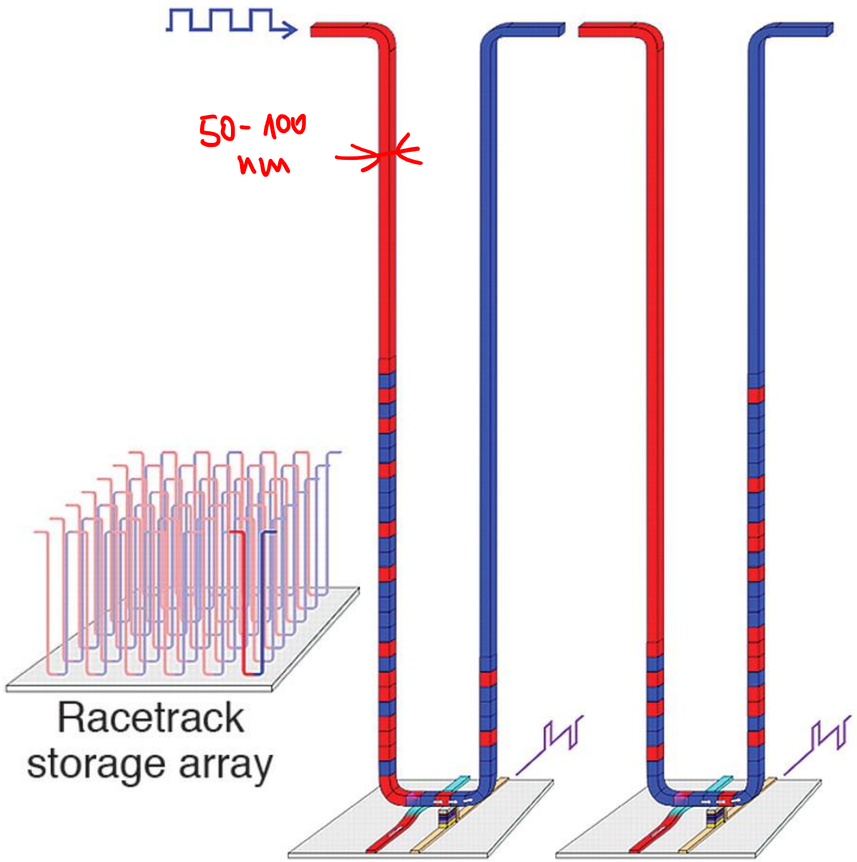
EFEKTY REDUKOVANÉ DIMENZE / MAGNETICKÉ REZONANCE

RACETRACK MEMORY



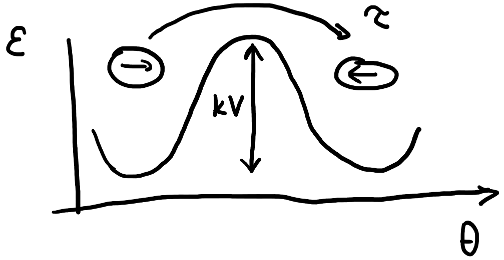
NUCLEAR MAGNETIC RESONANCE (NMR)

S. Parkin et al. *Science* **320**, 190 (2008)

S. Parkin & S. H. Yang. *Nature Nanotechnology* **10**, 195 (2015)

3 REDUKOVANÉ DIMENSE:

SUPERPARAMAGNETISMUS



částici podkrit. polom: $R_c = \dfrac{9\pi\sqrt{AK}}{\mu_0 M^2}$ $R<R_c$ θ jedna doména

uniax. aniz.

$E_A = KV$

term. fl. $\sim k_B T$

mat. vlastnost (~1 ns)

$$\tau = \tau_0 \, e^{\frac{KV}{k_B T}}$$

čas přechodu

měřicí okno t : $t \ll \tau$ částice stabilní $\langle M \rangle = M_S$

$t \gg \tau$ $\langle M \rangle = 0$

$\propto R_B^3$ blocking radius

$$\frac{KV}{k_B T} = \alpha$$ blocking constant

blocking T

α { >25 lab. stabilita $\tau \approx 100$ s

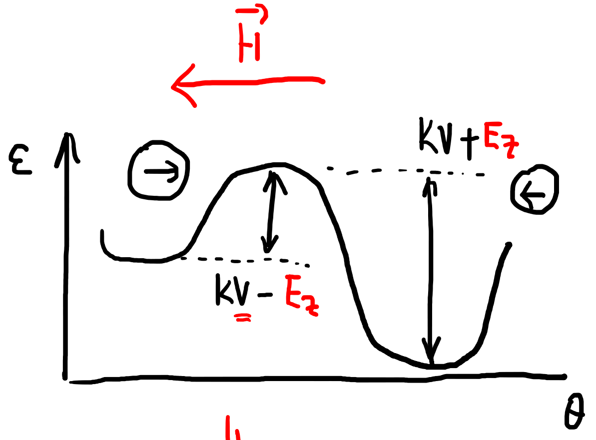
>60 pevné disky $\tau \sim 10^{12}$ let

Table 8.5. Superparamagnetic relaxation times for cobalt particles

Radius (~~n~~μm)	Temperature (K)	Relaxation time
3.5	260	332 s
3.5	300	10 s
3.5	340	0.6 s
3.5	380	76 ms
3.0	300	1.9 ms
4.0	300	223 h
5.0	300	L × 10^{12} y

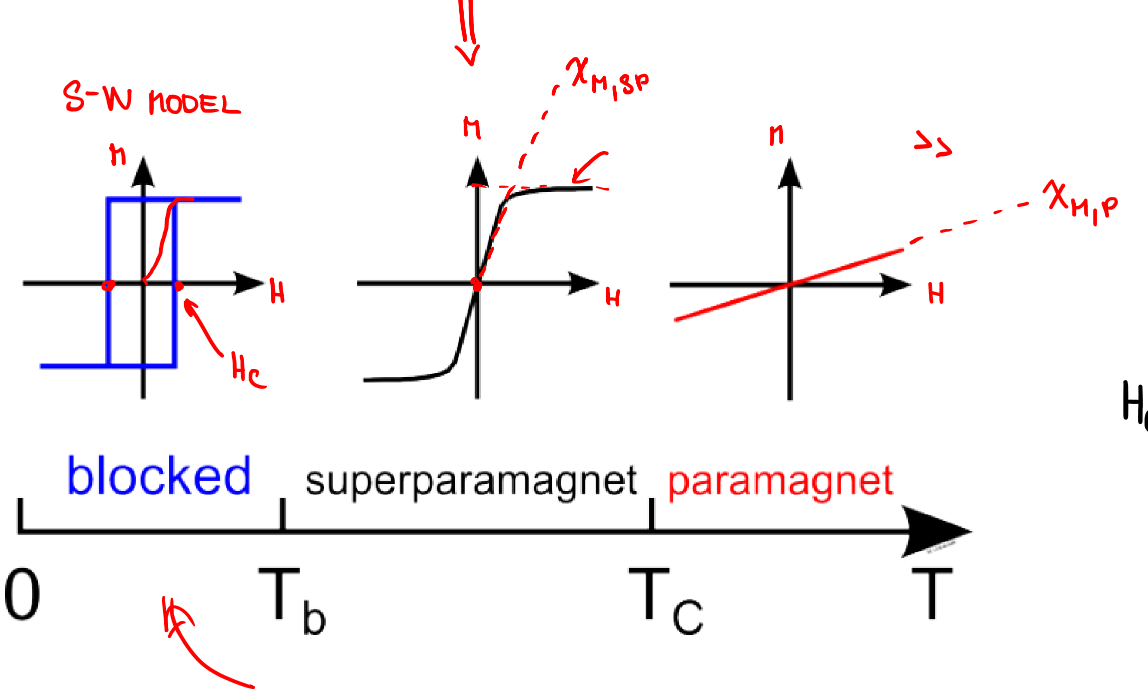
EFEKTY REDUKOVANÉ DIMENZE - SUPERPARAMAGNETISMUS

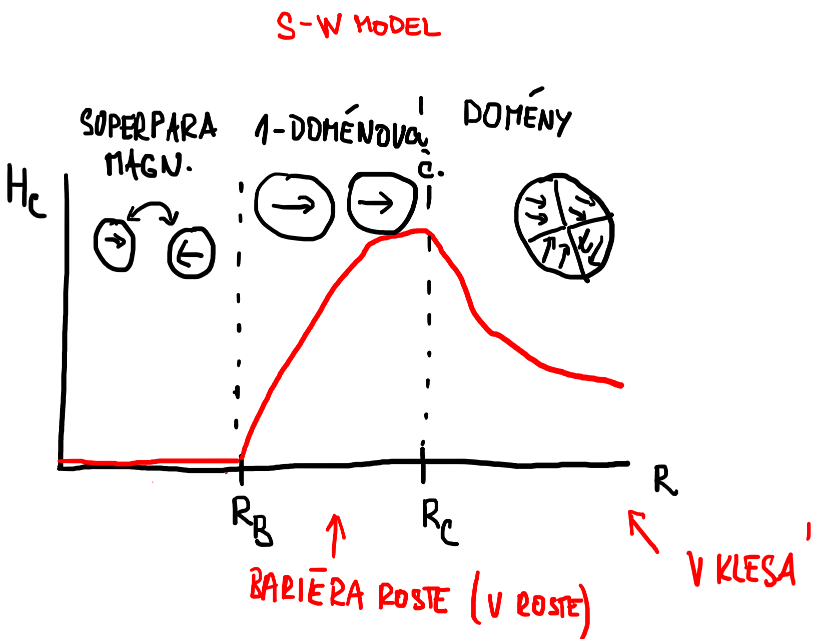
Série částic:



$E_Z = -\mu_0 M H \cos\theta$

$\alpha \propto V, \frac{1}{T}$ ($V \propto R^3$)

