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Search for the decays $\eta' \to e^+ e^-$ and $\eta \to e^+ e^-$ at the VEPP-2000 $e^+ e^-$ collider

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Abstract: A search for the rare decay $\eta' \to e^+ e^-$ has been performed with the SND detector at the VEPP-2000 $e^+ e^-$ collider. The inverse reaction $e^+ e^- \to \eta'$ and η' five decay chains have been used for this search. The upper limit $\Gamma_{\eta' \to e^+ e^-} < 0.002$ eV at the 90% confidence level has been set. A sensitivity of SND in a search for $\eta \to e^+ e^-$ decay has been studied. For this purpose a data sample with an integrated luminosity of 108 nb^{-1} collected in the center-of-mass energy range 520-580 MeV was analyzed. No background events for the reaction $e^+ e^- \to \eta$ with decay $\eta \to \pi^0 \pi^0 \pi^0$ have been found. In the absence of background, a sensitivity to $B(\eta \to e^+ e^-)$ of 10^{-6} can be reached during two weeks of VEPP-2000 operation.

Key words: VEPP-2000; SND; $e^+ e^-$; η'; η; electronic width

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在 VEPP-2000 正负电子对撞机上寻找 $\eta' \to e^+ e^-$ 和 $\eta \to e^+ e^-$

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摘要:在 VEPP-2000 正负电子对撞机上,用 SND 探测器研究了稀有衰变 $\eta' \to e^+ e^-$,研究中使用了逆过程 $e^+ e^- \to \eta'$ 和 η' 的五个衰变链. 90% 的置信度的 $\Gamma_{\eta' \to e^+ e^-}$ 上限被设定为 0.002 eV;还研究了用 SND 寻找 $\eta \to e^+ e^-$ 过程的灵敏度,为此分析了质心能量 520-580 MeV 之间积分亮度为 108 nb^{-1} 的数据,没有发现当 $\eta \to \pi^0 \pi^0 \pi^0$ 时,衰变 $e^+ e^- \to \eta$ 过程的本底事例. 在无本底情况下, VEPP-2000 运行两周时 $B(\eta \to e^+ e^-)$ 灵敏度即可达到 10^{-6}.

关键词:VEPP-2000; SND; 正负电子; 电子分宽度

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0 Introduction

Decays of pseudoscalar mesons to the pair of leptons $P \to l^+l^-$ are rare. In the standard model(SM) these decays proceed through the two-photon intermediate state as shown in Fig. 1 and therefore are suppressed as α^2 relative to the $P \to \gamma\gamma$ decays, where α is the fine structure constant. An additional suppression of $(m_l/m_P)^2$ arises from the approximate helicity conservation, where m_l and m_P are the lepton and meson masses, respectively. So, due to the low probabilitysuch decays are sensitive to possible contributions to new physics beyond the SM[1-2].

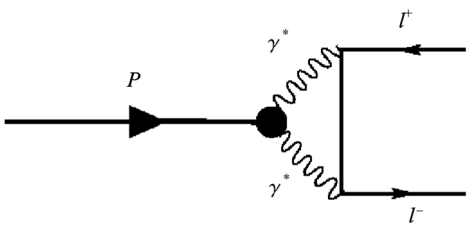

Fig. 1 Leading order QED contribution driving $P \to l^+l^-$ decays

The ranges of predictions for the $P \to l^+ l^-$ branching fractions obtained in different form-factors models[3-4] are listed in Tab. 1. For comparison, the last column of Tabl. 1 contains the current experimental values of the branching fractions. The value of $B(\pi^0 \to e^+e^-)$ differs from the theoretical prediction by about three standard deviations. This can have different explanations connected with theoretical uncertainty[5] or/and with new physics contributions[1-2].

