0	8.5	0.98
1.375	18.80	0	0	8.9	0.97
1.400	19.12	0	0	9.4	0.96
1.425	18.82	0	0	8.7	0.97
1.450	19.31	0	0	11.5	0.95
1.475	19.38	0	0	11.1	0.95
1.500	20.00	0	0	12.8	0.92
1.525	20.28	0	0	16.2	0.90

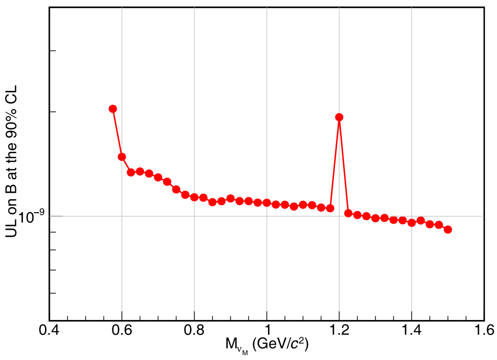

Fig. 4. (color online) ULs at the 90% CL for the data sample as a function of m_{ν_M} for the decay $J/\psi \to 2\nu_M\ (\to K^+e^-)$

VI. SUMMARY

In summary, by using $(10087\pm44)\times10^6$ J/ψ events collected by the BESIII detector, we search for the LNV decay $J/\psi \to K^+K^+e^-e^- + c.c.$ for the first time. One event survives in the signal region, and the UL on the decay branching fraction of $J/\psi \to K^+K^+e^-e^- + c.c.$ is determined to be 2.1×10^{-9} at the 90% CL. The Majorana mass dependent ULs on the branching fractions at the 90% CL are estimated, varying within the range of $[0.92, 2.04]\times10^{-9}$. By utilizing these results, constraints on the mixed matrix element $|V_{e\nu_M}|^2$ between the Majorana neutrino and the electron can be derived within the theoretical models.

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