ERC Advanced Grant 2019
Part B1

ERC Advanced Grant 2019 Research proposal [Part B1]

Axion Storage Ring Experiments

asterix

Cover Page:

- Name of the Principal Investigator (PI): Prof. Dr. Jörg Pretz
- Name of the PI's host institution for the project: Forschungszentrum Jülich (Germany)

- Proposal duration in months: 60

Among the deepest mysteries in natural sciences stands the question of what the universe is made of. Visible matter, comprising Standard Model (SM) particles, accounts only for a small fraction. As inferred from cosmological observations, about 5 times more matter is invisible and is called dark matter (DM). Intriguingly, next-to-nothing is known about DM: current understanding is that DM consists of (a) non-SM particle(s) of unspecified mass, which remain(s) to be discovered. Well-motivated candidates for DM are axions or axion-like particles (ALPs).

`asterix` (**A**xion **ST**orag**E** **RI**ng e**X**periments) will indirectly search for light DM particles by observing the impact of the field associated with ALPs on the polarization of particles. ALPs generate an oscillating electric dipole moment (EDM) in subatomic particles such as proton and deuteron with an oscillation frequency proportional to its mass. EDMs can be observed by studying their influence on the spin motion of particles. `asterix` will look for a resonance between the spin precession of a beam of polarized particles in a storage ring and the ALP oscillation. The observable is a frequency which can be determined with very high accuracy. The method allows one to either concentrate on a very narrow mass region or to scan an axion mass window of many orders of magnitude.

`asterix` proposes axion/ALP experiments at the existing storage ring COSY at Forschungszentrum Juelich, Germany and feasibility studies for a future dedicated storage ring for EDM measurements. It is important to note that COSY, with its available equipment and established techniques to handle polarized beams, is the only accelerator facility worldwide where this project can currently be realized.

As a pathfinder experiment `asterix` will provide a powerful sensitivity and offer a unique window to search for DM. Discovery of DM will be a major scientific breakthrough, while a non-observation will put essential constraints on the nature of DM.

Section a: Extended Synopsis of the scientific proposal

Motivation: The Quest for Dark Matter

Since the earliest times of mankind, people have looked at the night sky with awe, wondering what these tiny luminous objects in heaven might be. Today - though few of us have had a chance to see even our own galaxy (Milky Way) in full glory - it is known to most people that we are only able to see a fraction of the Milky Way and an even tinier part of the vast visible Universe, as e.g. observed through electromagnetic radiation, ranging from radio waves to visible light and beyond.
It may come as no surprise that astronomical observations over the past almost 100 years have accumulated more and more evidence that this luminous part (stars, galaxies and clusters) only constitutes a fraction of the mass in our Universe: in fact only about one-fifth of the matter is made of fundamental particles that we know and understand; the majority of the matter is not visible and thus dubbed dark matter (DM).
Dark matter has been postulated by the need for much more mass than actually seen in rotating galaxies in order to bind them by the gravitational force, compensating the centrifugal force. This is schematically shown in Figure 1.

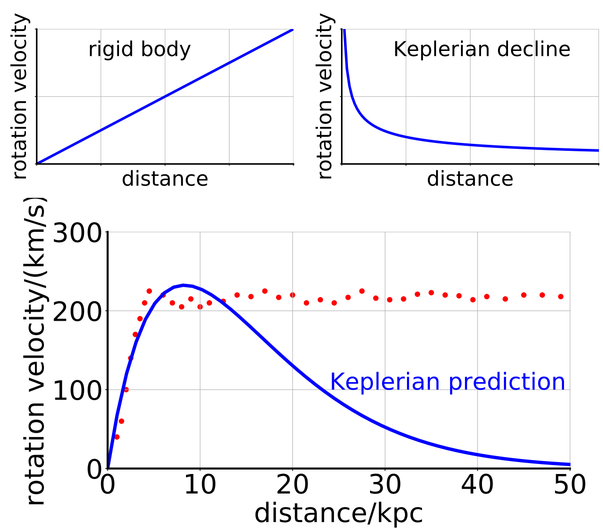

Figure 1: *Rotational speed for a rigid body (top left) and for Keplerian motion, e.g. our solar system, with most of the mass centered at zero (top right). Below the result (red dots) for a typical spiral galaxy is shown. The disagreement with the Keplerian prediction for $R > 10\,\mathrm{kpc}$ (i.e. the constant speed) was first observed by F. Zwicky in the 1930s in the Coma Cluster and indicates that more mass than visible must be present.*

There are further compelling observations indicating the existence of DM, e.g. gravitational lensing and its role in the evolution of structure in the Universe. However, what DM actually is, remains a mystery. It is important to note that none of the known building blocks of the (otherwise remarkably successful) Standard Model (SM) of elementary particle physics can serve as DM. This implies that the SM is incomplete and a discovery of DM particles would be conclusive evidence for physics beyond the SM (BSM).
There is mounting evidence for the need of DM and the search is ongoing by a suite of dedicated experiments [1], but no DM particle(s) has(have) been observed to date, although there have been claims [2]. The allowed DM-parameters of mass and coupling to SM particles spans a huge range, which requires very different techniques for discovery. The following principle search strategies for DM are currently exploited:

- Direct production of DM particles at accelerators
- Detection of galactic DM particles through interactions with SM matter
- Detection of DM as coherently oscillating waves

As will be detailed later, the `asterix` project will exploit the 3rd option, observing dark matter particles via their creation of oscillating electric dipole moments (oEDM) in nucleons and its resulting effect on the spin motion of an ensemble of particles (a beam) in a storage ring.

Dark matter candidates: Axions and axion-like particle (ALPs)

The SM of particle physics provides no solution to the DM problem. As a consequence new particles outside the realm of the SM have been proposed as dark matter candidates. Among them are so called WIMP (Weakly Interacting Massive Particles). In spite of enormous experimental effort, no DM particle was found up to now. It it thus important to widen the search to other, theoretically well motivated DM candidates [3]. These include ultralight particles like axions and axion-like particles (ALPs). Originally axions were introduced to solve the so called strong CP-problem in the Standard Model of particle physics [4, 5, 6, 7] (see information box: "Symmetries"). If axions are responsible for dark matter, they must be very light with their mass being below 10^{-6}eV, i.e. 15 orders of magnitudes lighter than the proton.

Symmetries

Symmetry considerations play an important role in modern physics. Until the middle of the last century it was assumed that left and right-handed processes occur with the same probability (symmetry under parity transformation $\mathcal{P}$), and that in the microscopic world a process is invariant under the reversal of the direction of time (time reversal symmetry, $\mathcal{T}$). Processes where all particles are replaced by their anti-particles occur with the same probability (symmetry under charge conjugation $\mathcal{C}$). Today we know that weak interactions violate all three symmetries.

The Standard Model allows also for $\mathcal{P}$ and $\mathcal{T}$ violation in strong interactions, but nature does not make use of this. The corresponding parameter, called θ_{QCD}, is very small and consistent with zero. This is known as the strong CP-problem. The introduction of a new symmetry naturally explains the smallness of θ_{QCD} [4, 5] and leads to a new particle, the axion [6, 7].

Axions may interact with ordinary matter in different ways. Most of the axion searches are based on the axion-photon interaction. Other experiments make use of the axion interaction with atomic nuclei or the coupling to the spin. To study the latter effects, the well known nuclear magnetic resonance technique [8] can be used.

We will look at the effect of axions on the spin motion of a particle ensemble in a storage ring [9]. Axions couple to gluons inducing an oscillating electric dipole moment (oEDM) on nucleons or nuclei [10]. These oEDM can be detected in a storage ring by making use of resonant methods enhancing the effect and allowing for unprecedented precision. More details on the connection between magnetic dipole moments (MDMs), EDMs and spin are given in the information box "MDM, EDM & Spin".

