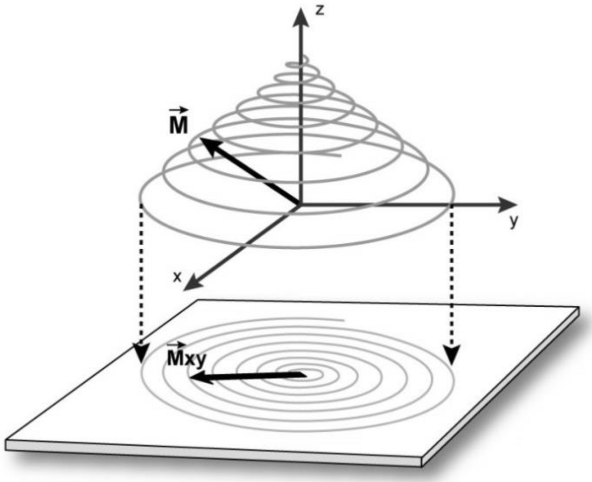
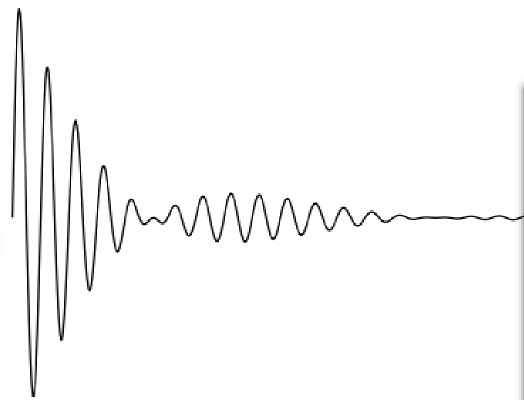
MAGNETISME & RMN

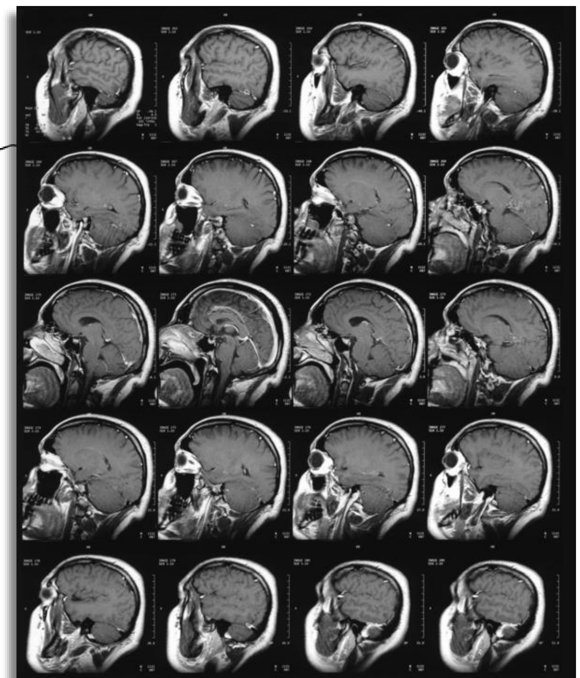
Bases physiques

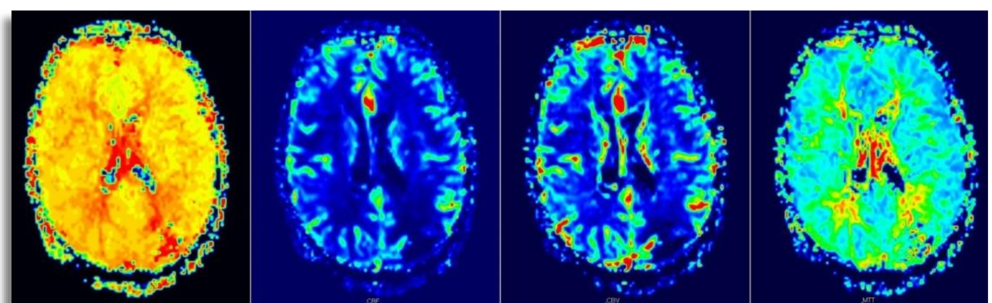
UE3 – Organisation des Appareils et des Systèmes

Bases physiques des méthodes d'exploration









Fayçal Ben Bouallègue
UM – CHU Montpellier
PACES 2018–2019

MAGNETISME & RMN

Bases physiques

Plan du cours

Contexte

- Champ et interaction électrique
- Champ et interaction magnétique

Electron atomique

Mécanique quantique

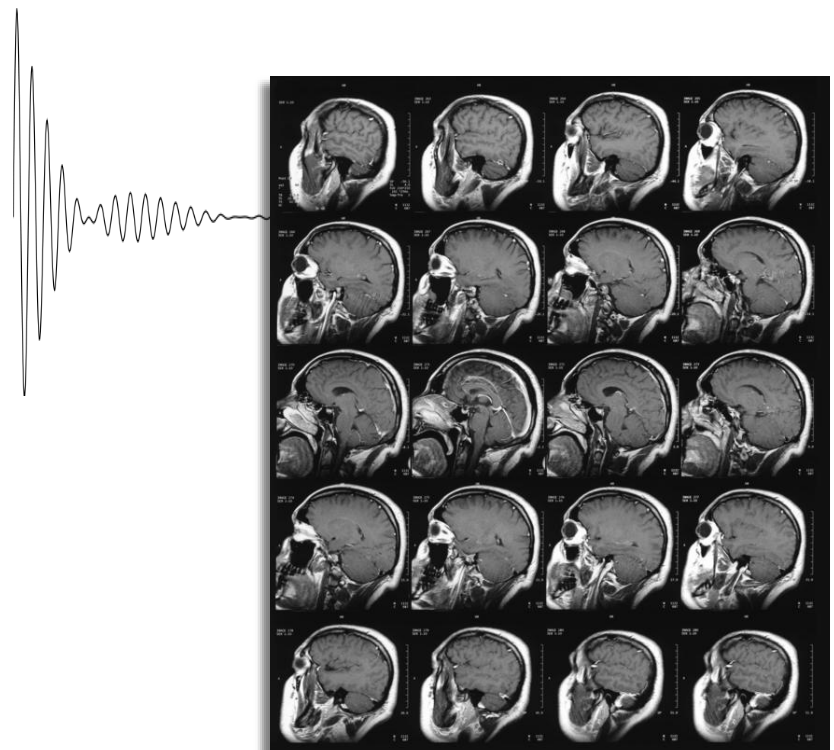
- Magnétisme dans la matière
- Magnétisme nucléaire

RMN – principe

RMN – séquence

RMN – contraste

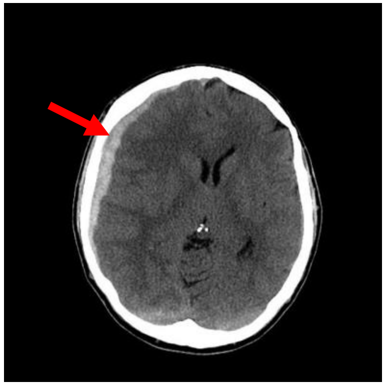
- Applications : IRM & SRM
- Illustrations



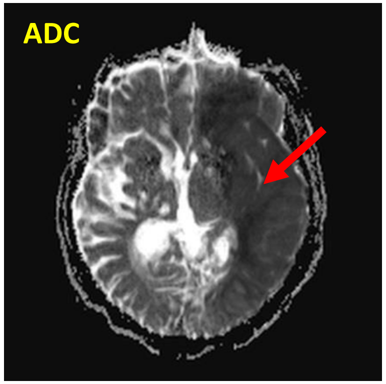
Contexte

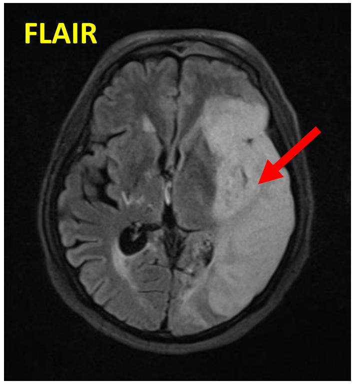
Explorations morphologiques en coupe

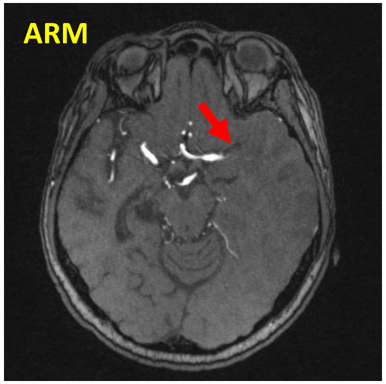
Scanner (TDM, tomodensitométrie)



Résonance magnétique (IRM)







Contexte

Explorations morphologiques en coupe

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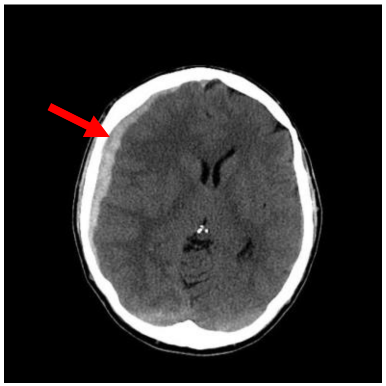
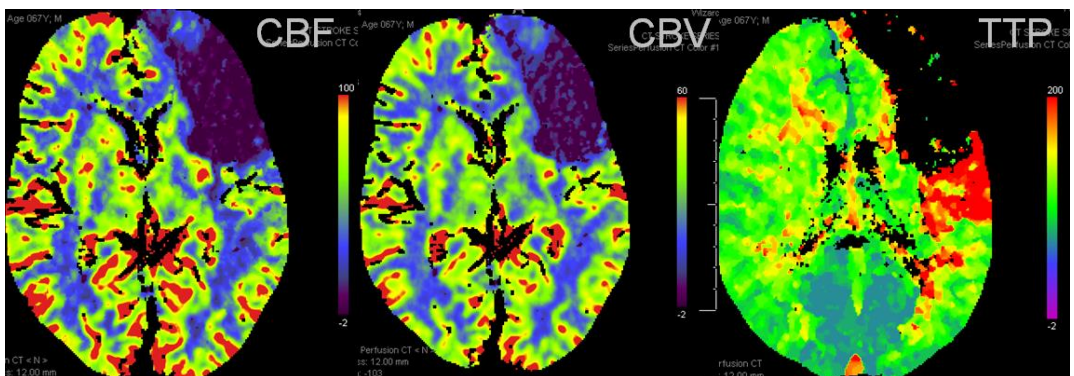



Résonance magnétique (IRM)

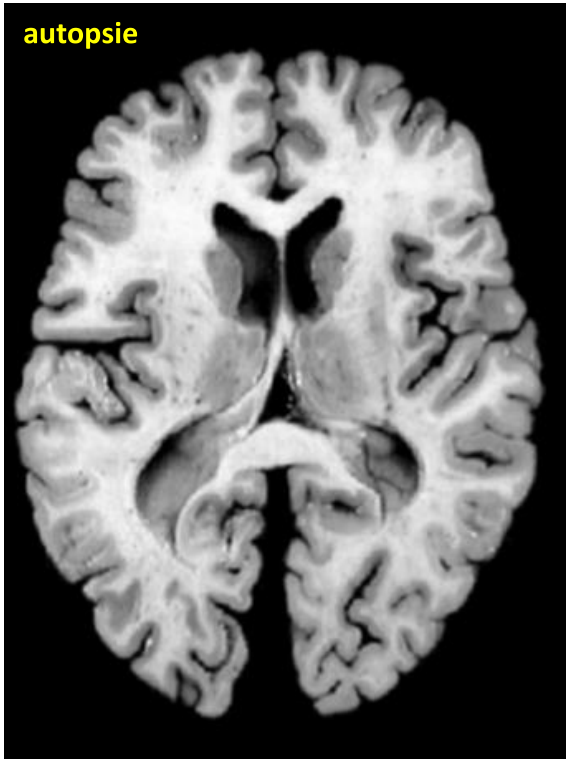



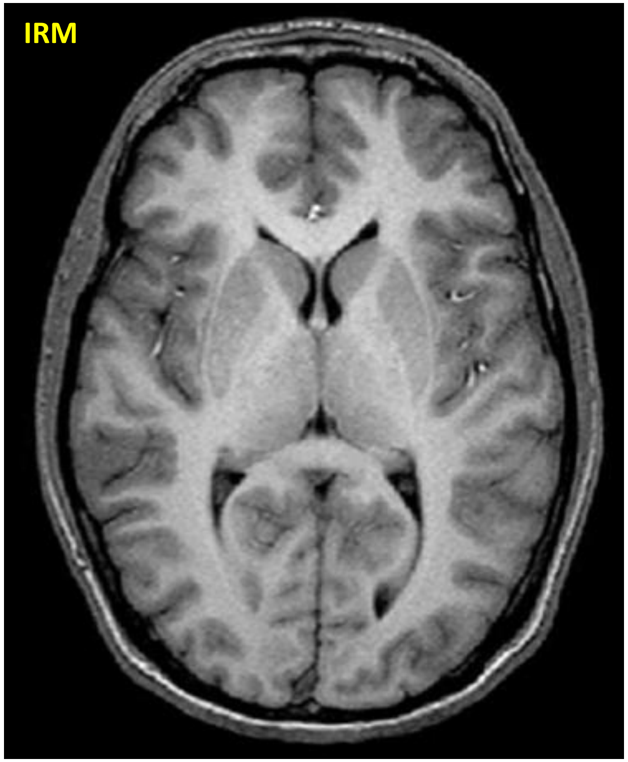
neuroangio.org

Contexte

Explorations morphologiques en coupe

IRM : excellent contraste des tissus mous





Contexte

Explorations morphologiques en coupe

IRM = examen de référence

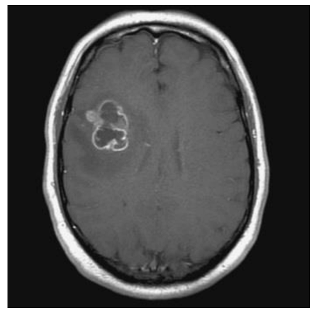
- Neurologie : neuro-vasculaire
  tumeurs
  pathologies SB
  infections
  MAV

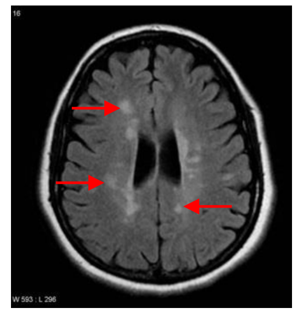
- Cardiologie : fonction VG/VD
  cardiopathies…

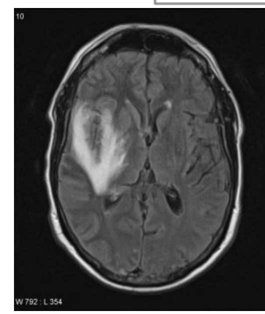
- Ostéo-articulaire
- Rachis

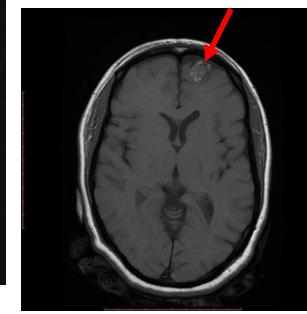
- Abdomen : foie, pancréas
- Pelvis : rectum, prostate

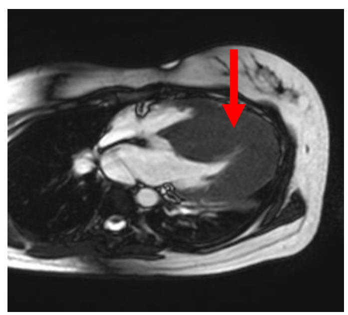
- Sein


glioblastome

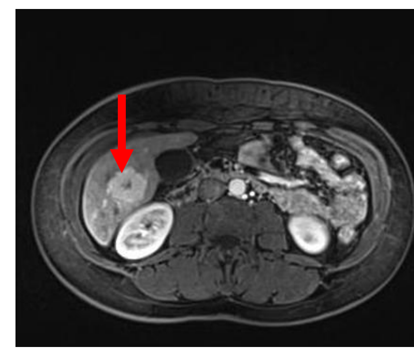

SEP

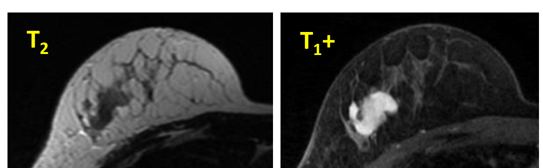

Encéphalite HSV


cavernome


CMH


Compression médullaire


HNF



CLI sein droit

Objectifs

- Expliciter les propriétés magnétiques de l'électron / du proton : spin, moment magnétique, énergie magnétique.
- Décrire le comportement d'un dipôle magnétique dans un champ magnétique externe : précession, fréquence de Larmor, alignement.
- Exposer le principe d'une expérience de RMN : préparation (aimantation), perturbation (résonance), recueil du signal.
- Détailler les étapes d'une séquence d'acquisition RMN ainsi que les différents paramètres ajustables (temps de répétition, temps d'écho, angle de bascule).
- Décrire les bases physiques des phénomènes de relaxation (T_1 et T_2).
- Analyser la manière dont le choix des paramètres ajustables influe sur le contraste dans l'image IRM.

Rappels & conventions

Grandeurs scalaires :

$$x, y, z, t$$
$$m, q, e$$
$$V(x, y, z)$$
$$\hbar = h/2\pi$$

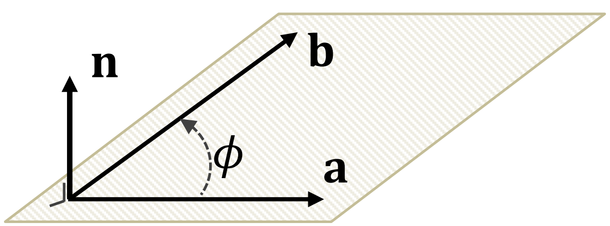
Grandeurs vectorielles :

$$\mathbf{x} = (x, y, z)$$
$$\mathbf{F}, \boldsymbol{\Gamma}$$
$$\mathbf{B}(\mathbf{x})$$
$$\mathbf{L} = (L_x, L_y, L_z)$$
$$\omega = |\boldsymbol{\omega}|$$

$$\boldsymbol{\nabla} f = \left(\frac{\partial f}{\partial x}\,;\frac{\partial f}{\partial y}\,;\frac{\partial f}{\partial z}\right)$$

Produit scalaire :

$$\mathbf{a} \cdot \mathbf{b} = a_x b_x + a_y b_y + a_z b_z$$
$$= a\ b \cos(\phi)$$



Produit vectoriel :

$$\mathbf{a} \wedge \mathbf{b} = (a_y b_z - a_z b_y, a_z b_x - a_x b_z, a_x b_y - a_y b_x)$$
$$= a\ b \sin(\phi)\ \mathbf{n}$$

Champ & interaction électrique

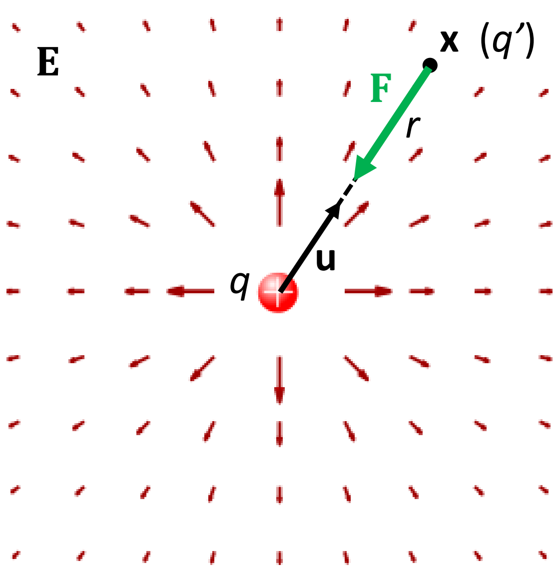
Source = charge *q* (monopôle électrique)

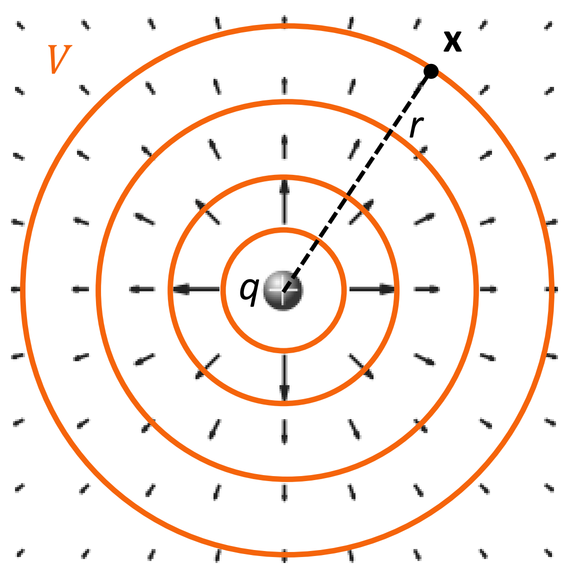
Champ : $\mathbf{E}(\mathbf{x}) = \dfrac{q}{4\pi\varepsilon_0\, r^2}\,\mathbf{u}$ [Vm[-1]]

Force : $\mathbf{F}(\mathbf{x}) = q'\mathbf{E}(\mathbf{x}) = \dfrac{q\,q'}{4\pi\varepsilon_0\, r^2}\,\mathbf{u}$ [N]

Potentiel : $V(\mathbf{x}) = \dfrac{q}{4\pi\varepsilon_0\, r}$ [V]

$\mathbf{E} = -\boldsymbol{\nabla} V$





Champ & interaction électrique

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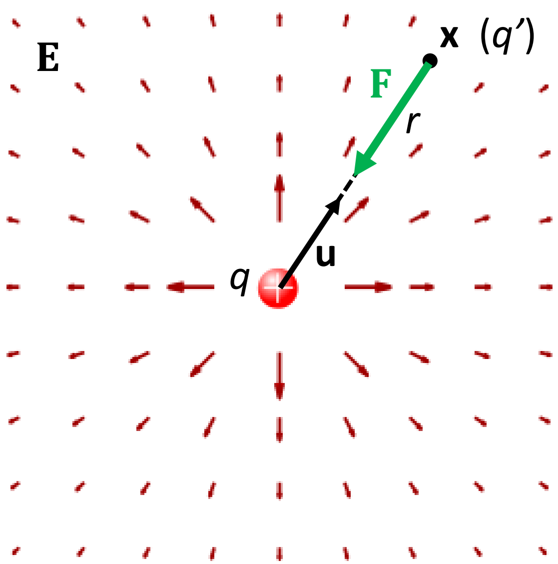
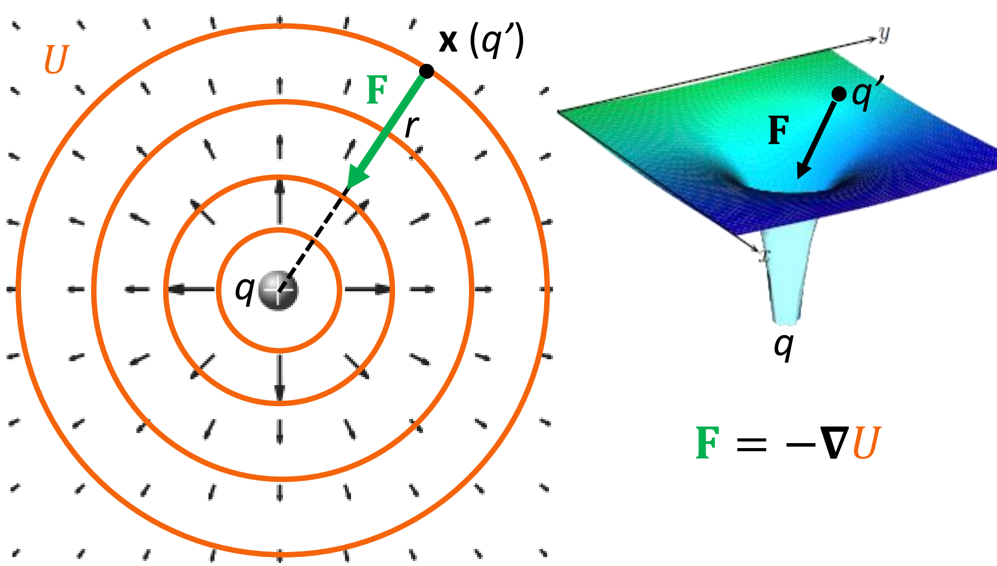
Force : $\mathbf{F}(\mathbf{x}) = q'\mathbf{E}(\mathbf{x}) = \frac{q\, q'}{4\pi\varepsilon_0\, r^2}\,\mathbf{u}$ [N]

Potentiel : $V(\mathbf{x}) = \frac{q}{4\pi\varepsilon_0\, r}$ [V]

Energie : $U(\mathbf{x}) = q'V(\mathbf{x}) = \frac{q\, q'}{4\pi\varepsilon_0\, r}$ [J]





$\mathbf{F} = -\boldsymbol{\nabla} U$

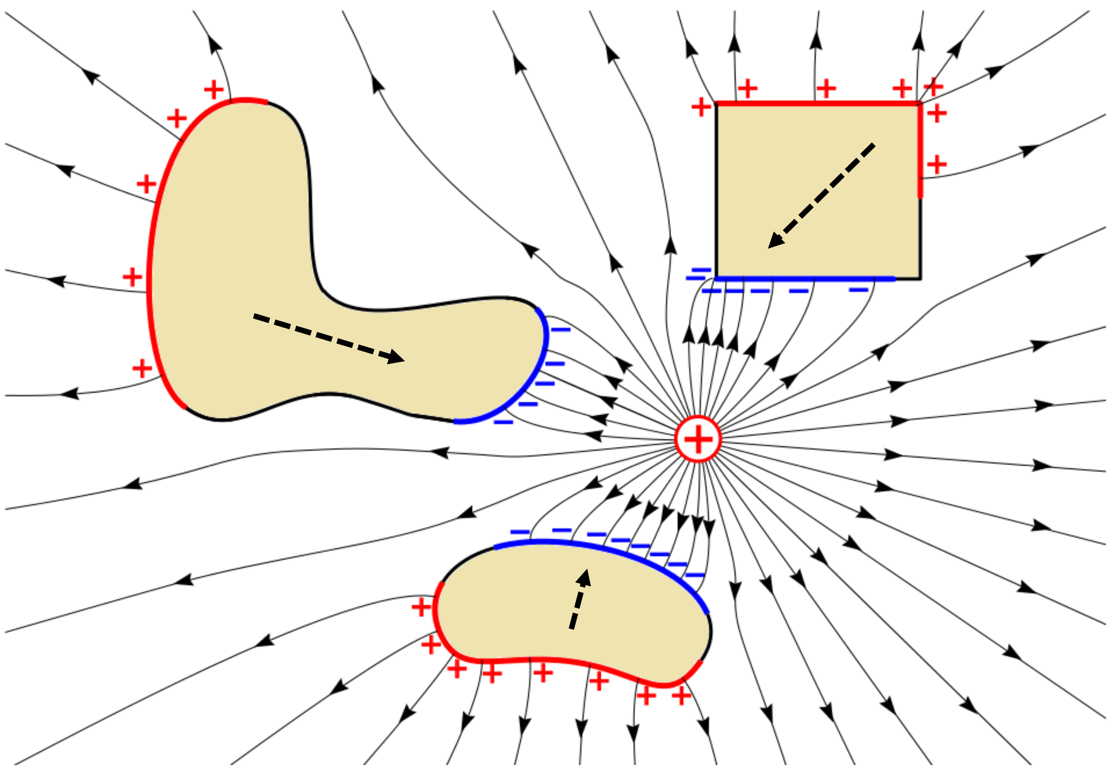
Champ & interaction électrique

Source = charge q (monopôle électrique)

Champ : $\mathbf{E}(\mathbf{x}) = \frac{q}{4\pi\varepsilon\, r^2}\mathbf{u}$ [Vm^{-1}]

Dans un matériau

$\varepsilon = (1+\chi)\varepsilon_0 > \varepsilon_0$

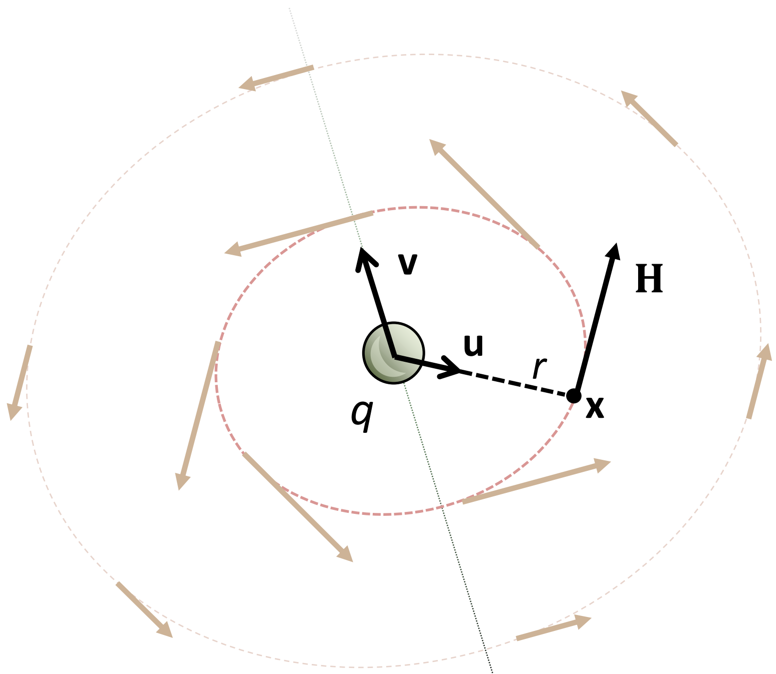


Champ & interaction magnétique

Source = charge en mouvement (q, $\mathbf{v}$)

Champ : $\mathbf{H}(\mathbf{x}) = \frac{q}{4\pi\, r^2}\, \mathbf{v} \wedge \mathbf{u}$ [Am^{-1}]

Champ (d'induction) : $\mathbf{B}(\mathbf{x}) = \mu\, \mathbf{H}(\mathbf{x}) = \mu \frac{q}{4\pi\, r^2}\, \mathbf{v} \wedge \mathbf{u}$ [T Tesla]



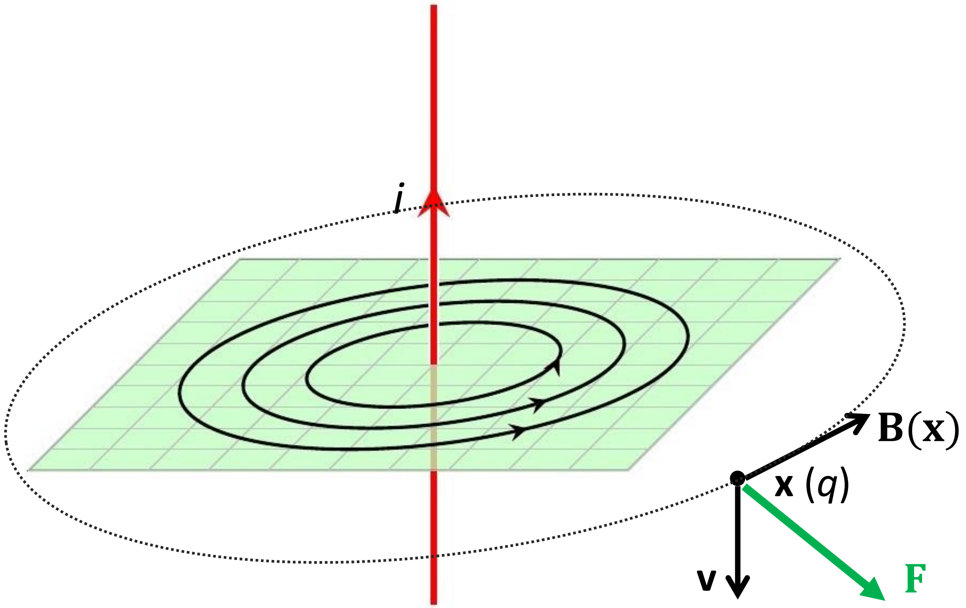
μ = perméabilité magnétique
Dans l'air : $\mu = \mu_0$

Champ & interaction magnétique

Source = courant $i = \mathrm{d}q/\mathrm{d}t$

Champ : $\mathbf{H}(\mathbf{x}) = \int_{fil} \frac{i}{4\pi\, r^2}\, \mathbf{dw} \wedge \mathbf{u} = \frac{i}{2\pi\, r} \mathbf{w} \wedge \mathbf{u}$ [Am^{-1}]

Champ **(d'induction)** : $\mathbf{B}(\mathbf{x}) = \mu\, \mathbf{H}(\mathbf{x}) = \frac{\mu\, i}{2\pi\, r} \mathbf{w} \wedge \mathbf{u}$ [T Tesla]



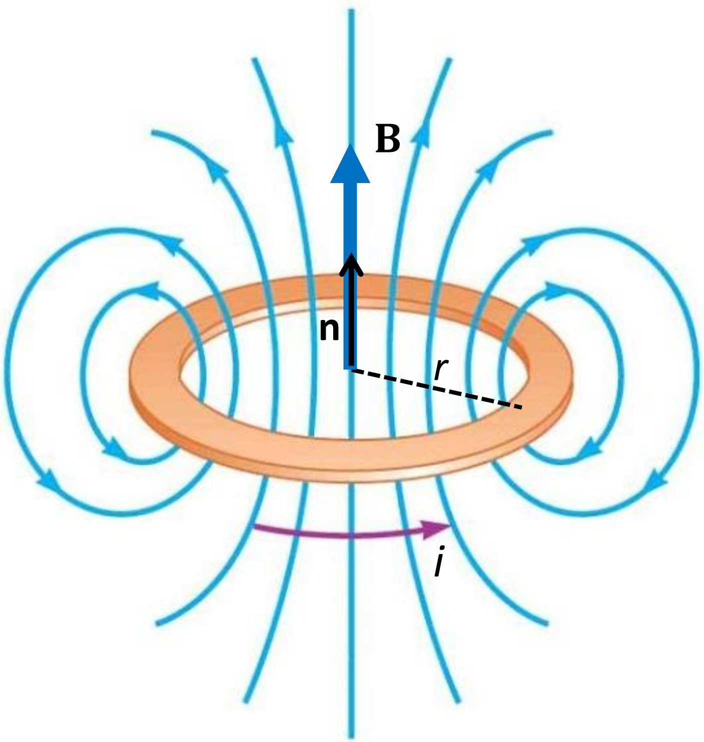
Force **(Lorentz)** :

$$\mathbf{F}(\mathbf{x}) = q\, \mathbf{v} \wedge \mathbf{B}(\mathbf{x}) \quad [\mathrm{N}]$$

Champ & interaction magnétique

Source = boucle de courant *i* = dipôle magnétique

Champ : $\mathbf{B} = \frac{\mu\, i}{2r}\mathbf{n}$

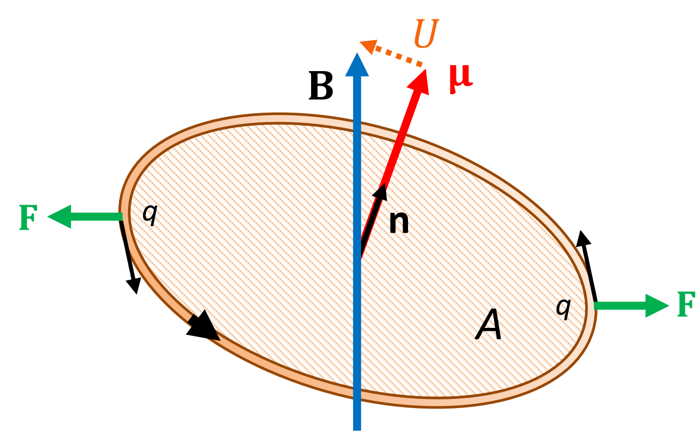


Cible = dipôle magnétique

Moment magnétique : $\boldsymbol{\mu} = A\, i\, \mathbf{n}$ [Am²]

Energie : $U = -\boldsymbol{\mu} \cdot \mathbf{B}$ [J]

Forces de Lorentz



Champ & interaction magnétique

Source = boucle de courant *i* = dipôle magnétique

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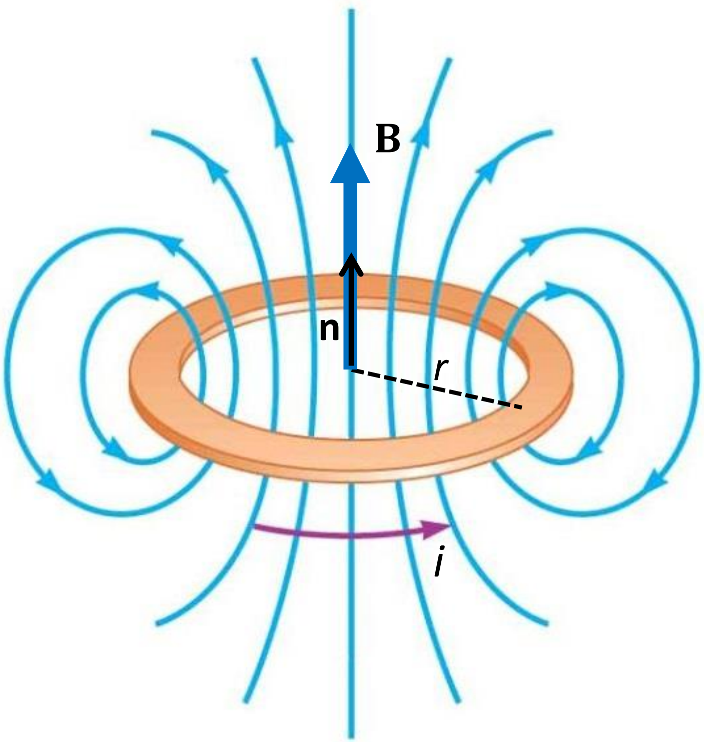

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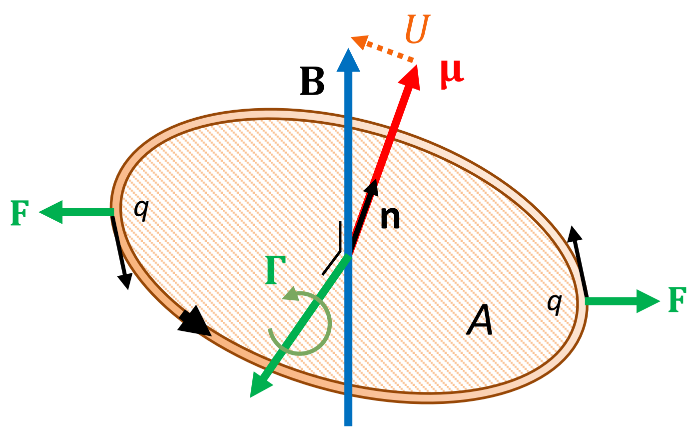
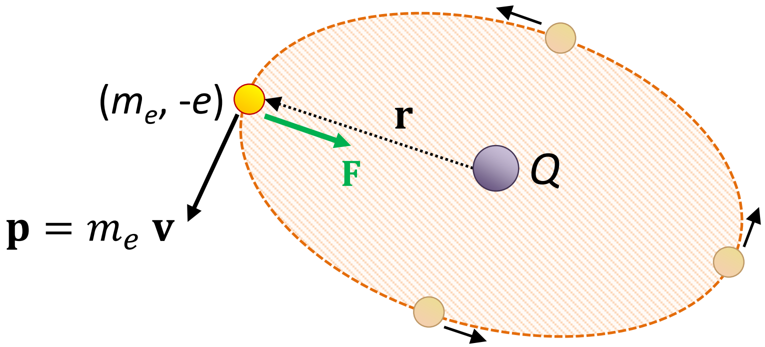
Energie : $U = -\boldsymbol{\mu} \cdot \mathbf{B}$ [J]

Couple : $\boldsymbol{\Gamma} = \boldsymbol{\mu} \wedge \mathbf{B}$ [Nm]



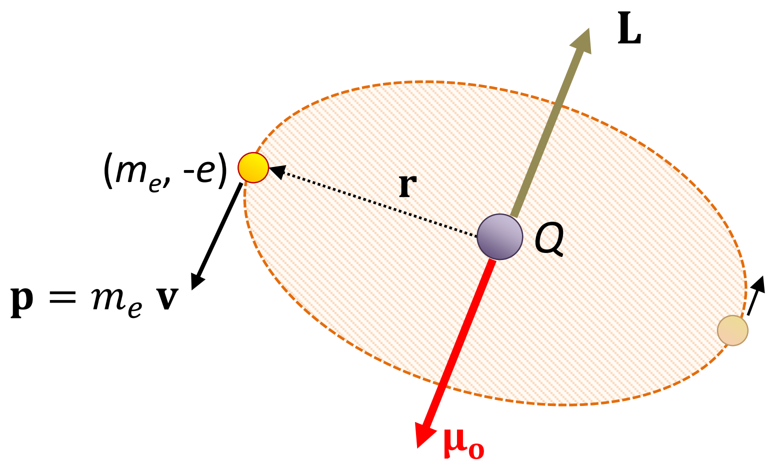
Cas de l'électron atomique



$$i = \frac{\mathrm{d}q}{\mathrm{d}t} = \frac{-e}{T} = \frac{-e}{2\pi r/v} = \frac{-e\,v}{2\pi r}$$

$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = \mathbf{F} \Rightarrow$$ mouvement circulaire uniforme

Cas de l'électron atomique



$$i = \frac{\mathrm{d}q}{\mathrm{d}t} = \frac{-e}{T} = \frac{-e}{2\pi r/v} = \frac{-e\ v}{2\pi r}$$

Moment cinétique : $\mathbf{L} = \mathbf{r} \wedge \mathbf{p} = r\, m_e v\, \mathbf{n}$

Moment magnétique : $\boldsymbol{\mu}_o = A\ i\ \mathbf{n} = -\ \pi r^2\ \frac{e\ v}{2\pi r}\ \mathbf{n} = -\ \frac{r\ e\ v}{2}\ \mathbf{n}$

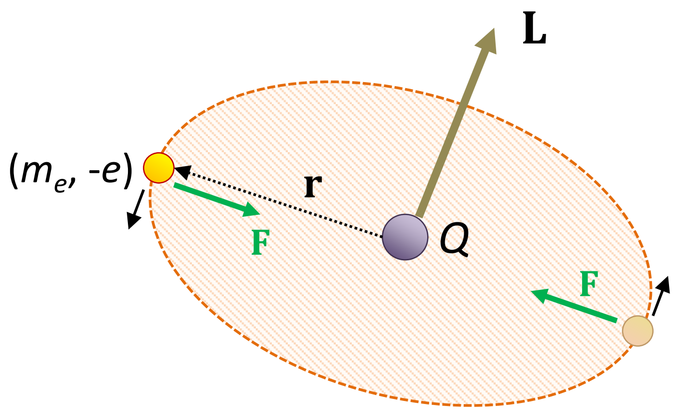
$$\boldsymbol{\mu}_o = -\frac{e}{2\ m_e}\ \mathbf{L} = \gamma_o\ \mathbf{L}$$

$$\boxed{\gamma_o = -\frac{e}{2\ m_e}}$$

Rapport gyromagnétique [C Kg^{-1}] *ou* [rad s^{-1} T^{-1}]

$\bar{\gamma_o} \simeq$ 14 GHz T^{-1} $\bar{\gamma} = \frac{\gamma}{2\pi}$ [Hz T^{-1}]

Cas de l'électron atomique



$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = \mathbf{F} \qquad \frac{\mathrm{d}\mathbf{L}}{\mathrm{d}t} = \mathbf{\Gamma}$$

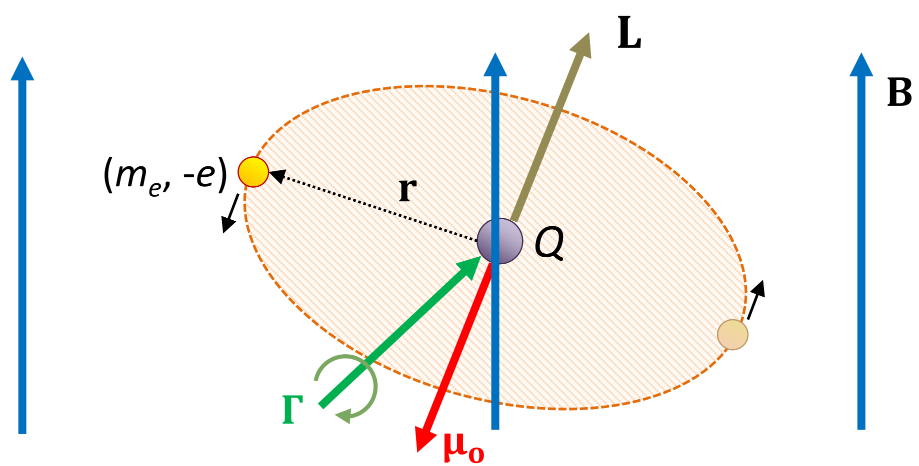
Dans le champ électrostatique du noyau

Energie : $U = \dfrac{-Q\,e}{4\pi\varepsilon_0\, r}$

Couple : $\mathbf{\Gamma} = \mathbf{r} \wedge \mathbf{F} = \mathbf{0}$ **(Force centrale F)**

Evolution : $\mathbf{L} = \mathbf{cste}$

Cas de l'électron atomique



$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = \mathbf{F} \qquad \frac{\mathrm{d}\mathbf{L}}{\mathrm{d}t} = \mathbf{\Gamma}$$

Dans le champ électrostatique du noyau + champ magnétique externe

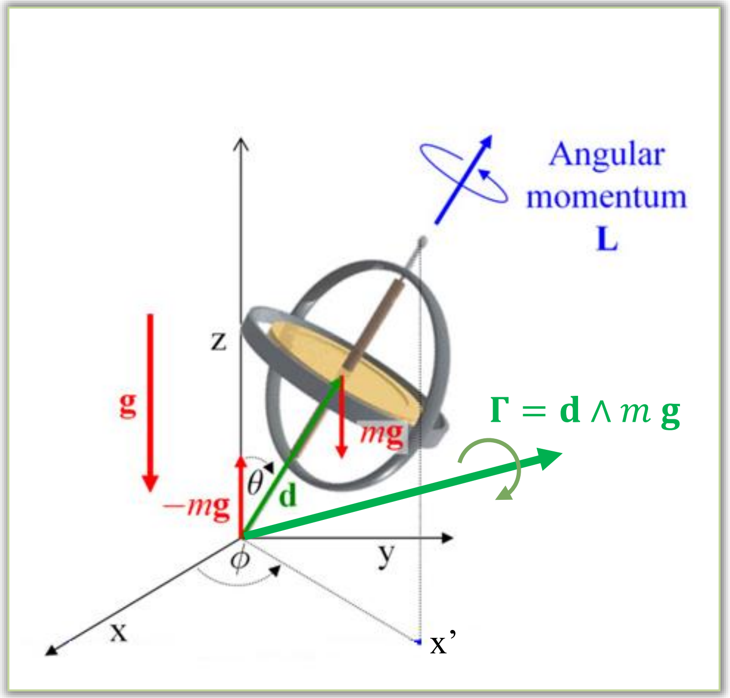
Energie : $$U = \frac{-Q\ e}{4\pi\varepsilon_0\ r} - \boldsymbol{\mu}_o \cdot \mathbf{B}$$

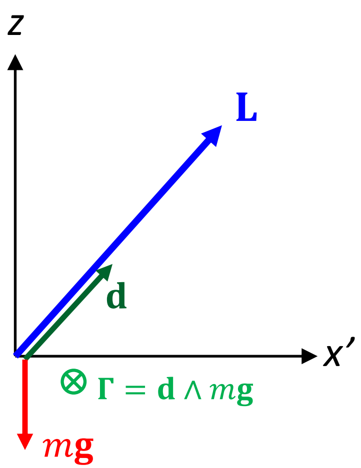
Couple : $$\mathbf{\Gamma} = \boldsymbol{\mu}_o \wedge \mathbf{B}$$

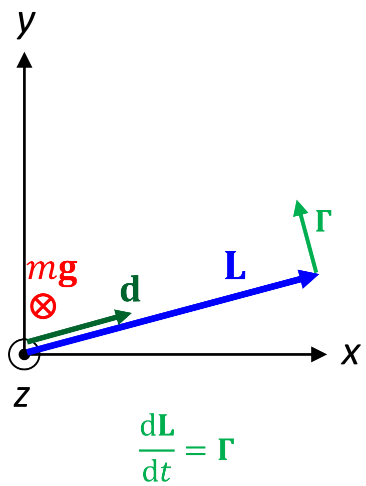
Evolution : $$\frac{\mathrm{d}\mathbf{L}}{\mathrm{d}t} = \boldsymbol{\mu}_o \wedge \mathbf{B}$$

Cas de l'électron atomique

Analogie de la toupie



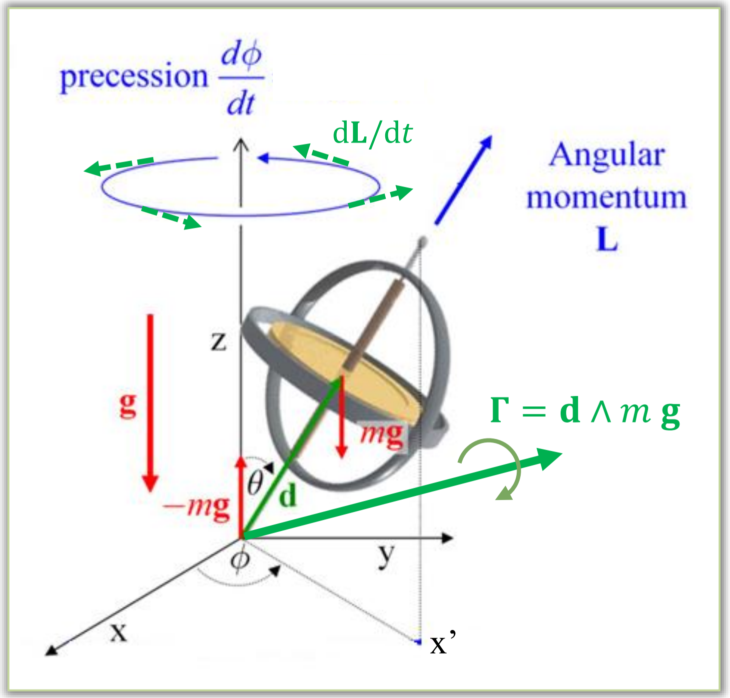


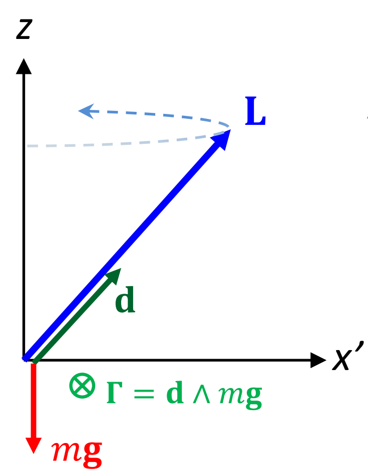


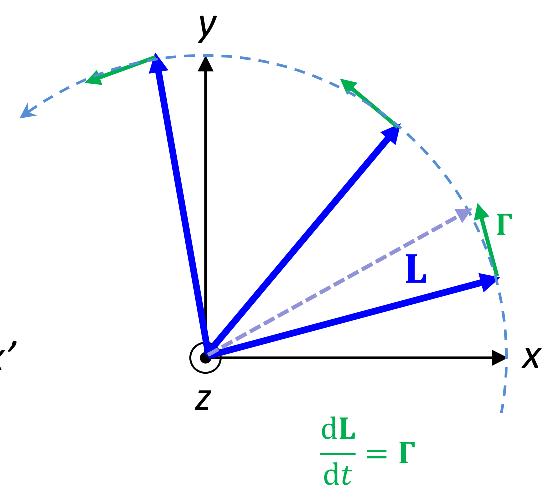
Evolution : $$\frac{d\mathbf{L}}{dt} = \Gamma$$

