Axion-EDM: An Axion Search at COSY

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ABSTRACT:

We propose to develop and demonstrate a method of using COSY with an in-plane polarized deuteron beam to search frequency space for a resonance associated with a hypothetical axion field that induces an oscillating electric dipole moment (EDM) on the deuteron. This experiment builds on techniques being developed to use a storage ring to search for a static EDM. If the oscillating EDM is in phase with the in-plane rotation of the deuteron polarization, then the vertical component of the polarization will accumulate over time, and this change will be the signature of the presence of the axion field. By scanning the revolution frequency, and hence the spin precession frequency, the search can cover a range of possible axion frequencies or masses. A successful completion of this experiment may lead to a larger program of axion searches associated with storage rings running polarized beams.

A. SCIENTIFIC MOTIVATION AND CONTEXT:

The theoretical prediction of neutron electric dipole moment in QCD theory is given by $\left|d_n^\theta\right| = \theta_{QCD} \cdot 10^{-16}\, e \cdot cm$ [1]. However, the most sensitive experimental result [2], $d_n = 2.9\times 10^{-26}\, e\cdot cm$ for the neutron, sets a very strict upper limit on the parameter $\left|\theta_{QCD}\right| < 10^{-10}$. Since there is no natural explanation for the extremely small value of θ_{QCD}, this is called the strong CP problem.

The axion originated from a symmetry postulated by Roberto Peccei and Helen Quinn to solve the strong CP problem in QCD physics [3]. The small θ_{QCD} parameter is explained by a dynamic field, rather than a constant value, and the dynamic field is called the axion. Furthermore, if the axion is very light, it interacts so weakly that it would be nearly impossible to detect in conventional experiments, but it would be an ideal dark matter candidate.

In 1983, Pierre Sikivie [4] suggested a sensitive method to look for the axion by using a high-Q microwave cavity permeated by a strong magnetic field. Since then, microwave cavities have become one of the most sensitive tools for axion searches. This method utilizes the axion-photon coupling in a strong magnetic field where axions may be converted into radio-frequency photons [5,6,7].

The axions also couple to gluons, fermions, nucleons, etc. The axion-gluon coupling induces an oscillating EDM in nucleons [8,9]. In this case, the EDM of the nucleon can be expressed as:

$$d_n = 1.2\times 10^{-16}\,\frac{a(t)}{f_a}\,e\cdot cm = 1.2\times 10^{-16}\,\frac{a_0\cos(m_a t+\phi_a)}{f_a}\,e\cdot cm$$

where a is the axion/dark matter field, m_a is the axion mass, and f_a is the axion decay constant. Φ_a is an unknown local phase that we will need to consider later.

In this proposal, we wish to search for the oscillating EDM by using a resonance between the g–2 precession of the deuteron and the axion frequency. In the presence of this resonance, the vertical polarization component can accumulate. The method is expected to have sensitivities comparable to the anticipated storage ring search for a static EDM. Because of the resonant nature of the signal, systematic errors are expected to be easier to handle. A variety of storage ring applications are possible across a frequency range from 10^{-9} Hz up to 100 MHz. At the lowest frequencies, the search may be conducted parasitically with a frozen spin EDM experiment in which the beam polarization is kept parallel to the beam velocity. By using crossed magnetic and electric fields to bend the beam in the storage ring, this frequency range may be extended upward. At the top end, one can make use of the polarization precession found in rings with only magnetic bending elements, provided a variety of beam momenta are explored. This proposed experiment operates in the latter regime where the electric field in the frame of the beam is large due to its origin in the $v \times B$ term in the relativistic transformation. This method also has the important feature that it can be used at specific frequencies to confirm axion claims made with other methods.

Most of the axion searches operate in the range above μeV [10]. This includes microwave resonance cavity experiments. The storage ring technique can potentially search from μeV down to 10^{-24} eV with high sensitivity. There has been little or no searching in the range to date. Some experiments such as ALPS or CAST operate here, but not with the sensitivity of the storage ring method. The ultra-cold neutron EDM experiment is the only experiment that has searched below 10^{-17} eV [11]. Any storage ring measurement in the axion range from 10^{-17} to 10^{-6} eV (mHz to 100 MHz) will be the highest sensitivity axion search in this range. Typical operating frequencies for COSY fit nicely into this range.

