Complementarity of low energy βNMR and μSR

W.A. MacFarlane

Chemistry Department

University of British Columbia, Vancouver

TRIUMF ISAC

UBC

Plan

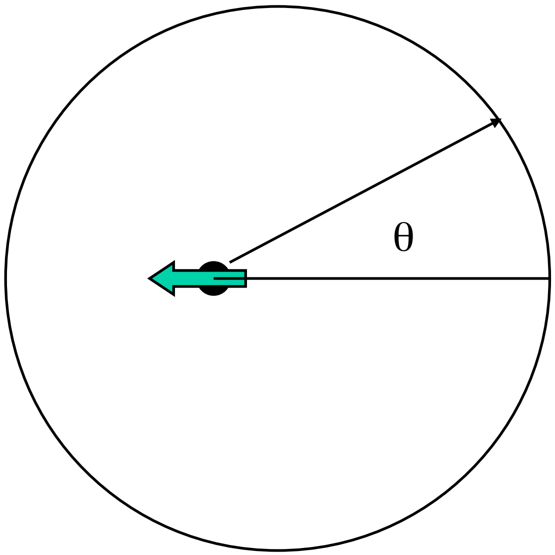
- Similarities of βNMR and LE μSR
- Some technical differences
- Some fundamental differences
- Types of measurements in βNMR
- An example

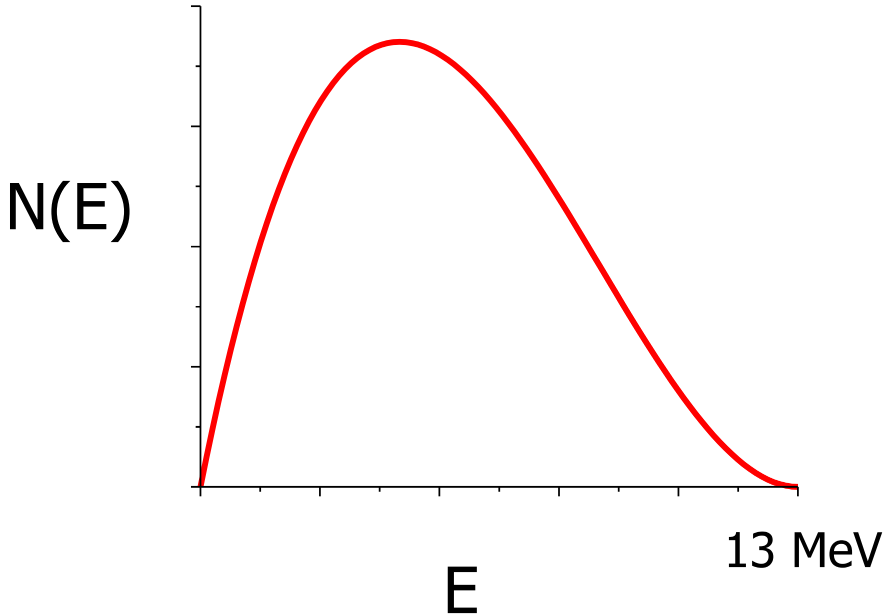
βNMR/μSR: similar basis, similar probes

- Implanted charged radioactive probes
- Parity violation of the weak decay
- observation of the asymmetry of beta particles yields local magnetic information like NMR

β–decay of ^8Li

$^8Li \rightarrow\ ^8Be + e^- + \nu_e$

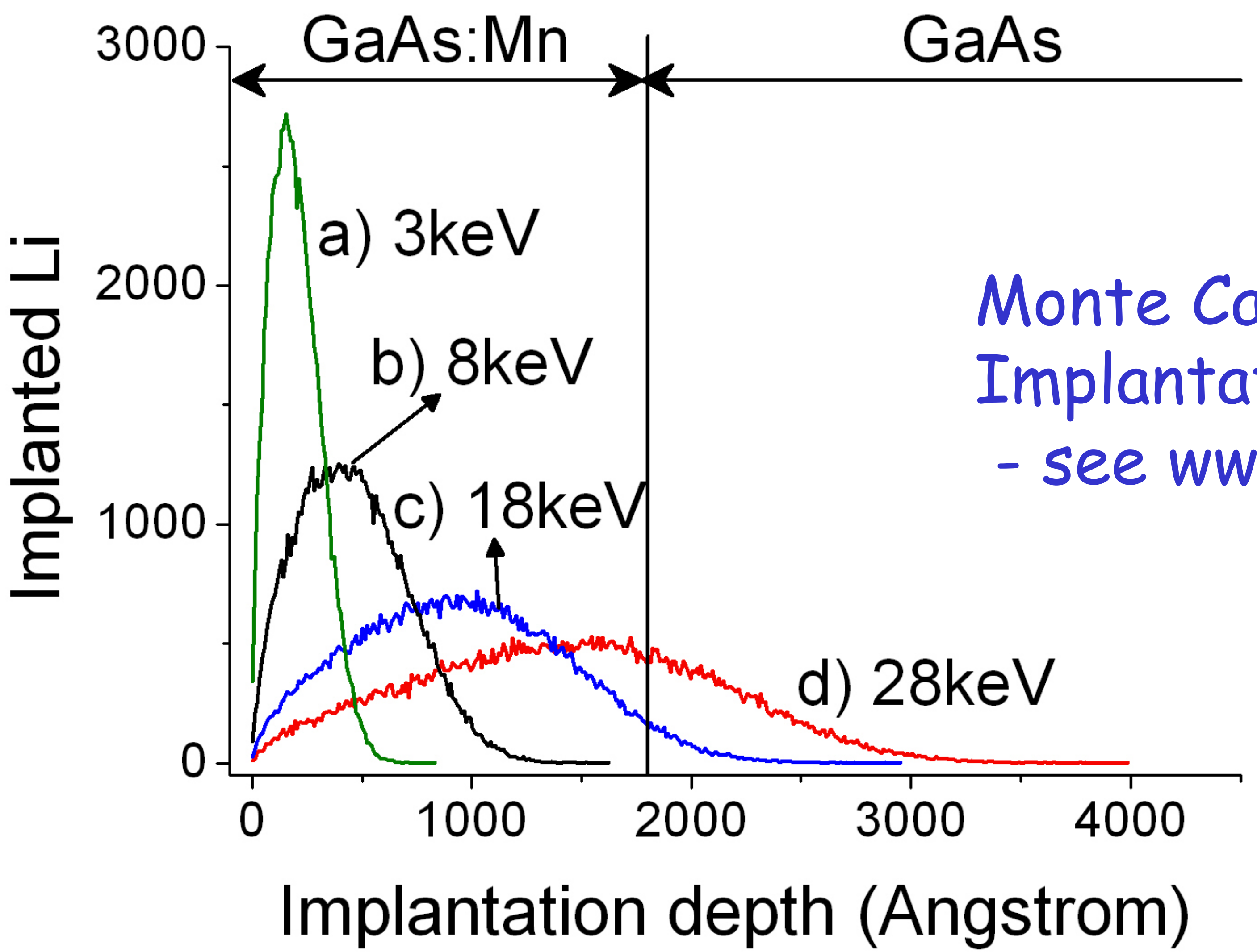




Low Energy

- Objective:
  thin films, heterostructures, near surfaces
- Electrostatic deceleration is possible
- Measurements *as a function of depth*
- Typical energy range 30 - 0.2 keV

Depth Resolution Example



Monte Carlo Implantation Profile
- see www.srim.org

$Ga_{1-x}Mn_xAs$ $^{8}Li^{+}$ Implantation, Q. Song

Some Technical Differences

- Production similar:

  spallation nuclear reactions

- Beam production:

  pion decay vs. surface ionization

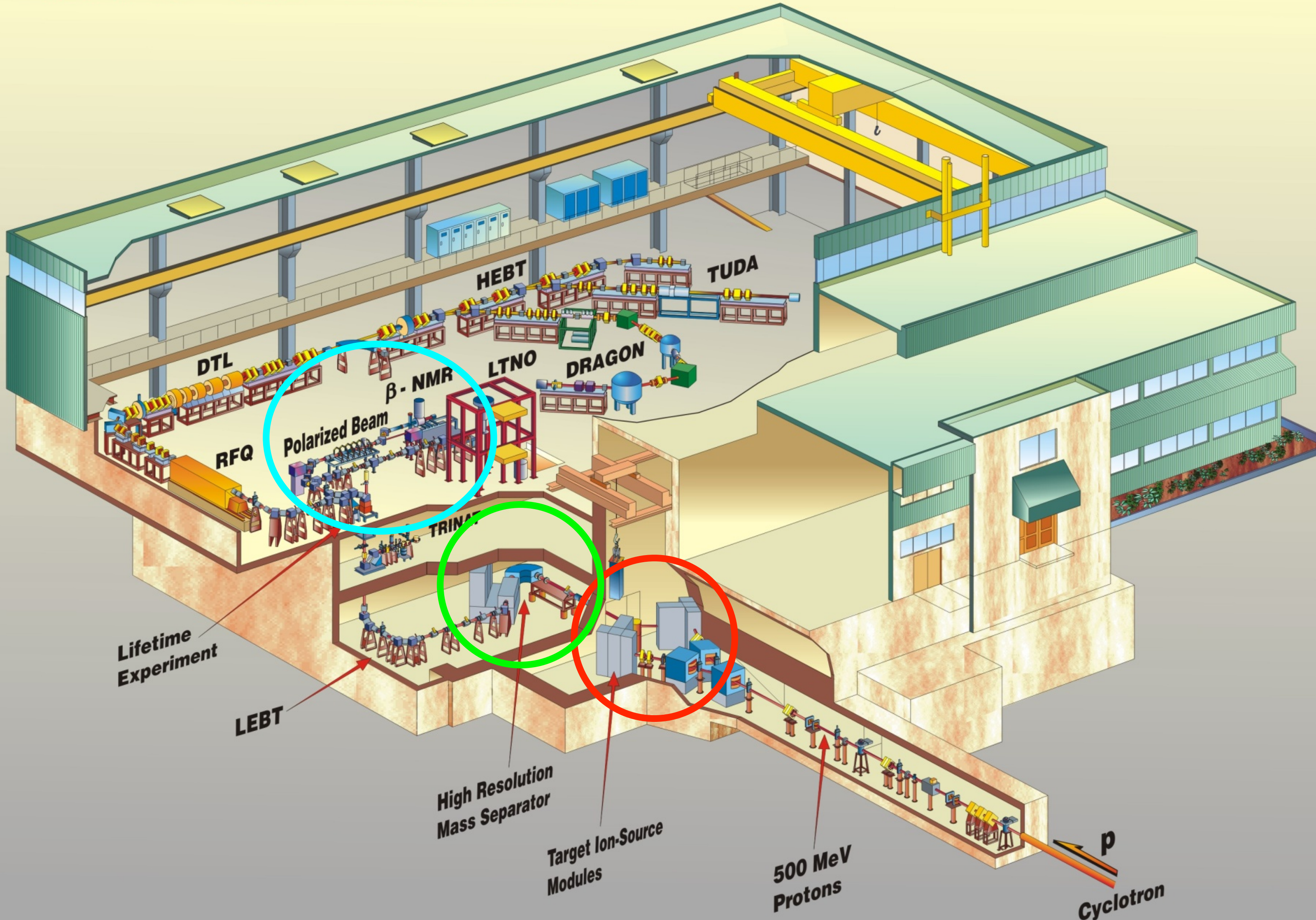
- Polarization:

  spontaneous vs. optical pumping

The TRIUMF Implementation of βNMR

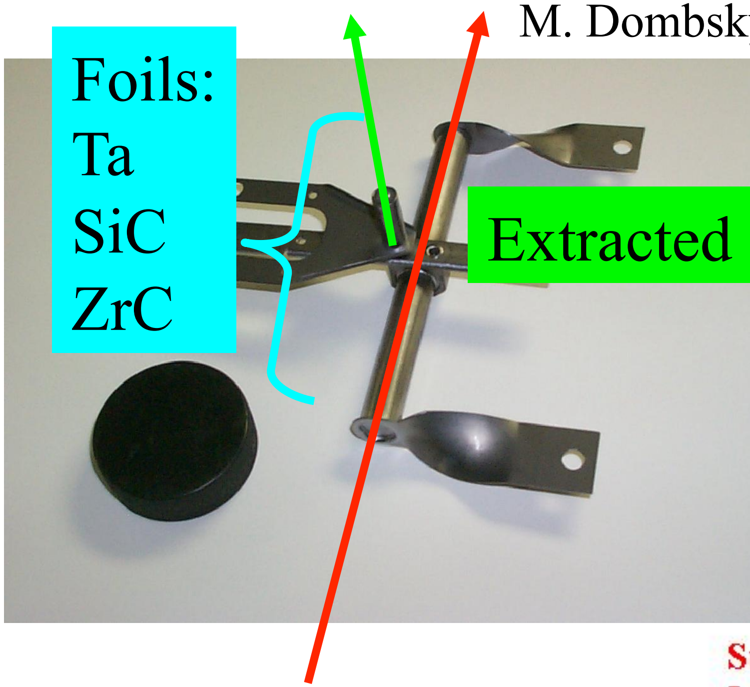
see
βNMR: Morris et al., Phys. Rev. Lett. **93**, 157601 (2004).
βNQR: Salman et al., Phys. Rev. B **70**, 104404 (2004).
facility: Kiefl et al., Physica B **326**, 189 (2003).
polarizer: Levy et al., NIMB **204**, 689 (2003).

