LONG-LIVED QUANTUM MEMORY USING NUCLEAR SPINS

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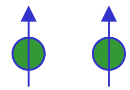
NUCLEAR SPINS HAVE LONG RELAXATION TIMES

Ground state He3 has a purely nuclear spin ½

Nuclear magnetic moments are small

→ Weak magnetic couplings

→ dipole-dipole interaction contributes for $T_1 \simeq 10^9$ s (1mbar)



Spin 1/2 → **No electric quadrupole moment coupling**

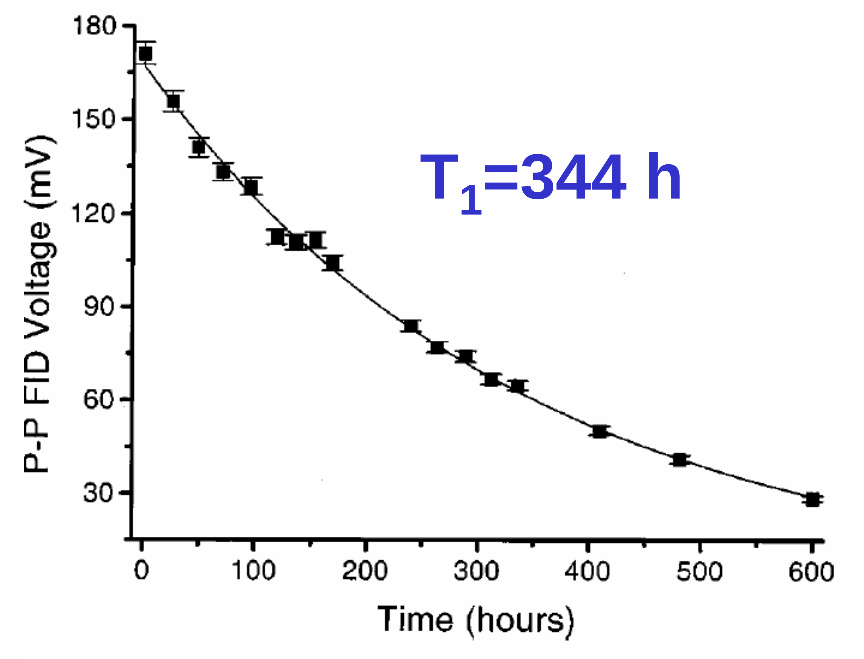
In practice

T_1 relaxation can reach **5 days** in cesium-cotated cells

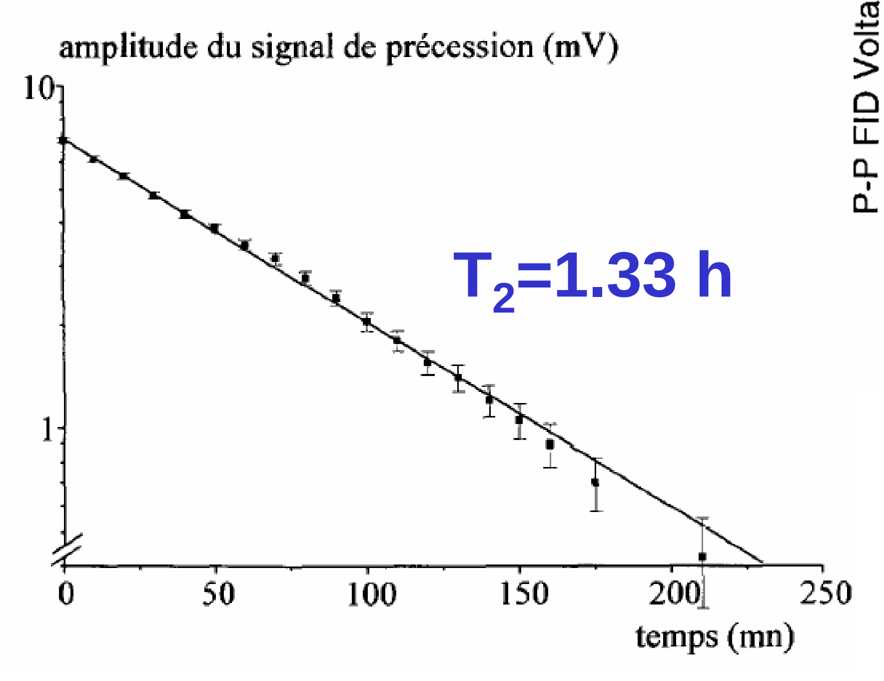
and 14 days in sol-gel coated cells

T_2 is usually limited by magnetic field inhomogeneity

Examples of Relaxation times in ^{3}He



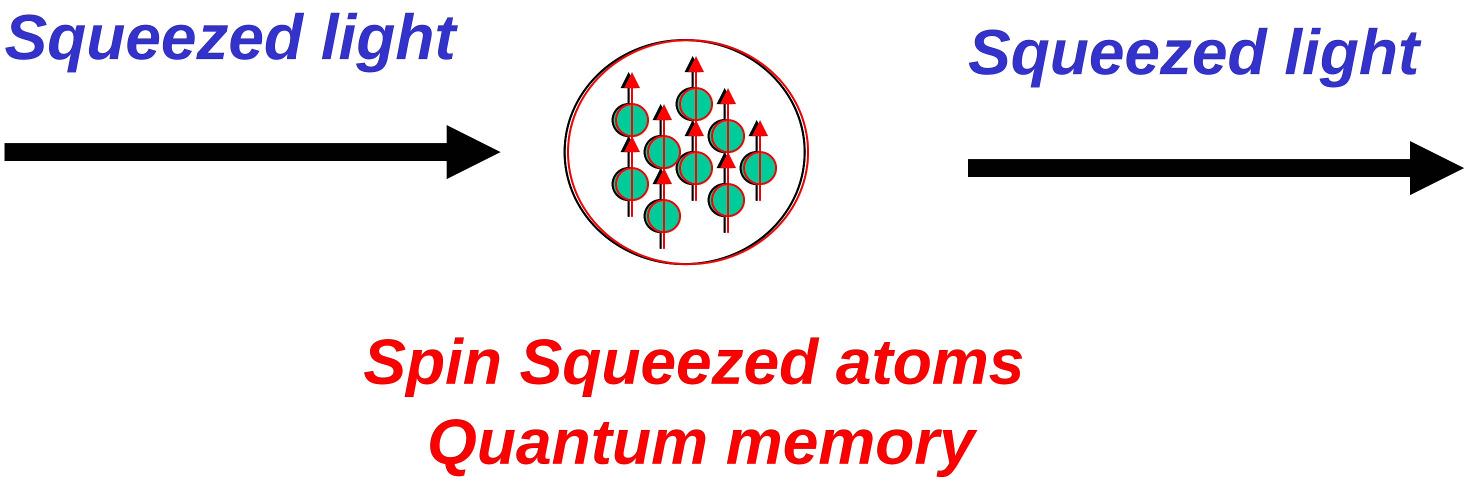
Ming F. Hsu et al.
Appl. Phys. Lett. (2000)
Sol-gel coated glass cells



0.Moreau et al. J.Phys III (1997)
Magnetometer with polarized ^{3}He

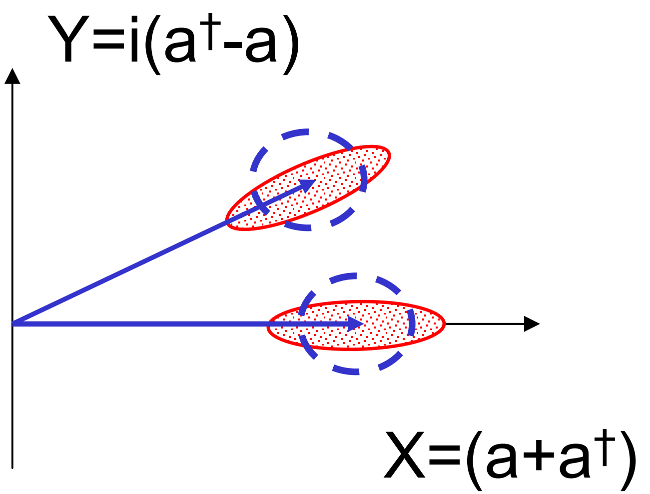
^{3}He NUCLEAR SPINS FOR Q-INFORMATION ?

