

**Limit on the electric charge-nonconserving  $\mu^+ \rightarrow$  invisible decay**

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The first limit on the branching ratio of the electric charge-nonconserving invisible muon decay  $\text{Br}(\mu^+ \rightarrow \text{invisible}) < 5.2 \times 10^{-3}$  is obtained from the recently reported results on new determination of the Fermi constant from muon decays. The results of a feasibility study of a new proposed experiment for a sensitive search for this decay mode at the level of a few parts in  $10^{11}$  are presented. Constraints on the  $\tau \rightarrow$  invisible decay rate are discussed. These leptonic charge-nonconserving processes may hold in four-dimensional world in models with infinite extra dimensions, thus making their searches complementary to collider experiments probing new physics.

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**I. INTRODUCTION**

The law of the electric charge conservation, related to the existence of the unbroken local U(1) gauge symmetry of the standard model (SM), is thought to be an absolute conservation law. However, "...the basic principles of theoretical physics cannot be accepted *a priori*, no matter how convincing they may seem, but rather must be justified on the basis of relevant experiments" [1]. Thus, new experimental tests of old and fully established laws of physics are of importance as they could provide new unexpected results [2–5].

The quantization of the electric charge has also been established with a high level of accuracy, while the question of why the electric charge is quantized seems to have a yet unknown answer. Going beyond the SM, it is possible to have particles with a small fractional (milli) charge, e.g. by introducing additional U'(1) symmetry of a hidden sector [6,7]. These considerations have stimulated new theoretical works and experimental tests reported in Ref. [8].

Not long ago, it has been pointed out that in some models with infinite extra dimensions, describing our world as a brane embedded in higher dimensional space [9,10], particles initially located on our brane may leave the brane and disappear into extra dimensions [11,12]. The experimental signature of this effect is the disappearance of the particles in our world, i.e. the particle  $\rightarrow$  invisible decay. These transitions have been found to be generic in a class of models of localization of particles on a brane. The localization becomes incomplete if particles get small masses and they could tunnel from the brane into extra dimensions [13,14].

An example of this process for a neutral system, orthopositronium ( $o - Ps$ ), a triplet bound state of an electron and positron, has been considered in Ref. [15]. It has been shown that the effect may occur at a rate within 2 orders of magnitude of the present best experimental limit on the branching ratio of the  $o - Ps \rightarrow$  invisible decay  $\text{Br}(o -$

$Ps \rightarrow \text{invisible}) < 4.3 \times 10^{-7}$  (90% C.L.) from the recent ETH-INR experiment [16,17].

If, however, particles that leave our brane are electrically charged, their disappearance into extra dimensions would result in the nonconservation of electric charge seen by our four-dimensional experiment. It should be pointed out, that, of course, in this scenario electric charge is conserved in the full multidimensional space [11,12]. As our experiment is not sensitive to the charge localized outside the brane it would detect the charge nonconservation through the particle  $\rightarrow$  invisible decay. In the example illustrated in Fig. 1, a muon produced in the  $\pi \rightarrow \mu + \nu$  decay escapes into extra dimensions resulting in the  $\mu \rightarrow$  invisible decay. Hence, one may conclude that an observation of the process of a particle disappearance would provide a strong evidence for the existence of an extra dimensional world. It may be worthwhile to remember that the process with the analogous experimental signature,

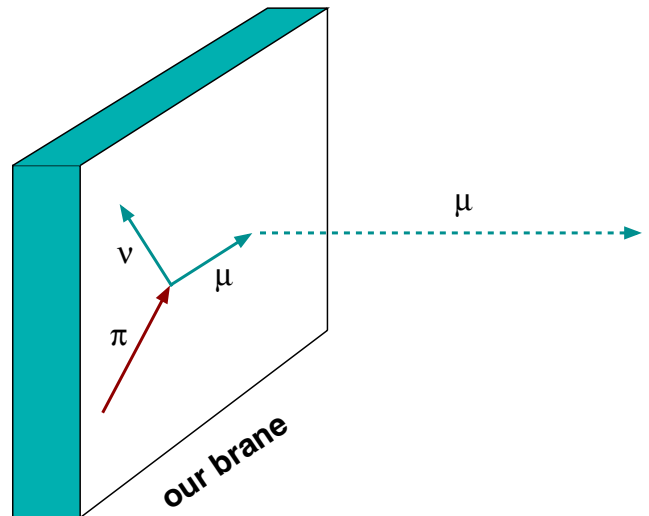


FIG. 1 (color online). Schematic illustration of the disappearance of a muon produced in the  $\pi \rightarrow \mu + \nu$  decay: neutrino propagates along the brane while the muon escapes into extra dimensions.