Cas de l’électron atomique

Analogie de la toupie





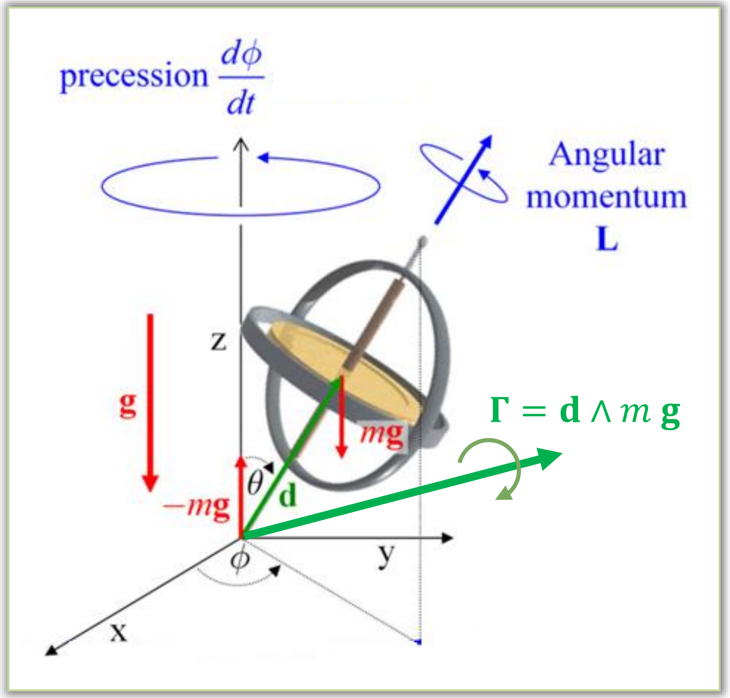


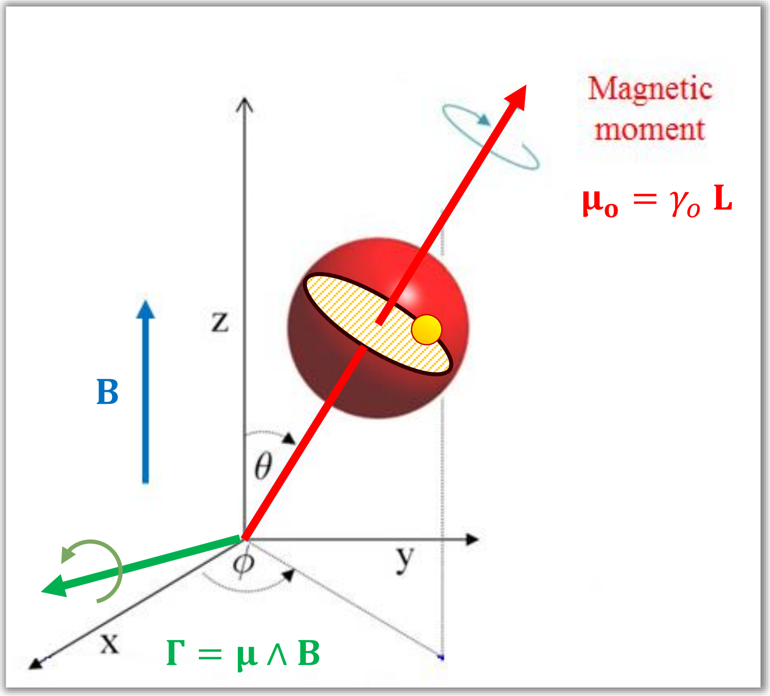
Evolution :

$$\frac{\mathrm{d}\mathbf{L}}{\mathrm{d}t} = \boldsymbol{\Gamma}$$

Cas de l'électron atomique

Analogie de la toupie





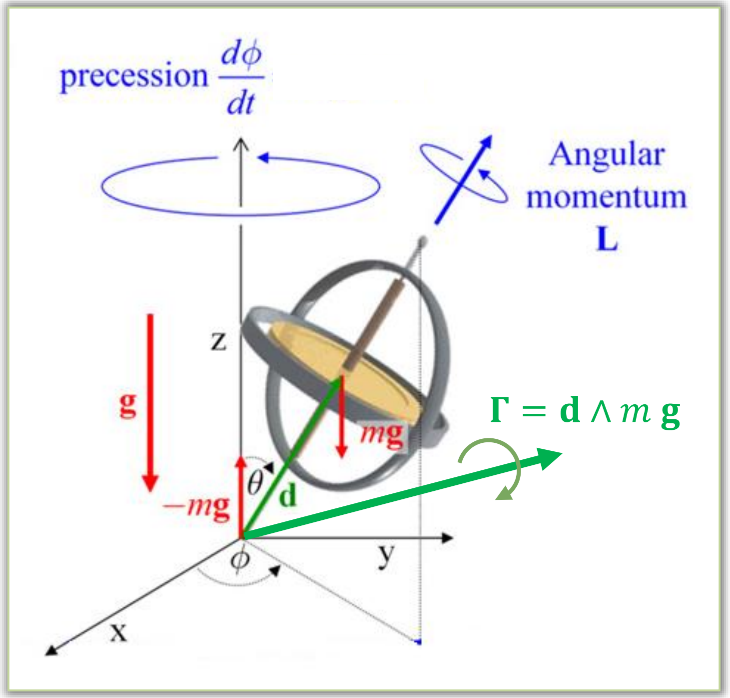
Evolution : $$\frac{d\mathbf{L}}{dt} = \boldsymbol{\Gamma}$$

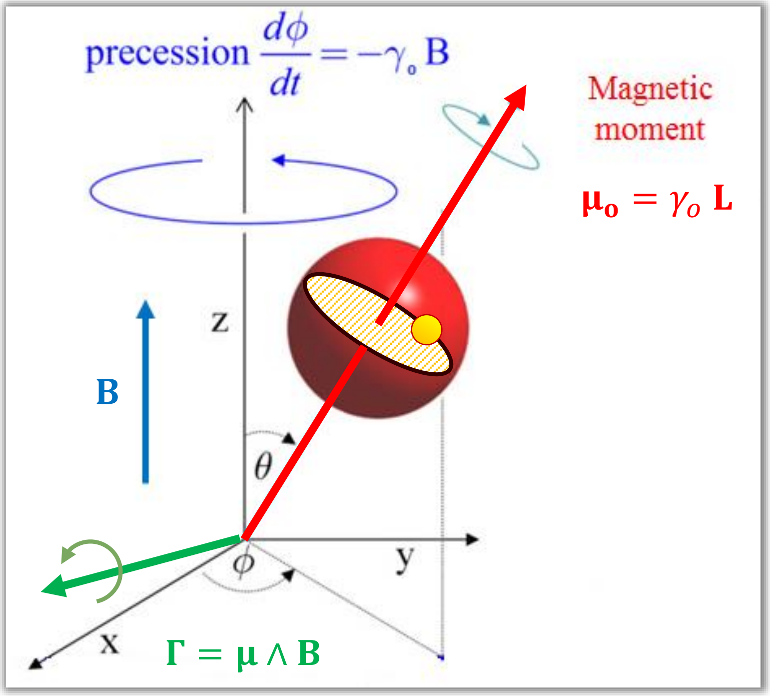
$$\frac{d\mathbf{L}}{dt} = \boldsymbol{\mu}_o \wedge \mathbf{B}$$

$$\boldsymbol{\mu}_o = \gamma_o\,\mathbf{L}$$

Cas de l'électron atomique

Analogie de la toupie



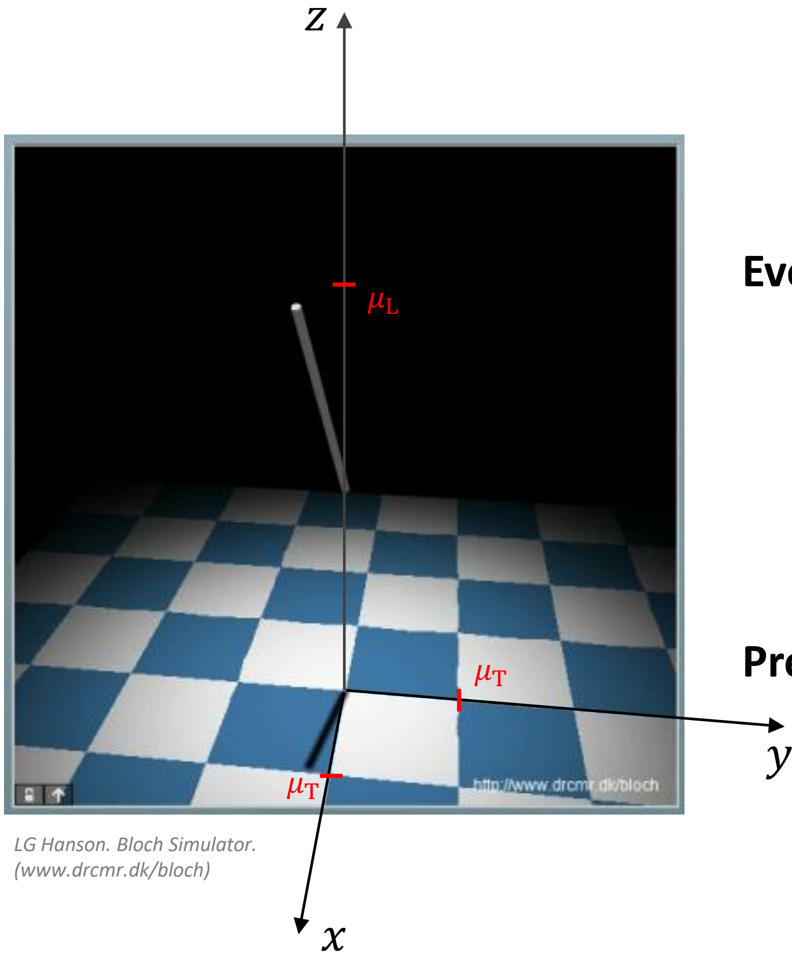


Evolution : $\frac{\mathrm{d}\mathbf{L}}{\mathrm{d}t} = \boldsymbol{\Gamma}$

$$\frac{\mathrm{d}\mathbf{L}}{\mathrm{d}t} = \boldsymbol{\mu}_o \wedge \mathbf{B} \qquad \frac{\mathrm{d}\boldsymbol{\mu}_o}{\mathrm{d}t} = \gamma_o \boldsymbol{\mu}_o \wedge \mathbf{B}$$

Précession de Larmor

Cas de l'électron atomique



LG Hanson. Bloch Simulator. (www.drcmr.dk/bloch)

Evolution : $\dfrac{\mathrm{d}\boldsymbol{\mu}_\mathrm{o}}{\mathrm{d}t} = \gamma_\mathrm{o}\boldsymbol{\mu}_\mathrm{o} \wedge \mathbf{B}$

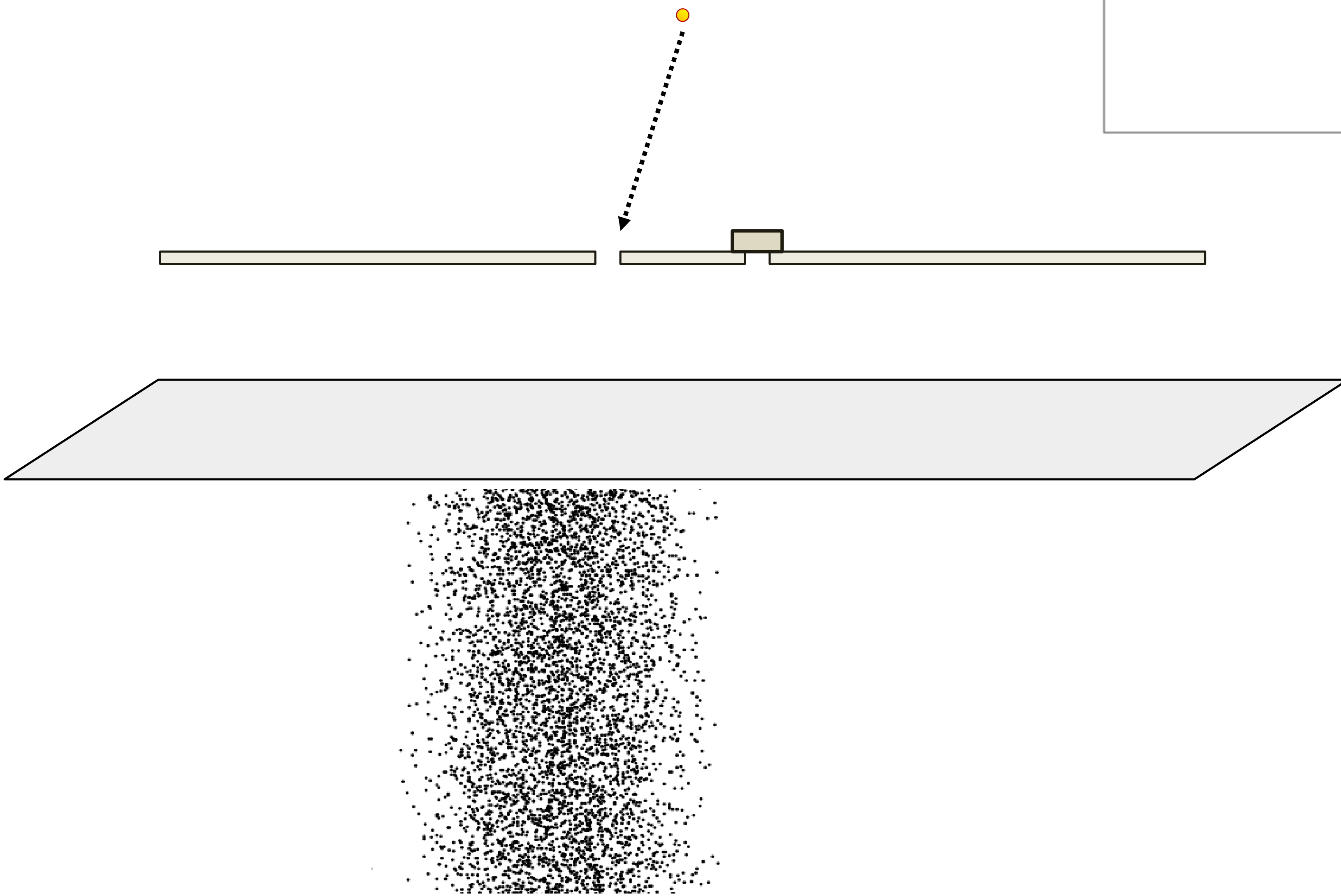
$$\begin{cases} \mu_{\mathrm{o}x} = \mu_\mathrm{T}\cos(\omega t) \\ \mu_{\mathrm{o}y} = \mu_\mathrm{T}\sin(\omega t) \\ \mu_{\mathrm{o}z} = \mu_\mathrm{L} \end{cases}$$

Précession de Larmor : $\boxed{\boldsymbol{\omega} = -\gamma_\mathrm{o}\,\mathbf{B}}$ $\boxed{\boldsymbol{\nu} = -\bar{\gamma}_\mathrm{o}\,\mathbf{B}}$

$$\boldsymbol{\mu}_\mathbf{o} = \begin{pmatrix} \mu_\mathrm{T}\cos(\omega t) \\ \mu_\mathrm{T}\sin(\omega t) \\ \mu_\mathrm{L} \end{pmatrix} \qquad \frac{d\boldsymbol{\mu}_\mathbf{o}}{dt} = \omega \begin{pmatrix} -\mu_\mathrm{T}\sin(\omega t) \\ \mu_\mathrm{T}\cos(\omega t) \\ 0 \end{pmatrix}$$

$$\gamma_\mathrm{o}\boldsymbol{\mu}_\mathrm{o} \wedge \mathbf{B} = \gamma_\mathrm{o} \begin{pmatrix} \mu_\mathrm{T}\cos(\omega t) \\ \mu_\mathrm{T}\sin(\omega t) \\ \mu_\mathrm{L} \end{pmatrix} \wedge \begin{pmatrix} 0 \\ 0 \\ B \end{pmatrix} = \gamma_\mathrm{o} B \begin{pmatrix} \mu_\mathrm{T}\sin(\omega t) \\ -\mu_\mathrm{T}\cos(\omega t) \\ 0 \end{pmatrix}$$

Ce que dit la mécanique quantique



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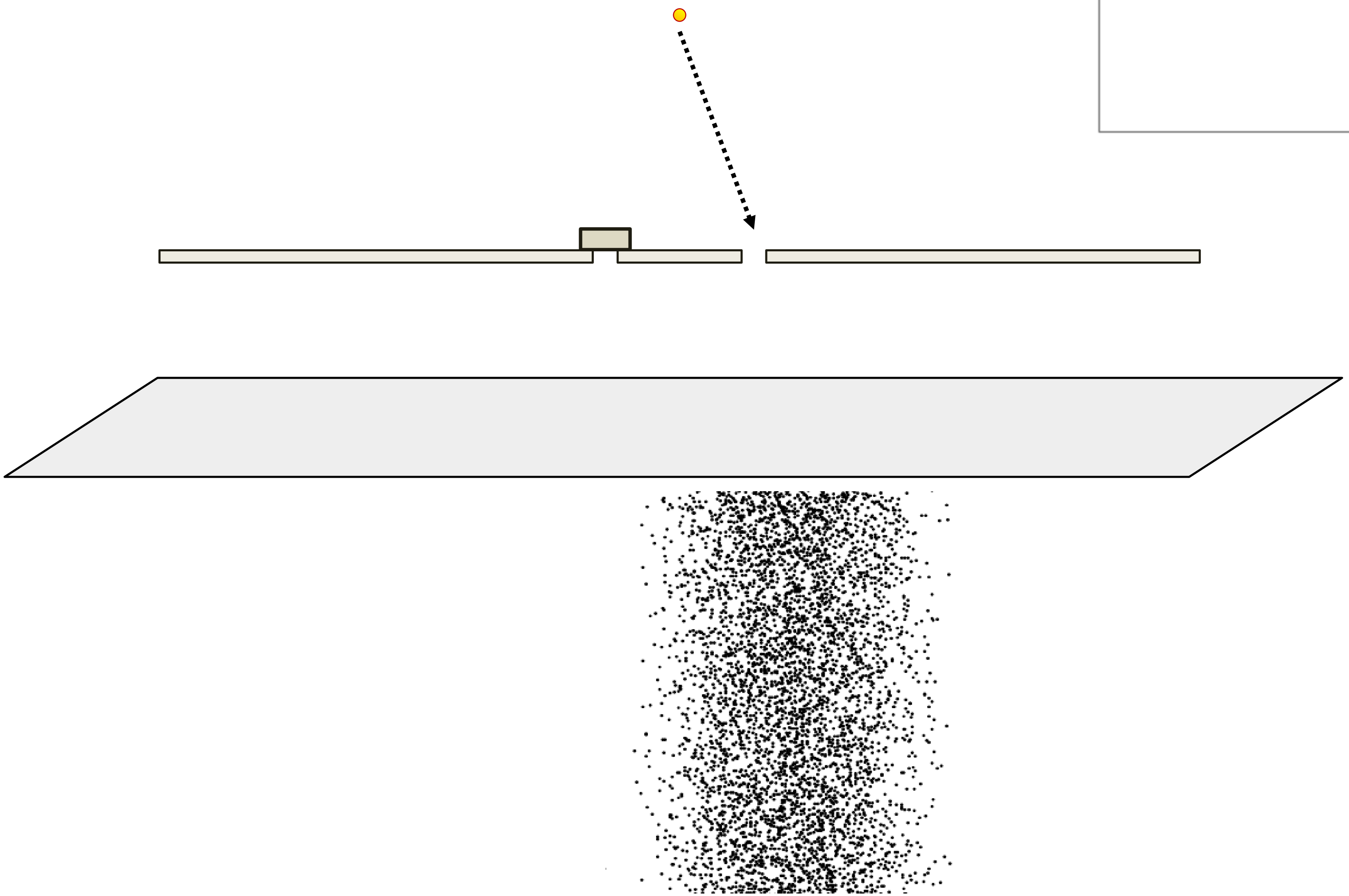

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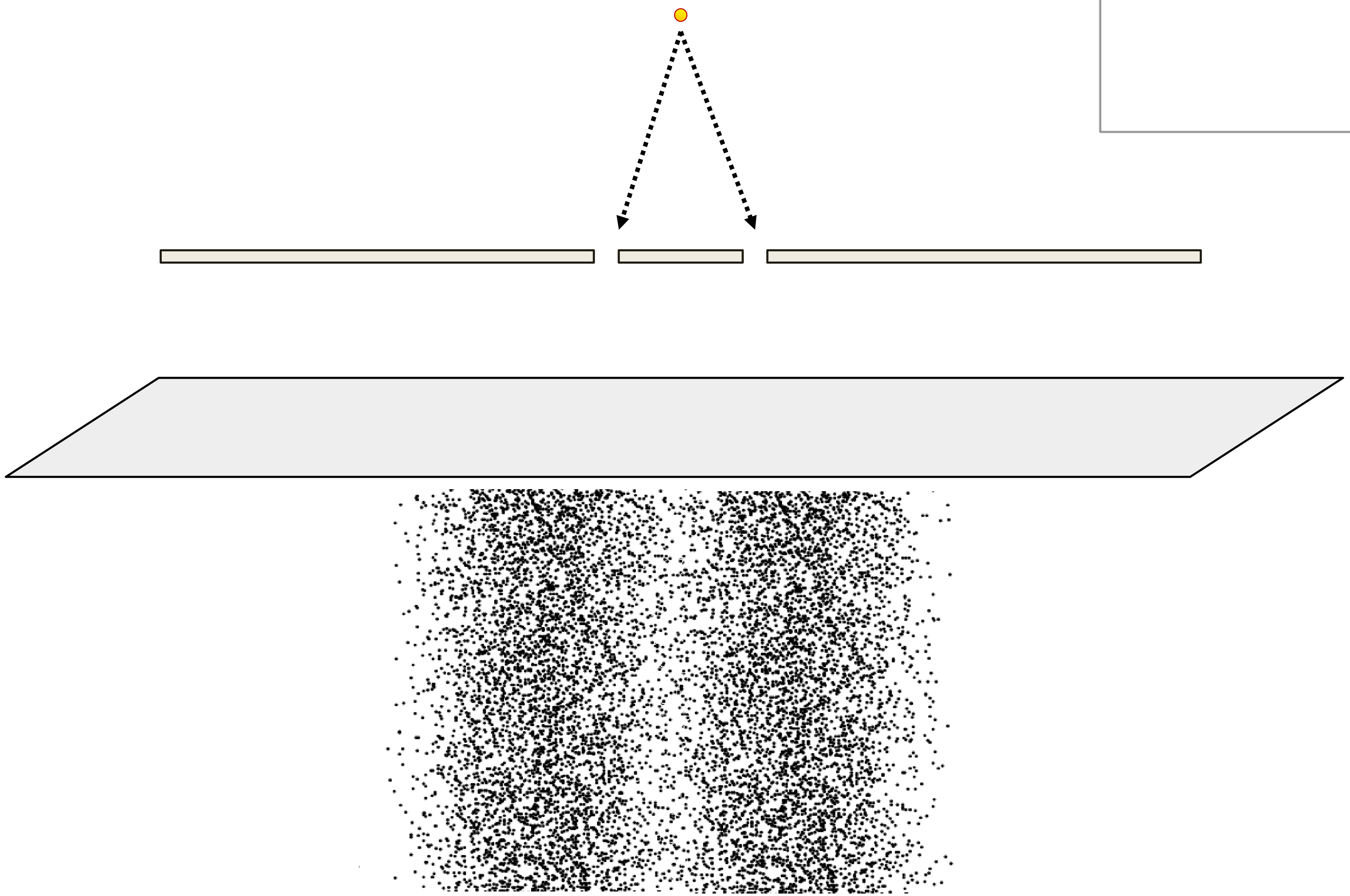

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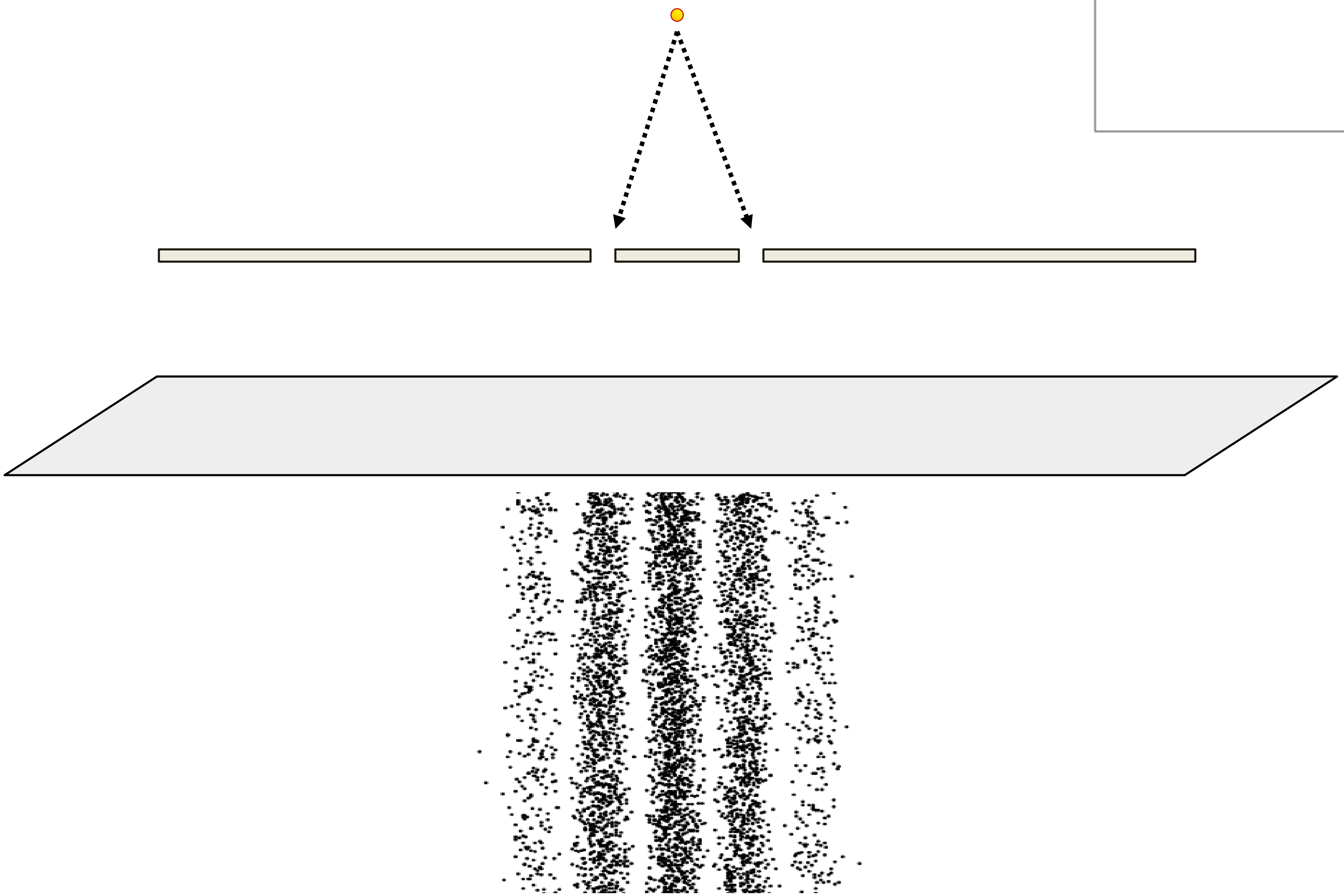

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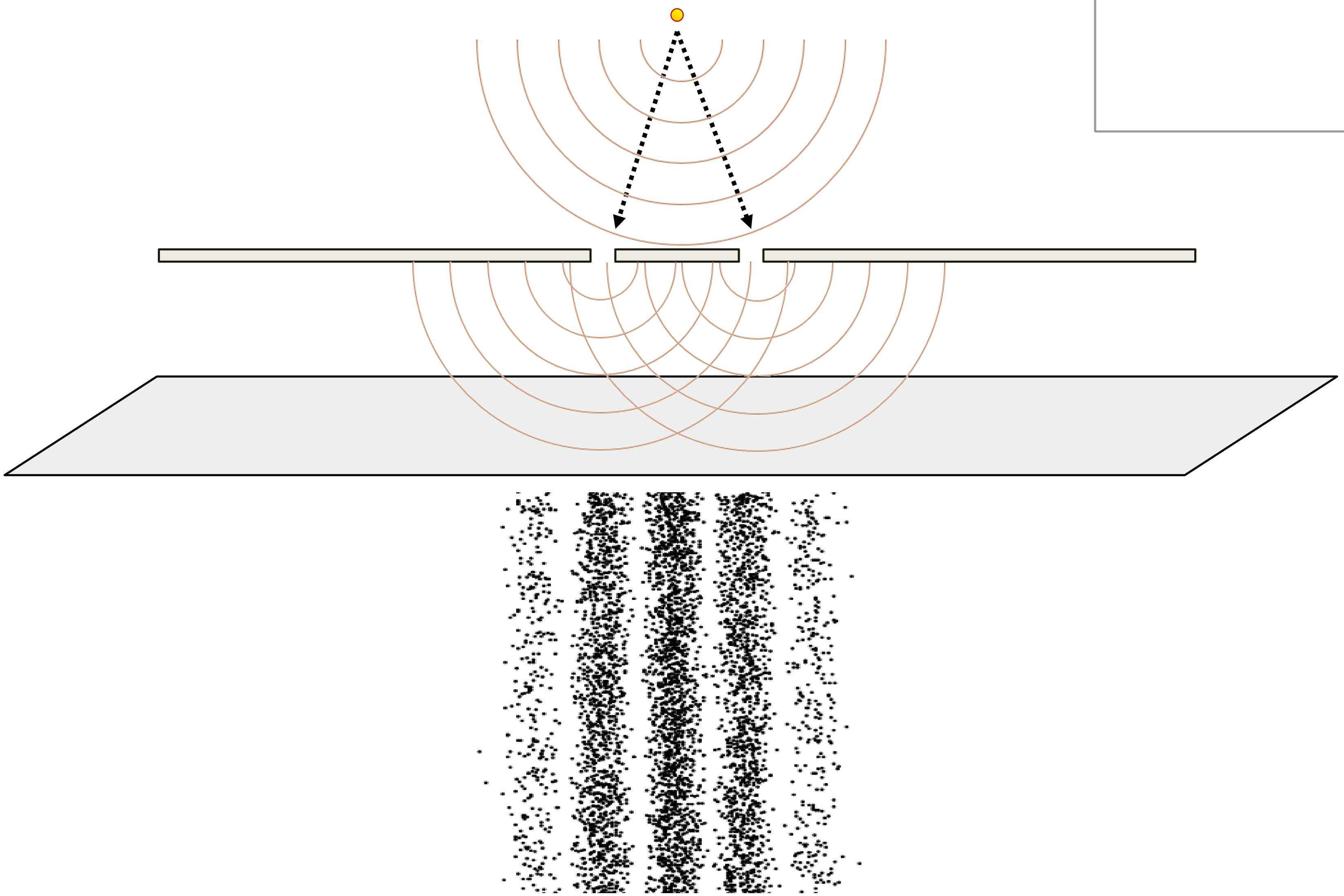
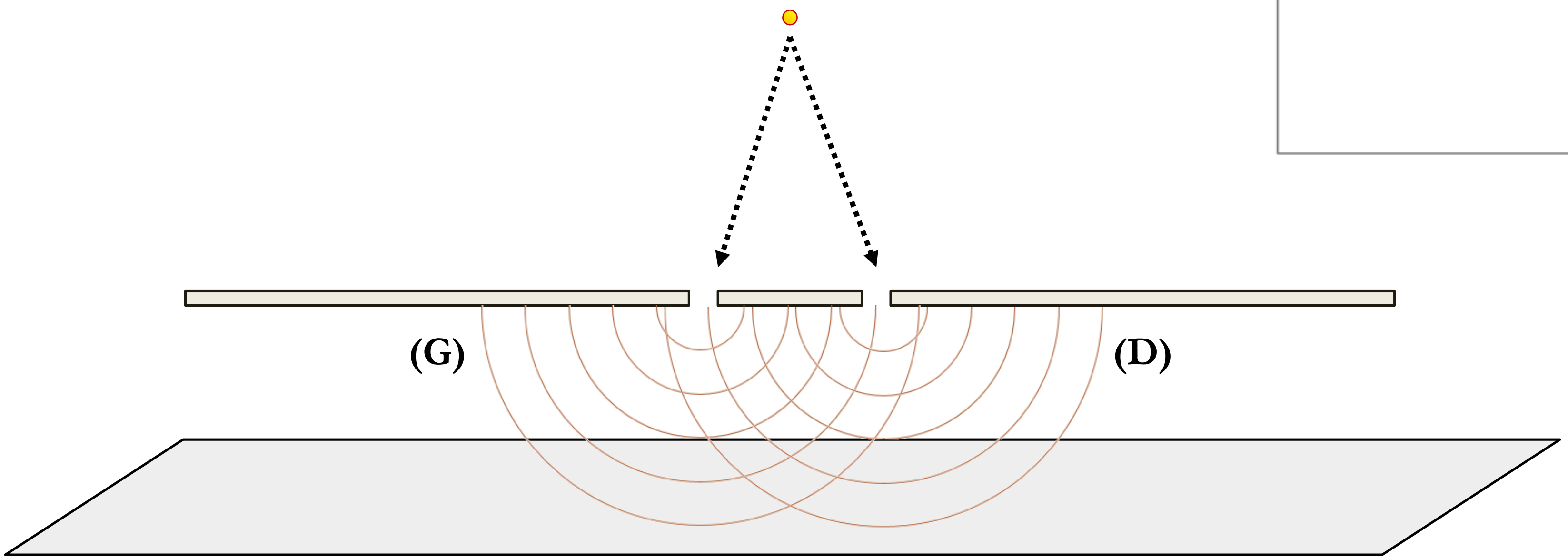
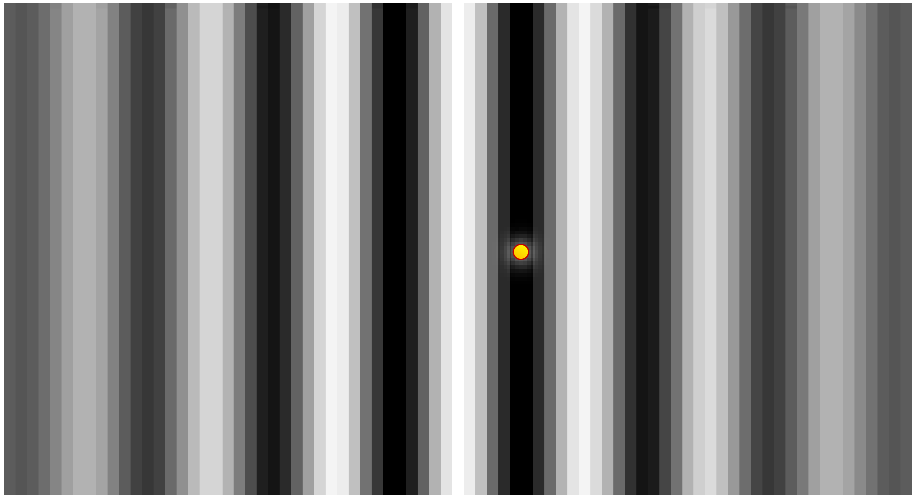


Ce que dit la mécanique quantique



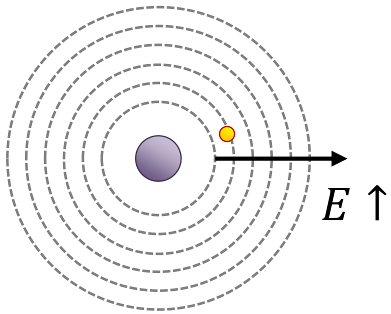


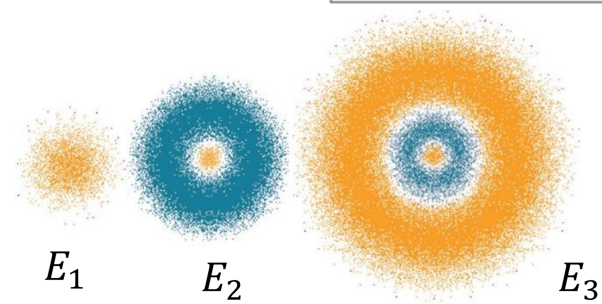
(G) + (D)

Ce que dit la mécanique quantique

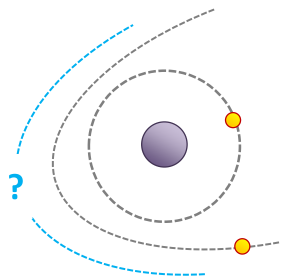
Classique | **Quantique**

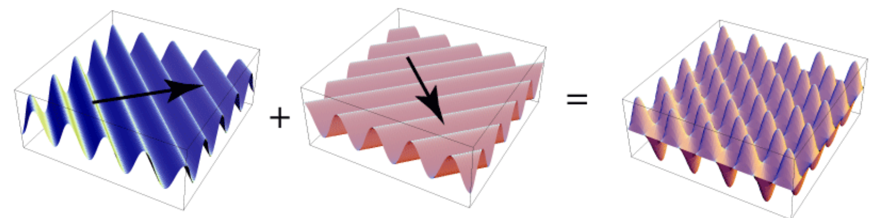
Valeurs Accessibles



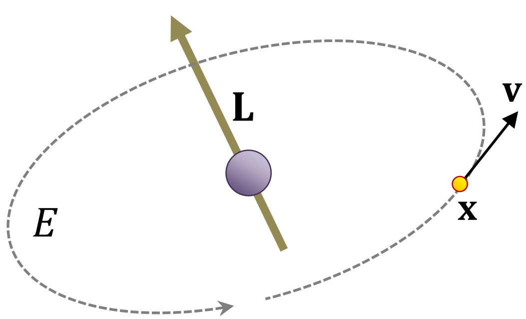


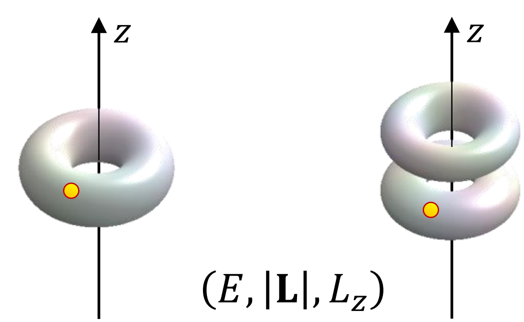
Linéarité





Déterminisme





Ce que dit la mécanique quantique

L'électron est décrit par une onde : $\Psi\,(\mathbf{x}, t) : \mathbb{R}^3 \times \mathbb{R}^+ \rightarrow \mathbb{C}$

La description complète fait apparaître 3 nombres quantiques

n : quantification de l'énergie E

l : quantification du moment cinétique $|\mathbf{L}| = \hbar\sqrt{l(l+1)}$

m : quantification de $L_z = m\hbar = -l\hbar \ \ldots\ 0\ \ldots\ l\hbar$

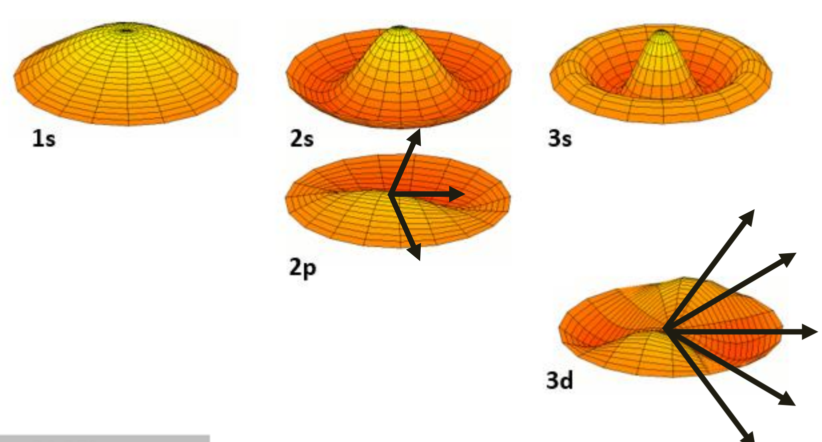
Indétermination de L_x et L_y : quelle est la longitude du pôle nord ?

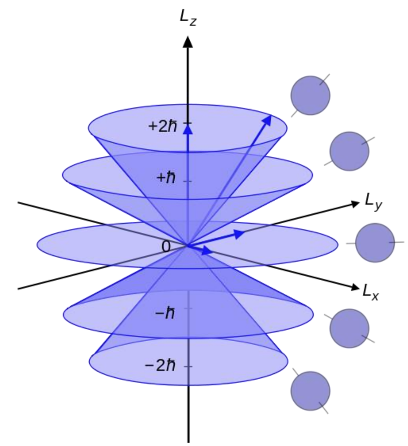
$n = 1$ $\quad$ $n = 2$ $\quad$ $n = 3$

$l = 0$

$l = 1$

$l = 2$





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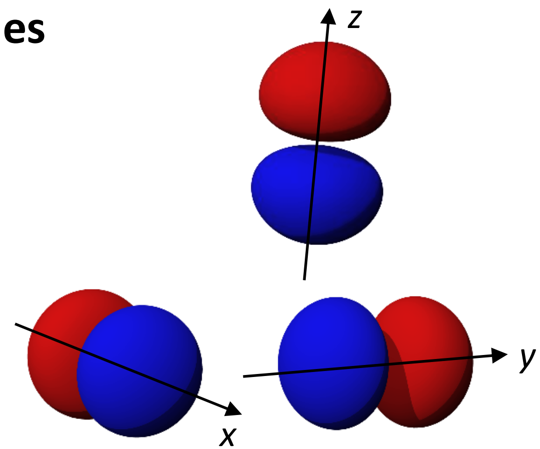

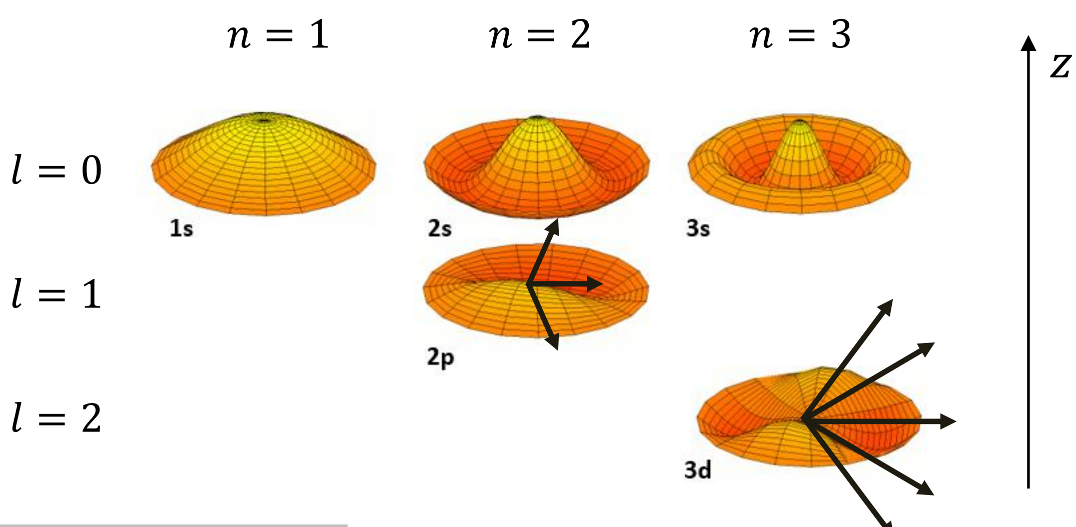

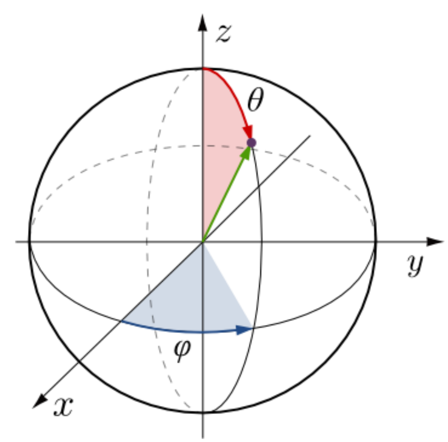

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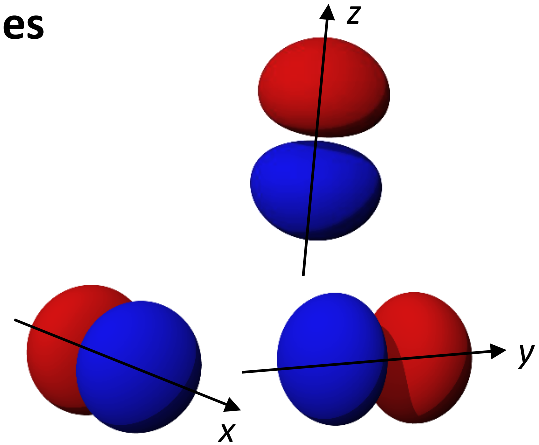

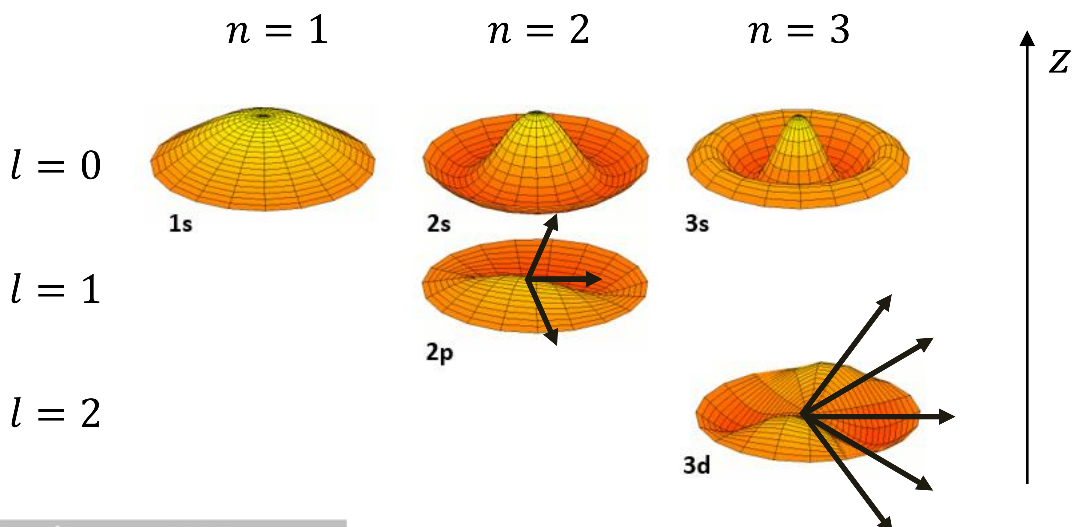

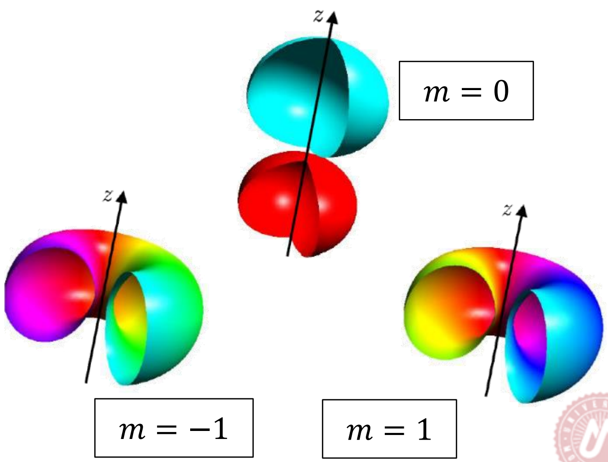

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La description complète fait apparaître 3 nombres quantiques

