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ESTIMATES OF THE MAIN BACKGROUNDS FOR THE COMET EXPERIMENT

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Abstract

The working notes on theoretical issues of the coherent neutrino less conversion of a negatively charged muon into an electron in the field of a nucleus, the so-called $\mu\to e$ *conversion, are presented. Here we briefly report on our studies of the physical backgrounds to*$\mu\to e$ *conversion. During the present reporting period our attention was paid to the study of theoretical problems related to the main background signals coming from the so-called muon decay-in-orbit (DIO), a process in which the muon decays in the normal way, i.e.* $\mu\to e\nu_\mu\bar{\nu}_e$*, while in the orbit of the atom. The existing literature on this s subject have been studied and the set of problem to be solved for improvement of theoretical estimates on DIO spectrum have been formulated. The first steps towards theoretical description of quantum correction due to the interaction of decaying particles have been undertaken.*

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1 Introduction

The muon is the lightest unstable particle. According to the Particle Date Group the muon mass and lifetime is

$$m_\mu = 105.658389 \pm 0.000034 \text{ MeV} \qquad (1)$$

$$\tau_\mu = (2.19703 \pm 0.00004) \times 10^{-6} \text{ s} \qquad (2)$$

Muon decays essentially only one channel

$$\mu \to e\nu_\mu\bar{\nu}_e \qquad (3)$$

For the next largest mode ($\mu \to e\nu_\mu\bar{\nu}_e e^+ e$) the decay rate is of order 10^{-5}. In both channels lepton favor numbers (L_e, L_μ) and the total lepton number L, are conserved. Conservation of L and lepton flavor numbers,$L_e, L_\mu$is the fundamental principle, the cornerstone of the Standard Model. Violations of any of them violation will indicate on New Physics. That is why the search for the “Charged-Lepton Flavor-Violation” (CLFV) processes are one of most intrigued topics in a contemporary fundamental physics. It should be note, that the CLFV has been the subject of intense experimental studies since the discovery of the muon but, to this date, no evidence for it has ever been uncovered.

Among the possible CLFV channels, three rare muon processes and out:

- $\mu \to e\gamma$;

- $\mu \to eee$;

- $\mu \to e$ conversion in nuclei.

The COMET experiment at J-PARC facilities is devoted to the detection of the last mentioned channel, conversion of the muon$\mu \to e$ in Aluminum. The Project – DI/32/6-200/14, supported by SRNSF, is aiming to contribute to the detector part of the COMET experiment and its main theoretical part consist in analysis of a possible background effects. The correct evaluations of all possible backgrounds are highly important for a successful observation of the CLFV $\mu - e$ conversion.

Our notes start with the presentation of some generic features of the phenomenological pattern of the $\mu \to e$ conversion.[1] The possible background processes will be outlined. The detailed calculations of the main background, the so-called Decay In Orbit(DIO) in the muonic atoms will be given.

2 μ→e conversion in muonic atom

One of the most prominent candidate on muon CLFV processes is coherent neutrino-less conversion of muons to electrons:

$$\mu^- + N(A; Z) \to e^- + N(A; Z)\,, \tag{4}$$

where N (A; Z) represents a nucleus with mass number A and atomic number Z. Here by coherent conversion we understand a process in which the nucleus N remains in its initial state (up to recoil effects).The rate of the coherent conversion is enhanced with respect to processes with a nuclear excitation by a factor of the order of the number of nucleons.

The $\mu \to e$ conversion process (4) happens when a muon stops in the material. Qualitatively it looks as follows. A negative muon targeting some material is trapped by an atom, substituting the electron, and a muonic atom is formed. After it cascades down energy levels in the muonic atom, to it's the muon 1sgroundstate.[2]

What is a fate of the captured muon?

The possible scenario, in the light of the Standard model, consist in the following alternatives,

- either the muon Michel-decays in orbit ($\mu^- + e^-\nu_\mu\nu_e$),

- or it is captured by a nucleus, converting into neutrinos in the field of the nucleus:

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[1]. There are many review articles on the theory and phenomenology of CLFV processes: among them one should mention the review of Kuno and Okada [2001] and more recent reviews by R.H. Bernstein and Peter S. Cooper [2013], de Gouvea and Vogel [2013]. The articles by Marciano et al. [2008], Raidal et al. [2008] and de Gouvea and Saoulidou [2010] update the subject.

