Kraft *et al. EPJ Techniques and Instrumentation* 2014, **1**:8
http://www.epjtechniquesandinstrumentation.com/content/1/1/8

EPJ Techniques and Instrumentation
a SpringerOpen Journal

RESEARCH ARTICLE Open Access

Development of a ^{3}He magnetometer for a neutron electric dipole moment experiment

Andreas Kraft[1,6*], Hans-Christian Koch[1,2], Manfred Daum[4], Werner Heil[1], Thorsten Lauer[1,7], Daniel Neumann[1], Anatoly Pazgalev[5], Yuri Sobolev[3,8] and Antoine Weis[2]

*Correspondence: kraftan@u.washington.edu
[1] Institute of Physics, Johannes Gutenberg University, 55128 Mainz, Germany
[6] Present address: CENPA, Department of Physics, University of Washington, WA 98195, Seattle, USA
Full list of author information is available at the end of the article

Abstract

We have developed a highly sensitive ^{3}He magnetometer for the accurate measurement of the magnetic field in an experiment searching for an electric dipole moment of the neutron. By measuring the Larmor frequency of nuclear spin polarized ^{3}He atoms a sensitivity on the femto-Tesla scale can be achieved. A ^{3}He/Cs-test facility was established at the Institute of Physics of the Johannes Gutenberg University in Mainz to investigate the readout of ^{3}He free induction decay with a lamp-pumped Cs magnetometer. For this we designed and built an ultra-compact and transportable polarizer unit which polarizes ^{3}He gas up to 55% by metastability exchange optical pumping. The polarized ^{3}He was successfully transfered from the polarizer into a glass cell mounted in a magnetic shield and the ^{3}He free induction decay was detected by a lamp-pumped Cs magnetometer.

Keywords: ^{3}He magnetometry; Ultra-compact ^{3}He polarizer; Neutron electric dipole moment; Ultracold neutrons

PACS numbers: 07.55.Ge Magnetometers for magnetic field measurements; 13.40 Electric and magnetic moments; 14.20 Protons and neutrons

Background

In 1950, Purcell and Ramsey [1] were the first to point out that the existence of an electric dipole moment (EDM) in an elementary particle with spin would violate the parity symmetry *P*. Although there were strong arguments favoring the view that elementary particles and their interactions conserve parity, Ramsey and Purcell called for an experimental search for EDMs. Shortly after the discovery of *P* violation in 1957 [2-5] in weak interactions, Smith, Purcell, and Ramsey [6] reported the first (null) result of an experimental search for a neutron EDM. Besides *P*, an EDM also violates time reversal invariance, *T*, and the discovery of *CP*-violation in the neutral K meson�s decay [7] in 1964 (being equivalent to *T*-violation when assuming *CPT* conservation) removed objections against the possible existence of an EDM in elementary particles. However, besides the recent observation of *CP*-violation in the B meson system [8,9], no other experimental evidence for *CP*- or *T*-violation has been revealed in elementary particle physics experiments nor in experiments on atoms or molecules up to date. Among all elementary particles, neutrons provide the best possibilities for the EDM search, since they are electrically neutral, may have a long-lived spin coherence, and can be stored for a long time in an environment which can hold a strong electric field.

The current upper limit of the neutron electric dipole moment (nEDM) [10], $d_n \leq 2.9 \cdot 10^{-26}$ e · cm (90% c.l.), represents one of the most precise measurements in physics and continues to challenge our understanding of fundamental physics, in particular the so-termed "Strong *CP*-Problem" and "SUSY *CP*-Problem", see, e.g. [11,12]. Today, various efforts to improve the sensitivity to an nEDM are underway [13-17]. The nEDM collaboration[a] at the Paul Scherrer Institute (PSI) in Villigen, Switzerland is currently developing a next generation EDM setup which will use ultracold neutrons (UCN) delivered by a new spallation-based UCN source with a solid deuterium moderator/converter combination [18]. The nEDM experiment at PSI uses the conventional approach of storing UCN in a trap at room temperature. Additional improvements of the experiment are aimed at a sensitivity gain of more than one order of magnitude. The gain in measurement sensitivity, sets new challenges to the monitoring of systematic effects, in particular effects associated with magnetic field changes that are correlated with the switching of the electric field and which may mimic a false nEDM signal.

In this paper, we describe the technical realization of a ^{3}He magnetometer system that shall be implemented into the PSI n2EDM experiment.

^{3}He magnetometer for the n2EDM experiment

The planned n2EDM experiment at PSI [19,20] is an attempt to increase the sensitivity of the neutron electric dipole measurement by more than one order of magnitude. The parallel electric and magnetic field configurations will be in the vertical plane, as shown in the left part of Figure 1. The spin precession chamber , i.e., the neutron storage volume will have a cylindrical double chamber geometry similar to the one used in [21] in order to minimize systematic effects. Further improvements are planned by the implementation of

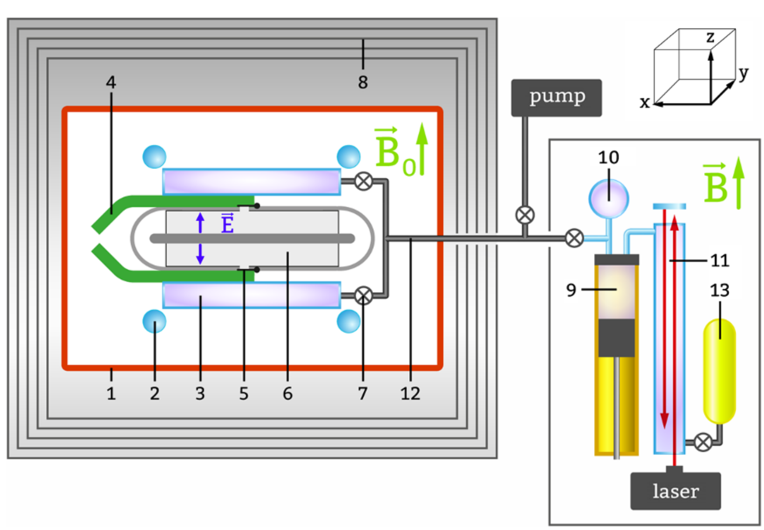

Figure 1 Projected layout of the spectrometer chamber (left) and UCPU of the n2EDM experiment. (1) coil system, (2) CsOPM, (3) ^{3}He magnetometer vessel, (4) neutron guides, (5) storage chamber shutter, (6) double neutron spin precession chamber surrounded by electrode system, (7) valve, (8) multi-layer magnetic shielding, (9) non-magnetic piston compressor, (10) polarized ^{3}He storage cell, (11) volume for metastable optical pumping, (12) transfer line and (13) ^{3}He reservoir.

a new and effective magnetic shield, a better control of the magnetic field and its gradients as well as an improved magnetometry system.

Precise knowledge of the magnetic field and its vertical gradient inside the neutron precession chamber during Ramsey cycles is of crucial importance for controlling several systematic effects. One approach described here, is to infer the magnetic field amplitude from the Larmor precession frequency of nuclear spin polarized ^{3}He, detected by its free induction decay (FID) [22].

The ^{3}He magnetometer will be placed in the electric field free region near the UCN storage chamber to avoid geometrical phase dependent systematic effects on the ^{3}He nuclei proper [23]. Since the helium magnetometer is based on the free precession of nuclear spins, it is not prone to many systematic frequency shifts that are inherent to phase-locked optically pumped alkali vapour magnetometers and additionally gains in overall sensitivity due to the long ^{3}He coherence times. The proposed ^{3}He sandwich configuration, Figure 1, enables the control of vertical gradients of the magnetic holding field with high precision, whose knowledge and control is of great importance for tracing tiny geometrical phase effects in the nEDM spectrometer.

