Measurement of the Polarization Vector of the Positrons from the Decay of Polarized Muons

as a Test of Time Reversal Invariance and a Quest for Physics Beyond the SM

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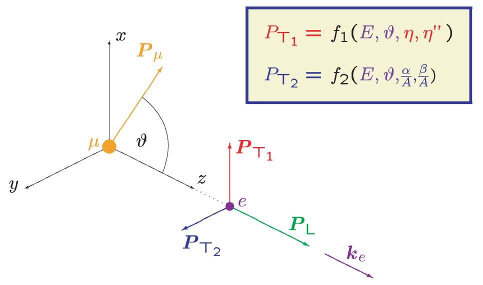
Observables



$$P_{T_1} = f_1(E, \vartheta, \eta, \eta'')$$
$$P_{T_2} = f_2(E, \vartheta, \tfrac{\alpha}{A}, \tfrac{\beta}{A})$$

The standard model predicts:

$$\langle P_{T_1}\rangle_E = 0.003$$
$$P_{T_2} \equiv 0$$

A nonzero P_{T_2} would signal violation of time reversal invariance. This is the only purely leptonic reaction for which TRI has been tested up to now.

Matrix Element

$$\mathcal{M} = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T\\ \varepsilon,\mu=R,L}} g^\gamma_{\varepsilon\mu} \langle \bar{e}_\varepsilon | \Gamma^\gamma | (\nu_e)_n \rangle \langle (\bar{\nu}_m | \Gamma_\gamma | (\mu)_\mu \rangle$$

The index γ labels the type of interaction:

Γ^S	=	4-scalar
Γ^V	=	4-vector
Γ^T	=	4-tensor

The indices ε, μ indicate the chiralities of the spinors of the observed (charged) leptons. The chiralities n, m of the neutrinos are uniquely determined for given γ, ε and μ.
The transverse polarization component P_{T_1} yields the low energy parameter η *without* the suppression factor m_e/m_μ of η in the energy spectrum of the decay positron. These interference terms allow for sizeable effects.

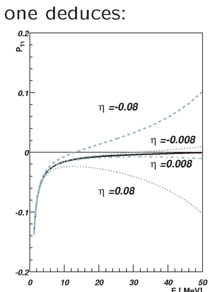
$$\eta = \frac{1}{2} Re\{ g^V_{LL} g^{S*}_{RR} + g^V_{RR} g^{S*}_{LL} + g^V_{LR}(g^{S*}_{RL} + 6 g^{T*}_{RL}) + g^V_{RL}(g^{S*}_{LR} + 6 g^{T*}_{LR}) \}$$

In the standard model: $g^V_{LL} = 1$
$g^\gamma_{\varepsilon\mu} = 0$
(all other interactions)

Assuming 1 additional interaction and knowing that

$g^V_{LL} \approx 1,$

one deduces:



$$P_{T_1}(E_e) \to \eta \approx \frac{1}{2} Re\{g^S_{RR}\}$$
$$P_{T_2}(E_e) \to \frac{\beta'}{A} \approx \frac{1}{4} Im\{g^S_{RR}\}$$

Main scientific interests:

P_{T_1}: Precise determination of Fermi coupling constant G_F

P_{T_2}: Test of time reversal invariance

Fermi Coupling Constant

Should be independent of masses and radiative corrections:

Universal coupling constant

$$G_F^2 = 192\pi^3 \cdot \frac{\hbar}{\tau_\mu} \cdot \frac{1}{m_\mu^5} \cdot \left\{1 + \frac{\alpha}{2\pi}\left(\pi^2 - \frac{25}{4}\right)\right\} \cdot \left\{1 - \frac{3}{5}\left(\frac{m_\mu}{m_W}\right)^2\right\} \cdot \left\{1 - 4\eta \cdot \frac{m_e}{m_\mu} - 4\lambda \cdot \frac{m_{\nu_\mu}}{m_\mu} + 8\left(\frac{m_e}{m_\mu}\right)^2 + 8\left(\frac{m_{\nu_\mu}}{m_\mu}\right)^2\right\}$$