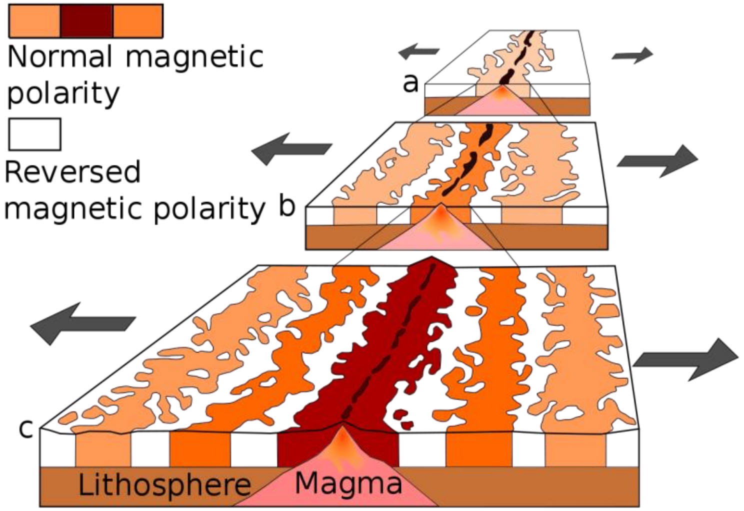


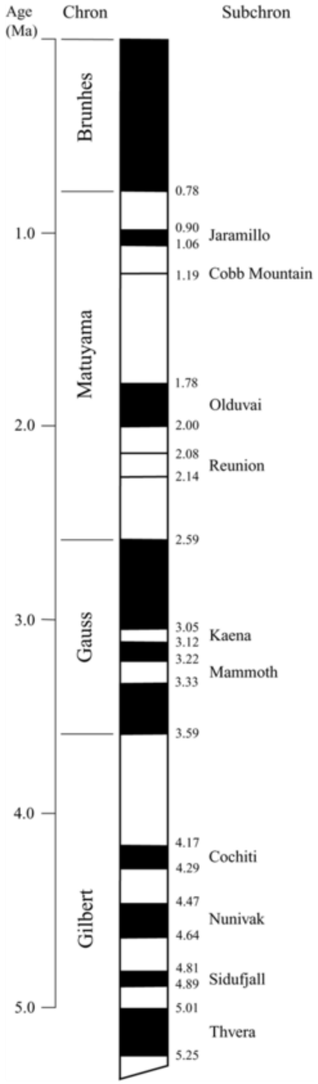


EFEKTY REDUKOVANÉ DIMENZE – SUPERPARAMAGNETISMUS

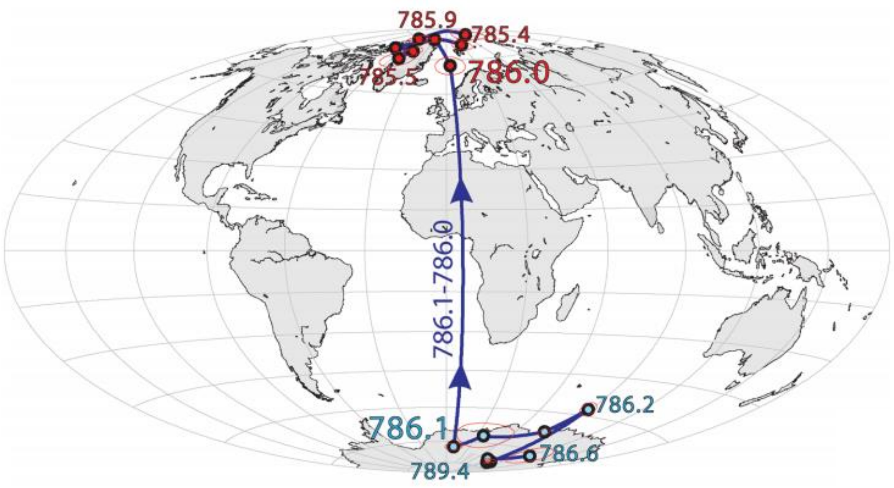
ČÁSTICE HEMATITU (OXID Fe) V LÁVĚ

SUPERPARAMG. $T > T_C, T_B$ $\xrightarrow{T \downarrow}$ FEROMG. 1DOMÉNOVÁ Č.



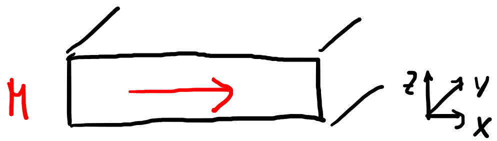


PŘEKMIT MG. PÓLU ZEMĚ

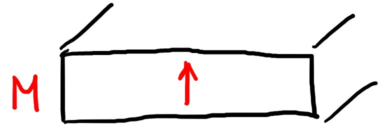


Sagnotti et al., Geophys. J. Int. (2014) 199, 1110–1124

2D OMEZENÍ: TENKÉ VRSTVY

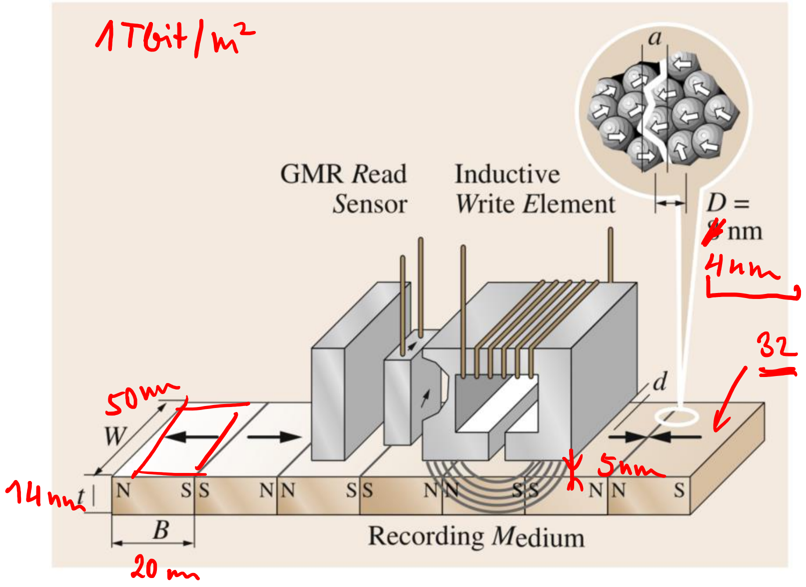


$\mathcal{N}_{y,x} = 0 \qquad H_D = 0 \Rightarrow$ $H_1^{\parallel}$, $H_2^{\parallel}$ $\Rightarrow H_{STRAY} = 0$

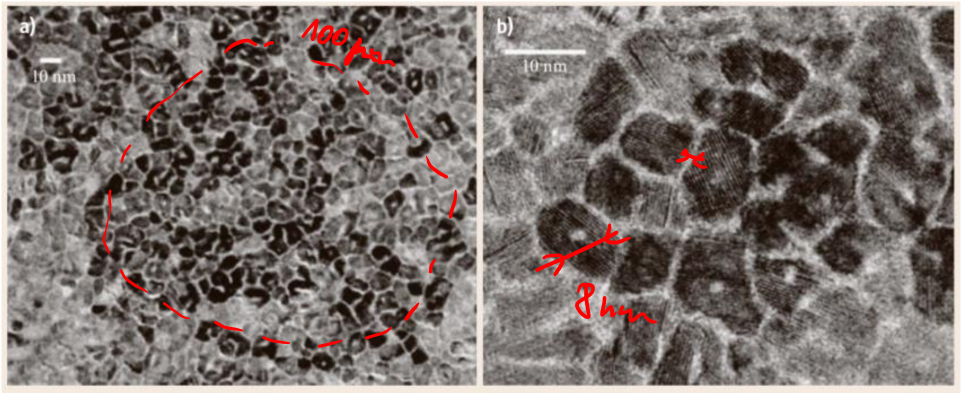


$\mathcal{N}_z = -1 \qquad H_D = -M \Rightarrow B = \mu_0 (H - M) = 0 \Rightarrow B_\perp^1 = B_\perp^2 = 0 \Rightarrow B_{STRAY} = 0$

$H_{STRAY} = 0$

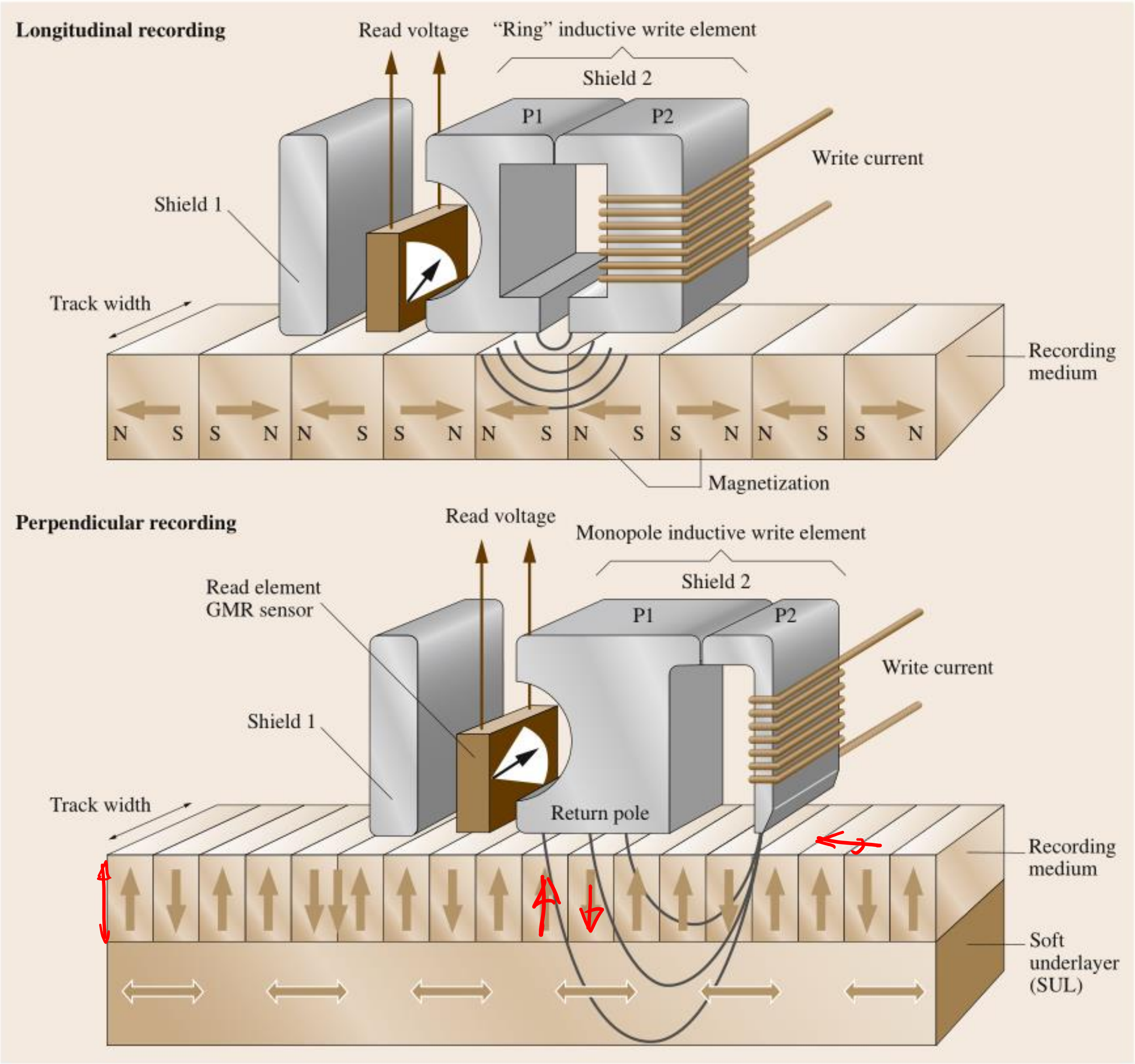


35 Gbit/m²



https://link.springer.com/chapter/10.1007/978-3-319-48933-9_49

S. Kasap, P. Capper (Eds.), Springer Handbook of Electronic and Photonic Materials



https://link.springer.com/chapter/10.1007/978-3-319-48933-9_49

S. Kasap, P. Capper (Eds.), Springer Handbook of Electronic and Photonic Materials

EFEKTY REDUKOVANÉ DIMENZE – TENKÉ VRSTVY

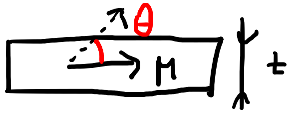
2D OMEZENÍ : TENKÉ VRSTVY

ANISOTROPIE: "3S"

