swiss physical society

Nr. 47
November 2015

SPG MITTEILUNGEN
COMMUNICATIONS DE LA SSP

Progress in Physics (51)

Will ultracold neutrons reveal their electric dipole moment?

Malgorzata Kasprzak, Uni Leuven, Belgium

Progress in Physics (51)

Will ultracold neutrons reveal their electric dipole moment?

Malgorzata Kasprzak, Uni Leuven, Belgium

Introduction

The neutron is a fermion with spin ½, but it is not an elementary particle; it consists of three valence quarks - two down quarks and one up quark. The three quarks, with their different fractional charges, are bound together by gluons and surrounded by the sea quarks. Although the neutron has no net electrical charge, the experimental data reveals that there is a charge distribution inside the neutron [1]. Moreover, despite its neutrality, the neutron possesses a magnetic moment. This phenomenon is to a certain extent explained by the quark model, introduced by Gell-Mann in 1964 [2], and confirmed by experimental results [3]. It is also interesting that the mass of the neutron m_n, which is 939.3 MeV/c^2, is only 0.14 % higher than the mass of the second nucleon, the proton. Calculations [4, 5] show that this difference is not only due to strong interactions between quarks, as described by quantum chromodynamics (QCD), but also due to the electromagnetic interaction, as modeled by quantum electrodynamics (QED). Different models, different approaches, huge efforts of experimental and theoretical physicists are being made to understand the structure of the neutron and of nucleons in general. The neutron in particular is not easy to examine due to both the lack of free neutron targets and also to the electric neutrality of the neutron, which rules out the possibility of accelerating them by means of electric fields. To understand the neutron structure and its implications for the physical laws governing the Universe, a family of experiments has been created wherein the neutron energy is extremely low – these neutrons are called ultracold neutrons (UCN). These experiments aim to tackle still unsolved issues such as with the neutron lifetime or with the permanent electric dipole moment of the neutron (nEDM). This article focuses on the properties of UCN, their production and application in the experimental quest for an nEDM.

Wave like nature of a neutron

UCN are neutrons with very low kinetic energies; typically $E_k = ½\, m_n v^2 < 300$ neV. They can be totally reflected from the surface of specific materials at all angles of incidence. This effect can be explained by analogy with the reflection of light. The neutron may be characterized by its de Broglie wavelength, $\lambda_n = h/m_n v$ (for UCN $\lambda_n > 80$ nm) where h is the Planck constant. Thus, the reflection of a neutron from a surface can be interpreted in terms of an index of refraction n given by:

$$n = \sqrt{1 - \frac{V(\vec{r})}{E_k}}$$

The term $V(\vec{r})$ in the above equation describes the interaction between the neutron and the matter. In the absence of interactions, $n = 1$. At the surface neutrons are affected by the so-called Fermi pseudo-potential V_F resulting from the coherent strong interactions with all the surface atoms' nuclei

$$V_F(\vec{r}) = \frac{h^2 b_{coh} N}{2\pi m_n}$$

where N is the number density of atoms and b_{coh} is the coherent scattering length of the material. Following Snell's law, we can define the critical incident angle θ_c above which total reflection occurs:

$$\sin\theta_c = n\ .$$

This can be further translated, for $\theta_c = 0$, into a critical velocity v_c, which determines the limit for the maximum velocity that UCN can have in order to be totally reflected:

$$v_c = \sqrt{\frac{2V_F}{m_n}}$$

Materials which are used in UCN physics are normally chosen to have large Fermi pseudo-potential, typically of the order of 10^{-7} eV, which corresponds to neutron velocities of up to ~ 5 m/s. For example, Be (V_F = 252 neV) and ^{58}Ni (V_F = 335 neV) are often incorporated as wall coatings in UCN equipment.

Figure 1. The interaction between neutron and atomic nuclei can be compared with a net stopping a football. Although the size of the neutron as a particle is 10^5 times smaller than the separation of atoms, its wavelength is larger than that spacing, resulting in the reflection of the neutron. However, in contrast to a football the interaction of the neutron with the surface is predominantly elastic and no lattice deformation occurs.

