HFI/NQI 2010, Sep 15, 2010

beta detected NMR: a new depth-resolved probe of materials at the nanoscale

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TRIUMF

Downtown
Vancouver

Whistler

123 km

UBC
2 km

Outline

1. TRIUMF βNMR/βNQR facility
2. Why use βNMR to study materials ?
3. A few examples:
    a. magnetic proximity effects in metals
    b. spin injection, dilute magnetic semiconductors
    c. interface properties of high Tc superconductors

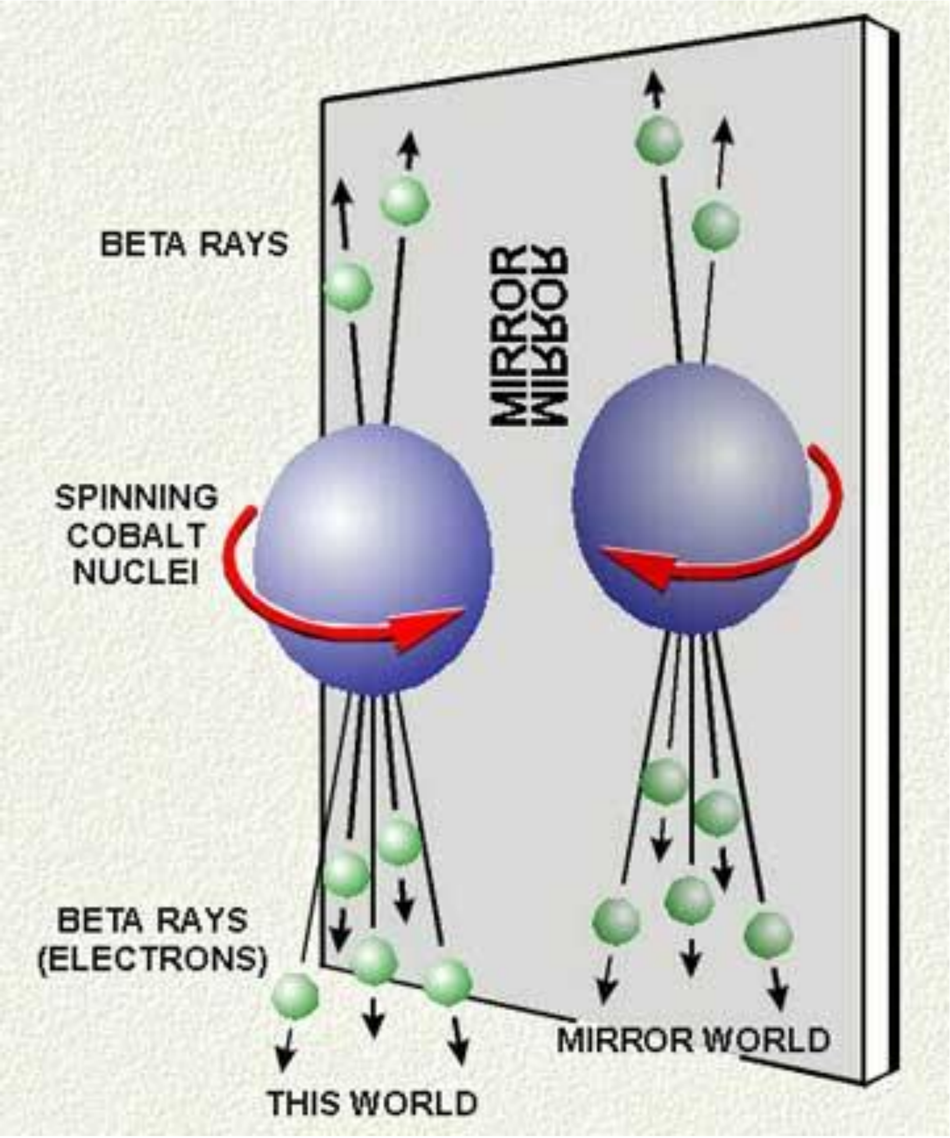
1. The βNMR Method

Parity Violation

ß emission is correlated with the spin direction of the decaying nucleus,

violating mirror symmetry

Lee and Yang 1957



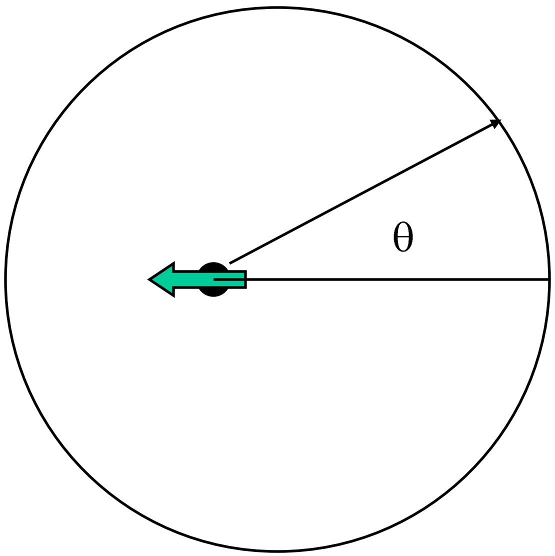
Asymmetric Nuclear β–decay of ^{8}Li

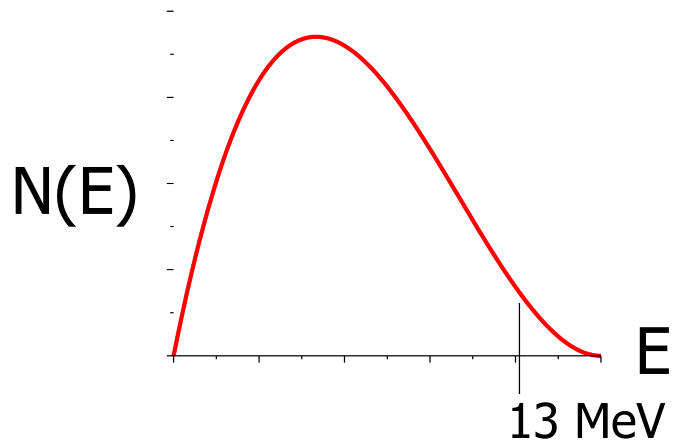
$$^{8}\mathrm{Li} \rightarrow {}^{8}\mathrm{Be} + e^{-} + \nu_e$$

Spin=2, Q=+31 mb

γ =6.3 MHz/T

$\langle A \rangle = -1/3$ τ= 1.2s





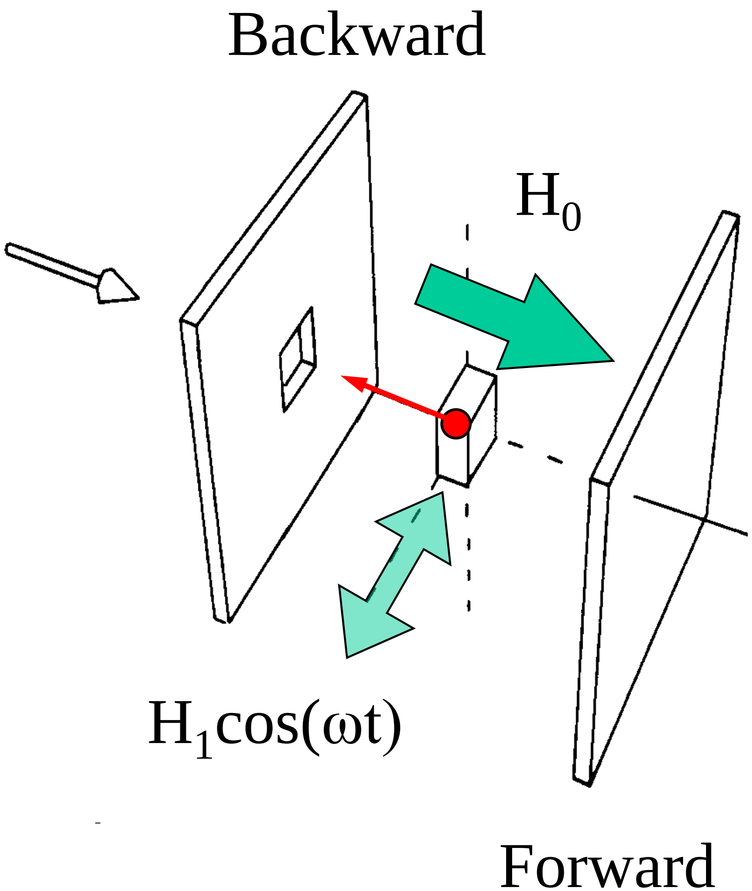
Polar plot representing the beta emission probability as a function of angle

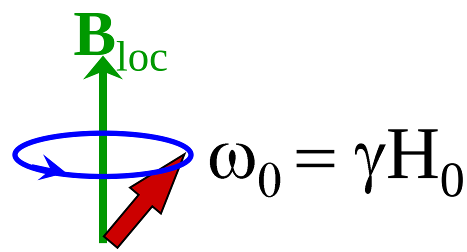
Isotopes for βNMR at ISAC

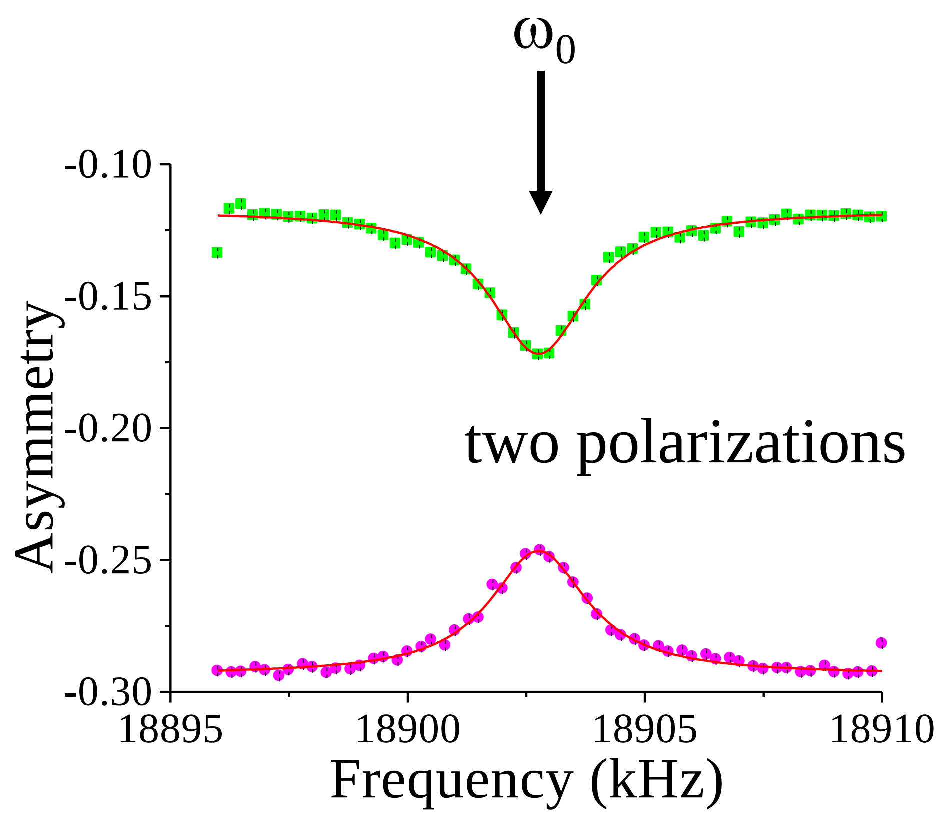
Isotope	Spin	$\tau_{1/2}$	γ (MHz/T)	β-Decay Asymmetry	Estimated Rate (s^{-1})
^{8}Li	2	0.8	6.3	0.33	10^{8}
^{11}Be	1/2	13.8	22	~0.3	10^{7}
^{15}O	1/2	122	10.8	0.66	10^{8}
^{19}O	5/2	26.9	4.6	0.71	10^{8}
^{17}Ne	1/2	0.1		0.33	10^{6}

require: light, short-lived,
high asymmetry

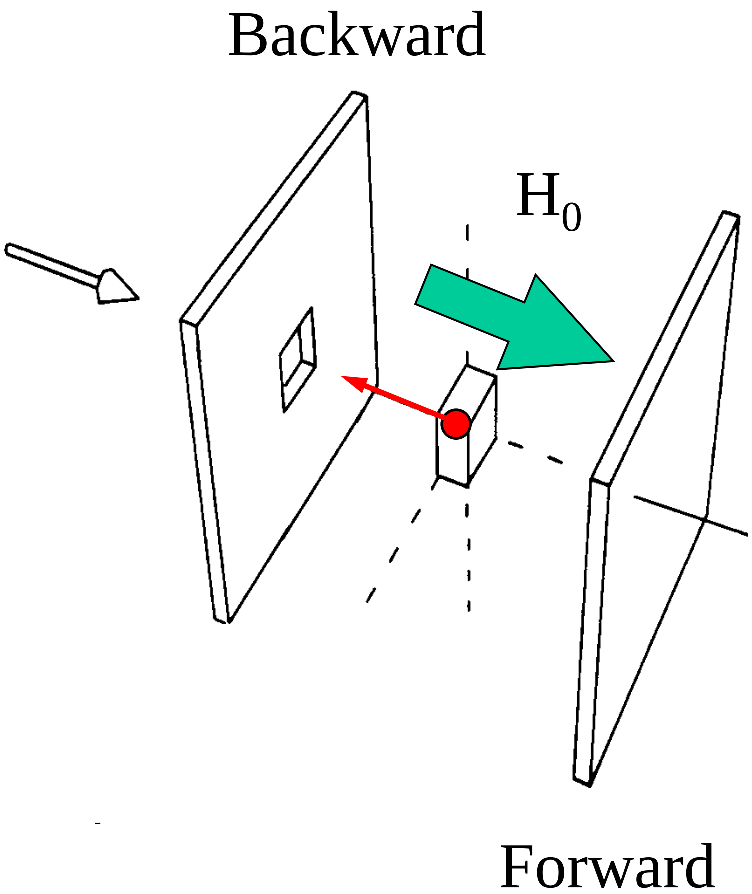
βNMResonance

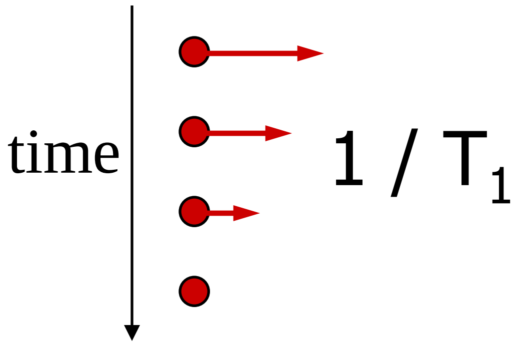






βNMR Measurement of the Spin Lattice Relaxation Rate

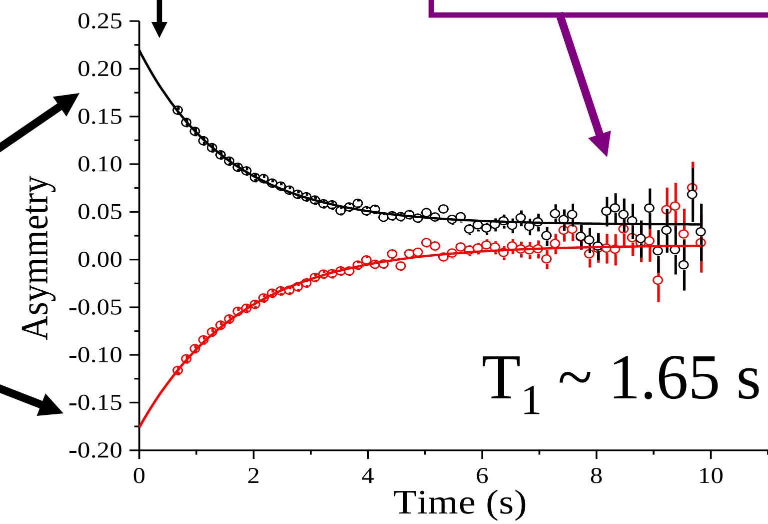




Pd Foil
T = 293 K
B_0 ~ 140 G
E_{Li} = 30 keV

Beam on
For 0.5s

nb: error bars grow as exp(t/τ)



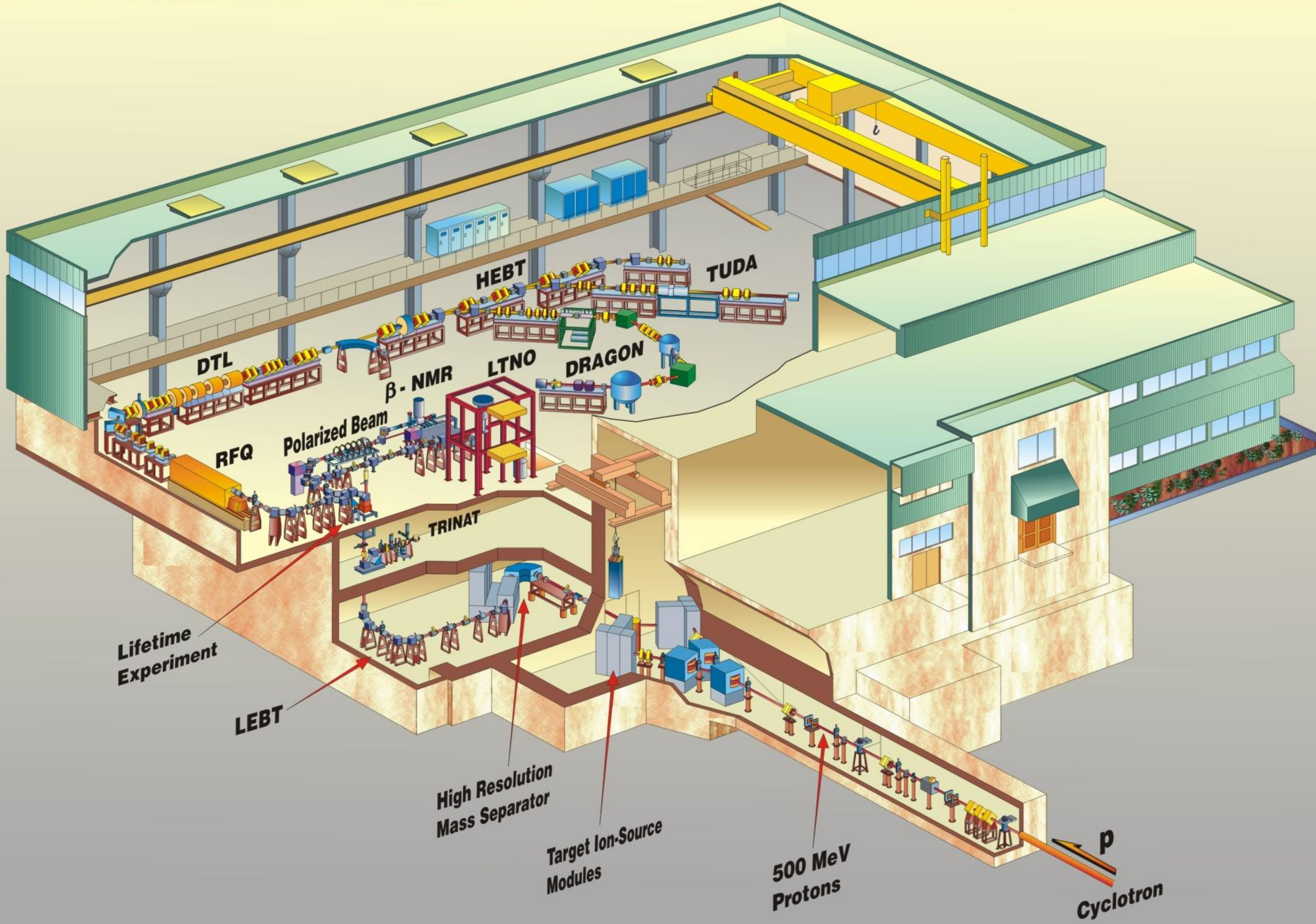
data for the
two polarizations

TRIUMF Implementation

see

βNMR: Morris et al., Phys. Rev. Lett. **93**, 157601 (2004).
βNQR: Salman et al., Phys. Rev. B **70**, 104404 (2004).
facility: Kiefl et al., Physica B **326**, 189 (2003).
polarizer: Levy et al., NIMB **204**, 689 (2003).