Quantum information with continuous variables



SQUEEZING OF LIGHT AND SQUEEZING OF SPINS

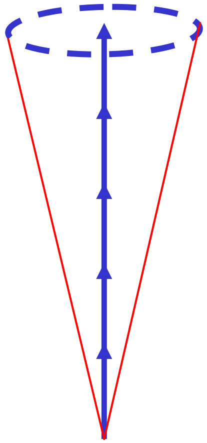
One mode of the EM field



Coherent state $\Delta X = \Delta Y = 1$

Squeezed state $\Delta X > 1$
$\Delta Y < 1$

N spins 1/2



Coherent spin state
CSS
(uncorrelated spins)

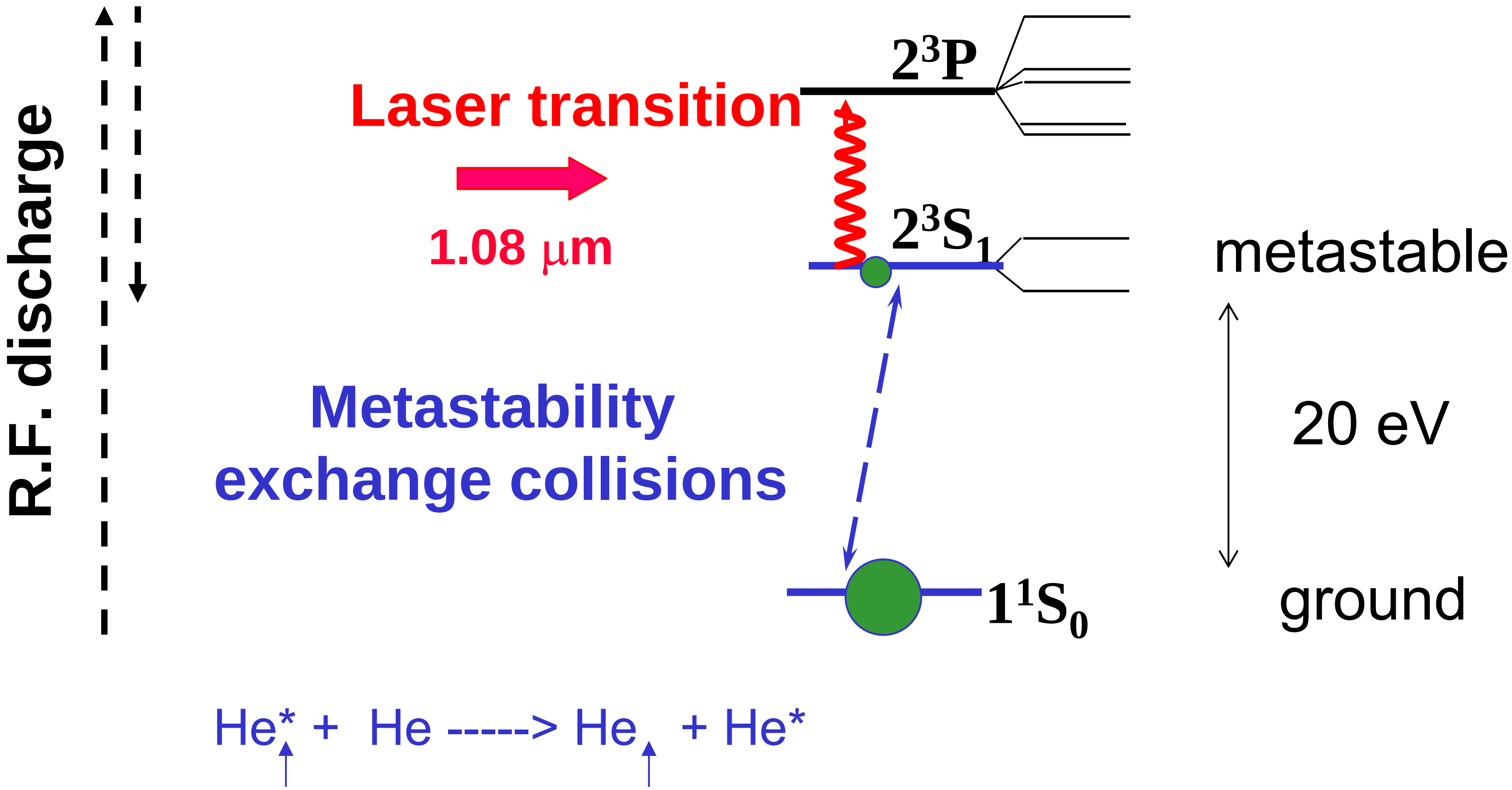
$\Delta S_x = \Delta S_y = |\langle S_z \rangle|/2$

Projection noise in atomic clocks

Squeezed state

$\Delta S_x^2 < N/4 \qquad \Delta S_y^2 > N/4$

How to access the ground state of ^3He ?

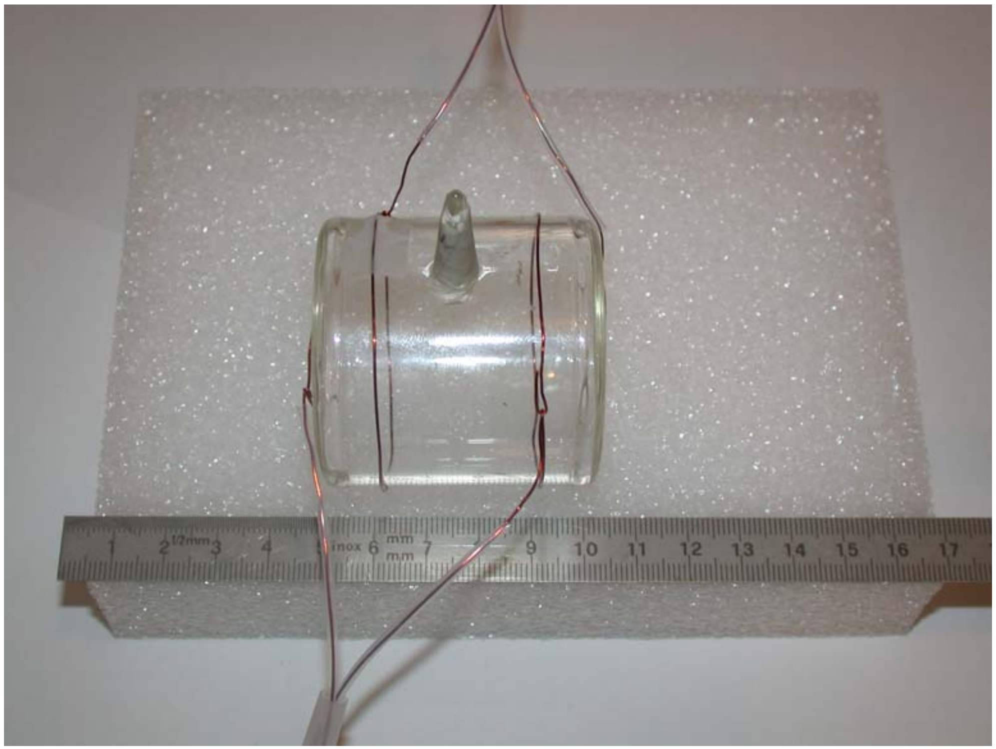


During a collision the metastable and the ground state atoms exchange their electronic variables

Colegrove, Schearer, Walters (1963)

Typical parameters for 3He optical pumping

An optical pumping cell filled with ≈ mbar pure ^{3}He



Metastables :

$n = 10^{10}$-10^{11} at/cm^3

Metastable / ground :

$n / N = 10^{-6}$

Laser Power for optical pumping

$P_L = 5$ W

The ground state gas can be polarized to 85 % in good conditions

A SIMPLIFIED MODEL : SPIN ½ METASTABLE STATE

n

N

$$S = \sum_{i=1}^{n} s_i \qquad I = \sum_{i=1}^{N} i_i$$

Partridge and Series (1966)

