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PARTICLE ACCELERATOR SPIN-TRANSPARENT STORAGE RINGS FOR BEYOND STATE-OF-THE-ART SCIENCE*

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Abstract

We describe spin-transparent storage rings that exhibit coherence times of many hours and store a large number of particles and their use in novel applications. For example, these rings can be used to directly measure the electric dipole moment of the electron, relevant to CP violation and matter-antimatter asymmetry in the universe, and to search for axion-mediated forces. These rings can also serve as a compelling platform for quantum computing. In particular, we will describe how spin-transparent rings can be used in conjunction with ion traps to enhance scalability and increase quantum-coherence times of ion quantum computing.

SPIN-TRANSPARENT STORAGE RING

A spin-transparent (ST) storage ring [1] is designed to make the spin dynamics degenerate, i. e., the spin transformation in one turn around the ring is an identity transformation. The spin-transparency feature of such a ring is independent of its exact geometry as long as the ring is flat and the net beam bending angle is zero. The most natural ST topology is a figure-8 ring configuration. A conventional magnetic ring has a distinct spin direction $\vec{n}_0$ which the spins of all particles precess about. The rate of this precession is called a spin tune ν. In the conventional magnetic ring, $\vec{n}_0$ is in the vertical direction. All the spins precess about the vertical magnetic fields of the bending dipoles. Since the spin precesses about magnetic field $G\gamma$ times faster than momentum, where G is the particle's anomalous gyro-magnetic ratio and γ is the relativistic factor, the spin makes $G\gamma$ revolutions about the vertical direction in one particle turn around a conventional circular ring ($\phi = G\gamma \oint d\theta = 2\pi G\gamma$ and $\nu = G\gamma$).

The spin components perpendicular to $\vec{n}_0$ decohere in the conventional ring. The main cause of this decoherence is the spread in ν due to the spread in the particle energies $\Delta\gamma$, which is always present in a particle beam: $\Delta\nu = G\Delta\gamma$. For practical beam parameters, full polarization decoherence occurs in several thousand turns.

The ST ring configuration offers a universal solution to this decoherence problem. Clearly, since the bending angle $\int d\theta$ in one turn is zero, the spin rotation in one turn is identically zero as well, independent of the particle energy ($\phi = G\gamma \oint d\theta = 0$). For a particle of any given energy, the spin rotation in one arc is completely compensated by an equal but opposite rotation in the other arc. This mechanism is also known as the spin-echo effect.

For an ideal ST ring, any initial spin orientation transforms back into itself in one turn around the ring, i. e., there is no change in the spin from turn to turn regardless of its initial state. The spin state is frozen. However, there are realistic effects that cause deviation from this ideal picture. Firstly, any real ring has imperfections that distort its closed orbit in relation to the ideal design orbit. Secondly, particles undergo betatron and synchrotron oscillations about the closed orbit. This particle oscillation effect is of higher order than the first dominant effect.

In the closed-orbit distortion effect, the vertical distortion level is of the main concern because it leads to a net spin rotation in one turn around the ring. Vertical orbit distortion is caused primarily by vertical quadrupole magnet misalignments and dipole magnet roll. The sensitivity of the spin to these errors can be readily evaluated using the spin response function formalism for ST rings [2]. This effect has been studied within the context of GeV rings. It has been theorized and demonstrated in simulations that the imperfection spin effect can be measured and suppressed by a local 3D spin corrector consisting of weak magnets [3]. The application of compensation measures combined with error control provides the necessary coherence time.

The strengths of the ST ring technology are the long coherence times of many hours that it offers, as well as the large number of stored particles. Other avenues for scaling beyond the maximum number of stored particles is the use of multiple rings, for example.

EDM OF FREE ELECTRON

The electric dipole moment (EDM) is very sensitive to physics beyond the Standard Model and new sources of Charge- conjugation and Parity (CP) violation [4]. Such CP violation, beyond what is present in the weak interaction, could signal the presence of new physics and explain the puzzle of the matter-antimatter asymmetry in the universe. EDM electron searches have been performed in tabletop experiments using electrons in atoms and molecules, with the best upper limit ($< 4.1 \times 10^{-30}$ e · cm) using HfF^+ ions [5]. In these experiments, the bound on the electron EDM is derived from the measured atomic or molecular EDM and a

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species-specific internal effective electric field calculated using ab initio theory. However, there is no direct measurement of the electron EDM using free electrons.

This proceeding briefly describes a method to directly measure the electron EDM in small ST rings with beam energy below 1 MeV. More details can be found in Ref. [6]. It is based on the figure-8 ST configuration where the magnetic dipole moment spin rotation is naturally suppressed at any energy due to the ring topology and symmetry. To reduce systematic effects, we consider an all-electric design with no magnetic fields to allow for two counter-rotating electron beams to circulate concurrently.

