PREDOMINANTLY ELECTRIC STORAGE RING WITH NUCLEAR SPIN CONTROL CAPABILITY

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Abstract

A predominantly electric storage ring with weak superimposed magnetic bending is shown to be capable of storing two different nuclear isotope bunches, such as helion and deuteron, co-traveling with different velocities on the same central orbit. "Rear-end" collisions occurring periodically in a full acceptance particle detector/polarimeter, allow the (previously inaccessible) direct measurement of the spin dependence of nuclear transmutation for center of mass (CM) kinetic energies ranging from hundreds of keV up toward pion production thresholds. These are "rear-end" collisions occurring as faster stored bunches pass through slower bunches. An inexpensive facility capable of meeting these requirements is described, with nuclear channel $h + d \rightarrow \alpha + p$ as example.

INTRODUCTION

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. 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 multi-keV scale energies are easily produced in vacuum, until now spin measurement in this region has been prevented by space charge and 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 relativistic) moving frame of reference. This is possible using "rear-end" collisions in a predominantly electric with a weak magnetic field ring, a so-called E&m storage ring. 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. "Rear-end" collisions occurring during the passage of faster bunches through slower bunches can be used to study spin dependence on 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.

CO-TRAVELING ORBITS WITH SUPERIMPOSED E&m FIELDS

By symmetry, stable *all-electric* storage ring orbits are forward/backward symmetric and there are continua of different orbit velocities and radii, one of which matches the design 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

$$\eta_E + \eta_M = 1, \text{ where } |\eta_M/\eta_E| \lesssim 0.5\,. \tag{1}$$

The resulting magnetic force dependence on direction causes an $\eta_M > 0$ (call this "constructive") or $\eta_M < 0$ ("destructive") perturbation to shift opposite direction orbit velocities of the same radius, one up, one down, resulting in two stable orbits in each direction. 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. Our proposed E&m storage ring is ideal for investigating low-energy nuclear processes and, especially, their spin dependence.

Consider the possible existence of a stable orbit particle pair (necessarily of different particle type) such as deuteron/proton (d, p) or deuteron/helion (d, h), traveling with different velocities 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 symmetry argument is not effective for "same particle" pairs, such as p, p or d, d. The resultant co-traveling bunch velocities remain identical and no "rear-end" collisions ensue; treatment of the fundamentally most important case of identical particle scattering, has to be deferred for now.)

With careful tuning of E and B, such nucleon bunch pairs have appropriately different charge, mass, and velocity for their rigidities to be identical. Both beams can then co-circulate indefinitely, with different velocities.

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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 by dual beam operation is that the "second" beam needs to be injected with accurate velocity, directly into stable RF buckets.)

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 [1]. As observed in the laboratory, to the extent the particles are composite, such collisions would classically be expected to be quite different and easily distinguishable.

Pavsic, in a 1973 paper reproduced in 2001 [2], develops a "mirror matter" Hamiltonian formalism, distinguishing between "external" and "internal" symmetry. He points out, for example, that "the existence of the anomalous proton or neutron magnetic moments indicates the asymmetric internal structure of two particles"; a comment that applies directly to the present paper. Otherwise, Pavsic is agnostic, suggesting that his formalism provides only a parameterization for experiments sensitive to internal structure, with possible implications concerning mirror matter.

STORAGE RING PTR WITH SUPERIMPOSED E&m BENDING

First suggested by Koop [3], (in the context of counter-rotating proton beams for proton EDM measurement), design of the E&m configuration has been described in a series of papers by or including the present author [4–6]. The acronym PTR chosen in Ref. [6] to stand for "prototype" has been retained, in spite of the much altered rationale for its existence. 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 lighter, yet slower, isotope type (or vice versa). A schematic diagram of the proposed PTR storage ring is shown on the left in Fig. 1, and its optimized beta functions are shown on the right. PTR lattice description "sxf" files can be obtained at Ref. [7].

Though the quadrupole strengths are minimal (as can be seen by the vanishing entrance and exit slopes) in the figure on the right of Fig. 1, they 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 $m_{\text{nom.}}$ value (defined bottom-left in Fig. 2) 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.