A magnetometric sensitivity in the femto-Tesla range has been demonstrated using SQUID (superconducting quantum interference device) magnetometers for the readout of the precessing ^{3}He spins [24]. However, the required cryogenic infrastructure is a severe obstacle for operating these magnetometers under the experimental conditions of an EDM experiment (vacuum, high voltage, stabilized temperature, exclusive use of non-magnetic materials). As shown for the first time by Cohen-Tannoudji et al. [25] in 1967 optically pumped alkali (Rb) magnetometers are a promising alternative for the readout of the ^{3}He precession signal. Based on the expertise with optically pumped Cs magnetometers (CsOPMs) gained in the ongoing phase of the PSI-nEDM experiment, we plan to deploy a CsOPM-based, rather than a SQUID-based detection of the ^{3}He FID signal. The CsOPM are developed by the Fribourg Atomic Physics group (FRAP) [26-28], member of the nEDM collaboration at PSI. The polarizer unit necessary for spin polarization of the ^{3}He gas was built at the Johannes Gutenberg University (JoGu), Mainz, and is described in detail below.

During nEDM measurement, ^{3}He at a pressure of 1 mbar will be polarized in an ultra-compact and transportable polarizer unit (UCPU) outside the n2EDM chamber in a field of 1 Gauss. The gas is then compressed to a pressure of ≈ 100 mbar and stored in low-relaxation glass cell. The whole UCPU is enclosed in a mu-metal cylinder to provide shielding from environmental fields and to allow generation of a homogeneous magnetic field by an internal cylindrical coil. Upon request, the compressed and polarized ^{3}He in the storage cell will be transferred into the magnetometer vessels through a polytetrafluoroethylene (PTFE) tube surrounded by coils producing a suitable magnetic holding and guiding field on the order of 1 to 200 μT.

The magnetometer vessels will be two flat cylindrical glass cells mounted inside the n2EDM vacuum tank, above and below (top, bottom) the neutron spin precession chamber, respectively (Figure 1). Since both magnetometer cells are traversed by almost the same magnetic flux as the UCN chambers, the average value of frequency measurements $\omega_{\mathrm{He}} = (\omega_{\mathrm{t,He}} + \omega_{\mathrm{b,He}})/2$ yields a best guess for the neutron spin precession frequency $\omega_{\mathrm{n}} = (\gamma_{\mathrm{n}}/\gamma_{\mathrm{He}})\,\omega_{\mathrm{He}}$, while the frequency difference determines the magnetic field gradient $\partial\,|\mathbf{B}|\,/\partial \mathrm{z} = (\omega_{\mathrm{t,He}} - \omega_{\mathrm{b,He}})/(\gamma_{\mathrm{He}} \cdot \Delta \mathrm{z})$ to a high precision. Here, Δz is the distance between the centers of gravity of the upper and lower magnetometer vessel, $\omega_{t,He}$ and $\omega_{b,He}$ are the free spin precession frequencies of the ^{3}He in the top and bottom magnetometer vessels, respectively, and γ_{He} is the ^{3}He gyromagnetic ratio.

The ^{3}He FID is started by applying a $\pi/2$ spin-flip pulse. The long coherence time of the ^{3}He FID signal, which strongly depends on the absolute magnetic field gradients ($\sim$ 20 pT/cm), the magnetometer cell material, the size of the magnetometer vessels as well as the ^{3}He pressure (p $\sim$ mbar)[29], reaches the order of one hour under the typical operating conditions of the EDM apparatus. Assuming a typical Ramsey cycle time for the ultracold neutrons of $\approx$ 200 s, it is thus possible to run 2–3 Ramey cycles with a single ^{3}He filling without significant decay of the ^{3}He FID signal amplitude. After these cycles the partly relaxed ^{3}He will be pumped out, eventually recovered [30] and replaced by freshly polarized gas that has been prepared by the UCPU during the Ramsey cycles. This procedure will require the UCPU to deliver freshly polarized ^{3}He gas every 10 to 15 min in order to ensure a high signal to noise ratio (SNR) of the recorded spin precession signal. A quasi-continuous operation of the ^{3}He magnetometer will thus be possible.

Results and discussion

^{3}He/Cs magnetometer test facility

A dedicated test facility was installed at the JoGu in order to construct and test the proposed ^{3}He/Cs magnetometer system. As main part of this facility, a cylindrical four layer mu-metal shield (MS) [31] with magnetic shielding factors of 100 (longitudinal) and 1000 (transverse) was adapted to the requirements imposed by the ^{3}He FID studies. In order to lower existing magnetic field gradients and to record the ^{3}He FID signal, the innermost mu-metal cylinder (610 mm diameter, 1300 mm length) was equipped with a magnetic coil system (solenoid and cosine-theta coil) providing magnetic fields parallel and perpendicular to the cylinder axis. The coils were wound on a double-walled cardboard cylinder which was then covered with five layers of Metglas [32]. With these arrangements, magnetic field gradients of 150 to 350 pT/cm could be achieved in the longitudinal direction. For the transverse field gradients, values in range of 350 to 450 pT/cm were determined. Within this magnetic environment two basic types of experiments have been performed:

- FID detection of in-situ polarized ^{3}He in a small cell, and
- FID detection of externally polarized and transferred ^{3}He.

The setup for in-situ polarization of ^{3}He is presented in Figure 2. The mechanical support of the components was produced from non-magnetic materials, e.g., acrylic glass and polyethylene. The optical axis was aligned to the cylinder axis of the solenoidal coil. A beam of linearly polarized light from a 5 W ytterbium doped 1083 nm fiber laser was sent via an optical fiber into the magnetic shield. A beam expander coupled to the fiber (Figure 2, item 1) widened the incoming laser beam to a diameter of 30 mm. The light was circularly polarized by a polarizing beam splitter cube (PBS) with an attached $\lambda/4$-plate, item 2 of Figure 2. The laser beam can be blocked after the $\lambda/4$-plate by means of a compressed-air driven shutter (item 3 of Figure 2). The cylindrical ^{3}He precession cell, made from borosilicate glass and filled with ^{3}He at a pressure of 1 mbar is positioned in the center of the setup. A capacitively coupled AC high voltage produced by a Tesla transformer (item 4 of Figure 2) driven at 1.7 MHz is used to ignite and sustain a discharge inside the ^{3}He cell during the metastability exchange optical pumping (MEOP)

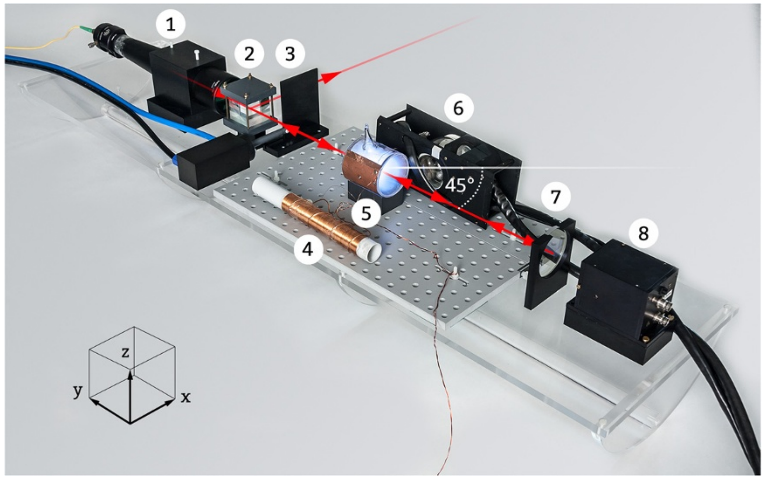

Figure 2 Inner setup of the ^{3}He/Cs test setup consisting of a beam expander (1), beam splitter cube (2), shutter (3), Tesla transformer coil (4), closed glass cell filled with ^{3}He (5), Cs-magnetometer (6), dichroic mirror (7) and optical polarimeter (8).

