Towards Storage Ring Electric Dipole Moment Measurements

744. WE-Heraeus-Seminar

29 Mar - 31 Mar 2021
ONLINE

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 744. WE-Heraeus-Seminar:

Not only from a particle physicist point of view our existence is still a mystery. According to our current understanding the early universe consisted of the same amount of matter and anti-matter. If the laws of physics obeyed certain symmetries, matter and anti-matter particles should have annihilated. Only due to symmetry breakings in the fundamental interactions, one part, that we call matter today, prevailed.

It turns out that one of the established symmetry breaking mechanisms of the standard model of particle physics, namely the CP-violation, is orders of magnitude too small to explain today's dominance of matter over antimatter. New *CP*-violating interaction are thus sought for. These new possible CP-violating effects could manifest themselves in electric dipole moments (EDMs) of fundamental non-selfconjugate particles with spin. A second source of possible CP-violation in the Standard Model is the so-called θ_{QCD} term. This parameter, which could in principle range from 0 to 2π, is bound to an unnatural small value $|\theta_{QCD}| < 10^{-10}$ by the neutron EDM measurement. This is known in the literature as the strong CP-problem.

In spite of many searches and ever increasing sensitivity, no electric dipole moments have been observed to date. The systems investigated so far include neutrons, muons, atoms and molecules. This workshop focuses on the direct measurement of EDMs of *charged* hadrons (e.g. proton, deuteron, ^{3}He). Such measurements have never been carried out before. They require the operation of a new kind of high precision storage rings using electric instead of magnetic fields such that simultaneously counter rotating beams will be made possible in order to control and reduce systematic uncertainties.

The aim of the workshop is to bring together experts in experimental, accelerator and theoretical physics to discuss the next steps towards the construction of such a new type of precision storage ring.

Introduction

Scientific Organizers:

Dr. Michael Lamont	CERN, Geneva, Switzerland E-mail: mike.Lamont@cern.ch
Prof. Dr. Jörg Pretz	Forschungszentrum Jülich and RWTH Aachen University, Germany E-mail: pretz@physik.rwth-aachen.de
PD Dr. Andreas Wirzba	Forschungszentrum Jülich, Germany E-mail: a.wirzba@fz-juelich.de

Administrative Organization:

Dr. Stefan Jorda Martina Albert	Wilhelm und Else Heraeus-Stiftung Postfach 15 53 63405 Hanau, Germany Phone +49 6181 92325-14 Fax +49 6181 92325-15 E-mail albert@we-heraeus-stiftung.de Internet : www.we-heraeus-stiftung.de

Program

Program

Monday, 29 March 2021

10:00 – 10:05	Jörg Pretz	**Welcome Words**

Session chair: Hans Ströher

10:05 – 10:35	Paolo Lenisa	**Strategy**
10:35 – 11:05	Christian Carli	**Systematic errors analysis for the charged particle electric dipole moment measurements**
11:05 – 11:35	*COFFEE BREAK*	
11:35 – 12:05	Richard Talman	**Lattice Design for a Prototype Proton EDM Storage Ring**
12:05 – 12:50	Yannis Semertzidis	**Storage-ring proton EDM with the hybrid, symmetric lattice**
12:50 – 13:50	*LUNCH BREAK*	

13:50 – 14:05	Jörg Pretz	**Introduction**
14:05 – 14:20	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**

Session chair: Andreas Wirzba

14:20 – 15:15	Susan Gardner	**CP Violation: Past, Present, and Future**
15:15 – 16:00	Kolya Nikolaev	**General Relativity Effects in Storage Ring Searches for EDM**
16:00 – 16:45	Rob Timmermans	**EDMs in EFT frameworks**
16:45 – 17:15	*COFFEE BREAK*	

Program

Monday, 29 March 2021

Session chair: Andreas Wirzba

17:15 – 18:00	Rajan Gupta	**Contributions of theta, quark and chromo CP violating operators to the neutron/proton EDM**
18:00 – 18:45	Peter Graham	**Direct Detection of Axion Dark Matter and Dark Energy**
18:45 – 19:30	Yuriy Uzikov	**Search for time-reversal invariance violation in double polarized pd scattering**

Program

Tuesday, 30 March 2021

Session chair: Paolo Lenisa

10:00 – 10:30	James Gooding	**A silicon based polarimeter for pEDM searches**
10:30 – 11:00	Falastine Abusaif	**Rogowski beam position monitors**
11:00 – 11:30	Jamal Slim	**Spin Manipulation at COSY**
11:30 – 12:00	*COFFEE BREAK*	
12:00 – 12:30	Jan Borburgh	**Challenges for the EDM main ring electric field elements**
12:30 – 13:00	Helmut Soltner	**Design Considerations for the EDM Prototype Ring**
13:00 – 14:00	*LUNCH BREAK*	

