Lepton Flavour Violation Experiments –
Some Recent Developments

Klaus P. Jungmann

Physikalisches Institut, Universität Heidelberg
Philosophenweg 12, D-69129 Heidelberg, Germany

Abstract. Dedicated experiments searching for lepton flavour violation can be performed very sensitively using K-decays and μ-decays as well as neutrinoless double β-decay and muonium to antimuonium conversion. Although there is no confirmed signal reported yet, stringent limits for parameters in speculative extensions to the standard model can be set. Some models could recently be ruled out.

I INTRODUCTION

All confirmed experimental data acquired to date indicate the conservation of lepton numbers. This fact can be described by several different empirical laws [1–5], some of which follow additive and some obey multiplicative, parity-like, schemes. Experiments have given no indication yet for favouring any of them. The standard model states for every lepton flavour a separate additively conserved quantum number. However, such lepton numbers have no status, unless their conservation can be associated with a local gauge invariance [6]. Mixings between different generations are well known in the quark sector and the Cabbibo-Kobayashi-Maskawa matrix [7] relates the weak quark eigenstates with their mass eigenstates. A familiar example are the K⁰−̅K⁰ oscillations. At present we are left puzzled why leptons do not show any similar mixing. Recent experimental hints for neutrino oscillations, which have a potential for changing this situation, are not covered here (see e.g. [8]).

Many extensions to the standard model have been proposed and are presently discussed which try to explain further some of its not well understood features like e.g. parity violation in weak interaction or particle mass spectra. They are put by hand into this remarkable theoretical framework which appears to serve as an extremely robust description of all confirmed particle physics. Lepton flavor violation (LFV) appears naturally in such models which include Left-Right-Symmetry, Supersymmetry, Technicolor, Grand Unification, String Theories, Compositeness, and many others. They continue to stimulate experimental searches in a large range of energies. With some low energy experiments new physics can be probed at mass scales far beyond the reach of present accelerators or such planned for the future.
FIGURE 1. Dedicated searches for lepton number violating processes involving muons ($\mu$) and kaons ($K$). Recent $K$ experiments and $\mu^+e^- - \mu^-e^+$ conversion exhibit the most significant gains in sensitivity. Points in 1998 and beyond are projections of possibilities by the respective experimenters.

Highest sensitivity has generally been reached in dedicated search experiments particularly on Kaons ($K$) and muons ($\mu$) (Table 1), where also a high discovery potential for new physics exists [9], as well as in non accelerator experiments searching for neutrinoless double $\beta$-decay. The decays of heavier objects created in high energy collisions, however, can be observed less accurately. The progress in the $K$ and $\mu$ (see sec. IV and V) field is indicated in Fig.1 which shows more than 10 decades of improvement since the first experiments in the late 1940’s. The highest recent gain in sensitivity is for muonium ($M=\mu^+e^-$) to antimuonium ($\overline{M}=\mu^-e^+$) conversion due to a new, yet unused signature (see sec. V C).

TABLE 1. Recently obtained upper limits on lepton number violating processes (90% C.L.).

| decay                  | limit       | reference |
|------------------------|-------------|-----------|
| $Z^0 \rightarrow \mu e$| $2.5 \cdot 10^{-6}$ | 10        |
| $Z^0 \rightarrow \tau e$ | $7.3 \cdot 10^{-6}$ | 10        |
| $Z^0 \rightarrow \tau\mu$ | $1.0 \cdot 10^{-5}$ | 10        |
| $D^0 \rightarrow \mu e$ | $1.9 \cdot 10^{-5}$ | 11        |
| $D^0 \rightarrow \pi^0\mu e$ | $8.6 \cdot 10^{-5}$ | 11        |
| $D^0 \rightarrow \Phi\mu e$ | $3.4 \cdot 10^{-5}$ | 11        |
| $B^0 \rightarrow \mu e$ | $5.9 \cdot 10^{-6}$ | 12        |
| $B^0 \rightarrow \tau e$ | $5.3 \cdot 10^{-4}$ | 12        |
| $B^0 \rightarrow \tau\mu$ | $8.3 \cdot 10^{-4}$ | 12        |
| $B^0 \rightarrow \tau K$ | $1.8 \cdot 10^{-5}$ | 12        |
| $\tau \rightarrow e\gamma$ | $2.7 \cdot 10^{-6}$ | 13        |
| $\tau \rightarrow \mu\gamma$ | $3.0 \cdot 10^{-6}$ | 13        |

