Towards experiments with polarized beams and targets at the GSI/FAIR storage rings

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The exploitation of polarization degrees of freedom of hadron beams and/or targets offers a wealth of observables that are not accessible with unpolarized particles. These observables can be used to test the conservation or violation of fundamental symmetries like parity, charge conjugation, time reversal or combinations thereof.

This paper describes some of the physics that can be pursued with polarized hadron beams or polarized targets using the CRYRING and the Experimental Storage Ring (ESR) at GSI/FAIR in Darmstadt after the completion of the experimental program with the Cooler Synchrotron COSY at Forschungszentrum Jülich.

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1. Introduction

The use of polarized beams and/or targets will enable a novel class of experiments in the realms of atomic, quantum, and fundamental physics with charged ions and exotic nuclei. This document discusses opportunities at the storage rings operated at GSI Helmholtz Center in Darmstadt (GSI). It is largely based on a Letter of Intent submitted and endorsed to/by the GSI Physics Advisory Committee, G-PAC [1].

The manuscript is structured as follows. The Experimental Storage Ring (ESR) and CRYRING are presented in Sec. 2. Section 3 describes the main features of an atomic beam source at the ESR, that could be employed for an experiment to study the spin transfer in Radiative Electron Capture (REC) with the ultimate goal to produce beams of spin-polarized heavy nuclei, as discussed in Sec. 4. Experiments to search for axions/axion-like particles and a time reversal violating/parity conserving asymmetry are discussed in Secs. 5 and 6, respectively.

2. Experimental Storage Ring (ESR) and CRYRING@ESR

GSI/FAIR provides two storage rings in operation where the experiments described below could be performed. The smaller of the two rings is the so called CRYRING with a circumference of 54 m and the bigger one is the Experimental Storage Ring ESR with a circumfernce of 108 m. Main parameters of the two rings are summarized in Table 1.

The ESR and CRYRING operate in complementary energy regimes. The CRYRING has a maximum ion energy of 30 MeV for protons and 14 MeV/u for Uranium, whereas the respective energies in the ESR are 2208 MeV and 555 MeV/u. Both rings can store beams all the way from protons ($Z = 1$) up to uranium ($Z = 92$) in basically any selected atomic charge state [2]. Small beam emittance is ensured by electron coolers. Further detail are given in [3].

	CRYRING	ESR
Circumference	54.17 m	108.36 m
Maximum energy for $p/\bar{p}$	30 MeV	2208 MeV
U^{92+}	14 MeV/u	555 MeV/u
Rigidity, $B\rho$	0.054-1.44 Tm	0.7-10 Tm
Expected proton intensity	5×10^9	$\approx 10^{10\ a}$
Electron cooling	yes ($E_e \leq 20$ kV)	yes ($E_e \leq 230$ kV)
Stochastic cooling	no	yes (fixed at $\beta = 0.71$)

[a] Value scaled from measured intensities of stored heavy-ion beams [2].

Table 1: Main parameters of the CRYRING and ESR [3–6].

3. Atomic Beam Source of the ANKE experiment at COSY

In Sec. 4 we propose an experiment on how to transfer an electron polarization to nuclei. Here we describe an atomic beam source which could serve as an polarized electron target in the ESR ring. In order to realize a polarized electron target, a polarized hydrogen jet target could be utilized (see e.g. [7]). For the production of the polarized atomic beam, the polarized atomic beam source [8] (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 (see e.g., ref. [9]).

The layout of the ABS is presented in Fig. 1. 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 7.5×10^{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 $10^{12}/\mathrm{cm}^2$. With storage cell targets, an increase by about two orders of magnitude 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 [7] or Lamb shift polarimeter [10]) is necessary to monitor the polarization parasitically during operation.

