Letter of Intent: Towards experiments with polarized beams and targets at the GSI/FAIR storage rings

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Abstract

The subject of this Letter of Intent is to establish the production and operation of spin–polarized ion beams at the GSI/FAIR storage ring facilities. It will enable a novel class of experiments for the realms of atomic, quantum, and fundamental physics with heavy highly charged ions and exotic nuclei. For this purpose, we plan to install the ANKE polarized atomic beam source that will provide polarized electrons at the ESR storage ring and to perform a very first experimental feasability study by exploiding the process of radiative electron capture (REC) for the transfer of the spin-polarized target electrons into the heavy bare ions. This will enable to investigate in detail the polarization transfer to the ion as well as the polarization build–up for the stored ion beam.

1 Introduction

As a starting point for this project, we intend to perform a detailed experimental feasibility study on the basis of the Radiative Electron Capture (REC) process that occurs in collisions of heavy, highly

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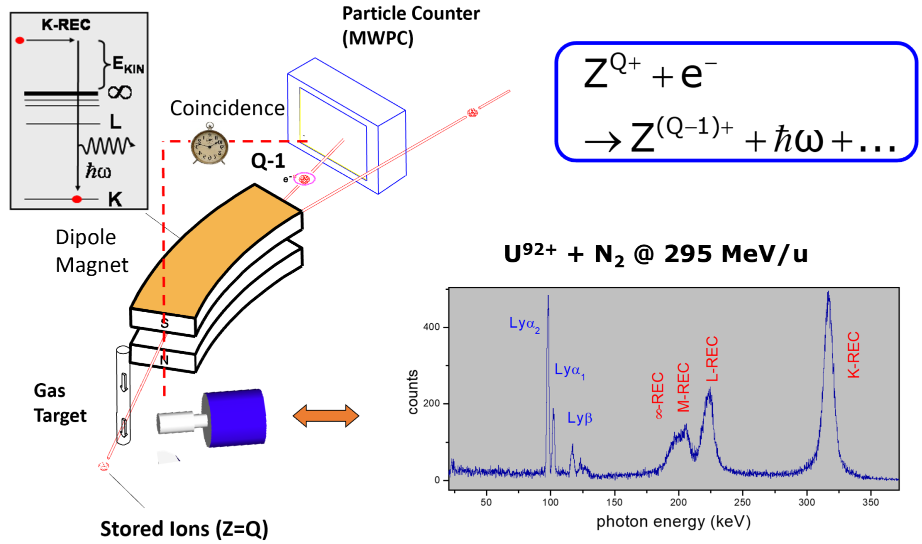

Figure 1: Experimental scheme for the detection of projectile X-ray emission at the internal target station of the ESR. X-ray emission associated with the transfer of target electrons into the projectile are measured in coincidence with the down-charged ions. An X-ray spectrum recorded for uranium projectiles colliding with N_2 molecules at the energy of 295 MeV/u is shown in addition. The spectrum is governed by REC into the projectile K-shell, indicating that for high beam energies REC is only relevant electron capture process.

charged ions with target atoms or molecules. At high relative energies, REC is by far the most dominant projectile charge–exchange and X–ray emission channel, known for its high sensitivity to the electron spin dynamics [1, 2]. Therefore, it is an excellent tool to study and control the transfer of spin–polarized electrons from the target to the ions as well as to investigate the polarization build up of the stored ion beams. For this purpose, we propose to conduct REC studies for spin-polarized electrons for a high-Z ion such as U^{92+} by using the ANKE target installed at the internal target station of the ESR. By means of Compton polarimetry [3, 4], the high sensitivity of the photon polarization to the initial electron spin polarization will be exploited to control the polarization transfer to the ion. The control of spin transfer from (spin–polarized) electrons to photons has already been successfully proven for the process of electron bremsstrahlung [5], a process closely related to radiative electron capture. Dedicated Compton polarimeters have already been developed at IKP in FZ Jülich within the framework of the SPARC collaboration and will be further optimized for the planned studies.

In principle, the preservation of the polarization in the ESR is of utmost importance and a prerequisite for numerous future applications. We are also planning to perform accurate studies of the spin-polarization build-up for the stored beams which are needed for a detailed comparison with spin tracking calculations in order to optimize the ESR accordingly. Therefore, subsequently performing total electron–capture cross–section studies along with the projectile X–ray emission for the capture of spin–polarized electrons into ions having already captured a spin–polarized electron, we should even be able to study the polarization build up for the stored ion beam. In case the electron polarization is preserved, REC into the K–shell of the initially H–like ion (with spin polarized electron) should be reduced due to Pauli blocking by almost 90%, which as a consequence should drastically reduce the overall total cross–section and basically block the occurrence of K–shell REC and its associated radiation.

Finally we plan to extend these studies to heavy, bare ions with large nuclear magnetic moment such as $^{209}Bi^{83+}$. Here, we aim to investigate whether capture of spin–polarized electrons will lead to the production of ion beams with spin–polarized nuclei.

We would like to note that a proof of principle for particle polarization in flight was succesfully done with unpolarized protons at the TSR storage ring via the interaction with a polarized hydrogen target by making use of the spin dependence of the scattering cross–section. However, and in contrast to these studies, we rely in the proposed experiment in an atomic charge-exchange process where cross-sections are in the region between 10 to 100 barn and which is expected to lead to polarization purities for the stored beam of the order of > 90% (e.g. for U^{92+} at 400 MeV/u the REC cross–section amounts to 40 barn).