New in G_F^2: $\lambda \approx \frac{1}{2} Re\{g^V_{LL} \cdot g^{V*}_{LR}\}$

In left-right symmetric models with mixing angle ζ:

$$\lambda \approx \frac{1}{2}\zeta$$

Contribution from	$\frac{\Delta G_F}{G_F}$ [10^{-6}]	
	$\mu^+ \to \bar{\nu}_\mu e^+ \nu_e$	$\tau^+ \to \bar{\nu}_\tau \mu^+ \nu_\mu$
Δm_W	0.0	1
$\Delta m_{\mu,\tau}$	0.2	421
$\Delta\tau$	9.1	2 070
$\Delta(\lambda m_{\bar{\nu}})$	70.0	22 500
$\Delta\eta$	193.0	6 500
$\Delta\Gamma_{\tau\to\mu}$	-	100 000

Experimental Method

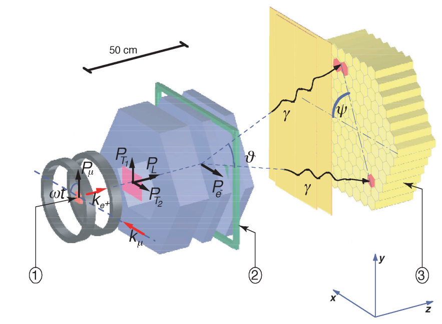
Measure the complete polarization vector of the decay positrons:

$$\boldsymbol{P}_{e^+} = \begin{pmatrix} P_{T_1} \\ P_{T_2} \\ P_L \end{pmatrix} \equiv \begin{pmatrix} P_T \cdot \cos\varphi \\ P_T \cdot \sin\varphi \\ P_L \end{pmatrix}$$

with 3 simultaneous and independent measurements:

Observable	Method
P_T	Time dependence of annihilation
φ	Remnant μSR effect
P_L	Spatial dependence of annihilation

Setup of the Experiment and Principle of Measurement :



①: Beryllium stop target within spin precession magnet

②: magnetized Vacoflux foil within iron return yoke

③: calorimeter consisting of 127 BGO crystals

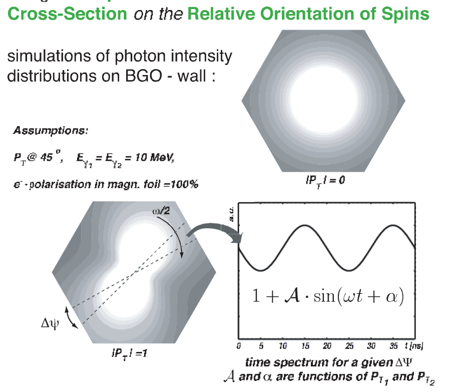
- Highly polarized μ^+ beam at μE1 area of PSI: (91%)
- Muon stop rate in Be target: $(20 - 80) \times 10^6$ s^{-1}
- Precession in homogeneous $\boldsymbol{B}$ field; precession frequency = cyclotron frequency (50.8 MHz)
- Burst width 3.9 ns (FWHM)
  $\Rightarrow$ 80% muon polarization in Be stop target
- Positron tracking with drift chambers
- Annihilation with polarized e^-
- Detection of annihilation quanta with 127 BGO crystals

Event Reconstruction and Data Analysis

- Energy calibration with cosmic rays
- Cluster recognition
- Background suppression
- Analysing power of annihilation events
- e^+ annihilation-in-flight as analysing reaction for transverse polarization

using the **Dependence** *of the* **Annihilation Cross-Section** *on the* **Relative Orientation of Spins**

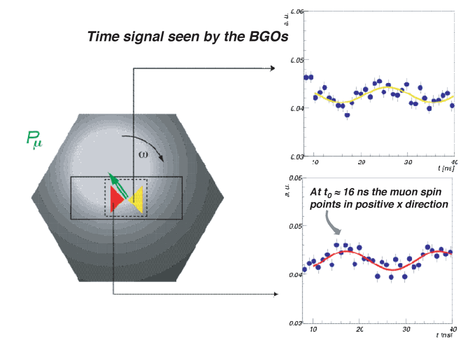
simulations of photon intensity distributions on BGO - wall :



time spectrum for a given $\Delta\Psi$
$\mathcal{A}$ and α are functions of P_{T_1} and P_{T_2}
ω : frequency of muon spin precession
t : time between stop of muon and its decay