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l : quantification du moment cinétique $|\mathbf{L}| = \hbar\sqrt{l(l+1)}$

m : quantification de $L_z = m\hbar = -l\hbar\ \ldots\ 0\ \ldots\ l\hbar$

$$\boldsymbol{\mu}_o = \gamma_o\,\mathbf{L}$$

$$|\boldsymbol{\mu}_o| = \gamma_o\,\hbar\sqrt{l(l+1)}$$

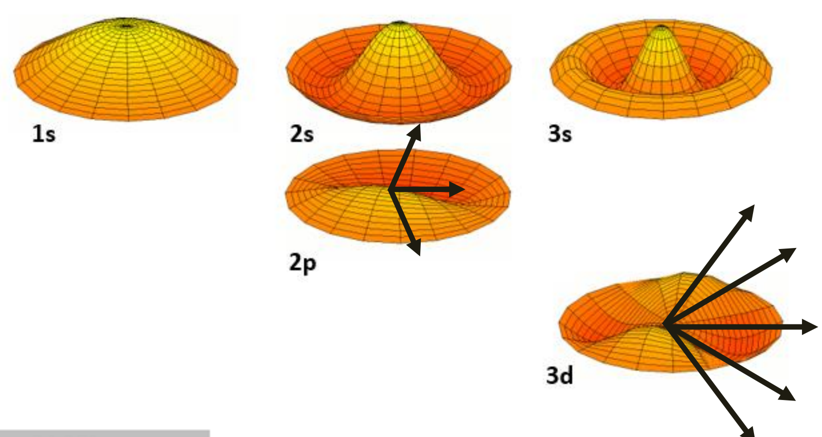
$$\mu_{oz} = \gamma_o m\,\hbar$$

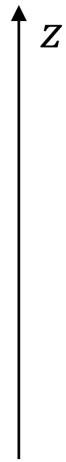
$n = 1$ $\quad n = 2$ $\quad n = 3$

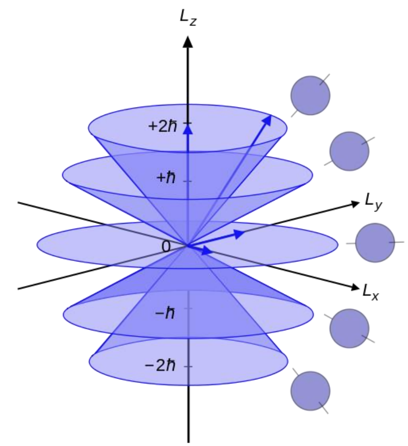
$l = 0$

$l = 1$

$l = 2$







Ce que dit la mécanique quantique

L'électron est décrit par une onde : $\Psi\,(\mathbf{x},t)\,:\;\mathbb{R}^3\times\mathbb{R}^+\;\rightarrow\;\mathbb{C}$

La description complète fait apparaître 3 nombres quantiques

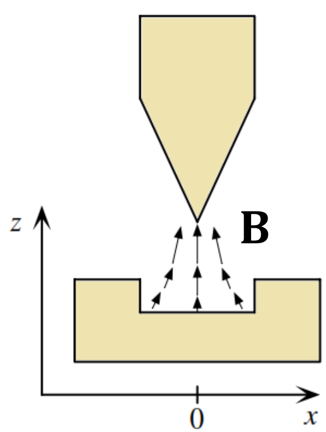
(n, l, m)

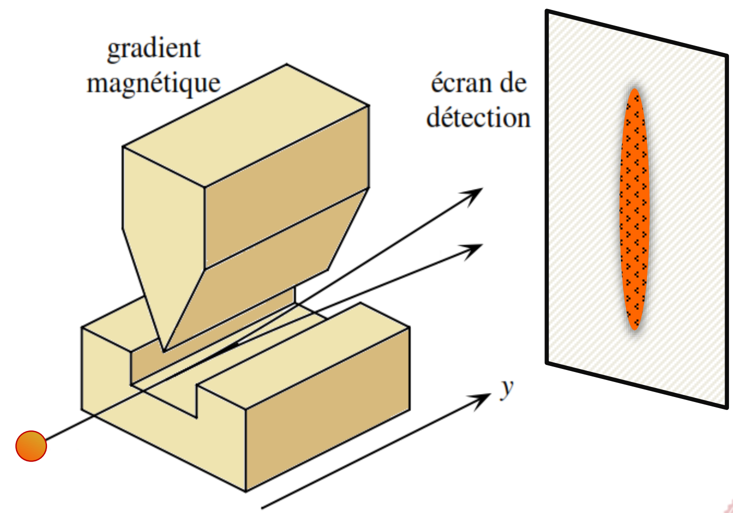
… MAIS

$L_z = m\hbar = -l\hbar\;\ldots\;0\;\ldots\;l\hbar$

2l +1 valeurs

Particules dans $\partial\mathbf{B}/\partial z$
déviées en fonction de L_z





Ce que dit la mécanique quantique

L'électron est décrit par une onde : $\Psi\,(\mathbf{x},t) : \mathbb{R}^3 \times \mathbb{R}^+ \to \mathbb{C}$

La description complète fait apparaître 3 nombres quantiques

(n, l, m)

… MAIS

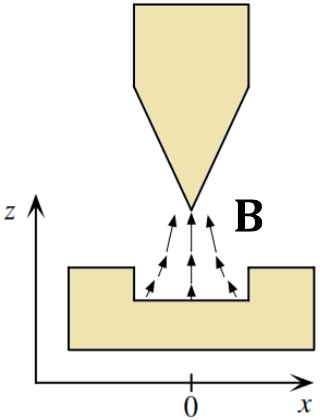
$L_z = m\hbar = -l\hbar\ \dots\ 0\ \dots\ l\hbar$

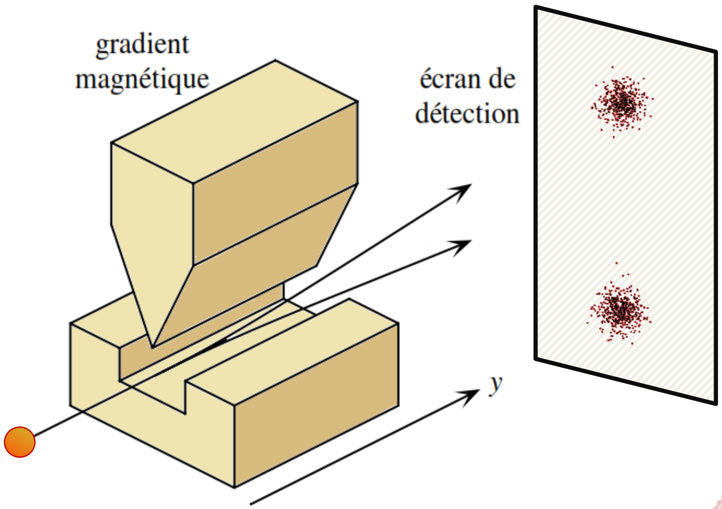
2l +1 valeurs

Particules dans $\partial\mathbf{B}/\partial z$ déviées en fonction de L_z

Nombre pair de taches

Il existe un moment cinétique demi-entier intrinsèque
SPIN





Ce que dit la mécanique quantique

L'électron est décrit par une onde : $\Psi\,(\mathbf{x}, t, \sigma) : \mathbb{R}^3 \times \mathbb{R}^+ \times \binom{+}{-} \to \mathbb{C}$

La description complète fait apparaître 4 nombres quantiques

(n, l, m, σ)

W. Pauli

SPIN S

tel que : $|\mathbf{S}| = \hbar\sqrt{s(s+1)}$ (s entier **OU** demi-entier)

$$S_z = \sigma\hbar = -s\hbar \ldots s\hbar$$

pour l'électron : $s = \frac{1}{2} \quad \sigma = \pm\frac{1}{2}$

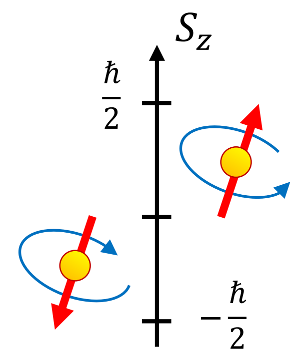
il s'y associe un moment magnétique :

$$\boxed{\boldsymbol{\mu}_s = \gamma_s\,\mathbf{S} = g\,\gamma_o\,\mathbf{S}}$$

$g \simeq 2$

facteur de Landé de spin

$\bar{\gamma}_s \simeq 28\ \mathrm{GHz\ T^{-1}}$

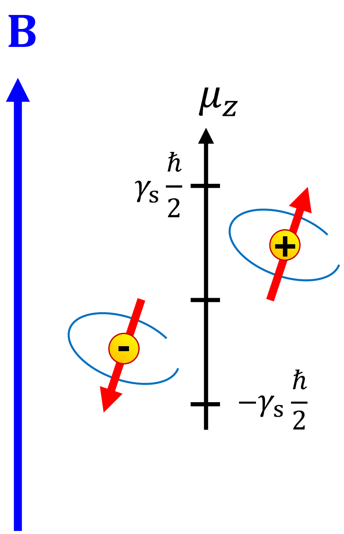


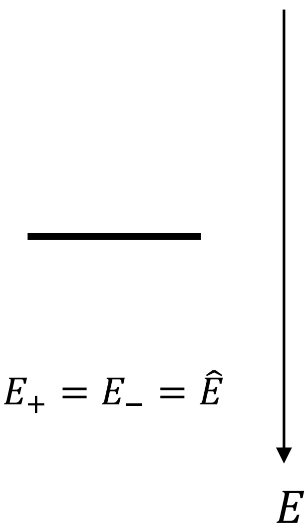
Ce que dit la mécanique quantique

Considérations énergétiques

$$\boxed{\mathbf{B} = 0}$$

$$U = \frac{-Q\ e}{4\pi\varepsilon_0\ r}$$





$$E_+ = E_- = \hat{E}$$

Ce que dit la mécanique quantique

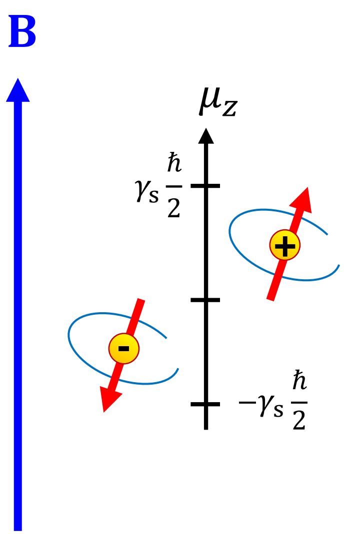
Considérations énergétiques

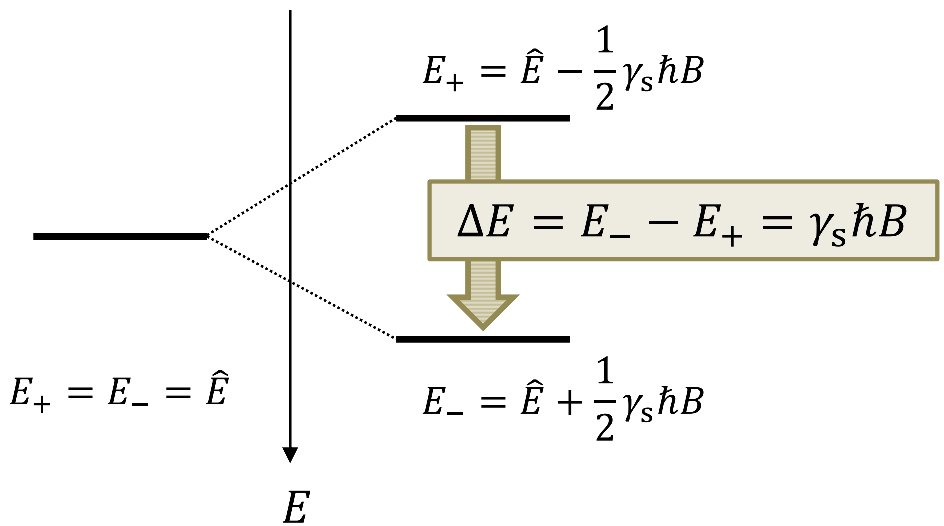
$\mathbf{B} = 0$

$$U = \frac{-Q\,e}{4\pi\varepsilon_0\,r}$$

$\mathbf{B} > 0$

$$U = \frac{-Q\,e}{4\pi\varepsilon_0\,r} - \boldsymbol{\mu}_s \cdot \mathbf{B} = \frac{-Q\,e}{4\pi\varepsilon_0\,r} - \gamma_s S_z B$$



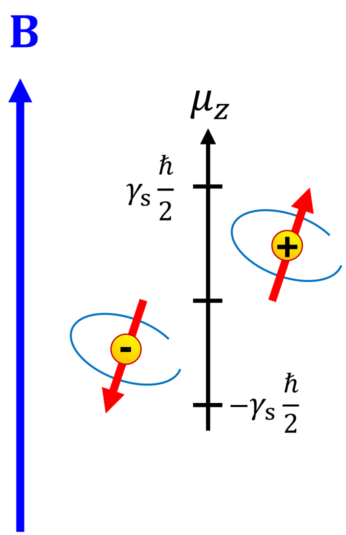


(levée de dégénérescence)

EFFET ZEEMAN

Ce que dit la mécanique quantique

Considérations énergétiques



B = 0

$$E_+ = E_- = \hat{E}$$

B > 0

$$E_+ = \hat{E} - \frac{1}{2}\gamma_s \hbar B$$

$$\boxed{\Delta E = E_- - E_+ = \gamma_s \hbar B}$$

$$E_- = \hat{E} + \frac{1}{2}\gamma_s \hbar B$$

Principe de superposition

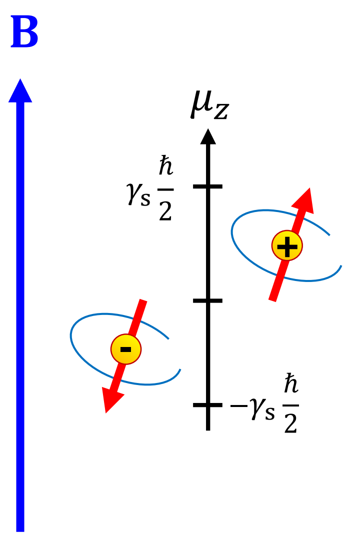
$$|\psi_s\rangle = \alpha|\oplus\rangle + \beta|\ominus\rangle$$

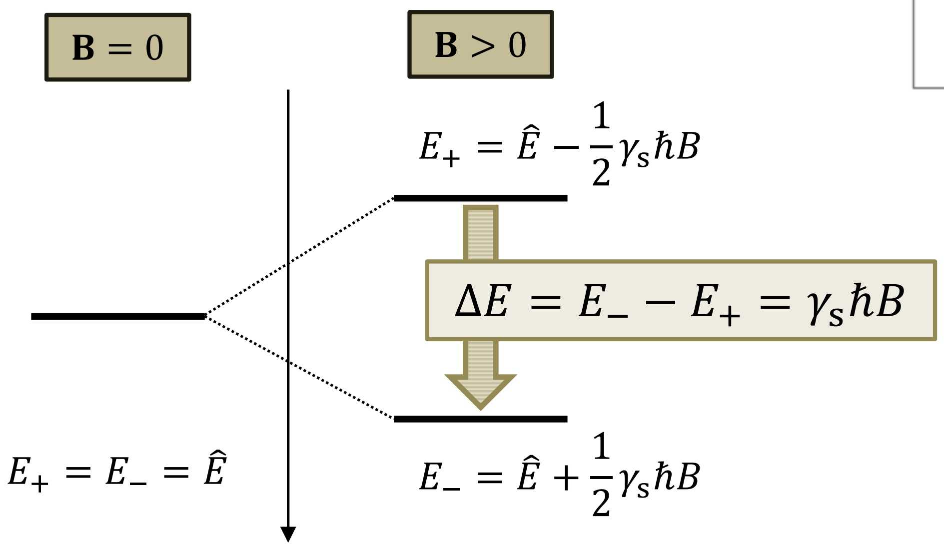
$$\wp(\oplus) = \alpha^2 \qquad \wp(\ominus) = \beta^2$$

$$\boxed{B = 0} \quad \left\{ \begin{array}{l} |\psi_s\rangle = \frac{1}{\sqrt{2}}|\oplus\rangle + \frac{1}{\sqrt{2}}|\ominus\rangle \\ \wp(\oplus) = \wp(\ominus) = 50\% \end{array} \right.$$

Ce que dit la mécanique quantique

Considérations énergétiques





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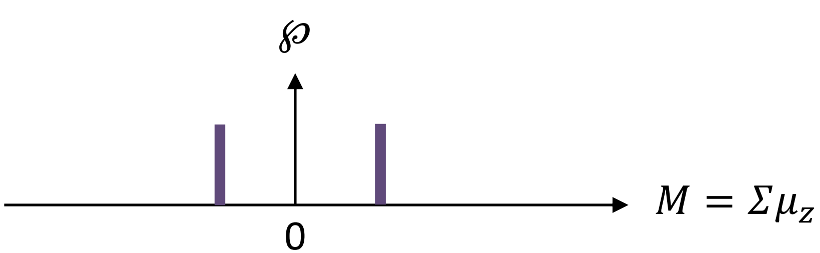
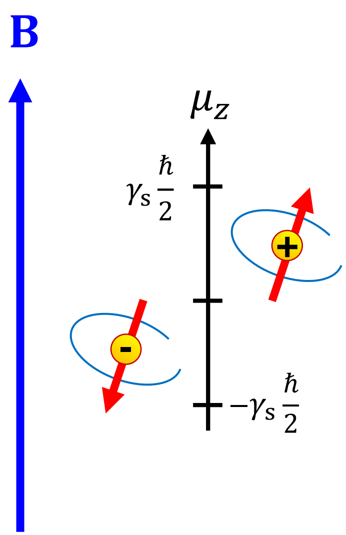
Un dipôle $|\oplus\rangle$: 50%

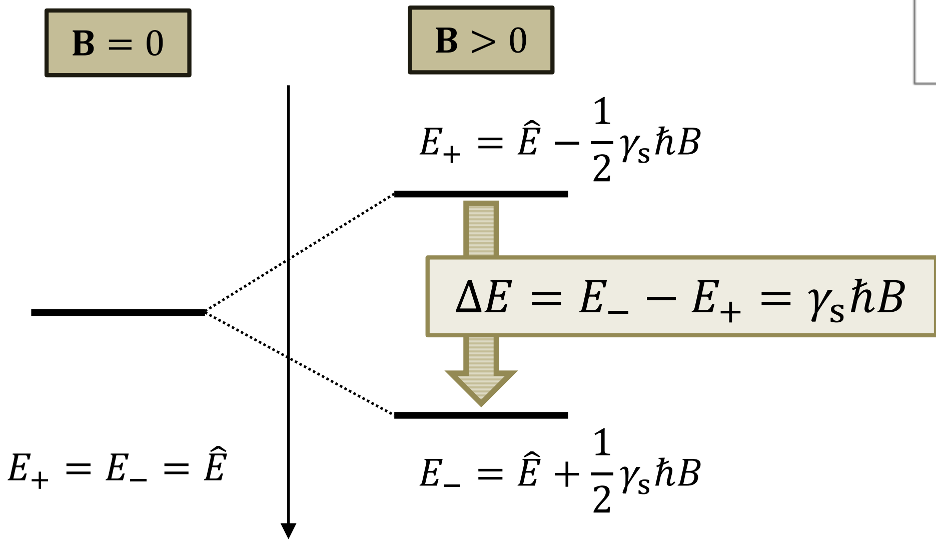
$|\ominus\rangle$: 50%



Ce que dit la mécanique quantique

Considérations énergétiques





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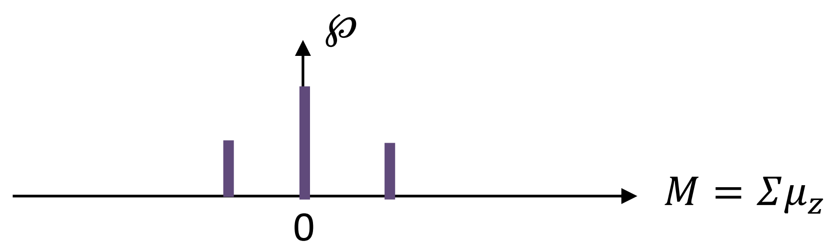
2 dipôles

$|\oplus\rangle\ |\oplus\rangle$: 25%

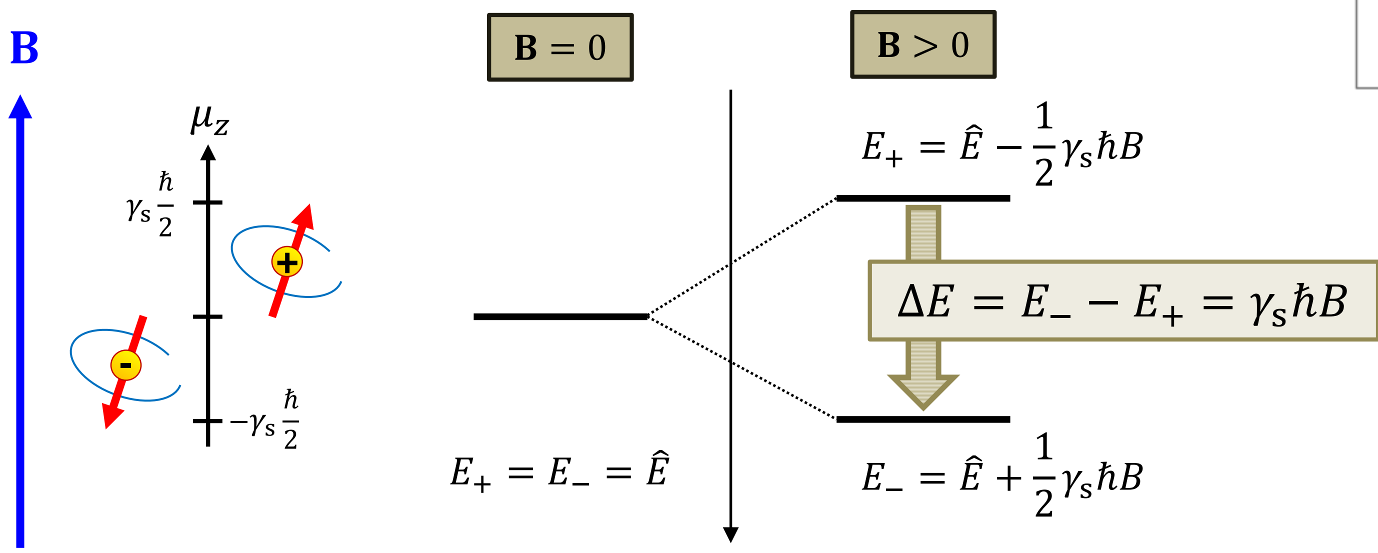
$|\ominus\rangle\ |\oplus\rangle$: 25% $\quad |\oplus\rangle\,|\ominus\rangle$: 25% $\quad$ 50%

$|\ominus\rangle\ |\ominus\rangle$: 25%



Ce que dit la mécanique quantique

Considérations énergétiques



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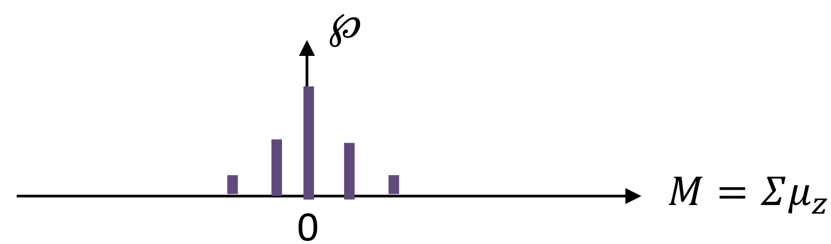
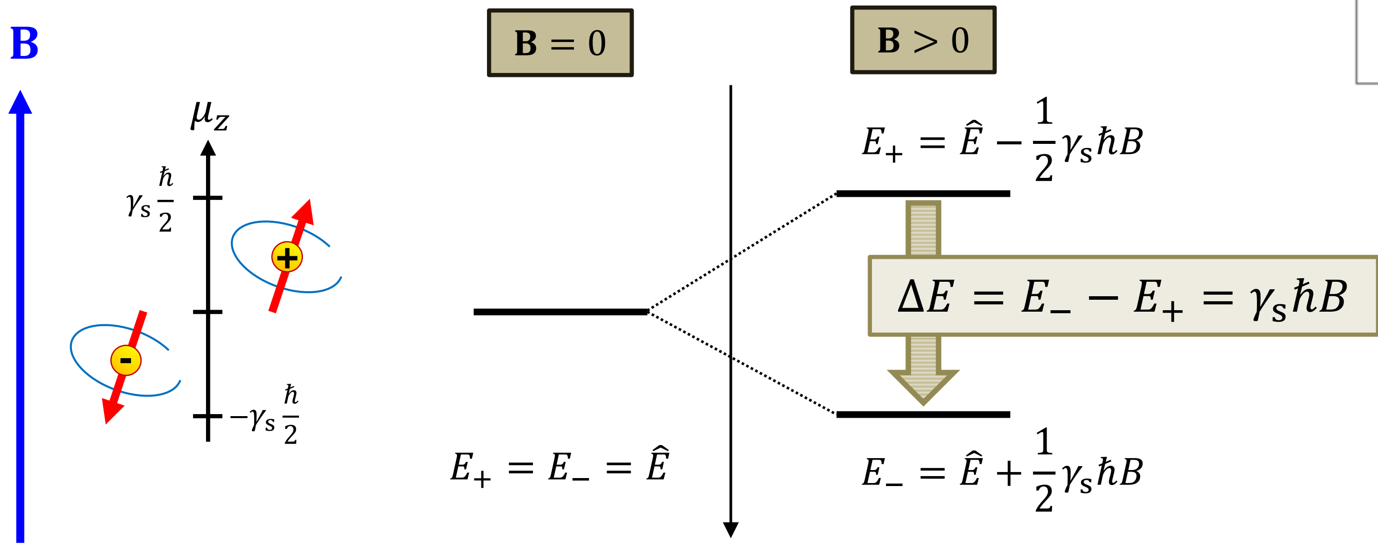
4 dipôles



Ce que dit la mécanique quantique

Considérations énergétiques



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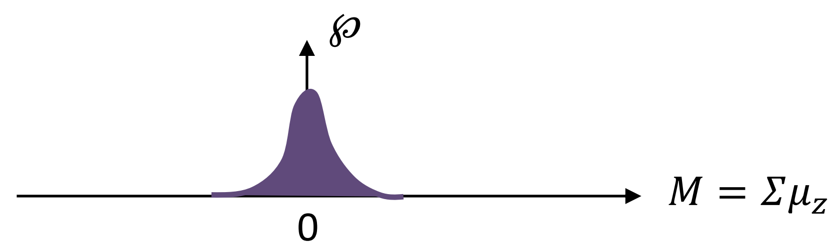
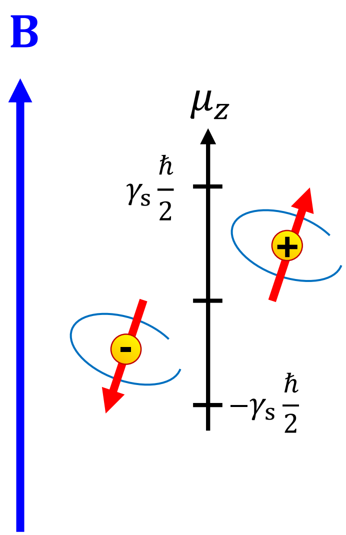
1000 dipôles



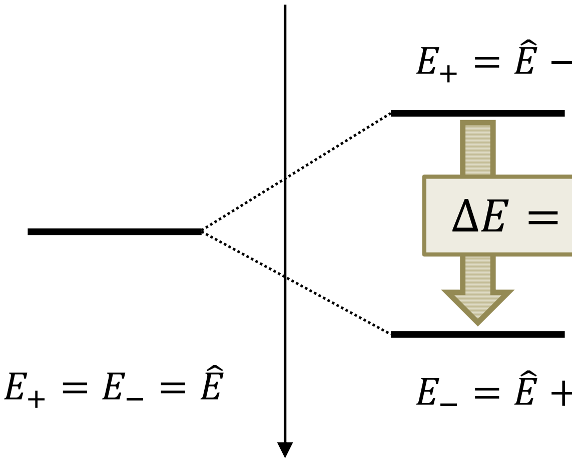
Ce que dit la mécanique quantique

Considérations énergétiques



B = 0

B > 0



$$E_+ = \hat{E} - \frac{1}{2}\gamma_s \hbar B$$

$$\Delta E = E_- - E_+ = \gamma_s \hbar B$$

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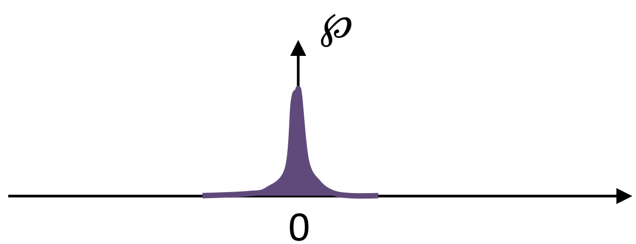
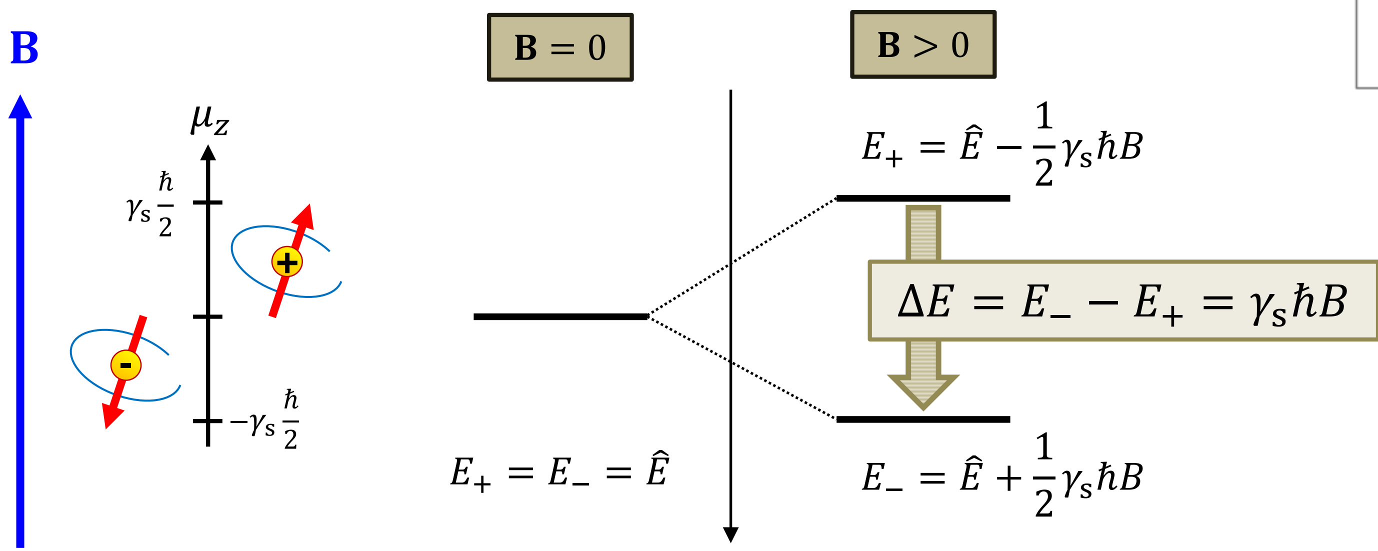
$$\boxed{B = 0} \quad \begin{cases} |\psi_s\rangle = \frac{1}{\sqrt{2}}|\oplus\rangle + \frac{1}{\sqrt{2}}|\ominus\rangle \\ \wp(\oplus) = \wp(\ominus) = 50\% \end{cases}$$

10^6 dipôles



Ce que dit la mécanique quantique

Considérations énergétiques



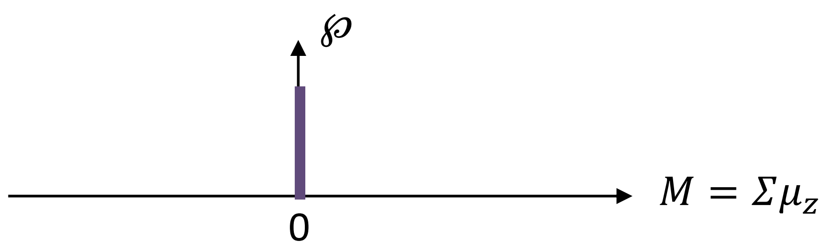
Principe de superposition

$$|\psi_s\rangle = \alpha|\oplus\rangle + \beta|\ominus\rangle$$

$$\wp(\oplus) = \alpha^2 \qquad \wp(\ominus) = \beta^2$$

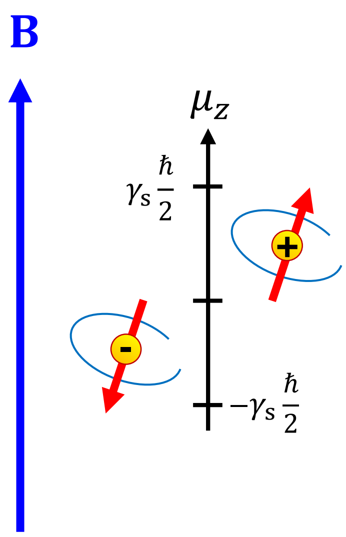
$$\boxed{B = 0} \quad \begin{cases} |\psi_s\rangle = \frac{1}{\sqrt{2}}|\oplus\rangle + \frac{1}{\sqrt{2}}|\ominus\rangle \\ \wp(\oplus) = \wp(\ominus) = 50\% \end{cases}$$

10^{20} dipôles



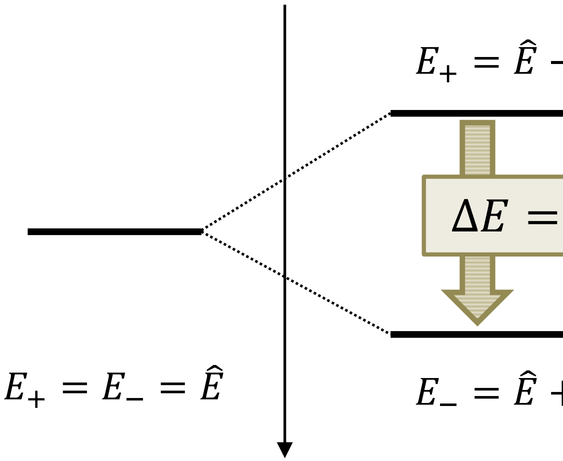
Ce que dit la mécanique quantique

Considérations énergétiques



$\mathbf{B} = 0$

$\mathbf{B} > 0$



$$E_+ = \hat{E} - \frac{1}{2}\gamma_s \hbar B$$

$$\Delta E = E_- - E_+ = \gamma_s \hbar B$$

$$E_+ = E_- = \hat{E}$$

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Principe de superposition

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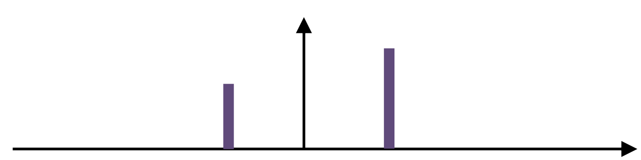
$$\wp(\oplus) = \alpha^2 \qquad \wp(\ominus) = \beta^2$$

$\boxed{B > 0}$ $\quad \wp(\oplus) > \wp(\ominus)$

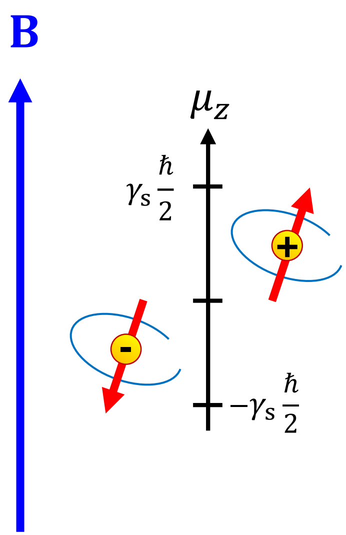
Un dipôle $\quad |\oplus\rangle \ > \ 50\%$

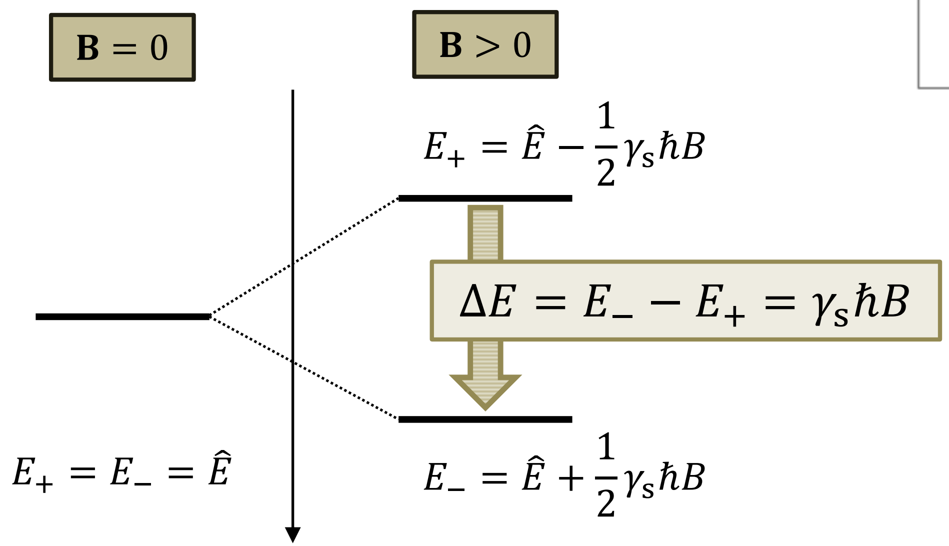
$|\ominus\rangle \ < \ 50\%$



Ce que dit la mécanique quantique

Considérations énergétiques





Principe de superposition

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$$\wp(\oplus) = \alpha^2 \qquad \wp(\ominus) = \beta^2$$

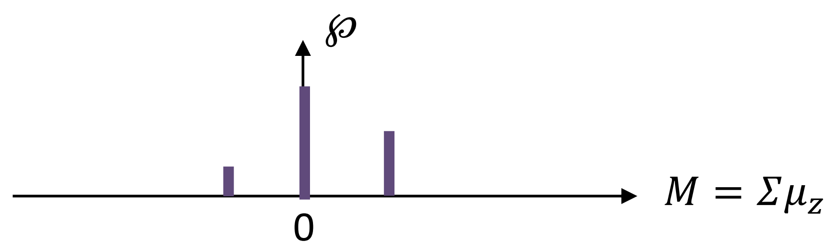
$\boxed{B > 0}$ $\quad \wp(\oplus) > \wp(\ominus)$

2 dipôles

$|\oplus\rangle\ |\oplus\rangle\ >\ 25\%$

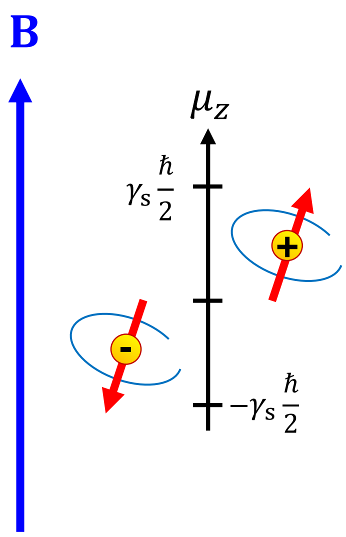
$|\ominus\rangle\ |\oplus\rangle\ \sim\ 25\%\quad |\oplus\rangle\,|\ominus\rangle \sim\ 25\%$

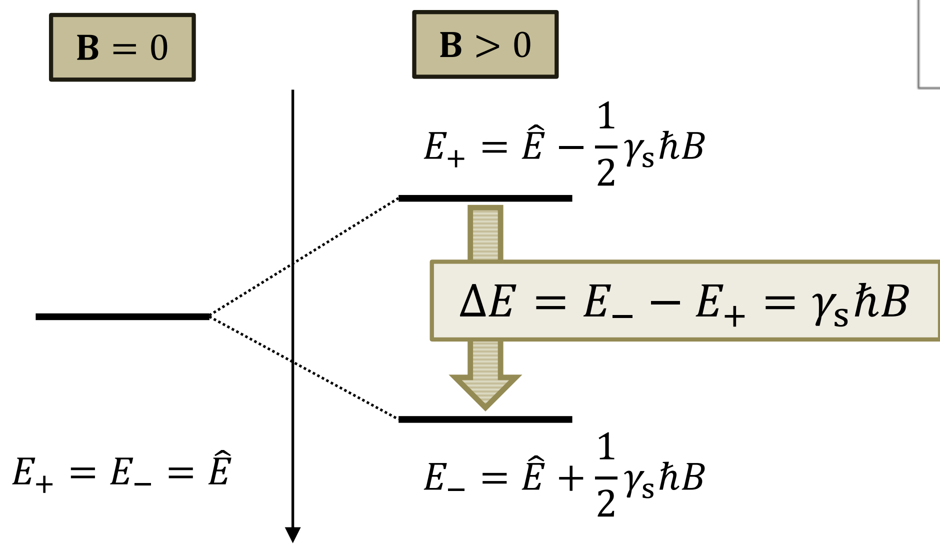
$|\ominus\rangle\ |\ominus\rangle\ <\ 25\%$



Ce que dit la mécanique quantique

Considérations énergétiques





Principe de superposition

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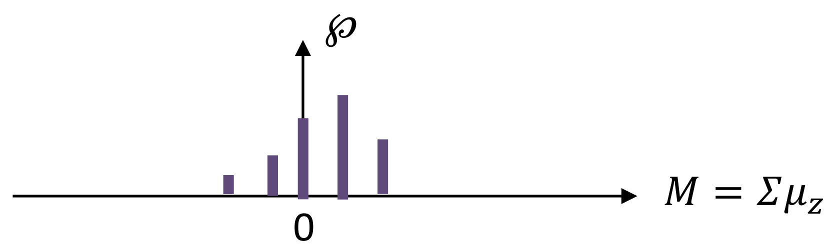
$\wp(\oplus) = \alpha^2 \qquad \wp(\ominus) = \beta^2$

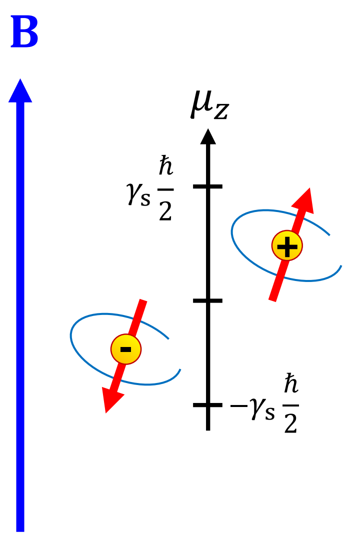
$\boxed{B > 0} \qquad \wp(\oplus) > \wp(\ominus)$

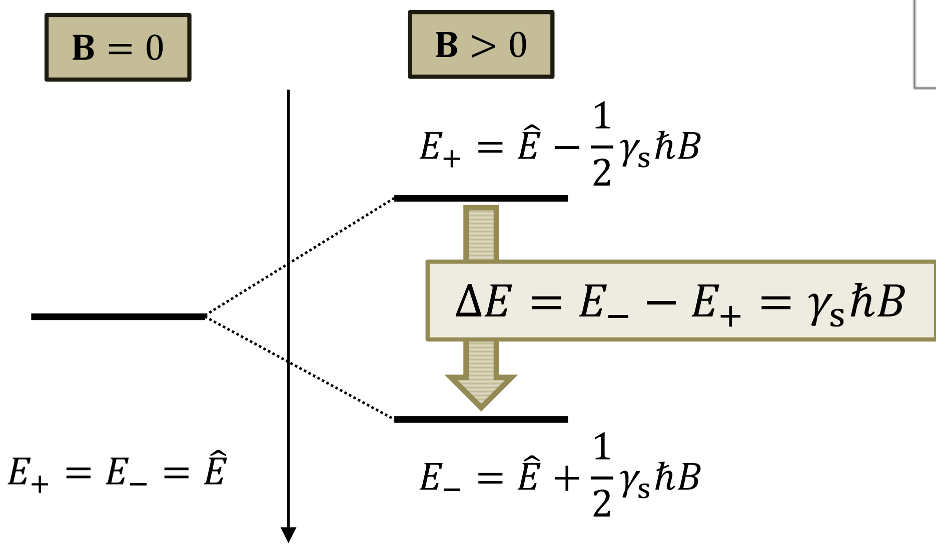
4 dipôles



Ce que dit la mécanique quantique

Considérations énergétiques





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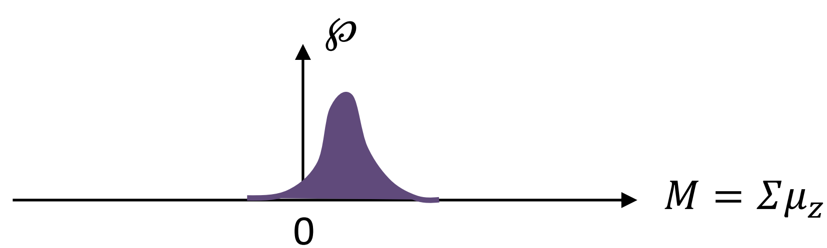
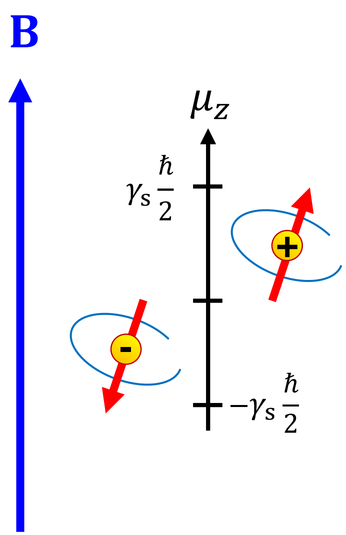
$\boxed{B > 0}$ $\quad \wp(\oplus) > \wp(\ominus)$

1000 dipôles

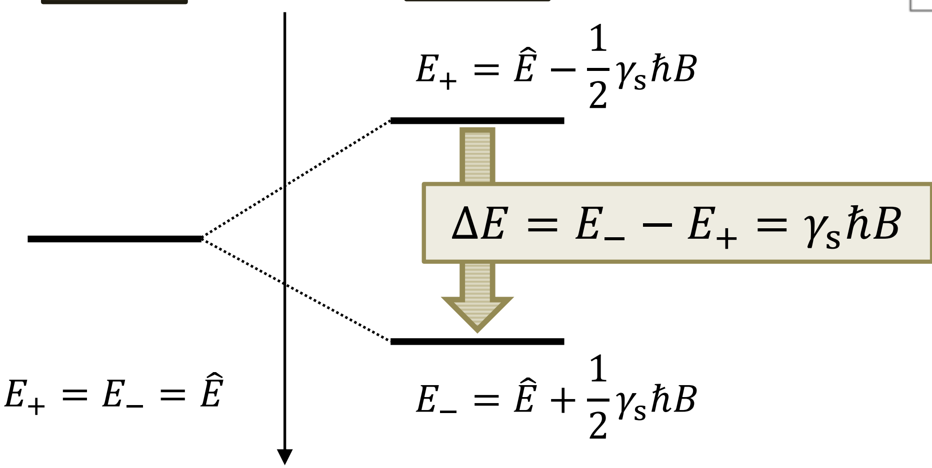


Ce que dit la mécanique quantique

Considérations énergétiques



$\mathbf{B} = 0$ | $\mathbf{B} > 0$



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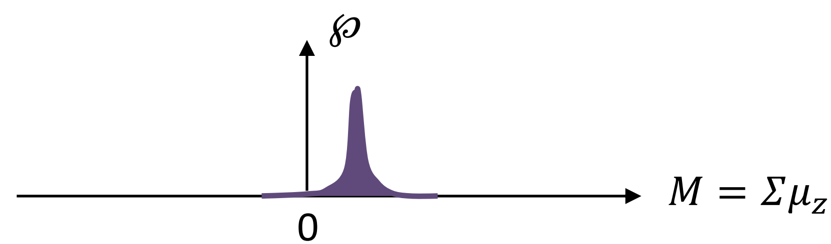
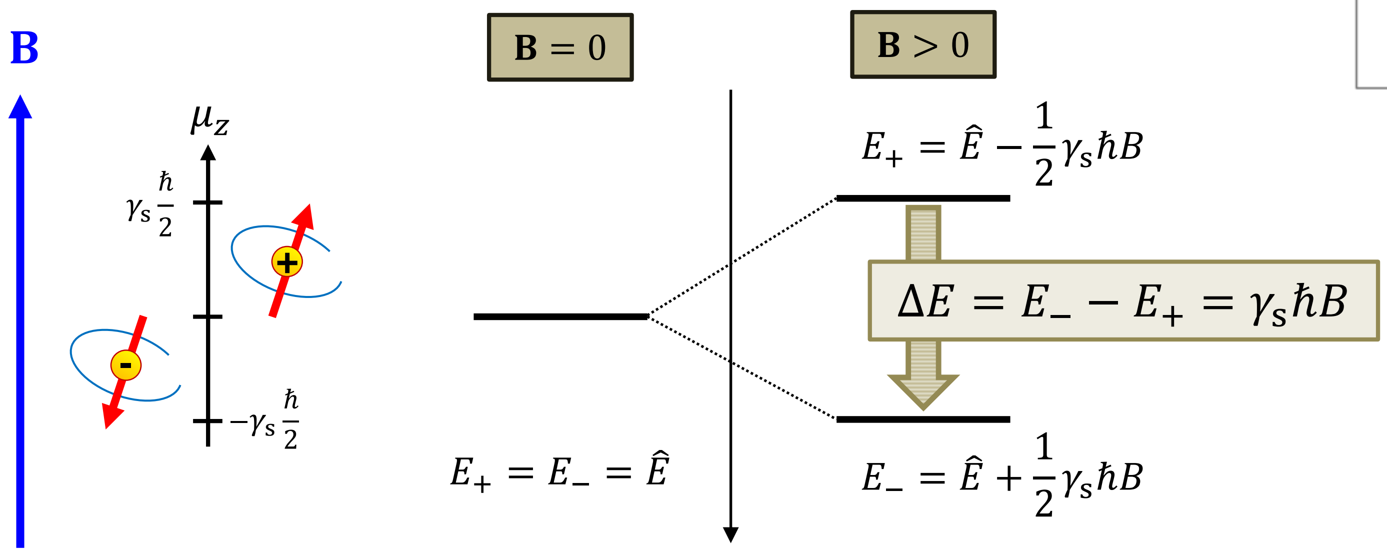
10^6 dipôles



Ce que dit la mécanique quantique

Considérations énergétiques



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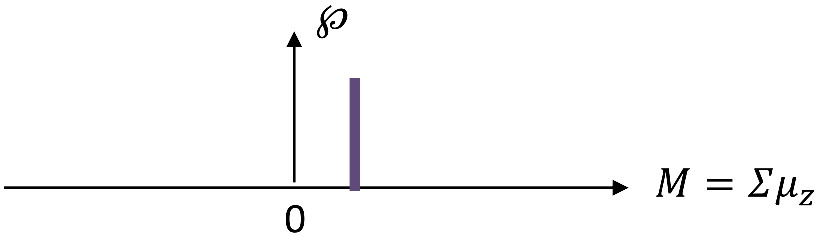
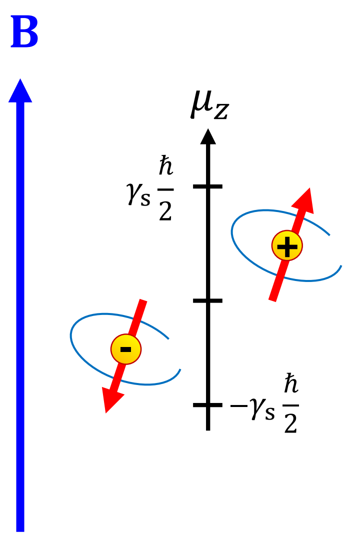
10^{20} dipôles