| decay                  | limit       | reference |
|------------------------|-------------|-----------|
| $K_L \rightarrow \mu e$ | $2 \cdot 10^{-11}$ | 14        |
| $K_L \rightarrow \pi^0\mu e$ | $3.2 \cdot 10^{-9}$ | 16        |
| $K^+ \rightarrow \pi^+\mu e$ | $4 \cdot 10^{-11}$ | 17        |
| $\mu^+ \rightarrow e^+\nu\mu\nu e$ | $2.5 \cdot 10^{-3}$ | 18        |
| $\mu \rightarrow eee$ | $1 \cdot 10^{-12}$ | 19        |
| $\mu \rightarrow e\gamma$ | $3.8 \cdot 10^{-11}$ | 20        |
| $\mu^-Ti \rightarrow e^-Ti$ | $6.1 \cdot 10^{-13}$ | 21        |
| $\mu^-Ti \rightarrow e^+Ca$ | $1.7 \cdot 10^{-12}$ | 22        |
| $\mu^+e^- \rightarrow \mu^-e^+$ | $G_{\text{MM}} < 3 \cdot 10^{-3}G_F$ | 23        |
| $^{76}\text{Ge} \rightarrow ^{76}\text{Se} \ e^-e^-$ | $T_{1/2} > 1.2 \cdot 10^{30}y$ | 24        |
| $m_{\nu_e}(\text{Maj.}) < 0.45eV$ | $m_{\nu_e}(\text{Maj.}) < 0.45eV$ | 24    |
II NEUTRINOLESS DOUBLE $\beta$-DECAY

A $\beta$-decay of a nucleus involving two electrons and no neutrinos would violate electronic lepton flavour by two units. It has been suggested in many models, particularly, such involving neutrinos of Majorana type. It is being searched for in many experiments (see Table 2) using $^{48}$Ca, $^{76}$Ge, $^{82}$Se, $^{100}$Mo, $^{116}$Cd, $^{130}$Te and $^{136}$Xe. Among those the Heidelberg-Moscow Germanium experiment provides the most stringent half life limit of $T_{1/2} \geq 1.2 \cdot 10^{25}$ y [24]. It uses most advantageously isotopically enriched material with 86% $^{76}$Ge as a semiconductor detector to watch its own nuclei decay. It is situated in a clean and carefully against background radiation shielded environment in the Gran Sasso underground laboratory. The measures include purging with purified nitrogen as well as using copper material in the cooling system in the vicinity of the actual detector which was selected for low intrinsic radiation. Remaining background counts were further suppressed by pulse shape analysis. The result achieved in 31.8 kg years with the 11.5 kg detector can be used to impose an upper limit on the electron neutrino Majorana mass of 0.45 eV, which is well below the electron neutrino mass limit of 3.9 eV established in model independent general direct searches using tritium decay [25].

With 1 ton enriched $^{76}$Ge distributed in 288 individual detectors, as suggested by the GENIUS proposal, one could expect in 10 years running time a limit of $T_{1/2} > 6 \cdot 10^{28}$ y corresponding to a Majorana neutrino mass limit of below 6 meV/c$^2$ [24]. It is a particularly nice feature of most experiments searching for neutrinoless double $\beta$-decay that they can also contribute to sensitive searches for cold dark matter, particularly weakly interacting massive particles (WIMPS) in mass regions above $\approx 20$ GeV/c$^2$.

