# Macroscopic multi-state Quantum Processors based on Stored High-Energy Polarized Beams

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In this talk, however,
errors & omissions only responsibility
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# OUTLINE.

I. THE ESSENTIAL QUANTUM NATURE OF SPIN

II. MACROSCOPIC QUANTUM SYSTEMS

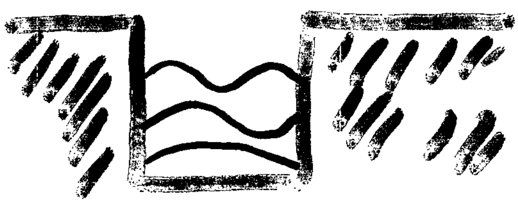
III. FROISSART - STORA ROTATIONS & COHERENCE
(ex. deuteron spin rotations)

IV. CONTROL SYSTEMS for MULTIPLE BEAMS

# I. THE ESSENTIAL QUANTUM NATURE OF SPIN

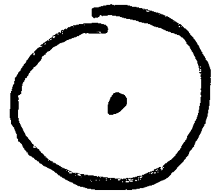
momentum is "quantized" by boundary conditions under translations

$x \to x + a$



i.e. particle in a box

angular momentum is "quantized" by boundary conditions under rotations



$e^{i\phi}$ $\quad \phi \to \phi + 2\pi n$

intrinsic angular momentum or "spin" of point particles

a) spin $\frac{2n+1}{2}$ fermions

b) spin $\frac{2n}{2}$ bosons

PCT & Spin Statistics Thm.

# Spin has <u>no</u> Classical Limit !!

Spin and Mass inbed forces into spacetime !!

a massive particle spinor is decomposed into two lightlike (chiral) spinors

$$P^\mu = l^\mu + k^\mu \qquad P^\mu P_\mu = m^2$$

$$W^\mu = l^\mu - k^\mu \qquad W^\mu W_\mu = -m^2$$

$$P^\mu W_\mu = 0$$

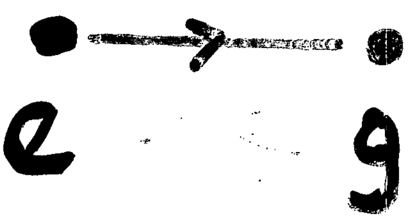
$W^\mu = m\, s^\mu$

gauge theories act <u>independently</u> on $l_\mu$ & $k_\mu$ (QED & QCD)

or on one of them ($l^\mu$ for V-A · $SU_2$)

$P^\mu$ & $W^\mu$ treated symmetrically in std. model.

# Dirac Magnetic monopole Quantization




Fields in a charge-monopole system carry angular momentum

$J_z = eg$

Dirac condition

$$eg = n/2$$

Relates quantization of charge to quantization of <u>angular momentum</u>

SPIN-½ (PAULI
EXCLUSION PRINCIPLE)
SUPPORTS SPACE-
TIME

# II. Macroscopic Quantum Systems

A stored polarized particle beam is a very special system

[illegible]
with quantum
behavior under
rotation.

1. timing - controlled by circulation frequency
2. orientation - controlled by e.m. fields

all accel.
physics
here

[illegible]
[illegible] - stored polarized beam.

# SMALL CLASS of MACROSCOPIC QUANTUM SYSTEMS

| | SCALE | CONTROL | APPS |
|---|---|---|---|
| LASERS | ✓ | ✓ | ✓✓ |
| B-E CONDENSATES | — | — | — |
| SUPERFLUIDS | ✓ | — | ✓ |
| SUPERCONDUCTORS | ✓ | ✓ | ✓ |
| POLARIZED BEAMS | ✓✓ | ✓✓ | |

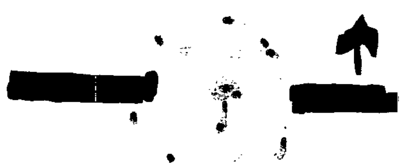
mention an orchestra in a symphony

APPLICATIONS NEED NOT DIRECTLY DISPLAY THE QUANTUM NATURE OF STATE (LASER COHERENCE → CLASSICAL)

ONE OF THE APPROACHES MIGHT BE TO EXPLOIT THE QUANTUM MECHANICS OF SPIN ROTATION

# SPINTRONICS & QUANTUM COMPUTERS

many spin-dependent effects are
being explored to create possible quantum-computers



Ferromagnetic material
(iron, nickel, copper)

transient electron spins allign with B!