[2] What is the signal of stopped muons? A muon that stops falls into a 1s state of sometarget nucleus; in so doing, X-rays are emitted and their characteristic spectrum serves as the signal of a stopped muon.

$$\mu- + N(A; Z)\ ^{-}\!\!\to \nu_{\mu} + N\,(A; Z-1)\ .$$

However, apart from these possibilities, one can imagine that the other exotic process occurs. Namely, assume the neutrino-less muon capture(4), takes place. This type of transition violates the conservation of lepton flavor numbers, $L_e$and $L_\mu$by one unit, but leaves the total lepton number, L, unchanged. In conversion channel (4), the final state of the nucleus N (A, Z) could be either the ground state or one of the excited states.[3]

The outgoing electron from a decaying muon can exchange a photon with the nucleus, which then distorts the Michel spectrum. The tail of the muon decay spectrum produces background called DIO (for decay-in-orbit) or MIO (muon decay-in-orbit) in the literature. The form of the DIO spectrum near the endpoint is approximately given by:

$$N(E_e) = CE_e^2\left(\frac{\delta_1}{m_\mu}\right)^5 dE_e \qquad (5)$$

With

$$\delta_1 = m_e - E_e - \frac{E_e^2}{2M_N}$$

The signal for μ– e conversion is a monoenergetic electron with energy Eμe, given by

$$E_{\mu e} = m_\mu - E_B - E_{rec} \qquad (6)$$

where

m_μ - the muon mass,

$E_B = \frac{1}{2}Z^2a^2m_\mu$- is the binding energy of the muonic atom, withα- the fine-structure constant,

$E_{rec} = \frac{m_\mu^2}{2M_N}$ - the nuclear-recoil energy, and M_N - the nucleus mass.

The conventional signal normalization for the conversion is given by the ratio:

$$R_{\mu e} = \frac{\Gamma[\mu + N(A;Z)^- \ \to e + N(A;Z)]}{\Gamma[\mu + N(A;Z)^- \ \to allcaptures]} \qquad (7)$$

With vanishing neutrino masses the Standard Model conserves lepton flavor number for each generation and $R_{\mu e}$ = 0.

It is now established that neutrinos oscillate, and are not (all) massless. Flavor number is not conserved in the SM. In the SM muon LFV decays do occur (due to neutrino oscillations, νμ→ νe in the virtual process) but it gives:

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[3] In general, the transition to the ground state, which is called coherent capture, is dominant. The rate of the coherent capture over non-coherent capture is enhanced by a fact or approximately equal to the number of nucleons in the nucleus, since all of the nucleons participate in the process.

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$$R_{\mu e} \propto \frac{\Delta m_{\nu}^{4}}{M_W} \approx 10^{-54}$$

is 40th orders of magnitude below experimental limits. What we know from experiment that Rμe < 10−13 at 90% CL.

Note that, the lifetime of muon on Al is 864 nsec (Measday [2001].)The lifetime of the muonic atom is known and the stopped muon either decays or is captured (or converts, which occurs at an unfortunately negligible rate for this calculation.) Both the decay lifetime of the free muon and the total lifetime in Aluminum are known, and therefore using

$$\frac{1}{\Gamma} = \frac{1}{\Gamma_{Decay}} + \frac{1}{\Gamma_{Capture}} \quad (8)$$

by measuring the number of stops one can infer the number of captures. Hence experiments count the number of stops, infer the number of captures, and use the calculated Rμe when reporting a result.

3 Backgrounds for $\mu^- \to e^-$conversion

N.B. Most of the background processes for the search for $\mu^- \to e^-$*conversion in Aluminum have never been measured.*

The main physics background for this signal comes from the so called muon decay-in-orbit (DIO), a process in which the muon decays in the normal way, i.e. $\mu^- + e^- \nu_\mu \nu_e$, while in the orbit of the atom. Whereas in a free-muon decay, in order to conserve energy and three-momentum, the maximum electron energy is$m_\mu/2$,for decay-in-orbit the presence of an additional particle (the nucleus), which can absorb three-momentum, causes the maximum electron energy to be $E_{\mu e}$.

Interestingly, the energy range of electrons produced in a decay of a muon bound in an atom (decay in orbit, DIO) reaches to about twice the maximum possible in a free-muon decay. When the muon decays in vacuum, momentum conservation requires that at least half of the energy be carried away by the neutrinos. In the DIO, the nucleus can absorb the momentum without taking much energy, because it is so much heavier than the muon.