![FIGURE 2. Experiments searching for neutrinoless double $\beta$-decay. The most sensitive ones use enriched $^{68}$Ge detectors. The dark areas represent the current status and the lighter color indicates near future possibilities. The dashed arrows are long term future plans. Among the most ambiguous projects ranks a 1 ton Ge detector which could be used to gain two orders of magnitude in sensitivity (from ref. [24]).]
III EXPERIMENTS AT ELECTRON-POSITRON COLLIDERS - \( Z^0 \) AND \( W^\pm \) BOSONS AND \( \tau \) LEPTONS

The general purpose detectors installed at the large high energy electron-positron colliders provide the possibility heavy elementary particles and gauge bosons like the \( \tau \) lepton or the \( W^\pm \) and \( Z^0 \) bosons to be observed for rare decays and particularly for lepton number violating effects. Their high mass offers for each particle a large number of different possible purely leptonic and semileptonic decay channels. \( Z^0 \) bosons were produced in large quantities at the LEP storage ring of CERN and the Stanford Linear Collider. With the LEP200 upgrade a significant number of \( W^\pm \) bosons became available. For \( \tau \)'s the CLEO detector at the Cornell CESR facility provided a significant amount of the available data particularly on neutrinoless \( \tau \) decays \cite{13,26} as well as on \( B^0 \) and \( D^0 \) decays \cite{11,12}.

The sensitivity of all analyses for lepton number violating (LNV) decays have a principle limit set by statistics. For a particular decay channel further restrictions arise from finite acceptances for the final state particles which explain the course differences in the upper bounds reported for the different channels although starting from the same initial state (Table 1). The limits on branching ratios are in general much higher than the ones obtained in dedicated experiments on K’s and \( \mu \)’s. For \( \tau \)'s one expects in the near future a sensitivity not better than \( 10^{-7} \) for any decay mode.

However, such bounds are of great value for discriminating theoretical models where mass scaling runs with a high power of the mass ratios. In the framework of superstring models, for example, the decay \( l \to e\gamma \), where \( l \) stands for \( \mu \) or \( \tau \), scales with the fifth power of the lepton mass \( m_l \). In this particular case the upper limit of \( 2.7 \times 10^{-6} \) for \( \tau \to e\gamma \) can compete with the present \( 3.8 \times 10^{-11} \) limit on \( \mu \to e\gamma \) due to the \( 1.3 \times 10^6 \) enhancement factor from the mass ratio \( m_\tau/m_\mu \approx 16.8 \). However in general the mass scaling is expected to be less dramatic.

IV EXPERIMENTS ON KAONS

With the availability of intense Kaon sources at the Fermi National Accelerator Laboratory (FNAL) and the Brookhaven National Laboratory (BNL) and with novel experimental techniques developed to cope with high data rates the search for LFV K-decays has gained a lot of interest. Here the experiments BNL-871 searching for \( K^+ \to \pi^+ e\mu \), BNL-865 searching for \( K_L \to \mu e \) and the Fermilab KTeV effort FNAL-799II investigating \( K_L \to \pi^0 \mu e \) promise significant improvements (see Table 2), where the LFV decays are searched along with measurements on very rare K decay channels. Among the new physics that could be revealed are new heavy gauge bosons with masses up to order 50-200 TeV/c\(^2\), far beyond the reach of even any planned accelerator \cite{27}. At the projected Japanese Hadron Facility (JHF) one could expect significant improvements beyond the present status.
TABLE 2. Three presently ongoing searches for lepton flavour violating K decays.

| Time | Experiment | Branching Ratio |
|------|------------|-----------------|
| Past | BNL-777    | $2 \cdot 10^{-10}$ |
|      | BNL-791    | $3 \cdot 10^{-11}$ |
|      | FNAL-799   | $3.2 \cdot 10^{-9}$ |
| Present | BNL-865   | $4 \cdot 10^{-11}$ |
|      | BNL-871    | $5 \cdot 10^{-12}$ |
|      | FNAL799II  | $3 \cdot 10^{-12}$ |
| Anticipated | BNL-865 | $\approx 3 \cdot 10^{-12}$ |
|      | BNL-871    | $\approx 8 \cdot 10^{-13}$ |
|      | FNAL799II  | $\approx 1 \cdot 10^{-11}$ |
| Future | BNL-865   | $10^{-13}$ |
|       | BNL-871    | $10^{-13}$ |
|       | FNAL799II  | $10^{-13}$ |

