Particle Physics with Cold and Ultra-Cold Neutrons

681. WE-Heraeus-Seminar

October 24 - 26, 2018
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation which supports research and education in science, especially in physics. A major activity is the organization of seminars. By German physicists the foundation is recognized as the most important private funding institution in their fields. Some activities of the foundation are carried out in cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft).

Aims and scope of the 681. WE-Heraeus-Seminar:

New physics beyond the standard model is required to understand many unexplained features both of particle physics and of cosmology. So when we search for phenomena beyond today's standard model it should be done where the discovery potential is highest. This WE-Heraeus Seminar will serve as a forum to discuss the prospects of particle physics with cold and ultra-cold neutrons, where it complements direct LHC-searches at the other end of the energy scale.

This WE-Heraeus seminar is intended as a focused 2.5 day seminar with time for intensive discussions. The programme covers all contemporary major areas of the field of particle physics with neutrons with a focus on

- Neutron Lifetime,
- Neutron Decay Correlations,
- Neutron Electric Dipole Moment,
- Quantum Interference and Gravitational Bound States.

An emphasis is put on recent results and upcoming experiments and facilities. Overview and theory talks will introduce the different subjects, discuss the potential reach, impact and experimental challenges.

Slides and conference Material: https://indico.ph-tum.de/event/4020
Password: ultra-cold-2018

Scientific Organizers:

Prof. Hartmut Abele — Technische Universität Wien, Austria
E-mail: abele@ati.ac.at

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Program

Program

Tuesday, October 23, 2018

16:00 – 21:00	Registration	
18:00	*BUFFET SUPPER and get-together*	

Wednesday, October 24, 2018

08:00 – 09:00	*BREAKFAST*	
09:00 – 09:05	Scientific organizers	**Welcome words**
09:05 – 09:20	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**

<u>Introduction and Neutron Lifetime</u>

09:20 – 10:20	Dirk Dubbers	**The role of neutrons in particle physics and cosmology**
10:20 – 10:50	*COFFEE BREAK*	
10:50– 11:50	Chen-Yu Liu	**A modern measurement of the neutron lifetime using ultracold neutrons in a magneto-gravitational trap**

<u>Electric Dipole Moment</u>

11:50 – 12:50	Vincenzo Cirigliano	**Electric dipole moments as probes of new physics**
12:50	*LUNCH*	

Program

Wednesday, October 24, 2018

<u>Electric Dipole Moment</u>

14:30 – 15:30	Stéphanie Roccia	**Efforts towards the measurement of the neutron EDM at PSI**
15:30 – 16:30	Peter Fierlinger	**Next generation experiments to measure the neutron electric dipole moment of the neutron**
16:30 – 17:00	*COFFEE BREAK*	

<u>Quantum Interference & Gravitational Bound States</u>

17:00 – 17:45	René Sedmik	**The quantum bouncing ball gravity spectrometer qBounce**
17:45 – 18:30	Stephan Sponar	**Weak values and weak measurements studied in neutron interferometry**
19:00	*DINNER*	

Program

Thursday, October 25, 2018

08:00 – 09:00	*BREAKFAST*	

<u>Correlation Coefficients</u>

09:00 – 10:00	Martín González-Alonso	**New physics searches in nuclear and neutron ß-decay**
10 :00 – 11:00	Leah Broussard	**Neutron decay correlations program in the US**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:30	Heiko Saul	**Correlation coefficients in neutron beta decay**
12:30 – 12:40	*Conference Photo (in the front of the lecture hall)*	
12:40	*LUNCH*	
14:00 – 15:00	**Poster Flash**	
15:00 – 17:00	**Poster Session** *and COFFEE*	

<u>Lattice QCD</u>

17:00 – 18:00	Evan Berkowitz	**The nucleon axial coupling from QCD**
18:30	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Friday, October 26, 2018

08:00	*BREAKFAST*	

<u>Heavy Flavour</u>

09:00 – 10:00	David Straub	**New physics searches with heavy flavours**
10 :00 – 11:00	Stephanie Hansmann-Menzemer	**Experimental highlights on heavy flavour physics**
11:00 – 11:30	*COFFEE BREAK*	

<u>Particle Physics at ESS</u>

11:30 – 12:15	Torsten Soldner	**Opportunities for particle physics with neutrons at the European spallation source**
12:15 – 12:30	Scientific organizers	**Closing words**
12:30	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Saturday morning

Posters

Posters

Karina Bernert	**A new detector for Beta spectroscopy with PERKEO III**
Stefan Bodmaier	**The vacuum pump system of PERC**
Armin Danner	**Observation of spin-rotation coupling in neutron optics**
Skyler Degenkolb	**A scalable approach to measure the neutron EDM with multiple storage cells**
Victor Ezhov	**Systematics in neutron lifetime measuring experiments with UCN magnetic storage**
Valery Fedorov	**Study of neutron fundamental properties in the perfect crystal optics and diffraction**
Robert Golub	**Search for an electric dipole moment of the neutron using superfluid Helium4**
Alexander Hollering	**Neutron optics for neutron beta decay studies with (PERC)**
Michael Huber	**Neutron spin-orbit states: Procedures for their generation and detection**
Jürgen Klepp	**What about next-generation cold-neutron interferometers?**
Michael Klopf	**Neutron decay and dark matter**
Ekaterina Korobkina	**nEDM@SNS as a new milestone in neutron EDM experimental technique**
Hartmut Lemmel	**Neutron interferometry and USANS Setup S18 at ILL**
Egor Lychagin	**Development of a new neutron source at JINR**

