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New bounds on lepton flavor violating decays of vector mesons and the Z^0 boson

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We give an estimate for the upper bounds on rates of lepton flavor violating (LFV) decays $M \to \mu^\pm e^\mp$ of vector mesons $M = \rho^0$, ω, ϕ, J/ψ, Υ and the Z^0 boson in a model-independent way, analyzing the corresponding lowest dimension effective operators. These operators also contribute to nuclear $\mu - e$-conversion. Based on this observation and using the existing experimental limits on this LFV nuclear process, we show that the studied two-body LFV decays of vector bosons are strongly suppressed independent on the explicit realization of new physics. The upper limits on the rates of some of these decays are significantly more stringent than similar limits known in the literature. In view of these results, experimental observation of the two-body LFV decays of vector bosons looks presently unrealistic.

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It is well known that lepton flavor violation (LFV) is strongly suppressed in the standard sodel (SM) by a very small neutrino mass. Therefore, the observation of any LFV process would be a signal of physics beyond the SM. Various avenues can be devised to study these issue. When elaborating on a strategy for searches of LFV, these processes should be considered, which have the best prospects for discovery. This includes both the prospects for experimental identification of the LFV events and possible theoretical limitations on the corresponding rates. Latter considerations may, for example, deal with model-independent relations between different processes, some of which are already strongly limited by experimental data.

In the present paper, we study from this point of view LFV decays of vector mesons and the Z^0-boson

$$M \to \mu^\pm e^\mp \quad \text{with} \quad M = \rho^0, \omega, \phi, J/\psi, \Upsilon, Z^0. \tag{1}$$

The abundant production of vector mesons and Z^0-bosons in current experiments naturally suggests that we search for their two-body decays in the $\mu^\pm e^\mp$ final state, which is rather convenient for event identification. Recently, the SND Collaboration at the BINP (Novosibirk) [1] reported on the search for the LFV process $e^+e^- \to e\mu$ in the energy region $\sqrt{s} = 984$–1060 MeV at the VEPP-2M e^+e^- collider. They give a model-independent upper limit on the $\phi \to e\mu$ branching fraction of

$$\mathrm{Br}\,(\phi \to e\mu) < 2 \times 10^{-6}. \tag{2}$$

Also, there exist experimental limits for the $e\mu$ decay mode of J/ψ and of the Z^0 boson [2]:

$$\mathrm{Br}(J/\psi \to e\mu) < 1.1 \times 10^{-6}, \quad \mathrm{Br}(Z^0 \to e\mu) < 1.7 \times 10^{-6} \tag{3}$$

and $\mu\tau$ decay mode of Υ [2]:

$$\mathrm{Br}\,(\Upsilon \to \mu\tau) < 6.0 \times 10^{-6}. \tag{4}$$

In the near future, this list may be extended by the results of other experimental collaborations. However, a natural question, which arises in this context, touches upon the prospects of this category of searches in view of possible theoretical limitations on the rates of these LFV decays.

In the literature, there already exist stringent limits of this sort. For example, unitarity relations between the vector boson LFV decays given in (1) and the pure leptonic LFV decay $\mu \to 3e$ have been exploited in Ref. [3]. From the existing experimental bounds on the latter process, the following stringent bounds were deduced [3]:

$$\mathrm{Br}(\phi \to e\mu) \le 4 \times 10^{-17}, \quad \mathrm{Br}(J/\psi \to e\mu) \le 4 \times 10^{-13},$$
$$\mathrm{Br}(\Upsilon \to e\mu) < 2 \times 10^{-9}, \quad \mathrm{Br}(Z^0 \to e\mu) < 5 \times 10^{-13}. \tag{5}$$

In the present article, we approach the LFV decays (1) from another point of view relating these processes to nuclear $\mu - e$ conversion, which is tightly constrained experimentally [4].

