Predominantly Electric Storage Ring "E&m-SR" for Nuclear Spin Physics

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2 Outline

- Crisis in low energy nuclear physics
- Proposed predominantly electric storage ring properties
- "Rear-end" $h + d \rightarrow \alpha + p$ collisions
- Storage ring PTR with superimposed E&m bending
- Electrical storage ring design
- "Rainbow" kinematic plots
- Recapitulation of the proposal
- Conclusion

- 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 (RQFT).
- 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 1 MeV, comparable with Coulomb potential barrier heights.

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

- Even though these 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 at least a weakly relativistically moving frame of reference.
- This is possible using predominantly electric storage rings.
- The weak magnetic bending makes it possible for two beams of different velocity (owing to their different particle type) to circulate in the same direction, at the same time, in the same storage ring.

5 "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 semi-relativistic 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.
- This permits incident beams to be established in pure spin states and the polarizations of scattered particles measured with high analyzing power and high efficiency.
- In this way the E&m-SR 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.

6 "Rear end" collisions (cont)

- As an example, this paper concentrates on d and h beams co-circulating concurrently in the same storage ring, with parameters arranged such that, in the process

$$d + h \to p + \alpha,$$

rear-end collisions always occur in a detector at the intersection point (IP).

- In a conventional (magnetic) contra-circulating colliding beam storage ring the energy would be far above the pion production threshold, with production into this channel negligibly small.

7 Superimposed magnetic field perturbation

- To represent a small part of the required bending force at radius r_0 being replaced by magnetic bending while preserving the orbit curvature we define "fractional electrical and magnetic bending fractions" η_E and η_M satisfying

$$\eta_E + \eta_M = 1, \text{ where } |\eta_M/\eta_E| < 0.15$$

- This perturbation "splits" a unique velocity solution into two slightly separated velocity solutions.
- As a result there are periodic "rear-end" collisions between two particles co-moving with substantial, but slightly different velocities in the laboratory, such that their CM KEs are in the several 100 KeV range.
- All incident and scattered particles then have convenient laboratory KEs, two orders of magnitude higher, in the tens of MeV range.

8 Predominantly electric storage ring properties

- Our proposed "E&m-SR" storage ring is ideal for investigating low energy nuclear processes.
- With careful tuning of E and B, certain nucleon bunch pairs of different particle type, such as d and h, or p and d, have appropriately different charge, mass, and velocity for their rigidities to be identical. Both beams can then co-circulate indefinitely, with different velocities.
- For nuclear beams *of different particle type*, depending on the sign of magnetic field B, either lighter or heavier particle bunches will be faster, "lapping" the slower bunches periodically, and enabling "rear-end" nuclear fusion events.

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 described would be indistinguishable.
- But, 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.

10 “Rear-end” $h + d \to \alpha + p$ collisions

- Consider d and h beams co-circulating concurrently in the same storage ring, with parameters arranged such that, in the process $d + h \to p + \alpha$, rear-end collisions always occur in the detector at an intersection point (IP).
- The center of mass kinetic energies (where their momenta are equal and opposite) are close to the Coulomb barrier height for this nuclear scattering channel.
- With judicious adjustment, all nuclear events will occur at the ring intersection point (IP) of a full acceptance interaction detector/polarimeter.

- In this configuration the rest mass of the h, d system will be fine-tunable on a KeV scale, for example barely exceeding the threshold of the $h + d \to \alpha + p$ channel, but below the pion production threshold.
- Tentatively neglecting spin dependence, the expected radiation pattern can be described as a "rainbow" circular ring (or rather cone) formed by the more massive (α-particles) emerging from, and centered on, the common beam axis.
- This "view" has not been observed previously in nuclear measurements since it requires a "rear end" collision in which a more massive but faster moving (in the laboratory) helion overtakes a lower mass but slower moving deuteron.