[33]. The optical pumping beam is retro-reflected by a dichroic optical mirror (item 7 of Figure 2) for a second passage through the cell. Fluorescense light of 668 nm transmitted by the dichroic mirror is analyzed by an optical polarimeter (OPN), item 8 of Figure 2. The degree of circular polarisation of the fluorescense light measured by the OPN is proportional to the degree of spin polarisation of the ^{3}He gas and can hence be used to monitor the ^{3}He polarisation build-up [34]. A discharge lamp pumped cesium magnetometer (Figure 2, item 6) operated in the self-oscillating M_x-mode [26,35] is positioned close to the ^{3}He cell. The output of this type of magnetometer is a continuous sinusoidal voltage signal of constant amplitude, whose frequency ω_{Cs} is related to the modulus of the magnetic field via the Cs gyromagnetic ratio

$$\omega_{Cs} = \gamma_{Cs} \, |\mathbf{B}| \, . \tag{1}$$

For the field ($\approx$ 1 μT) applied in the present study, $\omega_{Cs}/2\pi$ is $\approx$3.5 kHz. When the solenoid coil is powered and a discharge is ignited inside the cell, the ^{3}He pump laser produces nuclear spin polarization along the direction $\hat{B}_{sol}$ of the solenoid axis. The degree of polarization reaches approximately 65% after two minutes of optical pumping. There are two different ways to initiate the ^{3}He FID after the discharge and the laser have been switched off:

- The magnetic field can be switched rapidly from the longitudinal solenoid (along $\hat{y}$-axis) to the transverse cosine-theta coil (field-flip) along $\hat{z}$-axis, inducing a non-adiabatic field rotation when the switching time is much shorter than the ^{3}He precession period

$$\frac{1}{t_{switch}} \gg \nu_{He} \, . \tag{2}$$

- A pulse of resonant rf radiation can be applied with the cosine-theta coil to rotate the ^{3}He spin polarization by 90° ($\pi/2$ spin-flip pulse).

Please note that after a field flip the ^{3}He polarization will precess around $\hat{B}_{cos}$ in the $\hat{x}-\hat{y}$ plane, while a spin flip results in a precession around $\hat{B}_{sol}$ in the $\hat{x}-\hat{z}$ plane. The macroscopic magnetization $\mathbf{m}$ that is associated with the spin-polarisation of the ^{3}He atoms produces - outside of a spherical cell containing the ^{3}He gas - a magnetic dipole field that is given by

$$\mathbf{B}_{\text{dipole}}(\mathbf{r}) = \frac{\mu_0}{4\pi}\frac{3\mathbf{r}\,(\mathbf{m}\cdot\mathbf{r}) - \mathbf{m}\cdot \mathrm{r}^2}{\mathrm{r}^5} \quad . \tag{3}$$

When the magnetization precesses around the applied magnetic field $\mathbf{B}_0$ it thus gives rise to a small alternating magnetic field $\mathbf{b}_{\text{He}}(\mathrm{t}) = \mathbf{B}_{\text{dipole}} \cos\omega_{\text{He}}\mathrm{t}$ in the vicinity of the ^{3}He cell which is vectorially added to $\mathbf{B}_0$. The magnetic field at the position of a nearby CsOPM is thus modulated at the ^{3}He's larmor frequency

$$\omega_{\text{He}} = \gamma_{\text{He}}|\mathbf{B}_0 + \mathbf{b}_{\text{He}}(\mathrm{t})| \approx \gamma_{\text{He}}|\mathbf{B}_0 + \hat{\mathrm{B}}_0\cdot\mathbf{b}_{\text{He}}(\mathrm{t})|\,. \tag{4}$$

As a consequence the CsOPMs output signal becomes frequency modulated (FM) by the ^{3}He FID, the FM showing up as sidebands in the Fourier transform of the CsOPM's oscillatory signal. Eq. 4 shows that the Cs magnetometer reading is only sensitive (to first order in $|\mathbf{b}_{\text{He}}|/|\mathbf{B}_0|$) to the projection of $\mathbf{b}_{\text{He}}$ onto $\mathbf{B}_0$. Inspection of Eq. 3 shows that for a spherical cell in the FID-geometry of Figure 3 this projection is maximal when the Cs magnetometer is located on a cone with a half-opening angle of 45° with respect to $\mathbf{B}_0$. Numerical calculations have shown that the 45° condition is also a good approximation for the (60 mm long, 60 mm diameter) cylindrical cell used in the actual experiments. Consequently, the CsOPM was positioned such that the center of the Cs sensor cell was roughly on the 45° cone to maximize the measurement signal. It is equally important to minimize the distance between the CsOPM and the ^{3}He cell since the dipole field drops with $1/\mathrm{r}^3$, as can be seen from Eq. 3. The minimum achievable distance imposed by the sizes of the ^{3}He and Cs cells was $\mathrm{d} = 70\,\mathrm{mm}$. A typical result of a ^{3}He FID measurement is shown as the Fourier transform of the Cs magnetometer's oscillating signal in Figure 4. The displayed FFT spectrum was calculated from a 10 s long chunk of data. The

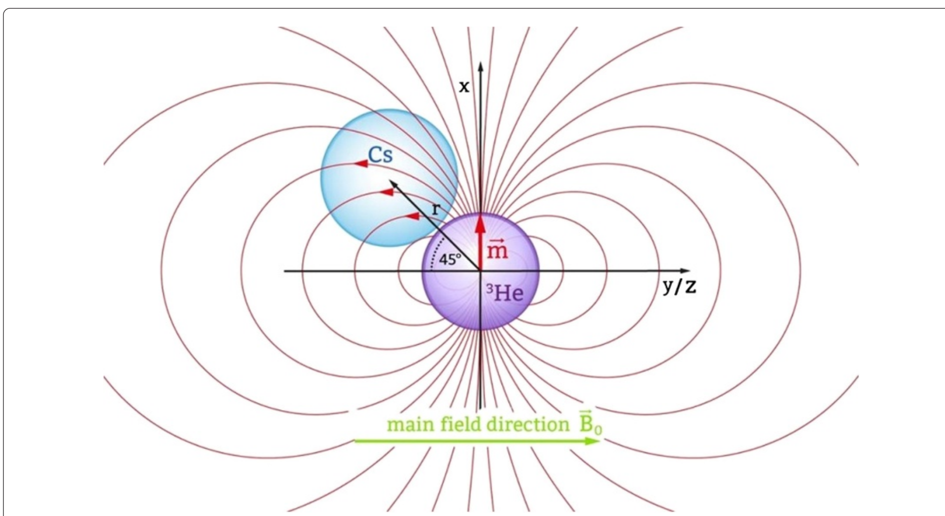

Figure 3 Alternating dipole field produced by the precessing magnetization m of spin polarized ^{3}He atoms around the main magnetic field $\mathbf{B_0}$. The sensor cell of the CsOPM must be positioned as close as possible in a 45° arrangement to maximize the CsOPM signal.

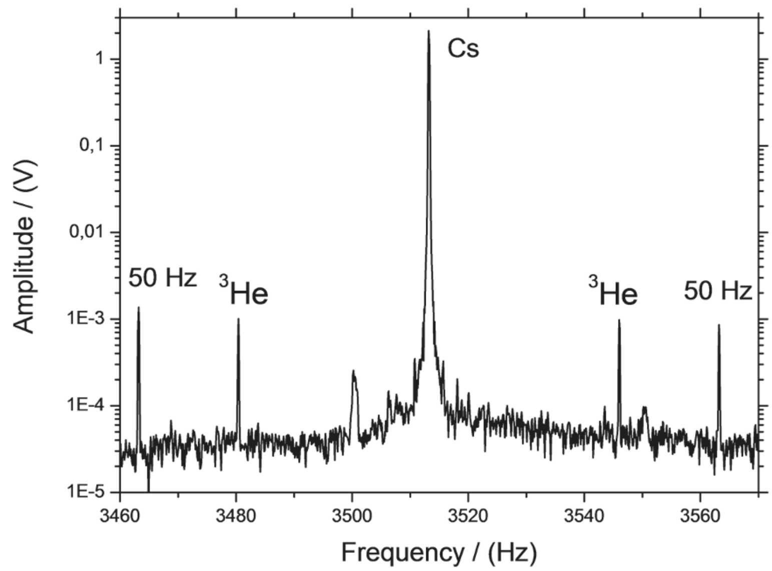

Figure 4 Discrete Fourier spectrum obtained from a 10 second long data sample from the lamp-pumped CsOPM. Peak of carrier frequency at 3513 Hz, sidebands from the ^{3}He FID and 50 Hz sidebands are visible. ^{3}He was polarized in situ and precession occured around the cosine-theta field direction. The output signal of the CsOPM was digitized at a sampling rate of 50 kHz with a resolution of 18 bits.