B. TECHNICAL CONSIDERATIONS:

Work is underway at COSY on studies of the feasibility of using a storage ring [12] to search for an electric dipole moment (EDM) aligned along the spin axis of the beam's polarization. With this proposal, we wish to explore the possibility to make use a resonance between the in-plane polarization precession of a beam in the ring and the frequency of an oscillating EDM component induced by the presence of an axion field. Such as exploration can begin with the established COSY operating parameters for a deuteron beam of p=0.97 GeV/c with a long in-plane polarization lifetime [13]. The signature of the resonance would be the accumulation of a vertical component in the beam polarization similar to that proposed for a static EDM [12] if the axion and spin tune ($f_{REV}G\gamma$) frequencies are matched (where f_{REV} is the machine revolution frequency and G is the deuteron's magnetic anomaly) . With the static EDM search, it is necessary to constrain the in-plane polarization to lie parallel to the beam velocity ("frozen spin") in order for such an accumulation to take place. If the EDM were allowed to freely precess in the ring plane, the periodic reversal of the polarization would cause any accumulation to be canceled. In the axion search, the reversal of the oscillating EDM is matched to the in-plane precession frequency so that the cancelling parts of the rotation cycle now add, making accumulation possible.

A priori, we do not know the EDM frequency of the axion field, so it will be necessary to slowly scan the spin tune frequency and look for a change in the vertical beam polarization component as the resonance is crossed. A model of such an event Is shown in Fig. 1.

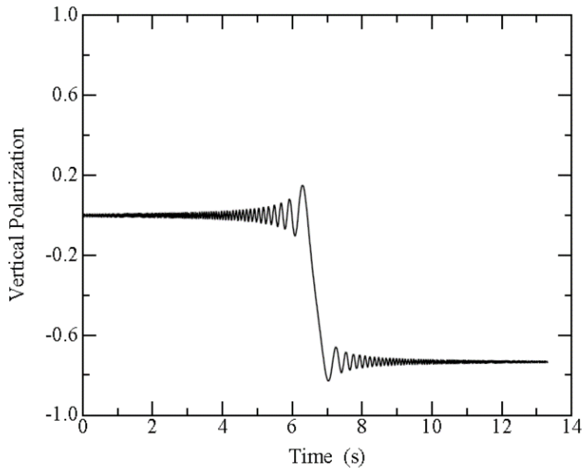


Figure 1: A "no-lattice" [14] calculation of the resonance crossing with a scan rate of 0.5 Hz/s. The strength of the oscillating EDM is 1.6×10^{-21} e·cm. Within the span of less than one second, this causes a jump of −0.75 in the p[Y] component of the beam polarization (assumed to initially be completely polarized in the ring plane).

In an actual scan, we could compare (for example) a 2-second region before and after the jump event to see if a change in p[Y] took place. These test regions would be located during times in the beam store when the frequency scan was not active. At present, such beam polarization effects are monitored using a 2-cm think carbon target and the WASA detector with trigger gates on the left and right quadrants. In such conditions, a typical left right asymmetry is 0.18. If each 2-second region yields 20,000 polarimeter events, the error in either of the two asymmetries would be 0.003. If we take a 2-σ change as the threshold for as axion candidate, we would be scanning with a sensitivity of about 2.5×10^{-23} e·cm. Running for one day at a single place would provide a sensitivity of about 1.0×10^{-24} e·cm.