Session chair: Mike Lamont

14:00 – 14:45	Klaus Kirch	**Electric Dipole Moment search experiments**
14:45 – 15:15	Vera Shmakova	**Progress toward a direct measurement of the deuteron Electric Dipole Moment at COSY**
15:15 – 15:45	Swathi Karanth	**New method to search for axion-like particles demonstrated with polarized beam at the COSY storage ring**
15:45 – 16:15	Rebecca Chislett	**The new g-2 experiment at Fermilab**
16:15 – 16:45	*COFFEE BREAK*	

Program

Tuesday, 30 March 2021

Session chair: Mike Lamont

16:45 – 17:15	Ola Wronska	**Long Spin Coherence Times and How to Find Them**
17:15 – 17:45	Philipp Schmidt-Wellenburg	**Search for the muon EDM using the frozen-spin technique**
17:45 – 18:15	Manfred Grieser	**The Cryogenic Storage Ring CSR**

Program

Wednesday, 31 March 2021

Session chair: Jörg Pretz

10:00 – 10:30	Tim Wagner	**Beam based alignment at the Cooler Synchrotron (COSY) and beyond**
10:30 – 11:00	Vera Poncza	**Simulation model improvements at COSY using the LOCO algorithm**
11:00 – 11:30	Andreas Lehrach	**Beam and Spin Tracking**
11:30 – 12:00	*COFFEE BREAK*	
12:00 – 12:30	Andras Laszlo	**On quantitative predictions for gravitational systematics in frozen spin storage rings**
12:30 – 13:00	Peter Porshnev	**Predicting outcomes of electric dipole and magnetic moment experiments**
13:00 – 14:00	*LUNCH BREAK*	
14:00 – 14:30	Alexander Silenko	**Extraordinary enhancement of sensitivity of a search for axion-induced EDMs of relativistic particles and nuclei in storage rings**
14:30 – 15:00	Michael Lamont	**Next steps, where do we go from here?**

Session chair: Frank Rathmann

15:00 – 15:30	**Discussion**	
15:30 – 15:45	Scientific organizers	**Closing remarks**

End of seminar

Abstracts of Lectures

(in alphabetical order)

Rogowski beam position monitors

Falastine Abusaif
Forschungszentrum Jülich & RWTH Aachen University
on behalf of the JEDI collaboration

f.abusaif@fz-juelich.de

Abstract

The ***J****ülich* ***E****lectric* ***D****ipole Moment* ***I****nvestigations* (*JEDI*) collaboration is preparing for a direct measurement of charged particles **E**lectric **D**ipole **M**oment (EDM). The *JEDI* investigations are carried with beams of polarized protons and deuterons using the **CO**oler **SY**nchrotron (COSY) located at the Forschungszentrum Jülich in Germany. A high precision experiment as the search for EDM requires a well suppression for a true *EDM* signal from systematic ones. The beam closed orbit for example, should be as close to zero as possible which entails a system of highly sensitive **B**eam **P**ositions **M**onitors (BPMs).

A new type of Rogowski BPM has been developed based on a segmented toroidal coil. In addition to the compactness of these new BPMs where their installation demands a free space of only about 10 cm, they provide a resolution of few micro meters (for one single position measurement, a sampling time of 1 s, a signal to noise ratio of few thousands and a beam intensity of 2×10^9).

This talk will include some results for testing and calibrating the Rogowski BPM in the laboratory, some electromagnetic computation results carried within COMSOL Multiphysics, some theoretical investigations for different geometrical representations of Rogowski winding, some commissioning results of installed Rogowski BPMs in COSY environment and in addition, future considerations for the use of Rogowski BPMs in the lattice design for a prototype EDM storage ring will be given.

Keywords
BPM, Rogowski, EDM, Storage rings

Challenges for the EDM main ring electric field elements

J. Borburgh[1]

[1]*CERN, Geneva, Switzerland*

In the framework of the Physics Beyond Colliders (PBC) study at CERN, the feasibility of building an approximately 500 m circumference storage ring to precisely measure the permanent electric dipole moment of the proton is being assessed. Protons are stored in this EDM ring at the so-called ‘magic’ energy of 233 MeV using only electric field elements in order to ensure that spin and momentum vectors precess horizontally at the same rate. Firstly, the talk will address the necessary boundary conditions, as well as the assumed limitations for the storage ring elements. A first attempt was made to translate the optics requirements of the ring elements into technical concepts, and the consequences of the hardware limitations on the optics layout will be highlighted. Finally, this talk will highlight the technical challenges associated with each of the following ring elements - the electric field main dipoles and quadrupoles, as well as the injection septum and fast deflector.