The planned experimental studies at the ESR are intended to be the beginning of a series of experiments whose ultimate goal is the generation of spin–polarized ion beams. To this end, the teams at IKP in Jülich (with their expertise in preparation, control and experiments with stored polarized particle beams) and the AP/SPARC group at GSI (with their experience in REC studies for high–Z projectiles as well as in photon polarization studies for hard X– and γ–rays) team up. Polarized beams of heavy ions have never been realized before and represent a new degree of freedom for heavy ion storage–ring experiments. They are in particular relevant for future studies in the realms of testing the fundamental symmetries of nature and search for the physics beyond the Standard Model, such as dark matter searches.

This Letter of Intent (LoI) is structured as follows: first short sections are given on the REC process and its sensitivity to the electron spin dynamics, X–ray Compton polarimetry, two-body weak decays as polarimetry tools as well as the ANKE polarized atomic beam source. Several examples for future studies have been added in a section related to ”Physics with polarized hadron beams and targets”. Finally, the research potential for future studies with polarized protons and antiprotons will be emphasized.

2 Experiment at the ESR

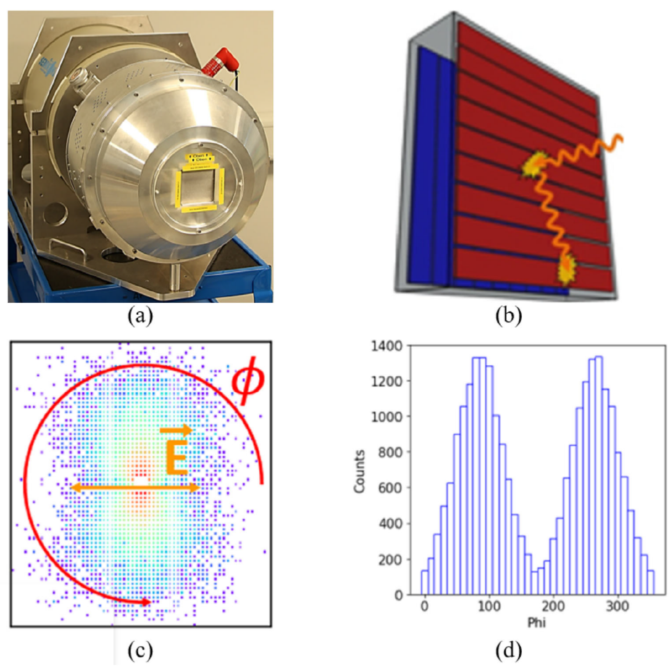

Figure 2: a) An image of the Compton polarimeter. b) Schematic principle of the segmented detector crystal is shown. When an incident photon is Compton scattered on the detector, the scattered photon can as well be absorbed inside the detector. With sufficent statistics the scattering distribution will approach the Klein–Nishina formula. (c) An example image of the Compton scattering distribution detected by the Compton polarimeter on the detector screen. The orientation of the polarization vector of the incident beam and the direction of the azimuthal scattering angle are shown as well. (d) The azimuthal scattering profile of (c) [6].

In Fig. 1 a scheme of a typical experimental arrangment for the study of projectile X–ray emission at the internal target station of the ESR is depicted. In addition, an X-ray spectrum recorded in coincidence with down–charged ions for the process of REC in collisions of U^{92+} with an N_2 target at the beam energy of 295 MeV/u is shown. As clearly visible from the spectrum, REC dominates the overall X–ray emission characteritics. For the current project we plan to replace the current versatile internal target by the ANKE polarized atomic beam setup (see section 5). This will be done in a modularized fashion, enabling an exchange of the target setups in typical time intervals of 6 to 12 months (the design work for the implementation of the ANKE target will be accomplished until the next GPAC call for beam time proposals). This scheme will be applied for the first step of the experiment, the measurement of the K-REC photon polarization characteristic for U^{92+} colliding with spin–polarized electrons of atomic hydrogen at the energy of 400 MeV/u. For the detection of the projectile X-ray (K-REC) emission, three Compton polarimeters will be used, placed at the observation angles of 60^0, 90^0, and 145^0, respectively. Consequently, the photon energies of the K-REC radiation are: 384 keV, 246 keV, and 155 keV, respectivly (see section 3.2).

For the second step of the experiment, the study of the spin-polarization build-up will be accomplished by making use of the multi-charge state operation capability of the ESR [7]. After breeding the H-like U^{91+} beam via REC of spin-polarized electrons, a study of the polarization of the stored beam will be conducted. This will require a shift of the beam trajectories of the stored beams in such a way that the trajectory of the U^{91+} beam will cross the position of the polarized H-target whereas the still circulating U^{92+} ions will be dumped. In case the electron polarization for the U^{91+} is preserved, REC into the K–shell of the initially H–like ions (with spin polarized electrons) is basically forbidden and the total cross-section will decrease accordingly. At the same time the emission of K-REC radiation should almost vanish.

The energy of 400 MeV/u is chosen since we rely on stochastic cooling only for the control of the polarization. Electron cooling would be of disadvantage since radiative recombination of unpolarized cooler electrons may lead to an unwanted contamination of the stored H-like ions. Once the polarimetry technique is established (see also next Section), it will be straightforward to quantify this contamination process.