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$Z \rightarrow$  invisible decay of the gauge boson  $Z$  plays a fundamental role in determination of the number of lepton families in the SM.

Some examples of charge-nonconserving processes involving leptons and baryons can be found in Particle Data Group [18]. Experiments searching for the electron  $\rightarrow$  invisible decay test the electron stability and yield lower half-lifetime limits in the range  $10^{23}$ – $10^{26}$  yr. For more recent results see, also [19]. One of the most stringent limits for charge-nonconserving decays of neutrons,  $\Gamma(n \rightarrow p + \nu_e + \bar{\nu}_e)/\Gamma(n \rightarrow p + e^- + \bar{\nu}_e) \leq 8 \times 10^{-27}$  has been extracted from the reported counting rates of solar neutrino experiments [20]. As far as the charge-nonconserving  $\mu$ ,  $\tau \rightarrow$  invisible decay modes are concerned, they have never been experimentally tested.

In extra-dimensional models the rate of processes, like  $e$ ,  $\mu$ ,  $\tau \rightarrow$  invisible, is small and might be enhanced for higher masses, but presently cannot be reliably predicted as it is depended on unknown parameters of extra-dimensional physics [12,14,21]. It would be interesting to perform direct high sensitivity searches for these unexpected decay modes, whose discovery would lead to discovery of new physics.

In this paper we obtain the first limit on the electric charge nonconservation in muon and tau decays and show that the muon bound can be significantly improved in a new proposed experiment.

## II. LIMIT ON THE $\mu^+ \rightarrow$ invisible DECAY

Recently, the MuLan collaboration has reported on measurements of the mean lifetime  $\tau_\mu$  of positive muons to a precision of 11 ppm [22]. Using the new world average

$$\tau_\mu = 2.197\,019(21) \mu\text{s} \quad (1)$$

and the relation between the muon lifetime and the Fermi constant  $G_F$

$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} (1 + \Delta), \quad (2)$$

where  $\Delta$  is the sum of phase space, QED and hadronic corrections, results in new determination of the Fermi constant

$$G_F = 1.166\,371(6) \times 10^{-5} \text{ GeV}^{-2} \quad (3)$$

to a precision of 5 ppm [22].

If the  $\mu \rightarrow$  invisible decay exists, it would contribute to the total muon decay rate:

$$\tau_\mu^{-1} = \Gamma_\mu(\mu \rightarrow \text{all}) = \Gamma_{\text{SM}} + \Gamma(\mu \rightarrow \text{invisible}) + \dots \quad (4)$$

and, hence increase the determined value of  $G_F$ . To estimate the allowed contribution of  $\Gamma(\mu \rightarrow \text{invisible})$  to Eq. (4), one could compare the measured muon decay rate of Eq. (1) to a predicted muon decay rate, calculated

from Eq. (2) by using  $G'_F$  extracted from other measurements which are not affected by the disappearance effect discussed above.

There are a number of indirect prescriptions for the extracting of precise values of  $G_F$ . Comparison of these quantities can be used to test the SM and to probe for new physics, for more detailed discussions, see Ref. [23]. For example, one can define

$$G'_F = \frac{4\pi\alpha}{\sqrt{2}m_Z^2 \sin^2 2\Theta_W(m_Z)(1 - \Delta r)}, \quad (5)$$

where  $\Theta_W$ ,  $m_Z$ , and  $\Delta r$  are the Weinberg angle, the mass of the  $Z$  gauge bosons, and a factor for radiative corrections, respectively.

