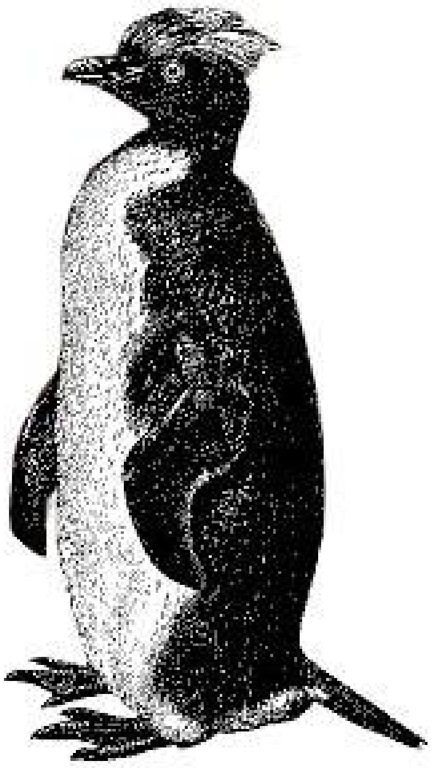

Frozen Spin Targets

In a Nutshell

Version 1.0

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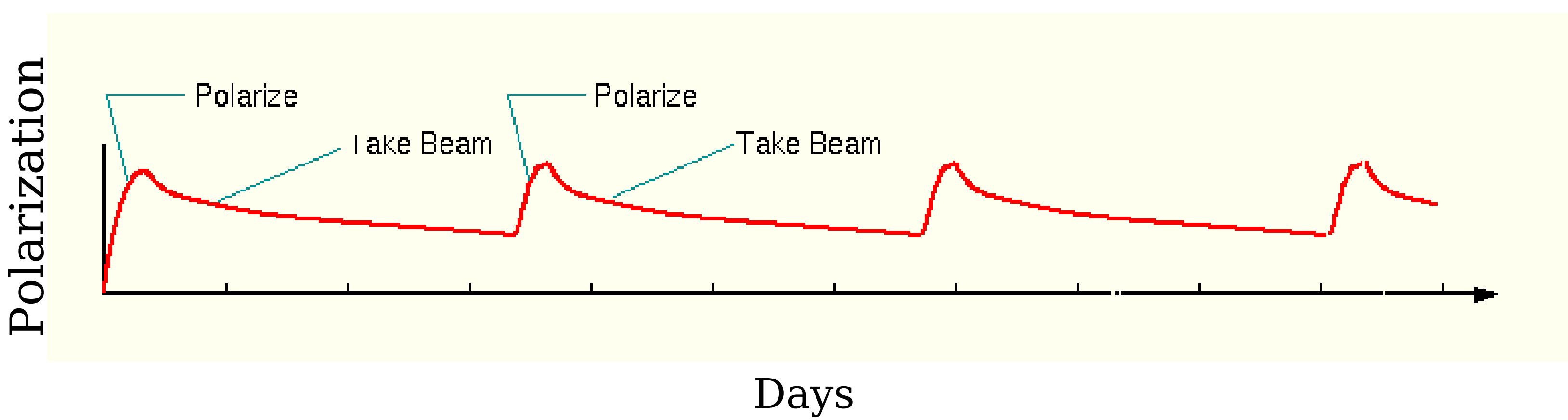
Four Easy Steps to a Frozen Spin Target

Step 1. Polarize the Target via DNP

Step 2. Freeze the Polarization at a Very Low Temperature
(and modest magnetic field)

Step 3. Take Physics Data while the Polarization (slowly) Decays

Step 4. Go to Step 1



Polarization and Thermal Equilibrium

An ensemble of atoms or nuclei with a magnetic moment can be polarized via the Zeeman interaction: $\vec{\mu}\cdot\vec{B}$

$$N(\uparrow)/N(\downarrow)=\exp[\frac{(-2\mu B)}{kT}]$$

T = temperature

$$P_{te}=\frac{[N(\uparrow)-N(\downarrow)]}{[N(\uparrow)+N(\downarrow)]}=\tanh(\frac{\vec{\mu}\cdot\vec{B}}{kT})$$