Posters

Jakob Micko René Sedmik	**Ramsey gravity resonance spectroscopy with ultracold neutrons**
Christoph Morkel	**Optical observations of hydrogen and deuterium crystal growth and their implications for ultracold neutron transmission experiments**
Yuri Pokotilovski	**Experimental investigation of the low molecular weight fluoropolymer for the ultracold neutrons storage**
Ulrich Schmidt	**A new limit of the ^{129}Xenon electric dipole moment**
Dmitrii Shapiro	**Search for the new short-range interaction by the neutron scattering technique**
Kylyshbek Turlybekuly	**On measurement of the neutron decay in a Helium vessel**
Kirill Zhernenkov	**The effect of nanodiamond fluorination on quasi-specular reflection of cold neutrons**

Abstracts of Talks

(in chronological order)

The role of neutrons in particle physics and cosmology

Dirk Dubbers

Physikalisches Institut der Universität Heidelberg

In my talk I shall present some personal views on the development of neutron-particle physics, up to this day and beyond, which will include also a look on competing methods other than neutron physics.

A Modern Measurement of the Neutron Lifetime Using Ultracold Neutrons in a Magneto-gravitational Trap

Chen-Yu Liu*
Center for Exploration of Energy and Matter and Physics Department, Indiana University, Bloomington, IN 47405
(Dated: October 24, 2018)

The mean neutron lifetime is an important observable in nuclear and particle physics and cosmology. The decay rate is a key input for predicting the helium abundance in the primordial universe and, together with measurements of neutron decay asymmetries, is used to search for new physics beyond the Standard Model of particle physics. For the past decade, there exists a 3.9 standard deviation discrepancy between neutron lifetimes measured by counting the decay rate of free neutrons in a beam (887.7 $\pm$ 2.2 s) and by counting surviving ultracold neutrons stored for different storage times in a material bottle (878.5 $\pm$ 0.8 s). I will describe the UCNtau experiment, which is designed to eliminate the loss mechanisms present in previous material bottle experiments by levitating polarized ultracold neutrons above the surface of a magnetic trap. This asymmetric trap facilitates the phase-space mixing, such that neutrons in quasi-stable orbits rapidly exit the trap. An *in-situ* neutron detector operated in a multi-step counting scheme enables spectral monitoring and constrains the possible systematic effect due to insufficient spectral cleaning and microphonic heating. As a result of this approach, the lifetime reported 877.7 $\pm$ 0.7 (stat) +0.3/-0.1 (sys) s [Science May 2018] is the first modern measurement of neutron lifetime that does not require corrections larger than the quoted uncertainties.

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Electric dipole moments as probes of new physics

V. Cirigliano

[1]*Los Alamos National Laboratory, MS B283, Los Alamos, NM 87545, USA*

I will discuss the theoretical framework for the interpretation of searches of permanent electric dipole moments (EDMs) of the neutron and other systems. I will discuss the discovery potential and physics reach of these searches, their complementarity in probing new sources of time-reversal violation, and their impact on properties of heavy particles such as the Higgs boson and the top quark, which are being directly probed at the Large Hadron Collider.

Efforts towards the measurement of the neutron EDM at PSI

S. Roccia[1], **on behalf of the nEDM collaboration**[2]

[1]*CSNSM, Orsay, France*
[2] *http://nedm.web.psi.ch/*

The quest for a non-zero electric dipole moment (EDM) in a non-degenerate system such as the neutron is a powerful way to search for CP violation in physics beyond the standard model. It is also a unique probe to test the electroweak baryogenesis.

So far, no evidence for such an intrinsic property was observed, neither for the neutron nor for any other system.

After a long and successful data taking at the ILL, where the best upper limit on the neutron EDM was established in 2006, the RAL/Sussex/ILL apparatus was moved to PSI in 2009. It was upgraded and used by a collaboration of 15 institutions until late 2017. The collected data set is the most sensitive one and the analysis is ongoing.

I will discuss some of the most recent technical developments and their impact on both the sensitivity and the control of the systematic effects. I will also present the improvement of the magnetic field homogeneity.

Additionally, I will present the design of the n2EDM spectrometer under construction at PSI. I will show how this new generation spectrometer is based on the technical expertise which our collaboration has gained during the first phase of the experiment.

Next generation experiments to measure the neutron electric dipole moment of the neutron

P. Fierlinger[1]

[1]*TU München, Garching, Deutschland*

Since several decades people search for the electric dipole moment (EDM) of the neutron, an unambiguous manifestation of parity (P) and time reversal symmetry (T) violation. Assuming the conservation of CPT, T violation in a fundamental system also means CP violation. This has only been observed in very few systems in the Standard Model of particle physics (SM) as a tiny effect. However, it would be needed in much larger quantities to help explain the matter-antimatter asymmetry in the Universe. With a long history of innovation and persistence, the neutron EDM is now limited to $d_n < 3 \cdot 10^{-26}$ e·cm, an extraordinarily small number, corresponding to an energy resolution of 10^{-22} eV. As a complementary system among a variety of possible options, it is still a very promising candidate due to its comparably simple composition, needed to understand the underlying fundamental physical processes. In this talk I will discuss experimental efforts and challenges to develop a next generation of neutron EDM searches, with one focus on magnetic fields and their implications for other precision experiments, as well as a new possibility to reach a sensitivity of 10^{-29} e·cm with existing neutron beams.

