

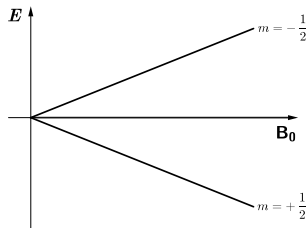
Mehanska detekcija signala magnetne resonance

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Enostavni kvantnomehanski opis

- ▶ $\boldsymbol{\mu} = \gamma \mathbf{J}$; $\mathbf{J} = \hbar \mathbf{I}$
- ▶ $\mathbf{B} = (0, 0, B_0) \implies$
 $H = -\boldsymbol{\mu} \cdot \mathbf{B} = -\gamma \hbar B_0 I_z$
- ▶ Lastna stanja energije:
 $E = -\gamma \hbar B_0 m$;
 $m = -j, -j + 1, \dots, j$



Zeemanov razcep za $j = \frac{1}{2}$

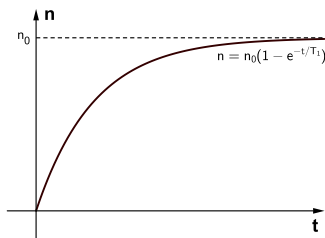
- ▶ Perturbacija: $\Delta H = -\gamma \hbar B_{x,0} I_x \cos \omega t$
- ▶ $\langle m' | I_x | m \rangle = 0$; $m' \neq m \pm 1 \implies \hbar \omega = \Delta E = \gamma \hbar B_0$

Spinsko-mrežna relaksacija

- ▶ Vzorec, v katerem imajo jedra spin $j = \frac{1}{2}$;
 N_{\uparrow} jeder z $m = +\frac{1}{2}$ in N_{\downarrow} jeder z $m = -\frac{1}{2}$
- ▶ Termodinamsko ravnovesje: $\frac{N_{\downarrow,0}}{N_{\uparrow,0}} = e^{-\Delta E/kT} = e^{-\gamma\hbar B_0/kT}$
- ▶ $\frac{dN_{\uparrow}}{dt} = N_{\downarrow}w_{\uparrow} - N_{\uparrow}w_{\downarrow}$
- ▶ Uvedemo $N = N_{\uparrow} + N_{\downarrow}$ in $n = N_{\uparrow} - N_{\downarrow} \implies \frac{dn}{dt} = \frac{n_0 - n}{T_1}$

- ▶ Vzorec, ki je ob času $t = 0$ nenamagneten:

$$n = n_0(1 - e^{-t/T_1})$$



Semiklasična obravnava

- ▶ $\mathbf{M} = \boldsymbol{\mu} \times \mathbf{B} = \frac{d\mathbf{J}}{dt}$; $\boldsymbol{\mu} = \gamma \mathbf{J} \implies \frac{d\boldsymbol{\mu}}{dt} = \boldsymbol{\mu} \times \gamma \mathbf{B}$
- ▶ Izberemo $\mathbf{B} = B_0 \hat{\mathbf{k}} \implies \boldsymbol{\mu}$ precedira z $\omega_L = \gamma B_0$ okrog \mathbf{B}
- ▶ Spremenljivo magnetno polje vzdolž x -osi:

$$B_x(t) = B_{x,0} I_x \cos \omega t$$

- ▶ Enačba gibanja v vrtečem sistemu, ki se vrti z $\omega \hat{\mathbf{k}}$:

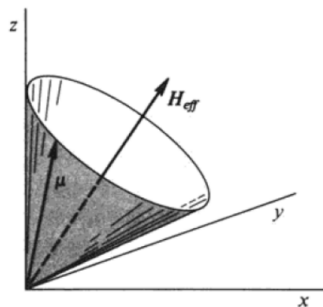
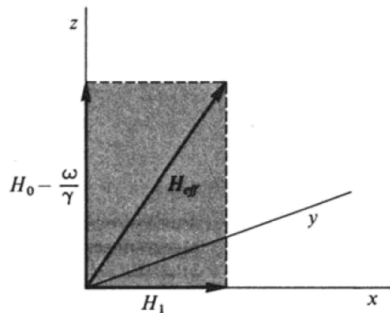
$$\frac{d\boldsymbol{\mu}}{dt} = \boldsymbol{\mu} \times \left((\gamma B_0 - \omega) \hat{\mathbf{k}} + \gamma \frac{B_{x,0}}{2} \hat{\mathbf{i}} \right) = \boldsymbol{\mu} \times \gamma \mathbf{B}_{ef}$$

Semiklasična obravnava

Vpliv spremenljivega magnetnega polja vzdolž x -osi

*V vrtečem sistemu:

$$\frac{d\boldsymbol{\mu}}{dt} = \boldsymbol{\mu} \times \left((\gamma \mathbf{B}_0 - \omega) \hat{\mathbf{k}} + \gamma \frac{B_{x,0}}{2} \hat{\mathbf{i}} \right) = \boldsymbol{\mu} \times \gamma \mathbf{B}_{ef}$$