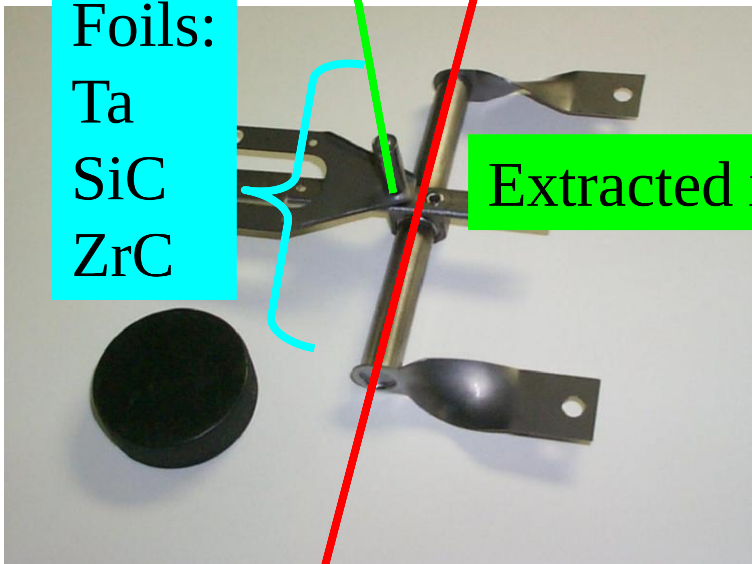
ISAC at TRIUMF



ISAC Production Target

M. Dombsky/TRIUMF

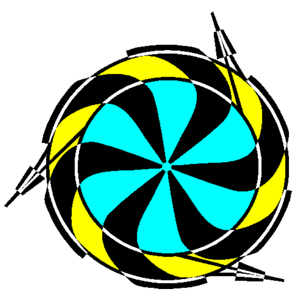
Foils:
Ta
SiC
ZrC

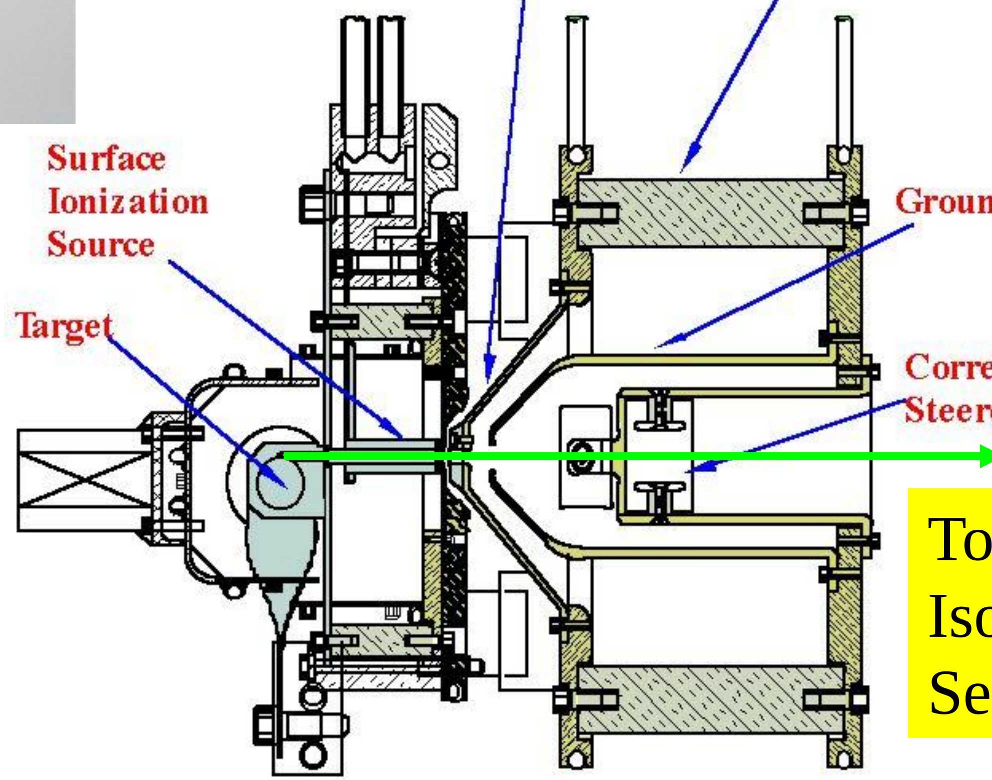


Extracted ion beam ~30 keV

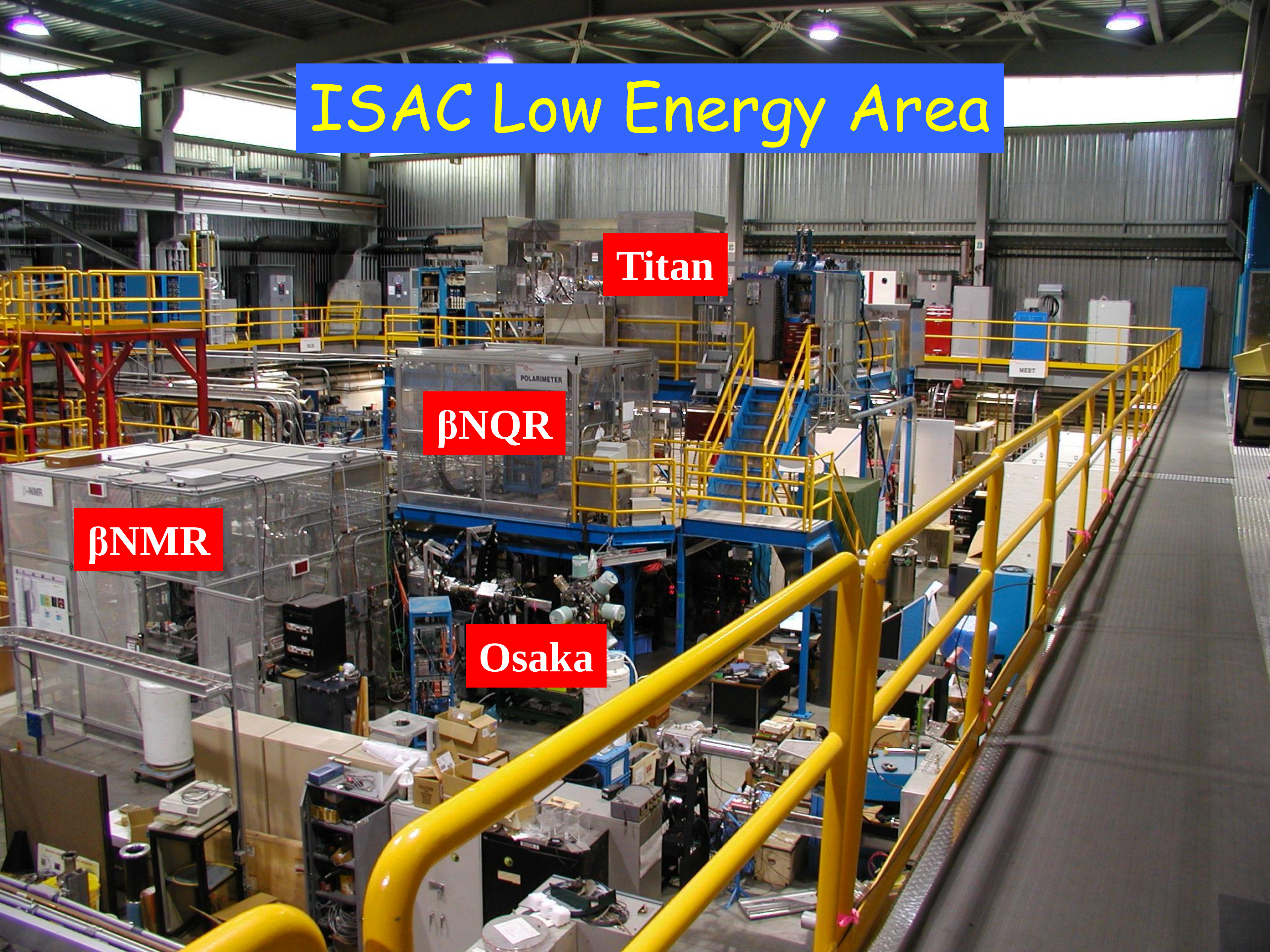
for Li^+: surface ionization

500 MeV
Proton Beam

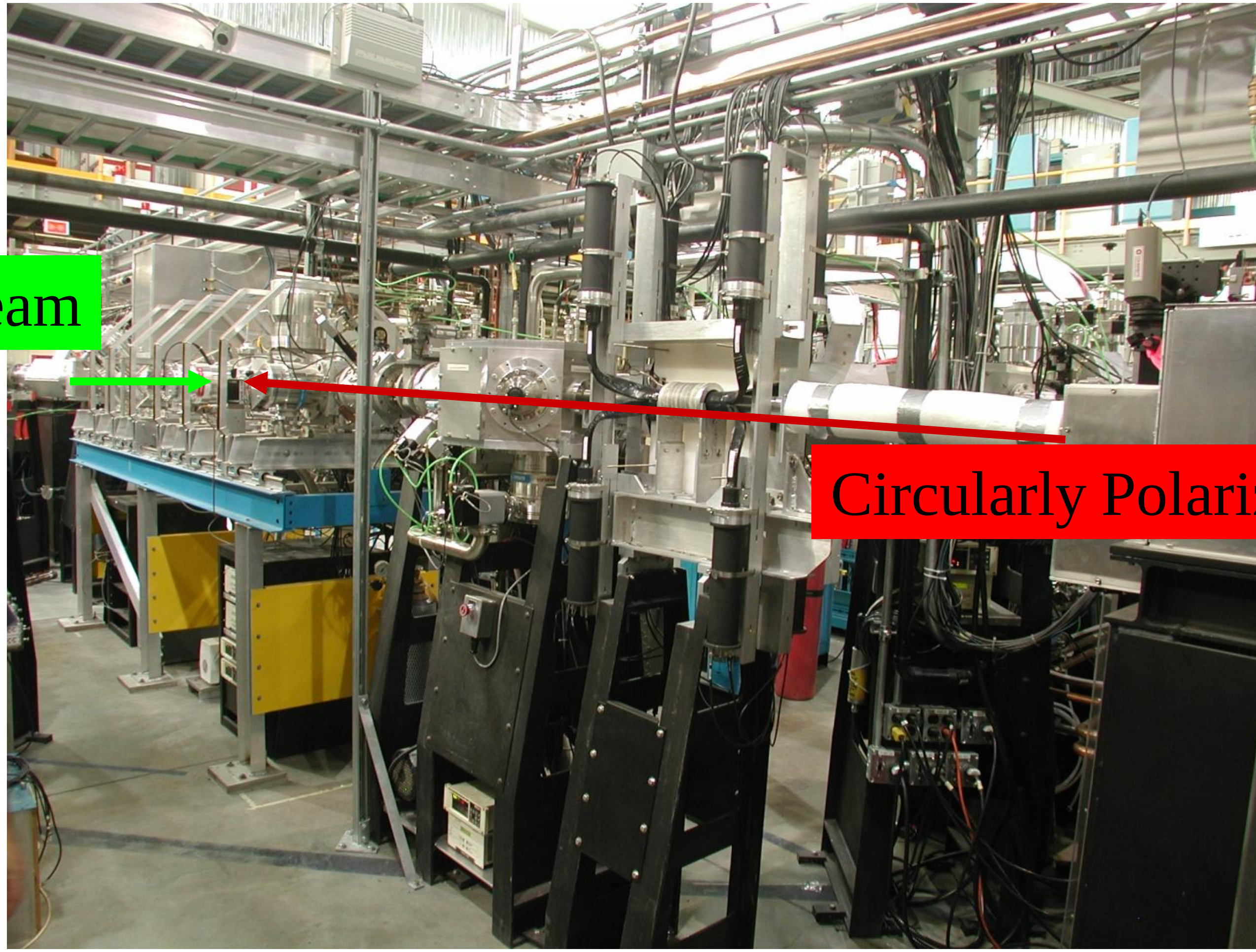




To Isotope Separator

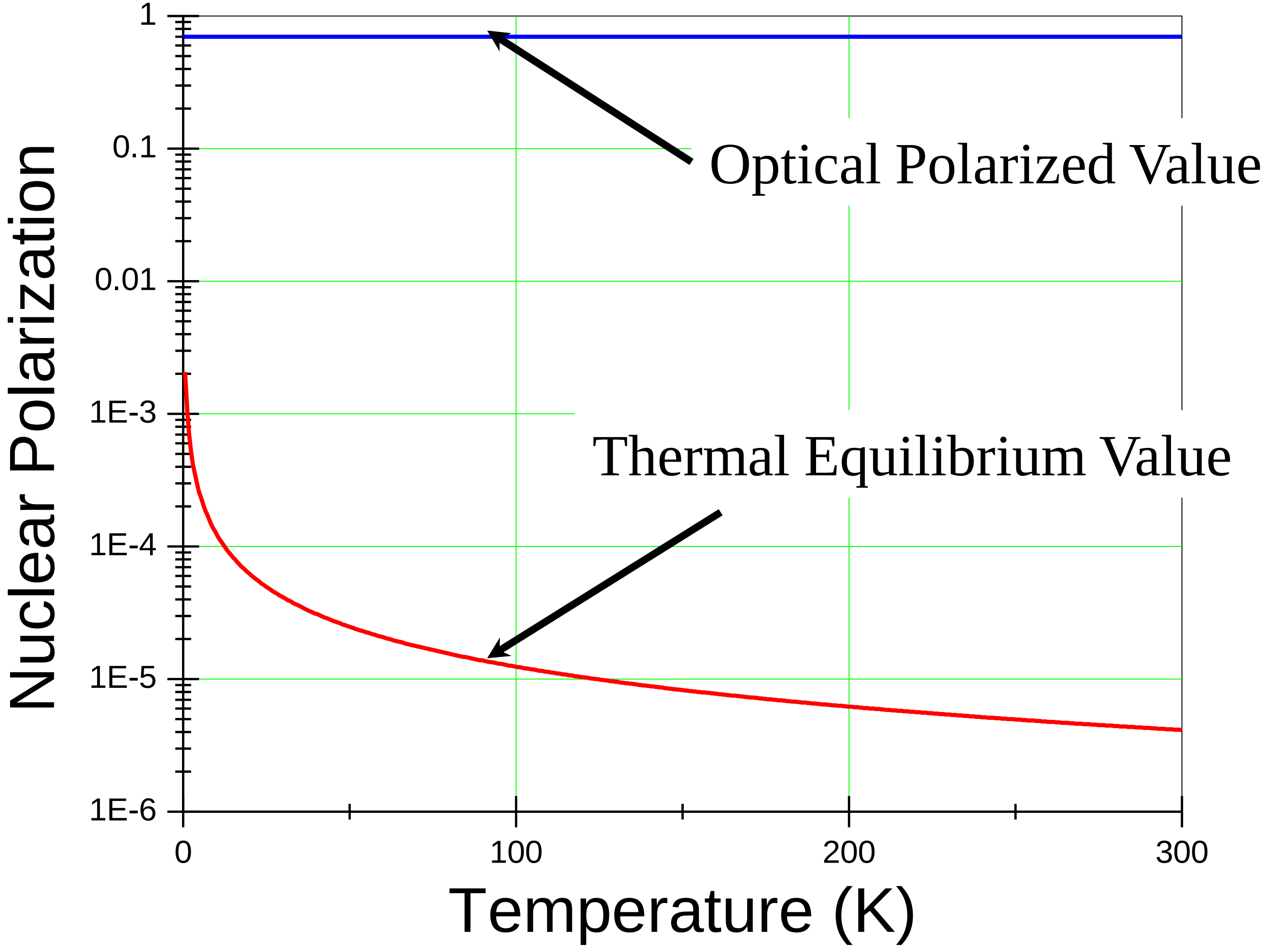

ISAC Low Energy Area
Titan
POLARIMETER
βNQR
βNMR
Osaka

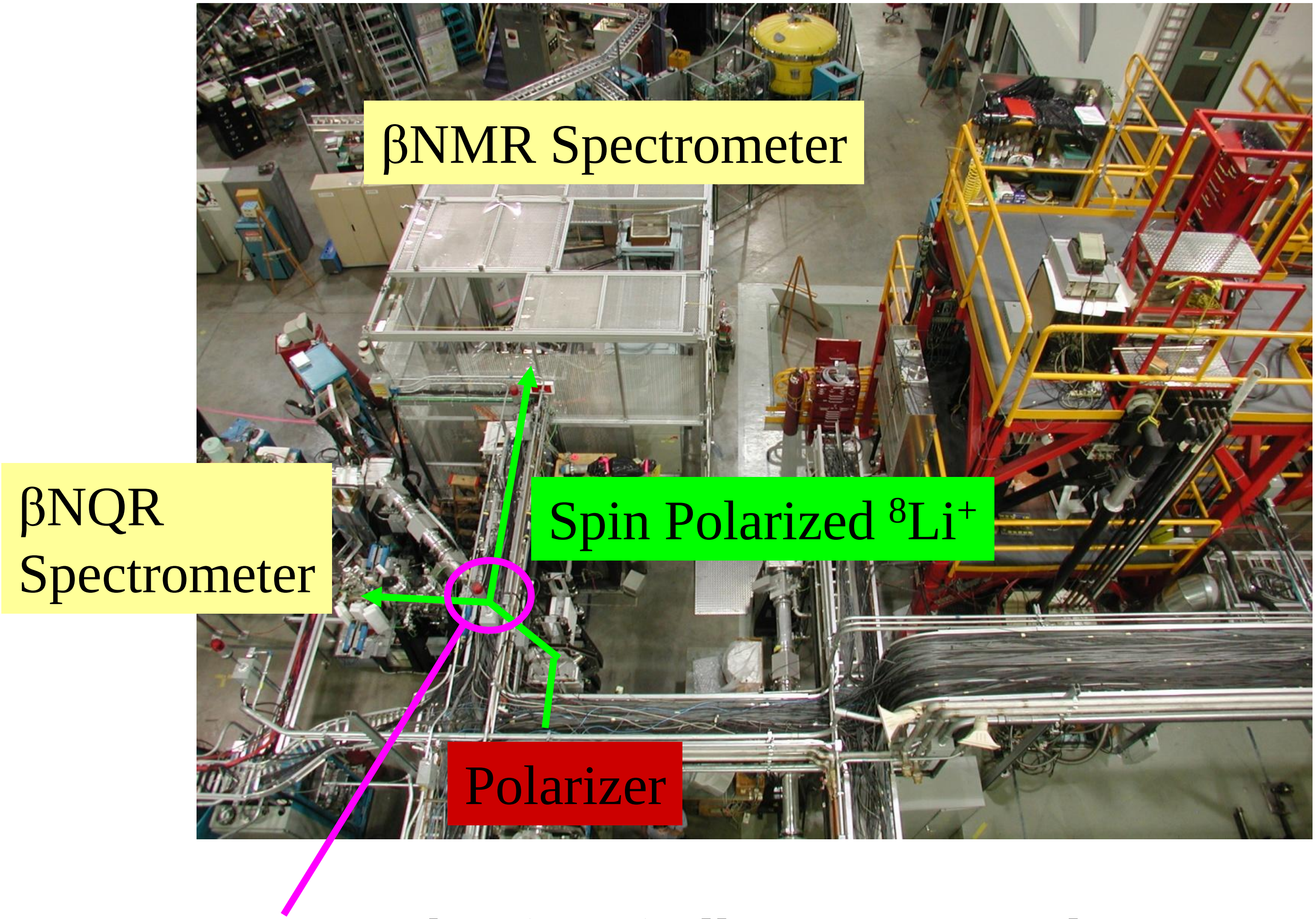
Optical Polarizer



D1 in Li: 671 nm

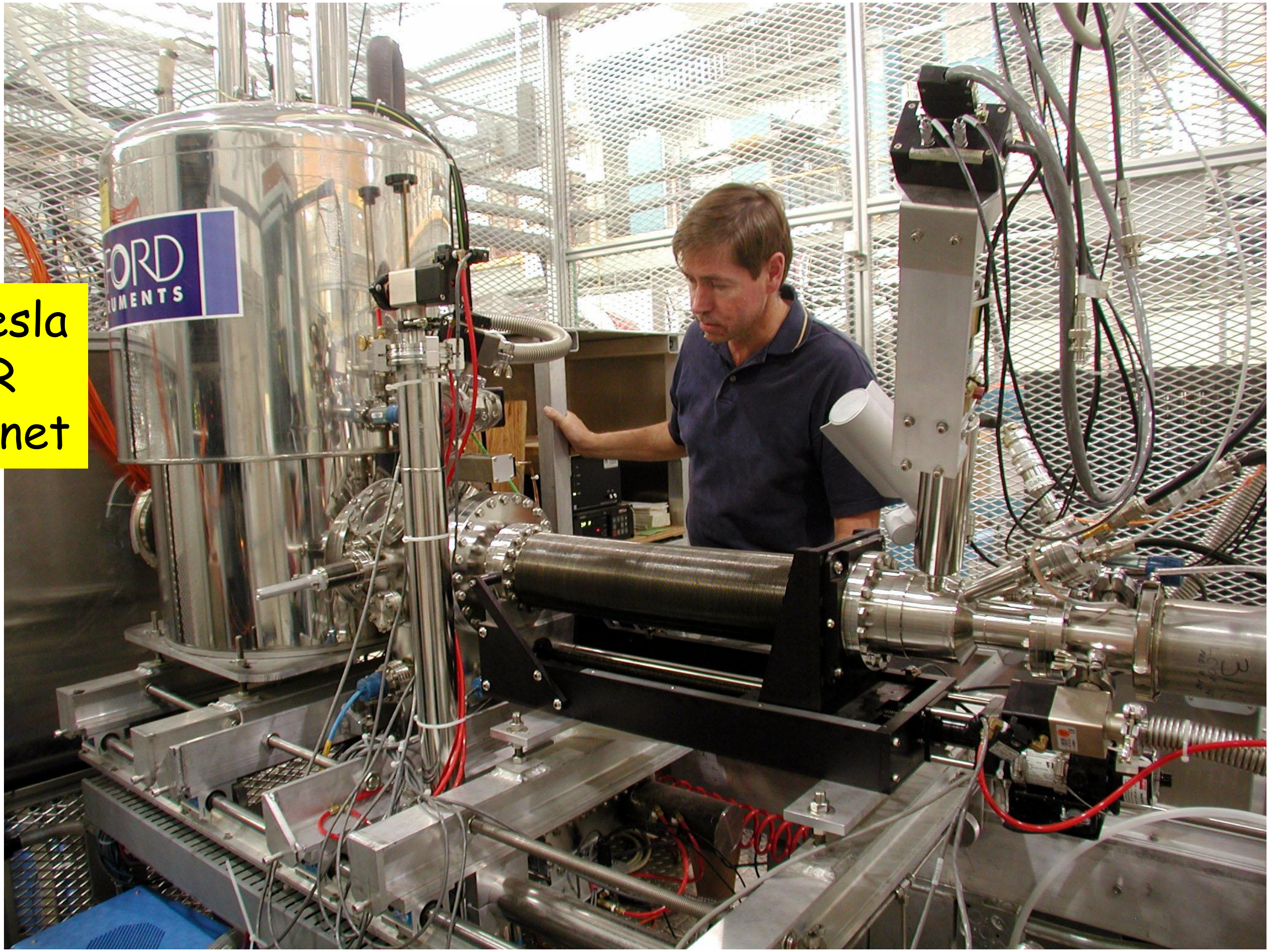
Polarization of ^{8}Li Nuclei in 4.1 T





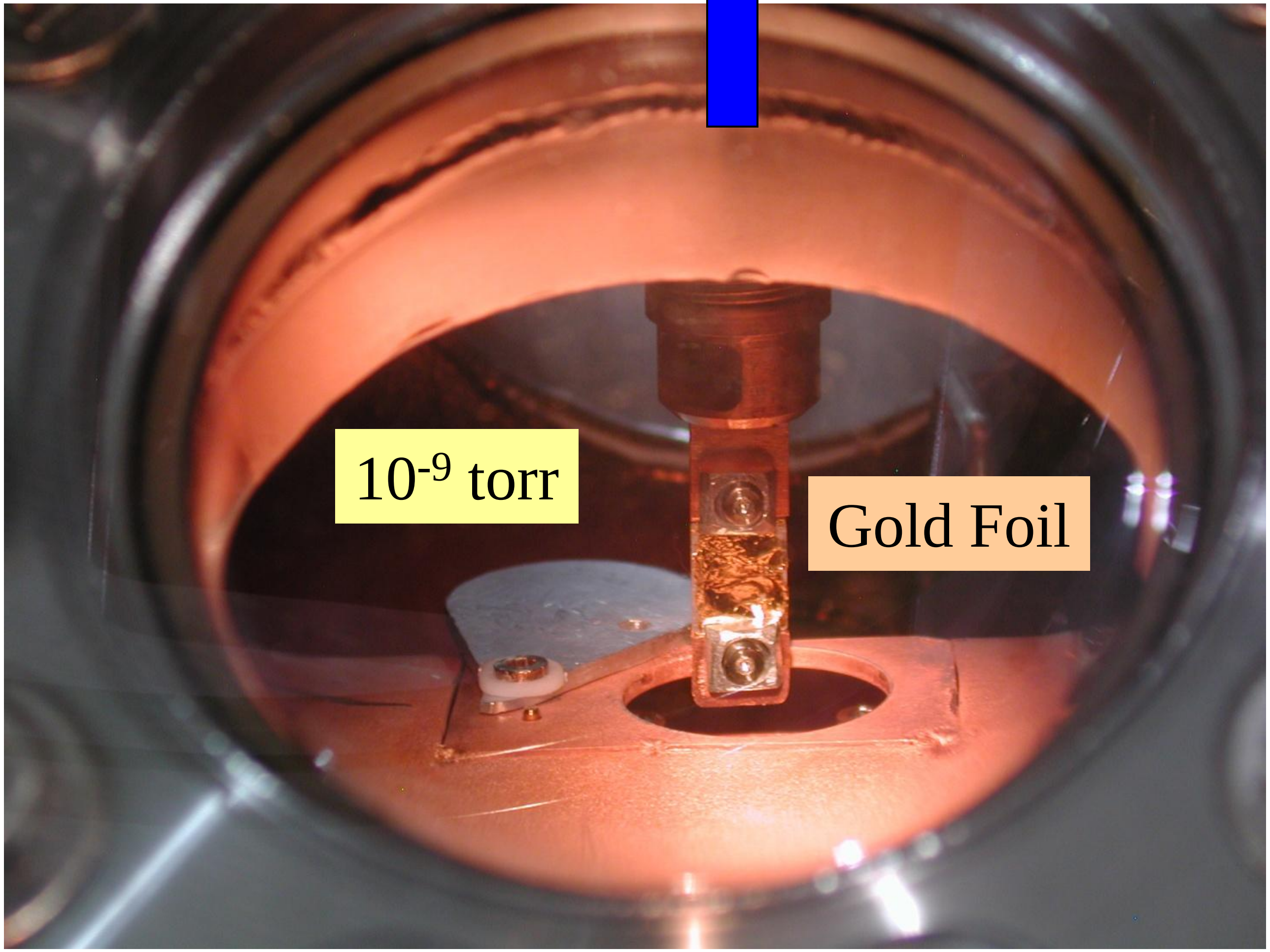
Fast Kicker (2005) allows semi-simultaneous operation