R. Jungblut, JAP 75 6424 (1994)

SHAPE

$N_{x,y} = 0$
$N_z = -1$



$E_A = K_u \sin^2\theta$

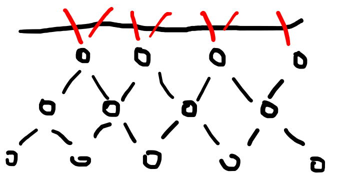
$\downarrow$

$K_u = -\frac{1}{2}\mu_0 M_S^2$

$\Rightarrow$ inplane

$K_{SH} \sim -1\ MJ/m^3$

SURFACE



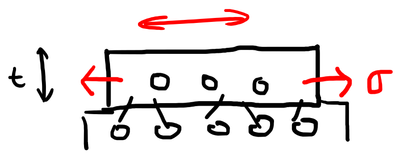
$K_u = K_S < 0$

OUT-OF PLANE

$K_S \sim 1\ mJ/m^2$

$K_u = K_V + K_S/t$

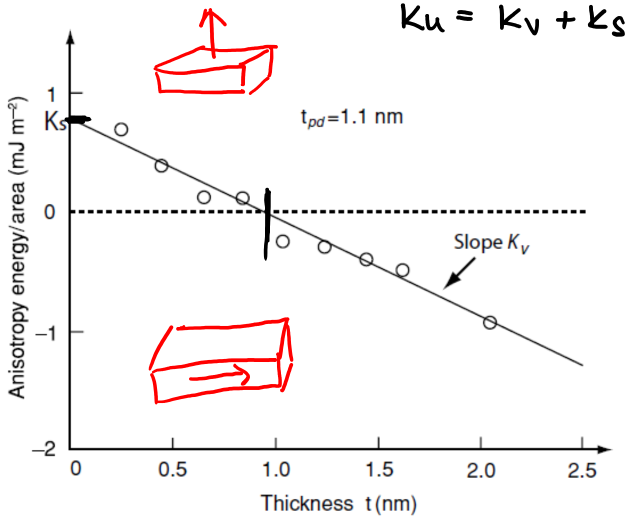
STRAIN

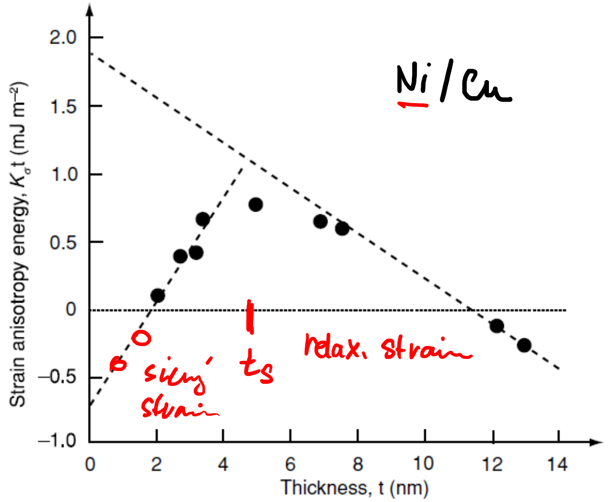


$K_\sigma \propto \lambda_S \sigma \propto e_u\, t_S/t \propto 1/t$

SPONTÁNNÍ MAGNETOSTRIKCE

$K_\sigma \sim -100\ kJ/m^3$

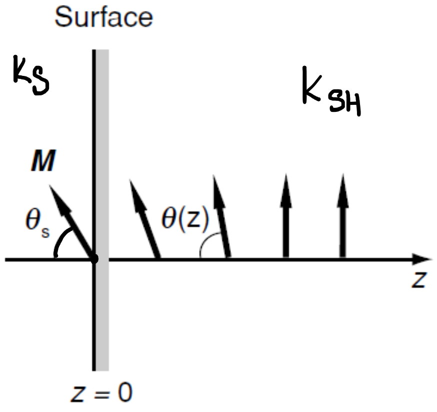




EFEKTY REDUKOVANÉ DIMENZE – TENKÉ VRSTVY

2D OMEZENÍ : TENKÉ VRSTVY

ANISOTROPIE :

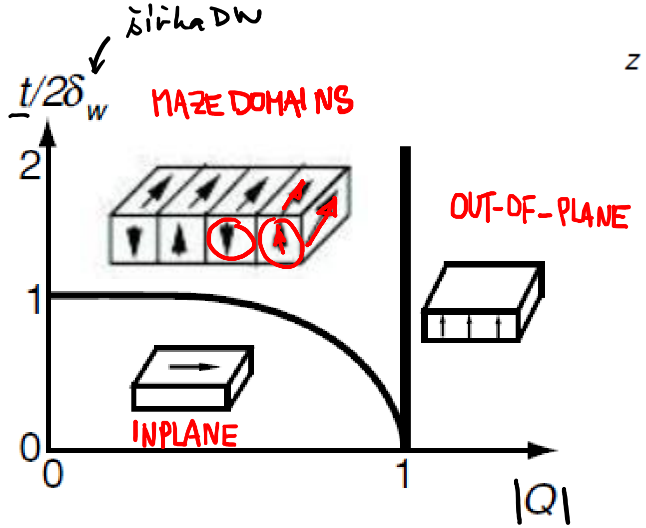


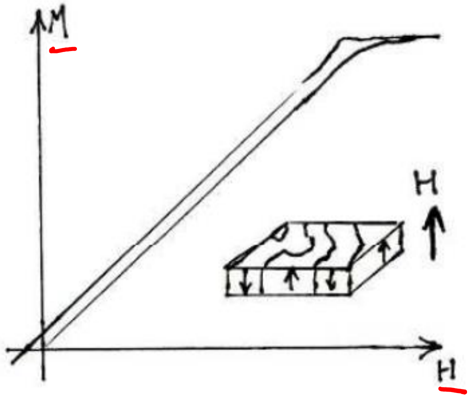
$$\theta(z) = 2\,\mathrm{tg}^{-1}\left[e^{\pi(z-z_0)/\delta_{DW}}\right]$$

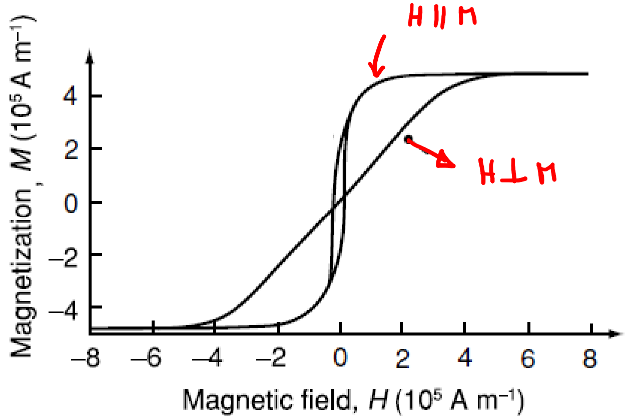
tloušťka

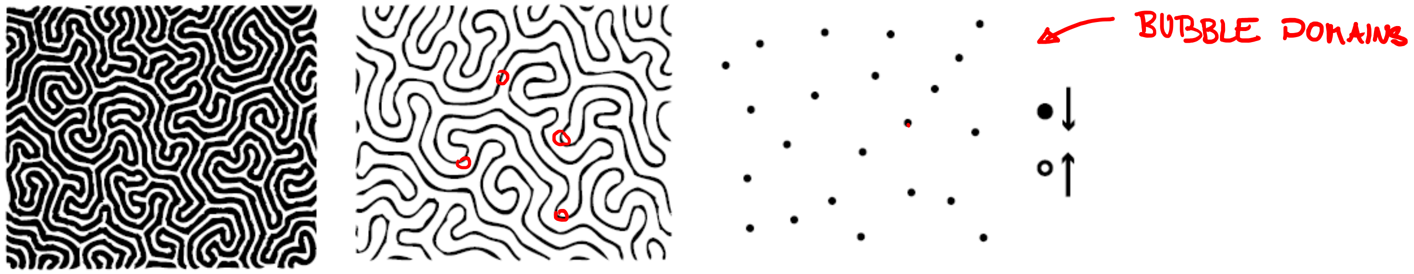
$z_0 : \theta(z=z_0) = \theta_s$

$$Q = -\frac{K_\perp}{K_{SH}}$$ quality factor









$H = 0$ ⊙ H ⊙H

EFEKTY REDUKOVANÉ DIMENZE - BUBBLE DOMAINS

2D OMEZENÍ: TENKÉ VRSTVY

BUBBLE MEMORY

(BELL LABS, IBM...) 70', 80'

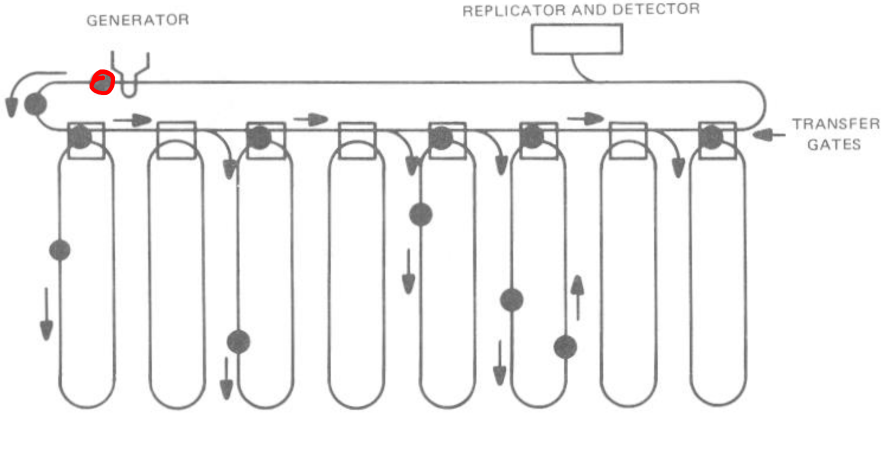
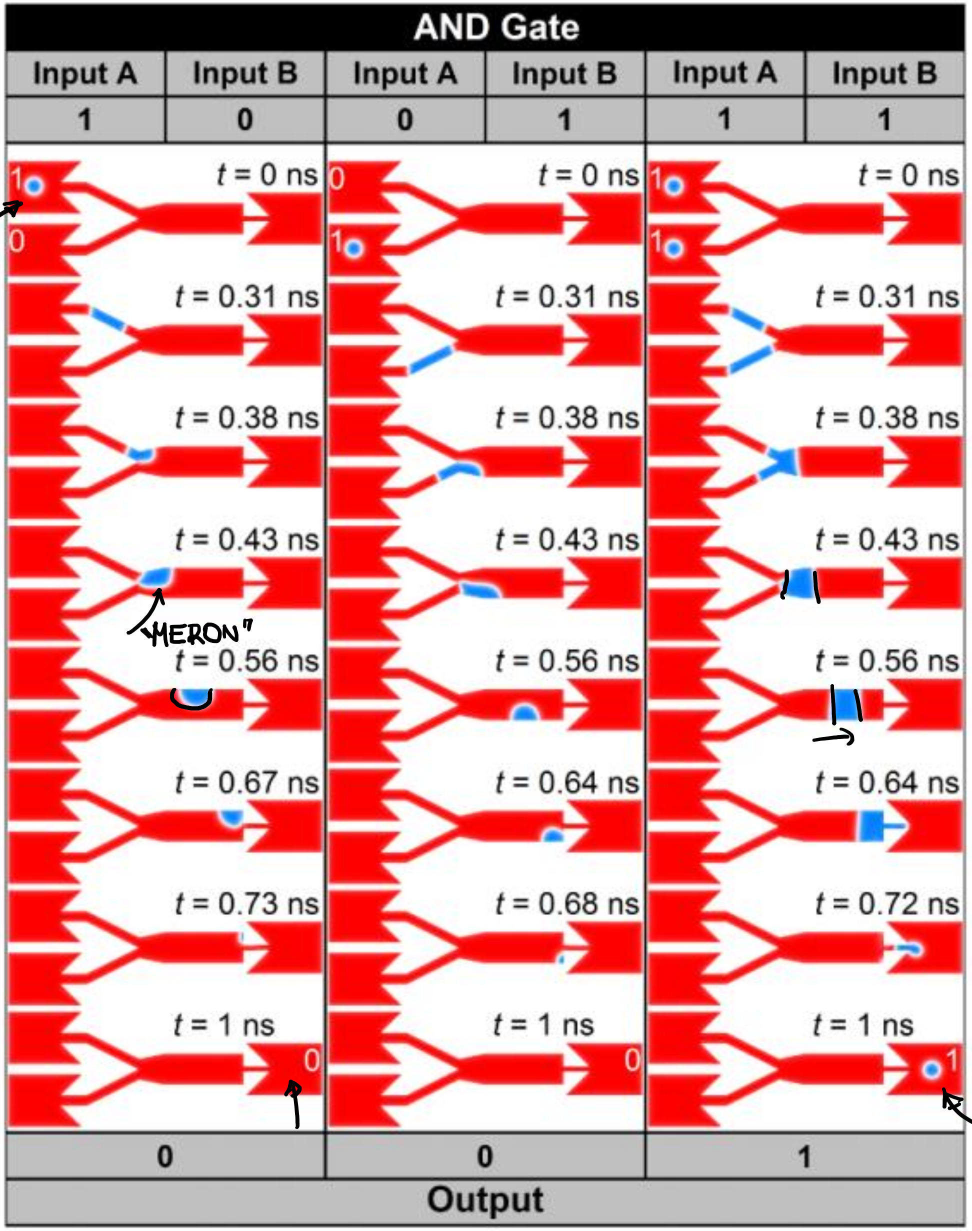