- Muon decay asymmetry (μSR) yields time zero

μSR Effect** is used to find the **direction of the muon spin

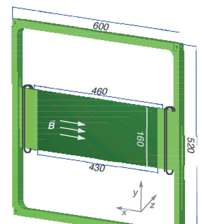


- Longitudinal polarization

using information about position on magnetized Vacoflux foil (determined by tracks reconstructed from drift-chamber data) where annihilations take place

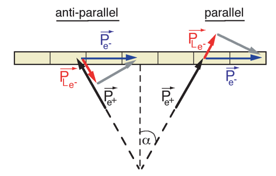
area on foil taken into account: 140^2 mm^2

area divided into rectangular bins (ij), 17 bins in x- and y-direction, respectively



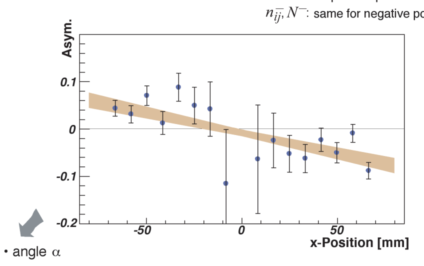
Tracks that do not hit the center of the foil 'see' a longitudinal component $P_{L_{e^-}}$ of the polarization of the electrons in the foil.

This $P_{L_{e^-}}$ can either be parallel or anti-parallel to the positron polarization :



The annihilation cross section depends on the relative orientation of the spins of positrons and electrons in the foil. It is larger if both spins are anti-parallel.

Asymmetry: $A_{ij} = \dfrac{\frac{n^-_{ij}}{N^-} - \frac{n^+_{ij}}{N^+}}{\frac{n^-_{ij}}{N^-} + \frac{n^+_{ij}}{N^+}}$ where n^+_{ij} : number of annihilations in bin ij for positive foil polarization; N^+ : total number of annihilations for positive polarization; n^-_{ij}, N^-: same for negative polarization



- angle α
- elektron polarization in foil (P_{e^-} = 7.2 %)
- analysing power of 0.79
- background factor of 0.75 (backgr. ratio 25 %, mainly due to bremsstrahlung)

$\Rightarrow \langle P_L \rangle_E$

Preliminary Results

P_T at the Time of Annihilation

Fitting the two perpendicular components P_1 and P_2 using a Log Likelihood parameter estimation

Use the diff. annihilation cross-section

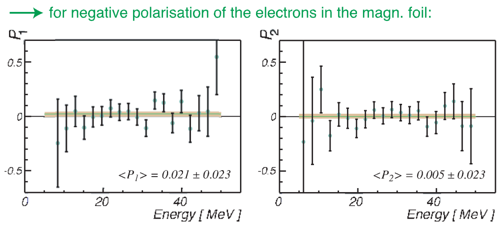
$$\frac{1}{\sigma_0} \cdot \frac{d\sigma}{d\Omega} = 1 + \mathcal{A} \cdot \sin(\omega t + \alpha) =: f(P_1, P_2, E_{\gamma_1}, E_{\gamma_2}, \Psi, t)$$

where amplitude and phase are functions of the Energy and Ψ $\quad \mathcal{A} = \mathcal{A}(P_1, P_2, E_{\gamma_1}, E_{\gamma_2}, \Psi)$, $\alpha = \alpha(P_1, P_2, E_{\gamma_1}, E_{\gamma_2}, \Psi)$

$$\mathcal{L}(P_1, P_2) := -\ln \prod_i^n f(P_1, P_2, E^i_{\gamma_1}, E^i_{\gamma_2}, \Psi^i, t^i) = -\sum_i^n \ln f^i(P_1, P_2)$$