βNMR Spectrometer



9 Tesla
NMR
Magnet

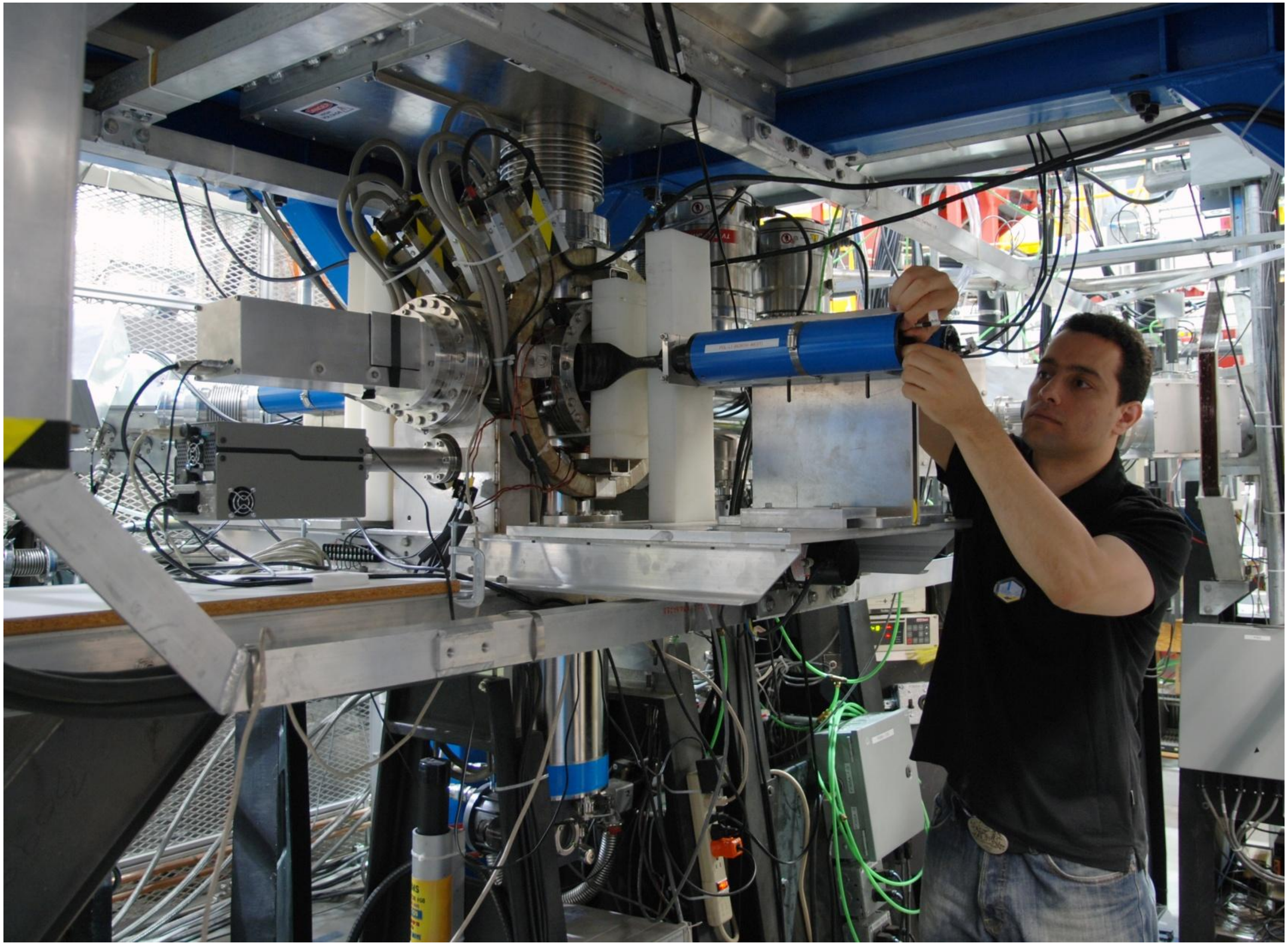
Loading a sample into the high-field βNMR spectrometer



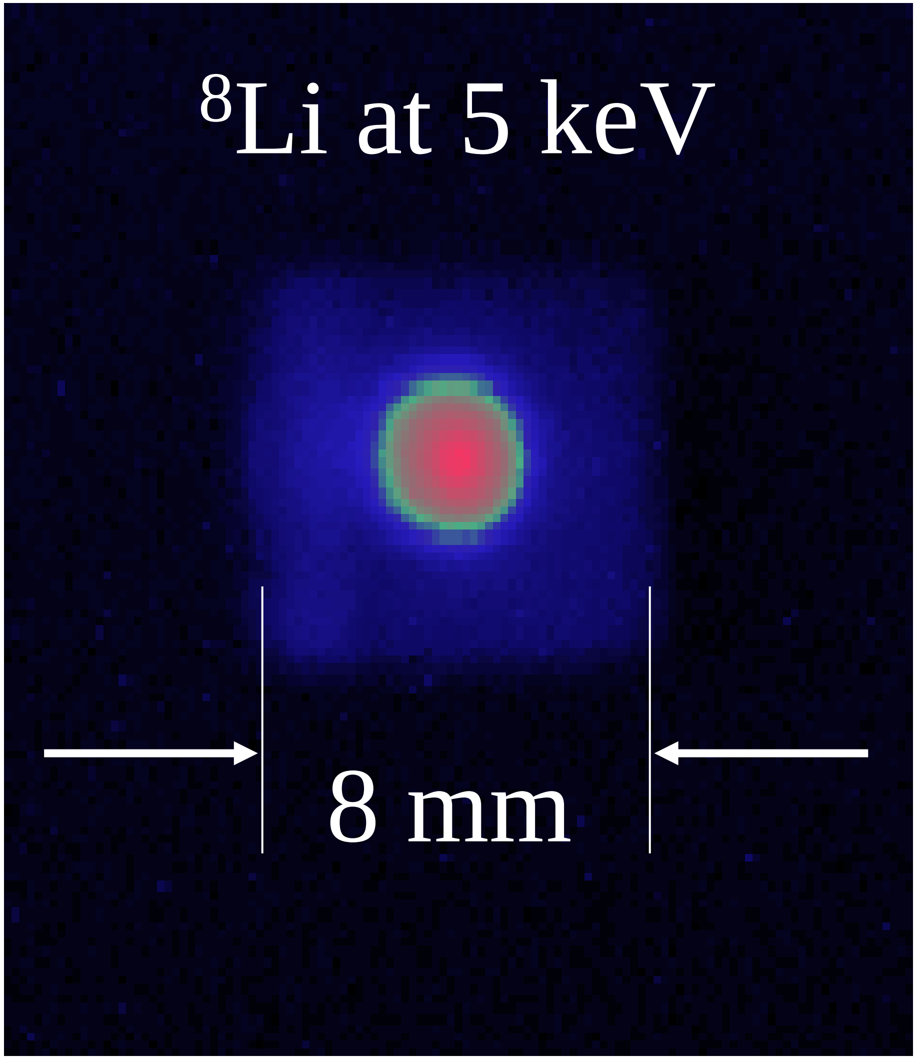
Hapke/TRIUMF

Cryostat drives into solenoid bore (9 Tesla)

βNQR Spectrometer



beam stopped
in scintillator,
imaged with CCD



Typical rate: ~10^6 spin polarized $^{8}Li^{+}$ per second

βNQR sample ladder

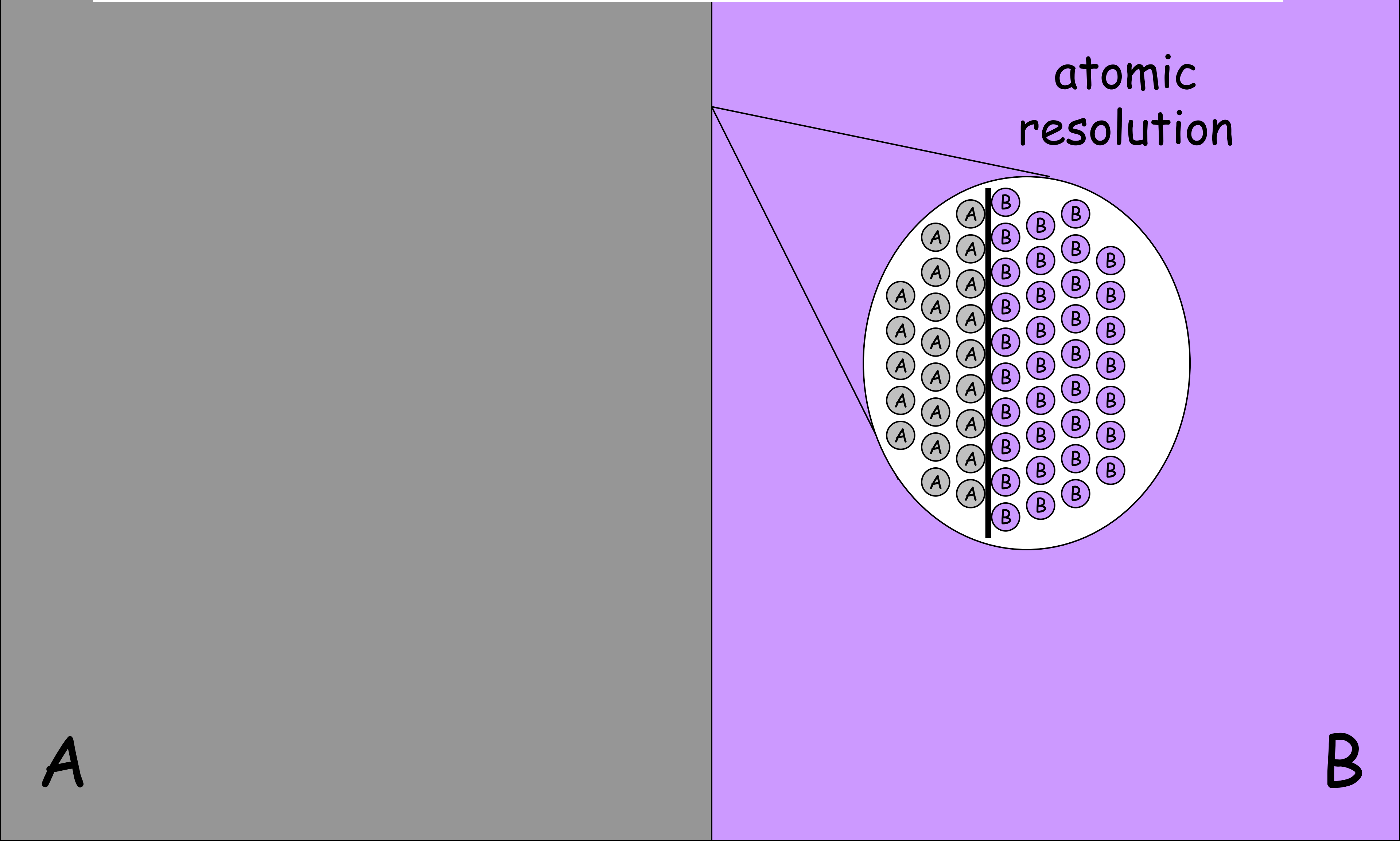
βNMR Cleanroom

Uses:
- Sample handling
- UHV cryostat maintenance

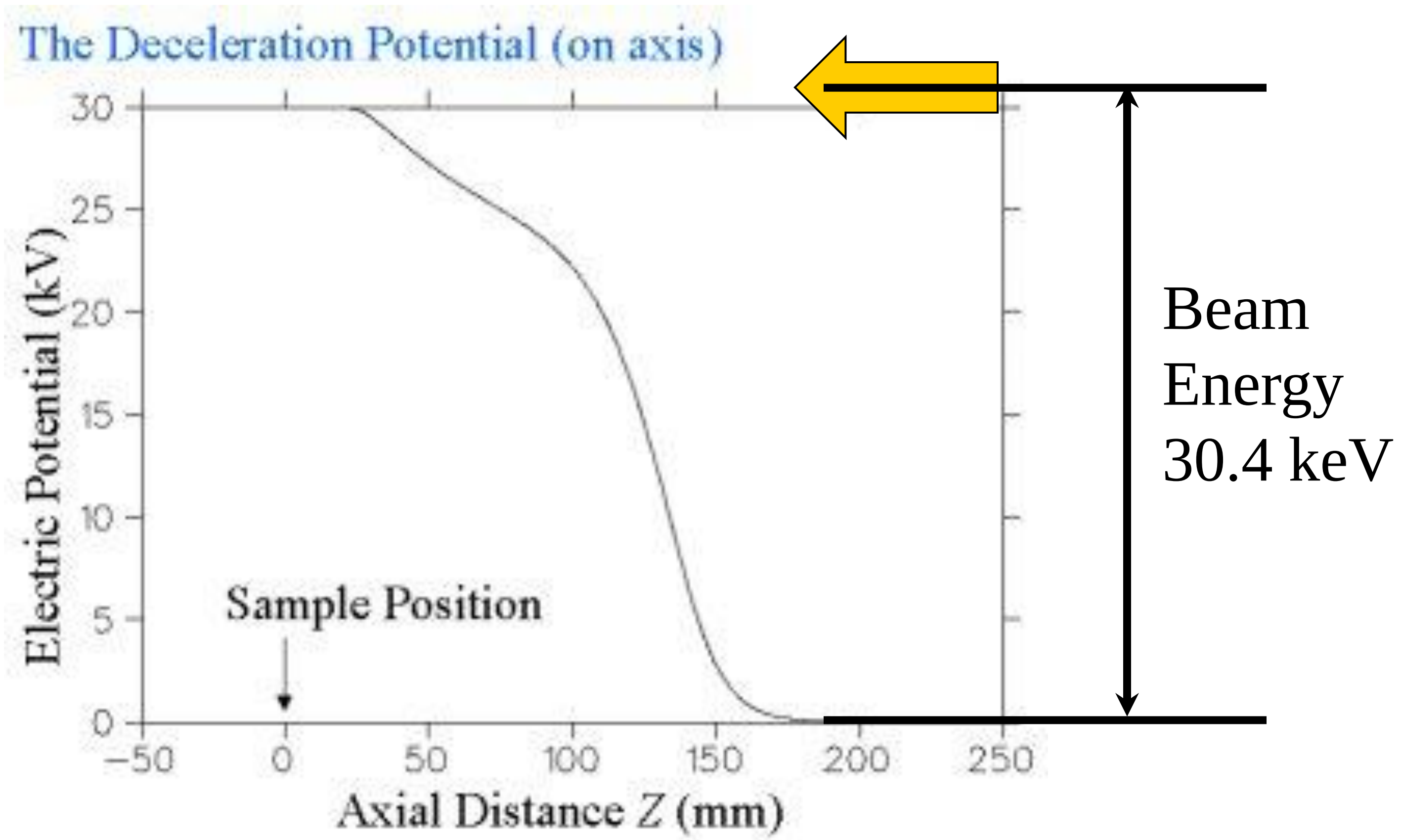
R. Abasalti

2. Why use βNMR to study materials?

Solid Interfaces



Deceleration of the Ion Beam



range in the probe ions: depth resolution!

Relation to Fundamental Properties

$$M = \chi H$$

Magnetic Susceptibility

$$\chi = \chi' - i\chi''$$

Shift: $\delta = A\chi'(0,0)$ ← can be multicomponent and/or inhomogeneous

Relaxation:

$$\frac{1}{T_1} \propto kT \sum_{\vec{q}} A^2(\vec{q}) \frac{\chi''_\perp(\vec{q},\omega_0)}{\omega_0}$$

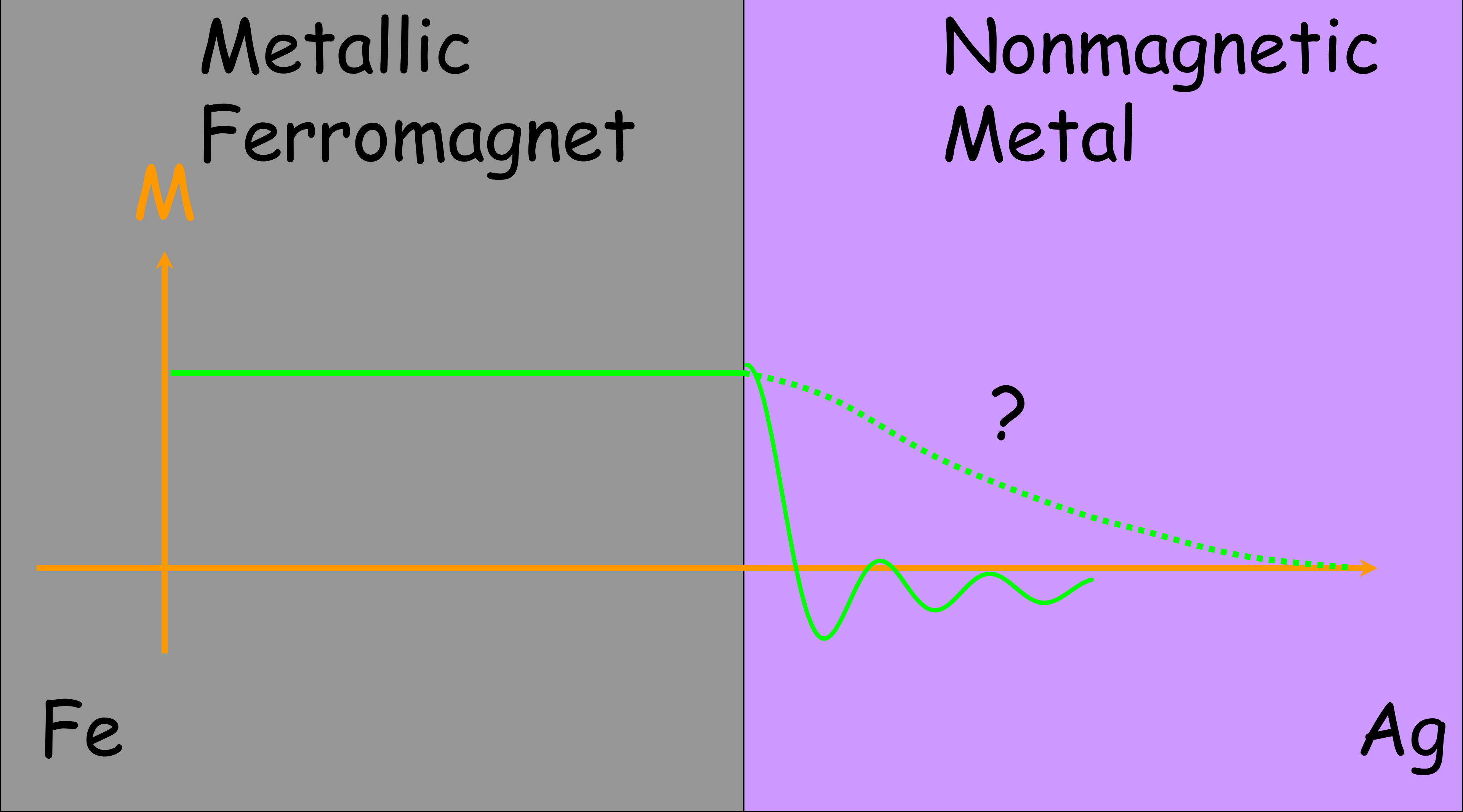
Moriya Expression

In the RF (μeV to zero)

also: quadrupolar effects, diamagnetic shielding, ...