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Systematic errors analysis for the charged particle electric dipole moment measurements

Christian Carli

Cern, ELENA, Geneva, Switzerland

Different proposals aiming to measure the Electric Dipole Moment (EDM) for charged particles in storage rings require a careful analysis of the systematic errors contributing to a spin build-up mimicking the EDM one.
In this talk, an overview of the leading sources of imperfections is presented and mitigation measures discussed.

The new g-2 experiment at Fermilab

Rebecca Chislett

Forschungszentrum Jülich, Jülich, Germany

The new g-2 experiment at Fermilab aims to measure the magnetic dipole moment of the muon to a precision of 140ppb, a factor 4 improvement on the previous experiment conducted at Brookhaven. The previous measurement, at 540ppb accuracy, was discrepant from the Standard Model prediction by more than 3.5 sigma. In addition, the experiment aims to improve upon the current worlds best limit on the EDM of the muon (also set at the Brookhaven experiment) by 2 orders of magnitude. This talk will explain how the experiment will reach these new levels of precision to make these measurements and the current status of the analysis.

CP Violation: Past, Present, and Future

Susan Gardner

University of Kentucky, Department of Physics and Astronomy, Lexington, Kentucky, USA

For more than ten years we have known that a single phase in the CKM matrix provides the dominant mechanism of the CP-violating effects we have observed in Nature. During this time, however, the mystery of the origin of the cosmic baryon asymmetry has only deepened: new ingredients in addition to new sources of CP violation are needed to explain its numerical size.

In this setting searches for new sources of CP violation, taken broadly, help address this larger problem. I will survey the possibilities, their current status, their connections and implications, while emphasizing the special role of storage ring measurements.

Contribution ID: Type: Oral

A silicon based polarimeter for pEDM searches

29-31 Mar 2021

Monolithic High Voltage-CMOS (HV-CMOS) and LGAD (Low Gain Avalanche Diode Detector) sensors are emerging as prime candidates for tracking systems in future physics experiments. The highly accurate spatial and time resolution these thin sensors offer make them an extremely attractive option for precision experiments where tracking of low energy particles with minimal material budget is required.

This presentation will discuss some of the challenges, constraints and features that a silicon-based proton EDM polarimeter needs to overcome and possess. Results of simulation studies on whether a polarimeter made of a combination of HV-CMOS and LGAS sensors meets such constraints will be presented. An experimental setup to demonstrate the capabilities of a silicon-based system will be shown and its potential place in the 30-40 MeV prototype ring stage of the experiment will be discussed.

Primary author: GOODING, James William (University of Liverpool (GB))

Co-authors: VILELLA FIGUERAS, Eva (University of Liverpool (GB)); CASSE, Gianluigi (University of Liverpool (GB)); ROMPOTIS, Nikolaos (University of Liverpool (GB)); BOWCOCK, Themis (University of Liverpool (GB)); VOSSEBELD, Joost (University of Liverpool (GB)); PRICE, Joe (University of Liverpool (GB));

Presenter: GOODING, James William (University of Liverpool (GB))

Direct Detection of Axion Dark Matter and Dark Energy

Peter Graham

Stanford University, Institute for Theoretical Physics, Stanford, CA, USA

If dark energy is not a cosmological constant but in fact dynamical, it is natural for it to have axion-like couplings to Standard Model particles. It is then in principle possible to do direct detection of dark energy in a laboratory experiment.

We found a technique using proton storage rings that could have the sensitivity needed to directly detect dark energy.

Additionally, since the local dark matter density is significantly higher than the dark energy density, such an experiment is also one of the most sensitive ways to directly detect ultralight (including ‘fuzzy’) axion dark matter.

The Cryogenic Storage Ring CSR

Manfred Grieser

Max-Planck-Institut für Kernphysik, Stored and cooled ions, Heidelberg, Germany

The cryogenic storage ring at MPIK in Heidelberg is a fully electrostatic storage ring used to store atomic, molecular and cluster ion beams in the energy range 20-300 keV, where q is the absolute value of the ion charge state. The entire storage ring can be cooled down to temperatures of only a few Kelvin. This very low temperature creates an extremely low residual gas density. The observations from first cryogenic operation indicate the residual gas densities below 100 molecules/cm^3. In March 2014 the functionality of CSR was demonstrated by storing a 50 keV 40Ar+ beam under room temperature conditions. Later, in 2015, the storage ring was cooled down to an average temperature below 10 K. At this temperature the storage time for singly charged ions achieved up to 2500 s. The CSR is also equipped with an electron cooler which has to serve as an electron target for high resolution recombination experiments. Typical injected ion currents ranged from 1 nA to 1 mA. Sometimes it is not well-known which ion species are coming out the ion source. To identity the kind of ion a very precisely mass measurement with a mass resolution of better than 10^(-5) is applied at the CSR. These mass measurements work for all available ion beams having a momentum spread of about 10^(-3) and a beam emittance of several mm·mrad. In the talk an overview about the CSR will be given.

