The neutron is a well-suited system to search for a violation of time reversal invariance beyond the Standard Model. Recent experiments and projects searching for time reversal violation in the neutron decay and in the neutron electric dipole moment will be presented.

1 Introduction

CP violation is implemented in the Standard Model (SM) of particle physics via a non-trivial phase in the Cabbibo-Kobayashi-Maskava matrix. Dedicated experiments and facilities have been built to check the predictions of the SM for CP violation, e.g. in the Kaon or the B meson sectors. Up to now, no significant deviations have been found. However, the CP violation implemented in the SM is insufficient to explain the baryon-antibaryon asymmetry observed in the Universe. Therefore, new sources of CP violation are searched for in various systems.

The neutron is well-suited to search for CP violation beyond the SM. The influence of the SM CP violation is so tiny that it will hardly ever be observed, whereas several scenarios beyond the SM permit observable effects. These effects can be searched for in properties of the neutron, namely in its electric dipole moment (EDM), or in triple correlations between the decay products. CP or T (time reversal) violation would become manifest in deviations of these values from 0. Therefore these effects would have an unambiguous experimental signature.

2 T violating observables

The EDM of an elementary particle describes the shift between the centre of the charge distribution and the centre of mass, i.e.

$$d = \int d^3 r \rho(r)(r - r_0),$$  (1)
where $\rho(r)$ denotes the charge distribution and $r_0$ the centre of mass of the particle. For particles with spin $\sigma$, the EDM must be directed parallel or antiparallel to the spin for symmetry reasons. The quantity $\sigma d$ therefore is a P pseudo-scalar and a T pseudo-scalar. If T invariance holds, a particle can not have spin and EDM at the same time.

The EDMs of atoms and elementary particles measured up to now are compatible with 0. Particularly the EDM of the electron and the neutron give some of the most stringent limits for T violation beyond the SM. For the neutron, the EDM is predicted to be in the range of $10^{-32} \ldots 10^{-31} \text{e} \cdot \text{cm}$ in the SM. The present experimental limit is $|d_n| < 0.63 \cdot 10^{-25} \text{e} \cdot \text{cm}$ (90% c.l.)\(^4\). An overview about predictions from theories beyond the SM can be found in\(^5\).

The neutron decays with a half live of 885.7(8)\(\text{s}\)\(^4\) into a proton, an electron, and an electron antineutrino. In this decay, different triple correlations between the decay products allow to search for time reversal violation\(^6\), e.g. the correlations $\sigma_n(p_e \times p_\nu)$ between the spin of the decaying neutron and the momenta of electron and antineutrino (D correlation) or $\sigma_e(p_e \times \sigma_n)$ between the spin and the momentum of the electron and the spin of the decaying neutron (R correlation). These correlations violate motion reversal. This is demonstrated in Fig. 1 for the D correlation: The operation $t \rightarrow -t$ inverts all vectors (which are first derivatives in time). The resulting diagram can not be transfered to the initial one by continuous transformations. On the other hand, motion reversal can be simulated by flipping the neutron spin.

Time reversal is motion reversal and the exchange of initial and final state. Since the latter can not be realised in this decay, final state effects have to be taken into account. They can mimic a finite correlation which is not due to time reversal violation. These effects were calculated to $D_{fs} \approx 10^{-5}$ and $R_{fs} \approx 10^{-3}$\(^a\). Experimental results above the final state effects would be unambiguous proofs for T violation. The world average for D given in\(^4\) is $D = -0.6(1.0) \cdot 10^{-3}$. R has not yet been measured in neutron decay. The prediction\(^10\) from the SM is $D, R \approx 10^{-12}$.