4. Radiative recombination of heavily charged ions

Radiative recombination (RR), which is the time reversed photo–ionization process, is a suitable tool both for production of spin-polarized ions in storage rings [11] and controlling the polarization transfer to ion [12]. In a recent theoretical study [13], a general theory was developed for the spin-polarization transfer between incident electrons and the emitted x-rays in the radiative recombination of heavy highly-charged ions, which accounts for arbitrary (longitudinal and/or transversal) polarization of electron beam. Applying the density matrix approach and solutions of relativistic Dirac equation, one could investigate the dependence of Stokes parameters P_1, P_2 and P_3 on three projections of electron polarization vector $\mathbf{P} = (P_x, P_y, P_z)$. Simple analytical expressions, which allow us to understand how the degree and direction of linear polarization of recombination photons depend on the spin state of captured electron, were obtained. The RR differential cross section takes a form:

$$\frac{d\sigma}{d\Omega} = \sqrt{2}\,\mathfrak{R}_{00}(1,1) + 2P_y\,\mathrm{Im}\,\mathfrak{R}_{11}(1,1)\,, \tag{1}$$

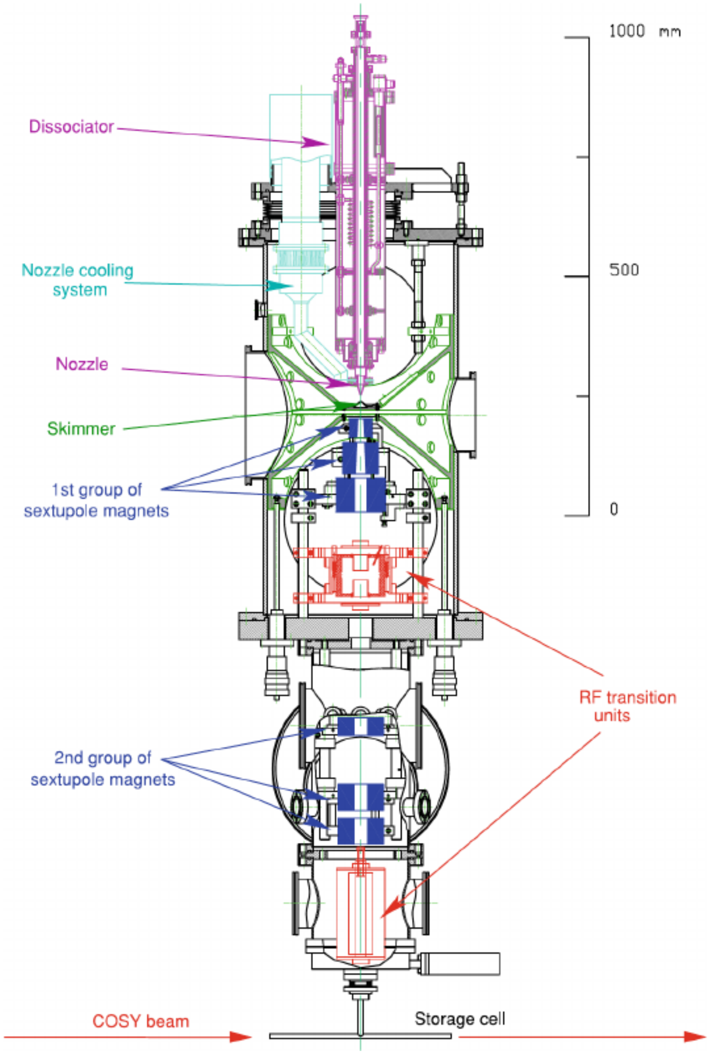

Figure 1: The ANKE polarized atomic beam source [8].

whereas the Stokes parameters of emitted photons are given by:

$$P_1 = \frac{\sqrt{2}\,\mathfrak{R}_{00}(1,-1) - \mathrm{i}P_y\,(\mathfrak{R}_{1-1}(1,-1) + \mathfrak{R}_{11}(1,-1))}{\sqrt{2}\,\mathfrak{R}_{00}(1,1) + 2P_y\,\mathrm{Im}\,\mathfrak{R}_{11}(1,1)}\,, \tag{2}$$

$$P_2 = \mathrm{i}\frac{\sqrt{2}P_z\,\mathfrak{R}_{10}(1,-1) + P_x\,(\mathfrak{R}_{1-1}(1,-1) - \mathfrak{R}_{11}(1,-1))}{\sqrt{2}\,\mathfrak{R}_{00}(1,1) + 2P_y\,\mathrm{Im}\,\mathfrak{R}_{11}(1,1)}\,. \tag{3}$$