Ce que dit la mécanique quantique

Considérations énergétiques



B = 0

$$E_+ = E_- = \hat{E}$$

B > 0

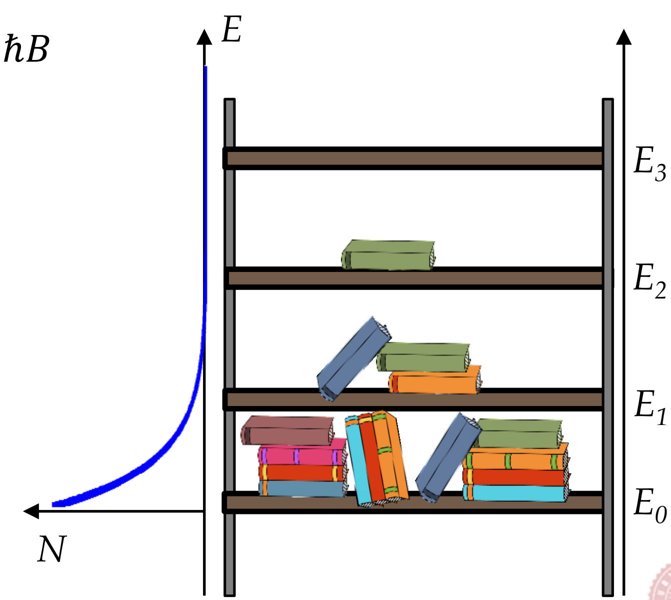
$$E_+ = \hat{E} - \frac{1}{2}\gamma_s \hbar B$$

$$\Delta E = E_- - E_+ = \gamma_s \hbar B$$

$$E_- = \hat{E} + \frac{1}{2}\gamma_s \hbar B$$

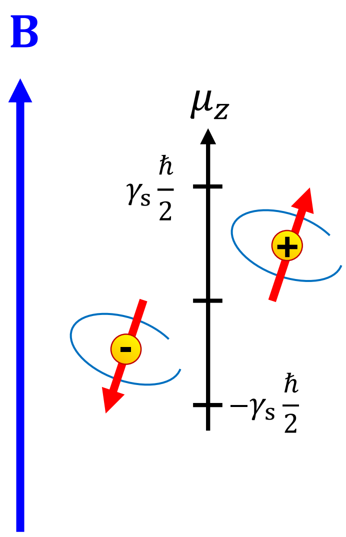
Ce que dit la physique statistique :

T° basse



Ce que dit la mécanique quantique

Considérations énergétiques



$\mathbf{B} = 0$

$E_+ = E_- = \hat{E}$

$\mathbf{B} > 0$

$E_+ = \hat{E} - \frac{1}{2}\gamma_s \hbar B$

$\Delta E = E_- - E_+ = \gamma_s \hbar B$

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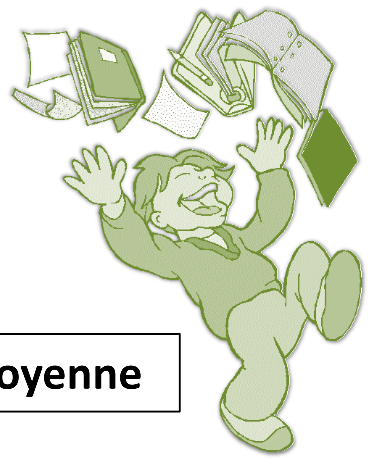
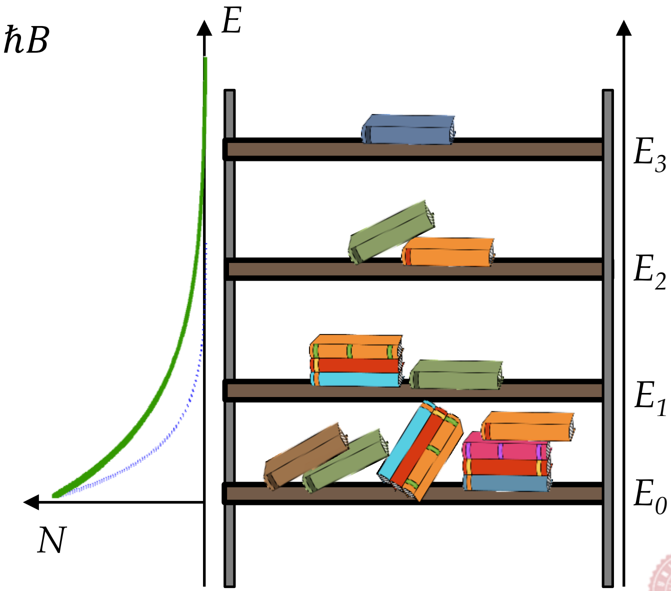
Ce que dit la physique statistique :

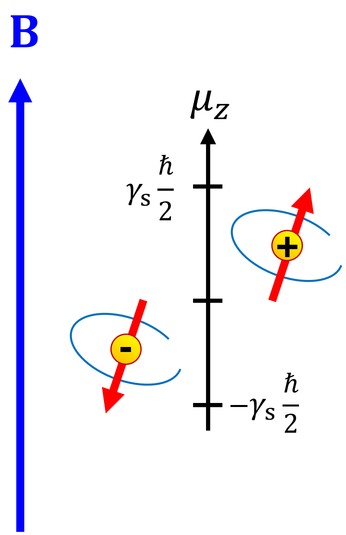


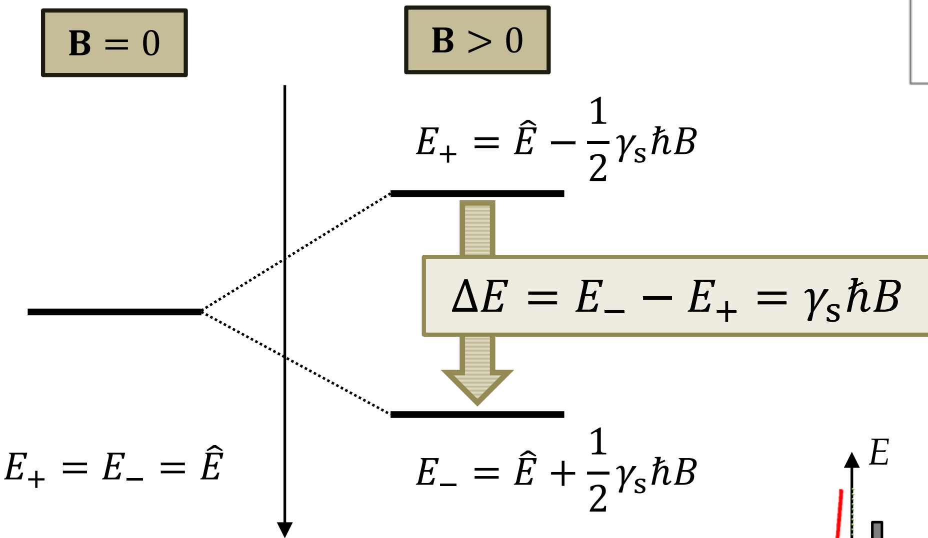
T° moyenne



Ce que dit la mécanique quantique

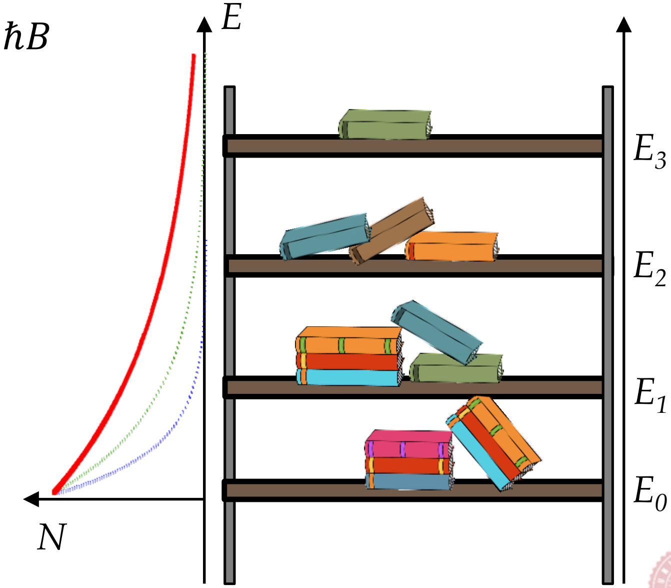
Considérations énergétiques





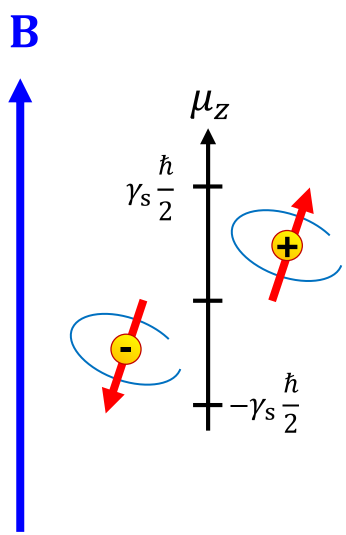
Ce que dit la physique statistique :

T° élevée



Ce que dit la mécanique quantique

Considérations énergétiques



B = 0

$$E_+ = E_- = \hat{E}$$

B > 0

$$E_+ = \hat{E} - \frac{1}{2}\gamma_s \hbar B$$

$$\Delta E = E_- - E_+ = \gamma_s \hbar B$$

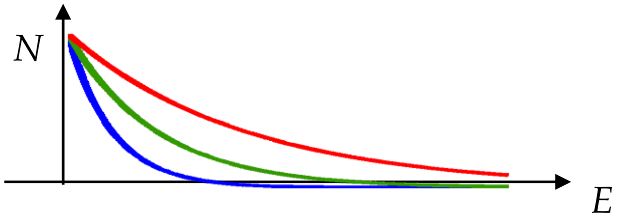
$$E_- = \hat{E} + \frac{1}{2}\gamma_s \hbar B$$

Ce que dit la physique statistique :

Particule indépendantes
Etats i d'énergie E_i
Température suffisante
Equilibre thermique

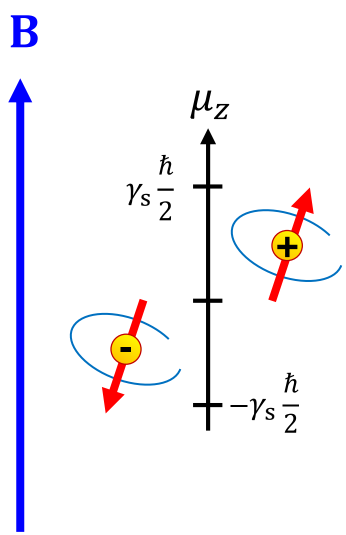
$$\wp_i \propto e^{-\frac{E_i}{k\,T}}$$

$$N_i = N \wp_i$$



Ce que dit la mécanique quantique

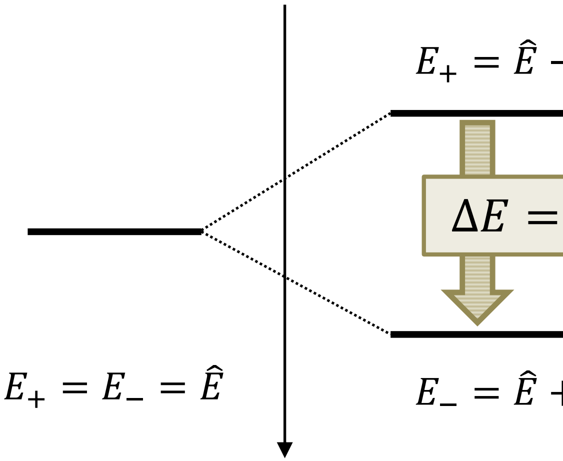
Considérations énergétiques



$\mathbf{B} = 0$

$\mathbf{B} > 0$

$$E_+ = \hat{E} - \frac{1}{2}\gamma_s \hbar B$$



$$\Delta E = E_- - E_+ = \gamma_s \hbar B$$

$$E_+ = E_- = \hat{E}$$

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Ce que dit la physique statistique :

Particule indépendantes
Etats i d'énergie E_i
Température suffisante
Equilibre thermique

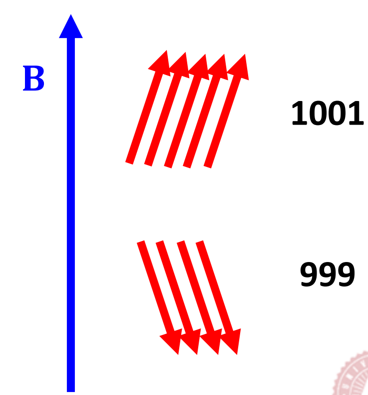
$$\wp_i \propto e^{-\frac{E_i}{k\,T}}$$

$$N_i = N \wp_i$$

$$\frac{\Delta N}{N} = \frac{N_+ - N_-}{N_+ + N_-} = \frac{\frac{N_+}{N_-} - 1}{\frac{N_+}{N_-} + 1}$$

$$= \frac{e^{\frac{\Delta E}{k\,T}} - 1}{e^{\frac{\Delta E}{k\,T}} + 1} \simeq \frac{\frac{\Delta E}{k\,T}}{\frac{\Delta E}{k\,T} + 2}$$

$$\sim \frac{\Delta E}{2\,k\,T} \sim \frac{1}{1000}$$

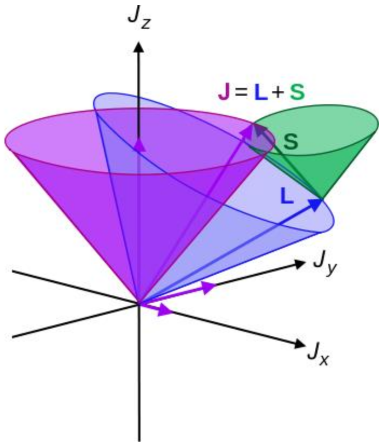


Ce que dit la mécanique quantique

Composition des moments cinétiques

Moment cinétique total $\mathbf{J}$

$\mathbf{J} = \mathbf{L} + \mathbf{S}$



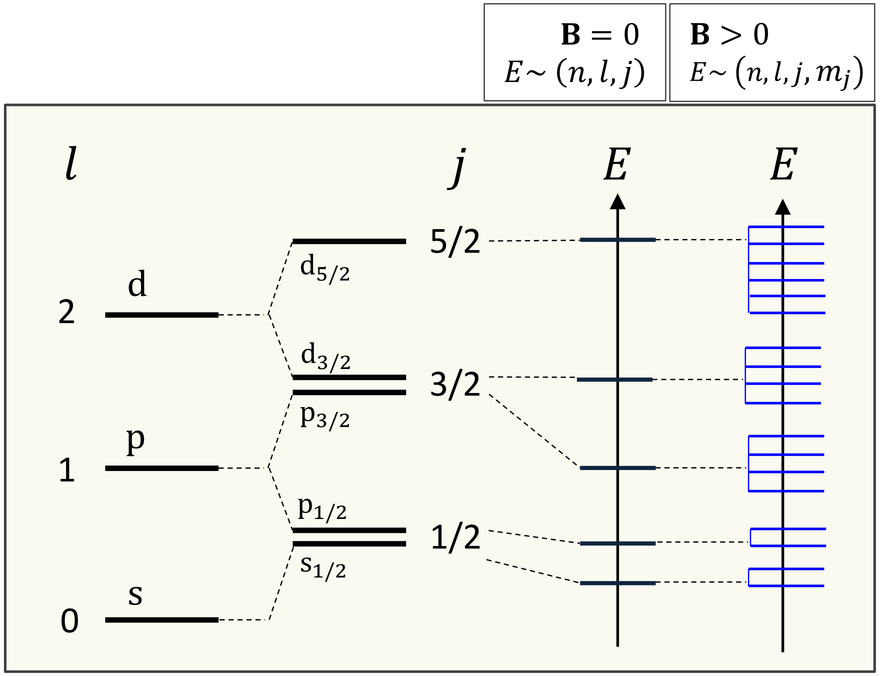
$|\mathbf{J}| = \hbar\sqrt{j(j+1)}$

$j = |l-s|, \dots, l+s$

Electron : $j = l - \frac{1}{2}, l + \frac{1}{2}$

$J_z = m_j\hbar = -j\hbar \dots j\hbar$

Etat (n, l, j, m_j)



Il s'y associe un moment magnétique :

$\boxed{\boldsymbol{\mu} = \gamma\,\mathbf{J} = g\,\gamma_0\,\mathbf{J}}$

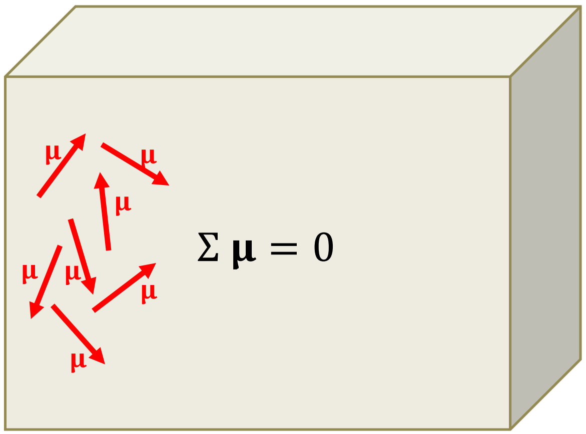
γ rapport gyromagnétique
g facteur de Landé

$$\Delta E = \Delta\mu_z\,B = \gamma\,\Delta J_z\,B = \gamma\,\hbar\,B = g\,\gamma_0\hbar\,B = g\,B\,\mu_B$$

magnéton de Bohr $\mu_B = \dfrac{e\,\hbar}{2\,m_e}$

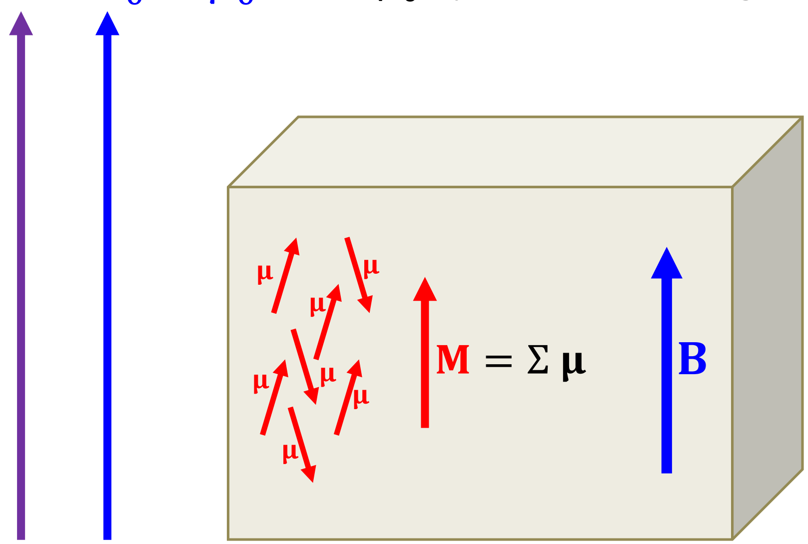
$\boxed{\mu_z = g\,m_j\,\mu_B}$

Magnétisme dans la matière



Magnétisme dans la matière

$\mathbf{H}$ $\quad \mathbf{B}_0 = \mu_0 \mathbf{H}$ $\qquad \mu_0$: perméabilité magnétique du vide



$$\mathbf{B} = \mu\, \mathbf{H}$$

μ : perméabilité magnétique du matériau

$$= \mu_0\,(1+\chi)\,\mathbf{H}$$

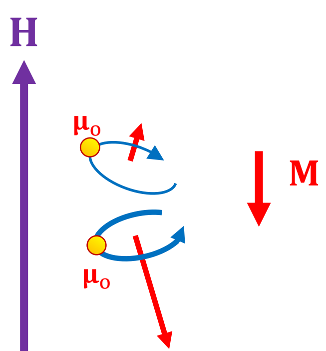
χ : susceptibilité magnétique

$$= \mu_0\,(\mathbf{H}+\mathbf{H}')$$

$\mathbf{H}' = \frac{\mathrm{d}\mathbf{M}}{\mathrm{d}V}$: aimantation volumique

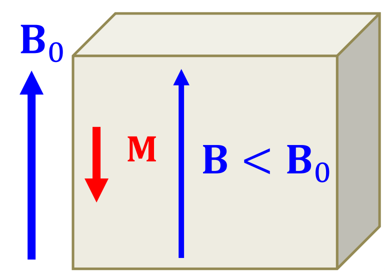
Diamagnétisme

Doublets d'électrons
Absence de moment permanent $\mathbf{J} = 0$
Modification du mouvement orbital



$\chi < 0$

$\chi \sim 10^{-5}$



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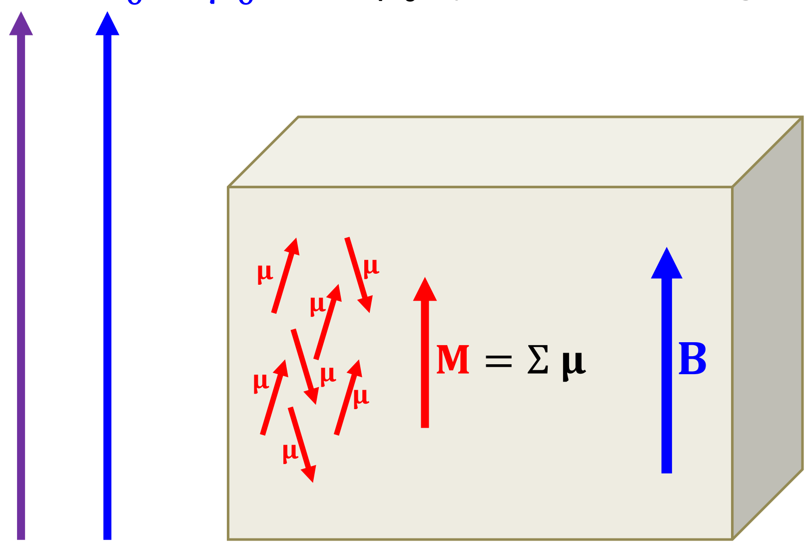


$$\mathbf{B} = \mu\ \mathbf{H}$$

μ : perméabilité magnétique du matériau

$$= \mu_0\ (1 + \chi)\ \mathbf{H}$$

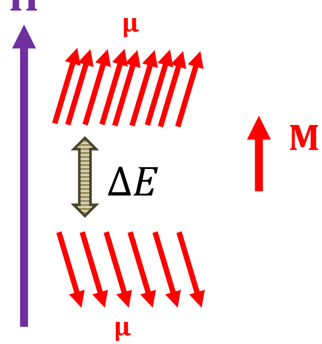
χ : susceptibilité magnétique

$$= \mu_0\ (\mathbf{H} + \mathbf{H}')$$

$\mathbf{H}' = \frac{\mathrm{d}\mathbf{M}}{\mathrm{d}V}$: aimantation volumique

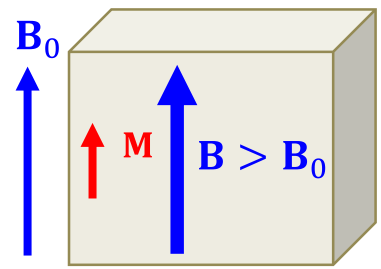
Paramagnétisme

Electrons de valence non appariés
Moment permanent $\mathbf{J}$
Alignement sur $\mathbf{B}_0$
Température dépendant



$\chi > 0$

$\chi \sim 10^{-3}$



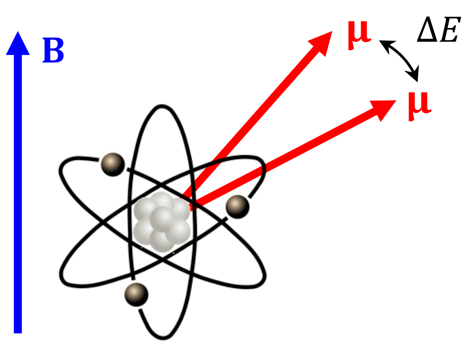
Magnétisme nucléaire

Magnétisme atomique essentiellement électronique

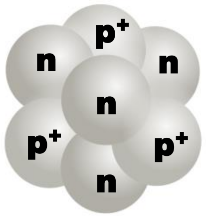
- Moment cinétique total $\mathbf{J}$
- Moment magnétique permanent $\boldsymbol{\mu}$

$\boldsymbol{\mu} = \gamma_e \, \mathbf{J} \qquad \overline{\gamma_e} \sim \mathrm{GHz\ T^{-1}}$

$\Delta E = \Delta\mu_z \, B = g \, B \, \mu_B$



Noyau = protons + neutrons



- Moment cinétique total $\mathbf{J}$: « SPIN »
- Moment magnétique permanent $\boldsymbol{\mu}$: « SPIN »

$\boldsymbol{\mu} = \gamma_N \, \mathbf{J} \qquad \overline{\gamma_N} \sim \mathrm{MHz\ T^{-1}}$

$\Delta E = \Delta\mu_z \, B = g \, B \, \mu_N$

magnéton nucléaire $\mu_N = \dfrac{e\,\hbar}{2\,m_p} \ll \mu_B$

$$\boxed{\gamma_N = g \, \frac{e}{2\,m_p}}$$

Proton : $g = 5{,}6$ **Neutron :** $g = -3{,}8$

Magnétisme nucléaire

Magnétisme atomique essentiellement électronique

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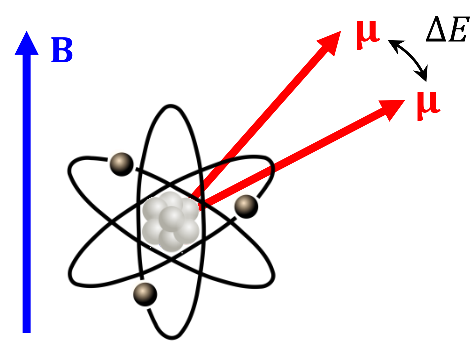

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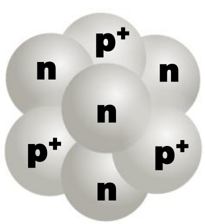

- Moment cinétique total $\mathbf{J}$: « SPIN »
- Moment magnétique permanent $\boldsymbol{\mu}$: « SPIN »

$$\boldsymbol{\mu} = \gamma_N \, \mathbf{J} \qquad \overline{\gamma_N} \sim \mathrm{MHz\ T^{-1}}$$

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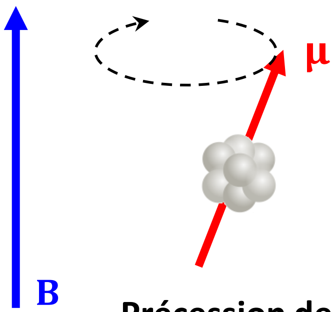
magnéton nucléaire $\mu_N = \dfrac{e \, \hbar}{2 \, m_p} \ll \mu_B$

Proton : $g = 5{,}6$ **Neutron :** $g = -3{,}8$



Précession de Larmor

$$\boldsymbol{\omega} = -\gamma_N \, \mathbf{B}$$

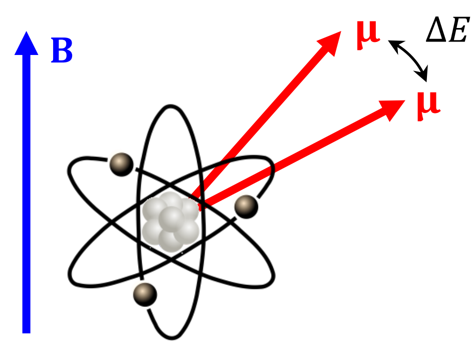
Magnétisme nucléaire

Magnétisme atomique essentiellement électronique

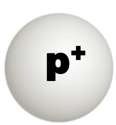
- Moment cinétique total $\mathbf{J}$
- Moment magnétique permanent $\boldsymbol{\mu}$

$$\boldsymbol{\mu} = \gamma_e\,\mathbf{J} \qquad \overline{\gamma_e} \sim \mathrm{GHz\,T^{-1}}$$

$$\Delta E = \Delta\mu_z\, B = g\, B\, \mu_B$$



Noyau ^1H = 1 proton

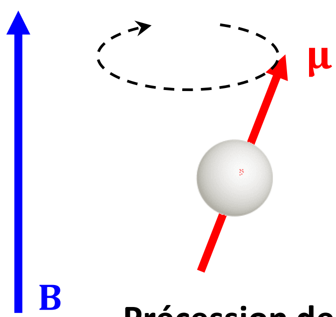


- Moment cinétique total $\mathbf{J}$: « SPIN »
- Moment magnétique permanent $\boldsymbol{\mu}$: « SPIN »

$$\boldsymbol{\mu} = \gamma_p\,\mathbf{J}$$

$$\Delta E = \Delta\mu_z\, B = g\, B\, \mu_N$$

$$\boxed{\overline{\gamma_p} = 42{,}6\ \mathrm{MHz\,T^{-1}}}$$



Précession de Larmor

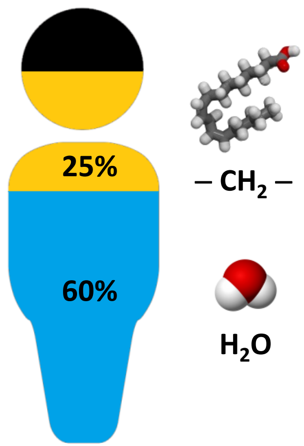
$B = 1{,}5\ \mathrm{T} :\ \nu = 64\ \mathrm{MHz}$
$B = 3\ \mathrm{T} :\ \nu = 128\ \mathrm{MHz}$
ondes radio

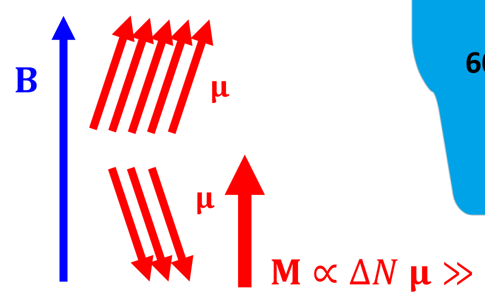
Magnétisme nucléaire

Nucleus	*Spin*	*Landé factor*
proton p	1/2	5.5883
neutron n	1/2	−3.8263
deuteron $^{2}_{1}D$	1	0.85742
$^{3}_{2}He$	1/2	−4.255
$^{4}_{2}He$	0	—
$^{12}_{6}C$	0	—
$^{16}_{8}O$	0	—
$^{39}_{19}K$	3/2	0.2609
$^{67}_{30}Zn$	5/2	0.35028
$^{85}_{37}Rb$	5/2	0.54108
$^{129}_{54}Xe$	1/2	−1.5536
$^{133}_{55}Cs$	7/2	0.7369
$^{199}_{80}Hg$	1/2	1.0054
$^{201}_{80}Hg$	3/2	−0.37113

- **Spin dépend de la composition du noyau**
- **Pas de spin ⇔ Pas de magnétisme**
- **$^{1}H = p^{+}$: magnétisme maximal**

$$g \gg \begin{cases} \gamma \gg \Rightarrow \boldsymbol{\mu} \gg \\ \dfrac{\Delta N}{N} \propto \Delta E \gg \end{cases}$$



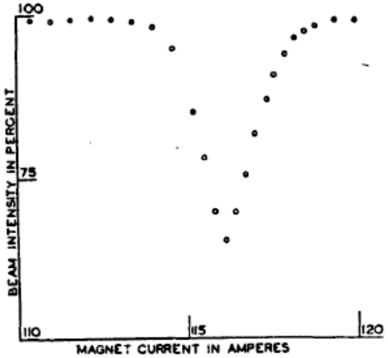


RMN – principe

Prix Nobel

Lauréats	*Année*	*Discipline*	*Travaux*
O. Stern	1943	Physique	Moment magnétique du proton (1933)
I. Rabi	1944	Physique	RMN
F. Bloch & E. Purcell	1952	Physique	RMN
R. Ernst	1991	Chimie	Spectroscopie RMN haute résolution
P. Lauterbur & P. Mansfield	2003	Médecine	IRM

I. Rabi



RMN – principe

Prix Nobel

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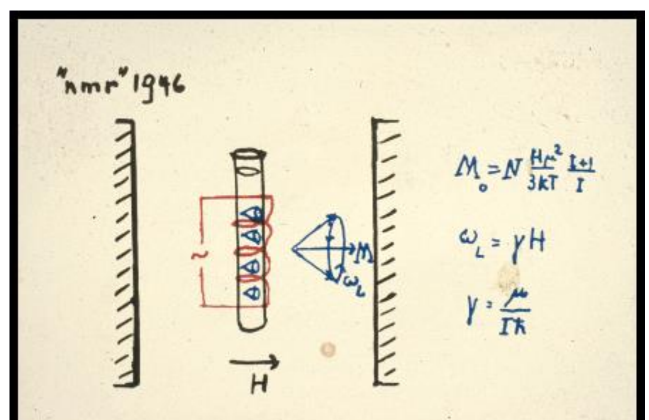
P. Lauterbur & P. Mansfield	2003	Médecine	IRM

Bloch & Purcell



RMN – principe

Prix Nobel

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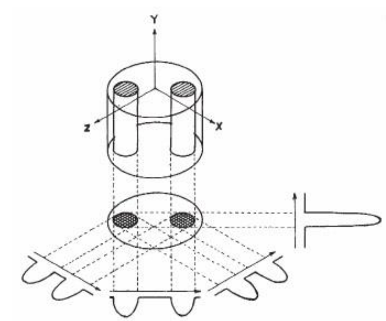
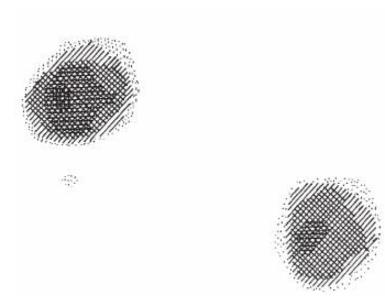
Lauterbur & Mansfield





RMN – principe

Prix Nobel

Lauréats	*Année*	*Discipline*	*Travaux*
O. Stern	1943	Physique	Moment magnétique du proton (1933)
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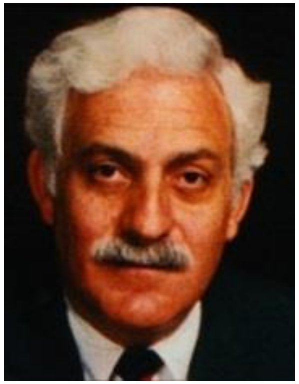
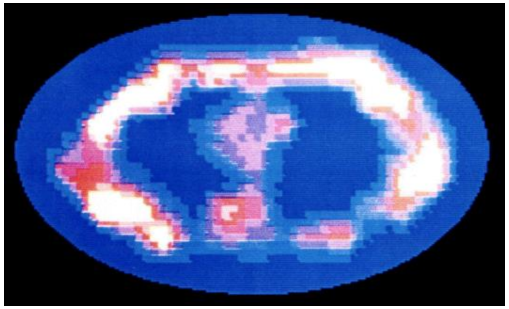
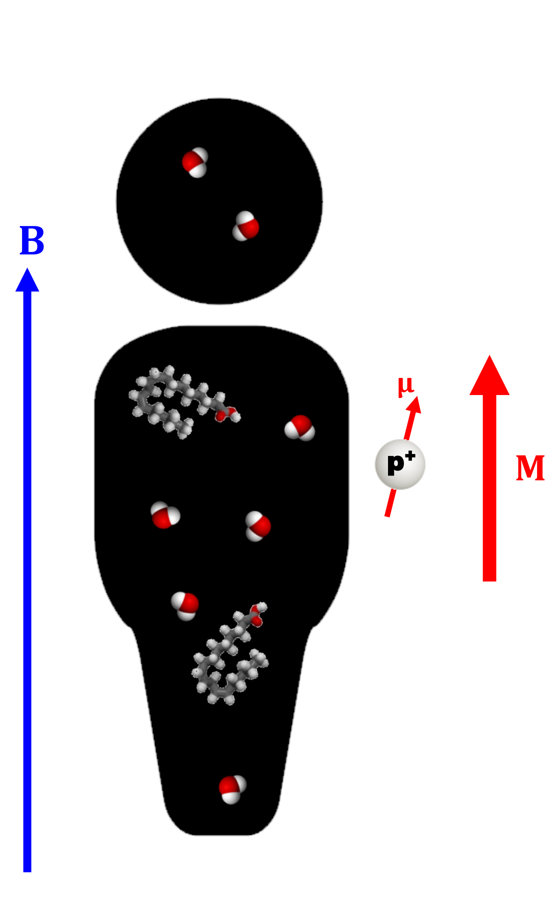


R. Damadian

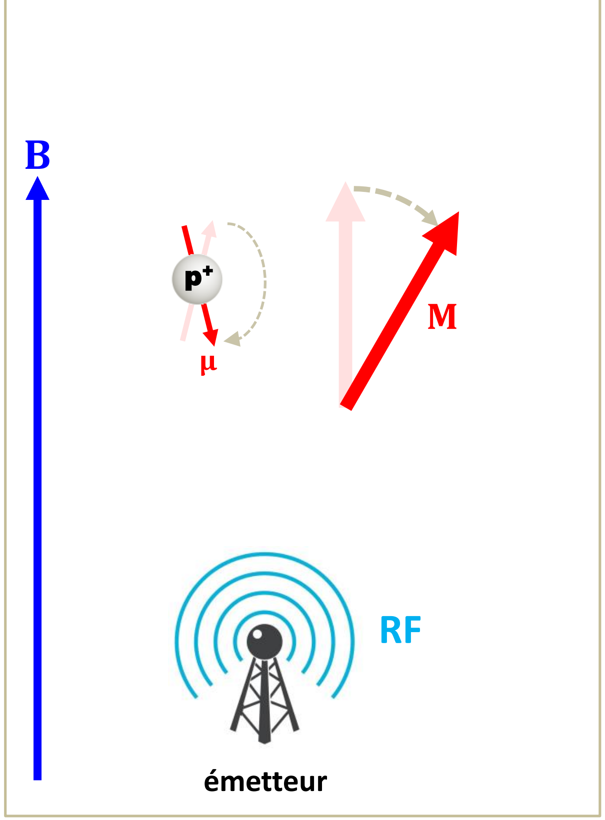


RMN – principe

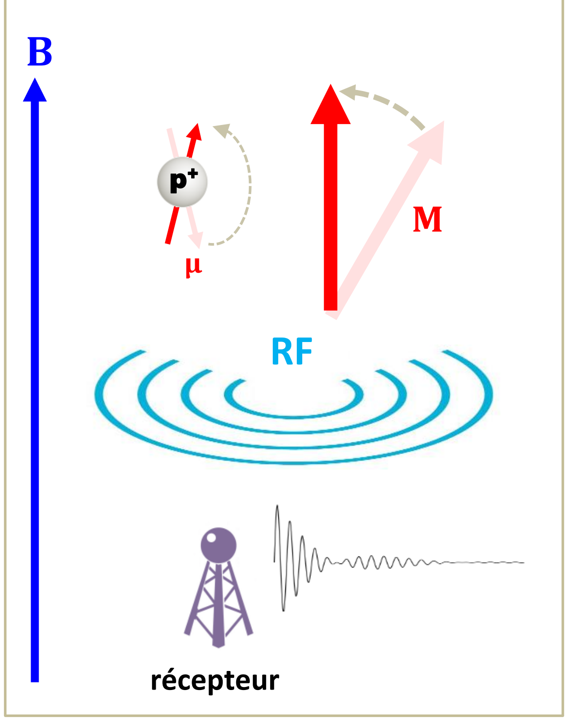
1. Préparation (aimantation)



2. Perturbation (résonance)

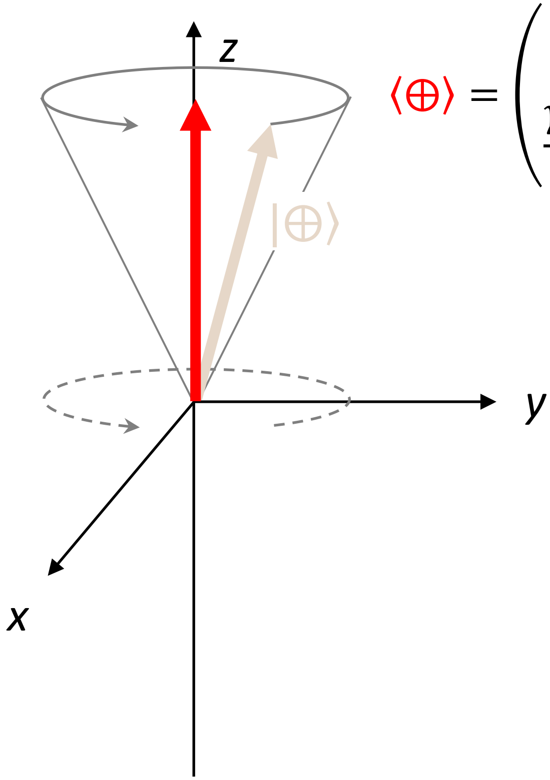


3. Mesure (relaxation)



RMN – principe

Représentation des spins μ via ⟨μ⟩

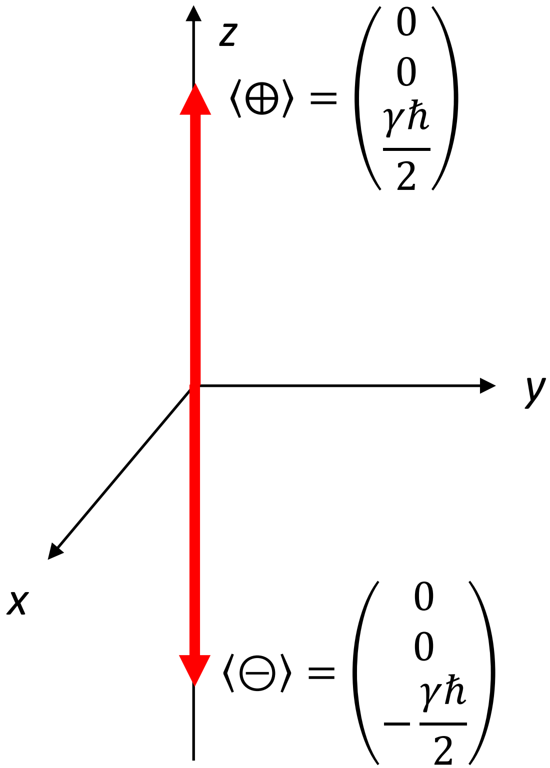


$$\langle \oplus \rangle = \begin{pmatrix} 0 \\ 0 \\ \dfrac{\gamma\hbar}{2} \end{pmatrix}$$

$$\langle \boldsymbol{\mu} \rangle = \begin{pmatrix} \langle \mu_x \rangle \\ \langle \mu_y \rangle \\ \langle \mu_z \rangle \end{pmatrix}$$

RMN – principe

Représentation des spins μ via ⟨μ⟩



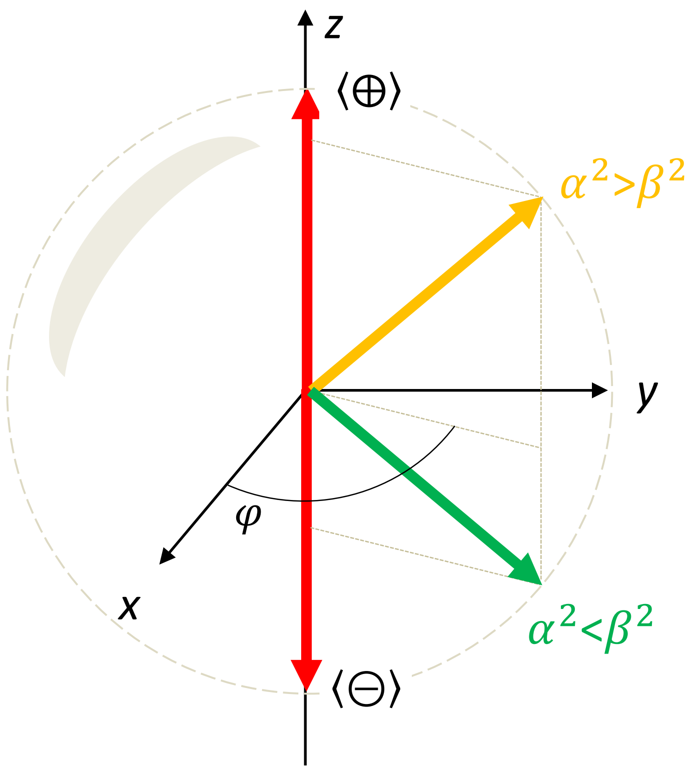
$$\langle \oplus \rangle = \begin{pmatrix} 0 \\ 0 \\ \dfrac{\gamma\hbar}{2} \end{pmatrix}$$

$$\langle \ominus \rangle = \begin{pmatrix} 0 \\ 0 \\ -\dfrac{\gamma\hbar}{2} \end{pmatrix}$$

$$\langle \boldsymbol{\mu} \rangle = \begin{pmatrix} \langle \mu_x \rangle \\ \langle \mu_y \rangle \\ \langle \mu_z \rangle \end{pmatrix}$$

RMN – principe

Représentation des spins μ via ⟨μ⟩



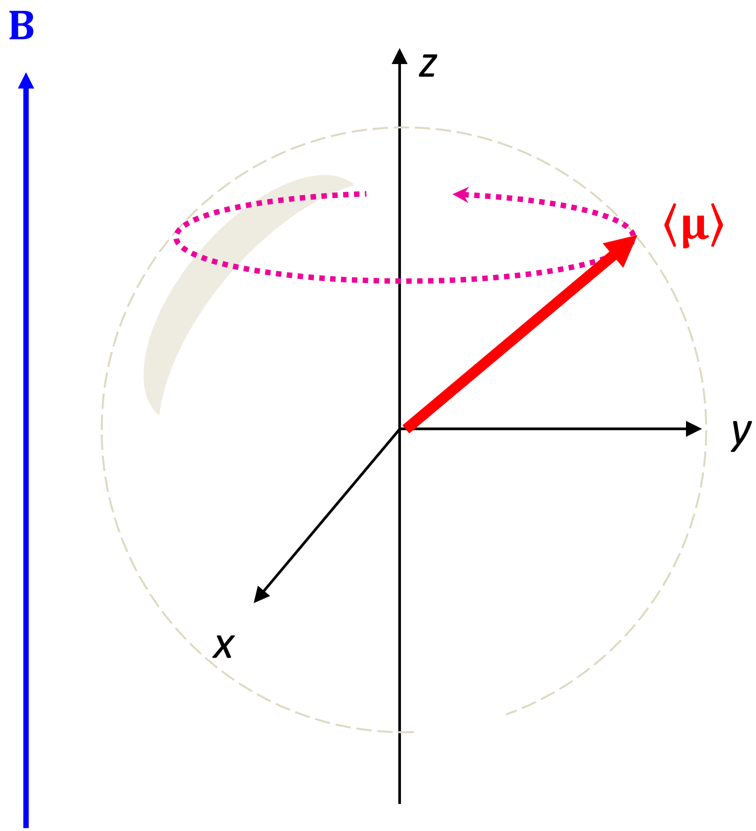
$$|\boldsymbol{\mu}\rangle = \alpha|\oplus\rangle + \beta|\ominus\rangle$$

$$\langle\boldsymbol{\mu}\rangle = \begin{pmatrix} \langle\mu_x\rangle \\ \langle\mu_y\rangle \\ \langle\mu_z\rangle \end{pmatrix}$$

$$\langle\boldsymbol{\mu}\rangle = \frac{\gamma\hbar}{2}\begin{pmatrix} 2\,\alpha\beta\cos(\varphi) \\ 2\,\alpha\beta\sin(\varphi) \\ \alpha^2-\beta^2 \end{pmatrix}$$

RMN – principe

Représentation des spins μ via ⟨μ⟩



$$|\boldsymbol{\mu}\rangle = \alpha|\oplus\rangle + \beta|\ominus\rangle$$

$$\langle\boldsymbol{\mu}\rangle = \begin{pmatrix} \langle\mu_x\rangle \\ \langle\mu_y\rangle \\ \langle\mu_z\rangle \end{pmatrix}$$

$$\begin{cases} \langle\mu_x\rangle = 2\,\alpha\beta\cos\boxed{(\omega t)} \\ \langle\mu_y\rangle = 2\,\alpha\beta\sin\boxed{(\omega t)} \\ \langle\mu_z\rangle = \alpha^2 - \beta^2 \end{cases}$$