The Quantum Bouncing Ball Gravity Spectrometer qBounce

R. I.P. Sedmik[1], J. Bosina[1], P. Geltenbort[2], T. Jenke[2], J. Micko[2], M. Pitschmann[1], T. Rechberger[1], and H. Abele[1]

[1]TU Wien, Atominstitut, Vienna, Austria
[2] Institut Laue Langevin, Grenoble, France

Despite the consistency and success of both the standard model of particle physics (SM) and general relativity separately, the unification of these theories seems out of sight – a fact rising concern that our present understanding of the universe is incomplete. Further indications for this incompleteness are the significant over-estimation (by 120 orders of magnitude) of the observed value of the vacuum energy density by the SM, and the presence of gravitating dark matter of unknown composition. Many theories have been developed to explain dark energy and dark matter, sparking a wave of new experiments to exclude or set limits on the parameters of these theories.
In this context, ultracold neutrons (UCN) seem ideal test particles, as with their vanishing electric charge and polarizability they avoid many problems usually plaguing experiments aiming to detect deviations from Newton's law at sub-mm separations.
Over the past decade, the qBounce collaboration has developed an instrument that measures the evolution and interference of UCN wave functions in the gravitational potential of the Earth. Starting from measurements of the quantum bouncing ball, the setup was continually enhanced. The non-equidistant peV-level energies of UCN bouncing on a horizontal plane translate to frequencies in the acoustic range, which enabled us to realize the first implementation of Rabi spectroscopy with mechanical excitation: gravity resonance spectroscopy (GRS). Using Rabi-GRS, qBounce was able to give competitive limits on dark energy forces (chameleon, symmetron) as well as axionic dark matter interactions. The quest for the highest possible precision naturally leads to an extension to Ramsey spectroscopy. This technique, known very well from EDM, NMR, and other measurements promises (despite its increased technical complexity) to reach the frontier regarding limits on hypothetical interactions again with qBounce.
In this talk, we give a review of the progress made with qBounce over the past decade, show recent results of Rabi-GRS, and, for the first time, present a proof of principle for Ramsey-GRS.

Weak Values and Weak Measurements studied in Neutron Interferometry

S. Sponar [1] and Y. Hasegawa[1,2]

[1]Atominstitut - TU Wien, Vienna, Austria
[2] Department of Applied Physics, Hokkaido University, Kita-ku, Sapporo, Japan

Weak measurements, introduced exactly 30 years ago, underwent a metamorphosis from a theoretical curiosity to a powerful resource for exploring foundations of quantum mechanics, as well as a practical laboratory tool. However, unlike in the original textbook experiment, where an experiment with massive particles is proposed, experimental applications are realized applying photonic systems. We have overcome this gap by developing a new method to weakly measure a massive particle's spin component. Our neutron optical approach is realized by utilizing neutron interferometry, where the neutron's spin is coupled weakly to its spatial degree of freedom [1]. This scheme was then applied to study a new counter-intuitive phenomenon, the so-called quantum Cheshire Cat: If a quantum system is subject to a certain pre- and post-selection, it can behave as if a particle and its property are spatially separated, which is demonstrated in an experimental test [2,3]. State tomography, the usual approach to reconstruct a quantum state, involves a lot of computational post-processing. So in 2011 a novel more direct method was established using weak measurements. Because of this weakness the information gain is very low for each experimental run, so the measurements have to be repeated many times. Our procedure is based on the method established in 2011, without the need of computational post processing, but at the same time uses strong measurements, which makes it possible to determine the quantum state with higher precision and accuracy. We performed a neutron interferometric [4] experiment, but our results are not limited to neutrons, but are in fact completely general. In our latest experiment [5] we investigated the paths taken by neutrons in a three-beam interferometer by means of which-way measurements, realized by a partial energy shift of the neutrons so that faint traces are left along the beam path. Final results give experimental evidence that the (partial) wave functions of the neutrons in each beam path are superimposed and present in multiple locations in the interferometer.

References

[1] S. Sponar, T. Denkmayr, H. Geppert, H. Lemmel, A. Matzkin, J. Tollaksen, and Y. Hasegawa, *Phys. Rev. A* **92**, 062121 (2015).

[2] T. Denkmayr, H. Geppert, S. Sponar, H. Lemmel, A. Matzkin, J. Tollaksen, and Y. Hasegawa *Nat. Commun*. **5**, 4492 (2014).

[3] S. Sponar, T. Denkmayr, H. Geppert, and Y. Hasegawa., *Atoms* **4**, 11 (2016).

[4] T. Denkmayr, H. Geppert, H. Lemmel, M. Waegell, J. Dressel, Y. Hasegawa, and S. Sponar., *Phys. Rev. Lett.* **118**, 010402 (2017).

[5] H. Geppert,T. Denkmayr, S. Sponar, H. Lemmel, T. Jenke, and Y. Hasegawa., *Phys. Rev. A* **97**, 052111 (2018).

New physics searches in nuclear and neutron β decay

Martín González-Alonso
Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland

I will discuss what kind of new phenomena can be probed through precision measurements in nuclear and neutron beta decays. Using a model-independent description I will review the interplay between the different experiments and which ones are the most sensitive and promising. I will discuss the synergy with searches at high-energy colliders, such as the LHC, and with other electroweak precision observables. The talk will be based on Ref. [1] and other previous works, such as Ref. [2, 3].

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[1] M. Gonzlez-Alonso, O. Naviliat-Cuncic and N. Severijns, arXiv:1803.08732 [hep-ph], Prog. Part. Nucl. Phys. (in press).
[2] T. Bhattacharya *et al.*, Phys. Rev. D **85**, 054512 (2012);
[3] V. Cirigliano, M. González-Alonso, M. L. Graesser, JHEP **1302** (2013) 046.