It is important to recognize that for such a polarization jump to take place, certain axion field properties must be true. First, the axion field must be coherent over a sufficiently large region of space. If so, that all of the particles in the beam will see the same field and oscillate coherently together. Thus the properties of the polarized beam may be assumed to represent the properties of one particle undergoing an EDM oscillation. This spatial coherence must extend to all parts of the COSY ring. Otherwise the accumulation could not take place. Second, the axion field must be coherent in time. This means that the *phase* of the axion field oscillation is fixed for a time long enough to generate a signal similar to the one shown in Fig. 1. Such times are governed by the speed at which the axion field is traveling through space. These fields must be confined by the gravitational attraction of the galaxy, which leads to estimates on the order of tens of seconds for the simulation shown in Fig. 1. Any resonance crossing must be completed in less than this time in order to observe the full strength. The last remaining assumption is that the phase difference between the spin tune and the EDM oscillations is such that the spin rotation due to the particle frame electric field of the ring is such that accumulation is favored.

B.1. Managing the unknown phase of the axion field

The unknown phase of the axion field leaves open the possibility that by chance a poor choice of starting time for the beam's in-plane rotation happens to be orthogonal to the oscillation of the EDM. In this case no accumulation would take place. This section shows how operating with more than one bunch in COSY allows the full space of axion phases to be sampled so that nothing is missed.

A better plan would be to simultaneously observe the axion field with two polarized beams whose polarization directions were separated by a right angle. In this case, we propose that COSY be operated at a harmonic, h=4, and that the RF solenoid that initially precesses the polarization from the initial vertical direction determined at injection operate on its first harmonic with the frequency being either $f_{REV}(1+G\gamma)$ or $f_{REV}(1-G\gamma)$ (630 or 870 kHz). It happens that either of these frequencies is easily within the operating range of the RF solenoid power equipment, and this harmonic is routinely used for this precession task during other experiments.

An understanding of why this scheme works begins with the three panels of Fig. 2.

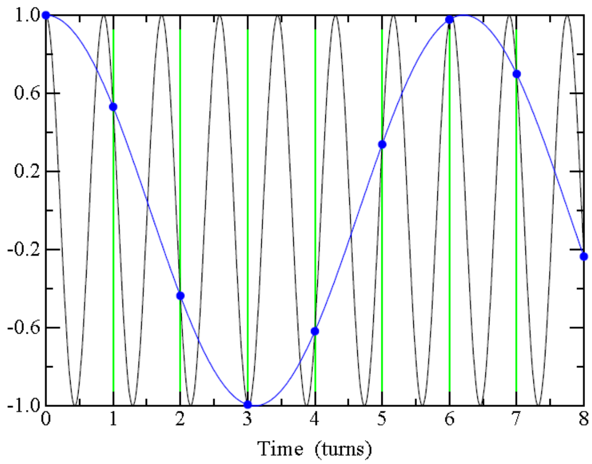
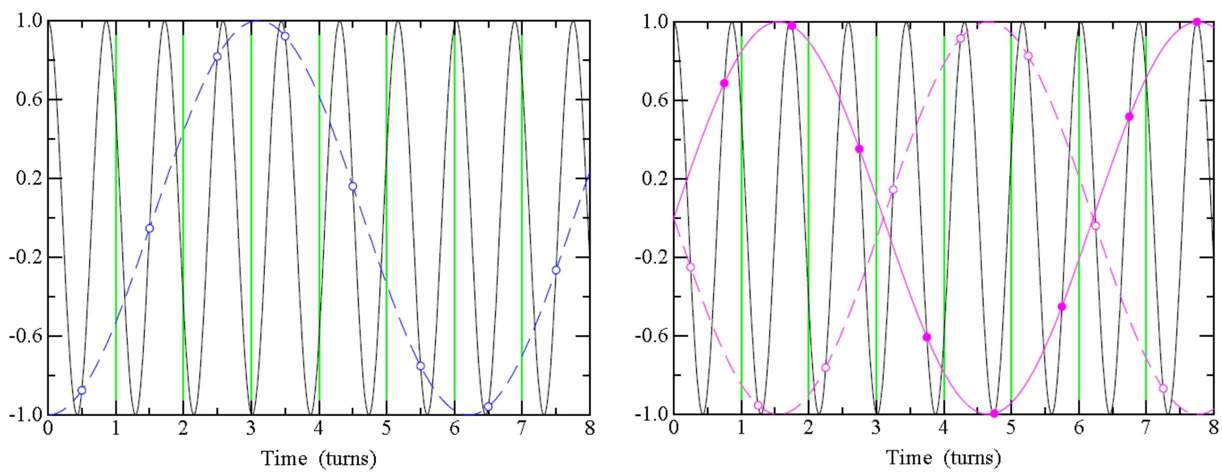