Experimental Method: Spin Precession in Storage Rings

Fig. 2 shows the principle of the experimental approach. Spin polarized particles are stored as a beam on a circular orbit in a storage ring. The polarization vector $\vec{P}$, given by the average over the spin vectors $\vec{S}$ in a particle ensemble, precesses due to the MDM, similar as in an NMR experiment, with a frequency Ω_{MDM}. If the axion oscillation frequency, ω_{axion}, equals Ω_{MDM} a resonance occurs and a vertical polarization build-up due to the oEDM can be observed as indicated in Fig. 2 (see also information box "MDM, EDM & Spin"). In a magnetic storage ring the precession

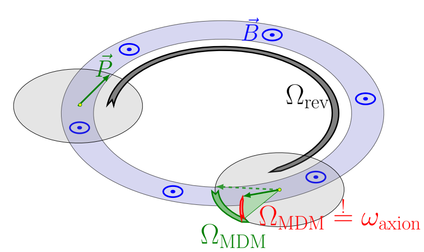

Figure 2: *Principle of axion experiment. The polarization $\vec{P}$ precesses in the horizontal plane with the angular frequency Ω_{MDM}. For $\Omega_{\mathrm{MDM}} = \omega_{\mathrm{axion}}$ a resonant build-up of the vertical polarization due to the oEDM can be observed.*

frequency Ω_{MDM} depends on the energy of the particle and the magnetic moment. It is given by

$$\Omega_{\mathrm{MDM}} = \gamma G \Omega_{\mathrm{rev}}$$

where γ denotes the relativistic Lorentz factor, G the magnetic anomaly and Ω_{rev} the angular revolution frequency of the beam.

The COoler SYnchrotron (COSY) is a storage ring with a circumference of 184 m at the Institut für Kernphysik (IKP) of Forschungszentrum Jülich (FZJ) [11, 12]. COSY stores and accelerates polarized proton and deuteron beams in the momentum range from $0.3\,\mathrm{GeV}/c$ to $3.7\,\mathrm{GeV}/c$. Given these conditions, Ω_{MDM} can be varied in the range $(0.3 - 70) \cdot 10^6\,\mathrm{s}^{-1}$. This corresponds to an axion mass region $1.5 \cdot 10^{-10} - 5 \cdot 10^{-8}\,\mathrm{eV}$. A much wider range in Ω_{MDM} can be covered using a combination of electric and magnetic fields to store the beam. Using appropriate field combinations Ω_{MDM} can even reach zero. This so called frozen spin condition allows to search for ALPs down to mass 0. These kind of measurements could be performed at a new class of storage rings planned for permanent electric dipole measurements [13, 14].

Building upon the capabilities at Forschungszentrum Jülich, within `asterix` we will perform measurements at the existing magnetic storage ring COSY for protons and deuterons. These measurements will also include systematic studies: The essential question how an oscillating magnetic or electric field or other parameters might lead to a fake axion signal will be studied. These results will have an important impact on the design and measurements at a dedicated storage ring where a combination of electric and magnetic fields can be applied.

Axion searches at storage rings have the advantage, compared to other experiments looking for axion production or absorption, that experimentally one can either span a large mass (frequency) region (with smaller sensitivity to the axion-gluon coupling) or concentrate on a very narrow mass region (with a much higher sensitivity). The second case is of interest if some other experiment would have indications for an axion/ALP at a given mass. In this case one would spend the measurement time available on exactly one frequency, corresponding to the mass m_a and look for a resonance signal thus scrutinizing any claim.

MDM, EDM & Spin

Sub-atomic particles with spin, like electron, neutron, proton and deuteron have a magnetic dipole moment (MDM), i.e. they act as a tiny dipole magnet. The effect of the proton MDM, e.g. its precession in external magnetic fields, is routinely exploited in nuclear magnetic resonance (NMR)/magnetic resonance imaging (MRI). An electric dipole moment (EDM), which is caused by the separation of the positive and the negative charge (centers) by some finite distance, must also exist. EDMs have not yet been observed due to their smallness, because finite EDMs violate both P and T symmetries. Both, MDM and EDM have to be aligned along the spin vector $\vec{S}$ of the particle as depicted in Figure 3. The spin vector precesses in a magnetic or electric field due to $\vec{\mu}$ and $\vec{d}$ respectively.

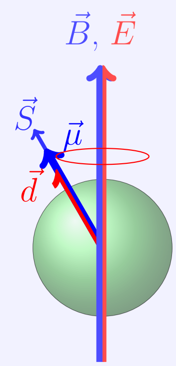

Figure 3: *Spin precession in a magnetic ($\vec{B}$) and electric ($\vec{E}$) field due to the MDM $\vec{\mu}$ and EDM $\vec{d}$ in a subatomic particle.*

Studying the spin precession gives thus access to the MDM and EDM of the particle. Axions and axion-like particles induce an oscillating EDM in nuclei, where the oscillation frequency is given by the Compton frequency

$$\omega_{\mathrm{axion}} = \frac{m_a c^2}{\hbar}\,,$$

where m_a is the axion mass. This oscillation of the EDM $\vec{d}$ can be studied in storage rings making use of resonance effects.

Objectives

`asterix` has two major objectives:

1. Perform a first search for axions/axion-like particles at the existing storage ring COSY at the Forschungszentrum Jülich, Germany.
2. Explore the sensitivity for measurements in a wide axion mass range $m_a < 10^{-8}$ eV at a dedicated storage ring planned for electric dipole moment measurements.

Impact

The search for DM belongs to the grand challenges of contemporary science, which has initiated huge experimental efforts at laboratories around the world to explore the vast possible parameter space (DM particle mass, coupling to SM particles). `asterix` will focus on DM candidates (axion, ALPs) and be sensitive, via an oscillating EDM, to the coupling to gluons; its expected impact comprises:

- Establishment of a new method for DM search, using polarized beams in storage rings;
- Generation of first results from DM searches with proton and deuteron experiments at COSY with a sensitivity comparable with existing limits in the same mass range ($1.5 \cdot 10^{-10} - 5 \cdot 10^{-8}$ eV);
- Foundation of the basis for measurements in largely uncharted territory ($m_a < 10^{-12}$ eV) at dedicated storage rings; and
- Training and education of students and young researchers in a wide range of scientific areas: accelerator physics, simulations, precision measurements and data analysis.

Feasibility and Team

The core team consists of members of the JEDI collaboration.[1] The JEDI collaboration has vast experience in running precision experiments at storage rings since 2011 in the search for permanent electric dipole moments. `asterix` will allow us to open a new research field by searching for oscillating EDMs in storage rings.
The experiment will be performed at the Cooler Synchrotron COSY at the Institut für Kernphysik (IKP) of Forschungszentrum Jülich. Equipment and techniques needed for spin-manipulations of polarized beams are available and routinely used by the JEDI collaboration for EDM measurements. COSY is worldwide unique for this kind of studies.
The local team at Forschungszentrum Jülich consists among others of the head of the accelerator institute, Dr. Ralf Gebel (expert in polarized sources, accelerator operation), and Prof. Dr. Andreas Lehrach, who has huge experience in beam/spin simulation studies. Dr. A. Wirzba, an expert in EDMs of hadrons and light nuclei, provides support from the theory side. Additional partners, having distinguished experience in axion searches, will also contribute to the project: Prof. Dr. Y. Semertzidis, Prof. Dr. S. Park from KAIST/IBS, Daejeon, South Korea and Prof. Dr. D. Budker and Prof. Dr. M. Schott from the University of Mainz, Germany.
For `asterix` to be successfully conducted, resources for a number of PostDocs and PhDs positions, requested in this proposal, are required.

Time line and work packages

The first two years will be used for accelerator studies (work package WP1), like increasing the beam intensity and studies for large spin coherence time for protons. In the third and fourth year

[1] http://collaborations.fz-juelich.de/ikp/jedi/

measurements with protons and deuterons are planned at COSY (WP2) yielding physics results after the five year running period of the grant. Concurrent to the experimental work simulations will be conducted to understand and interpret the measurements and to study the possibility of an axion/ALP measurement at a combined E/B storage ring (WP3). Finally, one work package is dedicated to the analysis of the data taken in WP1&2 (WP4).

