PREDOMINANTLY ELECTRIC "E&m" STORAGE RING WITH NUCLEAR SPIN CONTROL CAPABILITY

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2 Inadequacy of experimental spin data in low energy nuclear physics

- **The proton is the only stable elementary particle for which no experimentally testable fundamental theory predictions exist !**
- **Direct p, p and p, n coupling is too strong for their interactions to be calculable using relativistic quantum field theory** [1].
- **Next-best: the meson-nucleon perturbation parameter (roughly 1/5) is small enough for standard model theory to be based numerically on π and K meson nucleon scattering.**
- **This "finesses" complications associated with finite size, internal structure, and compound nucleus formation.**
- **These issues should be addressed experimentally, but this is seriously impeded by the absence of nuclear physics measurement, especially concerning spin dependence, for particle kinetic energies (KE) in the range from 100 KeV to several MeV, comparable with Coulomb potential barrier heights.**

- **Even though KeV scale energies are easily produced in vacuum, until now spin measurement in this region has been prevented by the negligibly short particle ranges in matter.**
- In this energy range, negligible compared to all nucleon rest masses, the lab frame and the CM frame coincide.
- **To study spin dependence in nuclear scattering, one must cause the scattering to occur in what is a (weakly) relativistic moving frame of reference.**
- **This is possible using “rear-end” collisions in predominantly electric storage rings.**
- **Superimposed weak magnetic bending makes it possible for two beams of different velocity to circulate in the same direction, at the same time, in the same storage ring.**

4 "Rear-end" collisions in a predominantly electric storage ring

- **"Rear-end" collisions occurring during the passage of faster bunches through slower bunches can be used to study spin dependence of nucleon, nucleon collisions in a moving coordinate frame.**
- **Such rear-end collisions allow the CM KEs to be in the several 100 KeV range, while all incident and scattered particles have convenient laboratory KEs, two orders of magnitude higher, in the tens of MeV range.**
- **Multi-MeV scale incident beams can then be established in pure spin states and the momenta and polarizations of all final state particles can be measured with high analyzing power and high efficiency.**
- **In this way the storage ring satisfies the condition that all nuclear collisions take place in a coordinate frame moving at convenient semi-relativistic speed in the laboratory, with CM KEs comparable with Coulomb barrier heights.**

5 Superimposed magnetic field perturbation

- By symmetry stable all-electric orbits are stable in both directions and there are continua of different orbit velocities and radii, one of which matches the ring radius in each direction.
- **To represent the required bending force at radius r_0 being augmented by magnetic bending while preserving the orbit curvature we define "electric and magnetic bending fractions" η_E and η_M satisfying**

$$\eta_E + \eta_M = 1, \ \textbf{where} \ |\eta_M/\eta_E| \ \tilde{<} \ 0.5$$

- The resulting magnetic force dependence on direction causes an $\eta_M > 0$ (call this "constructive") perturbation to shift opposite direction orbit velocities of the same radius, one up, one down.
- For stored beams, any further $\Delta\eta_M \neq 0$ change causes beam velocities to ramp up in energy in one direction, down in the other.

- **Consider the possible existence of a stable orbit particle pair (necessarily of different particle type) such as** d, p **or** α, h **traveling with different velociies in the same direction.**
- **This periodically enables "rear-end" collisions events whose CM KEs can be tuned into the several 100 KeV range by changing** η_M.
- **All incident and scattered particles will have laboratory KEs two orders of magnitude higher, in the tens of MeV range.**
- This is not possible for "same particle" pairs, such as p, p or d, d.

7 Proposed predominently electric "E&m" storage ring properties

- **Our proposed "E&m" storage ring is ideal for investigating low energy nuclear processes—and, especially, their spin dependence.**
- **With careful tuning of E and B, certain nucleon bunch pairs, such as** p, d **or** d, h**, have appropriately different charge, mass, and velocity for their rigidities to be identical. Both beams can then co-circulate indefinitely, with different velocities.**
- Depending on the sign of magnetic field B,**either the lighter or the heavier particle bunches can be faster, "lapping" the slower bunches periodically, and enabling "rear-end" nuclear collision events.**
- (The only longitudinal complication introduced is that the "second" beam needs to be injected with accurate velocity, directly into stable RF buckets.)

