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Search for Rare Decays of Charmed D Mesons*

BES Collaboration

ABLIKIM Medina BAI Jing-Zhi BAN Yong[4] BIAN Jian-Guo CAI Xiao CHEN Hai-Xuan CHEN He-Sheng CHEN Hong-Fang[1] CHEN Jiang-Chuan CHEN Jin CHEN Yuan-Bo CHI Shao-Peng[6] CHU Yuan-Ping CUI Xiang-Zong DAI You-Shan[3] DENG Zi-Yan DONG Liao-Yuan1) DONG Qing-Feng[13] DU Shu-Xian DU Zhi-Zhen FANG Jian FANG Shuang-Shi[6] FU Cheng-Dong GAO Cui-Shan GAO Yuan-Ning[13] GU Shu-Di GU Yun-Ting[16] GUO Ya-Nan GUO Yi-Qing HE Kang-Lin2) HE Mao[2] HENG Yue-Kun HU Hai-Ming HU Tao HUANG Guang-Shun3) HUANG Xing-Tao[2] HUANG Xiu-Ping JI Xiao-Bin JIANG Xiao-Shan JIAO Jian-Bin[2] JIN Da-Peng JIN Shan JIN Yi LAI Yuan-Fen LI Gang[6] LI Hai-Bo LI Hui-Hong LI Jin LI Ren-Ying LI Shu-Min LI Wei-Dong LI Wei-Guo LI Xiao-Ling[11] LI Xue-Qian[7] LI Yuan-Liu[16] LIANG Yong-Fei[12] LIAO Hong-Bo[5] LIU Chun-Xiu LIU Fang[1] LIU Feng[5] LIU Huai-Min LIU Hui-Hui LIU Jian-Bei LIU Jing[4] LIU Jue-Ping[9] LIU Rong-Guang LIU Zhen-An LU Gong-Ru[8] LÜ Feng LÜ Hai-Jiang[1] LÜ Jun-Guang LUO Cheng-Lin[15] MA Feng-Cai[11] MA Hai-Long MA Lian-Liang MA Qiu-Mei MA Xu-Bo[8] MAO Ze-Pu MO Xiao-Hu NIE Jing PENG Hai-Ping[1] QI Na-Ding QIN Hu[15] QIU Jin-Fa REN Zhen-Yu RONG Gang SHAN Lian-You SHANG Lei SHEN Ding-Li SHEN Xiao-Yan SHENG Hua-Yi SHI Feng SHI Xin[4;]4) SUN Han-Sheng SUN Jun-Feng SUN Sheng-Sen SUN Yong-Zhao SUN Zhi-Jia TAN Zhen-Qiang[16] TANG Xiao TIAN Yu-Run[13] TONG Guo-Liang WANG Da-Yong WANG Lan WANG Ling-Shu WANG Man WANG Pei-Liang WANG Ping WANG Wen-Feng5) WANG Yi-Fang WANG Zhe WANG Zheng[6] WANG Zheng WANG Zhi-Yong WEI Cheng-Lin WEI Dai-Hui WU Ning XIA Xiao-Mi XIE Xiao-Xi XIN Bo[11;]3) XU Guo-Fa XU Ye[7] YAN Mu-Lin[1] YANG Fan[7] YANG Hong-Xun YANG Jie[1] YANG Yong-Xu[14] YE Ming-Han[6] YE Yun-Xiu[1] YI Zhi-Yong YU Guo-Wei YUAN Chang-Zheng YUAN Jian-Ming YUAN Ye ZANG Shi-Lei ZENG Yu ZENG Yun[10] ZHANG Bing-Xin ZHANG Bing-Yun ZHANG Chang-Chun ZHANG Da-Hua ZHANG Hong-Yu ZHANG Jian-Yong6) ZHANG Jia-Wen ZHANG Qin-Jian ZHANG Xiao-Mei ZHANG Xue-Yao[2] ZHANG Yi-Yun[12] ZHANG Zhi-Qing[8] ZHANG Zi-Ping[1] ZHAO Di-Xin ZHAO Jing-Wei ZHAO Ming-Gang[7] ZHAO Ping-Ping ZHAO Wei-Ren ZHAO Zheng-Guo7) ZHENG Han-Qing[4] ZHENG Jian-Ping ZHENG Zhi-Peng ZHOU Li ZHOU Neng-Feng ZHU Ke-Jun ZHU Qi-Ming ZHU Ying-Chun8) ZHU Yong-Sheng ZHU Yu-Can ZHU Zi-An ZHUANG Bao-An ZHUANG Xu-Ai ZOU Bing-Song

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1)Iowa State University, Ames, IA 50011-3160, USA

