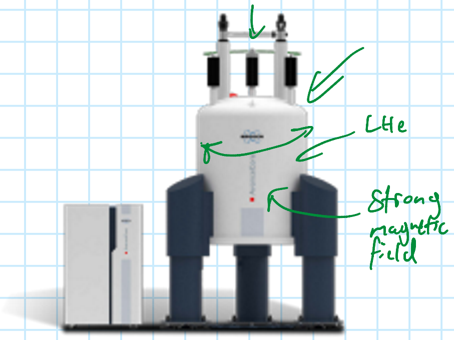
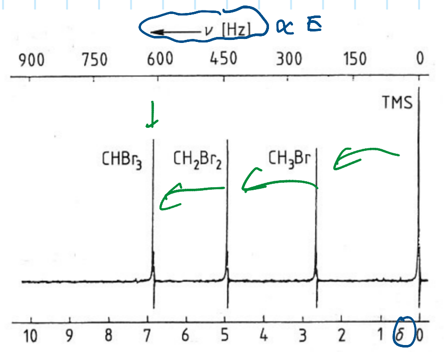
Lecture 27

Friday, January 28, 2022 12:07 PM

Review

- NMR
  - Works @ Room temperature ✓
  - Chemical sensitivity via
    1. Chemical shift ✓
    2. Spin-Spin coupling ✓



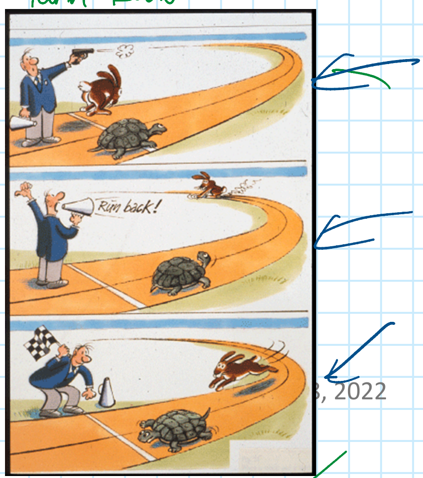


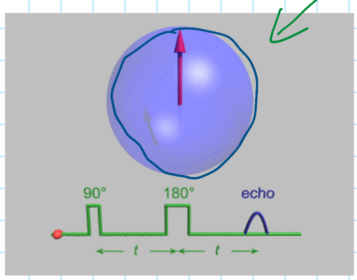
Spin dynamics

- Interaction with the environment
- inhomogeneous broadening (magnet) [Crucial for MRI]
- Can be prolonged by pulse-techniques (Hahn Echo)

↳ key ingredient for

Hahn Echo





$\hookrightarrow$ key ingredient for quantum information processing

Electron spin resonance

- Basically the same as NMR, but utilizing the e^- spin

$$\Delta E = [h \cdot \underset{\uparrow_{NMR}}{f} = g_J \cdot \underbrace{\mu_B} \cdot \underset{\uparrow_{ESR}}{B} \cdot \Delta m_J] \qquad \Delta m_J = \pm 1$$

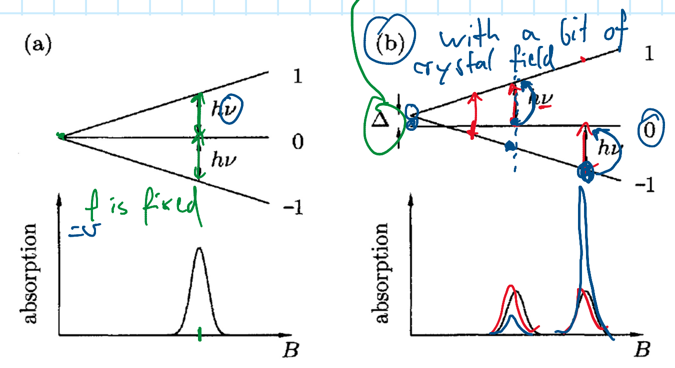
f is usually much higher $[(1-20 \text{ GHz})]$

$\hookrightarrow$ usually B is swept, with 2nd oscillatory B-field (lock-In)