Thermal equilibrium polarization

The polarization will approach thermal equilibrium with a characteristic *1/e* time constant called t_1, the "*spin-lattice relaxation rate*"

$$P(t)=P_{te}[1-e^{-t/t_1}]$$

Important: t_1 depends strongly on *B* and *T* (among other things)

Brute Force Polarization

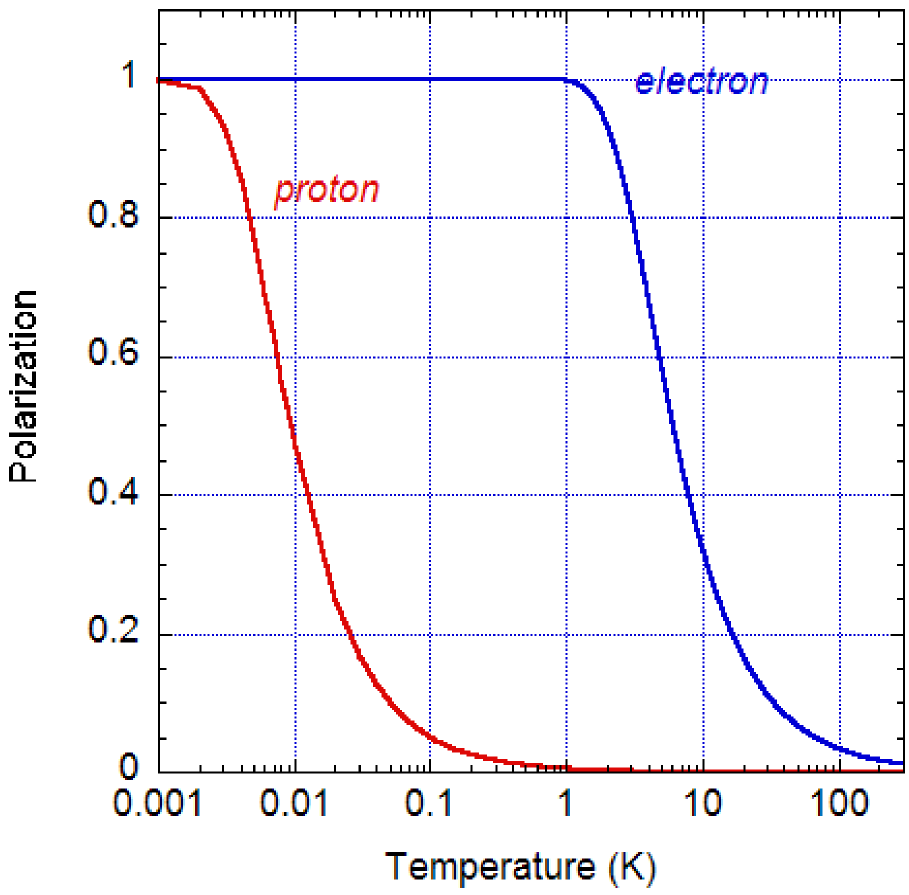
$$P = \tanh\left(\frac{\vec{\mu}\cdot\vec{B}}{kT}\right) \longrightarrow$$ maximize B, minimize T

Disadvantages:

1. Requires very large magnet
2. Low temperatures mean low luminosity
3. Polarization can take a very long time

We need a trick!

5 Tesla



The Trick -- **D**ynamic **N**uclear **P**olarization

Use brute force to polarize free electrons in the target material.
Use microwaves to “transer” this polarization to nuclei. Mutual electron-nucleus spin flips re-arrange the nuclear Zeeman populations to favor one spin state over the other.

For best results, DNP is performed at *B/T* conditions where electron t_1 is short (ms) and nuclear t_1 is long (minutes)