2)E-mail: hekl@ihep.ac.cn

3)Purdue University, West Lafayette, IN 47907, USA

4)Cornell University, Ithaca, NY 14853, USA

5)Laboratoire de l'Accélératear Linéaire, F-91898 Orsay, France

6)Corresponding author, E-mail: jyzhang@mail.ihep.ac.cn

7)University of Michigan, Ann Arbor, MI 48109, USA

8)DESY, D-22607, Hamburg, Germany

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(Institute of High Energy Physics, CAS, Beijing 100049, China)
1 (Department of Modern Physics, University of Science and Technology of China, Hefei 230026 , China)
2 (Department of Physics, Shandong University, Jinan 250100, China)
3 (Department of Physics, Zhejiang University, Hangzhou 310028, China)
4 (School of Physics, Peking University, Beijing 100871, China)
5 (Department of Particle Physics, Huazhong Normal University, Wuhan 430079, China)
6 (China Center for Advanced Science and Technology(CCAST), Beijing 100080, China)
7 (College of Physics, Nankai University, Tianjin 300071, China)
8 (College of Physics and Information Engineering, Henan Normal University, Xinxiang 453002, China)
9 (College of Physics and Electronic Information, Wuhan University, Wuhan 430072, China)
10 (Department of Applied Physics, Hunan University, Changsha 410082, China)
11 (Department of Physics, Liaoning University, Shenyang 110036, China)
12 (Department of Physics, Sichuan University, Chengdu 610064, China)
13 (Center of High Energy Physics, Tsinghua University, Beijing 100084, China)
14 (Department of Physics and Electronic Science, Guangxi Normal University, Guilin 541004, China)
15 (Department of Physics, Nanjing Normal University, Nanjing 210097, China)
16 (College of Physics Science and Technology, Guangxi University, Nanning 530004, China)

Abstract A search for flavor changing neutral current (FCNC) and lepton number violation (LNV) decays of charmed D mesons is performed using 33pb^{-1} data around $\Psi(3770)$ collected by BESⅡ detector at BEPC. Four decay modes of $D^0(\overline{K}^0e^+e^-$, Φe^+e^-, $\rho^0e^+e^-$ and $\overline{K}^{*0}e^+e^-)$ and six decay modes of $D^+(K^-e^+e^+$, $K^+e^+e^-$, $\pi^-e^+e^+$, $\pi^+e^+e^-$, $K^{*-}e^+e^+$ and $K^{*+}e^+e^-)$ are presented. No evidence is found for the above decays, therefore, the upper limits at 90% confidence level are set. The limits of two D^+ decays modes, $D^+\to K^{*-}e^+e^+$ 和 $D^+\to K^{*+}e^+e^-$ have not been reported previously.

Key words rare decay, D meson, upper limit

1 Introduction

The Standard Model(SM) is successful because it can account for the known decays of heavy quarks and also can predict the decay rates quantitatively. However this model is incomplete. It can not account for the number of quark and lepton families observed and can not account for their hierarchy of mass scales. To understand these physics phenomena, people dedicate to search for physics beyond the Standard Model. One way is to search for the decays which are forbidden in the first order, or are predicted to occur at a negligible level in SM. These measurements would provide experimental tests to the physics beyond the Standard Model.

In this paper, we present the results of a search for 10 rare decay modes of the neutral and charged D mesons. These decay modes fall into two categories. The first one is flavor changing neutral current (FCNC) decays (including: $D^0\to\phi e^+e^-$, $\rho^0e^+e^-$, $D^+\to\pi^+e^+e^-$), The FCNC decay mode can occur at one loop level in the Standard Model from box and penguin diagrams, as shown in Fig. 1, but are highly suppressed by the GIM mechanism[1]. The branching fractions of the sort of decay are estimated to be 10^{-8}—10^{-6}[2, 3], such small rates are below the sensitivity of current experiments. However, if supersymmetric squarks or charginos exist, they

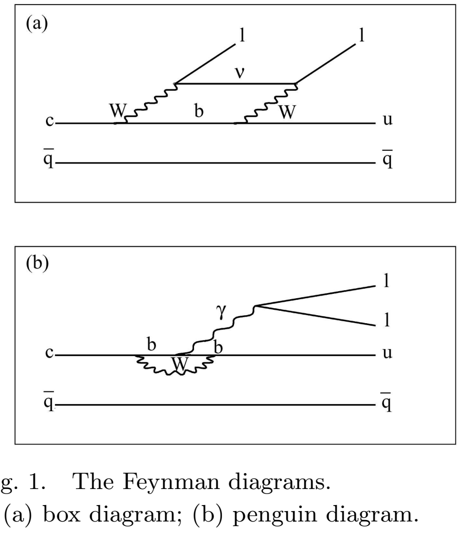

Fig. 1. The Feynman diagrams.
(a) box diagram; (b) penguin diagram.

would contribute additional amplitudes to make these modes observable. The second one is lepton number violation (LNV) decays (including $D^+ \to K^- e^+ e^+$, $\pi^- e^+ e^+$, $K^{*-} e^+ e^+$). The decay modes is strictly forbidden in the Standard Model. However, lepton number conservation is not required in some theories[4], which extend the Standard Model. Many experiments have searched for lepton number violation in K, D and B decays. Here we present our results for these rare decays.