Rates

$$d\langle S\rangle/dt = -\gamma_m \langle S\rangle + \gamma_g \langle I\rangle$$

$$d\langle I\rangle/dt = -\gamma_g \langle I\rangle + \gamma_m \langle S\rangle$$

$$\frac{\gamma_m}{\gamma_g} = \frac{N}{n}$$

Heisenberg Langevin equations

$$dS/dt = -\gamma_m S + \gamma_g I + f_s$$

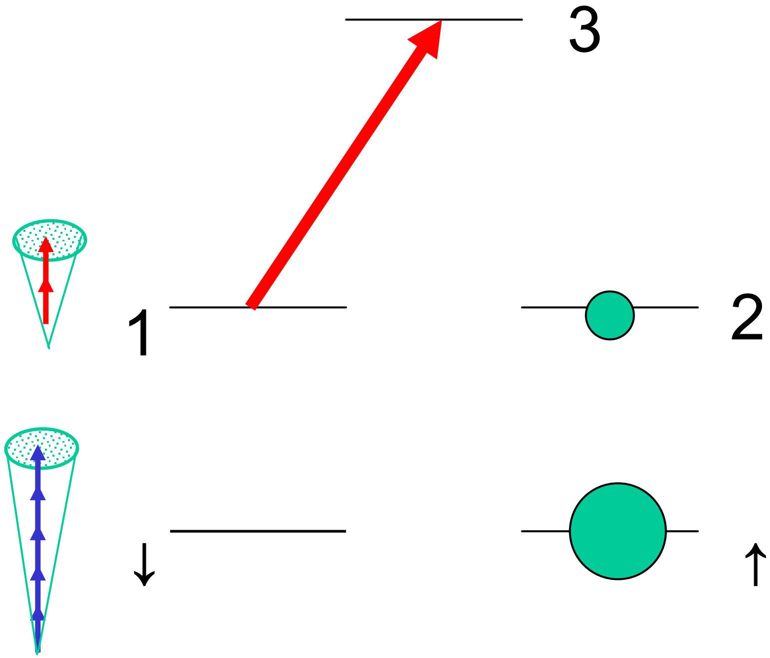
$$dI/dt = -\gamma_g I + \gamma_m S + f_i$$

Langevin forces

$$\langle f_a(t)\, f_b(t')\rangle = D_{ab}\, \delta(t-t')$$

PREPARATION OF A COHERENT SPIN STATE

Atoms prepared in the fully polarized **CSS** by optical pumping



Spin quadratures

$S_x=(S_{21}+S_{12})/2$; $S_y=i\,(S_{12}-S_{21})/2$

$\Delta S_x = \Delta S_y = n/4$

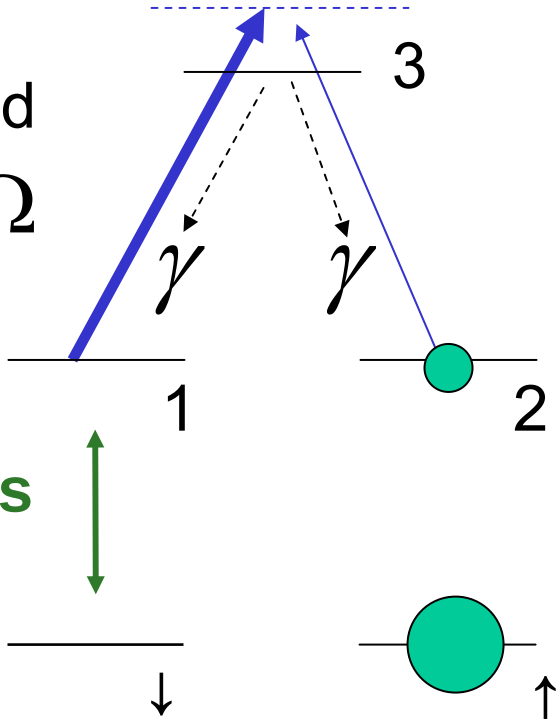
$\Delta I_x = \Delta I_y = N/4$

This state is ***stationary*** for metastability exchange collisions

SQUEEZING TRANSFER TO FROM FIELD TO ATOMS

Raman configuration $\Delta > \gamma, \delta$

Control classical field of Rabi freqency Ω



A , $A^{\dagger}$ cavity mode

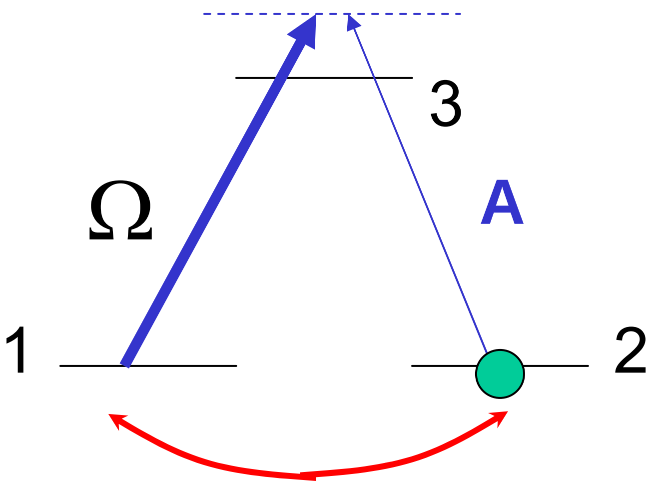
squeezed vaccum

H= g (S_{32} A + h.c.)

Exchange collisions

Linearization of optical Bloch equations for quantum fluctuations around the *fully polarized* initial state

SQUEEZING TRANSFER TO METASTABLE ATOMS



Linear coupling for quantum fluctuations between the ***cavity field*** and metastable atoms ***coherence S_{21}***

Adiabatic elimination of S_{23} →

$$\frac{d}{dt}S_{21} = i\left(\delta + \boxed{\frac{\Omega^2}{\Delta}}\right)S_{21} + \boxed{\frac{\Omega g n}{\Delta}}A$$

shift **coupling**

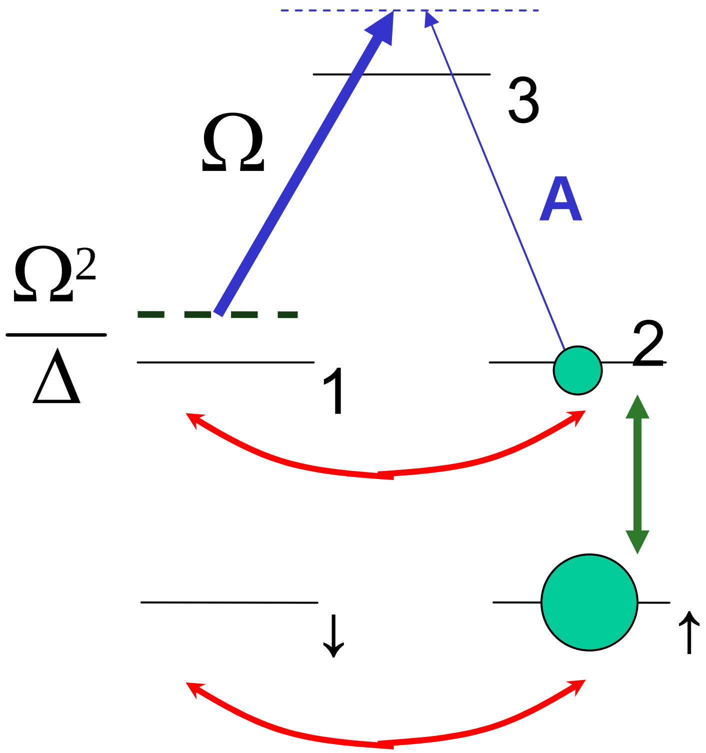
Resonant coupling condition : δ+shift = 0

$$\delta = (E_2 - E_1) - (\omega_2 - \omega_1)$$

Two photon detuning

Dantan et al. Phys. Rev. A (2004)

SQUEEZING TRANSFER TO GROUND STATE ATOMS



The metastable coherence S_{12} evolves at the frequency $(\omega_1 - \omega_2)$

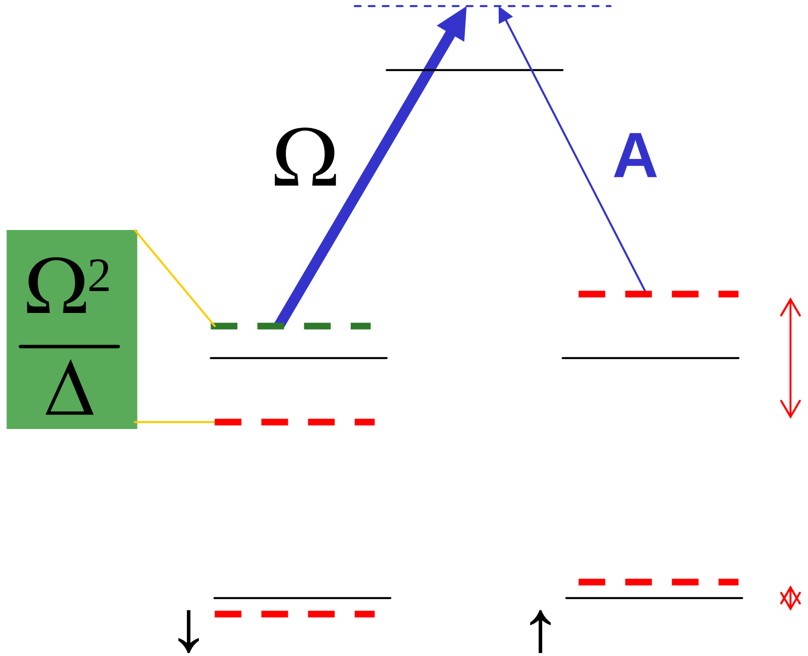
Exchange collisions give a linear coupling beween S_{12} and $I_{\uparrow\downarrow}$