12 Numerical values

bm 1	beta1	Qs1	KE1 MeV	E0 MV/m	etaM1	beta2	Qs2	KE2 MeV	beta*	gamma*	M* GeV	Q12 KeV	7*bratio	bm 2
h	0.1826	-0.666	48.000	4.96139	-0.14662	0.1597	-1.097	24.391	0.17343	1.01539	4.68432	311.21468	8.00083	d
h	0.1844	-0.666	49.000	5.06742	-0.14742	0.1613	-1.098	24.901	0.17519	1.01571	4.68432	317.54605	8.00015	d
h	0.1862	-0.666	50.000	5.17355	-0.14822	0.1630	-1.098	25.410	0.17693	1.01603	4.68433	323.87133	7.99947	d

Table 1: Fine-grain scan to center the collision point for KE1=49 MeV helion energy and 25 MeV deuteron energy, bend radius $r_0 = 11\,$m. "etaM1" is the fractional magnetic bend strength. The electric/magnetic field ratio then produces perfect β_h/β_d=8/7 velocity ratio so that, for every 7 deuteron turns, the helion makes 8 turns. Notice, also, the approximate match of Q12=317 KeV in this table, with Coulomb barrier energy, $V_{d,He3}$=313.1 KeV. This matches the incident kinetic energy to the value required to surmount the repulsive Coulomb barrier.

- The columns labeled Q_s are spin tunes. In this talk nothing 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-SR project.

13 “Rainbow” nuclear “rear-end” scattering pattern

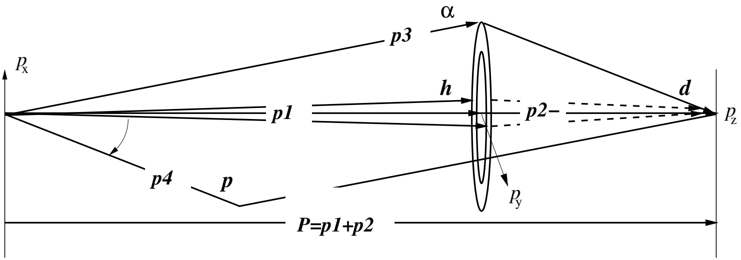


Figure 1: Laboratory frame momentum vector diagram. The vector $\mathbf{P} = \mathbf{p_1} + \mathbf{p_2}$ is the sum of the lab momenta of one particle from beam 1(h) and one from beam 2(d). Scattered alpha particle direction (3) is shown above the beam axis; the scattered proton direction (4) would 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.

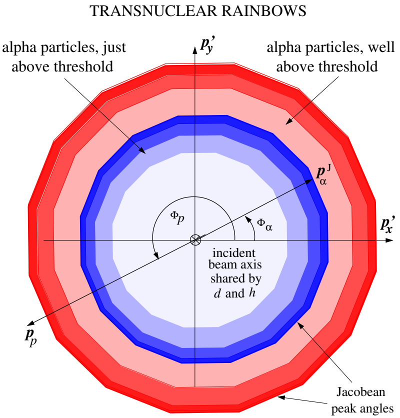


Figure 2: Transnuclear “rainbows” produced in the reaction $h + d \to \alpha + p$. Shading represents scattered differential cross section. Rainbow radii increase proportional to incident energy excess above threshold. Superscript “J” labels the rainbow divergence edge caused by the vanishing Jacobean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

15 Storage ring PTR with superimposed E&m bending

- First suggested by Koop[2], this superimposed magnetic bending storage ring "E&m-SR" configuration has been preceded by a series of papers, mainly by the present author, [3]-[10]
- It is possible, with superimposed electric and magnetic bending, for beam pairs 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.
- Bunches of the same particle type (but different momenta) can also contra-circulate simultaneously and collide (well above pion production threshold) as in any conventional colliding beam facility.

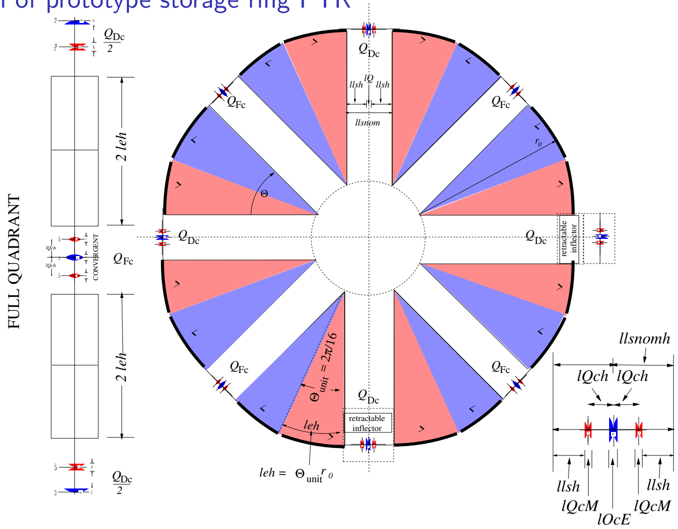


Figure 3: Lattice layouts for PTR, the proposed prototype nuclear transmutation storage ring prototype; "compromise" quadrupole lower right. The circumference has been taken to be 102 m, but the entire lattice can be scaled, e.g. to reduce peak field requirements.