In a similar way we can look at the interaction of a neutron with magnetic fields, which can be described in terms of the potential energy given by the scalar product of the magnetic dipole moment $\vec{\mu}_n$ and the magnetic field $\vec{\mathbf{B}}$:

$$V_M\,(neV) = -\vec{\mu}_n \cdot \vec{\mathbf{B}} = \pm 60B\,(T)$$

Just as for the nuclei of the material surface, the magnetic field creates a magnetic potential "wall" for the neutrons that have their magnetic moment antiparallel to the magnetic field lines, while pulling into the field the neutrons of the opposite orientation.

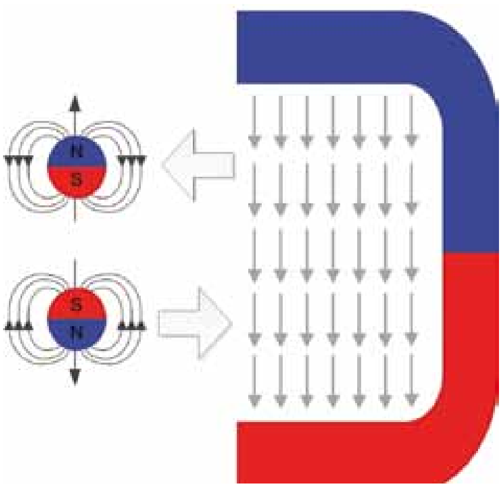

Figure 2. The neutron can be visualized as a small magnet and depending on its orientation is either attracted or repelled by the magnetic field gradient. UCN critical velocity, for which n = 0 is defined by $v_c = \sqrt{2V_M/m_n}$ *for magnetic moment antiparallel to the magnetic field lines. This effect is used in the storage of polarized UCN in magnetic bottles [6].*

Another unavoidable force acting on a free neutron comes from its interaction with gravity. According to classical mechanics, the neutron's potential energy in the terrestrial gravitational field is

$$V_g\,(neV) = m_n g H = 103\,H\,(m)\,,$$

implying that UCN with $E_k < 300$ neV in the Earth's gravitational field can rise to a maximum height H of about three meters. The sensitivity of UCN to gravitational effects is used in experimental studies of the laws of gravity and quantum mechanics by detecting quantum states of UCN in the Earth's field [7,8].

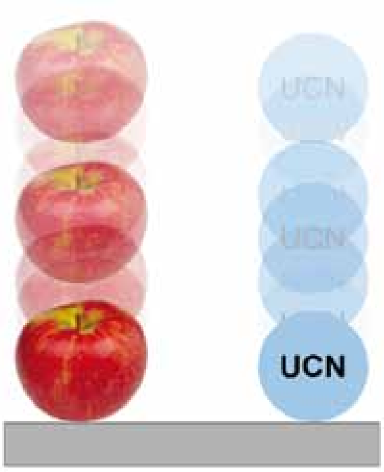

Figure 3. UCN experience free-fall under gravity very similarly to a falling apple. The energy of UCN in the Earth's gravitational field is quantized and the energy eigenstates have been observed experimentally [7]. The transitions between them are studied by gravity resonance spectroscopy testing the Newton's law of gravity [8].

It is clear from the above that UCN may be confined in traps. Such neutron "bottles" can be made of materials with high Fermi pseudo-potential. Alternatively they can use high magnetic fields of a few Tesla and its gradients to store the UCN. Combined magneto-material traps are also feasible. In the magnetic bottles only one spin state can be stored, while the non-magnetic material traps are spin independent. The optimal height of UCN storage volumes is determined by the gravitational effects, which shape the distribution of stored UCN [9]. Trapped UCN can also be considered as a non-interacting gas of about 3 mK temperature, according to $E_n = k_B T_n$, and as such be modeled. Interestingly, since the neutron-surface collisions are predominantly elastic, the UCN gas does not reach thermal equilibrium with the walls of the trap [10], and thus long storage times of UCN are readily achievable even at room temperature. Another factor enabling long observation times is the exceptionally long (for an unstable particle) neutron lifetime of 880.3(1.1) s [11], governed by weak interactions. Thus, stored UCN are an ideal system for high precision experiments such as searches for an electric dipole moment of the neutron, measurements of the neutron lifetime or studies of the neutron beta decay.