Here tensors $\mathfrak{R}_{kq}(\lambda,\lambda')$ are constructed from the (products of) transition matrix elements (for more details see [13]). The Stokes parameters are very convenient for the theoretical analysis of RR measurements. From the experimental viewpoint, however, it is more practical to visualize the linear polarization of light in terms of the polarization ellipse. The relative length of the principal axis of the ellipse defines the degree of linear polarization of light $P_L = \sqrt{P_1^2 + P_2^2}$, while the orientation of this axis with respect to the reaction plane is described by the tilt angle χ: $\cos 2\chi = P_1/P_L$, $\sin 2\chi = P_2/P_L$.

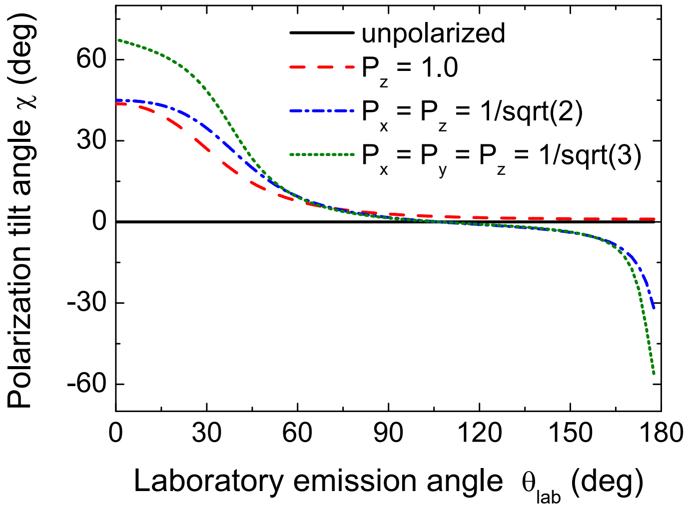

Figure 2: Tilt polarization angle χ as function of photon emission angle θ_{lab} in the laboratory frame and for different polarization states of incident electrons. Calculations have been performed for the radiative capture of polarized electrons into the ground $1s_{1/2}$ state of (initially) bare uranium projectile U^{92+} with energy $T_p = 400$ MeV/u. Taken from [13].

Figure 2 displays the numerical results for the radiative recombination of polarized electrons into the $1s_{1/2}$ state of hydrogen-like uranium U^{91+}. The calculations have been performed for the projectile energy $T_p = 400$ MeV/u which corresponds to the electron kinetic energy $T_e = 219.4$ keV in the ion rest frame. We presented the tilt polarization angle χ as functions of photon emission angle θ_{lab} in the laboratory frame, i.e. in the rest frame of the electron target. The results are presented for different electron beam polarizations: black solid line corresponds to the case of unpolarized electrons, $P_x = P_y = P_z = 0$, red dashed line is the case of longitudinally polarized electrons $P_x = P_y = 0, P_z = 1$, as well as electrons whose polarization vector has both longitudinal and transverse components: blue dash-dotted line is for the case of $P_x = 1/\sqrt{2}, P_y = 0, P_z = 1/\sqrt{2}$ and green dotted line corresponds to the case of $P_x = P_y = P_z = 1/\sqrt{3}$. As can be seen the tilt angle χ is strongly influenced by the polarization of incident electrons. For example, the tilt angle χ vanishes in the case of unpolarized incoming electrons (black solid line), while for the case of polarized electrons there is a significant rotation of the polarization axis. The most pronounced effect can be observed when photons are emitted forward, while the value of the tilt angle χ can reach 70 degrees. Such a remarkable rotation of the principal axis of the polarization ellipse can be observed by means of segmented Compton polarimeters.