SIMULTANEOUS BEAM BUNCHING OF BOTH BEAMS BY THE SAME RF CAVITY OR CAVITIES

The condition for bunch collision points to occur at fixed ring locations is met by the beam velocities being in the ratio of integers; e.g. $\beta_1/\beta_2 = 3/2$ in Table 1. *Both circulating beams can be bunched by a single RF cavity in spite of their different velocities.* For more nearly equal velocities the figure becomes more complicated. With 7/8 velocity ratio and 7×8 = 56, the RF frequency can be the 56th harmonic of a standard base frequency, f_{base}, itself a harmonic number h_n multiple $f_{\text{base}} = h_n f_{\text{rev.}}$ of the revolution frequency. Stable buckets are labeled for simple cases in Fig. 3. (Hint: when the second indices are both zero, the populated bunches superimpose.) A "remote" bunch collision point appears on the left, but not on the right.

"RAINBOW", "REAR-END" $p + d \rightarrow p + d$ COLLISIONS

An earlier paper [8] discussed the $h + d \rightarrow \alpha + p$ nuclear transmutation channel, illustrated as "rainbows" in Fig. 3. Here we consider $p + d \rightarrow p + d$ "elastic" (including weakly inelastic) 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 convenient 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 approximately isotropic [9, 10]. (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 yet to be seen in nuclear scattering experiments.

p, d SCATTERING TUNE-UP AND ENERGY SCAN

Kinematic parameters for a fine grained scan are shown in Table 1. Center row, the electric/magnetic field ratio produces perfect $\beta_p/\beta_d = 3/2$ 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. A coarse grained scan is shown in Table 2. In the "rear-end" collision of (laboratory) 10 MeV p bunches passing through 8.419 MeV d

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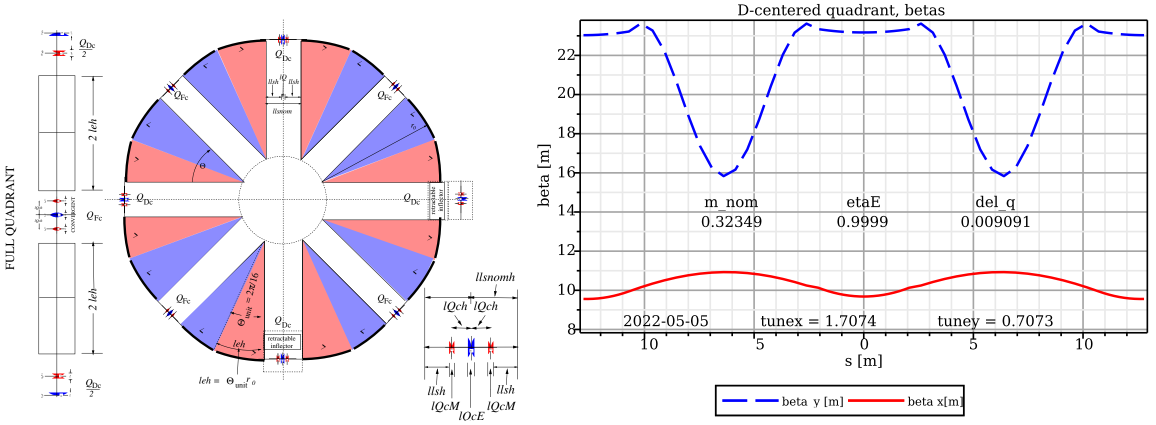
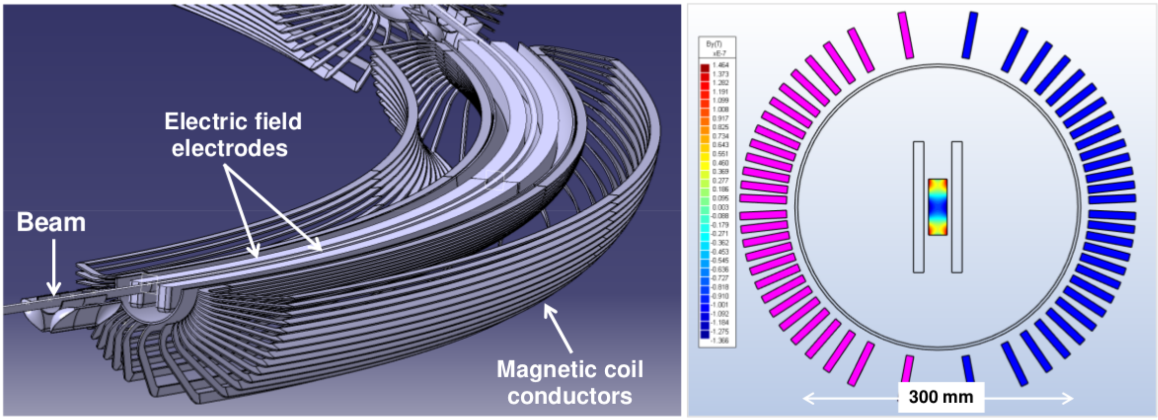