### 3 Physics sensitivity

For the neutron EDM as well as for the correlations D and R, the SM values are many orders of magnitude below the present experimental precision. Theories beyond the SM, however, allow effects up to the present experimental limits. A recent detailed comparison of the sensitivity of D and R for physics beyond the SM with that of EDMs of atoms and the neutron can be found in\(^11\). In general, the EDM is the more sensitive parameter, but the D correlation puts more stringent limits on leptoquark models. Tab.\(^11\) lists values allowed by different scenarios. The R correlation (at the presently attempted experimental precision) can be more sensitive than EDMs only for fine-tuned parameters in some theories\(^12\).

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\(^a\)The numerical values refer to neutron decay. The same correlations can be (and have been) investigated in nuclear beta decay. Here, the final state effects are different and in general larger than for the neutron.
| Model                          | $D$    | $d_n$ [e · cm] |
|-------------------------------|--------|----------------|
| Phase in CKM-Matrix           | $\approx 10^{-12}$ | $10^{-33} \ldots 10^{-31}$ |
| QCD $\theta$ Parameter       |        | $3 \cdot 10^{-18}\theta_{\text{QCD}}$ |
| SuSy                          | $\leq 10^{-7} \ldots 10^{-6}$ (from $^{13}$) | $\leq$ present limits |
| Left-right symmetric          | $\leq 10^{-5} \ldots 10^{-4}$ | $\leq$ present limits ($^{199}$Hg) |
| Exotic fermions               | $\leq 10^{-5} \ldots 10^{-4}$ | $\leq$ present limits ($^{199}$Hg) |
| Leptoquark                    | $\leq$ present limits | |
| Experiment $^{11}$            | $-0.6(1.0) \cdot 10^{-3}$ | $< 0.63 \cdot 10^{-25}$ |

Table 1: Sensitivity of $D$ and $d_n$ for new physics. Values from $^{11}$. For left-right symmetric models and exotic fermions, the limit from the EDM of $^{199}$Hg is more stringent than that of the neutron EDM.

It should be noted that $D$ is parity conserving whereas $R$ is parity violating. Therefore $D$ is sensitive to vector- and axial-vector-type, $R$ to scalar- and tensor-type T violating interactions. These interactions can appear on the tree level in $D$ and $R$ but only on the loop level in EDMs. Therefore, the limits from the correlations in the decay are theoretically cleaner than the limits from the EDM $^{11}$.

4 Experiments

4.1 $D$ correlation

The measurement principle for the $D$ correlation can be understood from Fig. $^{11}$. The coincidence count rates electron and proton (which is detected instead of the antineutrino) have to be measured for both directions of the neutron spin. The experiment is complicated by two reasons: On the one hand, the decay particles have low energies and are difficult to detect. Especially the proton with a maximal kinetic energy of 750 eV has to be accelerated by an electrostatic potential to energies of about 30 keV prior detection. On the other hand, other correlations in the decay can create systematic effects.

The full differential decay probability for polarised neutrons and the observation of electron and antineutrino momenta is $^{6}$:

$$
\frac{dW}{dE_e d\Omega_e d\bar{\Omega}_\nu} = g G_E(E_e) \left\{ 1 + a \frac{P_e P_\bar{\nu}}{E_e E_\bar{\nu}} + b \frac{m_e}{E_e} + P \left( A \frac{P_e}{E_e} + B \frac{P_\bar{\nu}}{E_\bar{\nu}} + D \frac{P_e \times P_\bar{\nu}}{E_e E_\bar{\nu}} \right) \right\}. \quad (2)
$$

$P$ is the polarisation of the neutrons, $E_i$, $p_i$, and $\Omega_i$ the energy, momentum, and solid angle of electron $e$ and antineutrino $\bar{\nu}$, $g$ a normalisation constant, $G_E$ the electron spectrum, and $m_e$ the electron mass. The correlation coefficients $a$, $b$, $A$, $B$, and $D$ are related to the coupling constants of the operators describing nuclear beta decay (see $^{6}$) and have to be determined experimentally. Since $A \approx -0.1$ and $B \approx 1$ are parity violating, these correlations are the main sources for systematic errors in a $D$ measurement and have to be suppressed carefully in the experiment. Therefore, $D$ measurements work with a symmetric set-up of electron and proton detector as shown in Fig. $^{11}$. The neutron beam is perpendicular to the plane of the drawing and longitudinally polarised. The set-up has two perpendicular mirror planes of the detectors and the decay volume (dash-dotted lines). The correlation $P (p_e \times p_\bar{\nu})$ changes its sign under reflection on these planes whereas $Pp_e$ and $Pp_\bar{\nu}$ remain unchanged. Therefore, the combination