Therefore, the high-energy tail of the electron spectrum in muon decay-in-orbit constitutes a background for conversion searches. A detailed study of that background is the main focus of this work.

3.1 Muon decay in orbit

There are no measured data of muon decay in orbit (DIO)at the momentum region at the endpoint energy.[4]

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[4] Electron spectrum in muon DIO (for aluminum) has been precisely measured recently by the TWIST Collaboration, in a wide range of electron energies 18MeV <Ee< 70MeV Grossheim et al. 09.

This measurement cannot be done by the exiting muon facility since a number of muons required cannot be obtained.

In COMET Phase-I, the Crystal detector would be used to measure the DIO electron spectrum with momentum resolution of about 400keV. The measurement can be compared with the theoretical prediction. Once the DIO rate and spectrum are precisely measured, they can be used to monitor the total number of muons stopped in the muon stopping target.

To study muon DIO one need to consider:

1. Effects of the Coulomb field of the nucleus on the electron and the muon;

2. Nuclear-recoil effects:$M_n \gg M_\mu$, but recoil modifies the end point energy;

3. Finite nuclear size;

4. Radiative corrections($O(\alpha)$):It was expected to be important in the high-energy region, however very recent studies [5] by Robert Szafron and Andrzej Czarnecki, claim on strong modification of a high-energy electrons spectrum from the muon decay in orbit due to the radiative corrections.

One need to produce an electron with $E_e \sim |p_e| \sim m_\mu$

1) Either muon has $|p_e| \sim m_\mu$ (at the tail of the wave function)

2)Or electron interacts with the nucleus to get $|p_e| \sim m_\mu$

In any case we cannot treat the muon nonrelativistic.

First we want to clarify how electrons can acquire the energy of the full muon mass, even though a free muon decay produces electrons with at most half that energy.

A large amount of three-momentum must be transferred to the nucleus, instead of sharing the energy with neutrinos.

3.2 Radiative muon capture

Radiative muon capture (external)

$$\mu^- + A \rightarrow \nu_\mu + A^- + \gamma ,$$

followed by $\gamma^- \rightarrow e^+ + e^-$. One must also include the internal conversion process $\pi^- N \rightarrow e^+ e^- N^*$.

There are no measured data of radiative muon capture(RMC) at the region of photon energy at the endpoint for Aluminum.

As in DIO, this type of background is removed only by momentum resolution, This measurement cannot be done by the existing muon facility since a number of muons required cannot be obtained.

Precise enough to be sensitive to radiative corrections around the free decay endpoint $E_e \approx m_\mu$ /2, where they are most important (logarithmically enhanced)

This measurement needs an energy resolution less than 1 MeV,since the endpoint and the conversion signal is a few MeV. In COMET Phase-I, the Crystal detector is used as a pair spectrometer with photon converter to measure photon energy of 100 MeV with energy resolution of about 400 keV .

T. Gorringe and H.W. Fearing (2004). ”Induced pseudoscalar coupling of the proton weak interaction”. Rev. Mod. Phys. 76: 3191.arXiv:nucl-th/0206039. RevModPhys.76.31.

V.A. Andreev et al. (2007). ”Measurement of the Rate of Muon Capture in Hydrogen Gas and Determination of the Proton’s Pseudoscalar Coupling gP”.arXiv:0704.2072.

3.3 Other backgrounds

There are no measured data of proton emission and neutron emission after nuclear muon capture. These measurements can be done by the existing facilities. The COMET collaboration will carry out the proton emission measurement after muon capture on aluminum at PSI (the AlCap experiment). Measurement and neutron emission after muon capture on aluminum is planned to be done at the same time. There are no measured data on radiative pion capture on aluminum. This measurement can be made by the Electromagnetic calorimeter at the StrEcal detector.

4 Theoretical issues of the DIO

4.1 The free muon decay at rest; the Michel spectrum

The spectrum of $\mu^- — e^-\nu_\mu\nu_e$ decays, commonly known as the Michel spectrum, for the free decay of a muon at rest.[5]

This calculation does not include radiative corrections.

