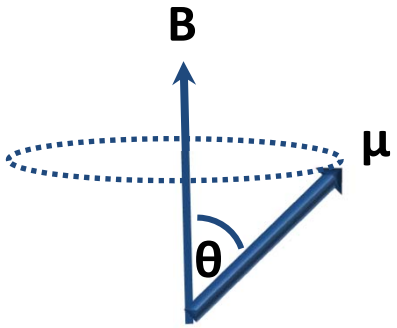
Beta-detected Nuclear Magnetic Resonance (β-NMR):
Towards Depth Resolved NMR

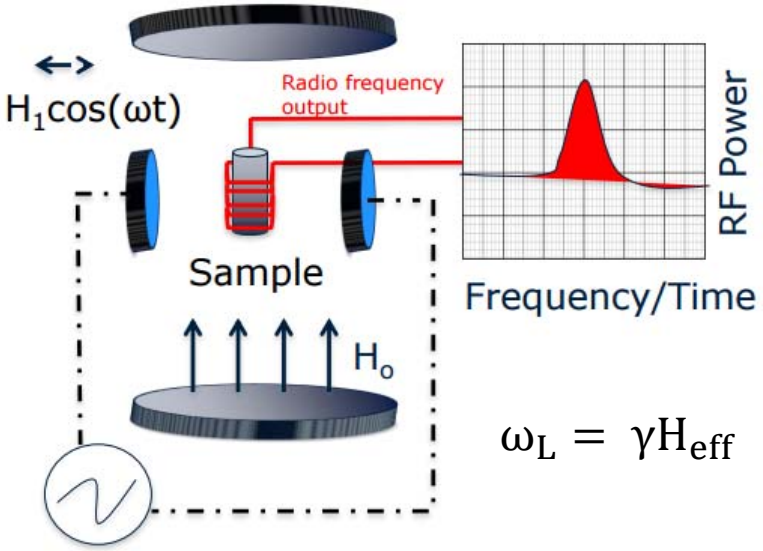
Victoria Karner, Rob Kiefl, Andrew MacFarlane

Outline

- NMR
- Beta detected NMR
  - Comparison to NMR
  - Detection
  - Measurement methods
- Examples from β-NMR
- Challenges
- Conclusions

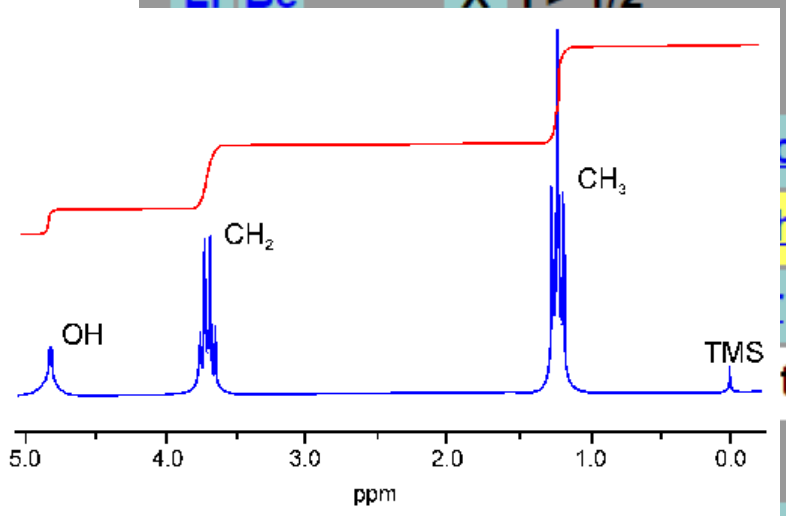
Nuclear Magnetic Resonance





Duer, M. J. *Introduction to Solid-State NMR Spectroscopy*; Blackwell Publishing Ltd: Oxford, 2004

Nuclear Magnetic Resonance



^{1}H NMR of Ethanol

900 MHz ⇒ 21.1 T

Periodic table of NMR active nuclei

National Ultrahigh-field NMR Facility for Solids. http://www.nmr900.ca/, Rider University NMR Facility, http://www-usr.rider.edu/~grushow/nmr/NMR_tutor/periodic_table/nmr_pt_frameset.html