## MAGNETIC TUNNEL JUNCTION


non magnetic
material

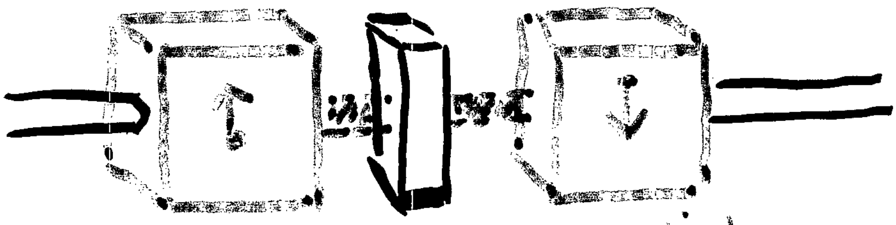
tunneling possible
current flows

no tunneling
no current

MRAMS {IBM - SONY}

tunneling =
quantum effect

# SPIN-FIELD-EFFECT TRANSISTOR
(Datta & Das, 1991)



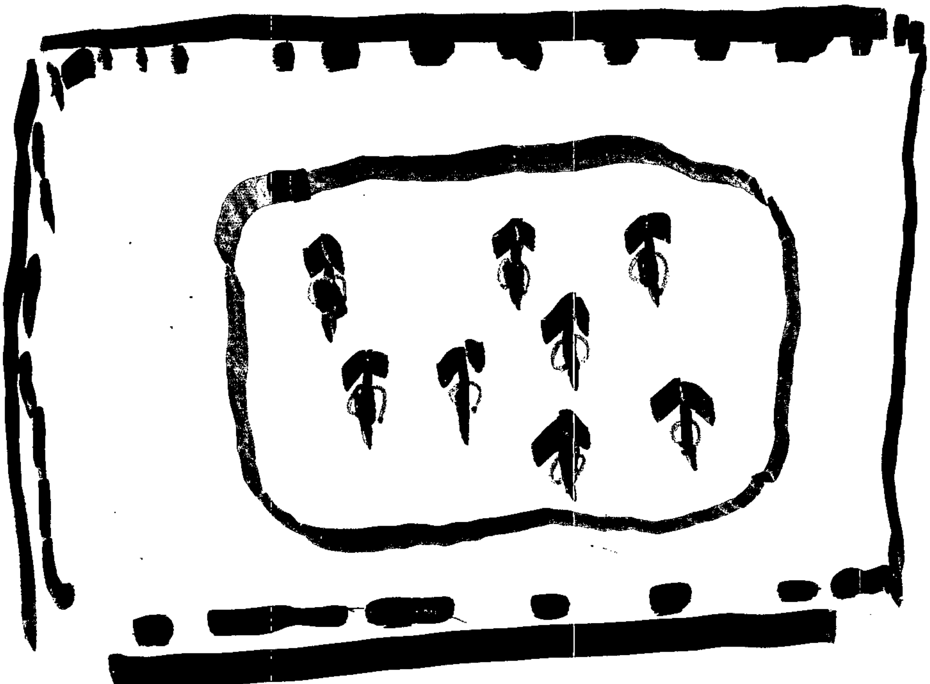

Full current when $\Delta\Theta = \pi$

No one has succeeded in making a working model

(for good reasons) →

We'll keep to large-scale systems & leave the field of spintronics

# QUANTUM SUPERPOSITION PRINCIPLE



electrons
μons
protons
Deuterons
others

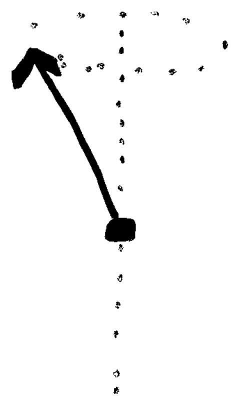
Ensemble of
Polarized Particles
visiting same spatial
region each cycle

# III FROISSART-STORA

$f_c$ = circ freq.