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:

$$\frac{d\sigma}{d\Omega}_{KN}(\theta, \phi) = \frac{1}{2} r_0^2 \cdot \left(\frac{h\nu'}{h\nu}\right)^2 \cdot \left(\frac{h\nu'}{h\nu} + \frac{h\nu}{h\nu'} - 2\sin^2\theta\cos^2\phi\right). \tag{4}$$

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 [14]. The detector shown in Fig. 3(a) was constructed within the SPARC collaboration for this purpose as a dedicated Compton polarimeter [15]. 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. 3(d). 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. 4(c). With this profile the degree of linear polarization and orientation of the polarization vector can be extracted as shown in [16].

In Fig. 5 a scheme of a typical experimental arrangement of the ESR for the study of the polarization of projectile X–ray emission at the internal target station 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 [17]. As clearly visible from the spectrum, REC dominates the overall X–ray emission characteristics. For the current project we plan to replace the current versatile internal target by the ANKE polarized atomic beam setup (see Sec. 3). 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 G-PAC 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°, 90°, and 145°, respectively.

The developed theory opens up opportunities for the spin diagnostics of ion beams by means of the analysis of the linear polarization of recombination photon.

5. Search for axions and axion-like-particles in storage rings

The JEDI collaboration pioneered the search for axion/axion-like-particles (ALPs) in storage rings [18]. An axion/ALP field has an influence on the spin motion of particles in a storage ring. They cause, e.g., an oscillating electric dipole moment (oEDM). The JEDI collaboration performed a measurement with a polarized deuteron beam at the Cooler Synchrotron COSY at

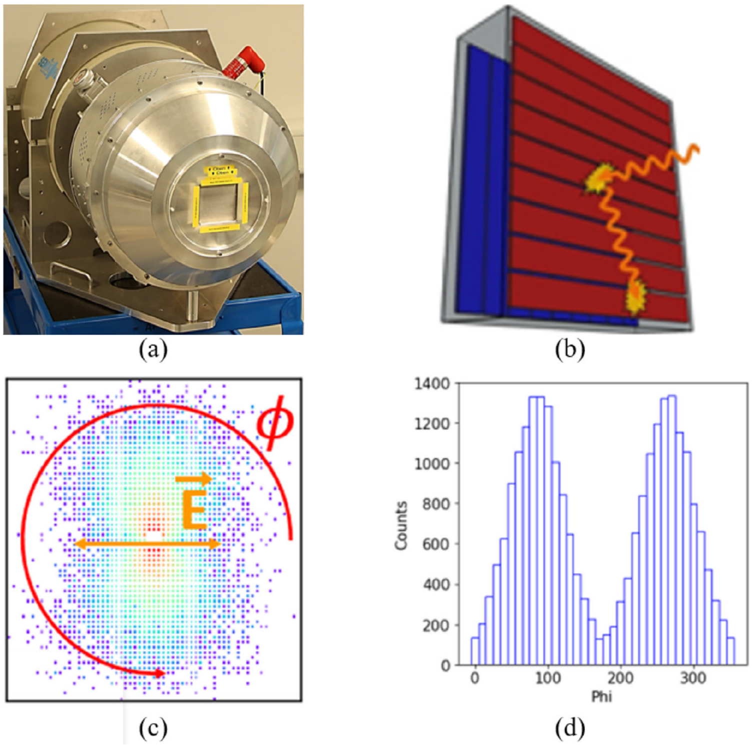

Figure 3: a) An image of the Compton polarimeter. b) Schematic principle of the segmented detector crystal is shown. When an incident photon is Compton scattered on the detector, the scattered photon can as well be absorbed inside the detector. With sufficient statistics the scattering distribution will 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) [15].

Forschungszentrum Jülich. In only a few days of data taking limits on the oEDM, shown in Fig. 6 were obtained. These limits can be converted into limits on various axion coupling constants.