	Month 1-12	Month 13-24	Month 25-36	Month 37-48	Month 49-69
WP1 COSY preparation					
WP2 COSY measurements					
WP3 simulations					
WP4 analysis					

Risk assessment

- As many as possible polarized particles stored are required to reduce statistical errors. Typically 10^9 particles are achieved at COSY. One work package will deal with intensity increase up to 10^{10} particles. Note that the space charge limit is around 10^{11} particles.
- For a successful measurement a long spin coherence time is needed, which allows for a polarization build-up due to an oEDM to be observed. For deuterons, 1000 s are now routinely reached at COSY. One work package includes studies to reach the same level for protons, which may be more difficult, due to the larger magnetic dipole moments of protons as compared to deuterons. No principle obstacle is expected - it may require longer beam development time.
- The high risk - high gain aspect is given by the fact that as for any precision experiment, one may find new systematic effects, not known today. This will not prevent the project from being successful, but eventually limit the sensitivity or require additional effort and time.

Summary

In conclusion, capitalizing on the unique capabilities of the existing infrastructure at Forschungszentrum Jülich and the world-leading expertise of local and international experts involved in `asterix`, a successful completion of the project will start a new era of precision DM searches and establish a new research field of physics. Completion of the `asterix` project after 5 years will yield a significant physics result and extremely valuable experience for further studies.

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Section b: Curriculum vitae

PERSONAL INFORMATION

Family name, First name:	Pretz, Jörg
Researcher unique identifier(s) (ORCID ID):	https://orcid.org/0000-0001-9128-419X
Date of birth:	01 June 1966
Nationality:	German
URL for web site:	Website Jülich Website RWTH Aachen

EDUCATION

2007	Habilitation University of Bonn, Germany
1997	PhD (Dr. rer. nat.) University of Mainz, Germany
1992	Diploma in physics University of Mainz, Germany
1990	Maîtrise de physique Université de Provence, Marseille

CURRENT POSITION(S)

2017 - present	Research Scientist Forschungszentrum Jülich, Jülich, Germany
2012 - present	Professor of physics RWTH Aachen University, Aachen, Germany

PREVIOUS POSITIONS

2000 - 2011	Research Scientist University of Bonn, Bonn, Germany
2004 - 2005	Scientific Associate CERN, Geneva, Switzerland
1998 - 2000	Associate Research Scientist Yale University, New Haven, USA

FELLOWSHIPS AND AWARDS

2016	Participant in program "Frontiers in Nuclear Physics" Kavli Institute for Theoretical Physics, University of California Santa Barbara, USA (3 months)
2005	Scientific associate at CERN, Genava, Switzerland (11 months)
1989 - 1990	Erasmus scholarship, Université de Provence, Marseille

SUPERVISION OF GRADUATE STUDENTS AND POSTDOCTORAL FELLOWS

2011 - present	Number of postdocs (3)/ PhD(7)/ master students(8)/bachelor students (14) RWTH Aachen University and University of Bonn

TEACHING ACTIVITIES

2008 - 2011	Privatdozent, University of Bonn, Germany Lectures: data analysis, particle physics, basic physics courses
2012 - present	Professor, RWTH Aachen University, Germany Lectures: data analysis (Bachelor and Master level), basic physics courses for engineers, laboratory courses in accelerator physics

ORGANISATION OF SCIENTIFIC MEETINGS

2018	Chair of 7th International Symposium on Symmetries in Subatomic Physics (SSP18), Aachen, Germany (≈ 100 participants)
2012 - 2017	Organization of 14 international collaboration meetings for the JEDI (Juelich Electric Dipole Investigations) collaboration, in Jülich, Germany, Ferrara, Italy and Cracow, Poland (≈ 40 participants)

INSTITUTIONAL RESPONSIBILITIES

2016 - present	Director of JARA-FAME (Jülich-Aachen Research Alliance-Forces And Matter Experiments)
2012 - present	Faculty member, RWTH Aachen University

REVIEWING ACTIVITIES

- Co-editor for proceedings of the conference
  Symmetry in Subatomic Physics, 2018, Aachen, Germany
- Review for experiment proposal,
  Jefferson Laboratory, Virginia, USA,
- committee for professor positions at IBS,
  Institute for Basic Science, Daejeon, South Korea
- Reviewer for various journals including Journal of physics G,
  Nuclear Instrument and Methods, Modern Physics Letters
- Reviewer for ETH Grants Research Proposal,
  ETH Zürch, Switzerland

MEMBERSHIPS OF SCIENTIFIC SOCIETIES

Member of "Deutsche Physikalische Gesellschaft (DPG)"

MAJOR COLLABORATIONS

2012 - present	**JEDI Collaboration** Forschungszentrum Jülich, Germany spokesperson since 2012, collaborators: Prof. Dr. H. Ströher (Jülich)
2000 - present	**COMPASS Collaboration** CERN, Geneva, Switzerland Coordination of trigger group, analysis coordinator, collaborators: Prof. Dr. D. von Harrach (Mainz), Prof. Dr. F. Klein (Bonn), Prof. Dr S. Paul (München)
1998 - 2000	**Muon g-2 collaboration** Brookhaven National Laboratory, Upton, NY, USA analysis coordinator, collaborators: Prof. Dr. V. Hughes (Yale), Prof. Dr. L. Roberts (Boston), Prof. Dr. D. Hertzog (Washington)

Appendix: All ongoing and submitted grants and funding of the PI (Funding ID)

Project Title	Funding source	Amount (Euros)	Period	Role of PI	Relation to current ERC proposal
srEDM 694340	EU	678 909	2016-21	beneficiary RWTH Aachen University	use of COSY

Section c: Ten years track-record

- Since the beginning of 2012, I am one of the spokespersons of the JEDI (Jülich Electric Dipole moments Investigations) collaboration. The goal is to perform measurements of permanent electric dipole moments of charged particles in storage rings [C1]. The collaboration comprises about 100 members. I was heavily involved in the key publications of the collaboration. In Ref. [C2] for the first time the 120 kHz precession of the polarization vector in a storage ring was measured to a relative precision of 10^{-9}. In Ref. [C3] a polarization feedback system is described, which allows to control a polarization direction to 0.21 mrad. Ref. [C4] describes how to obtain a 1000 s spin coherence time. Refs. [C2, 3] were based on PhD theses in my group.
- I am a member of the EDM working group of the PBC (physics beyond colliders) initiative at CERN, where a strategy for new dedicated EDM storage has been proposed.
- I widened my research field and started to investigate the possibility to search for axions and axions-like particles in storage rings. In June 2019, I was invited to give a presentation at one of the leading conferences in the field (15th Patras Workshop on Axions, WIMPs and WISPs, Freiburg, Germany).
- I co-authored articles for a broader audience in the Physik-Journal [C5] and CERN-Courier [C6].
- I am also active in outreach activities to explain my research to a general audience. This resulted in a invitation to the ”Campus Talks”, the German equivalent of TED talks, where a research field is presented to a lay audience in a 15 minute presentation.
- Previously I worked in the COMPASS experiment and the muon $g-2$ collaboration [C7]. In both collaborations I worked as a coordinator of the analysis group. The main goal of the COMPASS collaboration was the determination of the gluon helicity contribution to the nucleon spin [C8]. This was also the subject of my habilitation thesis.
- One common research interest I pursued in all activities is the development of algorithms to analyze data in a statistically optimal way. Several publications resulted in this area, e.g. [C9, 10].
- My current h-index is 41, 115 publications, 9132 citations (web of science, August 2019).