2 BESⅡ detector

The upgraded Beijing Spectrometer (BESⅡ) is a conventional cylindrical magnetic detector described in detail in Ref. [5]. A 12-layer Vertex Chamber (VC) surrounding the beryllium beam pipe provides input to the event trigger, as well as coordinate information. A forty-layer main drift chamber (MDC) located just outside the VC yields precise measurements of charged particle trajectories with a solid angle coverage of 85% of 4π; it also provides ionization energy loss ($\mathrm{d}E/\mathrm{d}x$) measurements which are used for particle identification. Momentum resolution of $1.78\%\sqrt{1+p^2}$ (p in GeV/c) and $\mathrm{d}E/\mathrm{d}x$ resolution for hadron tracks of $\sim 8\%$ are obtained. An array of 48 scintillation counters surrounding the MDC measures the time of flight (TOF) of charged particles with a time resolution of $\sim$ 200ps for hadrons. Outside the TOF counters, a 12 radiation length, lead-gas barrel shower counter (BSC), operating in limited streamer mode, measures the energies of electrons and photons over 80% of the total solid angle with an energy resolution of $\sigma_E/E = 0.22/\sqrt{E}$ (E in GeV). Outside the solenoidal coil, which provides a 0.4T magnetic field over the tracking volume, is an iron flux return that is instrumented with three double-layers muon counters that identify muons with momentum greater than 500MeV/c.

In this analysis, a GEANT3 based Monte Carlo package[6] with detailed consideration of the detector performance (such as dead electronic channels) is used. The consistency between data and Monte Carlo has been carefully checked in many high purity physics channels, and the agreement is reasonable.

3 Event selection

Four D^0 decay modes: $\overline{K}^0 e^+ e^-$, $\phi e^+ e^-$, $\rho e^+ e^-$, $\overline{K}^{*0} e^+ e^-$ and six D^+ decay modes: $K^- e^+ e^+$, $K^+ e^+ e^-$, $\pi^- e^+ e^+$, $\pi^+ e^+ e^-$, $K^{*-} e^+ e^+$, $K^{*+} e^+ e^-$ are selected to search for the FCNC and LNV decays.

A total integrated luminosity of about $33\mathrm{pb}^{-1}$[7] data around the center-of-mass energy of 3.773GeV were collected by BESⅡ detector at e^+e^- storage ring BEPC. $\psi(3770)$ is just above the threshold of $D\overline{D}$ and below the threshold of $D\overline{D}^*$, and decays to $D\overline{D}$ pair predominately. The pair production of $D\overline{D}$ at $\psi(3770)$ provides a powerful mass quantity known as beam-constrained mass:

$$M_{\mathrm{bc}} = \sqrt{(E_{\mathrm{b}})^2 - (p_{\mathrm{D}})^2}, \tag{1}$$

to identify D meson clearly, where E_{b} is beam energy, p_{D} is the D candidate momentum. As the beam energy spread is much smaller than the uncertainty of the reconstructed D candidate energy, this approach yields the mass resolution of 2—3MeV.

3.1 General section criterial

Charged tracks are required to satisfy $|\cos\theta| < 0.8$, where θ is the polar angle respect to beam axis, and to have good helix fit. Tracks that are not associated with K^0_S reconstruction are required to be from the interaction region. A charged track is identified as a kaon or pion if the measured time-of-flight and energy loss in drift chamber agree with that predicted for a kaon or pion

$$\begin{aligned} \chi(\mathrm{TOF}) &= \frac{T^{\mathrm{meas}} - T^{\mathrm{pred}}}{\sigma_{\mathrm{T}}}, \\ \chi(\mathrm{d}E/\mathrm{d}x) &= \frac{\mathrm{d}E/\mathrm{d}x^{\mathrm{meas}} - \mathrm{d}E/\mathrm{d}x^{\mathrm{pred}}}{\sigma_{\mathrm{d}E/\mathrm{d}x}}, \end{aligned} \tag{2}$$

to be within four standard deviations, where T^{meas}, T^{pred} and $\mathrm{d}E/\mathrm{d}x^{\mathrm{meas}}$, $\mathrm{d}E/\mathrm{d}x^{\mathrm{pred}}$ are the measured and predicted time of flight and energy loss, respectively. σ_{T} and $\sigma_{\mathrm{d}E/\mathrm{d}x}$ are the resolution of TOF and $\mathrm{d}E/\mathrm{d}x$. The combined confidence level $CL_{\pi,\mathrm{K}} = \mathrm{prob}(\chi^2(\mathrm{TOF}) + \chi^2(\mathrm{d}E/\mathrm{d}x),\ N_{\mathrm{dof}})$ is required to be greater than 0.1%, where N_{dof} is the degree of freedom. Kaon and pion candidates are further classified by comparing the normalized weights of TOF and $\mathrm{d}E/\mathrm{d}x$.

