T-violation detection in “elastic” pp scattering in single beam figure-8 collider

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Contents of (available) full paper:
"T-violation detection in elastic *pp* scattering in a Derbenev single beam FIGURE-8 collider"

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3 Subject of the talk: Elastic *pp* cross sections

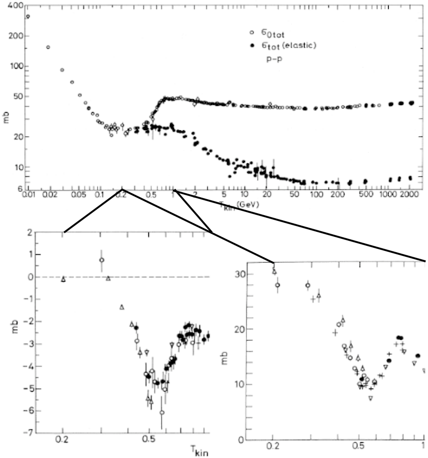


Figure 1 : (Copied from reference [11]) **Above:** Energy dependence of *pp* spin-independent total cross section (open circles) and total elastic cross section (solid curves). **Below left:** $\sigma_{1tot}(pp) = -(1/2)\Delta\sigma_T(pp)$ transverse spin energy dependence, **Below right:** $-\Delta\sigma_L(pp)$ longitudinal spin energy dependence.

4 Motivation

- Never has so much effort in physics produced so little understanding as elastic *pp* scattering
- especially as concerns spin dependence, i.e. the polarized beam, polarized target data in the bottom two figures
- The quality of the data is good—though, curiously, the error bars are greatest in the range from 100 Mev to 1000 MeV.
- Quality of data depends on quality of understanding!
- I believe it is the implicit (but never *properly* tested) theoretical assumption of time reversal invariance that has been mainly responsible for this breakdown.
- This is the subject of my talk.

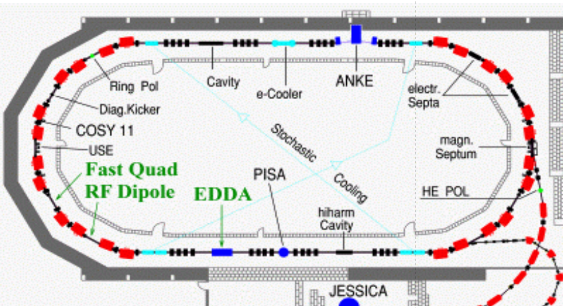
5 Motivation (continued)

- In a Derbenev-style figure-8 storage ring, independently polarized, diametrically opposite bunches of the same beam collide at the crossing point.
- All 4 particle energies, initial state and final state, are the same.
- This makes it practical to investigate spin dependence and time reversal T-symmetry of "elastic" *pp* scattering with unprecedented sensitivity.
- Recognizing that the proton is anomalous, e.g. anomalous MDM, "elastic" scattering may be accompanied by T-violating spin rearrangement with undetectably small energy excitation.

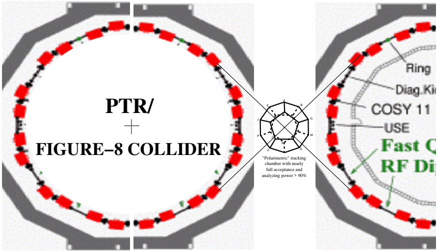
6 Method

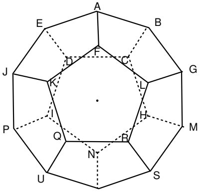
- Operating above the 69.5 MeV laboratory energy at which proton-carbon scattering asymmetry analyzing power exceeds 99% to roughly 400 MeV (the pion production threshold), both scattered protons come to rest in graphite polarimeter chambers providing nearly full directional coverage.
- Both initial proton polarization states are pure and both final state proton polarizations are measured with nearly ideal analyzing power.

