Proposal:
Polarimeter Development for a Search for a Permanent Electric Dipole Moment on the Deuteron

C.J.G. Onderwater,[1,*] E.J. Stephenson,[2,†] D. Babusci,[3] M. Bai,[4] N.P.M. Brantjes,[1] A. Ferrari,[3] R. Gebel,[5] K. Jungman,[1] A. Lehrach,[5] P. Levi Sandri,[3] B. Lorentz,[5] A. Luccio,[4] R. Messi,[6] J.P. Miller,[7] D. Moricciani,[6] W.M. Morse,[4] Yu.F. Orlov,[8] D. Prasuhn,[5] Y.K. Semertzidis,[4] M. da Silva,[1] G. Venanzoni,[3] L. Willmann,[1] H.W. Wilschut,[1] and G. Zavattini[9]

[1] *Kernfysisch Versneller Instituut, Groningen, The Netherlands*

[2] *Indiana University Cyclotron Facility, Bloomington, IN 47408 USA*

[3] *Laboratori Nazionali di Frascati dell' INFN, Frascati, Italy*

[4] *Brookhaven National Laboratory, Upton, NY 11973, USA*

[5] *COSY, IKP, Forschungszentrum Jülich, 52425 Jülich, Germany*

[6] *Dipartimento di Fisica, Universita' "Tor Vergata" and Sezione INFN, Rome, Italy*

[7] *Boston University, Boston, MA 02215, USA*

[8] *Cornell University, Ithaca, NY 14853, USA*

[9] *University and INFN, Ferrara, Italy*

We propose to perform an R&D program in the COSY storage ring at IKP/FZJ aimed at the design of a highly sensitive and efficient deuteron polarimeter. This polarimeter is intended for use on a storage ring set up to measure (or limit) a permanent electric dipole moment of the deuteron at the level of $10^{-29}\,\mathrm{e\cdot cm}$. The polarimeter would be designed for high efficiency, using Coulomb scattering from a thin target to slowly extract the deuteron beam onto a thick carbon analyzing target. The sensitivity for vector polarization is based on the large spin-orbit effects seen for deuteron elastic and inelastic scattering as well as transfer reactions in this energy region. We wish to explore two aspects of our design, *viz.* the statistical and systematic sensitivity on the one side, and the interaction with the beam on the other side. Our program consists of five parts. The first part of the program involves the measurement of the (presently unknown) cross sections and analyzing powers for reactions induced by polarized deuterons with momenta between 1000 and 1500 MeV/c striking a carbon target. We have identified the WASA detector as the most suited for this of all of the in-place detector facilities at COSY. The second part is aimed at the experimental verification of the predicted high efficiency of >1% and the investigation of systematic sensitivities of the double-target configuration using one of the existing gas targets and an annular carbon target upstream of the EDDA detector. The third part will involve the production of a transversely vector-polarized deuteron beam through an RF-dipole or solenoid. The natural coherence time of transverse polarization needs to be determined and

extended by bunching the beam and possibly making improvements to the ring lattice. The effect of the gas jet density on the resulting coherence time must be measured. The fourth part involves imposing a forced, coherent, synchrotron oscillation on the deuteron beam so that the sensitivity of the polarimeter to such oscillations can be investigated. Lastly, all of the information gleaned during these studies will be incorporated into a design for a prototype polarimeter that will be tested on the COSY ring. This proposal requests beam time to investigate the double-target scheme for high-efficiency polarimetry.

PHYSICS MOTIVATION

Symmetries play an important role in our understanding of physical phenomena and give rise to the form of the Standard Model (SM) used to describe them. In particular charge conjugation (C), parity (P) and time reversal (T) are especially powerful for understanding quantum phenomena because of their connection to a covariant theory. One concern of particular interest is the violation of CP. It is an important ingredient in explaining the dominance of matter over antimatter in the universe. However, the amount of violation inferred from experiments using K, and most recently B, mesons is insufficient to explain this cosmological asymmetry. Another concern centers on the scale at which grand unification is expected to occur, a scale that is not the same for strong, electromagnetic, and weak forces considered together within the SM. For these and other reasons, the SM is believed to be incomplete, despite its enormous success. The large number of unexplained (*i.e.* input) parameters in the model is considered by many theorists to be a sign that there is a more fundamental theory, of which the SM is merely a low energy approximation. Many theoretically well motivated, yet experimentally unverified, versions of such a new, encompassing theory exist. Here seminal experiments can point us in the right direction. One of the most successful methods in constraining new theories has been to put a tighter limit on possible permanent electric dipole moments (EDMs), *i.e.* on time reversal violation. The observation of an EDM within the reach of experiments now being planned would clearly require physics beyond the scope of the current SM (for a review, see [1]).

