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A SEARCH FOR A "NEW PHYSICS" IN LEPTON FLAVOUR VIOLATION PROCESSES*

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Precision measurements and searches for rare processes in flavour physics offer a unique opportunity to test extensions of the Standard Model *i.e.* so called a "New Physics". After general presentation of this subject a description of only ongoing experiment on the muon beams — a search for neutrinoless muon — electron conversion on nuclei (SINDRUM II project) is presented and last experimental results are discussed.

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Symmetries play a fundamental role in understanding of forces and constituents of our Universe. They are exact like a CPT invariance and broken like an isospin symmetry in nuclear physics. All (?) experiments till now confirm the Standard Model (SM) based on the local symmetry (no dependence on the wave function phase). In this model quarks and leptons are grouped together in three generations. Threefold symmetry of generations is not exact (the same forces but different masses) and there are transitions between generations.

The matter fields of each generation are fermions (spin 1/2): left- and right-handed quarks and charged leptons and only left handed neutrinos — ν are massless in the SM. The quarks are mixed in weak charged (exchange of W's) current interactions. There is no mixing of the lepton fields. Because no reason for different generations is known every fermion is labelled by a specific flavour.

The forces between fermions are generated by exchanges of vector bosons (spin 1^-): photon, W and Z bosons and gluons.

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The electric charge is exactly conserved and only one photon is known to be coupled to this charge and serves as a force (Coulomb field) as a result of this symmetry.

Three different leptonic quantum numbers:

$L_e = 1$ for e^-, ν_e; $= -1$ for $e^+, \tilde{\nu}_e$,; $= 0$ for other leptons

$L_\mu = 1$ for μ^-, ν_μ "

$L_\tau = 1$ for τ^-, ν_τ "

at the present level of our ignorance are conserved:

$$\Delta L_e = \Delta L_\mu = \Delta L_\tau = 0\,,$$

$\Delta L = 0$, where $L = \sum L_i$ is a total lepton number.

There is no electromagnetic muon decay $\mu \to e\gamma$, for example, at the level of branching ratio $BR < 5\times10^{-11}$. But $b \to s\gamma$ ($B \to K^*\gamma$) is known ($BR \approx 10^{-4}$). Lee and Yang [5] were the first to realize that baryon and lepton numbers could not be unbroken local symmetries, since there is no long range force (*i.e.* massless bosons) associated with them. If the lepton numbers are strictly conserved they should serve as corresponding charges emitting some electronic, muonic and tauonic photons and Coulomb-like fields have to exist between them. From the Eötvös type experiment (dependence of the gravitation force on the number of electrons in the different elements: Cu and Pb) one can find [6]:

$$\frac{\alpha_e}{\alpha} < 10^{-47}, \qquad \alpha = \frac{1}{137}\,,$$

where α_e is a coupling constant of the exchange of the hypothetical electronic photon, and α is a fine-structure constant of the "normal" photon. Thus an exact lepton flavour conservation is very unlikely (the same argument for baryon conservation) and is against the idea of quark–lepton unification (if there is a quark mixing a lepton mixing has to exist too). In the SM $b \to s\gamma$ is allowed via quark mixing. But $\mu \to e\gamma$ is strictly forbidden as a consequence of massless neutrino assumption. Lepton flavour conservation is an accidental symmetry of this model.

In almost every extension ("New Physics") of the SM lepton flavour violating processes are allowed. In particular, precise measurements and searches for these rare processes offer a unique opportunity to test Supersymmetric Unification (SUSY) competitive to the highest energy searches (LHC). But, if in the direct searches of SUSY particles a frontier of energy has to be reached, in the indirect discovery of new very weak interaction (via virtual particles) a frontier of sensitivity and precision is necessary to achieve.

In comparison to $\mu \to e\gamma$, a nuclear neutrinoless conversion $\mu^- + (A, Z) \to e^- + (A, Z)$, where the final nucleus is still in the ground state has more potential:

— the detection of only one particle is sufficient — no coincidence is needed;

— electrons are emitted with the highest possible energy, *i.e.* $E_e = m_\mu - B_\mu$, where m_μ is the muon mass and B_μ is the muon binding energy in the muonic atom. The reaction is then almost background free (see below);

— a transition to the ground state is a coherent process — a rate $\Gamma(\mu^-(A, Z) \to e^-(A, Z)) = |\sum M_i|^2$ is additionally enhanced by a number of participating nucleons in comparison to incoherent processes like a normal muon capture $\Gamma(\mu^-(A, Z) \to \nu_\mu(A, Z-1)) = |\sum M_i^2|$;

— processes without virtual photons are possible, thus a nuclear conversion can be still possible, even if in some models an electromagnetic muon decay $\mu \to e\gamma$ is forbidden.

Following Shanker [7] the branching ratio is written, quite generally, as the sum of an isoscalar and an isovector contribution:

$$BR = \frac{\Gamma(\mu(A, Z) \to e(A, Z))}{\Gamma(\mu(A, Z) \to \nu(A, Z-1))} = \left(g^0 + g^1 \frac{Z - N}{3A}\right)^2 \omega(A, Z)\,, \qquad (1)$$

where g^0 and g^1 are isoscalar and isovector coupling constants, respectively, in the Fermi weak interaction constant unit, and $\omega(A, Z)$ is a function determined by a nuclear physics (by an electron momentum transfer).