7 COSY Reconfiguration for T-violation detection in “elastic” pp scattering



building extention needed to preserve existing element placemens, injection and extraction, and electron cooling





"Polarimetric" tracking chamber with nearly full acceptance and analyzing power > 90%

8 Carbon foil, full aperture stopping-proton tracker/polarimeter

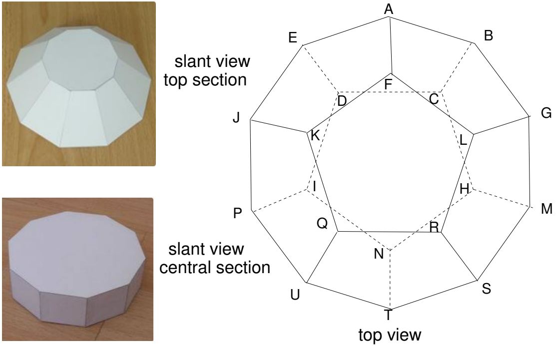


Figure 3 : On the right is an artist's conception top view of an almost full-acceptance tracking/stopping/polarimeter at the storage ring intersection point IP. Their dodecahedral faces subtend roughly equal solid angles. The figures shown on the left are slant views of horizontal slices. To accommodate passage of the colliding beams there is little useful particle detection in the up-down central section.

9 Figure-8 polarized *pp* collider

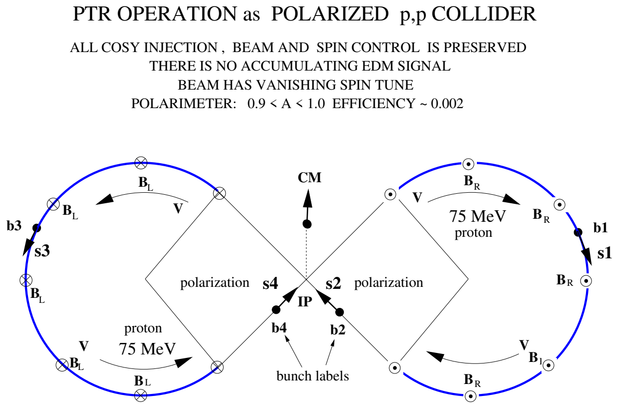


Figure 4 : Conversion of COSY implementation as a polarized *pp* collider. Since the spin tune vanishes ($Q_s = 0$) bunch polarizations can be set independently and can be phase locked (shown pointing forward as **s2** and **s4** for bunches **b2** and **b4**) to remain locally frozen indefinitely at every passage through the IP.

- The presence or absence of T-violation in nuclear forces is thought to bear significantly on important cosmological issues, especially missing mass, dark energy, and the matter, anti-matter imbalance.
- The possible existence of a semi-strong, T-violating, nuclear force with coupling strength compatable to the electromagnetic interaction was proposed independently by Lee and Wolfenstein, by Prentki and Veltman, and by Okun in 1965.
- Of the uncertain properties of nuclear physics, none is more fundamental, nor less well understood, than nucleon, nucleon interaction.

11 Theory—conjectural

- Current-day nucleon-nucleon theory is largely “spin-inert”; usually neither spin flips, but if one spin flips, so does the other.
- The electromagnetic-nuclear interaction is not at all “inert”; especially as regards anomalous MDM. .
- A “toy” theoretical model (“gedanken experiment”) incorporating the anomalous proton MDM predicts strong T-violation, in a “nuclear-electric married particle”, such as the proton.
- The Derbenov collider configuration promises unambiguous detection of this effect.

12 Derbenev geometry and T-violation signature

- Unlike fixed target experiments, rather than being colinear, in Derbenov geometry incident beams collide at right angles.
- All initial and final state laboratory proton energies being equal produces a huge statistical polarimetric advantage.
- *Persuasive visual evidence of T-violation will be provided by unexpected correlation between the p-carbon scattering directions of final state protons.*

13 COSY hall rearrangement

- Spin dependence is most easily detectable at low proton energy.
- Rearrangement of existing COSY components into a “FIGURE-8” storage ring allows diametrically opposite polarized proton bunches in a single stored beam to collide.
- “Spin transparency” in figure-8 geometry is used to enable Fourier enhancement of T-violation sensitivity.
- The required COSY lab rearrangement is also compatable with PTR, a prototype EDM measurement ring capable of measuring the deuteron anomalous EDM using easily achievable, superimposed electric and magnetic bending.

14 Events per nominal year for 0, 1, or 2 polarimetic *p*-carbon scatters

event class	symbol	fraction	symbol	events/year
pp scatter	1	1	N	2×10^9
single spin meas.	$2/E$	$2/400$	N_1	1×10^7
"gold-plated"	$2/E^2$	$2/400^2$	N_2	0.25×10^5

Table 1 : Anticipated event rates with increasing detection quality per nominal year running time for polarimetric detection efficiency $E = 1/400$.