Contributions of theta, quark and chromo CP violating operators to the neutron/proton EDM

Rajan Gupta

Los Alamos National Laboratory, Theoretical Division T-2,
Los Alamos, NM 87545, USA

I will present a summary of the calculations of the matrix elements of CP violating operators that arise in the standard model (Theta-term) and BSM (quark EDM, chromo EDM and Weinberg) using lattice QCD. The status of the calculations, challenges and future prospects of determining their contributions to nucleon EDM will be reviewed.

New method to search for axion-like particles demonstrated with polarized beam at the COSY storage ring

S. Karanth[1]

[1] *Marian Smoluchowski Institute of Physics, Jagiellonian University, Cracow, Poland*

The axion was originally proposed to explain the small size of CP violation in quantum chromodynamics. The axion would have small mass and be weakly coupled to nucleons. If sufficiently abundant, it might be a candidate for dark matter in the universe. Axions or axion-like particles (ALPs), when coupled to gluons, induce an oscillating Electric Dipole Moment (EDM) along the nucleon's spin direction. This can be used in an experiment to search for axions or ALPs using charged particles in a storage ring.

In the spring of 2019, at the Cooler Synchrotron (COSY) in Jülich, we performed a first test experiment to search for ALPs using an in-plane polarized deuteron beam with a momentum of 0.97 GeV/c. The field of the ring magnets precesses the deuteron polarization relative to the beam velocity at a rate determined by the deuteron anomalous magnetic moment. In the frame of the moving beam, the radial electric field due to the ring magnets ($v \times B$) may rotate the EDM. If the spin precession frequency equals the EDM oscillation frequency, which is proportional to the ALP mass, a resonance occurs that accumulates the rotation of the polarization out of the ring plane. This rotation is detected with a polarimeter that measures the transverse components of the beam polarization while the beam is stored. Since the axion frequency is unknown, the momentum of the beam was slowly ramped to search for a vertical polarization jump that would occur when the resonance is crossed. At COSY, four beam bunches with different polarization directions were used to make sure that no resonance was missed because of the unknown relative phase between the polarization precession and the EDM oscillations. We scanned a frequency window of about a 1-kHz width around the spin precession frequency of 121 kHz. This talk will describe the experiment and show preliminary results.

Electric Dipole Moment search experiments

K. Kirch[1,2]

[1] *Institute for Particle Physics and Astrophysics, ETH Zurich, Switzerland*
[2] *Paul Scherrer Institute, 5232 Villigen-PSI, Switzerland*

The 2020 update of the European Strategy for Particle Physics puts the search for electric dipole moments (EDM) high up as ‘essential scientific activities’ and ‘crucial components of the search for new physics’ [1]. An overview of experimental efforts to search for the EDM of particles and systems with spin will be presented. The focus is on non-storage-ring experiments. The leading experimental results to date are the limits on the EDM of the ^{199}Hg atom [2] for nuclear EDM, of the ThO molecule [3] for the electron EDM, and of the neutron [4]. A recent article reviews theoretical aspects and experiments [5]. A growing number of collaborations and efforts is working towards improving these experiments or devising new approaches, in particular with molecules, see e.g. [6] and references therein, or heavier baryons [7,8] or tau leptons [9,10]. Besides the search for permanent EDM, various side-analyses enrich and broaden the physics program of EDM experiments. Over the past decade, the nEDM collaboration at PSI has revived such and pioneered new activities. Among those are searches for oscillating EDM [11], searches for ‘exotic’ phenomena and interactions, reaching from Lorentz violation to short-range interactions and hidden sector transitions, e.g. [12-15], and measurements of physical constants [16].

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On quantitative predictions for gravitational systematics in frozen spin storage rings

Andras Laszlo

Wigner Research Centre for Physics, Department of High Energy Physics
Budapest, Hungary

In frozen spin storage rings, many environmental factors give systematic backgrounds to the EDM signal, including General Relativity (GR), due to the gravitational field of the Earth. As it is rather well-known by now (see e.g. Phys.Lett.A376(2012)2822), depending on the experimental scenario, the GR contribution can be well above the planned EDM sensitivity. Therefore, the GR contribution is of concern as a source
of EDM systematics, moreover it can provide an independent experimental test of GR. There are a handful of theoretical papers quantifying the GR systematics in the EDM observable in a frozen spin ring, delivering slightly different results (see Phys.Lett.A376(2012)2822 and Phys.Rev.D94(2016)044019 and
Class.Quant.Grav.35(2018)175003). The aim of this talk is to compare and clarify these claims, and to show that the difference comes from a kind of an interference between the GR effect and the geometric modeling of the magnetic field shape imperfection, in a mixed magnetic-electric ring. We conclude with their total experimental implications in the EDM observable, and show quantitatively that in a "doubly-frozen spin ring" (arXiv:1812.05949) to what extent one can cancel the magnetic field imperfection, and that the GR effect adds up constructively. The material of the talk is based on: arXiv:2009.09820