In Refs. [5,6] , we studied the LFV process of nuclear $\mu^- - e^-$ conversion in the framework of an effective Lagrangian approach without referring to any specific realization of physics beyond the SM responsible for LFV. We examined the impact of specific hadronization prescriptions on new physics contributions to nuclear $\mu^- - e^-$ conversion and stressed the importance of vector and scalar meson exchange between lepton and nucleon currents. In particular, we derived limits on various LFV

*On leave of absence from Department of Physics, Tomsk State University, 634050 Tomsk, Russia couplings of vector mesons to the $\mu - e$ current using existing experimental data on $\mu^- - e^-$ conversion in nuclei. The purpose of the present paper is to use these limits to set upper bounds on the rates of the vector boson LFV decays given in (1). In Ref. [7] we already indicated in this framework upper limits on the rates of the LFV decays of ρ^0, ω and ϕ mesons. Here we extend our analysis to J/ψ, Υ and the Z^0 boson and compare our results with exiting experimental bounds (2) and (3), and the theoretical predictions of Ref. [3].

The contribution of vector bosons to $\mu^- - e^-$ conversion in nuclei is shown in Fig. 1. In this diagram the upper vertex corresponds to the LFV interactions of vector bosons $M = \rho^0$, ω, ϕ, J/ψ, Υ, Z^0 with e, μ given by the following model-independent Lagrangian [3,5]:

$$\mathcal{L}_{\rm eff}^{lM} = M^\mu(\xi_V^M j_\mu^V + \xi_A^M j_\mu^A + \text{H.c.}). \tag{6}$$

Here the $\xi_{V,A}^M$ are effective vector and axial couplings of a vector boson M to the LFV lepton currents $j_\mu^V = \bar{e}\gamma_\mu\mu$ and $j_\mu^A = \bar{e}\gamma_\mu\gamma_5\mu$. The possible effect of additional non-minimal derivative couplings of vector bosons to the LFV lepton current will be considered later.

The lower vertex of the diagram in Fig. 1 is described by the nucleon-vector boson Lagrangian [7]:

$$\mathcal{L}_{MNN} = \frac{1}{2}\bar{N}\gamma^\mu N \sum_M g_{MNN} M_\mu, \tag{7}$$

where g_{MNN} are effective couplings. In this Lagrangian we neglected the derivative terms which are irrelevant for coherent $\mu^- - e^-$ conversion. The Lagrangian $\mathcal{L}_{MNN}$ is an extension of the conventional nucleon-vector meson Lagrangian [8–10]. In the case of the light ρ^0, ω, and ϕ mesons we use values for g_{MNN} which are taken from an updated dispersive analysis [9,11]

$$g_{\rho NN} = 4.0, \qquad g_{\omega NN} = 41.8, \qquad g_{\phi NN} = -0.24. \tag{8}$$

In addition, we need an estimate for these effective couplings involving J/ψ, Υ and Z^0. The couplings $g_{J/\psi NN}$ and $g_{\Upsilon NN}$ can be extracted from data [2] on $J/\psi \to N\bar{N}$ and $\Upsilon \to N\bar{N}$ decays:

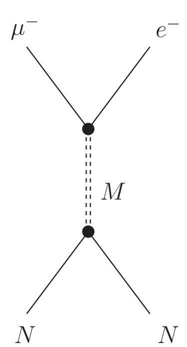

FIG. 1. Contribution of intermediate vector bosons to nuclear $\mu^- - e^-$ conversion.

$$\Gamma(J/\psi \to p\bar{p}) = 202 \pm 9 \text{ eV}, \qquad \Gamma(\Upsilon \to p\bar{p}) < 27 \pm 1 \text{ eV}. \tag{9}$$

The two-body decay rate for $M \to p\bar{p}$, where $M = J/\psi$ or Υ, is given in terms of the effective coupling constants g_{MNN} by:

$$\Gamma(M \to p\bar{p}) = \frac{g_{MNN}^2}{12\pi} m_M \left(1 - \frac{4m_N^2}{m_M^2}\right)^{1/2} \left(1 + \frac{2m_N^2}{m_M^2}\right). \tag{10}$$