- Allows to learn a lot more about localized spins in solids, molecules, compounds

Ni^{2+}: $\quad S = 1$ — Single ion anisotropy (zero field splitting) due to the crystal field

$$H_{CF} = \underset{\uparrow D}{\Delta} \cdot S_z^2$$



- Can probe:
  - g-factor
  - crystal field
  - spin-spin coupling (J or D)
  - hyperfine coupling (A)

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Electron Spin Resonance of Titanium (III) Acetylacetonate*

$3+$

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(Received 5 October 1960)

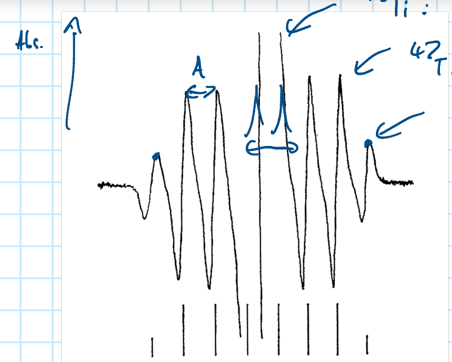


Fig. 3. Hyperfine spectra of Ti[47] and Ti[49] for titanium (III) acetylacetonate when the magnetic field is in the ac plane of the crystal. The large central line is from the titanium isotopes with zero spin.

B

^{48}Ti : $I = 0$ 90%

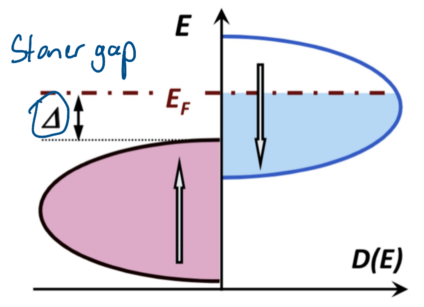
^{47}Ti $I = 5/2$ $\sim 5\%$ $5/2, 3/2 \ldots -5/2 = 6$

^{49}Ti $I = 7/2$ $\sim 5\%$ $7/2 \ldots = 8$

$$\Delta E = hf = g_J \cdot \mu_B \cdot B \cdot \Delta m_J \quad (\text{Zeeman})$$
$$+ A \cdot m_I \cdot \Delta m_J \quad (\text{Hyperfine})$$

8. Spin waves

- Experiment : Magnetization shows a diffrent dependence on temperature @ low T than what is expected from Stoner model or exchange interaction

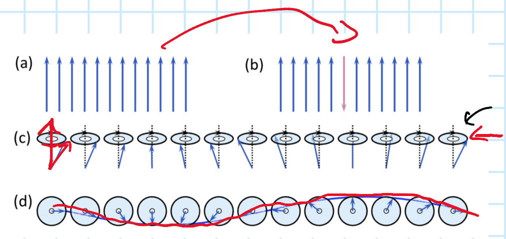


- smallest unit of change in M : $\uparrow\uparrow\uparrow\uparrow\uparrow \rightarrow \uparrow\uparrow\downarrow\uparrow\uparrow$ $\quad \Delta S = 1$

Other possibilities : Change all spins by a fraction
↳ collective excitation (like phonon)
↳ spin waves
- oscillation in the relative orientation of magnetic moments
- energy is quantized ; quanta are called magnons (ferro), or spinons (antiferro)

↳ Quasiparticles that obey Bose-Einstein-statistics

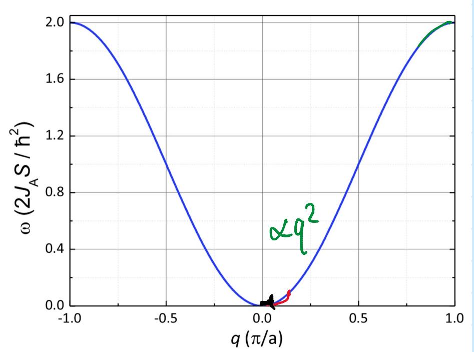
$$E_A = -\frac{2J}{\hbar^2} \sum_{i=1}^{N} \vec{S}_i \left(\vec{S}_{i-1} + \vec{S}_{i+1} \right)$$