Figure 2: (left) A schematic diagram of the oscillations of the RF solenoid (black curve, 870 kHz) and an ideal beam polarization (blue curve) as a function of time in turns. Each turn is marked by a vertical green line. The blue dots indicate moments when the beam passes through the RF solenoid. (lower left) Same for beam passage through the solenoid halfway through a turn. (lower right) Same for ¼ and ¾ of a turn.



The black curve each of the panels in Fig. 2 represents the oscillations of the RF solenoid running at 870 kHz. At each integer turn number for the upper left panel, the beam passes through the solenoid. These points are marked by solid blue dots. These dots form a pattern at a slower oscillation given by the solid blue line. This line represents an oscillation at about 120 kHz, or the spin tune frequency. If the RF solenoid field kicks the beam polarization following the blue dot pattern, then a vertical polarization is most efficiently rotated into the ring plane. These rotations take place on top of the normal in-plane precession (120 kHz) required by the ring bending magnetic fields and the magnetic moment of the deuteron. This is the pattern that is most often used to create this rotation.

If we now have four bunches instead of one, these bunches will pass through the solenoid at time represented by 0.25, 0.5, and 0.75 of a turn. The kicks from the solenoid are shown by the open purple circles at half of the turn number in the lower left panel. Again, a 120 kHz slower oscillation is present, but this time the phase is opposite the pattern in the upper left panel. When these two timings for beam passing the RF solenoid are completed, their respective polarizations will enter the horizontal plane with opposite polarization directions. In the lower right panel, the cases for 0.25 and 0.75 of the turn number are shown. These generate both signs of the sine function, and the polarizations are at right angles to the first two cases shown. If the in-plane polarizations produced by the solenoid follow these patterns, then we have an ideal right angle separation in the phase of each of the four bunches as the come to the ring plane.

In practice, however, these patterns arrive at different times and continue their g−2 precession. This has the effect of bringing the polarization direction back almost into alignment again. What keeps the polarization directions from overlapping is the anomalous part of the deuteron's magnetic moment. The final result is given by the pattern in Fig. 3.

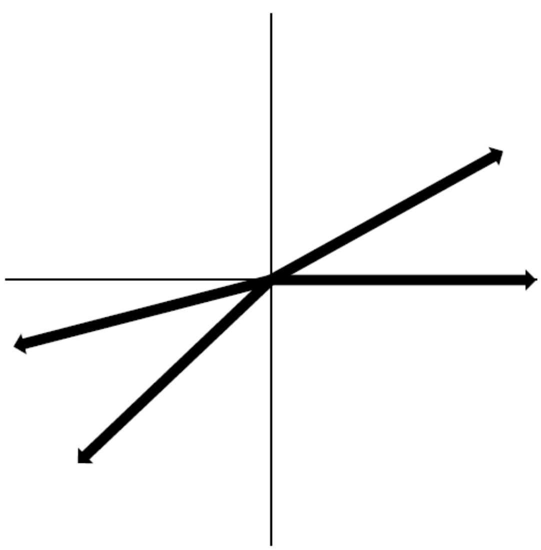


Figure 3: The relative polarization directions for the *h*=4 bunches following precession from the vertical direction into the horizontal plane. By choosing the 870 kHz harmonic, every other bunch is nearly reversed in direction from the next bunch. Had this been done with the 630 kHz harmonic, all of the bunches would be grouped together into one quadrant of the diagram. The maximum opening angle (considering opposite directions as equivalent) is 43°.

This grouping spans the space, but not with perfectly orthogonal reference directions. Instead, the maximum separation angle for identifying a separate component is 43°. One advantage to this grouping is that there are combinations of polarization states where the polarization is nearly opposite. This is the situation where we would normally employ a cross ratio analysis of the two asymmetries in order to remove (at least to first order) the systematic effects of geometry errors in making the measurement.