The Fermi interaction describing the muon decay is given by

$$L_F = -\sqrt{2}\bar{2}G_F\left[\bar{\psi}_{\nu_\mu}\Upsilon^\rho P_L\psi\right]\left[\bar{\psi}_e\Upsilon^\rho\psi_{\nu_e}\right]+H.c., \qquad (9)$$

where $P_L= (1 -\gamma_5)/2$

The differential rate as a function of the energy of the electronemitted in decay reads:

$$\Gamma(E)dE = \frac{G_F^2 m^5}{(8\pi)^3}\left[\left(1-\frac{2E}{m}\right)-\frac{2}{9}\,\rho\,\left(3-\frac{8E}{m}\right)\right]E^2dE\,, \qquad (10)$$

whereρ is the so-called Michel parameter.

The total rate of decay

$$\Gamma = \frac{G_F^2 m^5}{192\pi^2}\quad, \qquad (11)$$

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[5] The Michel spectrum is derived in Michel [1950], Kinoshita and Sirlin [1957].

where G_F - Fermi coupling.

4.2 μ^-- atom

The basic role in formation of μ^- - atoms plays electromagnetic forces. Moreover, as the first approximation the Bohr Theory of hydrogen atom can be adopted.

According to this theory the Coulomb bound two-body system hasa binding energy spectrum En, n = 1, 2, . . .

$$E_n = (Z\alpha)^2 \frac{m_\mu c^2}{2n^2}$$

and radius a_n

$$a_n = \frac{1}{\alpha m_\mu c^2} \frac{n^2}{Z} ,$$

where α is the fine structure constant, Z is the nuclear charge, $m_\mu$is the mass of the orbiting particle, i.e. the lighter one in the bound system.[6]

Since the $m_\mu \approx 207 m_e$ electrons in μ^- - atoms are remote from nucleus in comparison with muons, and in good approximation μ^- -atom represents the hydrogen atom with charge Z.

It is worth to mention that this interpretation works up to certain values of nuclear charge. Using the approximation for the radius R_N of a nucleus with atomic number A,

$$R_N = \frac{1}{\alpha m_\mu c^2} A^{1/3}$$

One can write down the validity region

$$a_1 \geq R_N \qquad (12)$$

(12) From the inequality (12) it follows that the critical value of charge when the hydrogen atom approximation breaks down is

$$Z_c = \frac{1}{2^{1/4}} \left(\frac{1}{\alpha}\right)^{\frac{3}{4}} \qquad (13)$$

A muon bound to a nucleus with Z 137 is nonrelativistic, but the first relativistic correction to its wave function is required.

There are various corrections due to the relativistic, recoil and QED effects and due to the nuclear structure.

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[6] Afterwards throughout the note we apply relativistic units, h = c = 1.

The conventional choice for the wave function is

$$\psi(q) = \psi_{NR}(q)\left(1 + \frac{q\gamma}{2m_v}\right)u(P) \quad (14)$$

where

$$\psi_{NR}(q) = \frac{8\pi Z\alpha m_\mu \psi(0)}{(q^2 + (Z\alpha m_m u)^2)^2}$$

is the nonrelativistic momentum-space wave function of the 1 ground state with

$$\psi(0) = \left(\frac{Z\alpha m_\mu}{\pi^{1/3}}\right)^{\frac{3}{2}}$$

andu(P)is a four-spinor of a muon at rest, P = (m_μ, 0).

4.3 Muon decay in orbit: Spectrum of high energy electrons

The first theoretical studies of the muon decay-in-orbit go back to the beginning of 50-th of the last century. The studies starting from the work by C.E Porter and H.Primakoff [1]. Nevertheless of such a long history a certain improvement of calculations is needed due to the high precession requirements on the knowledge of electron spectrum.

Up today the high-energy end of the electron spectrum has been studied by different authors and under different approximations, which allow for a quick rough estimate of the muon decay in orbit contribution to the background in conversion experiments.

The decays of bound muons differs from free muon decays in several points. As the μ^-loses energy and starts to come to rest, it gets bound to nuclei of charge Z due to their attractive Coulomb potential. The μ^- quickly cascades down to the lowest 1S atomic orbital, where it remains in a quantum wave function with a momentum distribution for which its average velocity is Z_α. The decreased energy of the bound muon causes (DIO) rate to slow down. In addition, the electron produced in the decay feels the same binding interaction, which increases its wave function near the decay region, and thus the decay probability. Interestingly, these two effects approximately cancel due to electromagnetic gauge invariance, and the difference between the overall decay rates of free and bound μ^- is mainly due to the time dilation resulting from the bound muon's motion. (In matter, a μ^- canal so undergo capture, $\mu^- p \to \nu_\mu n$, which changes its effective lifetime(see e.g. V. Andreev et al., Phys.Rev.Lett. 110, 012504 (2013). and A. Czarnecki,W. J. Marciano, and A. Sirlin, Phys. Rev. Lett. 99,032003 (2007).)

