Final results of the TWIST experiment at TRIUMF

Precision measurements of the muon decay

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

Introduction

The title needs some explanation:

TRIUMF = TRI-University Meson Factory: the meson factory of the three universities

TWIST = TRIUMF Weak Interaction Symmetry Test

The TRIUMF Laboratory was founded in 1968 by three universities of the province of British Columbia, Canada:

- The University of British Columbia (UBC), in the city of Vancouver,
- Simon Fraser University (SFU) also in the city of Vancouver,
- The University of Victoria (UVIC) in the city of Victoria.

The University of Alberta (in Edmonton, province of Alberta) joined the TRIUMF consortium almost immediately. The name of the laboratory (TRIUMF) did not change.

Several other Canadian universities have joined TRIUMF, which can now be considered as a national laboratory in Canada.

For more information consult the TRIUMF website: www.triumf.ca.

Universities affiliated with TRIUMF (from west to east):

- University of Victoria, Victoria, British Columbia
- UBC (University of British Columbia), Vancouver, British Columbia
- SFU (Simon Fraser University), Vancouver, British Columbia
- University of Alberta, Edmonton, Alberta
- University of Manitoba, Winnipeg, Manitoba
- University of Guelph, Guelph, Ontario
- University of Toronto, Toronto, Ontario
- York University, Toronto, Ontario
- Queen's University, Kingston, Ontario
- Carleton University, Ottawa, Ontario
- Université de Montréal, Montréal, Québec

Associate members (from west to east):

- University of Northern British Columbia, Prince George, British Columbia
- University of Calgary, Calgary, Alberta
- University of Regina, Regina, Saskatchewan
- University of Winnipeg, Winnipeg, Manitoba
- McMaster University, Hamilton, Ontario
- Saint Mary's University, Halifax, Nova Scotia

TRIUMF activities outside Canada:

At CERN (Geneva): participation in the ATLAS group activities with the LHC.

At JPARC (Japan Proton Accelerator Research complex):

- Participation in the TREK experiment: TREK = Time Reversal Experiment with Kaons, a measurement of the transverse polarization of the muon in the $K^+ \rightarrow \pi^0 \mu^+ \nu$ decay: search for physics beyond the Standard Model.

- Participation in activities on neutrino physics.

Other TRIUMF activities in Vancouver:

TRIUMF collaborates with Canadian industrial companies like MDS Nordion (see www.nordion.com). (Nordion is a world leader in providing medical isotopes).

TRIUMF is investigating the possibility of producing molybdenum isotopes by using accelerators. Canada has been the main provider of molybdenum isotopes by using the Chalk River reactors. There have been some problems which have imposed the shut-down of several reactors.

The TRIUMF cyclotrons

The main cyclotron can deliver proton beams up to a maximum energy of 500 MeV.

This cyclotron accelerates negative hydrogen ions H^{--}. These negative ions are easily converted into H^+ ions (protons).

Proton beams are extracted simply by inserting a thin foil into the circulating beam to strip the two electrons from that ion. Several proton beams can be extracted simultaneously at different energies.

Acceleration of negative ions in the TRIUMF accelerator permits extraction of up to six proton beams, each beam independently H^{--} variable in energy from 150 MeV to 500 MeV.

For information on the other cyclotrons, go to the TRIUMF web site: www.triumf.ca.

Why is the muon decay so interesting?

- Only the weak interaction is present in the final state, to a good approximation.
- The muon, positron and neutrinos are leptons, they dont feel the strong interaction (the strong interaction can be present in higher orders, but it is negligible).
- The electromagnetic interaction manifests itself via radiative corrections, which can be calculated from theory.

- The neutrinos have very small masses.
- The TRIUMF cyclotron produces intense clean muon beams.

The physics

The Standard Model of weak interactions has been very successful until now but there is no reason to believe that it is the final theory in particle physics. There are several possibilities for looking at possible violations of the Standard Model:

- Going to higher energies: for example CERN,
- or
- High-precision of low-energy experiments: for example TWIST.