Neutron Decay Correlations Program in the US

L. J. Broussard[1]

[1]Oak Ridge National Laboratory, Oak Ridge TN, USA

By measuring the correlation coefficients which characterize the beta decay of the neutron, we can precisely test our understanding of the weak interaction, probe for non-Standard Model contributions to the weak interaction such as from right-handed or scalar/tensor couplings, and search for violations of time-reversal symmetry [1]. A vigorous program targeting neutron decay correlations as a broader framework of fundamental neutron physics research has been built in the United States using reactor and spallation neutron sources at three national laboratories. The National Institute for Standards and Technology has produced leading measurements of the T-violating triple-correlation D in the emiT experiment using a highly symmetric detector array [2] and the beta-neutrino correlation a with the aCORN spectrometer [3], which has high sensitivity to the ratio of the weak axial-vector and vector form factors, $\lambda=g_A/g_V$. Los Alamos National Laboratory is the first to use ultracold neutrons to measure correlations coefficients: the UCNA experiment has recently produced a competitive determination of the beta-asymmetry parameter A [4], which is also highly sensitive to λ, and has established the first direct limits on a possible Fierz interference term b in neutron decay [5]. Next-generation versions for these experiments will probe for new physics with higher precision and access other correlation coefficients sensitive to non-Standard couplings. Oak Ridge National Laboratory is now staging a new experimental effort to determine the λ with the highest precision yet from the a coefficient, as well as place more stringent limits on the Fierz term b, in the Nab experiment [6]. Nab will utilize a 7 m long asymmetric spectrometer to precisely extract the decay proton time of flight and electron energy. I will review the recent progress in correlation coefficient measurements at these facilities and discuss the future sensitivity of planned efforts.

References

[1] M. González-Alonso, O. Naviliat-Cuncic, and N. Severijns, arXiv:1803.08732 (2018)
[2] T. E. Chupp *et al*, Phys. Rev. C **86**, 035505 (2012)
[3] G. Darius *et al*, Phys. Rev. Lett **119**, 042502 (2017)
[4] M. Brown *et al*, Phys. Rev. C **97**, 035505 (2018)
[5] K. P. Hickerson *et al*, Phys. Rev. C **96**, 059901 (2017)
[6] D. Počanić *et al*, Nucl. Instrum. Meth. A **611**, 211-215 (2009)

Correlation Coefficients in Neutron Beta Decay

H. Saul[1,2]

[1]Physik Department ENE, TU Munich, Germany
[2]Atominstitut, TU Vienna, Austria

Within the standard model of particle physics semi-leptonic weak decay is described by only two free parameters, the ratio of nucleon vector and axial vector couplings, λ, and the first element of the CKM-matrix V_{ud}. Due to the absence of nuclear structure, neutron beta decay is an ideal probe to test the structure of the weak interaction. Several correlation coefficients are accessible experimentally. In addition to the precise determination of λ, this also allows to test for potential couplings not predicted by the Standard Model especially when combined with other beta decay measurements.
In this talk I will give an overview of recent and future measurements of correlation coefficients in Europe. The neutron decay spectrometer PERKEO III has performed the most precise measurement the Beta Asymmetry A which also is the most precise measurement of the nucleon axial coupling. An independent determination of λ can be performed by measuring the Electron Neutrino Angular Correlaton a, which has been measured with the aSPECT spectrometer. Both measurements have been carried out at the PF1B beamsite at the Institut Laue-Langevin, Grenoble. The Proton Electron Radiation Channel (PERC) is a next generation instrument for Neutron Decay studies and allows to utilise different detector concepts dedicated to individual observables. PERC will be set up at the new MEPHISTO beamline at the FRM2 and aims to improve the precision of several correlation coefficients by one order of magnitude.

The Nucleon Axial Coupling from QCD

Evan Berkowitz
The CalLat Collaboration

Institut für Kernphysik & Institute for Advanced Simulation
Forschungszentrum Jülich
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The axial coupling of the nucleon, $g_A = 1.2723(23)$, is the strength of its coupling to the weak axial current of the Standard Model. It dictates the rate at which neutrons decay into protons, the strength of the attractive long-range force between nucleons, and other features of nuclear physics. To disentangle Standard Model effects from new physics, precision tests of the Standard Model in nuclear environments require a quantitative understanding of nuclear physics rooted in QCD.

The nucleon axial coupling has long been considered a critical benchmark for lattice QCD, and yet proved substantially more challenging to calculate than expected. I will describe our recent percent-level calculation, $g_A = 1.271(13)$, and how our method differs from existing approaches. I will discuss what is required for a calculation that can discriminate between existing experimental results.

References

[1] C.C. Chang *et al.*, "A per-cent-level determination of the nucleon axial coupling from Quantum Chromodynamics", *Nature*, 558:91-94, 2018, DOI:10.1038/s41586-018-0161-8. arXiv:1805.12130.

[2] Berkowitz *et al.*, "An Accurate Calculation of the Nucleon Axial Charge with Lattice QCD", 2017. arXiv:1704.01114.

New Physics Searches with Heavy Flavours

D. M. Straub[1]

[1]*Excellence Cluster Universe, TUM, Boltzmannstr. 2, 85748 Garching, Germany*

Searches for new physics in decays of b-flavoured hadrons have revealed a number of tantalizing deviations from the Standard Model expectations in recent years. I will give an overview of the current status of these “anomalies”, discuss their implications for new physics models, and discuss possible correlations with new physics searches in processes with light flavours.

References

[1] Aebischer, Bobeth, Buras, Straub, (arXiv:1808.00466 [hep-ph])
[2] Jung, Straub (arXiv:1801.01112 [hep-ph])
[3] Altmannshofer, Stangl, Straub Phys.Rev. D**96** (2017) no.5, 055008 (arXiv:1704.05435)
[4] Altmannshofer, Niehoff, Stangl, Straub, Eur.Phys.J. C**77** (2017) no.6, 377 (arXiv:1703.09189)

Experimental Highlights on Heavy Flavour Physics

S. Hansmann-Menzemer

Physikalisches Institut, Heidberg University,
INF 226, 69120 Heidelberg, Germany

The talk will present selected measurements, results and prospects in the area of Heavy Flavour Physics at hadron colliders (LHCb at the LHC) and e^+e^- colliders (BaBar at SLAC, Belle and Belle II at KEK). Links to the field of neutron physics are highlighted when possible.