Resonant coupling condition :

$$E_{\uparrow} - E_{\downarrow} = (\omega_1 - \omega_2)$$

Resonant coupling in **both** metastable and ground state is Possible **in a magnetic field** such that the Zeemann effect in the metastable compensates the light shift of level 1

SQUEEZING TRANSFER TO GROUND STATE ATOMS



Zeeman effect :

E_2-E_1 = 1. 8 MHz/G

$E_\uparrow$ –$E_\downarrow$= 3.2 kHz/G

Resonance conditions in a magnetic field

$$E_2 - E_1 + \frac{\Omega^2}{\Delta} = E_\uparrow - E_\downarrow = (\omega_1 - \omega_2)$$

GROUND AND METASTABLE SPIN VARIANCES

When polarization and cavity field are adiabatically eliminated

$$\Delta I_y^2 = \frac{N}{4}\left[1 - \frac{\gamma_m}{\Gamma + \gamma_m}\left(1 - \Delta {A_x^{in}}^2\right)\right]$$

$$\Delta S_y^2 = \frac{n}{4}\left[1 - \frac{\Gamma}{\Gamma + \gamma_m}\left(1 - \Delta {A_x^{in}}^2\right)\right]$$

Pumping parameter

$$\Gamma = \frac{\gamma\,\Omega^2}{\Delta^2}(1 + C)$$

Cooperativity

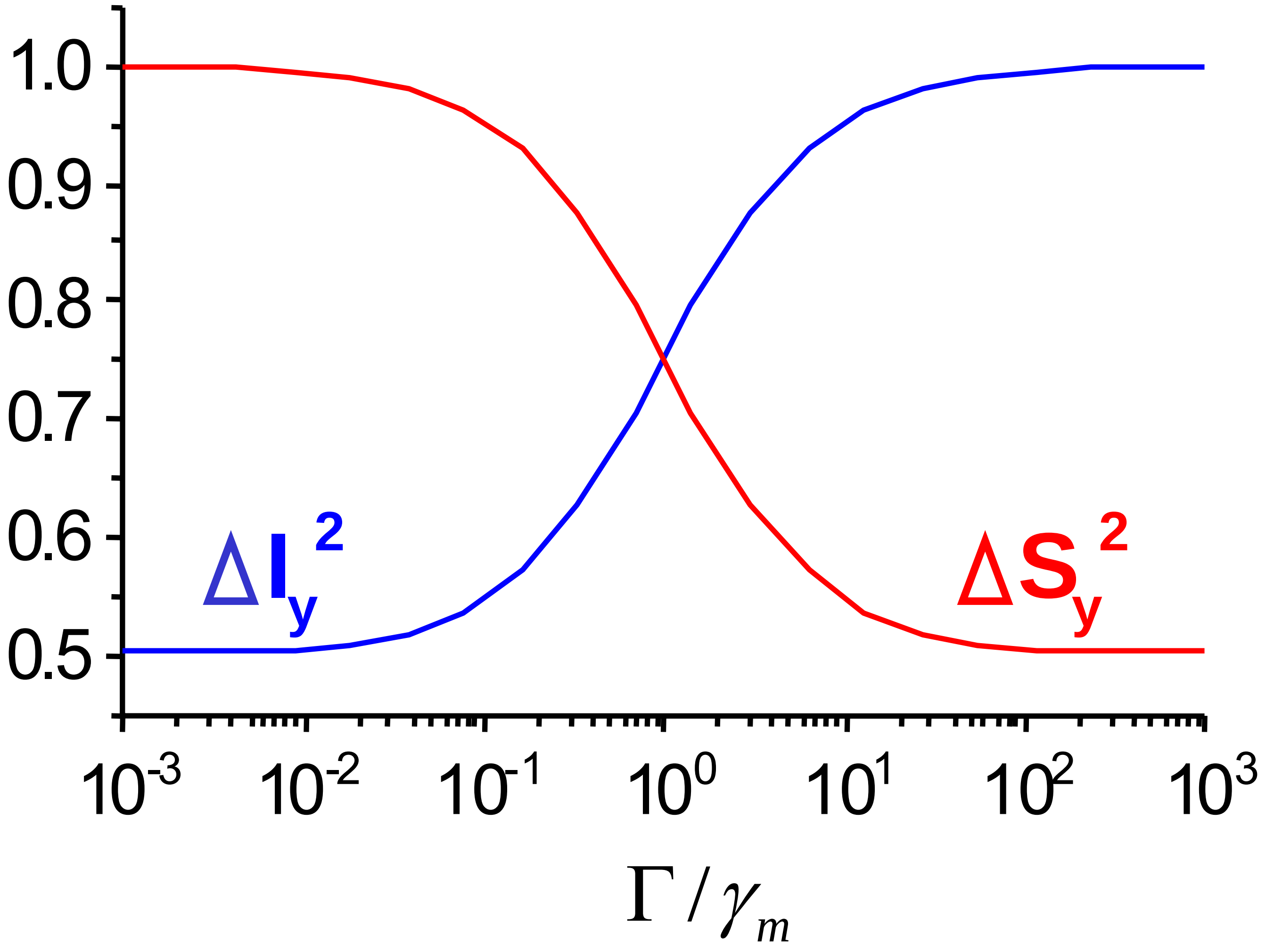
$$C = \frac{g^2 n}{\kappa\gamma} \simeq 100$$

Strong pumping $\Gamma >> \gamma_m$ the squeezing goes to **metastables**

Slow pumping $\Gamma << \gamma_m$ the squeezing goes to **ground state**

GROUND AND METASTABLE SPIN VARIANCES

$$(1-\Delta A_x^{in\,2}) = 0.5 \qquad C = 500$$



EXCHANGE COLLISIONS AND CORRELATIONS

$$<S^2> = \sum_{i=1}^{n} <s_i^2> + \sum_{i\neq j}^{n} <s_i s_j> = \frac{n}{4} + n(n+1) <s_i s_j>$$

$$||$$

$$<I^2> = \sum_{i=1}^{N} <i_i^2> + \sum_{i\neq j}^{n} <i_i i_j> = \frac{N}{4} + N(N+1) <i_i i_j>$$

Exchange collisions tend to equalize the correlation function

When exchange is dominant $(\gamma_m >> \Gamma)$, and for $n, N >> 1$

$$\left(\frac{\Delta I^2}{N/4} - 1\right) = \frac{N}{n}\left(\frac{\Delta S^2}{n/4} - 1\right)$$

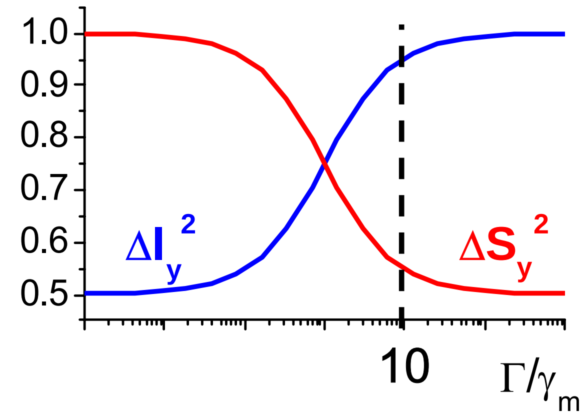
A weak squeezing in metastable maintains strong squeezing in the ground state

WRITING TIME OF THE MEMORY

Build-up of the spin squeezing **in the metastable state**

$$< S_y^2 > (t) - < S_y^2 >_s = 0.55 \exp(-2\Gamma t)$$

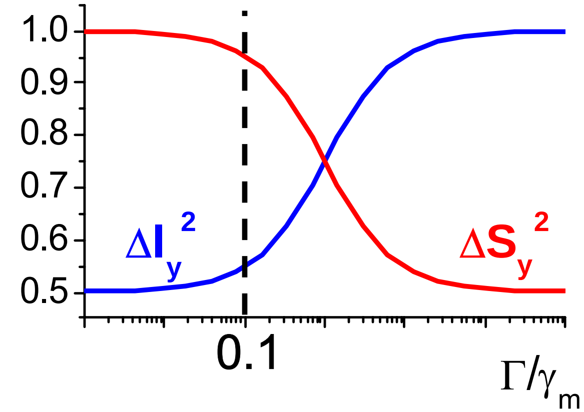
$$\Gamma = 10\ \gamma_m = 5 \times 10^7\ s^{-1}$$