Tab. 1 The theoretical predictions and experimental values for the $P \to l^+l^-$ branching fractions

parameter	prediction	experoment
$B(\pi^0 \to e^+e^-) \times 10^8$	6.23-6.38	7.49 ± 0.38[6]
$B(\eta \to e^+e^-) \times 10^9$	4.60-5.24	<2300[7]
$B(\eta \to \mu^+\mu^-) \times 10^7$	4.64-5.12	5.8 ± 0.8[8]
$B(\eta' \to e^+e^-) \times 10^{10}$	1.15-1.86	<56[9-10]
$B(\eta' \to \mu^+\mu^-) \times 10^7$	1.14-1.36	

This paper is devoted to the recent search for the $\eta' \to e^+e^-$ decay[9] with the SND detector[11-12] at the VEPP-2000 e^+e^- collider[13], in which the inverse reaction $e^+e^- \to \eta'$ is used. Also we consider the recent study of SND sensitivity in search for the $\eta \to e^+e^-$ decay with the use of the same technique[14].

1 SND detector

A detailed description of the SND detector can be found in Refs. [11-12]. It is a nonmagnetic detector, the main part of which is a three-layer spherical electromagnetic calorimeter based on NaI(Tl) crystals. The solid angle covered by the calorimeter is 90% of 4π. Its energy resolution for photons is $\sigma_E/E = 4.2\%/(E\ \mathrm{GeV})^{1/4}$, and the angular resolution is about 1.5°. The directions of charged particles are measured by a tracking system, which consists of a 9-layer drift chamber and a proportional chamber with readout from cathode strips. The tracking system covers a solid angle of 94% of 4π. The calorimeter is surrounded by a muon system, which is used, in particular, for cosmic-background suppression.

2 Search for $\eta' \to e^+e^-$ decay

For search for the decay $\eta' \to e^+e^-$ data with an integrated luminosity of about 2.9 pb^{-1} are used. They were accumulated in 2013 at the c. m. energy close to $m_{\eta'}c^2 = 957.78 \pm 0.06$ MeV[8]. During the data taking period the beam energy was monitored with an absolute accuracy of about 60 keV by the back-scattering-laser-light system[15]. As the collider energy spread (FWHM = 0.590 MeV) is significantly larger than the η' width $\Gamma_{\eta'} = (0.198 \pm 0.009)$ MeV[8], the resulting cross section is proportional to the electronic width.

$$\sigma_{\mathrm{vis}}(\mathrm{nb}) = (6.38 \pm 0.23)\Gamma_{\eta' \to e^+e^-}(\mathrm{eV}) \quad (1)$$

It should be noted that the radiative corrections and the energy spread lead to a reduction of the cross section compared to the Born one by a factor of four.

The search for the process $e^+e^- \to \eta'$ is performed in five decay chains: $\eta' \to \eta\pi^+\pi^-$ with the η decays to $\gamma\gamma$ and $3\pi^0$, and $\eta' \to \eta\pi^0\pi^0$ with the η decays to $\pi^+\pi^-\pi^0$, $\gamma\gamma$ and $3\pi^0$.

Detailed description of selection criteria for all decay chains can be found in Ref. [9]. Only main selection parameters will be discussed in this paper.

2.1 Decay chain $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$

For events passing a preliminary selection the kinematic fit to the $e^+e^- \to \pi^+\pi^-\eta$ hypothesis is performed. The input parameters for kinematic fit are

the polar and azimuthal angles of charged tracks and the angles and energies of photons measured in the calorimeter. The quality of the fit is characterized by the parameter χ^2_η. Another important parameter used for the final selection is the sum of energy depositions of charged particles in the second and third layers of the calorimeter $E_{2+3,\mathrm{char}}$. Since pions in the process under study are soft, they stop predominantly in the first calorimeter layer. The two-dimensional distributions of the parameters χ^2_η and $E_{2+3,\mathrm{char}}$ for data events and simulated events of the process under study are shown in Fig. 2. The rectangle in the bottom left corner corresponds to the selection criteria applied. No data events are selected.