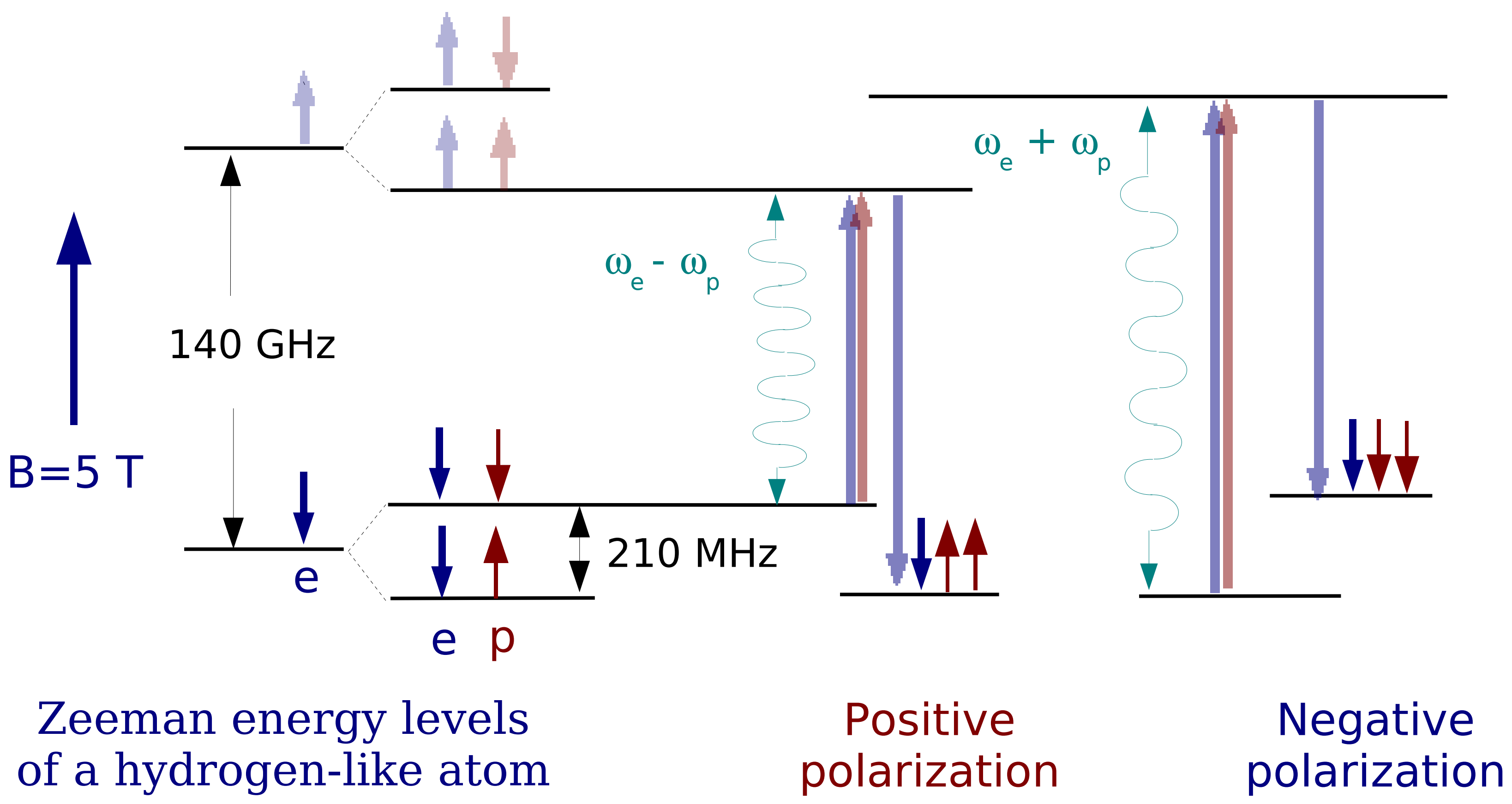
JLab: *B = 5 Tesla*
T = 1 Kelvin

Materials for DNP Targets, examples

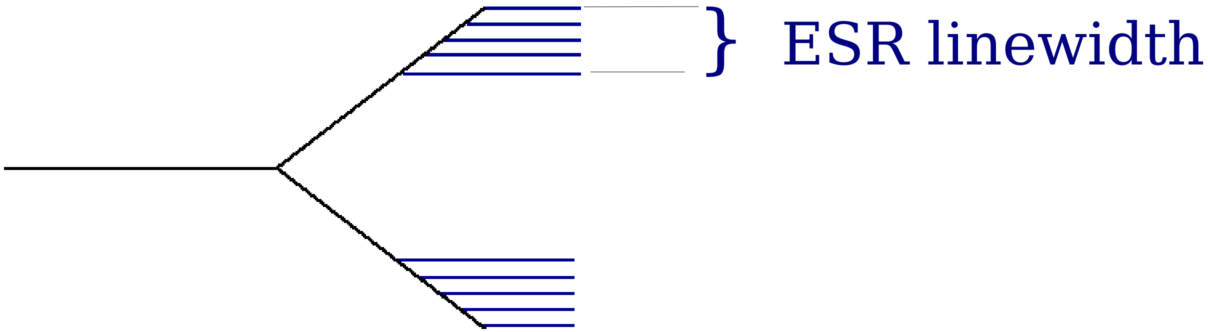
Name	Dopant	f	Rad. Resistance
Polyethelyne, C_2H_4	chemical	0.12	low
Polystyrene, C_8H_8	chemical	0.07	low
Propandiol, $C_3H_6(OH)_2$	chemical	0.11	moderate
Butanol, C_4H_9OH	chemical	0.13	moderate
Ammonia, $^{15}NH_3$	radiation	0.17	high
Lithium Hydride, ^{7}LiH	radiation	0.12	very high

In all cases, unpaired electron (aka *Paramagnetic Centers*) are added to the material, and are essential to the DNP process