Beam and Spin Tracking

Andreas Lehrach

RWTH Aachen University, FZJ, Physik IIIB, Aachen, Germany

Full spin-tracking simulations of the entire experiment are absolutely crucial to explore the feasibility of storage ring EDM experiments and to investigate systematic limitations. Existing spin tracking codes like Bmad (Software Toolkit for Charged-Particle and X-Ray Simulations) have been extended to properly simulate spin motion in presence of an electric dipole moment. The appropriate EDM kick and electromagnetic field elements (static and RF) have been implemented and benchmarked with other simulation codes. For a detailed study of particle and spin dynamics during the storage and buildup of the EDM signal, various systematic effects and their impact on the spin motion have been investigated.

Strategy

Paolo Lenisa

Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, Ferrara, Italy

The talk will provide an update about the latest activity of the JEDI and CP-EDM collaborations and briefly outline the strategy for the coming steps.

General Relativity Effects in Storage Ring Searches for EDM

N. N. Nikolaev

Landau Institute of Theoretical Physics, 142432 Chernogoloovka, Russia

The storage ring EDM experiments aim at sensitivity to the proton EDM about 10^{-29} e cm. Weak though the gravitational interaction is, the gravity induced spin rotations overwhelm the EDM induced ones. The effects of the Earth's gravity pull and of the geometric magnetic field caused in electrostatic systems residing on the rotating Earth will be reviewed.

References

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Simulation model improvements at COSY using the LOCO algorithm

V. Poncza[1,2]

[1]RWTH Aachen University, Aachen, Germany
[2] Institut für Kernphysik 4, Forschungszentrum Jülich, Jülich, Germany

The JEDI (Jülich Electric Dipole moment Investigations) collaboration is specialized in the search for EDMs of hadrons using storage rings. It is engaged in design studies for dedicated storage rings for the investigation of protons and deuterons and uses the magnetic storage ring, the cooler synchrotron, COSY at Forschungszentrum Jülich for the first direct deuteron EDM experiment. In this experiment, an EDM leads to a vertical polarization buildup that is directly proportional to the size of the EDM. However, the vertical polarization component is also inuenced by systematic effects such as magnet misalignments. In order to investigate systematic e_ects individually and to support the data analysis, a realistic simulation model is required. In this presentation the development of such a model based on the Bmad software library is presented. Furthermore, various systematic effects and their impact on the spin motion in COSY are investigated and quantified using tracking simulations.
For a more realistic description of the experimental situation, algorithms are implemented which fit the simulation model to the real conditions by variation of selected machine parameters. The algorithms are successfully tested by means of simulations and afterwards applied to measurement data. The fit results confirm additional magnetic displacements and lead overall to a significantly increased agreement between simulation model and reality.

Predicting outcomes of electric dipole and magnetic moment experiments

V. G. Baryshevsky[1] **and P. I. Porshnev**[2]

[1] Institute for Nuclear Problems, Belarusian State University, Minsk, Belarus

[2] Past affiliation: Physics Department, Belarusian State University, Minsk, Belarus

March 2021

Abstract. The search for electric dipole moment (EDM) has been the focus of intense experimental and theoretical efforts, since it can point toward new CP-violating interactions outside the standard model. We argue that existing phenomenological models that are used in matching QFT predictions with high precision measurements might require an extension to fully capture possible $T(CP)$-violating effects. The extended model adds new pseudoscalar corrections to spin motion equation. In the quantum field framework, real fermions are surrounded by virtual pairs which partially screen bare fermion charges. With the pseudoscalar correction, we effectively take into account the existence of such a screening cloud around real fermions. The new phenomenological model is directly applicable to storage ring experiments and high precision atomic measurements. It also becomes possible to explain why EDMs are so difficult to measure, since the $T(CP)$-odd effects that are fully accounted for might lead to the effective screening of electric dipole moments. Within the same model, it is possible to explain the discrepancy between experimental and theoretical values of muon magnetic anomaly under assumption that the pseudoscalar correction is the dominant source of this discrepancy.

Abstract for online talk at 744. WE-Heraeus-Seminar “Towards Storage Ring Electric Dipole Moment Measurements”, Germany, 29-31 March, 2021

Speaker: Dr. Porshnev plans to present on behalf of both Prof. Baryshevsky and himself.