Using the central value of $\Gamma(J/\psi \to p\bar{p})$ and the upper limit for $\Gamma(\Upsilon \to p\bar{p})$ [2], we get

$$g_{J/\psi NN} \approx 1.6 \times 10^{-3}, \tag{11}$$

$$g_{\Upsilon NN} < 3.3 \times 10^{-4}. \tag{12}$$

For our purposes the upper bound, as far the latter case, coupling is not sufficient. As it will be seen later from Eq. (20), for the derivation of upper bounds on the effective couplings $\xi_{V,A}$ entering in (6), we need a definite estimate for the value of $g_{\Upsilon NN}$. This can be done on the basis of a QCD analysis of exclusive processes of heavy quarkonia as $M \to p\bar{p}$ [12,13]. The corresponding transition amplitudes are generated by three-gluon annihilation between the heavy and the light quarks. In this approach, the following expression for the coupling g_{MNN} of a heavy quarkonium state M of mass m_M with the nucleon was derived as

$$g_{MNN} = g\alpha_s^3(m_M^2)\frac{f_M}{m_M^5}. \tag{13}$$

Here, $g = 95.4 \text{ GeV}^4$ represents the loop integral over nucleon wave functions. Using data for the leptonic decay constants $f_{J/\psi} = 416.4$ MeV and $f_\Upsilon = 715.5$ MeV [2], we get:

$$g_{J/\psi NN} = 0.14\alpha_s^3(m_{J/\psi}^2), \tag{14}$$

$$g_{\Upsilon NN} = 0.9 \times 10^{-3}\alpha_s^3(m_\Upsilon^2). \tag{15}$$

The above value (14) for the coupling $g_{J/\psi NN}$ coincides with the value (11) extracted from the experimental data for the strong coupling constant $\alpha_s(m_{J/\psi}^2) = 0.226$, which is in a good agreement with the world average of $\alpha_s(m_{J/\psi}^2) \simeq 0.26$ [14]. This exercise can also be regarded as a consistency check of the approaches evaluated in Refs. [12,13]. Similarly, using the central value of the latest result for $\alpha_s(m_\Upsilon^2) = 0.184^{+0.015}_{-0.014}$ [15] extracted from radiative Υ decays, we find from Eq. (15) the value of

$$g_{\Upsilon NN} = 5.6 \times 10^{-6}. \tag{16}$$

This result is significantly smaller than the upper bound (12) set by experiment (for a discussion see also Ref. [16]).

The coupling of a Z^0 boson to nucleons is well known (see, for instance, [17]). Since the axial nucleon current does not contribute to the dominant coherent channel of nuclear $\mu - e$ conversion, we only need the coupling to the vector nucleon current, which in view of Eq. (7) we denote as g_{ZNN}. Neglecting a possible but small contribution of strange and heavy sea quarks in the nucleon, it is given as [17]

$$g_{Z^0NN} = \frac{g}{2\cos\theta_W}(1 - 4\sin^2\theta_W) \approx 0.31. \qquad (17)$$

Here, we used the following values of the SM parameters: $M_W = 80.399$ GeV, $\sin^2\theta_W = 0.2322$, $G_F = 1.16637 \times 10^{-5}$ GeV^{-2}.

Starting from the Lagrangian $\mathcal{L}_{\rm eff}^M = \mathcal{L}_{\rm eff}^{lM} + \mathcal{L}_{MNN}$ of Eqs. (6) and (7) it is straightforward to derive the contribution of the diagram in Fig. 1 to the total $\mu^- - e^-$ conversion branching ratio [5]. To the leading order in the nonrelativistic reduction, the coherent $\mu^- - e^-$ conversion branching ratio takes the form [18]

$$R_{\mu e^-}^{\rm coh} = \frac{\mathcal{Q}}{2\pi}\frac{p_e E_e}{\Gamma(\mu^- \to {\rm capture})}, \qquad (18)$$

where p_e, E_e are 3-momentum and energy of the outgoing electron (for details, see Ref. [5,6]); $\Gamma(\mu^- \to {\rm capture})$ is the total rate of the ordinary muon capture reaction. The factor $\mathcal{Q}$ in Eq. (18) has the form [5,19]

$$\mathcal{Q} = |(\mathcal{M}_p + \mathcal{M}_n)\alpha_{VV}^{(0)} + (\mathcal{M}_p - \mathcal{M}_n)\alpha_{VV}^{(3)}|^2 + |(\mathcal{M}_p + \mathcal{M}_n)\alpha_{AV}^{(0)} + (\mathcal{M}_p - \mathcal{M}_n)\alpha_{AV}^{(3)}|^2. \qquad (19)$$