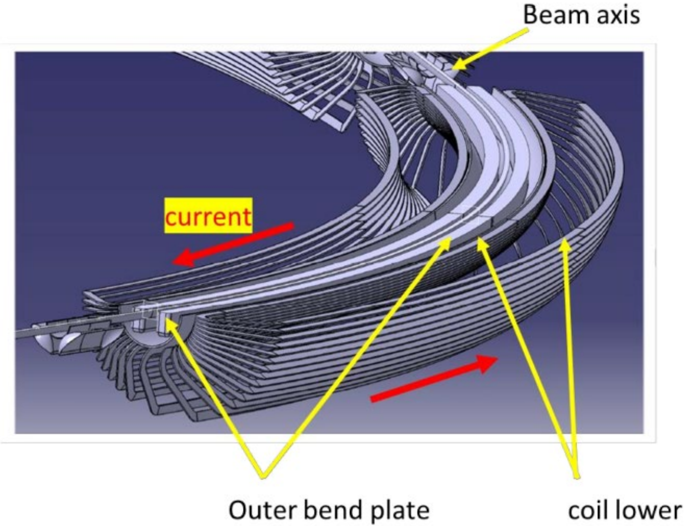


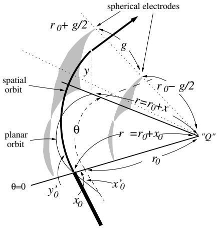
Figure 4: Perspective mock-up of one sector of PTR, the superimposed E&m prototype ring. "Short-circuited end" $\cos\theta$-dipoles surround the beam tube, within which are the capacitor plate electrodes. The (brilliant) superimposed magnetic coil design is due to Helmut Söltner[9].

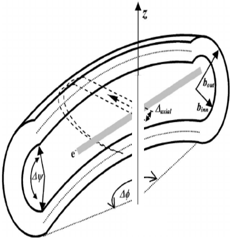
ELECTRODE SHAPE PARAMETER *m*

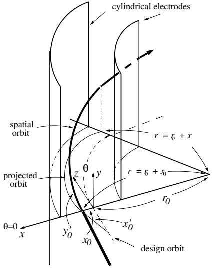
$$\mathbf{E}(r) = -E_0 \frac{r_0^{\,1+m}}{r^{\,1+m}}\, \hat{\mathbf{r}}$$

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

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







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

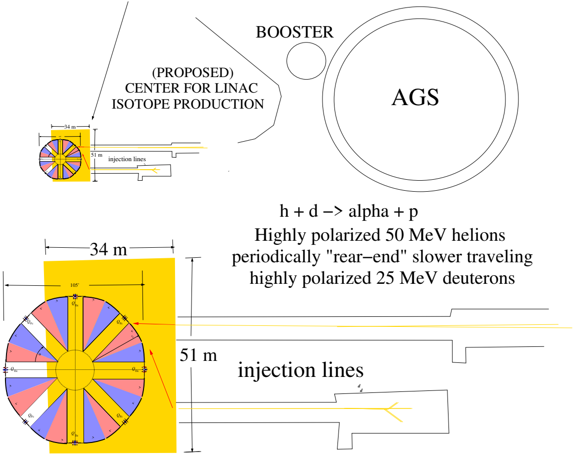


Figure 6: **Above:** Tentative PTR location near the AGS at BNL, using existing, high current isotope sources. **Below:** Magnified image insert of PTR complex.

20 PTR, quads “off”, electrode shape (*m*-parameter) dependence

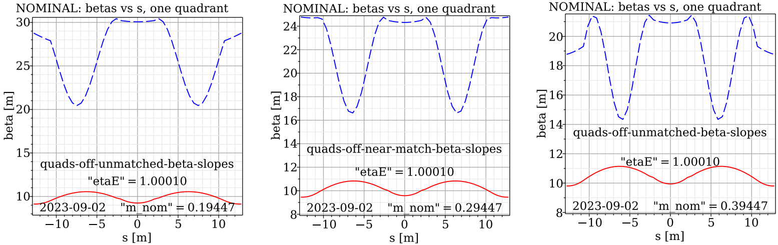


Figure 7: MAPLE-BSM, “Heisenberg-picture” transfer matrix evolution, through one quadrant, demonstrates marginally stable, 8-fold periodicity. Weak quadrupole strengths produce periodic matched beta functions of roughly correct period length in the central case, but stronger quadrupole focusing is needed in the outer cases. ETEAPOT:PTR, “Schrödinger-picture”, particle tracking evolution agrees well (at the +/-10 % level). “Quads off” text in the figures should be interpreted as “quad strengths as weak as possible”.

