Measurement of the transverse polarization of electrons emitted in neutron decay: A search for weak exotic couplings


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First results are presented from an experiment that aims at the simultaneous determination of both transversal polarization components of electrons emitted in the decay of free neutrons—two observables that have never before been addressed experimentally. A non-zero value of the R correlation coefficient, due to the e⁻ polarization component perpendicular to the plane spanned by the spin of the decaying neutron and the electron momentum, would signal a violation of time reversal invariance. The value of the N correlation coefficient, given by the transverse e⁻ polarization component within that plane, is expected to be finite. The measurement of N, both, probes the Standard Model and serves as an important systematic check of the experimental apparatus with respect to the R correlation measurement. Data taking using the polarized cold neutron beam FUNSPIN from the SINQ spallation source at the Paul Scherrer Institute, Villigen, Switzerland, has been completed. Preliminary results of the data analysis are presented. Two options for a possible future experiment leading to the accuracy of about \(3 \times 10^{-4}\) are discussed.

1. Introduction

The Standard Model (SM) predictions of T-violation originating from the quark mixing scheme, for systems consisting of u and d quarks, are 5–10 orders of magnitude lower than the experimental accuracies available to date. This applies to determinations of the T-violating electric dipole moments as well as to T-violating correlations in decay or scattering processes. With such a strong suppression of the SM these experiments provide a large window to search for physics beyond the Standard Model. It is a general presumption that time reversal violation phenomena are caused by a tiny admixture of exotic interaction terms. Therefore, weak decays provide a favorable testing ground in the search for such feeble forces. Mixed beta transitions like neutron decay provide a direct access to the weak scalar and tensor interactions that are not present in the SM. Physics with very slow, polarized neutrons has a great potential in this respect. The experiment presented here measures two observables, the R and N correlations, that have not been so far addressed experimentally in neutron decay.

The correlation coefficients N and R appear in the decay rate \(\omega\) of polarized neutrons when both the electron momentum \(p_e\) and the direction of the electron spin \(\sigma\) are being observed [2]:

\[
\omega (\langle J_\parallel \rangle \delta |E_e\Omega_e) \cdot dE_e d\Omega_e
\]

\[
\propto \left(1 + \cdots + \left[R \frac{p_e \times \sigma}{E_e} + N\sigma\right] \cdot \langle J_\parallel \rangle\right) \cdot dE_e d\Omega_e.
\]

\(\langle J_\parallel \rangle\), \(E_e\), \(\Omega_e\) describe the neutron polarization, electron energy and emission angle, respectively. They can be expressed in terms of the weak interaction coupling constants \(C_i\) where \(i\) stays for V (vector), A (axial vector), S (scalar) and T (tensor) interaction, as shown in Ref. [2]. Applying the SM assumptions: \(C_V = C_A = 1\), \(C_S = C_T = 0\), neglecting the terms quadratic in \(C_V\), \(C_A\) and \(C_T\), substituting the neutron decay matrix elements \(M_V = 1\), \(M_{GT} = \sqrt{3}\) and inserting \(C_S/C_V = -1.269\) [3] one obtains

\[
N = -0.2175 \cdot \Re\left(\frac{C_S + C_A}{C_V}\right) + 0.3350 \cdot \Re\left(\frac{C_T + C_A}{C_A}\right) - \frac{m}{E_e} \cdot \text{ASM},
\]

\(\text{ASM}\) refers to the strong interaction matrix elements.
\[ R = -0.2175 \cdot \frac{C_V}{C_A} - \frac{1}{137} \frac{m}{p_e} A_{SM} \]

where \( m \) is the electron mass. From Eq. (2) it is clear that the \( N \) and \( R \) coefficients are well suited for direct searches of physics beyond SM, provided the final state effects (FSI) that are represented by the last terms in these expressions are well under control. The energy averaged value of the FSI contribution to the \( R \) coefficient is \( 0.001 \) and beyond the precision of the current experiment while a \( 0.07 \) large electromagnetic correction in the \( N \) correlation is measurable and can be used for a direct sensitivity check of the apparatus. FSI contributions scale with the beta asymmetry parameter \( A_{SM} \).

The \( R \) and \( N \) correlation coefficients can be inferred from the two components of the electron polarization: \( R \) is proportional to the component perpendicular to the decay plane (spanned by the neutron spin and the electron momentum vectors) while \( N \) scales the component parallel to that plane.