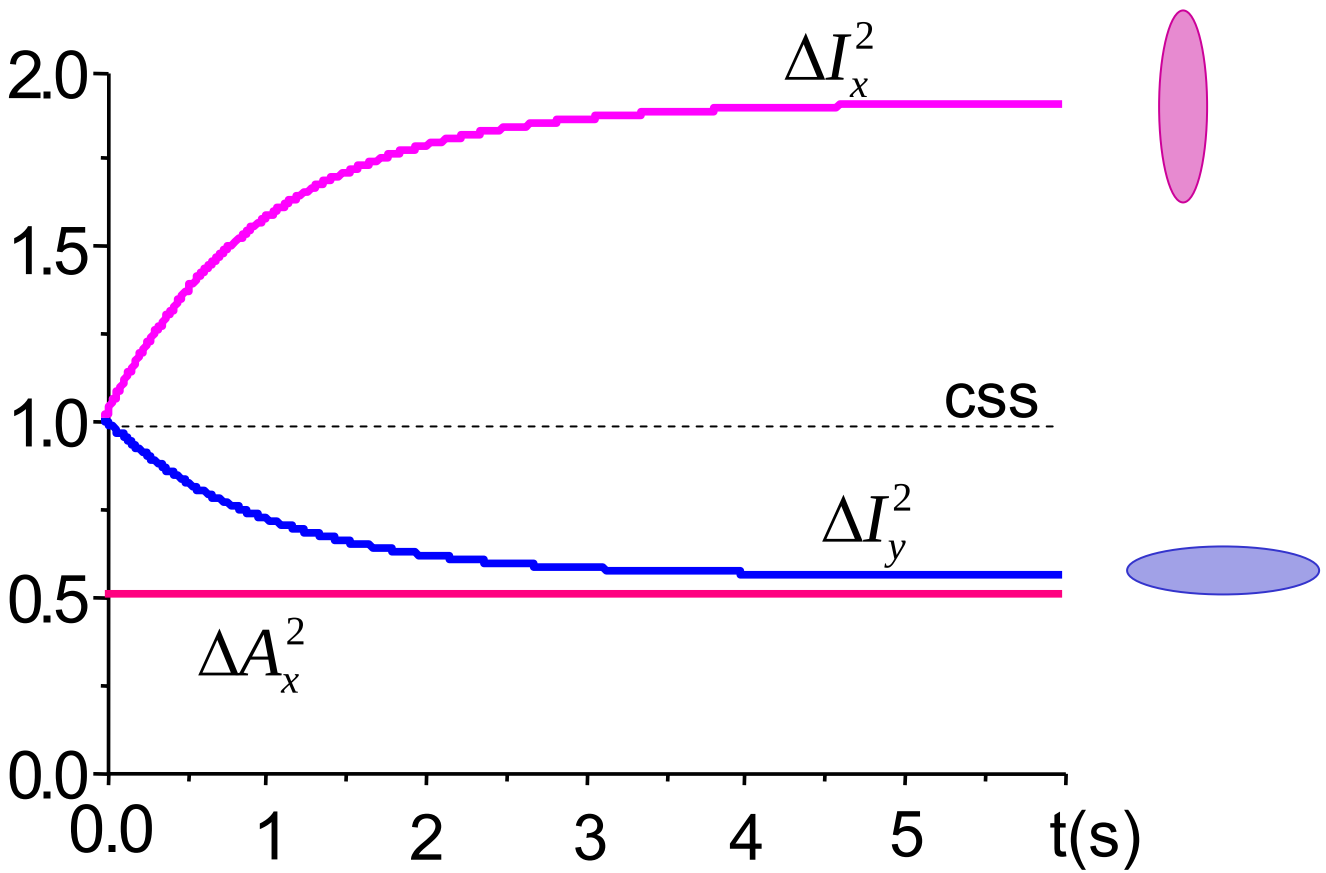
Build-up of the spin squeezing **in the ground state**

$$< I_y^2 > (t) - < I_y^2 >_s = 0.55 \exp(-2\Gamma_g\ t)$$

$$\Gamma_g = \frac{2\Gamma\gamma_g}{\gamma_m + \Gamma} \approx 1\, s^{-1}$$

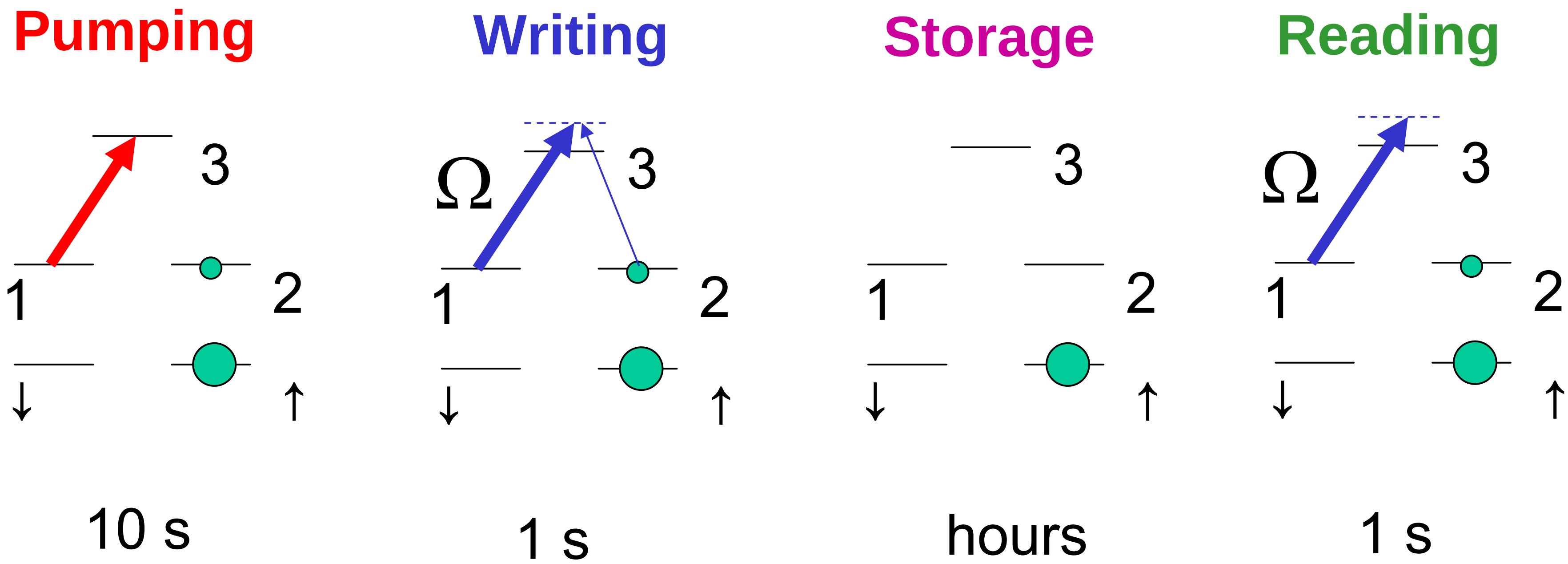


TIME EVOLUTION OF SPIN VARIANCES



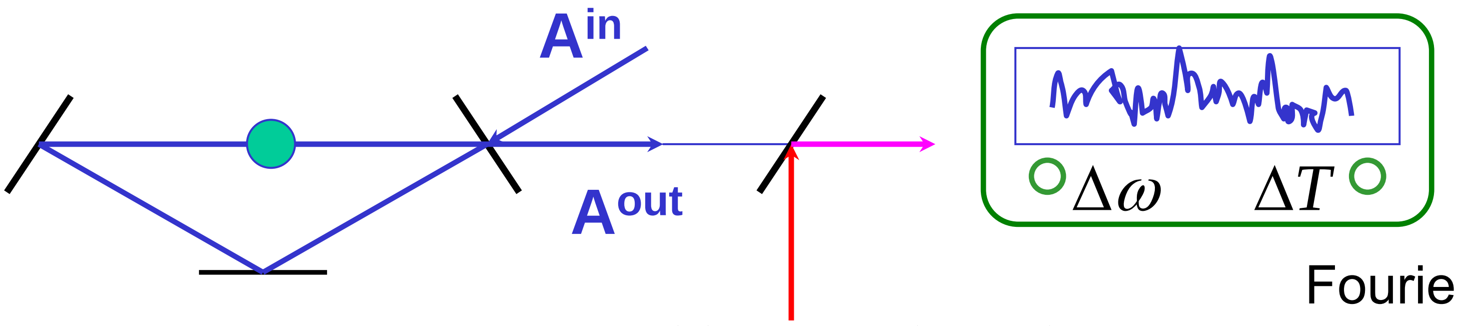
The writing time is limited by $\gamma_g \propto n$ (density of metstables)