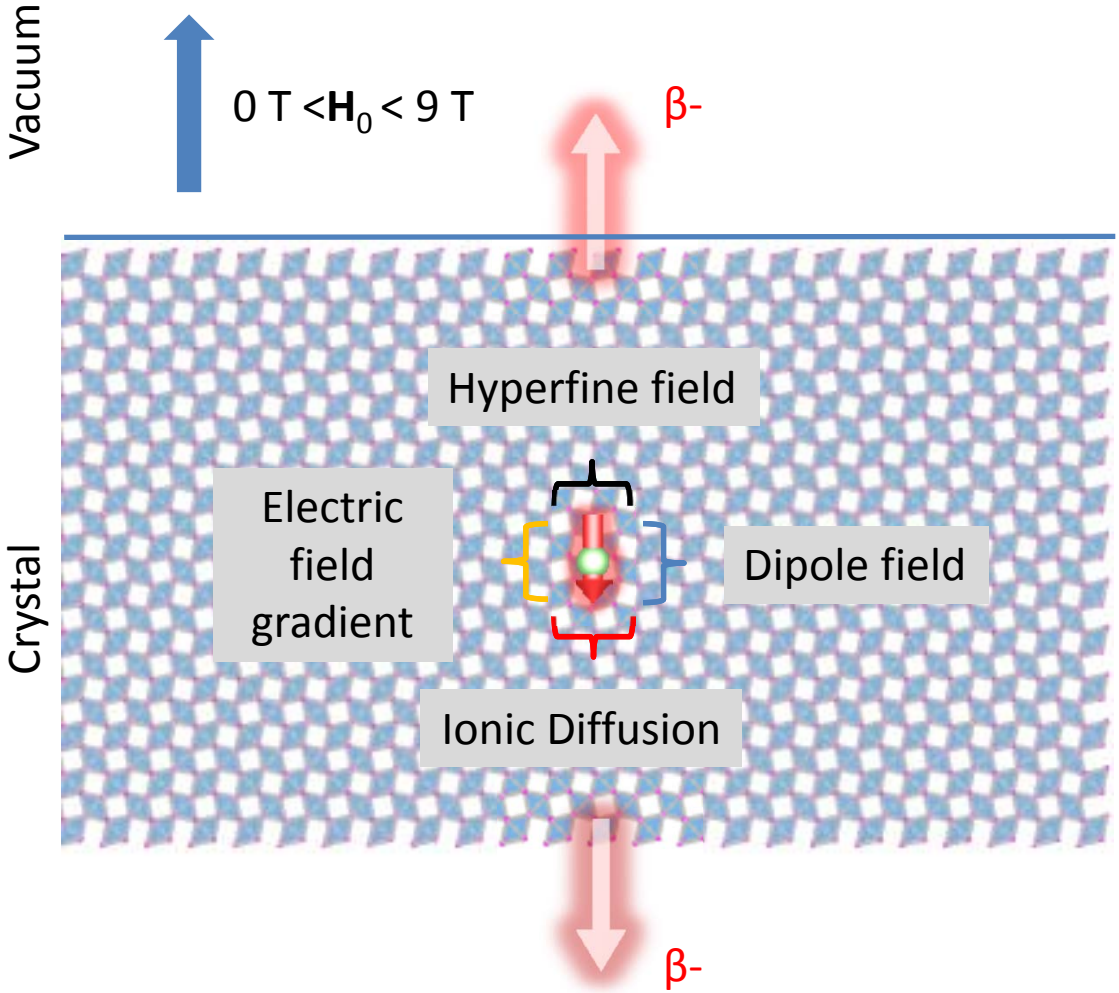
NMR vs. β-NMR

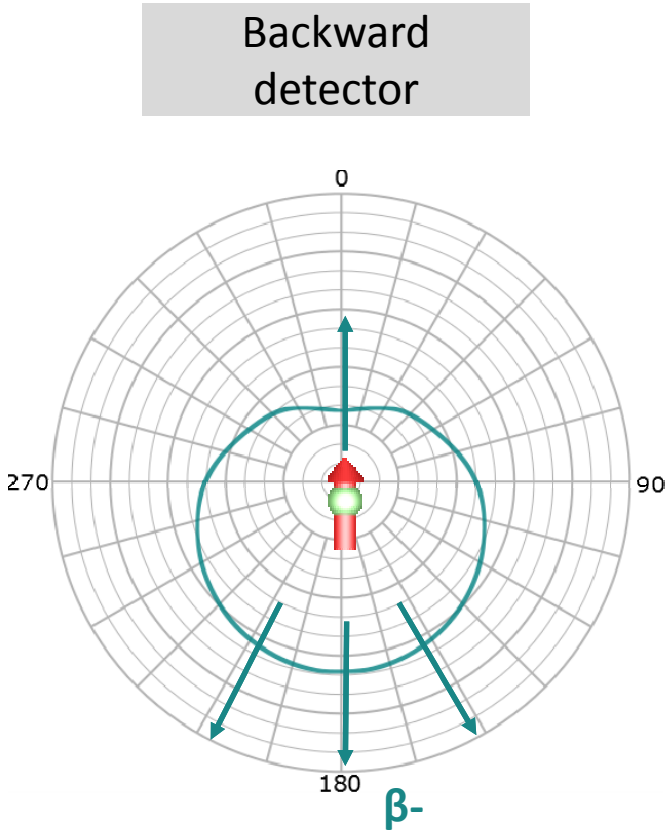
	NMR	β-NMR
Polarization	< 1%	>70%
Probing particle/nuclei	^{1}H, ^{13}C, ^{57}Fe, ^{17}O	$^{8}Li^{+}$, $^{9}Li^{+}$, $^{31}Mg^{+}$
Sensitivity	10^{17} spins	10^{4} spins
Detection Method	EM inductive decay	Anisotropic beta decay
$1/T_1$ range (s^{-1})	10^{-5} - 10^{2}	10^{-2} – 10^{2}
Resolution mechanism	Gradient fields (typically >> nm)	Ion beam implantation depth (1 – 100 nm)

$$^{8}_{3}\mathrm{Li} \rightarrow {}^{8}_{4}\mathrm{Be} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$$