Predominantly electric storage ring properties (cont)

- **Only in such a storage ring can “rear-end” collisions occur with heavier particle bunches passing through lighter particle bunches, or vice versa.**
- **From a relativistic perspective, treated as point particles, the two configurations just mentioned would be indistinguishable.**
- **As observed in the laboratory, to the extent the particles are composite, such collisions would classically be expected to be quite different or, at least, distinguishable.**
- **(As a car driver, would you prefer to “rear-end” a heavy truck, or vice versa?)**

9 “Rear-end” $p + d \rightarrow p + d$ “elastic” scattering

- An earlier paper[2] concentrated on the $h + d \rightarrow \alpha + p$ nuclear transmutation channel.
- **Here we consider $p + d \rightarrow p + d$ “elastic” scattering in the E&m storage ring.**
- p **and** d **beams co-circulate concurrently with different velocities in the same ring, such that rear-end collisions always occur at the same intersection point (IP).**
- **The CM kinetic energies are to be varied continuously, KeV by KeV, from below the several hundred KeV Coulomb barrier height**, through the (previously inaccessible for spin control) range up to tens of MeV and beyond.
- **With the scattering occurring in a moving frame, initial and final state laboratory momenta are in the tens of MeV range.**

- **All nuclear events occur within a full acceptance interaction detector/polarimeter.**
- Temporarily neglecting spin dependence, the CM angular distributions will be isotropic[3][4].
- **(Especially with heavier particles being faster) most final state particles end up traveling "forward" to produce "rainbow" circular rings (or rather cones) formed by the final state particles.**
- (In the absence of "rear end" collisions) this "view" has not been observed previously in nuclear scattering experiments.

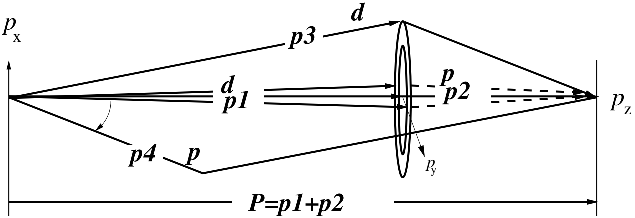


Figure 1: **Laboratory frame momentum vector diagram.** The vector $\mathbf{P} = \mathbf{p_1} + \mathbf{p_2}$ is the sum of the lab momenta of one particle from beam 1(p) and one from beam 2(d). Scattered beam-3(d) direction is shown above the beam axis; the scattered p direction (4) would then be below, as displayed by parallelogram construction. Rolled around the longitudinal axis, the figure is intended to show how azimuthal symmetry imposes the rainbow scattering pattern with cone angle increasing proportional to the incident energy excess over threshold energy.

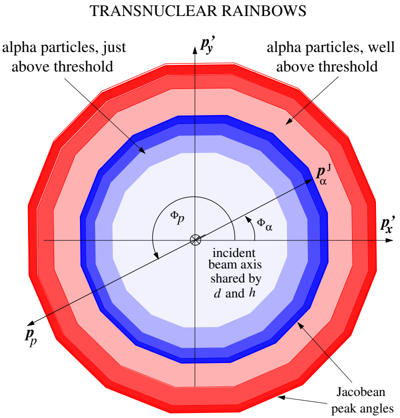


Figure 2: Transnuclear "rainbows" produced in the reaction $h + d \to \alpha + p$. Shading represents scattered differential cross section. **Rainbow radii increase proportional to incident energy excess above threshold.** Superscript "J" labels the rainbow divergence edge caused by the vanishing Jacobean at the laboratory scattering angle maximum.

13 Storage ring PTR with superimposed E&m bending

- First suggested by Koop[5], (in the context of counter-rotating proton EDM measurement), this superimposed magnetic bending storage ring "E&m" configuration has been preceded by a series of papers, mainly by the present author, [6]-[14]
- It is possible, with superimposed electric and magnetic bending, for beam pairs of different momentum or of different particle type to co-circulate simultaneously.
- This opens the possibility of "rear-end" collisions occurring while a fast bunch of one nuclear isotope type passes through a bunch of less heavy, yet slower, isotope type.