5 Muon DIO; QFT calculations

Let us consider the system of spinor fields, massive nucleus $\Psi_N(x)$,muon and electron $\psi_e(x)$ and $\psi_\mu(x)$ with masses (M_N,m_μ, m_e) respectively, and two massless neutrino fields $\nu_\mu(x)$ and $\nu_e(x)$.

The model consist from standard electrodynamic part

$$L = L_{QED}(\psi_N, A) + L_{QED}(\psi_\mu, A) + L_{QED}(\psi_e, A) + L_F \quad (15)$$

plus the Fermi point interaction LF describing the muon decay

$$L_F = -\sqrt{2}\bar{2}G_F\left[\bar{\psi}_{\nu_\mu} y^0 P_L \psi_\mu\right]\left[\bar{\psi}_e y^0 \psi_{\nu_e}\right] + H.c. \quad (16)$$

Ignoring for a moment the weak Fermi interaction, the particle contents of system besides the fundamental particles (nucleus, muon and electron) consist from two types of bipartite composite states: atoms, (eN) -bound states, and muonic atoms (μN)-bound states. These bounds state evolution can be studied within the B-S or the quasipotential (equal time) formalism, studying the corresponding pole structure of the B-S Green functions,

$$G(x,y) := \langle 0|T(\psi_N(x), \psi_N(y))|0\rangle \quad (17)$$

$$G(x,y) := \left\langle 0\left|T\left(\psi_N(x), \psi_\mu(y)\right)\right|0\right\rangle, \quad (18)$$

of the following form

$$G(p) = \mathrm{i}\,\frac{\Phi_A(P)\bar{\Phi}_A(P)}{P^2 - M_A} + G'_A(P) \quad (19)$$

$$G(p) = \mathrm{i}\,\frac{\Phi_{\mu A}(P)\bar{\Phi}_{\mu A}(P)}{P^2 - M_{\mu A}} + G'_A(P) \quad (20)$$

6. Quantum effects

It is natural to define an elementary particle as one whose field appears in the fundamental field equations or, as usually formulate these theories, in the Lagrangian of the theory. It doesn’t matter if the particle is heavy or light, stable or unstable if its field appears in the Lagrangian, it is elementary; if not, not.

What Is An Elementary Particle?

by Steven Weinberg

In order to describe correctly, with a high precession, processes in which unstable particles are involved it is necessary to make a rigorous distinction between the stable fundamental particles, bound states and resonances

Let us give a rigorous mathematical definition of the resonance in terms of the nonrelativistic resolvent for free theory with HamiltonianH_0

$$R^0_\psi(z) = \left\langle \psi \left|\frac{1}{z-H_0}\right| \psi\right\rangle \quad (21)$$

and resolvent for interaction theory with Hamiltonian $H = H_0 + H_1$

$$R_\psi(z) = \left\langle \psi \left|\frac{1}{z-H}\right| \psi\right\rangle \quad (22)$$

Suppose that both functions $R_{\psi}^{0}(z)$and R_{ψ}^{0} (z) admit analytical continuation to the second Riemann sheet (over positive real axis of the first sheet).

If the function R_{ψ}^{0} is analytic at

$$Z_0 = E_r - \frac{i}{2}\Gamma$$

and Rψ for some ψ has pole at z0 , then z0 , represents the resonance pole and Γ is its width.

6.1 Decays in mixed states

Another interesting issue that requires a special analysis is related to the following question:

What is the difference between spectrum of decay particles produced from a mother particle which is either in pure or in mixed initial states?

When the decaying particle is heavy and in rest one can suppose that the final state is pure, while taking into account the recoil effects we came with the necessity deal with density matrix (%) decaying system.

The DIO electron is describing by the reduced density matrix

$$\rho_e = Tr_{\nu_e \nu_{\mu N}} \qquad (23)$$

where indexes of trace operations indicate summation over the neutrino sand nuclei degrees.

Since we are looking for the tail high-energetic part of the electron the relativistic generalization of the reduced density matrix (23)should be considered. Here we faced with the problem of its correct definition (see e.g. [21]).

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