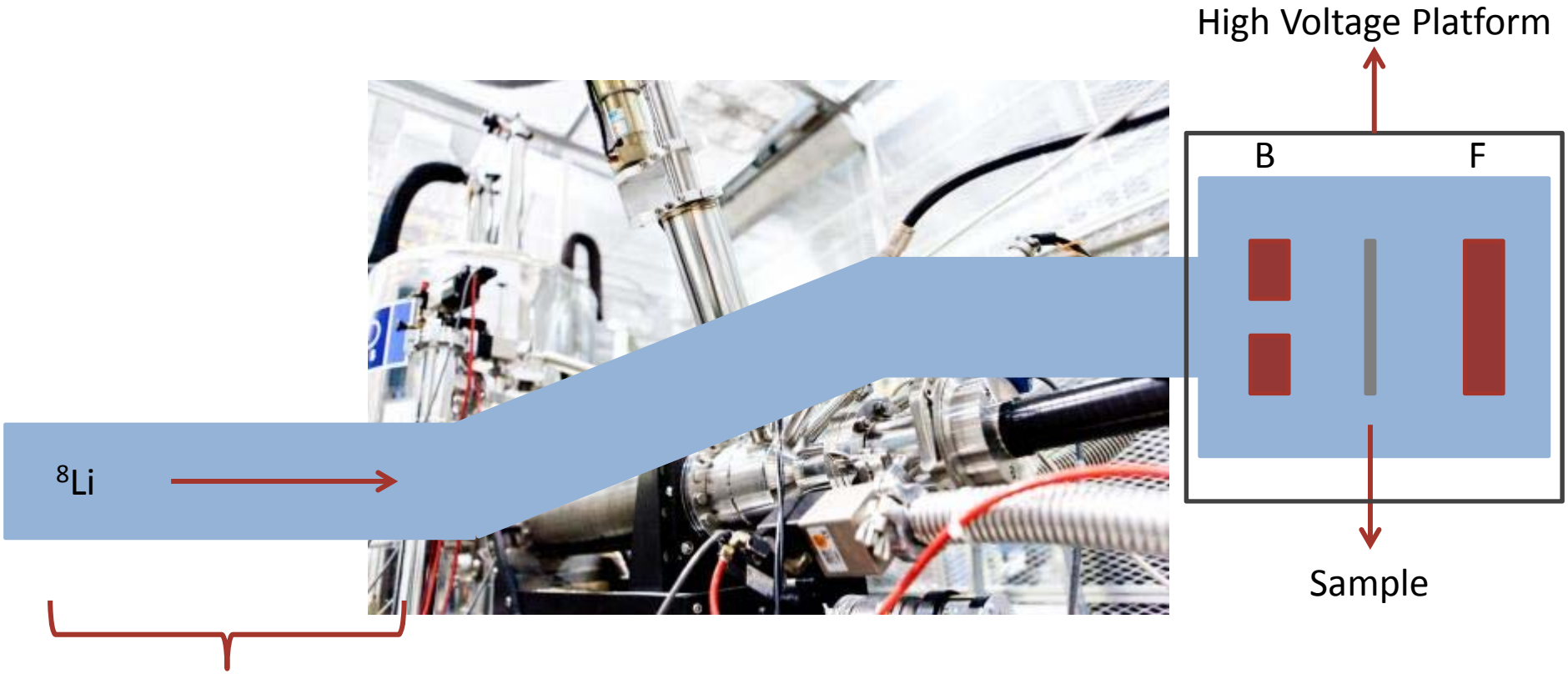
I=2, q=+31.4 mb , τ=1.21 s

β decay as a means of detection

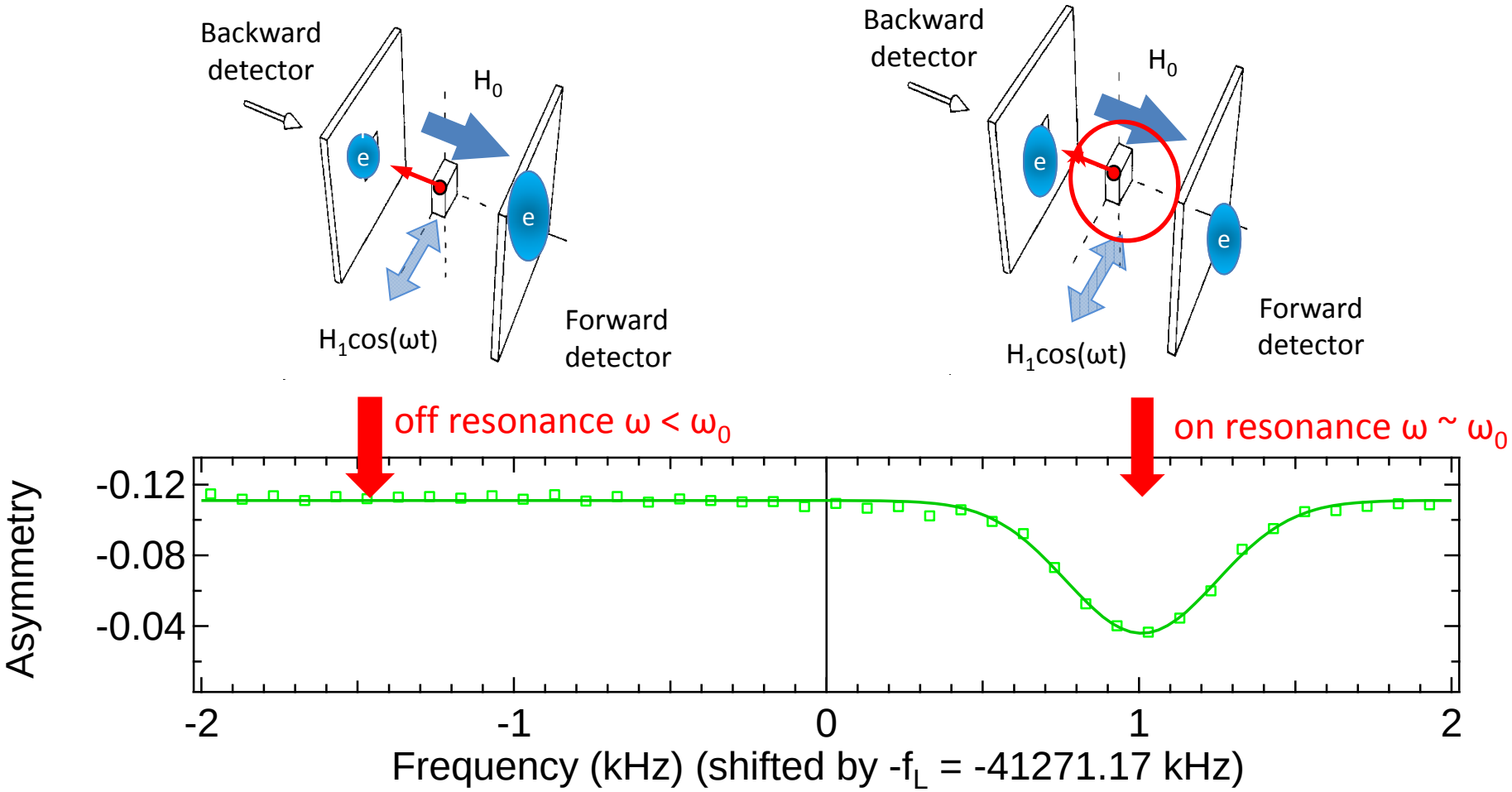




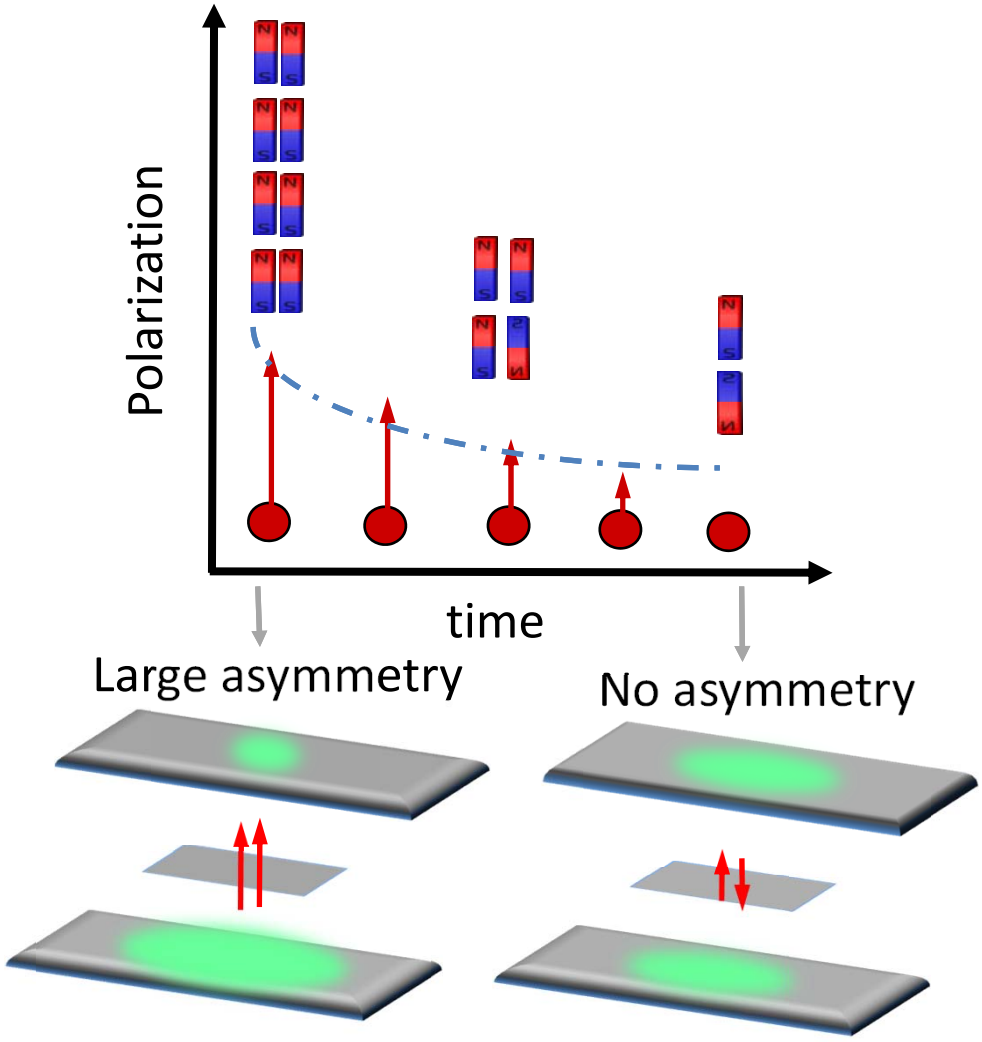
β-NMR Setup at TRIUMF