The most stringent EDM limits on single particles are for the neutron ($d_n < 2.9\times 10^{-26}$ e·cm [2]), the electron ($d_e < 1.6 \times 10^{-27}$ e·cm [3]) and the proton ($d_p < 1.2 \times 10^{-22}$ e·cm [4]). While the even lower bound on an EDM for ^{199}Hg ($d_{\mathrm{Hg}} < 2.1 \times 10^{-28}$ e·cm [5]) does not translate into a lower limit on the neutron because of screening by the atomic electrons [6], this extremely small limit sets the present bound on T-odd nuclear forces, something we would explore further in the deuteron EDM experiment.

The relative comparison of the deuteron EDM (dEDM) to other hadronic EDM efforts is summarized in Table I. Clearly, the strength of the dEDM experiment is that it could provide the next significant increase in sensitivity level in the hadronic EDM field. The reach of a search on the deuteron is enhanced by its particular sensitivity to chromo-EDMs manifest in the nuclear interaction through one-loop diagrams that contain super-symmetric particles [7–10]. Expressed in terms of an equivalent exchanged-particle mass, the physics reach of a search on the deuteron is at the 10^3 TeV energy scale for a CP-violating phase of order one or, if SUSY exists at the LHC energy scale, its sensitivity is 10^{-5} rad for a CP-violating phase. Both sensitivity levels are well beyond the design sensitivity of the LHC. These limits are typically obtained in experiments that

TABLE I: Comparison of hadronic EDM efforts[11]. All bounds are in $\mathrm{e \cdot cm}$.

	Current Bound	Future Goal	$\sim d_n$ Equivalent
neutron	$d_n < 3 \times 10^{-26}$	$\sim 10^{-28}$	10^{-28}
^{199}Hg atom	$d_{Hg} < 2 \times 10^{-28}$	$\sim 2 \times 10^{-29}$	$10^{-25 \cdots 26}$
^{129}Xe atom	$d_{Xe} < 2 \times 10^{-27}$	$\sim 10^{-30 \cdots 33}$	$10^{-26 \cdots 29}$
Deuteron	—	$\sim 10^{-29}$	3×10^{-29}–5×10^{-31}

look for a shift in the precession frequency of the particle in a magnetic field when a parallel (or anti-parallel) electric field is applied. These experiments, which rely on confinement in a trap or box, can be used only for neutral particles. In complex systems such as ^{199}Hg, the upper limit on the EDMs of their constituents must be inferred using theoretical models.

STORAGE RING FOR EDM SEARCH

A novel experimental method, based on confining charged particles in a magnetic storage ring, allows the EDM of charged particles to be measured *directly* and is being developed by the Storage Ring EDM Collaboration [12]. In our earlier Letter of Intent to the COSY PAC [13] we described a method based on the application of a radial electric field to 'freeze' the spin precession that normally occurs for the horizontal component of the polarization in the dipole fields of the ring [14]. With this method we expected to be able to reach a level of (systematic) sensitivity as low as $10^{-27}\,\mathrm{e \cdot cm}$, which already significantly tests a number of extensions to the Standard Model.

Since the submission of our Letter of Intent, we have investigated a second concept which not only eliminates the limiting systematic error source of the earlier method, but also allows for a much smaller setup [15]. This method is analogous to the highly-sensitive oscillatory fields technique in atomic physics, originally proposed to study nuclear magnetic moments [16].