The energy deposit in BSC is quite different for electrons and hadrons. The measured BSC energy deposition is nearly a Gaussian distribution for electrons, but a Landau distribution with long tails for hadrons. Pure electrons and hadrons are selected from radiative Bhabha, $\mathrm{J}/\psi \to \rho\pi$ and $\mathrm{J}/\psi \to \omega\pi^+\pi^-$ data samples to understand their characteristics. The χ(BSC) quantity for electrons is defined as:

$$\chi_{\mathrm{e}}(\mathrm{BSC}) = \frac{E^{\mathrm{meas}} - E_{\mathrm{e}}^{\mathrm{pred}}}{\sigma_{\mathrm{E}}}, \tag{3}$$

where E^{meas} is the measured energy deposited in BSC, $E_{\mathrm{e}}^{\mathrm{pred}}$ is the predicted energy deposition of electron, σ_{E} is the energy resolution of BSC. To construct χ(BSC) for hadrons, the energy deposit distributions in different momentum range are studied. A histogram integration technique is developed to convert the probability $P(E,p)$ to $\chi(E,p)$.

Combining TOF, $\mathrm{d}E/\mathrm{d}x$ and BSC, the total χ^2 for electrons and hadrons is given by:

$$\chi^2_{\mathrm{e},\pi,\mathrm{K}} = \chi^2_{\mathrm{e},\pi,\mathrm{K}}(\mathrm{TOF}) + \chi^2_{\mathrm{e},\pi,\mathrm{K}}(\mathrm{d}E/\mathrm{d}x) + \chi^2_{\mathrm{e},\pi,\mathrm{K}}(\mathrm{BSC}). \tag{4}$$

The combined confidence level of the electron (CL_{e}) is required to be greater than 0.1% and the ratio:

$$R = \frac{CL_{\mathrm{e}}}{CL_{\mathrm{K}} + CL_{\pi} + CL_{\mathrm{e}}} \tag{5}$$

is required to be greater than 0.8. The electron identification efficiencies for both data and Monte Carlo events are shown in Fig. 2.

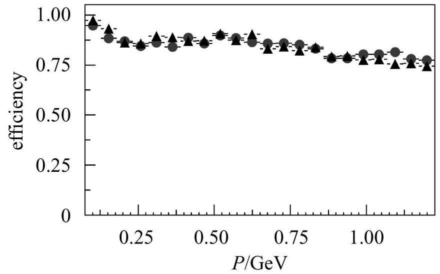

Fig. 2. The identification efficiency between data and Monte Carlo in different range of momentum. The dot and the triangle represent data and Monte Carlo respectively.

The neutral kaon candidates are selected via the decay mode $\mathrm{K}_{\mathrm{S}}^0 \to \pi^+\pi^-$. All pairs with oppositely charged tracks are considered (even they are not identified as pions by TOF and $\mathrm{d}E/\mathrm{d}x$). The momentum vector of $\pi^+\pi^-$ pair should align with the position vector of decay vertex in the transverse plane, $|\cos\theta| > 0.9$ is required, where θ represents the alignment angle. The distance between decay vertex and primary vertex is required to be greater than 3mm. The $\pi^+\pi^-$ invariant mass is required to be within $20\mathrm{MeV}/c^2$ of $\mathrm{K}_{\mathrm{S}}^0$ nominal mass value.

To remove the gamma conversion background, the angle between two opposite charged tracks is required to be greater than 12°.

3.2 Search for the rare decay signal

Appropriate combinations of particles are constructed for each of the rare decay modes. To reduce the particle misidentification and wrong combinational background, the difference between the total energy of D candidates (E_{tag}) and the beam energy (E_{b}), $\Delta E = |E_{\mathrm{tag}} - E_{\mathrm{b}}|$ cut is applied. ΔE cut value of each rare decay mode is referenced to the similar Cabibbo favored channel. Table 1 lists the rare decay modes and the referenced Cabibbo favored decay modes.