characteristic carrier and sideband components of the FM signal are clearly visible. The sidebands resulting from the ^{3}He FID are offset by 32.8 Hz with respect to the carrier, each one having an amplitude $A_{He} = 0.1$ mV with a carrier amplitude of $A_{Cs} = 2.2$ V. One can show that [36] the amplitude b_{He} of the oscillatory field produced by the precessing ^{3}He nuclear spins and the characteristic parameters of the Fourier spectrum is given by

$$b_{He} = \frac{4\pi \nu_{He}}{\gamma_{Cs}} \frac{A_{He}}{A_{Cs}} . \quad (5)$$

For the measurement presented in Figure 4, Eq. 5 yields $b_{He} = 8.5$ pT which represents a SNR of about 34 in a bandwidth of 1 Hz. We inferred the T_2^*-time from a measurement of the time dependent decay of the amplitude A_{He}. For different measurements in both the B_{sol} and B_{cos} field configurations spin coherence times of up to one hour were obtained. The feasibility of the new test setup for further investigations of the functionality of an ultra-compact ^{3}He polarizer unit (UCPU) is successfully demonstrated.

Methods

Ultra compact polarizer unit

As mentioned above the main component of the future ^{3}He magnetometer system, the ^{3}He polarizer unit (UCPU) should be able to deliver periodically i.e., every 10-15 min, $\sim$ 16 mbar·l of spin-polarized ^{3}He gas, corresponding to a ^{3}He pressure of about 1 mbar in the two magnetometer vessels that have a total volume of 16 l. The UCPU is an ultra-compact transportable ^{3}He polarizer following several generations of polarizer facilities which were developed at JoGu for medical application respectively fundamental research [37-45]. It has been specifically designed to fulfill the needs of the planned n2EDM experiment at PSI.

As shown in Figures 5 and 6, the working principle of the polarizer can be described as follows. ^{3}He from a high pressure reservoir is fed into the gas system of the polarizer. The pressure inside the system is controlled by a Barocel pressure sensor (item B100 in Figure 5) from the company Edwards Vacuum and a feedback-driven electrically adjustable valve from the company MKS. After purification by means of a getter-based purifier from the company SAES (impurities < ppm), the ^{3}He gas is filled via a specific nonmagnetic valve (item EV in Figure 5) into the optical pumping cells OPZ1 and OPZ2. The EV is a custom-made all-metal construction that is actuated by compressed air. The optical pumping cells consist of two connected borosilicate glass tubes (length 1.1 m, diameter 54 mm) with vacuum tight antireflection-coated (λ =1083 nm) fused silica windows at the ends. The vacuum grease Apiezon H is used as a sealing agent between the fused silica windows and the glass tubes. Specific cover flanges allow differential pumping to prevent capillary cracks in the vacuum grease induced by outer air pressure [36]. The total optical pumping volume is approximately 5 l. The pressure inside the pumping cells is controlled by a second Barocel pressure sensor (item B10 in Figure 5) to ensure efficient optical pumping. Thin stripes of cooper foil at top and bottom of both cells serving as electrodes connected to the power-amplified output of a frequency generator for sustaining a weak discharge in the ^{3}He gas, necessary for MEOP. The light beams enter both pumping cells through a polarizer-$\lambda/4$ plate combination and are back-reflected by dichroic mirrors after the cells’ exit windows. A tunable fiber laser from the company Keopsys with a maximal output power of 5 W (linewidth $\approx$ 2 GHz) is used for optical pumping. The laser is tuned to the C8-line[b] of the ^{3}He line spectrum and its frequency stability can be monitored by measuring the fluorescence light from a small auxilliary ^{3}He reference cell. The linearly polarized laser beam is widened by a beam expander to a diameter of 30 mm to illuminate the whole cross-section of the pumping cells. The light

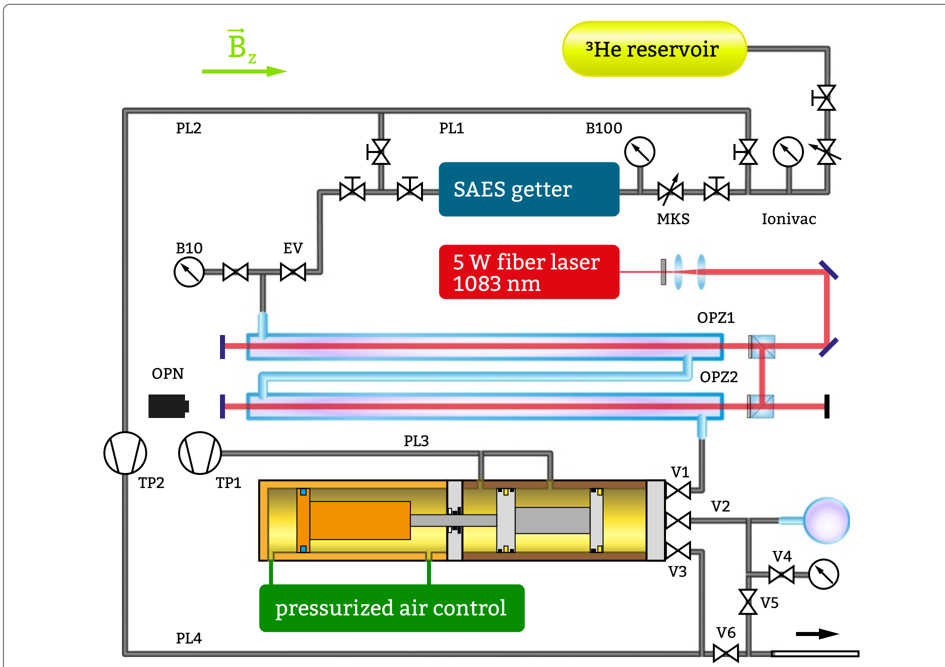

Figure 5 Schematic sketch of the UCPU. Details, see text. Solenoid and magnetic shielding are not shown.

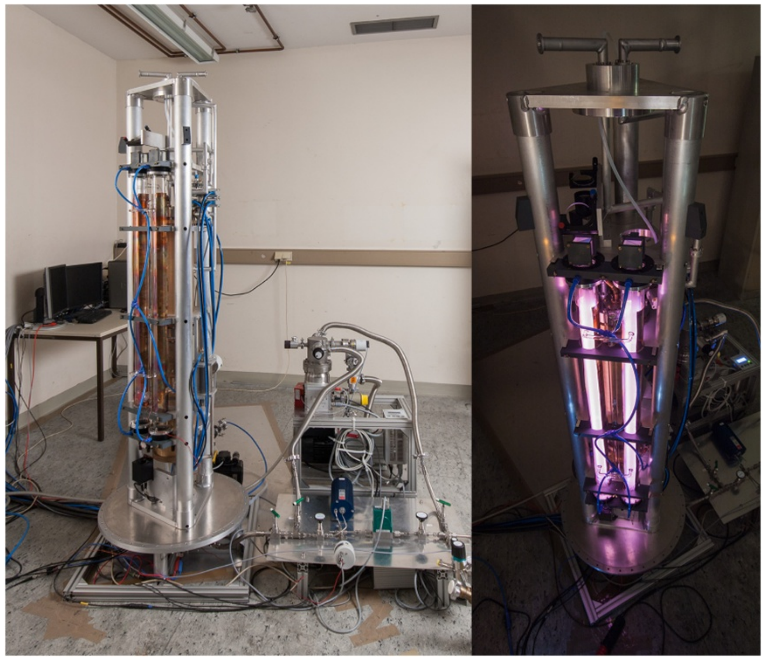

Figure 6 Ultra-compact polarizer (height ≈ 2 m, width of mounting plate 70 × 70 cm^2), gas system and vacuum pumps. Right: Optical pumping cells with ignited discharge.