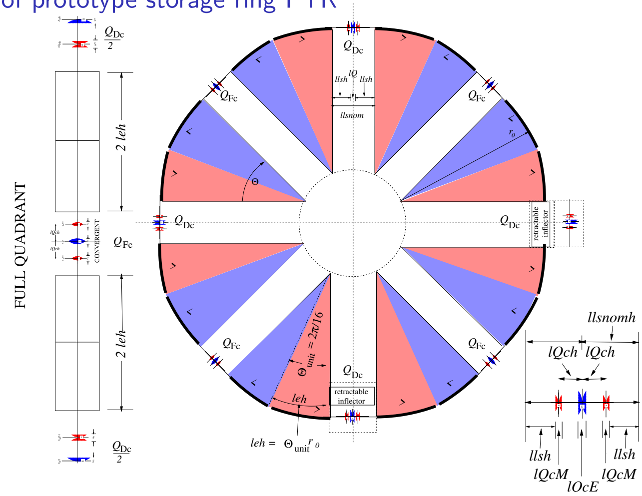


Figure 3: Lattice layouts for PTR, the proposed prototype nuclear transmutation storage ring prototype; "compromise" quadrupole lower right. **The circumference has been taken to be 102 m, but the entire lattice can be scaled, e.g. to reduce peak field requirements.**

15 PTR ring design

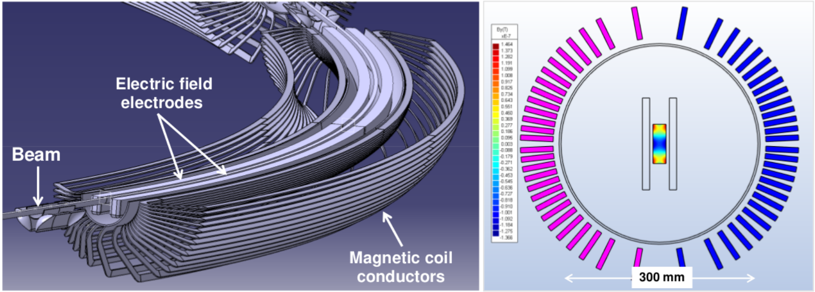


Figure 4: **Left:** Cutaway drawing of one sector of the PTR ring. **Right:** A transverse section showing an end view of the (inner legs of the) magnet coil, as well as a field map of the good magnetic field region. The (brilliant) design is due to Helmut Söltner[13].

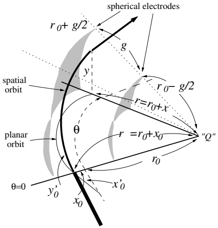
The magnet is "air core", limited to quite weak magnetic field, but sufficient for the application. Current design maximum values for electric and magnetic fields are 10 MeV/m and 30 mT.

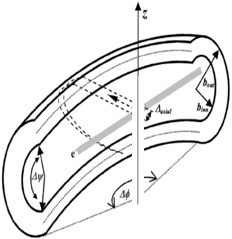
ELECTRODE SHAPE PARAMETER *m*

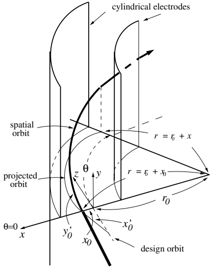
$$\mathbf{E}(r) = -E_0 \frac{r_0^{\,1+m}}{r^{\,1+m}}\, \hat{\mathbf{r}}$$

$$V(r) = -E_0 r_0 \left(\frac{r_0}{r} - 1\right) \qquad V(r) = -\frac{E_0 r_0}{m}\left(\frac{r_0^m}{r^m} - 1\right) \qquad V(r) = E_0 r_0 \ln(r/r_0)$$

***m* = 1** spherical	(optimal) ***m* = 1/3** toroidal	***m* = 0** cylindrical







Newton Kepler Coulomb	Neumann, 1864 Albrecht, 1956	Courant–Robinson (BNL)