UCN production

Free neutrons produced either in nuclear or fission reactions have average energies of a few MeV, ten trillion times higher than UCN energies. The typical moderation process, based on elastic scattering with moderator molecules, is efficient until the neutrons reach thermal equilibrium with the medium, at an energy of ~ 25 meV in a room-temperature heavy-water moderator. To obtain UCN energies in such a way, one would need a large volume of non-absorbing material at about 4 mK temperature, which is not existing. Therefore, other cooling methods need to be applied, one of those being the so-called superthermal production [10]. In this process, the neutron energy is transferred not to a single molecule but rather to phonons, quasiparticles representing the collective motion of the atoms or molecules in for example a crystal lattice. The maximum possible energy transfer from neutrons to phonons is defined by the phonons' frequency spectrum.

In the UCN source [12] at the Paul Scherrer Institute (PSI), the phonon-based cooling of neutrons happens in solid deuterium at 5 K. The pulse of the proton beam from PSI's high intensity proton accelerator hits a lead target. The neutrons released in the spallation reaction are thermalized in heavy water and subsequently downscattered to ultracold neutron energies in a solid deuterium converter [13]. UCN are further transported with neutron guides to experiments, one of them being the search for the neutron EDM.

Electric Dipole Moment of a neutron

The possible existence of a neutron electric dipole moment has intrigued scientists since it was first suggested by Purcell and Ramsey in 1950 [15]. The reason for the ongoing interest is that the coexistence of the spin ½ and an electric dipole moment violates parity P symmetry (mirror reflection of physical processes) and time reversal invariance T (Fig. 5). Through the conservation of the combined symmetry CPT [16], it also violates CP symmetry (C being the charge conjugation operator replacing particles by their antiparticles). A violation of CP symmetry in the very early stages of the Universe is required to explain why there is almost no antimatter in our world. In the Big Bang scenario matter and antimatter should have been created in equal amounts from the primordial energy. The observed baryon to photon density ratio $\eta = n_B/n_\gamma \approx 6 \cdot 10^{-10}$ [11] indicates that in the early Universe the symmetries of the fundamental interactions were not conserved, leading to the observed dominance of

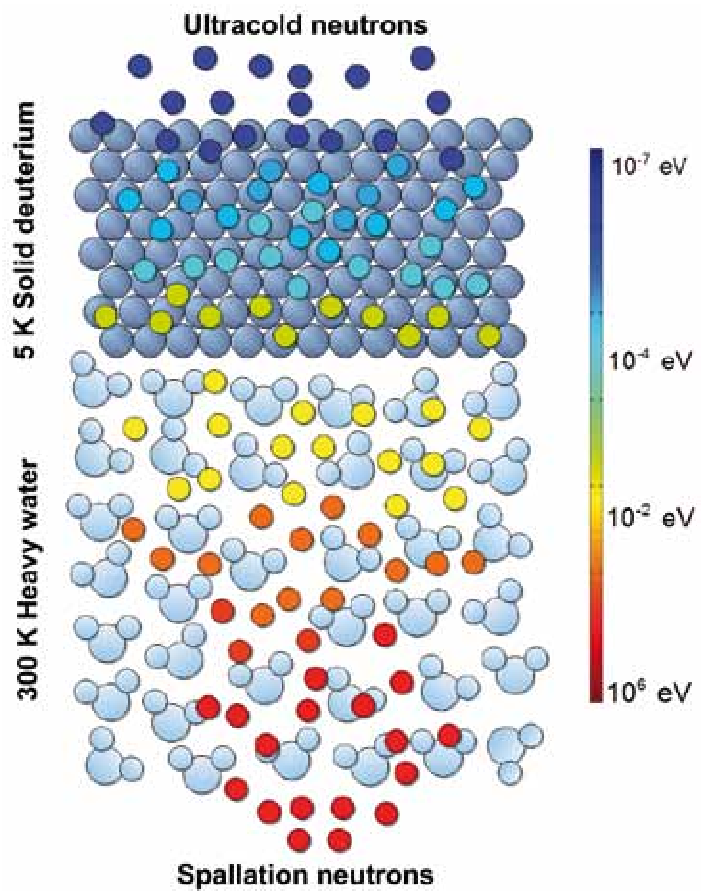

Figure 4. This picture illustrates the cooling process of fast neutrons in the PSI UCN source. Spallation neutrons with energies of few MeV are thermalized in heavy water and subsequently moderated in the solid deuterium at 5 K to cold neutron energies (meV). The last phase of neutron conversion takes place in the solid deuterium crystal where the cold neutrons are downscattered to ultracold neutron energies by transferring their momenta to phonons [14].