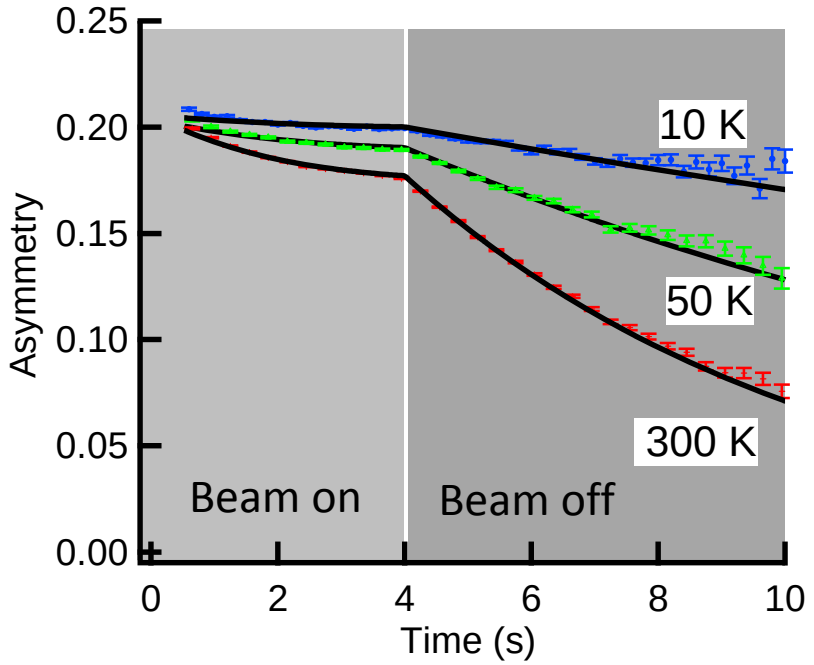


Continuous Wave Measurements



Pulsed Beam Measurements

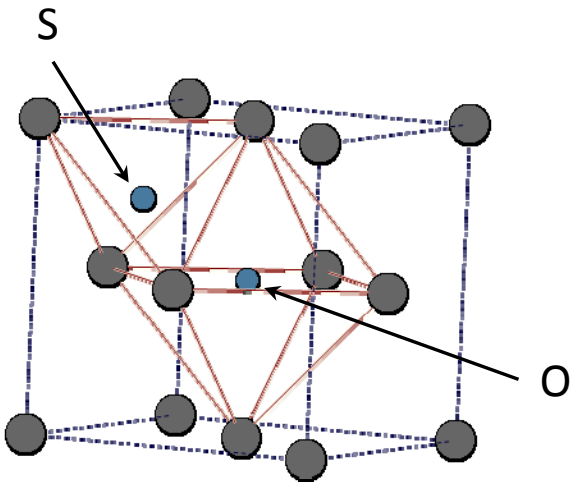


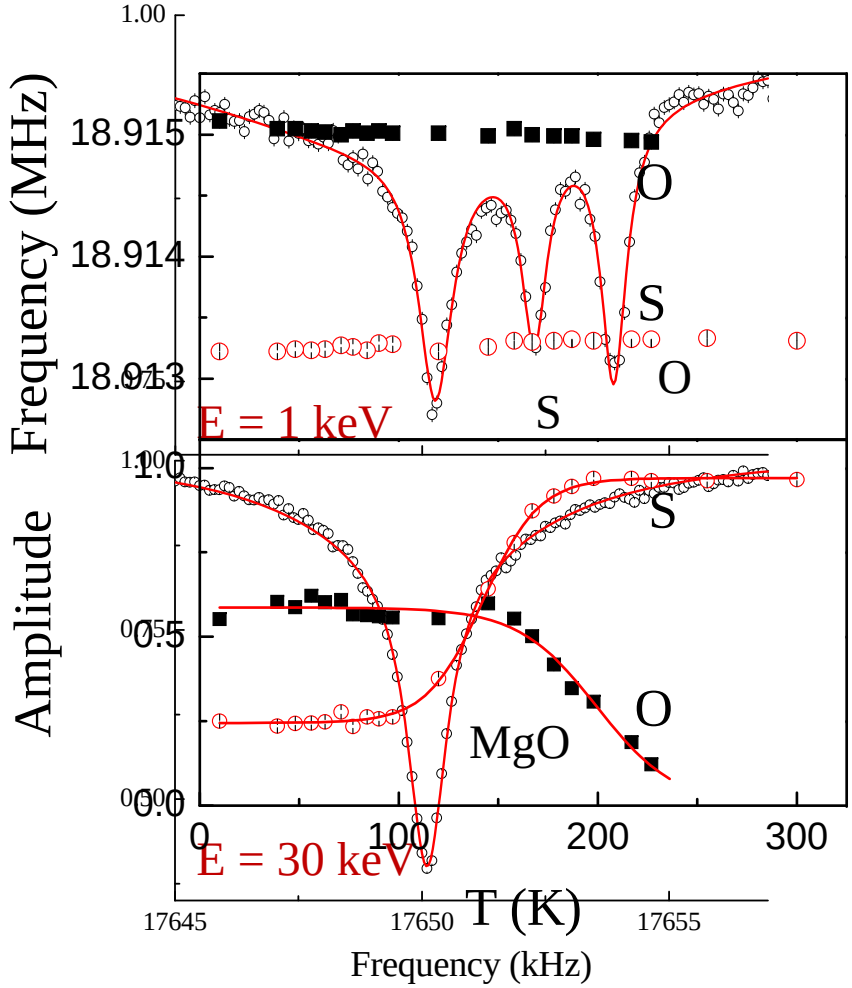


$$A = \frac{N_F - N_B}{N_F + N_B}$$