ISAC at TRIUMF



ISAC Production Target

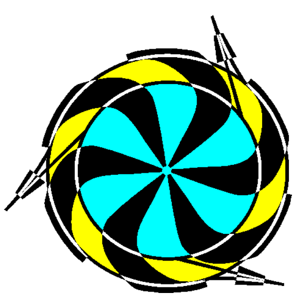
M. Dombsky/TRIUMF

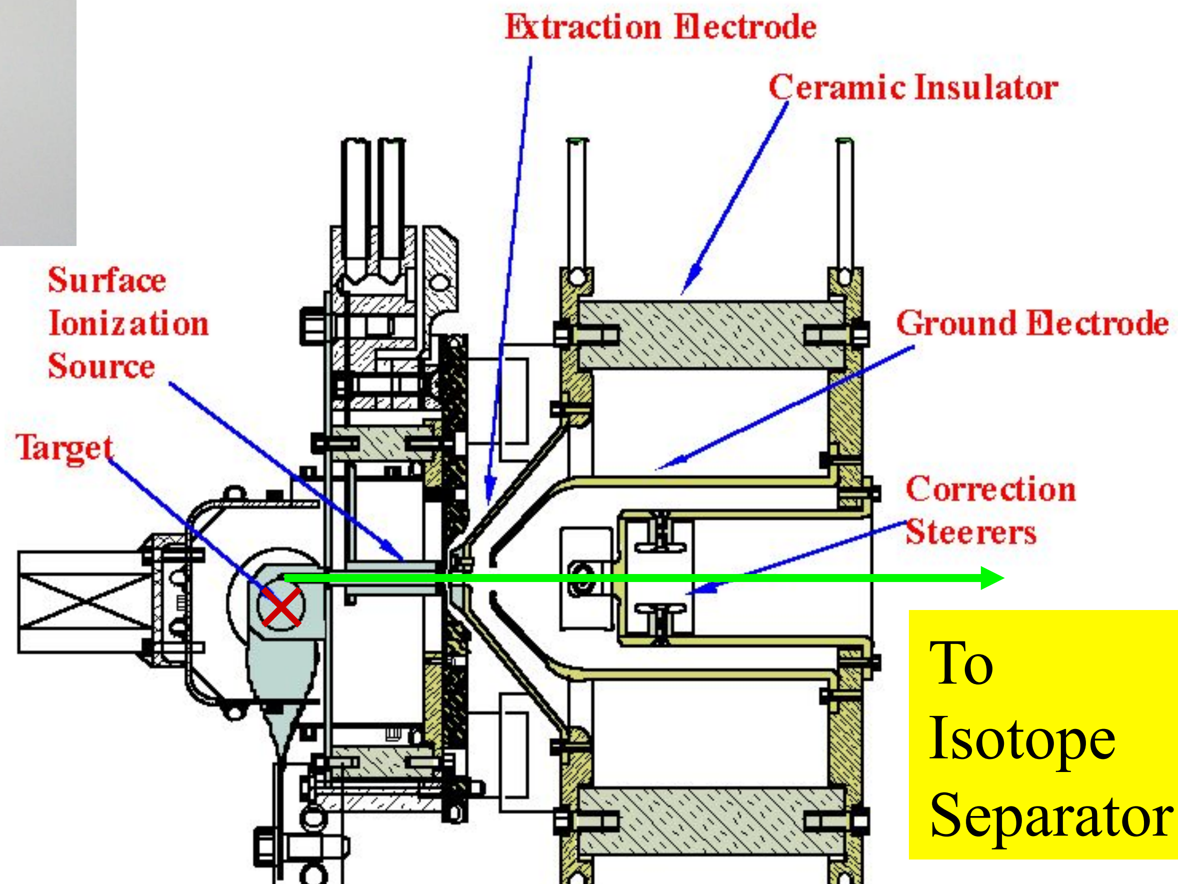


for Li^{+}: surface ionization

Extracted ion beam ~30 keV

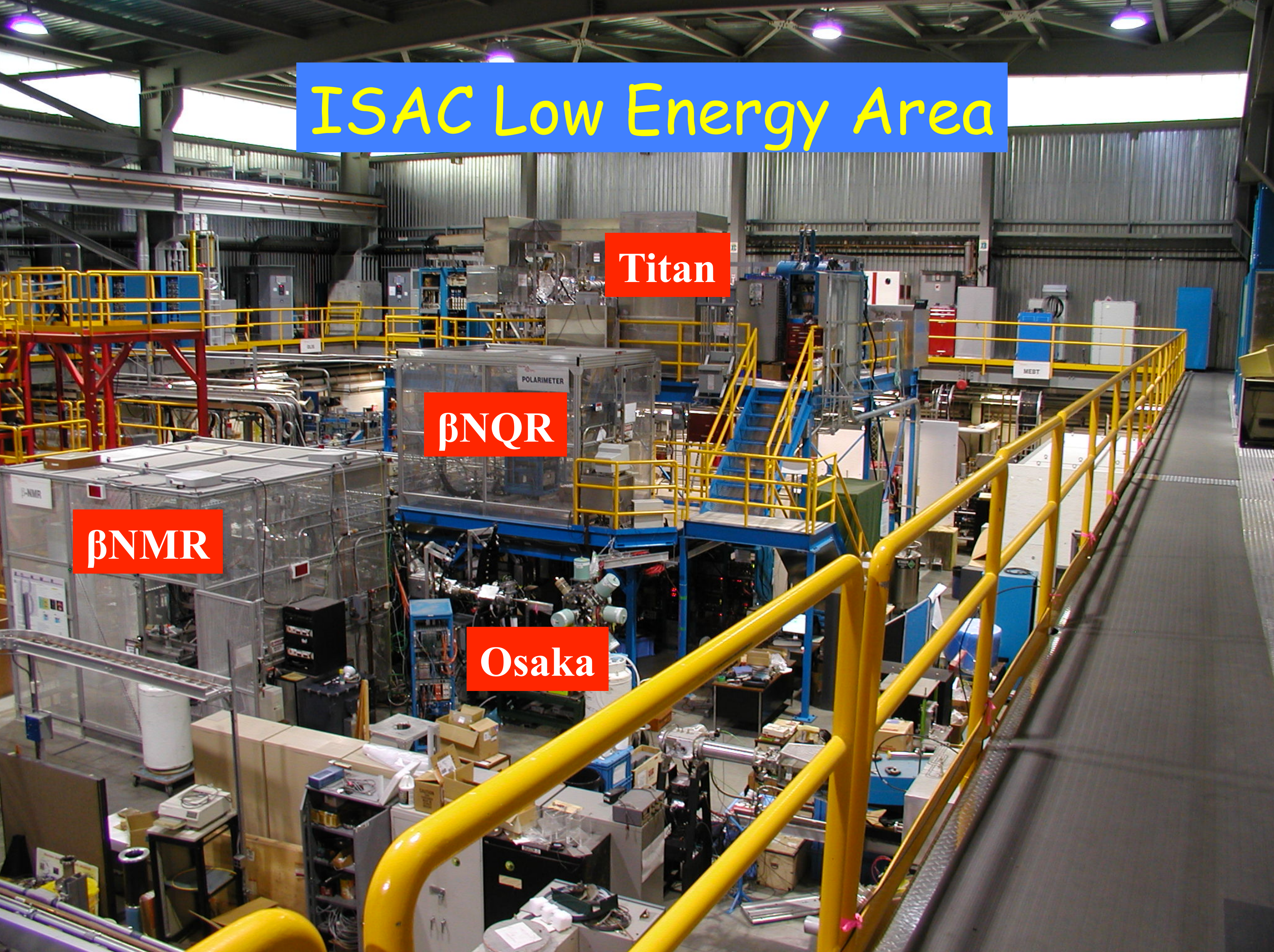
500 MeV
Proton Beam



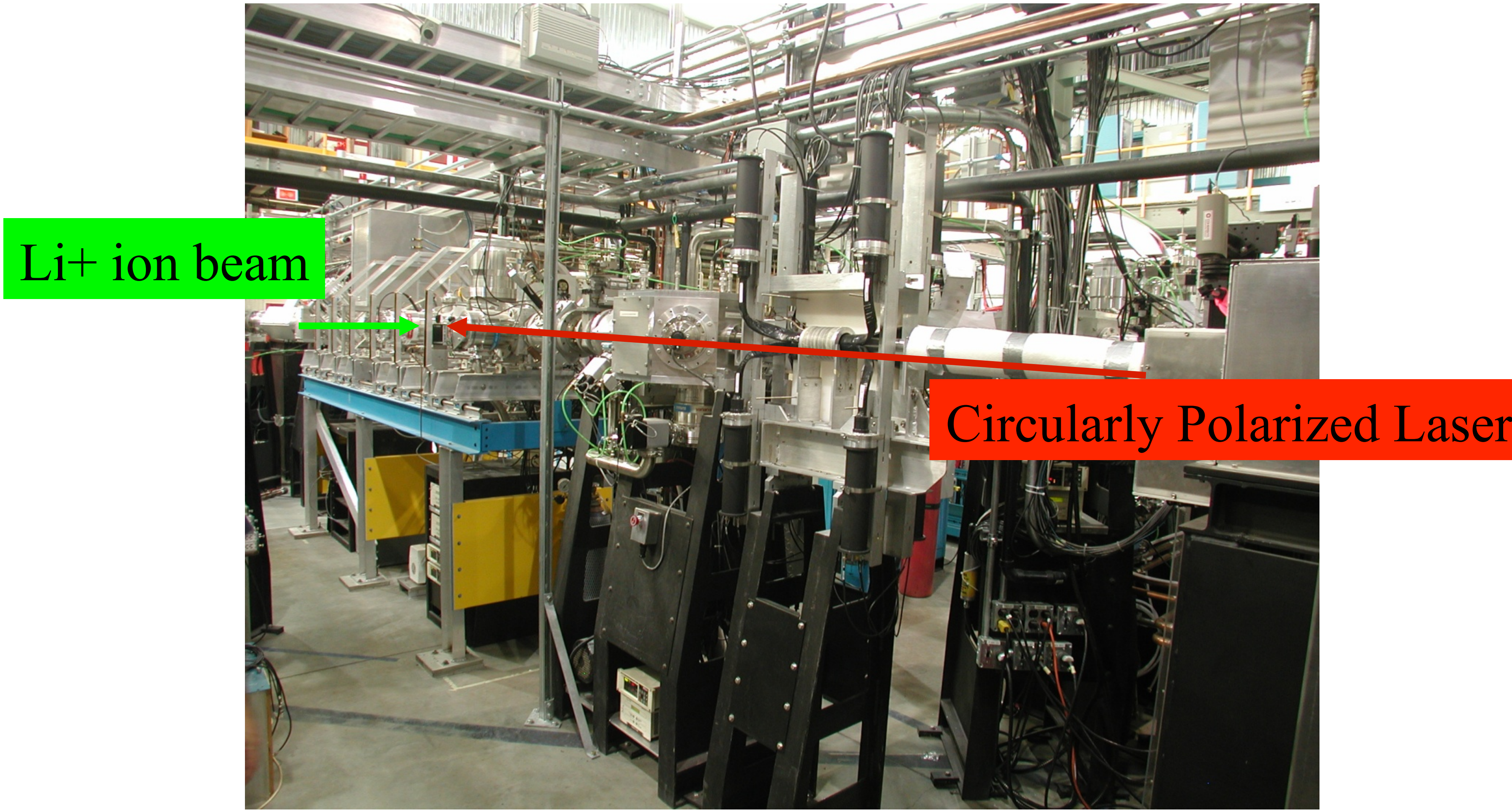


To
Isotope
Separator

ISAC Low Energy Area

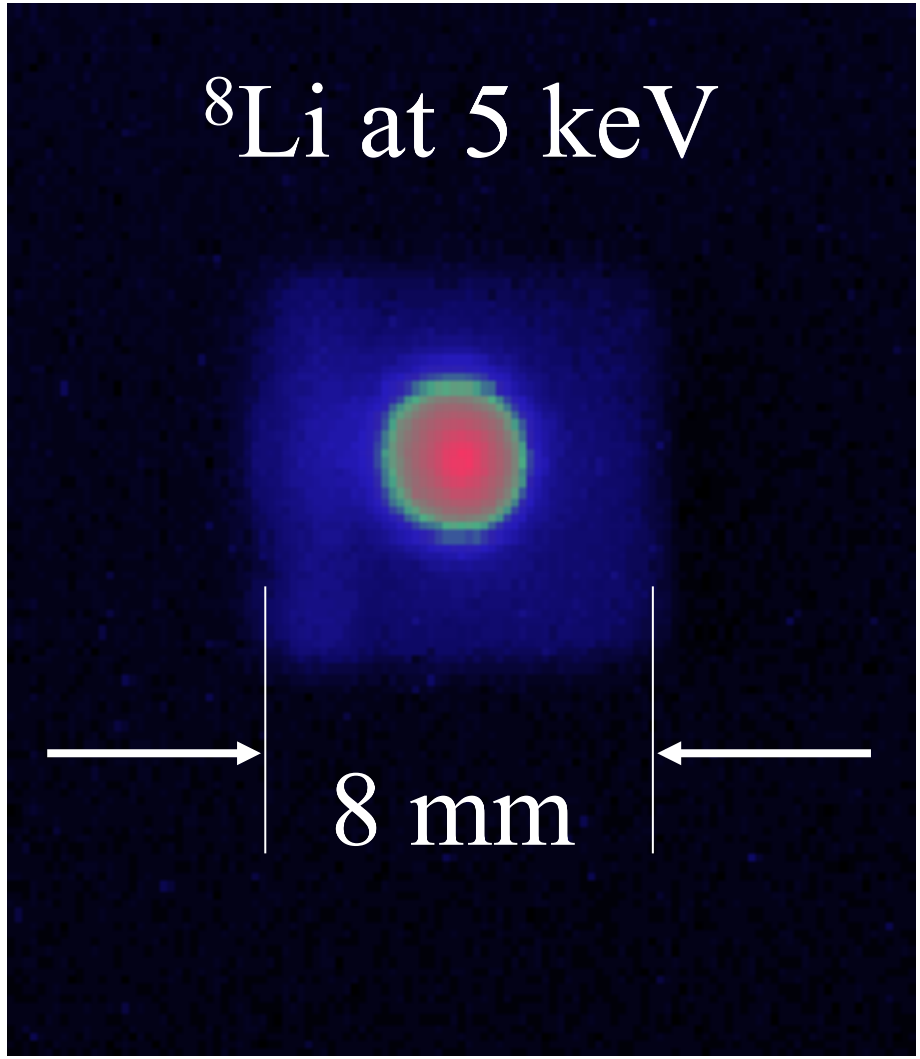


Optical Polarizer



D1 in Li: 671 nm

beam stopped
in scintillator,
imaged with CCD



Typical rate: ~10^7 spin polarized $^8Li^+$ per second

sample ladder

UHV

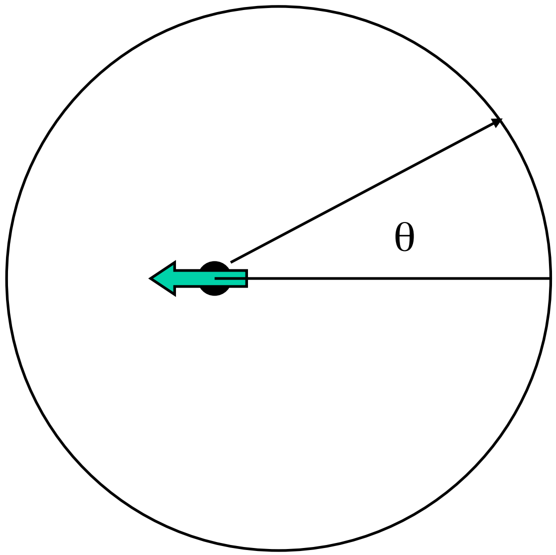
Ultra High
Vacuum

Fundamental Differences

- Probe Properties:
  - time range, fields sensed
  - mass difference ~72x
- One probe at a time:
  - βNMR no TM counter, history effects
- Beam flux:
  - $^{8}Li^{+}$ at TRIUMF ~10^{7} /sec typical
  - systematics limited, not statistics

