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DETERMINATION OF THE POLARIZATION VECTOR OF POSITRONS FROM THE DECAY OF POLARIZED MUONS

KAI-U. KÖHLER for the ETH Zürich – Cracow – PSI – Collaboration
ETH Zürich - Institute for Particle Physics, Hönggerberg, CH-8093 Zürich , Switzerland

In the standard model of electroweak interactions the positrons from the decay of polarized positive muons are mainly longitudinally polarized. The measurement of the two transverse polarization components P_{T_1}, which lies in the plane spanned by muon-spin and positron momentum, and P_{T_2}, which is perpendicular to this plane, is a sensitive tool to look for contributions from additional, exotic interactions. The energy dependence of P_{T_1} yields the low energy Michel parameter η and thus an improved model-independent value of the Fermi coupling constant. A non-zero value of P_{T_2} would be the first observation of time reversal violation in a purely leptonic decay. The muon decay experiment at the Paul Scherrer Institut is the first experiment to measure all three positron polarization components, P_{T_1}, P_{T_2}, and the longitudinal polarization component P_{L}. In this contribution results from a small data-sample taken in 1999 are presented. The values obtained are $P_{\mathrm{T}_1} = (5 \pm 16) \times 10^{-3}$, $P_{\mathrm{T}_2} = (1 \pm 16) \times 10^{-3}$, and $P_{\mathrm{L}} = 1.09 \pm 0.15$. More than ten times more data was taken in October / November 2000, the analysis of which will further reduce the statistical errors.

1 Introduction

Though it has been shown fifteen years ago by Fetscher et al. [1] that $V - A$, which is one of the basic assumptions of the standard model, follows from the results of a selected set of muon decay experiments, the experimental limits obtained up to now still allow for substantial contributions from non-standard couplings. Limits on these couplings can be efficiently reduced by studying polarized muons and positrons.

The muon decay experiment [2] performed at PSI was designed for the measurement of the transverse polarization components of the positrons from the decay of polarized muons. Being able to additionally measure the longitudinal polarization, it is the first experiment to determine the complete polarization vector of the positrons.

One distinguishes two orthogonal transverse polarization components P_{T_1} and P_{T_2}. P_{T_1} lies in a plane spanned by the muon polarization and the positron momentum, and P_{T_2} is perpendicular to that plane. Within the standard model the energy averaged value of P_{T_1} is 0.003, whereas P_{T_2} is exactly zero. Both components can be expressed in terms of the Michel parameters η, η'', $\frac{\alpha'}{A}$ and $\frac{\beta'}{A}$ [3]. For the $V-A$ theory these four parameters are all zero.

However, assuming one additional coupling one can obtain substantial transverse polarization components of which P_{T_2} violates time reversal invariance. Neglecting exotic contributions in second order, one derives from the energy dependence of the two transverse polarization components

$$P_{\mathrm{T}_1}(E_{\mathrm{e}}) \rightarrow \eta \approx \frac{1}{2}\Re\{g^S_{RR}\} \qquad \text{and} \qquad P_{\mathrm{T}_2}(E_{\mathrm{e}}) \rightarrow \frac{\beta'}{A} \approx \frac{1}{4}\Im\{g^S_{RR}\}, \tag{1}$$

where g^S_{RR} represents a scalar, charge-changing interaction with right-handed charged leptons.

A fit to all currently available data [4] gives $\eta = (-7 \pm 13) \times 10^{-3}$. A more precise value of η is needed for a model-independent determination of the Fermi coupling constant G_{F}: The influence of the uncertainty in the experimental value of η on the value of G_{F} is at present 20 times larger than the one of the muon lifetime [3].

2 The Experiment

2.1 Experimental Setup

The experimental setup is shown in Fig.1. Highly polarized muons arrive in bunches every 20 ns and are stopped in a Be target (1). Their polarization precesses in a homogeneous magnetic field induced by two Helmholtz coils (2). A high polarization of the muons in the target is preserved by tuning the precession frequency to be equal to the accelerator RF. This ensures that the arriving muon bunches are added coherently to the muons already in the target. The decay e^+ passing the trigger scintillators (3) and (5) are tracked by a set of drift chambers (4) and can annihilate with polarized e^- in a magnetized foil (6). The two annihilation quanta are detected as two separated clusters in a BGO calorimeter (7) consisting of 127 hexagonal crystals. For more details on the apparatus, see ref. ([2]).