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 by 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 could 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

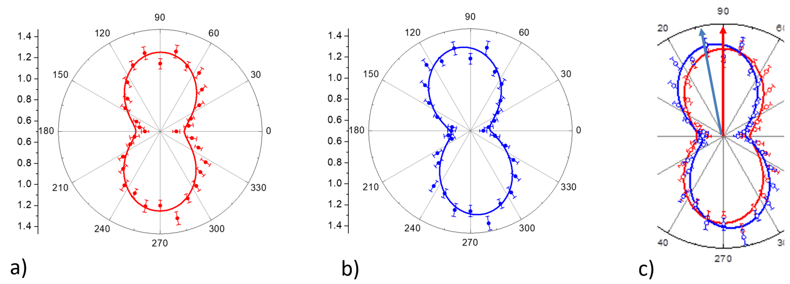

Figure 4: Azimuthal distribution of Compton scattered X-rays for incident bremsstrahlung photons with an energy of 92.5 keV: a) unpolarized electrons; (b) transversely polarized electrons and c) direct comparison between a) and b). The solid and dashed lines result from an adjustment of the Klein- Nishina equation to the experimental data. The rotation of the distribution for transversely polarized electrons is clearly visible [16].

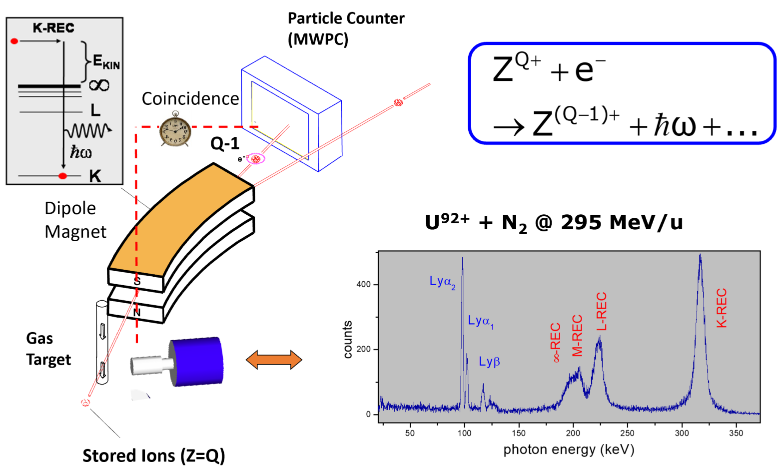

Figure 5: Experimental scheme for the detection of projectile X-ray emission at the internal target station of the ESR. X-ray emission associated with the transfer of target electrons into the projectile are measured in coincidence with the down-charged ions. An X-ray spectrum recorded for uranium projectiles colliding with N_2 molecules at the energy of 295 MeV/u is shown in addition [17]. The spectrum is governed by REC into the projectile K-shell, indicating that for high beam energies REC is only relevant electron capture process.

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 [19, 20]. 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.

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, heavier nuclei), the possibility to manipulate the polarization vector and to preserve its precession in the horizontal plane for hundreds of seconds and a polarimeter to measure the polarization. Work

