THE DOUBLY-MAGIC FROZEN SPIN EDM ROUTE TO PHYSICS BEYOND THE STANDARD MODEL (PBSM)

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2 Structure of the talk

- Speakers at this celebration have two tasks: to reminisce about our interactions with Alex, but also, this being SLAC, the talk has to contain real, preferably novel, and certainly understandable, physics. Furthermore, one has to be brief.
- The physics I want to explain is a proposed experiment "The **doubly-magic** frozen spin EDM route to physics beyond the standard model (PBSM)".
- As well as acknowledging Alex's contributions to this topic in particular, one needs also to understand what makes Alex special in general.
- I'm going to say that two of these things are that "Alex understands stuff" and that "Alex can explain stuff".
- If you want to test this, if there is something in my talk you don't understand, I suggest you ask Alex. You are likely to understand his explanation better than mine.

3 Incompatibility of vector-ness and pseudo-vector-ness in the standard model—over-simplified, abbreviated, time-reversal-free discussion

- I start by reviewing magnetic dipole moments (MDM) and electric dipole moments (EDM), and explaining why any measurably-large non-zero proton EDM would demonstrate the existence of physics beyond the standard model (FBSM)".
- Consider a compass needle; label "N" at one end, "S" at the other.
- The labels "N" and "S" suggest the presence of opposite sign magnetic poles at the two ends of the needle, and the needle can be said to have the "vector-character" of an arrow pointing from N to S. Describing an arrow from particle centroid to charge centroir, **an EDM has vector-character**.
- For the compass needle this is fundamentally misleading. Rather than magnetic poles, there are "Amperian currents" circulating around the periphery of the needle, thereby defining a **pseudo-vector** having the same axis as the N-S arrow, but with different "orientation"
- Assigning a "sense of direction" along the axis requires a (conventional) choice of left or right-hand rule.
- The compass needle therefore has "pseudo-vector-character", fundamentally more natural than its previously established "vector-character"

- For compound (many-particle) objects, like compass needles or human beings (with hearts (almost) always on the same side), this is all OK.
- But, for any **elementary** particle in the standard model this is **not OK**. **An elementary-particles is forbidden to have both vector and pseudo-vector character**—with only the tiniest of exceptions.
- **A proton, because of its compass-needle-like magnetic dipole moment (MDM) manifestly has pseudo-vector character and cannot therefore have non-zero EDM**.

5 History of EDM measurement—Why do it?

- The importance of a fundamental particle having non-zero EDM is not a new idea.
- This was first emphasized in 1950 by Edward Purcell and Norman Ramsey, long before there was a "standard model"—the main difference being that their statement was made about the **neutron** EDM; my talk will apply to the **proton**.
- Until 20 years ago it was implicitly assumed that measuring the EDM of a charged particle, such as the proton would be impossible—the required strong electric field would immediately attract the negative electrode where the proton would be lost.
- But in circular motion a particle can always be accelerating centripetally, without its radius ever changing.

6 History of EDM measurement—Results?

- Led for decades by Ramsey, the goal of testing fundamental physics by measuring the neutron EDM, has been actively pursued ever since.
- Since the first reported measurement in 1957, Herculean efforts have reduced the upper limit on the neutron EDM by 12 orders of magnitude—to about 10^{-24} e-cm—corresponding to a charge 24 orders of magnitude smaller than the electron's, displaced 1 cm from the particle centroid.
- Even so, theoretical understanding has advanced even more impressively. So the neutron EDM upper limit nowadays still exceeds any plausibly-expected EDM value by perhaps 5 orders of magnitude.
- By now it has been understood that it will be possible to measure the proton EDM with much greater accuracy than the neutron EDM, using a **"frozen spin" polarized proton beam, stored in an electrostatic storage ring.**
- For this to be understood one has to understand the terms "frozen spin" and "magic" noting that a proton beam satisfying the "magic condition" and a "frozen-spin" proton beam are the same thing.

7 “Frozen” spins and “magic” energies

- In a purely electric ring, there is a ”magic” proton kinetic energy (232.8 MeV) at which a polarized beam polarization pointing, say, forward, precesses at the same rate as the beam momentum, therefore continuing to point in the forward direction indefinitely everywhere in the ring.
- The spins are then said to be ”frozen” and ”in-plane”—meaning horizontal.
- In a purely electrostatic ring the electric field is purely radial.
- Acting on the proton EDM this field causes a small but measurable ”out-of-plane” precession of the beam polarization.
- Measurement of the out-of-plane precession provides an EDM measurement.
- This precession accumulates monotonically if and only if the beam is frozen. **Any chance of detecting non-zero EDM depends upon the spins being (otherwise) frozen.**

8 Spurious EDM-mimicking out-of-plane precession

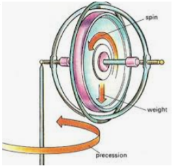
- By far the worst spurious out-of-plane "background" precession is caused by unintended average radial magnetic field $< B_r >$ acting on the proton MDM.
- By matching the orbits of simultaneously counter-circulating frozen spin proton beams $< B_r >$ can, in principal, be exactly cancelled.
- Regrettably, estimation of the irreducible systematic error of the resultant EDM measurement is about $\sigma_{EDM} = 10^{-27}$ e·cm, some two or three orders of magnitude too large to threaten the standard model.