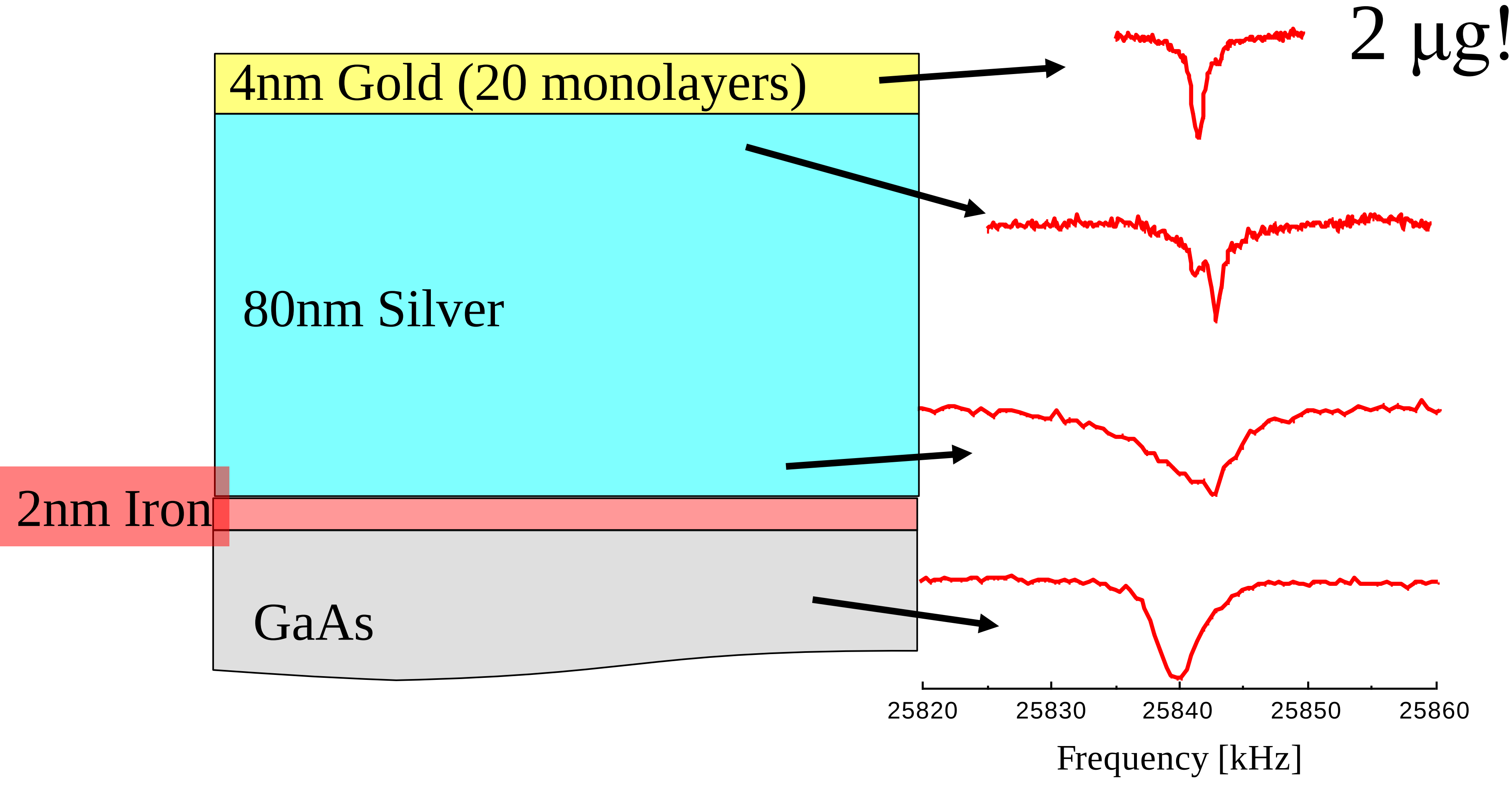
3. Examples

Magnetic Proximity Effect



Depth Resolved βNMR in Magnetic Multilayers

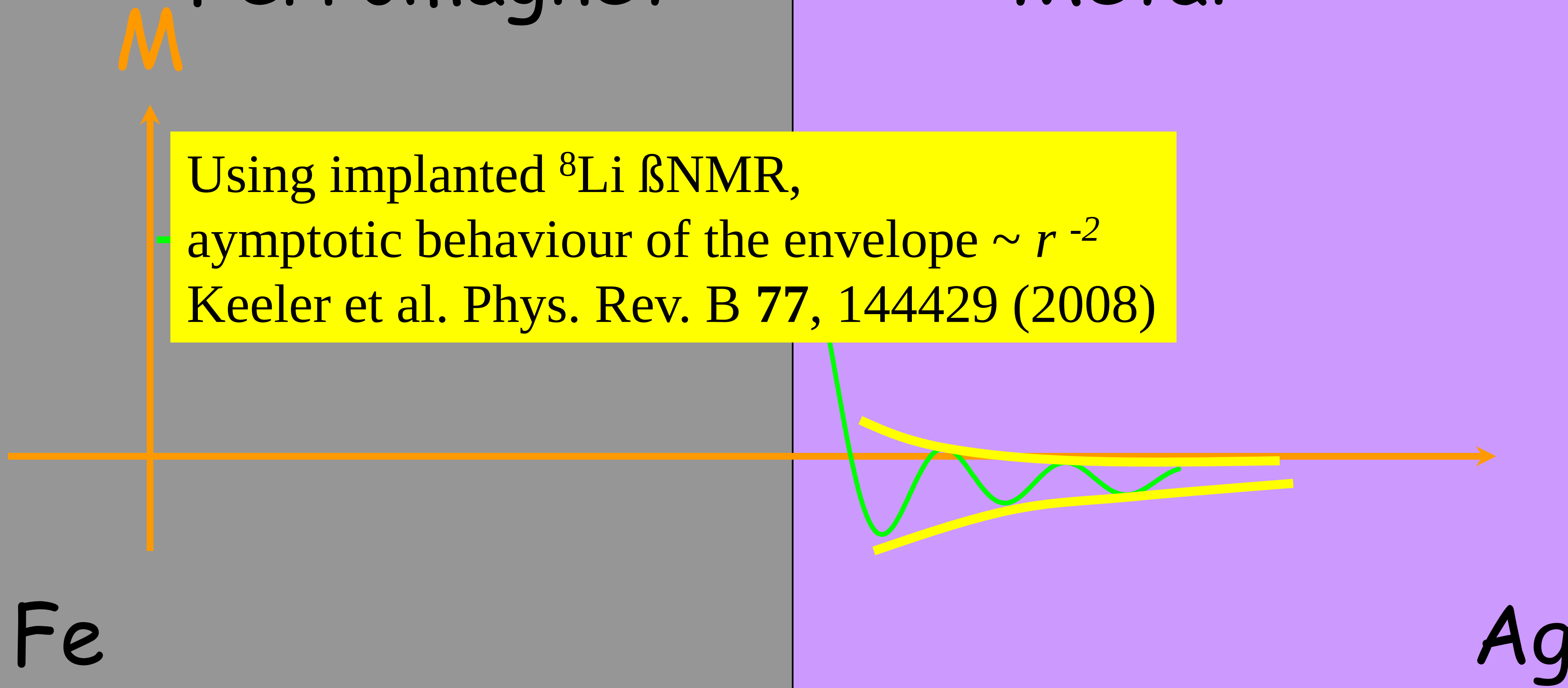
- Ag/Fe epitaxial heterostructures
- T.A. Keeler *et al.*, *Phys. Rev. B* **77,** 144429 (2008)



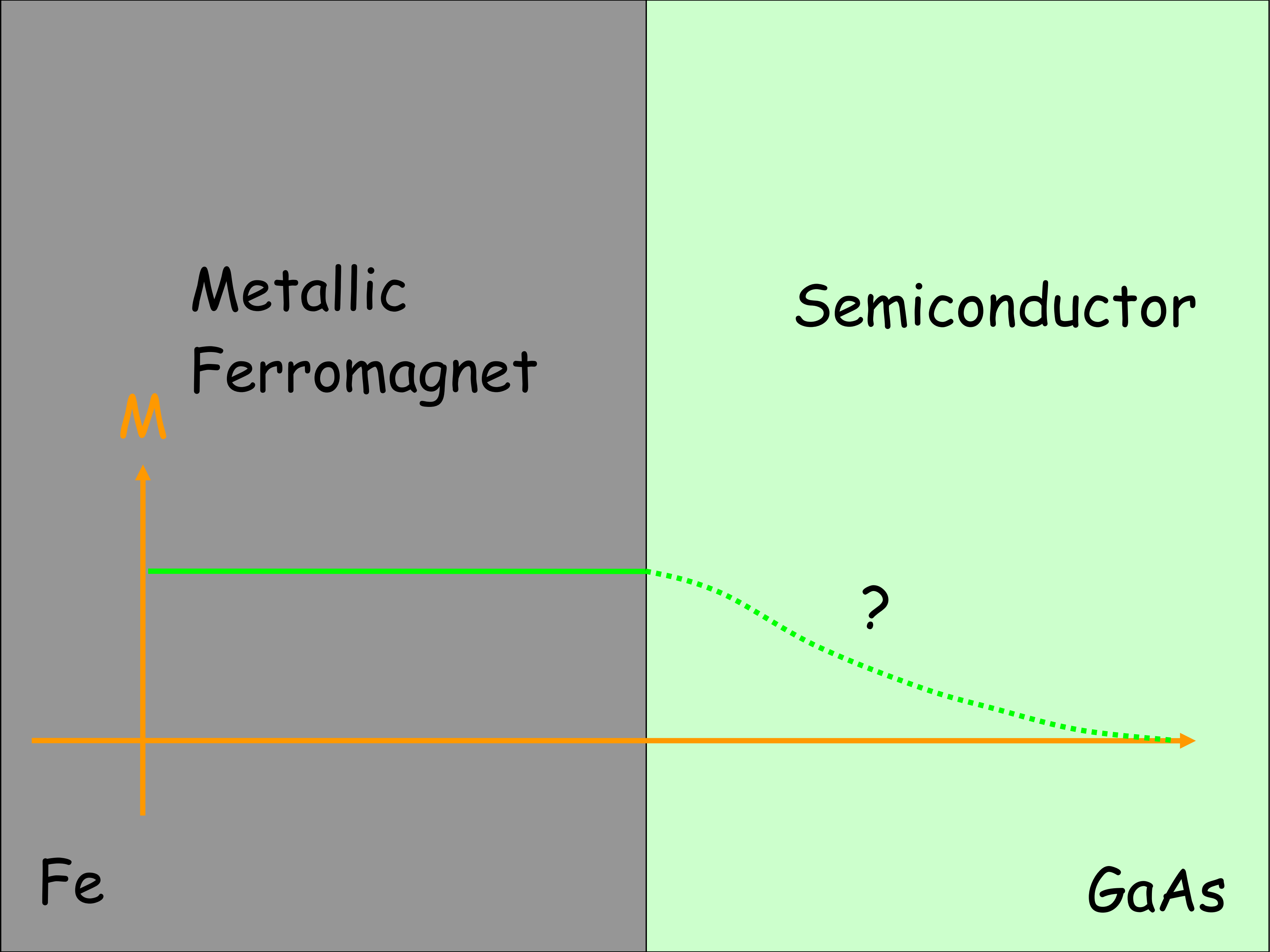
e.g. Magnetic Proximity Effect

Metallic Ferromagnet

Nonmagnetic Metal

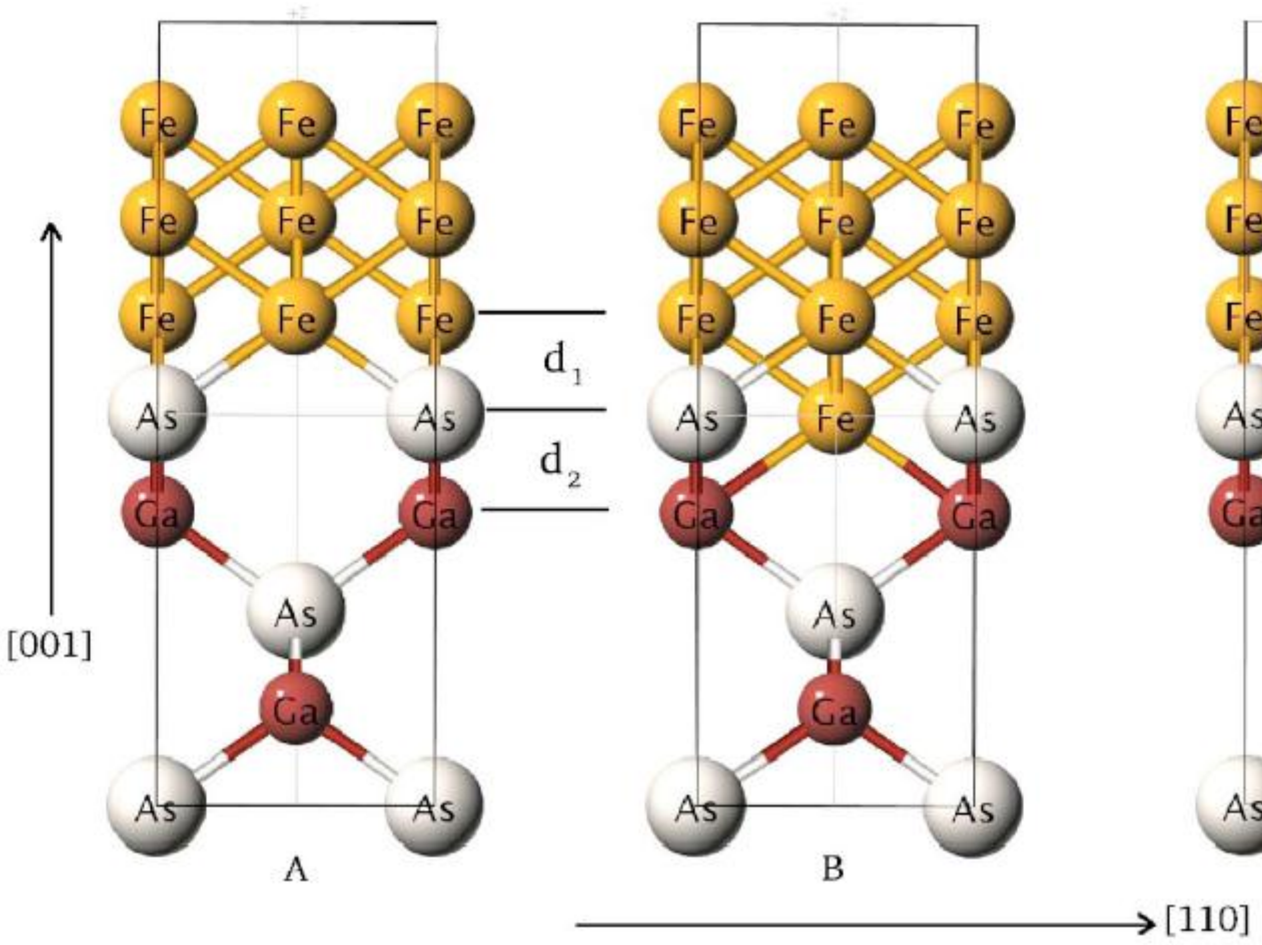


Using implanted ^{8}Li ßNMR,
aymptotic behaviour of the envelope ~ r^{-2}
Keeler et al. Phys. Rev. B **77**, 144429 (2008)