The EDM ring consists of two low-energy and two high-energy arcs connected by longitudinal static electric field sections to provide acceleration/deceleration. They preserve suppression of the magnetic dipole moment effect but remove the degeneracy of the EDM spin precession. The beam directions in the two arcs of each energy are opposite, making the net bending angle zero. The statistical uncertainty of the EDM measurement per fill is expected to be 2.5×10^{-28} e · cm. After five years of data taking, the projected statistical limit is about 5.8×10^{-30} e · cm.

The presented approach has the following advantages: (a) spin dynamics features: spin-achromatic beam transport with energy-independent spin tune and long spin-coherence time at any energy, (b) suppression of systematic effects: bunched counter-rotating beams, no synchrotron radiation, and good control of systematic effects and imperfections including background magnetic fields, (c) practical aspects: low-energy low-cost room-sized facility with minimum safety issues and straightforward polarimetry. Finally, such rings can serve as testbeds for larger-scale experiments.

SEARCH FOR AXIONS

The ultra-light axion particles are compelling candidates for new physics beyond the Standard Model, motivated by the dark matter puzzle and the strong CP problem, where no violation of the CP-symmetry has ever been seen in any experiment involving only the strong interaction of Quantum Chromodynamics (QCD) in spite of the fact that the Standard Model as a whole violates this symmetry [7]. Axions represent very light spinless fields that couple to matter and mediate long-range macroscopic forces.

Recently, it has been proposed [6] to look for dark matter axions by measuring the spin precession of electrons in an ST ring. In this proceeding, we will consider sensitivity of ST rings to axion gradients sourced by the earth or test masses through the monopole interaction with nucleons. In an axion gradient background, the dipole interaction with electrons appears as an effective background magnetic field, which generates precession of spins. For axions, the force that affects the electron motion is extremely small.

The ST ring, designed to measure the electron EDM, can also be used to search for spin precession induced by axion interaction. Such ring can measure spin precession as small as 0.2 nRad/s (or 0.2 nHz). Figure 1 shows the expected sensitivity to axion-mediated forces in the ring sourced from the earth or from test masses in the lab. The ST ring results would surpass any existing or near-future search by several orders of magnitude [8, 9].

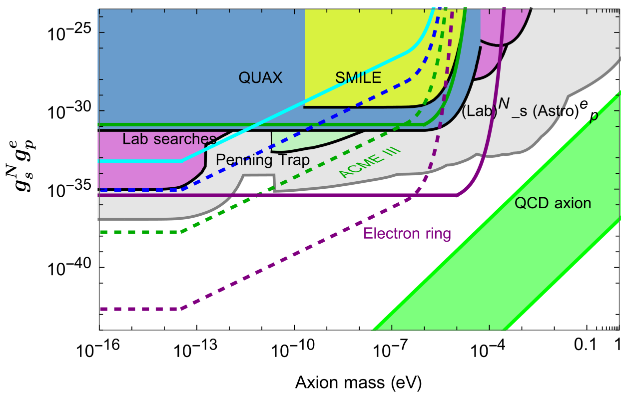

Figure 1: Axion-mediated monopole-dipole forces on electrons at different spin precession experiments with their bounds projected on the parameters space of scaler-pseudoscalar nucleon-electron couplings versus axion mass. The QCD axion band is shown in green. Cyan corresponds to the current sensitivity at the Penning trap experiment. Dashed blue and dashed green correspond to future improvements. Also shown is the expected sensitivity in the electron ST ring. The purple solid line corresponds to cubic lead bricks, 10 cm size around the ring at a distance of 10 cm from the beam, covering only 10% of the ring circumference (sensitivity increases linearly with this fraction). The purple dashed line corresponds to the limits due to the axion field from the earth nucleons. The combination of both configurations gives the strongest bounds surpassing any existing or near-future search by several orders of magnitude. More details can be found in Refs. [8, 10, 11].

QUANTUM COMPUTING

Quantum computers [12] have the potential to make significant impacts in the fields of cryptography [13], machine learning [14], and pharmacology [15] to name a few due to their ability to run critical algorithms with significantly increased computational efficiency compared to classical computers. Many technologies are being developed for quantum computation spanning much of modern physics. However, it remains unclear which technology will ultimately prove to be the most successful dealing with the myriad challenges facing quantum computing.

Two of the greatest challenges involved with constructing quantum computers are preserving quantum coherence and implementing scalability. The loss of coherence in the qubit comes from its interactions with external world and fluctuations of control parameters in quantum operations. Ultimately, the ratio of the coherence time to the gate time, the time it takes to perform an operation on one or more qubits, determines the maximum achievable algorithmic complexity of the device. Scalability is the measure of a

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quantum system's ability to increase the number of qubits without an exponential increase in cost of resources (such as time, space, or energy). Accordingly, a device that can provide long coherence times for large, scalable systems of qubits is needed.