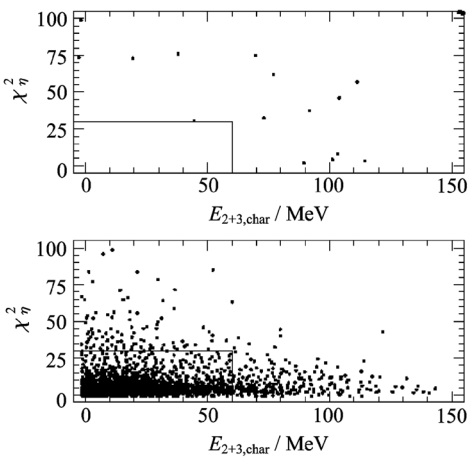

Fig. 2 The two-dimensional distribution of the parameters

In Fig. 2, the two-dimensional distribution of χ^2_η versus $E_{2+3,\mathrm{char}}$ for data events (top) and simulated events of the $e^+e^-\to\eta'\to\pi^+\pi^-\eta$, $\eta\to\gamma\gamma$ process (bottom). The rectangle in the bottom left corner of the plot corresponds to the selection criteria used.

The dominant sources of background for this decay mode are the processes $e^+e^-\to\eta\gamma$, $\eta\to\pi^+\pi^-\pi^0$ and $e^+e^-\to\pi^+\pi^-\pi^0\pi^0$. Additional fake photons can appear as a result of the splitting of electromagnetic showers, nuclear interaction of pions in the calorimeter, or superimposing beam-generated background. The number of background events estimated using MC simulation is 0.7 ± 0.1 and 0.10 ± 0.05 for the first and second processes, respectively.

There is also the nonresonant reaction $e^+e^-\to\pi^+\pi^-\eta$, that proceeds through the $\rho\eta$ intermediate state. It is suppressed due to the small phase space of the final particles. The contribution of the nonresonant process is estimated to be 0.2 events.

2.2 Decay chain $\eta'\to\pi^+\pi^-\eta$, $\eta\to3\pi^0$

For preliminary selected events the kinematic fit is performed to the hypothesis $e^+e^-\to\pi^+\pi^-3\pi^0$. The two-dimensional distributions of χ^2 of the kinematic fit ($\chi^2_{3\pi^0}$) versus the three π^0 invariant mass ($M_{3\pi^0}$) for data events and simulated events of $e^+e^-\to\eta'\to\pi^+\pi^-\eta$, $\eta\to3\pi^0$ processes are shown in Fig. 3.

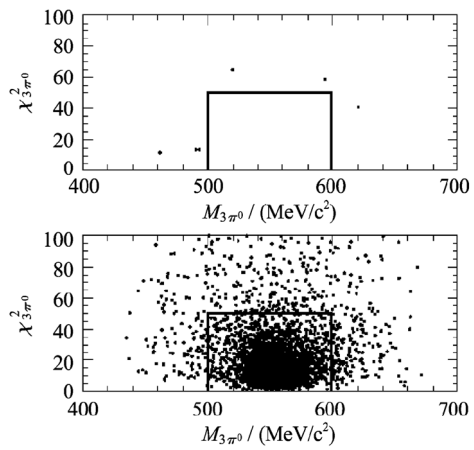

Fig. 3 The two-dimensional distribution of the parameters

In Fig. 3, the two-dimensional distribution of the parameters $\chi^2_{3\pi^0}$ and $M_{3\pi^0}$ for data events (top) and simulated $\eta'\to\pi^+\pi^-\eta$, $\eta\to3\pi^0$ events (bottom). The rectangle corresponds to the selection criteria used: $\chi^2_{3\pi^0}<50$ and $500<M_{3\pi^0}<600$ MeV/c^2.

The dominant background source for the $\pi^+\pi^-\pi^0\pi^0\pi^0$ final state is the process $e^+e^-\to\pi^+\pi^-\pi^0\pi^0$. The number of background events obtained using MC simulation is 2.7 ± 0.5. The contribution of the nonresonant background from the $e^+e^-\to\pi^+\pi^-\eta$ process discussed above is about 0.1 events.