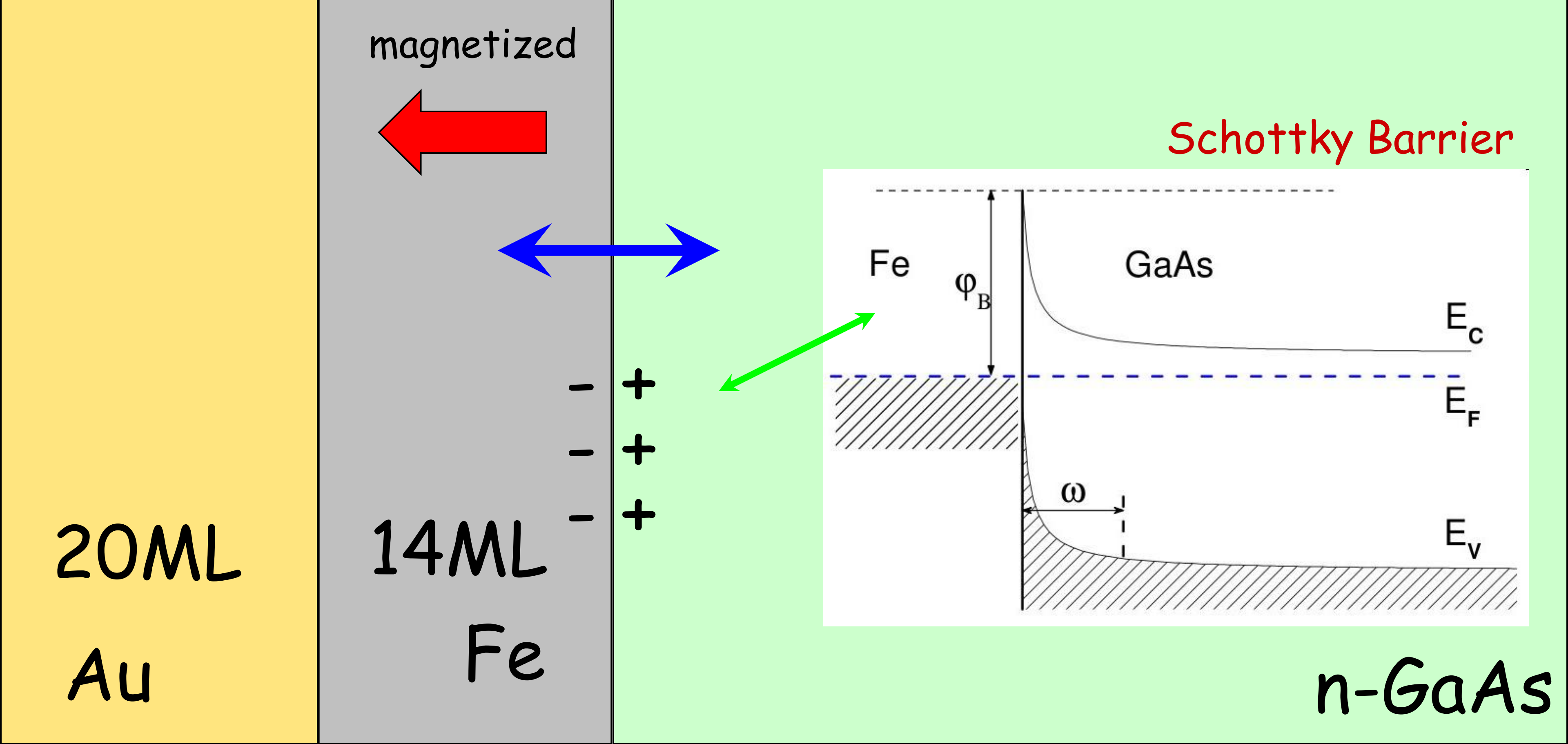


Metallic
Ferromagnet
Semiconductor
M
?
Fe
GaAs

Epitaxial Relation Fe/GaAs



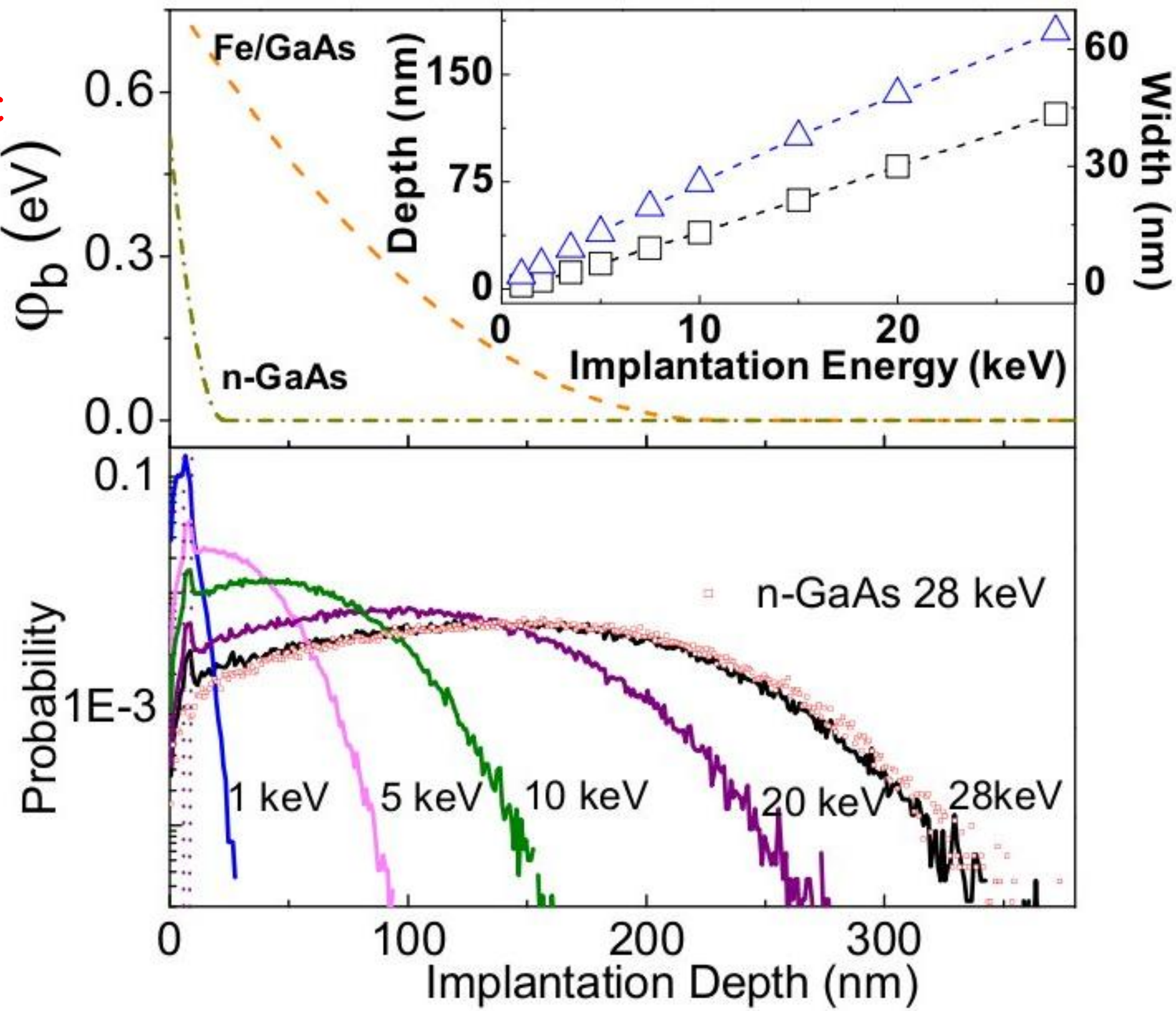
Samples from B. Heinrich Lab, SFU



Access to the Schottky Barrier Region

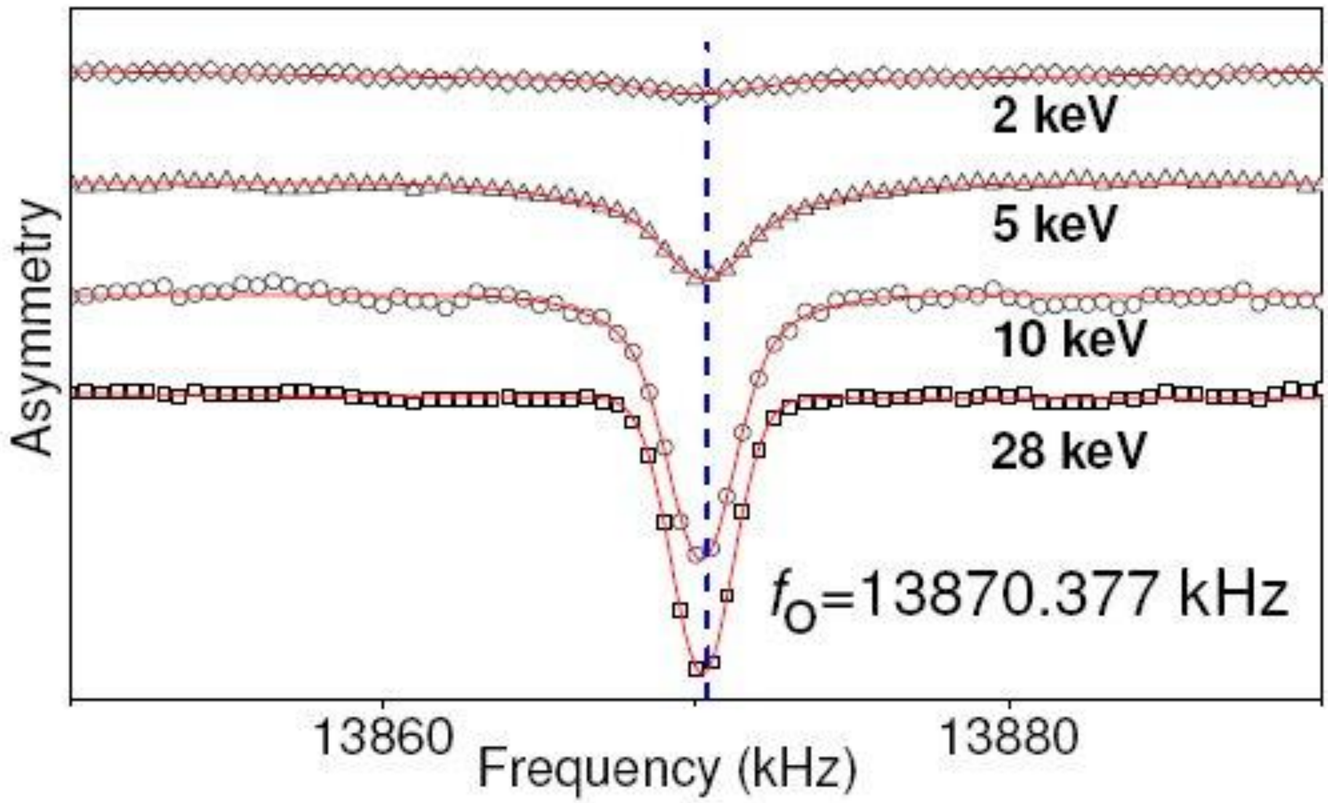
electrostatic potential within GaAs

implantation profiles from SRIM



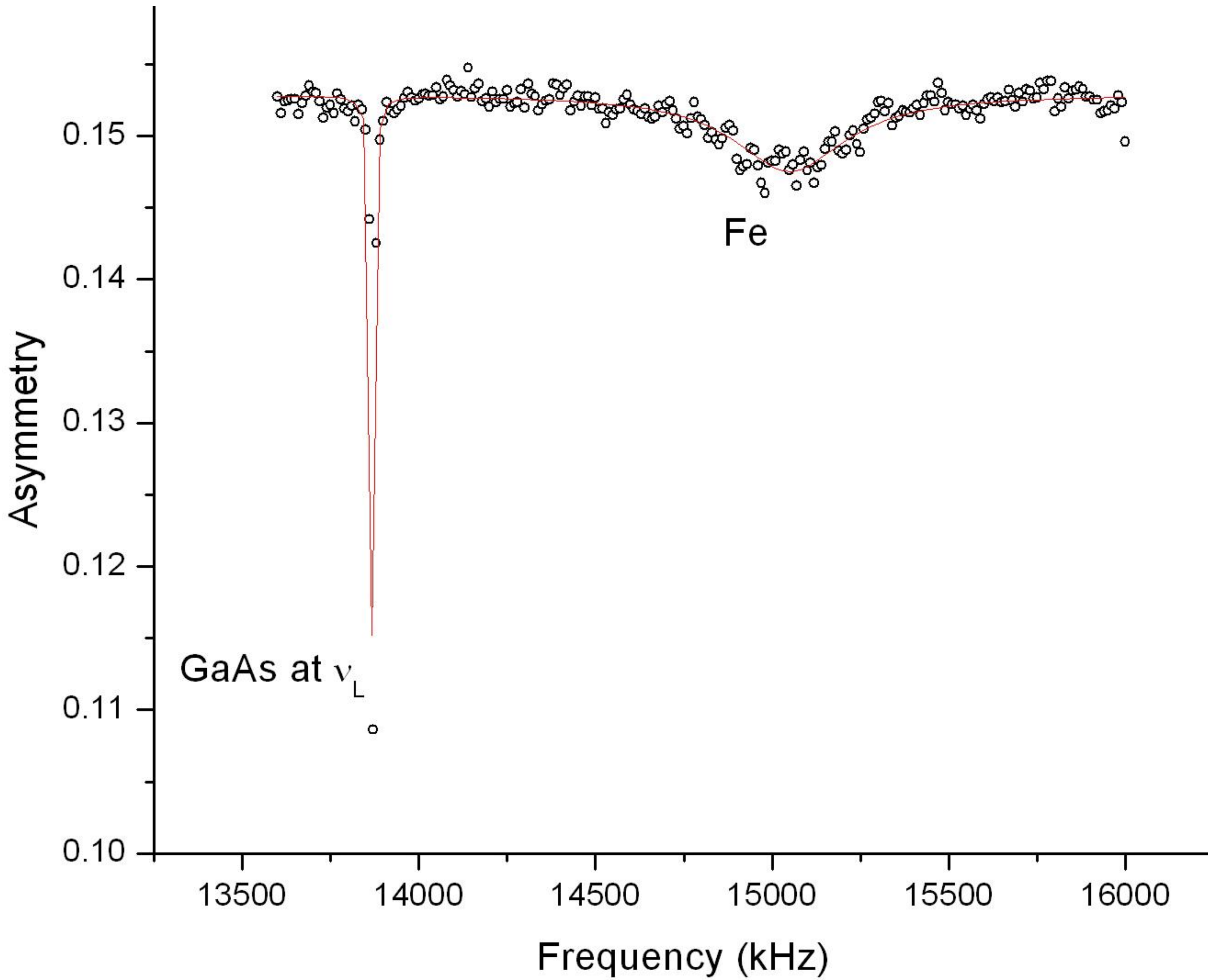
Q. Song

Systematic Depth Dependence (Unbiased Junction)

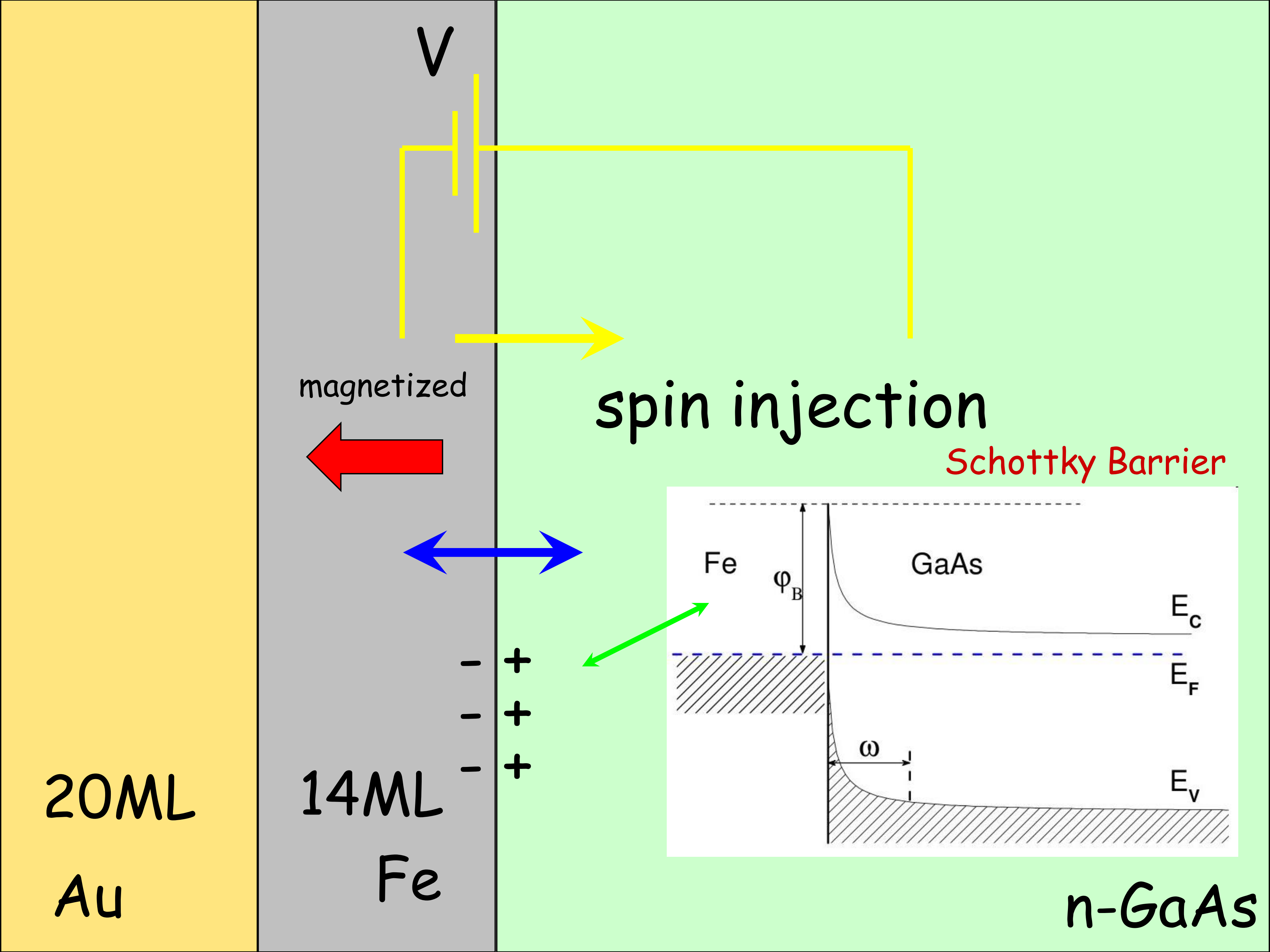


T = 150 K

Resonance Spectrum in Fe



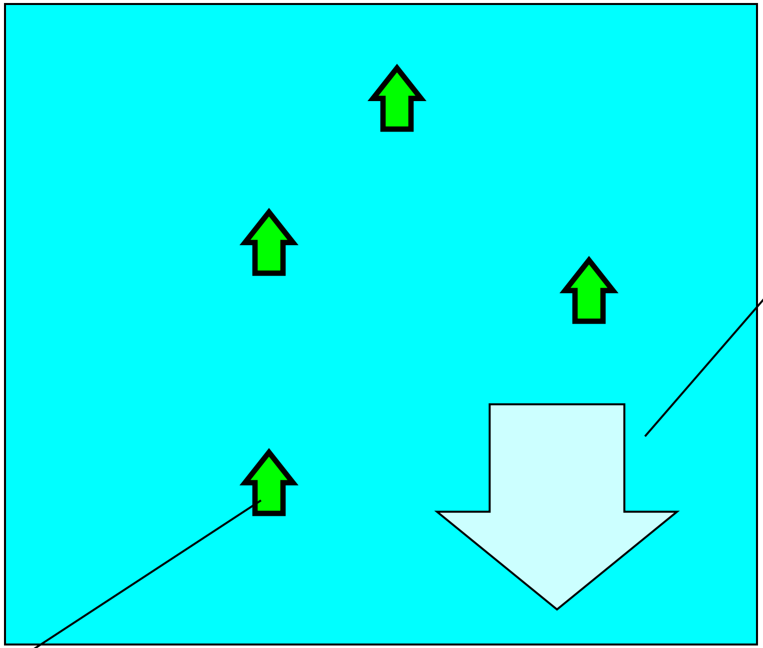
Towards Spin Injection


V
magnetized
spin injection
Schottky Barrier
Fe
GaAs
φB
Ec
EF
Ev
ω
- +
- +
- +
20ML
Au
14ML
Fe
n-GaAs

Avoiding the Schottky Barrier with Dilute Magnetic Semiconductors: GaAs:Mn

Q. Song

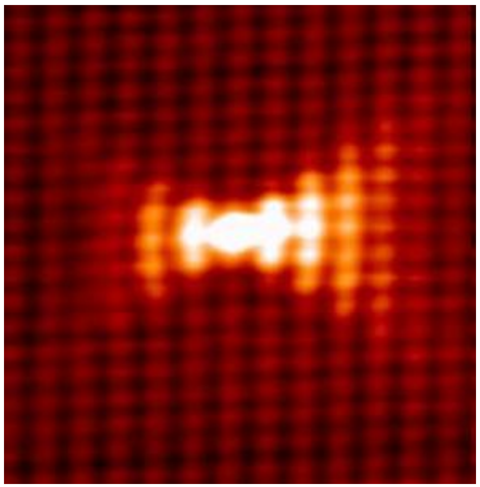
Dilute Magnetic Semiconductors



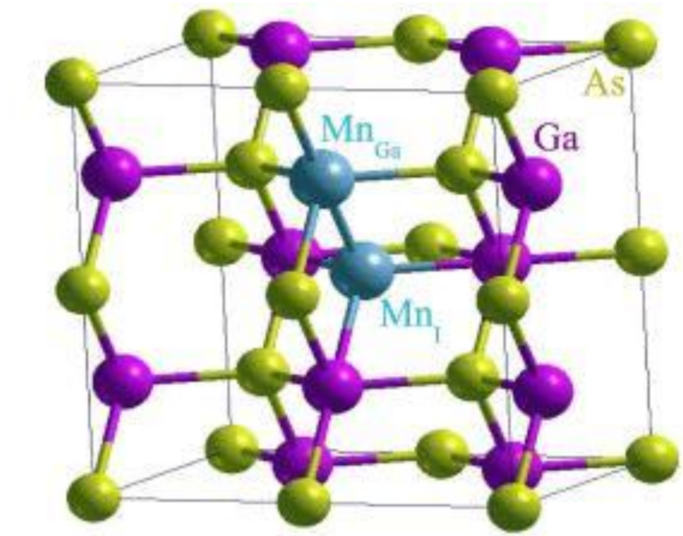
a background
of free carriers
(holes)

dilute local (atomic) magnetic moments
Mn^{2+} $S = 5/2$

Mn doped GaAs



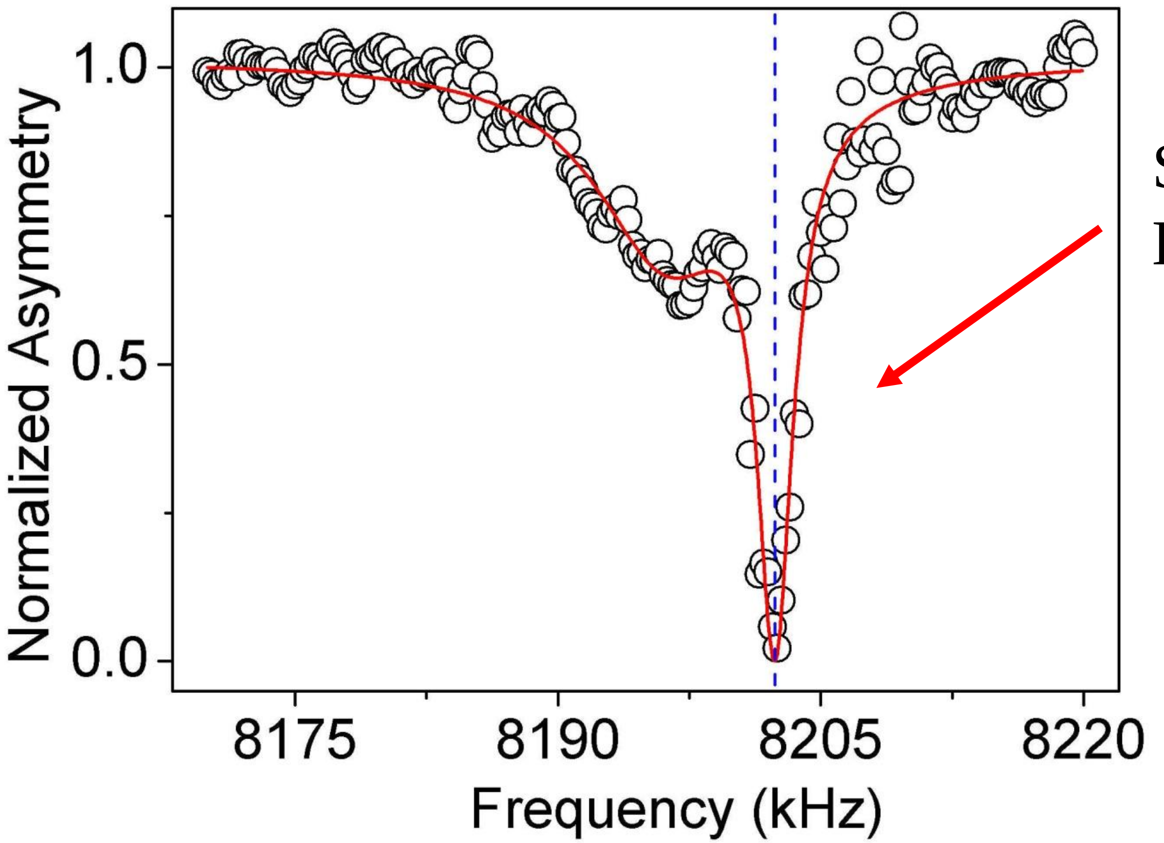
Mn acceptor (STM)
Yakunin et al. PRL **92**, 216806 (04)



Substitutional (Ga): Acceptor
Interstitial: Double Donor

$Ga_{1-x}Mn_xAs$ is not stable in bulk

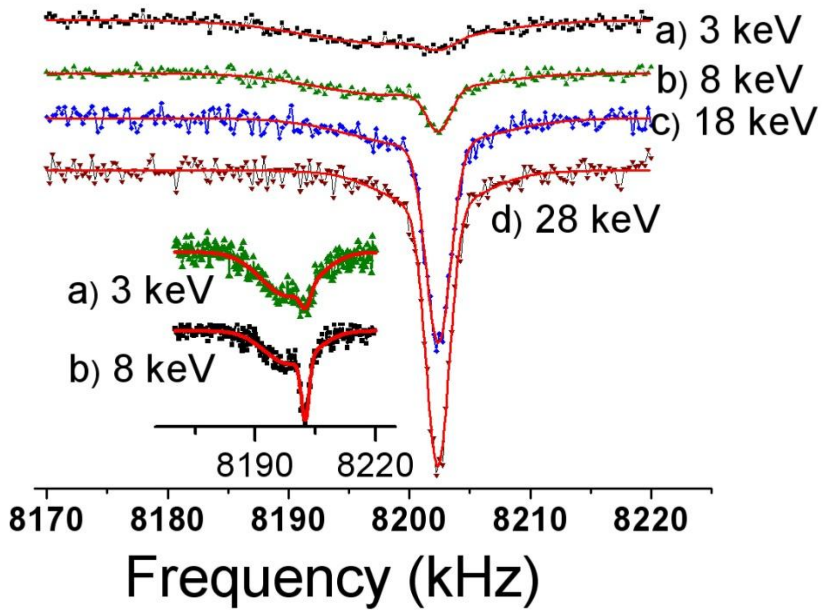
180 nm $Ga_{0.95}Mn_{0.05}As$ / GaAs

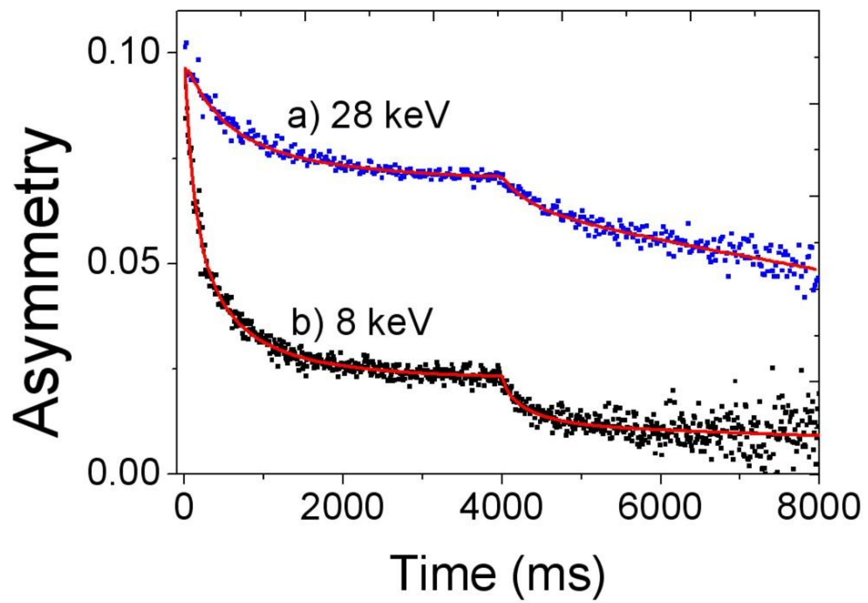


Sharp Substrate Line

Depth Dependence at 50 K (< T_C)

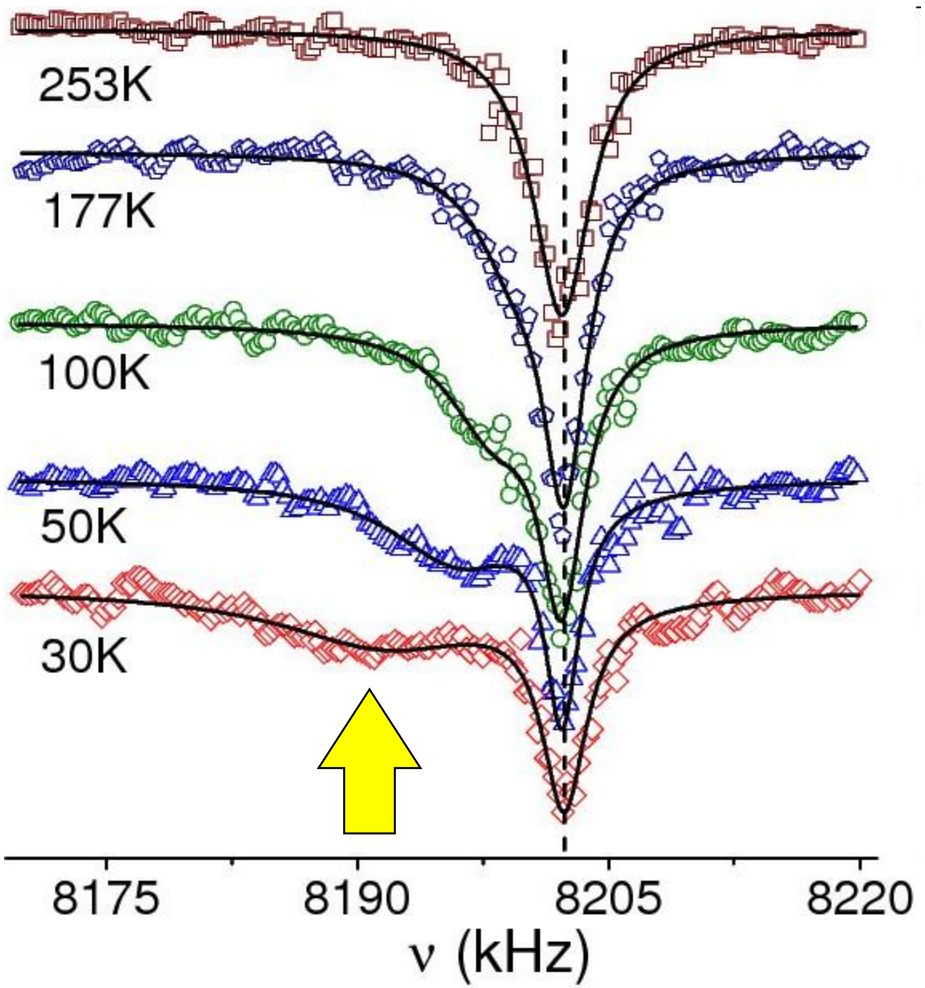
Q. Song et al., Physica B (2009)