2. Experiment and results

2.1. Mott scattering

Mott scattering from high \( Z \) nuclei is an ideal polarization analyzer for low energy electrons. The sensitivity to the electron spin is provided by the spin–orbit force emerging from the parity and time reversal conserving electromagnetic interaction and thus is strictly limited to its transverse components. For energies below 1 MeV, the analyzing power of the Mott scattering (in the literature referred to as the “Sherman function” [4]) from Pb nuclei reaches \(-0.5\) at backward angles. The overall efficiency of the electron spin analysis is limited by the thickness of the analyzing target: it must be sufficiently thin in order to minimize depolarizing multiple scattering effects. A relatively flat dependence of the figure-of-merit reaches its optimum between 1 and 3 \( \mu m \). For 2 \( \mu m \) thick Pb foil roughly one electron per thousand is scattered at backward angles.

2.2. Setup and data taking

The experiment was performed at the Paul Scherrer Institute, Villigen, Switzerland. The neutron beam from the cold neutron facility FUNSPIN [5] with an intensity of about \( 10^{10} \) s\(^{-1} \) and the average (vertical) polarization \( P_n > 80\% \) was guided to the decay volume. The Mott polarimeter consists of two sets of electron detectors with integrated Pb scattering foils arranged in a planar geometry as sketched in Fig. 1. A detailed description of this device as well as of the data analysis methodology can be found in Ref. [6].

2.3. Single-track events and beam polarization

Decay electrons are tracked in low-\( Z \), low-mass multi-wire proportional chambers (MWPC) and are stopped in plastic scintillators. A typical energy spectrum obtained from the off-line analysis of the recorded electrons which directly reached the energy detector (“single-track” events) is shown in Fig. 2. As the beta asymmetry parameter \( A \) is known with a sufficient precision [3], the analysis of the “single-track” events provides important information: the neutron polarization averaged over the beam fiducial volume as accepted by the detecting system, \( P_n = 0.80 \pm 0.02 \), which is necessary for the extraction of the correlation coefficients \( N \) and \( R \). This value is different from that published in Ref. [7] (\( P_n = 0.89 \pm 0.01 \)). Therein the average neutron beam polarization was inferred from a number of measurements made with a small acceptance super mirror polarimeter at the exit of the neutron beam line. It is believed that the up-down asymmetry method should provide a more realistic averaging over the neutron beam phase space including the complicated geometry and acceptance effects of the detecting system.

![Fig. 1. Scheme of the experimental setup in planar geometry and the measuring principle. Vertical cross-section of the Mott polarimeter is shown. Rectangular area in the middle represents the neutron beam cross-section.](image-url)
system. The precision of this method improves with the collected statistics. It is expected that for the final data set it should be better than 0.01.

2.4. V-track events and transverse electron polarization

Roughly one out of a thousand electrons undergoes backward Mott scattering from a 2 μm thick Pb foil and can be identified by a characteristic “V-track” pattern seen in two projections, c.f. Fig. 1. The requirement that the scattering vertex must be localized on the Pb foil significantly reduces background. Fig. 3 shows an example of the reconstructed vertex position distribution along the x-axis. The correlation coefficients \( N \) and \( R \) are extracted from the rate asymmetry \( \mathcal{A}(x) \) between two properly normalized data sets taken with the neutron spin up (+) and down (−), respectively

\[
\mathcal{A}(x) = \frac{\sigma(+P_n, x) - \sigma(-P_n, x)}{\sigma(+P_n, x) + \sigma(-P_n, x)}
= AP_n \mathcal{F}(x) + P_n \mathcal{F}(x) [N \overline{\mathcal{F}}(x) + R \overline{\mathcal{F}}(x) \mathcal{F}(x)]
\]

Fig. 2. Experimental energy spectrum of electrons compared with theory. Instrumental effects like energy loss and resolution are included in the Monte Carlo simulation. The discrepancy on the low energy side is caused by the electronic threshold not included in the simulation.