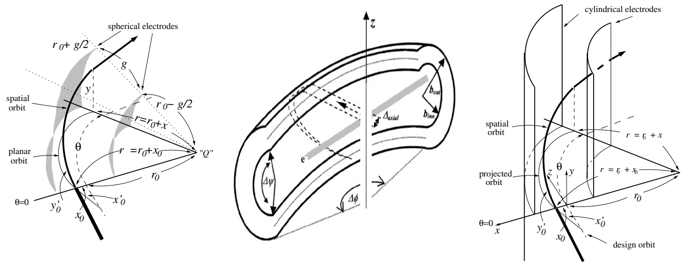
Figure 1: Left: Lattice layouts for PTR, the proposed prototype nuclear transmutation storage ring. "Compromise" quadrupoles [5] are shown lower right. The circumference is 102.2 m. Right: Refined PTR tuning, with quad strengths and $m_{\mathrm{nom.}}$ (adjusted to 0.32349) for (distortion-free) equal-fractional-tune, $Q_x = Q_y + 1$, operation on the difference resonance. Not counting geometric horizontal focusing, thick lens pole shape horizontal and vertical focusing strengths are then identical [11] (mnemonic: $m_{\mathrm{nom.}} = 1/3$). The entire lattice design can be scaled, e.g. to reduce peak field requirements.



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

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

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



Newton
Kepler
Coulomb

Neumann, 1864
Albrecht, 1956

Courant–Robinson
(BNL)

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

Figure 2: Top Left: Cutaway drawing of one sector of the PTR ring. Top 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 field region. The (brilliant) design is due to Helmut Söltner [6]. 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 MV/m and 30 mT. Bottom Left: Electrode shapes are shown with their focusing strength parameters m, for spherical, (optimized) toroidal, and cylindrical bending fields [12–15]. Bottom Right: 2021 CERN Yellow report cost estimate [6] for the apparatus shown.

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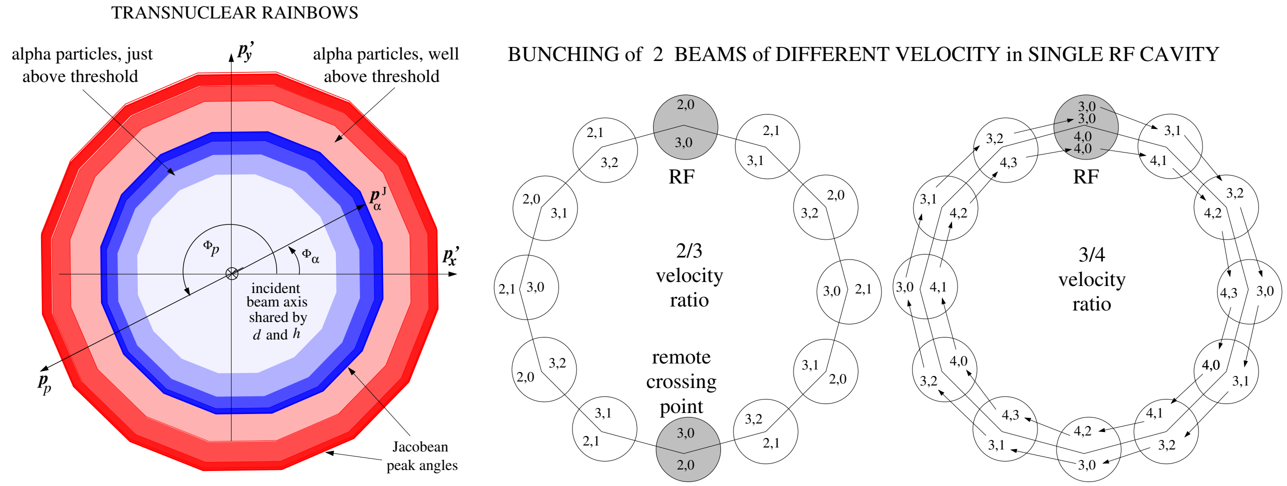

