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ON MECHANIZM 0F μ → e CONVERSION INDUCED BY DARK MATTER

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A possible mechanism of muon-electron conversion based on the spin-charge separation and hypothesis of an existence of the fermionic dark matter is suggested. Using the effective field theory, describing DM interactions with non-relativistic nucleons one can proceed with computations of the different CLFV processes.

Key words: muon, dark matter, preons, haplons.

I. INTRODUCTION

The observations of neutrino oscillations certainly indicates that Standard Model (SM) requires modification and at the same time open windows for further searches of the processes with flavor violation in the charged sector of theory as well.

It is commonly accepted that the existence of massive non-degenerate light neutrinos causes the neutrino oscillation. However, the existence of neutrino masses also implies non-vanishing, though unobservable small, rates for flavor non-conserving processes such as $\mu\to e\gamma$. The rates for these processes are suppressed by a factor $(\Delta m_\nu/M_W)^4$, where Δm_ν denotes the splitting of neutrino masses and M_W is the W-boson mass. However, supposing scenarios for physics beyond the Standard Model (BSM) one can allow for significantly larger rates for such Charged Lepton Flavor Violation (CLVF) processes (cf. discussions in [1], [2], [3], [4],[5],[6],[7]).

II. THEORETICAL AND EXPERIMENTAL SETTINGS

Analyzing the conversion in the presence of a nucleus the quantity of interest is the branching ratio

$$Br(\mu\to e)=\frac{\mu^-+A(Z,N)\to e^-+A(Z,N)}{\mu^-+A(Z,N)\to \nu_\mu+A(Z-1,N)} \qquad (1)$$

Where the denominator is the rate for muon capture on a nucleus with Z protons and N neutrons with A=Z+N. The Standard Model branching ratio for this process is predicted to be of the order $\mathrm{Br}(\mu\to e)\approx 10^{-54}$ [3]. At present, the best experimental bounds are from the SINDROM II collaboration which has constrained $\mathrm{Br}(\mu\to e)<7\times 10^{-13}$ [1]. The next generation experiments, COMET andMu2e, are expected to improve these bounds by roughly four orders of magnitude [2].

A. Muon-electron conversion: probes various types of interactions

Traditionally the contributions to muon-electron conversion process are divided into two groups, the photonic (dipole) and the non-photonic contributions. Correspondingly, the low energy effective

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+ Also at A Razmadze Mathematical Institute, Tbilisi State University and Joint Institute for Nuclear Research, Dubna interaction Lagrangian responsible for the processes allowing the change of flavor can be written as [1],[2]:

$$L$$

$$= \frac{1}{1+k}\frac{m_\mu}{\Lambda^2}\left[\bar{\mu}_R\sigma^{\mu\nu}e_L F\mu\nu + \frac{k}{m_\mu}\left(\bar{\mu}_L\gamma^\mu e_L\right)\left(\bar{q}_L\gamma_\mu q_L\right)\right]$$

$$\mathcal{L} = \frac{1}{1+k}\frac{m_\mu}{\Lambda^2}\left[\bar{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu} + \frac{k}{m_\mu}(\bar{\mu}_L\gamma^\mu e_L)(\bar{q}_L\gamma_\mu e q_L)\right] \quad (2)$$

Where the parameter Λ sets the energy scale of the CLFV physics and k describes the relative strength of photonic and non-photonic contributions. The first term represents a dipole modification to the free lepton and the second term describes a four-fermion contact interaction.

Below we state a microscopic model, whose effective low energy sector corresponds to CFLV interaction Lagrangian (2).

III. MODEL FORMULATION

In order to formulate our microscopic CFLV model we point out its primary experimental and theoretical sources and state its basic ingredients.

A. Basic principles and assumptions

Our model of the muon-electron conversion is motivated by two observations from different branches of physics, one from the condensed matter physics and other from the cosmology. These interesting facts are:

1. . the *spin-charge separation* effect which was theoretically predict long-time ago and recently finally observed under a special environmental conditions [8],[9],[10];
2. . the comparisons of a diverse astrophysics data with results of phenomenological models of the Universe point out on the existence of the so-called dark matter (DM);

In order to formulate our model we start with a brief sketch of the corresponding aspects of above mentioned phenomena an draw an attention to their potential relation to the CLFV processes.