V EXPERIMENTS INVOLVING MUONS

The decay $\mu \to e\gamma$ was the first being searched for shortly after the muon’s nature as a heavy electron-like particle became apparent. Searches for rare and forbidden muon decays have been among the most precise experiments in physics since and have always been of special interest in the context of unified gauge theories, as they can provide accurate tests of speculative models and because of the achievable experimental precision they may be able to discriminate between such [28]. Recently forbidden muon decays have attracted attention, when their possible sensitivity to effects arising in minimal supersymmetry (SUSY) were discussed in theoretical studies [29]. It was pointed out that for values of $\tan\beta$ (the ratio of the vacuum expectation values of the two Higgs fields involved) which exceed about 3, the branching ratio should be above $\approx 10^{-14}$ for a decay $\mu \to e\gamma$ and above $\approx 10^{-16}$ for $\mu \to e$ conversion on a Ti nucleus, almost independent of all other parameters in the model. This has stimulated a letter of intent to the Paul Scherrer Institute (PSI), Switzerland, and a proposal to BNL to search for the respective processes.

In the field of searching for SUSY effects in low energy experiments rare decay experiments are in some competition with the just started new precision measurement [30] of the muon magnetic anomaly $a_\mu$ where the contribution from SUSY is of order $a_\mu(SUSY) = 140 \cdot 10^{-11} \tan\beta \times (100\text{GeV}/\tilde{m})^2$ with $\tilde{m}$ the mass of the lightest SUSY particle (see [31]). The measurement goal is $\Delta a_\mu(exp) = 40 \cdot 10^{-11}$ and should be reached around the year 2001.

A $\mu \to e\gamma$ decay

The signature of a $\mu \to e\gamma$ event is a 52.8 MeV positron emitted back to back with a 52.8 MeV photon. The MEGA experiment at the late Los Alamos Meson Physics Facility (LAMPF) consisted of a magnetic spectrometer to observe the charged final state particle and three pair spectrometers for detecting the photon through its $e^+e^-$ pair creation in lead converters. Random coincidences at high rates are reported as major background. Data taking is completed and 16% of the data could be analyzed leading to an upper limit on the branching ratio of
which slightly improves the value of $4.9 \cdot 10^{-11}$ established in a crystal box detector also at LAMPF [32].

At PSI new efforts are being discussed to reach a sensitivity of about $5 \cdot 10^{-14}$ for this decay mode within the next couple of years. The suggested instruments include solutions like a large solid angle magnetic spectrometer for the $e^+$ surrounded by a crystal calorimeter for the $\gamma$, or liquid Xe calorimeters for the $\gamma$ and others [33].

It should be noted that the tightest bounds on bileptonic gauge bosons, which are common to many speculative standard model extensions, come from $\mu \rightarrow e\gamma$, if flavour democracy is assumed [34].

### B $\mu \rightarrow e$ conversion

Many constraints for speculative models arise from the present experimental bound on the conversion process $\mu + Z \rightarrow e + Z$ (Table 1), which is the tightest for all studied LNV decays. The variety of theoretically possible processes that can be tested includes, e.g. supersymmetric loop graphs, heavy neutrinos, leptoquarks, compositeness, Higgs bosons and heavy $Z'$ bosons with anomalous couplings. Generally it is more sensitive to new Physics than $\mu \rightarrow e\gamma$ in a wide class of models where the process is generated at the one loop level [35].

The process needs to involve a nucleus to assure elementary conservation laws. If the nucleus is left in its ground state, a conversion event is signaled through the release of a 105 MeV electron, which is uniquely distinguishable from normal muon decay electrons ranging up to 53 MeV. Among the physically relevant intrinsic background processes is $\mu$ decay in the atomic orbit after a muonic atom has been formed, which can release much higher energetic electrons, and radiative muon capture, where the photokinematic end point can be close to the signal electron energy.

