Hyperfine Interact (2006) 172:41–43
DOI 10.1007/s10751-007-9522-7

Towards a new measurement of the neutron electric dipole moment

G. Ban · K. Bodek · M. Daum · R. Henneck · S. Heule · M. Kasprzak · N. Khomytov · K. Kirch · A. Knecht · S. Kistryn · P. Knowles · M. Kuzniak · T. Lefort · O. Naviliat-Cuncic · A. Pichlmaier · C. Plonka · G. Quémener · M. Rebetez · D. Rebreyend · G. Rogel · B. M. Sabirov · M. Tur · A. Weis · J. Zejma

Published online: 6 June 2007

Abstract Precision measurements of particle electric dipole moments (EDMs) provide extremely sensitive means to search for non-standard mechanisms of T (or CP) violation. For the neutron EDM, the upper limit has been reduced by eight orders of magnitude in 50 years thereby excluding several CP violation scenarios. We report here on a new effort aiming at improving the neutron EDM limit by two orders of magnitude, down to a level of 3×10^{-28} e·cm. The two central elements of the approach are the use of the higher densities which will be available at the new dedicated spallation UCN source at the Paul Scherrer Institute, and the optimization of the in-vacuum Ramsey resonance technique, with storage chambers at room temperature, to reach new limits of sensitivity.

Keywords CP-violation · Electric dipole moment · Tests of the standard model

G. Ban (✉) · T. Lefort · O. Naviliat-Cuncic · G. Rogel
Laboratoire de Physique Corpusculaire de Caen, Caen, France
e-mail: ban@lpccaen.in2p3.fr

K. Bodek · S. Kistryn · M. Kuzniak · J. Zejma
Jagellonian University, Cracow, Poland

N. Khomytov · B. M. Sabirov
Joint Institute for Nuclear Research, Dubna, Russia

P. Knowles · M. Rebetez · A. Weis
University of Fribourg, Friboug, Switzerland

C. Plonka · G. Rogel
Institute Laue-Langevin, Genoble, France

G. Quémener · D. Rebreyend · M. Tur
Laboratoire de Physique Subatomique et de Cosmologie, Grenoble, France

M. Daum · R. Henneck · S. Heule · M. Kasprzak · K. Kirch · A. Knecht · M. Kuzniak · A. Pichlmaier
Paul Scherrer Institute, Villigen, Switzerland

1 Motivation

The interest in the EDM of the neutron, d_n, stems from the fact that a non-vanishing value at the present level of sensitivity would provide an unambiguous evidence for the breaking of parity (P) and time-reversal symmetry (T). Assuming CPT invariance, a finite value for d_n also implies the violation of CP invariance, which has so far only been observed in the K and B meson systems. These observations can phenomenologically be accommodated in the standard model (SM) through the complex phase in the Cabibbo–Kobayashi–Maskawa matrix. Within QCD there is another explicit source of "standard" CP-violation associated with the product of the gluonic field operators G and $\widetilde{G}$ which appears in the effective QCD Lagrangian. The strength of this contribution is driven by the so-called θ-term which reflects the coupling to quarks and appears to produce the dominant contribution to d_n, while its contribution to the electron EDM and to the K and B decays is small. In fact, the presently accepted limit $10^{-10} \leq \theta \leq 10^{-8}$ [1] is essentially determined by d_n and the EDM of the Hg atom. The explanation of the unexpected smallness of the θ-term (the "strong CP problem") is one of the major open questions in QCD and has generated significant activity, with no satisfactory solution so far.

EDMs are also connected with another fundamental puzzle: the baryon asymmetry of the universe. The asymmetry is generally described by the ratio r_B, between the number of baryons and the number of photons in the universe today. This ratio can be related to the number of baryons and antibaryons at the time of baryon freeze-out in baryogenesis models [2]. The observations indicate that $r_B \sim 10^{-10}$, which is about eight orders of magnitude larger than expected in baryogenesis models based on the SM. A possible explanation for this huge discrepancy was suggested by Sakharov [3]. As a consequence, it is expected that observation and theory could be reconciled if additional sources of CP violation are at work.