becomes circularly polarized after passing the PBS and $\lambda/4$ plate and is then sent through the pumping cells. The mirrors at the far ends of the cells have a high reflectivity in the 1083 nm range but high transmission for the 668 nm fluorescence light, providing a low-loss double-passage of the 1083 nm light through each cell while permitting to monitor the degree of ^{3}He spin polarization with an optical polarimeter (OPN) by polarization analysis of the 668 nm fluorescence light. The longitudinal relaxation time T_1 was measured by using the OPN to observe the decay of polarization after switching off the laser. With a burning discharge we find $T_{1,\mathrm{bright}} = 1.5$ min while without gas discharge the measurement yields $T_{1,\mathrm{dark}} = 8$ min. When the nuclear spin polarization of ^{3}He in the optical pumping cells has reached the steady state value of typically 50-55%, a valve (item V1 in Figure 5) is opened to suck out part of the polarized gas into the empty compressor volume of V = 3 l. The piston compressor then pumps the gas into a small storage cell of 0.33 liter volume. The storage cell is made of a special glass mixture GE180 to minimize ^{3}He polarization relaxation during wall collisions [46]. The compressor is built entirely from non-magnetic parts and driven entirely by compressed air. The compressor volume is closed by a head with six vacuum tight valves (items V1-V6 in Figure 5), which open and close the connections between the compressor volume, the optical pumping volume, the storage cell and the vacuum system. All valves are operated by custom-modified compressed air driven actuators from the company Festo. Great care was taken to isolate the ^{3}He gas system from the compressed-air line. In places where compressed air could possibly leak into the ^{3}He circuit, small separation volumes connected to a vacuum pump were introduced to remove any possible leakage flow i.e., item PL3 in Figure 5. All relevant volumes of the system are connected by four tubes (items PL1-PL4 in Figure 5) to two turbo molecular pumps (items TP1 and TP2 in Figure 5) and can be evacuated. During movement of the piston we measure a residual gas pressure as low as 10^{-6} mbar in the compression volume. The UCPU is mounted inside a solenoid coil (length 1.8 m, diameter 0.52 m) which produces a magnetic field of 250 μT at a coil current of 200 mA. In order to minimize stray fields and to improve the homogeneity of the magnetic field the coil is enclosed in a cylindrical single layer mu-metal shield. Additionally, a correction coil is mounted at each of the flat end-caps of the shield to further homogenize the field inside. All components inside the shielding, except the pressure sensors, are manufactured from non-magnetic materials (e.g. titanium, brass, aluminum) to avoid any degradation of the field homogeneity. As a result, the relative magnetic field gradients in the area of the optical pumping volume and the storage cell are below $(\partial B_z/\partial z)/B_z < 3.8 \cdot 10^{-4}\,\mathrm{cm}^{-1}$, where z is the direction along the cylinder axis. The automatic operation of the UCPU is established by a software package written under the LABVIEW environment. The system can work autonomously and no user interaction is required under normal conditions. In various tests the polarizer unit has successfully demonstrated its working performance by periodically delivering polarized and compressed ^{3}He. In a cyclic mode of operation the degree of spin polarization in the optical pumping volume reaches up to 52%, as shown in Figure 7. The losses of polarization occuring during compression into the storage cell are below 1% and thus negligible. We have also demonstrated that the required 16 mbar·l of polarized ^{3}He for the planned magnetometer setup can be produced within an optical pumping time of less than seven minutes (within 9 cycles of 45 s).

Polarization maintaining transfer

Once the polarized ^{3}He is prepared by the UCPU it is delivered to the installed magnetometer vessels using polarization-stabilizing magnetic guiding fields. As shown in

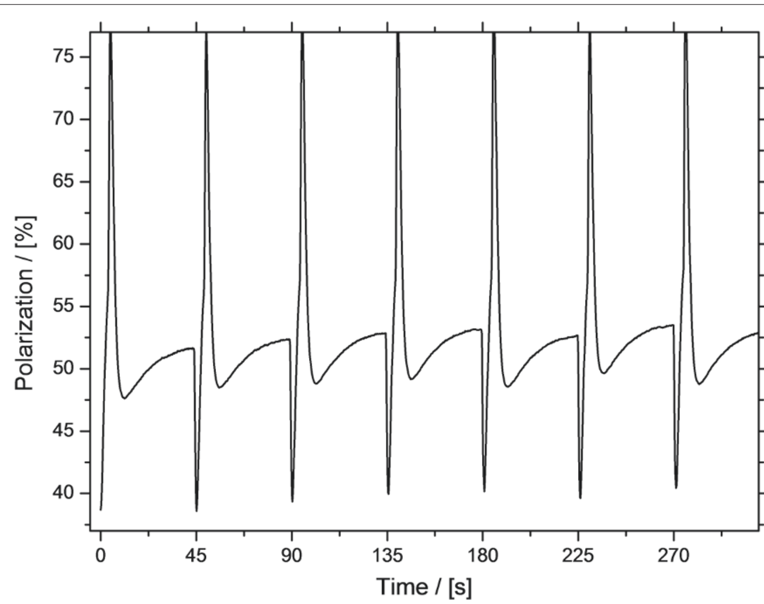

Figure 7 Time course of polarization observed with OPN demonstrating the cyclic operation of the UCPU. The maximum polarization of ≈ 52% is reached seven times in sequence. The sharp peaks are artefacts that result from changes in discharge color and brightness when polarized gas is transferred into the compression volume or when non-polarized gas is filled into the optical pumping volume.

Figure 1, the distance between the polarizer unit and the n2EDM setup is on the order of several meters and may contain a few bended sections. In order to investigate and, if necessary, to optimize polarization losses during transfer, we have installed a demonstration transfer line system consisting of a 6 m long PTFE tube with an inner diameter of 6 mm, as shown in Figure 8. This transfer line connects an outlet valve of the compressor head (see Figure 5, item V5) with a spherical glass cell (GE180, volume $V_{mag} = 0.09\,l$) inside the test setup (see Figure 9, item 3). After injection of the gas the cell is shut off by a separate compressed air driven nonmagnetic valve (see Figure 9, item 2). The main challenge in the polarized gas transfer was to provide a suitable holding field along the transfer line which has two 90° bends. In order to minimize polarization losses by gradient-induced spin-flips, the gradients along the transition from the 250 μT field inside the UCPU's shield to the 1 μT field of the cosine-theta coil in the test facility had to be minimized. Along the vertical parts of the line, above the UCPU and at the transition through the MS, solenoid coils (Figure 8, (1) and (3)) provided these fields. The relative gradients $(\partial B_z/\partial z)/B_z$ were found to be $1 - 6 \cdot 10^{-2}\,\mathrm{cm}^{-1}$ for the first solenoid and $3 - 5 \cdot 10^{-2}\,\mathrm{cm}^{-1}$ for the second respectively, where $\hat{z}$ is the solenoid axis. For the horizontal part of the transfer line Figure 8 (2), a dedicated arrangement of four wires running along each side of the tube was used to generate the required holding field. Field simulations were done to ensure small gradients in the $\hat{x}$ and $\hat{y}$ direction. Measurements of the relative field gradient along the horizontal part of the transfer line yielded $(\partial B_z/\partial x)/B_z \leq 3 \cdot 10^{-3}\,\mathrm{cm}^{-1}$. To quantify the transport losses, 16 mbar·l of ^{3}He with a polarization of about 52% were prepared by