FIGURE 5. ARCHITECTURE USING MAJOR AND MINOR LOOPS

USSR

"SKYRMIONS"



"MERON"

Xichao Zhang, Sci. Rep. 5 9400 (2015)

EFEKTY REDUKOVANÉ DIMENZE – EXCHANGE BIAS

2D OMEZENÍ : TENKÉ VRSTVY

HETEROSTRUKTURY :

- $H_x \parallel \vec{L}$

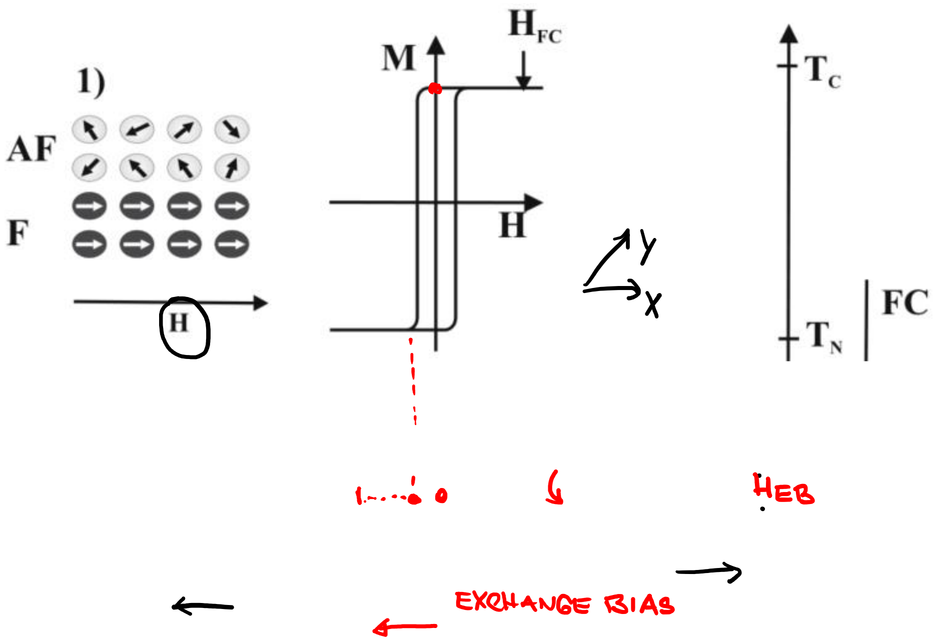
UNIDIRECTIONAL

UNIAXIAL

$$E_x = -\mu_0 M H_x \cos\theta \underbrace{- \underbrace{K_{EB}}_{\frac{\sigma_{EX}}{t}} \cos^1\theta}_{} + K_U \sin^2\theta$$

$$-\mu_0 M H_x' \cos\theta \qquad H_x' = H_x + H_{EX} \qquad H_{EX} = \frac{\sigma_{EX}}{\mu_0 M t}$$

- $H_y \perp \vec{L}$



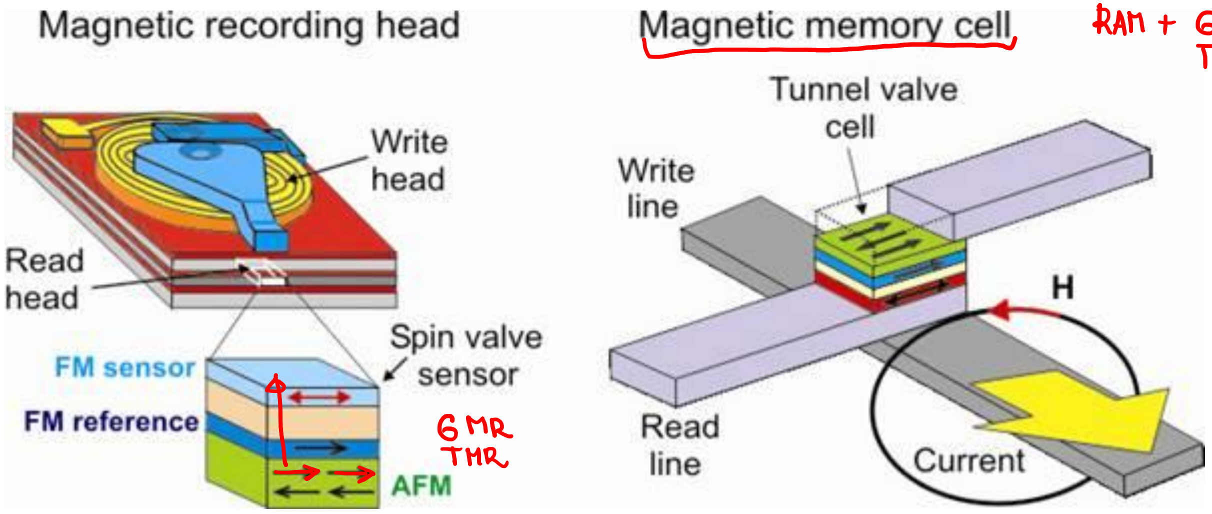
Radu F., Zabel H. (2008) Exchange Bias Effect of Ferro-/Antiferromagnetic Heterostructures. Springer Tracts in Modern Physics

EFEKTY REDUKOVANÉ DIMENZE – EXCHANGE BIAS

2D OMEZENÍ : TENKÉ VRSTVY

HETEROSTRUKTURY :

MRAM



RAM + GMR
TMR

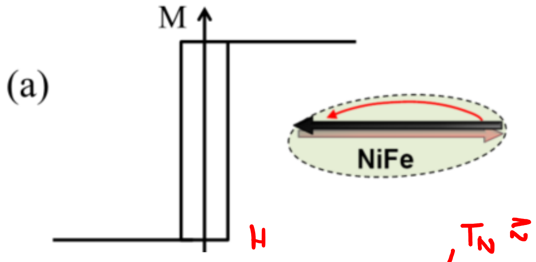
0 ⟷ 1

EFEKTY REDUKOVANÉ DIMENZE – EXCHANGE BIAS

2D OMEZENÍ: TENKÉ VRSTVY

HETEROSTRUKTURY:

→ EXCHANGE BIAS OVLÁDÁNÍ AFM

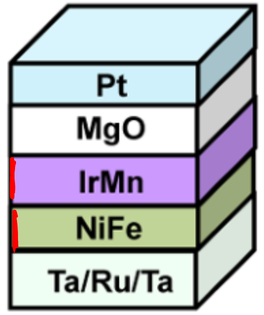


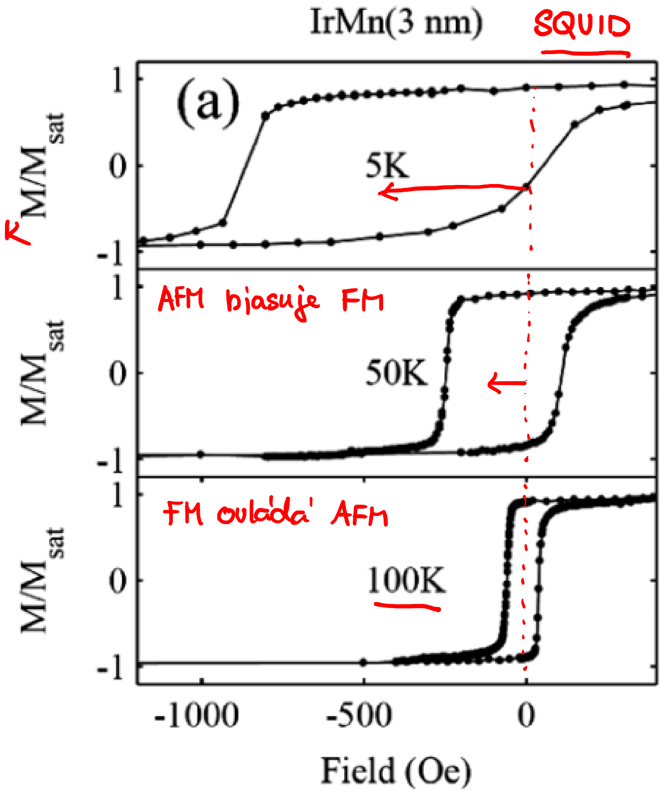
$T_N \approx 700K$

úhel

AFM

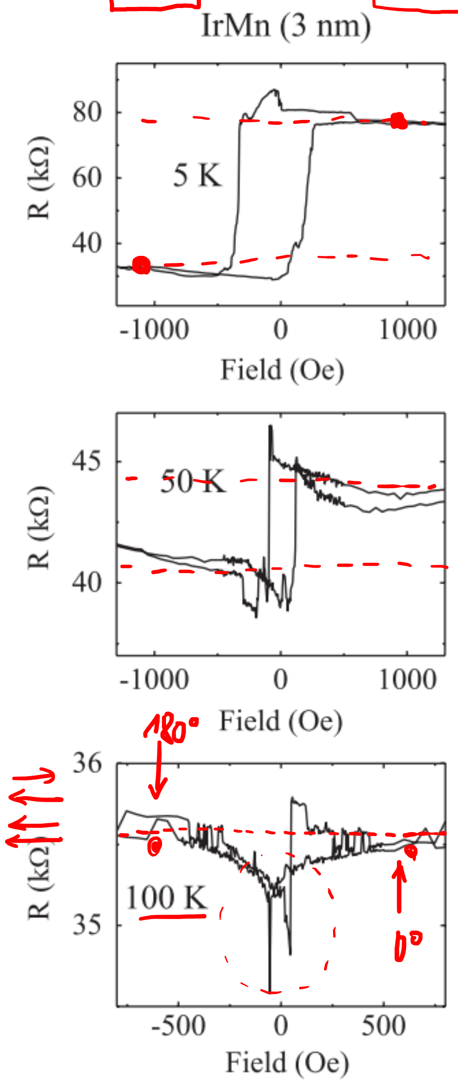
FM





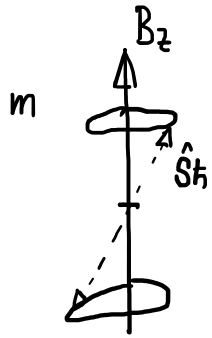
TUNNELLING ANISOTROPIC MAGNETORESISTANCE → "GMR" MLD AMR

$R(0°) = R(180°) \neq R(90°)$



X. Marti et al., PRL 108, 017201 (2012)

MAGNETICKÁ REZONANCE



KVANTOVĚ

$\vec m = \gamma \hbar \hat S$

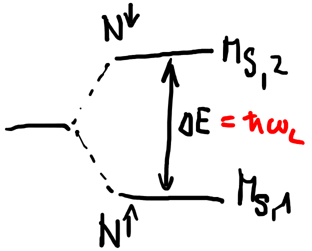
$\hat H = -\vec m \cdot \vec B_0 = -\gamma \hbar \hat S_z B_0$

$E = \gamma \hbar B_0 m_s \qquad m_s = s, s-1, \dots, -s$

$\Delta E = \hbar \omega_L \qquad \omega_L = \gamma B_0 = \frac{eg}{2m} B_0$

← také $\frac{\mu_B}{\hbar}$

$\Delta E = \mu_B g B_0$



PŘECHOD:

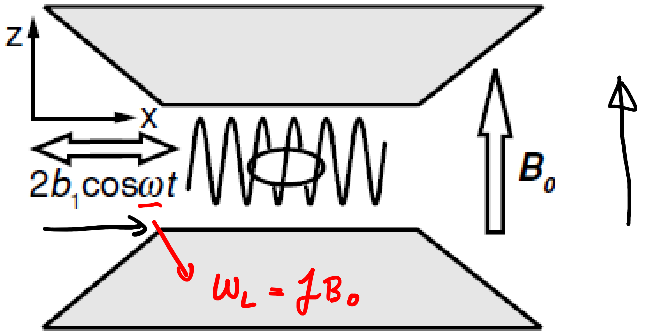
$\langle m_{s,2} | \hat H | m_{s,1} \rangle$

$\hat H \propto \hat S_z \rightarrow \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

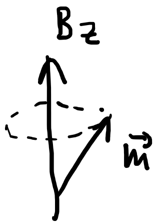
⇒ čisté stavy ⇒ 0

$\hat H \propto \hat S_x$

$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ "DIPOLAR SELECTION RULES"



KLASICKY

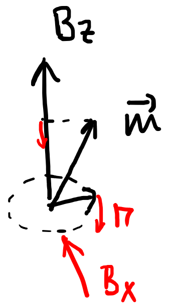


$\Gamma = \vec m \times \vec B_0$

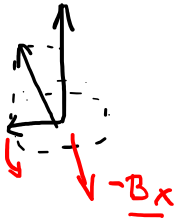
torque = změna ang. mom. $\vec L$: $\vec m = \gamma \vec L$

$\frac{d\vec m}{dt} = \dot{\vec m} = \gamma\, \vec m \times \vec B_0$ → řešení ve složkách

m_z = konst. → $\omega_L = \gamma B_0$



B musí být ⊥ na $\hat z$



⇒ B_x harmonicky kmitá na ω_L

rezonance

MAGNETICKÁ REZONANCE

Numbers:

$f_L = \frac{\omega_L}{2\pi} = \frac{eg}{2\pi\, 2m} B_0$

pro e^- : $g \sim 2$ (vakuum)

1T ... 28 GHz

pro p^+ : 1T ... 43 MHz

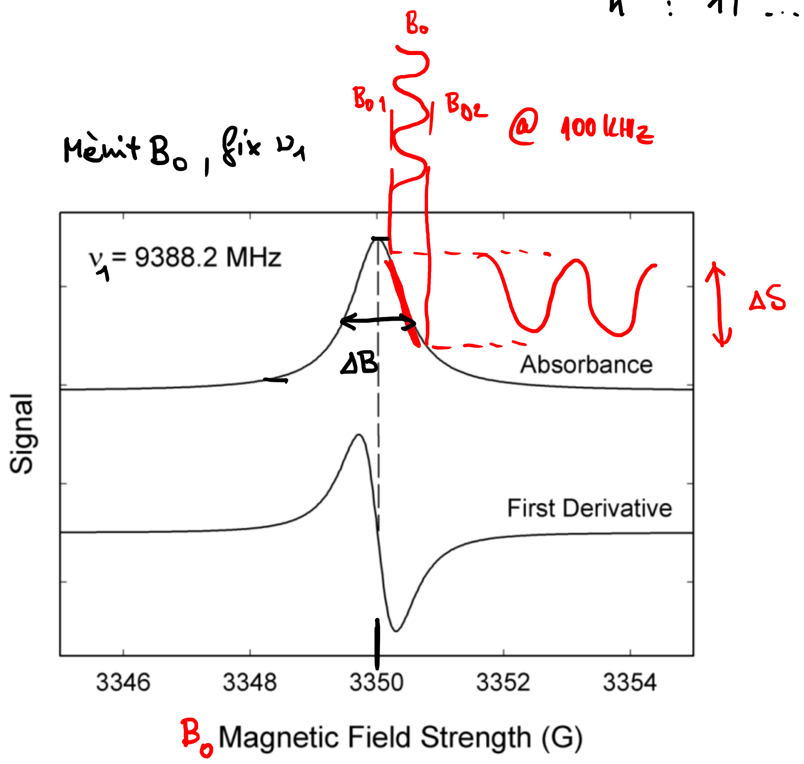
n^0 : 1T ... 29 MHz

$\underbrace{\left(\frac{N^\downarrow}{N^\uparrow}\right)_0 \sim e^{-\frac{\hbar\omega}{kT}}}$

$P = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \sim \underline{\underline{10^{-3}}}$ @ 300 mT RT

Měnit B_0, fix ν_1

B_0 B_{01} B_{02} @ 100 kHz

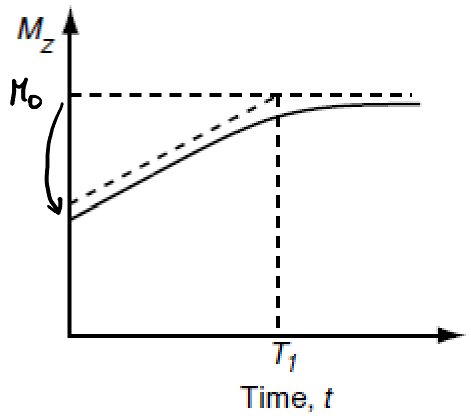


$\Downarrow$ g

RELAXAČNÍ ČAS (LONGITUDINÁLNÍ)

SPIN - LATTICE RELAX. TIME

$M_z = 1 - e^{-t/T_1}$



$\Delta t \Delta E \sim \hbar$

$\downarrow$

$T_1 \Delta B \sim \frac{\hbar}{\mu_B g}$

$\Delta B \sim 1\,\text{mT} \rightarrow T_1 \sim \underline{\underline{5\,\text{ns}}}$

→ preference $L=0$, $S \neq 0$ ⇒ $J = S$ ⇒ small coupling to lattice

$T_1 \uparrow$ $\Delta B \downarrow$ pozorovatelné

MAGNETICKÁ REZONANCE

REZONANCE **PARAMAGNETICKÁ (ELEKTRONOVÁ)**

$E = g \mu_B B m_J$ (2)

→ často $L=0$ $\qquad g = \underbrace{\frac{S(S+1) - L(L+1)}{2J(J+1)}}_{} + \frac{3}{2} = 2 = g_e$

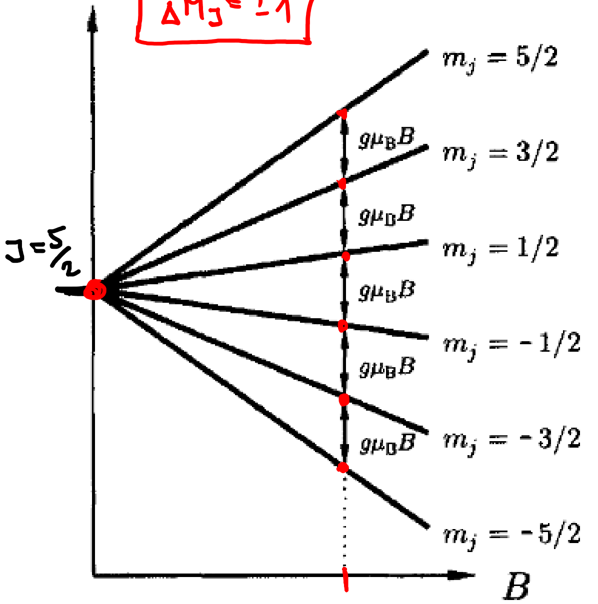
Př. Mn^{2+} $(3d^5)$: $l=2$ $\qquad m_l$: $-2\ -1\ 0\ 1\ 2$ ($\uparrow\ \uparrow\ \uparrow\ \uparrow\ \uparrow$), $1/2$ $\qquad L=0 \quad S = 5 \cdot \frac{1}{2} = \frac{5}{2}$

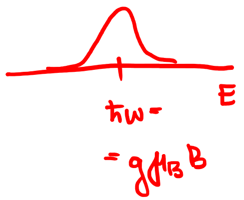
$J = ?$ $\qquad |L-S| \le J \le |L+S|$

$J = 5/2$

$m_J = -J, -J+1 \ldots J$

$\boxed{\Delta M_J = \pm 1}$



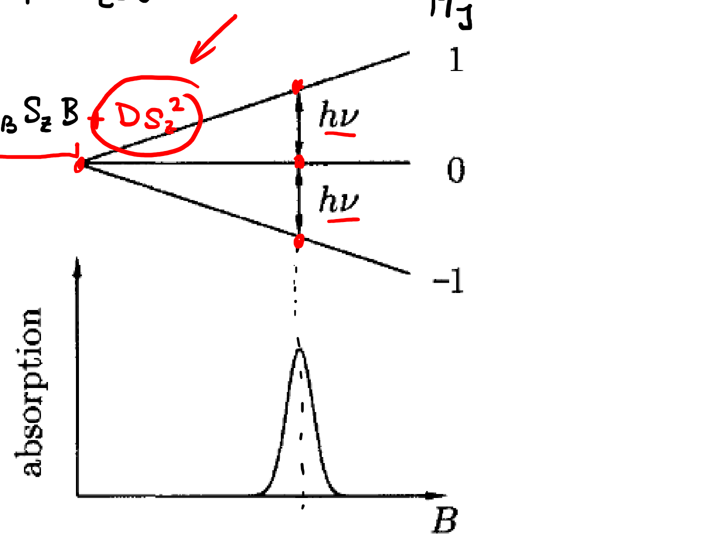


→ Efekt krystal. pole :

pro $J = S = 1 \quad L=0$

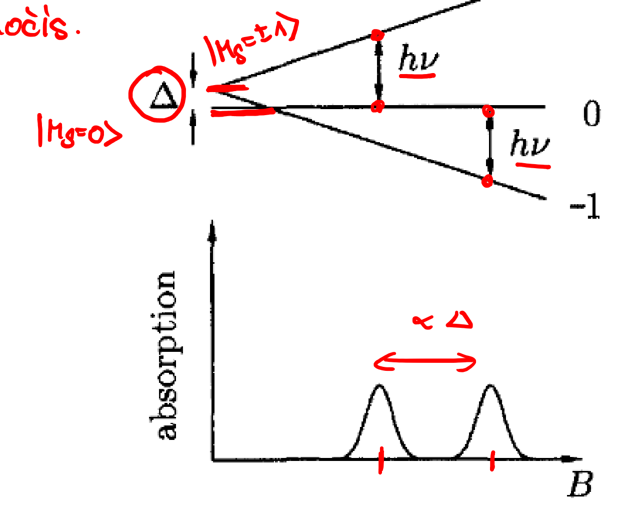
UNIAXIÁLNÍ SYMETRIE KRYST. POLE

$\hat{H}_{EF} = \underbrace{-g_{EF} \mu_B S_z B}_{} + DS_z^2$



Kramer's doublets

J : celočís.