3 REC and its polarization properties

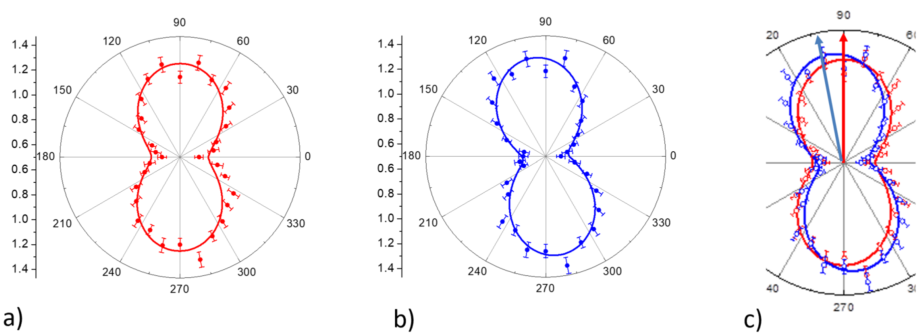

Figure 3: Azimuthal distribution of Compton scattered X-rays for incident bremsstrahlung photons with an energy of 92.5 keV: a) unpolarized electrons; (b) transverseley polarized electrons and c) direct comparison between a) and b). The solid and dashed lines result from an adjustment of the Klein-Nishina equation to the experimental data. The rotation of the distribution for transversely polarized electrons is clearly visible [5].

Radiative electron capture (REC), which is the time reversed photo–ionization process, has been studied in great detail in ion–atom collisions for projectile nuclear charges covering virtually the entire periodic table of elements up to fully stripped uranium ions [1]. With regard to the beam energies, the available data span from the low–collision energy regime up to high relativistic energies of almost $\gamma \approx 200$, where γ denotes the relativistic Lorentz factor. Beside total electron-capture cross-sections, photon angular distributions and even the associated photon polarization phenomena were subject of these studies with an—in general—excellent agreement with rigorous relativistic calculations.

For radiative electron capture into the K shell of bare uranium ions, a study of the polarization properties of emitted X–rays has been performed. For this purpose a position sensitive germanium detector has been used as an efficient Compton polarimeter. This enabled us to measure the degree of linear polarization of radiation by analyzing Compton scattering inside the detector and to determine the orientation of the polarization plane [2]. Depending on the observation angle and the beam energy used, the radiation is found to be linearly polarized by up to 80%. In all cases studied, the plane of polarization coincides with the collision plane, which indicates that target electrons were unpolarized. A good agreement with rigorous relativistic calculations can be stated, showing that relativistic effects tend to lead to a depolarization of the radiation emitted. However, for a mid–Z system such as Xe^{54+} the latter is not the case. Recently, REC into the K shell of bare Xe ions colliding with a hydrogen gas target has been investigated [8, 9]. In that study, the degree of linear polarization of the K–REC radiation was measured and compared with rigorous relativistic calculations as well as with the previous results recorded for U^{92+}. The obtained data confirms that for medium–Z ions such as Xe, the REC process is a source of highly polarized X rays which can easily be tuned with respect to the degree of linear polarization and the photon energy. We argue, in particular, that for relatively low energies the photons emitted under large angles are almost fully linear polarized.

With regard to spin transfer from spin–polarized electrons to photons, first studies were performed for the process of electron bremsstrahlung occuring in collisions between spin polarized electrons and a neutral Au target. Bremssstahlung is a process closely related to radiative electron capture. Again, by means of Compton polarimetry we performed for the first time an energy–differential measurement of the complete properties of bremsstrahlung emission related to linear polarization, i.e., the degree of linear polarization as well as the orientation of the polarization axis (see Fig. 3). For the high–energy end of the bremsstrahlung continuum the experimental results for both observables show high sensitivity on the initial electron spin polarization and prove that the polarization orientation is virtually independent of the photon energy [5].

3.1 Compton Polarimetry

Compton scattering being the inelastic scattering of a photon on a free electron can be described by the Klein–Nishina formula, which gives the angular differential cross section of the process:

$$\frac{d\sigma}{d\Omega}_{KN}(\theta,\phi) = \frac{1}{2} r_0^2 \cdot \left(\frac{h\nu'}{h\nu}\right)^2 \cdot \left(\frac{h\nu'}{h\nu} + \frac{h\nu}{h\nu'} - 2\sin^2\theta\cos^2\phi\right) . \tag{1}$$

Here r_0 is the classical electron radius, while ν and $\nu'(\theta)$ are the frequencies of incident and scattered (under the polar angle θ) photons, respectively. With ϕ being the azimuthal scattering angle between the electrical field vector of the incident photon and the propagation direction of the scattered photon it is clear, that Compton scattering is highly polarization–dependent. This can be used to reconstruct the degree of linear polarization and the orientation of the polarization axis of a photon beam from the azimuthal emission pattern of Compton scattered photons, as described e.g. in [3].

The detector shown in Figure 2(a) was constructed within the SPARC collaboration for this purpose as a dedicated Compton polarimeter [6]. Up to now it consists of a lithium–diffused silicon crystal allowing an efficient use of the detector for photon energies up to 200 keV. The detector crystal has a thickness of 9 mm and an active area of 32 mm×32 mm which is segmented on front and back side into 32 strips of 1 mm width each with the strips on front and backside being perpendicular to each other. This segmenting of the crystal leading to a 1024 pseudopixel grid makes it into a high–resolution position–sensitive detector. The detector crystal serves as Compton scatterer and detector at the same time. If an incident photon is Compton scattered inside the detector crystal and the scattered photon is absorbed inside the crystal as well, information about time, energy and position of both interactions can be used to reconstruct the Compton event. A typical reconstructed scattering profile can be seen in Fig. 1(b). Here the center of scattering was set to zero while the x-y profile shows the detected Compton scattered photons. From this reconstruction of the scattering events the azimuthal scattering profile can be received as shown in Fig. 3(c). With this profile the degree of linear polarization and orientation of the polarization vector can be extracted as shown in [5].