17 PTR optics, super-periodicity=8, Maple:BSM program

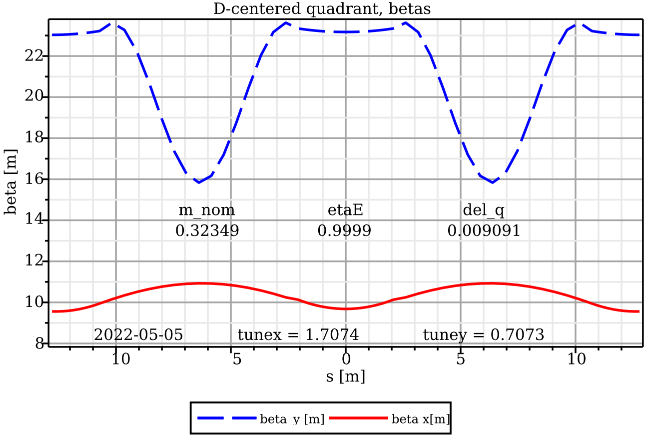


Figure 6: Refined PTR tuning, with quad strengths and $m_{\rm nom.}$ **(adjusted to 0.32349) for (distortion-free) equal-fractional-tune,** $Q_x = Q_y + 1$**, operation on the difference resonance.** Not counting geometric horizontal focusing, thick lens pole shape horizontal and vertical focusing strengths are then identical[9]. **Mnemonic:** $m_{\rm nom.}$**=1/3**.

18 Notes concerning Figure 6

- Though of minuscule strengths, the quads have been adjusted for equal *fractional* x, y tune values (0.7074, 0.7073).
- The optimal thick lens optics (i.e. with quadrupoles turned off) is uniquely determined, with $m_{\mathrm{nom.}}$ value curiously close to $1/3$, closer to $m = 0$ (cylindrical) than to $m = 1$ (spherical) electrode shape.
- With obvious scaling changes, such as electric, E_0, and magnetic, B_0, field strengths varying inversely with r_0. **The same design applies from microscopic to cosmological scales, with no other kinematic alteration.**
- For example, by doubling r_0 to 22 m, the value of E_0 would be reduced from 5.06 MV/m to 2.53 MV/m.

19 2021 PTR Cost Estimate (CERN Report: 132-127-PB.pdf)

Table 5: Preliminary cost estimates for the prototype ring first stage

Component	Cost (k€)
Bends	9200
Electric quads	1700
Vacuum	1800
Pick-ups	900
Control	1500
Polarimeter	1200
RF equipment	300
Total	16600

Figure 7: 2021 PTR Cost Estimate[13]

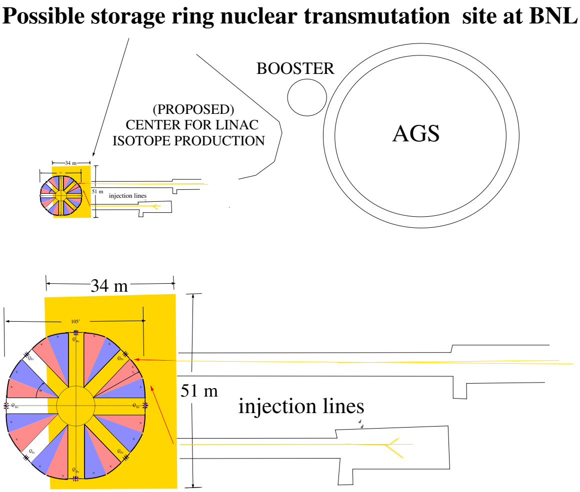


Figure 8: **Above:** Tentative PTR location near the AGS at BNL, using existing, high current isotope sources. **Below:** Magnified image insert of PTR complex.