The Resolved Solid Effect



Many Electrons in a Magnetic Field

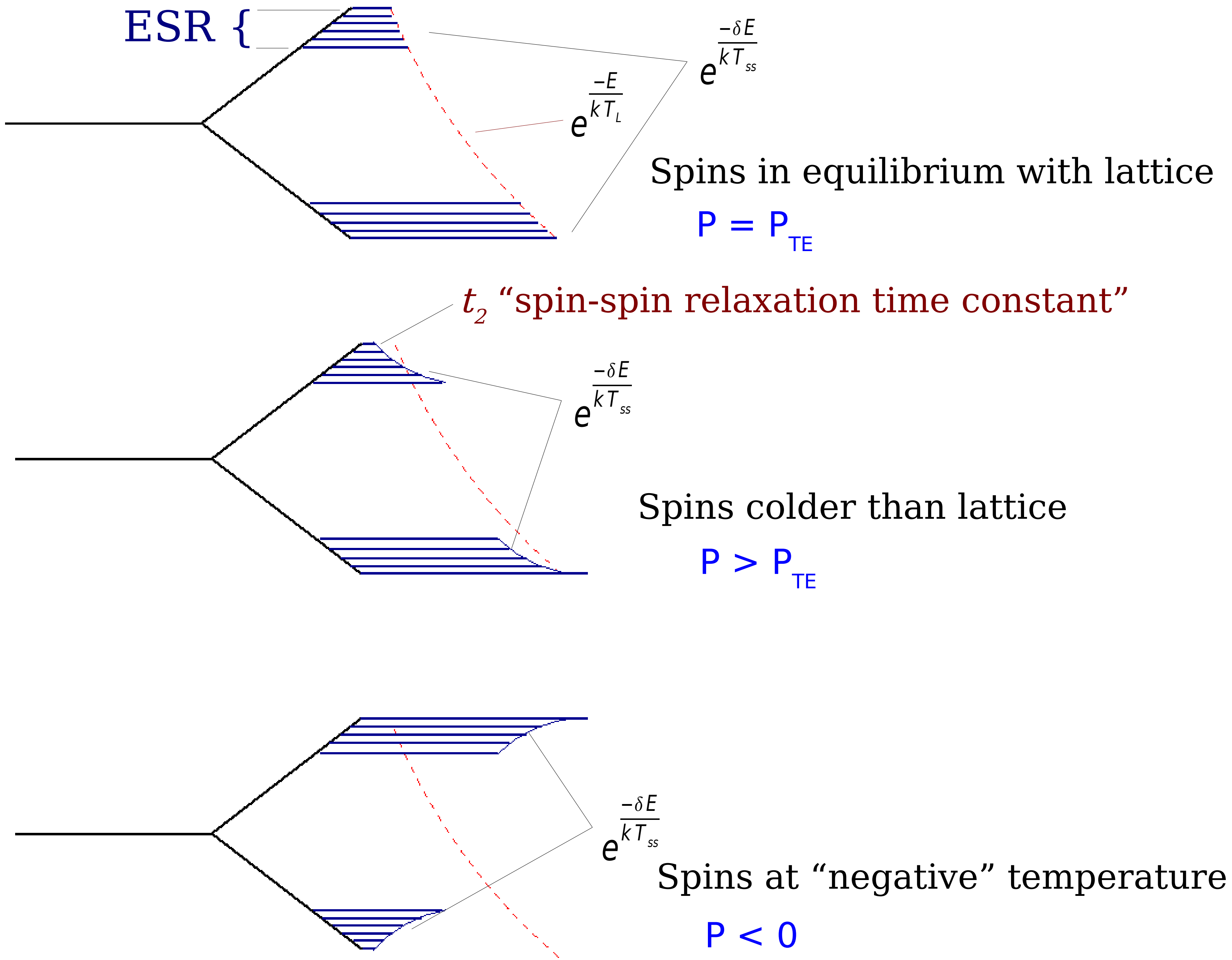


Electron Zeeman levels broadened due to
dipolar interaction between spins.

No longer possible to pump desired nuclear spin state (without pumping the other)

DNP process still works, but we need a new model to supplant *Resolved Solid Effect*

→ *Equal Spin Temperature Model*



ESR {
$e^{\frac{-\delta E}{kT_{ss}}}$
$e^{\frac{-E}{kT_L}}$
Spins in equilibrium with lattice
$P = P_{TE}$
t_2 “spin-spin relaxation time constant”
$e^{\frac{-\delta E}{kT_{ss}}}$
Spins colder than lattice
$P > P_{TE}$
$e^{\frac{-\delta E}{kT_{ss}}}$
Spins at “negative” temperature
$P < 0$