REZONANCE

PARAMAGNETICKÁ (ELEKTRONOVÁ)

$Ce^{3+}\ (4f^1)$

$L = 3 \quad S = 1/2$

$J = \frac{5}{2}, \frac{7}{2}$

NUKLEÁRNÍ MOMENT:

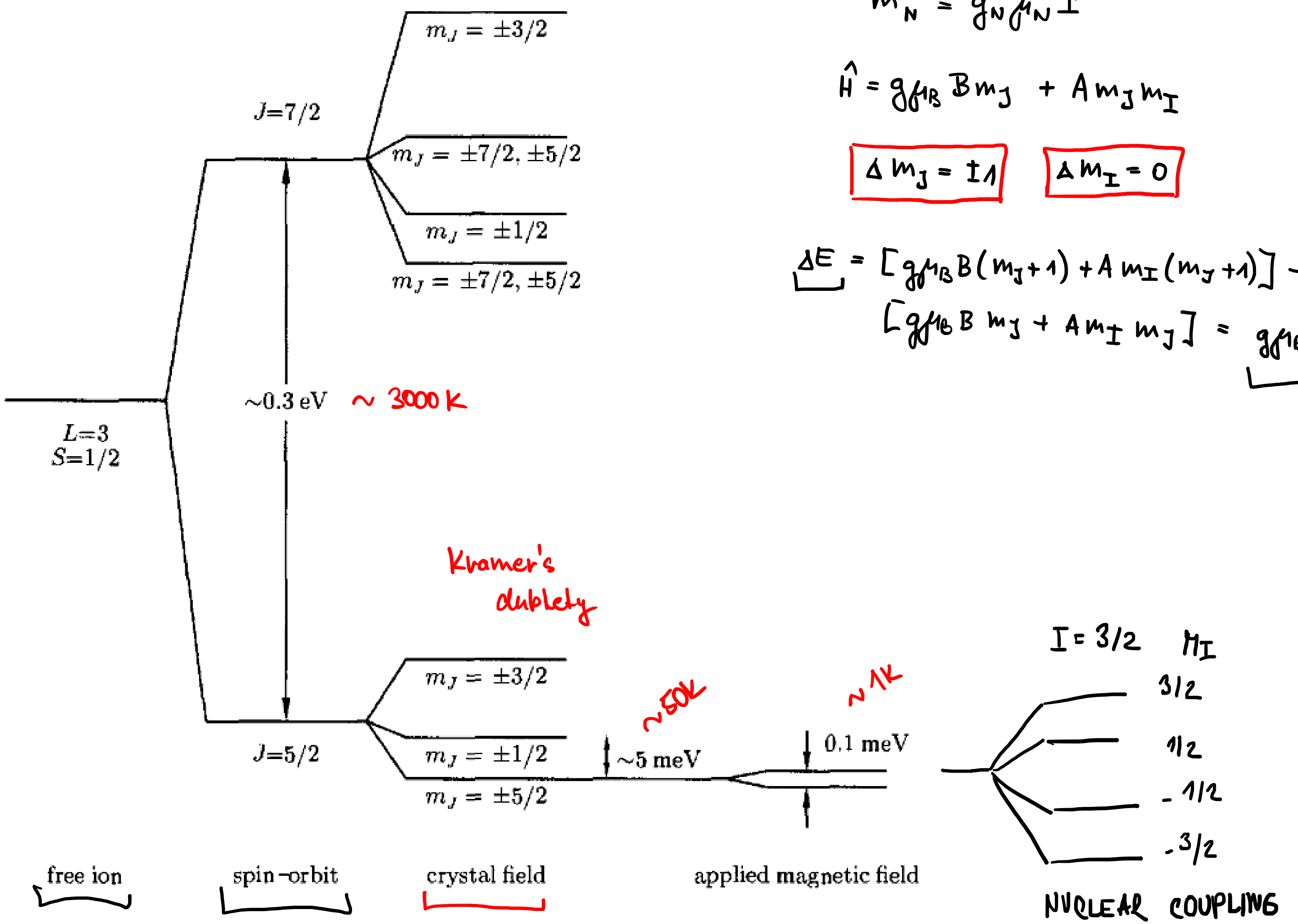
$\hbar I$

$m_N = g_N \mu_N I$

$\hat{H} = g\mu_B B m_J + A m_J m_I$

$\boxed{\Delta m_J = \pm 1}$ $\boxed{\Delta m_I = 0}$

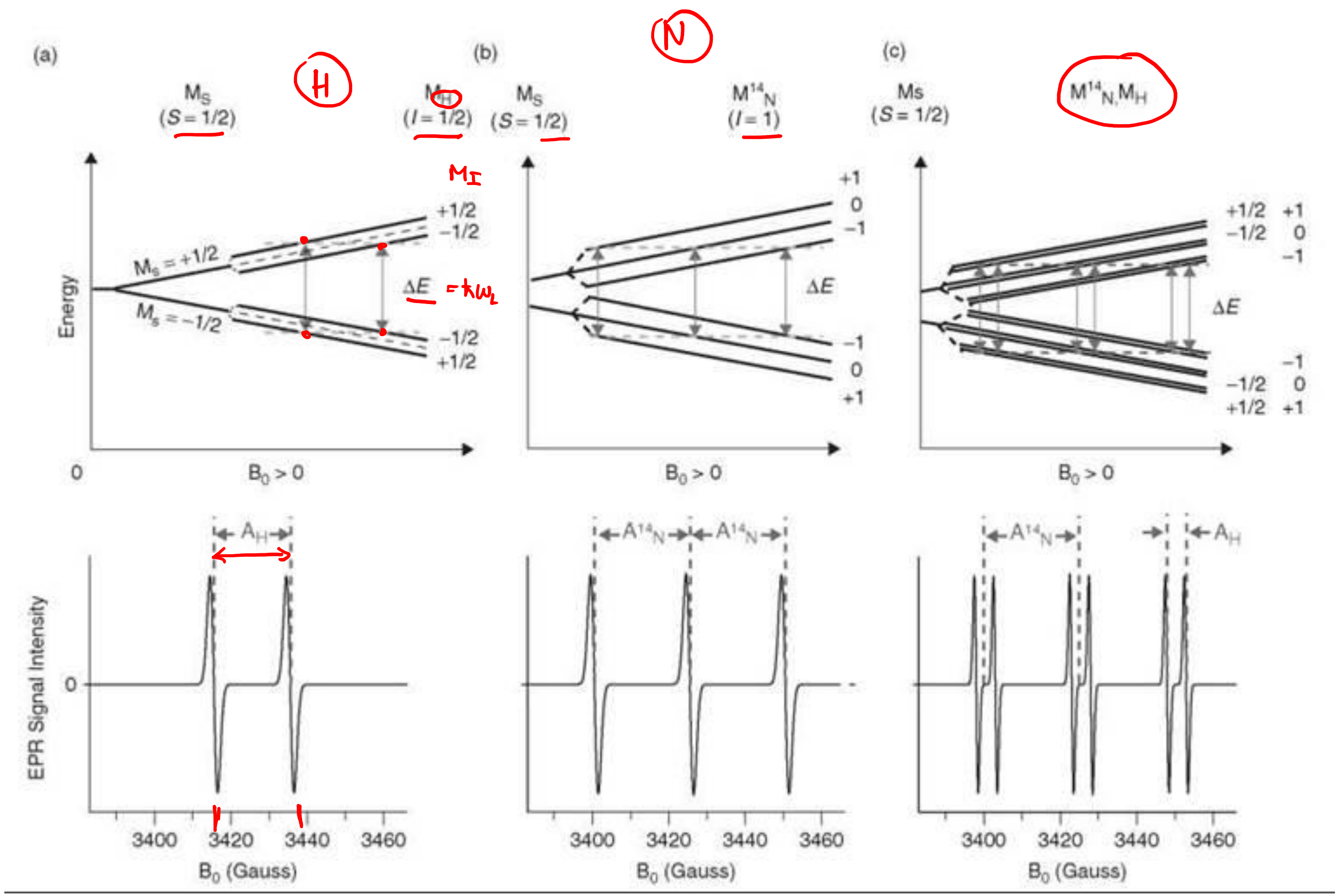
$\Delta E = [g\mu_B B(m_J+1) + A m_I (m_J+1)] - [g\mu_B B m_J + A m_I m_J] = g\mu_B B + A m_I$



REZONANCE

PARAMAGNETICKÁ (ELEKTRONOVÁ)

($1s^2 2s^2 2p$)



MAGNETICKÁ REZONANCE

REZONANCE $\boxed{\text{FEROMAGNETICKÁ}}$

$B_0' = \mu_0 H_0'$ vnější pole

$$\boxed{\dot{M} = \gamma \vec{M} \times \vec{B}_0'} \qquad \gamma = -\frac{e}{m_e}$$

$$\rightarrow \nu = \frac{\omega_L}{2\pi} = \frac{\gamma \overset{0.3T}{B_0}}{2\pi} \sim \underbrace{10\,GHz} \text{ jako ESR}$$

→ spin dominantní přísp. v kovech

VNITŘ FM: $H = H' + H_D + H_A$

$$H_D = -\mathcal{N} M \qquad \mathcal{N} = \begin{pmatrix} \mathcal{N}_x & 0 & 0 \\ 0 & \mathcal{N}_y & 0 \\ 0 & 0 & \mathcal{N}_z \end{pmatrix} \qquad \left(H_A = -\frac{2K_1}{M} \right)$$

→ rezonance $H' = H_0' \hat{z}$

$$M = M_s \hat{z} + m(t) \qquad m(t) = m_0 e^{i\omega t} \text{ inplane}$$

$$\rightarrow H_D = -[\mathcal{N}_x m_x, \mathcal{N}_y m_y, \mathcal{N}_z \overbrace{(m_z + M_s)}^{M \equiv M_z}]$$

$$\vec{H} = H_D + H' = \dots \qquad \vec{M} = (m_x, m_y, M)$$

pro m:

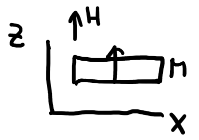
$$\dot{m}_x = i\omega m_x = \mu_0 \gamma (m_y H_z - M H_y) = \mu_0 \gamma \underbrace{[H_0' + (\mathcal{N}_y - \mathcal{N}_z) M]}_{[\,]_1} m_y$$

$$\dot{m}_y = i\omega m_y = -\mu_0 \gamma \underbrace{[H_0' + (\mathcal{N}_x - \mathcal{N}_z) M]}_{[\,]_2} m_x$$

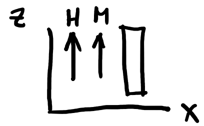
$$\begin{bmatrix} i\omega & -[\,]_1 \\ [\,]_2 & i\omega \end{bmatrix} = 0 \Rightarrow \omega^2 = \mu_0^2 \gamma^2 [H_0' + (\mathcal{N}_x - \mathcal{N}_z) M][H_0' + (\mathcal{N}_y - \mathcal{N}_z) M]$$

Kittel rce

pro kouli: $\mathcal{N}_{x,y,z} = 1/3$ $\quad \omega = \mu_0 \gamma H_0'$ ← H_A



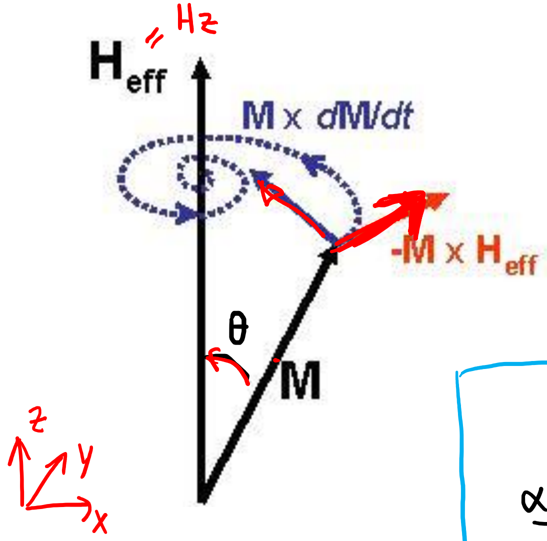
$\mathcal{N}_z = 1, \mathcal{N}_{x,y} = 0 \Rightarrow \omega = \mu_0 \gamma (H_0' - M)$



$\mathcal{N}_x = 1, \mathcal{N}_{y,z} = 0 \Rightarrow \omega = \mu_0 \gamma \sqrt{H_0'(H_0' + M)}$

MAGNETICKÁ REZONANCE

REZONANCE $\boxed{\text{FEROMAGNETICKÁ}}$ S DAMPINGEM (TLUMENÍ)



$$\dot{M} = \mu_0 \gamma M \times H - \gamma \frac{\lambda}{M} M \times (M \times H)\, \mu_0$$

$$\boxed{\dot{M} = \mu \gamma M \times H - \frac{\alpha}{M} M \times \dot{M}}$$

α DAMPING KONST.