2.3 Decay chain $\eta'\to\pi^0\pi^0\eta$, $\eta\to\gamma\gamma$

For events passing initial selection the kinematic fit to the $e^+e^-\to\eta'\to\eta\pi^0\pi^0\to6\gamma$ hypothesis is performed. The quality of the fit is characterized by the parameter $\chi^2_{\eta\pi^0\pi^0}$. The distributions of this parameter for data events, simulated signal events, and simulated background events from the process $e^+e^-\to\eta\gamma$, $\eta\to3\pi^0$ are shown in Fig. 4. The condition $\chi_{\eta\pi^0\pi^0}<15$ is applied. No data events satisfying the selection criteria

have been found.

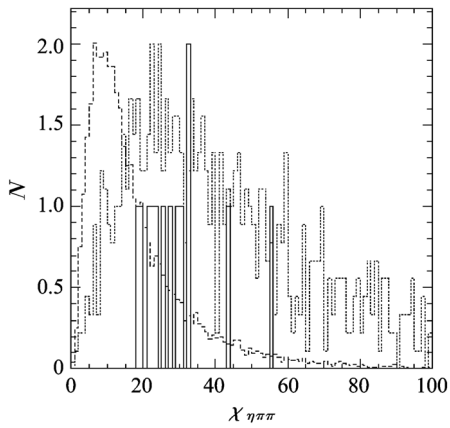

Fig. 4　The $\chi^2_{\eta\pi^0\pi^0}$ distribution

In Fig. 4, the $\chi^2_{\eta\pi^0\pi^0}$ distribution for data events (solid histogram), simulated signal $e^+e^- \to \eta' \to 2\pi^0\eta \to 6\gamma$ events (dashed histogram), simulated background events from the process $e^+e^- \to \eta\gamma$, $\eta \to 3\pi^0$ (dotted histogram).

The main background sources for this decay mode are the processes $e^+e^- \to \eta\gamma \to 3\pi^0\gamma$ and $e^+e^- \to \pi^0\pi^0\gamma$. The number of background events from these sources is calculated to be 1.3 ± 0.3 and 0.4 ± 0.1, respectively.

2.4　Decay chain $\eta' \to \pi^0\pi^0\eta$, $\eta \to 3\pi^0$

For this decay mode with ten photons in the final state there is no background from e^+e^- annihilation. The main source of background is cosmic-ray showers. We select events containing nine or more photons and no tracks in the drift chamber. The total energy deposition $E_{\rm cal}$ and the event momentum $P_{\rm cal}$ calculated using energy depositions in the calorimeter crystals must satisfy the following conditions:

$$\left.\begin{aligned} &0.7 < E_{\rm cal} < E_{\rm cm} < 1.2,\ cP_{\rm cal} < E_{\rm cm} \\ &E_{\rm cal}/E_{\rm cm} - cP_{\rm cal}/E_{\rm cm} > 0.7 \end{aligned}\right\} \quad (2)$$

No data events are selected after applying these criteria.

2.5　Upper limit

Since the number of selected data events is equal to zero, we set the upper limit on the cross section. The technique of Cousins and Highland[16] following the implementation of Barlow[17] is used to calculate the limit with all uncertainties included:

$$\sigma^{\rm exp}_{\rm vis} < 12.7 \text{ pb at } 90\% \text{ CL} \quad (3)$$

The limit on the cross section is translated using Eq. (1) to the upper limit on the η' electronic width

$$\Gamma_{\eta' \to e^+e^-} < 0.0020 (\text{eV}) \text{ at } 90\% \text{ CL} \quad (4)$$

The obtained limit is slightly better than the limit set recently in the CMD-3 experiment $\gamma_{\eta' \to e^+e^-} < 0.0024$ eV[10].