15 Experimental strategy

- Both initial protons are prepared into pure polarization states.
- Both scattered protons produce clean orthogonal tracks, coming to rest in nearly full acceptance graphite polarimeter tracking chamber plates.
- One or both scattered protons occasionally scatters from a carbon chamber plate, thereby measuring final state polarization(s) with analysing power in excess of, say, 80%.
- In one (nominal) year of running 25,000 "gold-plated" events will have perfect initial state kinematics and pure polarizations, perfect final state kinematics, and nearly certain measured final state polarizations.

16 Experimental strategy (continued)

- Unlike fixed target (Wolfenstein) geometry, in Derbenev geometry incident beams collide at right angles.
- Lab system kinematics is even more constrained than CM—incident and scattered energies are all equal
- Elastically scattered protons have equal energies, 45 degree scattering angles, defining a plane (not horizontal in general) but rolled by angle Φ relative to horizontal.
- This provides a huge polarimeter analyzing power advantage.
- "Gold-plated" events exhibit clean *pp* elastic scatters in the carbon tracking chamber, producing clean *p*-carbon polarization measurement of both scattered protons.

17 Experimental strategy (continued)

- Beam-bunch-specific polarization preparation capability has already been partially demonstrated at COSY, using polarized deuterons.
- Rearrangement of existing COSY components is proposed for a “FIGURE-8” (pp collider) T-violation detector.
- Diametrically opposite beam bunches, with adiabatically adjustable polarizations, collide at the crossing point.
- Both scattered protons come to rest in graphite polarimeter chambers which provide nearly full directional scattering angle coverage.
- Later, with electric and magnetic bending superimposed, the deuteron EDM can be measured, potentially confirming T-violation.

18 Spin flip probability

The spin tune in a purely electric ring is given by

$$Q_s^E = G\gamma - \frac{G+1}{\gamma}, \tag{1}$$

where γ is the usual relativistic factor, and G is the anomalous MDM, whose value for the proton is $G_p = 1.7928474$. For a circulating proton with spin pointing forward at time $t = 0$, the spin-forward probability after n_t turns is,

$$P = \frac{1}{2}\left(1 + \cos(2\pi\, Q_s^E n_t)\right) \tag{2}$$

where turn number n_t is an integer only for complete turns around the ring.

19 Ring parameter size scaling over 17 orders of magnitude

bm	m1	G1	q1	etaE1	p1c/q1	E0	B0	m2	G2	q2	etaE2	p2c/q2	bratio	Qs2	bm
1	GeV				GeV	MV/m	mT	GeV				GeV			2
	$r_0 =$ 95 m														
d	1.8756	-0.1430	1	-0.17243	0.3432	-0.1253	4.7341	1.8756	-0.1430	1	0.52631	-0.0447	-0.13237	-5.93955e-01	d
d	1.8756	-0.1430	1	-0.17243	0.3432	-0.1253	4.7341	1.8756	-0.1430	1	-0.17243	0.3432	1	-4.00000e-15	d

bm	m1	G1	q1	beta1	K1	E0	B0	m2	G2	q2	beta2	KE2	bratio	Qs2	bm
1	GeV				MeV	MV/m	mT	GeV				MeV			2
	$r_0 =$ 11.0 m														
d	1.8756	-0.1430	1	0.18000	31.1438	-0.9684	36.5816	1.8756	-0.1430	1	-0.02383	0.5326	-0.13237	-5.93955e-01	d
d	1.8756	-0.1430	1	0.18000	31.1438	-0.9684	36.5816	1.8756	-0.1430	1	0.18000	31.1438	1	-3.00000e-15	d

bm	m1	G1	q1	beta1	K1	E0rho	QsE1	m2	G2	q2	beta2	KE2	bratio	QsE2	bm
1	GeV				MeV	MV						MeV			2
	r_0	=	$1.0e^{-15}$ m	=	1.0 Fermi	"**Toy**"	**ring**								
p	0.9383	1.7928	1	0.31377	49.9039	86.3327	-0.7636	0.9383	1.7928	1	-0.27989	39.0610	-0.89201	-0.81	p

Table 2 : Variable storage ring size: The top two tables are for practical bending radii, $r_0 = 95$ m and $r_0 = 11$ m. The bottom is for the "toy ring" with bending radius of 1 Fermi. The toy ring spin tune is $Q_s^E = -0.7636$.

