Search for Lepton Flavor Violation Process $e^+e^- \rightarrow e\mu$ in the Energy Region $\sqrt{s} = 984 – 1060$ MeV and $\phi \rightarrow e\mu$ decay

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Abstract

The search for lepton-flavor-violation process $e^+e^- \rightarrow e\mu$ in the energy region $\sqrt{s} = 984 – 1060$ MeV with SND detector at VEPP-2M $e^+e^-$ collider is reported. The model independent 90% CL upper limits on the $e^+e^- \rightarrow e\mu$ cross section, $\sigma_{e\mu} < 11$ pb, as well as on the corresponding $\phi \rightarrow e\mu$ branching fraction, $B(\phi \rightarrow e\mu) < 2 \times 10^{-6}$, for the final particles polar angles $55^\circ < \theta < 125^\circ$, were obtained.
For the most of fundamental fermions (quarks and neutrinos) the processes with flavor violation, quarks decays and neutrinos oscillation, are known. At the same time the LFV processes with charged leptons has never been observed. Theoretically the processes of this kind are not strictly forbidden and can occur in many extensions of the Standard Model.

For the LFV hunting, the decays of $\mu$ and $\tau$ leptons, as well as of the $Z$-boson and of various quark-antiquark mesons ($K, B, D, \eta, J/\psi, \Upsilon$), along with a conversion process $\mu N \rightarrow e N$ are used \cite{1, 2}. The annihilation processes $e^+ e^- \rightarrow e\mu, e\tau, \mu\tau$ are also suitable for this purpose. Theoretically these processes and related gauge boson and vector meson decays were studied, for example, in \cite{3}. On the experimental side, the searches for the decays $J/\psi \rightarrow e\mu, e\tau, \mu\tau$ \cite{4}, $\Upsilon \rightarrow \mu\tau$ \cite{5}, $Z \rightarrow e\mu, e\tau, \mu\tau$ \cite{6}, as well as for the annihilation processes $e^+ e^- \rightarrow e\tau, \mu\tau$ in the $\Upsilon(4S)$ energy domain \cite{7}, and for the processes $e^+ e^- \rightarrow e\mu, e\tau, \mu\tau$ in the energy region $\sqrt{s} = 189 - 209$ GeV \cite{8} were performed. However, in the energy region below the $J/\psi$ production threshold such studies were not done yet. In the $\phi(1020)$-meson energy domain, it is possible to search for the LFV process $e^+ e^- \rightarrow e\mu$ and the corresponding decay $\phi \rightarrow e\mu$ (Fig.1).

![Diagram](image)

**FIG. 1:** The diagrams of the $e^+ e^- \rightarrow e\mu$ process.

Existing stringent bounds on LFV $\mu \rightarrow 3e$ decay can be transformed to a severe constraint on the two-body $\phi \rightarrow e\mu$ branching fraction: $B(\phi \rightarrow e\mu) \leq 4 \times 10^{-17}$ unless some magic cancellations take place in the $\mu \rightarrow 3e$ decay amplitude \cite{9}. At first sight, such a strong constraint makes doubtful any experimental effort to search this decay. However, the magic cancellations mentioned above, although unlikely, cannot be absolutely excluded.

This work reports the results of studies of the process $e^+ e^- \rightarrow e\mu$ in the energy region $\sqrt{s} \sim 1$ GeV with SND detector at $e^+ e^-$ collider VEPP-2M.
The SND detector [10] operated from 1995 to 2000 at the VEPP-2M [11] collider in the energy range $\sqrt{s}$ from 360 to 1400 MeV. The detector contains several subsystems. The tracking system includes two cylindrical drift chambers. The three-layer spherical electromagnetic calorimeter is based on NaI(Tl) crystals. The muon system consists of plastic scintillation counters and two layers of streamer tubes. The calorimeter energy and angular resolutions depend on the photon energy as $\sigma_E/E(\%) = 4.2%/\sqrt{E(\text{GeV})}$ and $\sigma_\phi,\theta = 0.82^\circ/\sqrt{E(\text{GeV})} \oplus 0.63^\circ$. The tracking system angular resolution is about $0.5^\circ$ and $2^\circ$ for azimuthal and polar angles respectively.

This work is based on the data collected in the scans of the $\phi$-meson energy region. The total integrated luminosity used is $IL = 8.5$ pb$^{-1}$. The luminosity was measured using the process $e^+e^- \rightarrow e^+e^-$ with the accuracy of about 2%.