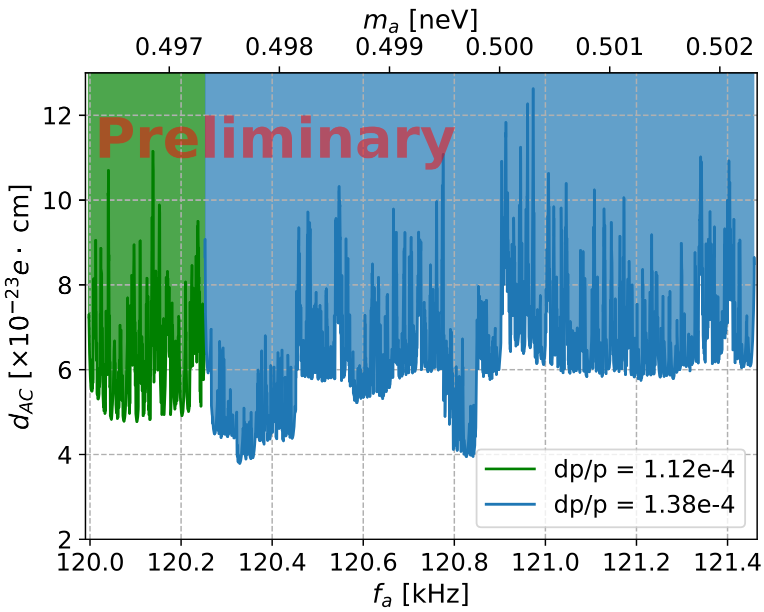

Figure 6: Preliminary 90% upper confidence level sensitivity for an oscillating EDM in the frequency range from 120.0 to 121.4 kHz (mass = $4.95 - 5.02 \times 10^{-9}$ eV). The green and blue colors show two scanning ramp rates in momentum change. Taken from [18].

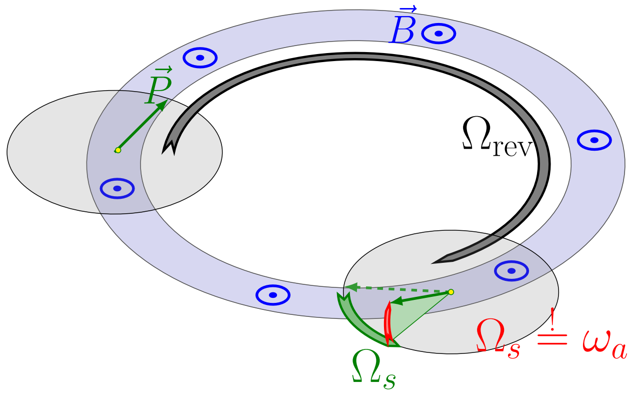

Figure 7: Principle of an axion experiment at storage rings. The polarization vector is precessing in the horizontal plane. If the axion frequency ω_a given by the axion mass ($\omega_a = mc^2/\hbar$), a resonance occurs causing a build-up of a vertical polarization.

is ongoing to investigate the possibility of a storage ring axion measurement at the ESR and/or CRYRING.

6. Search for a time reversal violating/parity conserving asymmetry

A flagship project for the ESR would be to constrain or even discover physics beyond the Standard Model (BSM) by investigating time reversal symmetry violations (T-V) 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 ESR 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 and detector. The required experimental expertise in beam and target polarization technologies is uniquely positioned to meet these objectives (see, e.g., Ref. [21] for further details regarding T-V).

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-V, P-V) is to look for an EDM of an elementary particle. 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.

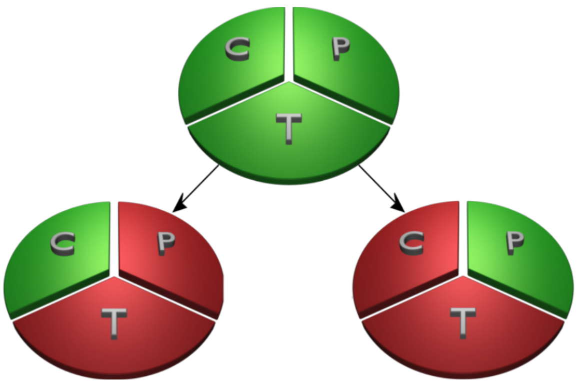

Figure 8: Assuming the validity of the CPT theorem, the project addresses one of the most fundamental challenges in modern physics, namely the baryon asymmetry of the Universe (BAU), in an approach which is independent, and yet complementary to searches for Electric Dipole Moments (EDM). While EDMs test 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).

There are model-dependent ways to estimate the strength of the T-V P-C interaction using the current result for the neutron EDM: $\alpha_T < 1.1 \times 10^{-5}$ [22]. A more recent analysis [23] 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 [24] 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-V P-C interaction, suggested here, provide the potential to discover BSM physics, *independent* of the EDM measurements. The very upper limit improvements will provide most valuable constraints for the Standard Model extensions. The discovery of T-V P-C-interactions would be a strong indication for the nature of BSM physics. 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 [25]. 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 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 [26] 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).