## SPIN ROTATIONS & COHERENCE

$f_c \nu_s$ = spin precession frequency of stored beam

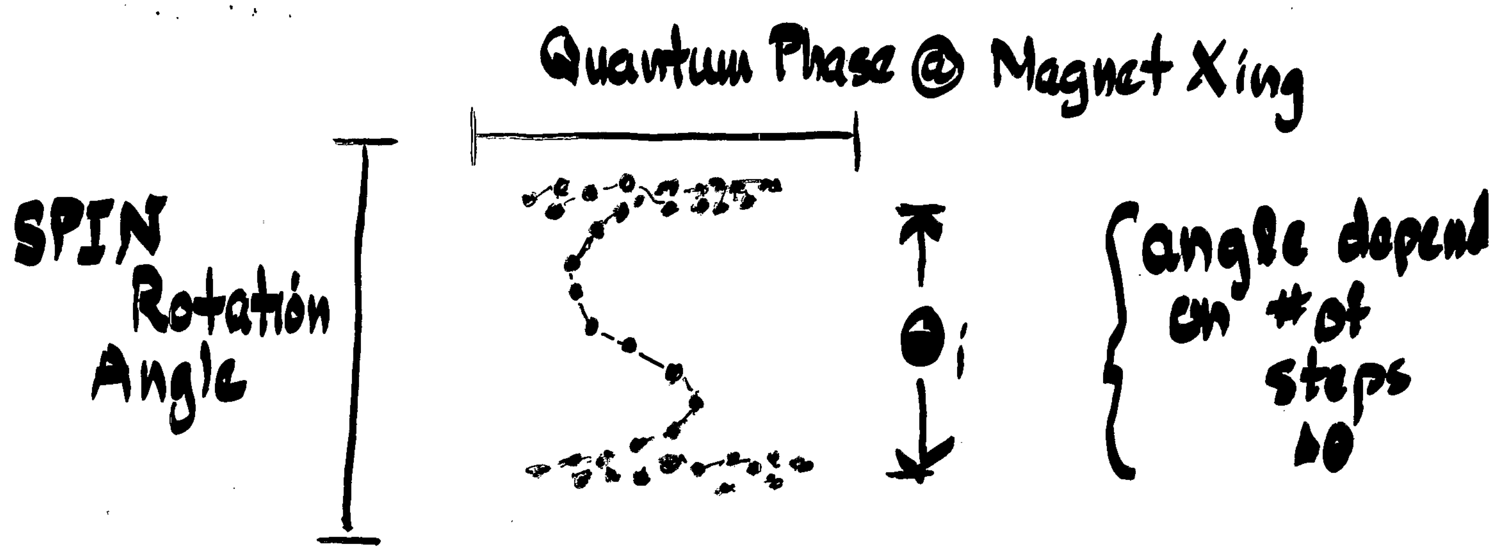


$\nu_s$ = spin tune

$f_c \nu_m$ = frequency of dipole (or solenoidal) magnet

($\nu_s$, $\nu_m$) mod 1. for this talk

Quantum Phase $\exp\left[ie\int dl^{\mu}A_{\mu}\right] \sim e^{i\nu g\gamma/2\pi}$




[illegible] small steps each cycle add up coherently) $\boxed{\Theta_i = 180' = \text{"flip"}}$

Example for rotation of a polarized $\vec{d}$ illustrates some important points

PURE STATES $(x,y,z)$ $S_z$

$|+\rangle = \begin{pmatrix}1\\0\\0\end{pmatrix}$ $|0\rangle = \begin{pmatrix}0\\1\\0\end{pmatrix}$ $|-\rangle = \begin{pmatrix}0\\0\\1\end{pmatrix}$

$|\vec{\eta}\rangle = \left(\frac{1}{2}\right)^{1/2}\begin{pmatrix}1\\0\\e^{i\eta}\end{pmatrix}$

With a symmetry plane normal to z-axis (stored beam in x-y plane) the most general density matrix is (from parity)

$N_+ + N_0 + N_- = 1$

$$\rho = \begin{pmatrix} N_+ & 0 & (N_+N_-)^{1/2} e^{i\eta} \\ 0 & N_0 & 0 \\ (N_+N_-)^{1/2} e^{-i\eta} & 0 & N_- \end{pmatrix}$$

Not coherence of $J_z = \pm 1$ states with $J_z = 0$ states ($|+\rangle + |0\rangle$) violates parity