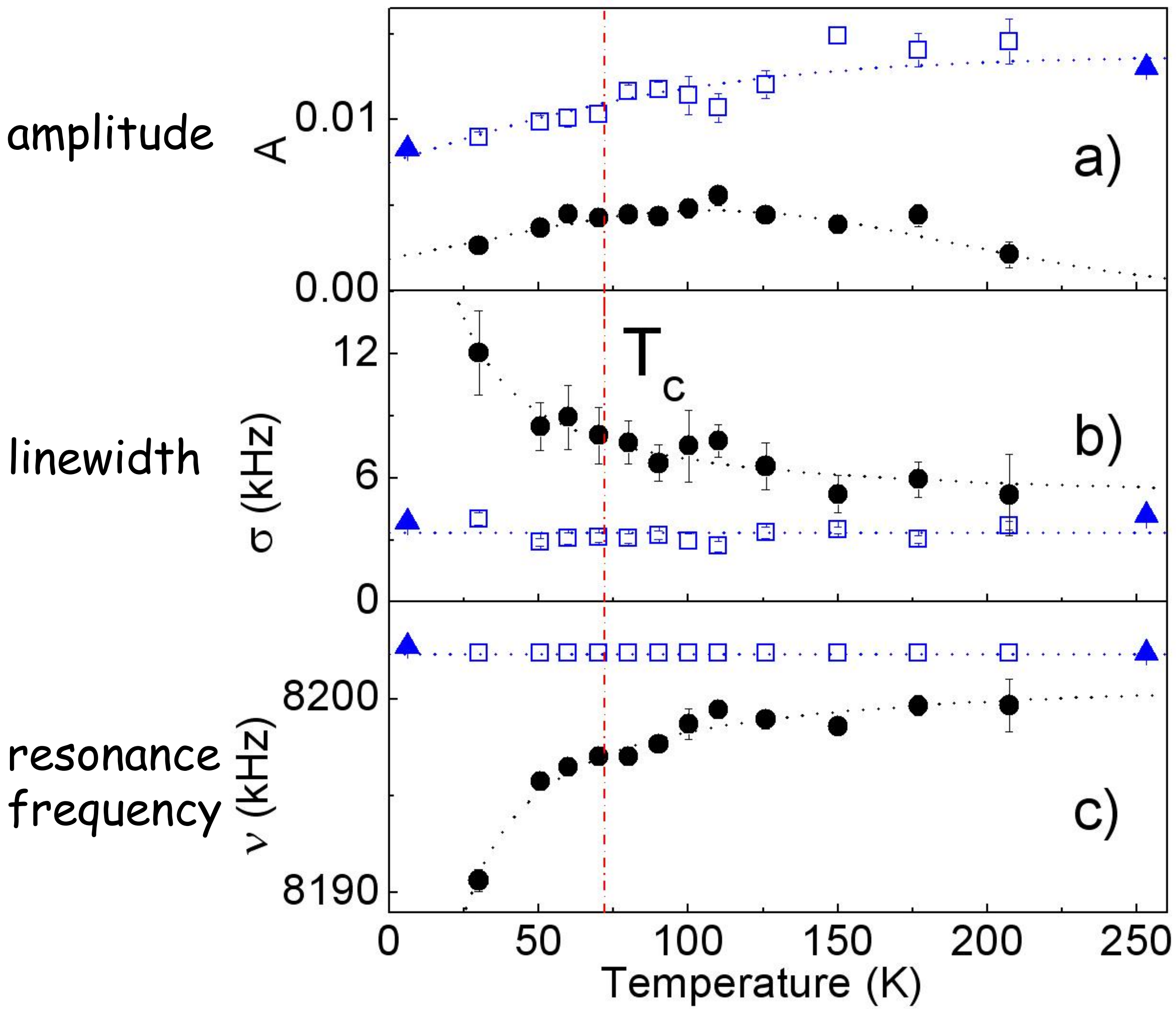


broad, negatively shifted line,
fast spin relaxation from the
Mn doped layer

Temperature Dependence



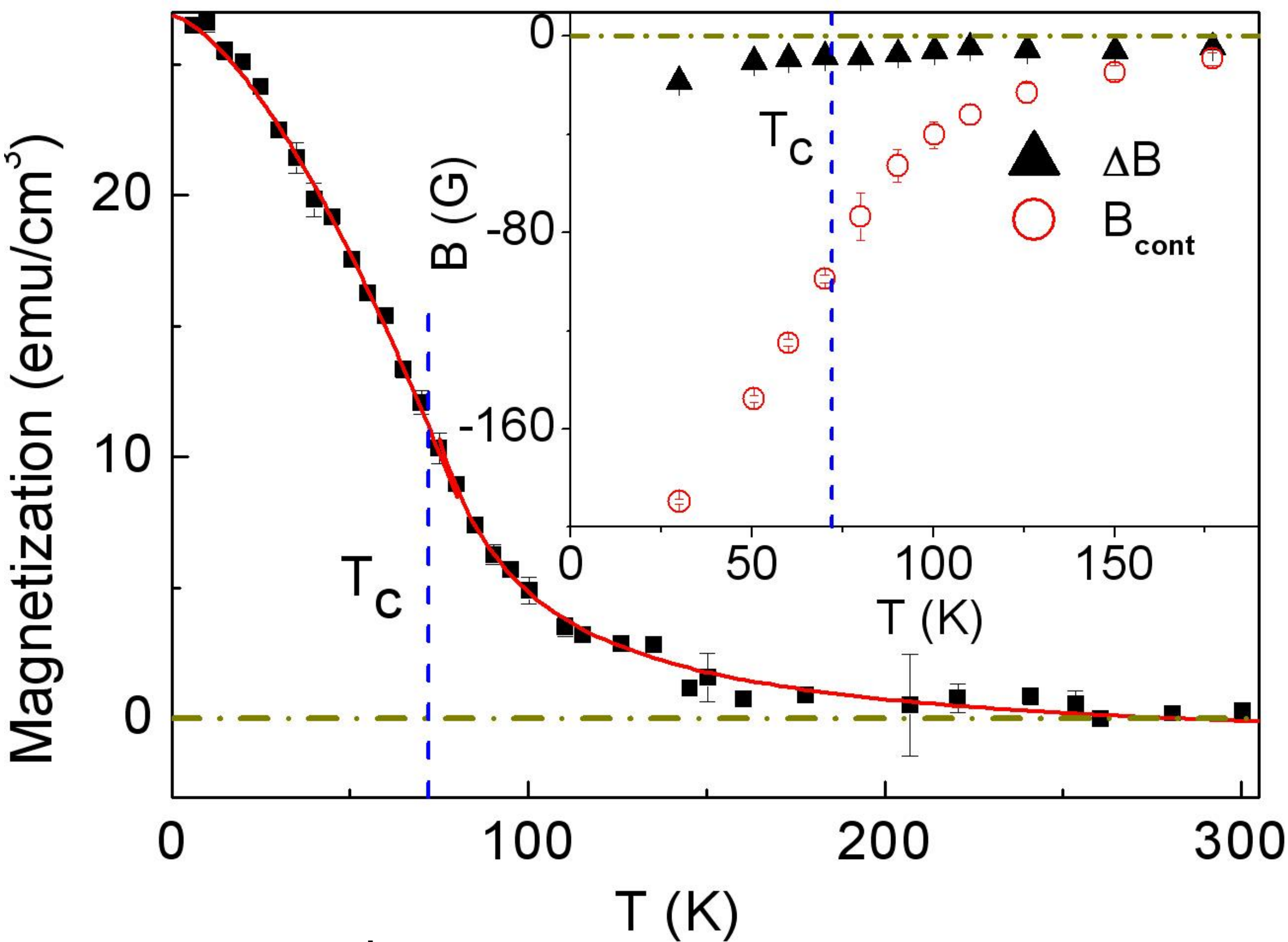
Temperature Dependence



$$k = A\chi_{holes}$$

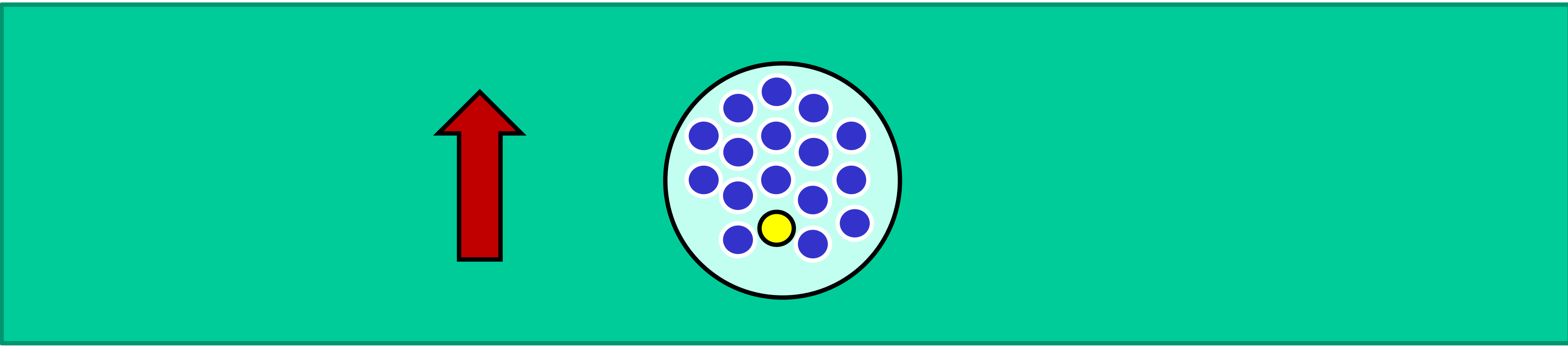
A measure of the hole susceptibility!

SQUID Magnetization in 1.3 T



$$\chi_{GaMnAs} = \chi_{Mn} + \chi_{holes}$$

Contributions to the Local Field



$$B = B_0 + B_{demag} + B_{Lor} + B_{loc}$$

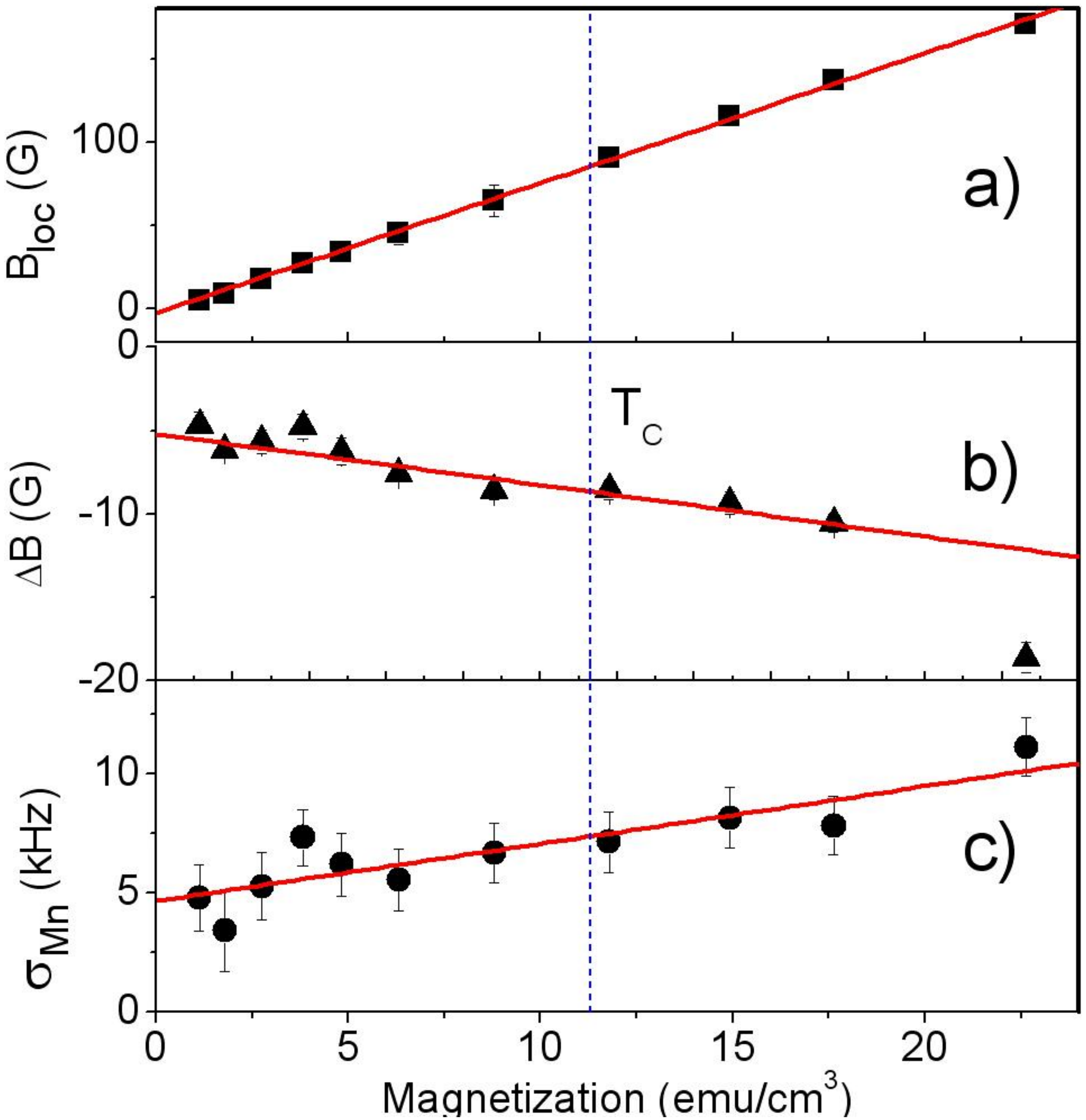
$$= B_0 - 4\pi M + (4\pi/3)M + B_{loc}$$

Clogston Jaccarino Analysis

Corrected for Demagnetization

Raw shift of resonance

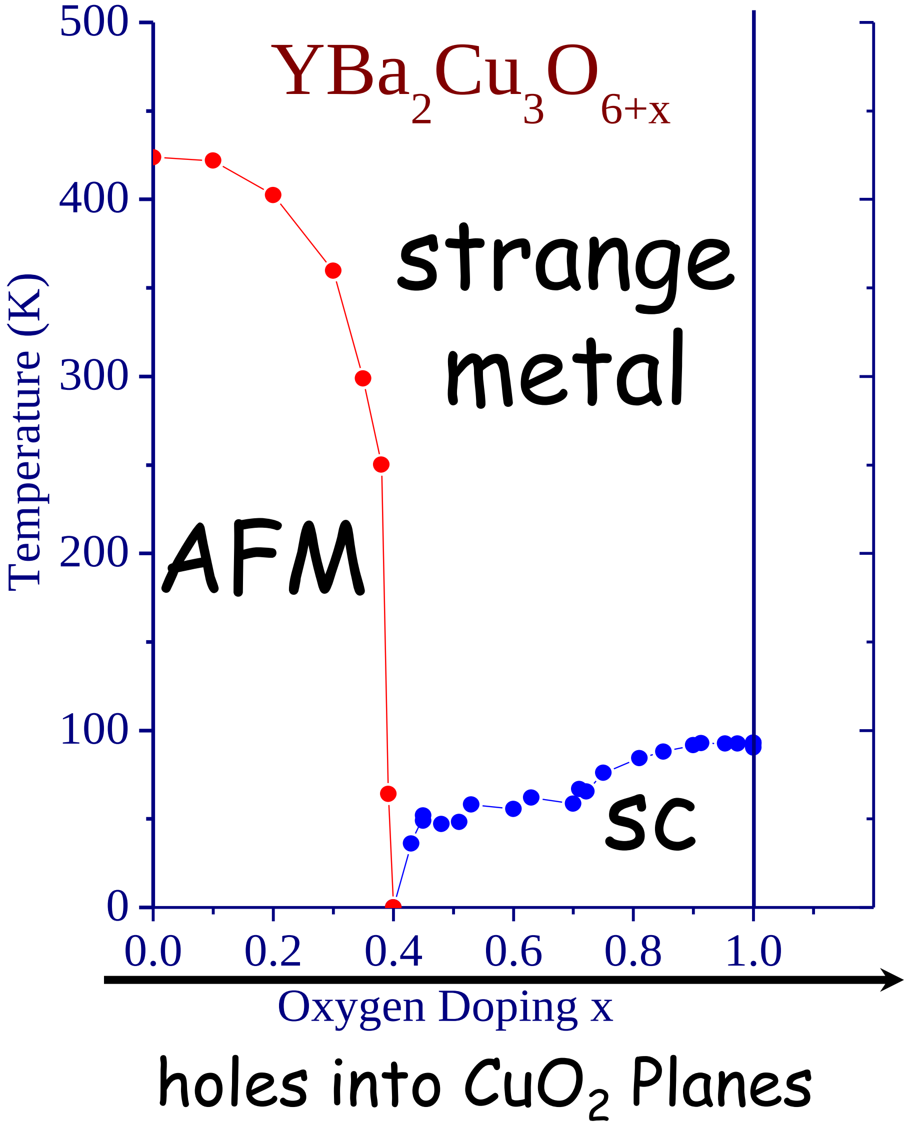
linewidth

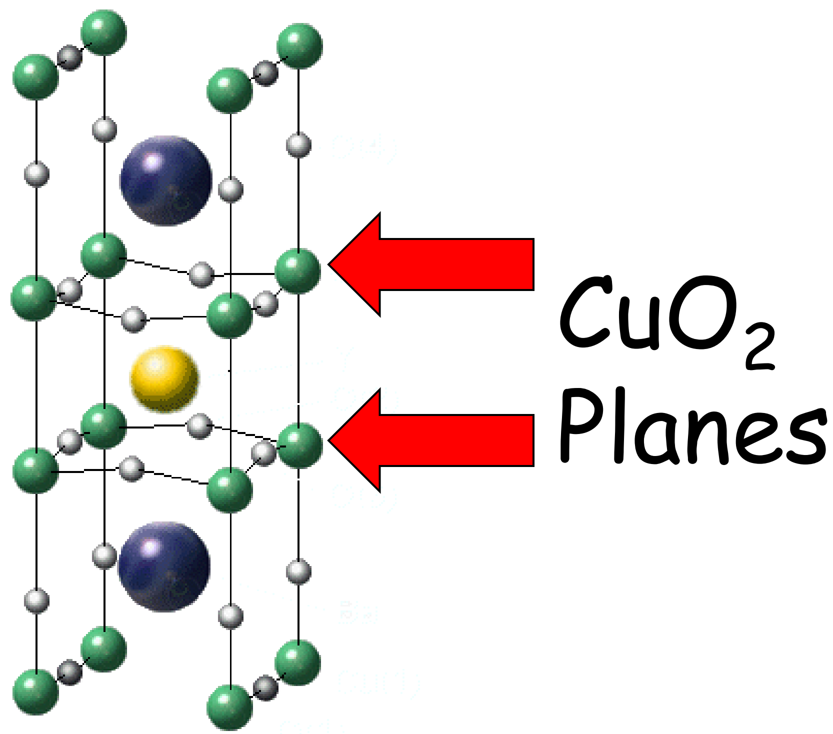


Time Reversal Symmetry Breaking Superconductivity?