Blochove enačbe

- ▶ $M_z = n \gamma \frac{\hbar}{2}$; $\mathbf{n} = \mathbf{N}_\uparrow - \mathbf{N}_\downarrow$
- ▶ Za M_z : $\frac{dM_z}{dt} = \frac{M_0 - M_z}{T_1} + (\mathbf{M} \times \gamma \mathbf{B})_z$
- ▶ Za $M_{x,y}$: $\frac{dM_{x,y}}{dt} = (\mathbf{M} \times \gamma \mathbf{B})_{x,y} - \frac{M_{x,y}}{T_2}$

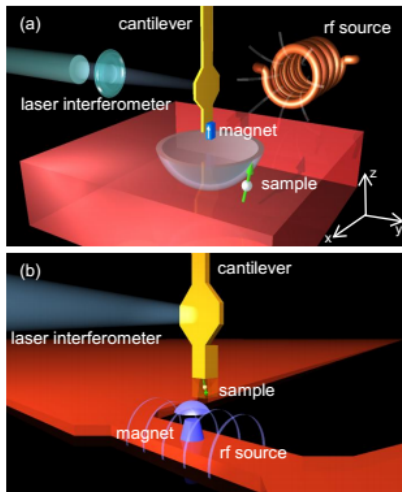
Detekcija signala magnetne resonance

Induktivna detekcija

- ▶ Običajna metoda detekcije je **induktivna detekcija**
- ▶ Signal je odvisen le od **skupnega št.** magnetnih momentov v vzorcu, ne pa tudi od njihove **prostorske porazdelitve**

⇒ uporabimo **gradientne tuljave**
- ▶ Rekonstrukcija slike temelji na **Fourierovi transformaciji** signala
- ▶ Lahko preučujemo **makroskopske** vzorce, preučevanje manjših vzorcev pa onemogočata **(pre)šibek signal** in **omejena ločljivost**

Mehanska detekcija



Zasnova naprave pri dveh različnih postavitvah vzorca in feromagneta

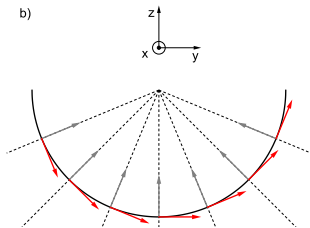
Mehanska detekcija

Presek resonančne rezine z yz -ravnino

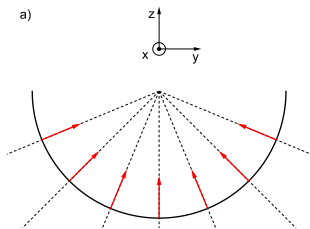
$$\mathbf{F} = \nabla(\boldsymbol{\mu} \cdot \mathbf{B})$$

$$F_y = \frac{\partial}{\partial y}(\boldsymbol{\mu} \cdot \mathbf{B})$$

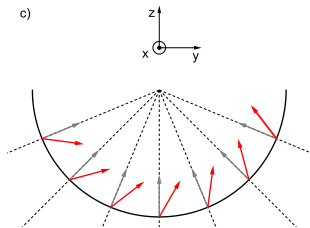
b)



a)



c)



Primerjava induktivne in mehanske detekcije

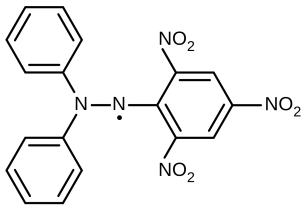
Induktivna detekcija

- ▶ Vzorec mora vsebovati vsaj 10^{15} oz. 10^{17} spinov, njegova prostornina mora znašati vsaj $3 \mu\text{m}^3$
- ▶ Gradientne tuljave
- ▶ Ločljivost nekaj $10 \mu\text{m}$
- ▶ Rekonstrukcija slike temelji na Fourierovi transformaciji signala

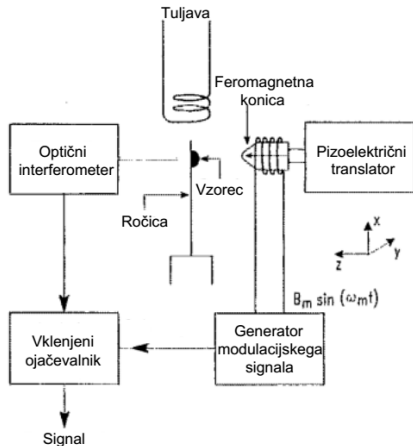
Mehanska detekcija

- ▶ Detektiramo lahko silo 10^{-20} N \rightarrow sila na magnetni moment **enega** 1H pri gradientu 10^6 T/m
- ▶ Piezoelektrični translator
- ▶ Ločljivost pod 10 nm
- ▶ Zapletene rekonstrukcijske metode

