PHYSICS WITH LOW-ENERGY MUONS AT A NEUTRINO FACTORY COMPLEX

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December 9, 2006

Abstract

The physics potential of an intense source of low-energy muons is studied. Such a source is a necessary stage towards building the neutrino factories and muon colliders which are being considered at present. The CERN Neutrino Factory could deliver muon beams with intensities 3–4 orders of magnitude higher than available now, with large freedom in the choice of the time structure. Low-energy muon physics contributes to many fields of basic research, including rare muon decays, i.e., decays that do not conserve muon number, measurements of fundamental constants, the muon anomalous magnetic moment, determination of the Lorentz structure of the weak interaction, QED tests, CPT tests, proton and nuclear charge distributions (even for short-lived isotopes), and condensed matter physics. In studying the experimental programme, we analyse the present limitations, list the requirements on the new muon beams, and describe some ideas on how to implement these beam lines in a CERN neutrino factory complex.

CERN-TH/2001–231

Contents

0.0.1 $\mu - e$ conversion

Neutrinoless $\mu^- - e^-$ conversion in muonic atoms, $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$ with a nucleus of a mass number A and an atomic number Z, offers some of the best tests of lepton flavor violation (LFV). For conversions leaving the nucleus in its ground state the nucleons act coherently, which boosts the conversion probability relative to the rate of the dominant process of ordinary nuclear muon capture.

Assuming LFV one may wonder how the conversion probability $B_{\mu-e}$ varies as a function of A and Z, and with what probability the nucleus stays in its ground state. Earlier calculations [100, 101, 102] and the latest calculation [103] predicted a steady rise of the branching ratio until $Z \approx 30$, from where on it was expected to drop again. For this reason most experiments were performed on medium-heavy nuclei. The nuclear physics calculations predict the coherent fraction to be larger than 80% for all nuclear systems [104, 105].

When negative muons stop in matter, they quickly get captured and form muonic atoms, which mostly reach their ground state before decaying. The main decay channels are muon decay in orbit (DIO) $\mu^- + (A, Z) \rightarrow e^- + \overline{\nu}_e + \nu_\mu + (A, Z)$ and nuclear muon capture $\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)$. Experimentally coherent $\mu - e$ conversion offers a number of advantages. Since the observation of the process requires the detection of only one particle in the final state, there are no problems with accidental coincidences, which constitute one of the major limitations in searches for $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$. The electron is emitted with energy $E_e \approx m_\mu c^2$, which coincides with the endpoint of muon DIO, which is the only intrinsic physics background. Since the energy distribution of muon decay in orbit falls steeply above $m_\mu c^2/2$ the experimental set-up may have a large signal acceptance and the detectors can still be protected against the vast majority of decay and capture background events. Energy distributions for DIO electrons have been calculated for a number of muonic atoms [106, 107, 108] and energy resolutions in the order of 0.1% are sufficient to keep this background below 10^{-18}.

There are several other potential sources of electron background in the energy region around 100 MeV, involving either beam particles or cosmic rays. Beam-related background may originate from muons, pions or electrons in the beam. Apart from DIO, muons may produce background by muon decay in flight or radiative muon capture (RMC). Pions may produce background by radiative pion capture (RPC). Capture gammas from RMC and RPC produce electrons mostly through e^+e^- pair production inside the target.

Beam-related background can be suppressed by various methods:

- Beam pulsing
  Since muonic atoms have lifetimes of order 100 ns, a pulsed beam with buckets short compared to this lifetime would allow one to remove prompt background by measuring in a delayed time window. As will be discussed below there are stringent requirements on beam extinction during the measuring interval. Two approaches to achieve beam extinction of required levels are considered. One is extinction for protons and the other is that for muons. For the latter, a muon storage ring with kicker-magnets of injection/extraction is considered for additional extinction devices.

- Beam purity
  A low-momentum (< 70 MeV/c) μ^- beam with no pion contamination (10^{-20}) would keep prompt background at a negligible level. it could be done by adopting a muon storage ring where pions decay out in their flight length of order of a few 100 meters. A major advantage of the method is that heavy targets such as gold with lifetimes around 70 ns can be studied. This scheme was applied by PRISM which will be described below.