In the reaction $e^+e^- \rightarrow e\mu$ the final particles are detected by the tracking system and have substantively different energy depositions in the calorimeter. The muon system detects muons with a probability of greater than 90%, while electrons are detected by this system with the probability of less than 0.2%. To search for $e^+e^- \rightarrow e\mu$ process, the so called collinear events containing two charged particles were used. We assume that the charged particle with higher energy deposition in the calorimeter (particle number one) is an electron, while the particle with lower energy deposition (particle number two) is a muon. The events were selected using the following criteria (subscripts 1 and 2 denote the particle number):

1. $N_{cha} = 2$, where $N_{cha}$ is the number of the charged particles originated from the interaction point: $|z_{1,2}| < 10$ cm and $r_{1,2} < 1$ cm. Here $z$ is the coordinate of the charged particle production point along the beam axis (the longitudinal size of the interaction region $\sigma_z$ about 2.5 cm), $r$ is the distance between the charged particle track and the beam axis in the $r - \phi$ plane;

2. $|\Delta\theta| = |180^\circ - (\theta_1 + \theta_2)| < 20^\circ$, where $\theta$ is the particle polar angle;

3. $|\Delta\phi| = |180^\circ - |\phi_1 - \phi_2|| < 5^\circ$, where $\phi$ is the particle azimuthal angle;

4. $55^\circ < \theta_{1,2} < 125^\circ$;

5. the angular region $240^\circ < \phi_{1,2} < 300^\circ$ not covered with the muon system was excluded;

6. the muon system was hit by the second particle and was not hit by the first one;
7. $20 < E^I_2 < 50 \text{ MeV}$, $40 < E^{II}_2 < 80 \text{ MeV}$ and $50 < E^{III}_2 < 90 \text{ MeV}$, where $E^j_i$ are the energy depositions in the calorimeter layers, $i$ denotes the particle number and $j = I, II, III$ is the layer number;

8. $E^I_1 > 70 \text{ MeV}$, $E^{II}_1 > 130 \text{ MeV}$ and $20 < E^{III}_1 < 100 \text{ MeV}$.

As a result 146 events were selected. The visible cross section (the events number divided by the integrated luminosity) varies weakly with beam energy. No contribution from the $\phi$-meson decays $\phi \to K^+K^-, K_SK_L, \pi^+\pi^-\pi^0$ is seen. This agrees with the expectations from the Monte-Carlo (MC) simulation. The events from the background process $e^+e^- \to \pi^+\pi^-$ can pass the selection if one of the pions looses its energy due to the ionization, while the other pion – due to nuclear interactions.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2.png}
\caption{The first particle $E^*_e/E_e$ for selected events (dots with errors). Solid curve – fit by a sum of the distribution for electrons (histogram) and Gaussian. Dashed curve – fit by a sum of the distribution for electrons (histogram) and third-order polynomial.}
\end{figure}

In order to obtain the cross section of the process $e^+e^- \to e\mu$ in the whole energy region $\sqrt{s} = 984 - 1060 \text{ MeV}$, the $E^*_e/E_e$ distribution (Fig.2) was analyzed. Here $E^*_e$ and $E_e$ are the electron energies measured by the calorimeter and expected from the process kinematics.
respectively. To obtain the number of $e^+e^- \rightarrow e\mu$ events ($N_{e\mu}$), the $E^*_e/E_e$ spectrum was fit by a sum of distributions for electrons and background. The distribution for electrons was obtained using experimental data. The background was approximated either by Gaussian function or by a third-order polynomial. The coefficients of the background function and $N_{e\mu}$ were free parameters of the fit. When the background was approximated with Gaussian, it was found that

$$N_{e\mu} = 12 \pm 14^{+16}_{-16}. $$

This corresponds to the upper limit

$$N_{e\mu} < 30 \ \text{CL}=90\%. $$

In the case of the third-order polynomial it was obtained

$$N_{e\mu} = 7 \pm 11^{+9}_{-9}. $$

The corresponding upper limit is

$$N_{e\mu} < 21 \ \text{CL}=90\%. $$

The higher limit $N_{e\mu} < 30$ was used for the further considerations.

Tracking system detection efficiency for the $e^+e^- \rightarrow e\mu$ events, $\varepsilon_{\text{track}}$ (cuts 1 – 5), was obtained from MC simulation \[10, 12\]. The MC events were generated with $1 + \cos^2 \theta$ distribution. The detection efficiency obtained for the angular region $55^\circ < \theta < 125^\circ$ actually does not depend on the model of the $\theta$-distribution. It’s equal to $\varepsilon_{\text{track}} = 0.59$. The experimental and simulated $\theta$, $\Delta \theta$ and $\Delta \phi$ distributions for the processes $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow \pi^+\pi^-$, $e^+e^- \rightarrow \mu^+\mu^-$ are in a good agreement \[12, 13\]. The systematic uncertainty associated with $\varepsilon_{\text{track}}$ determination is estimated to be less than 3 %.