β–decay of ^{8}Li

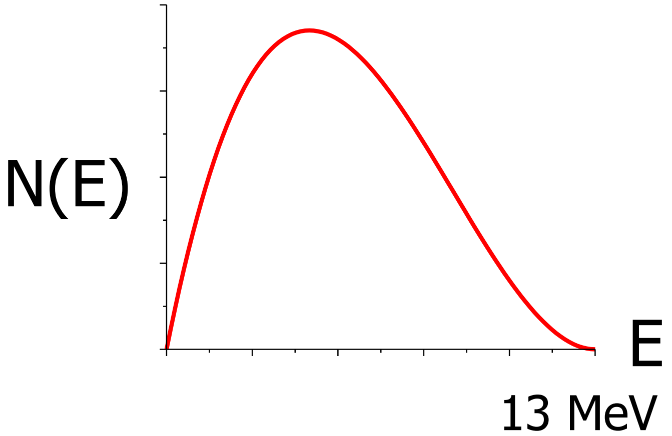
$^{8}Li \rightarrow {}^{8}Be + e^- + \nu_e$



Spin=2, Q=+31 mb

γ =6.3 MHz/T

<A>=-1/3



Radioactive lifetime: 1.2 seconds

i.e. ~10^6 times the μ^+

Probe Differences

- T_1: ^{8}Li 10 ms - 100 s, μ^+ 10 ns - 100 μs
- βNMR *timescale* like conventional NMR
- Sensitive to different phenomena

  μ^+ good for strongly magnetic systems, paramagnetic states etc.

  $^8Li^+$ slower relaxing systems, narrower field distributions
- resolution limit from probe lifetime
- No ZF βNMR (Kubo-Toyabe+ too fast)

except…

More Probe Differences

Quadrupolar vs. pure magnetic ($s = \frac{1}{2}$) probe

- Q couples to EFG
- EFG=0 at cubic sites, so no effect
- Quadruplar splitting and broadening can complicate data interpretation
- But EFG may be interesting (charge order…):

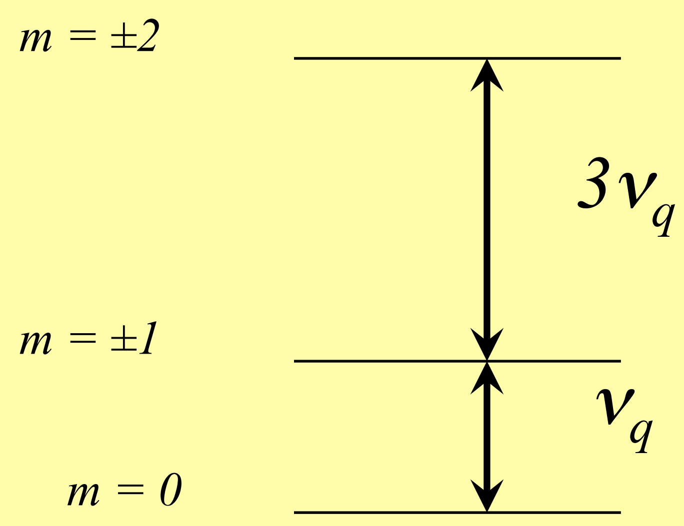
  direct coupling to the lattice
- Pure (zero field) NQR may be possible

The Zero Field Hamiltonian for the implanted ^{8}Li (I=2) in an axially symmetric electric field gradient (EFG) q is

$$H = h\nu_q (I_z^2 - 2)$$

$$\nu_q = \frac{e^2 q Q}{8}$$

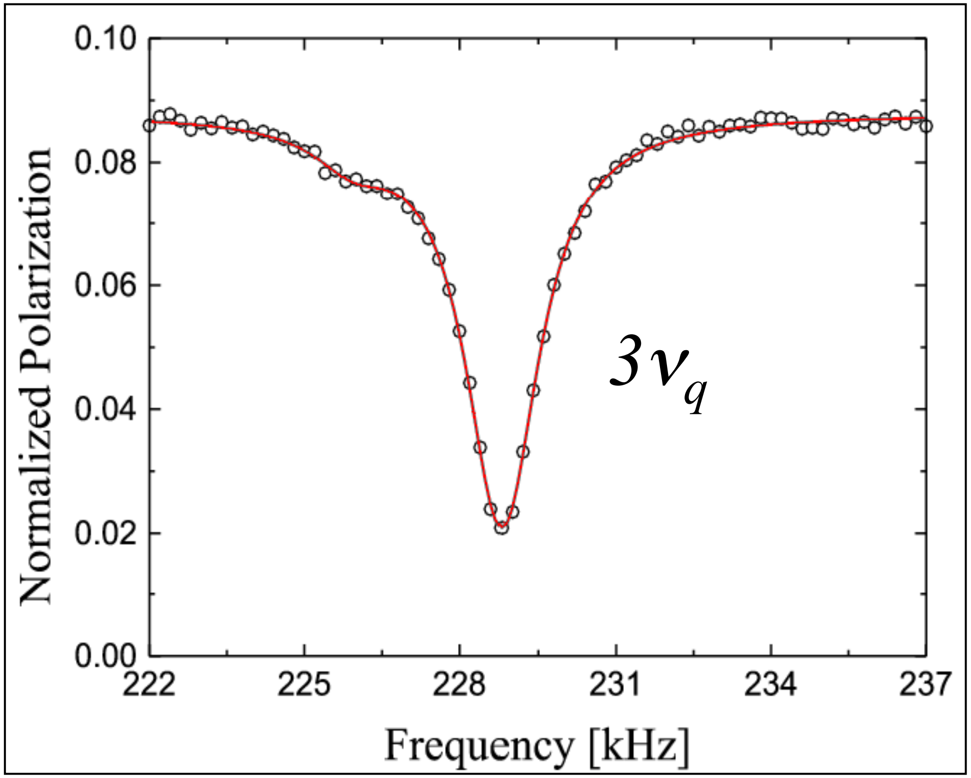
$$E_m = h\nu_q (m^2 - 2)$$



β-NQuadrupoleR

Phys. Rev. B **70** 104404 (2004)