9 “Doubly-magic” simultaneously counter-circulating frozen spin beams

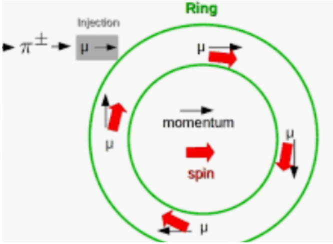
- There is a way to overcome this systematic error problem.
- Instead of measuring the EDM of a particle type (such as “proton”) one can measure the EDM difference between two distinct particle types (such as “proton” and “helion” (misnamed bare He3 nucleus) or (“proton” and “positron”)
- The idea is that the $< B_r >$ systematic error cancels in this difference measurement.
- It would constitute PBSM if one out-of-plane precession vanishes, while the other does not.)
- To meet the "doubly-magic" condition the storage ring bending field has to have superimposed electric and magnetic bending. (Constructive for CW, destructive for CCW.)
- Though only the EDM difference is obtained, **any measurably-large EDM difference would be evidence for physics beyond the standard model.**
- The expected EDM difference error is about $\sigma_{EDM}=10^{-30}\,$e·cm.

10 Distinguishing MDM-induced and EDM-induced precessions

side view



gyroscope
daviddarling.info



top view

- Like the angular momentum of a horizontal gyroscope in the earth's gravitational field, or the spin direction of a horizontally-polarized muon in the muon G-2 experiment
- in a storage ring, **the axis of a horizontally polarized beam performs only MDM-induced precession "in-plane" ;** and remains permanently "in-plane" i.e. horizontal.
- But, in an electric storage ring, the electric bending field is radial. Acting on a horizontal ED, it causes the **ED to perform "out-of-plane" precession** vertically, "out-of" the horizontal plane.
- This is how MDM-induced and EDM-induced precessions can be distinguished.

11 Experimental EDM measurement method

- The proton EDM measurement starts by injecting a longitudinally-polarized proton beam (say pointing forward) and tuning onto the "magic" frozen spin condition, for which, except for out-of-plane precession caused by the torque applied to the EDM, the polarization would stay pointing forward forever.
- Though said to be "frozen", to keep up with the proton's momentum rotation, at say 2×10^6 revolutions per second, the magic protons are rotating at the same $4\pi \times 10^6$ radians/s rate.
- Terrifyingly though, the optimistically-expected EDM-induced rate is a factor of 10^{-15} times less than the (perfecly phase-locked) MDM-induced rate.
- Taking advantage of the 7 orders of magnitude frozen-spin frequency-division factor, one is looking, therefore, for a "stroboscopic" out-of-plane precession rate of about 10^{-8} radians/s.
- **After a run of, say, 1000 s duration, the proton MDM will have precessed out-of-plane by $10\,\mu$radian, which is a small, but measureably-large, precession angle.**

12 The dominant source of systematic EDM error

- By far the greatest source of systematic error is the (inadvertent) presence of radial magnetic field component B_r. The torque exerted by B_r acting on the MDM mimics exactly the effect of radial electric field E_r acting on the EDM.
- One must therefore, to the extent possible, suppress the average radial magnetic field component $\langle B_r \rangle$.
- (Except by the doubly-magic method) the only way to suppress $\langle B_r \rangle$ is to **require the orbits of simultaneously counter-circulating beams to coincide vertically—for the average vertical displacements of counter-circulating beams to cancel requires $\langle B_r \rangle = 0$.**
- Even with state-of-the-art beam position measurement and control, this source of EDM error is expected to force the proton EDM upper limit to be as much as 100 times too great to demonstrate physics beyond the standard model (PBSM).

13 Doubly-magic trick to cancel systematic EDM error

- Expert opinion anticipates systematic error of about $\sigma_d^{\rm syst.} \approx \pm 10^{-27}$ e-cm in a proton EDM measurement.
- Some breakthrough in reducing the EDM systematic error by, say, three orders of magnitude is needed.
- **The doubly-magic trick:** freeze two particle types concurrently and measure their EDM difference; e.g. protons and helions (${\rm He}^3$ nuclei)

$$\Delta d = d^{\rm proton} - d^{\rm helion}$$

- **The dominant systematic error cancels out from this difference.**
- **For Δd to be measurably large one or the other of $d^{\rm proton}$ and $d^{\rm helion}$ would have to be measurably large. This would prove the existence of physics beyond the standard model**.
- To obtain $d^{\rm proton}$ a follow-up, practical (but harder and more expensive) measurement possibility assumes $d^{\rm positron} \overset{\rm effect.}{=} 0$:

$$\Delta d = d^{\rm proton} - d^{\rm positron} = d^{\rm proton}$$

- Before providing more details, I will describe how interactions between Alex and me have contributed to my understanding of all these issues.