It contains the nuclear matrix elements $\mathcal{M}_{p,n}$ which have been calculated numerically in Refs. [19] for various nuclei. Here, we consider $\mu^- - e^-$ conversion in ^{48}Ti studied by the SINDRUM II Collaboration [4]. For this nucleus, we have $\mathcal{M}_p \approx 0.104$, $\mathcal{M}_n \approx 0.127$. The $\mathcal{Q}$ factor also contains the LFV lepton-nucleon parameters $\alpha_{VV,AV}$. For the contribution of the vector boson-exchange diagram in Fig. 1, these coefficients are expressed in terms of the LFV couplings $\xi_{V,A}^{\rho,\omega,\phi}$ of Eq. (6) as [5–7]

$$\alpha_{aV}^{(3)} = -\frac{1}{2}\frac{g_{\rho NN}}{m_\rho^2 + m_\mu^2}\xi_a^\rho, \quad \alpha_{aV}^{(0)} = -\frac{1}{2}\sum_H \frac{g_{HNN}}{m_H^2 + m_\mu^2}\xi_a^H, \quad (20)$$

where $a = V, A$; $H = \omega, \phi, J/\psi, \Upsilon, Z^0$; m_M and m_μ the vector boson and muon masses, respectively.

In Ref. [5], we extracted upper limits on the couplings $\alpha_{aV}^{(i)}$ from the experimental upper bounds on $\mu^- - e^-$ conversion in ^{48}Ti reported by the SINDRUM II Collaboration [4]. These limits can be translated into bounds on the LFV couplings $\xi_{V,A}^{\rho,\omega,\phi}$. Assuming that no accidental cancellations occur between the different terms in (20) and using the values of the vector boson-nucleon couplings from Eq. (8), (11), (16), and (17), we get for nonderivative couplings

$$\begin{aligned} &\xi_a^\rho \le 3.6 \times 10^{-12}, && \xi_a^\omega \le 3.6 \times 10^{-14}, \\ &\xi_a^\phi \le 1.0 \times 10^{-11}, && \xi_a^{J/\psi} \le 1.4 \times 10^{-8}, \\ &\xi_a^\Upsilon \le 3.5 \times 10^{-5}, && \xi_a^{Z^0} \le 6.4 \times 10^{-8}. \end{aligned} \qquad (21)$$

Note that the Lagrangian (6) also governs the LFV decay $M \to e\mu$ of vector bosons. Thus, using the limits from Eq. (21) we can set upper bounds on the rates of these two-body decays. Their branching ratios are given by:

$${\rm Br}(M \to e\mu) \simeq \frac{(\xi_V^M)^2 + (\xi_A^M)^2}{12\pi\Gamma_{\rm tot}^M} m_M\left(1 - \frac{3}{2}r_M^2\right), \qquad (22)$$

where $r_M = m_\mu/m_M$ and $\Gamma_{\rm tot}^M$ is the total decay width of boson M. Here, we neglect the electron mass. With the limits set by Eq. (21) we get the following upper limits on the branching ratios of the vector boson LFV decays

$$\begin{aligned} {\rm Br}(\rho^0 \to e\mu) &\le 3.5 \times 10^{-24}, \\ {\rm Br}(\omega \to e\mu) &\le 6.2 \times 10^{-27}, \\ {\rm Br}(\phi \to e\mu) &\le 1.3 \times 10^{-21}, \\ {\rm Br}(J/\psi \to e\mu) &\le 3.5 \times 10^{-13}, \\ {\rm Br}(\Upsilon \to e\mu) &\le 3.9 \times 10^{-6}, \\ {\rm Br}(Z^0 \to e\mu) &\le 8.0 \times 10^{-15}. \end{aligned} \qquad (23)$$

The limit for the $J/\psi \to e\mu$ mode is compatible with the corresponding number extracted from $\mu \to 3e$ as done in Ref. [3] and shown in Eq. (5). For the cases of the $\phi \to e\mu$ and $Z^0 \to e\mu$ decay modes we obtain significantly more stringent upper limits than in Ref. [3], while for $\Upsilon \to e\mu$ our limit is considerably weaker. The existing experimental upper bounds on some of these rates listed in (2) and (3) are by far much weaker than the limits set by theory, both as in Ref. [3] and as discussed here.