D. Cortie, *et al*. *Phys Rev B,* **91**, 241113 (2015)

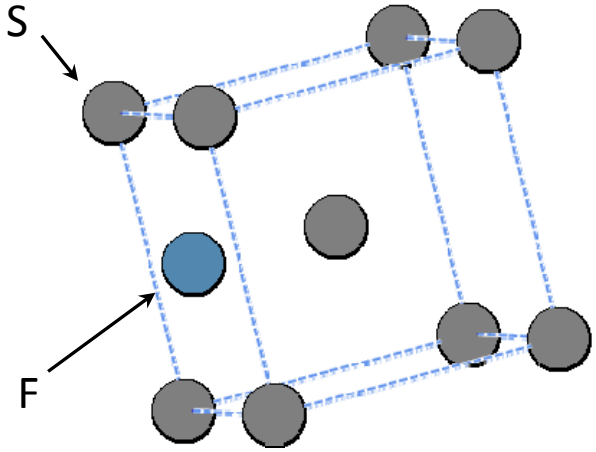
Example – Ag/MgO

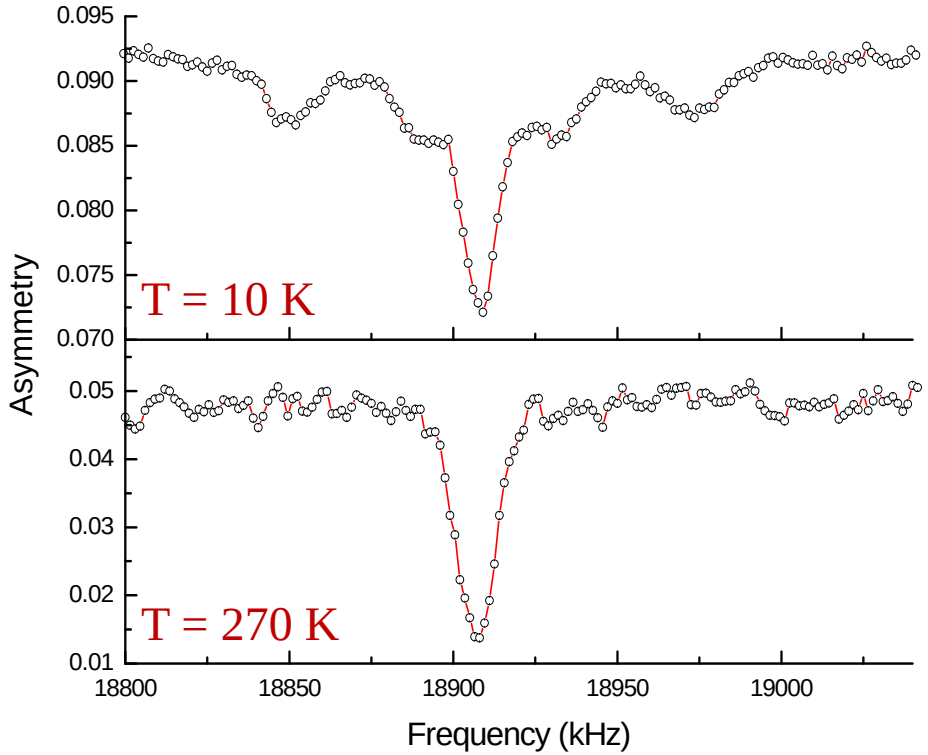




G.D. Morris, *et al*. *Phys Rev Lett,* **93**, 157601 (2004)

Example – Nb film