Most important invited presentations at conference, schools and seminars

- 15th Patras Workshop on Axions, WIMPs and WISPs,
  June 2019, Freiburg, Germany
- 6th Symposium on Prospects in the Physics of Discrete Symmetries, DISCRETE 2018,
  Nov. 2018, Vienna, Austria
- Discrete Symmetries in Particle, Nuclear and Atomic Physics and implications for our Universe,
  Oct. 2018, ECT* workshop, Trento, Italy
- Caucasian German School and Workshop in Hadron Physics 2018 (CGSWHP18)
  Aug. 2018, Tiblisi, Georgia
- Seminar “Electric Dipole Moment Measurements at Storage Rings”
  Nov. 2016, UCSB, Santa Barbara & UW, Seattle, USA

- Bethe Forum on Axions & the Low Energy Frontier
  Mar. 2016, Bonn, Germany

Contribution to early career scientists

- Marcel Rosenthal, former PhD student, received the JARA excellent Junior award 2015. He now holds a fellowship at CERN.

Most important publications relavant to the project

[C1] Pretz, Jörg, "Measurement of Permanent Electric Dipole Moments of Charged Hadrons in Storage Rings," *Hyperfine Interact.*, vol. 214, no. 1-3, pp. 111–117, 2013. [Online]. Available: https://doi.org/10.1007/s10751-013-0799-4, (34 citations, inspire, August 2019)

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ERC Advanced Grant 2019
Part B2

Section a. State-of-the-art and objectives

The case for dark matter

There is overwhelming cosmological and astrophysical evidence for the existence of cold dark matter (DM). It all started with the observation by Fritz Zwicky in the 1930s that galaxies in the so called Coma-cluster were moving too fast to be bound together by the gravitational interaction of its visible matter. He also invented the name "dunkle Materie" (German for dark matter) for the speculative unidentified matter, which he estimated to be 200 times as abundant as the luminous part. We now know that the ratio is more likely less than 10, but the puzzle is still with us. In the meantime, further observational support for DM has been obtained, e.g. from gravitational lensing: predicted by Einstein, it has become a very powerful tool to locate mass in the Universe. Astronomers have learned a lot about the distribution of mass in galaxies and clusters, and realized that DM must be present: in fact, one now is even able to reconstruct the distribution of DM in clusters. It is possible to generalize the need for DM to an even more fundamental level: if scientists try to reproduce the formation of large-scale structures in the Universe they are forced to include DM for their simulations to agree with observation or to modify the gravitational interaction at large distances. While the specific details depend on the type of DM, it seems that it has to be cold, meaning that it moves at velocities, very small compared to the speed of light; hot DM would prevent galaxy formation.
In recent years, the Hubble expansion has been found to accelerate as a function of time. This observation constituted a breakthrough discovery, for which the Noble prize was awarded in 2011. It implies that yet another source of energy must be present in the universe, which is called Dark Energy (DE): very little is known about DE as well. In fact, DE is the predominant part of the total energy density (the estimated fraction is 68%), while DM accounts for 27% and the well-known ordinary matter (as inferred e.g. from the Cosmic Microwave Background and the element abundances from primordial nucleosynthesis) represents a mere 5% [1]. Dark Energy will not be considered any further, while the next part discusses the nature of Dark Matter.

The nature of Dark Matter

Dark Matter interacts only very weakly with normal matter and does essentially not emit, absorb or reflect light - it is only seen by its gravitational effect on normal matter. Initially, scientists were first resorting to ordinary matter, e.g. dust, rocks, faint stars (brown and white dwarfs), neutron stars etc., to account for DM. However, observational and theoretical work showed that MACHOs (Massive Astrophysical Compact Halo Objects), comprising ordinary baryonic matter, are not likely to contribute a large fraction of DM; the Big Bang, as currently understood, could not have produced enough baryons. Electrically neutral and only weakly interacting with matter, neutrinos were also considered as a possible source of DM. The right value for the combined neutrino mass to explain DM would have been around 100 eV. However, in addition to being relativistic, we now know that the summed mass of the 3 neutrino species

(notwithstanding the hypothetical sterile neutrinos, which might be heavier) is less than 1 eV, which implies that they only provide less than a percent of the energy density of the universe and thus play a minor role in cosmology.
Today, the conviction of a very large fraction of scientists (from cosmology, astrophysics and elementary particle physics) is that DM comprises some exotic form of non-baryonic elementary particle(s). Detailed properties like its mass are highly unconstrained: it could range over almost 40 orders of magnitude, from 10^{-22} eV (if responsible for structure formation) to 10^{14} eV (thermal production in early Universe). WIMPs (Weakly Interacting Massive Particle) in the range around the nucleon mass and above have dominated the experimental searches in the past with no positive result. Thus, more recently, the emphasis has been extended to much smaller masses, including ultralight bosonic fields (10^{-22} to 0.1 eV): in contrast to WIMPs, which would manifest themselves as a dilute gas of single particles, ultralight DM would behave as a wave-like field due to their presence in very high numbers (more precisely: "Whether DM is best described by a particle picture or a wave picture is determined by the occupation number of particles within a volume of radius equal to the de Broglie wavelength. If the occupation number is much larger than unity, the DM is best described as a wave. The crossover occurs at a DM particle mass of about 1 meV, i.e., below this mass the wave description is better." [2].)

A theoretically very attractive candidate for dark matter particles are axions. Originally they were introduced to solve the so called strong CP-problem: The strong interaction sector of the Standard Model contains a parameter called θ_{QCD} which allows for a violation of parity P and time reversal symmetry T. Measurements of the neutron EDM indicate that $|\theta_{QCD}|$, which could in principle take any value between 0 and 2π, is smaller than 9×10^{-11}, i.e. nature does not make use of this term. The unnatural smallness of this parameter is called the strong CP problem. One possible solution to this problem is the introduction of an additional global symmetry (Ref. [3, 4]) by considering θ_{QCD} as a field rather then a fixed parameter. The introduction of such a symmetry leads to the prediction of a new light pseudoscalar particle, the QCD-axion [5, 6]. Axions may only be representatives for a new particle family, so called Weakly Interacting Slim Particles (WISPs). Among them are also so called axion-like particles (ALPs) predicted by string-theory extensions of the Standard Model. Astrophysical observations like the transparency of the universe to TeV photons and the evolution of stars are also indications for the existence of ultra-light ALPs [7].

Axion/ALP Dark matter Experiments

Given the theoretical motivation for axion and ALPs (in the following we often use the word axion for both), it is not surprising that a huge experimental effort goes into the search for axions. For a detailed review, we refer the reader to Refs. [7, 8].
Axions and ALP can interact with ordinary matter in various ways. Ref. [9] identifies three terms:

$$\frac{a}{f_0} F_{\mu\nu}\tilde{F}_{\mu\nu}, \quad \frac{a}{f_a} G_{\mu\nu}\tilde{G}_{\mu\nu}, \quad \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi \tag{1}$$

describing the coupling to photons, gluons and to the spin of fermions, respectively. The vast majority of experiments makes use of the first term (e.g. Cavity experiments (ADMX), helioscopes (CAST), light-through-wall experiments (ALPS)). In addition, astrophysical observations also provide sensitive limits to the axion-photon coupling. In general, it is rather difficult for these experiments to reach masses below 10^{-6} eV, one reason being that the axion

wave length becomes too large.
Furthermore, these experiments are measuring rates proportional to at least a small amplitude squared $\propto A^2$. For the second (and third) term in the list (1) this is different. It turns out that the second term has the same structure as the QCD-θ term which is also responsible for an electric dipole moment (EDM) of nucleons. The axion field gives rise to an effective time-dependent θ-term and oscillates at a frequency proportional to its mass m_a (see information box "Axions and oscillating EDMs"). This gives rise to an oscillating EDM as well. New opportunities to search for axions/ALPs with much higher sensitivity arise, because the signal is proportional to an amplitude A and not to its square. To date, NMR based methods are being used to look at oscillating EDMs [10].
While none of the axion experiments reported a (undisputed) positive signal, the negative results constrain more and more theoretical models extending the Standard Model.
`asterix` (**A**xion **ST**orag**E** **RI**ng e**X**periments) proposes to widen the search and to look for axions in a mass range not well covered yet using a completely new method - the observation of a resonant polarization build-up of a particle beam in a storage ring.