matter over antimatter. The explanation of the baryon asymmetry of the Universe requires, according to the criteria proposed by A. Sakharov [17], a source of CP-violation. A CP non-conserving mechanism, discovered in the neutral K meson decays [18], is implemented in the weak interaction sector of the Standard Model as a complex phase in the Cabbibo-Kobayashi-Maskawa quark mixing matrix. Based on this, the nEDM is calculated to be of order 10^{-32} e·cm [19], which is six orders of magnitude below the experimental upper limit of $3 \cdot 10^{-26}$ e·cm [20] and far beyond the reach of currently running experimental efforts. On the other hand, the known (and parametrised) level of CP violation cannot account for the observed matter-antimatter asymmetry, so that other sources of CP violation have been postulated in different New Physics scenarios. A possible origin of CP violation in the Standard Model could arise in the strong interaction sector from non-perturbative QCD effects parametrized by the so-called Θ term [21]. Additional sources of CP violation are also proposed in different theories beyond the Standard Model (such as Supersymmetry) that attempt to quantitatively account for the matter-antimatter asymmetry. Most of these models provide theoretical predictions for nEDM values that are larger than 10^{-28} e·cm [22, 23], i.e. considerably larger than the value predicted by the Standard Model and potentially within the reach of experiments at proposed and running new UCN sources.

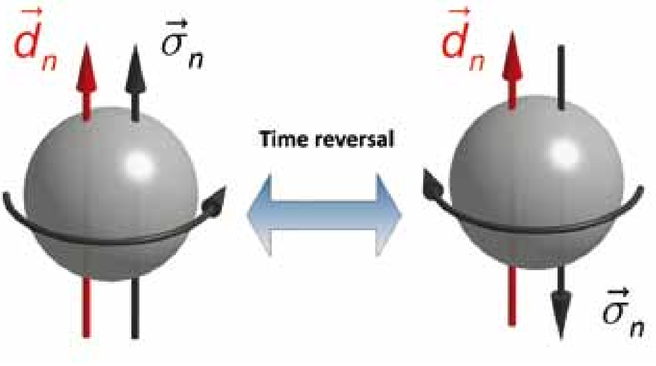

Figure 5. In a simplified interpretation the electric dipole moment can be pictured as separation of positive and negative electrical charges inside the neutron. The orientation of the neutron is specified only by its spin. The time reversal operation T, which changes the direction of the arrow of time, will not affect the charge distribution, but will reverse the neutron spin $\vec{\sigma}_n$, creating a different state for the time-reversed neutron.

With the development of UCN sources it has become possible to significantly increase the experimental nEDM sensitivity due to the ability to store UCN for hundreds of seconds. In the nEDM experiment [24] currently collecting data at the PSI, spin-polarized UCN from the PSI UCN source are trapped in a chamber and exposed to a static magnetic field B of 10^{-6} T, within which they undergo Larmor precession at a frequency $\nu_L \approx 30$ Hz. An nEDM signal would manifest itself via an increase or decrease of the neutrons' precession frequency ν_L induced by an electric field E of about 10 kV/cm, which is applied alternately parallel (ξ = +1) and anti-parallel (ξ = -1) to the static magnetic field:

$$h\nu_L^{\xi} = 2\vec{\mu}_n \cdot \vec{\mathbf{B}}_{\xi} + 2\xi \vec{d}_n \cdot \vec{\mathbf{E}}_{\xi}$$
$$\xi = \hat{E} \cdot \hat{B}$$

where $\mu_n \approx 6 \times 10^{-8}$ eV/T is the magnetic dipole moment of the neutron. The presence of an nEDM (d_n) will manifest itself in a non-zero difference between the ξ = +1 and ξ = -1 configurations

$$\frac{h}{2E}(\nu_L^{+} - \nu_L^{-}) = d_n + \mu_n \frac{B_+ - B_-}{2E}$$

A precise determination of the neutron spin precession frequency in the magnetic and electric fields is carried out using the Ramsey technique of (time-)separated oscillatory fields [25].