1. Spin-charge separation in condensed physics

According to SM the electron is a fundamental particle with spin-1/2 and electric charge −e. However, in highly correlated condensed matter systems, particularly in one-dimensional (1D) electron systems, theory predicts that collective excitations of electrons lead, instead of the quasiparticles in ordinary Fermi liquids, two new particles termed as *spinons*, carrier of spin and *chargons*, quasiparticle which carry electric charge. Unlike ordinary quasiparticles, these particles do not carry the spin and charge information of electrons together. Instead, they carry spin and charge information separately and propagate with different velocities. This exotic phenomenon was predicted theoretically decades ago and is commonly known as *spincharge separation*. A definite signature of spin-charge separation was the observation of the two corresponding branches of excitations in the single particle spectral function [10].

This condensed matter spin-charge phenomenon has many common points with composite models of quarks, leptons and electroweak bosons such as “preons” an “haplons”. Furthermore, it was supposed that three haplons can bound in the fermion state which can be a candidate for the dark matter fermion [11] [12].

2. Dark matter and neutron lifetime anomaly

Recently it was suggested that the dark matter existence can be related to the so-called neutron decay anomaly [13], [14],[15],[16],[17],[18]. Namely, a possible explanation of anomaly is due to existence of a new neutron decay channel into DM fermion; If the branching ratio of the dark matter decay to standard β decay is 1%, this would account for the observed neutron lifetime anomaly.

There are two qualitatively different types of neutron life time measurements: bottle and beam experiments. The longstanding problem, the so-called neutron lifetime anomaly, consist in the discrepancy between the rates of decays of neutrons in these methods. The average from the five bottle experiments included in the Particle Data Group bottle technique give the neutron lifetime,

$$\tau_{botle} = 879.6 \pm 0.6 \text{ s},$$

which is less, at the 4σ level, with the exclusive measurement of the neutron lifetime given by beam experiments,

$$\tau_{beam} = 888.0 \pm 2.0 \text{ s}.$$

This discrepancy suggest that either there is systematic error in one of the methods or the theory itself is not complete. In recent paper by Fornal and Grinstein [13] it was proposed mechanism explaining the neutron decay anomaly by a new dark decay channel for the neutron, when neutron mixes with fermionic dark matter (DM) χ, whose mass is in narrow range $m_p - m_e < m_\chi < m_n$ consistent with proton stability.

One of the possible final states discussed includes a decay $n \to \chi + e^+e^-$ However, according to a the recentexperimental studies on a direct search for neutron decay to a dark particle, if $n \to \chi + e^+e^-$ is dominant dark matter decay channel with branching ratio required to resolve the neutron lifetime discrepancy, it is ruled out at 5σ level for all masses DM fermion χ corresponding to $100\text{keV} < E_{e^+e^-} < 644\text{keV}$ [18].

B. Using WIMP for muon-electron conversion

Now we will tangle together two above described facts, from one hand the possibility of separation of spin and charge of neutron into neutral fermion and charged scalars, and from another, the explanation of the neutron anomaly by interaction with DM particles. Based on this ideas we propose a model for muon-electron conversion. With this aim we need understanding of DM in the frame- work of particle physics. On of most promising option for DM interpretation in terms of particle is the paradigm of Weakly Interacting Massive Particles (WIMPs) (see e.g., [19]). The WIMPs interact with standard-model parti- cles through a cross section that are suppressed compared to standard electromagnetic interactions.