Search for the muon EDM using the frozen-spin technique

P. Schmidt-Wellenburg

[1]*Paul Scherrer Institute, 5232 Villigen, Switzerland*

The discovery of an electric dipole moment (EDM) of the muon would break time invariance and violate the combined symmetry of charge and parity (CP). Quite naturally many extensions to the standard model of particle physics (SM) provide new CP-violating interactions which could give rise to measurable EDMs while at the same time might explain the cosmologically observed baryon asymmetry of the Universe (BAU) [1,2,3]. Although, the complex phase of the CKM in the SM is close to maximal, it is not sufficient to explain the observed BAU, strongly motivating searches for and models of new sources of CP-violation.

At PSI we propose an experiment to search for the EDM of the muon based on the frozen-spin technique. We intend to exploit the high electric field, $E = 1\mathrm{GV/m}$, experienced in the rest frame of the muon with a momentum of $p = 125\mathrm{MeV}/c$ when passing through a large magnetic field of $B = 3\mathrm{T}$. Measured muon fluxes at the muE1 beamline of PSI permit an improved search with a sensitivity of $\sigma(d_\mu) \approx 6 \times 10^{-23}\ e\mathrm{cm}$, about three orders of magnitude more sensitive than for the current upper limit of $|d_\mu| \leq 1.8\ \times 10^{-19}\ e\mathrm{cm}$ [4]. With the advent of the new high intensity beam, HIMB, and the cold muon source, muCool, at PSI the sensitivity of the search could be further improved by tailoring a re-acceleration scheme to match the experiments injection phase space. While a null result would set a significantly improved upper limit on an otherwise un-constrained Wilson coefficient, the discovery of a muon EDM would establish the existence of physics beyond the Standard Model.

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Storage-ring proton EDM with the hybrid, symmetric lattice

Yannis K. Semertzidis[1,2]

for the Storage-ring EDM Collaboration

[1]Center for Axion and Precision Physics Research, IBS, Daejeon 34051, Republic of Korea

[2]Department of Physics, KAIST, Daejeon 34141, Republic of Korea

Electric dipole moments (EDM) of fundamental particles require the violation of parity (P) and time reversal (T) discrete symmetries. Assuming CPT conservation, T-violation also means CP-violation, a requirement, according to Sakharov, for our matter-dominated universe to evolve from an originally symmetric one. Studies of EDMs provide the most stringent tests of New Physics beyond the standard model with the neutron, ^{199}Hg, and electron EDM exps. being the most sensitive ones.

The storage ring proton EDM using the so-called frozen spin method [1], opened up the way to probe directly the EDM of charged particles. The first complete storage ring proton EDM method [2] consists of electric field plates to steer the beam horizontally and electrostatic quadrupoles to keep it focused. It has provided the first path to hadronic EDMs of better than 10^{-29}*e*-cm, albeit with quite strict systematic error requirements, mainly referring to the level of the average radial magnetic field integrated around the ring needed to be below 10 aT. This requirement is no longer needed with the hybrid ring [3], where the focusing has been replaced by magnetic quadrupoles, effectively relaxing the radial B-field requirements by more than five orders of magnitude. Alternate magnetic focusing allows simultaneous clock-wise (CW) and counter-clock-wise (CCW) storage, eliminating the main systematic error, that of the vertical electric field, while being the only lattice that accomplishes this cancellation. A number of additional, smaller but important, systematic error sources are also reduced by several orders of magnitude by paying attention to ring lattice symmetry [4], requiring the beam to be at the same level to 0.1mm around the ring and by requiring the relative split of the counter-rotating beams to be less than 10μm; easily within the sensitivity of the SQUID-based beam position monitors [5]. Additional effective tools include utilizing longitudinal, radial and vertical beam polarizations simultaneously. The method is under consideration by the current Snowmass process that will set the priorities of the US Particle Physics community.

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Progress toward a direct measurement of the deuteron Electric Dipole Moment at COSY

V. Shmakova[1] **for the JEDI collaboration**

[1]*Institut für Kernphysik (IKP), Forschungszentrum Jülich GmbH, Jülich, Germany*
v.shmakova@fz-juelich.de

One of the main problems of modern particle physics is the inability of the Standard Model to explain the matter-antimatter asymmetry in the Universe. Permanent electric dipole moments (EDMs) of particles violate both time reversal and parity invariance and, through the CPT-theorem they also violate the combined CP symmetry. Therefore, EDM measurements of fundamental particles are capable to probe new sources of CP-violation, and finding an EDM would be a convincing indicator for physics beyond the Standard Model.

Storage rings make it possible to measure EDMs of charged particles by observing the effect of the EDM on the spin motion in the ring [1], [2]. The direct search for proton and deuteron EDMs using a magnetic storage ring, where the sensitivity is lower than in a dedicated EDM ring, is motivated by the need to improve the required experimental methods and techniques. It has been shown that EDM-like spin rotations accumulate when an RF Wien filter [3] operates in phase with the spin precession of the stored circulating particles. In this talk I discuss the latest results of the “precursor” deuteron EDM experiment, currently being carried out at the Cooler Synchrotron COSY at IKP of Forschungszentrum Jülich.