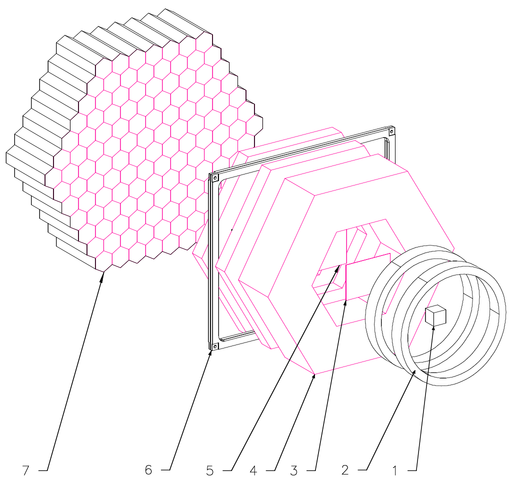

Figure 1: Setup of the experiment. The various components are described in the text.

2.2 Experimental Methods

The polarization vector of the positrons can be split into components in the following way:

$$\vec{P}_{e^+} = \begin{pmatrix} P_{\mathrm{T}_1} \\ P_{\mathrm{T}_2} \\ P_{\mathrm{L}} \end{pmatrix} \equiv \begin{pmatrix} P_{\mathrm{T}} \cdot \cos\varphi \\ P_{\mathrm{T}} \cdot \sin\varphi \\ P_{\mathrm{L}} \end{pmatrix} \tag{2}$$

The observables that define the complete vector are the absolute value P_{T} of the transverse polarization, a phase φ and the longitudinal polarization component P_{L}. In order to determine these three observables, three simultaneous but independent measurements are performed:

Measurement of P_{T} via the time dependence of annihilation

The cross-section for annihilation between polarized e^+ and e^- depends on the relative orientation of electron polarization and a possible transverse component of the positron polarization. Due to the muon-spin rotation, a transverse positron polarization would be detected as a harmonic time dependence of the annihilation rate for a given BGO-detector pair which can be written in the form

$$f(t) = 1 + A \cdot \sin(\omega t + \alpha), \tag{3}$$

where A and α are functions of the energy, the position of the two annihilation quanta and two orthogonal transverse polarization components P_1 and P_2. Eq. 3 is used to perform a log-likelihood parameter estimation of P_1 and P_2. As these components are selected regardless of the orientation of the muon polarization, they only represent the absolute value of the transverse polarization.

Determination of the phase φ of the transverse polarization using the μSR effect

Since the accepted decay positrons are emitted into a cone with the axis being perpendicular to the precession plane of the muon polarization, there is a small remnant μSR effect (i.e. a time-dependent rate variation due to the decay asymmetry with respect to the precessing muon spin [3]). One uses this effect to determine time zero, i.e. the position of the precessing polarization vector $\vec{P}_\mu$ of the muon. Since P_{T_1} and P_{T_2} are defined relative to $\vec{P}_\mu$, this finally allows to determine the two components separately.

Measurement of the longitudinal polarization P_{L} via the spatial dependence of annihilation

Positrons hitting the magnetized foil off the symmetry axis have a component of their longitudinal polarization in the direction of the electron polarization. The annihilation cross-section depends on the relative orientation of these two components, which can be either parallel or antiparallel. Thus, by dividing the fiducial area of the magnetized foil into rectangular bins and calculating the asymmetry of the annihilation rate for each bin resulting from reversing the foil magnetization, one can deduce the longitudinal polarization.

3 Preliminary Results

In a first data taking run in fall of 1999, 240×10^6 annihilation-like events were recorded. Appropriate geometry and energy cuts efficiently reduce the background and yield a data sample of 11×10^6 valid annihilation events on which the following results are based.