In this new configuration, the horizontally-oriented spins of the deuterons are allowed to precess in the magnetic field of the ring at a rate determined by the (anomalous) magnetic moment. The interaction of any electric dipole moment with the motional electric field $\vec{v} \times \vec{B}$ in the frame of the deuteron will add to this precession. To first order, the precession vector $\vec{\omega}$ will only slightly tip, proportional to the magnitude of the EDM. Because of the rapid precession, the EDM signal is not large enough to detect for any EDM that we expect to encounter. This limitation can be circumvented by modulating the velocities of the deuterons while they circulate. As a consequence, the motional electric field experienced by the deuteron is also modulated. When the velocity is modulated in phase with the spin orientation, the oscillating part of the motional electric field interacts coherently with the EDM. The strength of the resulting spin-synchrotron resonance is proportional to the EDM. For a deuteron beam which is initially polarized *perpendicular* to the magnetic field, the EDM manifests itself as a spin precession about the motional electric field that is pointing radially inward. In practice, this precession rate is so small that only a growing average polarization component *along* the magnetic field may be observed.

The storage ring presently being investigated has a circumference of about 25 m for deuteron momenta of $p = 1500\,\mathrm{MeV}/c$ and bending dipoles with $B = 2\,\mathrm{T}$. Velocity modulation is accomplished by a set of two RF-cavities, the first of which is used to determine the free synchrotron oscillation frequency, whereas the second is used to actively drive the oscillation and thus to maintain coherence. The layout of the ring is dictated by the requirement to suppress possible systematic error sources and will not be discussed here. A detailed consideration of the design of such a ring has revealed no systematic problems that would prevent us from attaining a precision as low as $10^{-29}\,\mathrm{e\cdot cm}$.

The second concept for an EDM storage ring involving forced synchrotron oscillations to build up the EDM signal over time was presented as a Letter of Intent [17] to the Brookhaven National Laboratory PAC in September, 2006. The PAC expressed "enthusiasm" for the physics goals and the idea of a storage ring search. At the same time, they recognized that such a device would press accelerator and polarimeter technologies toward much greater than the usual precision and that it would be important to demonstrate the feasibility of our plan through a program of computer simulations and actual tests with beam. To meet these requirements, we have started an extensive R&D program that will be supported in part with BNL funding. The COSY storage ring, with its energy range, polarized deuteron beam, and extensive experimental facilities already in place, represents the best possible site for exploring and finally demonstrating the practical aspects of our polarization measurement.

POLARIMETER CONCEPT

To match statistical and systematic uncertainties, besides an intense source of highly polarized deuterons, a highly efficient and sensitive method is needed to continuously determine the evolution of the polarization during the course of a store. The rapidly oscillating horizontal polarization component will be used to phase-lock the spin-synchrotron resonance, whereas the vertical polarization component contains the EDM signal.

The most efficient polarimeters for particles in the range of energies of interest to us are based on the large spin-dependence of the nuclear scattering amplitude. The best sensitivity to the vector component of the polarization comes from the first interference maximum in the analyzing power, which arises from the deuteron-nucleus spin-orbit interaction. It is likely that this effect is most pronounced on targets in the carbon mass range.

In a storage ring, lifetimes on the order of 100–1000 s require targets whose thickness is about an atomic monolayer (gas jet or small pellet). Scattering from such a target into detectors arrayed around the beam produces efficiencies less than 10^{-5} (number of particles usefully detected divided by the number of particles removed from the circulating beam), a value that is low compared to what is desirable for a sensitive EDM search.

For this project, we wish to explore another concept in which there are two targets. The first is the thin target described above. This target is followed by a thick second target that encircles the beam. The hole through this target is small enough that it becomes the limiting aperture in the ring. So particles scattered, mostly through the spin-independent Coulomb interaction, from the first target penetrate the second. This target is thick enough that the probability of a nuclear interaction is high. It is followed by the detectors that observe mainly elastic scattering. In effect, this arrangement amounts to a slow extraction system for the beam that makes use of the Coulomb interaction and sends the extracted particles onto the second target.

Efficiencies for this scheme may be as high as 1%. This requires that the carbon target be thick enough that most of the deuteron's range is expended in passing through the target. In addition, the large analyzing powers noted for elastic deuteron scattering apply also to inelastic scattering and transfer reactions [18], and these charged particles should be included in the measurement of the polarization. This should simplify the design of the detector system, since particle identification is not crucial. The measurement would be inclusive of all charged particles. At the same time, we would need to greatly reduce or eliminate the bulk of protons that come from deuteron breakup as these protons carry almost no dependence on the polarization of the incoming deuterons. In an arrangement with a thick carbon scattering target, this separation is most easily achieved by placing an inert absorber just ahead of the charged particle detectors.