Opportunities for Particle Physics with Neutrons at the European Spallation Source

T. Soldner

Institut Laue Langevin, Grenoble, France

The European Spallation Source will be the most intense neutron source in Europe and provide unique opportunities for particle physics experiments with neutrons. I will present an overview about the instruments that have been proposed so far and discuss the cold neutron beam line ANNI in more detail.

References

[1] E. Klinkby and T. Soldner, J. Phys.: Conf. Ser. **746**, 012051 (2016)
[2] O. Zimmer, arXiv:1611.07353 (2016)
[3] C. Theroine, G. Pignol, and T. Soldner (eds.), Physics Procedia **51** (2014)

Abstracts of Posters

(in alphabetical order)

A new Detector for Beta Spectroscopy with PERKEO III

Karina Bernert[1], **Christoph Roick**[1], **Heiko Saul**[1], **Bastian Märkisch**[1]

[1]*Physics Department, Technical University of Munich, Garching, Germany*

Neutron beta decay provides an excellent toolkit for the investigation of the structure of the weak interaction and potential deviations from the predictions of the standard model of particle physics.
The neutron decay spectrometer PERKEO III was used to perform the most precise measurement of the beta asymmetry at the PF1B beam at the Institut Laue-Langevin, Grenoble.
For future improvements, the dominant systematic effects related to the detector are addressed: A scintillation detector with improved uniformity was designed and is under construction. The gain of the Photomultiplier tubes will be monitored with light pulses from a Kapustinsky flasher, whose intensity will be controlled with a Silicon Photomultiplier.

The vacuum pump system of PERC

S. Bodmaier[1], J. Klenke[2], C. Roick[1], H. Saul[1], B. Märkisch[1]

[1] *Technische Universität München, Germany*
[2] *FRM II, Germany*

PERC is a next generation neutron decay experiment currently being set-up at the MEPHISTO beam site at the FRM II. The aim of PERC is to improve the precision on several correlation coefficients by one order of magnitude. Its main component is an 8m long superconducting solenoid containing a non-depolarizing neutron guide as decay volume. Specialized detector systems for electron and proton detection can be utilized with PERC.

For an undisturbed guidance of protons, a vacuum in the UHV regime with pressures around $1 \cdot 10^{-8}$ mbar throughout the warm bore of 12m length is required. Challenges like high magnetic fields, as well as restricted placement and temperatures due to the surrounding superconducting magnetic coils and the neutron guide, limit the choice of applicable vacuum pump types. In this work, the performance of Ion Getter Pumps (IGPs) utilizing the high magnetic field of PERC is investigated. The possible placement inside PERC and different pump parameters are optimized via simulation.

While the prototype test setup requires some improvement, current simulation results show that the desired pressure limit is achievable with the developed distributed, in-situ pumping system.

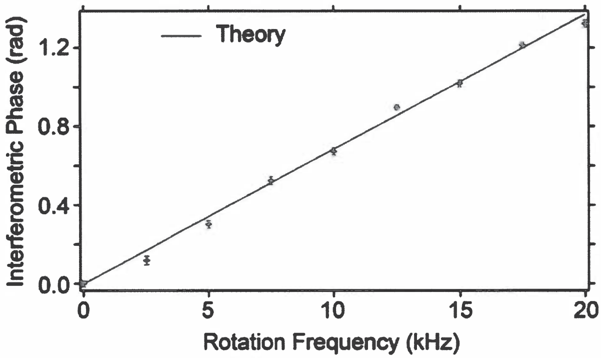
Observation of Spin-Rotation Coupling in Neutron Optics

A. Danner[1], B. Demirel[1], S. Sponar[1] and Y. Hasegawa[1,2]

[1] *Atominstitut, Stadionallee 2, 1020 Vienna, Austria*

[2] *Department of Applied Physics, Hokkaido University, Kita-ku, Sapporo 060-8628, Japan*

A versatile miniaturised spin rotator, suitable for application in neutron interferometer experiments, was developed. [1] Its performance was tested by repeating the neutron polarimeter experiment by Demirel *et al.* [2] regarding spin-rotation coupling by implementing a rotating magnetic field. The device was then used to carry out a corresponding neutron interferometer experiment [3] in a modification of a suggestion by Mashhoon and Kaiser. [4] In both experiments, the phase was linearly dependent on the rotation frequency of the magnetic field.



References

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[2] B. Demirel *et al.*, New J. Phys. **17**, 023065 (2015)

[3] A. Danner *et al.*, to be published

[4] B. Mashhoon and H. Kaiser, Physica B **385-386**, 1381 (2006)

A Scalable Approach to Measure the Neutron EDM with Multiple Storage Cells

S. Degenkolb[1], **P. Fierlinger**[2], **and O. Zimmer**[1]

[1] *Institut Laue-Langevin, Grenoble, France*
[2] *Technische Universität München, Munich, Germany*

The physics reach of permanent electric dipole moment (EDM) searches is limited by two classes of errors: statistical and systematic. Modern experiments using trapped ultracold neutrons (UCN) have statistical limits resulting from low in-source phase-space densities, exacerbated by storage and transport losses. Systematic errors arise from imperfect knowledge or control of experimental conditions; these can often be partially compensated by techniques such as comagnetometry, but not without introducing additional systematic errors and practical limitations. In-situ UCN production simultaneously addresses both classes of errors: production densities are preserved in the measurement, and the high-quality measurement volume is identical with the source. Such approaches have nonetheless posed two significant challenges: (1) disentangling complex diagnostic problems that affect both source and spectrometer, and (2) scaling prototyped components for use in a final measurement.