The transverse polarization components as a function of energy are shown in Fig. 2. The energy-averaged values for the two transverse polarization components are $< P_{\mathrm{T}_1} >= 0.005 \pm 0.016_{\mathrm{stat}} \pm 0.003_{\mathrm{sys}}$ and $< P_{\mathrm{T}_2} >= 0.001 \pm 0.016_{\mathrm{stat}} \pm 0.003_{\mathrm{sys}}$. The statistical errors are by a factor of 1.3 smaller than the current experimental limits and corroborates the findings of ([4]).

The result for the longitudinal polarization is $P_{\mathrm{L}} = 1.09 \pm 0.15$. This agrees well with the prediction $P_{\mathrm{L}} = 1$ of the standard model and confirms that our apparatus is sensitive to positron polarization.

Using the measured energy dependence of P_{T_1} and P_{T_2}, the functions describing the transverse polarization components in terms of the Michel parameters can be fitted (see Fig. 2). As it is known [1] that the weak interaction is dominated by $V - A$, it is explicitly assumed, that

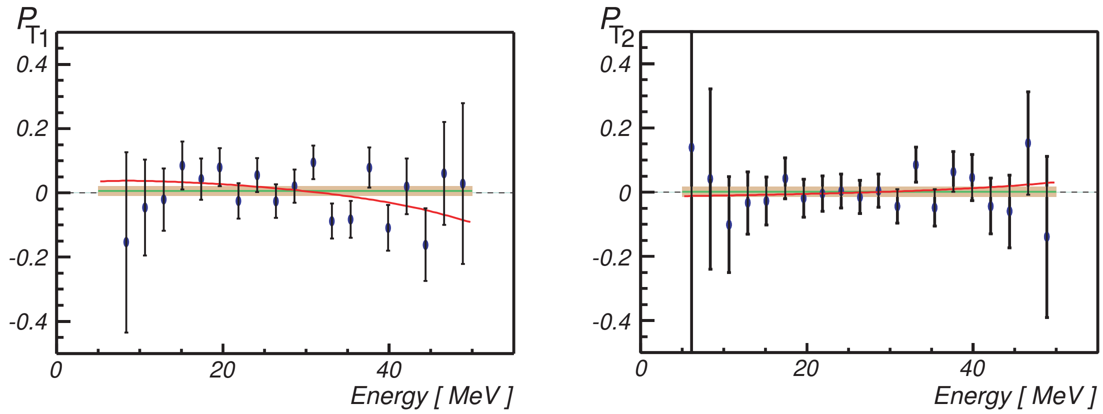

Figure 2: Transverse polarization components P_{T_1} and P_{T_2} at the time of annihilation. The horizontal lines indicate the averages, the boxes correspond to their errors. The curved lines represent the results of fits to the energy dependence of P_{T_1} and P_{T_2} to determine the Michel parameters.

only one additional coupling contributes to the transverse positron polarization, which then has to be g^S_{RR}. This leaves only η and $\frac{\beta'}{A}$ as free parameters for the fit. This assumption is supported by small values of α and α' [5], which implies $\eta \approx -\eta''$. The results of this fit are $\eta = -0.004 \pm 0.014_{\rm stat} \pm 0.002_{\rm sys}$ and $\frac{\beta'}{A} = 0.001 \pm 0.007_{\rm stat} \pm 0.001_{\rm sys}$.

4 Conclusion and Outlook

From the analysis of 11×10^6 annihilation events one obtains new limits for P_{T_1} and P_{T_2}. Based on the Michel parameters η and $\frac{\beta'}{A}$ resulting from a fit to the energy dependence of these two positron polarization components, limits on the coupling constant g^S_{RR} for a scalar, charge-changing interaction with right-handed leptons can be derived. According to eq. (1) one obtains $\Re\{g^S_{RR}\} = -0.008 \pm 0.028$ and $\Im\{g^S_{RR}\} = 0.004 \pm 0.028$, respectively $|g^S_{RR}| = 0.009 \pm 0.028$.

All results presented agree with the expectations from the standard model. However, in a longer data taking run in October/November 2000 the event statistics were improved by more than a factor of 10. The analysis of this data will improve all quoted limits or give a hint for physics beyond the standard model.

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