Table 1. Rare decay modes and reference decay modes.

rare decay modes	reference decay modes
$\mathrm{D}^0 \to \overline{\mathrm{K}}^0\mathrm{e}^+\mathrm{e}^-$	$\mathrm{D}^0 \to \overline{\mathrm{K}}^0\pi^+\pi^-$
$\mathrm{D}^0 \to \phi\mathrm{e}^+\mathrm{e}^-, \rho\mathrm{e}^+\mathrm{e}^-, \overline{\mathrm{K}}^{*0}\mathrm{e}^+\mathrm{e}^-$	$\mathrm{D}^0 \to \mathrm{K}^-\pi^+\pi^+\pi^-$
$\mathrm{D}^+ \to \mathrm{K}^-\mathrm{e}^+\mathrm{e}^+, \mathrm{K}^+\mathrm{e}^+\mathrm{e}^-,$ $\pi^-\mathrm{e}^+\mathrm{e}^+, \pi^+\mathrm{e}^+\mathrm{e}^-$	$\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$
$\mathrm{D}^+ \to \mathrm{K}^{*-}\mathrm{e}^+\mathrm{e}^+, \mathrm{K}^{*+}\mathrm{e}^+\mathrm{e}^-$	$\mathrm{D}^+ \to \overline{\mathrm{K}}^0\pi^+\pi^+\pi^-$

The ΔE distribution of Cabibbo favored modes is shown in Fig. 3, the arrows represent the $2\sigma_{\mathrm{E}}$ cut. The ΔE is required to be less than 48, 36, 45, 36MeV for the decay modes $\mathrm{D}^0 \to \overline{\mathrm{K}}^0\pi^+\pi^-$, $\mathrm{D}^0 \to \mathrm{K}^-\pi^+\pi^+\pi^-$, $\mathrm{D}^+ \to \mathrm{K}^-\pi^+\pi^+$ and $\mathrm{D}^+ \to \overline{\mathrm{K}}^0\pi^+\pi^+\pi^-$, respectively.

The vector meson candidates are reconstructed through the decays $\phi \to \mathrm{K}^+\mathrm{K}^-$, $\rho^0 \to \pi^+\pi^-$, $\overline{\mathrm{K}}^{*0} \to \mathrm{K}^-\pi^+$, and $\mathrm{K}^{*\pm} \to \overline{\mathrm{K}}^0\pi^{\pm}$. The invariant mass of candidates is required to be within 15, 150, 60 and $60\mathrm{MeV}/c^2$ of their nominal mass, respectively.

The beam-constrained mass spectra for 4 neutral and 6 charged D decay modes are shown in Fig. 4 and Fig. 5. No signals are observed in any of the rare decay modes. The mass and resolution (σ) of D meson signals are determined by the reference Cabibbo favored modes.

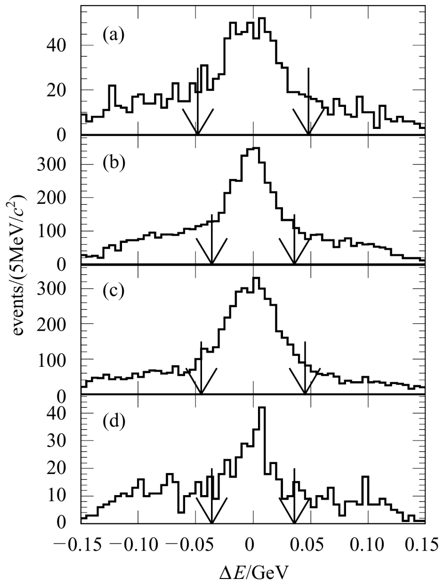

Fig. 3. ΔE distribution for referenced Cabibbo favored decay modes.
(a) $D^0 \to \overline{K}^0\pi^+\pi^-$; (b) $D^0 \to K^-\pi^+\pi^+\pi^-$;
(c) $D^+ \to K^-\pi^+\pi^+$; (d) $D^+ \to \overline{K}^0\pi^+\pi^+\pi^-$.
The ΔE cuts illustrated by arrows are shown in the plot, and the values are listed in the text.

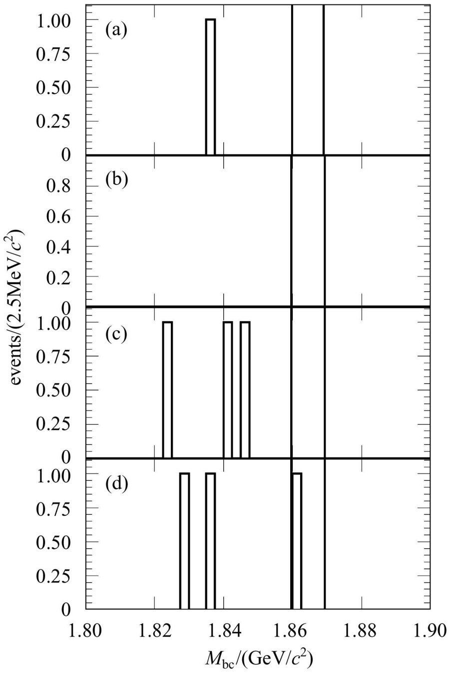

Fig. 4. Beam-constrained mass distribution of neutral D meson.
(a) $D^0 \to \overline{K}^0 e^+e^-$; (b) $D^0 \to \phi e^+e^-$;
(c) $D^0 \to \rho e^+e^-$; (d) $D^0 \to \overline{K}^{*0} e^+e^-$.
The solid lines show the signal window.