A novel experimental approach: Axion searches in storage ring

Since many years, there is an increasing effort to search for permanent EDMs of charged hadrons in storage rings [11, 12, 13]. An ideal starting point for this kind of studies is the Cooler Synchrotron COSY of Forschungszentrum Jülich (Germany), which provides polarized proton and deuteron beams in the momentum range $0.3 - 3.7\,\mathrm{GeV}/c$. This effort can be extended to oscillating EDMs caused by axions. Experimentally, this may even be simpler because the measurement of an oscillating (frequency) quantity is usually less plagued by systematic uncertainties.
`asterix` has two main objectives:

1. Perform a first search for axions/ALP particles at the existing storage ring COSY at the Forschungszentrum Jülich, Germany.
2. Explore the possibility for measurements in a wider axion/ALP mass range $m_a < 10^{-8}\,\mathrm{eV}$ at a dedicated storage ring planned for electric dipole moment measurements.

Theoretical Background: Axions and oscillating EDMs
In the so called pre-inflationary Peccei-Quinn symmetry breaking scenario [3], the axion field oscillates coherently at the Compton frequency

$$\omega_{axion} = \frac{m_a c^2}{\hbar}\,,$$

where m_a is the axion mass. The energy density of the axion field is given by

$$\rho = \frac{m_a^2 a_0^2}{2}$$

where a_0 is the amplitude of the axion field.
The ratio a_0/f_a, where f_a denotes the axion decay constant, corresponds to an oscillating contribution to the QCD-θ angle which in turn induces an oscillating contribution to the EDM d of the nucleon [9, 14]:

$$d^{\mathrm{osc}} \approx 10^{-16}\,\frac{a_0}{f_a}\cos(\omega_{\mathrm{axion}} t)\,,$$

Equating the energy density of the axion oscillations with the energy density of the local dark matter in our universe ($\rho_{\rm LDM} \approx 0.4{\rm GeV/cm}^3$ [15]), one arrives at an oscillating contribution to the EDM of the nucleon

$$d^{\rm osc} \approx 10^{-16} \frac{\sqrt{2\rho_{\rm LDM}}}{m_a f_a} \cos(\omega_{\rm axion} t)\,.$$

Since for axions the mass and decay constant are related by $m_a f_a \approx m_\pi f_\pi/2$, one obtains a contribution to the electric dipole moment on nucleons of the size

$$d^{osc} \approx 5 \cdot 10^{-35} \cos(\omega_{\rm axion} t)\, e\,{\rm cm}\,.$$

To detect an oscillation of an EDM of such small amplitude is very challenging. However, in case of an ALP there is no strict relation between the decay constant f_a and the mass m_a. This leaves room for much larger oscillation amplitudes accessible with the experiments proposed in the `asterix` project. The oscillation amplitude is usually quantified by the ALP-gluon coupling C_g/f_a, where C_g is a dimensionless parameter.

Section b. Methodology

This section describes first the experimental method used by `asterix` in more detail, followed by the methodology how this can be implemented given the available and requested resources.

Experimental Method

`asterix` will make use of the fact that axions induce an oscillating electric dipole moment (oEDM) on a subatomic particle like proton and deuteron (see information box "Theoretical background: Axions and oscillating EDMs"). EDMs in turn influence the spin motion of particles, which then can be measured with high precision at storage rings.

Spins of sub-atomic particles precess in magnetic and electric fields due to their magnetic dipole moment (MDM) and EDM, as indicated in Fig. 1 for a particle at rest. For particles with a finite velocity $\vec{v} = \vec{\beta}c$, the spin precession is more complex and offers more possibilities to manipulate the spin vector compared for example to NMR experiments.

Considering only vertical magnetic and radial electric fields to force particles on a circular orbit in a storage ring, as indicated in Fig. 2, the spin motion relative to the momentum vector is

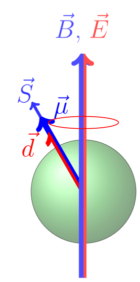

Figure 1: *Spin precession due to the EDM $\vec{d}$ and MDM $\vec{\mu}$ in a subatomic particle.*

given by the Thomas-BMT equation [16, 17]:

$$\begin{aligned}
\frac{d\vec{S}}{dt} &= (\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}}) \times \vec{S}, \\
\vec{\Omega}_{\mathrm{MDM}} &= -\frac{q}{m}\left[G\vec{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \\
\vec{\Omega}_{\mathrm{EDM}} &= -\frac{\eta q}{2mc}\left[\vec{E} + c\vec{\beta}\times\vec{B}\right].
\end{aligned} \tag{2}$$

$\vec{S}$ denotes the spin vector in the particle rest frame, t the time in the laboratory system, β and γ the relativistic Lorentz factors, and $\vec{B}$ and $\vec{E}$ the magnetic and electric fields in the laboratory system, respectively. The magnetic dipole moment $\vec{\mu}$ and electric dipole moment $\vec{d}$ both pointing in the direction of the particle spin $\vec{S}$ are related to the dimensionless quantities G (magnetic anomaly) and η in equation 2:

$$\vec{\mu} = g\frac{q\hbar}{2m}\vec{S} = (1+G)\frac{q\hbar}{m}\vec{S} \quad \text{and} \quad \vec{d} = \eta\frac{q\hbar}{2mc}\vec{S}\,. \tag{3}$$

Because axions lead to an oscillating EDM $\vec{d}$, the parameter η has the form:

$$\eta = \eta_0 + \eta_1 \sin(\omega_{\mathrm{axion}} t + \varphi_a)\,.$$

The oscillation frequency is directly related to the axion mass m_a and is given by the Compton frequency

$$\omega_{\mathrm{axion}} = \frac{m_a c^2}{\hbar}\,.$$

The parameter φ_a denotes the unknown phase between the axion field and the spin precession. It depends on the starting time of the experiment.

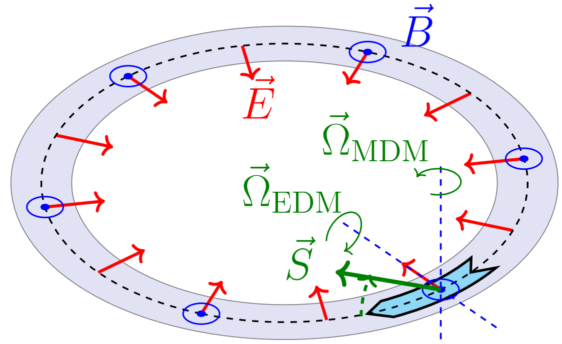

Figure 2: *Principle of the experiments.*

Solving the differential equation 2 to first order in η_1 one finds for the vertical spin component, S_v, for a beam initially polarized along the momentum vector, ignoring fast oscillating terms

$$\begin{aligned}
S_v(t) &= \frac{\eta_1\Omega_{\mathrm{EDM}}}{2(\omega_{\mathrm{axion}} - \Omega_{\mathrm{MDM}})}\left(-\frac{2\omega_{\mathrm{axion}}\sin(\varphi_a)}{\omega_{\mathrm{axion}} + \Omega_{\mathrm{MDM}}} + \sin\left((\omega_{\mathrm{axion}} - \Omega_{\mathrm{MDM}})t + \varphi_a\right)\right) && (4)\\
&\quad \text{for} \quad \Omega_{\mathrm{MDM}} \neq \omega_{\mathrm{axion}} \\
&= \frac{\eta_1\Omega_{\mathrm{EDM}}}{2}\cos(\varphi_a)\,t && (5)\\
&\quad \text{for} \quad \Omega_{\mathrm{MDM}} = \omega_{\mathrm{axion}}\,.
\end{aligned}$$