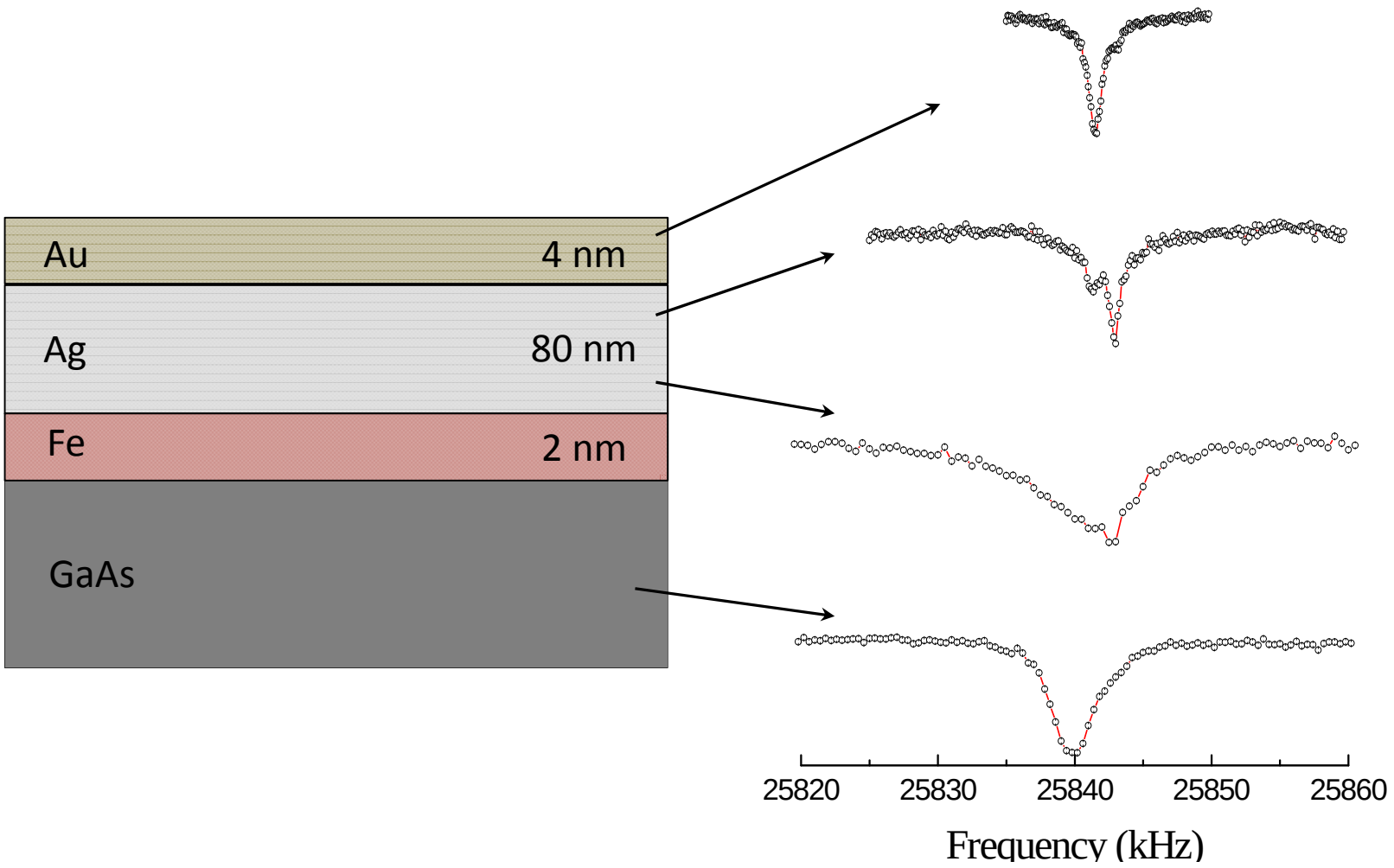




$$\mathcal{H} = -\gamma\hbar H_0 I_{z'} + \frac{e^2 qQ}{4I(2I-1)}(3I_z{}^2 - I^2) \neq 0$$

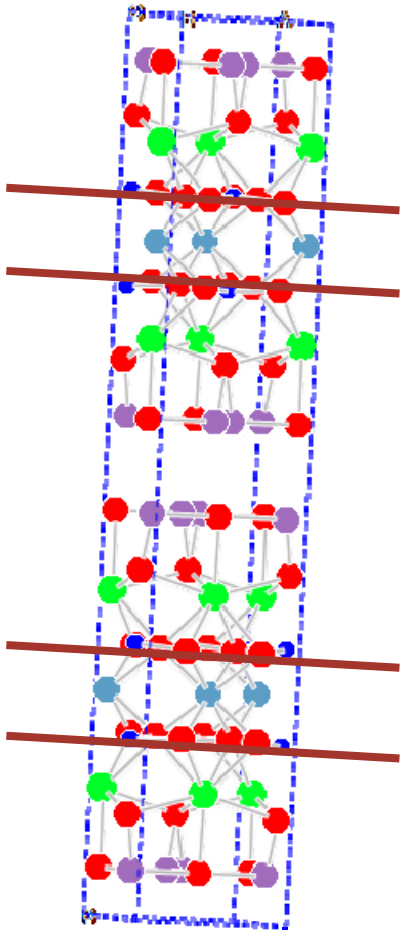
T. Parolin, *et al*. *Phys Rev B,* **80**, 174109 (2009)