Possibility of rear-end collisions of identical particles, e.g. $p + p$

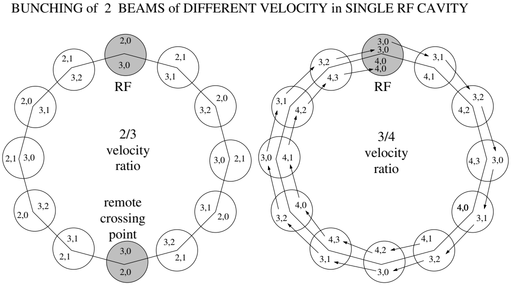


Figure 9: Stable RF buckets for different velocity ratio beams.

- With 7/8 velocity ratio and $7 \times 8 = 56$, the RF frequency can be the 56'th harmonic of a standard base frequency, $f_{\rm base}$, itself a harmonic number h_n multiple $f_{\rm base} = h_n f_{\rm rev.}$ of the revolution frequency; **both circulating beams can be bunched by a single RF cavity in spite of their different velocities**.

22 Rate calculation: $h + d \to \alpha + p$

Typical parameters include

$$
\begin{aligned}
f_{\rm sr} =&\ \text{storage ring revolution frequency} && = 10^6\,\mathrm{Hz},\\
N_d, N_h =&\ \text{numbers of stored particles} && = 10^{10}\,,\\
A_b =&\ \text{beam area }\ = 0.1\,\mathrm{cm}\times 0.1\,\mathrm{cm} && = 10^{-2}\,\mathrm{cm}^2,\\
\sigma =&\ \text{nuclear cross section} && = 10^{-24}\,\mathrm{cm}^2,
\end{aligned}
$$

The (deuterium) "target bunch nuclear opacity" is

$$
O_{\rm N} = N_d\sigma/A_b = 10^{10}\times 10^{-24}/10^{-2} = 10^{-12}, \qquad (1)
$$

which gives the fraction of bunch passages which result in a nuclear event

$h + d \to \alpha + p$ event rate (cont)

The rate of particle passages is

$$r_{\rm pass} = \frac{f_{\rm sr}}{7}\, N_h = \frac{10^6}{7} \times 10^{10} = 0.142 \times 10^{16}/{\rm s}. \tag{2}$$

The resulting nuclear event rate is

$$r_{\rm event} = O_{\rm N} \times r_{\rm pass} = 10^{-12} \times 0.142 \times 10^{16} = 1.42 \times 10^3/s. \tag{3}$$

p, d scattering tune-up and energy scan

Table 1: Fine-grain scan to center the collision point

bm 1	beta1	Qs1	KE1 MeV	E0 MV/m	etaM1	beta2	Qs2	KE2 MeV	beta*	gamma*	M* GeV	Q12 KeV	t,t*bratio 2	bm 2
p	0.2996	0.294	45.190	4.77556	0.40511	0.1998	-0.723	38.578	0.23366	1.02847	2.81744	3558.4	3.00019	d
p	0.3000	0.294	45.290	4.78686	0.40499	0.2000	-0.724	38.665	0.23391	1.02853	2.81745	3565.9	3.00001	d
p	0.3003	0.294	45.390	4.79817	0.40487	0.2002	-0.724	38.751	0.23416	1.02860	2.81746	3573.4	2.99983	d

The two beams are lab KE1=45.2 MeV protons and 38.665 MeV deuterons. The ring bending radius is $r_0 = 11\,$m. The electric/magnetic field ratio produces perfect β_p/β_d=3/2 velocity ratio such that, for every t=2 deuteron turns, the protons make 3 turns. The CM kinetic energy in this case is 3.5659 MeV.

Table 2: p, d scattering energy scan

bm 1	beta1	Qs1	KE1 MeV	E0 MV/m	etaM1	beta2	Qs2	KE2 MeV	beta*	gamma*	M* GeV	Q12 KeV	t,t*bratio 2	bm 2
p	0.1448	0.284	10.000	1.00030	0.44692	0.0944	-0.702	8.419	0.11131	1.00625	2.81470	818.5	3.06776	d
p	0.2032	0.287	20.000	2.03242	0.43519	0.1334	-0.708	16.906	0.15685	1.01253	2.81550	1618.9	3.04789	d
p	0.2470	0.29	30.000	3.09668	0.42334	0.1631	-0.714	25.459	0.19142	1.01884	2.81629	2401.7	3.02856	d
p	0.2830	0.293	40.000	4.19343	0.41137	0.1881	-0.720	34.079	0.22024	1.02517	2.81705	3167.5	3.00976	d
p	0.3140	0.296	50.000	5.32300	0.39927	0.2100	-0.726	42.763	0.24535	1.03153	2.81780	3916.7	2.99145	d
p	0.3415	0.299	60.000	6.48572	0.38706	0.2297	-0.732	51.510	0.26781	1.03791	2.81853	4649.7	2.97362	d