At resonance, i.e. $\omega_{\mathrm{axion}} = \Omega_{\mathrm{MDM}}$, one observes a linear build-up of the vertical spin component, which is maximal for $\varphi_a = 0$. Since the experiment is performed with an ensemble of particles, the observed polarization P_v is related to S_v via the relation

$$P_v(t) = PAS_v(t)\,, \tag{6}$$

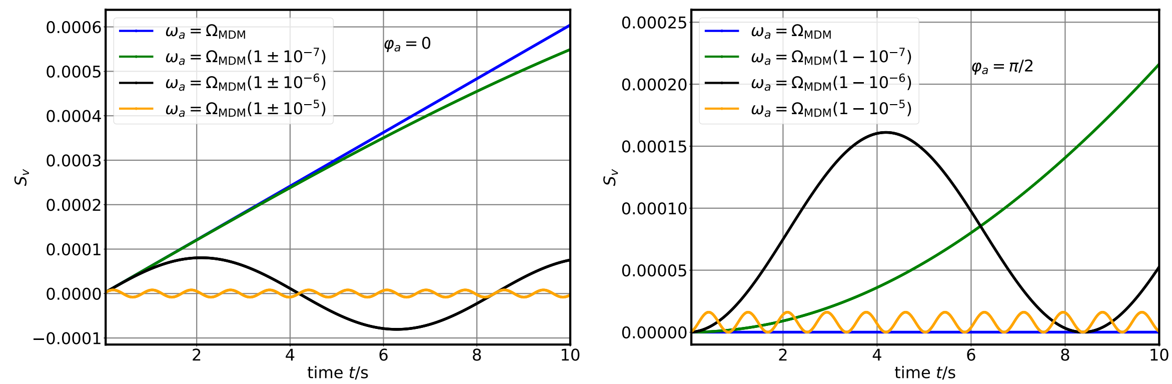

Figure 3: *Vertical spin component S_v as a function of time t for $\varphi_a = 0$ (left) and $\varphi_a = \pi/2$ (right) and for different axion frequencies $\omega_{\rm axion}$ and $\Omega_{\rm MDM} = 750000.0\,{\rm s}^{-1}$, $\Omega_{\rm EDM} = 1200000\,{\rm s}^{-1}$, $\eta_0 = 0$ and $\eta_1 = 10^{-10}$.*

where P is the total polarization of the beam (assuming $P \gg P_v$) and A is the analyzing power of the scattering process used to determine the polarization. Because the phase φ_a of the axion field relative to the spin precession is not accessible in the experiment, one has to use two bunches in the storage ring which differ in polarization phase by $\Delta\varphi_a = \pi/2$ in order not to miss the signal.

The experiment is performed as follows: Spin polarized particles are injected into the accelerator in two bunches. The spin phase difference has to be approximately $\pi/2$. The particles will be accelerated to the desired momentum. Using a solenoid operating at a resonance frequency, the initially vertically polarized beam is rotated into the horizontal plane. As soon as the polarization vector acquires a horizontal component, this component starts to precess with an angular velocity $\Omega_{\rm MDM}$. The solenoid is switched off once the vertical polarization reaches 0. Now the axion experiment can start. If $\Omega_{\rm MDM}$ is close to $\omega_{\rm axion}$ and φ_a has the "correct" value, a vertical polarization will build-up again. The polarization is measured using elastic proton-carbon or deuteron-carbon scattering. A left-right counting rate asymmetry is proportional to the vertical polarization. Fig. 3 shows S_v for various cases. In general, we plan measurement cycles of $\tau = 1000\,{\rm s}$ duration. For $\eta_1 = 10^{-10}$ the vertical polarization P_v reaches a few percent during this time. Note, that for $\Omega_{\rm MDM} = 750000\,{\rm s}^{-1}$ and $\tau = 1000\,{\rm s}$ the quality factor of this oscillation is $Q = \Omega_{\rm MDM}\tau = 7.5 \cdot 10^8$.

First experiments will be performed at the COoler SYnchrotron (COSY) at the Institut für Kernphysik (IKP) of Forschungszentrum Jülich (FZJ) [18]. COSY is a storage ring with a circumference of 184 m able to store and accelerate polarized proton and deuteron beams in the momentum range between 0.3 GeV/c and 3.7 GeV/c. This allows $\Omega_{\rm MDM}$ to vary in the range given in Table 1 together with the corresponding range in m_a. A closer look at equation 3 reveals that the combination of magnetic and electric fields allows for coverage of a much wider range in $\Omega_{\rm MDM}$, even down to $\Omega_{\rm MDM} = 0$ (frozen spin condition). Such a storage ring with combined electric and magnetic fields is planned for permanent electric dipole measurements [13]. It has a radius of about 9 m and an electric field of $E \approx 7.4\,{\rm MV/m}$. The angular frequency $\Omega_{\rm MDM}$ can be varied by applying an additional magnetic field varying from 0 to 0.033 T. Fig. 4 shows the spin revolution frequency $\Omega_{\rm MDM}$ and the particle momentum p as function of the magnetic field applied: Left panel for the pure magnetic ring COSY, in the right picture for the planned E/B storage ring.

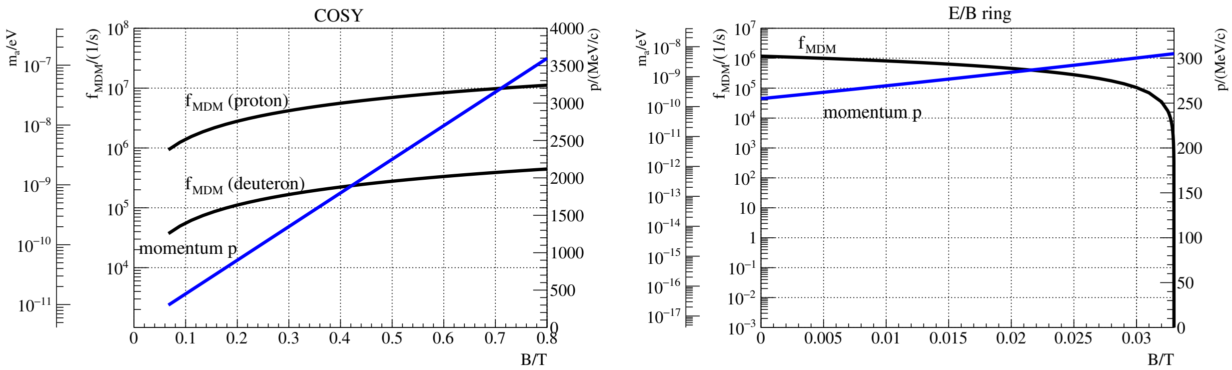

Figure 4: *Spin revolution frequency* $f_{\mathrm{MDM}} = \Omega_{\mathrm{MDM}}/(2\pi)$ *and the particle momentum* p *as function of the vertical magnetic* B*. Left panel: for the pure magnetic ring COSY, right panel: for the planned* E/B *ring where in addition an electric field of* $E \approx 7.35\,\mathrm{MeV/m}$ *is used to store the beam.*

Table 1 summarizes the accessible range in Ω_{MDM} and the corresponding mass range m_a. Table 1 lists in addition other relevant parameters, like the polarization P, the analyzing power A, number of beam particles N, the fraction f of elastically scattered detected particles and the duration τ of one measurement cycle limited by the spin coherence time reached. Based on these numbers, statistical errors can be estimated for various scenarios, like running at one fixed frequency or scanning of a frequency range.
Fig.5 shows the sensitivity that could be reached with storage ring methods for the axion-gluon coupling C_g/f_a as a function of m_a. The areas indicate regions where a signal could be discovered. The stars give the statistical error which could be reached in one year (10^7 s) of running time. With COSY, running at a fixed frequency one is able to reach existing limits from nuclearsynthesis. Note that the estimates assume conservatively 10^9 particles per fill for COSY, an intensity routinely reached. The aim of `asterix` is to reach 10^{10}. With a dedicated