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

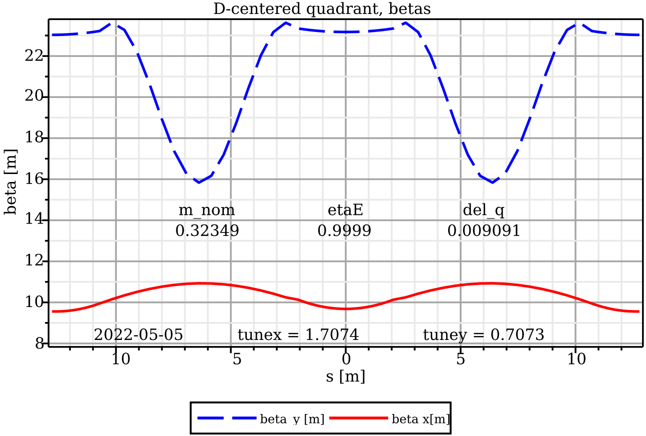
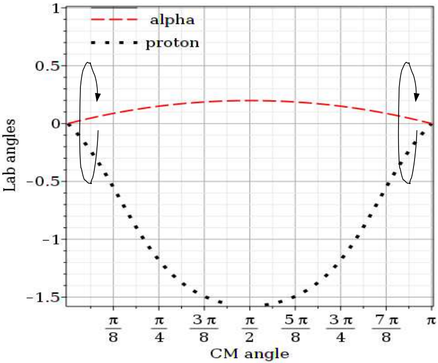


Figure 8: Refined PTR tuning, with quad strengths and $m_{\rm nom.}$ (adjusted to 0.32349) for (distortion-free) equal-fractional-tune, $Q_x = Q_y + 1$, operation on the difference resonance. Not counting geometric horizontal focusing, thick lens pole shape horizontal and vertical focusing strengths are then identical. Mnemonic: $m_{\rm nom.}$=1/3.

22 Notes concerning Figure 8

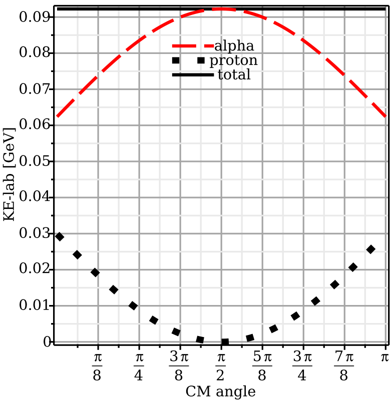
- Though of minuscule strengths, the quads have been adjusted for equal *fractional* x, y tune values (0.7074, 0.7073).
- The optimal thick lens optics (i.e. with quadrupoles turned off) is uniquely determined, with $m_{\rm nom.}$ value curiously close to $1/3$, closer to $m = 0$ (cylindrical) than to $m = 1$ (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.

23 "Rainbow" kinematic plot



- This planar plot of laboratory angle vs CM angle should be visualized as if rolled around its horizontal axis, as indicated by the rotation arrows.
- α particles are contained within a cone half-angle of 0.2 radians.
- At the α-particle maximum scattering angle the vanishing slope in this view produces a "Jacobean peak" at the rim of the rainbow shown previously.
- The rainbow radius increases with incident energy, say from blue to red in earlier rainbow plot.

Final state kinetic energies



- Relation between c.m angles and lab kinetic energies.
- That the process is exothermic is shown by the fact that the 92.2 MeV sum of final state kinetic energies exceeds the 49.0+24.9=73.9 MeV initial state energy by 18.3 MeV, which is the exothermic energy.

25 Pure physics goals

- 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.

- This paper has described an E&m-SR 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 (in the context of counter-rotating proton EDM measurement), 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.

27 Conclusion

- Emphasizing the measurement of spin dependence, the goal is to provide experimental data to refine our understanding of the nuclear force and its influence on high energy physics.
- Thanks for your attention

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