The polarimeter has to meet several demanding requirements. In the experiment, as many as 10^{12} deuterons may be circulating in the ring. Over the course of $100-1000\,\mathrm{s}$, they are extracted onto the analyzer target, where at least 1% will scatter into the detector acceptance, yielding a rate of several MHz over the whole detector. Furthermore, one of the measures to control systematic errors is to have multiple (20–40) bunches circulating in the ring. Consecutive bunches will have different spin-synchrotron phases, and consequently different EDM signal strengths (proportional to $\cos(\phi_{spin}-\phi_{synch})$). Individual bunch-passings, several ns apart, thus have to be resolved. Lastly, to maintain the phase relation between the spin and synchrotron oscillations, feedback based on ϕ_{spin}, the phase of the horizontal spin component, is required.

At the same time, we must be able to observe vertical polarization components as small as 10^{-7} if we are to reach a sensitivity of $10^{-29}\,\mathrm{e}\cdot\mathrm{cm}$. This requires a tight control of the beam properties and the use of various false signal subtraction techniques. The accumulation of sufficient statistics to reach this goal will require several months of storage ring running time.

PLAN OF APPROACH

The study of systematic errors in a deuteron polarization measurement involves identifying a set of error driving terms (shift of position or angle, spot size, divergence, velocity modulation, difference in up and down polarization magnitudes, rate effects, dispersion, *etc.*) that may appear singly or in combinations, as well as a set of strategies (comparison of plus and minus effects, cancellation in analysis, *etc.*) to cope with them. For the short term, it is sufficient that we conduct this investigation using existing equipment with minor modifications.

For some mock polarimeter configuration for which we understand the cross section and analyzing power angular distributions that give rise to the observed polarimeter rates, we will measure the sensitivity of the polarimeter results to various combinations of driving terms. These sensitivities are just the partial derivatives of the polarimeter cross section and analyzing power with respect to any driving term. This will both demonstrate our ability to identify and measure such error terms and to determine which ones pose significant constraints on the design of the ring and the handling of the beam.

At the KVI, Groningen, the Netherlands, we plan to use an existing polarimeter in the main beam line to measure the sensitivities for a polarimeter configuration similar to our polarimeter using detectors already in place. The driving terms will come from carefully calibrated manipulations of the beam. This will demonstrate that we have in place a method that will allow us to estimate reliably the effects of such driving terms on the final EDM polarimeter measurements. Operating at the final deuteron energy or in a storage ring is of lesser importance for this initial study. Beam time for such studies is already available and approved as part of a proposal submitted to the KVI-Groningen in 2004. We expect that running can be scheduled between now and the end of 2007.

The cooled storage ring COSY at the Forschungszentrum Jülich offers a unique environment, as it is similar to the storage ring to be used in the EDM search. There are a number of detector stations around the COSY ring, including the EDDA detector which is in use as a deuteron polarimeter by the SPIN@COSY Collaboration based at the University of Michigan [19]. A second thrust of our study will be to make use of this polarimeter to come as close as possible to the running conditions on the EDM ring and to observe what, if any, systematic effects emerge as issues with a measurement of the beam polarization. This will involve the following efforts,

I. demonstrate viability of slow extraction via Coulomb scattering using the EDDA detector;

II. demonstrate viability of producing, maintaining and measuring transverse polarization using an RF-dipole or solenoid and the EDDA detector;

III. using existing or new equipment, induce a forced synchrotron oscillation to investigate the sensitivity of the polarimeter to such oscillations;

IV. measure the exclusive cross sections and analyzing powers of deuteron induced reactions in the momentum range $p_d = 1000-1500\,\mathrm{MeV}/c$ using the WASA detector and a newly constructed carbon or polypropylene fiber target;

V. build, commission, and calibrate a prototype polarimeter as similar as possible to one that we would expect to use with the deuteron EDM search itself. This would require a separate setup at COSY, possibly downstream of the EDDA detector. Sensitivity to false asymmetries could be checked.