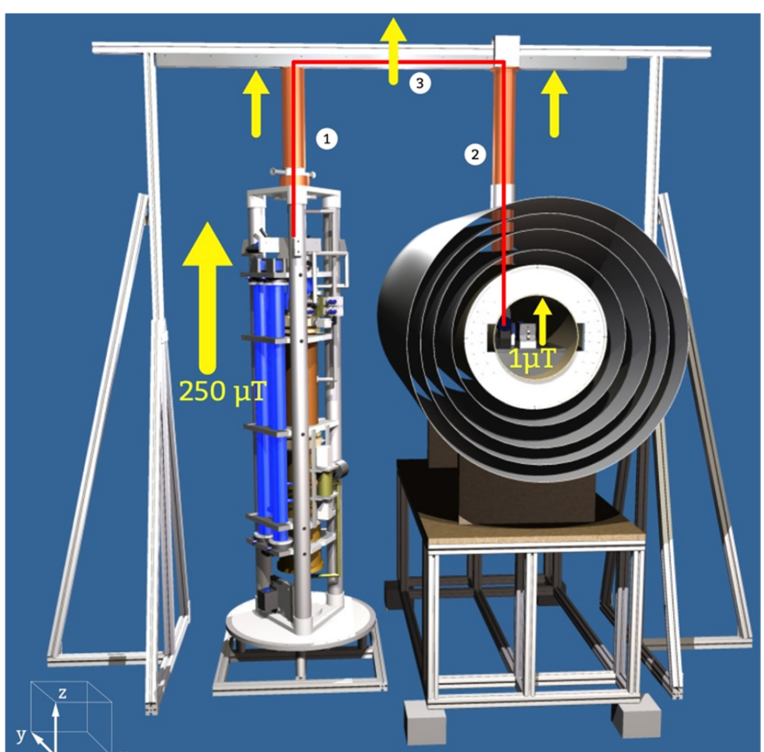

Figure 8 CAD drawing of the transfer setup: The storage cell of UCPU (shown without solenoid coil and shielding) at the left is connected via a transfer line (red) to a magnetometer vessel inside the MS on the right. (1) - (3) Coils to provide polarization conserving guiding fields along the transfer line.

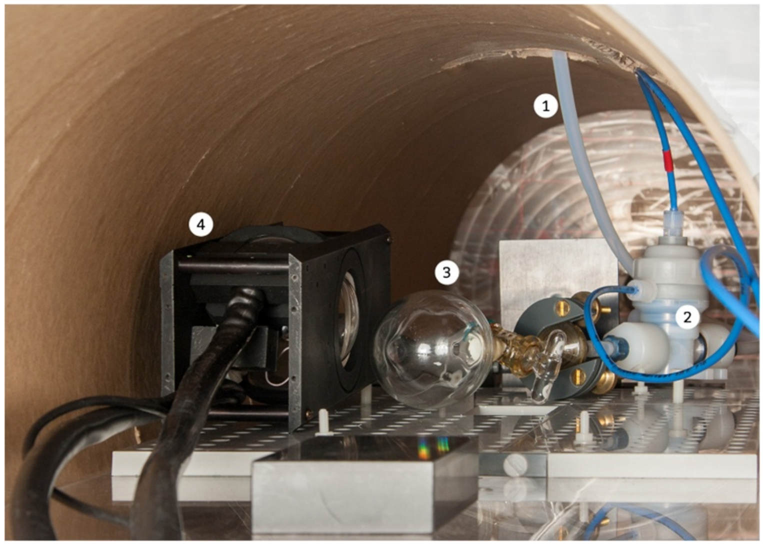

Figure 9 Interior of the MS coil system for transfer measurement. (1) PTFE transfer tube, (2) non-magnetic pressed air driven valve, (3) ^{3}He magnetometer cell and (4) lamp pumped Cs-magnetometer.

the UCPU and filled via the transfer line into the evacuated magnetometer cell. The filling process took less than 0.5 s and yielded an inner cell pressure of approximately 30 mbar. The ^{3}He FID was initiated by a non-adiabatic field switch and the FID was measured as described in Sec.^{3}*He/Cs magnetometer test facility*. The 10 s FFT spectrum of the CsOPM signal shows a ^{3}He amplitude of $A_{He} = 18$ mV with a carrier amplitude of $A_{Cs} = 2,2$ mV (see Figure 10). Using Eq. 5 we infer that the magnetic field seen by the CsOPM is 157 pT,

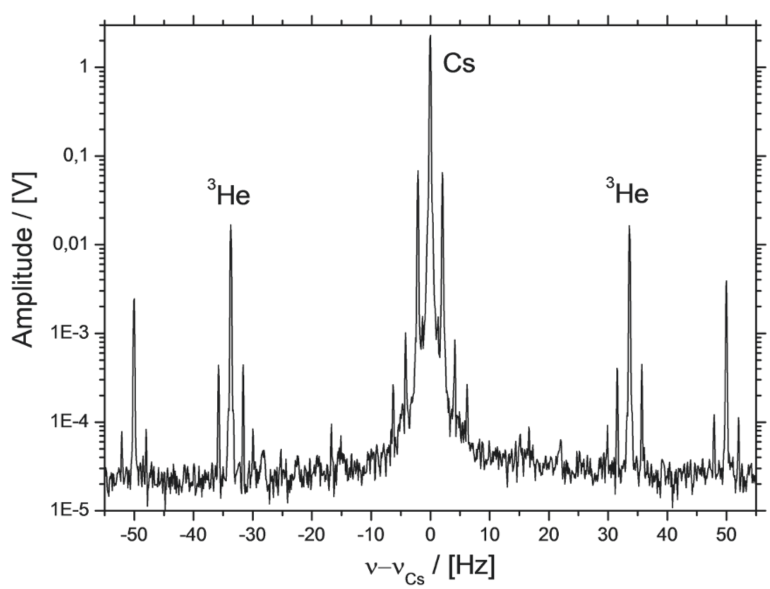

Figure 10 Discrete Fourier spectrum of lamp pumped Cs-magnetometer signal with 30 mbar magnetometer cell pressure and 52% initial polarization. Cs-carrier frequency shifted to zero. Sidebands at ± 32 Hz resulting from ^{3}He FID and 50 Hz perturbations are visible. The small satellite peaks result from vibrations of the setup during measurement.

which corresponds to a SNR of 21 per 1 mbar and 1 Hz bandwidth. Assuming no transfer losses we can estimate the expected field strength from Eq. 3. The magnetic moment m inside the magnetometer cell is given by

$$m = \mu_{He} \, P \, N = \frac{2.127 \mu_K P \, N_A \, p \, V}{R \, T} \, . \tag{6}$$

With a polarization P of 52%, a pressure p of 30 mbar and a volume V of 0.09 l one obtains $m = 3.66 \cdot 10^{-7}\,Am^2$. Assuming that at $t = 0$ the magnetic moments are oriented in the $\hat{x}$-direction and knowing that the centers of the ^{3}He cell and the CsOPM cell are placed in the $\hat{x} - \hat{y}$ plane of the MS coil system on the 45° cone (Figure 3) at a distance r of 70(2)mm the expected ^{3}He magnetic field seen by the CsOPM is $b_{He} = 160(14)$ pT. The difference between the prediction, assuming a lossless transfer, and the measured value is below 10%. From this we expect the transfer losses to be 2.0(9)%.

Conclusion

A test facility for the recording of ^{3}He FID by a lamp-pumped CsOPM was installed at University of Mainz. A compact, transportable ^{3}He polarizer was built and its functionality demonstrated. It was shown that the device is capable of delivering the required amounts of polarized gas for the n2EDM experiment with 52% of spin polarization during cyclic operation. For the first time the transfer of polarized ^{3}He gas from a cyclically working polarizer into a multilayer mu-metal shield, even through a transfer line having two 90° bends, with negligible depolarization was successfully demonstrated. Thus, together with ^{3}He magnetometers made of flat cylindrical cells [22], all essential ^{3}He magnetometer parts (see Figure 1) were built and tested. Further improvements of the magnetometer largely depend on the magnetic field conditions in the next generation nEDM spectrometer (longer ^{3}He transverse relaxation times, lower magnetic field noise, higher SNR in the ^{3}He precession detection). Besides this the construction of a recovery and recycling system for used ^{3}He gas will help to drive the whole magnetometer setup in a more economical way [30]. A detailed analysis of the achievable sensitivity and possible systematic effects in the n2EDM spectrometer with a combined ^{3}He/Cs-magnetometer is ongoing and will be published elsewhere.

Endnotes

[a] list of n2EDM members, see also http://nedm.web.psi.ch.
[b] C8: $2\,^3S_1$, $F = 1/2 \;\rightarrow\; 2\,^3P_0$, $F = 1/2$, $\quad \lambda = 1083,06\,nm$.

Competing interests

The authors declare that they have no competing interests.