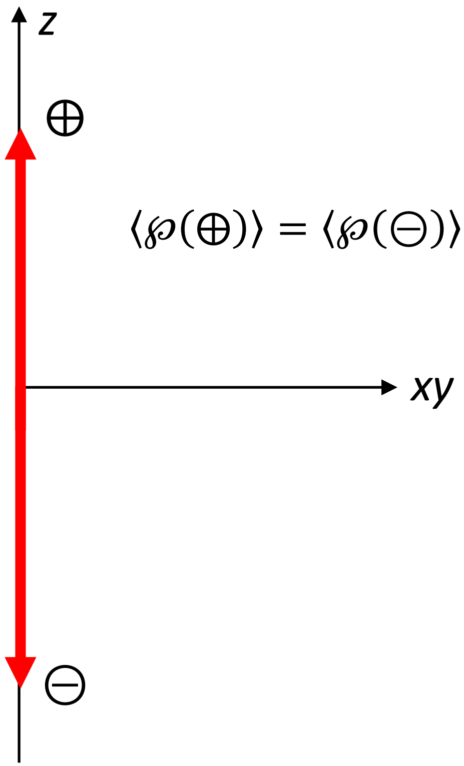
$$\boxed{\omega = \gamma B}$$

RMN – principe

Représentation statistique (fréquentiste) des spins

$\mathbf{B_0 = 0}$

Mesures individuelles accessibles

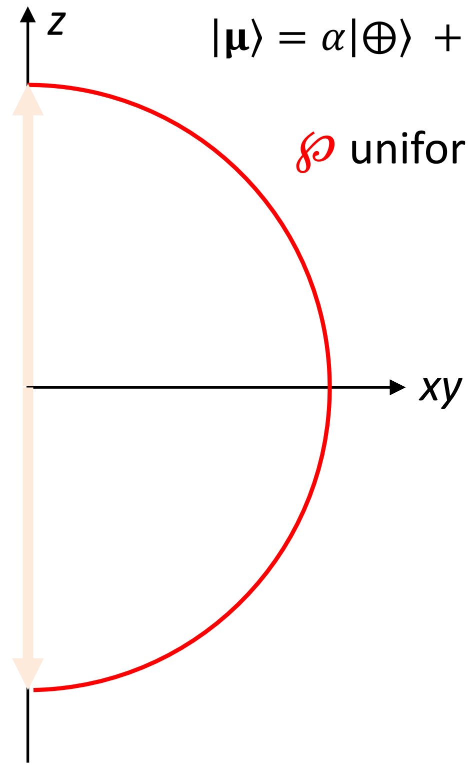


$\langle \wp(\oplus) \rangle = \langle \wp(\ominus) \rangle = 50\%$

Etats superposés

$|\boldsymbol{\mu}\rangle = \alpha|\oplus\rangle + \beta|\ominus\rangle$

$\wp$ uniforme

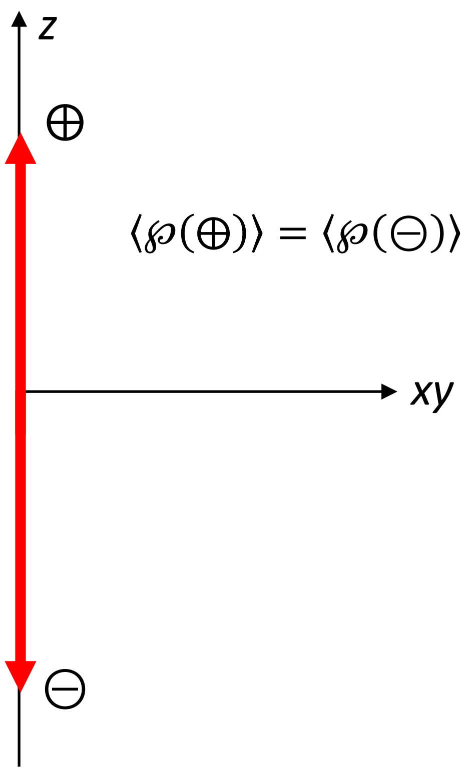


RMN – principe

Représentation statistique (fréquentiste) des spins

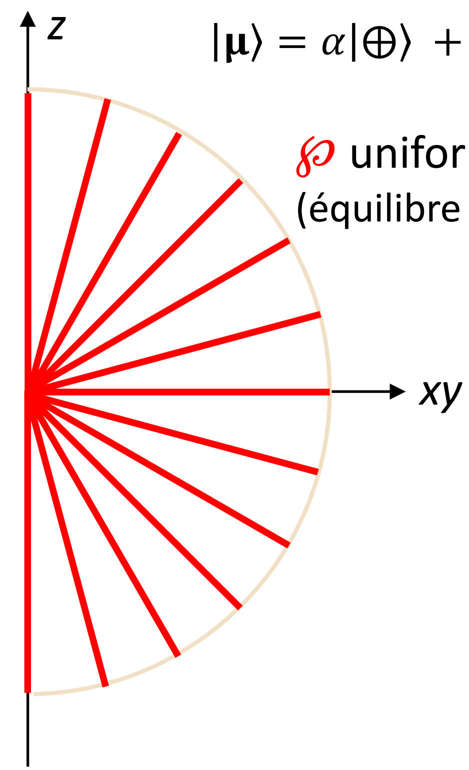
$\mathbf{B_0 = 0}$

Mesures individuelles accessibles



$$\langle \wp(\oplus) \rangle = \langle \wp(\ominus) \rangle = 50\%$$

Etats superposés



$$|\boldsymbol{\mu}\rangle = \alpha|\oplus\rangle + \beta|\ominus\rangle$$

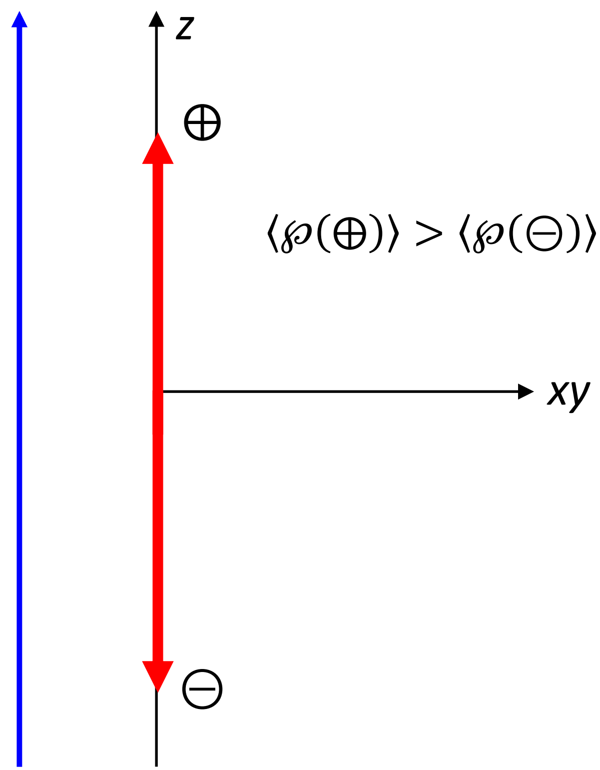
$\wp$ uniforme
(équilibre des populations)

RMN – principe

Représentation statistique (fréquentiste) des spins

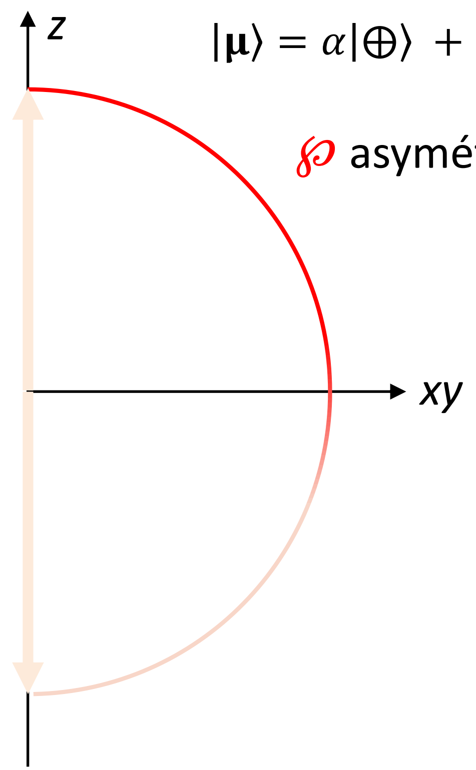
$\mathbf{B_0 > 0}$

Mesures individuelles accessibles



$$\langle \wp(\oplus) \rangle > \langle \wp(\ominus) \rangle$$

Etats superposés



$$|\boldsymbol{\mu}\rangle = \alpha|\oplus\rangle + \beta|\ominus\rangle$$

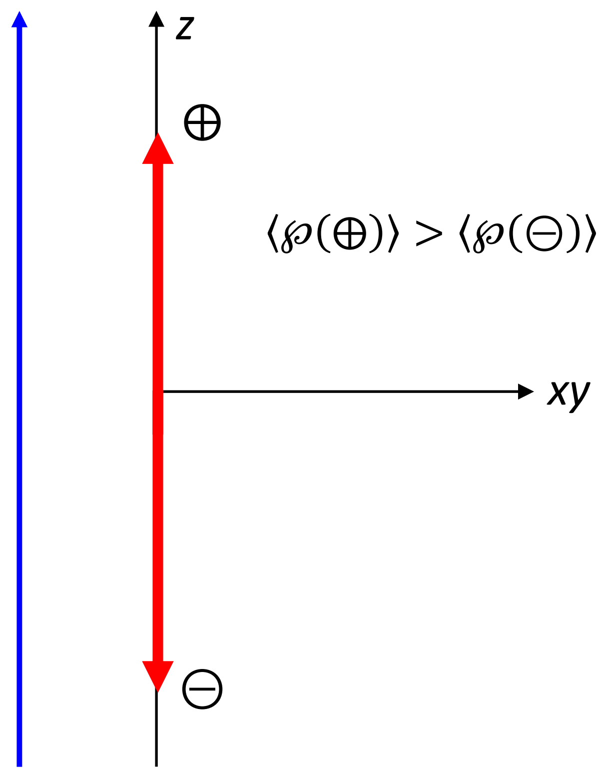
$\wp$ asymétrique

RMN – principe

Représentation statistique (fréquentiste) des spins

$\mathbf{B_0 > 0}$

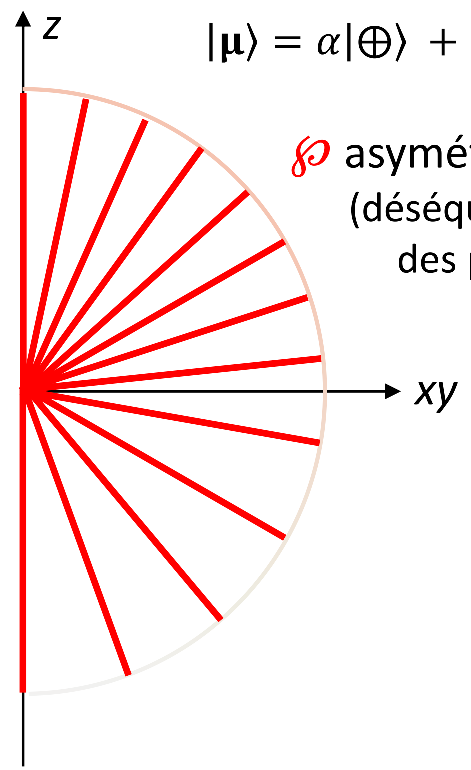
Mesures individuelles accessibles



$\langle \wp(\oplus) \rangle > \langle \wp(\ominus) \rangle$

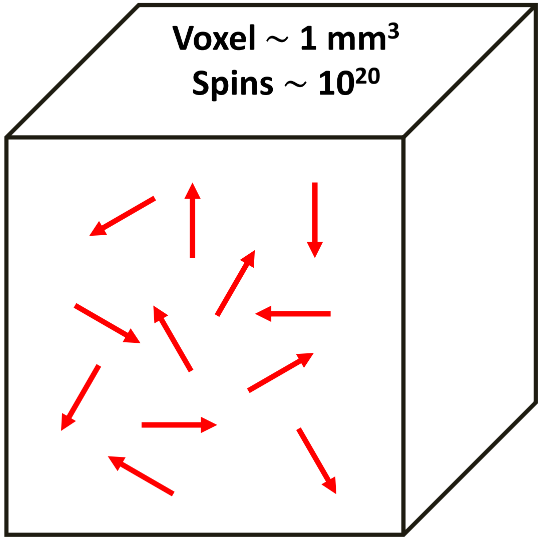
Etats superposés

$|\boldsymbol{\mu}\rangle = \alpha|\oplus\rangle \ + \ \beta|\ominus\rangle$



$\wp$ asymétrique
(déséquilibre
des populations)

RMN – principe

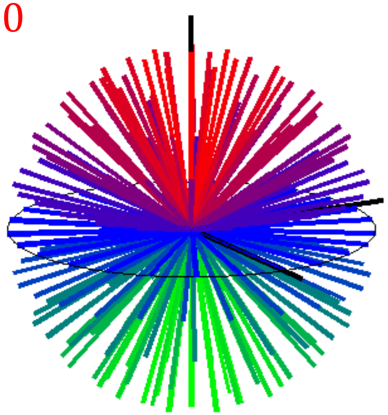


$\mathbf{B}\sim 0$ (champ magnétique terrestre = 47 µT)

Agitation thermique >> effets magnétiques

$$\langle \mathbf{M} \rangle = \sum \langle \boldsymbol{\mu} \rangle = 0$$

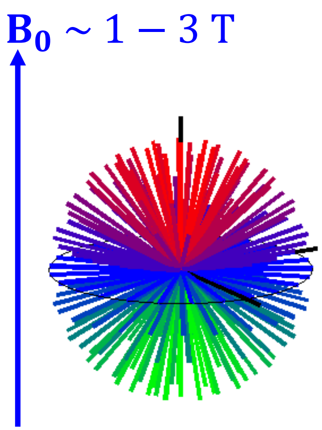
$$\mathbf{M} = 0$$

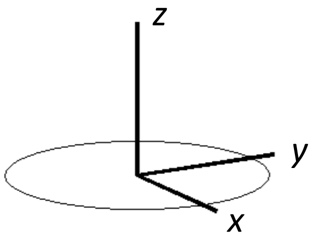


RMN – principe

1. Préparation (aimantation)

Précession de Larmor : $\omega_0 = \gamma B_0$





RMN – principe

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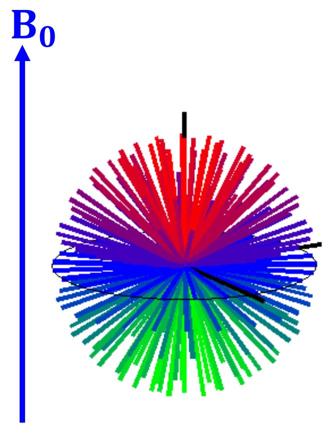
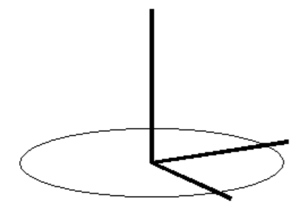
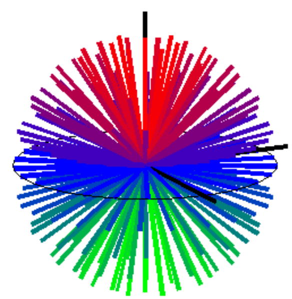
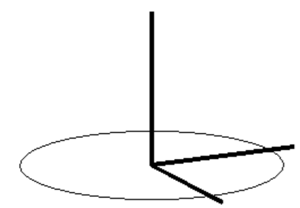


référentiel fixe





référentiel tournant
" $\mathbf{B_0 = 0}$ "



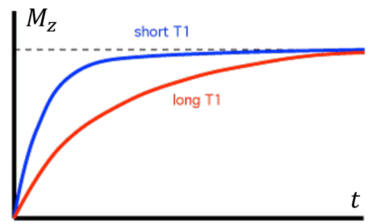
RMN – principe

1. Préparation (aimantation)

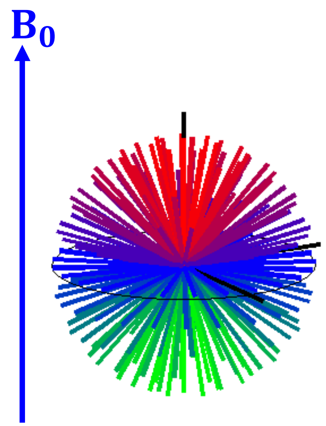
Précession de Larmor : $\omega_0 = \gamma B_0$

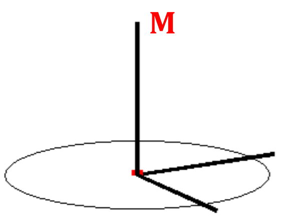
Alignement sur le champ

- **Aimantation longitudinale M_z**
- **Cinétique exponentielle T_1**

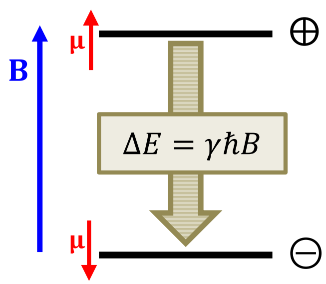


$$M_z(t) = M_L\left(1 - e^{-t/T_1}\right)$$

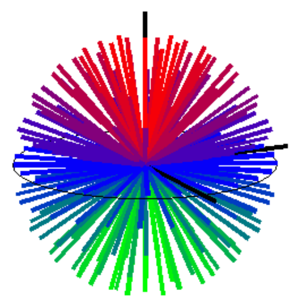


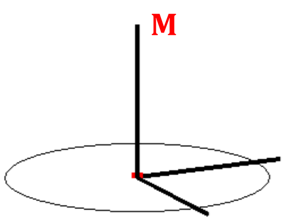


- **Echanges énergétiques :** $E = -\boldsymbol{\mu} \cdot \mathbf{B}$



$\langle \wp(\oplus) \rangle > \langle \wp(\ominus) \rangle$



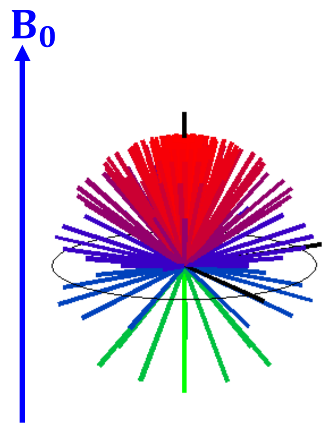


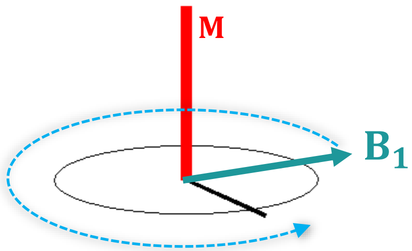
RMN – principe

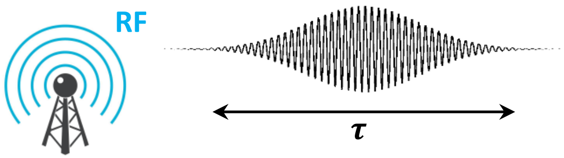
2. Perturbation (résonance)

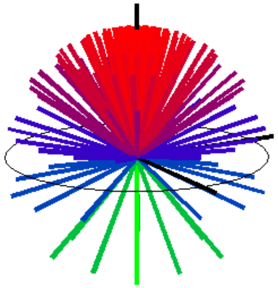
Application d'un champ tournant B_1
- **de** **fréquence $\omega_0/2\pi$**
- **pendant une durée τ (~ms)**

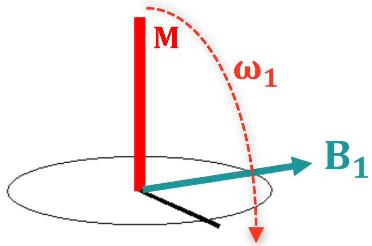
Précession de M autour de B_1
- $\omega_1 = \gamma B_1$
- **Bascule (nutation) d'un angle $\eta = \tau\,\omega_1$**











RMN – principe

2. Perturbation (résonance)

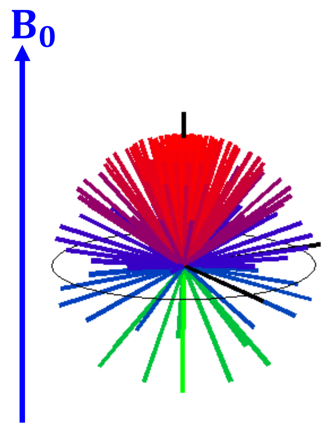
Application d'un champ tournant B_1

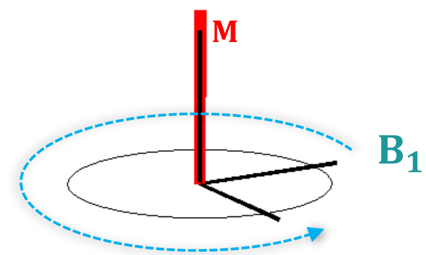
- **de** $\boxed{\textbf{fréquence } \omega_0/2\pi}$
- **pendant une durée** τ **(~ms)**

Précession de M autour de B_1

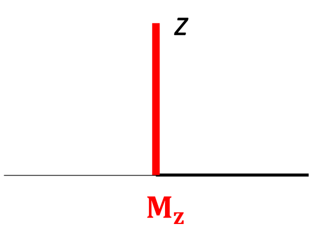
- $\omega_1 = \gamma B_1$
- **Bascule (nutation) d'un angle** $\eta = \tau\,\omega_1$

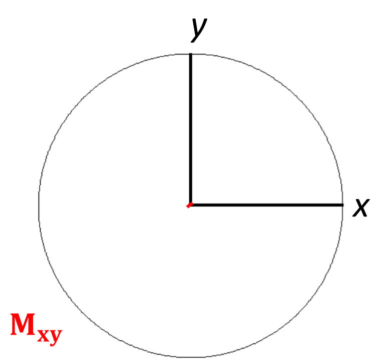
Disparition de M_z
Apparition de M_{xy} (aimantation transverse)

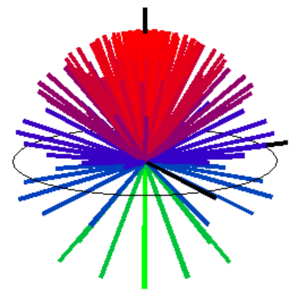


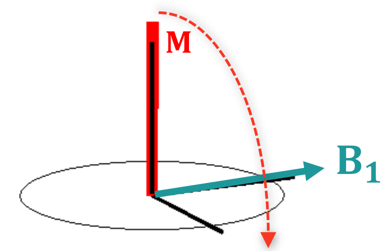


$$\eta = \frac{\pi}{2}$$







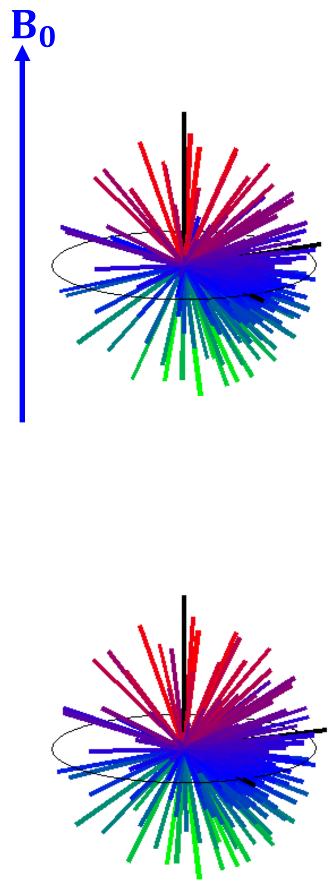


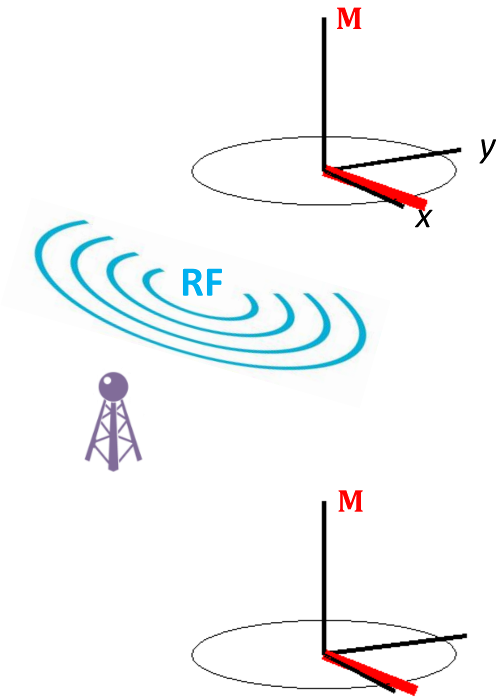
RMN – principe

3. Mesure (relaxation)

Arrêt de la stimulation RF B_1

Signal = M_x



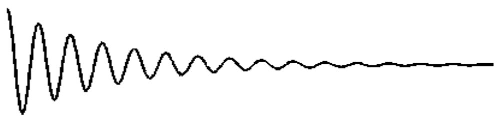


RMN – principe

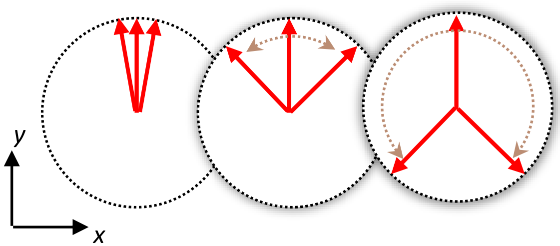
3. Mesure (relaxation)

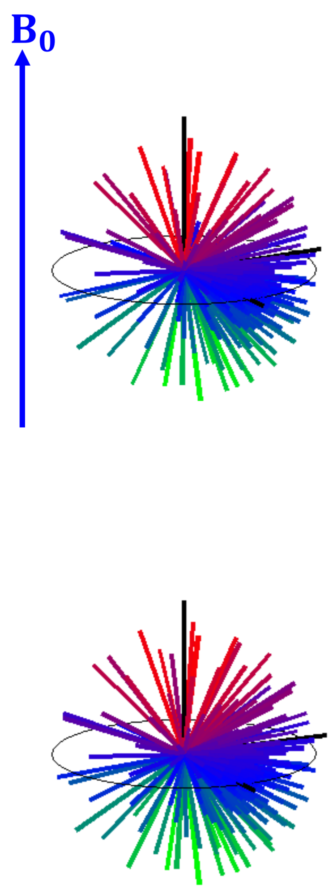
Arrêt de la stimulation RF B_1

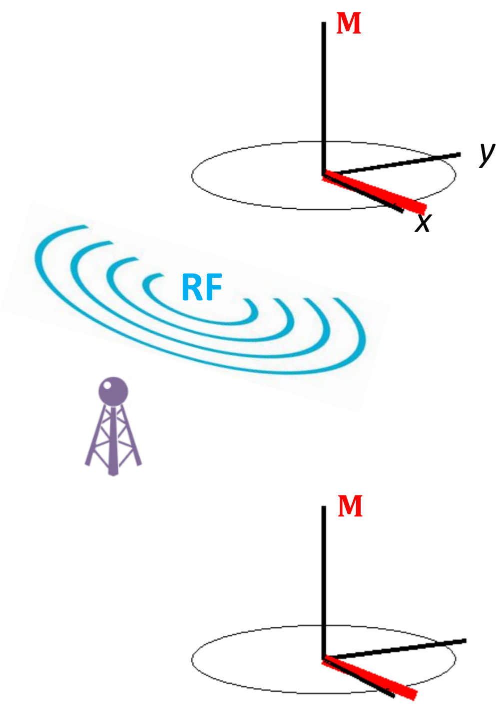
Signal = M_x



- **Déphasage progressif**
- **Inhomogénéités de champ**
- **Phénomène entropique**





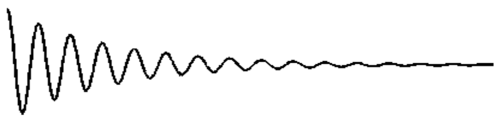


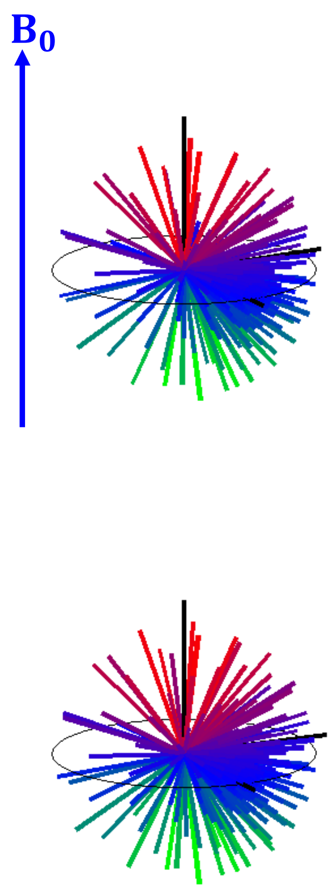
RMN – principe

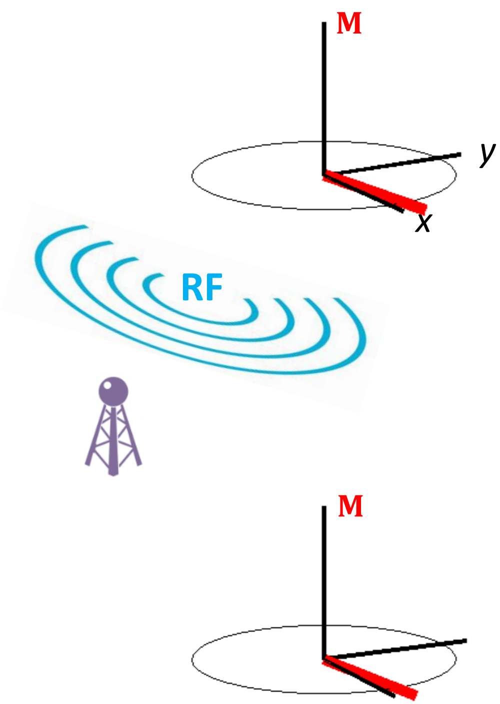
3. Mesure (relaxation)

Arrêt de la stimulation RF B_1

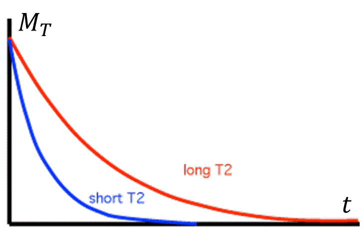
Signal = M_x







- **Déphasage progressif**
- **Inhomogénéités de champ**
- **Phénomène entropique**
- **Cinétique T_2**



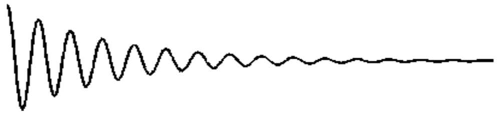
$$M_{xy}(t) = M_{\mathrm{T}}\, e^{-t/T_2}$$

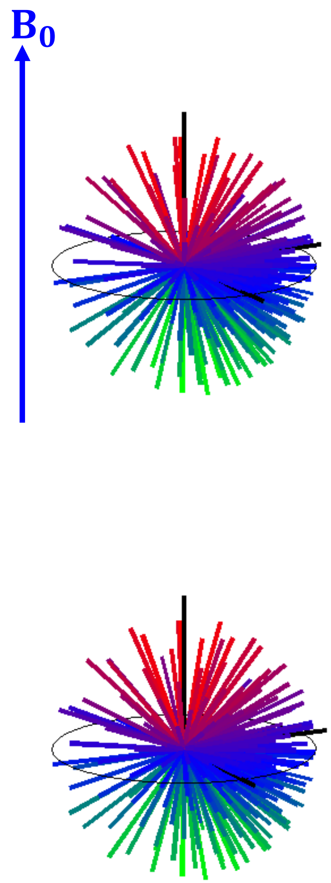
RMN – principe

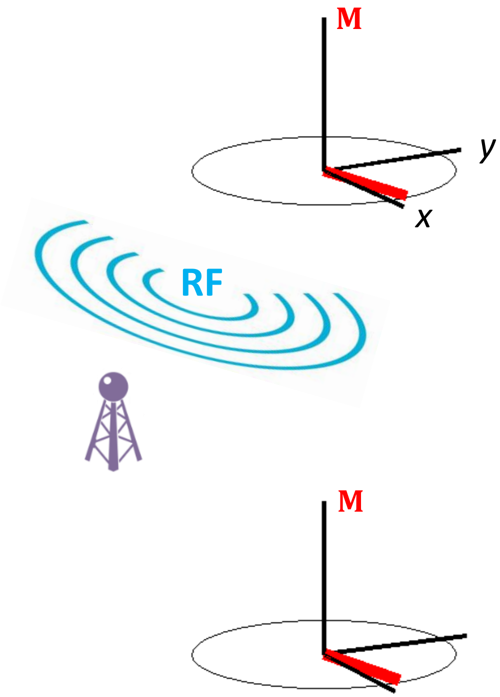
3. Mesure (relaxation)

Arrêt de la stimulation RF B_1

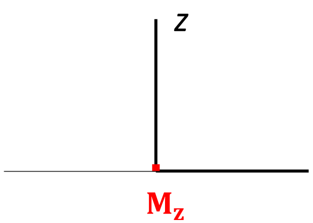
Signal = M_x

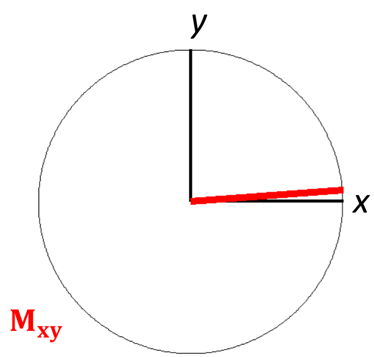






Disparition de M_{xy}
Repousse de M_z



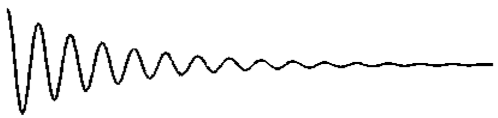


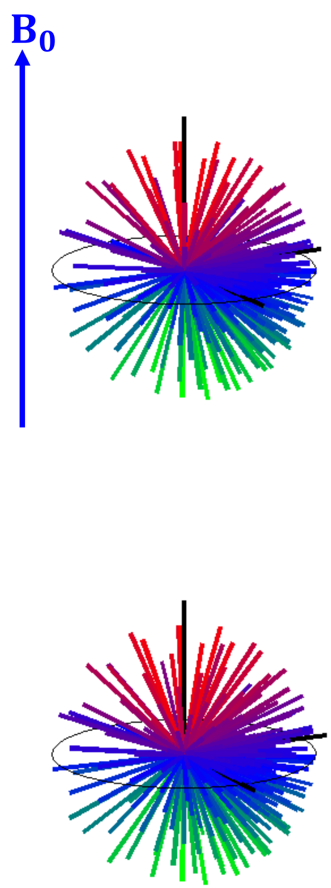
RMN – principe

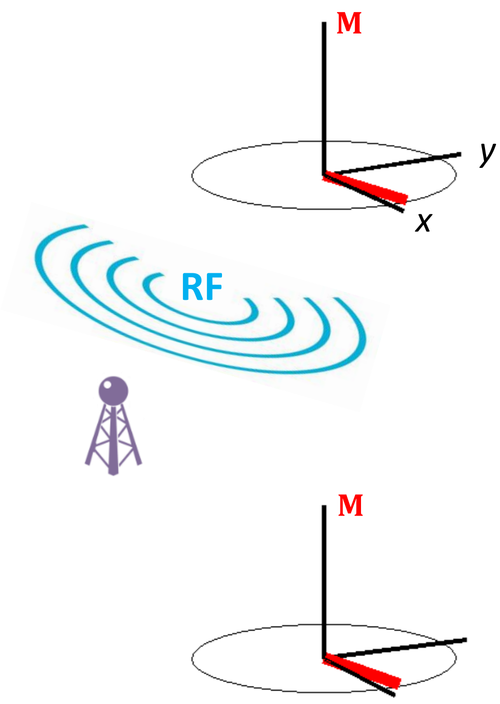
3. Mesure (relaxation)

Arrêt de la stimulation RF B_1

Signal = M_x

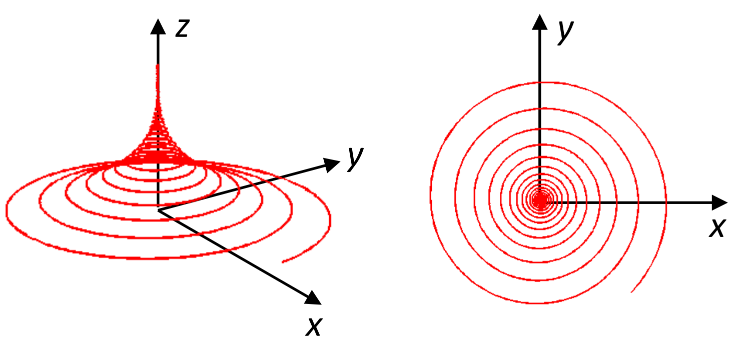






Disparition de M_{xy}
Repousse de M_z

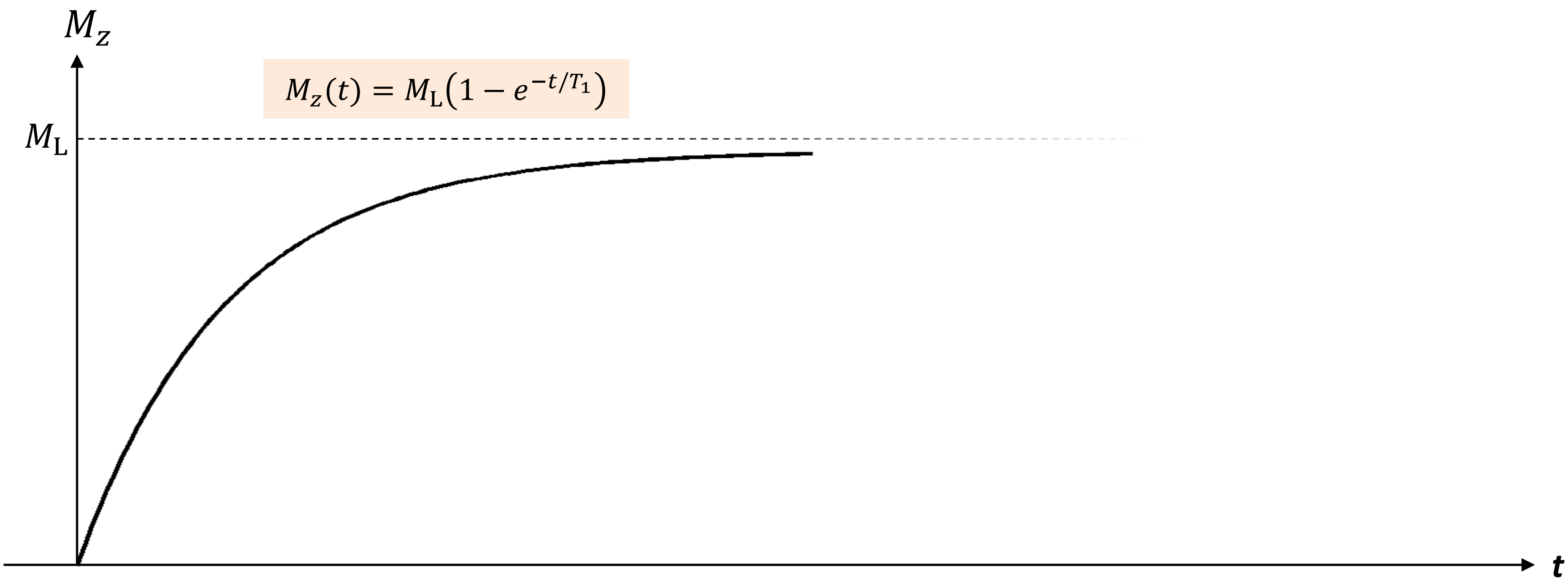
Dans les tissus biologiques : $T_1 \sim 10\ T_2$



RMN – séquence

Préparation

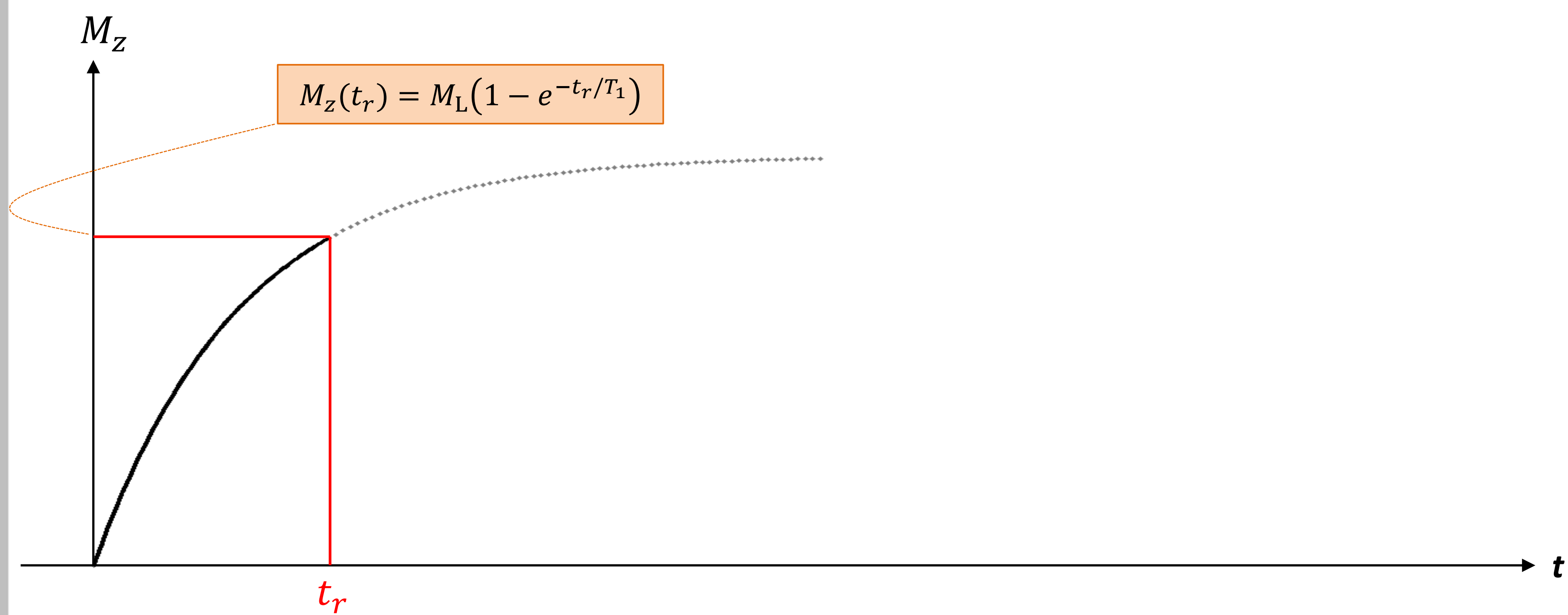
Aimantation longitudinale dans B_0
Relaxation T_1



RMN – séquence

Préparation

Aimantation longitudinale dans B_0
Relaxation T_1
Durant un temps t_r (temps de répétition)



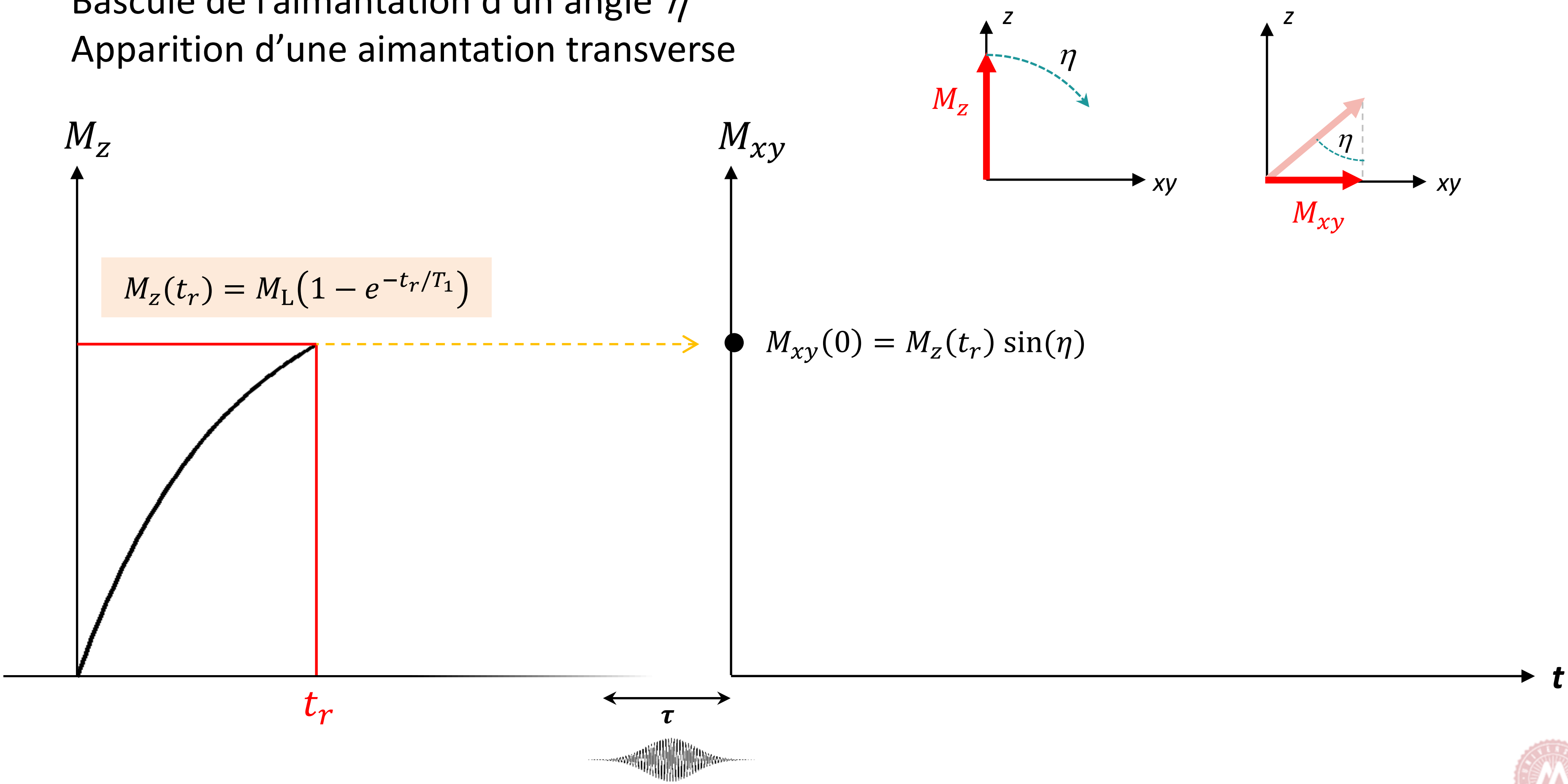
RMN – séquence

Préparation **RF**

Stimulation RF durant un temps τ

Bascule de l'aimantation d'un angle η

Apparition d'une aimantation transverse

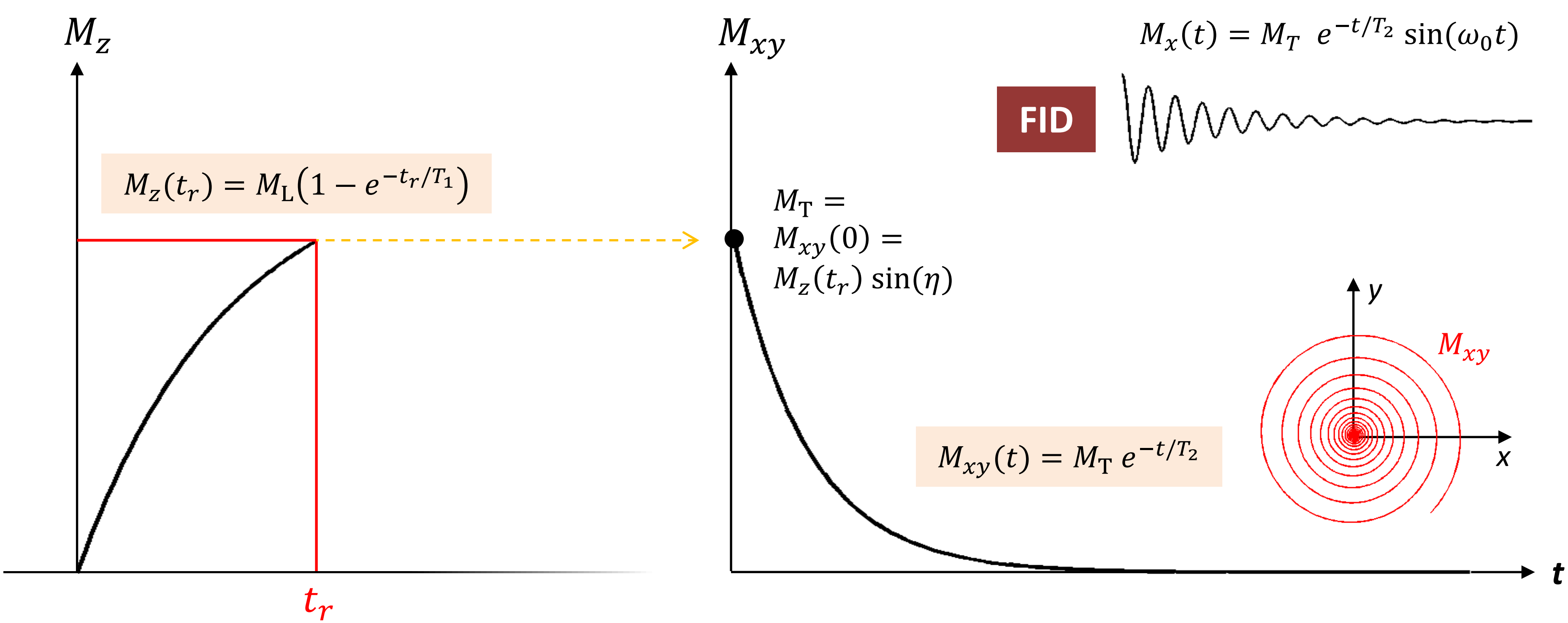


RMN – séquence

Préparation | **RF** | **Mesure**

Retour à l'équilibre

Relaxation T_2



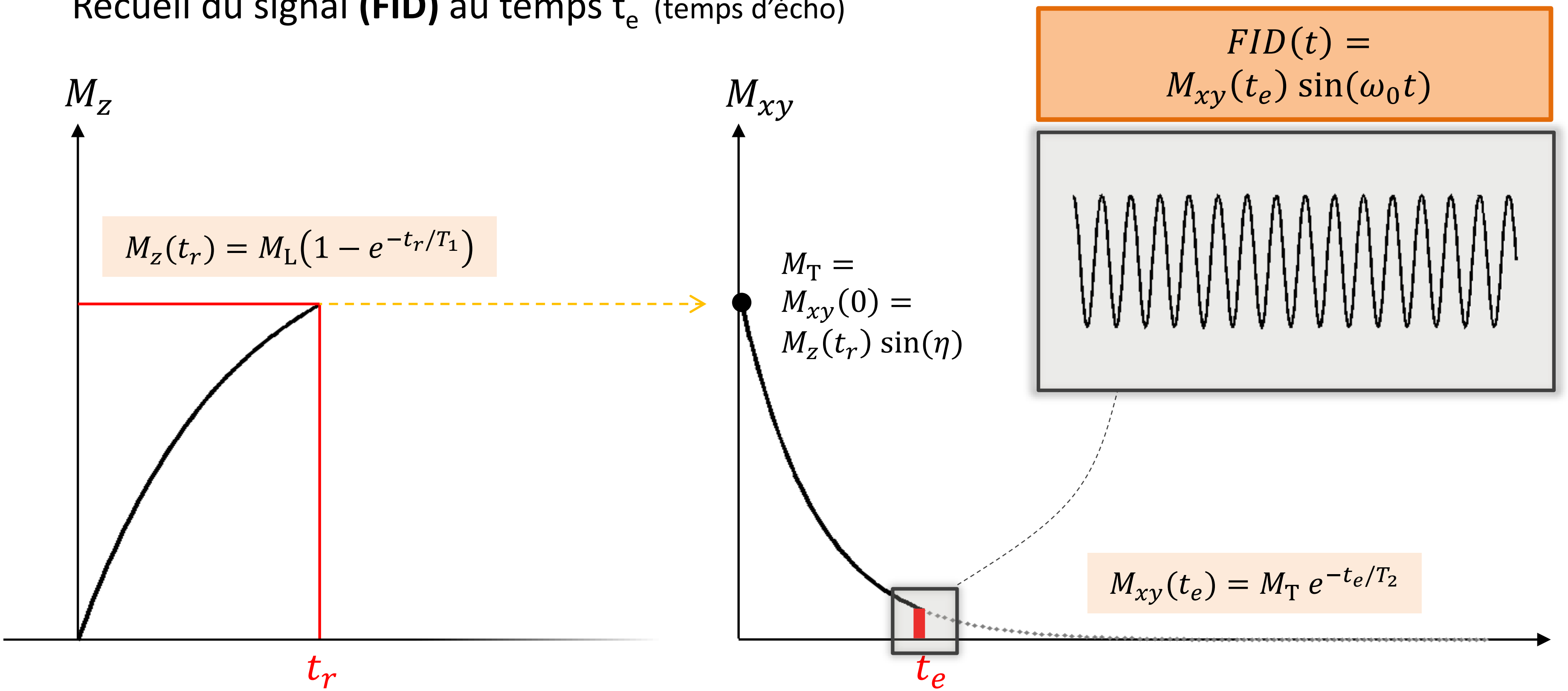
RMN – séquence

Préparation | **RF** | **Mesure**

Retour à l'équilibre

Relaxation T_2

Recueil du signal **(FID)** au temps t_e (temps d'écho)