20 Nuclear and electromagnetic spin precession interference

- Even with no nuclear force the final proton spin states would differ from the inital spin states as a result of their near electrical encounter
- Electric-induced spin precession masks any purely-nuclear T-conservation constraint.
- Since electric and nuclear fields are married so inseparably in every nucleus, on an event by event basis, any T-symmetry constraint imposed by purely nuclear force is over-ridden by the effect of anomalous MDM.
- Table 2 provides parameters for our toy storage ring.
- Figure 5 our "toy storage ring proton element" bending a proton beam through $2\pi/4$.
- The resulting full ring spin tune 0.7636.
- This precession advance applies only to the component of incident proton spin that lies in the scattering plane.
- The out-of-plane component of proton 1 suffers no precession.

- A purely nuclear interaction might have left both final states purely polarized, perhaps parallel.
- After one quarter turn the anomalous MDM effect can be expected to result in proton 1 remaining in its not-flipped state with probability,

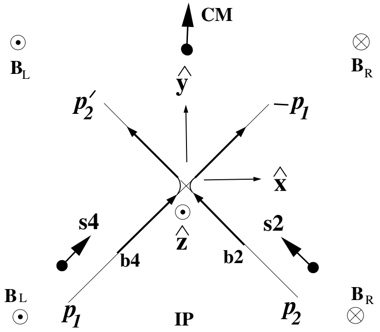
$$P = \frac{1}{2}\left(1 + \cos(2\pi Q_s^{\mathrm{E}}/4)\right) = \frac{1}{2}\left(1 + \cos(2\pi 0.7636/4)\right) \approx 0.5 \neq 1. \quad (3)$$

Because a 90 degree turn in the laboratory is not the same as a 90 degree turn in the center of mass, further work is needed to complete this calculation.

22 Extra slides

Thanks for your attention

Conversion from Wolfenstein to Derbenev geometry



Conversion from Wolfenstein notation

$$p = \frac{p_1 - p_2'}{\sqrt{2}} = \hat{x}$$

$$q = \frac{p_1 + p_2'}{\sqrt{2}} = \hat{y}$$

$$n = p_1 \times p_2' = \hat{z}$$

Figure 5 : In orthogonal beam collisions the Wolfenstein incident momentum unit vectors **p** and **q**, along with normal to the scattering plane $\mathbf{n} = \mathbf{p}\times\mathbf{q}$, become Cartesian unit vectors $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$, $\hat{\mathbf{z}}$.

Detectable signature of T-violation in *pp* scattering

- The T- and P-conserving Wolfenstein operators, for beam particle "1" incident on target particle "2" are "scalars"; [26]

$$\mathbf{1}, \;\; \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2, \;\; (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2).\boldsymbol{n},$$

$$(\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2).\boldsymbol{n}, \;\; (\boldsymbol{\sigma}_1 \cdot \boldsymbol{p})(\boldsymbol{\sigma}_2 \cdot \mathbf{p}), \;\; (\boldsymbol{\sigma}_\mathbf{1} \cdot \boldsymbol{n})(\boldsymbol{\sigma}_\mathbf{2} \cdot \mathbf{n}), \;\; (\boldsymbol{\sigma}_\mathbf{1} \cdot \boldsymbol{q})(\boldsymbol{\sigma}_\mathbf{2} \cdot \mathbf{q})$$

- where "**1**" is the identity matrix, the three components of the $\boldsymbol{\sigma}$ "pseudo-vectors" are the three Pauli 2x2 matrices.
- *If one spin flips, so also must the other.*
- Two "pseudo-scalar" forms,

$$(\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2) \cdot \boldsymbol{n}, \text{ and } (\boldsymbol{\sigma}_1 \cdot \boldsymbol{p})(\sigma_2 \cdot \boldsymbol{q}) + (\boldsymbol{\sigma}_1 \cdot \boldsymbol{q})(\sigma_2 \cdot \boldsymbol{p})$$

  have conventionally been excluded on the basis that they violate T- and P-symmetry;
- *they also have the property that, if one spin flips, the other does not.*