READ OUT OF THE NUCLEAR SPIN MEMORY



By lighting up only the coherent control field Ω , in the same conditions as for writing, one retrieves transient squeezing in the output field from the cavity

READ OUT OF THE NUCLEAR SPIN MEMORY



Fourier-Limited
Spectrum Analyzer

$$E_{LO}(t) = \exp(-\Gamma_g t)$$

Temporally matched local oscillator

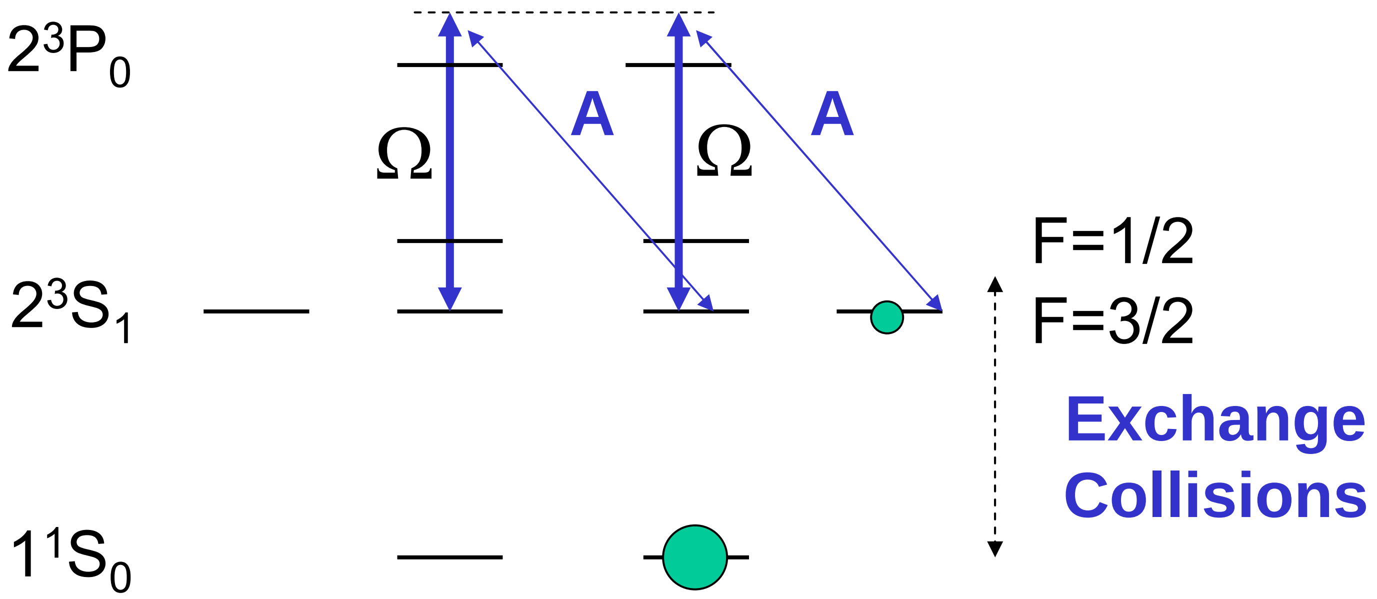
$$P(t_0) = \int_{\Delta\omega} \frac{d\omega}{\Delta T} \int_{to}^{to+\Delta T} dt\, e^{-i\omega(t-t')} E_{LO}(t)\, E_{LO}(t') \langle A^{out}(t)\, A^{out}(t') \rangle$$

Read-out function for $\Delta T > 1/\Gamma_g$

$$R_{out}(t_0) = 1 - \frac{P(t_0)/\Delta\omega}{\left[P(t_0)/\Delta\omega\right]_{CCS}} = (1-\Delta I_y^2)\exp(-2\Gamma_g t_0)$$