First ever beta-detected NQR in $SrTiO_3$

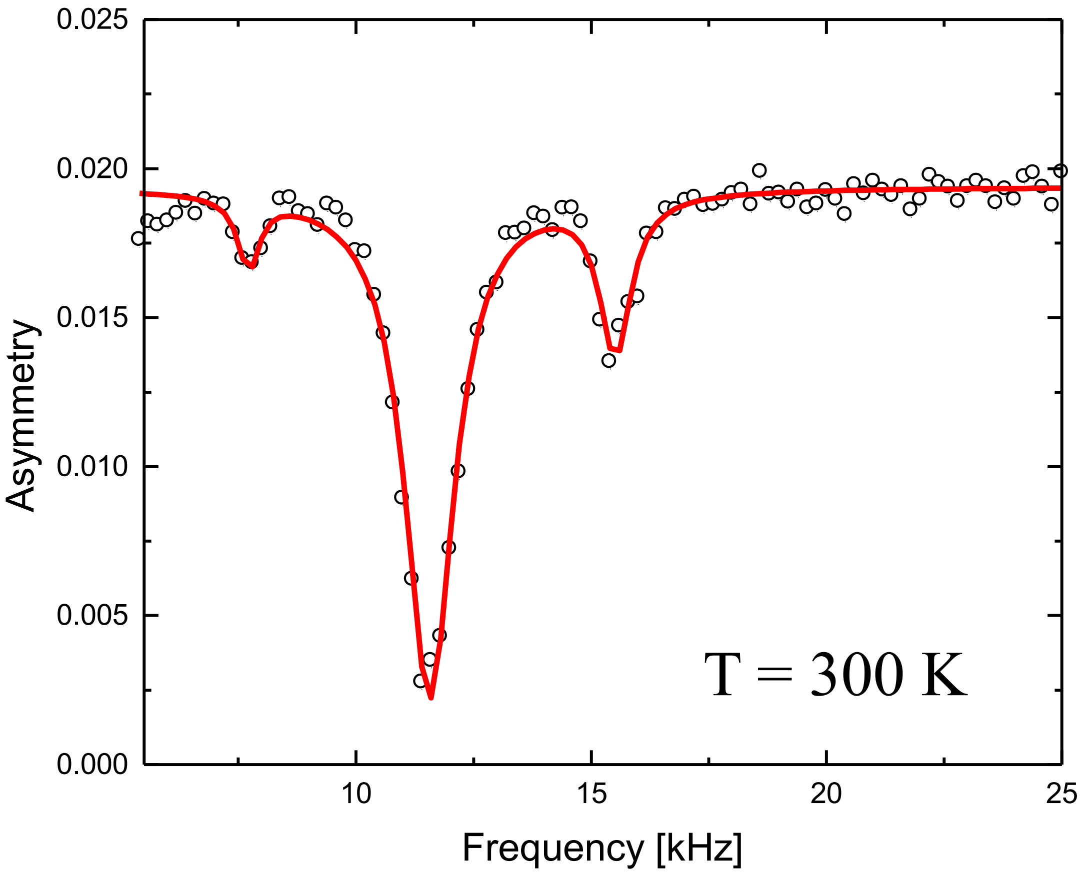


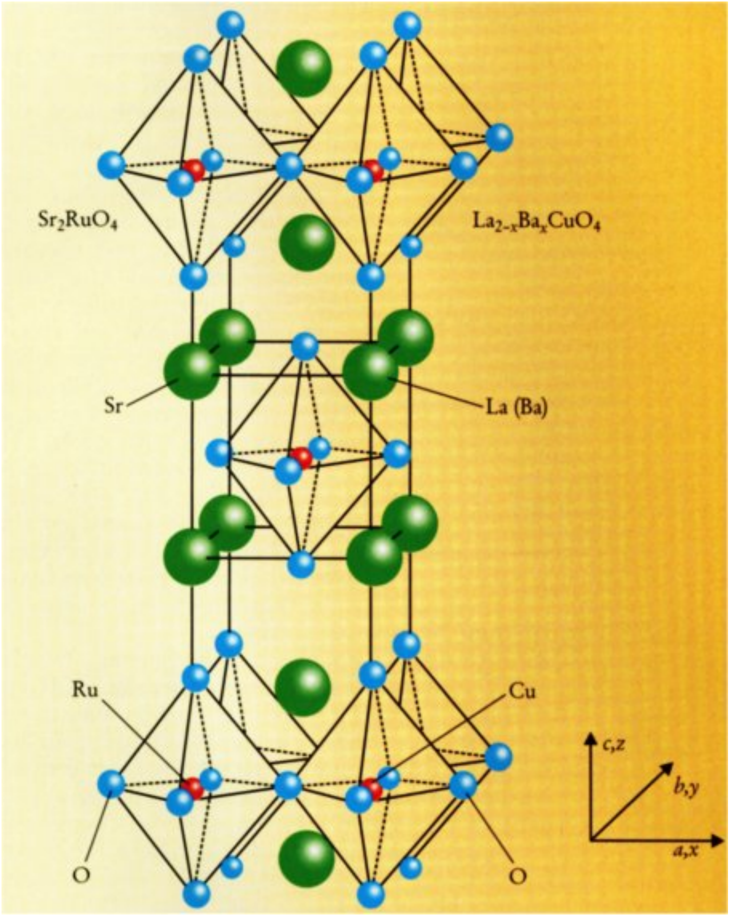
Room Temperature β-NQR Resonance in $SrTiO_3$

Physica B **374-375** (2006) 239-242

Other materials

^8Li βNQR in Sr_2RuO_4



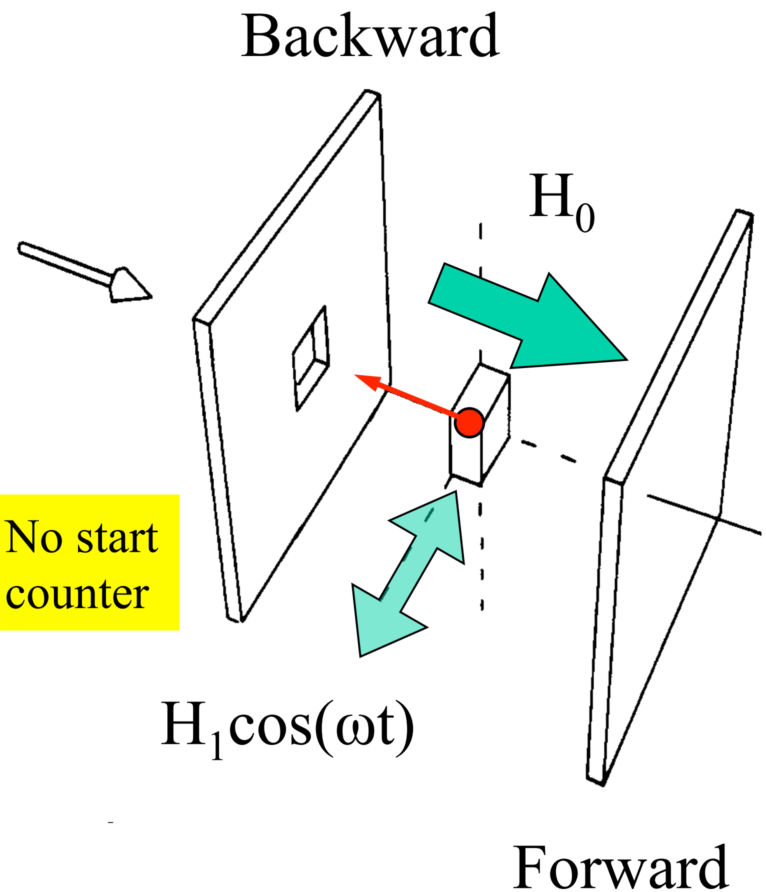


(Maeno, Kyoto)

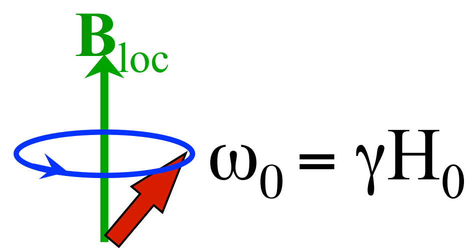
Low T (300 mK) capability funded and in design