The SM predictions for d_n are on the order of $10^{-32\pm1}\mathrm{e}\cdot\mathrm{cm}$ [4], what is well below the present limit, $d_n \leq 3 \times 10^{-26}$ e·cm [5], and out of experimental reach in the near future.

2 Measuring principle and precision goal

The most sensitive measurements of the neutron EDM use the Ramsey's technique of "separated oscillatory fields." The basic principle is analogous to the measurement of a tiny frequency difference between two oscillating pendulae via the phase difference accumulated after some time. The neutron spin precesses in parallel static magnetic and electric fields and the signature of a finite EDM is given by a shift in the precession frequency under electric field inversion.

The statistical uncertainly on the EDM can be derived as

$$\sigma(d_n) = \frac{\hbar}{2\alpha TE\sqrt{N}} \quad (1)$$

where E is the magnitude of the applied electric field, T the time of free precession in the static low magnetic field, N the total number of neutrons analyzed and α the so-called "visibility" figure of the setup (typically 0.75) which is a sensitivity factor including the efficiency of maintaining the spin polarization throughout the entire manipulation, the effect of background counts and the inefficiency of the polarizer and analyzing devices.

The key for an improved neutron EDM measurement is the improvement of the statistical sensitivity while maintaining at the same time the systematic effects under control. In a first phase, our collaboration aims at improving the sensitivity on the neutron EDM down to the level of 5×10^{-27} e·cm.

3 The new neutron EDM experiment

In the present effort the central element to improve the statistical sensitivity is the use of higher UCN densities which will be available at the new dedicated spallation UCN source at the Paul Scherrer Institute (PSI) [6]. The anticipated initial UCN density is about $\rho_{\mathrm{UCN}} \approx 2,000\,\mathrm{cm}^{-3}$, what is two orders of magnitude larger than those presently available at the PF2 UCN source at the Institut-Langevin (ILL). After production and moderation the UCNs will be maintained in a 2 m^3 storage volume from where they can be distributed to the experiment. In such an arrangement the experimental setup with the EDM spectrometer is fully decoupled from the UCN production source.

In the present scheme the EDM setup—including the neutron polarizer, guides, Ramsey precession chamber, magnetic shieldings, magnetometers, spin analyzers and UCN detectors—is at room temperature and the spin precession process will take place in vacuum. The challenge is then to push the "in-vacuum-room-temperature" technique, which has provided so far the most stringent limit on the neutron EDM [5], to a new limit of sensitivity. This naturally requires that the dominant systematic effects be controlled at a comparable or lower level.

The main difficulty of the EDM measurement is to provide sufficient stable magnetic conditions during the free spin precession time. The use of a ^{199}Hg "co-mangetometer" has so far be sufficiently sensitive to correct magnetic field variations but would become a limiting factor for the new sensitivity levels. An alternative solution, using an array of laser optically pumped Cs magnetometers, is being studied and tested. The magnetometers will actively stabilize the coherence of the Ramsey pulses and their frequency. In addition, an active control of the static magnetic field will be implemented.

Since 2005 the collaboration has initiated an R&D program centered around the Sussex-RAL-ILL spectrometer [5] located at ILL. The activities include tests for the improvement of the UCN polarization, the magnetometry in the Ramsey chamber and in its surroundings, the replacement of the high-voltage system, the possible implementation of simultaneous analysis of the two spin components, improvements in the coatings of large area cells and guides, the use of faster UCN counters as well as extensive Monte-Carlo simulations of the full setup. The results of these tests will serve for the design of a new EDM spectrometer best adapted for a high precision measurement at PSI.

References

1. Bigi, I.I., Sanda, A.I.: CP Violation. Cambridge University Press (2000)
2. Riotto, A., Trodden, M.: Ann. Rev. Nucl. Part. Sci. **49**, 35 (1999)
3. Sakharov, A.D.: JETP Lett. **5**, 24 (1967)
4. He, X., McKellar, B.H., Pakvasa, S.: Int. J. Mod. Phys. **A4**, 5011 (1989)
5. Backer, C.A., et al.: Phys. Rev. Lett. **97**, 131801 (2006)
6. Atchinson, F., et al.: ICANS XVII. Santa Fe (2005)