Adiabatic Demagnetization of Electrons

Curie's Law: $\vec{M} = C\frac{\vec{B}}{T_z}$ Total Energy: $E_z = -\vec{M}\cdot\vec{B} = -C\frac{B^2}{T_z}$

(T_z along with B determines Boltzmann dist. of spin states)

Lower B_i in time $t < t_1$ → $\vec{M}_f = \vec{M}_i$

Final spin temperature → $T_{ss} = \frac{B_f}{B_i}T_i = \frac{B_f}{B_i}T_L$

Spin temperature much lower than lattice temperature!

In reality field is sum of external and internal (local) fields and total energy contains a term involving the dipolar coupling between the spins

$$E = E_z + D = -C\left(\frac{B_o^2}{T_z} + \frac{B_l^2}{T_{ss}}\right)$$

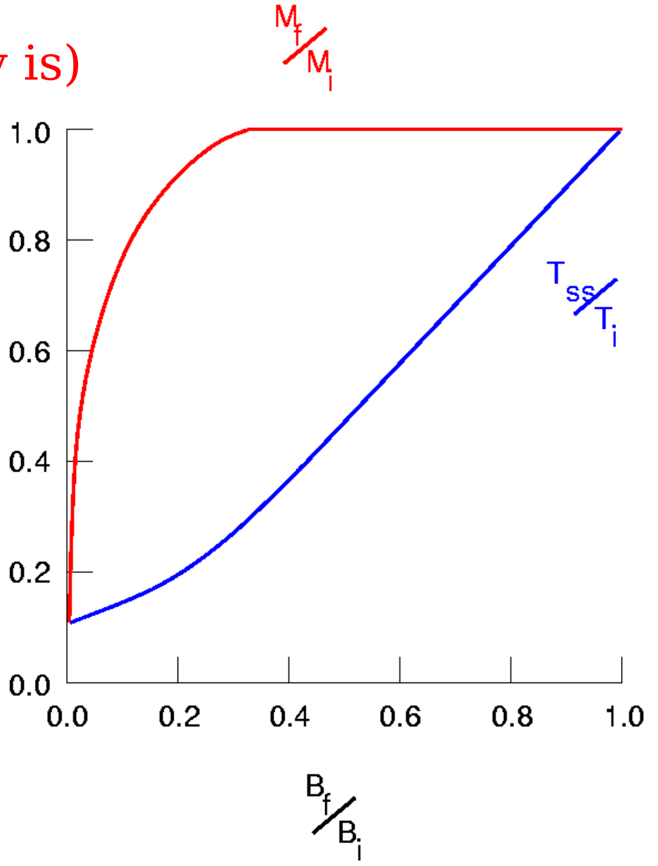
Magnetization is no longer constant (but entropy is)