With "rotator" magnet symmetry in x-y plane broken

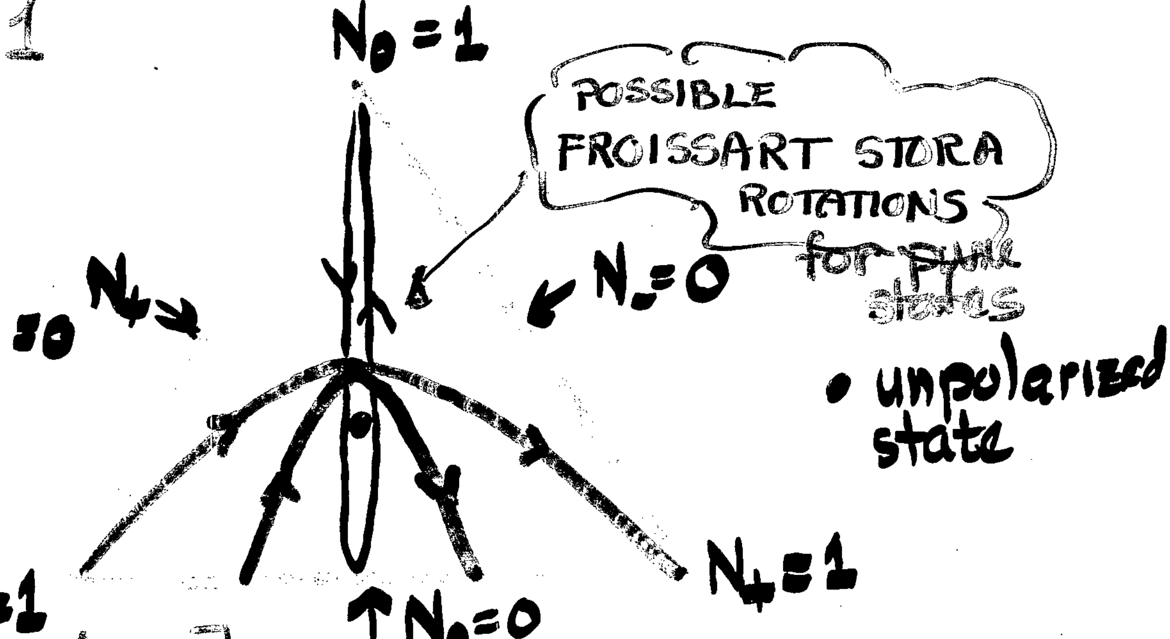
$$R(\theta) = \frac{1}{2} \begin{pmatrix} 1+c & -\sqrt{2}s & 1-c \\ \sqrt{2}s & 2c & -\sqrt{2}s \\ 1-c & \sqrt{2}s & 1+c \end{pmatrix}$$

$c = \cos\theta$
$s = \sin\theta$

"[illegible]tating" states [illegible] phase + [illegible]
[illegible]

$P_{zz} = 3N_0 - 1$

$P_z = N_+ - N_-$




[Beam Polarization]

density matrices $\rho$

$$\rho_+ = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \rho_0 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \rho_- = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\rho_\eta = \frac{1}{2}\begin{pmatrix} 1 & 0 & e^{-i\eta} \\ 0 & 0 & 0 \\ e^{i\eta} & 0 & 1 \end{pmatrix} \qquad \text{unpolarized} \quad \rho_u = \frac{1}{3}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Pure states have idempotent density matrices

$\rho^2 = \rho$

"active" states

$$|\theta,+\rangle_A = R(\theta)\begin{pmatrix}1\\0\\0\end{pmatrix} = \frac{1}{2}\begin{pmatrix}1+c\\ \sqrt{2}s\\ 1-c\end{pmatrix}$$

$$|\theta,0\rangle_A = R(\theta)\begin{pmatrix}0\\1\\0\end{pmatrix} = \frac{1}{2}\begin{pmatrix}-\sqrt{2}s\\ 2c\\ \sqrt{2}s\end{pmatrix}$$

$$|\theta,-\rangle_A = R(\theta)\begin{pmatrix}0\\0\\1\end{pmatrix} = \frac{1}{2}\begin{pmatrix}1-c\\ -\sqrt{2}s\\ 1+c\end{pmatrix}$$