We propose a modular scheme to simultaneously develop source and spectrometer technologies, the core element being one cell with an integrated, polarization-sensitive detector. In-situ spectroscopy eliminates extraction and transfer losses, while use of liquid ^{4}He as a production medium also enables application of high electric fields. Many cells are finally arranged along the axis of a cold neutron beam for superthermal downconversion, but are fully independent to exclude any moving elements or guides. Control of magnetic field gradients and drift, and cryogenics, have been demonstrated at the needed levels. Thus, the final apparatus is fully scalable from a single working cell using established techniques.

Each measurement probes many cells in parallel, with different electric and magnetic fields applied to constrain systematic errors. In particular, superconducting detector elements are also used to evaluate systematic errors related to magnetic field gradients, and for hardware-linked data blinding based on an intentionally-applied geometric phase in certain cells.

Systematics in neutron lifetime measuring experiments with UCN magnetic storage

V.F. Ezhov[1,2]

[1]*Petersburg Nuclear Physics Institute NRS KI, Gatchina, Russia*
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Precision measurements of the neutron lifetime provide stringent tests of the standard electroweak model [1] as well as crucial inputs for Big-Bang nucleosynthesis calculations [2]. The neutron lifetime is also one of the key parameters for the determination of yields of light elements in BBN since the ratio between the free neutron and proton abundances drives the extent of fusion reactions during the first few minutes of the Universe [2].

Main parts of ultracold (UCN) neutron lifetime experiments were made using UCN storage in material traps. They have similar systematics connected with abnormal UCN losses in traps. So it is desirable to use another type of experiments to exclude this systematics.

Magnetic trapping of neutrons UCN permits to control neutron losses during neutron lifetime measuring. To realize this advantage of UCN magnetic storage is possible only using of magnetic shutter. Without this unique opportunity, magnetic storage experiments are indistinguishable from experiments with storage in material traps. Systematics in neutron lifetime measuring experiments using UCN magnetic storage is discussed.

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Study of neutron fundamental properties in the perfect crystal optics and diffraction

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A review of crystal-diffraction methods to study the neutron fundamental properties is presented.

1. Features of neutron optics in crystal without center of symmetry is discussed. Recently strong electric interplanar fields have been discovered, which affect the neutrons moving in noncentrosymmetric crystals. Value of the field can reach about 10^9 V/cm. Experimentally measured value for quartz crystal was $\sim 2\cdot 10^8$ V/cm. Such fields give rise to a new method of a search for the neutron electric dipole moment (EDM). The accuracy of that is expected at the level $\sim 2\cdot 10^{-26}$ e cm for the available quartz crystals. It can reach $\sim 2\cdot 10^{-27}$ e cm with using the BSO crystal and the proposed "storage" variant of the setup. Moreover, in the non-centrosymmetric crystal new effect of a neutron spin rotation arises due to hypothetic CP-violating short-range pseudomagnetic nucleon-nucleon interaction. That already allowed us to get a best direct constraint on the parameters of such interaction for the interaction range $\lambda < 10^{-6}$ m.

2. Also a possibility to develop ultra-precise neutron spectroscopy using Laue diffraction in a perfect crystal is discussed. The prototype of two-crystal experimental setup was build and two-crystal focusing effect in Laue diffraction was studied. The sensitivity of ultimate setup to external force applied to the neutron can reach values of σ $(Fext) \sim 10^{-17}$eV/cm= $10^{-8} m_n g$. Such ultra-precise spectroscopy technique could be used for a wide range of experiments, such as: a search for the neutron electric charge; a test of the equivalence principle, measurements of the neutron scattering amplitudes; crystal quality studies.

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Search for an electric dipole moment of the neutron using superfluid Helium4

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A non-zero value of the electric dipole moment of an elementary particle would be direct evidence of the violation of time reversal invariance and the first observation of physics beyond the standard model. An experiment with the goal of increasing the current upper limit by two orders of magnitude is under construction at Oak Ridge National Laboratory. It is based on the use of polarized He3 as a polarizer analyzer and detector for the UCN, and as a co-magnetometer, The He4 serves as an electrical insulator and scintillator.
We explain the basic ideas of the method including the use of spin dressing and report on the current state of development of the experiment.

Neutron optics for neutron beta decay studies with (PERC)

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The PERC (Proton Electron Radiation Channel) [1] experiment is currently under construction at the new beam port MEPHISTO at the FRMII. It aims to measure correlation coefficients of the neutron beta decay with an accuracy improved by one order of magnitude to a level of 10^{-4}.

The author will present an overview of the demanding experimental constraints for this precision experiment, concerning the beamline with its' neutron optical components. A neutron supermirror coating is built from hundreds of thin layers of two materials with high scattering contrast. The overall thickness lies typically in the range of one micrometer. By this technique the critical angle of reflection can be increased, compared to that of natural nickel. Therefore, the neutron flux can be increased significantly. In the framework of this experiment, the author will present the current status of the development of a completely non-depolarizing supermirror coating from Copper/Titanium. First tests were made in 2014 by N.Rebrova in the scope of her PhD-thesis [2]. Based on the work of A. K. Petukhov et. al., the author will present the results for a solid-state neutron polarizer made from Iron/Silicon coating [3].