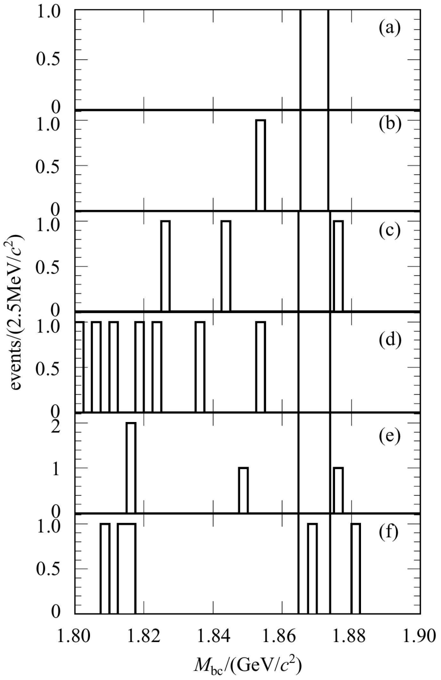

Fig. 5. Beam constrained mass distribution of charged D meson.
(a) $D^+ \to K^{*-}e^+e^+$; (b) $D^+ \to K^{*+}e^+e^-$;
(c) $D^+ \to K^-e^+e^+$; (d) $D^+ \to K^+e^+e^-$;
(e) $D^+ \to \pi^-e^+e^+$; (f) $D^+ \to \pi^+e^+e^-$.
The solid lines show the signal window.

4 Results

4.1 Detection efficiency

The detection efficiency is determined by detailed Monte Carlo simulation. DDGEN generator is developed for $\psi(3770) \to D\overline{D}$ study. In DDGEN, $D\overline{D}$ are produced with a $\sin^2(\theta_D)$ distribution. The decay branching fractions of neutral and charged D meson are quoted from PDG[8]. Some unseen decay modes(containing many π^0's) are added according to the rules of isospin conservation. For multi-body final states, such as $D^0 \to K^-\pi^+\pi^+\pi^-$, $D^0 \to K^-\pi^+\pi^0$, the decay branching fractions in DDGEN are calculated by several sub-resonance decay modes. As far as the rare decay is concerned, some models are developed to describe the M_{ee}^2 distribution[9]:

1) Phase space model, the momentum distribution follows the kinematic of phase space;

2) Pole model, the M_{ee}^2 distribution is proportional to $\dfrac{1}{M_{ee}^2}$;

3) VDM model, in the M_{ee}^2 distribution, enhancement appears near the vector meson mass region, such as: ρ, ω, ϕ, etc.

In this analysis, the phase space model is used to obtain the detection efficiencies. 50000 Monte Carlo samples for each decay mode are generated, in which D decays into rare mode, $\overline{\mathrm{D}}$ decays to any possible modes.

4.2 Upper limits at 90% confidence level

The upper limit on branching fractions for FCNC and LNV decay modes is given by

$$B=\frac{n_{0.9}}{\varepsilon\times 2\times N_{\mathrm{D}\overline{\mathrm{D}}}}, \tag{6}$$

where $n_{0.9}$ is the Poisson 90% upper limit for the observed events, ε is the detection efficiency as mentioned above , $N_{\mathrm{D}\overline{\mathrm{D}}}$ is the total number of $\mathrm{D}\overline{\mathrm{D}}$, $N_{\mathrm{D}^0\overline{\mathrm{D}}^0}=(9.44\pm0.82\pm0.39)\times10^4$, $N_{\mathrm{D}^+\mathrm{D}^-}=(5.98\pm0.70\pm0.23)\times10^4$[10]. Wrong combination and particle misidentification may contribute to the background. In this analysis, no events are observed within the signal window for the most modes. As a conservative estimation, no background event is subtracted.

4.3 Systematic errors

The systematic uncertainties come from the total number of $\mathrm{D}\overline{\mathrm{D}}$, tracking simulation, $\mathrm{K_S^0}$ reconstruction, ΔE cut and particle identification.

The main source of systematic error is due to uncertainty of the total number of produced neutral and charged D mesons, namely $N_{\mathrm{D}^0\overline{\mathrm{D}}^0}$ and $N_{\mathrm{D}^+\mathrm{D}^-}$, which contribute 9.6% for $N_{\mathrm{D}^0\overline{\mathrm{D}}^0}$ and 12.4% for $N_{\mathrm{D}^+\mathrm{D}^-}$ (including statistical and systematic errors)[10].

About 1%—2% per track is estimated as the tracking simulation uncertainty in drift chamber by comparing Monte Carlo and data[6], 2% per track is taken as systematic uncertainty of tracking in the range of $|\cos\theta|<0.8$.