RMN – séquence

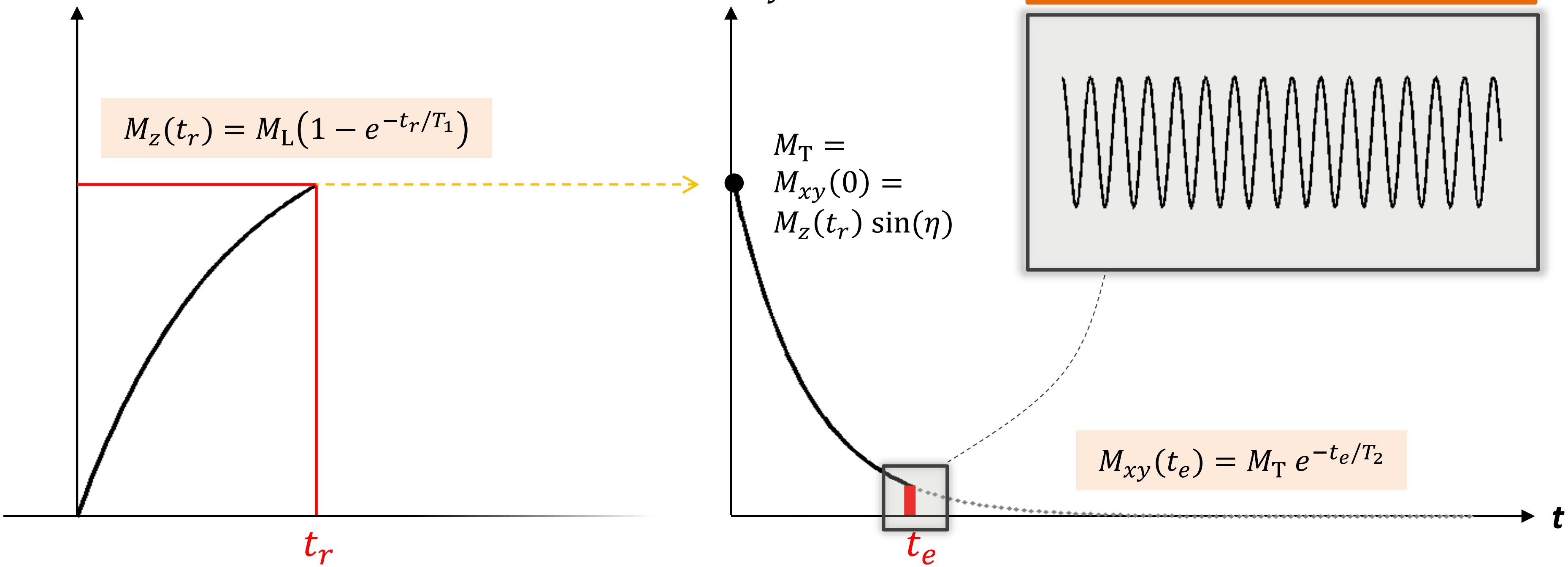
Préparation | **RF** | **Mesure**

Retour à l'équilibre

Relaxation T_2

Recueil du signal **(FID)** au temps t_e (temps d'écho)

$$FID(t) = M_T\ e^{-t_e/T_2} \sin(\omega_0 t)$$



RMN – séquence

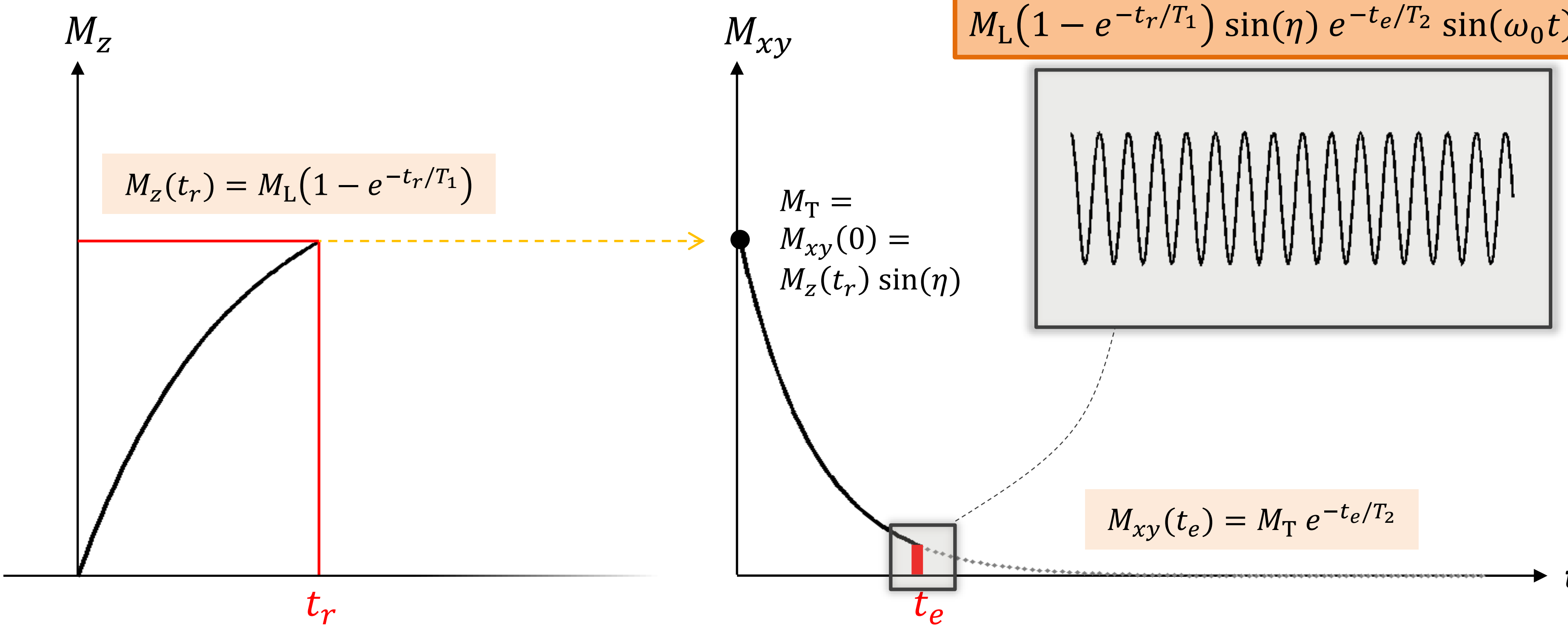
Préparation | **RF** | **Mesure**

Retour à l'équilibre

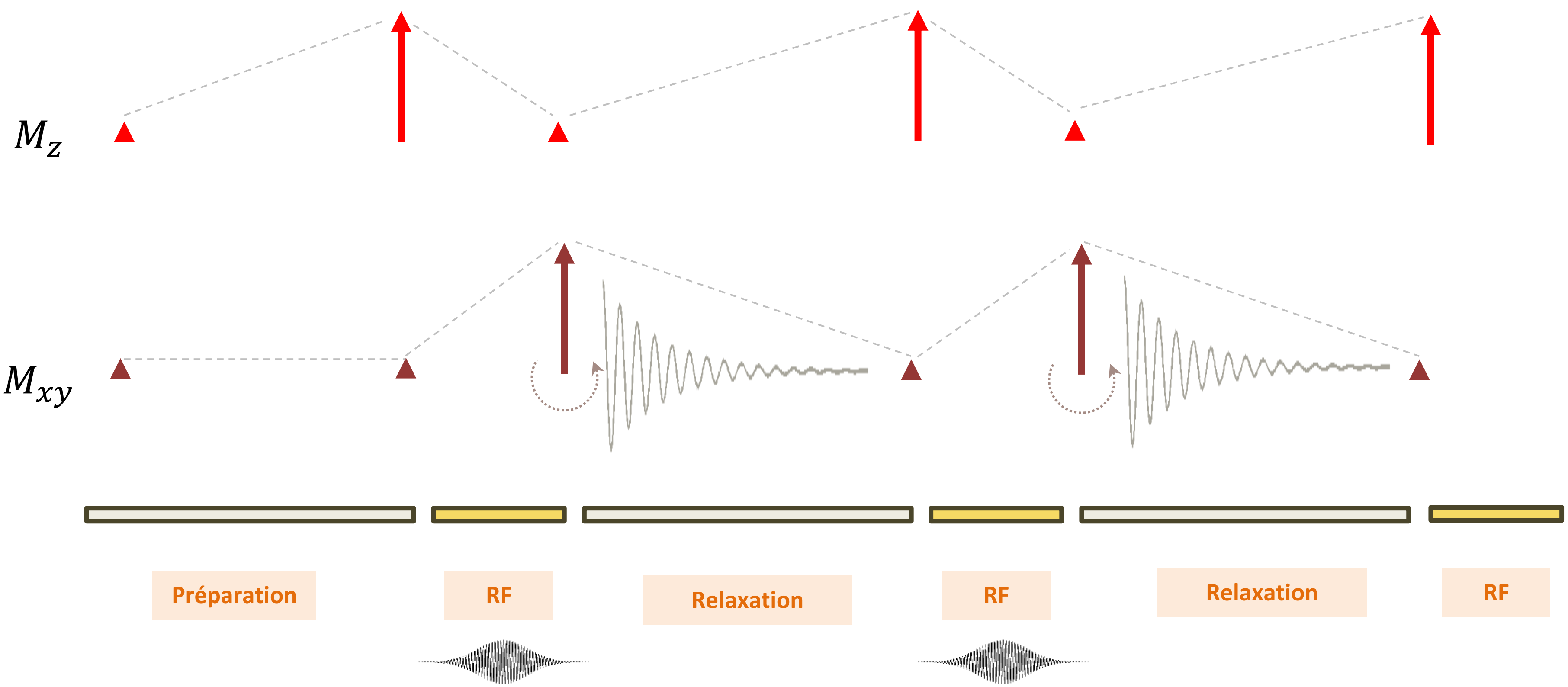
Relaxation T_2

Recueil du signal **(FID)** au temps t_e (temps d'écho)

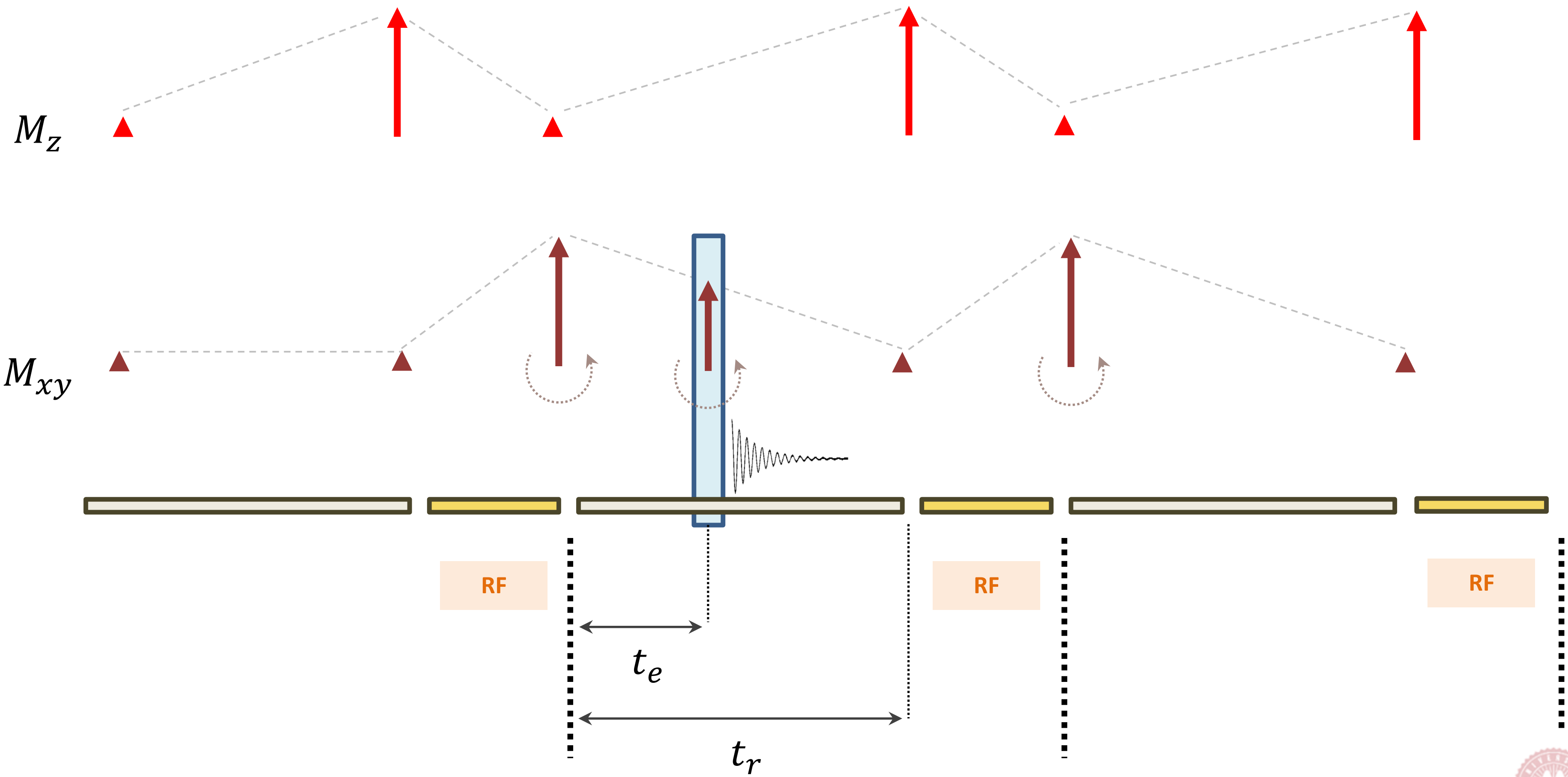
$$FID(t) = M_L\left(1 - e^{-t_r/T_1}\right) \sin(\eta)\, e^{-t_e/T_2} \sin(\omega_0 t)$$



RMN – séquence



RMN – séquence



RMN – contraste

$$FID(t) = M_\mathrm{L}\left(1 - e^{-t_r/T_1}\right) \sin(\eta)\, e^{-t_e/T_2} \sin(\omega_0 t)$$

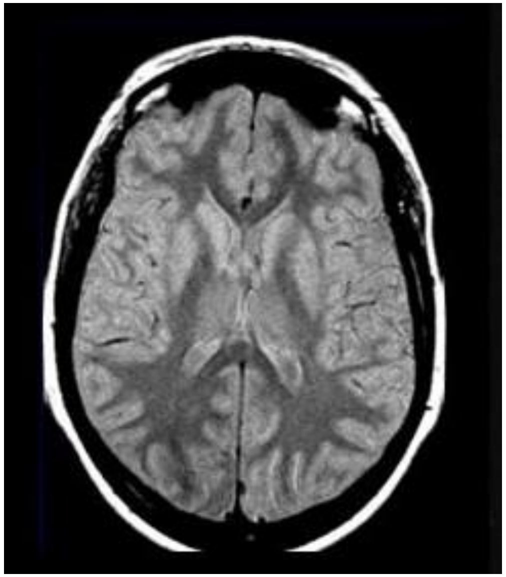
Déterminants du signal :

$$M_\mathrm{L} = \sum \mu_z \quad \begin{cases} \propto \boldsymbol{\mu} \propto \gamma & \textit{intrinsèque} \\ \propto \rho(\,^1\mathrm{H}) & \textit{intrinsèque} \\ \propto \dfrac{\Delta \mathrm{N}}{\mathrm{N}} \propto \dfrac{\mathrm{B}_0}{\mathrm{T}} & \textit{extrinsèque} \end{cases}$$

T_1, T_2 ***intrinsèque***

t_r, t_e, η ***extrinsèque***

Densité de protons ρ :
Degré d'hydratation / lipidation



RMN – contraste

$$FID(t) = M_L\left(1 - e^{-t_r/T_1}\right)\sin(\eta)\, e^{-t_e/T_2}\sin(\omega_0 t)$$

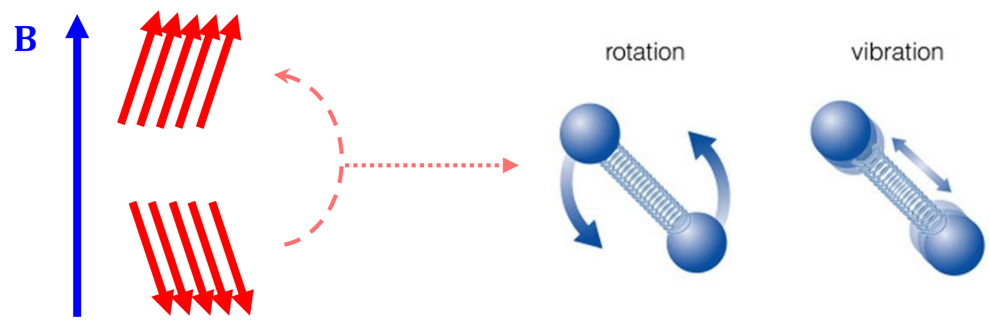
Déterminants du signal :

$$M_L = \sum \mu_z \quad \begin{cases} \propto \boldsymbol{\mu} \propto \gamma & \textit{intrinsèque} \\ \propto \rho(\,^1\mathrm{H}) & \textit{intrinsèque} \\ \propto \dfrac{\Delta \mathrm{N}}{\mathrm{N}} \propto \dfrac{\mathrm{B}_0}{\mathrm{T}} & \textit{extrinsèque} \end{cases}$$

T_1, T_2 ***intrinsèque***

t_r, t_e, η ***extrinsèque***

Relaxation T_1 : échanges énergétiques avec le réseau



RMN – contraste

$$FID(t) = M_L\left(1 - e^{-t_r/T_1}\right)\sin(\eta)\, e^{-t_e/T_2}\sin(\omega_0 t)$$

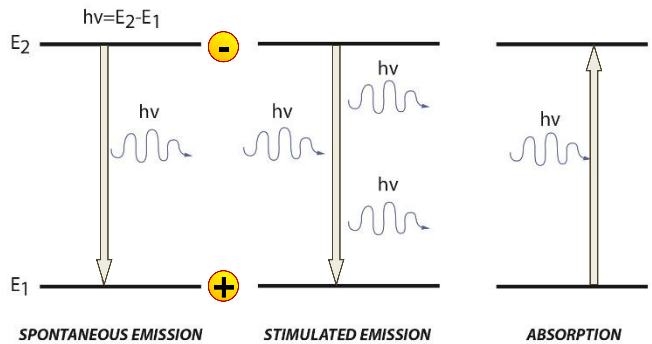
Déterminants du signal :

$$M_L = \sum \mu_z \begin{cases} \propto \boldsymbol{\mu} \propto \gamma & \textit{intrinsèque} \\ \propto \rho(\,^1\mathrm{H}) & \textit{intrinsèque} \\ \propto \dfrac{\Delta \mathrm{N}}{\mathrm{N}} \propto \dfrac{\mathrm{B}_0}{\mathrm{T}} & \textit{extrinsèque} \end{cases}$$

T_1, T_2 *intrinsèque*

t_r, t_e, η *extrinsèque*

Relaxation T_1 : échanges énergétiques avec le réseau



RMN – contraste

$$FID(t) = M_\mathrm{L}\left(1 - e^{-t_r/T_1}\right) \sin(\eta)\, e^{-t_e/T_2} \sin(\omega_0 t)$$

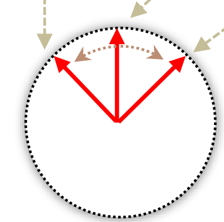
Déterminants du signal :

$$M_\mathrm{L} = \sum \mu_z \begin{cases} \propto \boldsymbol{\mu} \propto \gamma & \textit{intrinsèque} \\ \propto \rho(\,^1\mathrm{H}) & \textit{intrinsèque} \\ \propto \dfrac{\Delta \mathrm{N}}{\mathrm{N}} \propto \dfrac{\mathrm{B}_0}{\mathrm{T}} & \textit{extrinsèque} \end{cases}$$

T_1, T_2 ***intrinsèque***

t_r, t_e, η ***extrinsèque***

Relaxation T_2 : déphasage des spins



- Inhomogénéités technologiques de champ B_0 (T_2^*)
- Fluctuations locales dues à l'environnement chimique (T_2)

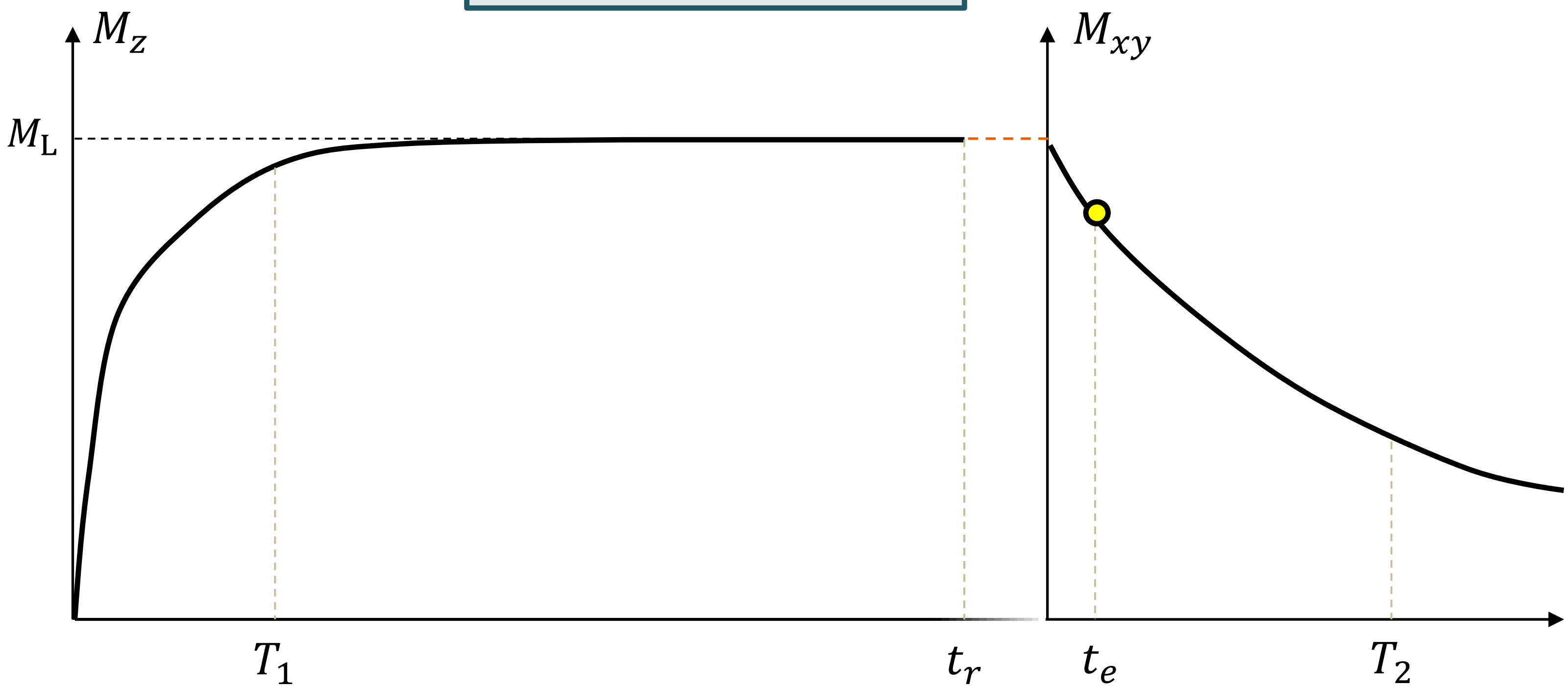
RMN – contraste

Pondération ρ (densité de protons)

$$t_r \gg T_1 \qquad t_e \ll T_2$$

$$FID(t) = M_L\left(1 - e^{-t_r/T_1}\right)\sin(\eta)\, e^{-t_e/T_2}\sin(\omega_0 t)$$

Signal $\propto M_L \propto \rho(\,^1\mathrm{H})$



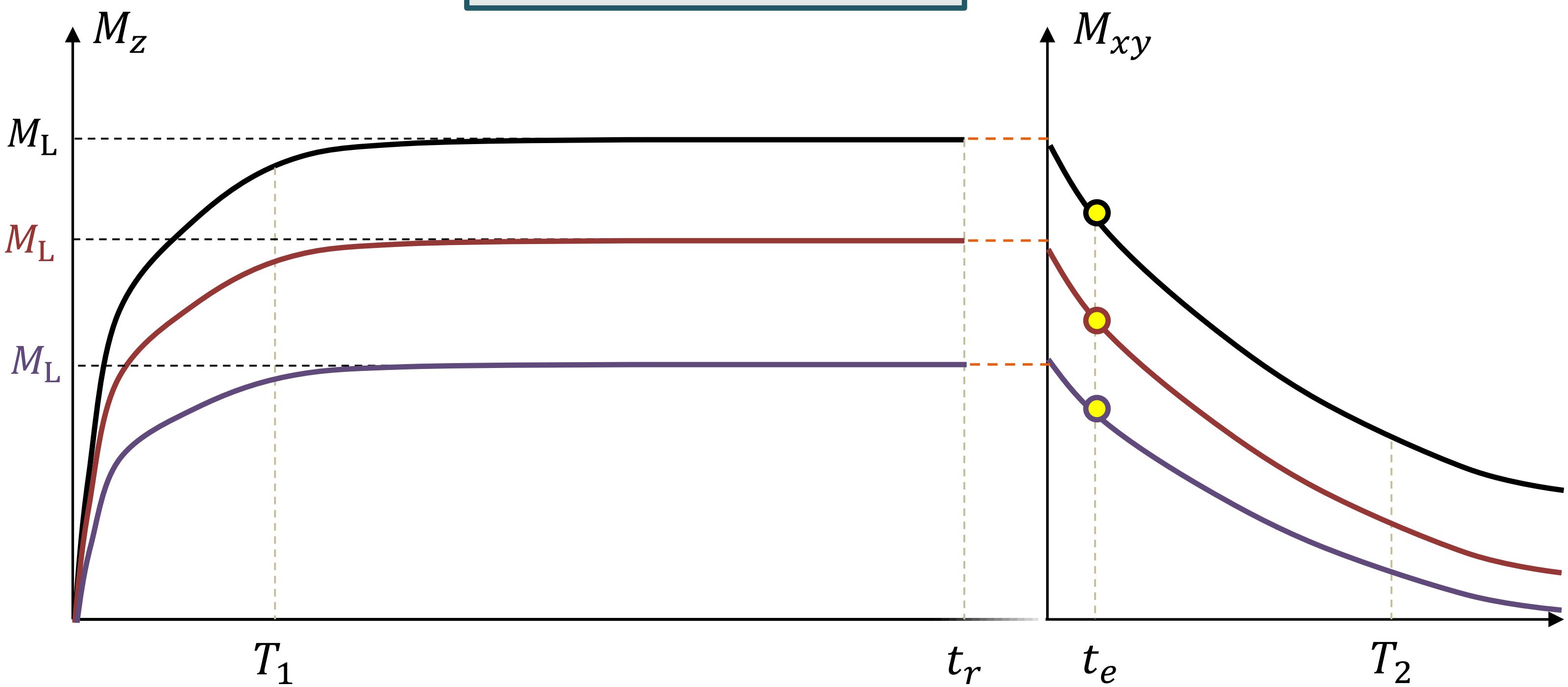
RMN – contraste

Pondération ρ (densité de protons)

$t_r \gg T_1$
$t_e \ll T_2$

$$FID(t) = M_L\left(1 - e^{-t_r/T_1}\right) \sin(\eta)\, e^{-t_e/T_2} \sin(\omega_0 t)$$

Signal $\propto M_L \propto \rho(\,^1\mathrm{H})$



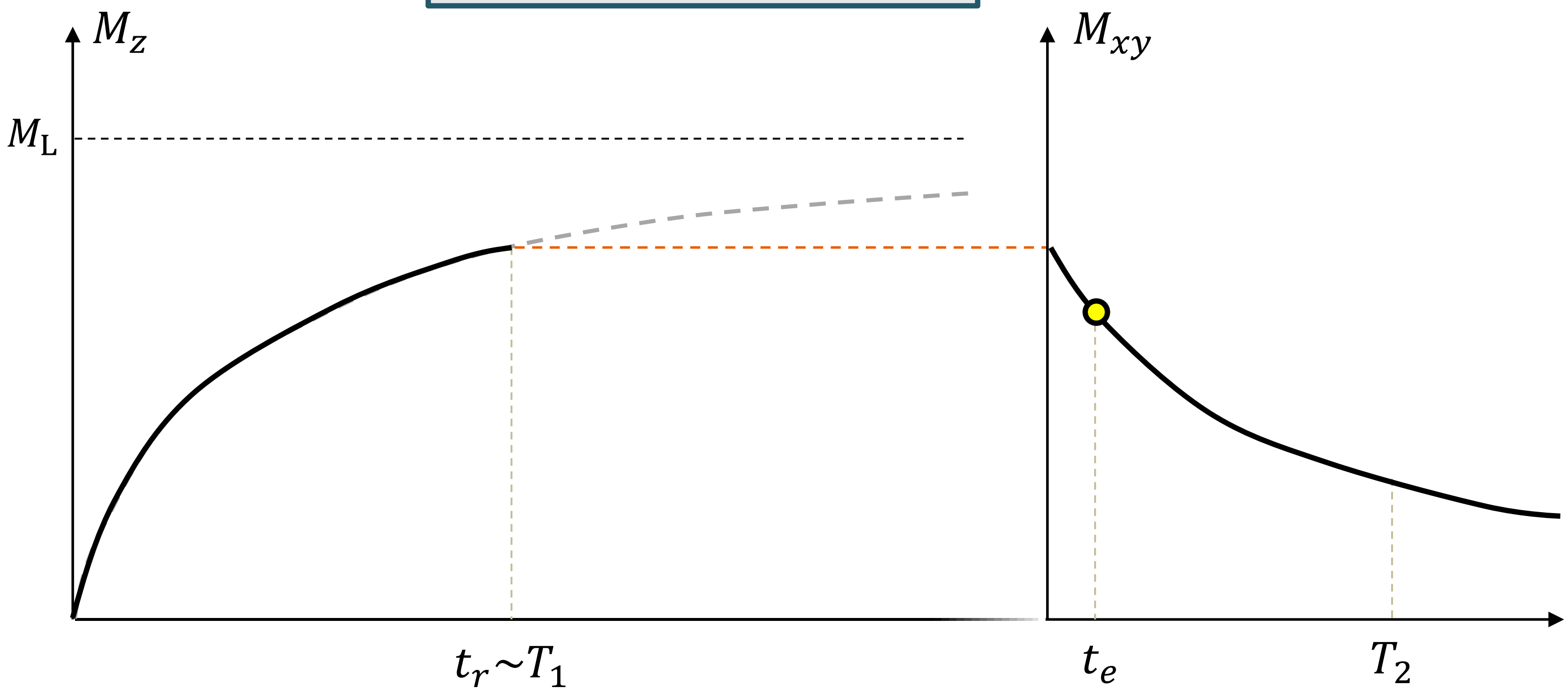
RMN – contraste

Pondération T_1

$$t_r \sim T_1$$
$$t_e \ll T_2$$

$$FID(t) = M_L\left(1 - e^{-t_r/T_1}\right)\sin(\eta)\, e^{-t_e/T_2}\sin(\omega_0 t)$$

Signal $\propto M_L\left(1 - e^{-t_r/T_1}\right)$



RMN – contraste

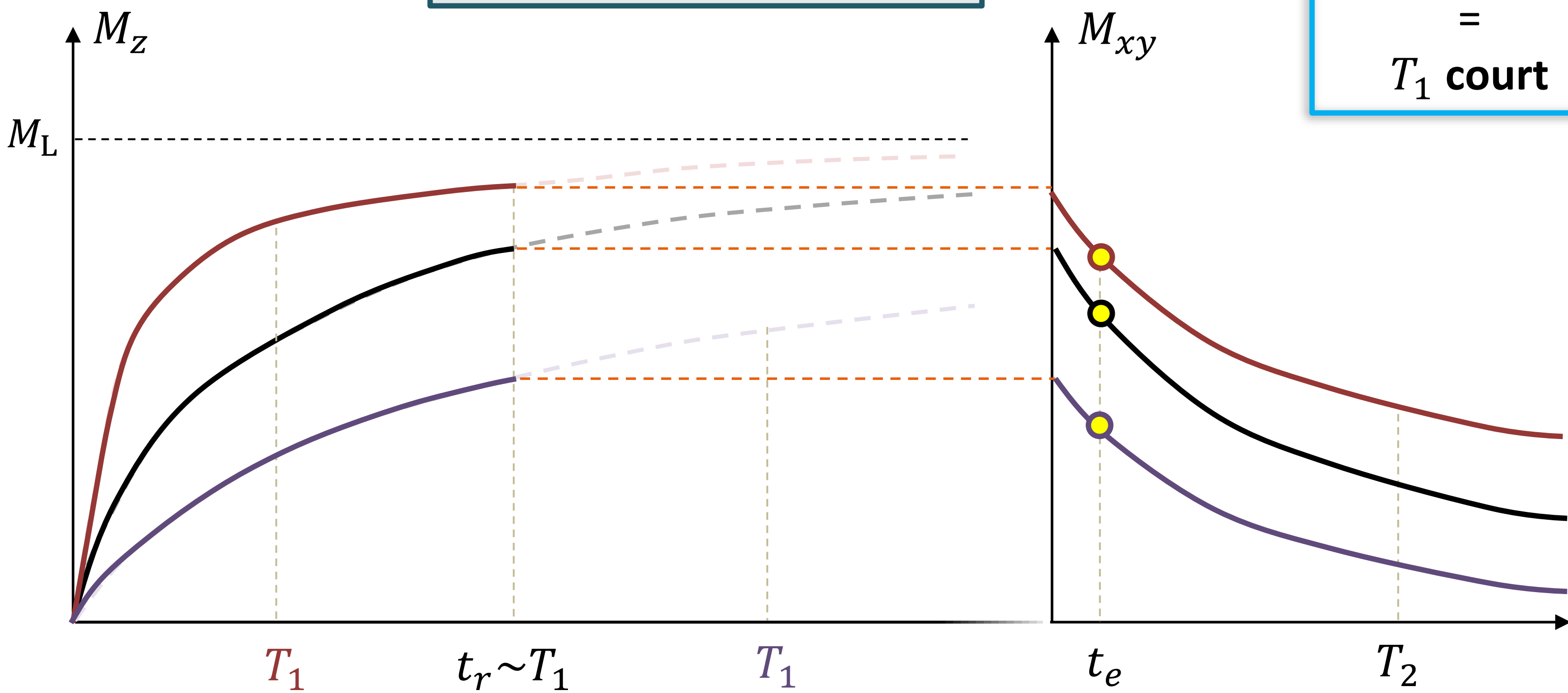
Pondération T_1

$$t_r \sim T_1$$
$$t_e \ll T_2$$

$$FID(t) = M_L\left(1 - e^{-t_r/T_1}\right)\sin(\eta)\, e^{-t_e/T_2}\sin(\omega_0 t)$$

Signal $\propto M_L\left(1 - e^{-t_r/T_1}\right)$

Hyper-T_1
=
T_1 **court**



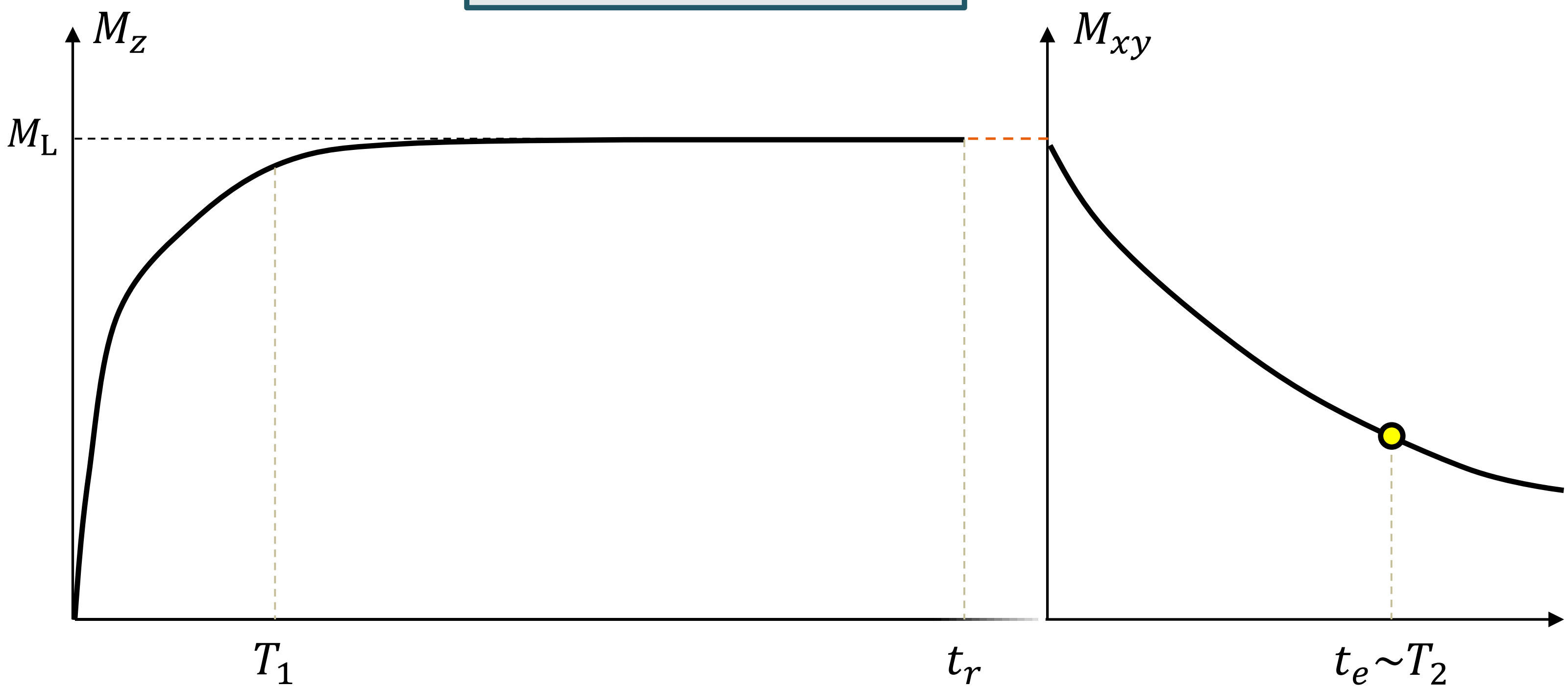
RMN – contraste

Pondération T_2

$t_r \gg T_1$
$t_e \sim T_2$

$$FID(t) = M_\mathrm{L}\left(1 - e^{-t_r/T_1}\right) \sin(\eta)\, e^{-t_e/T_2} \sin(\omega_0 t)$$

Signal $\propto M_\mathrm{L}\left(e^{-t_e/T_2}\right)$



RMN – contraste

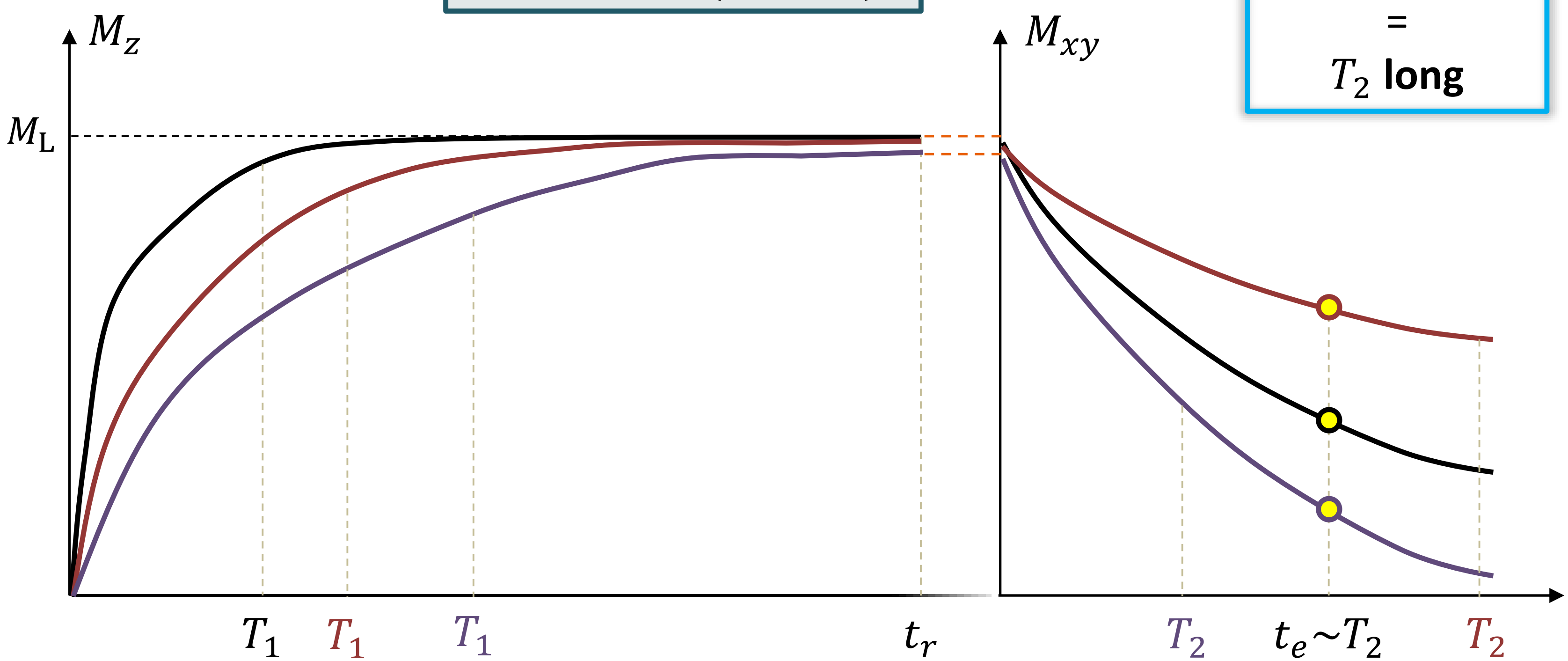
Pondération T_2

$t_r \gg T_1$
$t_e \sim T_2$

$$FID(t) = M_L\left(1 - e^{-t_r/T_1}\right)\sin(\eta)\, e^{-t_e/T_2} \sin(\omega_0 t)$$

Signal $\propto M_L\left(e^{-t_e/T_2}\right)$

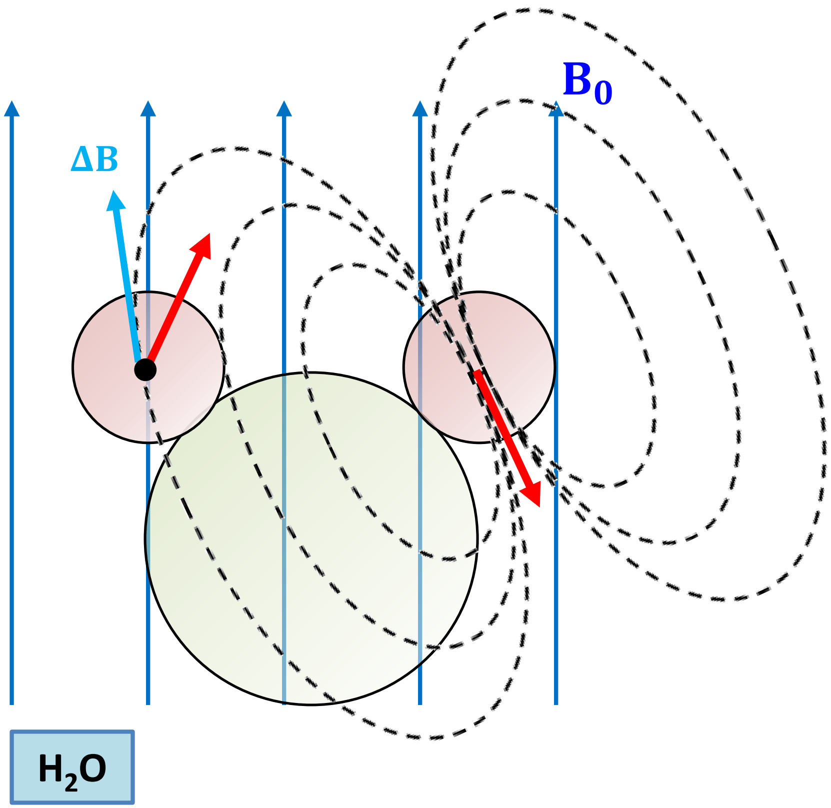
Hyper-T_2
=
T_2 **long**



RMN – contraste

Relaxation :

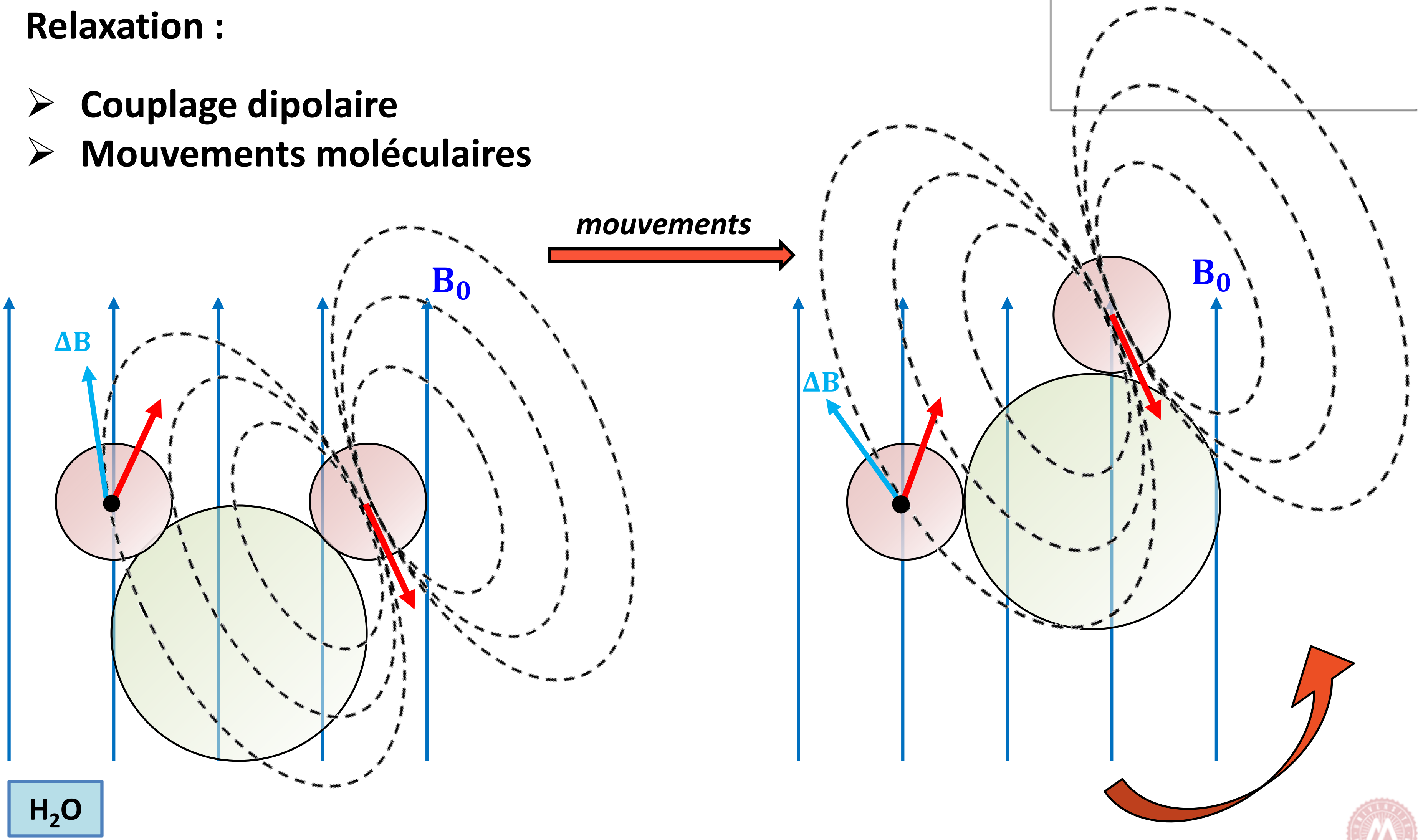
- **Couplage dipolaire**
- **Mouvements moléculaires**



RMN – contraste

Relaxation :

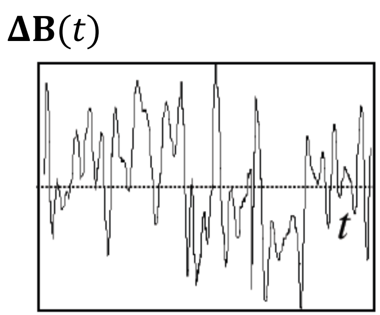
- **Couplage dipolaire**
- **Mouvements moléculaires**