Fig. 3. Distribution of the reconstructed Mott scattering vertices. Distinct peaks are located at the Pb foil position (arrows). Black markers define the windows for events accepted for further analysis. The neutron beam center is at \( x = 0 \).
where \( \alpha \) is the azimuthal angle of the normal unit vector \( \hat{s} \) representing the Mott scattering plane with respect to the decay plane spanned by the neutron spin and the electron initial momentum vectors. Average values of the kinematical factors 
\[
\mathcal{F}(\alpha) = \langle \hat{J}_n \cdot \hat{p}_e \rangle, \quad \mathcal{H}(\alpha) = \langle \hat{\sigma} \cdot \hat{J}_n \rangle, \quad \mathcal{J}(\alpha) = \langle \hat{\sigma} \cdot (\hat{J}_n \times \hat{p}_e) \rangle, \quad \mathcal{K}(\alpha) = \langle \hat{v}/c \rangle
\]
are calculated event-by-event from reconstructed momenta and are known to a high precision similarly as the Sherman function \( \mathcal{S}(\alpha) \) representing the analyzing power of the Mott scattering. An example of a fit to the data sample collected in the 2007 run is shown in the left panel of Fig. 4. In the right panel, the results from the 2003, 2004 and 2006 data sets are shown. The analysis of all data collected during the 2007 run has not yet been completed. Preliminary results are in agreement with but more precise than those from the 2003, 2004 and 2006 runs and agree with the SM predictions of \( N_{SM} = 0.066, R_{SM} = 0.001 \) within the current precision of about 0.02–0.04 (statistical). It has been estimated that the final statistical error should not exceed 0.01. The main sources of systematic errors are (i) background subtraction, (ii) average beam polarization and (iii) corrections due to electron depolarization effects in multiple scattering. From the preliminary assessment it can be concluded that the total systematic error is lower than 0.008.

3. Future plans

The described experiment was pioneering in the field and it was accomplished with prototype detectors. The experience gained in its long development and in the analysis of the collected data allows for planning of 2nd generation experiments with a sensitivity of \( \Delta N = \Delta R = 3 \times 10^{-4} \). With such a sensitivity the FSI effect in the \( R \) correlation which is of the order \( 10^{-3} \) should be detectable. The main challenge is the statistics. To achieve that one needs about \( 10^9 \) reconstructed Mott scattering events. Currently, two options are under discussion: (i) with a cold...
neutron beam (CN) and cylindrical geometry, as already proposed in Ref. [8] and (ii) with ultra-cold neutrons (UCN) in a storage trap.

3.1. 2nd generation experiment with CN

An experiment of this kind became feasible because of two reasons. The first one is the large progress in high intensity, high polarization, low divergence CN beams available at ILL Grenoble, FRM2 Munich, SNS Oak Ridge and NIST Gaithersburg. Secondly, the electron tracking gas detectors were further developed and became still thinner, larger and more reliable. It has been shown that they can operate at reduced pressure of 300 mbar helium–isobutane (90–10%) gas mixture and can be read out in the drift time mode (see Ref. [9]). The proposed experimental setup is shown in Fig. 5. The longitudinally polarized CN beam is transported in pure helium at reduced pressure along the axis of a 2 m long Mott polarimeter. Decay electrons are detected with almost 4π acceptance. Realistic estimates show that in order to acquire 10⁹ Mott scattering events the data taking time should not exceed 30 weeks. As compared to the present setup, the gain factors in the statistics are: 10—beam intensity, 5—beam fiducial volume, 10—detector acceptance, 1.2—beam polarization. It is expected that the main systematic uncertainty due to the background subtraction procedure will be reduced by a factor of at least 10 (3–4 times lower background in the reduced pressure). A factor of 5 can be gained in the precision of the average neutron polarization while the uncertainty in the multiple scattering effects can be reduced by a factor of 3 with a dedicated electron scattering experiment on Pb. Such an experiment would be necessary to calibrate Monte Carlo simulations in the energy range 0.3–1.0 MeV.

3.2. 2nd generation experiment with UCN

With the advent of high intensity UCN sources like the one at PSI Villigen [10] the neutron decay correlation experiments may become competitive to the experiments utilizing CN beams. It is expected that they will profit from lower background. An example is the UCN-A project [11] designed for a high precision measurement of the beta asymmetry parameter $A$. The feasibility of the $N$ and $R$ correlation measurement has been considered for a similar geometry as that described previously. The CN beam has been replaced by an UCN storage trap made of thin Mylar foil coated with deuterated polyethylene (Fermi potential of 212 neV) and supported by a stainless steel mesh structure. Although vacuum conditions in the storage volume are not stringent (1 mbar of pure helium is allowed) such an UCN storage trap is a technical challenge. A sketch of the apparatus is shown in Fig. 6. Performed Monte Carlo simulations assuming the densities which will be available at the PSI UCN source (with 5 pulses per hour) result in an estimated data taking time of 125 weeks which is hardly acceptable. However, the system still needs to be optimized. The systematic effects in such a setup are not yet assessed.

References