Authors? contributions

AK designed and built the apparatus especially the UCPU, carried out the experiments and drafted the manuscript. DN constructed essential parts of the ^{3}He/Cs magnetometer test facility. HCK, TL, DN, AP and YS participated in the experiments. HCK, MD and TL participated in manuscript preparation. WH supervised the described work. WH and AW both gave scientific advises and helped draft the manuscript. All authors read and approved the final manuscript.

Acknowledgement

The described work benefited from the excellent support of the mechanical workshops of the Institute of Physics and the Institute of Nuclear Chemistry of the University of Mainz, especially L. Funke and glassblower R. Jera. We also thank Yu. V. Borisov, Konstantinov Nuclear Physics Institute, St. Petersburg, who did some preliminary studies including prototyping of the flat magnetometer vessels and ^{3}He polarimetry. The research was enabled by the loan of the mu-metal test shield by K. Kirch and B. Lauss, PSI, Switzerland. This work was supported by the DFG under the contract number HE 2308/10-1. We wish to thank M. J. Kraft, Wiesbaden, Germany providing support in the creation of the illustrations.

Author details
[1]Institute of Physics, Johannes Gutenberg University, 55128 Mainz, Germany. [2]Physics Department, University of Fribourg, CH-1700, Fribourg, Switzerland. [3]Institute of Nuclear Chemistry, Johannes Gutenberg University, 55128 Mainz, Germany. [4]Paul Scherrer Institute, CH-5232, Villigen, Switzerland. [5]Ioffe Institute, St Petersburg 194021, Russian Federation. [6]Present address: CENPA, Department of Physics, University of Washington, WA 98195, Seattle, USA. [7]Present address: Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM-II), Lichtenbergstrasse 1, 85748 Garching, Germany. [8]Petersburg Nuclear Physics Institute, Gatchina 188300, Russian Federation.

Received: 3 July 2014 Accepted: 30 July 2014
Published online: 01 October 2014

References

1. Purcell EM, Ramsey NF: **On the possibility of electric dipole moments for elementary particles and nuclei.** *Phys Rev* 1950, **78:**807.
2. Lee TD, Yang CN: **Question of parity conservation in weak interactions.** *Phys Rev* 1956, **104:**254.
3. Wu CS, Ambler E, Hayward RW, Hoppes DD, Hudson RP: **Experimental test of parity conservation in beta decay.** *Phys Rev* 1957, **105:**1413.
4. Garwin RW, Lederman LM, Weinrich M: **Observation of the failure of conservation of parity and charge conjugation in meson decays: the magnetic moment of the free muon.** *Phys Rev* 1957, **105:**1415.
5. Friedman JI, Telegdi VL: **Nuclear emulsion evidence for parity nonconservation in the decay chain $\pi^+ \rightarrow \mu^+ \rightarrow e^+$.** *Phys Rev* 1957, **106:**1290.
6. Smith JH, Purcell EM, Ramsey NF: **Experimental limit to the electric dipole moment of the neutron.** *Phys Rev* 1957, **108:**120.
7. Christenson JH, Cronin JW, Fitch VL, Turley R: **Fundamental aspects weak interaction.** *Phys Rev Lett* 1964, **13:**138.
8. Aubert B, Boutigny D, Gaillard DJM, Hicheur A, Karyotakis Y, Lees JP, Robbe P, Tisserand V, Zghiche A, Palano A, Pompili A, Chen GP, Chen JC, Qi ND, Rong G, Wang P, Zhu YS, Eigen G, Stugu B, Abrams GS, Borgland AW, Breon AB, Brown DN, Button-Shafer J, Cahn RN, Gill MS, Gritsan AV, Groysman Y, Jacobsen RG, Kadel RW, et al.: **Search for T and CP violation in $B^0 - = B^0$ mixing with inclusive Dilepton events.** *Phys Rev Lett* 2002, **88:**231801.
9. Abe K, Abe K, Abe T, Adachi I, Aihara H, Akatsu M, Asano Y, Aso T, Aulchenko V, Aushev T, Bakich AM, Banas E, Bay A, Behera PK, Bizjak I, Bondar A, Bozek A, Bracko M, Brodzicka J, Browder TE, Casey BCK, Chang P, Chao Y, Chen KF, Cheon BG, Chistov R, Choi Y, Choi YK, Danilov M, Dong LY, et al.: **Improved measurement of mixing-induced CP violation in the neutral B meson system.** *Phys Rev D* 2002, **66:**071102(R).
10. Baker CA, Doyle DD, Geltenbort P, Green K, van der Grinten MDG, Harris PG, Iaydjiev P, Ivanov SN, May DJR, Pendlebury JM, Richardson JD, Shiers D, Smith KF: **Improved experimental limit on the electric dipole moment of the neutron.** *Phys Rev Lett* 2006, **97:**131801.
11. Khriplovich IB, Lamoureux SK: *CP Violation Without Strangeness*. Berlin, Heidelberg: Springer; 1997.
12. Pospelov M, Ritz A: **Electric dipole moments as probes of new physics.** *Ann Phys* 2005, **318:**119.
13. Matsuta K, Masuda Y, Hatanaka K, Kawasaki S, Matsumiya R, Mihara M, Jeong SC, Watanabe Y, Adachi T, Nishimura D, Asahi K, Martin JW, Konaka A, Miller A, Bidinosti C, Dawson T, Lee L, Davis CA, Ramsay WD, van Oers WTH, Korkmaz E, Buckman L: **An EDM measurement with a new comagnetometer and a high density UCN source.** *AIP Conf Proc* 2013, **1560:**152.
14. Serebrov AP, Kolomenskiy EA, Pirozhkov AN, Krasnoshekova IA, Vasiliev AV, Polyushkin AO, Lasakov MS, Fomin AK, Shoka IV, Solovey VA, Zherebtsov OM, Geltenbort P, Zimmer O, Ivanov SN, Alexandrov EB, Dmitriev SP, Dovator NA: **New measurements of neutron electric dipole moment.** *arXiv* 2013,1310.5588. [nucl-ex].
15. Zenner J: **The search for the neutron electric dipole moment.** *PhD dissertation*. University of Mainz; 2013.
16. Altarev I, Beck DH, Chesnevskaya S, Chupp T, Feldmeier W, Fierlinger P, Frei A, Gutsmiedl E, Kuchler F, Link P, Lins T, Marino M, McAndrew J, Paul S, Petzoldt G, Pichlmaier A, Stoepler R, Stuiber S, Taubenheim B: **A next generation measurement of the electric dipole moment of the neutron at the FRM II.** *Nuovo Cimento-C* 2012, **35**(4):122.
17. Ito TM: **Plans for a neutron EDM experiment at SNS.** *J Phys: Conference Series* 2007, **69**(1):012037.
18. Anghel A, Atchison F, Blau B, van den Brandt B, Daum M, Doelling R, Dubs R, Duperrex PA, Fuchs A, George D, Gültl L, Hautle P, Heidenreich G, Heinrich F, Henneck R, Heule S, Hofmann T, Kasprzak M, Kirch K, Knecht A, Konter JA, Korhonen T, Kuzniak M, Lauss B, Mezger A, Mtchedlishvili A, Petzoldt G, Pichlmaier A, Reggiani D, Reiser R, et al.: **The PSI ultra-cold neutron source.** *Nucl Instrum Methods Phys Res A* 2009, **611:**133.
19. Altarev I, Bison G, Ban G, Bodek K, Burghoff M, Cvijovic M, Daum M, Fierlinger P, Gutsmiedl E, Hampel G, Heil W, Henneck R, Horras M, Khomutov N, Kirch K, Kistryn S, Knappe-Grüneberge S, Knecht A, Knowles P, Kozela A, Kratz JV, Kuchler F, Kuzniak M, Lauer T, Lauss B, Lefort T, Mtchedlishvili A, Naviliat-Cuncic O, Paul S, Pazgalev AS, et al.: **Towards a new measurement of the neutron electric dipole moment.** *Nucl Instrum Methods Phys Res A* 2009, **611**(2–3):133–136.
20. Altarev I, Bison G, Ban G, Bodek K, Burghoff M, Chowdhuri Z, Daum M, Düsing C, Fertl M, Fierlinger P, Franke B, Grab C, Gutsmiedl E, Hampel G, Heil W, Henneck R, Horras M, Khomutov N, Kirch K, Kistryn S, Knappe-Grüneberg S, Knecht A, Knowles P, Kozela A, Kraft A, Kuchler F, Kratz JV, Lauer T, Lauss B, Lefort T, et al: **An improved measurement of the electric dipole moment of the neutron.** *Nucl Phys A* 2010, **844**(1–4):47C.
21. Altarev IS, Borisov Yu V, Brandin AB, Egorov AI, Ezhov VF, Ivanov SN, Lobashov VM, Nazarenko VA, Porsev GD, Ryabov VL, Serebrov AP, Taldaevet RR: **A search for the electric dipole moment of the neutron using ultracold neutrons.** *Nucl Phys A* 1980, **341**(2):269.
22. Borisov Y, Heil W, Leduc M, Lobashev V, Otten EW, Sobolev Yu: **Feasibility study of a ^{3}He-magnetometer for neutron electric dipole moment experiments.** *Nucl Instrum Methods Phys Res A* 2000, **440**(3):483.
23. Pendlebury JM, Heil W, Sobolev Yu, Harris PG, Richardson JD, Baskin RJ, Doyle DD, Geltenbort P, Green K, van der Grinten MGD, Iaydjiev PS, Ivanov SN, May DJR, Smith KF: **Geometric-phase-induced false electric dipole moment signals for particles in traps.** *Phys Rev A* 2004, **70:**032102.