14 Alex Chao at the SSC Supercollider Central Design Group (CDG)

- Not all SSC stories are sad!
- Alex led the accelerator theory group at the CDG. Among his tasks was to prioritize/lead/contibute-to, etc. radically different approaches to accelerator simulation, and to their experimental testing. Some examples follow:
- One was the transfer-map-independent, TEAPOT simulation approach introduced by Lindsay Schachinger and RT.
- A totally different, truncated-power-series-of-arbitrary-order approach, Yiton Yan's ZLIB, was developed at the same time, and subsequently integrated by Nikolay Malitsky, into TEAPOT.
- An E778 experiment at the Fermilab Tevatron was performed primarily to test these (and other) codes—(an un-anticipated side observation was the first demonstration of beam capture onto stable nonlinear resonance islands—effectively **proving experimentally that the SSC magnet bore dimension in the CDG design was amply conservative**)
- These efforts were largely coordinated by Alex Chao.

15 Central Design Group E778 celebration

L to R: Steve Peggs, Lindsay Schachinger, RT, and Alex. etc.

16 Central Design Group-continued

- These investigations showed that a bending magnet bore dimension of 4 cm would be satisfactory for the SSC.
- Later, in Dallas, the CDG advice was ignored, and the SSC magnet bore dimension was increased—bad idea!
- The rest is history (or rather, the absence of history).
- Subsequent SSC stories are mainly sad!
- But not for me, since most of my subsequent work (currently for EDM storage ring measurement) has amounted to continuing along the same path.

17 Digression: Alex and RT on "Yuri Orlov and the Robinson Theorem"

- Who knew that the Robinson Theorem (concerning radiation damping partition numbers) was obtained independently, at the same time, by Orlov and Terasov ?
- Answer: Yuri Orlov, vociferously
- Alex and RT were asked by Phys Rev to investrigate this. Alex, perhaps fearing unhappiness, criticism and futility, resisted, but eventually relented
- Our report: The Orlov/Terasov paper appeared at about the same time (though in Russian) and was more or less equivalent to the Robinson paper.
- We made no comment, one way or the other, on whether the theorem's name should be changed accordingly
- Reward: much unhappiness, criticism, and futility.

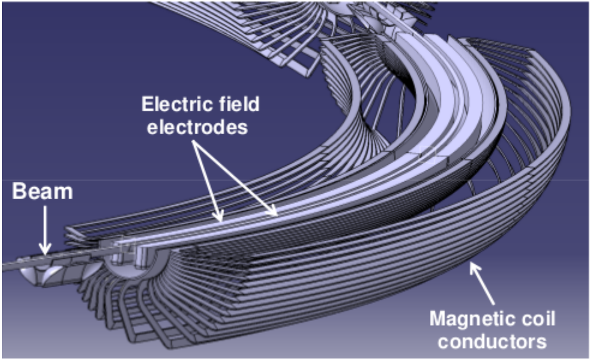
18 Spin tracking advice from Alex

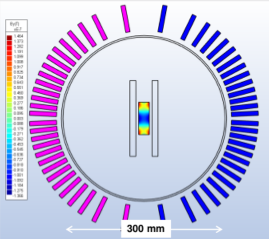
- At IPAC 2015, Richmond VA, in a session "Spin Tracking for Precision Measurements" I described the ETEAPOT program (evolved from the CDG TEAPOT, now including electric bending and spin propagation in electrostatic storage rings).
- After the meeting Alex and I set out for dinner, aimlessly getting lost, while looking for a restaurant and discussing stuff from the workshop, etc.
- This was long enough for Alex to point out an error in ETEAPOT he had picked up from my presentation.
- Later, in 2017, Alex invited me to submit a Volume 9, RAST Review paper on "Prospects for EDM Measurement Using Electrostatic Storage Rings".

19 Doubly-magic test of PBSM

- The "doubly-magic" idea came to me a few months after I had finished the RAST manuscript.
- My doubly-magic paper was uploaded 14 Dec 2018 as arXiv article 1812.05949 [physics.acc-ph].
- Essentially unchanged, this now appears as Appendix G of A CERN Yellow Report, CERN-2019-001-M, "Feasibility Study for a Storage Ring to Search for EDMs of Charged Particles" scheduled for release soon.
- I return now to EDM as route to physics beyond the standard model.