3.2 Compton polarimeter setup for the γ-ray regime

With the described Compton polarimeter setup using a segmented silicon crystal highly efficient polarimetry measurements are possible in a wide energy range from a few keV to around 200 keV. However for higher photon energies the detector efficiency strongly decreases due to the reduced stopping power of the crystal material as well as due to the fact that for higher photon energies Compton scattering under forward angles becomes more and more likely. To overcome this drawback and realize a polarimeter setup for even higher photon energies a new detector setup was developed. For this novel setup an additional segmented germanium crystal will be installed behind the already existing segmented Si(Li) crystal in a telescope structure. The higher stopping power of germanium compared to silicon allows for an efficient use of the detector at higher photon energies. Additionally the problem of more pronounced forward scattering for higher photon energies is overcome by the telescope structure of the new setup as now photons being Compton scattered under a forward angle in the silicon crystal can be detected in the following germanium crystal. With these improvements of the existing setup we expect to be able to perform efficient polarization analysis for higher photon energies up to the MeV-range.

4 Two-body weak decays as polarimetry tools

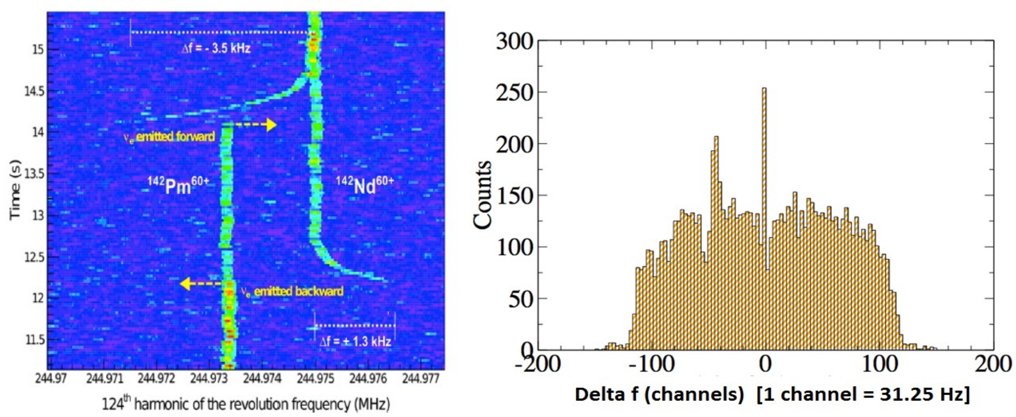

Figure 4: Left: Measured in the ESR orbital electron capture (EC) decays of two stored hydrogen-like ^{142}Pm^{60+} parent ions [10]. The electron cooling is always on. The revolution frequency (horisontal axis) is a direct measure of the particle mass-over-charge ratio. The time after injection of the ions into the ESR (vertical axis) runs upwards. The first EC decays happens at about 12 s. The decay energy is shared between the emitted (quasi)monochromatic neutrino and the recoiling daughter ion. The neutrino in this decay is emitted against the momentum of the ion, accelerating it, which is reflected in the need to slow-down the daughter ion by electron cooling. The second EC decay occurs at about 14 s, where the neutrino is emitted in the forward direction. Since the neutrino has defined helicity, the spatial orientation of the spin of the parent nucleus is undoubtedly determined. Right: The distribution of the "cooling tails" as illustrated in the left panel, but for all measured decays in this experiment. The polarization degree would be visible through left-right asymmetry of this distribution.

Alternatively to X-ray polarimetry, two body weak decays can be employed for high precision determination of the beam polarization. One possibility is to use allowed Gamow-Teller orbital electron capture (EC) decays of hydrogen-like ions. An example is illustrated in Fig. 4 showing the EC decay of two parent ^{142}Pm^{60+} ions stored in the ESR [10]. The parent ^{142}Pm^{60+} ions have spin-parity 1^+ and the daughter ^{142}Nd^{60+} nuclei have 0^+. The conservation of the total angular momentum in this $1^+ \rightarrow 0^+$ decay and the defined neutrino helicity demand the emission of the electron neutrino to be strictly in the direction opposite to the spin of the parent nucleus [11, 12]. By counting the number of left-sided versus righ-sided "cooling tails" as in Fig. 4, precision determination of the spatial orientation of the spins of the parent ions at the moment of respective EC decays is obtained. This technique can as well be employed for studying temporal variation of the beam polarization degree. Furthermore, in the limiting case that the beam polarization is suffiently precisely known and is kept under control, an experiment constraining the neutrino helicity might be considered.

5 The ANKE polarized atomic beam source as a source for a polarized electron jet target

In order to realize a polarized electron target a polarized hydrogen jet target could be utilized (see e.g. [13]). For the production of the polarized atomic beam the polarized atomic beam source [14] (ABS) of the former ANKE experiment at COSY Jülich will become available. It was developed for the polarized internal storage-cell gas target at the magnet spectrometer ANKE of COSY in Jülich.

The layout of the ABS is presented in Fig. 5. The ABS consists of a radio frequency driven dissociator, a sextupole system to separate the atoms according to the electron spin state and radio frequency transition units to exchange the population of the hydrogen hyperfine states. These components are installed in two main cylindrical vacuum vessels, which are fixed above and below a central support plate in order to achieve a fast installation.

At ANKE the intensities of the hydrogen beams injected into the storage cell, measured with a compression tube, were $7.5 \cdot 10^{16}$ hydrogen atoms/s (two hyperfine states). The achieved vector polarizations were $p_z \approx \pm 0.92$ (one hyperfine state). Electron polarizations were in the same range. The ANKE-ABS is optimized for maximal intensity for cell injection. It would need to be optimized for maximal density. Typical areal number densities for jet targets are $10^{12}/\mathrm{cm}^2$. For target cells two orders of magnitude more can be reached.