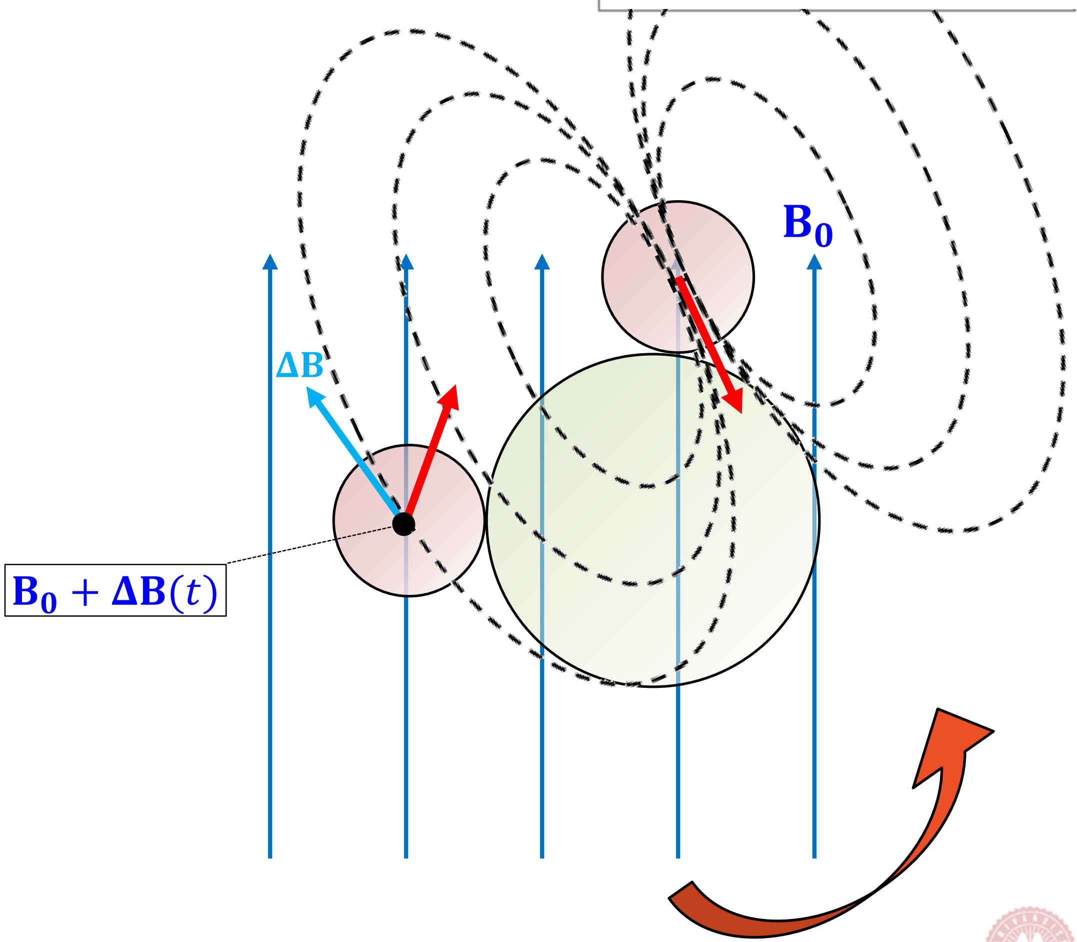


RMN – contraste

Relaxation :

- **Couplage dipolaire**
- **Mouvements moléculaires**





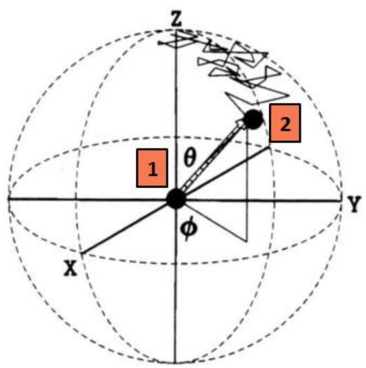
$$\langle \mathbf{\Delta B} \rangle = 0$$

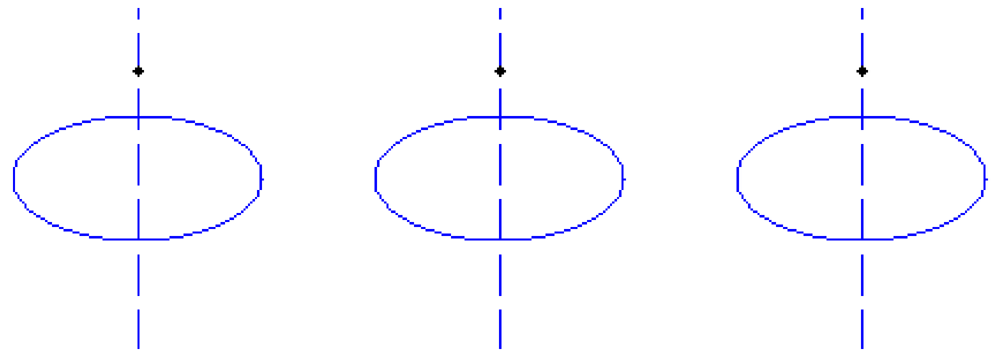
$$\langle \Delta B_x^2 \rangle = \langle \Delta B_y^2 \rangle = \langle \Delta B_z^2 \rangle = \langle \Delta B^2 \rangle$$

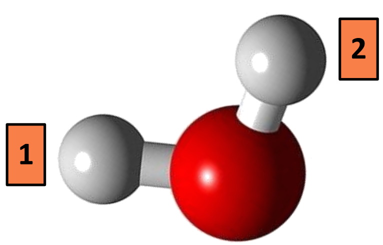
RMN – contraste

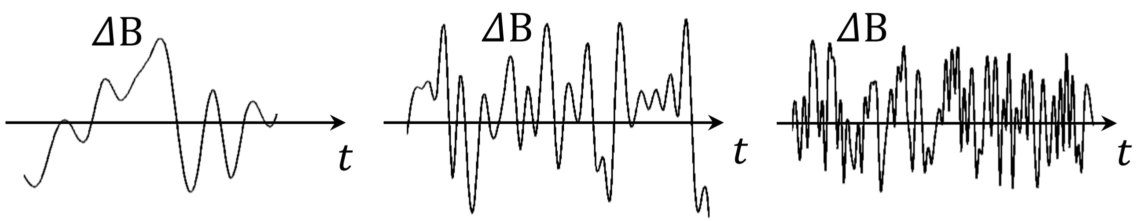
Relaxation :

- **Couplage dipolaire**
- **Mouvements moléculaires**





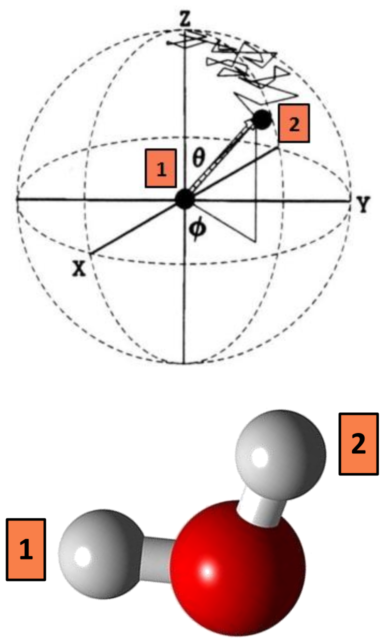


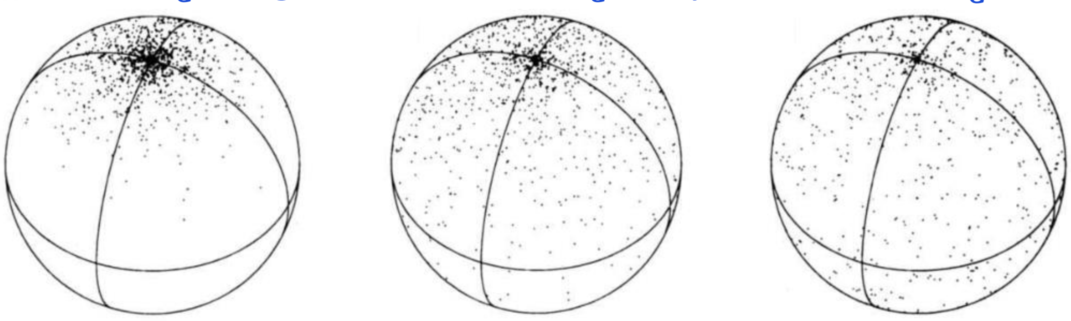


RMN – contraste

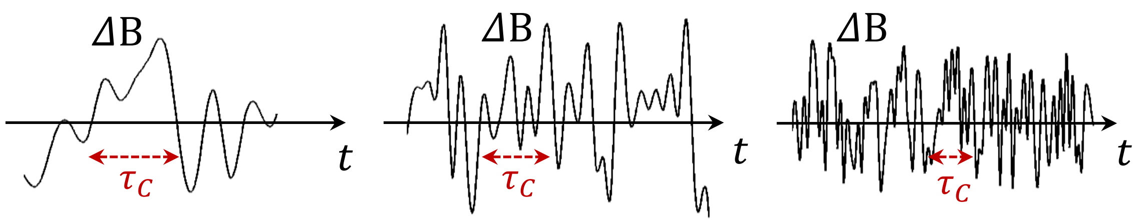
Relaxation :

- **Couplage dipolaire**
- **Mouvements moléculaires**





Temps d'autocorrélation τ_C



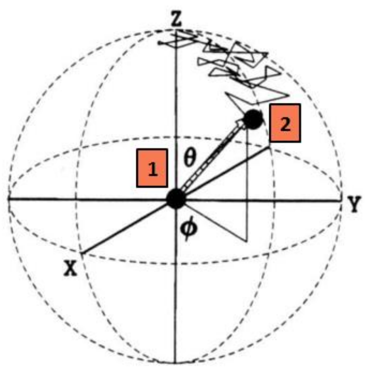
$$\boxed{\tau_c \propto \frac{V\,\eta}{kT}}$$

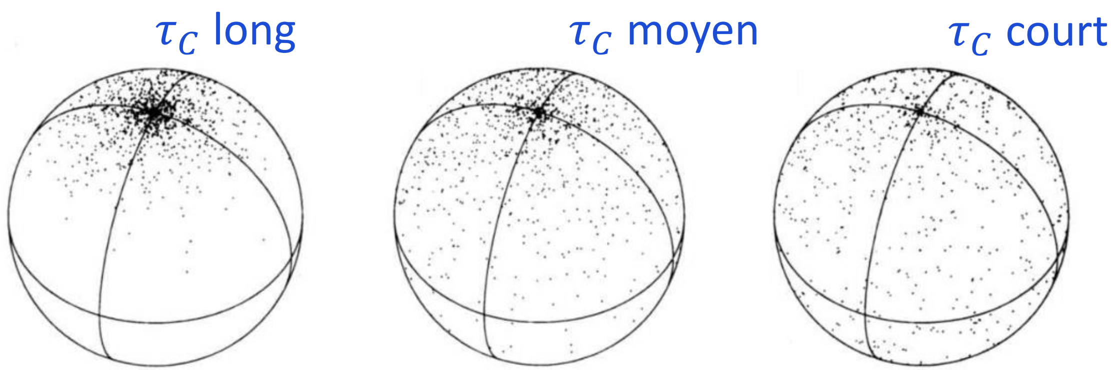
V volume moléculaire
η viscosité

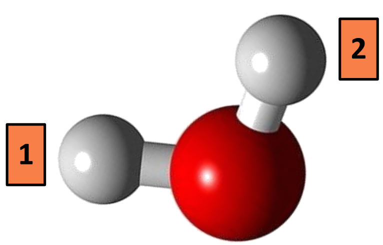
RMN – contraste

Relaxation :

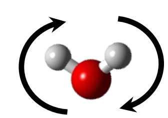
- **Couplage dipolaire**
- **Mouvements moléculaires**

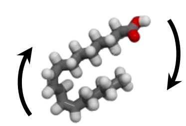


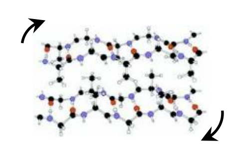




Temps d'autocorrélation τ_C

Eau libre : mouvement rapide : τ_C court 

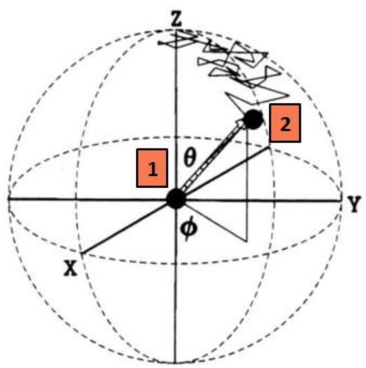
Eau liée / lipides : τ_C moyen 

Macromolécules : mouvement lent : τ_C long 

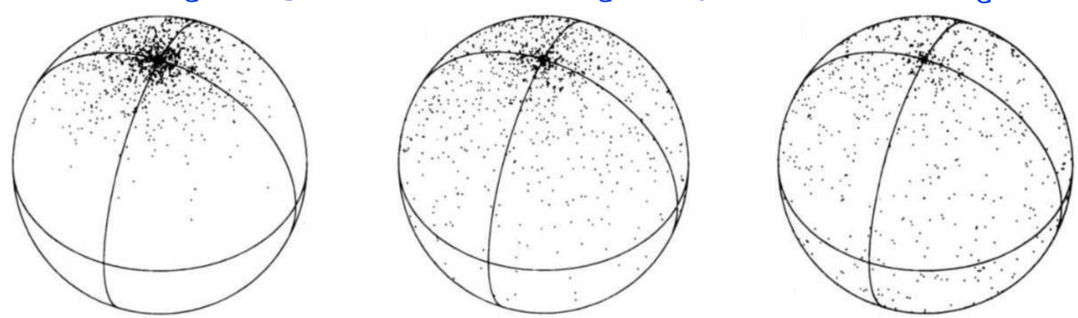
RMN – contraste

Relaxation :

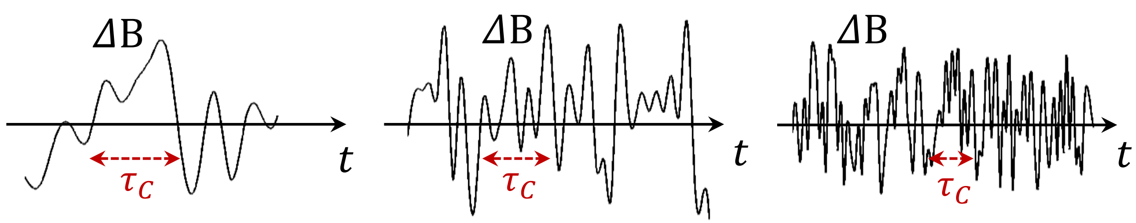
- **Couplage dipolaire**
- **Mouvements moléculaires**



τ_C long | τ_C moyen | τ_C court

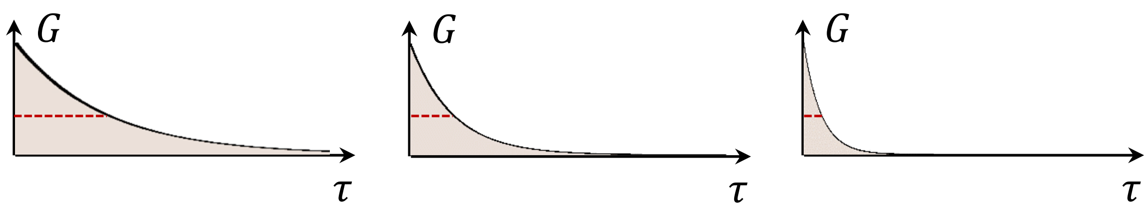


Temps d'autocorrélation τ_C



Fonction d'autocorrélation

$G(\tau) \propto e^{-\tau/\tau_C}$

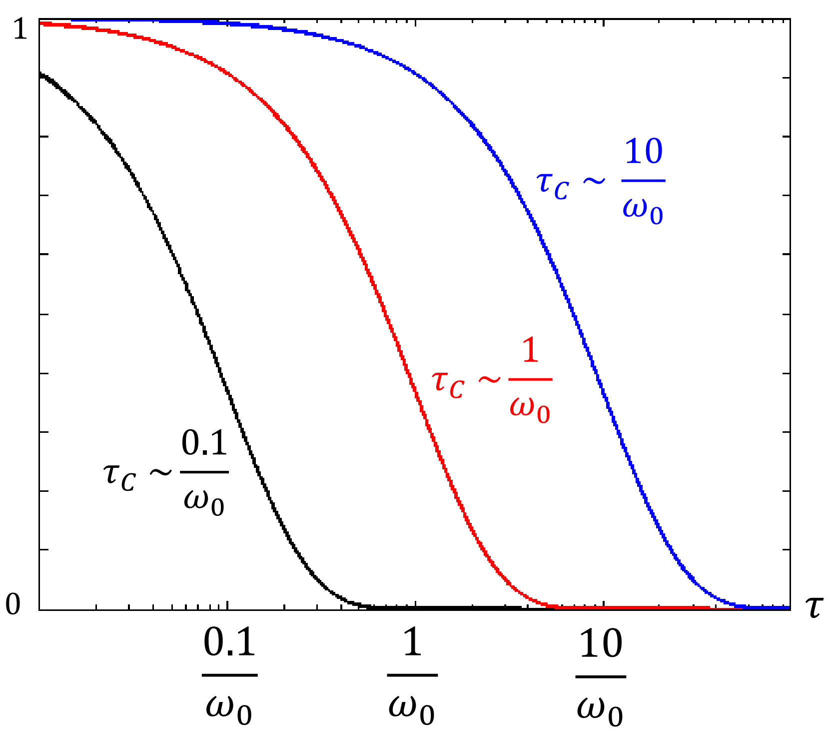


RMN – contraste

Relaxation :

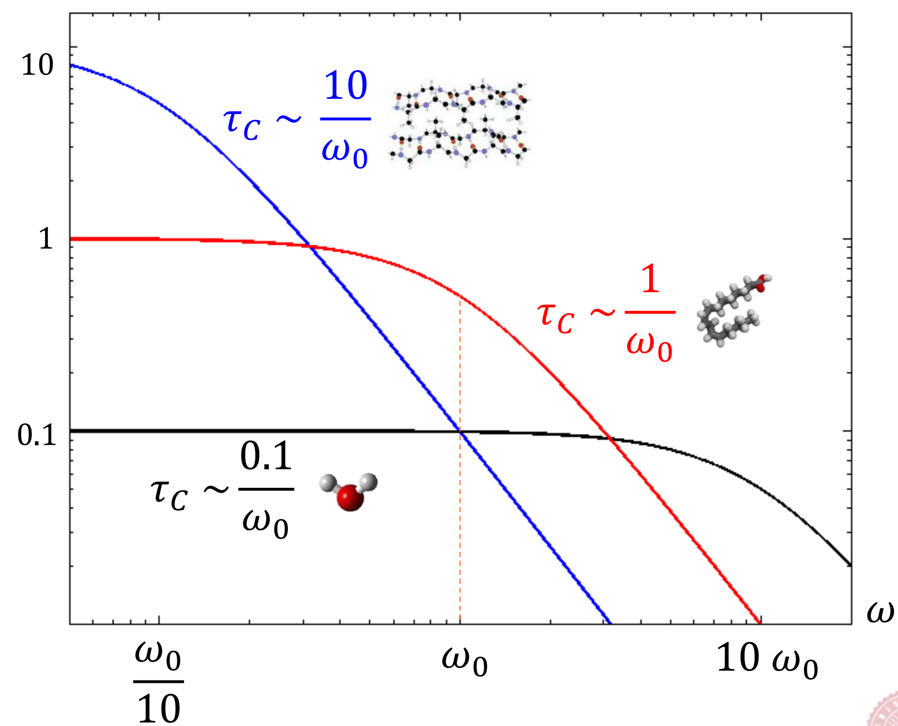
Fonction d'autocorrélation $G(\tau)$

$G(\tau) \propto e^{-\tau/\tau_C}$



$J(\omega)$: spectre de $G(\tau)$

$J(\omega)$



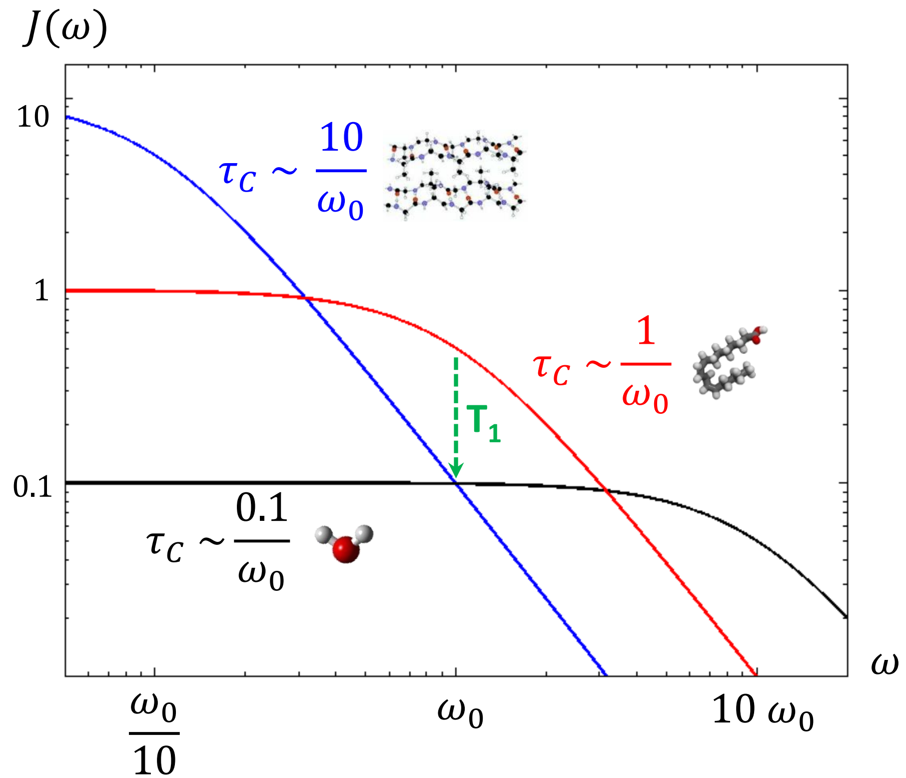
RMN – contraste

Relaxation :

$\boxed{T_1}$

Fluctuations transverses
→ Échanges d'énergie

$$\frac{1}{T_1} = \gamma^2 \left(\langle \Delta B_x^2 \rangle + \langle \Delta B_y^2 \rangle \right) J(\omega_0)$$
$$= 2\gamma^2 \underbrace{\langle \Delta B^2 \rangle}_{\text{Intensité du champ fluctuant}} \underbrace{J(\omega_0)}_{\text{Proportion de fluctuation à la fréquence de Larmor}}$$



RMN – contraste

Relaxation :

T_1

Fluctuations transverses
→ Échanges d'énergie

$$\frac{1}{T_1} = \gamma^2 \left(\langle \Delta B_x^2 \rangle + \langle \Delta B_y^2 \rangle \right) J(\omega_0)$$

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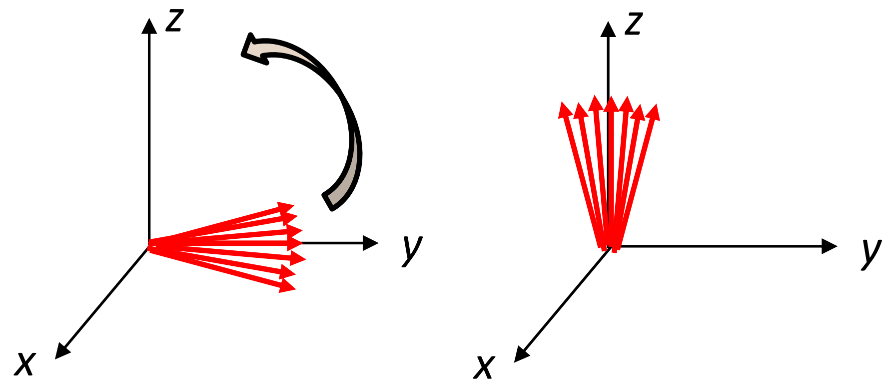
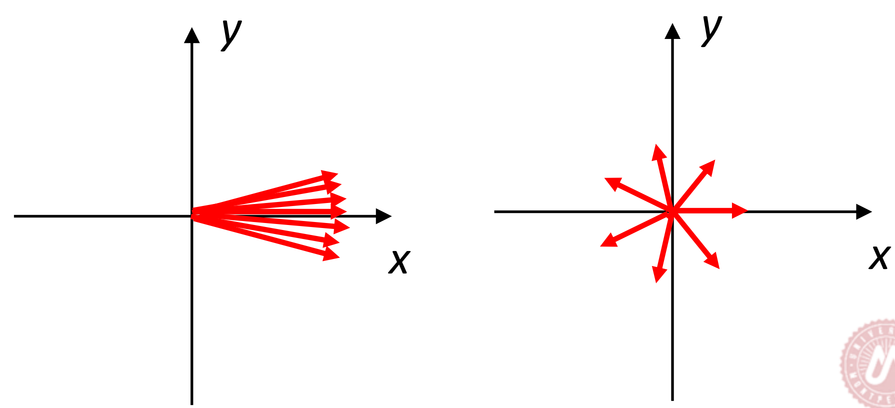


T_2

$$\frac{1}{T_2} = \frac{1}{2T_1} + \gamma^2 \langle \Delta B_z^2 \rangle J(0)$$

$$= \gamma^2 \langle \Delta B^2 \rangle \left(J(0) + J(\omega_0) \right)$$



RMN – contraste

Relaxation :

T_1

Fluctuations transverses
→ Échanges d'énergie

$$\frac{1}{T_1} = \gamma^2 \left(\langle \Delta B_x^2 \rangle + \langle \Delta B_y^2 \rangle \right) J(\omega_0)$$
$$= 2\gamma^2 \, \langle \Delta B^2 \rangle \, J(\omega_0)$$

Intensité du champ fluctuant

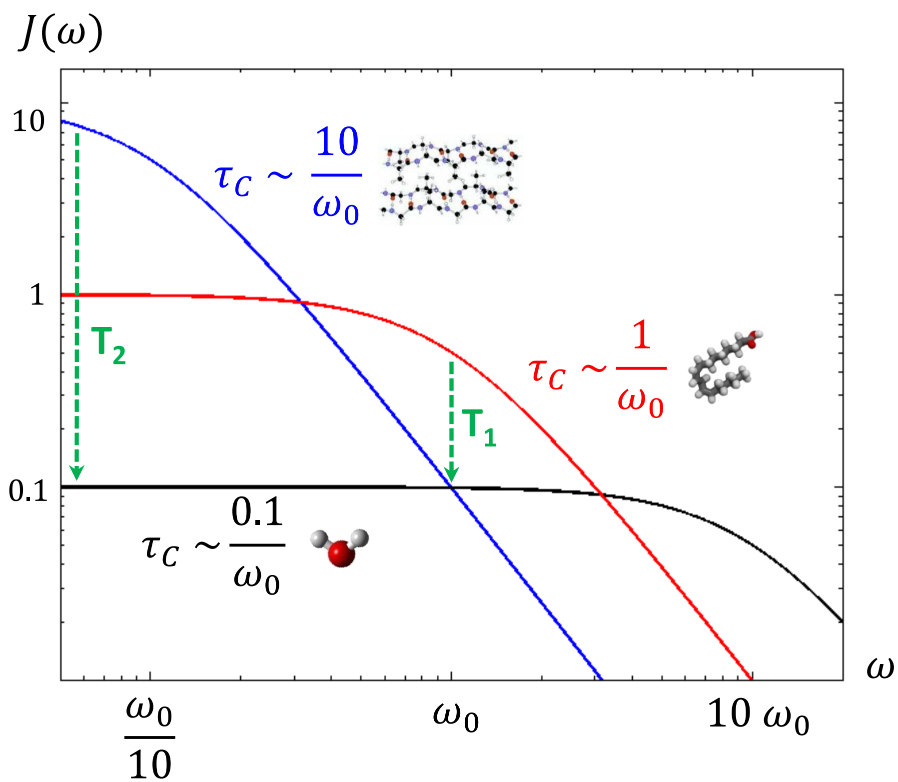
Proportion de fluctuation à la fréquence de Larmor

T_2

Fluctuations longitudinales
→ Déphasage des spins

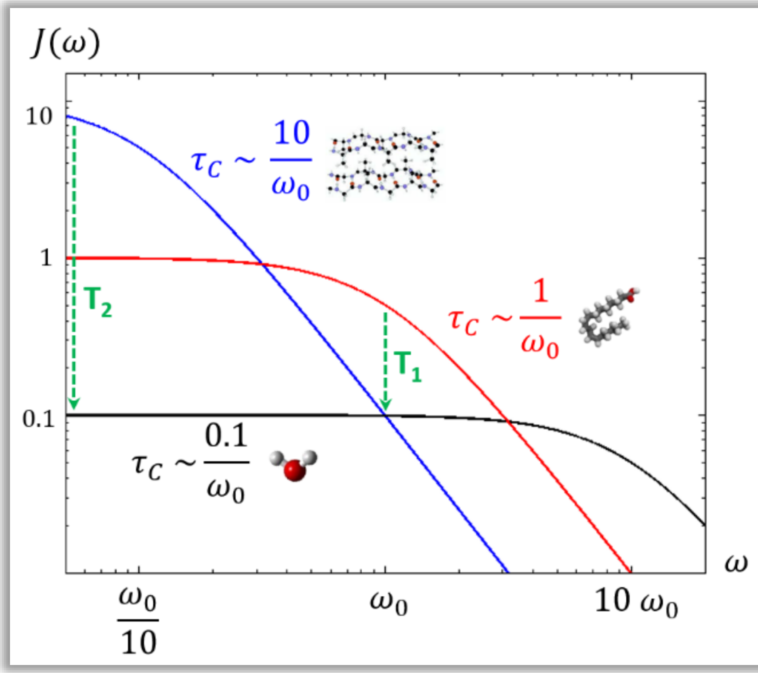
$$\frac{1}{T_2} = \frac{1}{2T_1} + \gamma^2 \langle \Delta B_z^2 \rangle J(0)$$
$$= \gamma^2 \, \langle \Delta B^2 \rangle \, \left(J(0) + J(\omega_0) \right)$$

Proportion de champ statique

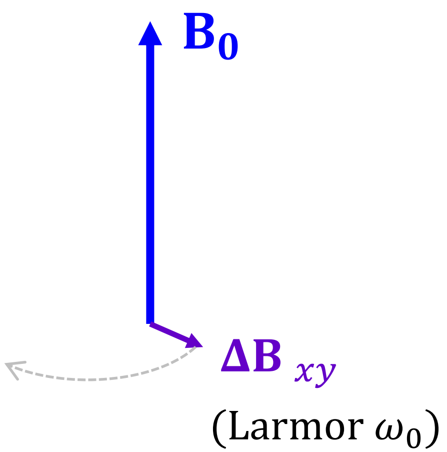


RMN – contraste

Relaxation :

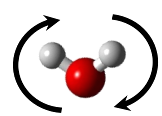


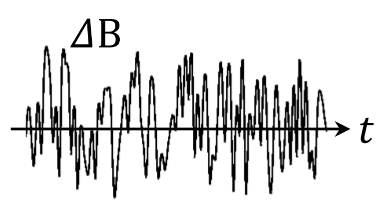
T_1



>> LENT

EAU LIBRE





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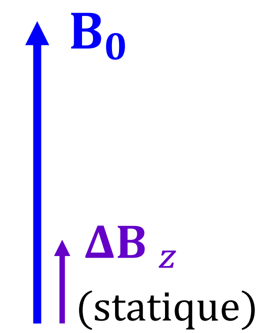
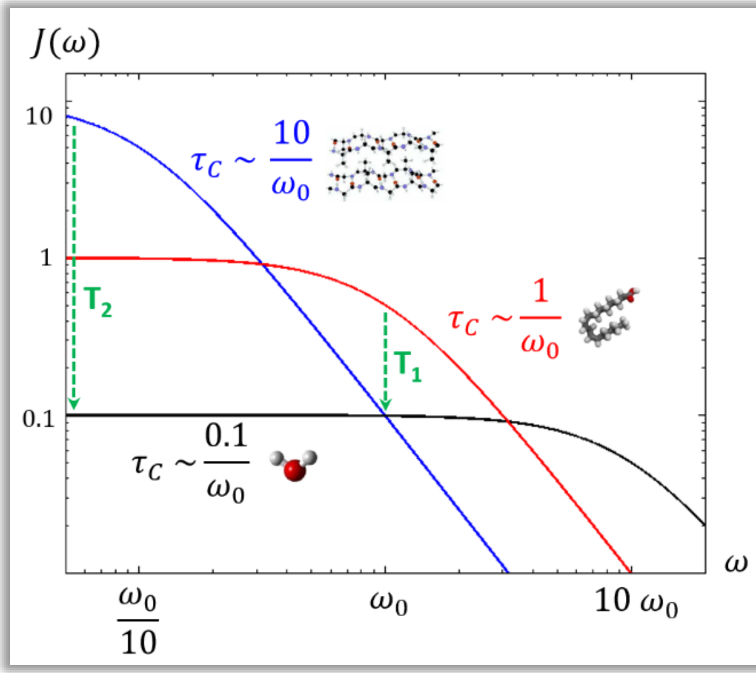


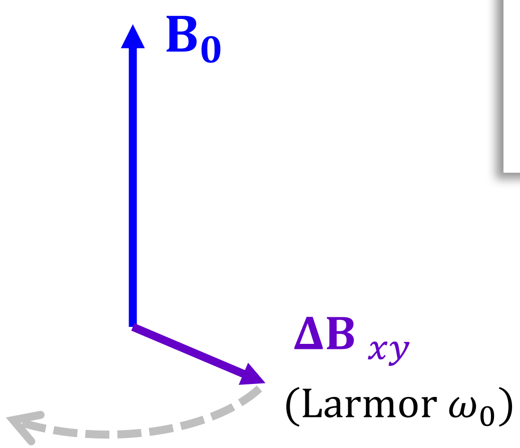
>> LENT

RMN – contraste

Relaxation :

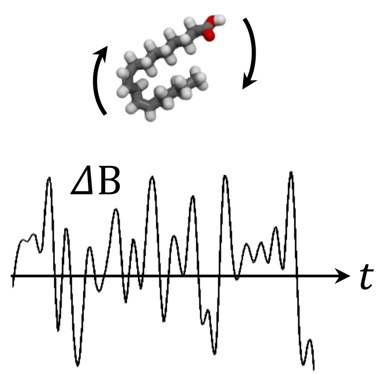


T_1

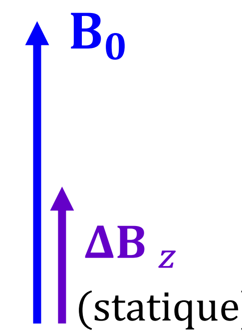


>> RAPIDE

LIPIDES



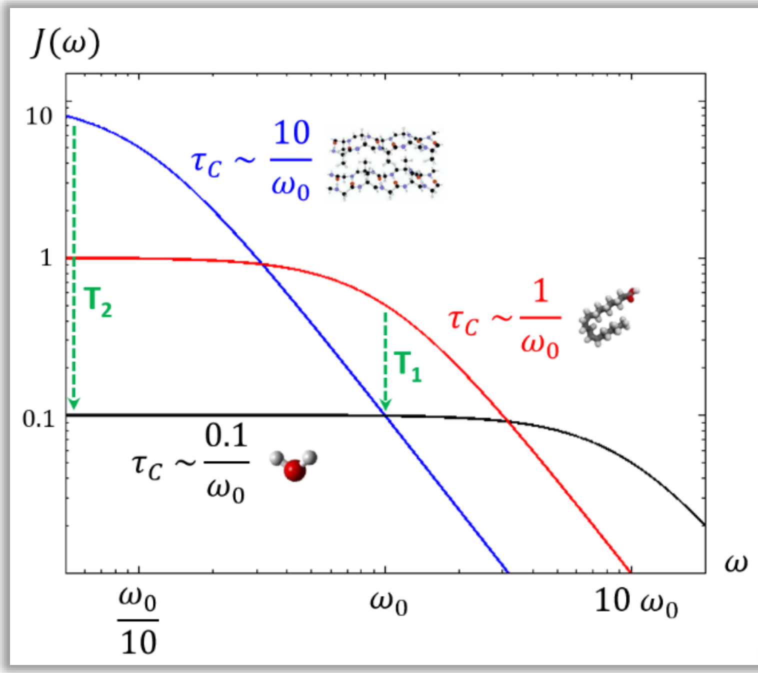
T_2



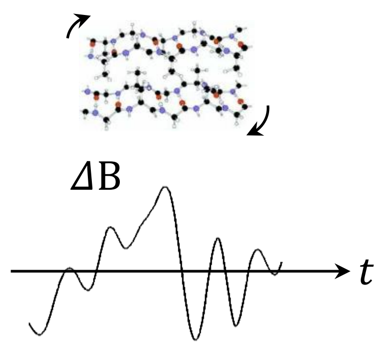
>> ± RAPIDE

RMN – contraste

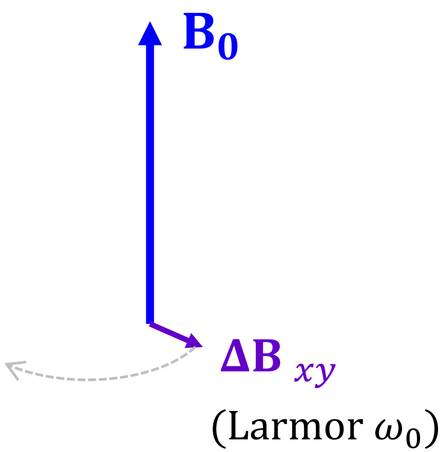
Relaxation :



MACROMOLECULES

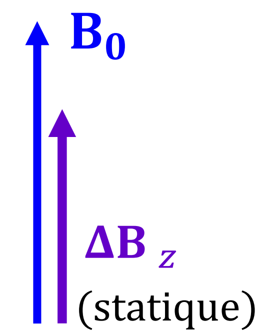


T_1



>> LENT

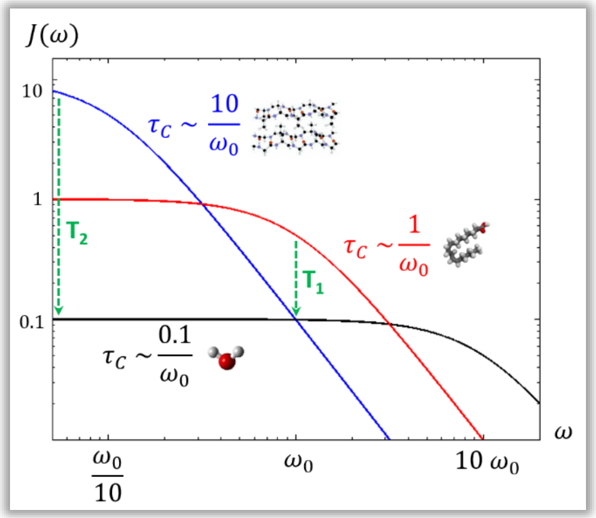
T_2

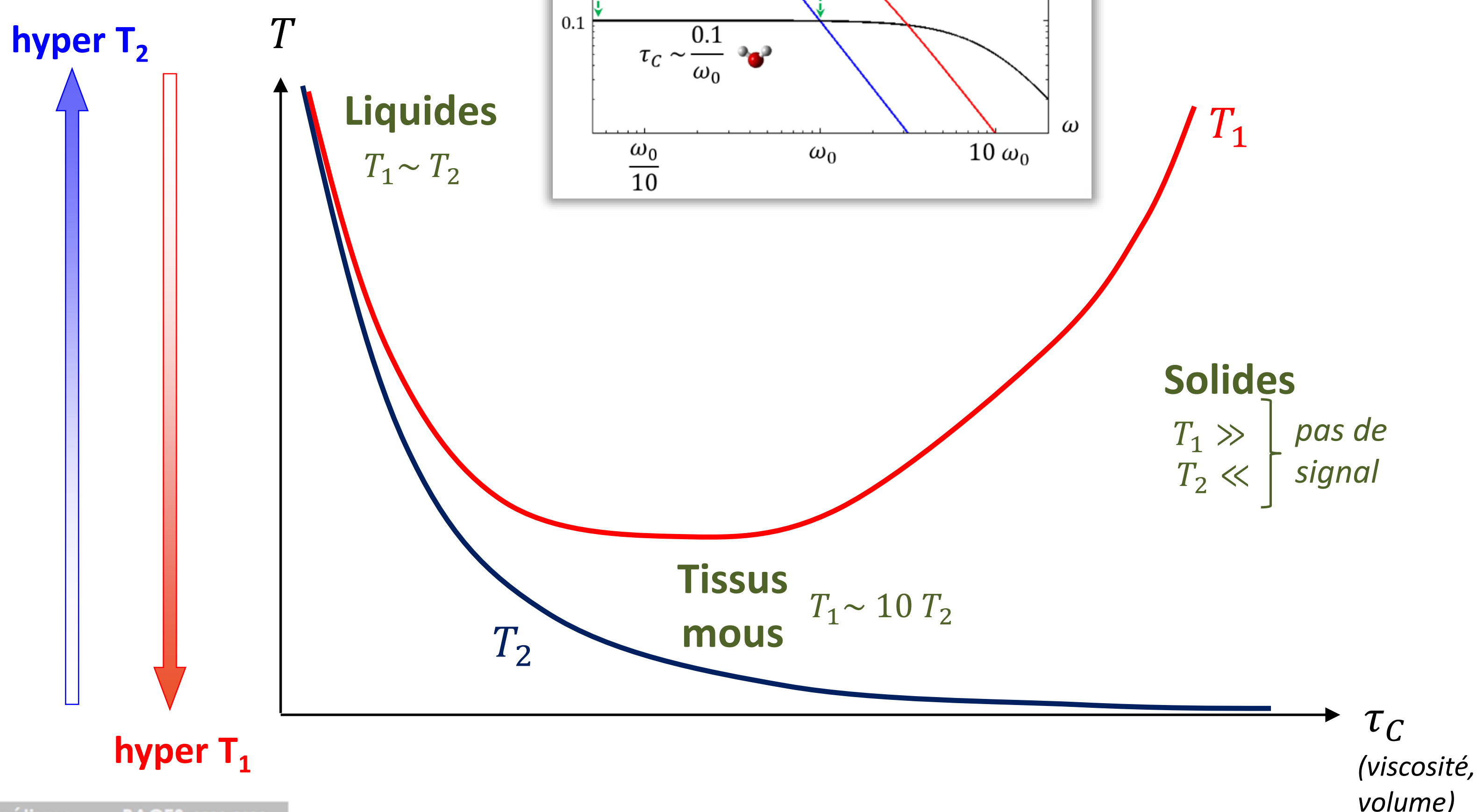


>> RAPIDE

RMN – contraste

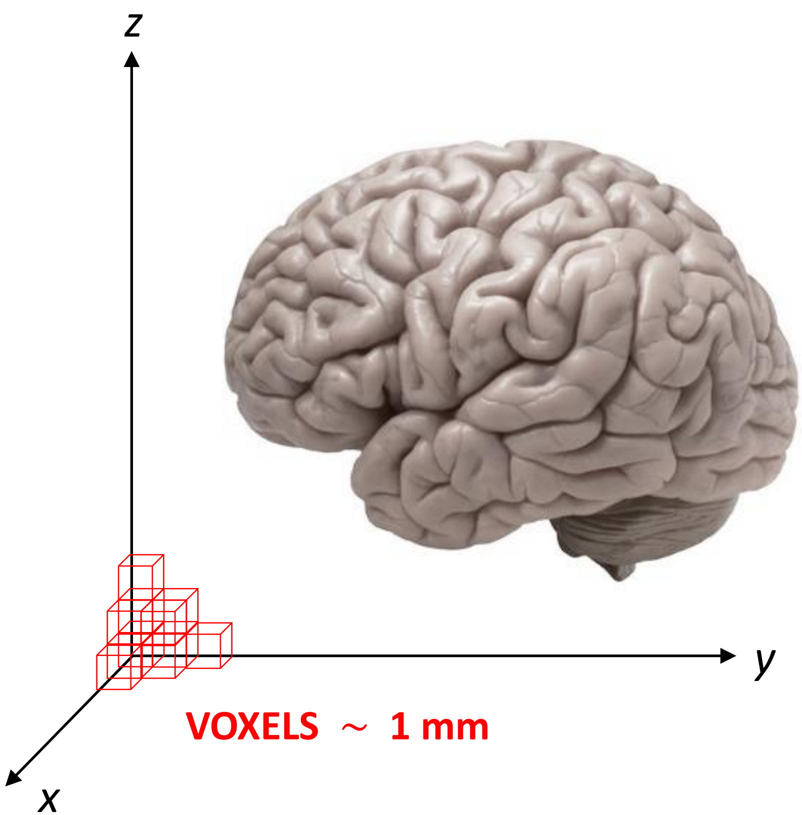
Relaxation :