20 One quadrant of a EDM prototype ring with superimposed E/B bending





end view showing electrodes and $\cos\theta$ magnetic coil

Singly-magic frozen spin possibilities according to BMT equation

Field configuration	Particle type	G-factor	Kinetic energy (MeV)	Beams CW/CCW	comment
all-electric	proton	+1.79285	232.8	concurrent	nominal final "holy grail" ring
	electron	+0.001	14.5	concurrent	challenging polarimetry
	muon	+0.001	2991	concurrent	impractically short lifetime
E/B combined	proton	+1.793	45	consecutive	compromised EDM precision
	deuteron	-0.143	variable	consecutive	E/B technological challenge
	helium-3	-4.191	39	consecutive	must develop polarimetry
all-magnetic					used for precursor no frozen spin possibility

- Shaded rows are unsatisfactory. For realistic test of PBSM, long lifetime, concurrent CW/CCW beam circulation is obligatory, i.e. top two rows
- Otherwise the EDM measurement error is too great
- The only realistic **all-electric** possibilities are singly-magic 232.8 MeV protons or 14.5 MeV electrons
- Even singly-magic electrons are dubious, since existing polarimetry has insufficient analyzing power

22 Doubly-magic spin solutions (with superimposed E/B bending allowed)

Table : Doubly-magic possibilities.

Field configuration	Particle type	G-factor	Kinetic energy (MeV)	Beams CW/CCW	comment
E/B	proton	+1.793	45	concurrent	
combined	helium-3	-4.191	39	concurrent	needs polarized source development
E/B	proton	+1.793	45	concurrent	
combined	positron	+0.001	14.5	concurrent	Stern-Gerlach polarimetry ?

- Only the concurrent helion-proton, doubly-magic case can be done cheaply today, **using only already-demonstrated technology**

More details for concurrent doubly-magic cases:

r0 m	beam1	KE GeV	E0 V/m	B0 T	η_E	beam2	KE2 GeV	pc2 GeV	QS2
10	CW h	0.03924	5.265e+06	-0.028	1.351	CCW p	0.03859	-0.2719	-6e-06≈0
10	CW p	0.03859	5.265e+06	0.028	0.6958	CCW h	0.03924	-0.4711	1e-05≈0
20	CW p	0.08663	6.355e+06	0.016	0.766	CCW e+	0.03009	-0.0306	5e-06≈0
20	CW e+	0.03009	6.355e+06	-0.016	4.155	CCW p	0.08664	-0.4124	6e-05≈0

EDM error analysis for PBSM

(Dropping inessential dependences, e.g. on β and γ):

$$\text{out} - \text{of} - \text{plane angle} : \theta = \theta_{\text{meas.}} \Longrightarrow \sigma_{\text{EDM}} : \overset{\text{syst.}}{\pm} 10^{-27} \overset{\text{rand.}}{\pm} 10^{-30}\,\text{e.cm}$$

$$\text{sensitivity} - \text{coefficients} : D_B = \frac{\partial\theta}{\partial\langle B_r\rangle},\ D_{\text{EDM}} = \frac{\partial\theta}{\partial d},$$

$$\text{proton measurement} : \theta^{\text{p}} = D_B\langle B_r^{?}\rangle + D_{\text{EDM}}\,d^{\text{p}}, \tag{1}$$

$$\text{helion measurement} : \theta^{\text{h}} = D_B\langle B_r^{?}\rangle + D_{\text{EDM}}\,d^{\text{h}}, \tag{2}$$

$$\text{Subtract (1)} - \text{(2) and solve for } d^{\text{p}} - d^{\text{h}},$$

$$d^{\text{p}} - d^{\text{h}} = \frac{\theta^{\text{p}} - \theta^{\text{h}}}{D_{\text{EDM}}} \pm \sigma^{\text{rand.}} \text{ with error } \sigma^{\text{rand.}} \approx 10^{-30}\,\text{e.cm}$$

- **This experiment could be performed inexpensively within the next several years !**
- **with a precision good enough to distinguish unambiguously between the presence or absence of physics beyond the standard model !**

24 Repeat of invitation to test Alex's qualification as "explainer-in-chief"

- I encourage anyone who feels like it, to go up and ask Alex the following two questions:
  1. Did Alex understand the talk? —his predictably modest answer will be "no".
  2. Ignoring this, the actual question is, "can Alex explain "the doubly-magic route to physics beyond the standard model"
- To qualify, Alex has to explain those things that I have failed to make clear.

Acknowledgements

Along with others too numerous to mention, I would like to acknowledge especially my Juelich co-authors of the CERN EDM Feasibility Study, and my Cornell LEPP colleagues.