The interaction of the neutron's magnetic moment with the magnetic field (characterized by the Larmor frequency) is clearly, because of the smallness of d_n, orders of magnitude larger than the corresponding "electric" Larmor frequency describing the interaction of a possible electric dipole moment with the electric field. Therefore, any changes of the magnetic field have to be precisely known and controlled in order to sufficiently suppress any systematic effects associated with magnetic field drifts. Hence, the experiment is placed in a multi-layer magnetic shield. The Earth magnetic field and the time dependent ambient magnetic field are reduced and stabilized by actively controlled coils [26]. Residual magnetic field changes inside the shield are monitored by a Hg magnetometer [27] filling the same volume as the neutrons and by a laser-driven array of optically pumped Cs magnetometers [28] located below and above the neutrons' precession chamber. The Cs magnetometers, which were developed at the University of Fribourg, play an important role in the experiment not only because of the monitoring of the field distribution. They also allow the preparation of excellent homogenous magnetic field conditions.

Conclusions and outlook

Research with ultracold neutrons covers a broad range of topics, from neutron quantum optics to experiments searching for physics beyond the Standard Model of Particle Physics. UCN experiments are truly multidisciplinary; they encompass aspects of nuclear physics, condensed matter physics, atomic physics and particle physics. They allow probing fundamental questions concerning the matter-antimatter asymmetry of the Universe. The world-leading nEDM experiment located at the UCN source at the PSI is expected to improve over the best sensitivity by factor of two in the next 2-3 years. At the same time the nEDM collaboration is building a new apparatus. This new project is expected to be sensitive to an nEDM at the 10^{-27} e·cm level. With such improved sensitivity, either the nEDM will be found, or a new limit will set tight constraints on CP-violating physics beyond the Standard Model.

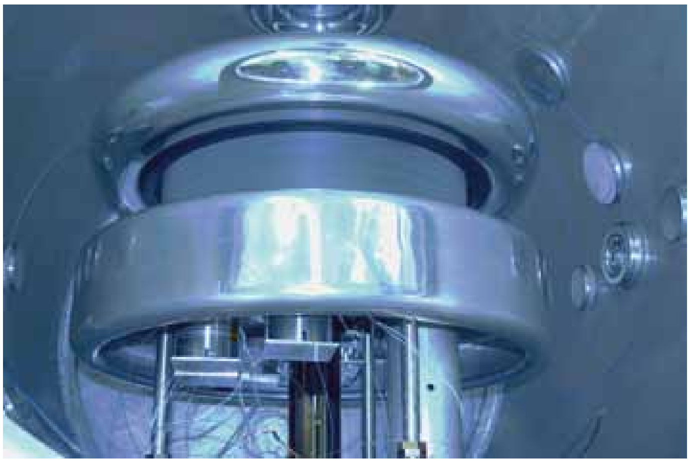

Figure 6. This photo of the nEDM experiment shows two aluminium electrodes encapsulating the UCN storage chamber. Below the lower (ground) electrode a number of Cs magnetometers are mounted. A second group of Cs magnetometers, fully optically coupled, is located on the upper (HV) electrode. With this configuration the spatial distribution of the magnetic field is continuously measured.

Acknowledgements

I would like to thank my colleagues; H. P. Beck, M. Daum, P. Harris, K. Kirch, B. Lauss, N. Severijns, A. Weis and G. Zsigmond for careful reading and corrections of the manuscript.