The ongoing SINDRUM II experiment uses the worldwide brightest continuous muon channel $\pi E5$ at PSI. Their new results limit the branching ratios $\mu^{-}\text{Ti} \rightarrow e^{+}\text{Ca}^{gs}$ to below $1.7 \cdot 10^{-12}$ for the Ca nucleus in the ground state [22], $\mu^{-}\text{Ti} \rightarrow e^{+}\text{Ca}^{GDR}$ to below $3.6 \cdot 10^{-11}$ leaving Ca with giant dipole resonance excitation [22], and $\mu^{-}\text{Ti} \rightarrow e^{-}\text{Ti}$ to below $6.1 \cdot 10^{-13}$ for Ti in the ground state [21]. For the ground state processes the nucleons interact coherently which enhances the possible effect. In order to boost accuracy in the near future the SINDRUM II collaboration wants to take advantage in the gain of muon flux through a $\pi - \mu$ converter, a novel superconducting device in the beam line which collects $\pi$'s and releases only $\mu$'s with very low $\pi$ contamination. The latter point is essential as $\pi$'s are a source of potential background due to nuclear reactions. The projections of the collaboration for the achievable limit in the coherent $\mu^{-}\text{Ti} \rightarrow e^{-}\text{Ti}$ case are in the $10^{-14}$ region.

The new Muon Electron Conversion (MECO) experiment proposed at BNL [36] (see Fig.3) is very close in its design to a proposal by Lobashhev and collaborators for the Moscow Meson Factory. The setup consists of a target station for $\pi/\mu$ production which uses a proton beam from the AGS accelerator, an S-shaped transport.
and purification section and a detector the basic idea of which is to let electrons from normal muon decay pass without being seen and to observe only the 105 MeV signal electrons. The goal is the $10^{-16}$ level in sensitivity, which will stringently test supersymmetric models; there is an anticipated ultimate capability for $10^{-18}$ [15].

\[ \mu^+ e^- \rightarrow \mu^- e^+ \text{ conversion} \]

The hydrogen-like muonium atom consists of two leptons from different generations. The close confinement of the bound state offers excellent opportunities to explore precisely fundamental electron-muon interactions [37,38]. Since the effect of all known fundamental forces in this system are calculable very well mainly in the framework of quantum electrodynamics (QED), it renders the possibility to search sensitively for yet unknown interactions between both particles.

**FIGURE 4.** Muonium-antimuonium conversion in theories beyond the standard model. The interaction could be mediated by (a) a doubly charged Higgs boson $\Delta^{++}$ [39,40], (b) heavy Majorana neutrinos [39], (c) a neutral scalar $\Phi_N$ [41], e.g. a supersymmetric $\tau$-sneutrino $\tilde{\nu}_\tau$ [6,42], or (d) a dileptonic gauge boson $X^{++}$ [43].
An $\mathbf{M-\overline{M}}$-conversion would violate additive lepton family number conservation and is discussed in many speculative theories (see Fig. 4). It would be an analogy in the lepton sector to $K^0-\overline{K^0}$ oscillations.

The setup at PSI (Fig. 5) [44] is designed to employ the signature developed in a predecessor experiment at LAMPF, which requires the coincident identification of both particles forming the antiatom in its decay [45,46]. Muonium atoms in vacuum with thermal velocities, which are produced from a SiO$_2$ powder target, are observed for antimumonium decays. Energetic electrons from the decay of the $\mu^-$ in the antiatom can be observed in a magnetic spectrometer at 0.1 T magnetic field consisting of five concentric multiwire proportional chambers and a 64 fold segmented hodoscope. The positron in the atomic shell of the antiatom is left behind after the decay with 13.5 eV average kinetic energy [47]. It can be accelerated to 7 keV in a two stage electrostatic device and guided in a magnetic transport system onto a position sensitive microchannel plate detector (MCP). Annihilation radiation can be observed in a 12 fold segmented pure CsI calorimeter around it.

The relevant measurements were performed during in total 6 month distributed over 4 years during which $5.7 \cdot 10^{10}$ muonium atoms were in the interaction region. One event fell within a 99% confidence interval of all relevant distributions (Fig. 6). The expected background due to accidental coincidences is 1.7(2) events. Thus an upper limit on the conversion probability of $P_{\mathbf{M-\overline{M}}} \leq 8.2 \cdot 10^{-11}/S_B$ (90% C.L.) was found, where $S_B$ accounts for the interaction type dependent suppression of the conversion in the magnetic field of the detector due to the removal of degeneracy between corresponding levels in $\mathbf{M}$ and $\overline{\mathbf{M}}$. The reduction is strongest for $(V\pm A)\times(V\pm A)$, where $S_B=0.35$ [48,49]. This yields for the traditionally quoted upper limit on the coupling constant in effective four fermion interaction $G_{\mathbf{M-\overline{M}}} \leq 3.0 \cdot 10^{-3} G_F$ (90% C.L.) with $G_F$ the weak interaction Fermi constant.