Charged particles in ST rings can exhibit long spin coherence times of up to several hours and represent a large number of qubits making them an interesting but untested prospect for quantum computing. In the case of ion qubits, ion traps [16] can be combined with the ST ring to greatly enhance both quantum coherence time and scalability. The spins of the nuclei of these ions, such as $^{171}Yb^+$, couple to the spins of the outer-shell atomic electrons through the hyperfine interaction [17]. The qubits are represented by the two hyperfine ground states: $|F = 0, m_F = 0\rangle$ and $|F = 1, m_F = 0\rangle$.

Polarized $^{171}Yb^+$ can be prepared in the ion trap by optical pumping of $^{171}Yb^+$ atoms into a single hyperfine state, which are then injected into the ring. The ion trap is used to prepare the single-ion qubits and the entangled ion qubits. The $^{171}Yb^+$ atomic ion is highly suitable for use as a qubit in a ring because of its long-lived hyperfine qubit, which has been demonstrated in radio-frequency Paul traps. The spin of the $^{171}Yb^+$ qubit can be measured using state-dependent resonant fluorescence, where the $^{171}Yb^+$ ion interacts with a laser beam and fluoresces photons when it is in only one hyperfine spin state. This fluorescence method provides an efficient and robust readout mechanism of the qubit in the ring.

The layout of the ring, shown in Fig. 2, is designed to store about three thousand $^{171}Yb^+$ ions and fits in a 12 m by 6 m footprint. Qubit motion is transversely stabilized by alternating focusing. A radio-frequency (RF) bunching cavity provides longitudinal confinement of the individual ions. The maximum number of stored qubits is determined by their minimum longitudinal separation sufficient for their independent manipulation – chosen to be about 1 cm, so that the fringe fields of pulsed elements, such as the injection kicker, do not overlap the adjacent ions.

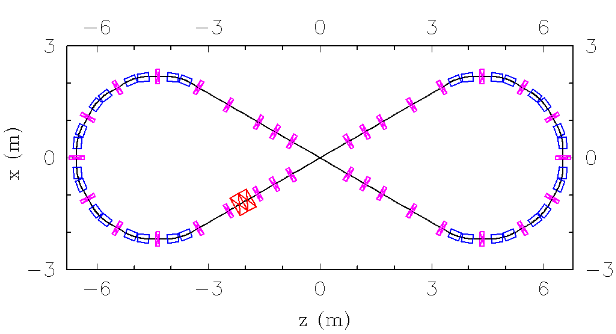

Figure 2: Layout of an all electric ST ring for $^{171}Yb^+$ ions. Shown are the bending electrodes (blue), focusing elements (magenta), and the RF bunching cavity (red).

The ring design is electrostatic. It is necessary to preserve its spin transparency feature for ions. Unlike an elementary particle, an ion is a compound particle, and its anomalous gyro-magnetic ratio is a function of the applied magnetic [18] and electric fields. The field dependence is such that the spin phase advance is not necessarily zero for zero integrated magnetic field while it is zero for zero integrated electric field. Some of the ring parameters are listed in Table 1.

Table 1: ST Ring Parameters for $^{171}Yb^+$ Ion

Kinetic energy, K	10 keV
Momentum, p	56.4 MeV/c
Velocity, β	3.54×10^{-4}
Relative longitudinal momentum offset, $\Delta p_\parallel/p$	$< 10^{-3}$
Longitudinal temperature, $T_\parallel = mc^2\beta^2(\Delta p_\parallel/p)^2/k_B$	< 200 K
Angular deviation, $\Delta\theta_\perp$	1 mrad
Transverse temperature, $T_\perp = mc^2\beta^2\gamma^2(\Delta\theta_\perp)^2/k_B$	232 K
Ring circumference, L	33.5 m
Circulation frequency, f_c	3.17 kHz
No. of qubits / RF harmonic number	3, 300
Time separation of qubits, Δt	95.7 ns
Electric bending field, E	17.3 kV/m

The limit on the maximum transverse and longitudinal offsets of a stored particle comes not from the spin coherence or ring acceptance but from the Doppler shift of the state transition frequencies. Unlike techniques relying on quantization of the orbital motion [19, 20], the spin-based qubit states are robust. The spin state is practically decoupled from the orbital motion. Once set, aside for resonant situations, the spin state is stable to external factors. However, deviation of the particle momentum from the design value results in a Doppler shift of its transition frequency. If the shift is greater than the frequency difference between the states, the two states cannot be discerned. Despite being the greatest limitation, this constraint still allows for momentum offsets of hundreds of Kelvin in terms of the transverse and longitudinal beam temperatures.

CONCLUSION

ST rings have many exciting applications which will push the boundaries of the state-of-the-art. In the case of quantum computing, we propose a new platform for quantum computing based on polarized particles in an ST ring. Advantages of ST rings for quantum computing include: large numbers of stored qubits; long quantum coherence times of up to several hours; long storage lifetimes; and room temperature operation. These exceptional qualities mean rings could provide a scalable way to implement algorithms with deep complexity requiring many quantum operations while simultaneously providing a large number of qubits. This new platform where the qubit has long quantum coherence time can also be used as a quantum sensor or a part of a quantum memory.

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