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Neutron Spin-Orbit States: Procedures for Their Generation and Detection

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We discuss methods to prepare and measure an entangled spin-orbit state [1] between the neutron's spin and orbital angular momenta (OAM) [2]. Further we show that these states can be constructed such that a lattice of coupled states can be formed. We demonstrate this lattice of OAM states with photons [3] but using methods which are analogous and applicable to neutron beams. Our preparation techniques, utilize special geometries of magnetic field gradients (neutrons) [4] or pairs of birefringent prisms (optical) to generate these states. We also define efficient protocols for controlling and manipulating the lattice characteristics. The proposed detection method directly measures the correlations of spin state and transverse momentum, and overcomes the major challenges associated with neutrons, which are low flux and small spatial coherence length. Our techniques provide new tools using light or matter beams for investigations of topological materials, quantum communication, and quantum information.

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What about next-generation cold-neutron interferometers?

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In the past, neutron interferometers for cold neutrons have played a considerable role in fundamental physics. We discuss long wavelength examples and the shortcomings/advantages of their designs as well as possible and impossible improvements of some present and future designs.

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Neutron Decay and Dark Matter

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The neutron life-time plays an important role, both in cosmology and particle physics. However, the life-time is known only on the 10^{-3} level and different experiments yield results with a significant deviation. A recent publication[1] shows the possibility to explain this effect by proposing a decay of the neutron into a dark matter particle. One of the proposed decay channels is $n \rightarrow \chi + e^{+} e^{-}$, where χ is a dark matter particle with a mass similar to mass of the neutron. We are currently re-analysing data taken by the PERKEO II experiment at the ILL, which was used to determine the electron asymmetry parameter *A*[2] . Since the experiment is sensitive to the proposed decay mode, we explore the possibility to set limits for this branching fraction. With this poster we will present the status of the analysis.

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nEDM@SNS as a new milestone in neutron EDM experimental technique

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There have been several milestones in the development of the experimental technique to search for a nedm, leading to the present level of nEDM uncertainties. The most recent being a switch to ultra-cold neutrons and the use of a co-magnetometer in the the measurement cell. At present, with efficient UCN sources, the systematic effects have become the dominant factor restricting the neutron EDM sensitivity. Our poster will briefly review past techniques and describe present innovations and improvements of nEDM techniques, which will be realized at the nEDM@SNS cryogenic experiment and which will allow another two orders of magnitude improvement of the sensitivity. As part of the project, nEDM@SNS is commissioning a new test-bed for these innovative techniques, (SOS@PULSTAR), at a 2 MW reactor at North Carolina State University (PULSTAR reactor).

Neutron Interferometry and USANS Setup S18 at ILL

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The instrument S18 at the Institut Laue Langevin (ILL) is the neutron interferometry setup with the world's highest neutron flux. A silicon perfect crystal splits and recombines the neutron beam (triple Laue technique, Mach-Zehnder type). Thermal neutrons in the range of 1.9 to 2.7 Å are used. Applications range from basic quantum physics, e.g. demonstration of the Quantum Cheshire Cat [1], and search for new physics, e.g. Chameleon Fields [2], to applied measurements like determination of neutron scattering lengths. The setup is regularily used also for USANS (Ultra Small Angle Neutron Scattering) of Bonse-Hart geometry. Typical measurements are pore size characterizations of geological samples. Structure sizes of 0.5 to 30µm are accessible (Q range $2*10^{-5}$ to 30^{-3} Å^{-1}).

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Development of a new neutron source at JINR

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The service life of the IBR-2 reactor, one of the leading pulse neutron sources in the world, is expected to end in 2032. Therefore, Frank Laboratory of Neutron Physics started developing a new source. Possible source concepts [1, 2] will be presented. We would like to have a wide discussion on new promising/perspective physics ideas related to the source and its infrastructure such as advanced moderators and special resources/features required for solving physics tasks, in particular in the field of particle and nuclear physics. We definitely want to have UCN and VCN neutron sources and are open for proposals and discussion of their arrangement.

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Ramsey gravity resonance spectroscopy with ultracold neutrons

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Despite the consistency and success of the standard model of particle physics (SM) and general relativity, our present understanding of the universe seems incomplete. Indications for this incompleteness are the significant over-estimation (by 120 orders of magnitude) of the observed value of the vacuum energy density by the SM, and the presence of gravitating dark matter of unknown composition. Many theories have been developed to explain dark energy and dark matter, sparking a wave of new experiments to exclude or set limits on the parameters of these theories.
In this context, ultra-cold neutrons (UCN) are ideal test particles, as with their vanishing electric charge and polarizability they avoid many problems plaguing other experiments. Over the past decade, the qBounce collaboration has developed gravity resonance spectroscopy (GRS) – a tool combining the highest known precision of spectroscopy with the benefits of UCN. Using Rabi-type GRS, qBounce was able to give the strongest limits at their time on hypothetical chameleon and symmetron dark energy forces as well as axionic dark matter. An extension of the setup towards Ramsey GRS promises a significant increase in sensitivity that should again enable us to give competitive limits. We present the current status of the project, a proof of principle for Ramsey-GRS, and prospects for the results expected soon.

Optical Observations of Hydrogen and Deuterium Crystal Growth and Their Implications for Ultracold Neutron Transmission Experiments

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In recent years, serveral ultracold neutron (UCN) sources based on solid ortho-deuterium (sD_2) [1] have been built across Europe and North America. To the surprise of many, their neutron density output is comparable to or lower than that of the 30-year-old "turbine" (PF2 at ILL) [2]. Initially, sD_2-based UCN sources were predicted to outperform the turbine by a factor of 100 [3]. A host of reasons can explain this underperformance. The two most important ones are the scattering of UCNs on rough surfaces and on defects inside the sD_2 crystal. Both were not fully taken into account during the measurement of the sD_2 scattering cross sections that provided the reference data used in computer simulations today [4].The most substantial drawback of these measurements was that they were performed in non-transparent, rough-surface aluminium sample containers.