This new result, which exceeds bounds from previous experiments [45,50] by a factor of 2500 and the one from an early stage of the experiment [44] by 35, has
some impact on speculative models. A certain $Z_8$ model is ruled out with more than 4 generations of particles where masses could be generated radiatively with heavy lepton seeding [51].

A new lower limit of $m_{X^{\pm\pm}} \geq 2.6 \text{ TeV/c}^2 * g_{3l}$ (95% C.L.) on the masses of flavour diagonal bileptonic gauge bosons in GUT models is extracted which lies well beyond the value derived from direct searches, measurements of the muon magnetic anomaly or high energy Bhabha scattering [43,34]. Here $g_{3l}$ is of order 1 and depends on the details of the underlying symmetry. For 331 models this translates into $m_{X^{\pm\pm}} \geq 850 \text{ GeV/c}^2$ which excludes their minimal Higgs version in which an upper bound of 600 GeV/c$^2$ has been extracted from an analysis of electroweak parameters [52,53]. The 331 models may still be viable in some extended form involving a Higgs octet [54]. In the framework of R-parity violating supersymmetry [42,6] the bound on the coupling parameters could be lowered by a factor of 15 to $|\lambda_{132}\lambda_{231}| \leq 3 \times 10^{-4}$ for assumed superpartner masses of 100 GeV/c$^2$. Further the achieved level of sensitivity allows to narrow slightly the interval of allowed heavy muon neutrino masses in minimal left-right symmetry [40] (where a lower bound on $G_{MM}$ exists, if muon neutrinos are heavier than 35 keV) to $\approx 40 \text{ keV/c}^2$ up to the present experimental bound at 170 keV/c$^2$.

In minimal left right symmetric models, in which $\text{MM}$ conversion is allowed, the process is intimately connected to the lepton family number violating muon decay $\mu^+ \rightarrow e^+ + \nu_\mu + \overline{\nu}_e$. With the limit achieved in this experiment this decay is not an option for explaining the excess neutrino counts in the LSND neutrino experiment at Los Alamos [55,56].

The consequences for atomic physics of muonium are such that the expected level splitting in the ground state due to $M - \overline{M}$ interaction is below 1.5 Hz/$\sqrt{S_B}$ reassuring the validity of fundamental constants determined in muonium spectroscopy.

A future $M - \overline{M}$ experiment could take particularly advantage of high intense pulsed beams. In contrast to other LNV muon decays, the conversion through its nature as particle - antiparticle oscillation, has a time evolution in which the probability for finding $\overline{M}$ in the ensemble remaining after muon decay increases.
quadratically in time, giving the signal an advantage growing in time over major exponentially decaying background [46].

VI LONG TERM FUTURE POSSIBILITIES

It appears that the availability of particles limits the ability to find very rare processes or to impose significantly improved limits in continuation of the search program of dedicated experiments. Therefore any measure to boost the respective particle fluxes is a very important step forward. The \( \pi - \mu \) converter at PSI or the dedicated tailored muon production of the planned MECO experiment at BNL are examples of novel attempts to overcome this problem. In principle, we need significantly more intense accelerators, such as they are presently discussed at various places. In the intermediate future the Japanese Hadron Facility (JHF) or a possible European Spallation Source (ESS) are important options. Also the discussed Oak Ridge neutron spallation source could in principle accommodate intense muon beams. The most promising facility would be, however, a muon collider [57], the front end of which could provide muon rates 5-6 orders of magnitude higher than present beams (see Table 3).