Example – Ag/Fe Heterostructures

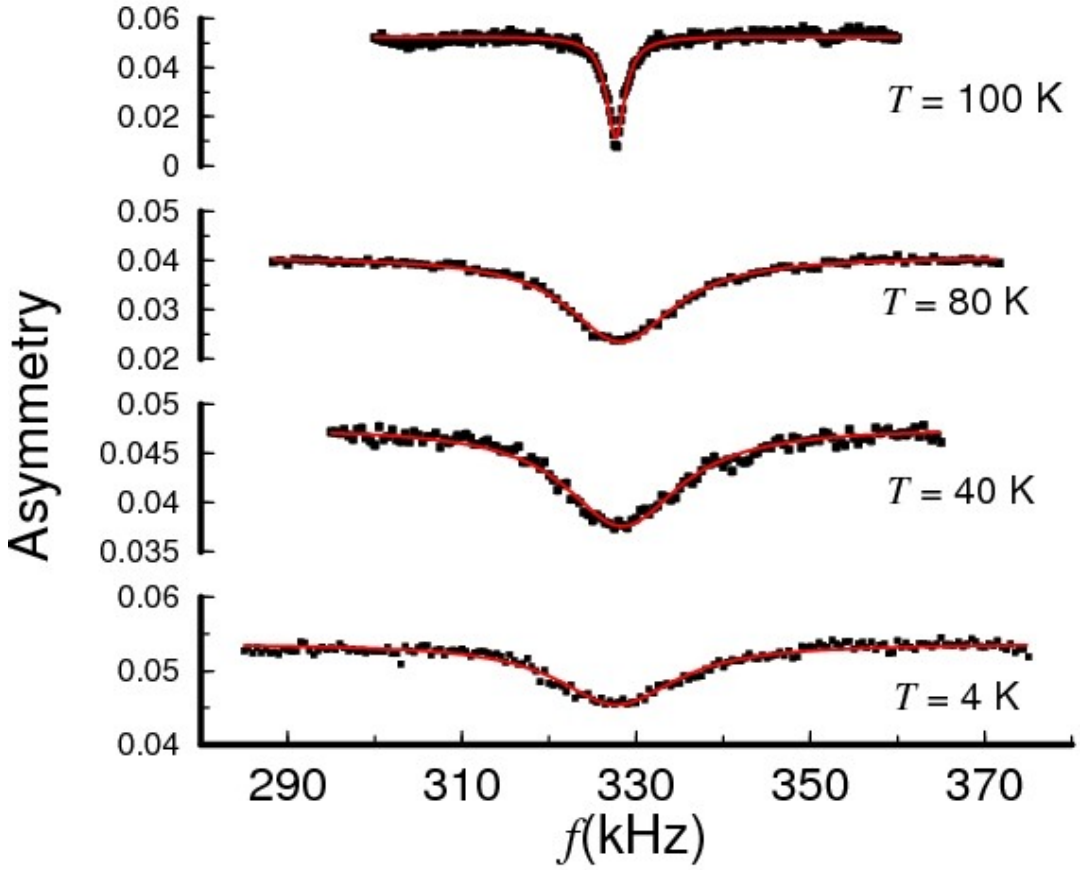


T.A. Keeler, *et al*. *Physica B,* **374-375**, 79 (2006)