Using the Eq. (1) we combine the SND and CMD-3 data and obtain the combined upper limits on the electronic width

$$\Gamma_{\eta' \to e^+e^-} < 0.0011 (\text{eV}) \text{ at } 90\% \text{ CL} \quad (5)$$

and the branching fraction [$\gamma_{\eta'} = (0.198 \pm 0.009)$ MeV[8]].

$$B(\eta' \to e^+e^-) < 5.6 \times 10^{-9} \text{ at } 90\% \text{ CL} \quad (6)$$

The obtained upper limit is most stringent but still 30-50 times larger than theoretical predictions[1-2] made in the framework of the standard model.

3　Search for $\eta \to e^+e^-$ decay

For this study, VEPP-2000 parameters at c. m. energy close to $m_\eta c^2 = 548.862 \pm 0.018$ MeV[8] such as luminosity, accuracy of the energy setting, energy spread, are important. In 2013 SND did not record data exactly at this energy. Therefore, we analyze data from four energy points near $m_\eta c^2$, with c. m. energies of 520, 540, 560, and 580 MeV. The integrated luminosity collected at these energy points measured using the reaction $e^+e^- \to \gamma\gamma$ is 108.1 ± 2.0 nb^{-1}.

In the proposed experiment the collider energy must be set and monitored with an accuracy better than the collider c. m. energy spread of about 150 keV. This is provided by the beam-energy-measurement system described above.

The most suitable η decay mode for the search for the $e^+e^- \to \eta$ reaction at SND is $\eta \to \pi^0\pi^0\pi^0 \to 6\gamma$, for which physical background is small. The main source of background is cosmic-ray events. For the search for $e^+e^- \to \eta$, events with six or more detected photons and with the energy deposition in the calorimeter larger than $0.6E$ are selected. Background from events with charged particles is rejected by the selection condition that the number of fired wires in the drift chamber is less than four. Cosmic-ray background is suppressed by the veto from the muon detector.

For events passing the preliminary selection, a kinematic fit to the $e^+e^- \to \pi^0\pi^0\pi^0 \to 6\gamma$ hypothesis is performed. The quality of the kinematic fit is

characterized by the parameter χ^2. The condition $\chi^2 < 100$ is used to select η candidates. No events satisfying the selection criteria are found. So, we set the upper limit on the $e^+e^- \to \eta$ cross section

$$\sigma_{\exp} < 170 \text{ pb at } 90\% \text{ CL} \quad (7)$$

corresponding to $N_s = 0$ and integrated luminosity 108 nb^{-1}. Using the same technique as in section 2.5, we can estimate sensitivity to the search for the decay $\eta \to e^+e^-$ to be

$$B(\eta \to e^+e^-) < 2.9 \times 10^{-6} \text{ at } 90\% \text{ CL} \quad (8)$$

This result is close to the upper limit $B(\eta \to e^+e^-) < 2.3 \times 10^{-6}$ set recently in the HADES experiment[7]. With a VEPP-2000 luminosity of $0.34 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}$ the current upper limit can be reached in a week of data taking. In two weeks a sensitivity at the level of 10^{-6} can be reached.

4 Conclution

A search for the rare decay $\eta' \to e^+e^-$ has been performed with the SND detector at the VEPP-2000 e^+e^- collider. The inverse reaction $e^+e^- \to \eta'$ and five decay chains of η' have been used for this search. The following upper limit has been set on the decay width: $\Gamma_{\eta' \to e^+e^-} < 0.002$ eV at the 90% confidence level. Also a sensitivity of SND in a search for decay $\eta \to e^+e^-$ has been studied. For this perpose we have analyzed a data sample with an integrated luminosity of 108 nb^{-1} collected with the SND detector in the center-of-mass energy range 520-580 MeV. There are no background events for the reaction $e^+e^- \to \eta$ with decay $\eta \to \pi^0\pi^0\pi^0$ have been found. In the absence of background, a sensitivity to $B(\eta \to e^+e^-)$ of 10^{-6} can be reached duringtwo weeks of VEPP-2000 operation.

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