| TABLE 3. Muon fluxes of some existing and future facilities, Rutherford Appleton Laboratory (RAL), Japanese Hadron Facility (JHF), European Spallation Source (ESS), Muon collider (MC). |
|-------------------------------------------------------------|
| **Intensity (\( \mu/s \))** | RAL(\( \mu^+ \)) | PSI(\( \mu^+ \)) | PSI(\( \mu^- \)) | JHF(\( \mu^+ \))\(^\dagger\) | ESS(\( \mu^+ \)) | MC (\( \mu^+, \mu^- \)) |
| **Momentum bite \( \Delta p_m/p [\%] \)** | 10 | 10 | 10 | 10 | 10 | 5-10 |
| **Spot size (cm \( \times \) cm)** | 1.2 \( \times \)2.0 | 3.3 \( \times \)2.0 | 3.3 \( \times \)2.0 | 1.5 \( \times \)2.0 | 1.5 \( \times \)2.0 | few \( \times \)few |
| **Pulse structure** | 82 ns | 50 MHz | 50 MHz | 300 ns | 300 ns | 50 ps |
| | 50 Hz | continuous | continuous | 50 Hz | 50 Hz | 15 Hz |

\(^\dagger\) Recent studies indicate that the \( 10^{11} \) particles/s region might be reachable [58].

It was noted already in the early 60ies that, e.g. the process \( e^-e^- \rightarrow \mu^-\mu^- \) is closely related to muonium-antimuonium conversion [59]. Indeed such scattering experiments were carried out at the Princeton-Stanford storage rings at Stanford yielding the at the time best limit on the coupling constant \( G_{\mu \mu} \) [60]. Today, similar proposals have been made for scattering of high energy \( e^- \) on \( e^- \), \( e^- \) on \( e^+ \), \( \mu^- \) on \( \mu^- \) and \( \mu^- \) on \( \mu^+ \) [61–63]. They were mainly discussed in connection with bispelic gauge bosons. Even a lower limit for the cross section of the process \( e^-e^- \rightarrow \mu^-\mu^- \) was found, provided the sum of the light neutrino masses exceeds \( \approx 90 \) eV [63]. Pronounced resonances have been predicted particularly for such experiments at the Next Linear Collider or the high energy end of a muon collider.

Although lepton flavour conservation remains a mystery and searches for its violation were not blessed with a successful observation yet, both the theoretical and
experimental work in this connection have led to a deeper understanding of particle interactions. One particular value of the experiments are their continuous contributions towards guiding theoretical developments by excluding various speculative models.