	COSY				E/B ring	
	proton		deuteron		proton	
p/GeV/c	0.3	3.7	0.3	3.7	0.25	0.30
$\Omega_{\mathrm{MDM}}/\ 10^6\mathrm{s}^{-1}$	5.86	72.3	0.233	2.88	7.35	0.0
m_a/eV	$4 \cdot 10^{-9}$	$5 \cdot 10^{-8}$	$1.5 \cdot 10^{-10}$	$2 \cdot 10^{-9}$	$5 \cdot 10^{-9}$	0
B/T	0.07	0.8	0.07	0.8	0.0	0.033
E/MV/m	–	–	–	–	7.4	7.4
N	10^9				10^{10}	
f	0.005				0.005	
A	0.6				0.5	
P	0.8				0.8	
τ /s	1000				1000	

Table 1: *Parameters used for statistical uncertainty estimates.* N *is the number of particles per cycle,* f *the fraction of events elastically scattered and detected,* A *the analyzing power of the scattering process,* P *the beam polarization and* τ *the duration of one measurement cycle.*

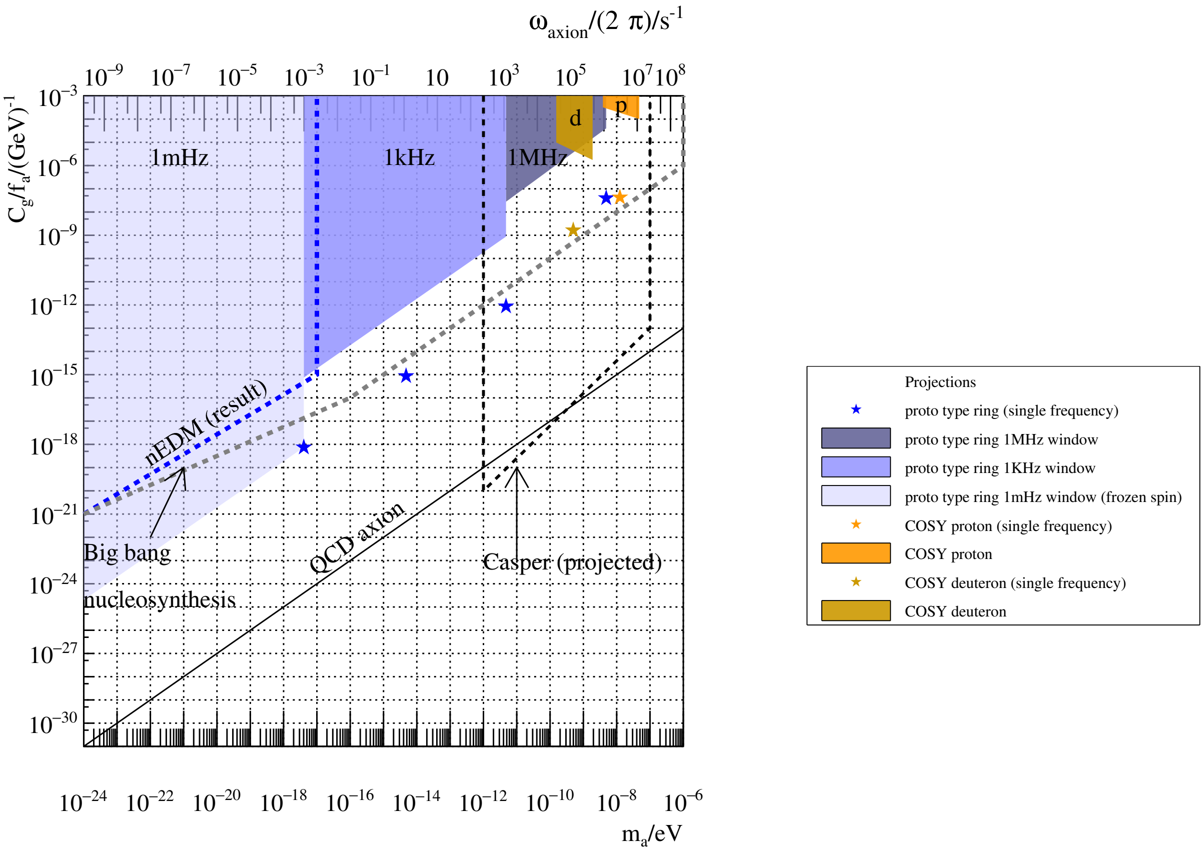

Figure 5: *One σ limits on the axion-gluon coupling C_g/f_a reachable within one year (10^7 s) running at a fixed frequency (stars) or over a given frequency range (areas) for COSY (orange) or the E/B ring (blue). In addition limits reached by the nEDM experiments [20], nucleosynthesis [21] and prospects for NMR experiments [10] are shown schematically. For a fixed frequency one covers roughly a frequency range $1/\tau = 1\,\mathrm{mHz}$. The figure is taken from Ref. [19].*

storage ring one could search for ALPs in a region not covered by other experiments.
More details on the estimates for statistical uncertainties and on the derivation of equations. 4 and 5 can be found in Ref. [19].

Work packages

Based on the experimental method described in the previous subsection, the following work packages have been identified to successfully accomplish the proposed measurement program.

- **WP0 Management, dissemination, outreach**

  The PI will be responsible for the management of the project. This includes the organization of regular meetings and workshops and the maintenance of a website. Care will be taken that results will not only be presented in specialized scientific journals and conferences but also to a broader audience.

  Responsible: Jörg Pretz

- **WP1 COSY preparation**
  Since the axion field phase φ_a with respect to the spin precession is unknown, one has to store two bunches with orthogonal polarization states in the ring. Although first tests at COSY look very promising, this subject has to be studied in more detail.

  As the axion measurement is most likely statistics limited, it is pivotal to reach the highest possible polarized beam intensity. Currently, we are able to store 10^9 particles per fill in COSY. The statistical estimates are based on this number. The goal of `asterix` is to reach at least 10^{10} particles by increasing the polarized source intensity, optimizing the injection into COSY and increasing the bunching efficiency.

  At COSY, running with protons gives access to higher precession frequencies because of the larger magnetic moment of protons compared to deuterons, which allows one to scan higher values for m_a. For deuterons, spin coherence times of 1000 s are routinely reached. For an axion measurement with protons, the same level must be obtained to be able to measure a signal with high precision.

  Guided by simulations (see WP3), resonances causing a coherent betatron oscillation at COSY will be investigated. Running with a spin precession at this frequency will be an important tool to study systematic limits also for next generation experiments at a dedicated storage ring. Deliberately introducing oscillating electric or magnetic fields will allow us to mimic an oEDM. This provides an important tool to study systematic effects.

  Objectives

  - Increase beam intensities for polarized protons and deuterons to 10^{10} particles. per fill
  - Obtain a spin coherence time for the proton of 1000 s, i.e. similar to the value reached for deuterons.
  - Provide systematic limits on axion mass searches at COSY and for an dedicated storage ring.

  Responsible: Ralf Gebel

  requested man power: 2 postdocs (2 years), 1 PhD

- **WP2 COSY measurement**
  With WP1 completed, we plan production runs with deuterons and protons in the third and fourth year, respectively. Depending on results from other DM experiments we will decide whether scanning a larger frequency range or staying on one frequency is preferable.

  It is important to note that the sensitivity estimates in Fig. 5 assume for COSY a running time of one year (10^7 s) with 10^9 particles per cycle. If a higher intensity (10^{10}) is reached, the running time is accordingly shorter or the sensitivity higher.

  Objectives

  - Reach the limits indicated in Fig. 5 for protons and deuterons at COSY.

  Responsible: Jörg Pretz

  requested man power: 1 postdoc (2 years)

- **WP3 simulations**
  In this kind of precision experiment simulations are required in order to understand systematic effects. Using existing programs (COSY Infinity, BMAD) and developing new code, we will perform beam and spin tracking. Simulations will for example be performed to investigate the influence of effects such as coherent betatron oscillations or time varying electric and magnetic fields on the vertical polarization build-up. All possible effects leading to a fake axion signal should be studied.

  In addition to the simulation studies accompanying the measurements at COSY detailed simulations are planned to investigate the possibility for axion measurements at a proposed E/B EDM ring.

  Objectives

  – Get an understanding of systematic effects which could create a fake ALP signal.