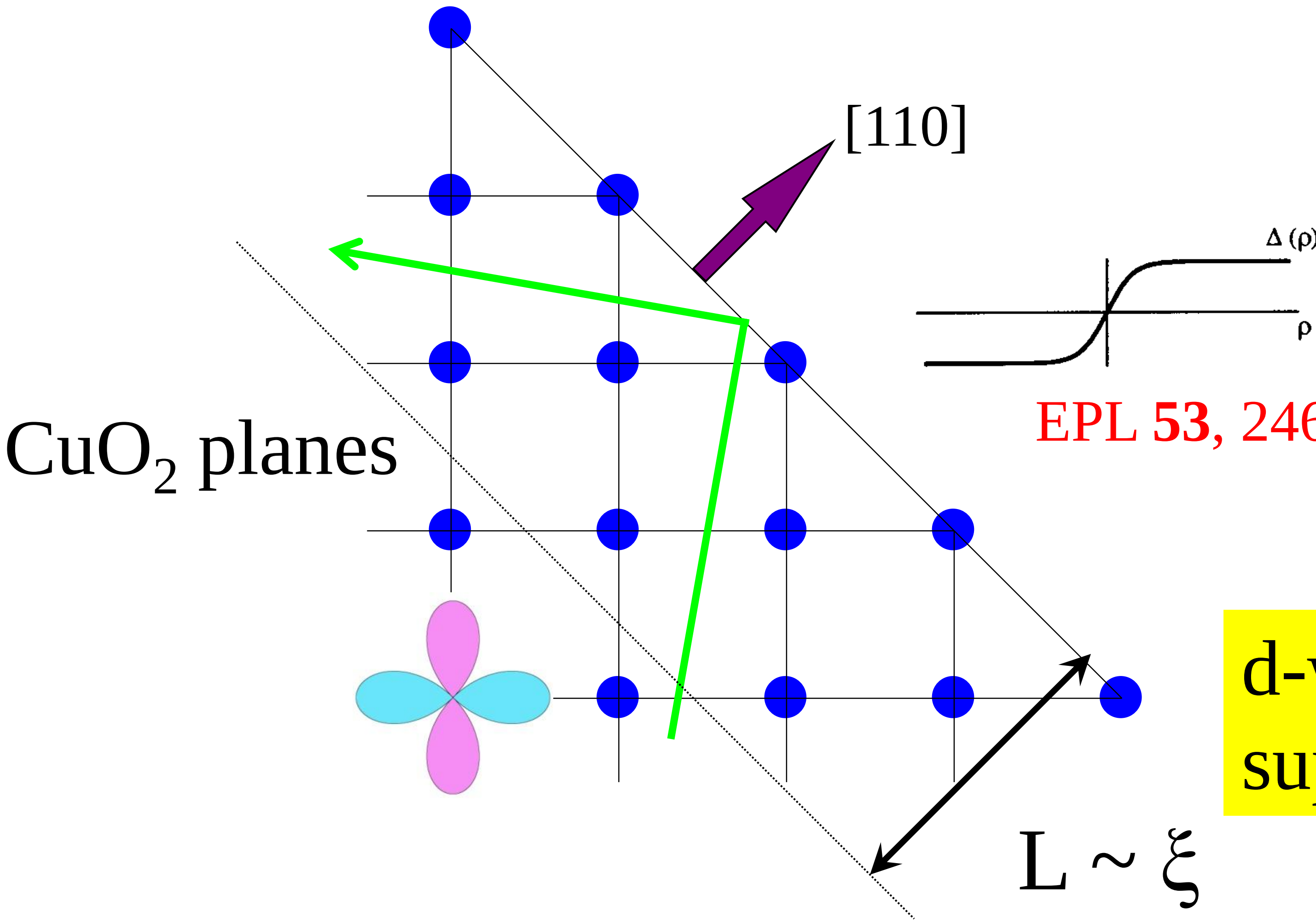
H. Saadaoui

High Tc Superconductor Phase Diagram





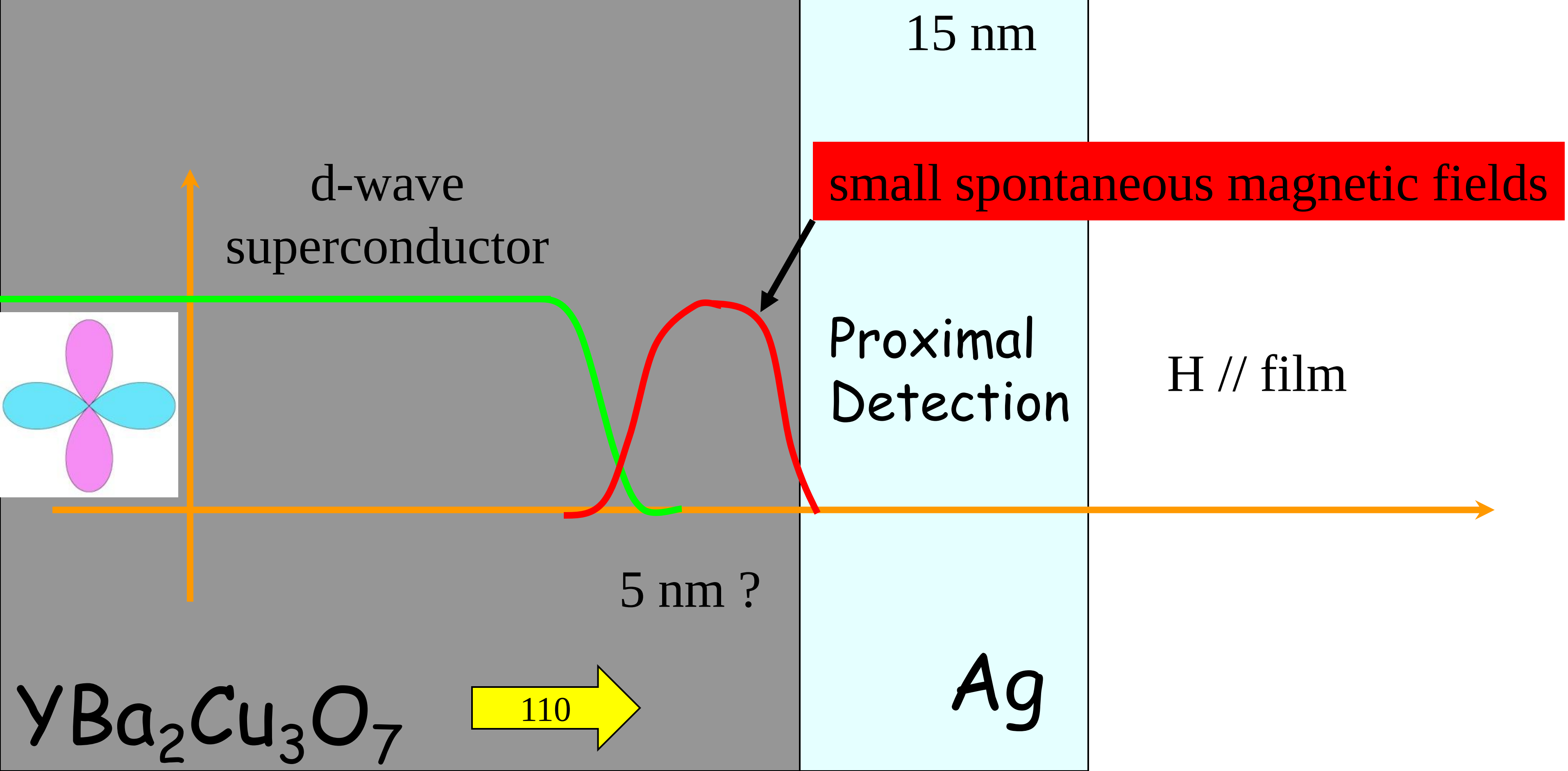
Surface Effects in a d-wave SC



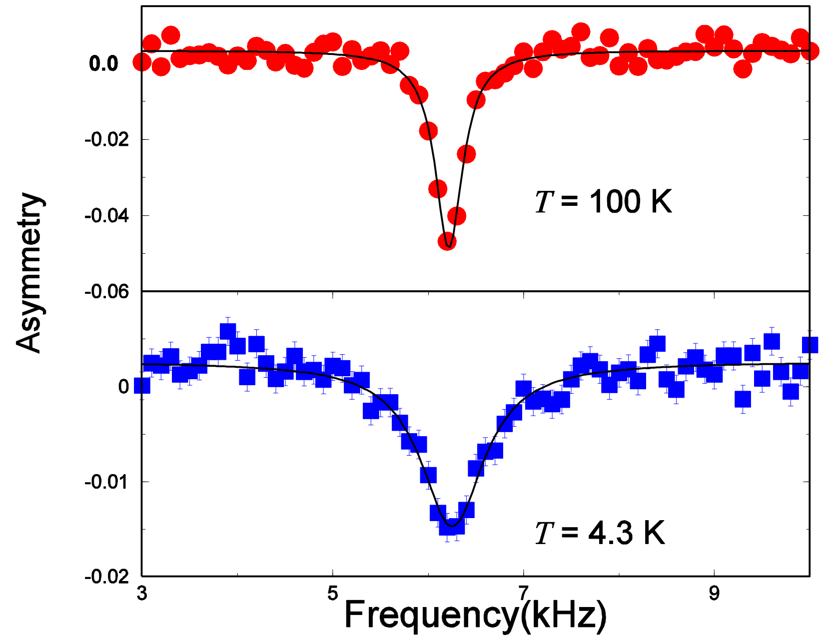
EPL **53**, 246 (01)

d-wave order suppressed

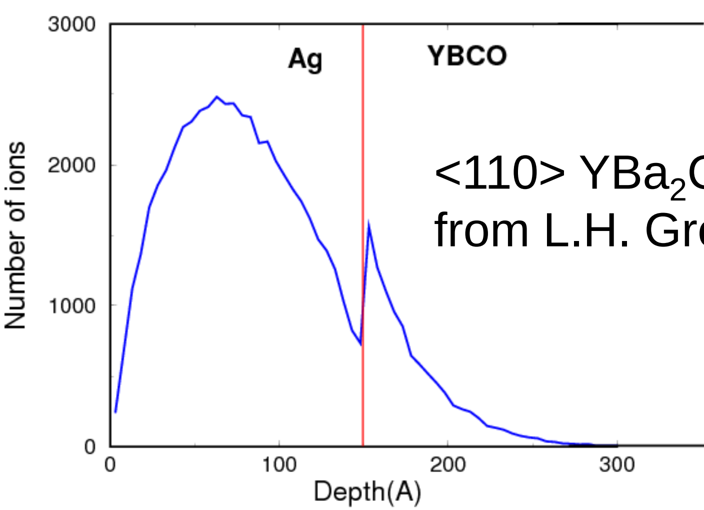
Surface Effects in d wave SC



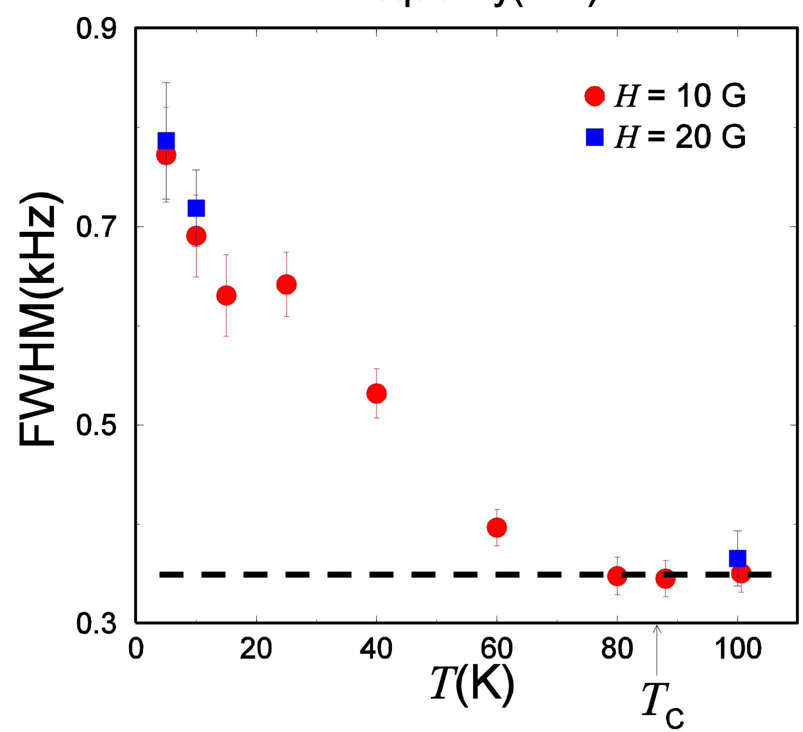
Search for broken time reversal symmetry near the surface of <110> $YBa_2Cu_3O_7$ (Urbana Tc=86.7K) (Hassan Saadaoui)



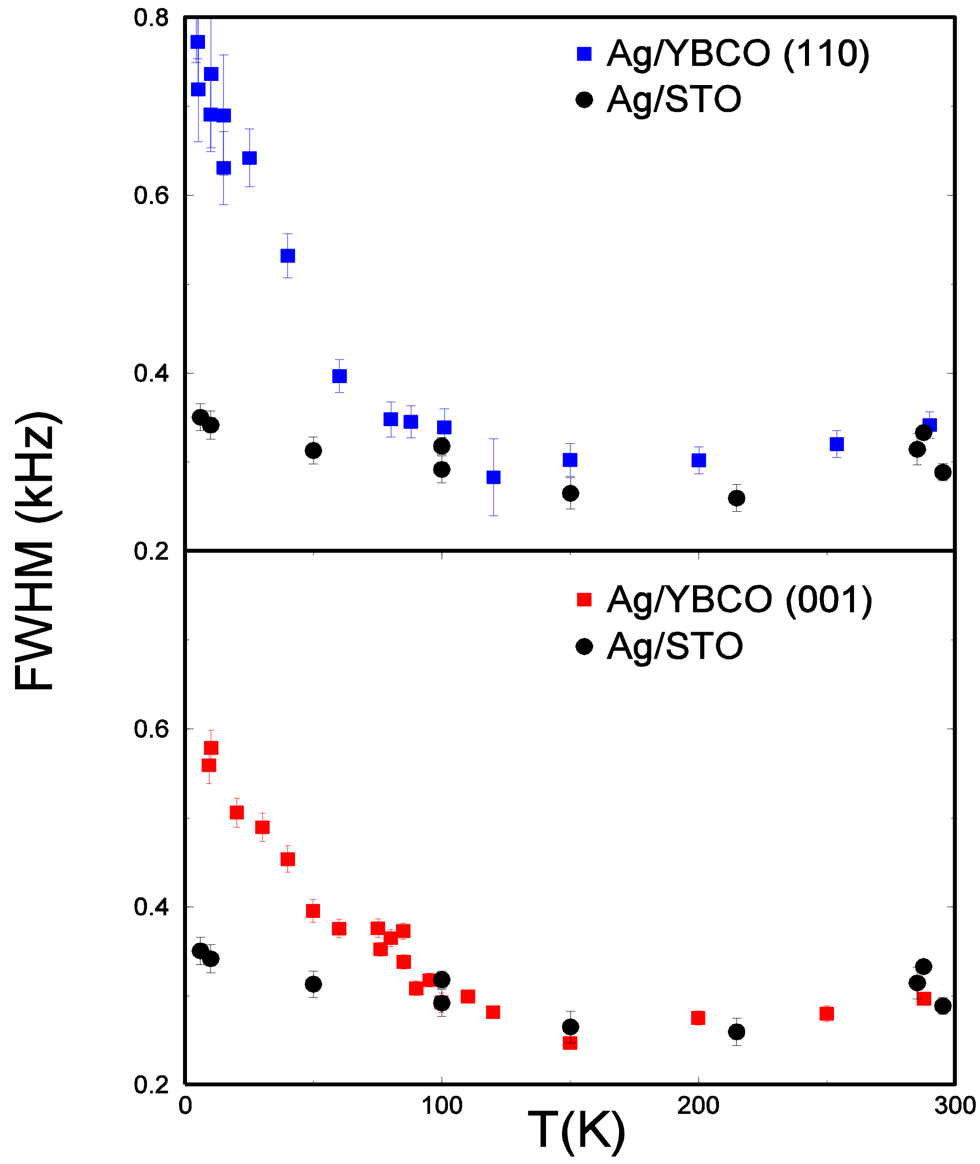
Beam energy 2 keV



<110> $YBa_2Cu_3O_7$ film from L.H. Greene

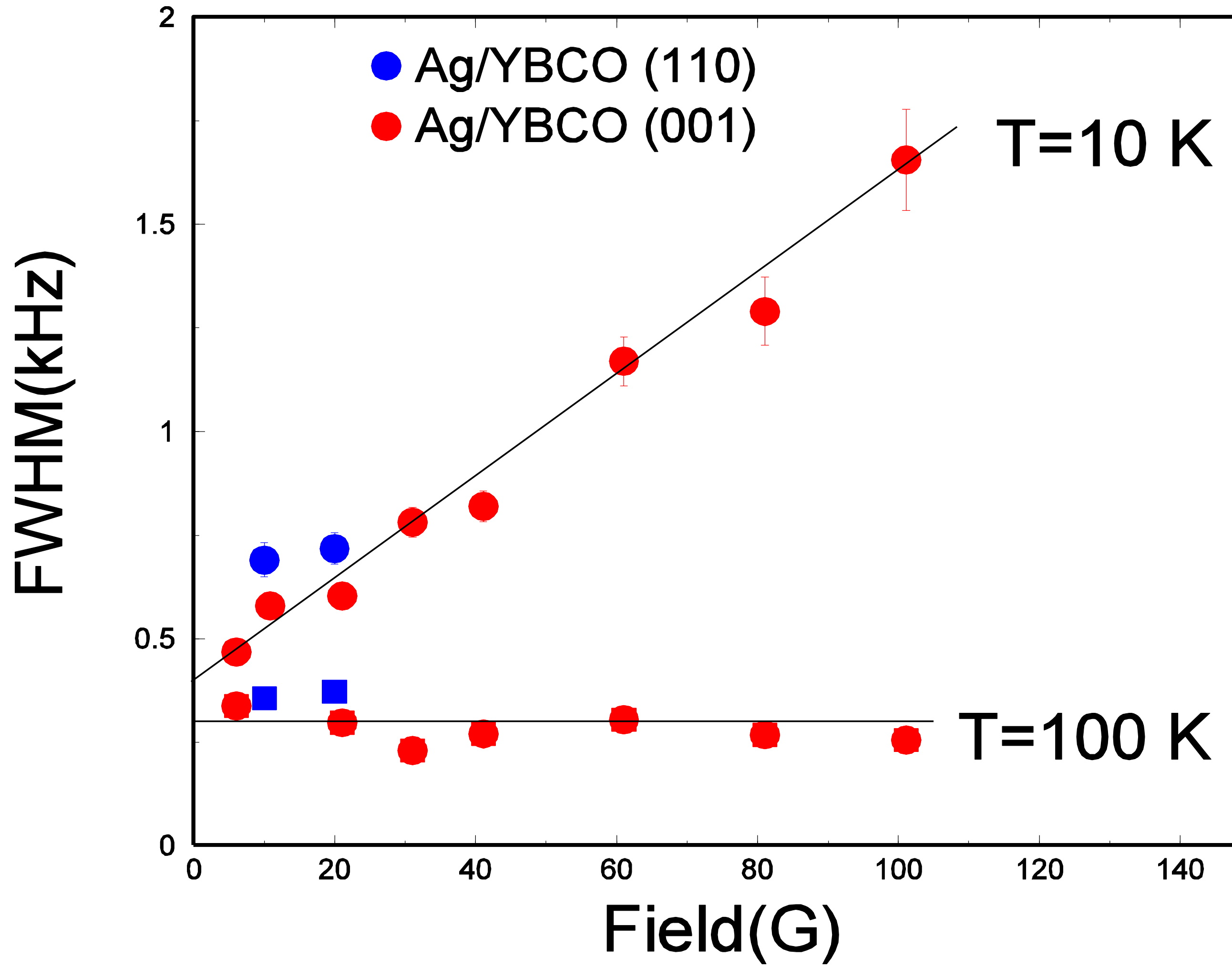


β-NMR resonance linewidth in Ag (15nm)/YBa2Cu3O7 Versus T; E=2 keV B=10G; (Hassan Saadaoui)

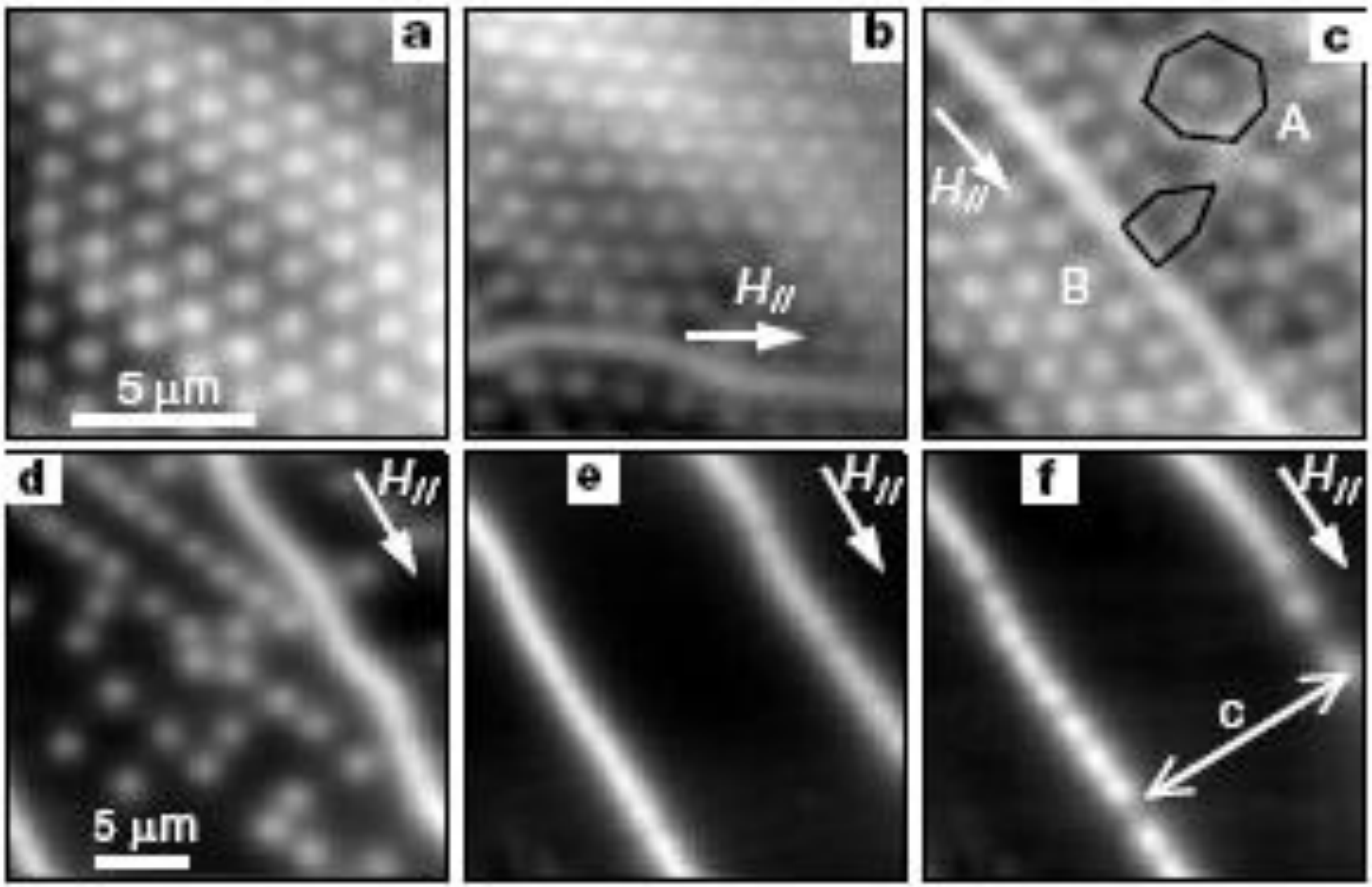


β-NMR resonance linewidth versus magnetic field
in Ag (15nm) on YBa2Cu3O7 E=2 keV; (Hassan Saadaoui)

zero-field cooled

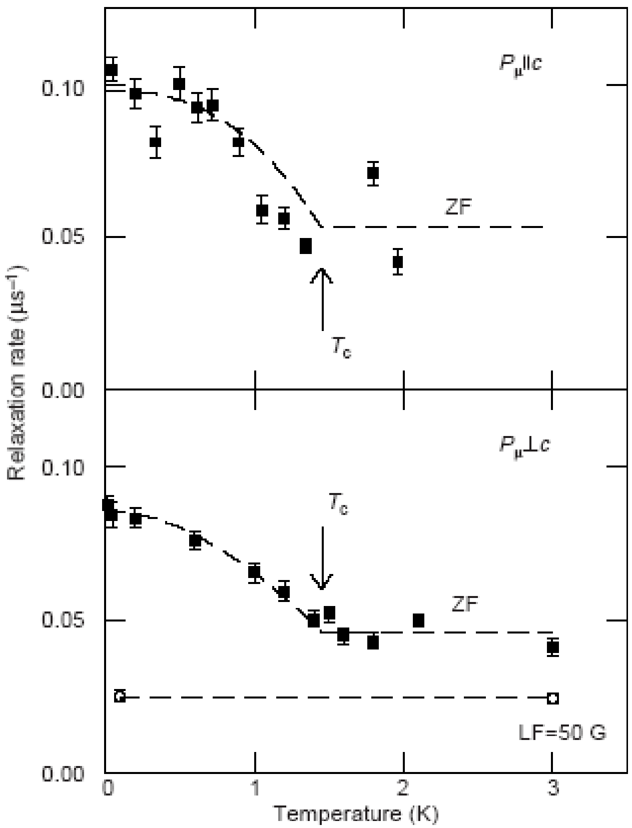


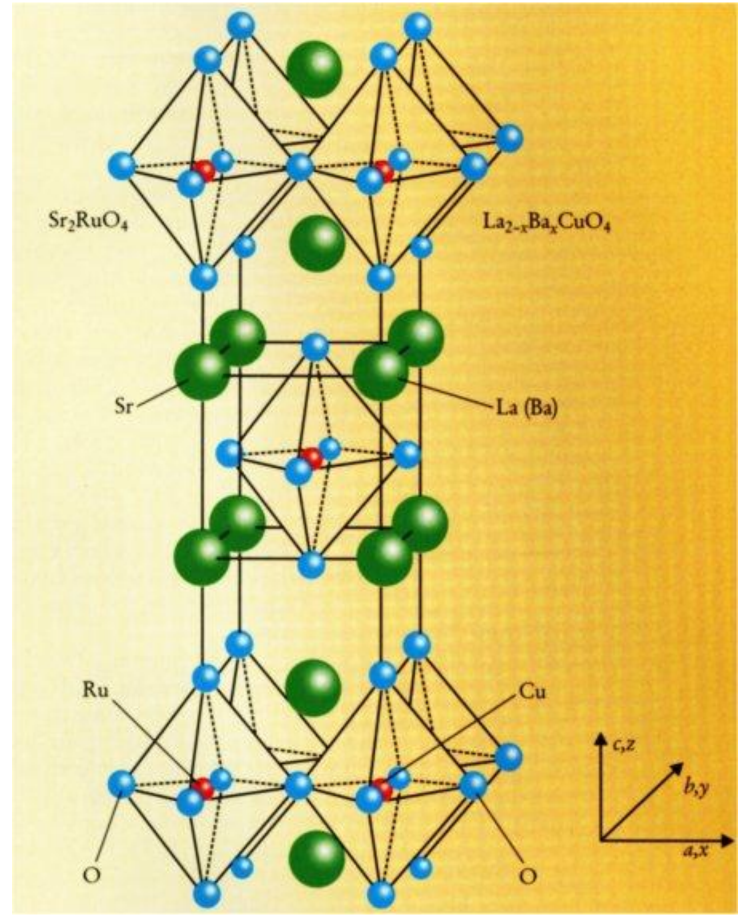
Josephson vortices in Bi2Sr2CaCu2O8 H//=35G
81K (Grigorenko et al., Nature **414,** 728 2001)



Spontaneous Field at Tc (Sr_2RuO_4)