Eksperiment z vzorcem DPPH



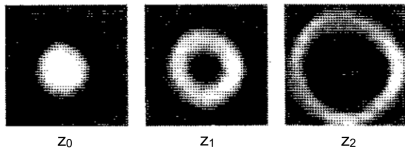
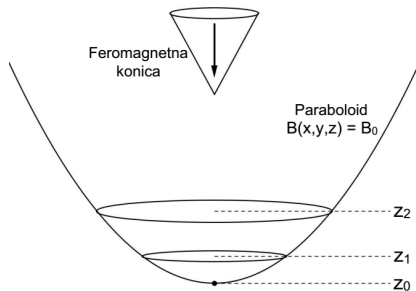
1,1-difenil-2-pikril-hidrazil radikal



Zasnova naprave

Eksperiment z vzorcem DPPH

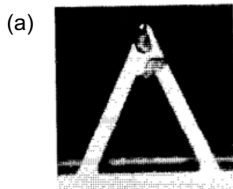
Rezultati



$$z_0 \approx 200 \mu\text{m}, z_1 = 197 \mu\text{m}, z_2 = 192 \mu\text{m}$$

Eksperiment z vzorcem DPPH

Rezultati

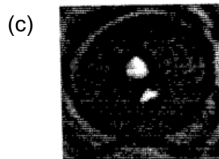


- ▶ (a) Optični mikroskopski snemek

(b) Diagram relativne amplitude nihanja ročice v odvisnosti od lege feromagnetne konice



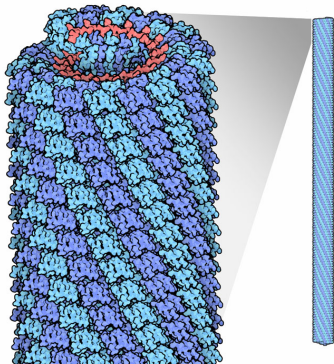
(c) Rekonstruirana relativna številna gostota magnetnih momentov



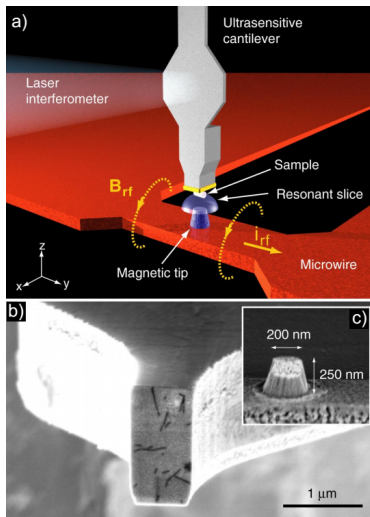
- ▶ Velikost območja $200 \mu\text{m} \times 200 \mu\text{m}$, velikost diagrama 128×128 slikovnih točk

⇒ 90-minutna meritev

Eksperiment z virusom tobačnega mozaika



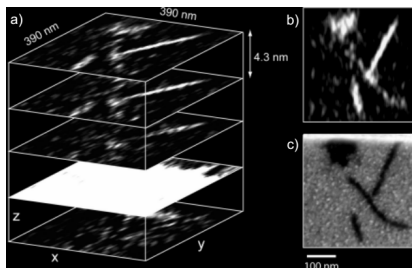
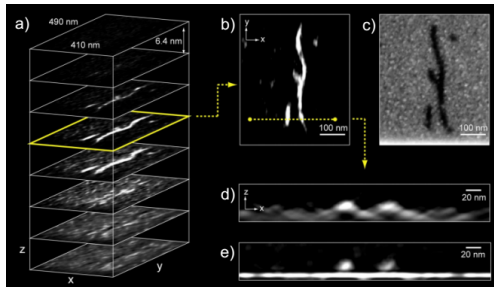
Virus tobačnega mozaika








- (a) Zasnova naprave
(b) Mikrograf konca ročice
(c) Mikrograf feromagnetne konice

Eksperiment z virusom tobačnega mozaika

Rezultati



Viri slikovnega gradiva

-  C. P. Slichter, *Principles of Magnetic Resonance*, Springer, (1996).
-  M. Poggio, C. L. Degen, *Force-detected nuclear magnetic resonance: recent advances and future challenges*, *Nanotechnology* **21**, 342001 (2010).
-  O. Züger, D. Rugar, *First images from a magnetic resonance force microscope*, *Applied Physics Letters* **63**, 2496 (1993).
-  C. L. Degen, M. Poggio, H. J. Mamin, C. T. Rettner, D. Rugar, *Nanoscale magnetic resonance imaging*, *Proceedings of the National Academy of Sciences of the United States of America* **106**, 1313 (2009).
-  D. Goodsell, *Tobacco Mosaic Virus* (2009). URL: <http://pdb101.rcsb.org/motm/109>.