Final Spin Temperature:

$$T_{ss} = T_z = \sqrt{\frac{B_f^2 + B_l^2}{B_i^2 + B_l^2}}\, T_L = \frac{B_l}{B_i} T_L$$

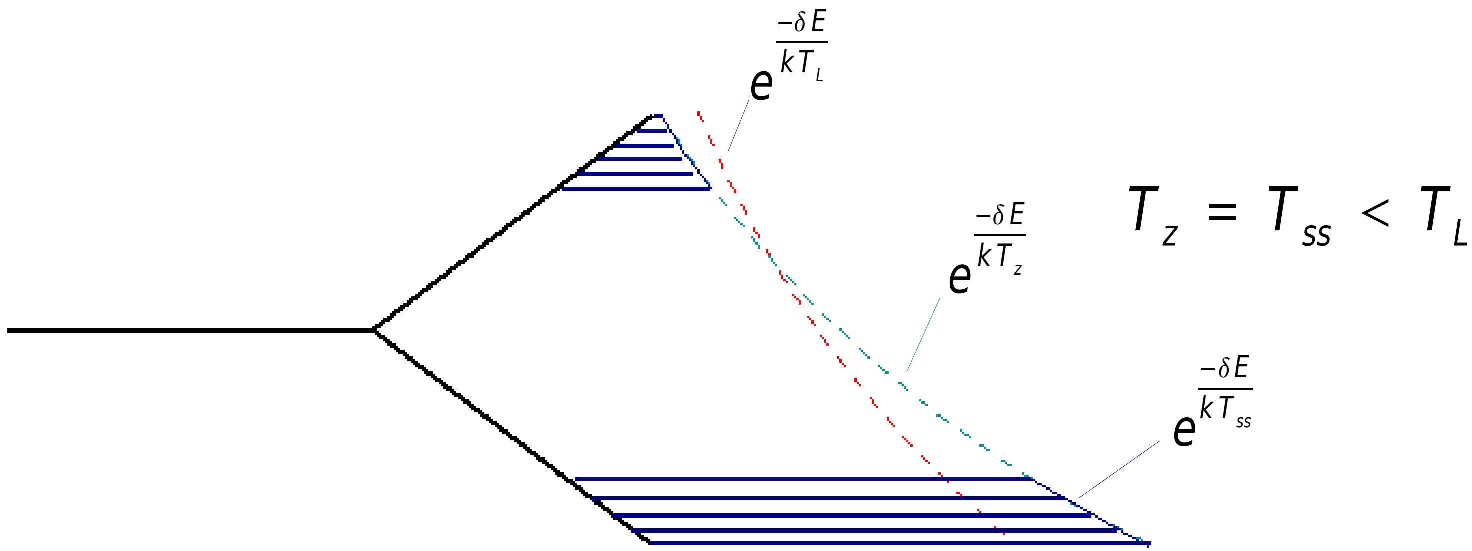
Final Magnetization:

$$M_f = C\frac{B_f}{T_{ss}}$$



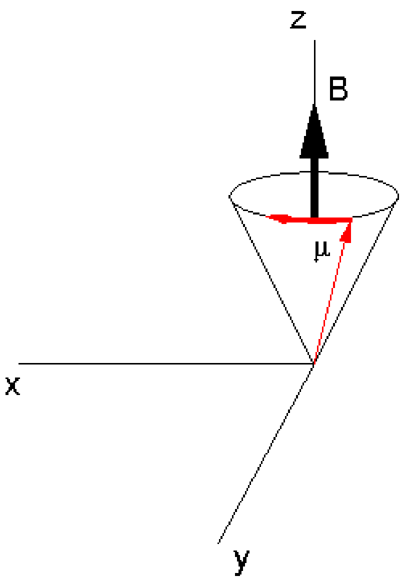
As $B_f \rightarrow B_l$ energy is transferred from "Zeeman reservoir" to "Dipole reservoir"

Global order → Local order



$e^{\frac{-\delta E}{kT_L}}$
$e^{\frac{-\delta E}{kT_z}}$
$e^{\frac{-\delta E}{kT_{ss}}}$
$T_z = T_{ss} < T_L$