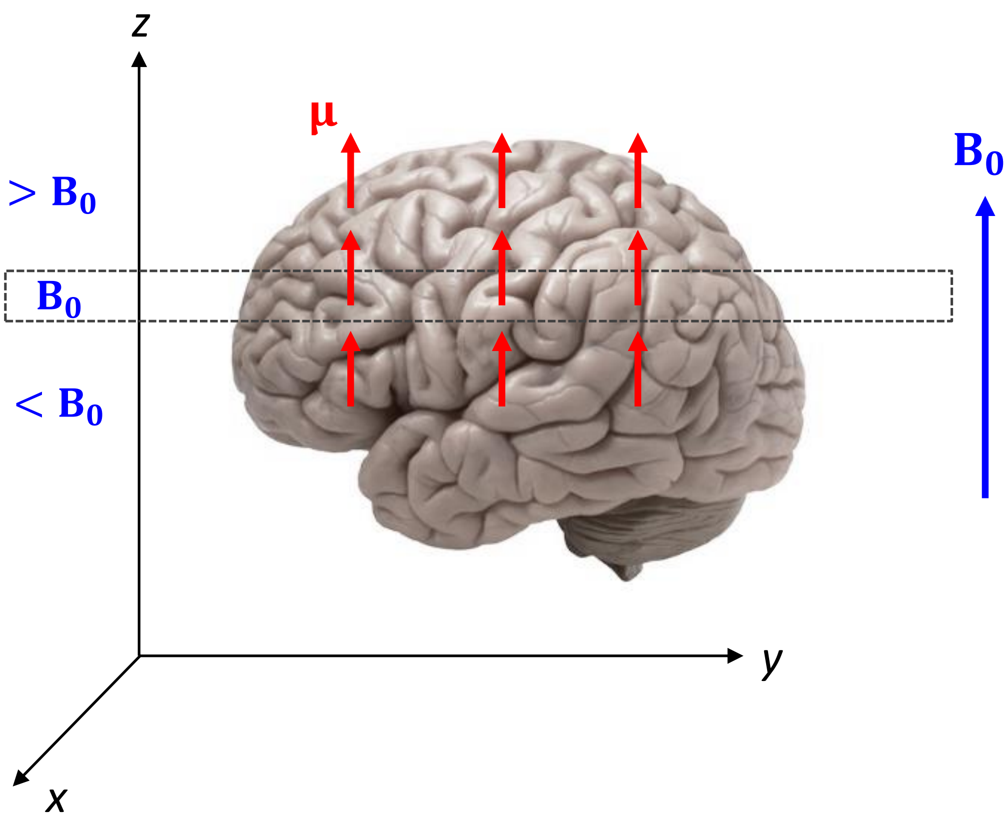
Applications : IRM & SRM

Imagerie : IRM



Applications : IRM & SRM

Imagerie : IRM

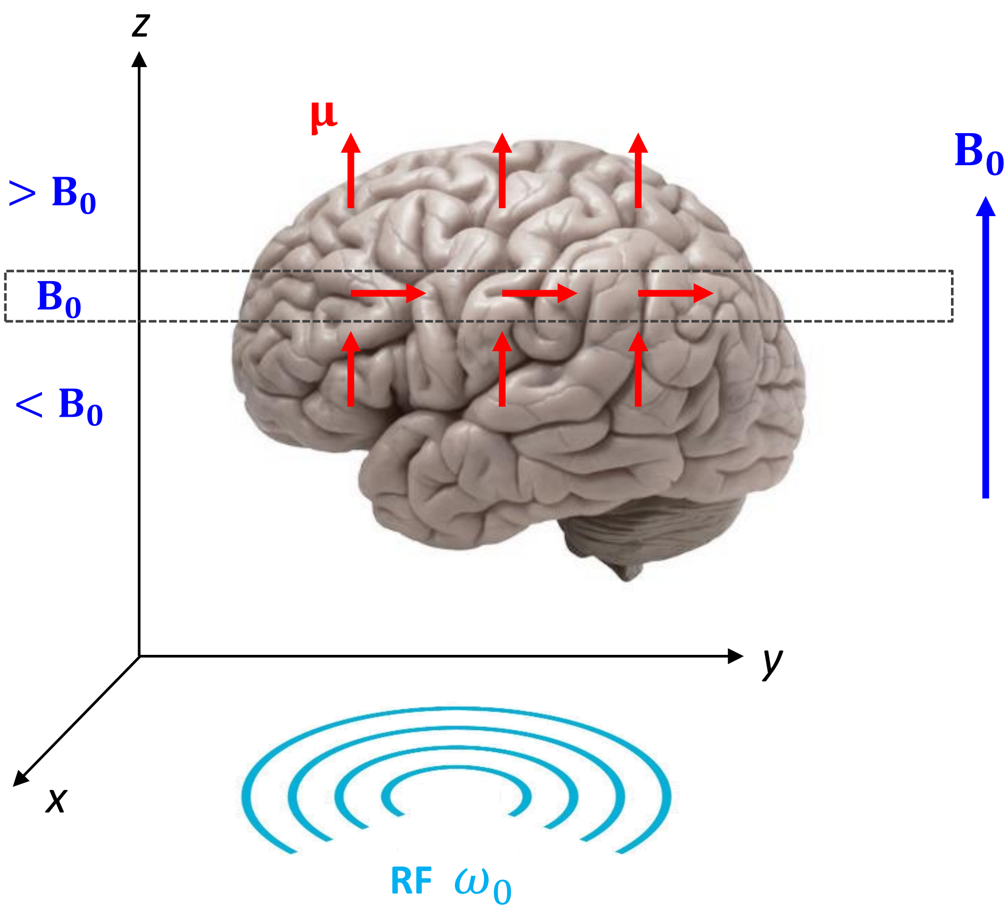


B_0 variable

> *gradient d'encodage*

Applications : IRM & SRM

Imagerie : IRM

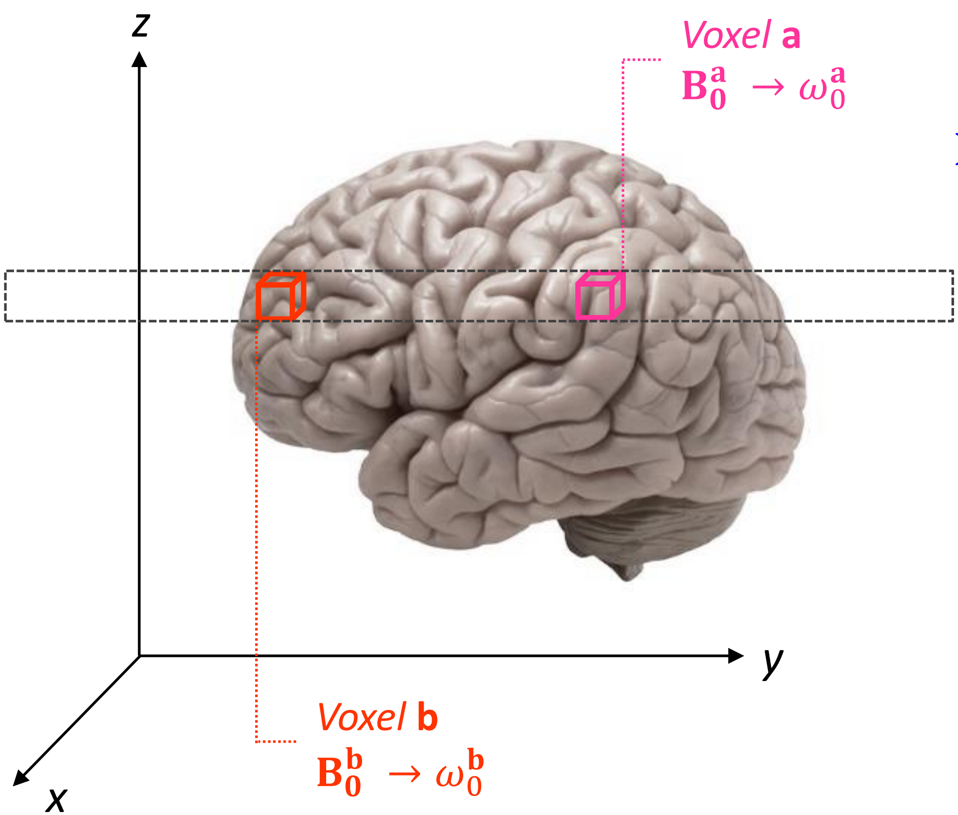


$\mathbf{B_0}$ variable

> gradient d'encodage

Applications : IRM & SRM

Imagerie : IRM



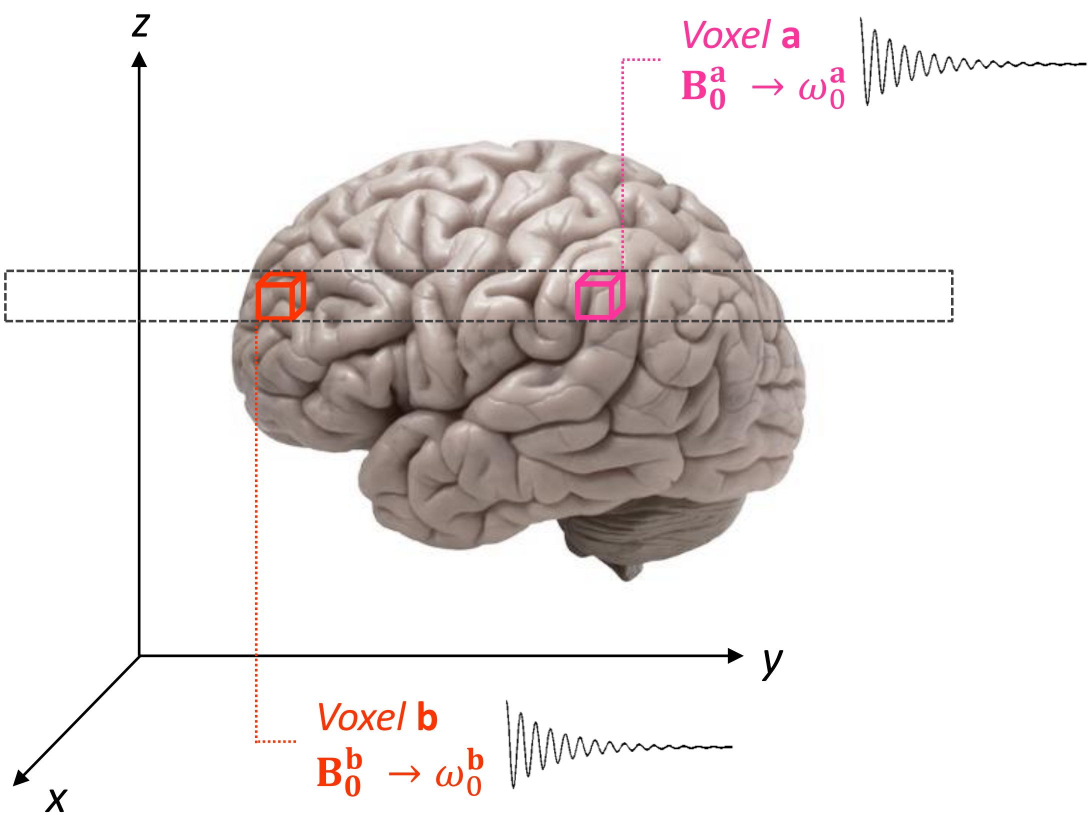
$\mathbf{B_0}$ variable

> *gradient d'encodage*

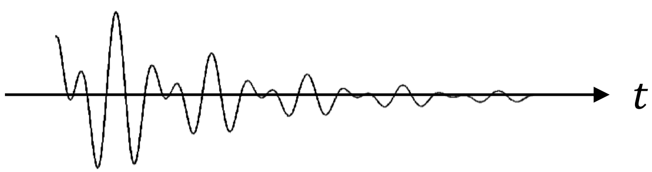
> *gradient de lecture*

Applications : IRM & SRM

Imagerie : IRM

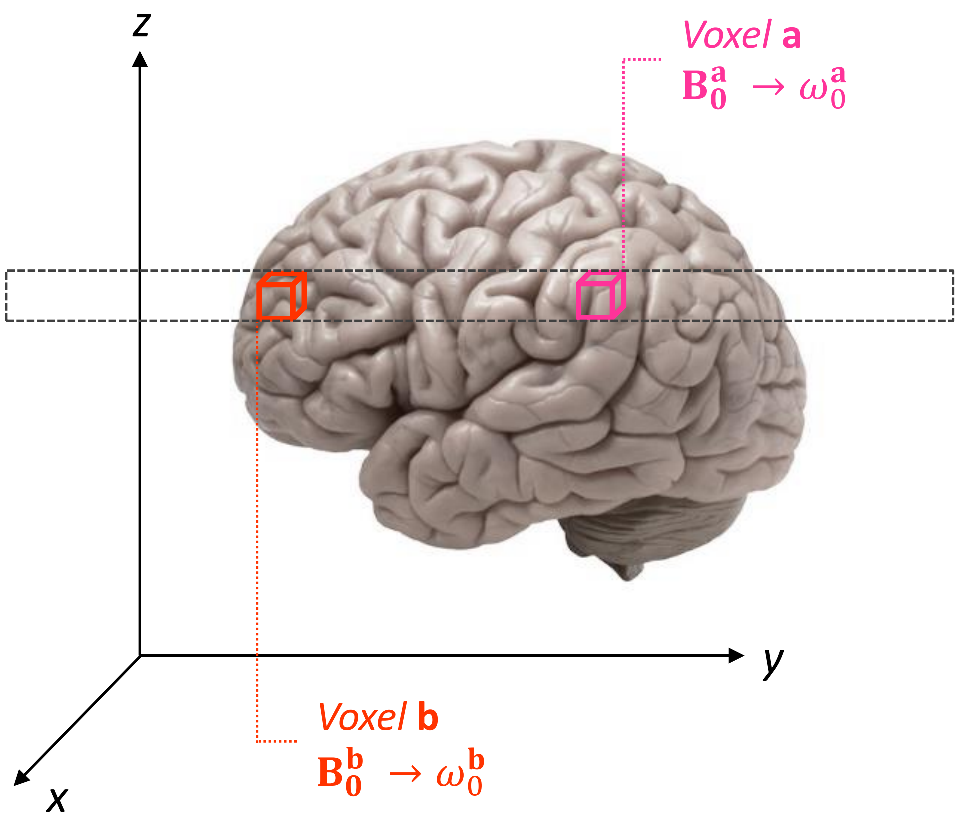


FID = signal (**a**) + signal(**b**)

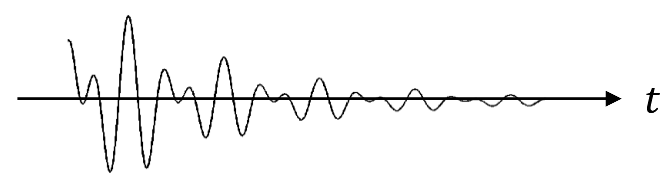


Applications : IRM & SRM

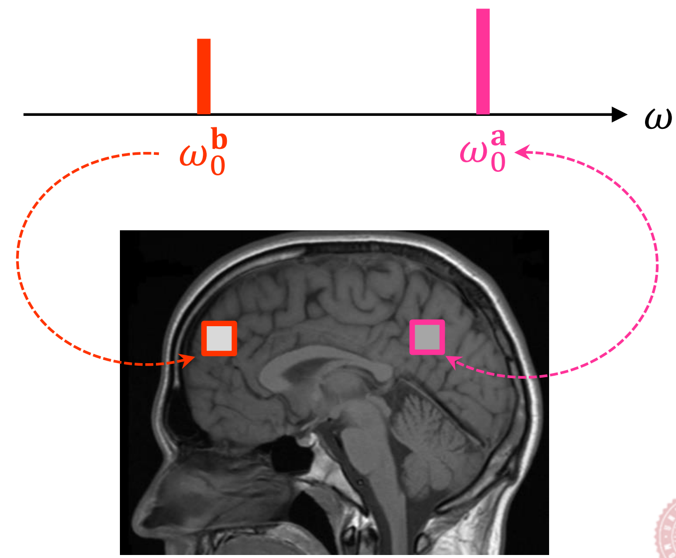
Imagerie : IRM



FID = signal (**a**) + signal(**b**)



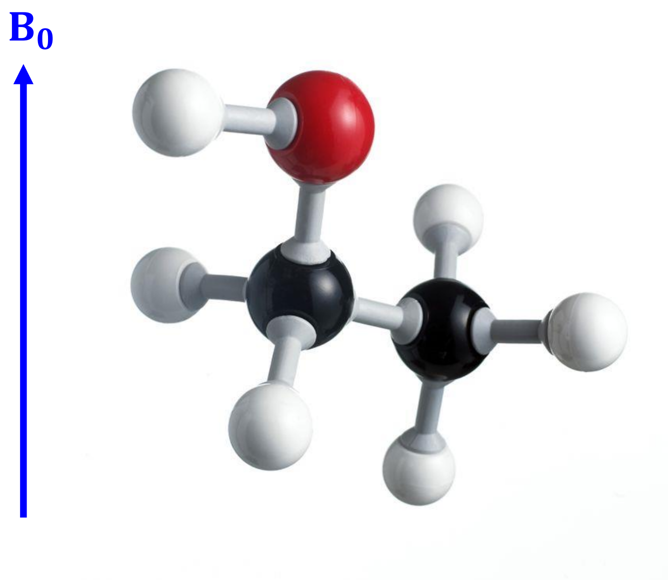
Spectre (**FID**)

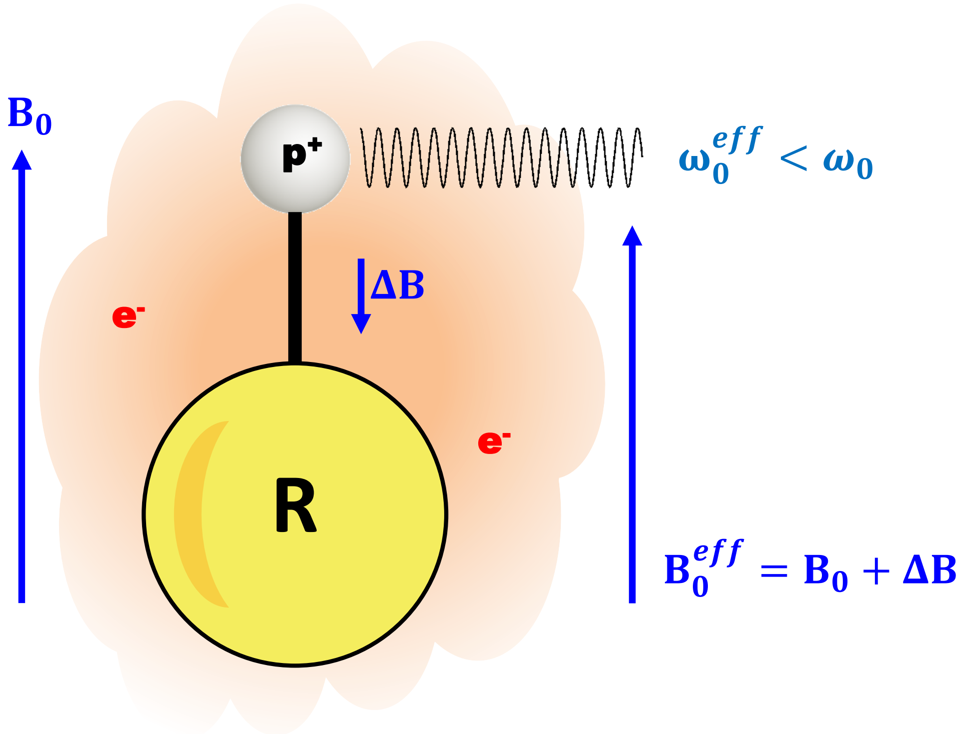


Applications : IRM & SRM

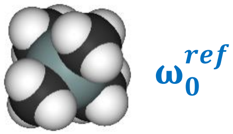
Spectroscopie : SRM

Ethanol **CH_3-CH_2-OH**





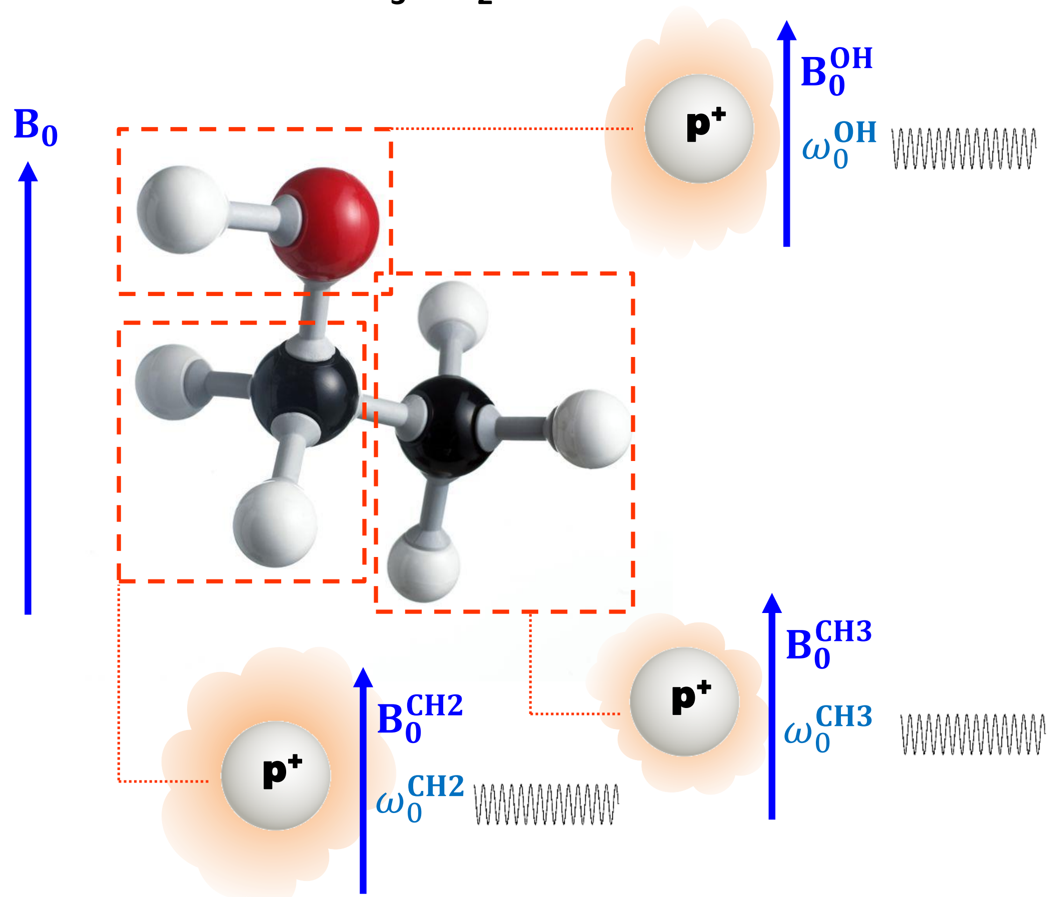
Déplacement chimique : $\delta = 10^6 \dfrac{\omega_0^{eff} - \omega_0^{ref}}{\omega_0^{ref}}$ [ppm]



Applications : IRM & SRM

Spectroscopie : SRM

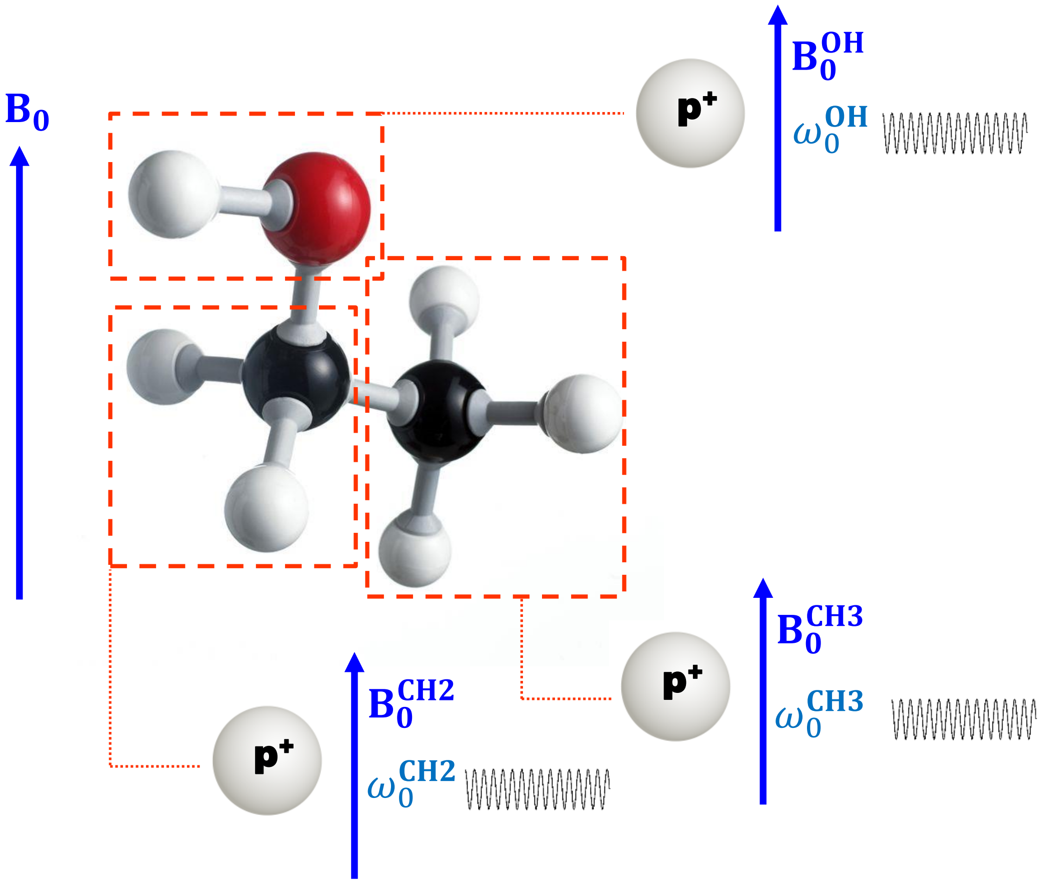
Ethanol $\mathbf{CH_3\text{-}CH_2\text{-}OH}$



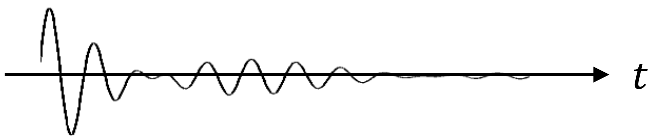
Applications : IRM & SRM

Spectroscopie : SRM

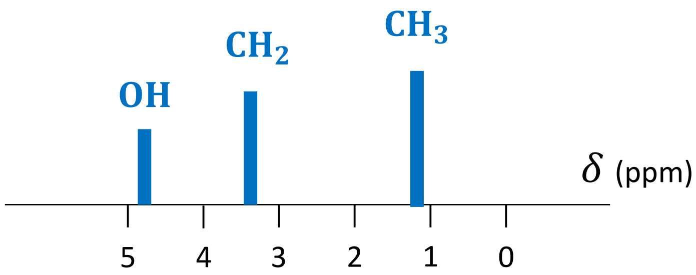
Ethanol **CH_3-CH_2-OH**



FID = signal (**OH**) + signal(**CH_2**) + signal(**CH_3**)

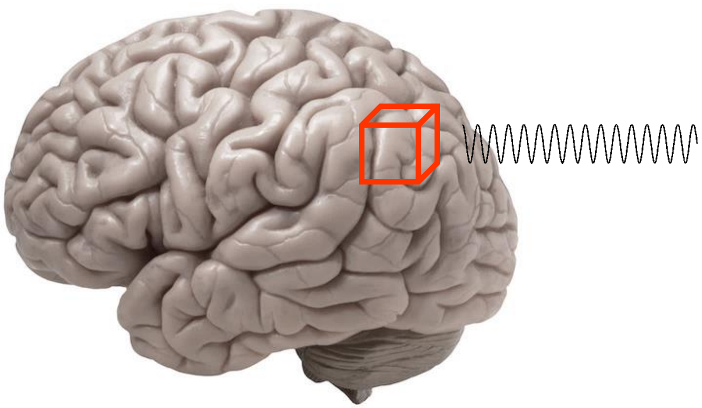


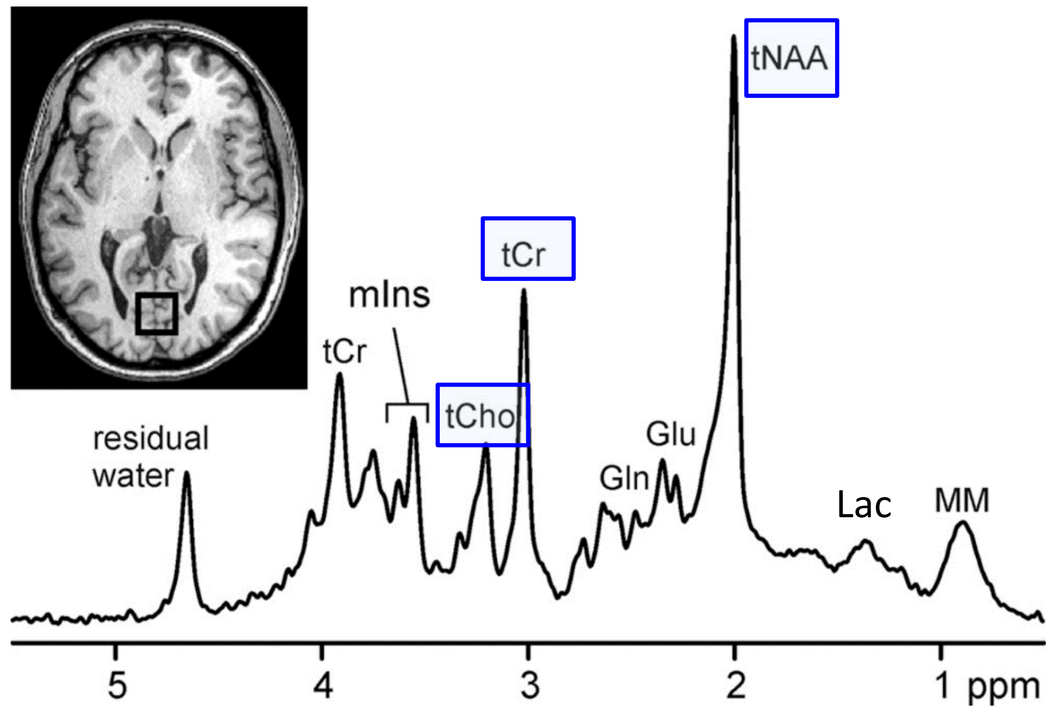
Spectre **(FID)**



Applications : IRM & SRM

Spectroscopie : SRM





Gülin et al. Radiology 2014.

Cho : choline - catabolisme membranaire
Cr : créatine - métabolisme aérobie
NAA : N-acétylaspartate - viabilité cellulaire
Lac : lactates - métabolisme anaérobie
MM : macro-molécules

IRM – exemples

Reprinted from
19 March 1971, Volume 171, pp. 1151-1153

DOCUMENT 1

SCIENCE

Tumor Detection by Nuclear Magnetic Resonance

Raymond Damadian

IRM – exemples

Table 1. Spin-lattice (T_1) and spin-spin (T_2) … sues.

Rectus muscle T_1	Rectus muscle T_2	Liver T_1	Liver T_2	Kidney T_1	Brain T_1
0.493	0.050	0.286	0.050	…44	0.573
.548	.050	.322	.060	…03	.573
.541	.050	.241	.050	…23	.596
.576 (0.600)*	.070	.306 (0.287)*	.048	…41 (0.530)*	.620 (0.614)
.531		.300		…89	.612
Mean and …					
0.538 ± 0.015	0.055 ± 0.005	0.293 ± 0.010	0.052 ± 0…	…480 ± 0.026	0.595 ± 0.007

… relaxation time after the specimen stood overnight at room …

Table 2. Spin-lattice (T_1) and spin-spin (T_2) relaxation times (in seconds) in tumors.

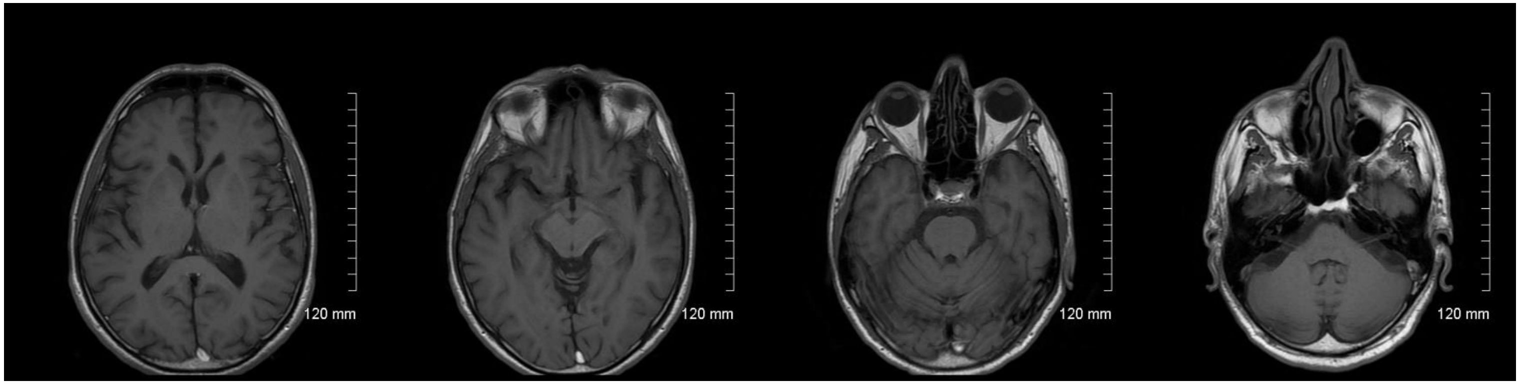
Rat No.	Weight (g)	T_1	T_2
Walker sarcoma			
6	156	0.700	0.100
7	150	.750	.100
8	495	.794 (0.794)*	.100
9	233	.688	
10	255	.750	
Mean and S.E.		0.736 ± 0.022	.100
P		< .01†	
Novikoff hepatoma			
11	155	0.798	0.120
12	160	.852	.120
13	231	.827	.115
Mean and S.E.		0.826 ± 0.013	0.118 ± 0.002
P		< .01†	
Fibroadenoma (benign)			
14		0.448	
15		.537	
Mean		.492	
Distilled water			
		2.691	
		2.690	
		2.640	
Mean and S.E.		2.677 ± 0.021	

* Spin-lattice relaxation time after the specimen stood overnight at room temperature. † The P values are the probability estimates of the significance of the difference in the means of T_1 for the malignant tumor and for brain.

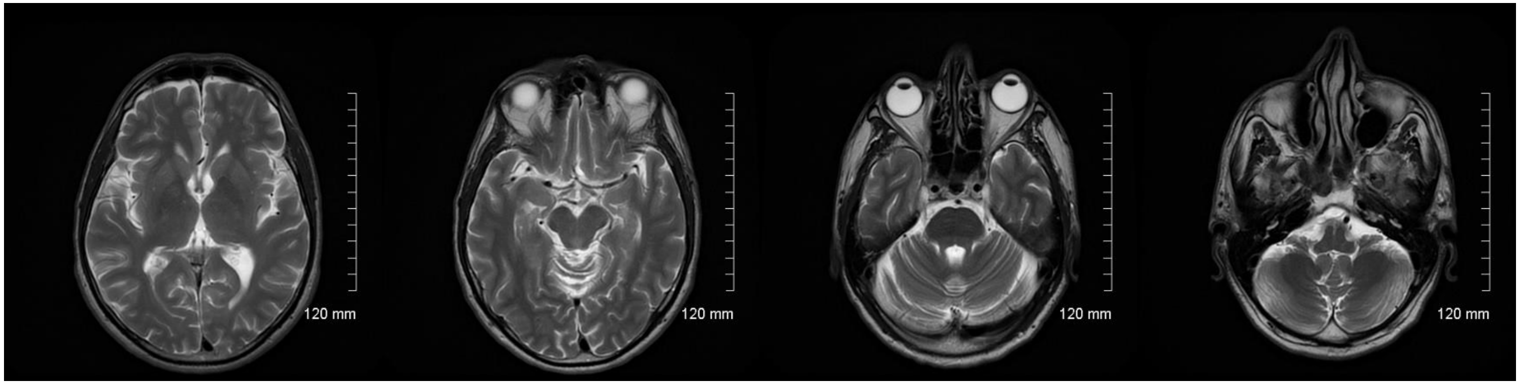
IRM – exemples

T_1 : contraste anatomique
T_2 : contraste « inversé »

T_1



T_2



IRM – exemples

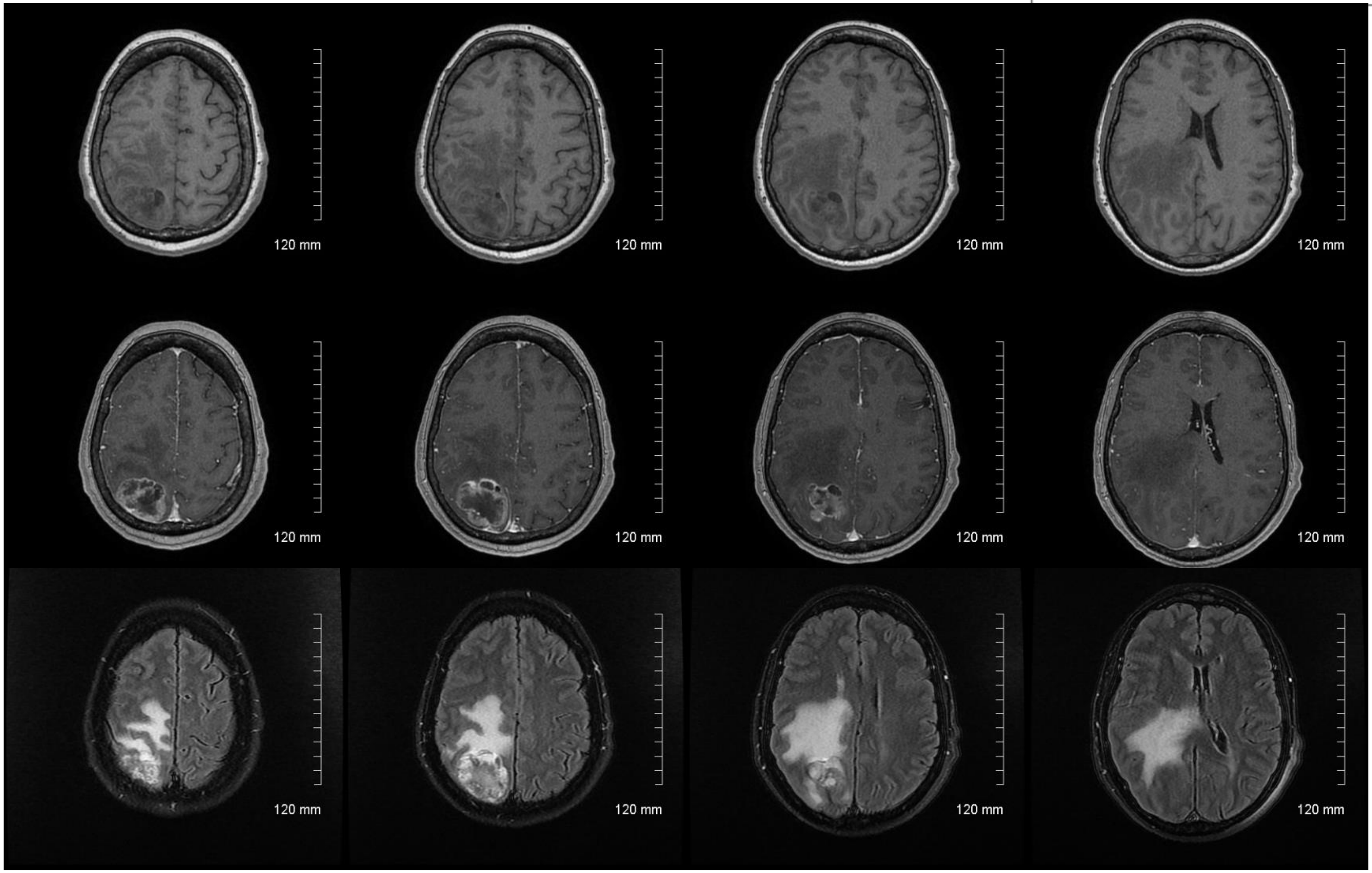
Métastase cérébrale

- Rupture BHE
- Effet de masse
- Oedème

T_1

T_1 gado.

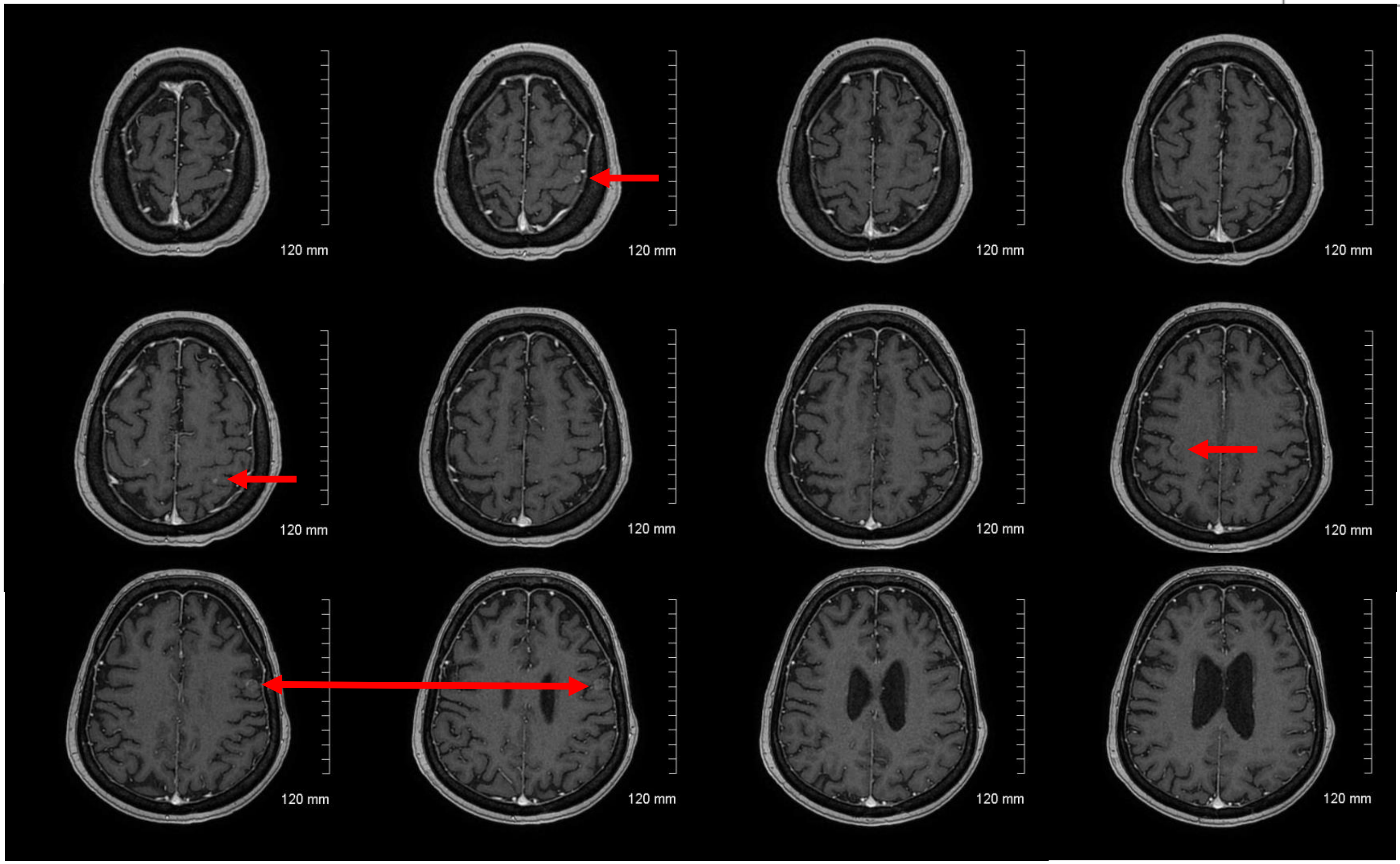
T_2 FLAIR



IRM – exemples

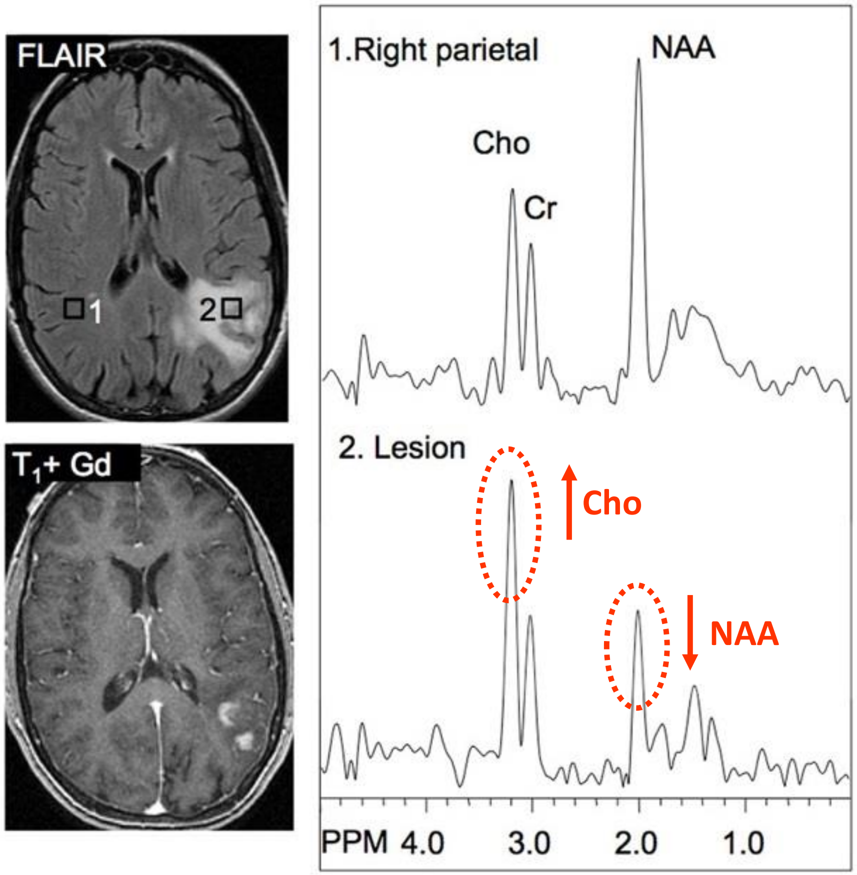
Bilan initial ADK pulmonaire

T_1 gado.

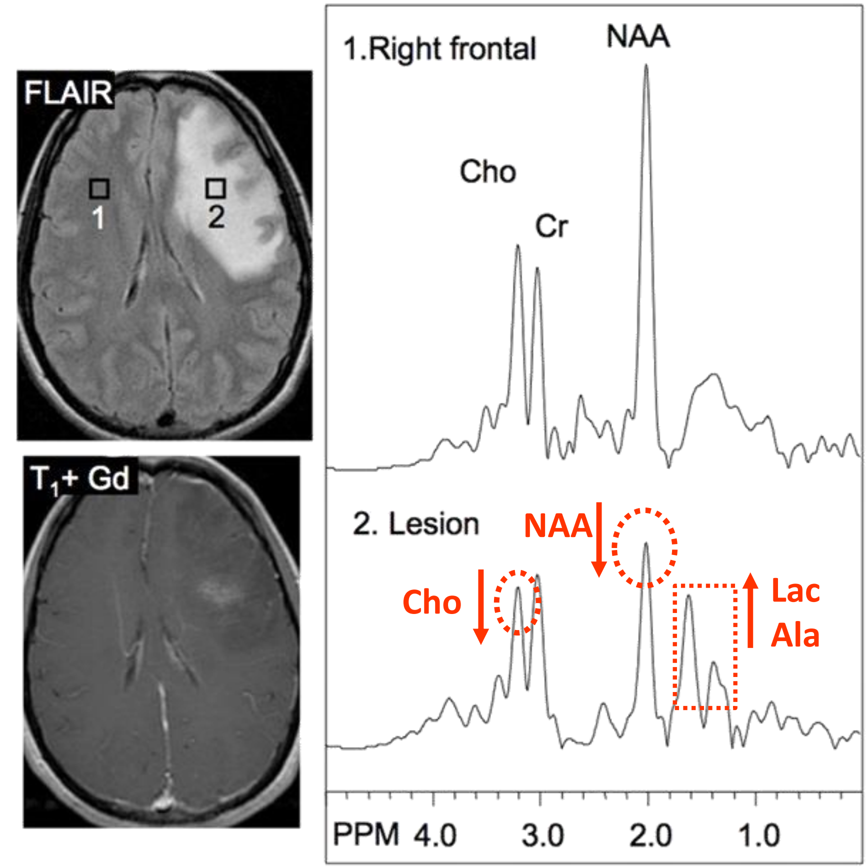


IRM – exemples

Lymphome cérébral



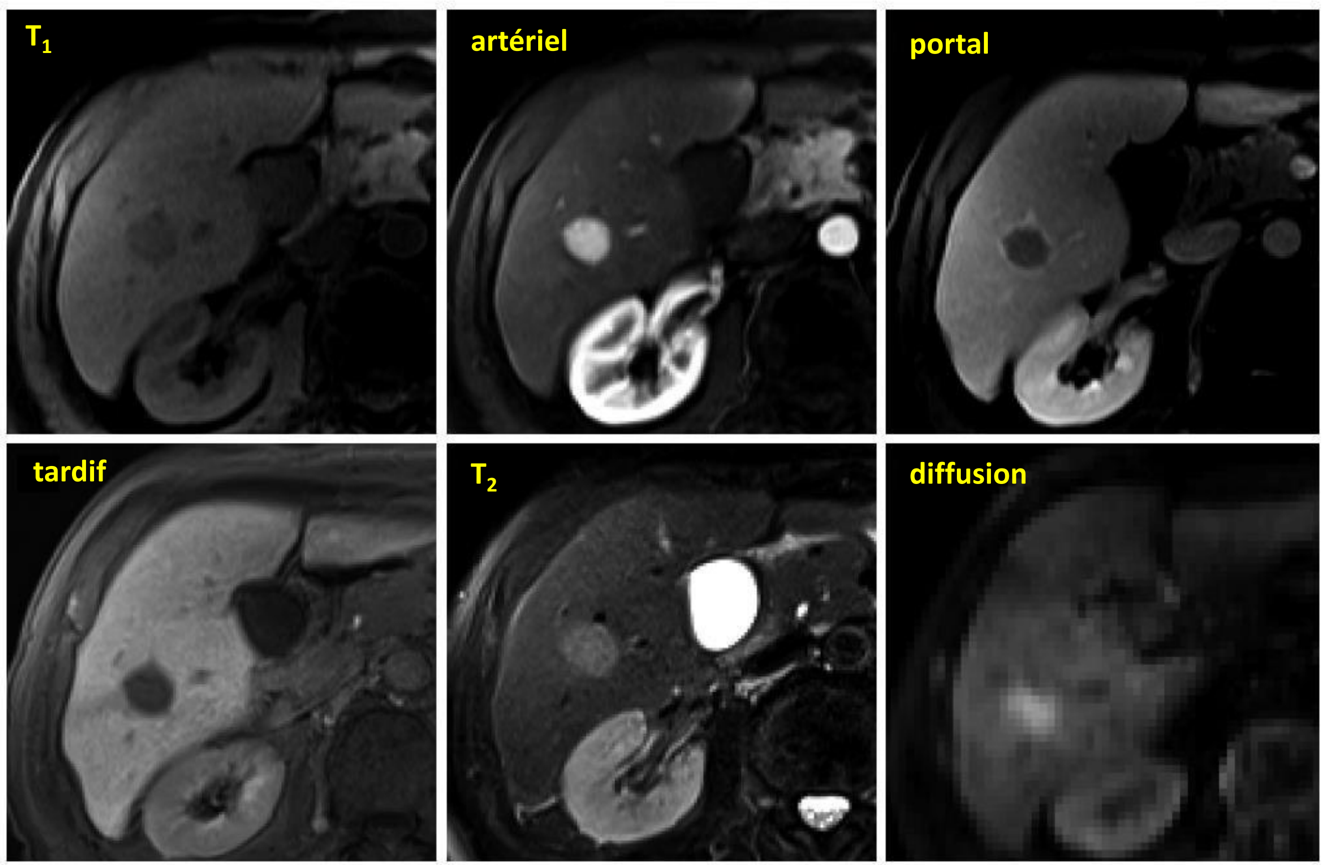
Méningoencéphalite



Horská et al. Neuroimaging Clin N Am 2010.

IRM – exemples

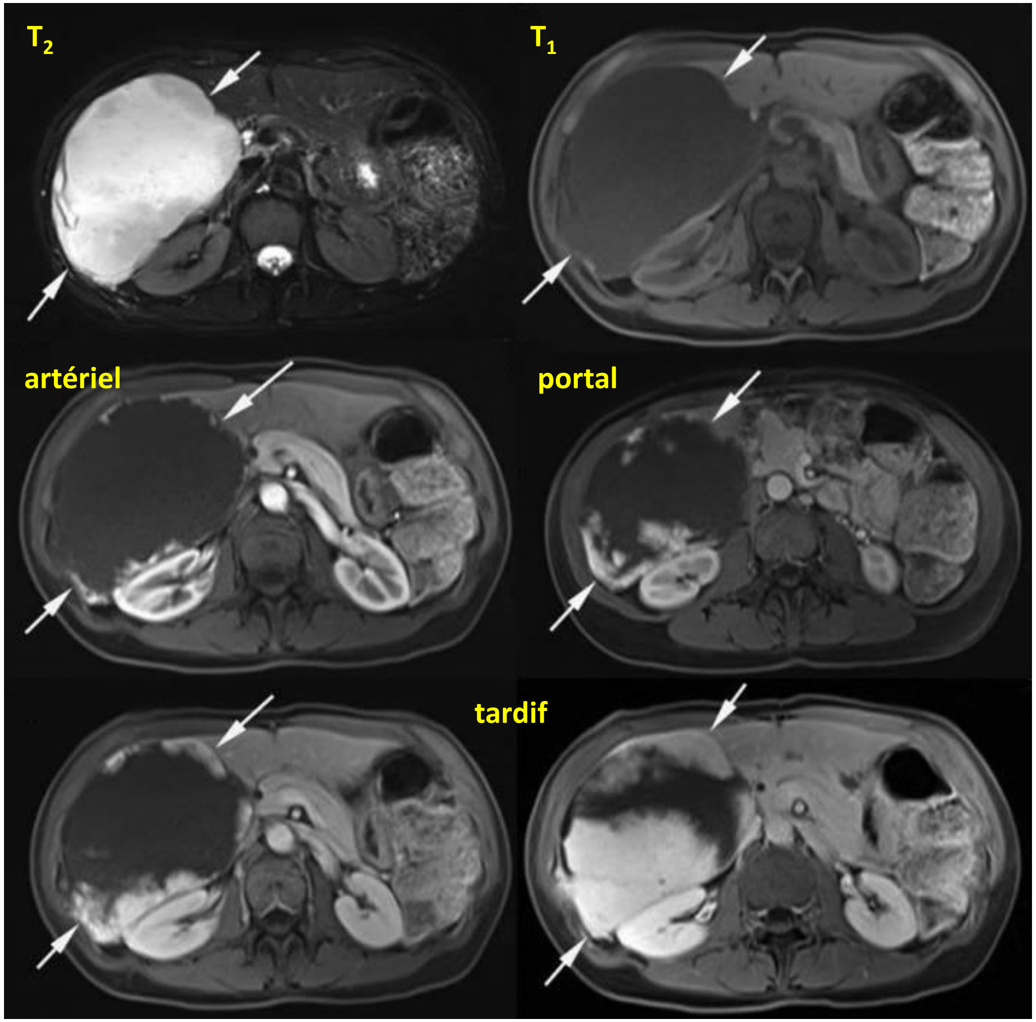
Carcinome hépatocellulaire



Park et al. World J Gastroenterol 2016.

IRM – exemples

Angiome hépatique



SIDES