$$
\alpha_D := \alpha^{10} - \alpha^{01} - \alpha^{00} + \alpha^{11} = 4D P_\nu^{00}
$$

with

$$
\alpha^{ij} = \frac{N^{ij}_+ - N^{ij}_-}{N^{ij}_+ + N^{ij}_-}
$$

of the asymmetries $\alpha^{ij}$ of the four detector combinations is sensitive to $D$ but not to $A$ and $B$. 


Figure 2: Left: Cross-section of the Trine detector: 1 – detector chamber containing the counting gas, 2 – inner vacuum chamber, 3 – neutron beam, 4 – plastic scintillator, 5 – MWPC, 6 – electrode for proton acceleration, 7 – PIN diode, 8 – housing for PIN preamplifier. The polarisations points in z direction perpendicular to the plane of the drawing. Right: Top view.

The present most precise measurement of $D$ was carried out by the Trine collaboration.\cite{14}

The detector is shown in Fig. 2. The electrons are detected by plastic scintillators in coincidence with multiwire proportional chambers (MWPCs), the protons after acceleration by special low noise PiN diodes. The detector consists of 16 planes defined by 4 PiN diodes per plane which use all the same MWPCs and scintillators (see top view in Fig. 2). The wire chambers permit an offline selection of a symmetric range for electron detection (shaded area in Fig. 2), depending on the PiN diode hit by the proton. This increase in detector symmetry compared to the minimum requirements further reduces the influence of the parity violating correlations $A$ and $B$.

The final result is\cite{14}$ D = (−2.8±6.4^{\text{stat}}±3.0^{\text{syst}}) \cdot 10^{-4}$. The leading systematic errors are due to asymmetries in electron detection. A measurement with improved statistics and systematics was carried out in 2003 at the Institut Laue Langevin and is presently under analysis.

The emiT collaboration uses a detector geometry that is optimised for the highest statistical sensitivity to $D$. The kinematics of neutron decay favours large angles between electron and proton. The statistical sensitivity for $D$ is maximum for angles of about 135° between electron and proton detectors. The emiT detector uses an octagonal detector arrangement, resulting in this optimum angle. The collaboration published a first result $D = (−6 ± 12^{\text{stat}} ± 5^{\text{syst}}) \cdot 10^{-4}$ in 2000.\cite{13} In 2003 a run with improved detector performance was carried out at the National Institute of Standards and Technology.\cite{15}

4.2 $R$ correlation

The $R$ coefficient was not yet measured in neutron decay, but in several nuclear decays (e.g.\cite{16}). The technical difficulty consists in the detection of the polarisation of the electron. This can be done by Mott scattering on thin Gold or Lead foils, in combination with tracking of the electron. An $R$ measurement for neutron decay is in preparation at the Paul Scherrer Institut, Villingen. The experiment attempts for a precision of $10^{-3}$ in the final run. A first data run is planned for 2004. Details about the apparatus can be found in\cite{17}. 

Deviations from these symmetries are sources for systematic effects. $N_{ij}^{\uparrow\downarrow}$ denote the count rates for the both spin directions, $\kappa_D$ the sensitivity of a detector combination to $D$. 

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4.3 Neutron EDM

All recent experiments and proposed projects for the neutron EDM use the Ramsey resonance method\textsuperscript{18}, with ultra-cold neutrons (UCNs)\textsuperscript{b}. The precision of the running experiment is limited by the UCN density available from existing sources (and by systematic effects). Proposals for new experiments therefore rely on the significant progress in the UCN density possible with upcoming super-thermal UCN sources (see e.g.\textsuperscript{5}).