25 Suggested "spin transparent" bunch spin preparation

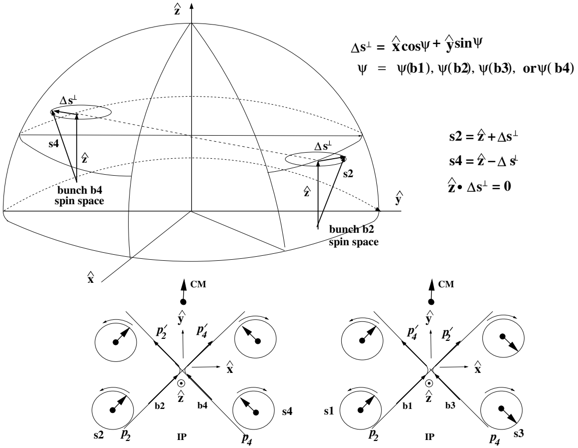
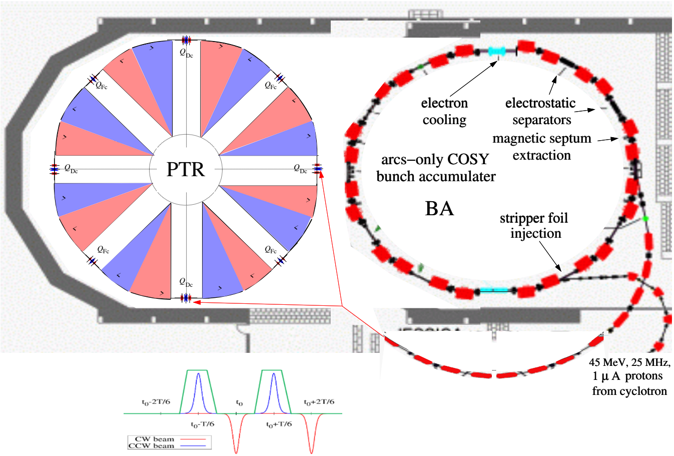


Figure 6 : **Top:** Bunch spin vectors are shown for two (of four) beam bunches that collide at the IP. **Bottom:** Colliding pairs are **b1**,**b3** and **b2**,**b4**. Spins of bunches **b1** and **b2** are the same, **b3** and **b4** are opposite. To prevent depolarization, all spins vectors are predominantly vertical.

Proposed proton EDM Prototype; COSY, Juelich, Germany



- Stripper foil injection from cyclotron, bunch acccumulation and rebunching occurs in BA
- Polarized bunch pairs are transferred to PTR in successive injection cycles

27 proton/carbon left/right asymmetry analyzing power

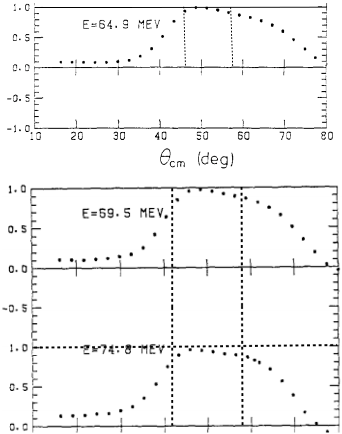


Figure 7 : Analyzing powers for left/right carbon-scattering proton polarimetry[37]. Extended from 100° to 170°, the plots are mirror symmetric about $\pi/2$. Especially valuable will be the one in 400 fraction of single scatters for which the polarizations of both scattered particle are measured with high analyzing power.

Quoting Bethe and Morrison, throughout the range from 150 to 400 MeV, the CM *pp* elastic differential cross section is *constant* and given by

$$\frac{d\sigma}{d\Omega} = 3.4 \pm 0.4\,\mathrm{mb/sr}. \tag{4}$$

This implies that, as well being isotropic, the *total elastic scattering cross section is independent of energy*. The total cross section is

$$\sigma = 3.4 \times 2\pi = 21.3\,\mathrm{mb}; \tag{5}$$

(multiplication by 4π solid angle would double count the scattering events) in agreement with plot shown peviously.