Adiabatic Demagnetization in Rotating Frame

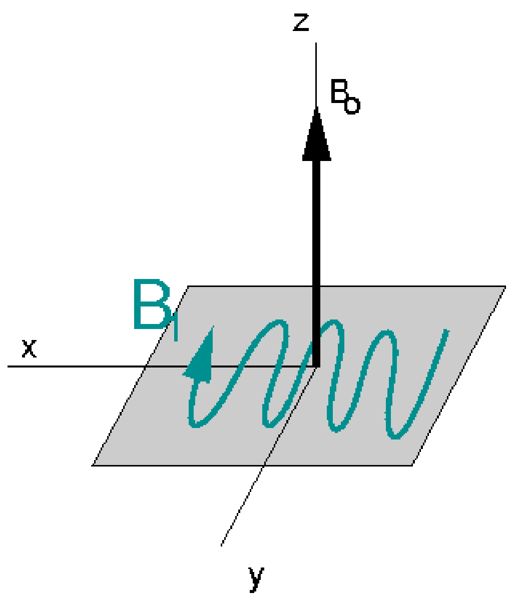


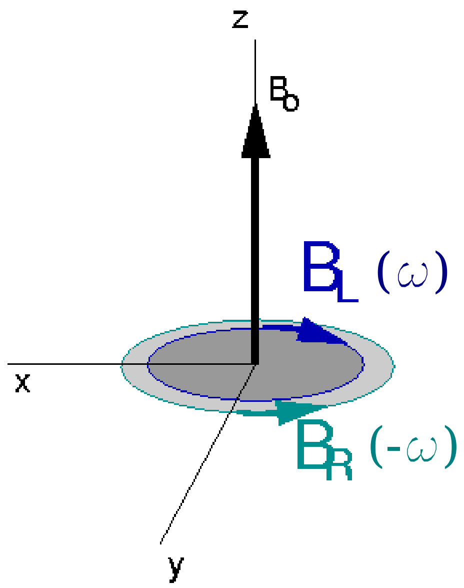
Magnetic moment precesses around $\mathbf{B_o}$ at the Larmor frequency

$$\omega_o = \gamma B_o$$

Apply oscillating field $\mathbf{B_1}$ perpendicular to $\mathbf{B_o}$ in x,y plane

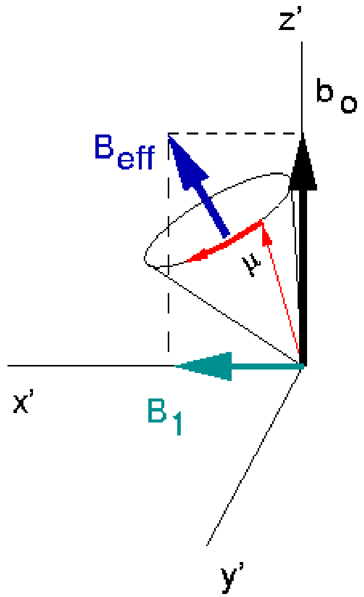
Field oscillates at frequency ω





In frame rotating at frequency ω, the total (or effective) is fixed in the x', z' plane

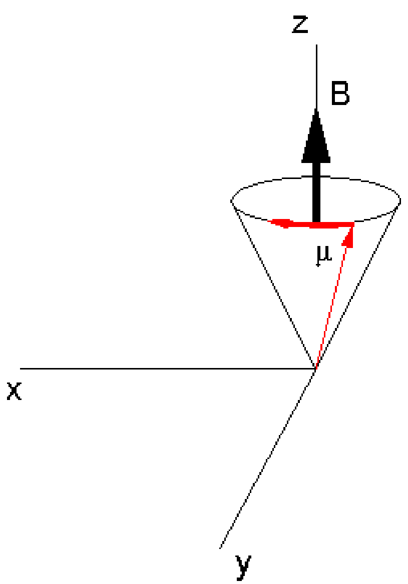
$$\vec{B}_{eff} = (B_o - \frac{\omega}{\gamma})\hat{z}' + \vec{B}_1 \hat{x}'$$
$$= b_o \hat{z}' + \vec{B}_1 \hat{x}'$$



μ will follow B_{eff} so long as changes to B_o or B_1 are made on a time scale $t_2 \ll t \gg t_1$