We describe each effort in more detail below.

I. EFFICIENCY DETERMINATION OF TWO-TARGET POLARIMETER CONCEPT

Slow extraction using Coulomb scattering is a novel concept that has not been used before and should be tested experimentally. We propose to make such a test using the polarized deuteron beam in COSY and a mock polarimeter setup.

We propose to use the detector elements of the EDDA detector as the sensitive elements of the polarimeter. The EDDA detector is presently used as a polarimeter for circulating COSY beams. The beam is scattered from a polypropylene or carbon fiber mounted on a 'fork', which is in turn mounted on a remote-controlled arm. The fiber is slowly moved towards the beam to extract the beam in a few seconds. The scattered particles are detected in two layers of scintillator detectors. The scattering angle ϑ is determined from the outer (R) layer of scintillators, which are segmented along the beam direction (29 segments of variable width), whereas the azimuthal angle ϕ is determined from the inner (B) layer, which is segmented around the beam direction (32 segments). In the present configuration, the acceptance is $10^\circ < \vartheta < 72^\circ$.

The scintillator elements are read out by photomultipliers and a collection of discriminators. The DAQ system in use by the SPIN@COSY Collaboration consists of a set of scalers, which record the counting rate in the various detector elements during the extraction of the beam. Such a system will be important for rapid setup and initial evaluation of the system.

The thick annular analyzer target could be either a single ring that is present permanently in the beam line or be split into two halves that would be brought together on two separate motor drives once the beam is injected, cooled, and ramped. If it is a single piece, then tuning must be set up so that the beam can be prepared without excessive losses from hitting the inner walls of the annular target. Such an arrangement has been investigated with the ANKE Chicane [20] and apertures of 3.0 cm horizontal and 2.0 cm vertical opening can retain most of the injected beam. With a similar arrangement, a carbon target of about 3.0 cm thickness can be placed in the present EDDA target station. This size is compatible with target spot sizes measured previously [21] at the EDDA detector.

The improved efficiency of the polarimeter can be tested at either end of the momentum range at which we might expect to operate the deuteron storage ring for an EDM search. An exploration of this energy range at three or four places is important for deciding where to operate the polarimeter for the subsequent parts of this study. One energy to test would be the operating point for the SPIN@COSY Collaboration [22], even though this is higher than the energy we expect to use in the dEDM ring. At this energy, the analyzing power from carbon is about $A_y = 0.1$ [23]. With 10°

as the minimum angle in the EDDA scintillator system and the thickness of the annular carbon target limited to 3 cm, the best efficiency that can be obtained is likely to be less than 0.01%. Nevertheless, meeting this goal would represent a success for this design.

We can also operate at a lower energy more suitable for the thickness of the carbon target and the minimum angle of EDDA. At momenta near 1.0 GeV/c we would expect to observe efficiencies near 0.5%, much closer to the 2.6% in our present designs. Again the limitation is the minimum scattering angle observed. The analyzing power to be expected is harder to estimate. In previous efforts iron absorbers were used to block the bulk of the breakup protons, which exhibit a negligible analyzing power; this is not readily an option here. With an absorber we would expect analyzing power values near $iT_{11} = 0.25$, and less without one.

Any one of the existing gas jets at the COSY ring could be used to serve as the extraction target, as long as the gas-inlet can be remote-controlled. Particles scattered through small angles from the gas jet target would undergo large betatron oscillations that are within the ring acceptance until they come to the limiting aperture represented by the polarimeter target. The gas flow should be adjusted so that about half of the beam is extracted in 100 — 1000 s.

To determine the polarimeter efficiency, we need to have a reasonable measure of both the circulating current as well as the rates in the polarimeter. To determine the figure of merit of the polarimeter, we must also measure the asymmetry for a known beam polarization. The latter can be checked at injection energy. Since the COSY ring has few depolarizing resonances [24], the polarization at the operating momentum should be similar. If needed, use of a hydrocarbon fiber target offers the opportunity to compare against the analyzing power for d+p elastic scattering at beam momenta where that analyzing power is known. We plan to cycle through the various vector and tensor polarizations, to establish the efficiency for measuring them. The sensitivity of the polarimeter to tensor contaminations of the beam polarization is one of the systematic sensitivities that we wish to study.