$$\boxed{\hbar\omega = g\cdot\mu_B\cdot B + \frac{2J_A\cdot S}{\hbar}\left[1-\cos(q\cdot a)\right]}$$

wave vector, lattice constant

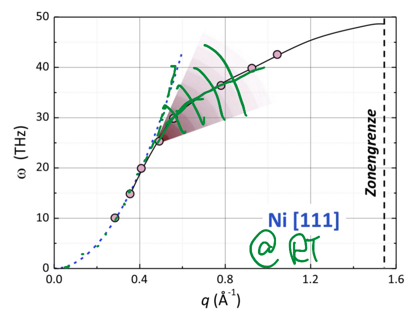
in 1D



- no energy gap: gapless excitations

↳ long wavelength excitations with vanishing energy cost

Goldstone modes / boson: Excitation here: magnon



- lifetime decay due to Stoner excitations

Temperature-dependence of ferromagnets @ low temperatures

- Spin-wave excitation (magnon) lowers magnetization:

@ $T=0$ total spin: $N\cdot S/\hbar$

@ $T>0$: $N\cdot S/\hbar - \sum_q \langle n_q\rangle$

- $\langle n_q\rangle = \left[\exp\left(\frac{\hbar\omega}{k_BT}\right)-1\right]^{-1}$ (BE-statistics)

$$\sum_q \langle n_q\rangle = \int d\omega\, \underbrace{D(\omega)}\, \langle n(\omega)\rangle$$

1. $\frac{V}{(2\pi)^3}\cdot 4\pi\cdot q^2\,dq$ }

2. $\omega \approx \frac{J_A\cdot S\cdot a^2}{\ldots}\cdot q^2$ }

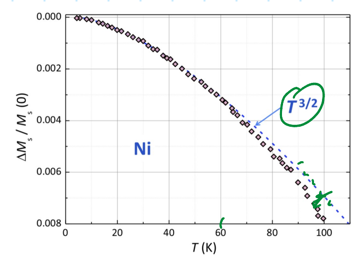
2. $\omega \approx \frac{J_A \cdot S \cdot a^2}{\hbar^2} \cdot q^2$

$$= \frac{V}{4\pi^2}\left(\frac{\hbar^2}{J_A \cdot S \cdot a^2}\right) \cdot \int_0^\infty d\omega \, \frac{\sqrt{\omega}}{e^{\hbar\omega/k_B T} - 1}$$

$$= \frac{V}{4\pi^2}\underbrace{\left(\frac{k_B T}{J_A \cdot S \cdot a^2}\right)}^{3/2} \int_0^\infty dx \, \frac{\sqrt{x}}{e^x - 1}$$

$$\boxed{\frac{\Delta M}{M_S(T=0)} \propto \left(\frac{k_B T}{J_A \, S/\hbar}\right)^{3/2} \qquad \text{Bloch } T^{3/2} \text{ law}}$$

- Describes the LT-dependence of a ferromagnet well



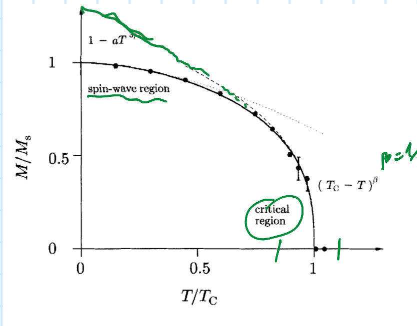


Fig. 6.15 The spontaneous magnetization in a ferromagnet. At low temperatures this can be fitted using the spin-wave model and follows the Bloch $T^{3/2}$ law. Near the critical temperature, the magnetization is proportional to $(T - T_C)^\beta$ where β is a critical exponent. Neither behaviour fits the real data across the whole temperature range. The data are for an organic ferromagnet which has $T_C \approx 0.67$ K for which $\beta \approx 0.36$, appropriate for the three-dimensional Heisenberg model.