$\underline{\alpha = 0}$

$\dot{M}_x = \mu_0 \gamma M_y H_z \qquad \dot{M}_y = -\mu_0 \gamma M_x H_z \qquad \dot{M}_z = 0$

$$\ddot{M}_x = \mu_0 \gamma H_z \dot{M}_y = \underbrace{-\mu_0^2 \gamma^2 H_z^2}_{\omega_0^2} M_x$$

$\omega_0 = \mu_0 \gamma H_z$

$M_x = M_s e^{i\omega t} \sin\theta$

$M_y = i e^{i\omega t} \sin\theta$

$M_z = M_s \cos\theta \Rightarrow$ konst.

$\underline{\alpha \neq 0}$

$$\dot{M}_x = \omega_0' \left[M_y - \alpha \frac{M_x M_z}{M_s} \right] \quad \& \quad \dot{M}_z \neq 0 \Rightarrow \theta(t)$$

$$\omega_0' = \frac{\omega_0}{1 + \alpha^2}$$

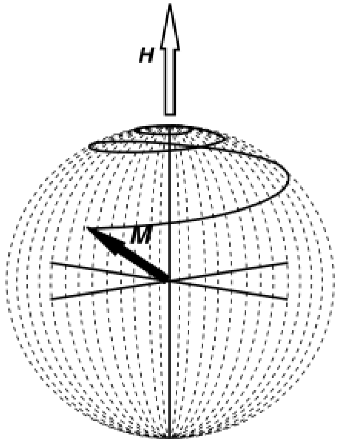
frekv. $\downarrow$ s $\alpha \uparrow$

$$\dot{M}_x = i\omega M_s e^{i\omega t} \sin\theta + M_s e^{i\omega t} \cos\theta \cdot \dot{\theta} = \omega M_y + \frac{M_z M_x}{M_s \sin\theta} \dot{\theta}$$

$\Rightarrow \omega = \omega_0'$ skutečně preceduje na ω_0'

$\Rightarrow \underbrace{\dot{\theta} = -\omega_0' \alpha \sin\theta}$

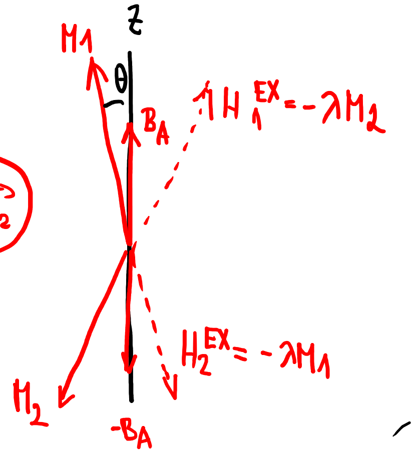
→ kam $\vec{M}$ odchází? "SPIN PUMPING"



MAGNETICKÁ REZONANCE

REZONANCE $\boxed{\text{ANTIFEROMAGNETICKÁ}}$

$\vec{L} = \vec{M_1} - \vec{M_2}$



$H_A = \frac{2K}{M}$ $\quad E_A = K\sin^2\theta$

$H_1^z = H_A + \lambda M$

$H_1 = H_A - \lambda M_2$ $\quad M_1^z = M \quad M_2^z = -M$

$H_2 = -H_A - \lambda M_1$ $\quad H_2^z = -H_A - \lambda M$

$$+\begin{cases} \dot{M}_1^x = \gamma\mu_0 [\overset{M_y}{M_1^y} (\overset{H_z}{\lambda M + H_A}) - \overset{M_z}{M} (\overset{H_y}{-\lambda M_2^y})] \\ \times i \quad \dot{M}_1^y = \gamma\mu_0 [\overset{M_z}{M} (\overset{H_x}{-\lambda M_2^x}) - \overset{M_x}{M_1^x} (\overset{H_z}{\lambda M + H_A})] \end{cases}$$

$$+\begin{cases} \dot{M}_2^x = \gamma\mu_0 [M_2^y (-\lambda M - H_A) - (-M)(-\lambda M_1^y)] \\ \times i \quad \dot{M}_2^y = \gamma\mu_0 [(-M)(-\lambda M_1^x) - M_2^x (-\lambda M - H_A)] \end{cases}$$

$M_1^+ = M_1^x + i M_1^y \qquad M_2^+ = M_2^x + i M_2^y$

$\underbrace{M_1^+ \to M_1^+ e^{-i\omega t}}$

$$\dot{M}_1^+ = -i\omega t M_1^+ = -i\gamma\mu_0 [M_1^+ (H_A + \lambda M) + M_2^+ (\lambda M)]$$

$$\dot{M}_2^+ = -i\omega t M_2^+ = i\gamma\mu_0 [M_2^+ (H_A + \lambda M) + M_1^+ (\lambda M)]$$

(zkusit doplnit M_1^+ a vyjde to)

$\underbrace{\lambda M = H_E}$

→ řešení existuje, pokud $\begin{vmatrix} \gamma\mu_0 (H_A + H_E) - \omega & \gamma\mu_0 H_E \\ \gamma\mu_0 H_E & \gamma\mu_0 (H_E + H_A) + \omega \end{vmatrix} = 0$

$(A-B)(A+B) = A^2 - B^2$

$\Rightarrow \gamma^2\mu_0^2 (H_E + H_A)^2 - \omega^2 - \gamma^2\mu_0^2 H_E^2 = 0$

$\omega^2 = \gamma^2\mu_0^2 [(H_E + H_A)^2 - H_E^2] = \gamma^2\mu_0^2 [H_A^2 + 2 H_A H_E] \Rightarrow$

$\boxed{\omega = \gamma\mu_0 \sqrt{H_A (H_A + 2H_E)}} \sim 54\,T/\mu_0 \quad \underbrace{+\ \gamma\mu_0 H_0}$

$\boxed{1\,THz}$ $\quad 1\,T/\mu_0$

spin flop

→ záleží, zda jsme pod H_{SF}, nebo nad ním

S. Rezende et al., Introduction to AFM magnons, JAP 126 151101 (2019)

MAGNETICKÁ REZONANCE

REZONANCE $\boxed{\text{NUKLEÁRNÍ}}$ → podobné jako ESR : $g_N \sim 5{,}58$ $g_P \sim -3{,}83$ $\mu_N \approx \frac{e\hbar}{2m_p} \ll \mu_B$

→ $\frac{\omega_L}{2\pi} \sim$ 10 - 15 MHz | 0.3T
500 - 800 MHz / 12-20T

⇒ vlnovodů (ESR) → RF cívky (NMR)

$$\hat{H}_N = -g_N \mu_N \hat{I} \cdot B_{HF} + \dots .$$

B_0' + coupling na e^- spin (Knight's shift ... pro vodivostní e^-)
+ chemical shift (molekulární pole)

MAGNETICKÁ REZONANCE

$\boxed{\text{RELAXACE}}$

$\hat{z}$ $B_0 \uparrow$ $\rightarrow B_1 e^{i\omega t}$

$$\dot{M}_z = \gamma (M\times B)_z + \frac{M_0 - M_z}{T_1}$$

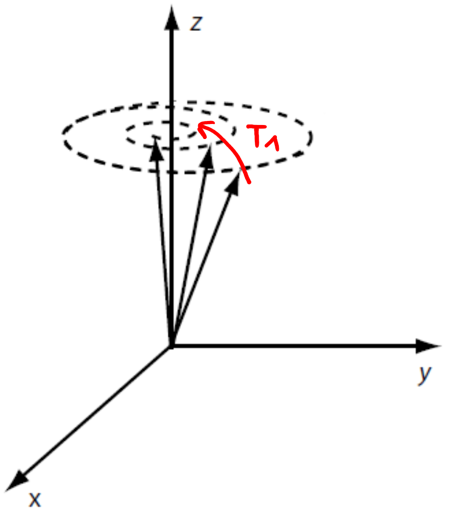
$$\dot{M}_x = \gamma (M\times B)_x - \frac{M_x}{T_2}$$

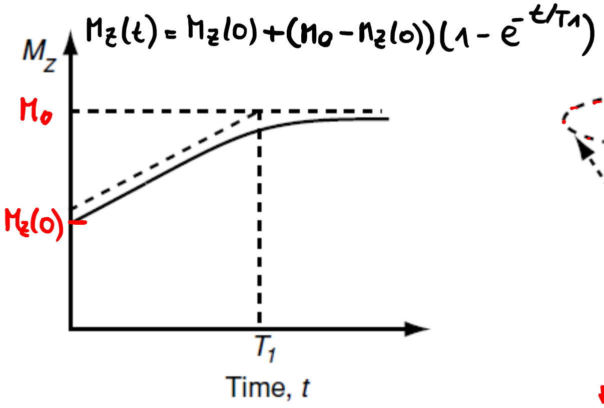
$$\dot{M}_y = \gamma (M\times B)_y - \frac{M_y}{T_2}$$

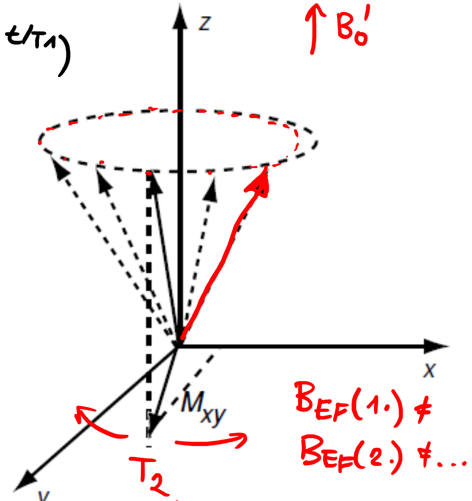
M_0 – rovnovážná pro $B_1 = 0$

LONGITUDINÁLNÍ RELAXAČNÍ ČAS (SPIN-TO-LATTICE)

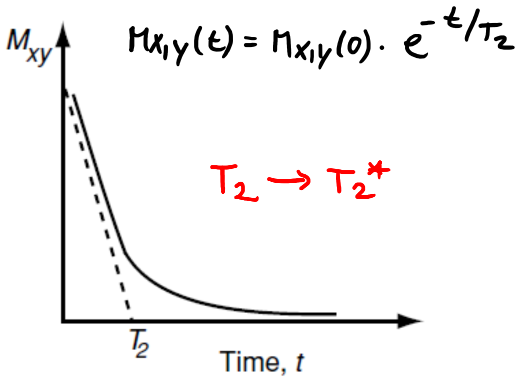
TRANSVERZÁLNÍ REL. ČAS (SPIN-TO-SPIN) – DEPHASING TIME







ROZFÁZOVÁNÍ ENSEMBLU SPINŮ



ČASOVĚ PROMĚNNÉ POLE B^{EF} A SPIN-SPIN VÝMĚNA

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \frac{1}{T_2^{INH.}}$$

PROSTOROVÁ NEHOMOG. B_{EF} B_0' (CHEMICAL SHIFTS)

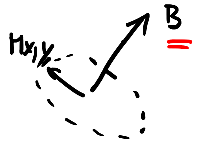
$T_1 > T_2$ pro NMR

$T_1 \sim T_2$ polovod. e^- spiny

MAGNETICKÁ REZONANCE

$\boxed{\text{PULZNÍ NMR | ESR...}}$

procese



$M_x \sim e^{i\omega t}$, φ

B_1

$\varphi = \overbrace{\gamma B}^{\omega} t$

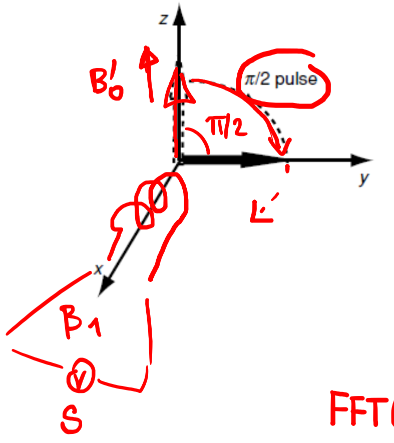
$t_{\pi/2} = \dfrac{\pi/2}{\gamma B}$ $t_\pi = \dfrac{\pi}{\gamma B}$