A total of 10 days of polarized deuteron beam time should suffice. The number of stored particles would need to approach 10^{10} per store if we are to test the operation of the polarimeter making multiple measurements across a store of up to 1000 s. The polarization states from the ion source should include cases with a large vector polarization ($p_z = \pm 1$ with $p_{zz} = 1$) and a large tensor polarization change (include $p_z = -1/3$ and $p_{zz} = -1$). Scheduling of this run in the fall of 2007 would be ideal. If approved, we would start immediately on the construction of a suitable carbon target and check the installation before the next run cycle in the fall.

II. TRANSVERSE SPIN @ COSY

The second item we wish to study experimentally is the ability of the polarimeter to track the rapidly precessing horizontal polarization component. At COSY, the stable spin axis is oriented along the magnetic field, *i.e.* oriented vertically. An extensive program to study the possibility to induce a spin-flip in circulating deuterons is being executed by the SPIN@COSY Collaboration based at the University of Michigan [19]. A study aimed at efficiently inducing a full spin reversal by adiabatically sweeping an RF-dipole through a spin resonance was recently reported [22]. The mechanism of spin flipping could be adequately described by the Froissart-Stora mechanism, and yielded a single flip efficiency of nearly 99% (per flip).

We intend to determine under what circumstances it may be possible to rotate the polarization of the beam circulating in COSY into the horizontal direction. One focus will be on the study of the polarization lifetime. In the dEDM ring, the polarimeter must be able to provide timely information for the measurement of the relative phase between the spin precession and the velocity modulation of the circulating beam. Thus the high efficiency obtained in our first effort becomes crucial to progress here.

The polarization lifetime of a coasting beam is (in general) strongly affected by the momentum spread of the beam, because it leads to spread in the spin tune $\nu_s = G\gamma$. Together with the lattice properties, in particular the momentum compaction, it determines the polarization lifetime. In a recent paper by Morozov [22], the width (FWHM) of the spin-flip resonance at COSY is found to be about 40 Hz with a central frequency of 917 kHz for $p = 1.850$ GeV/c and $\Delta p/p = 5 \times 10^{-4}$. The latter suggests a maximum polarization lifetime of about 70 ms (some 10^4 spin turns), compatible with the observed width of the resonance.

The polarization lifetime can be enhanced by cooling the beam (reducing the momentum spread) and maintaining bunching by leaving the RF on after acceleration. In this case, the depolarization due to the momentum spread is overcome by the RF which forces momentum outliers in the beam to have a momentum that oscillates about the average so that a common average cyclotron frequency is maintained. Thus the spread of the polarization directions that occurs in the first half of the synchrotron period will be compensated in the second half of the period. As a result, the polarization will acquire a modulation at the synchrotron frequency. The modulation depth is determined by the polarization lifetime (in unbunched mode a consequence of the momentum spread) and the synchrotron frequency.

Typically, the frequency for synchrotron oscillations is about $\nu_L \simeq 10^{-3}$ of the cyclotron frequency, which at COSY is of order MHz. The synchrotron period ($\sim$ms) is short compared to the depolarization time, so that a modest modulation depth is expected. In this case, we would expect that the polarization lifetime would be lengthened by a large factor, and limited finally by field imperfections and (higher order) beam dynamics (some of which may be correctable).

The direct observation of a horizontal polarization will require the ability to bin the data from the polarimeter by the polarization phase of the circulating beam. Thus we will need to record either time or the number of the bunch when traversing the polarimeter. This requires modification of the EDDA data acquisition system to include this expanded capability.

We are planning to make detailed simulations of the COSY ring in order to better understand the limitations on the polarization lifetime and the best scheme for precessing the polarization into the horizontal plane.

Measurement of the short spin coherence times can be accomplished without requiring additional modifications to the detectors or the data acquisition scheme by using a $\pi/2$ double pulse. The first will rotate the spin from vertical to horizontal using an RF-dipole or solenoid operating at a fixed frequency (set to the maximum resonance strength frequency). After a predetermined delay, during which the spins will decohere, a second pulse will complete the spin flip. After this pulse, the remaining polarization can be measured using normal detection techniques. By observing the remaining polarization as a function of the delay-time, coherence times of the order of tens of ms can be determined. The RF-phase between the first and second pulse must remain fixed, as in the separated oscillatory field technique introduced by Ramsey. This offers a chance to make initial investigations of the polarization lifetime before polarization precession and improved data acquisition schemes are fully operational.