The statistical sensitivity for the neutron EDM is given by

\[
\sigma_{d_n} = \frac{\hbar \sigma}{\alpha E T \sqrt{N}},
\]

with \(\alpha\) describing the efficiency of polarisation and polarisation analysis, \(E\) the electric field applied to the neutron, \(T\) the time the neutrons spend in this field, and \(N\) the number of neutrons. All proposed projects attempt to increase \(N\) by orders of magnitude. Some increase of \(E\) is also planned by exploiting liquid \(^4\)He as buffer liquid, but this improvement is limited to a few \(10\) kV/cm.

A completely different approach to measure the neutron EDM was proposed in\textsuperscript{19}. In non-centrosymmetric crystals, much higher electric fields than can be created in vacuum are provided by nature. For the \((110)\) plane of quartz this field has been measured\textsuperscript{20} to be \(E = 1.8(2) \cdot 10^5\) kV/cm, about 4 to 5 orders of magnitude above the fields available in the laboratory. Also the neutron density for cold neutrons to be used in this experiment is an order of magnitude above the state-of-the-art UCN density. On the other hand, the time the neutrons spend in the crystal is short and can be maximised by using Bragg angles close to \(90^\circ\). In Tab.\textsuperscript{21} the sensitivity of this Laue diffraction method is compared with the most precise UCN EDM experiment.

The principle of the method is shown in Fig.\textsuperscript{3}. A longitudinally polarised neutron beam is Laue diffracted by the \((110)\) plane of a quartz crystal. In this case, the diffracted beam inside the crystal can be described as superposition of two type of Bloch waves, one travelling in the plane of the nuclei, the other in the plane between. Both beams are exposed to opposite electric fields. In their rest frames, the neutrons are exposed to opposite magnetic fields, originating from the magnetic field produced by the electric fields.

\textsuperscript{b}UCNs are defined as neutrons with an energy low enough that they can be stored in material bottles.
from the electric field in the crystal, and precess in contrary directions. Therefore, the effective polarisation of the diffracted beam depends on the crystal thickness but stays always in the scattering plane. A neutron EDM would now lead to the appearance of a polarisation $P_{\text{EDM}}$ perpendicular to this plane. This polarisation is related to the neutron EDM as follows:

$$P_{\text{EDM}} = \frac{2e^2 d_n}{v_\parallel \mu_n} = 6 \cdot 10^{20} \frac{d_n}{e \cdot \text{cm}},$$  \hspace{1cm} (5)

with $c$ the speed of light, $\mu_n$ the neutron magnetic moment, and $v_\parallel$ the component of the neutron velocity parallel to the (110) plane. The numerical value is given for a thickness of the quartz crystal of 3.5 cm, corresponding to a precession of $\pi/2$ for the both Bloch waves, i.e. a complete depolarisation of the diffracted neutron beam. A first test of the statistical sensitivity of the method resulted in $d\sigma_{dn}/dt = 6 \cdot 10^{-25} e \cdot \text{cm/dag}$. A full scale test of the statistical sensitivity and systematic effects was carried out recently at the Institut Laue Langevin.

The Laue diffraction method provides a statistical sensitivity which is comparable with the state-of-the-art UCN EDM experiment but a completely different set of systematics. Even if it should not be competitive with the proposed UCN projects, it is worthwhile to exploit this technique for checks with independent systematics.

5 Summary

Low energy searches for physics beyond the SM can compete with direct searches for new particles. Particularly sensitive are searches for asymmetries which would not exist in the SM (or have unobservable small values) but which may be created by contributions from new interactions at orders of magnitude above the SM values. Examples are the EDM of the neutron and time reversal violating correlations in neutron decay (especially the $D$ coefficient). Great progress is to expect for the neutron EDM from different new projects; correlation measurements have been improved recently and will provide new results within one year.

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