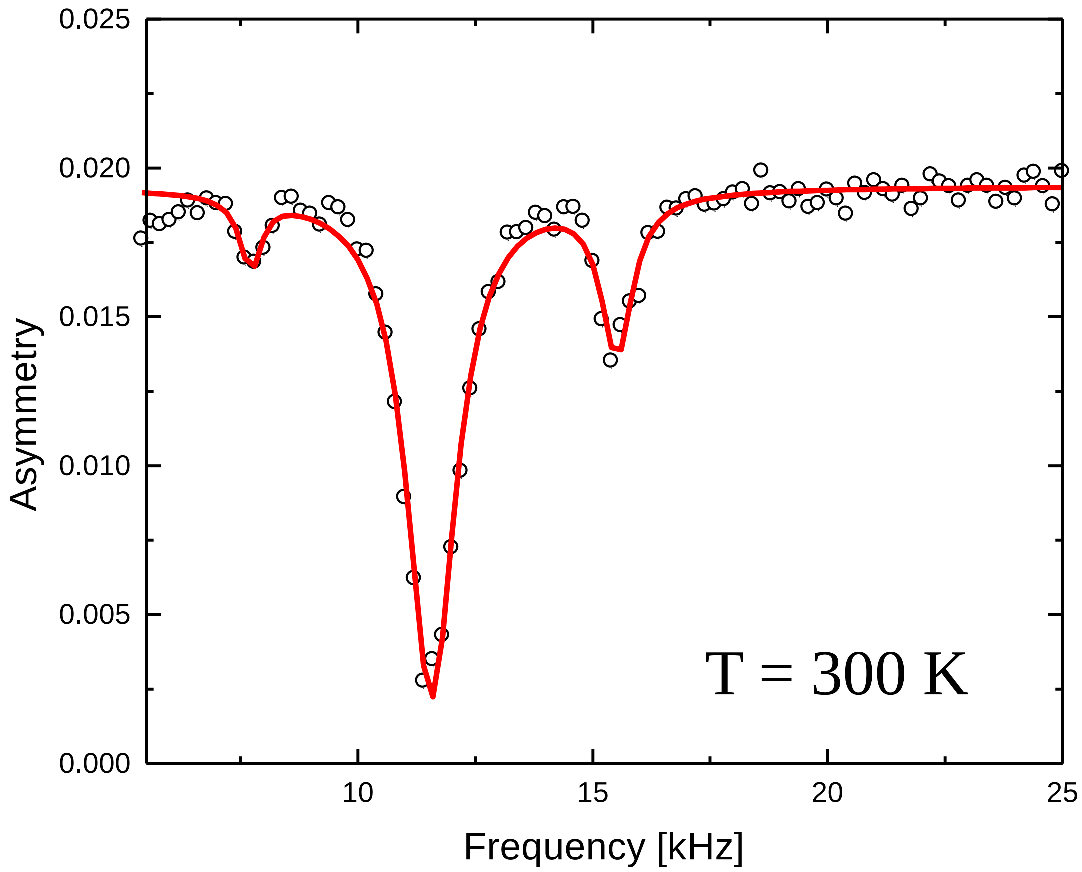
μSR
Relaxation Rate

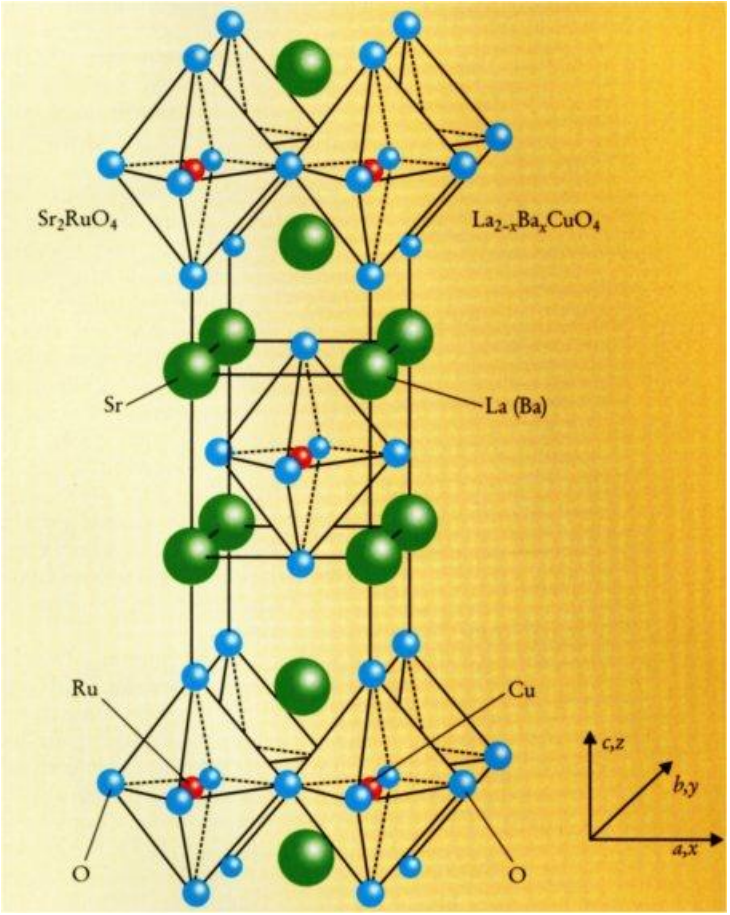




G.M. Luke *et al.*, Nature **394,** 558 (1998)

^{8}Li βNQR in Sr_2RuO_4



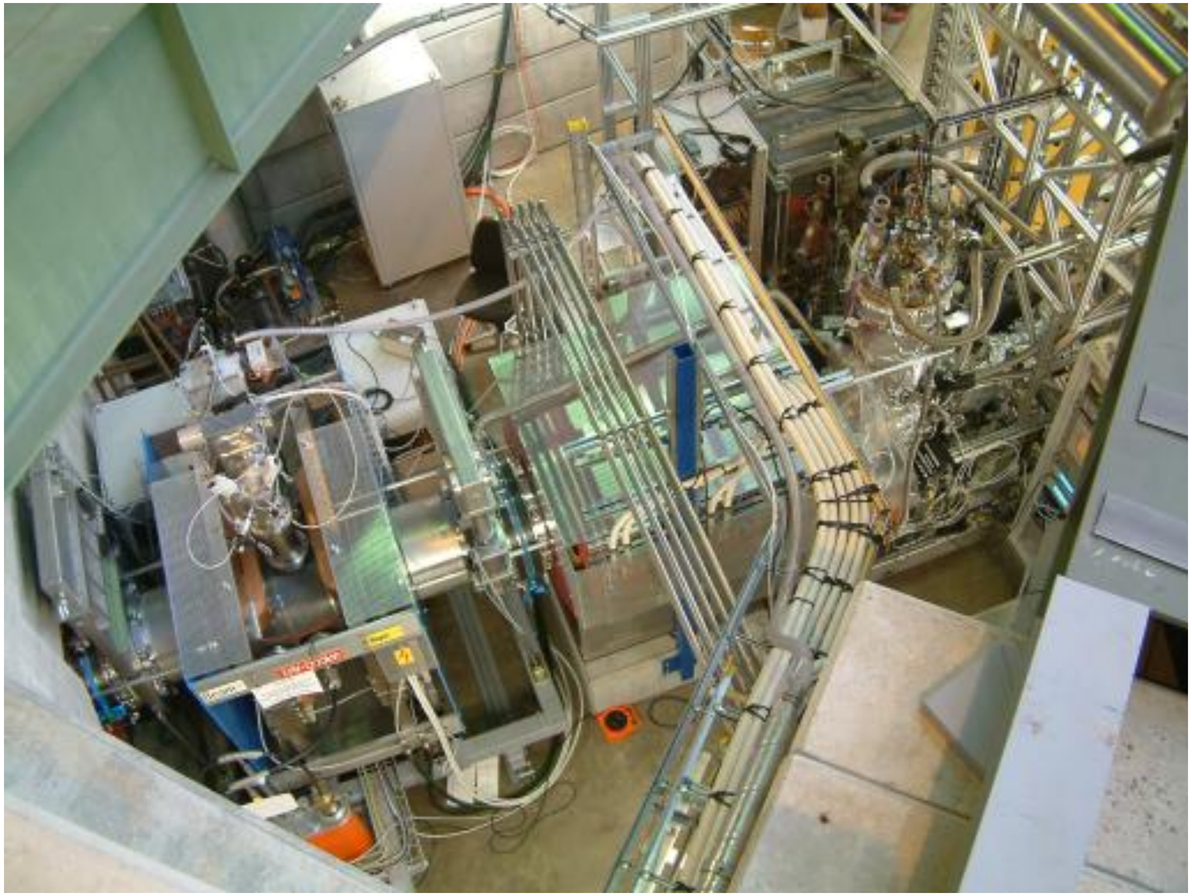


(Maeno, Kyoto)

Low T (300 mK) capability funded and in design

Competition

Low Energy Muon Facility at PSI



low energy via moderation, reacceleration

http://lmu.web.psi.ch/

Collaboration

R.F. Kiefl (UBC, Phys), **K.H. Chow** (Alberta, Phys) S.R. Dunsiger (TU Munich), Z. Yamani (NRC-CINS, Chalk River), E. Morenzoni, Z. Salman (PSI)

Students: T. Parolin, H. Saadaoui, M.D. Hossain, Q. Song, A. Mansour, D. Wang, M. Smadella, T. Keeler, I . Fan, and many undergrads

TRIUMF: G.D. Morris, C.D.P. Levy, M.R. Pearson, A. Hatakeyama (Tokyo), S. Daviel, R. Poutissou, D. Arseneau, R. Baartman, M. Olivo, S.R. Kreitzman

SAMPLES: L.H. Greene (Urbana), T. Hibma, S. Hak (Groningen), B. Heinrich (SFU), Y. Maeno (Kyoto), P. Fournier (Sherbrooke), J.Y.T. Wei (Toronto), J.W. Brill (Kentucky), J. Chakhalian (MPI-Stuttgart, Arkansas), G. Condorelli, R. Sessoli (Florence), C. Ferdeghini (Genoa), J.K. Furdyna (Notre Dame), K.M. Yu (LBL), N.J.C. Ingle (UBC), R. Liang, D.A. Bonn, W.N. Hardy (UBC), E. Katz (Beer Sheva), F. Fujara (TU Darmstadt), R. Neumann (GSI), T. Tiedje (UBC, UVic)

more info:
bnmr.triumf.ca

End

µSR 2011

The **12th International Conference on Muon Spin Rotation, Relaxation, and Resonance** will be held in Cancun, Mexico,

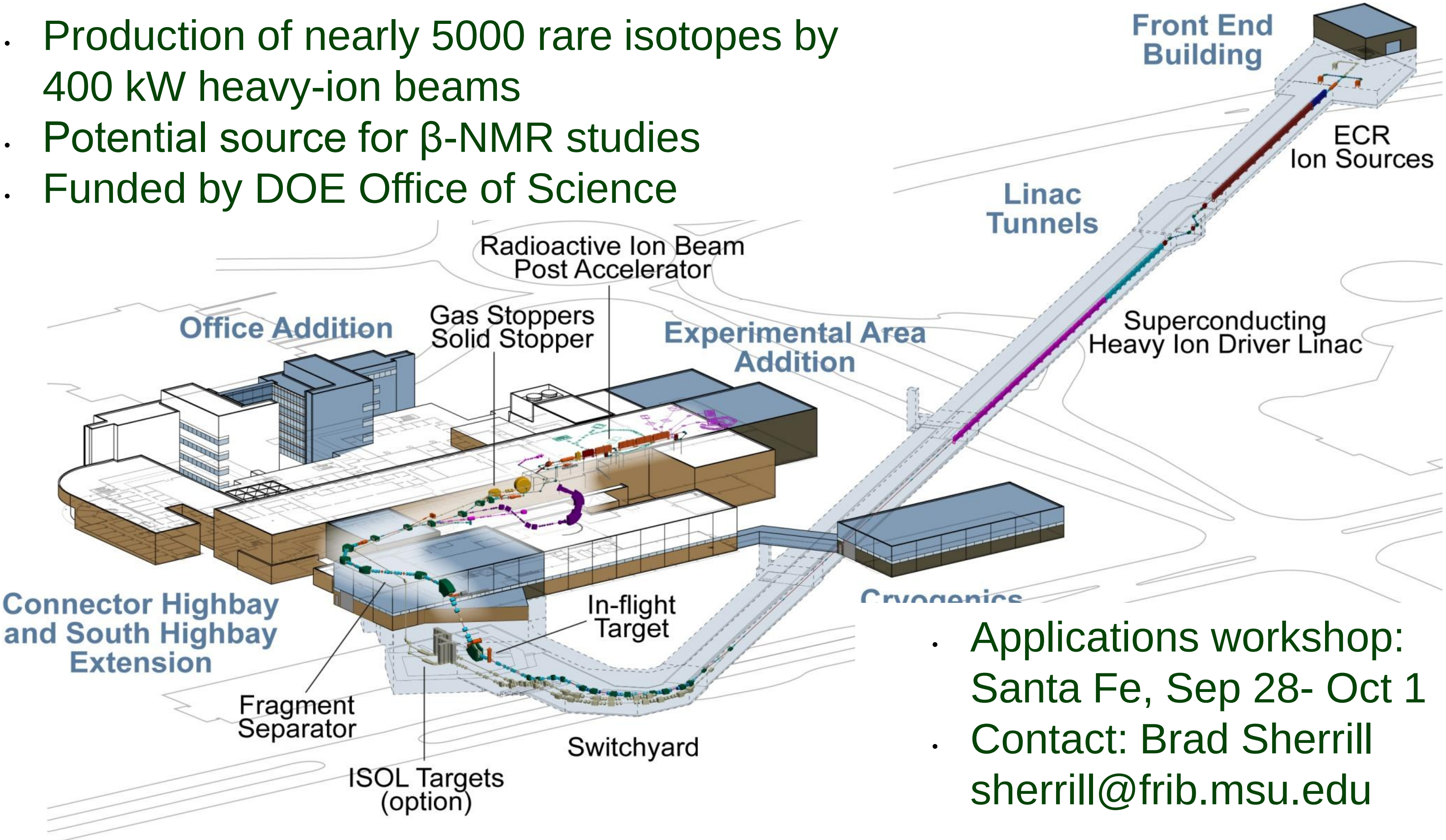
May 16-20, 2011.

All sessions and accommodations will be at the **Fiesta Americana Condesa**, which is an all-inclusive resort located on one of the most beautiful beaches in Cancun with a magnificent view of the Caribbean Ocean and the Nichupte Lagoon.

Further information is available on the conference web site: **http://muSR2011.triumf.ca**.

Facility for Rare Isotope Beams, FRIB

- Production of nearly 5000 rare isotopes by 400 kW heavy-ion beams
- Potential source for β-NMR studies
- Funded by DOE Office of Science

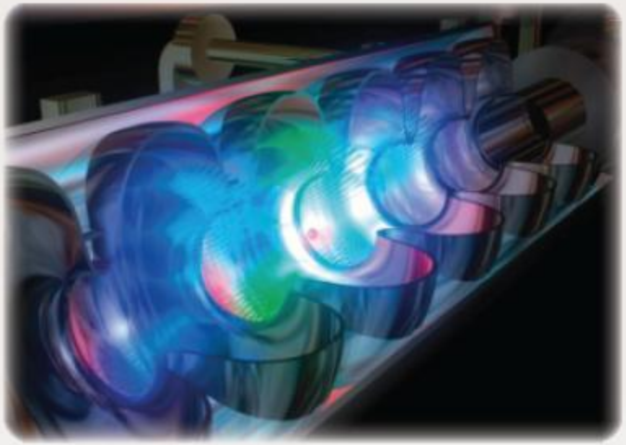


- Applications workshop: Santa Fe, Sep 28- Oct 1
- Contact: Brad Sherrill sherrill@frib.msu.edu

ARIEL Project Funded: $63M

TRIUMF ARIEL

ADVANCED RARE ISOTOPE LABORATORY



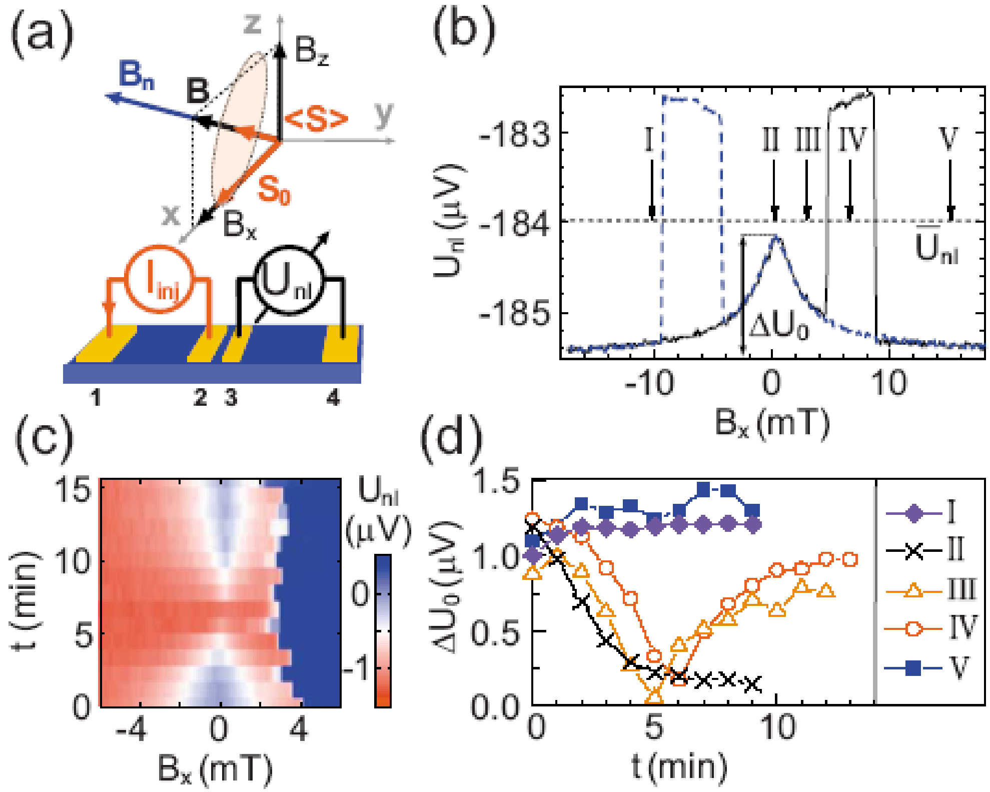
ARIEL is a new underground beam tunnel surrounding a next-generation linear accelerator – an e-linac, led by the University of Victoria. The project will allow TRIUMF to develop technology to advance Canada's supply of critical medical isotopes, capitalize on existing investments, and broaden its research capabilities in particle physics, nuclear physics, nuclear medicine, and materials science.

Summer School on
muon spin rotation and
beta NMR,
TRIUMF, Vancouver, July 2011

http://www.triumf.info/hosted/TSI/

Xtras

Transport Measurements of Spin Injection from Fe to GaAs



G. Salis et al., IBM Zurich, PRB 80, 115332 (2009)

Fundamental Interactions

Zeeman: $$h\nu_{\mathrm{Larmor}} = \boldsymbol{\mu}\cdot\mathbf{B}$$

magnetic dipole moment

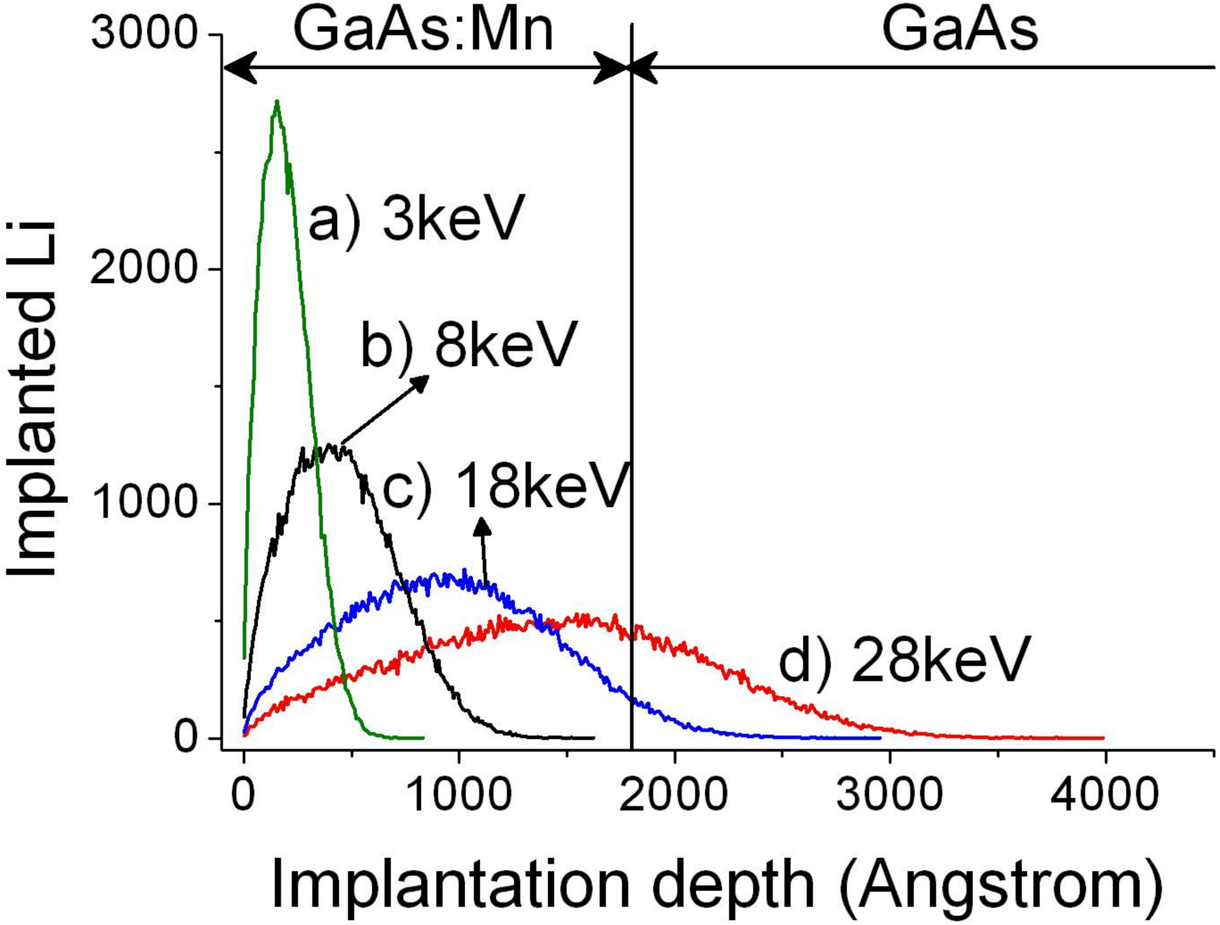
Quadrupolar: $$V_{ij} = \frac{\partial^2 V}{\partial x_i \partial x_j}$$ EFG

$$\nu_{\mathrm{Q}} = a \times eQ \times V_{zz}$$

electric quadrupole moment

$$H_Q = \frac{\nu_Q}{2}\left[3I_z^2 - I(I+1)\right]$$

$Ga_{1-x}Mn_xAs$ $^8Li^+$ Implantation



Temperature dependence of T_1