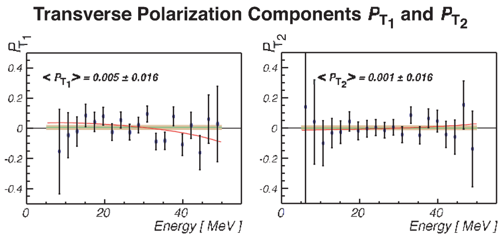
where n is the number of 'good' annihilation events

→ for negative polarisation of the electrons in the magn. foil:



→ time zero from μSR Effect (→ orientation of muon spin relative to P_1 and P_2)
→ rotation of transverse polarization components in the field of the spin precessing magnet (MC)
→ convolution with energy loss of the positron in the apparatus (MC)
→ sums of P_{T_1} and P_{T_2} for negative and positive foil polarization

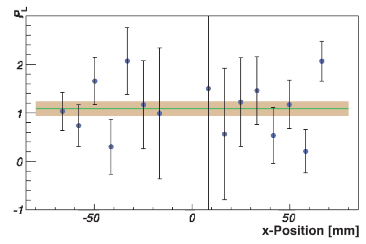
Transverse Polarization Components P_{T_1} and P_{T_2}



Longitudinal Polarization P_L

Asymmetry A_{ij}

- angle α
- elektron polarization P_{e^-}
- analysing power
- background factor



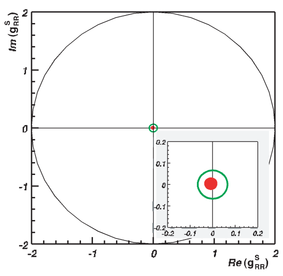
$\langle P_L \rangle_E = 1.09 \pm 0.15$

Summary of Preliminary Results and Implications

	General analysis	V - A + g^S_{RR}
$10^3 \times \langle P_{T_1}\rangle_E$	5 ± 16	5 ± 16
$10^3 \times \langle P_{T_2}\rangle_E$	1 ± 16	1 ± 16
$10^3 \times \eta$	95 ± 60	-4 ± 14
$10^3 \times \eta''$	98 ± 57	$-10^3 \times \eta$
$10^3 \times \alpha'/A$	-13 ± 29	0
$10^3 \times \beta'/A$	8 ± 16	1 ± 7
$10^3 \times$ Re g^S_{RR}	–	-8 ± 28
$10^3 \times$ Im g^S_{RR}	–	4 ± 28
$10^3 \times |g^S_{RR}|$	–	9 ± 28

Implications from these preliminary results :

1. No Evidence for Additional Scalar Couplings in Muon Decay



Green circle: Result of a general analysis including all possible left- and righthanded scalar, vector and tensor couplings.
Red circle: Only one additional coupling interferes with the lefthanded vector coupling in the SM.

η = - 0.004 ± 0.014
$\frac{\beta'}{A}$ = 0.001 ± 0.007
Im (g^S_{RR}) = 0.004 ± 0.028
Re (g^S_{RR}) = - 0.008 ± 0.028
$|g^S_{RR}|$ = 0.009 ± 0.028

2. Model Independent Measurement of G_F

The model independent Fermi coupling constant is :[1)]

$$G_F = \sqrt{\frac{192\pi^3}{\tau_\mu m_\mu^5}} \left(1 - 4\eta \frac{m_e}{m_\mu}\right)$$

using the measured value of η = 0.095 ± 0.061 yields:

G_F = 1.16532 ± 0.00069 x 10^{-5} $(\hbar c)^3$ GeV^{-2}

1) For illustrational purposes radiative corrections are not given.

Outlook

Improve precision of previous experiment [1] by almost one order in magnitude to:

$$\Delta < P_{T_1} > = 0.004$$
$$\Delta < P_{T_2} > = 0.004$$

Assuming $V - A$ and one additional coupling , this will reduce the limits for η and g^S_{RR} to:

$$\Delta\eta = 0.004$$
$$\Delta Re\{g^S_{RR}\} = 0.009$$
$$\Delta Im\{g^S_{RR}\} = 0.009$$

[1] H. Burkard *et al.*, Phys. Lett. **160 B** (1985) 343

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