Using the values of  $\Theta_W$ ,  $m_Z$ , and  $\Delta r$  reported in [23], one can obtain

$$G'_F = 1.1672(\pm 0.0008) \begin{pmatrix} +0.0018 \\ -0.0007 \end{pmatrix} \times 10^{-5} \text{ GeV}^{-2}. \quad (6)$$

Comparing Eqs. (3) and (6) and adding statistical and systematic errors in quadrature, one finds

$$\Delta G_F = G_F^\mu - G'_F < 2.6 \times 10^{-3} \text{ GeV}^{-2} \quad (90\% \text{ C.L.}) \quad (7)$$

which leads to the bound

$$\begin{aligned} \text{Br}(\mu^+ \rightarrow \text{invisible}) &= \frac{\Gamma(\mu^+ \rightarrow \text{invisible})}{\Gamma(\mu^+ \rightarrow \text{all})} \\ &< 5.2 \times 10^{-3}. \end{aligned} \quad (8)$$

In close analogy with muon decays, the leptonic decay rates of the tau  $\Gamma(\tau \rightarrow e\nu\bar{\nu})$  and  $\Gamma(\tau \rightarrow \mu\nu\bar{\nu})$  [18] can also provide corresponding Fermi constants [23]

$$G_F^{\tau e} = 1.1666(28) \times 10^{-5} \text{ GeV}^{-2}, \quad (9)$$

$$G_F^{\tau \mu} = 1.1679(28) \times 10^{-5} \text{ GeV}^{-2}. \quad (10)$$

They agree with  $G_F$  of Eq. (3) within 240 ppm and, similar to the above considerations, they can be used to constrain the  $\tau \rightarrow$  invisible decay rate. Taking into account the branching ratio of the leptonic decay rate of tau, the best limit obtained is

$$\text{Br}(\tau \rightarrow \text{invisible}) = \frac{\Gamma(\tau \rightarrow \text{invisible})}{\Gamma(\tau \rightarrow \text{all})} < 1.6 \times 10^{-3}. \quad (11)$$

The limit of Eq. (8) could be improved by more than 7 orders of magnitudes in the proposed experiment discussed below, while to improve significantly the bound on the  $\tau \rightarrow$  invisible decay rate might be more difficult due to the problem with the efficient tagging of the tau appearance. A special study has to be performed in this case.

### III. DIRECT EXPERIMENTAL SEARCH FOR THE $\mu^+ \rightarrow \text{invisible}$ DECAY

The main components of the detector to search for the  $\mu \rightarrow \text{invisible}$  decay are shown in Fig. 2. The basic ideas are as follows. Charged pions are stopped in an active target ( $T$ ) instrumented with energy deposition and time readout. The source of muons is the  $\pi \rightarrow \mu + \nu$  decay at rest in  $T$ . The target is surrounded by a hermetic  $4\pi$  electromagnetic calorimeter (ECAL) to detect energy deposition from the decay  $\mu \rightarrow e + \text{anything}$  of muons stopped in  $T$ . The light signals produced in  $T$  could be read out through the ECAL endcap crystal (EC) which acts as a light guide as shown in Fig. 2. The  $T$  signals could be distinguished from the EC signals due to their significantly different decay times by using the technique described in detail in Ref. [16].

The readout of the energy deposition in the ECAL is triggered by a tag signal of the muon appearance, which is defined by a coincidence of a signal from a stopped pion and a delayed signal from the stopped decay muon. The latter should correspond to the 4.2 MeV energy deposition in the target from the muon kinetic energy.

The experimental signature of the  $\mu \rightarrow \text{invisible}$  decay is the apparent disappearance of the energy deposition in the ECAL from the ordinary electric charge-conserving  $\mu \rightarrow e + \text{anything}$  decay, i.e. observation of an event with the ECAL energy deposition below a certain threshold  $E_{\text{th}}$ .

To estimate the sensitivity of the proposed experiment a feasibility study based on GEANT4 [24] Monte Carlo simulations has been performed. However, to investigate the background down to the level  $\text{Br}(\mu \rightarrow \text{invisible}) \lesssim 10^{-10}$  with the full simulation would require the generation of a very large number of muon decays resulting in a prohibitively large amount of computer time. Consequently, only the most dangerous background processes

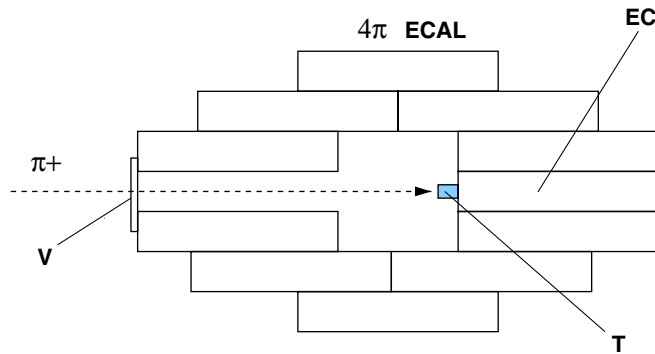


FIG. 2 (color online). Schematic illustration of the experimental setup to search for the  $\mu \rightarrow \text{invisible}$  decay. Shown are the beam defining scintillator counter  $V$ , which is also used as a veto against decay positrons, the active target  $T$ , the electromagnetic calorimeter ECAL, and the ECAL endcap counter EC used as a light guide for the light produced in the target.

are considered and estimated with a smaller statistics combined with numerical calculations.