We would expect to explore these techniques using the enhanced efficiency of the double-target scheme and the EDDA detectors. Two runs of 1.3 weeks each will be proposed at a future date.

III. FORCED SYNCHROTRON OSCILLATIONS

An important test for the feasibility of the polarimeter for the deuteron EDM search is the demonstration that systematic effects from the velocity oscillations (which in the EDM experiment must be synchronized with the precession of the polarization) can be handled in the data analysis. For this we would like to pursue setting up forced oscillations of the COSY beam (to guarantee a long synchrotron coherence time). During these oscillations, we would measure the polarization to test the polarimeter for any sensitivity to such velocity oscillations. It is not necessary that the synchrotron tune matches the spin tune as we are interested in errors only. Further investigation is needed to determine to what extent we can achieve this condition with the existing components of the COSY RF system.

IV. MEASUREMENT OF ^{12}C$(d, X)Y$ CROSS SECTION AND ANALYZING POWERS

To fully optimize the statistical sensitivity of the final dEDM polarimeter, it is mandatory to know the scattering cross sections and analyzing powers of all relevant reactions over the energy range at which the polarimeter operates, *i.e.* beam energy and downwards. Except for reports on deuteron polarimeters at Saturne [25, 26], there is essentially no information on the cross section and polarization dependence of deuteron-induced reactions in the momentum range between 1.0 and 1.5 GeV/c. The Saturne results did not separate the effects of deuteron elastic scattering from inelastic scattering and deuteron breakup. The latter process has essentially no polarization dependence, as demonstrated by our earlier studies between 76 and 113 MeV at the KVI. Better data are essential to the design of our polarimeter since it is likely that a better optimization of the detectors to record predominantly elastically scattered deuterons will result is a doubling of the analyzing power of the polarimeter. Such an enhanced analyzing power is important both for the sensitivity of the search and the suppression of systematic errors.

The best detector for the purpose appears to be the forward tracking system of the newly-installed WASA detector. This system allows 4-π coverage in azimuth, a feature crucial to the separation of polarization effects. It also has a stack of plastic scintillation detectors that are capable of separating tracks from deuterons and protons. Reaction losses will be an issue, but it is hoped that the information from the scintillator stack will allow checking of the cross sections used to compute such losses so that the corrections will be under firmer control.

Our study requires a carbon target, which is presently not available with the WASA pellet target. The construction of a movable holder for a fiber target to go into the pellet tube for WASA would overcome this. To determine the cross sections, the use of a composite fiber (*e.g.* polyproylene) in addition to the carbon fiber is necessary to normalize the luminosity against the cross section for d+p elastic scattering. There are a number of measurements in the energy range of interest [27–30] that may be used for reference.

This is likely to require a run of about 2 weeks.

V. TESTING THE PROTOTYPE POLARIMETER

Following a thick carbon target and a range absorbing system, the detectors used in the final dEDM polarimeter must be able to handle high rates and provide some degree of segmentation so that horizontal and vertical asymmetries may be separated and systematic limits determined from their scattering angle dependence. At present, a segmented scintillator or a multigap resistive plate chamber [31] appear to have the time resolution needed to resolve the in-plane precession of the polarization and provide information for checking the phase of the forced synchrotron oscillation system.

Once the features of the design are available, we intend to build a prototype and to test and calibrate it using the COSY beam.

SUMMARY

We have outlined a plan to investigate, and experimentally demonstrate, the feasibility of the deuteron vector polarization measurements that are needed to search for a permanent EDM on the deuteron. This plan involves several technical developments that will be implemented on the COSY ring, the ring that is most like the one that we will design for the EDM search. The major thrusts of the plan are to demonstrate the ability of the polarimeter to observe the precession of the polarization of a horizontally polarized proton beam without undue systematic errors, to measure the cross sections and analyzing powers for polarized deuteron induced reactions on carbon, and to commission a prototype polarimeter.