  – Estimates for systematic uncertainties (COSY and E/B ring)

  Responsible: Andreas Lehrach

  requested man power: 1 Postdoc (4 years), 1 postdoc (2 years)

- **WP4 analysis**
  This work package starts with development of analysis tools and devising strategies to analyze the data: Define optimal observables to extract polarization information. What is the best strategy to scan frequencies to obtain smallest error. The analyzing power of the scattering process depends on the beam energy. Since we have to modify the beam energy in order to scan the axion mass, more detailed studies are needed to assess to which extend the varying analyzing power affects the estimated sensitivities. From the third year on the main task is of course the analysis of the data taken at COSY.

  Objectives

  – Devise a strategy how to perform the measurement (at fixed frequency, scan of frequency, observables)

  – Obtain experimental results on axion searches.

  Responsible: Volker Hejny

  requested man power: 2 postdocs (3 years), 1 PhD

Table 2 summarizes the requested man power for the different work packages.

Team & Resources

It is evident that the proposed task can only be achieved in a large and experienced team. The beam times will be covered by the members of the JEDI[1] collaboration. It is important to note that the operation of COSY is guaranteed by the management of Forschungszentrum Jülich for conducting the experiments for `asterix`. While the local team at FZJ and the JEDI collaboration are strong in performing precision experiments at storage rings, we also included additional partners with experience in axion searches.

[1] `http://collaborations.fz-juelich.de/ikp/jedi/`

<table>
<tr><th></th><th>Month 1-12</th><th>Month 13-24</th><th>Month 25-36</th><th>Month 37-48</th><th>Month 49-69</th><th>sum/months</th></tr>
<tr><td rowspan="2">WP1 COSY preparation</td><td colspan="2">FZJ</td><td></td><td></td><td></td><td>24</td></tr>
<tr><td colspan="2">JGU Mainz</td><td></td><td></td><td></td><td>24</td></tr>
<tr><td>WP2 COSY measurements</td><td></td><td></td><td colspan="2">FZJ</td><td></td><td>24</td></tr>
<tr><td rowspan="2">WP3 Simulations</td><td></td><td colspan="4">FZJ</td><td>48</td></tr>
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<tr><td rowspan="2">WP4 Analysis</td><td></td><td></td><td colspan="3">JGU Mainz</td><td>36</td></tr>
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</table>

Table 2: *Required Resources for postdoc positions FZJ: Forschungszentrum Jülich, JGU: Johannes Gutenberg Universität, IBS: Institute for Basic Science*

We have already a long-standing collaboration with KAIST/IBS Daejeon, South Korea (Prof. Dr. Y. Semertzidis, Prof. Dr. S. Park). They have experience in axion searches and simulation studies for storage rings. Consequently we ask for a postdoc position in WP3 (simulations) and later in WP4 (analysis).

In addition, Prof. Dr. D. Budker and Prof. Dr. M. Schott (both University of Mainz, Mainz, Germany) will strengthen the team. Both are involved in other axion experiments. Prof. Budker works on the CASPER experiment looking at similar observables as `asterix`, but with completely different techniques. From this collaboration we expect synergy effects in understanding of common systematic uncertainties and analysis of data. For Mainz we ask for a postdoc position for 5 years which will split his/her effort between the work packages 1 and 4.

The running and set-up of COSY is guaranteed by the staff of the Institute for Nuclear Physics at Forschungszentrum Jülich. The requested postdoc position will be filled with a candidate who works on higher beam intensities and the spin coherence time studies for protons. The same person will also be involved in WP2 during the data taking periods in year 3 and 4. One additional postdoc is requested for WP3 (simulation studies).

In addition, we ask for 2 PhD positions (WP1 & WP4) based at Jülich. Depending on the candidates, the PhD could be obtained at one of the partner institutions or at RWTH Aachen University under the supervision of the PI.

The work package leaders are experienced scientists working at Forschungszentrum Jülich. Dr. Ralf Gebel, as head of the accelerator institute, is an expert in polarized sources and accelerator operation. Prof. Dr. Andreas Lehrach is professor for accelerator physics at RWTH Aachen University and an expert in polarized beams and simulation studies for accelerator design. Dr. Volker Hejny is currently the analysis coordinator of the JEDI collaboration.

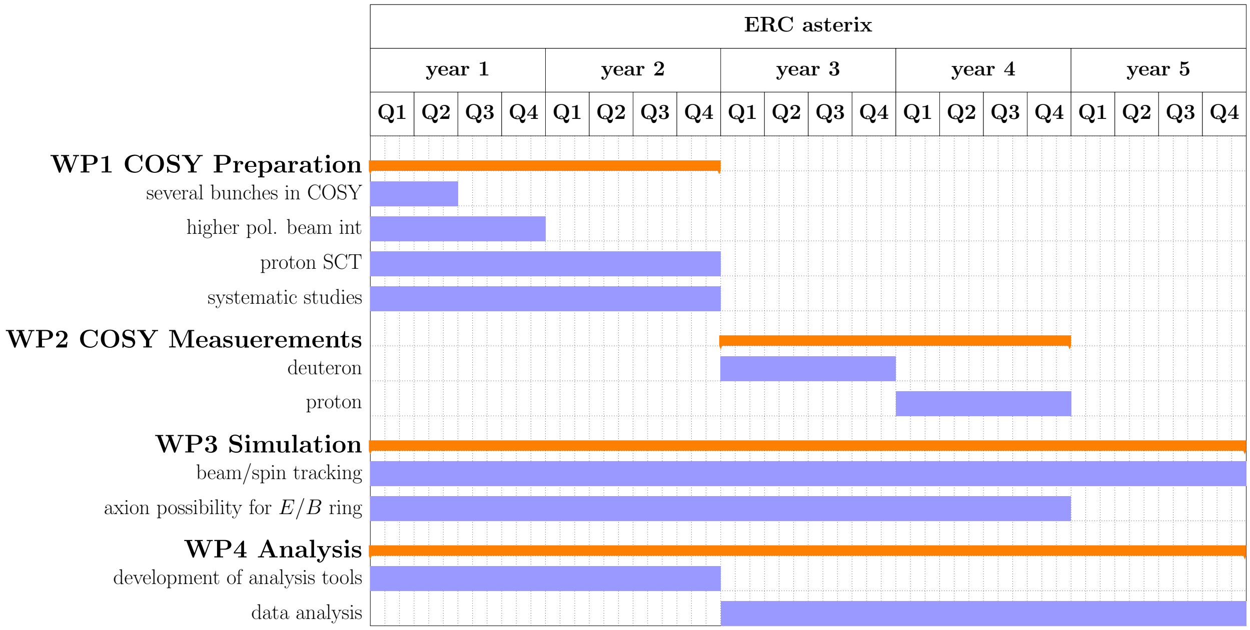

Figure 6: *Work packages and timelines.*

Risk assessment and mitigation

The high risk - high gain nature of the project is given by several aspects:

- In precision experiments (we are looking for a tiny polarization build-up) unexpected systematic effects may overshadow the signal.
- The statistical precision is proportional to $1/\sqrt{N\tau}$. It is thus mandatory to reach the highest possible beam intensity N and a measurement cycle duration $\tau \approx 1000$ s. During this time the polarization in the horizontal plane has to be maintained. Whereas for a deuteron beam a spin coherence time of this order has already been reached [22], for a proton beam this still needs to be accomplished.

We are convinced that with the proposed program at COSY, combined with the simulation studies, we are able to meet these challenges.

Impact

The expected impact comprises:

- Establishment of a new method for DM search, using polarized beams in storage rings.
- Generation of first results from DM searches with proton and deuteron experiments at COSY (see Fig. 5).
- Foundation of the basis for measurements in largely uncharted territory ($m_a < 10^{-12}$ eV) at dedicated storage rings (see Fig. 5).

Summary

Dark matter searches are well motivated by several observations in cosmology and particle physics. With `asterix`, we propose a novel approach to search for DM by looking at a resonant polarization build-up in a storage ring. With a successful application of the grant we will open a new research field in DM searches.

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