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Extraordinary enhancement of sensitivity of a search for axion-induced EDMs of relativistic particles and nuclei in storage rings

Alexander Silenko

Joint Institute for Nuclear Research, Bogoliubov Laboratory of Theoretical Physics, Dubna (Moscow region), Russia

We have derived the relativistic Hamiltonian in the Foldy-Wouthuysen representation describing electromagnetic interactions of a Dirac particle with allowance for a pseudoscalar field conditioned by dark matter axions. The result obtained demonstrates an extraordinary increase of an influence of the axion field on the particle spin dynamics in comparison with the previously considered nonrelativistic approximation. This increase manifests itself in accelerator and storage ring experiments fulfilled by the resonance method.

Spin Manipulation at COSY

Jamal Slim

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

Along with many milestones achieved so far, one of the first ever new devices, developed and commissioned at COSY, and to be used as a spin rotator in the EDM experiment, is an RF Wien filter. The rate of resonant rotation of the in plane precessing spin to the vertical one is a signal used to determine the EDM. In order to retain the resonance condition, one needs a continuous monitoring the of the precessing horizontal polarization which is impossible for polarizations close to the vertical one. We achieved a solution by adopting an unconventional multibunch scheme in the storage ring.

Two bunches that simultaneously orbit in COSY will be used in the experiment, where the RF Wien filter is gated out for one bunch. A spin of this gated-out bunch shall remain in the ring plane and its precession frequency will be measured by the JEDI technique. Consequently, it will serve as a co-magnetometer for the second bunch the polarization of which will be subjected to the RF Wien filter driven rotation at exactly the parametric spin resonance frequency. We report the results of the first ever experimental test of this new approach to a continuous co-magnetometry for the RF resonance spin rotations in storage rings.

Design Considerations for the EDM Prototype Ring

<u>H. Soltner</u>

Forschungszentrum Jülich, Jülich, Germany

Prior to the establishment of the final EDM ring a prototype ring (PTR) will be required to carry out technical feasibility studies as well as hardware and software developments. This PTR will allow for two operational modes, an all-electric setup that allows for the simultaneous storage of both clockwise and counter-clockwise travelling beams, and a combined electric and magnetic field ring that creates the conditions for frozen-spin operation.
The talk will highlight the mechanical design of the PTR, specifically the combined electric and magnetic bending elements and present the results on the corresponding field simulations.

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Lattice Design for a Prototype Proton EDM Storage Ring

Richard Talman

Laboratory for Elementary-Particle Physics, Cornell University, Ithaca NY, 14850, USA

Motivated by the investigation of time reversal symmetry (T-symmetry) in particle physics, the main recommendation of the recently completed (CYR) CERN Yellow Report "Storage Ring to Search for Electric Dipole Moments of Charged Particles" is the immediate commencement of planning for the construction of a reduced scale, Prototype Proton EDM Storage Ring (PTR). A multi-year timetable for the phased achievement of well-defined goals is explained in the CYR. My presentation provides evolving, site-independent, scale-independent, (rounded-square) lattice designs to match this CYR timetable.

From there, with the same T-symmetry physics motivation, the same Juelich-developed spin control technology, and the same lattice design, my talk proposes a continuing evolution to a post-PTR colliding beam configuration. By measuring \$pp\$ and \$pd\$ elastic scattering from pure initial spin states to pure (better than 0.95 analyzing power statistics and nearly 4-pi acceptance) final spin states, 1965 suggestions of Lee and Wolfenstein, Prentki and Veltman, and Okun can finally be seriously tested. As a colliding beam facility, the colliding beams would be passed back and forth between two partial rings (each 3/4 of the original rounded-square design) in a figure-eight configuration.

EDMs in chiral EFT

Rob Timmermans

University of Groningen, Faculty of Science and Engineering,
Groningen, The Netherlands

I will review the theory of hadronic electric dipole moments (EDMs) in the framework of chiral effective field theory (EFT), starting from the QCD vacuum angle and P- and T-violating dimenstion-six quark-gluon operators. I cover predictions for the EDMs of the nucleons, light nuclei, and heavy diamagnetic atoms. The successes and some outstanding issues of the approach are discussed.