References

[1] G. A. Miller, *Charge Densities of the Neutron and Proton*, Phys. Rev. Lett. **99**, 112001 (2007)
[2] M. Gell-Mann, *A schematic model of baryons and mesons,* Phys. Lett. **8**, 214 (1964)
[3] S. Afach et al., *A measurement of the neutron to* ^{199}*Hg magnetic moment ratio*, Phys. Lett. **B 739**, 128 (2014) (nEDM collaboration)
[4] Sz. Borsanyi et al., *Ab inito calculation of the neutron-proton mass difference*, Science **347**, 1452 (2015)
[5] F. Wilczek, *A weighty mass difference*, Nature **520**, 303 (2015)
[6] D. J. Salvat et al., *Storage of ultracold neutrons in the magneto-gravitational trap of the UCNτ experiment*, Phys. Rev. **C 89**, 052501 (2014)
[7] V. V. Nesvizhevsky et al., *Quantum states of neutrons in the Earth's gravitational field*, Nature **415**, 297 (2002)
[8] T. Jenke et al., *Gravity resonance spectroscopy constrains dark energy and dark matter scenarios*, Phys. Rev. Lett. **112**, 151105 (2014)
[9] J. M. Pendlebury and D. J. Richardson, *Effects of gravity on the storage of ultracold neutrons*, Nucl. Instr. Meth. **A 337**, 504 (1994)
[10] R. Golub, D. Richardson, S. K. Lamoreaux, *Ultra-Cold Neutrons*, Adam Hiliger, Bristol, 1991.
[11] K. A. Olive et al. (Particle Data Group), Chin. Phys. C, **38**, 090001 (2014)
[12] B. Lauss, *Ultracold Neutron Production at the second spallation target of the Paul Scherrer Institute*, Phys. Proc. **51**, 98 (2014)
[13] F. Atchison et al., *Production of ultracold neutrons from cryogenic 2*H_2*,* O_2*, and* C_2H_4 *converters*, Eur. Phys. Lett. **95**, 12001 (2011)
[14] F. Atchison et al., *Cold Neutron Energy Dependent Production of Ultracold Neutrons in Solid Deuterium*, Phys. Rev. Lett. **99**, 262502 (2007)
[15] E. M. Purcell and N. F. Ramsey, *On the possibility of Electric Dipole Moments for Elementary Particles and Nuclei*, Phys. Rev. **78**, 807 (1950)
[16] G. Lüders, Proof of the TCP theorem, Ann. Phys. **281**, 1004 (2000)
[17] A. D. Sakharov, *Violation of CP invariance, C asymmetry, and baryon asymmetry of the universe*, Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32 (1967)
[18] J. H. Christenson, J. W. Cronin, V. L. Fitch and A. Turlay, *Evidence for the 2π Decay of the* K_2^0 *Meson*, Phys. Rev. Lett. **13**, 138 (1964)
[19] A. Czarnecki and W. Marciano, *Electromagnetic Dipole Moments and New Physics*, In B. L. Roberts, W. J. Marciano "Lepton Dipole Moments", World Scientific Publishing (2010)
[20] J. M. Pendlebury et al., *A Revised Experimental Upper Limit on the Electric Dipole Moment of the Neutron*, arXiv:1509.04411, submitted to Phys.Rev. D
[21] R. J. Crewther et al., *Chiral estimate of the electric dipole moment of the neutron in quantum chromodynamics*, Phys. Lett. **B 88**, 123 (1979)
[22] M. Pospelov and A. Ritz, *Electric dipole moments as probes of new physics*, Ann. Phys. **318**, 119 (2005)
[23] J. Ellis et al., *A cosmological lower bound on the neutron electric dipole moment*, Phys. Lett. **B 99**, 101 (1982)
[24] C. A. Baker et al.,*The search for the neutron electric dipole moment at the Paul Scherrer Institute*, Phys. Proc. **17**, 159 (2011) (nEDM collaboration)
[25] N. F. Ramsey, *A Molecular Beam Resonance Method with Separated Oscillating Fields*, Phys. Rev. **78**, 695 (1950)
[26] S. Afach et al., *Dynamic stabilization of the magnetic field surrounding the neutron electric dipole moment spectrometer at the Paul Scherrer Institute*, J. Appl. Phys. **116**, 084510 (2014) (nEDM collaboration)
[27] C. A. Baker et al., *Apparatus for measurement of the electric dipole moment of the neutron using a cohabiting atomic-mercury magnetometer*, Nucl. Instr. Meth. **A 736**, 184 (2014)
[28] P. Knowles et al., *Laser-driven Cs magnetometer arrays for magnetic field measurement and control*, Nucl. Instr. Meth. **A 611**, 306 (2009)

Malgorzata Kasprzak received an MSc degree in Physics from Jagiellonian University in Krakow (PL) for her work on thermal up-scattering of very cold and ultracold neutrons. She continued this research during her PhD studies investigating neutron scattering and ultracold neutron production in cryogenic crystals. In 2008 she received a PhD degree in Physics from Vienna University (AT). Willing to understand more she decided to change her focus to atomic physics and joined the FRAP (Fribourg Atomic Physics) group at Fribourg University (CH), where she was studying the high resolution spectroscopy and optical detection of magnetic resonance. This resulted in the development of Cs sensors array for the nEDM experiment at the Paul Scherrer Institute. Presently she is working at the University of Leuven (BE) on the optimization of magnetometry for the nEDM project.