Operation of the bunching system must be able to handle the creation of four beam bunches with a minimal about of mixing between bunches. The usual RF pickups are not able to quantify this, but the data acquisition system generates a 2-D plot of ring circumference versus time in the store for all polarimeter events. One version of such a figure is shown in Fig. 4.

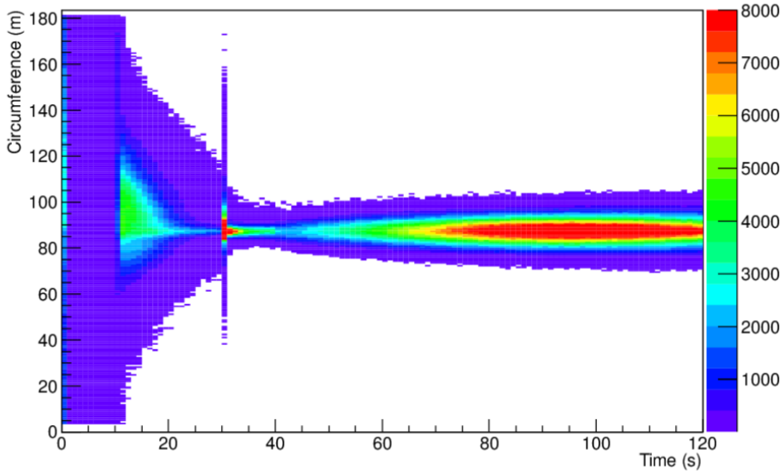


Figure 4: A graph of particle flux at the EDDA polarimeter as a function of time in the store and position around the ring circumference. Channels with less than 5 events/bin have been suppressed. The history shows injection, cooling, the start of DAQ, and a long storage time for gathering data. See the text for more details.

This particular 2-D presentation of the event rate contains several features that represent injection, initial cooling for 30 s, a spike as the beam is moved to the polarimeter target, a 10-s preparation of the beam, and finally about 80 s of data acquisition time for polarization tests. Note that all bins with fewer than 5 events has been suppressed, which accounts for the clean, white areas. This is important as we would like to rebunch into h=4, which would generate four data acquisition bands instead of just one. The narrowness of the band shown here suggests that this should be possible while maintaining reasonably clean separation between the bands. (The vertical position of the bands depends on an arbitrary timing offset to define the beginning of the circumference axis.) With this spectrum, or vertical slices of it, we should have adequate diagnostics for adjusting the bunching system. It may prove necessary to consider adding harmonics through the barrier bucket system to sharpen the bunch edges.

We will continue to look for ways to improve this beam preparation scheme.

C. FURTHER COMMENTS:

With the scanning rate shown in Fig. 1, a 150-s scan might cover a change of 10^{-4} in revolution frequency. After this, it would be necessary to scale the ring magnets up to take the next step. All of the machine parameters noted here are flexible, depending on running conditions with COSY and the extent to which we want to improve the sensitivity. Running for perhaps one shift or one day with a single scan can yield information on the stability and reproducibility of COSY.

Any polarization jump above threshold would be followed by a repeat of the scan. Scanning rates could be changed to improve sensitivity. If anything were observed, repeat observations would be subject to possible changes of the axion field, a point of study with value in its own right.

It is possible that we would encounter machine resonances, such as the imperfection resonances that appear whenever the polarization in-plane precession rate is tied to an integer or the ratio of small integers. In these cases, the fact that the relevant phase is between the axion field and the polarization precession should easily distinguish an axion from other types of resonances. In the latter case, all of the polarization directions should show a similar result.

D. ACKNOWLEDGEMENTS:

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E. RUNNING TIME REQUEST:

This running request is for two weeks of production time with an additional week of machine development (which might be scheduled in order to share the setup with another polarized deuteron beam effort.). Some of the running time will be devoted to machine development for the h=4 operation and commissioning changes to the data acquisition software in order to handle multiple bunches with separate analyses and ramping of the revolution frequency. (In principle, the software now checks this and modifies its internal parameters to match to the COSY ring.)

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