The efficiencies of muon and electron detection by the muon system were obtained using $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow e^+e^-$ data events. The $e^+e^- \rightarrow \mu^+\mu^-$ events were selected according to the criteria 1–5 described above. The additional cut $r_{1,2} < 0.1$ cm was used for suppression of the cosmic ray background. The cut 7 was imposed on both particles. One particle was required to hit the muon system, while the other particle was used to determine the detection efficiency. The residual cosmic background was subtracted using the distribution of the $z$-coordinate of the particles production point \[13\]. Detection efficiency $\varepsilon_{\mu_{\text{muon}}}$ depends on the muon energy. Its value varies from 0.90 to 0.95 with the average value
of $\varepsilon_{\mu\text{on}}$ being equal to 0.94. The $e^+e^- \rightarrow e^+e^-$ events were selected by the cuts 1–5 and the condition $E_{1,2}/E_0 > 0.7$. It was found that $1 - \varepsilon_{e\text{on}} = 0.998$.

Probabilities for muons and electrons to pass condition on the energy deposition in the calorimeter were obtained in a similar way. The $e^+e^- \rightarrow \mu^+\mu^-$ events were selected using cuts 1–5 and additional requirements $r_{1,2} < 0.2$ cm, $E_{1,2}/E_0 < 0.6$. It was required that the muon system was hit by both particles. The cosmic background was suppressed by the restriction $|\tau_1 - \tau_2| < 5$ ns, where $\tau_{1,2}$ are time intervals between the signals from the scintillation counters and the beam collision moment. The probability for muons to pass cut 7 was found to be $\varepsilon_{\mu\text{cal}} = 0.86$. The $e^+e^- \rightarrow e^+e^-$ events were selected using criteria 1–5 and requiring that the muon system was not fired by any particle and that the energy deposition of a randomly chosen particle was greater than $0.85 \times E_0$. Other particle was used to obtain probability to satisfy the criterion 8, $\varepsilon_{e\text{cal}} = 0.70$. The values of $\varepsilon_{\mu\text{cal}}$ and $\varepsilon_{e\text{cal}}$ do not depend on the beam energy.

![FIG. 3: The visible cross section obtained after additional cut $0.9 < E_*/E_e < 1.1$. The solid curve is expected resonance line shape corresponding to the upper limit on $B(\phi \rightarrow e\mu)$, dashed curve is background approximation.](image_url)
The detection efficiency of the $e^+e^- \rightarrow e\mu$ process was calculated as follows

$$\varepsilon_{e\mu} = \varepsilon_{\text{track}} \times \varepsilon_{\mu}^{\text{muon}} \times (1 - \varepsilon_{\mu}^{\text{muon}}) \times \varepsilon_{\text{cal}}^{\mu} \times \varepsilon_{\text{cal}}^e$$

and the $e^+e^- \rightarrow e\mu$ cross section as

$$\sigma_{e\mu} = \frac{N_{e\mu}}{IL\varepsilon_{e\mu}},$$

where $N_{e\mu} < 30$, $\varepsilon_{e\mu} = 0.31$ (the average value $\varepsilon_{\mu}^{\text{muon}} = 0.94$ was used), $IL = 8.5$ pb$^{-1}$. The following upper limit for the angular region $55^\circ < \theta < 125^\circ$ was obtained

$$\sigma_{e\mu} < 11 \text{ pb} \quad \text{CL}=90\%.$$ 

The upper limit on the $\phi \rightarrow e\mu$ decay was obtained assuming absence of any non-resonance contribution and by using the additional cut $0.9 < E_{e}^{*}/E_0 < 1.1$ (then $\varepsilon_{\text{cal}}^e = 0.64$). The energy dependence of the visible cross section is shown in Fig.3. It was fit by the function:

$$\sigma = \varepsilon_{e\mu} \times (1 + \delta_{\text{rad}}) \times \frac{4\pi\alpha^2}{3s} \left| \frac{3}{\alpha} \sqrt{B(\phi \rightarrow e^+e^-)B(\phi \rightarrow e\mu)} \frac{m_{\phi}\Gamma_{\phi}}{m_{\phi}^2 - s - i\sqrt{s}\Gamma_{\phi}(s)} \right|^2 + P_2(s), \quad (1)$$

where $(1 + \delta_{\text{rad}})$ is the radiative correction factor [14], $P_2(s)$ is a second-order polynomial describing the background, $m_{\phi}$, $\Gamma_{\phi}$ are the $\phi$-meson mass and total width, respectively. The branching ratio and the coefficients of the $P_2(s)$ were free fit parameters. For the angular region $55^\circ < \theta < 125^\circ$, it was obtained

$$B(\phi \rightarrow e\mu) = (0.0 \pm 1.5) \times 10^{-6},$$

which corresponds to the upper limit

$$B(\phi \rightarrow e\mu) < 2 \times 10^{-6} \quad \text{CL}=90\%.$$ 

The presented upper limits do not depend on the angular distribution of the process $e^+e^- \rightarrow e\mu$.

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