Finally, let us comment on the effect of nonminimal derivative couplings of vector bosons to the LFV lepton current in the upper vertex of the diagram in Fig. 1. One could imagine a situation where the minimal nonderivative couplings in the effective Lagrangian (6) are substituted by the following derivative couplings [3,5]:

$$\mathcal{L}_{\rm eff}^{lM} = \frac{1}{m_M}(\xi_T^M j_{\mu\nu}^T + \xi_{\tilde{T}}^M j_{\mu\nu}^{\tilde{T}})M^{\mu\nu} + {\rm H.c.}, \qquad (24)$$

where $M^{\mu\nu} = \partial^\mu M^\nu - \partial^\nu M^\mu$ is the stress tensor. Here, the $\xi_{T,\tilde{T}}^M$ are effective tensor and pseudotensor couplings of the bosons M to the LFV lepton currents $j_{\mu\nu}^T = \bar{e}\sigma_{\mu\nu}\mu$ and $j_{\mu\nu}^{\tilde{T}} = \bar{e}\sigma_{\mu\nu}\gamma_5\mu$. As was noted in Ref. [3], the derivative couplings (24) would lead to significant weakening of the bounds in (5). This happens because the contribution of the virtual vector bosons to $\mu \to 3e$ is reduced in comparison to the case of the nonderivative couplings (6). This is also true for nuclear $\mu - e$-conversion and the derived bounds of (23). These bounds would have to be divided by the following factors [3]: $q^2/m_M^2 \approx m_\mu^2/(2m_M^2) = 10^{-2}[\rho^0, \omega]$; $5 \times 10^{-3}[\phi]$; $5.7 \times 10^{-4}[J/\psi]$; $6.1 \times 10^{-5}[\Upsilon]$. However, even with this weakening the limits (23) still exclude experimental observation of the LFV decays of vector mesons ρ^0, ω, ϕ, J/ψ, $\Upsilon \to \mu^\pm e^\mp$ in the near future. The situation with derivative coupling of the Z^0 boson to the leptons is different from the case of the mesons and was studied in Ref. [20]. This coupling is induced by a $SU_L(2) \times U_Y(1)$-invariant effective operator of dimension higher than four. Because of the electroweak gauge invariance couplings both of the Z^0-boson and of the photon to the LFV lepton current are induced by the same operator. Therefore, $Z^0 \to e\mu$ can be constrained from the existing experimental data on $\mu \to e\gamma$ and the electron electric dipole moment. In this way, a very stringent bound $\mathrm{Br}(Z^0 \to e\mu) < 10^{-23} - 10^{-22}$ was derived in Ref. [20]. This is significantly more stringent than both our bound in Eq. (23) and the bound (5) derived in Ref. [3].

In conclusion, we extracted from the experimental bounds on nuclear $\mu^- - e^-$ conversion new upper limits on the LFV couplings of the vector mesons and the Z^0 boson to the $e - \mu$ lepton current. Then we applied these limits to deduce upper bounds on the branching ratios of LFV decays of vector mesons and the Z-boson. The obtained upper bounds are shown in Eq. (23). Our bounds for the decays ρ^0, $\omega \to e\mu$ are new. The bounds for $\phi \to e\mu$ are significantly more stringent than the corresponding bounds existing in the literature. This conclusion indicates, in particular, that the nuclear $\mu - e$- conversion is more sensitive probe of LFV than the decays of Z^0 boson and vector mesons. In the latter case this is true at least in the sector of the lepton interactions with the mesons made of quarks of the first and second generation. On the other hand, searches for the LFV decays of Z^0 boson and mesons remain an important experimental effort since their observation at the rates above the limits (23) would be a manifestation of new LFV physics, which does not fit into the present analysis. In particular, it may imply a nontrivial mechanism of self cancellation of different terms in (19), which we considered as unnatural. Then $\mu - e$-conversion rate could remain below the experimental bound [4] while allowing large rates of the LFV decays of Z^0 boson and vector mesons.

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