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REFERENCES

1. Y.B. Zeldovitch, Dan. SSR 86, 505 (1952)
2. B. Pontecorvo, Sov. Phys.-JETP 37, 1751 (1959) and Sov. Phys. JETP 6, 381 (1958)
3. N. Cabbibo and R. Gatto, Phys. Rev. Lett. 5, 114 (1960); N. Cabbibo, Nuovo Cim. 19, 612 (1961)
4. E.J. Konopinski and H.M. Mahmoud, Phys. Rev. 92, 1045 (1953)
5. G. Feinberg and S. Weinberg, Phys. Rev. Lett. 6, 381 (1961)
6. A. Halprin and A. Masiero, Phys. Rev. D 48, 2987 (1993)
7. M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973)
8. J. Stone, this volume
9. R.N. Mohapatra, Prog. Part. Nucl. Phys. 31, 39 (1993)
10. O. Adriani et al., Phys. Lett. B 316, 427 (1993); L. Bugge et al., in: Proc. Europhysics Conference on High-energy Physics, Brussels, J. Lemonne et al. (eds.), World Scientific, Singapore (1996); P. Abreu et al., Z. Phys. C 73, 243 (1997)
11. A. Freyberger et al., Phys. Rev. Lett. 76, 3065 (1996)
12. R. Ammar et al., Phys. Rev. D 49, 5701 (1994)
13. K. Edwards et al., Phys. Rev. D 55, 3919 (1997)
14. W. Molzon, JHF98 workshop, Tsukuba, (1998); see also ref. [15]
15. T. Kirk, JHF98 workshop, Tsukuba (1998)
16. J. Belz, Proc. Intersections between Particle and Nuclear Physics, 6th conf, T.W. Donnelly (ed.), AIP Press, New York, p. 763 (1997); R. Ray, JHF98 workshop, Tsukuba (1998)
17. M. Zeller, priv. com.; see also ref. [15] and S. Eilerts, loc. cit. [16], p. 779 (1997)
18. K. Eitel, doctoral thesis, University of Karlsruhe (1995)
19. W. Bertl et al., Nucl. Phys. B 260, 1 (1985)
20. M.D. Cooper et al., loc. cit. [16], p. 34 (1997)
21. S. Eggli et al., publication in preparation (1998)
22. J. Kaulard et al., submitted for publication (1998)
23. V. Meyer et al., loc. cit. [16], p. 429 (1997)
24. H.V. Klapdor-Kleingrothaus and M. Hirsch, Z.Phys. A359, 361 (1997); H.V. Klapdor-Kleingrothaus, Proc. Beyond the Desert Conference, Institute of Physics Publishing, Bristol, p.485 (1998)
25. V.M. Lobashev, in: Proc. Neutrino 96, World Scientific, Singapore (1997)
26. D. Bliss et al., Phys.Rev.D 57, 5903 (1998)
27. S.H. Kettei, hep-ex/9801016 (1998) and references therein
28. T.S. Kosmas, G.K. Leontaris, J.D. Vergados, Prog.Part.Nucl.Phys. 33, 397 (1994)
29. R. Barbieri, L. Hall and A. Strumia, Nucl.Phys. B445, 219 (1995)
30. J.P. Miller et al, loc. cit. [16], p. 792 (1997)
31. U. Chattopadhyay and P. Nath, Phys.Rev. D53, 1648 (1996)
32. T. Bolton et al., Phys. Rev D38, 2077 (1988)
33. A. v.d. Schaaf et al., Letter of Intent to PSI, R98-05.0 (1998)
34. F. Cuypers and S. Davidson, Eur.Phys.J. C2, 503 (1998)
35. M. Raidal and A. Santamaria, hep-ph/9710389 (1997)
36. W. Molzon et al., Proposal to BNL E-940 (1997)
37. V.W. Hughes and G. zu Putlitz, in: Quantum Electrodynamics, World Scientific, Singapore, T. Kinoshita (ed.), p. 822 (1990)
38. K. Jungmann, in: Atomic Physics 14 (New York: AIP Press), D. Wineland et al. (ed.), p. 102 (1994)
39. A. Halprin, Phys.Rev.Lett. 48, 1313 (1982)
40. P. Herczeg and R.N. Mohapatra, Phys.Rev.Lett. 69, 2475 (1992)
41. W.S. Hou and G.G. Wong, Phys.Rev. D53, 1537 (1996)
42. R.N. Mohapatra, Z.Phys. C56, S117 (1992)
43. H. Fujii et al., Phys.Rev. D 49, 559 (1994)
44. R. Abela et al., Phys.Rev.Lett. 77, 1951 (1996)
45. B.E. Matthias et al., Phys.Rev.Lett. 66, 2716 (1991)
46. L. Willmann and K. Jungmann, Lecture Notes in Physics, Vol. 499, (1997)
47. L. Chatterjee et al., Phys. Rev. D46, 46 (1992)
48. K. Horikawa and K. Sasaki, Phys. Rev. D53, 560 (1996)
49. G.G. Wong and W.S. Hou, Phys.Lett.B357, 145 (1995)
50. V.A. Gordeev et al, JETP Lett. 59, 589 (1994)
51. G.G. Wong and W.S. Hou, Phys.Rev.D50, R2962 (1994)
52. P. Frampton, Phys.Rev.Lett69, 1889 (1994); see also: hep-ph/97112821 (1997)
53. P. Frampton and S. Harada, hep-ph/9711448 (1997)
54. P. Frampton, priv. comm. (1998)
55. P. Herzeg, Conference "Beyond the Desert 97", Castle Ringberg (1997)
56. C. Athanassopoulos et al., Phys.Rev. C54, 2685 (1996); see also: nucl-ex/9709006
57. R.B. Palmer and J.C. Gallardo, physics/9802002 (1998); R.B. Palmer, physics/9802005 (1998)
58. Y. Kuno, priv. com. (1998)
59. S. Glashow, Phys.Rev.Lett. 6, 196 (1961)
60. W.C. Barber et al, Phys.Rev.Lett. 22, 902 (1969)
61. P. Frampton, Phys.Rev. D 45, 4240 (1992)
62. W.S. Hou, Nucl. Phys. B51A, 40 (1996)
63. M. Raidal, Phys.Rev.D57, 2013 (1998)