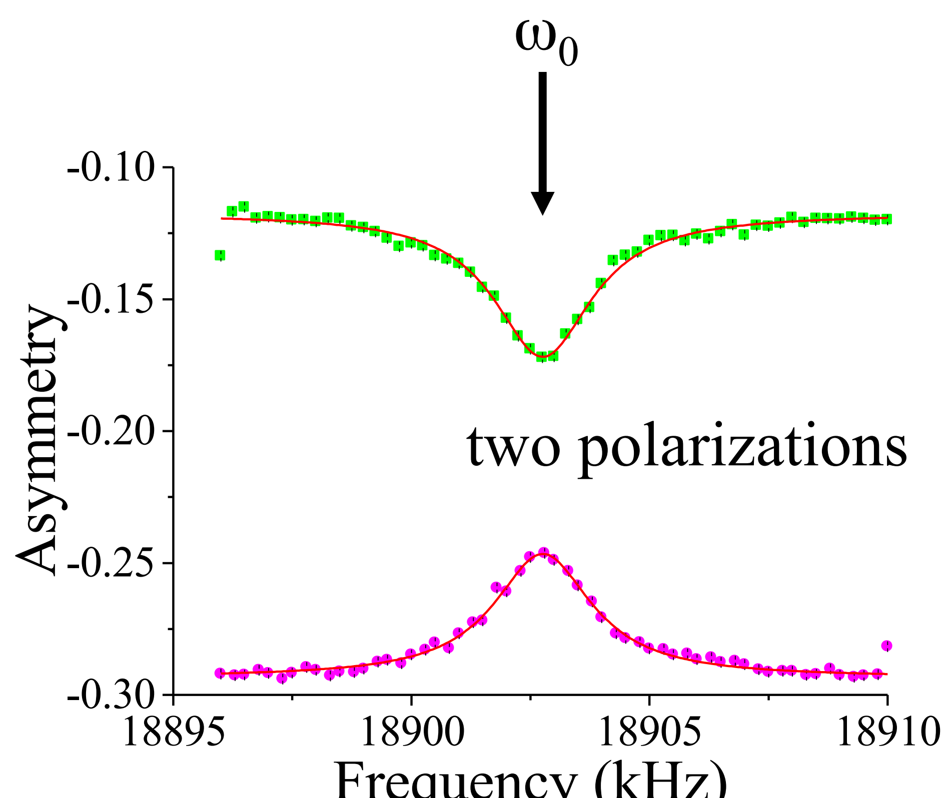
βNMR: Types of Measurements

βNMResonance



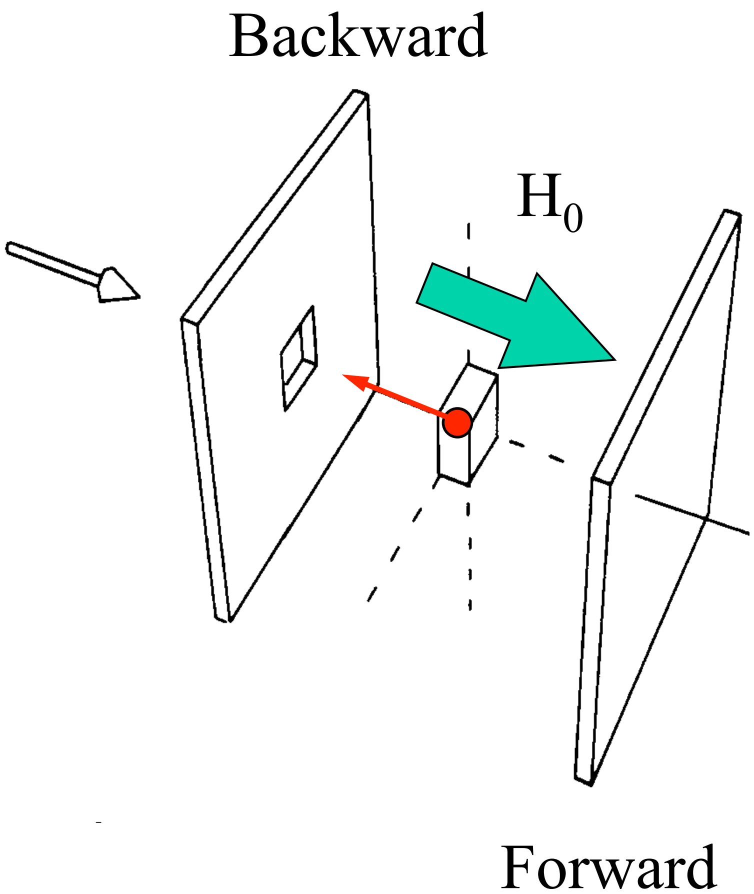
No start counter

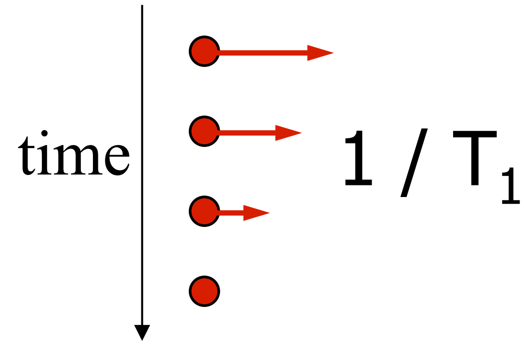




measure directly in the frequency domain
no FFT, no apodization

βNMR Measurement of the Spin Lattice Relaxation Rate



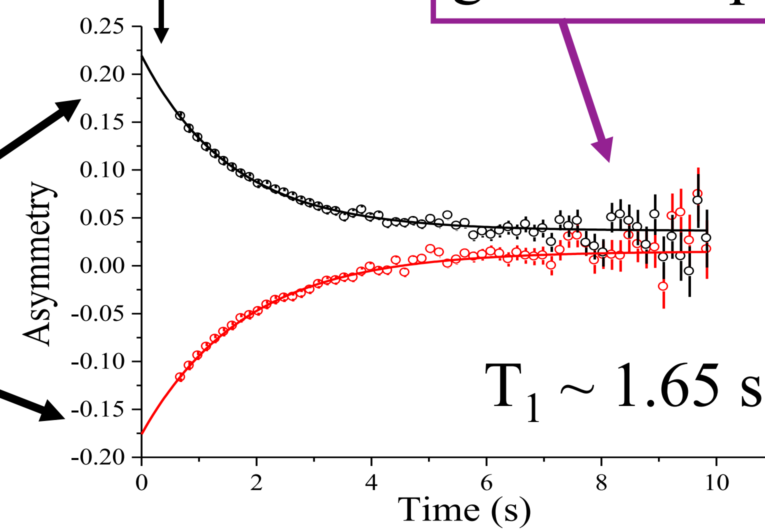


Pd Foil
T = 293 K
B_0 ~ 140 G
E_{Li} = 30 keV

Beam on
For 0.5s

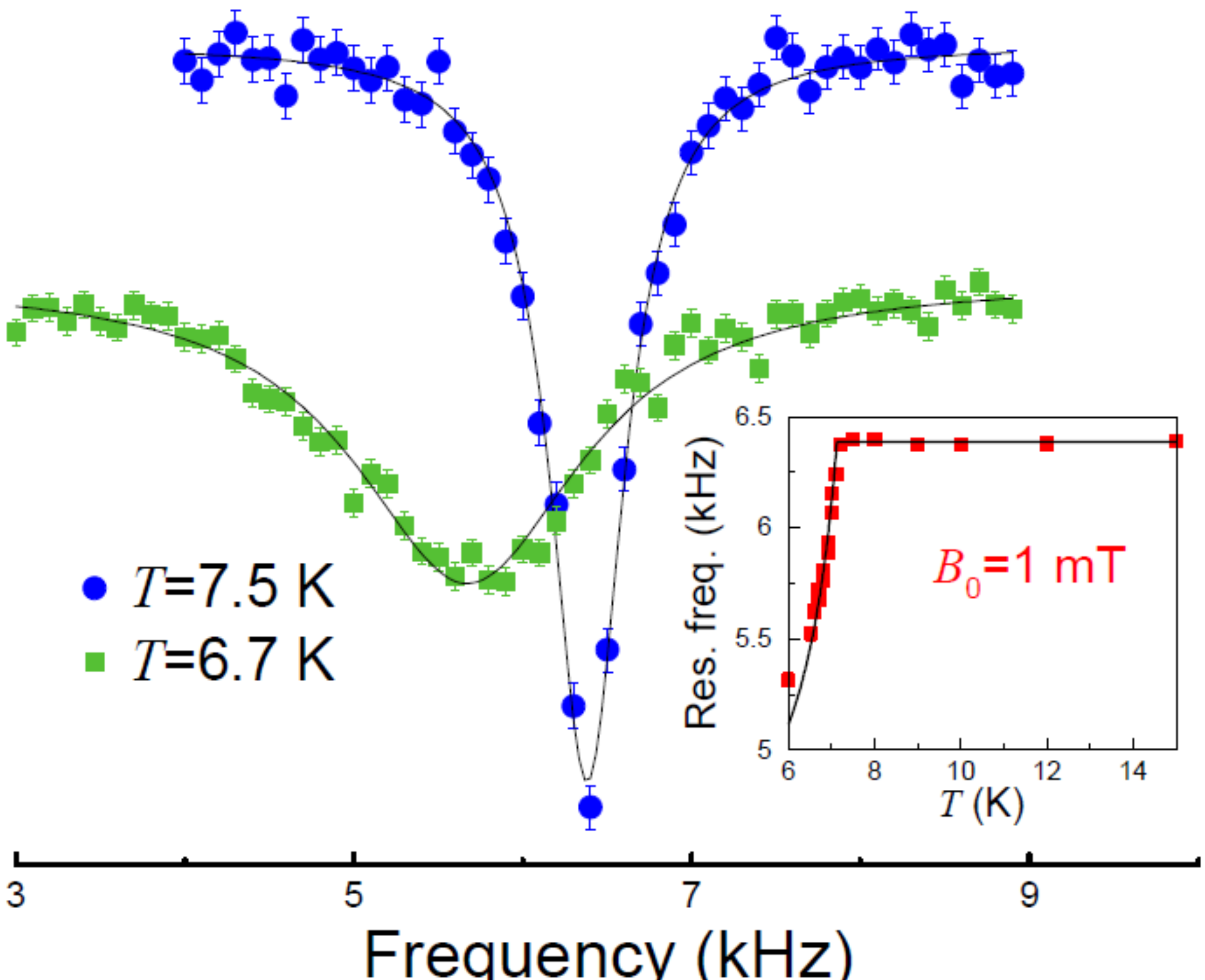
nb: error bars
grow as exp(t/τ)