during resonance sweep

$$|\theta,+\rangle\langle+,\theta| = \rho^A_{+\theta} = \frac{1}{4}\begin{pmatrix}(1+c)^2 & (1+c)\sqrt{2}s & (1-c^2)\\ (1+c)\sqrt{2}s & 2s^2 & (1-c)\sqrt{2}s\\ (1-c^2) & (1-c)\sqrt{2}s & (1-c)^2\end{pmatrix}$$

after <u>rotator</u> <u>magnet</u> <u>turned</u> <u>off</u>

$$\rho^A_{+\theta} \to \rho^S_{+\theta} = \frac{1}{4}\begin{pmatrix}(1+c)^2 & 0 & s^2\\ 0 & 2s^2 & 0\\ s^2 & 0 & (1-c)^2\end{pmatrix}$$

phases for $|0\rangle\langle+|$ average to 0

$$|\theta,+\rangle_S = \frac{1}{2}\begin{pmatrix}1+c\\0\\1-c\end{pmatrix} + e^{i\varepsilon}\frac{1}{2}\begin{pmatrix}0\\ \sqrt{2}s\\ 0\end{pmatrix}$$

"stored" states

phase averages x terms → 0

For Spin $\geq 1$ Quantum Rotations other than multiples of $\pi$ - Followed by decoherence destroys polarization (but in a controlled way)

can only access

$|0,+\rangle_A$ by interactions during the sweep → timing $\Theta(t)$ with ramp through resonance

$f_c$ gives control

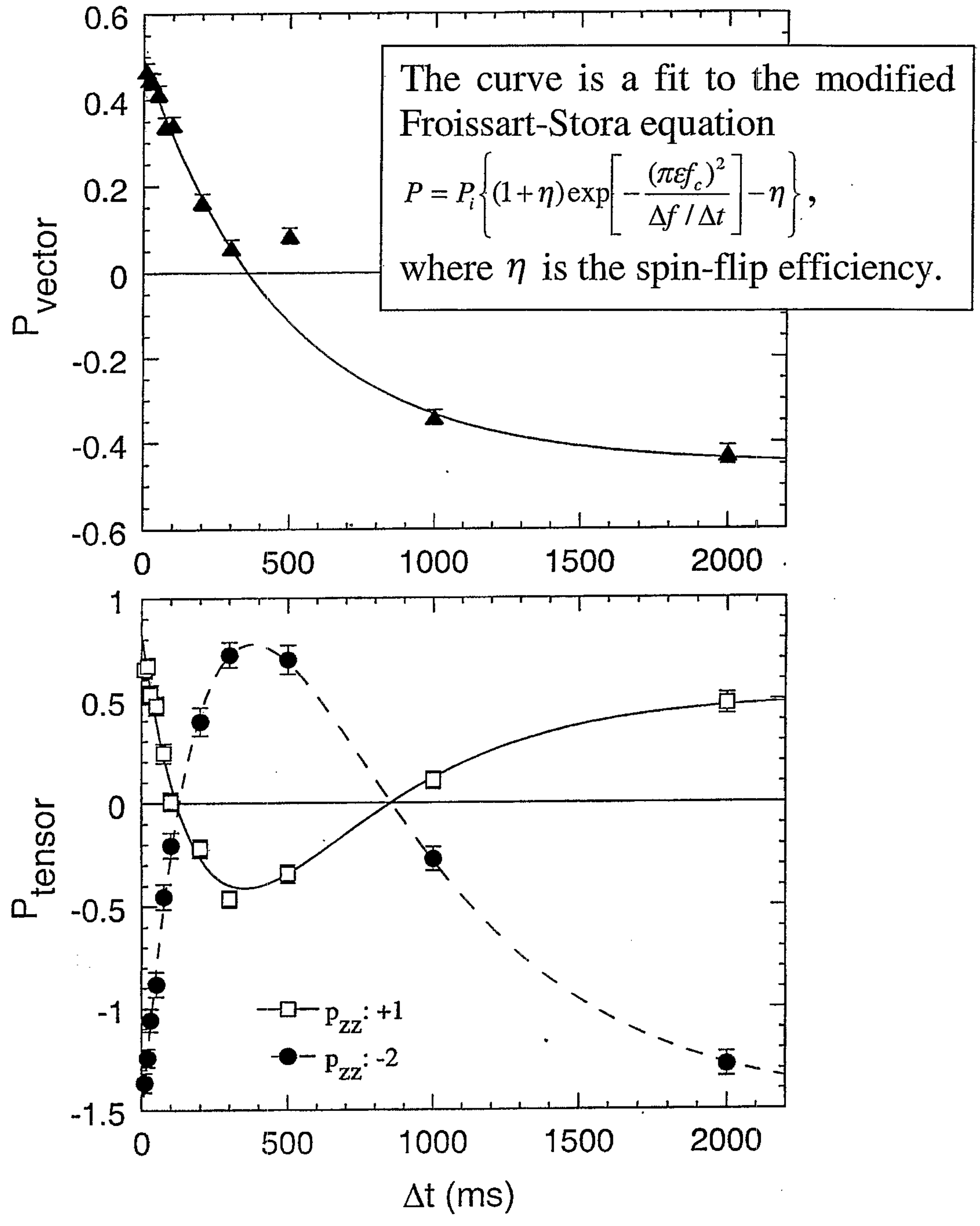
Spin-1/2 systems don't have this extra coherence constraint.