We have conceived, constructed and tested a copper sample container for cryogenic liquids and solids that does away with these problems. With the help of this hydrogen-tight, transparent sample container and a retractable mirror, the proper preparation of the sample can be verified optically before the neutron measurement is started. The highly polished silica (amorphous SiO_2) windows suppress surface scattering as much as possible and did not bulge under pressure. This way the sample thickness remained well defined throughout the experiment [5].

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Experimental investigation of the low molecular weight fluoropolymer for the ultracold neutrons storage

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An accurate neutron lifetime value is needed to refine the Standard Model parameters (matrix element Vud) and in cosmology and astrophysics.

One of the most precise methods of the neutron lifetime measurements is the storage of ultracold neutrons (UCN) in material traps. Neutron losses in material traps are caused by the UCN capture and heating in collisions with walls and residual gas atoms. The accuracy of determining the neutron lifetime depends on these losses. In an effort to enhance this accuracy, experimenters try to reduce the losses and find the optimum way of extrapolating the measured UCN storage time to the decay constant of a free neutron.

We describe the experimental setup and report the results of measurements of the ultracold neutrons storage in the chamber covered with the low molecular weight fluoropolymers $CF_3(CF_2)_3$-O-CF_2-O-$(CF_2)_3CF_3$. This polymer is the promising coating material for the storage of ultracold neutrons in closed volumes covered with polymer film.

Interpretation of the results of measurements was performed in a model of complex multilayer quantum potentials, describing the walls of storage volume.

A new limit of the ^{129}Xenon Electric Dipole Moment

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The Baryon asymmetry is one of the unsolved big questions of Cosmology. Most explanations for the Baryon asymmetry involve modifications of the Standard Model which generate additional CP violating interactions. This is one reason to search for CP violating interactions beyond the Standard Model. These CP violating interactions will also generate Electric Dipole Moments (EDM) of elementary particles and nuclei, which are experimentally detectable.
On my poster, I will present the current status of our setup to set a limit on the ^{129}Xe-EDM. Experimentally our method is based on a He-Xe-spin clock setup [1]. He-Xe-spin clocks are the most accurate clocks today and we reached already an accuracy level well beyond nHz. Beside the EDM search we employed and will employ them for other searches for physics beyond the Standard Model [2],[3].
Our current setup is located at the Forschungszentrum Jülich and I will present the first preliminary result of our ongoing ^{129}Xe EDM search performed by the MIXed collaboration (**M**easurement and **I**nvestigation of the **X**enon-129 **e**lectric **d**ipole moment).

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Search for the new short-range interaction by the neutron scattering technique

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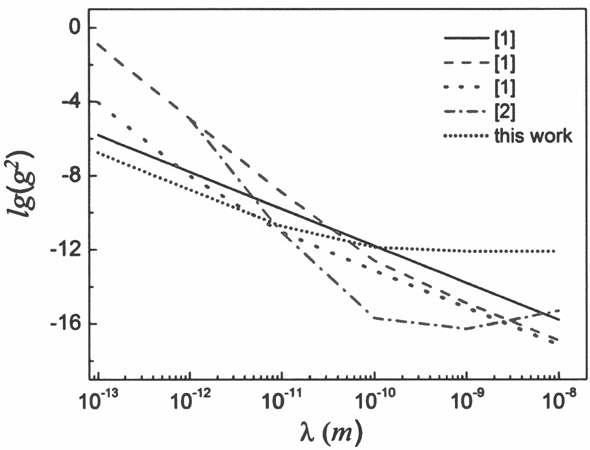
There are 4 known types of interaction in nature, but nowadays the existence of a new force mediated by new unknown bosons is widely discussed in the literature [1], [2]. This work deals with the application of neutron scattering technique for the search for a new short-range interaction and for setting constrains on the coupling constant of such interaction.

The main idea is to perform an experiment of neutron scattering on the powder of silicon (powder diffraction) and to get the information on scattering amplitude dependence on scattering angle. Within this work the calculations showing the possibility of the idea were made. The coupling constant constrains were obtained using the data of silicon powder diffraction from the FRM II reactor, Munich, Germany. It is shown that a new constrain is competitive to the existing one.



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ON MEASUREMENT OF THE NEUTRON DECAY IN A HELIUM VESSEL.

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Parameters of experiment on ultracold neutrons storage in a vessel with superfluid helium walls at temperatures 0.5 K and below are estimated. ^{4}He has no neutron capture cross section, and in superfluid form it has very low inelastic scattering cross section of ultracold neutrons. Therefore a vessel with the walls covered by superfluid ^{4}He is an ideal one for measurement of a free neutron life time.
The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

The effect of nanodiamond fluorination on quasi-specular reflection of cold neutrons

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In recent years, powders of detonation diamond nanoparticles provided a record efficiency of quasi-specular reflection of cold neutrons and a record efficiency of diffusive reflection of slower neutrons. The fluorination of diamond nanoparticles increases even further the efficiency of both these process at all relevant neutron energies and incident angles. The removal of hydrogen contaminations from the nanodiamond surface, due to its fluorination, decreases neutron losses associated with their travel through the powder. Besides, the neutron optical potential of the nanoparticle gets sharper on the surface. Thus, the probability of neutron scattering increases. The results of reflectometry measurements with fluorinated and raw nanodiamond powder samples, comparison them to each other and to computer simulations, and possible applications will be presented [1].

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