data for the
two polarizations

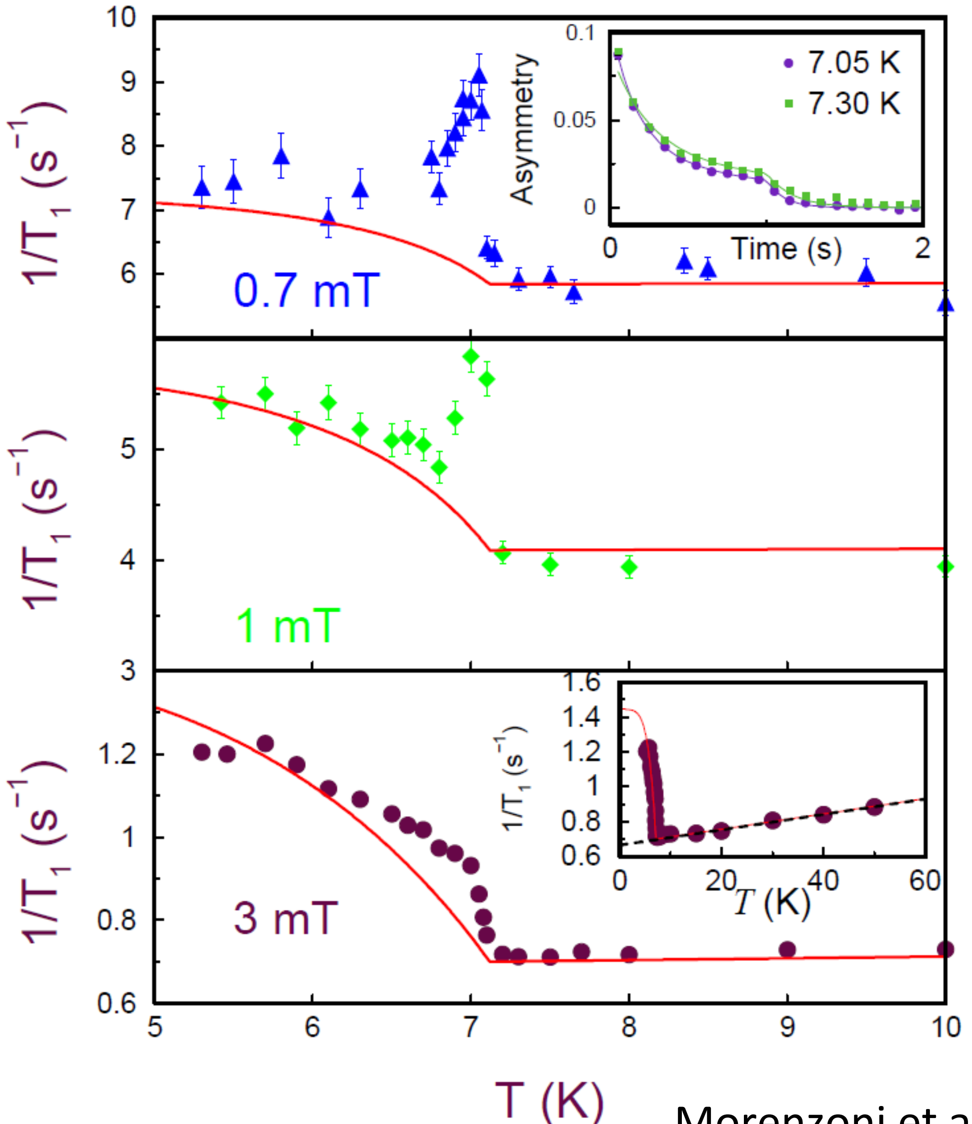


One Example

Meissner Effect in a Pb film



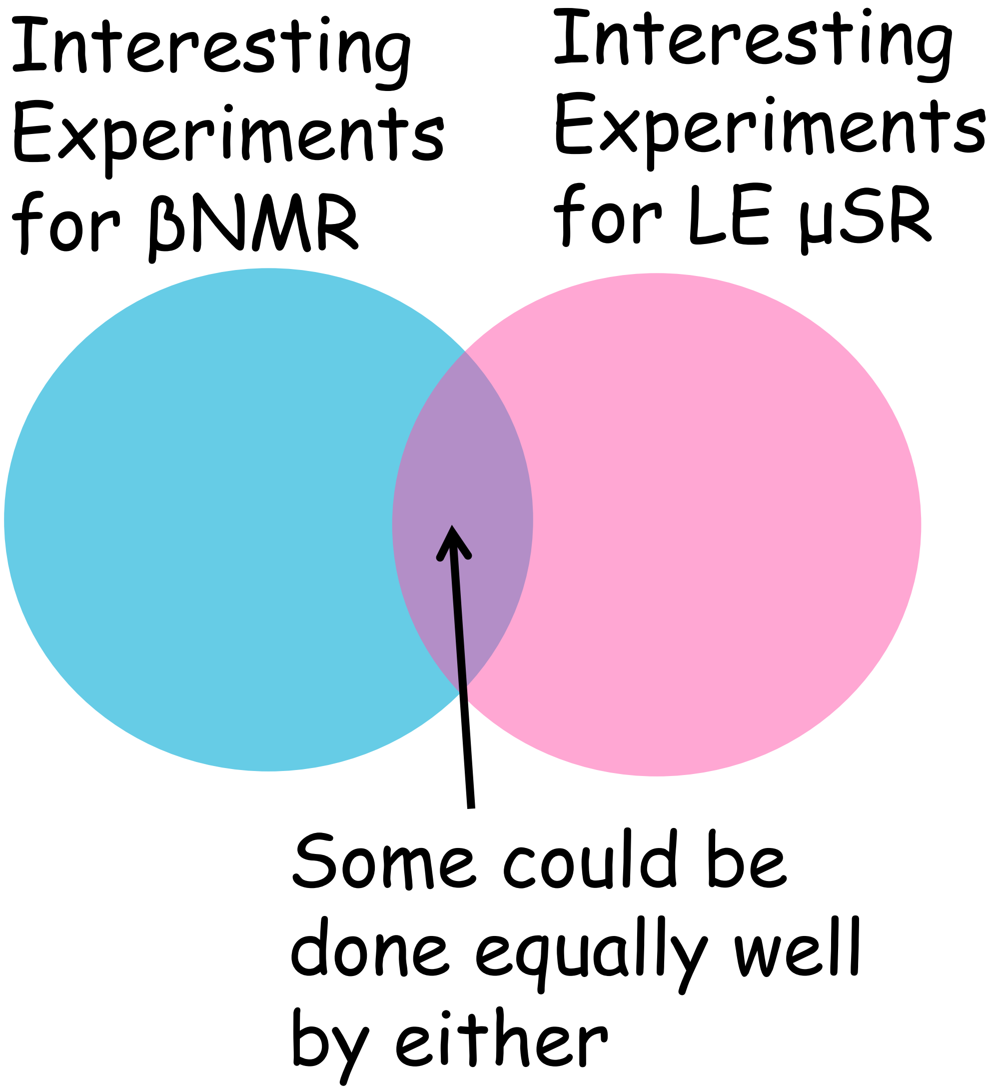
Superconducting Fluctuations in Pb

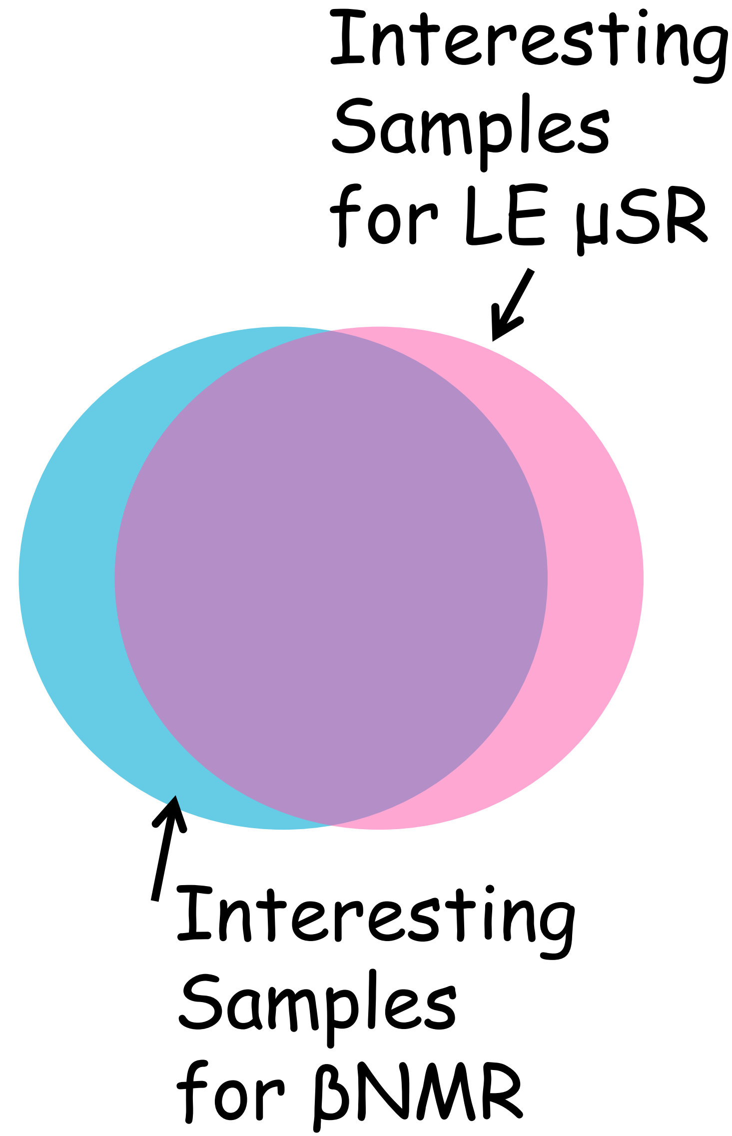


Morenzoni et al, submitted to Phys. Rev.

A BIG Difference

Experience





End

more info: bnmr.triumf.ca

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)

“Hyperfine” Local Probes

$$M = \chi H$$

Magnetic Susceptibility

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

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

Relaxation:

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

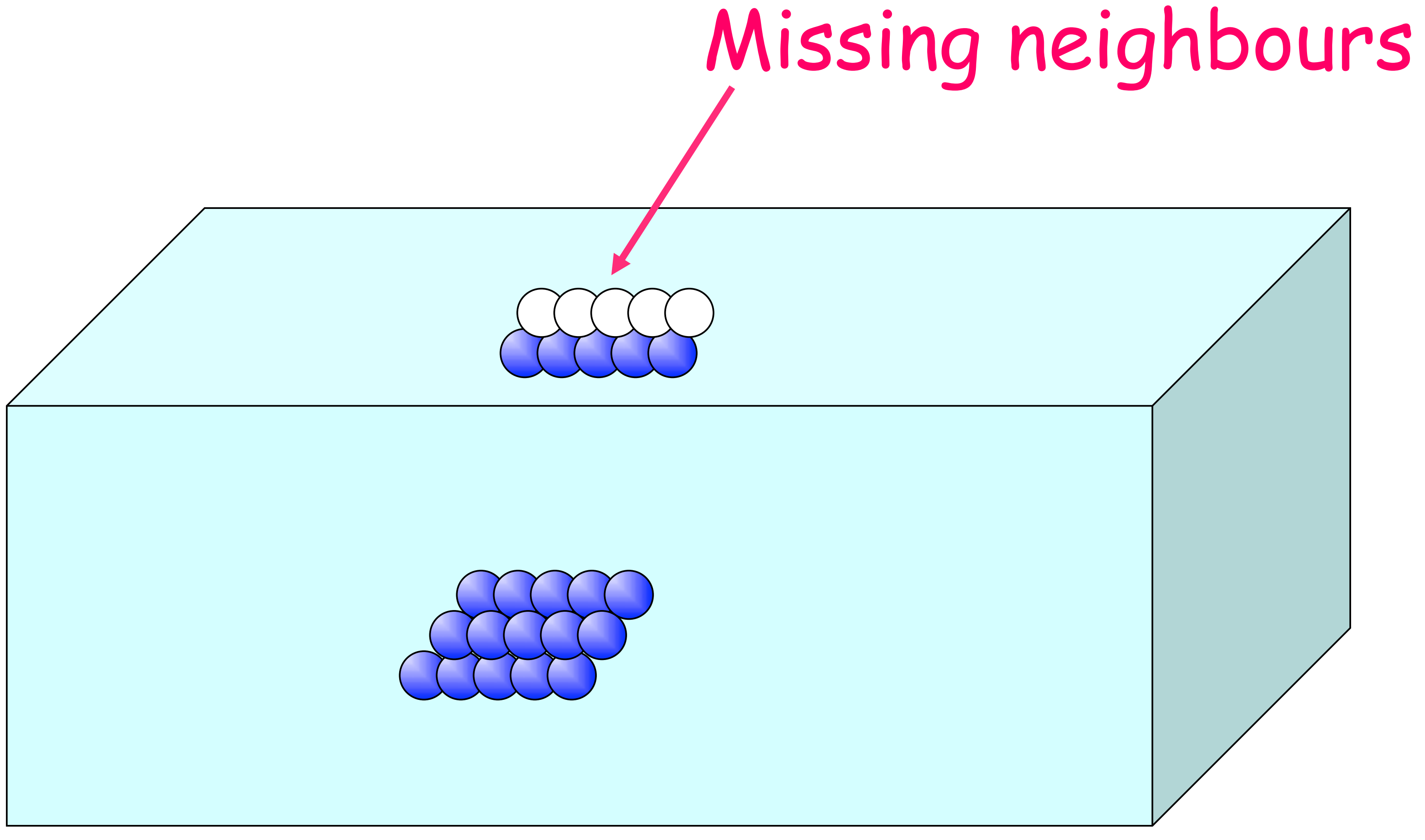
Moriya Expression

In the RF (μeV to zero)

also: quadrupolar effects, diamagnetic shielding, ...