A magnetic holding field around the interaction point will be necessary in order to provide a quantization axis for the spins. When using only one pure hyperfine state, high polarizations can be achieved with a low magnetic holding field of a few Gauss (with half the mentioned intensities). To employ the full intensities a high magnetic holding field of about 300 mT is necessary in order to have a high polarization. Transversal as well as longitudinal polarization could be feasible with 3 pairs of Helmholtz coils.

In order to assure high polarization during the experiments a polarimeter (e.g. Breit-Rabi [13] or Lamb shift polarimeter [15]) is necessary to monitor the polarization parasitically during operation.

6 Physics with polarized hadron beams and targets

6.1 Axion searches

The JEDI collaboration pioneered the search for axion/axion-like-particles (ALP) in storage rings [16]. Axions cause an oscillating electric dipole moment (EDM). Figure 6 shows a limits on this oscillating EDM contribution obtained in only a few days of beam time with a polarized deuteron beam at the COoler SYnchrotron COSY.

The principle of the measurement is indicated in Fig. 7. A horizontally polarized ion beam is stored in the accelerator. Due to the magnetic anomaly, denoted as G for hadrons, the polarization vector precesses with an angular velocity $\Omega_s = \gamma G \Omega_{rev}$. A hypothetical ALP with mass m_a would lead to a spin resonance at $\Omega_s = \Omega_a$, where the axion frequency is given by the axion mass: $\Omega_a = m_a c^2/\hbar$. This resonance leads to a build-up of a vertical polarization component of a beam initially polarized in the horizontal plane of the accelerator. This vertical polarization component can be measured with a polarimeter by looking at the left–right asymmetry of nuclei-carbon scattering for example. Storage ring experiments would allow ALP searches at a specific mass by the appropriate choice of $\Omega_s = \Omega_a$. Moreover, a wide mass range could be covered by varying the three parameters γ, G and Ω_{rev}. To vary G various type of nuclei have to used. To vary the factors γ and Ω_{rev} the beam energy has to be changed. Additional electric fields allow for even more degrees of freedom to modify the spin precession frequency, even down to zero (frozen spin mode). The spin motion is influenced by ALPs due to two effects. First ALPs introduce the above mentioned oscillating electric dipole moment (EDM) causing a spin rotation around a radial axis in the storage ring and second, the so-called axion wind effect resulting in a spin rotation around the longitudinal axis [17, 18]. Storage ring experiments are specifically sensitive to the second effect because it scales with the velocity of the particles with respect to the axion field. In storage rings one has $v \approx c$ (c being the vacuum speed of light), whereas for particles at rest in the laboratory system, like in NMR experiments, the relative velocity is given by the velocity of the Earth with respect to the center of our Galaxy, i.e. $v \approx 250$ km/s.

In summary, storage ring experiments are well suited to search for axions/ALPs and are complementary to other searches. These experiments require a polarized hadron beam (proton, deuteron,

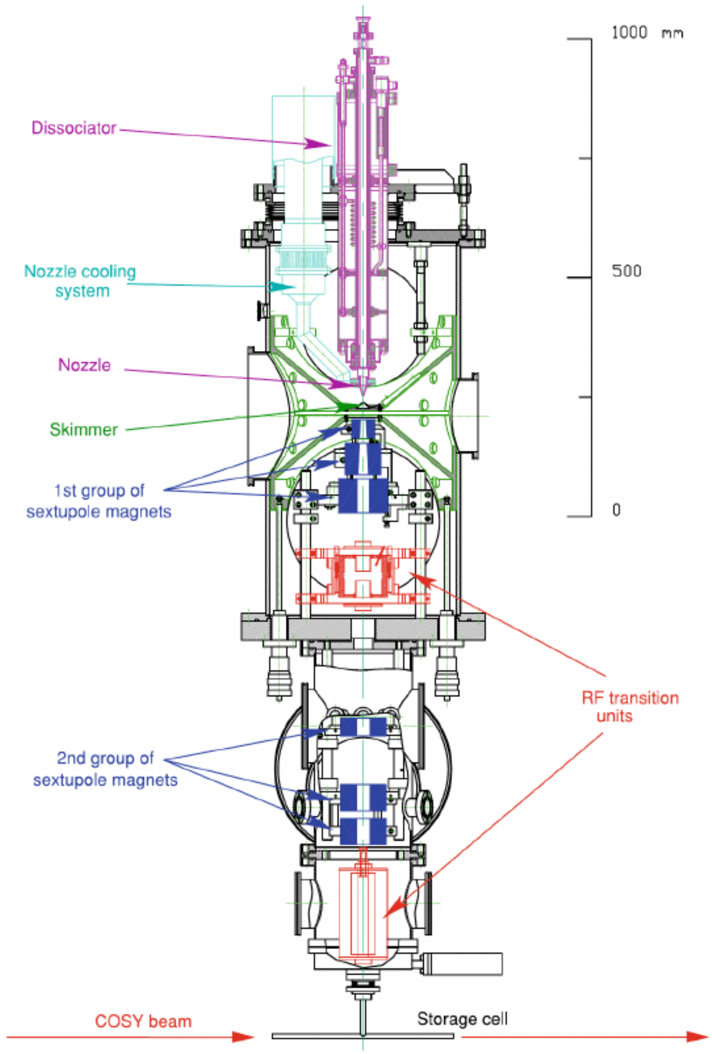

Figure 5: The ANKE polarized atomic beam source.

heavier nuclei), the possibility to manipulate the polarization vector and a polarimeter to measure the polarization.