Figure 3: Left: Jacobean peak "rainbow" production patterns for the nuclear transmutation process $h + d \longrightarrow \alpha + p$. The $p + d \longrightarrow h + \gamma$ channel would exhibit only a single, more acute angle h rainbow. Center and right: Stable RF buckets for beam velocity ratios of 2/3 or 3/4. Shaded circles indicate locations at which bunch positions coincide. The undesirable collisions at the RF location should be removable with symmetrically split RF locations.

bunches, the (CM) KE is 818.5 keV. With both beams polarized, spin tunes Q_s are given in the tables. *Nothing more is said about polarization in this paper, 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.* In recent years there have been many developments in beam polarization control and in polarimetric spin orientation detection, many of which have been produced at the COSY storage ring in Jülich, Germany [16–21].

RATE CALCULATION: $h + d \longrightarrow \alpha + p$

In this case the β-ratio is 7/8. Typical parameters include

$$\begin{aligned} f_{\rm sr} &= \text{storage ring revolution frequency} = 1 \times 10^6\,\text{Hz}, \\ N_d, N_h &= \text{numbers of stored particles} = 10^{10}, \\ A_b &= \text{beam area} = 0.1\,\text{cm} \times 0.1\,\text{cm} = 1 \times 10^{-2}\,\text{cm}^2, \\ \sigma &= \text{nuclear cross section} = 1 \times 10^{-24}\,\text{cm}^2\,. \end{aligned}$$

The (deuterium) "target bunch nuclear opacity" is

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

which gives the fraction of particle passages that results in a nuclear event The rate of particle passages is

$$r_{\rm pass} = \frac{f_{\rm sr}}{7}\, N_h = \frac{10^6}{7} \times 10^{10} = 0.142 \times 1 \times 10^{16}\,\text{s}^{-1}\,.$$

The resulting nuclear event rate is

$$r_{\rm event} = O_{\rm N} \times r_{\rm pass} = 10^{-12} \times 0.142 \times 10^{16} = 1.42 \times 1 \times 10^3\,\text{s}^{-1}\,.$$

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 below the pion production threshold. 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.

CONCLUSIONS AND OUTLOOK

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.

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Table 1: Fine-grain scan to center the collision point for co-traveling beams: (lab) KE1 = 45.290 MeV protons and 38.665 MeV deuterons. Beam 1 (labeled in first column) parameters are shown on the left, followed by E_0 and (fractional) M value η_M, then Beam 2 (labeled in final column) parameters and, finally, CM parameters indicated by asterisks *. The columns labeled Q_s are spin tunes. Q^*_{12} is the sum of initial state kinetic energies in the CM system. In this fine-grained scan, the cryptic, comma-separated, $t, t^*\beta_1/\beta_2$ column heading, t labels the entry in the top row (namely 2) which, multiplying a value close to 3/2 yields 3 as exactly as necessary to enable feedback stabilization of this condition. Entries in Table 2 have not been pre-tuned to the same degree.

bm 1	β_1	**Q**$_{\mathbf{s1}}$	**KE1** (MeV)	**E**$_\mathbf{0}$ (MV/m)	$\eta_{\mathbf{M_1}}$	β_2	**Q**$_{\mathbf{s2}}$	**KE2** (MeV)	β^*	γ^*	**M*** (GeV)	**Q**$^*_{\mathbf{12}}$ (keV)	**t, t**$^*\beta_1/\beta_2$ 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

Table 2: Coarse-grained p, d scattering energy scan. Entries in the second to last column have not been pre-tuned to the same precision as in Table 1.

bm 1	β_1	**Q**$_{\mathbf{s1}}$	**KE1** (MeV)	**E**$_\mathbf{0}$ (MV/m)	$\eta_{\mathbf{M_1}}$	β_2	**Q**$_{\mathbf{s2}}$	**KE2** (MeV)	β^*	γ^*	**M*** (GeV)	**Q**$^*_{\mathbf{12}}$ (keV)	**t, t**$^*\beta_1/\beta_2$ 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

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