Recent calculations [4] predict the largest BR for the heaviest nuclei as a clear demonstration of the coherence, but the measurements on different target allow to extract both constants, and if a positive effect will be found to fix the new interaction mechanism.

The strongest source of 2nd Generation leptons (muons) is a PSI cyclotron (in Villigen, Switzerland) with 1.5 mA of 570 MeV protons where pions are copiously produced in proton interactions with the carbon target, and then decay into muons:

$$p + \mathrm{C} \to \pi + X,$$

$$\pi \to \mu + \nu\,.$$

A SINDRUM-SIN [1] Detector of Rare and Unexpected Modes — an unofficial collaboration constructed two magnetic spectrometers:

— SINDRUM I (conventional magnet), which was used to measure the best known (lowest) limits for $\mu^+ \to e^+e^+e^-$ and $(\mu^+e^-) = (\mu^-e^+)$;

[1] SIN — The former name of PSI.

— SINDRUM II (superconducting magnet) for the searches of the $\mu^-(A,Z) \to e^-(A,Z)$ and $\mu^-(A,Z) \to e^+(A,Z-2)$ processes.

Below the results of the searches of these processes on the titanium and lead targets will be presented.

If negative muons are stopped in the target muonic atoms are formed which live for some time (330 ns for Ti and 75 ns for Pb), and disappear in the following ways (shown for the Ti target):

$\mu^- + \mathrm{Ti} \to (\mu^-\mathrm{Ti})_{1S} \to \mathrm{Sc}^* + \nu_\mu$ — nuclear muon capture (NMC);
$\to \mathrm{Ti} + e^-\nu_e\nu_\mu$ — muon decay on orbit (MIO);
$\to \mathrm{Sc}^* + \nu_\mu + \gamma$ — radiative muon capture (RMC);
$\to \mathrm{Ti} + e^-$ — coherent neutrinoless conversion;
$\to \mathrm{Ti}^* + e^-$ — incoherent conversion;
$\to \mathrm{Ca}^* + e^+$ — Δ L=2 conversion.

To resolve conversion events from the MIO electrons the instrumental resolution has to be very good (better than 2 MeV for the BR of 10^{-14}). Some prompt background coming from pion and electron beam contamination can be recognized by the beam counter and the cosmic ray background by an active and passive shielding.

The measurements were done at $\mu E1$ beam line at PSI. Detailed information can be found in [2, 3]. 60% of muons with the intensity of 11 MHz were stopped in the target. The SINDRUM II magnet of 70 tons has an active diameter of 1354 mm and length of 1800 mm and in this magnet a cylindrical spectrometer consisting of the beam counter, 2 drift chambers, scintillation and Cerenkov hodoscopes in the 1.2 T field was mounted. The electron momenta are obtained by precise measurements of the electron helix curvatures and polar angles.

The geometrical acceptance was larger then 60%. The detector response was studied by stopping π^+ in the low mass target and by measuring the trajectories of the 69.8 MeV positrons from the decay $\pi^+ \to e^+ + \nu$. The momentum resolution of 1.3% has been achieved. The calculated resolution for the Ti target is 2.3 MeV determined essentially by the energy losses.

After 2 months (effective) beam time on the Ti target no effect has been found and a new upper limits of the branching ratios were obtained:

$BR(\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}^{\mathrm{g.s.}}) < 7 \times 10^{-13}$ (90% CL) — factor of 6 improvement on our previous result [2];

$BR(\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^{\mathrm{g.s}}) < 1.7 \times 10^{-12}$ (90% CL) — factor of 3 improvement on our previous result [2].

No effect on the Pb target (effective 10 days of the beam) has been found either, and the result for the branching ratio is [3]:

$BR(\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}^{\mathrm{g.s.}}) < 4.6 \times 10^{-11}$ (90% CL) — factor of 10 improvement on the previous result [1].

From this study one can conclude that the effective coupling constants introduced in Eq. (1) are smaller than 10^{-6} of the Fermi coupling constant for the scalar interaction and smaller then 10^{-5} for the vector one. In the case of the Yukawa coupling these limits show that there is no new boson mediating this process with the mass below 800 GeV.

These limits give strong constrains (model dependent) on many other postulated particles, like heavy neutrinos, Z' — a postulated heavy partner of Z, leptoquarks and SUSY particles.

Our Ti result gives a branching ratio for $Z \to \mu e$, which is 9 orders of magnitude lower than direct searches on LEP.

In the ongoing experiment it is planned to reach the sensitivity below 10^{-13} with the additional 8m superconducting solenoid at the exit of the $\pi E5$ beam line, where the stop intensity is higher for very thin targets.

Beside the importance of new limits to constrain possible models, it is important to remember that there is no fundamental reason why this process should not be observed in nature.

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