The columns labeled Q_s are spin tunes. In this talk nothing more will be said about polarization, but support for scattering highly polarized beam particles with high quality final state polarimetry capability provides the main motivation for the proposed E&m storage ring project.

- The goals are to provide experimental data sufficient to refine our understanding of the nuclear force and nuclear physics.
- Pure incident spin states, high analyzing power final state polarization measurement, and high data rates should initiate a qualitatively and quantitatively new level of experimental observation of nuclear reactions.
- **Especially important is the investigation of wave particle duality and spin dependence of "elastic" p, d scattering approaching the pion production thresholds.**
- **Precision comparison of "fast on slow" and "slow on fast" collisions, which would be identical for point particles, can also probe the internal nuclear structure; perhaps distinguishing experimentally between "prompt" and "compound nucleus" scattering.**

26 Recapitulation of the proposal

- **This paper has described an E&m storage ring capable of the room temperature laboratory spin control of two particle nuclear scattering or fusion events.**
- **The novel equipment making this possible is a storage ring with superimposed electrical and magnetic bending.**
- Rings like this were introduced by Koop but have not yet been built.
- Serving as a demonstration of nuclear to electrical energy conversion, such apparatus can perform measurements needed to refine our understanding of thermonuclear power generation and cosmological nuclear physics.
- It is the novel capability of such rings to induce “rear-end” nuclear collisions that makes this possible.

- **Emphasizing the measurement of spin dependence in low energy nuclear physics, the goal is to provide experimental data to refine our understanding of nucleon composition along with the nuclear force and its influence on elementary-particle physics.**
- Thanks for your attention

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- Possible parameters include

$$
\begin{aligned}
f_{\rm sr} = &\ \text{storage ring revolution frequency} && = 10^6\,\mathrm{Hz},\\
N_d, N_h = &\ \text{numbers of stored particles} && = 10^{10}\,,\\
A_b = &\ \text{beam area } = 0.1\,\mathrm{cm} \times 0.1\,\mathrm{cm} && = 10^{-2}\,\mathrm{cm}^2,\\
\sigma = &\ \text{nuclear cross section} && = 10^{-24}\,\mathrm{cm}^2,
\end{aligned}
$$

- The (deuterium) ”target bunch nuclear opacity”

$$
O_{\rm N} = N_d\sigma/A_b = 10^{10} \times 10^{-24}/10^{-2} = 10^{-12}, \tag{4}
$$

  gives the fraction of bunch passages which result in a nuclear transmutation event
- The rate of particle passages is

$$
r_{\rm pass} = \frac{f_{\rm sr}}{7}\,N_h = \frac{10^6}{7} \times 10^{10} = 0.142 \times 10^{16}/\mathrm{s}. \tag{5}
$$

Estimated power production

- The nuclear transmutation event rate is

$$r_{\mathrm{event}} = O_{\mathrm{N}} \times r_{\mathrm{pass}} = 10^{-12} \times 0.142 \times 10^{16} = 1.42 \times 10^{3}/s. \quad (6)$$

- The conversion factor from MeV to Joule is 1.602×10^{-13} J/MeV and the maximum possible energy extraction is $Q_{D-He3} = 18.3\,\mathrm{MeV/event}$.
- The power averaged over one second

$$P_{\mathrm{average}} = 1.42 \times 10^{3} \times 16.35 \times 1.602 \times 10^{-13}\,\mathrm{W}. \quad (7)$$

- From a nuclear power perspective this is utterly negligible, down by many orders of magnitude compared to the KW energy consumption rate of a typical individual.