For this meeting of the PAC, we are requesting time to begin the examination of the polarimeter effects using the EDDA detectors as a substitute for our prototype polarimeter. In particular, we wish to demonstrate that the beam can be extracted slowly using Coulomb scattering onto a thick annular carbon target that will provide polarimeter efficiencies in the range of 1%. These tests may be scheduled in 2007.

* Electronic address: `onderwater@kvi.nl`

† Electronic address: `stephene@indiana.edu`

[1] E.N. Fortson, P. Sanders, and S. Barr, Physics Today **56** (June, 2003) p. 33.

[2] C.A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006).

[3] B.C. Regan, E.D. Commins, C.J. Schmidt, and D. Demille, Phys. Rev. Lett. **88**, 071805 (2002).

[4] K. Hagiwara *et al.*, Phys. Rev. D **66**, 010001 (2002).

[5] M.V. Romalis, W.C. Griffith, J.P. Jacobs, anad E.N. Fortson, Phys. Rev. Lett. **86**, 2505 (2001).

[6] V.F. Dmitriev and R.A. Sen'kov, Phys. Rev. Lett. **91**, 212303 (2003).

[7] M. Pospelov and A. Ritz, Ann. Phys. **318**, 119 (2005).

[8] C.P. Liu and R. Timmermans, Phys. Rev. C **70**, 055501 (2004).

[9] J. Hisano *et al.*, Phys. Lett. B **604**, 216 (2004); J. Hisano *et al.*, Phys. Rev. D **70**, 093001 (2004).

[10] O. Lebedev, K.A. Olive, M. Pospelov, and A. Ritz, LANL/Cornell Archive hep-ph/0402023.

[11] William Marciano, *private communication.*

[12] see `http://www.bnl.gov/edm/`

[13] *Letter-of-Intent: Polarimeter Commissioning for a Search for an Intrinsic Electric Dipole Moment on the Deuteron*, COSY Experiment No. 138, Presented at COSY-PAC session 28, I/2004 Spokesmen: E.J. Stephenson and C.J.G. Onderwater.

[14] F.J.M. Farley *et al.*, Phys. Rev. Lett. **93**, 052001 (2004).

[15] Y.F. Orlov, W.M. Morse, and Y.K. Semertzidis, Phys. Rev. Lett. **96**, 214802 (2006).

[16] I.I. Rabi, J.R. Zacharias, S. Millman, and P. Kusch, Phys. Rev. **53**, 318 (1938).

[17] D. Babusci *et al.*, *Letter of Intent: Development of a Resonance Method to Search for a Deuteron Electric Dipole Moment using a Charged Particle Storage Ring*, Presented at BNL-PAC session September 2006.

[18] H. Sakai *et al.*, Phys. Rev. C **24**, 2766 (1981); and E.J. Stephenson *et al.*, IUCF Scientific and Technical Report - 1981, p. 95.

[19] SPIN@COSY collaboration, web-site at COSY/Julich:
`http://www.fz-juelich.de/ikp/spin@cosy/spinflipping.html`

[20] K. Grigoryev *et al.*, "Storage cell tests and commissioning of the Polarized Internal Gas Target," COSY internal report.

[21] M. Altmeier *et al.*, Eur. Phys. J. **A23**. 351 (2005).

[22] V.S. Morozov *et al.*, Phys. Rev. ST-AB **8**, 061001 (2005).

[23] B. Lorentz, private communication.

[24] D. Chiladze *et al.*, Phys. Rev. ST-AB **9**, 050101 (2006).

[25] B. Bonin *et al.*, Nucl. Instrum. Methods A **288**, 389 (1990).

[26] V.P. Ladygin *et al.*, Nucl. Instrum. Methods A **404**, 129 (1998).

[27] N.E. Booth *et al.*, Phys. Rev. D **4**, 1261 (1971).

[28] J.C. Alder *et al.*, Phys. Rev. C **6**, 2010 (1972).

[29] M.G. Albrow *et al.*, Phys. Lett. **35B**, 247 (1971).

[30] E. Gülmez *et al.*, Phys. Rev. C **43**, 2067 (1991).

[31] A.V. Akindinov *et al.*, Nucl. Instrum. Methods A **532**, 611 (2004).