24. Gemmel C, Heil W, Karpuk S, Lenz K, Ludwig Ch, Sobolev Yu, Tullney K, Burghoff M, Kilian W, Knappe-Grüneberg S, Müller W, Schnabel A, Seifert F, Trahms L, BaeÎer St: **Ultra-sensitive magnetometry based on free precession of nuclear spins.** *Eur Phys J D* 2010, **57**(3):303–320.
25. Cohen-Tanudji C, DuPont-Roc J, Haroche S, Laloë F: **Detection Of the static magnetic field produced by the oriented nuclei of optically pumped ^{3}He gas.** *Phys Rev Lett* 1969, **22**(15):758–760.
26. Groeger S: **Laser-pumped cesium magnetometers for the PSI-nEDM experiment.** *PhD. dissertation*. University of Fribourg; 2005.
27. Groeger S, Bison G, Schenker J-L, Wynands R, Weis A: **A high-sensitivity laser-pumped M_x magnetometer.** *Eur Phys J D* 2006, **38:**239.
28. Knowles P, Bison G, Castagna N, Hofer A, Mtchedlishvili A, Pazgalev A, Weis A: **Laser-driven Cs magnetometer arrays for magnetic field measurement and control.** *Nucl Instrum Methods Phys Res A* 2009, **611**(2-3):306.
29. Cates GD, Schaefer SR, Happer W: **Relaxation of spins due to field inhomogeneities in gaseous samples at low magnetic fields and low pressures.** *Phys Rev A* 1988, **37**(8):2877–2885.
30. Zimmer St: **Optimierung und Charakterisierung eines ^{3}He Magnetometers fuer nEDM-Experimente.** *Diploma thesis*. University of Mainz; 2013.
31. Brys T, Czekaj S, Daum M, Fierlinger P, George D, Henneck R, Kasprzak M, Kirch K, Kuzniak M, Kuehne G, Pichlmaier A, Siodmok A, Szelc A, Tanner L, Assmann C, Bechstein S, Drung D, Schurig Th, Ciofi C, Neri B: **Magnetic field stabilization for magnetically shielded volumes by external field coils.** *Nucl Instrum Methods Phys Res* 2005, **554**(1–3):527–539.
32. Kubo S, Sasada I, Harada K: **Effective shielding for low?level magnetic fields.** *J Appl Phys* 1988, **64**(10):5696–5698.
33. Happer W: **Optical pumping.** *Rev Modern Phys* 1972, **44:**169–250.
34. Hasse J: **Charakterisierung und Optimierung eines ^{3}He-Kompressors.** *Diploma thesis*. University of Mainz; 2000.
35. Groeger S, Pazgalev AS, Weis A: **Comparison of discharge lamp and laser pumped cesium magnetometers.** *Appl Phys B* 2005, **80**(6):645.
36. Kraft A: **Aufbau und Inbetriebnahme eine hochsensitiven ^{3}He-Magnetometers fuer ein zukuenftiges Experiment zu Bestimmung eines elektrischen Dipolmoments des freien Neutrons.** *PhD. dissertation*. University of Mainz; 2012.
37. Becker J, Heil W, Krug B, Leduc M, Meyerhoff M, Nacher PJ, Otten EW, Prokscha Th, Schearer LD, Surkau R: **Study of mechanical compression of spin-polarized ^{3}He gas.** *Nucl Instrum Methods Phys Res Sect A* 1994, **346**(1–2):45–51.
38. Ebert M, Grossmann T, Heil W, Otten EW, Surkau R, Thelen M, Leduc M, Bachert P, Knopp MV, Schad LR: **Nuclear magnetic resonance imaging with hyperpolarised helium-3.** *The Lancet* 1996, **347**(9011):1297–1299.
39. Surkau R, Becker J, Ebert M, Grossmann T, Heil W, Hofmann D, Humblot H, Leduc M, Otten EW, Rohe D, Siemensmeyer K, Steiner M, Tasset F, Trautmann N: **Realization of a broad band neutron spin filter with compressed, polarized ^{3}He gas.** *Nucl Instrum Methods Phys Res A* 1997, **384**(2–3):444–450.
40. Deninger AJ, Eberle B, Ebert M, Grossmann T, Heil W, Kauczor H, Lauer L, Markstaller K, Otten E, Schmiedeskamp J, Schreiber W, Surkau R, Thelen M, Weiler N: **Quantification of regional intrapulmonary oxygen partial pressure evolution during apnea by ^{3}He MRI.** *J Magn Reson* 1999, **141**(2):207–216.
41. Ebert M: **Entwicklung eines leistungsstarken Polarisators und Kompressors fuer ^{3}He fuer medizinische MR Tomographie.** *Ph. D. dissertation*. University of Mainz; 2000.
42. Schmiedeskamp J: **Weiterentwicklung einer Produktionsanlage und der Speicherungs- bzw. Transportkonzepte fuer hochpolarisiertes ^{3}He, Anwendungen in Kernspintomographie und physikalischer Grundlagenforschung.** *PhD. dissertation*. University of Mainz; 2004.
43. Thien F, Friese M, Cowin G, Maillet D, Wang D, Galloway G, Brereton I, Robinson PJ, Heil W, Thompson B: **Feasibility of functional magnetic resonance lung imaging in Australia with long distance transport of hyperpolarized helium from Germany.** *Respirology* 2008, **13**(4):599–602.
44. Krimmer J, Distler M, Heil W, Karpuk S, Kiselev D, Salhi Z, Otten EW: **A highly polarized ^{3}He target for the electron beam at MAMI.** *Nucl Instrum Methods Phys Res A* 2009, **611**(1):18–24.
45. Tullney K, Allmendinger F, Burghoff M, Heil W, Karpuk S, Kilian W, Knappe-Grüneberg S, Müller W, Schmidt U, Schnabel A, Seifert F, Sobolev Yu, Trahms L: **Constraints on spin-dependent short-range interaction between nucleons.** *Phys Rev Lett* 2013, **111**(1–5):100801.
46. Schmiedeskamp J, Heil W, Otten EW, Kremer RK, Simon A, Zimmer J: **Paramagnetic relaxation of spin polarized ^{3}He at bare glass surfaces.** *Eur Phys J D* 2006, **38**(3):427–438.

doi:10.1140/epjti/s40485-014-0008-0
Cite this article as: Kraft *et al.*: Development of a ^{3}He magnetometer for a neutron electric dipole moment experiment. *EPJ Techniques and Instrumentation* 2014 **1**:8.