The systematic uncertainty in $\mathrm{K_S^0}$ reconstruction is checked with the decay of $\psi\to\mathrm{K_S^0K^\pm}\pi^\mp$, about 2% per $\mathrm{K_S^0}$ is estimated[11]. To estimate the systematic errors due to the ΔE cut, the window of ΔE is varied, 2%—3% difference is found between Data and Monte Carlo. so, 3% is taken as the systematic error caused by ΔE cut.

For particle identification of π and K, 4 standard deviations' cut for kaons and pions will not introduce additional systematic uncertainty. The ratio of normalized weight $R=CL_{\mathrm{K}}/(CL_{\mathrm{K}}+CL_{\pi})$ cut is studied, respectively. 2% per tag is taken as the systematic uncertainty.

Another source of systematic uncertainty is from identification of electron. Radiative Bhabha events are used from ψ(3770) sample. Before and after electron identification, the difference between data and Monte Carlo are carefully studied. 1.5% per electron is taken as the systematic uncertainty of electron identification.

The total systematic errors are in the range of 13.4%—16.6% for different modes. The systematic errors $\varDelta_{\mathrm{sys}}$ are linearly transfered to the upper limit of 90% confidence level by:

$$B_{\mathrm{up}}=\frac{B}{1-\varDelta_{\mathrm{sys}}}. \tag{7}$$

The upper limits on the branching fractions for flavor changing neutral current and lepton number violation decay modes are listed in Table 2.

Table 2. Summary of the numbers of signal events, acceptance and 90% C.L. upper limits on the FCNC and LNV decay modes. The efficiencies(ε) we used are based on the phase space model.

mode	signal events	acceptance	upper limit @90%	PDG (2004)
$\overline{\mathrm{K}}^0\mathrm{e}^+\mathrm{e}^-$	0	2.64%	5.7×10^{-4}	1.1×10^{-4}
$\phi\mathrm{e}^+\mathrm{e}^-$	0	0.64%	2.4×10^{-3}	5.2×10^{-5}
$\rho\mathrm{e}^+\mathrm{e}^-$	0	4.32%	3.5×10^{-4}	1.0×10^{-4}
$\overline{\mathrm{K}}^{*0}\mathrm{e}^+\mathrm{e}^-$	1	2.06%	1.3×10^{-3}	4.7×10^{-5}
$\mathrm{K}^-\mathrm{e}^+\mathrm{e}^+$	0	9.64%	2.5×10^{-4}	1.2×10^{-4}
$\mathrm{K}^+\mathrm{e}^+\mathrm{e}^-$	0	9.20%	2.6×10^{-4}	2.0×10^{-4}
$\pi^-\mathrm{e}^+\mathrm{e}^+$	0	10.20%	2.4×10^{-4}	9.6×10^{-5}
$\pi^+\mathrm{e}^+\mathrm{e}^-$	1	10.49%	4.1×10^{-4}	5.2×10^{-5}
$\mathrm{K}^{*-}\mathrm{e}^+\mathrm{e}^+$	0	0.40%	6.2×10^{-3}	
$\mathrm{K}^{*+}\mathrm{e}^+\mathrm{e}^-$	0	0.39%	6.3×10^{-3}	

5 Summary

In summary, using about 33pb^{-1} data collected with BESⅡ detector at BEPC around ψ(3770), four neutral and six charged D rare decay modes are studied. No signal is found, therefore, upper limits at 90% confidence level are set. The upper limits of D^+

decay modes are comparable to those from PDG[8], but for D^0, our measurements are worse than those from PDG. However, the upper limits on the branching fractions for $D^+ \to K^{*-}e^+e^+$ and $D^+ \to K^{*+}e^+e^-$ decays are set in the first time by the BES Collaboration in this analysis.