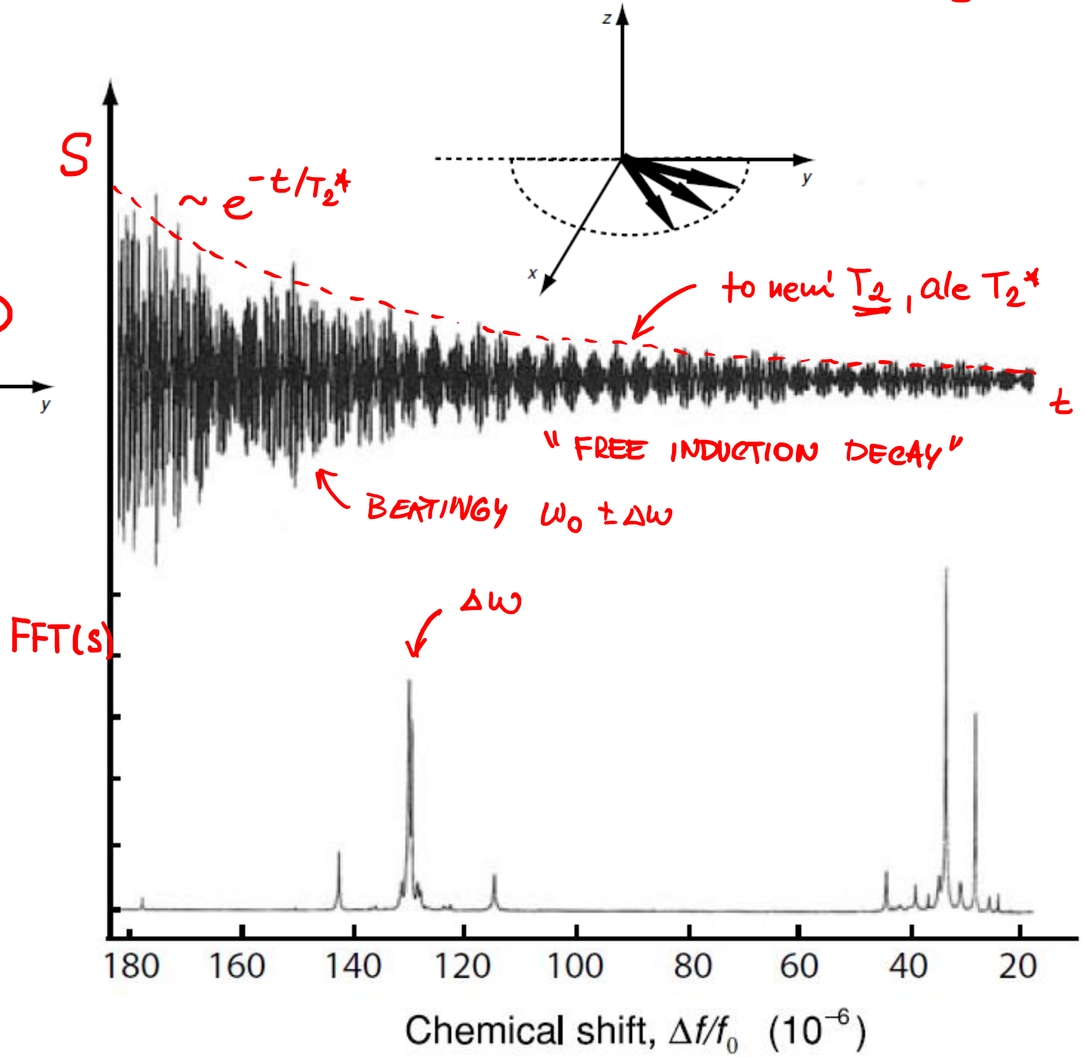
$\frac{\pi}{2}$-pulz π- pulz

→ pro B_1:

RF cívka v $\hat{x}$:

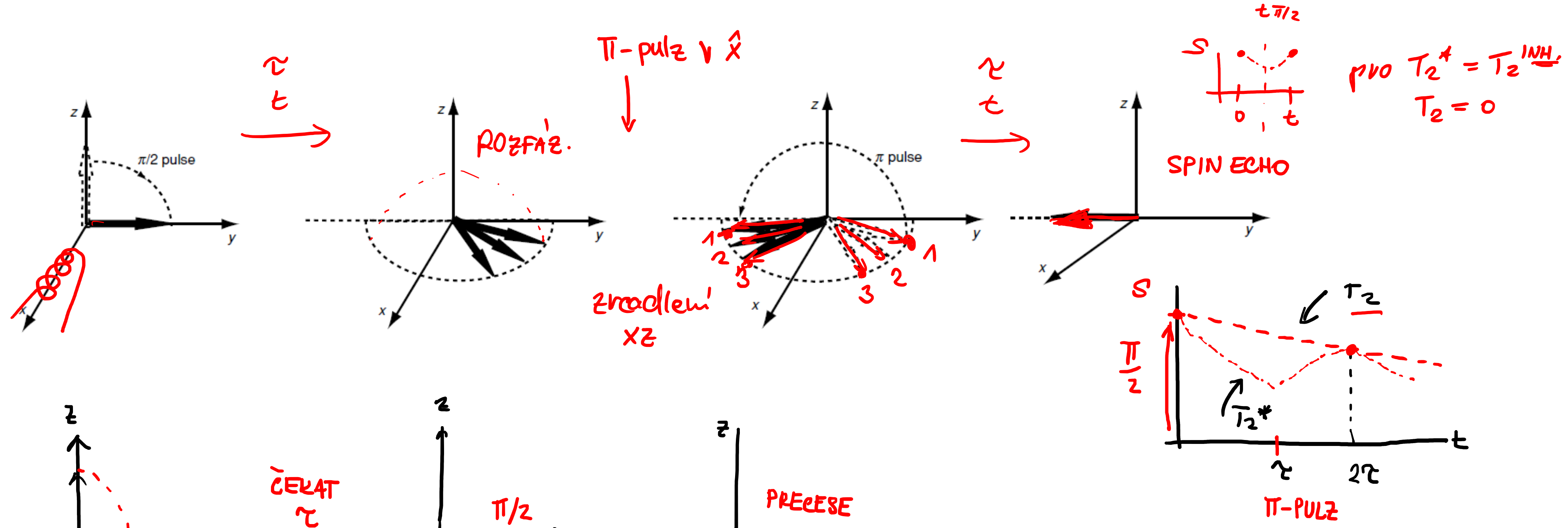
INDUKCE PŘI PRECESI



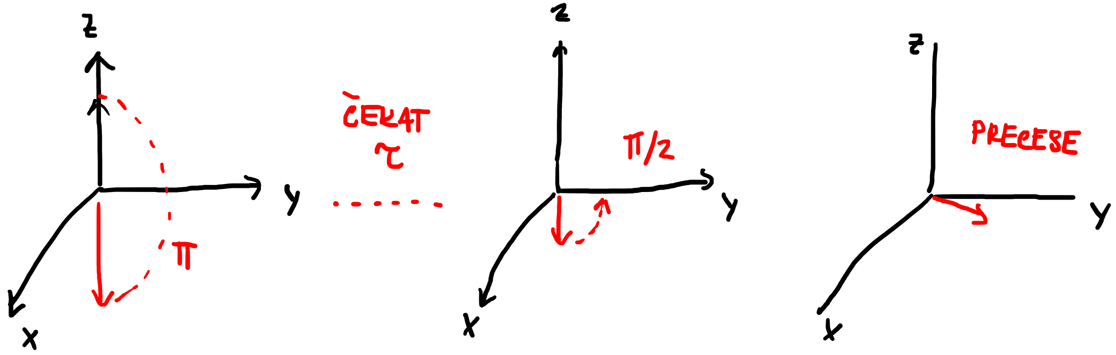


PULZNÍ NMR | ESR ...

$T_2 = ?$

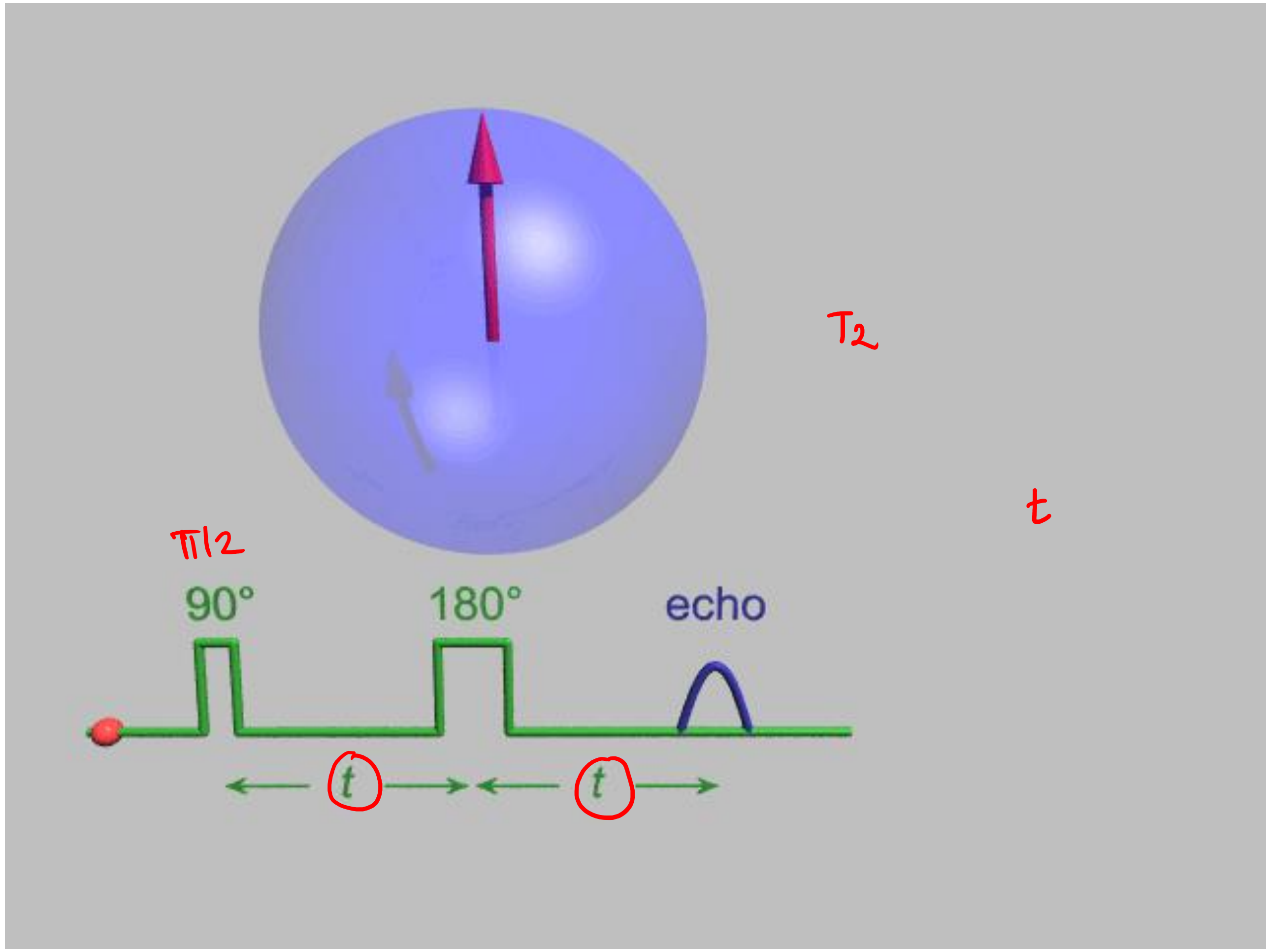


$T_1 - ?$



$\underbrace{M_z(\tau)} = S(0)$

MAGNETICKÁ REZONANCE



T_2

t