Measurement of the polarization vector of the $e^+$ from the decay of polarized $\mu^+$ as a test of time reversal invariance

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Abstract

The complete polarization vector of the positrons from the decay of polarized muons has been measured for the first time with one experimental setup. The $\mu P_1 T$ experiment at the Paul Scherrer Institute determines the three polarization components simultaneously with the same apparatus by making use of three different effects (spatial and temporal dependence of annihilation-in-flight with polarized electrons as well as muon decay asymmetry). The use of a stroboscopic method greatly reduces systematic errors. The energy dependence of the transverse polarization component $P_{T1}$, which lies in the plane spanned by muon spin and positron momentum, yields the low energy parameter $\eta$ and thus an improved model-independent value of the Fermi coupling constant. A non-zero value of the transverse component $P_{T2}$, which is perpendicular to the above-mentioned plane, would be the first observation of time reversal violation in a purely leptonic decay. The preliminary results are $P_{T1} = (5 \pm 16) \times 10^{-3}$, $P_{T2} = (1 \pm 16) \times 10^{-3}$ and $P_L = (1.09 \pm 0.15)$.

1. Introduction

Measurements of muon decay are low energy tests of the standard model. In fact, only a few years ago it has been shown that $V = A$, as one of the basic assumptions of the standard model, follows from the results of a selected set of muon decay experiments (including inverse muon decay) [1]. The experimental limits obtained up to now, however, still allow for substantial contributions from non-standard couplings which differ in their spin structure from
the $V - A$ interaction. The limits on these couplings can be efficiently improved by performing experiments with polarized muons and positrons. The measurement of the transverse positron polarization $P_{T_1}$ as a function of the positron energy, in particular, offers the possibility of obtaining the low energy parameter $\eta$ without the suppression factor $m_e/m_\mu$, which makes the determination of $\eta$ from the electron energy spectrum extremely difficult. The simultaneous measurement of the polarization component $P_{T_2}$ allows one to test time reversal invariance.

2. Observables and interactions

Figure 1 shows the kinematic variables for muon decay. While the $e^+$ from $\mu^+$ decay is mainly longitudinally polarized (polarization $P_L$), there also is a transverse polarization component $P_{T_1}$ lying in the plane of muon polarization $P_\mu$ and positron momentum $k_e$. Within the standard model $P_{T_1}$ is negligibly small at large positron energies, but substantial at lower energies and reaches the value $-1/3$ in the limiting case of a positron at rest (see figure 1, $\eta = 0$). Due to the low rate at small positron energies the energy-averaged transverse polarization predicted by the standard model is $\langle P_{T_1} \rangle = -0.003$ and therefore at present cannot be detected.

The transverse polarization component $P_{T_1}$ yields the low energy parameter $\eta$ without the suppression factor $m_e/m_\mu$ of $\eta$ in the energy spectrum of the decay positron. With the experimental knowledge that $V - A$ is dominant [1], and neglecting exotic contributions in second order, one obtains

$$\eta = \frac{1}{2} \Re \left\{ \frac{g_{RR}}{g_{RR}} \right\}.$$  \hspace{1cm} (1)

Here, $g_{RR}^S$ represents a scalar, charge-changing interaction with right-handed charged leptons [1]. In the general case there will be a phase between $V - A$ and an additional interaction which leads to a transverse component $P_{T_2}$ perpendicular to the plane of muon polarization and positron momentum, and which violates time reversal invariance. Correspondingly one derives a value for $\Im \left\{ g_{RR}^S \right\}$ from the energy dependence of $P_{T_2}$.

The transverse polarization has been measured previously with a precision of $\Delta P_{T_1} = 23 \times 10^{-3}$ [2]. A more precise value of $P_{T_1}$ and thus of $\eta$ is urgently needed for a model-independent determination of the Fermi coupling constant $G_F$: The influence of the
uncertainty in the experimental value of $\eta$ on the value of $G_F$ is at present 20 times larger than that of the more precisely known muon lifetime [3].

3. Experimental setup

The experimental setup [4] is shown in figure 2. A beam of highly polarized muons ($P_{\mu} \approx 91\%$) enters the beryllium stop target with bunches every 20 ns. The polarization of the stopped muons precesses in a homogeneous magnetic field with the same frequency as the accelerator RF. Thus every new muon bunch is added coherently with the muon spins pointing in the same direction as the polarization vector. Decay $e^+$ emitted parallel to the B-field are tracked by drift chambers and can annihilate with polarized $e^-$ in a magnetized foil. The two annihilation quanta are then detected by a hexagonal array of 127 BGO crystals. A valid annihilation event requires a coincidence of two plastic scintillator counters before the magnetized foil with two separated clusters of BGO detectors and an anticoincidence with a plastic counter array in front of the BGO wall. A possible transverse polarization would be detected as a harmonic time dependence of the annihilation rate for a given detector pair.

4. Experimental results

In the fall of 1999 we had the first data taking run. The data have been analysed and preliminary results are given here.
The time distribution of the annihilation events contains two effects.

(i) Since the accepted decay positrons are emitted into a cone whose axis coincides with the symmetry axis of the apparatus and is perpendicular to the precession plane of the muon polarization, there is a small remnant $\mu$SR effect (i.e., a time-dependent rate variation due to the decay asymmetry with respect to the precessing muon spin). This effect depends on the azimuthal angle of emission $\varphi$ of the positron and yields time zero, i.e. the position of the precessing polarization vector $P_\mu$ of the muon.

(ii) The effect due to a possible transverse polarization $P_T$, in contrast, does not depend on $\varphi$, but only on the relative orientation of $P_T$ and the electron polarization in the magnetized foil. This measurement yields the absolute value of $P_T$.

Both $P_{T1}$ and $P_{T2}$ are consistent with zero at the present precision (see figure 3). Here the question arises: Could we have detected a nonzero signal if there is a nonzero transverse polarization? The answer is yes. By making use of the fact that positrons hitting the magnetized foil off the symmetry axis have a component of the longitudinal polarization in the direction of the electron polarization or opposite to it we can simultaneously measure the longitudinal polarization. The preliminary result is $P_L = 1.09 \pm 0.15$.

References