REALISTIC MODEL FOR HELIUM 3

Real atomic structure of 3He

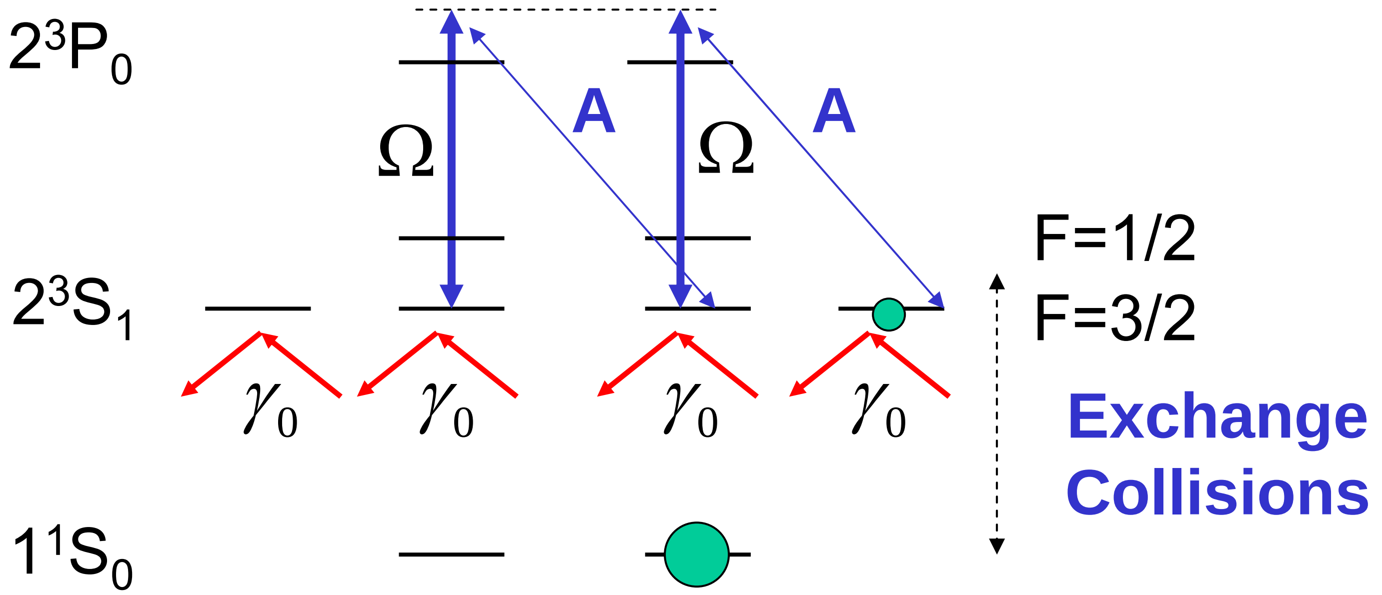


$$\dot{\rho}_g = \gamma_g(-\rho_g + Tr_e\,\rho_m)$$

$$\dot{\rho}_m = \gamma_m(-\rho_m + \rho_g \otimes Tr_n\,\rho_m)$$

REALISTIC MODEL FOR HELIUM 3

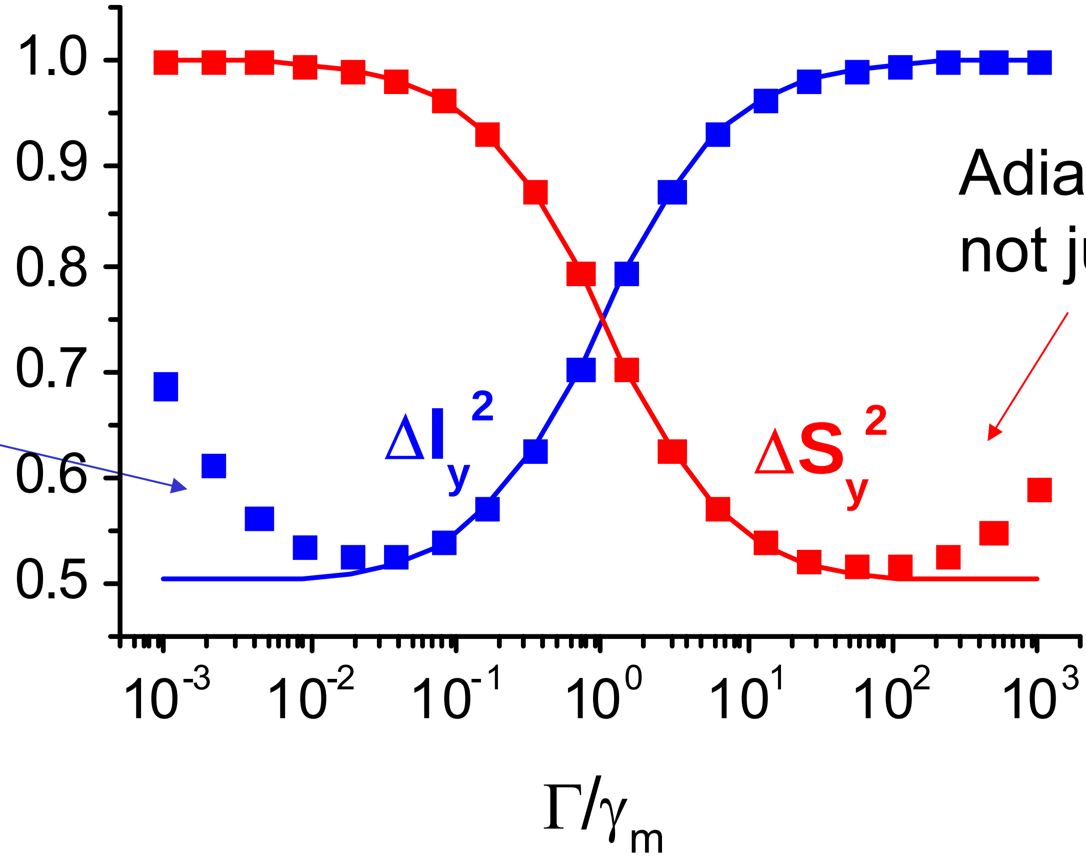
Real atomic structure of 3He



Lifetime of metastable state coherence: $\gamma_0 = 10^3 s^{-1}$ (1torr)

NUMERICAL AND ANALYTICAL RESULTS

We find the *same* analytic expressions *as for the simple model* if the field and optical coherences are adiabatically eliminated



Effect of $\gamma_0 \approx \Gamma$

Adiabatic elimination not justified

$\Gamma \approx \gamma$

1 mbarr
T=300K

$\gamma_m = 5\times10^6 \quad, \gamma = 2\times10^7, \quad \gamma_0 = 10^3, \quad \kappa = 100\gamma, \quad C = 500, \quad \Delta = -2\times10^3$

EFFECT OF A FREQUENCY MISMATCH IN GROUND STATE

We have assumed resonance conditions **in a magnetic field**

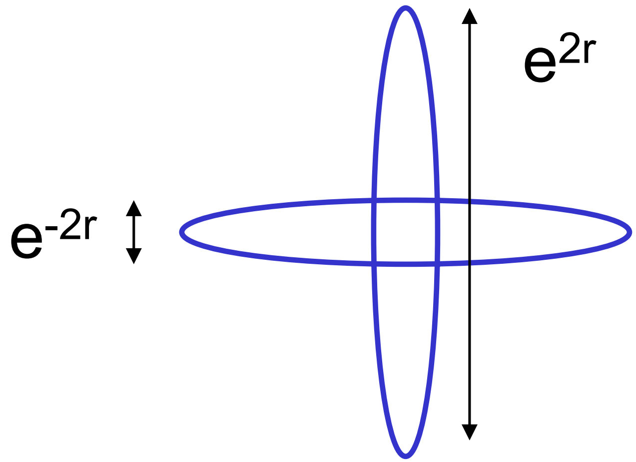
$$E_4 - E_3 + \frac{\Omega^2}{\Delta} = E_\uparrow - E_\downarrow = (\omega_1 - \omega_2)$$

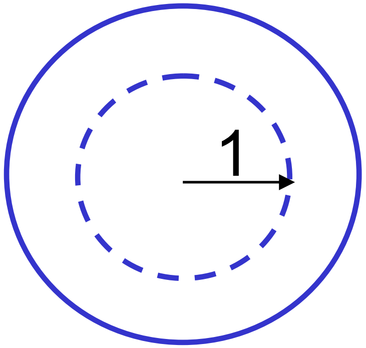
$E_4 - E_3 \simeq$ **1. 8** MHz/G

$E_\uparrow - E_\downarrow =$ **3.2** kHz/G

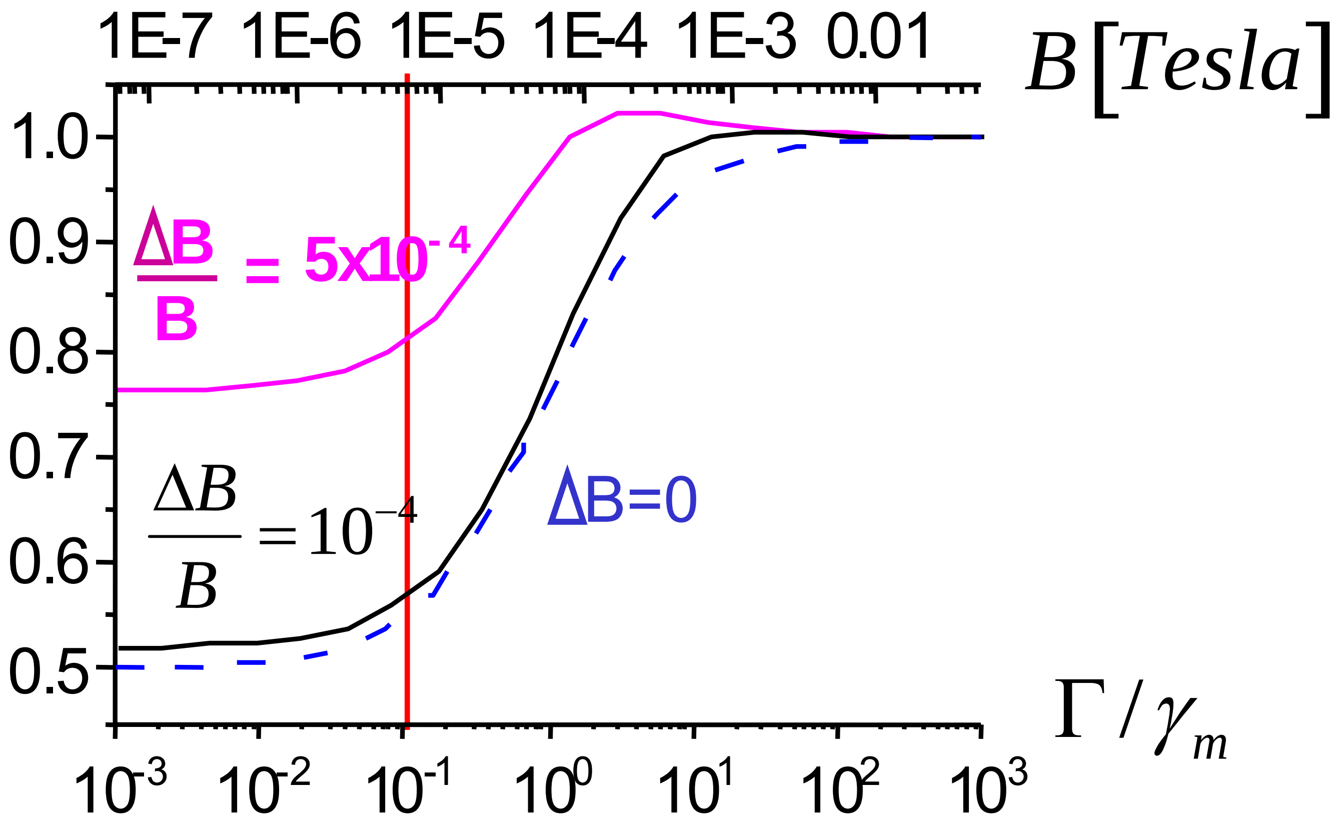
What is the effect of a magnetic field inhomogeneity ?