The latest search for $\mu - e$ conversion was done by the SINDRUM II collaboration at PSI [109]. During an effective measuring period of 75 days, about 4×10^{13} muons stopped in the gold target. Figure 1 shows their result of various momentum distributions. The main spectrum, taken at 53 MeV/c, shows the steeply falling distribution expected from muon decay in orbit. Two events were found at higher momenta, but just outside the region of interest. The agreement between measured and simulated positron distributions from μ^+ decay gives confidence in the momentum calibration. At present there are no hints about the nature of the two high-momentum events: they might be induced by cosmic rays or RPC, for example. Both processes result in flat momentum distributions such as shown by the data taken at 63 MeV/c.

There was another proposal at BNL ,which is the MECO experiment [110] aiming at a search with a sensitivity of 10^{-16}. It planed to combat beam-related background with the help of a pulsed 8 GeV/c proton beam. Figure 2 shows the proposed layout. Pions are produced by 8 GeV/c protons crossing a 16 cm long tungsten target, and muons from their decays are collected efficiently with the help of a graded magnetic field. Negatively

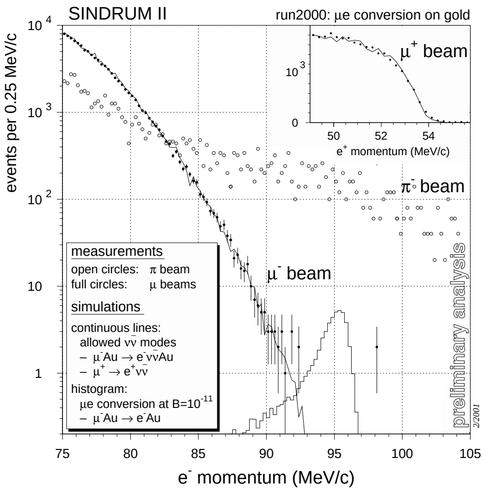

Figure 1: Recent results by SINDRUM II. Momentum distributions for three different beam momenta and polarities: (i) 53 MeV/c negative, optimized for μ^- stops, (ii) 63 MeV/c negative, optimized for π^- stops, and (iii) 48 MeV/c positive, for μ^+ stops. The 63 MeV/c data were scaled to the different measuring times. The μ^+ data were taken at reduced spectrometer field.

charged particles with 60–120 MeV/c momenta are transported by a curved solenoid to the experimental target. In the spectrometer magnet a graded field is applied as well. A major challenge is the requirement for proton extinction in between the proton bursts. In order to keep the pion stop rate in the 'silent' interval, a beam extinction factor better than 10^{-8}–10^{-9} is required. Unfortunately, the MECO experiment was cancelled in 2005, owing to their funding problem. The revival of the MECO experiment (the mu2e experiment) is now being seriously considered at Fermi National Laboratory.

Aiming for future large improvements in searches for muon lepton flavor violation, what would the best mode to search for be ? The following table is a short summary on potential muon rare processes, their backgrounds and issues and their required beam conditions.

Modes	Backgrounds	Issues	Beam
$\mu^+ \to e^+\gamma$	accidentals	detector resolution	continuous
$\mu^+ \to e^+e^+e^-$	accidentals	detector resolution	continues
$\mu^- N \to e^- N$	beam-related	muon beam	pulsed

For the first two decay modes, accidental background is the most important. To suppress accidental backgrounds, improvement of detector resolution is critical. It is however known to be very difficult to improve further, since

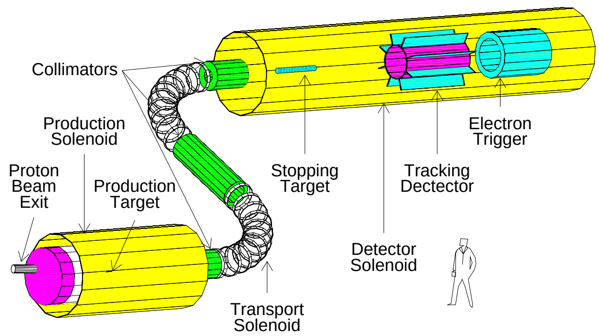

Figure 2: MECO setup

these involve detection of low energy photons and electrons (positrons). On the other hand, for the $\mu - e$ conversion, no accidental background exists because of single measurement, but rather the beam quality should be improved. The beam requirements for μ^e conversion are summarized as follows;