6.2 Search for physics beyond the Standard Model at the ESR

Newtonian mechanics, Maxwell's electrodynamics and Einstein's general relativity, all respect time reversal (T) symmetry. Nevertheless, it is now well understood that time reversal violation (T-V), like the equivalent violation of the combined symmetries of charge (C) and parity (P) (CP-V), is a necessary ingredient for any theory aiming to address the mystery of the matter-antimatter asymmetry of our Universe – one of the biggest unsolved problems in contemporary physics and cosmology. It is widely accepted that a solution of this puzzle will involve new physics beyond the Standard Model (SM) of elementary particle physics (BSM). A flagship project for the ESR would be to constrain or even discover BSM physics by investigating T-symmetry violations complementary to searches for Electric Dipole Moments (EDM) or axions, as outlined in the previous section. The objectives of such an enterprise entail (i) a search for direct T-V through a precise measurement of double polarized proton-deuteron elastic scattering, exploiting the particle spin as a "time reversal knob", and (ii) the development of a solid theoretical basis for the interpretation of T-V interactions. The unique experimental environment offered by the storage ring ESR at GSI promises to improve the present upper limit on T-V by one to two orders of magnitude, using the machine as a zero degree spectrometer

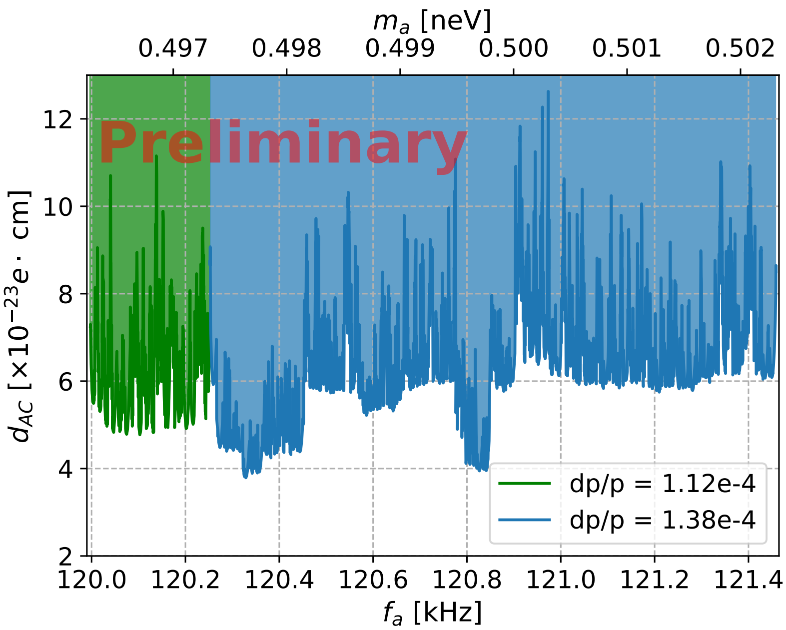

Figure 6: Preliminary 90% upper confidence level sensitivity for an oscillating EDM in the frequency range from 120.0 to 121.4 kHz (mass = $4.95 - 5.02 \times 10^{-9} eV$). The green and blue colors show two scanning ramp rates in momentum change.

and detector. The required experimental expertise in beam and target polarization technologies is uniquely positioned to meet these objectives.

The CPT symmetry has been tested to a very high precision and it is believed to be a genuine symmetry of nature. If this is accepted then CP-V implies T-V to compensate each other. All T-symmetry violating mechanisms implemented in the SM inevitably violate P. One of the established ways to search for the simultaneous violation of T and P symmetries (T-VP-V) is to look for an Electric Dipole Moment (EDM) of an elementary particle. The SM predicts the EDM of the neutron to be less than 1×10^{-31} e cm [19], while the current experimental upper limit is of the order of 10^{-26} e cm [20]. In the next generation of experiments it is planned to reach a precision of 10^{-28} e cm for the EDM of the neutron on a time scale of roughly ten years. Complementary to the EDMs searches dealing with T-V P-V interactions, the proposed project will focus on gaining new insights into T-V P-C (parity conserving) interactions as schematically shown in Fig.8.

There are model-dependent ways to estimate the strength of the T-V P-C interaction using the current result for the neutron EDM: $\alpha_T < 1.1 \times 10^{-5}$ [21]. A more recent analysis [22] suggests that there are in fact ways to generate an EDM of an elementary particle without implicating a limit on a T-V P-C interaction. Hence, any upper limit for the T-V P-C interaction obtained from the EDM of an elementary particle will involve significant model dependence, which is difficult to control. Furthermore, it has been demonstrated [23] that the discovery of an EDM of only one of the particles, e.g., electron, proton, neutron, deuteron, or ^{3}He, will not allow one to identify uniquely the origin of the EDM effect. Taking into account the time lines of EDM projects all over the world, which typically plan for an order-of-magnitude improvement over the next decade, the studies of the T- VP- C interaction, suggested here, provide the potential to discover physics beyond the Standard Model, *independent* of the EDM measurements. The very upper limit improvements will provide most valuable constraints for SM extensions. As no indications for T-V P-C-interactions have been reported in the literature, such effects have yet to be implemented into the Standard Model of the particle physics and their discovery would be a strong indication for the nature of physics beyond the Standard Model. Experimental upper limits on the strength of T-V P-C interaction α_T are relatively weak. A limit $\alpha_T < 7.1 \times 10^{-4}$ has been obtained using a polarized neutron beam and tensor polarized ^{165}Ho target [24]. It is important to stress that there is some uncertainty in this value due to corrections associated with the use of the complex tensor polarized nuclear target. The aim here could be to improve the upper limit on α_T by at