De-phasing between the squeezed field and the ground state coherence during the squeezing build-up time





HOMOGENEITY REQUIREMENTS ON THE MAGNETIC FIELD

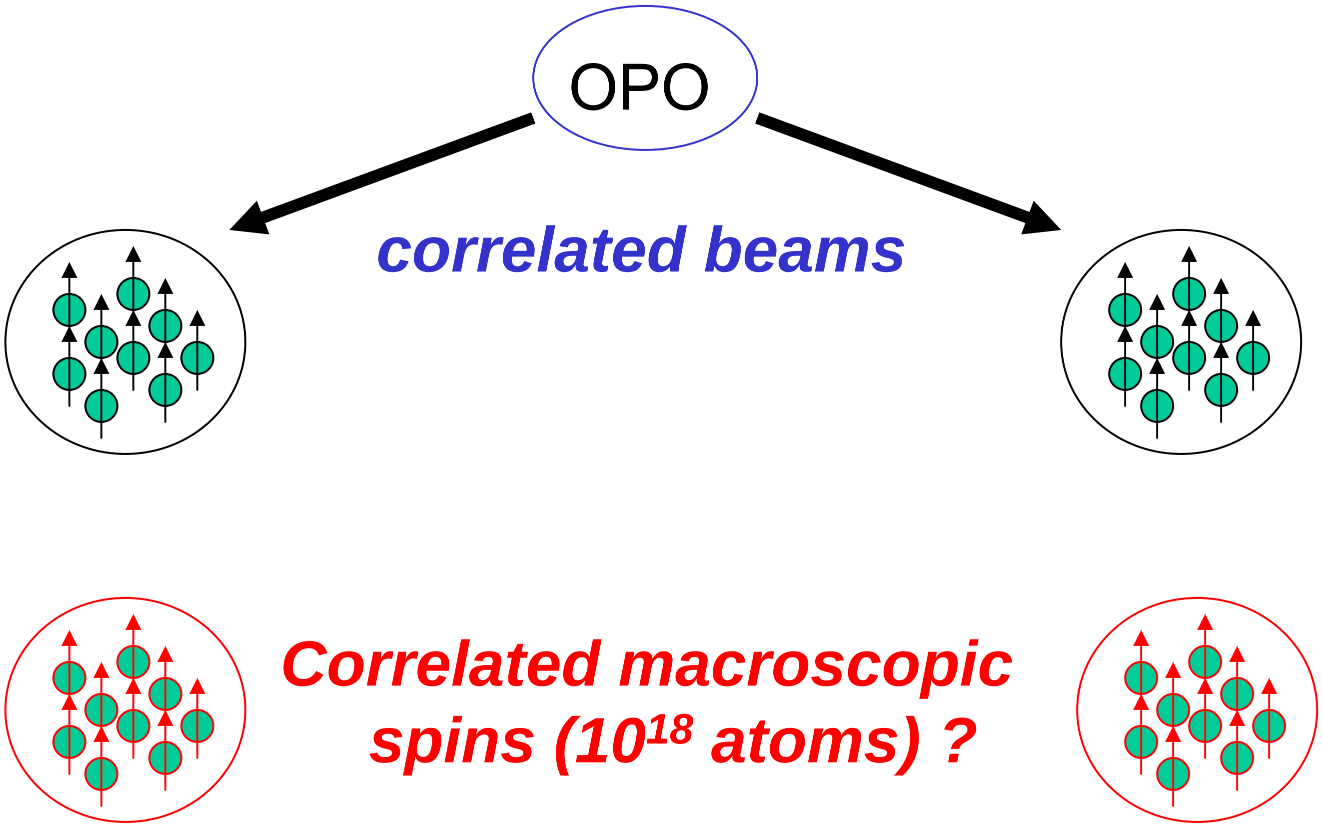


Example of working point :

$$\Gamma = 0.1\gamma_m\ ,\quad B = 57\ mG,\quad Larmor = 184\ Hz$$

LONG-LIVED NON LOCAL CORRELATIONS BETWEEN TWO MACROSCOPIC SAMPLES

Julsgaard et al., Nature (2001) : 10^{12} atoms τ=0.5ms



INSEPARABILITY CRITERION

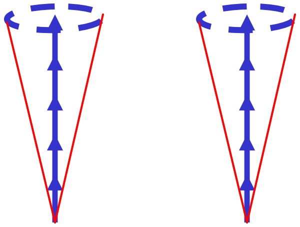
Duan et al. PRL 84 (2000), Simon PRL 84(2000)

Two modes of the EM field

Quadratures $A_{x1(2)} = (A_{1(2)} + A_{1(2)}{}^{+}) \qquad A_{y1(2)} = i(A_{1(2)}{}^{+} - A_{1(2)})$

$$\Im_F = \frac{1}{2}\left[\Delta^2(A_{x1} - A_{x2}) + \Delta^2(A_{y1} + A_{y2})\right] < 2$$

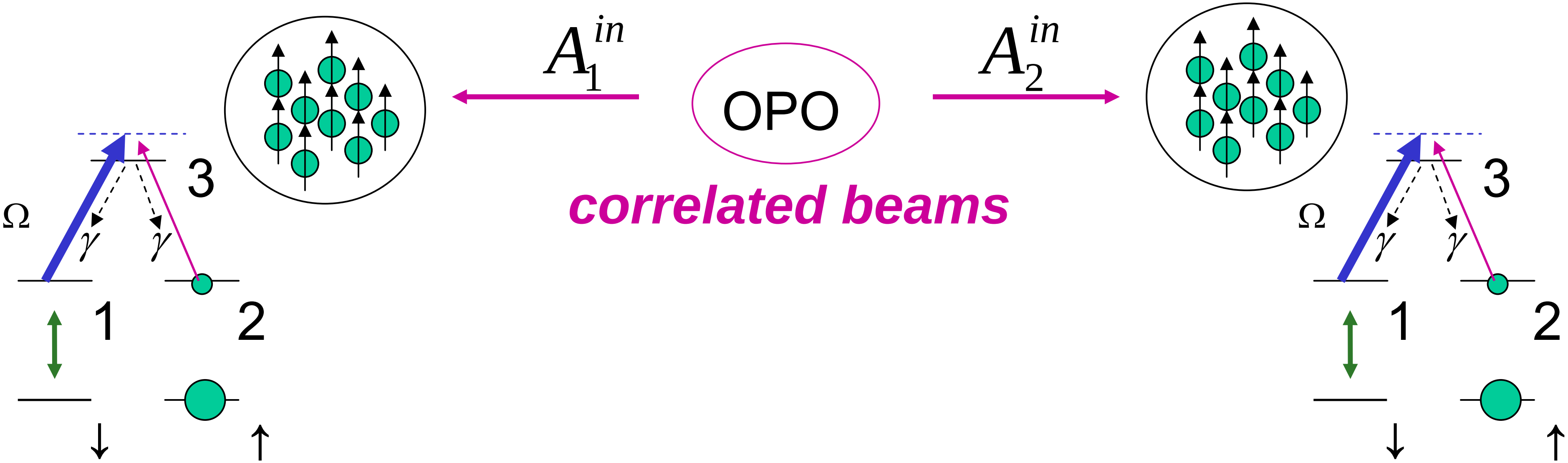
Two collective spins



$$\langle I_{z1} \rangle = \langle I_{z2} \rangle \approx \frac{N}{2}$$

$$\Im_A = \frac{2}{N}\left[\Delta^2(I_{y1} - I_{y2}) + \Delta^2(I_{x1} + I_{x2})\right] < 2$$

LONG-LIVED NON LOCAL CORRELATIONS BETWEEN TWO MACROSCOPIC SAMPLES



coupling

$$\left(\Gamma_g - i\omega\right) I_{y1(2)} = \beta\, A_{x1(2)}^{in} + noise$$

$$\left(\Gamma_g - i\omega\right) I_{x1(2)} = -\beta\, A_{y1(2)}^{in} + noise$$

LONG-LIVED NON LOCAL CORRELATIONS BETWEEN TWO MACROSCOPIC SAMPLES

In terms of inseparability criterion of Duan and Simon

coupling

$$\Im_A = \frac{\gamma_m}{\gamma_m + \Gamma} \Im_F + 2\left(\frac{\Gamma}{\gamma_m + \Gamma} + \left(\frac{\gamma_m}{\gamma_m + \Gamma} \right) \frac{1}{C} \right)$$

noise from Exchange collisions

Spontaneous Emission noise

$$C = \frac{g^2 n}{\kappa \gamma} >> 1$$

$$\Gamma << \gamma_m$$

$$\boxed{\Im_A = \Im_F}$$