The beam of positive pions is stopped in the central part of the cylindrical target in a volume of  $\lesssim 1 \text{ cm}^3$ . The active target  $T$  is a plastic scintillator with a diameter of 5–10 mm and a height of 10 mm. According to simulations the 4.2 MeV muon came to rest passing about 1 mm in  $T$ . The ECAL is an array of  $\approx 100$  Bismuth Germanate (BGO) counters each of 52 mm in diameter and 220 mm long, which was previously used in the PSI experiment on precise measurements of the  $\pi \rightarrow e + \nu$  decay rate [25] and then in the ETH-INR positronium experiment [16]. The following sources of background are considered

- (i) the principal muon decay  $\mu \rightarrow e \nu \bar{\nu}$  into the final state with the electron kinetic energy  $E_{\text{kin}}$  less than the detection energy threshold  $E_{\text{th}}$  (typically 100–300 keV). Indeed, if  $E_{\text{kin}} < E_{\text{th}}$  the event becomes invisible. The partial muon decay rate  $\Delta\Gamma_\mu$  into the final state, assuming  $E_{\text{kin}} < m_e$  (here,  $m_e$  is the electron mass), is

$$\Delta\Gamma_\mu \simeq \left(\frac{p_e}{p_e^{\text{max}}}\right)^4 \Gamma_\mu = 3.6 \times 10^{-4} \left(\frac{E_{\text{th}}}{m_\mu}\right)^2 \Gamma_\mu, \quad (12)$$

where  $p_e$ ,  $p_e^{\text{max}}$  is the momentum and the maximum allowed momentum of the decay electron, respectively, and  $p_e \simeq (2m_e E_{\text{th}})^{1/2}$ . To suppress this background, one has to use as low as possible threshold  $E_{\text{th}}$  and to performed the experiment with a well separated *positive* pion beam with an extremely small contamination of negative pions (or muons). In this case, if positive muon decays into a low-energy positron, the latter will stop in the target and annihilate into two photons at a lifetime scale of the order of a few ns. Thus, for events with  $E_{\text{kin}} < E_{\text{th}}$  the minimum energy deposition in the ECAL will be about 1 MeV, i.e. well above the threshold, thus making these events visible. For example, in the ETH-INR experiment the probability to observe  $2\gamma$ -annihilation energy deposition in the BGO ECAL less than the energy threshold of  $E_{\text{th}} \approx 80 \text{ keV}$  was about  $P_{2\gamma} \approx 10^{-8}$  [16,17]. Thus, in the background free experiment one potentially can reach sensitivity in the branching ratio of the invisible muon decay as small as:

$$\text{Br}(\mu \rightarrow \text{invisible}) \sim \frac{\Delta\Gamma_\mu}{\Gamma_\mu} \cdot P_{2\gamma} \approx 10^{-18} \quad (13)$$

assuming the detection energy threshold to be as low as  $E_{\text{th}} \approx 100 \text{ keV}$ .

- (ii) fake tags of the muon appearance could be due to the following effect. A muon from the pion decay in flight stops in  $T$  and decays quickly, within, say, few tens of ns into a low-energy positron which subsequently came also to rest in  $T$  and annihilates into

two photons. If the sum of energies deposited by the positron and annihilation photons, due to their photo-absorption or Compton scattering in  $T$ , is around 4.2 MeV this results in the fake muon tag signal. In the case when the positron kinetic energy is about 3 MeV and almost all annihilation energy is deposited in  $T$  the event becomes invisible. To suppress this background the target should be optimized in size and made of a low- $Z$  material to minimize cross section of the photo-absorption which is  $\sigma_{\text{pha}} \sim Z^5$ . For example, for plastic scintillator the probability of both 511 keV photons energy absorption in a volume of  $\approx 1 \text{ cm}^3$  is found to be less than  $10^{-8}$ . The size of the target is important in order to minimize the number of low-energy positrons stopped in  $T$ . The Monte Carlo simulations of low-energy positrons suggests that for suppression of this background the beam spot size and the diameter of  $T$  have to be as small as possible. If the  $T$  diameter is  $\approx 5 \text{ mm}$ , the requirements to get simultaneously the 4.2 MeV deposited energy and the positron track stopped in  $T$  results in suppression of this background processes to the level  $\leq 10^{-11}$ .