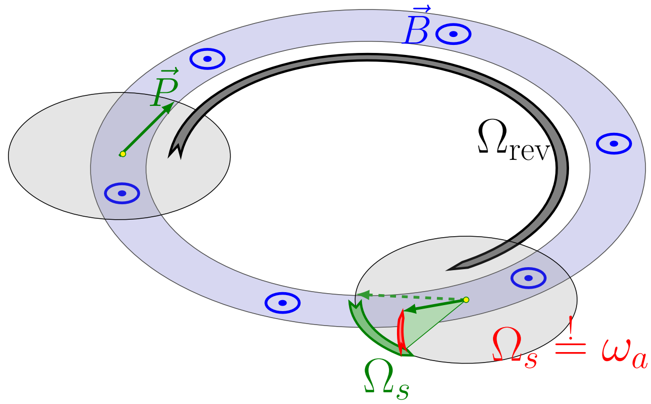

Figure 7: Principle of an axion experiment at storage rings. The polarization vector is precessing in the horizontal plane. If the axion frequency ω_a given by the axion mass ($\omega_a = mc^2/\hbar$), a resonance occurs causing a build-up of a vertical polarization.

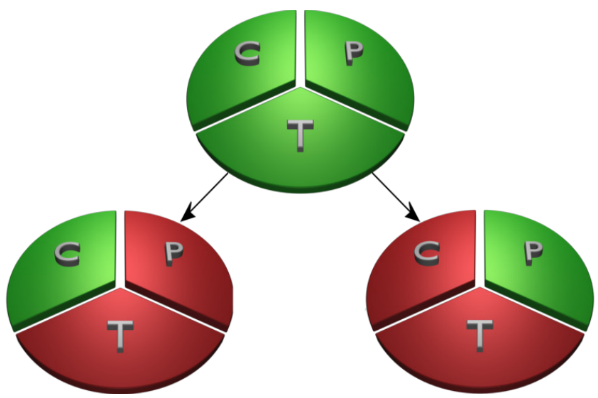

Figure 8: Assuming the validity of the CPT theorem, the project addresses one of the most fundamental challenges in modern physics, namely the baryon asymmetry of the Universe (BAU), in an approach which is independent, and yet complementary to searches for Electric Dipole Moments (EDM). While EDMs test interactions that violate Time Reversal Invariance and Parity simultaneously (T-V P-V), the suggested experiment will investigate those interactions which violate Time Reversal Invariance, while obeying P-symmetry (T-V P-C).

least an order of magnitude by using a vector polarized proton beam in the ESR and a tensor polarized deuterium target. Due to the use of the deuteron as the simplest tensor polarized nucleus, the upper limit on the extracted strength of the T-violating potential, will be free from the model-dependent corrections associated with the ^{165}Ho target.

It has been shown [25] that, in double-polarized proton-deuteron elastic scattering, the spin-correlation parameter $A_{Y,XZ}$ is a true T-odd P-even "null observable": any finite value of $A_{Y,XZ}$ will thus be a signature of a T-V P-C interaction (see Fig. 9).

This fact provides unique experimental advantages over any other investigations of T-violating observables, since it reduces the sources of systematic uncertainties. A storage ring like ESR at GSI offers an unmatched opportunity to access this quantity in a transmission experiment by using a polarized proton beam in combination with a tensor polarized deuterium target. While it is extremely difficult to measure double-polarized total cross sections in a standard particle-physics experiment to very high precision, the suggested experiment relies on the determination of total cross sections by a measurement of the reduction of the beam current as a function of time for different polarizations of proton and deuteron rather than the detection of the scattered particles [26, 27].

The beam-lifetime in a storage ring is affected by the beam losses all over the ring, but only the losses in the polarized target are sensitive to the beam and target polarizations. When the tensor

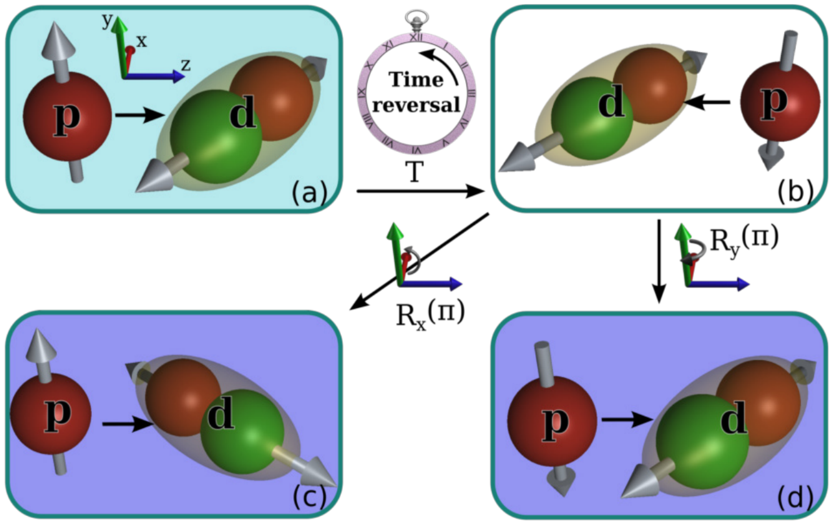

Figure 9: The experiment will test a T-V P-C interactions in double polarized proton-deuteron elastic scattering. The figure illustrates the concept. (a) The basic system is shown. (b) The time reversal operation is applied. In order to enable a direct comparison between (a) and (b), two rotations R_x or R_y by 180° about the y- or x- axes are applied, leading to the situations c) and d), respectively. This is allowed, since the scattering process is invariant under spatial rotations.