(1) high beam intensity	$> 10^{11}\mu^-/\text{sec}$
(2) beam pulsing	suppression of beam-related backgrounds
(3) high purity:	no pions in a beam
(4) narrowed energy spread	use of thiner targets

It is noted that the detection resolution of the e^-s from $\mu - e$ conversion is mostly determined by a thickness of the muon stopping target. To allow using a thin muon stopping target, beam energy spread should be as narrow as possible. To meet all of these requirements, R&D works on a neutrino factory and a muon collider would help tremendously to realize the beam suitable for $\mu - e$ conversion experiments.

In this regards, a new project to construct a new-generation muon source with high intensity, high luminosity and high purity, is being carried out in Japan. It is called the PRISM project [111], where PRISM stands for Phase Rotated Intense Slow Muon source. The phase rotation technique, which is to make beam energy spread narrower by accelerating slow muons and decelerating fast muons by high RF electric fields, is adopted in PRISM. PRISM consists of solenoid pion capture, transport solenoid, a muon storage ring to carry out phase rotation. The muon storage ring is a fixed field alternating gradient (FFAG) machine, which has large acceptance in transverse and longitudinal. The ultimate goal of PRISM is to search for the $\mu - e$

conversion at a sensitivity of less than 10^{-18}. The beam requirements from (1) to (4) for $\mu - e$ conversion are sufficiently met by PRISM. In particular, in several turns in the FFAG muon storage ring, pions in a beam decay out and the residual fraction would be down to less than 10^{-18}. A preliminary design of a detector for the $\mu - e$ conversion is made (a PRIME detector). The layout of PRISM / PRIME is shown in Fig.3. The PRISM-FFAG ring is under construction.

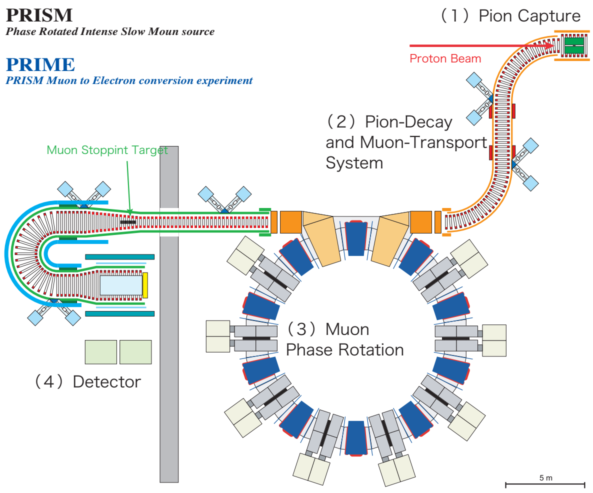

Figure 3: Layout of PRISM/PRIME. It consists of solenoid pion capture, muon transport system, muon phase rotation system based on FFAG ring, and a PRIME detector.

Table 1 compares the μ^- intensity and single-event sensitivity obtained by SINDRUM II, MECO, PRISM and the case for a neutrino factory based on extrapolation from the near-future proposals. At a neutrino factory, one might use *a cooled muon beam*. Such a beam would probably be not only free of pions but also allow one to use a point-like target of muon-stopping. As a second by-product of the cooling the extinction factor should be much higher at this stage.

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Table 1: Rates in $\mu - e$ conversion searches

	SINDRUM II PSI	MECO BNL	PRISM J-PARC	NUFACT –
Status	Stopped	Cancelled	Proposed	Discussed
Proton energy [GeV]	0.6	8	40	10
Proton rate [s^{-1}]	1×10^{16}	4×10^{13}	10^{14}	10^{15}
μ^- rate [s^{-1}]	3×10^{7}	2×10^{11}	10^{12}	10^{14}
μ^- stops [s^{-1}]	$(1 \ldots 2) \times 10^{7}$	1×10^{11}	10^{12}	10^{14}
Single event sensitivity	2×10^{-13}	2×10^{-17}	5×10^{-19}	10^{-21}

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