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D介子稀有衰变研究*

BES 合作组

阿布里克木·麦迪娜 白景芝 班勇[4] 卞建国 蔡啸 陈海璇 陈和生 陈宏芳[1] 陈江川 陈进 陈元柏 迟少鹏[6] 初元萍 崔象宗 戴又善[3] 邓子艳 董燎原1) 董清风[13] 杜书先 杜志珍 方建 房双世[6] 傅成栋 高翠山 高原宁[13] 顾树棣 顾运厅[16] 过雅南 郭义庆 何康林2) 何瑁[2] 衡月昆 胡海明 胡涛 黄光顺3) 黄性涛[2] 黄秀萍 季晓斌 江晓山 焦健斌[2] 金大鹏 金山 金毅 赖元芬 李刚[6] 李海波 李会红 李金 李仁英 李树敏 李卫东 李卫国 李晓玲[11] 李学潜[7] 黎元柳[16] 梁勇飞[12] 廖红波[5] 刘春秀 刘芳[1] 刘峰[5] 刘怀民 刘汇慧 刘建北 刘晶[4] 刘觉平[9] 刘荣光 刘振安 鲁公儒[8] 吕峰 吕海江[1] 吕军光 罗成林[15] 马凤才[11] 马海龙 马连良 马秋梅 马续波[8] 毛泽普 莫晓虎 聂晶 彭海平[1] 漆纳丁 秦虎[15] 邱进发 任震宇 荣刚 单连友 尚雷 沈定力 沈肖雁 盛华义 石峰 史欣[4;4)] 孙汉生 孙俊峰 孙胜森 孙永昭 孙志嘉 谭振强[16] 唐晓 田雨润[13] 童国梁 王大勇 王岚 王灵淑 王曼 王佩良 王平 王文峰5) 王贻芳 王喆 王铮[6] 王征 王至勇 魏诚林 魏代会 吴宁 夏小米 谢小希 辛波[11;3)] 许国发 徐晔[7] 阎沐霖[1] 杨帆[7] 杨洪勋 杨杰[1] 杨永栩[14] 叶铭汉[6] 叶云秀[1] 易智勇 俞国威 苑长征 袁建明 袁野 臧石磊 曾瑜 曾云[10] 张丙新 张炳云 张长春 张达华 章红宇 张建勇6) 张家文 张勤俭 张晓梅 张学尧[2] 张一云[12] 张志清[8] 张子平[1] 赵棣新 赵京伟 赵明刚[7] 赵平平 赵维仁 赵政国7) 郑汉青[4] 郑建平 郑志鹏 周莉 周能锋 朱科军 朱启明 朱莹春8) 朱永生 祝玉灿 朱自安 庄保安 庄胥爱 邹冰松

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(中国科学院高能物理研究所　北京　100049)
1 (中国科学技术大学近代物理系　合肥　230026)
2 (山东大学物理系　济南　250100)
3 (浙江大学物理系　杭州　310028)
4 (北京大学物理学院　北京　100871)
5 (华中师范大学粒子物理研究所　武汉　430079)
6 (中国高等科学技术中心　北京　100080)
7 (南开大学物理学院　天津　300071)
8 (河南师范大学物理与信息工程学院　新乡　453002)
9 (武汉大学物理与电子信息学院　武汉　430072)
10 (湖南大学应用物理系　长沙　410082)
11 (辽宁大学物理系　沈阳　110036)
12 (四川大学物理系　成都　610064)
13 (清华大学高能物理中心　北京　100084)
14 (广西师范大学物理与电子科学系　桂林　541004)
15 (南京师范大学物理系　南京　210097)
16 (广西大学物理科学与工程技术学院　南宁　530004)

摘要　利用工作在北京正负电子对撞机(BEPC)上的北京谱仪(BES)收集到的33pb^{-1}的$\Psi(3770)$ 数据，寻找D介子味道改变中性流(FCNC)和轻子数不守恒(LNV)的稀有衰变，包括4个D^0介子的衰变模式($\overline{\mathrm{K}}^0\mathrm{e}^+\mathrm{e}^-$, $\Phi\mathrm{e}^+\mathrm{e}^-$, $\rho^0\mathrm{e}^+\mathrm{e}^-$ 和$\overline{\mathrm{K}}^{*0}\mathrm{e}^+\mathrm{e}^-$)和6个$\mathrm{D}^+$介子的衰变模式($\mathrm{K}^-\mathrm{e}^+\mathrm{e}^+$, $\mathrm{K}^+\mathrm{e}^+\mathrm{e}^-$, $\pi^-\mathrm{e}^+\mathrm{e}^+$, $\pi^+\mathrm{e}^+\mathrm{e}^-$, $\mathrm{K}^{*-}\mathrm{e}^+\mathrm{e}^+$和$\mathrm{K}^{*+}\mathrm{e}^+\mathrm{e}^-$). 没有发现信号，给出90%置信水平的上限. 其中，D^+介子的两个衰变模式$\mathrm{D}^+\to\mathrm{K}^{*-}\mathrm{e}^+\mathrm{e}^+$和$\mathrm{D}^+\to\mathrm{K}^{*+}\mathrm{e}^+\mathrm{e}^-$的上限是首次测量.

关键词　稀有衰变　D介子　上限

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1)Iowa State University, Ames, IA 50011-3160, USA
2)E-mail: hekl@ihep.ac.cn
3)Purdue University, West Lafayette, IN 47907, USA
4)Cornell University, Ithaca, NY 14853, USA
5)Laboratoire de l'Accélérateur Linéaire, F-91898 Orsay, France
6)联系人, E-mail: jyzhang@mail.ihep.ac.cn
7)University of Michigan, Ann Arbor, MI 48109, USA
8)DESY, D-22607, Hamburg, Germany