1. Decomposing leptons in DM spin-charge components

We assume that the lepton sector of our model instead of being fundamental consist from the composite states. Suppose that the state labeled by flavor quantum number a and electric charge q is composite state, i.e., $|l_\alpha, qi \in H_L$, and represents the element of the tensor product of “spin” and “charge” Hilbert spaces:

$$H_L = H_{spin} \otimes H_{charge} \qquad (3)$$

Furthermore, we suppose that the spin part is described by neutral DM fermions χ, while their electric charge carrier components, chargons, are given by the scalar φ

$$e = \chi_e \otimes \varphi\,, \qquad \mu = \chi_\mu \otimes \varphi$$

These neutral fermions χ_e, $\chi_m u$ are DM fermions with a definite flavor. They represent a mixture of states with a definite masses:

$$\begin{pmatrix} \chi_e \\ \chi_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_\chi & \sin\theta_\chi \\ -\sin\theta_\chi & \cos\theta_\chi \end{pmatrix} \begin{pmatrix} \chi_{m_e} \\ \chi_{m_\mu} \end{pmatrix}, \qquad (4)$$

where θ_χ is mixed angle.

c. Effective theory of DM interaction with nucleons

Dark Matter scattering on a target nucleus, is well described by Effective Field Theory (EFT) (see e.g. [22] and references therein). From the effective field theory, describing DM interactions with quarks and gluons one can pass to the effective theory of non-relativistic DM interacting with non-relativistic nucleons [21], [20],[22].

The maximal momentum exchange between DM and the nucleus is less than $200 MeV$ and therefore one is able to use chiral counting. Particularly, recently it was shown that the leading-order (LO) results in such chiral expansion are given by a single-nucleon form factors [22].

D. Representation for conversion amplitude

Using the effective field theory, describing DM interactions with non-relativistic nucleons one can proceed with computations of the different CLFV processes. In particular, the conversion amplitude $\mu \to e$ is determined by the matrix element for conversion on nucleon

$$M(\mu + N(Pi) \to e(k) + N(Pf))$$

The effective microscopic Lagrangian describing interaction of DM fermion χ with a dark photon A' is

$$L_{Eff} = \overline{\chi}(iD - m_\chi)\chi + \overline{n}(i\hat{\partial} - m_n - \mu_n \sigma_{ij} F^{ij}) - \frac{1}{4} F'_{ij} F'_{ij} - \frac{1}{2} m_{A'}^2 A'_i A'^i - \delta m n_R \chi_L + \varepsilon F_{ij} F^i_{ij} + h.c, \quad (5)$$

where and $D = i\hat{\partial} - q' A'$ and μ_n is the neutron magnetic dipole moment. Kinetic mixing with the photon is included so that A' will eventually decay to photons
through a loop diagram, or electrons if $m_{A'} > 2m_e$.

Let us introduce the vertex function $\Gamma_{n \to \chi A}$; describing process of neutron decay to the DM fermion χ and DM photon A'.

$$n \to \chi A'$$

According to [17]

$$\Gamma_{n \to \chi A'} = \frac{g'^2 \delta m^2 m_n}{8\pi m_{A'}^2} (1 - r^2)^{3/2} \qquad (6)$$

Where $r = \frac{m_{A'}}{m_n - m_\chi}$. The generic form of non-photonic contribution to the amplitude for muon-electron conversion on the neutron reads

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$$T=\sum_{i,j}\int\overline{\Gamma}_{n\to x_i A^{'}}\overline{\Gamma}_{e\to\chi_e\varphi}\mathrm{M}^{\chi_e\chi_\mu}_{\chi_i\chi_f}\Gamma_{n\to\chi_j A^{'}}\Gamma_{\mu\to\chi_\mu\phi} \qquad (7)$$

where $\mathrm{M}^{\chi_e\chi_\mu}_{\chi_i\chi_f}$ denote the amplitude of DM fermions contact interaction

$$\mathrm{M}^{\chi_e\chi_\mu}_{\chi_i\chi_f}=\left\langle\chi_i,\chi_j\middle|\chi_e\chi_\mu\right\rangle \qquad (8)$$

Using the representation (7) and values for constants determined from the neutron decay in DM channel [17,18] one can derive certain bounds on the muon-electron conversion. The evaluation of these bounds requires detailed studies of all possible contributions from the effective interactions of DM fermions with nucleons. This work is in progress and in due time the result of computations will be given in our forthcoming publications.

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