- For beam energy of 80 MeV, $\gamma = 1.082$, $\beta = 0.381$, $v = \beta c = 1.143 \times 10^8$ m/s, revolution period$=T_0 = 1.916\,\mu$s, revolution frequency$=f = 0.522$ MHz.
- Sands gives the total luminosity for 2 circulating bunches with one IP in a circular ring

$$\mathcal{L}_{\mathrm{circular}} = \frac{f}{4}\frac{N_p^2}{A_{\mathrm{int}}} \tag{6}$$

  where N_p is the number of protons in each bunch, and A_{int} is an effective interaction area.
- Head-on short bunches have effective interaction area

$$A_{\mathrm{int}} = \pi\sigma_x\sigma_y = 0.634 \times 10^{-6}\,\mathrm{m}^2. \tag{7}$$

- For luminosity calculation we assume the IP beta function values are $\beta_x^* = \beta_y^* = 0.1$ m.

- Major deficiency—the formulas apply to head-on collisions, not to our orthogonal figure-8 collisions.
- For circular geometry the CYR assumed two bunches, each with $N_p = 10^{10}$ particles.
- Eq. (8) assumes one IP per revolution; we have four, but at half the frequency.
- The figure-8 luminosity is

$$\mathcal{L}_{\rm fig8} = f\,\frac{N_p^2}{A_{\rm int}} = \frac{0.522\times10^6\times10^{20}}{0.634\times10^{-6}\times10^4} \approx 10^{28}\,/{\rm cm}^2/{\rm s}. \qquad (8)$$

  where the extra denominator factor of 10^4 accounts for the luminosity being quoted in its customary c.g.s. units.
- The estimated luminosity is 10 inverse millibarns per second.
- Using the total elastic scattering cross section $\sigma = 21.3\,$mb, multiplying this by the luminosity gives the total expected rate of detected scatters;

$$\text{detected scatters} \approx 2\times10^9 \text{ per nominal year}. \qquad (9)$$

31 Proton stopping power in carbon

K.E.	Stopping	Power		range
		MeV cm^2/g		gm/cm^2
MeV	electronic	nuclear	total	
20	23.31	1.006E-02	23.32	0.4764
40	13.31	5.221E-03	13.31	1.664
60	9.642	3.553E-03	9.645	3.457
80	7.714	2.703E-03	7.717	5.794

Table 3 : Stopping power for protons stopping in graphite, density $1.7\,gm/cm^2$. NIST[43]

Elastic and inelastic recoils of neutrons (mimicking protons) in carbon

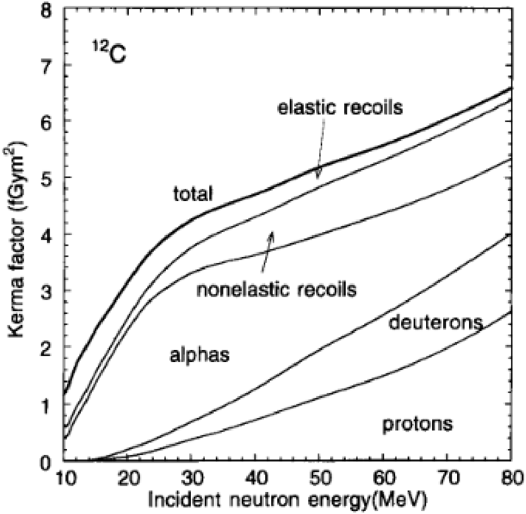


Fig. 19 Calculated partial kerma factors for each emitted particle and elastic and nonelastic recoils

33 Deuteron EDM spin and field configuration

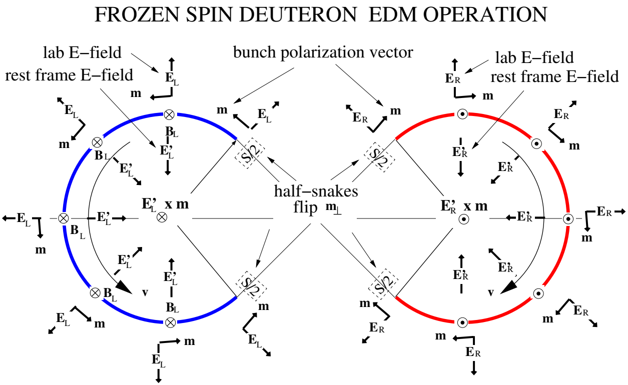


Figure 9 : Lab and CM electric and (dominant) magnetic fields are shown for figure-8 deuteron EDM measurement. A longitudinally polarized deuteron beam circulates as indicated by the curved velocity arrows. Curiously, the superimposed electrical bending is centrifugal and weak, but the magnetic bending is dominant and centripetal, as in the Senichev design.

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