In the TWIST experiment the positive muon has been selected to avoid muon capture by the nucleus.

Theoretical predictions

The most general representation of the weak interaction would include the following mathematical terms:

S	Scalar
V	Vector
T	Tensor
A	Axial vector (pseudo-vector)
P	Pseudoscalar

The present experimental situation of the weak interaction is in favor of a (V - A) interaction. It is surprising to conclude that nature is favoring such a combination of V and A and ruling out the other terms.

Assuming a (V - A) interaction (Standard Model), the muon decay can be described by few parameters.

It may be that this form of the interaction is valid at low energies only. Experiments performed at higher energies may reveal the presence of other terms.

or:

The other terms may exist at low energy but at a very small level. Very precise experiments may reveal the presence of these terms. This is the motivation for the TWIST experiment.

If the detector is not sensitive to the polarization of the positron, the decay probability is given by:

$$\frac{d^2\Gamma}{dx\,d\cos\theta} = \frac{m_\mu}{4\pi^3}\; W_{e\mu}^4\; G_F^2\; \sqrt{x^2 - x_0^2} \times \{F_{IS}(x) + P_\mu \xi\, \cos\theta\, F_{AS}(x)\}$$

With the following definitions:

$$W_{e\mu} = \frac{(m_\mu^2 + m_e^2)}{2m_\mu} \text{ (Maximum positron energy)}$$

$$G_F = \text{(Fermi constant)}$$

$$x = \frac{E_e}{W_{e\mu}} \qquad x_0 = \frac{m_e}{W_{e\mu}} = 9.67 \times 10^{-3}$$

1) Isotropic part of the spectrum:

$$F_{IS}(x) = x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x) + F_{IS}^{RC}(x)$$

2) Non-isotropic part of the spectrum:

$$F_{AS}(x) = \frac{1}{3}\sqrt{x^2 - x_0^2}\left[1 - x + \frac{2}{3}\delta(4x - 3 + \left(\sqrt{1-x_0^2} - 1)\right) + F_{AS}^{RC}(x)\right]$$

$F_{IS}^{RC}(x)$ and $F_{AS}^{RC}(x)$ are radiative corrections which can be calculated theoretically. We benefited very much from the presence of Andrej Arbuzov (Joint Institute for Nuclear Research, Dubna), an expert in the field, at the University of Victoria.

The results:

$\rho = 0.749\,77 \pm 0.000\,12(stat.) \ \pm\ 0.000\,23(\text{syst.})$ SM value $= 0.750\,00$

$\delta = 0.750\,49 \pm 0.000\,21(stat) \ \pm\ 0.000\,27(syst)$ SM value $= 0.750\,00$

$P_\mu\xi = 1.000\,84\ \pm 0.000\,29(stat)^{+0.001\,65}_{-0.000\,63}(syst)$ SM value $= 1.000\,00$

The parameter η cannot be extracted with good precision since its main value is located at the low-energy part of the spectrum.

The results are in good agreement with the Standard Model prediction.

Recent publications

"Precision muon decay measurements and improved constraints on the weak interaction", A. Hillairet et al., to be published in Physical Review.

"Precise measurement of parity violation in polarized muon decay", J.F Bueno et al., Phys. Rev. D84 (2011) 032005.

"Experimental Constraints on Left-Right Symmetric Models from Muon Decay", R. Bayes et al., Phys. Rev. Lett. 106 (2011) 041804

See also all the publications quoted in the three preceeding ones.

Other publications

W. Fetscher and H.-J. Gerber in K. Nakamura et al. (Particle Data Group), JPG **37**, 075021 (2010) (URL: http://pdg.lbl.gov)

Yoshitaka Kuno and Yasuhiro Okada (KEK, Tsukuba), Rev. Mod. Phys. 73 (2001) 151-202, a detailed article on the subject: "Muon decay and physics beyond the standard model."