polarization of the deuterium target lies in the horizontal (XZ) plane and the polarization of the proton beam is vertical (along the y axis), the $A_{Y,XZ}$ term remains the only (T-odd, P-even) null observable contributing to the total cross section and it can be directly measured by observing a change in the beam-lifetime as a function of time (see inset in Fig. 10 above). In this respect, the experiment proposes a novel method by which to measure a double-polarized total cross-section in a storage ring by transmission through a polarized internal target. Thus, ESR will serve not only as an accelerator, but also as an ideal zero degree spectrometer/detector allowing for the application of the optical theorem, which relates the forward scattering amplitude to the total cross-section. In addition, the experiments will study total cross-sections and its results will therefore be *independent* of corrections associated with final state interactions (FSI) [28] compared to other approaches that make use of nuclear targets and require detailed modeling [29].

6.3 Towards polarized antiprotons

Once antiprotons become available at FAIR, polarizing them constitutes a unique opportunity for the laboratory. The physics opportunities since the PAX proposal was written [30] will have to be reinspected. The main physics results on the subject and the required experimental and technical details are described in refs. [31, 32, 33, 34, 35].

6.4 Sequence of actions

Below we discuss the major steps in the sequence of actions required to realize the ambitious goals briefly exposed in the previous sections.

1. As a first step, the installation of a hydrogen or deuterium polarized gas jet target (see Sec. 5) to study REC, as outlined in Sec. 3 is straightforward, kind of minimally invasive to the present ESR environment.

2. To unambigously interprete spin asymmetries, e.g., measured from proton or deuteron beams, but in particular for polarized antiprotons from spin-filtering at the ESR will make necessary to feed the ring with polarized protons first. This requires:

   (a) a polarized ion source, the colliding beams source operated at COSY appears suitable [36].

   (b) Measurement of beam polarization needs to be enabled along the accelerator chain.

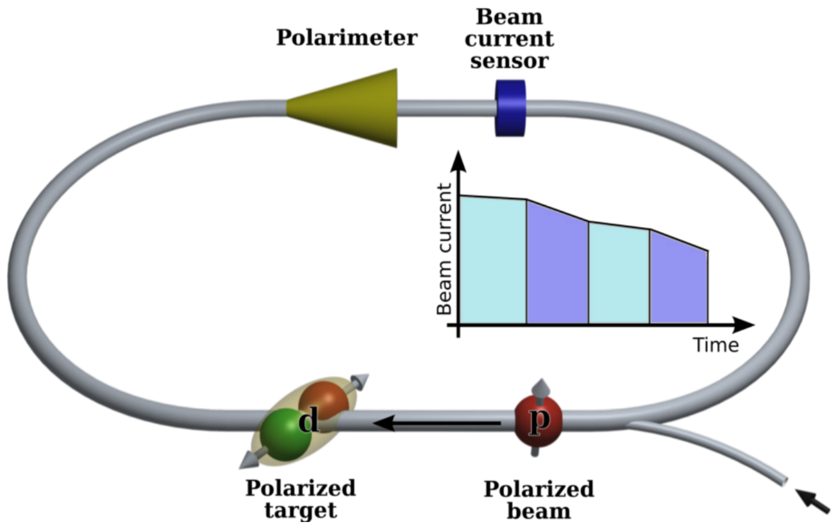

Figure 10: Main components of the experimental setup: polarized beam from the injector (accelerator), polarized deuteron target from an atomic beam source (ABS), polarimeter and beam current sensor. Time reversal invariance will be accessed by detecting the difference in the beam lifetime between the situations a) and c) or d) presented in Fig. 9 as schematically indicated in the inset.

(c) Polarization preservation inside the SIS 18 accelerator must be ensured, so that the polarized beam can be transported to the ESR. This entails an internal polarimeter, a detector system, and a tune jump quadrupole system to overcome depolarizing resonances [37].

(d) Inside ESR, the requirements are similar compared to SIS18. One needs a polarimeter and in addition, a system that allows one to maintain the beam polarization during acceleration to the desired experimental energy.

3. The studies related to time-reversal violation (T-V), discussed in Sec. 6.2, require an upgrade of the polarized gas target to include a storage cell. This entails inserting a low-β section in the ESR, as exemplified for COSY in ref. [33].

4. The extension of the investigations toward spin coherent ensembles of polarized stored particles, as indicated in Fig. 7, is needed for both, the search for EDMs or axions. (It should be noted that for the time-reversal violation experiment, discussed in Sec. 6.2, this feature is not needed.) Long spin coherence times require the use of chromaticity correctors and from experience a very careful control of the closed orbit in the machine during the measurements.

We expect a time horizon of about ten years for steps 1 to 3 It is envisaged to employ –where applicable– also the possibilities, offered by, e.g., the local injector of CRYRING, to test/commission various techniques and instruments. Furthermore, depending on the overall time scale, the experiment(s) might be re-located to the HESR, where more space is available than at the ESR.

7 Conclusion and request

Installation of the proposed infrastructure will enable an additional degree of freedom for precision experiments aiming at tests of the Standard Model interaction as well as searching for physics beyond it. With this LOI we ask the GPAC of GSI to assess the added value of such instrumentation at the ESR. If approved this LOI will be the basis for raising the necessary funds to accomplish this setup. After the successful installation, we will approach the GPAC with a series of physics proposals, where the ideas merely for some of them are sketched here.

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