Example – $YBa_2Cu_3O_7$



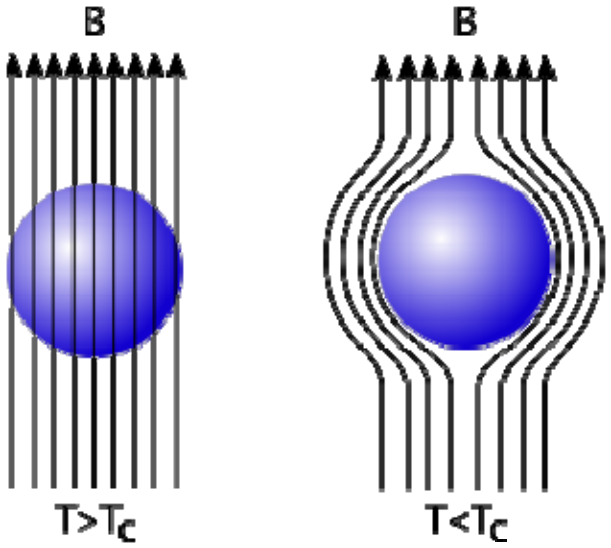
T_c = 92.5 K

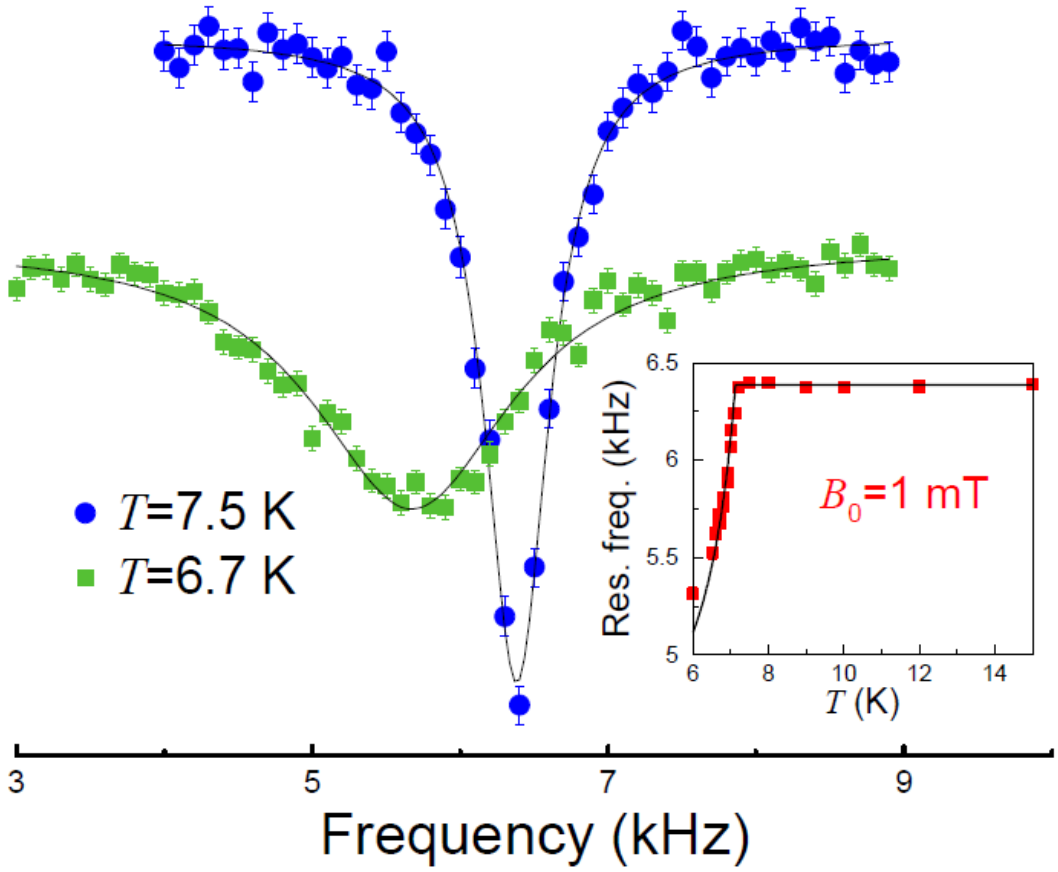


H. Saadoui, *et al*. *Phys Rev B,* **80**, 224503 (2009)

Example – Pb film

Evidence of the Meissner effect above T_c



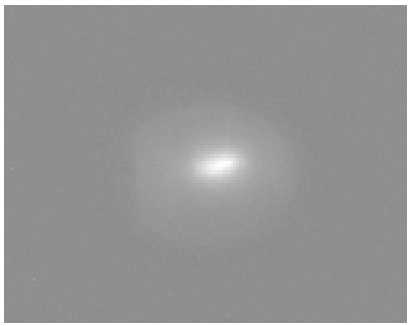


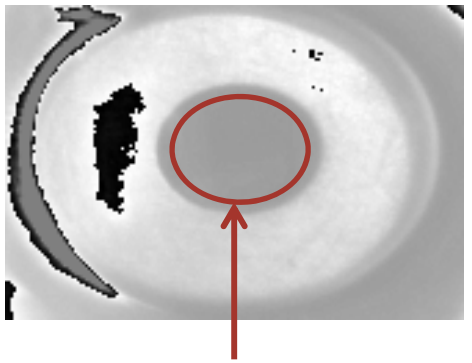
E. Morenzoni, *et al*. *Phys Rev B,* **85**, 220501 (2012)

Challenges

- Backscattering
- Depth profile
  - Accuracy of TRIM
  - Channeling effects
- $^{8}Li^{+}$ in a magnetic field
  - Not a simple trajectory

Beamspot





Size of sample

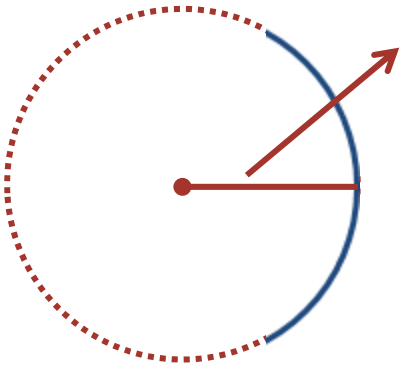
8 x 10 mm^2

Radius of Curvature

$$R = \frac{mv}{qB}$$

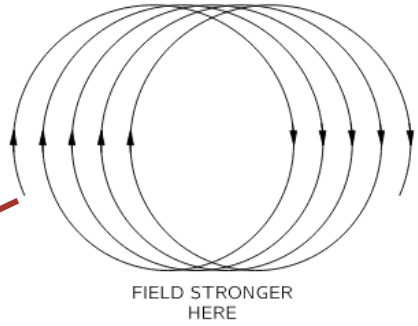
20 keV ^{8}Li vs. 6 MeV electron in a 9 T field

Radius of curvature (R)

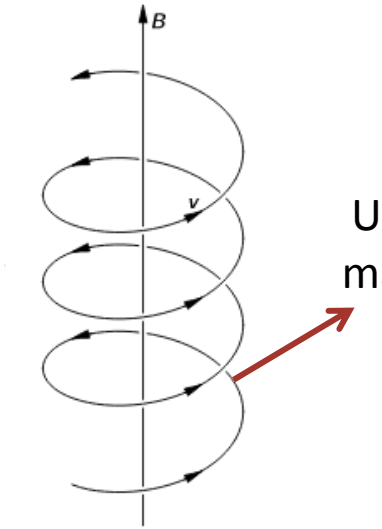


$R(^{8}Li)$ = 6.4 mm

$R(e^{-})$ = 0.92 mm



Non-uniform magnetic field



Uniform magnetic field

Conclusions

- β-NMR is a technique capable of studying various materials and phenomena
  - Superconductors
  - Polymers
  - Heterostructures
- Currently there are challenges associated with very low energy measurements (< 1 keV)

Acknowledgements

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