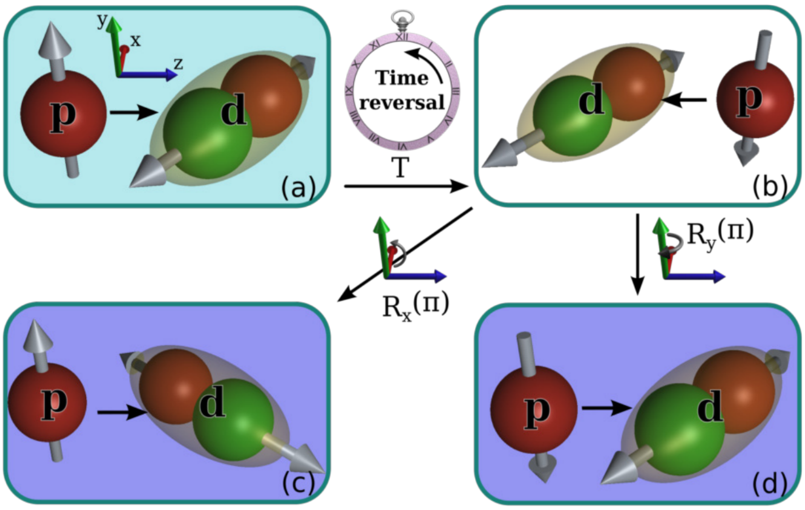

Figure 9: The experiment will test a T-V P-C interactions in double polarized proton-deuteron elastic scattering. The figure illustrates the concept. (a) The basic system is shown. (b) The time reversal operation is applied. In order to enable a direct comparison between (a) and (b), two rotations R_x 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. Taken from Ref. [21].

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 the ESR 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 [27, 28].

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 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, the 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) [29] compared to other approaches that make use of nuclear targets and require detailed modeling [30].

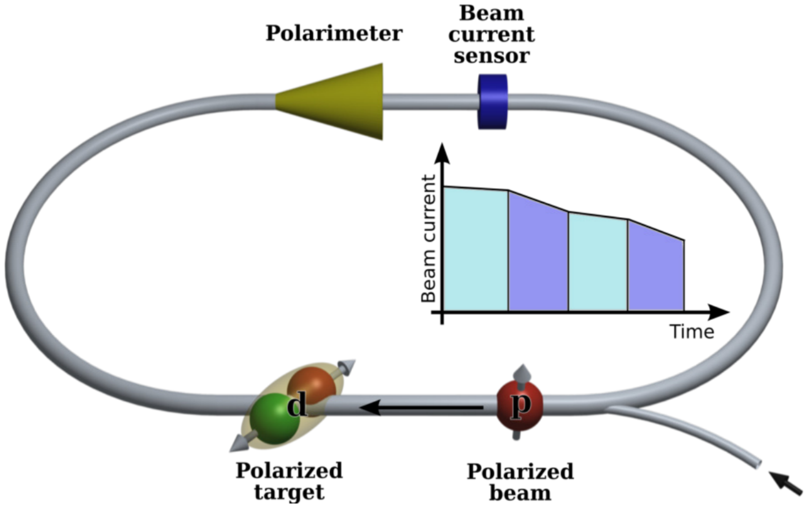

Figure 10: Main components of the experimental setup: polarized beam from the injector (accelerator), polarized deuteron target from an atomic beam source (ABS), polarimeter and beam current sensor. Time reversal invariance will be accessed by detecting the difference in the beam lifetime between the situations a) and c) or d) presented in Fig. 9 as schematically indicated in the inset. Adopted from Ref. [21].

7. Summary & Outlook

We sketched a few visions towards experiments with polarized hadron targets and beams at the GSI storage rings CRYRING and ESR. These ideas were initially presented in a Letter of intent communicated to the G-PAC (GSI Physics Advisory Committee). A full proposal is being worked out.

References

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