Search for time-reversal invariance violation in double polarized pd scattering

Yu.N. Uzikov

[1] *JINR, Joliott-Curie 6, Dubna, Moscow reg. 141980 Russia*

Baryon asymmetry of the Universe is not explained by the Standard Model with CP violation effect known from physics of kaons and B-mesons and suggests additional sources of CP violation. One of such sources is the time-reversal violating and parity-conserving (TVPC) millistrong interaction suggested in 1965. A possible manifestations of TVPC interaction is the T-odd asymmetry in the transmission of tensor-polarized deuterons through a vector-polarized hydrogen gas target [1]. Experimental study of this effect was suggested at COSY [2,3] for pd collision. The null-test signal of the TVPC was studied in Ref. [4] within the Glauber theory of the double-polarized pd scattering in the GeV region. Full spin dependence of the ordinary T-even P-even pN scattering and phenomenological T-odd P-even NN-interaction [5] was included. It was show that the non-zero null-test signal influenced by the deureon D wave and drastically variates with the proton beam energy in the region 100-1000 MeV. One problem of asymmetry measurement in [2,3] is caused by the ordinary strong interaction contribution connected with nonzero magnitude of the vector polarization of the deuteron Py [5].

A new approach for measurement of the same asymmetry with polarized deuterons stored in a ring, interacting with internal polarized proton target which allows to avoid the above mentioned problem is suggested recently [6]. Upon the rotation of the deuteron polarization from the vertical direction into the ring plane, the T-odd asymmetries, odd against the reversal of the proton polarization in the target, will continuously oscillate with first or second harmonics of the spin precession frequency. The Fourier analysis of the oscillating T-odd asymmetries allows for an easy separation from background persistent in conventional experiments [2,3] employing static vector and tensor polarizations.

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Beam based alignment at the Cooler Synchrotron (COSY) and beyond

T. Wagner[1,2]

[1]Institut für Kernphysik, Forschungszentrum Jülich, Germany
[2]III. Physikalisches Institut B, RWTH Aachen University, Germany

t.wagner@fz-juelich.de

In order to measure the electric dipole moment (EDM) of charged hadrons in storage rings with a high precision one needs to have a small systematic error on the measurement. A large contribution to the systematic error is due to unknown magnetic fields, which are picked up when one is off of the optimal orbit. This can be reduced by controlling the orbit to a high precision and thus obtaining a small orbit root mean square (RMS).

In order to achieve a good orbit RMS in an accelerator one needs to know the size of the offsets between the beam position monitors (BPMs) and the quadrupoles. In order to determine these offsets one can use the beam-based alignment method, which finds the magnetic center of a quadrupole with respect to the electric center of a BPM. When the offsets between the BPMs and quadrupoles are then known, one can re-calibrate the BPMs to have the zero orbit going through the magnetic centers of the quadrupoles.

The working principle of this method will be explained and the results of the beam-based alignment measurement done at the storage ring COSY will be shown. Additionally, ideas on how to make the beam-based alignment easier in future accelerators will also be discussed.

Long Spin Coherence Times and How to Find Them

A. Wrońska[1] **for the JEDI Collaboration**

[1]*Marian Smoluchowski Institute of Physics, Jagiellonian University, Łojasiewicza 11, 30-348 Kraków, Poland*

One of the requirements for measuring the electric dipole moments (EDMs) of light hadrons using a storage ring is a sufficiently long lifetime for the in-plane polarization component of the circulating beam [1]. The JEDI Collaboration performed extensive experimental studies to optimize the settings of the COSY ring for long spin coherence times (SCT) using a deuteron beam of 0.97 GeV/c momentum. This talk will give an overview of those efforts and describe the results.

In a magnetic storage ring like COSY, the polarization vector of a horizontally polarized beam precesses in the ring plane. The ratio of that precession frequency to the revolution frequency is the spin tune $\nu_s = G\gamma$, where G is the deuteron magnetic anomaly and γ is the Lorentz factor. Even with a bunched beam, the spread of γ values is directly related to the spread of spin tunes that leads to depolarization of the beam. For COSY, the different values of γ arise from beam particles in the bunched beam that have different orbit lengths due to different betatron oscillation amplitudes.

The first success in the quest for long SCT values was described in [2], where an SCT of over a thousand seconds was reported. It required a combination of beam bunching, electron cooling and a careful setting of sextupole fields. Additionally, the beam current was limited in order to suppress collective effects. A more detailed analysis of experimental data confirmed the connection between maximal SCT values and *x*- and *y*- chromaticity values of zero [3]. Subsequent study dedicated to electron cooling showed that continuous cooling throughout the whole beam cycle led to even longer SCT values [4], but this scheme remains incompatible with EDM measurements. A fast chromaticity measurement tool was developed at COSY to facilitate efficient SCT optimization.

Proton beams are significantly different in terms of polarization handling from deuteron beams. This is due to the much larger magnetic anomaly of protons and the larger strength of multiple spin resonances in the storage ring. The preliminary results from simulation studies along with the prospects of their experimental verification will be presented as an outlook.

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