For Spin-1 system to successfully "flip" from $|+\rangle \xrightarrow[0]{} |-\rangle$ through a sequence of "small" rotations during a resonance sweep requires coherence of form not permitted by a classical superposition.

See previous talk on D flipping & decoherence

V.S. Morosov (Wednesday)

## **Polarizations vs. frequency ramp time** ($\Delta f = \pm 2\ kHz$)

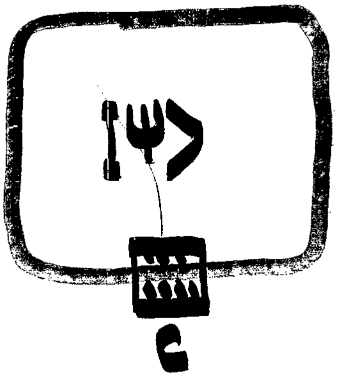



The curves on the bottom plot are fits to the data using

$$P = P_i\left[\frac{3}{2}\left\{(1+\eta)\exp\left[-\frac{(\pi\varepsilon f_c)^2}{\Delta f/\Delta t}\right]-\eta\right\}^2-\frac{1}{2}\right],$$

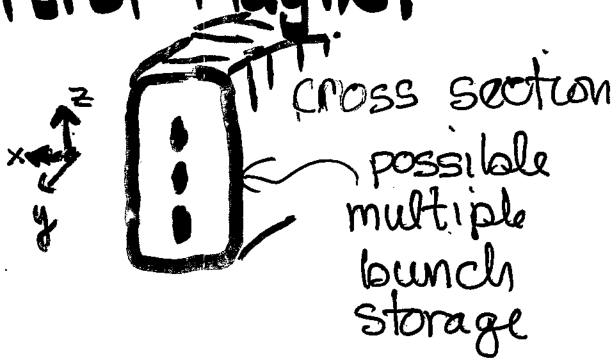
which is a version of the Froissart-Stora formula extended to tensor polarization.

# V. Control Systems for (multiple) Polarized Beams




small loops with augmented straight sections

Control Magnet




## Controls Possible

1. Split Bunches
2. Mix Bunches
3. Rotate Spin Direction $[\theta_x, \theta_y]$

{Solenoid}$_y$ or {Dipole}$_x$

Splitting or mixing can use spatial information or Spin {Stern-Gerlach effect}

Concentrate on Spin Rotations

# Multiple Beams


(includes colliding beams)

Direct Product States

$|\Psi_1\rangle \otimes |\Psi_2\rangle$ $\quad$ $\Psi_i$ (only display the spin degree of freedom)

$R(\theta_1)|\Psi_1\rangle \otimes R(\theta_2)|\Psi_2\rangle$

# controlled coherent rotations

state "includes" the accelerator fields

Froissart - Stora system can be combined with other rotators (but not Snakes)

# Schrödinger's Cat Meets Alice's Chesire Cat

The quantum part of this state is the spin

1. have Froissart · Stora sweep start & stop based on some other quantum events.

2. This gives a · real spin · interaction