- (iii) the loss of the muon decay energy due to noncomplete hermeticity of the ECAL or due to the presence of passive materials. In the present version Monte Carlo simulations include active materials of the ECAL and the target and negligible amount of passive materials from the ECAL crystals and the target wrapping. It is found that the most dangerous background process is associated with energetic positrons escaping the ECAL through the beam entrance aperture. To suppress this background the aperture should be reduced to as much as possible size and should be closed by a high efficiency veto counter  $V$ , as shown in Fig. 2, which could also act as the beam defining counter.

An additional suppression factor came from the fact that the backward moving decay positrons deposit in  $T$  about 1 MeV in addition to 4.2 MeV deposited by stopped muons. Assuming 10% resolution (FWHM) for measurements of energy in  $T$ , the diameter of the entrance aperture of 1 cm and the inefficiency of  $V \approx 10^{-3}$  leads to the final suppression of this source of background down to the level  $\leq 10^{-11}$ .

Finally let us discuss several additional limitation factors. The first one is related to the relatively long muon lifetime. For example, to get the branching ratio  $\text{Br}(\mu \rightarrow \text{invisible}) \approx 10^{-10}$ , the ECAL gate duration  $\tau_g$ , and hence the dead-time per trigger, has to be

$$\tau_g \gtrsim -\tau_\mu \times \ln(\text{Br}(\mu \rightarrow \text{invisible})) \approx 50 \mu\text{s} \quad (14)$$

in order to avoid background from the muon decays outside the gate. In the ETH-INR positronium experiment, the

ECAL gate  $\tau_{Ps}$  was about  $\approx 2 \mu\text{s}$  for orthopositronium lifetime in the target of 132 ns. This resulted in distribution of the sum of pedestals of all ( $\approx 100$ ) ECAL counters corresponded to the threshold of 80 keV used to define the signal range for the  $o - Ps \rightarrow \text{invisible}$  decay. In the proposed experiment the longer gate will lead to an increase of the pile-up and pick-up electronic noise and hence to the overall broadening of the signal range, approximately by a factor  $\sqrt{\tau_g/\tau_{Ps}} \approx 5$  and, hence to an increase of the energy threshold roughly up to  $E_{\text{th}} \approx 400 \text{ keV}$  [17]. For this threshold the probability of the annihilation energy loss is about  $P_{2\gamma} \approx 10^{-4}$  [17] and the overall sensitivity of Eq. (13) drops to a few parts in  $10^{13}$ .

Another limitation factor is related to the dead time of Eq. (14) and, hence to the maximally allowed muon counting rate, which according to Eq. (14) has to be  $\leq 1/\tau_g \approx 10^4 \mu/\text{s}$ . To avoid this limitation, one could implement a fast first-level trigger rejecting events with the ECAL energy deposition greater than  $E_{\text{th}}$  and, hence run the experiment at the rate  $\approx 1/\tau_\mu \approx 10^5 \mu/\text{s}$ . Thus, in the background free experiment one could expect a sensitivity in the  $\mu \rightarrow \text{invisible}$  decay branching ratio of the order of  $10^{-11}$ , assuming that the exposure to the muon beam with this rate is  $\approx 1$  month. The performed Monte Carlo simulations give an illustrative correct order of magnitude for the sensitivity of the proposed experiment and may be strengthened by more accurate and detailed Monte Carlo simulations of the concrete experimental setup.

#### IV. CONCLUSION

In this work the first limits on the electric charge-nonconserving  $\mu, \tau \rightarrow \text{invisible}$  decay modes are obtained. If the  $\mu^+ \rightarrow \text{invisible}$  decay exists at the level of a few parts in  $10^{11}$ , it could be observed in the new proposed experiment. The preliminary study shows that the quoted sensitivity could be obtained with a setup optimized for several of its properties. Namely, (i) the primary beam and the entrance aperture size, (ii) the energy resolution, material composition, and dimensions of the target, (iii) the efficiency of the veto counter, and (iv) the pile-up effect and zero-energy threshold in the ECAL are of importance. This low-energy experiment might be a sensitive probe of extra-dimensional physics that is complementary to collider experiments.

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