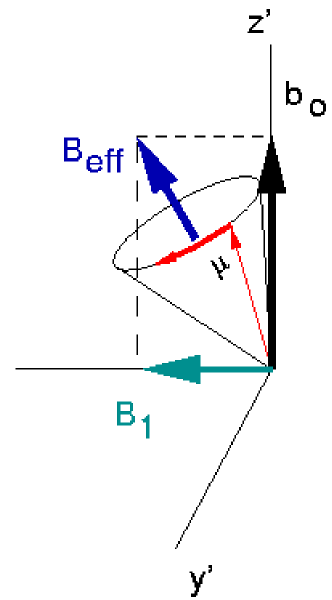
Adiabatic Demagnetization In Rotating Frame (ADRF)

1. Establish thermal equil.



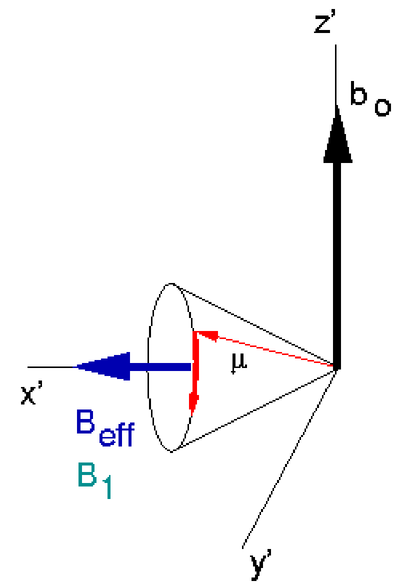
$$T_{ss} = T_L$$

2. Sweep $\omega \rightarrow \omega_0$



$$T_{ss} = \sqrt{\frac{B_{eff}^2 + B_l^2}{B_o^2 + B_l^2}}\, T_L \approx \frac{B_{eff}}{B_o} T_L$$

3. Reduce $B_1 \rightarrow 0$



$$T_{ss} = \frac{B_l}{B_o} T_L$$

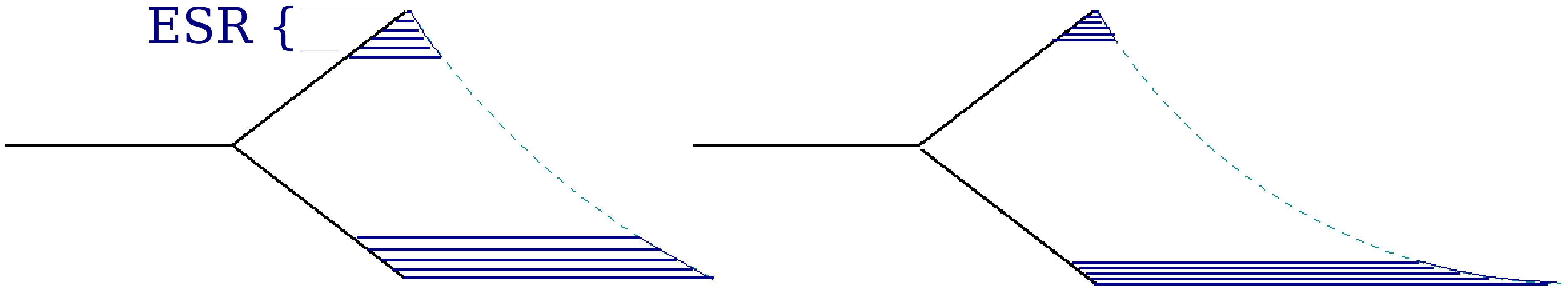
Thus far we have only considered process t_2 « t » t_1

In the case of continuous RF radiation we cannot ignore spin-lattice relaxation

For a complete description refer to the Redfield (strong B_1) and Provotorov (weak B_1) equations

Result: Under constant saturation, the temperature of the electron Dipolar and Zeeman systems (T_D and T_Z) equilibrate to temperature below T_L

The maximum degree of cooling depends on the width of the ESR linewidth



Narrower ESR line means lower spin temperature

Nuclear Polarization

If the nuclear Zeeman splitting is of comparable size to the electron dipolar splitting (i.e. Narrow ESR line), then the two systems can share energy

In this case the Nuclear Zeeman system will be cooled to the same extent (and with the same sign) as the electron dipolar system

If the ESR linewidth becomes broader (e.g. Radiation damage) the spin temperature rises and the nuclear polarization drops

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