Structural Phase Transitions near a Free Surface: $SrTiO_3$

Free Surface: Breaks Symmetry



Phase Transitions at Surfaces and Interfaces

Original theory:

Binder and Hohenberg, PRB **9** 2194 (1974)

Mills, PRB **3**, 3887 (1971)

Recent review:

M. Pleimling, J. Phys. A **37**, R79 (2004)

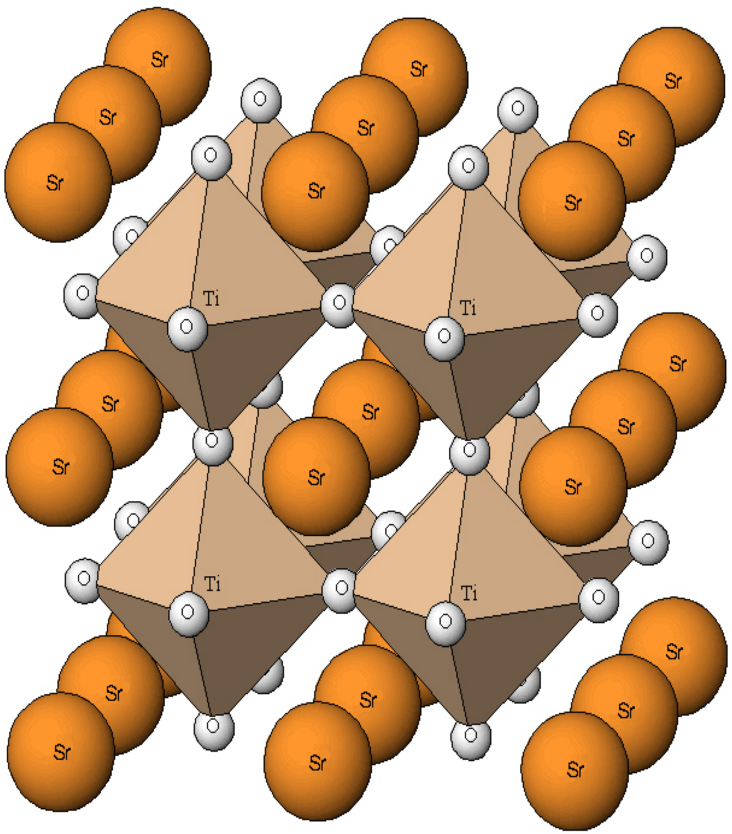
Experiments: see, e.g., H. Dosch

$SrTiO_3$

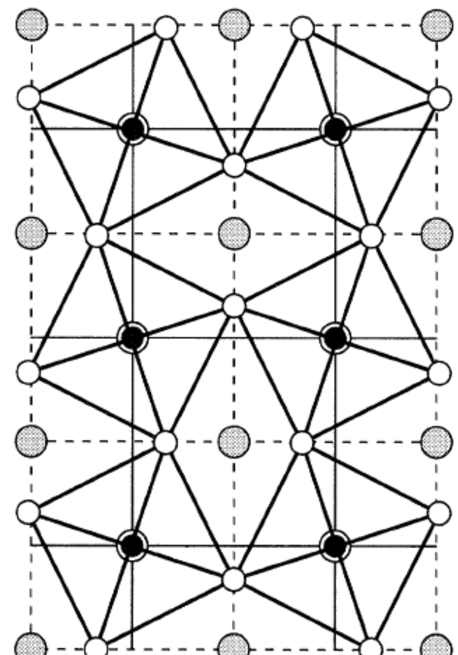
Cubic to tetragonal (105 K)

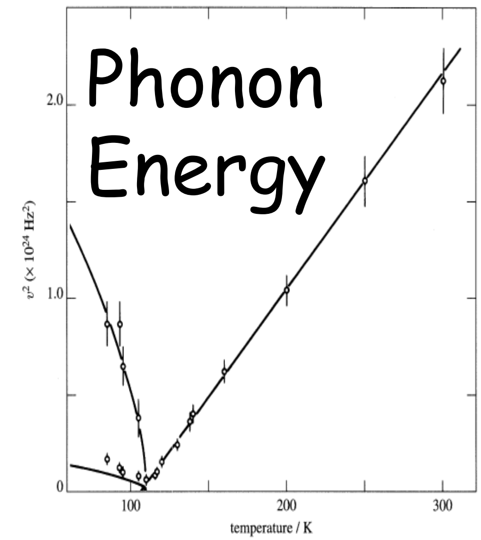
Soft Mode Phase Transition

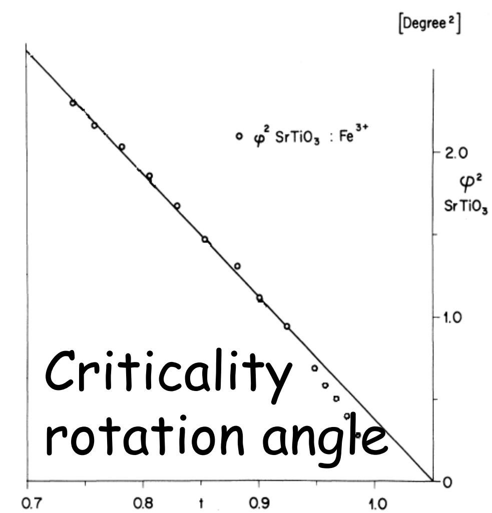
- Cubic Perovskite structure



$SrTiO_3$ Cubic Perovskite Lattice Structure



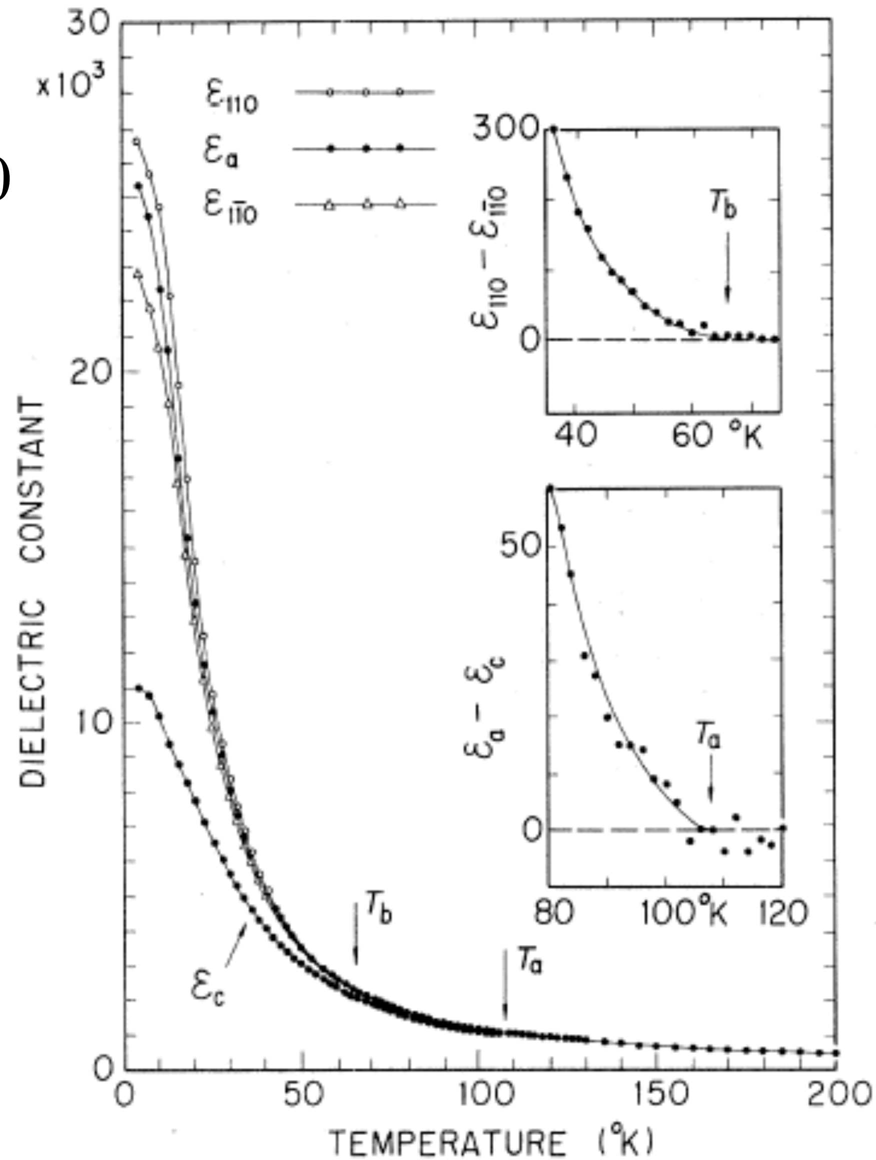




TiO_6 Octahedra Rotation, T dependence of the phonon frequencies, and T dependence of the order parameter

Dielectric Constant of $SrTiO_3$

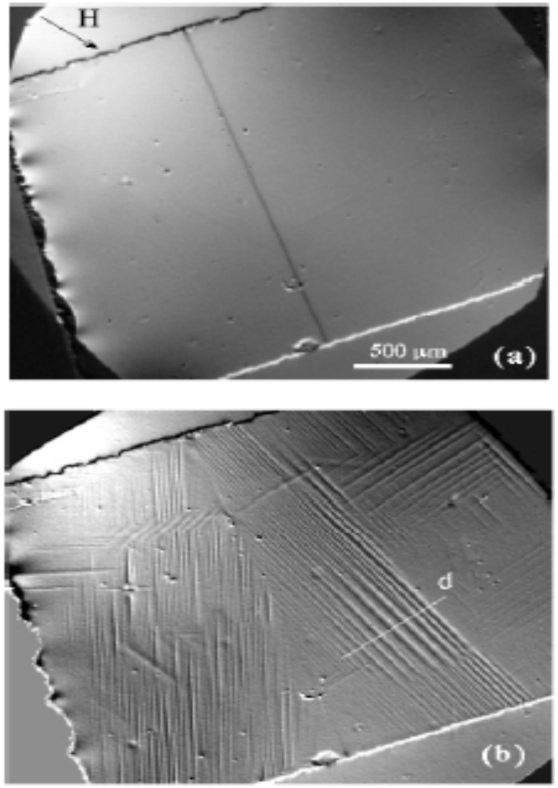
25000



A quantum paraelectric

Sakudo and Unoki
PRL **26,** 851 (1971)

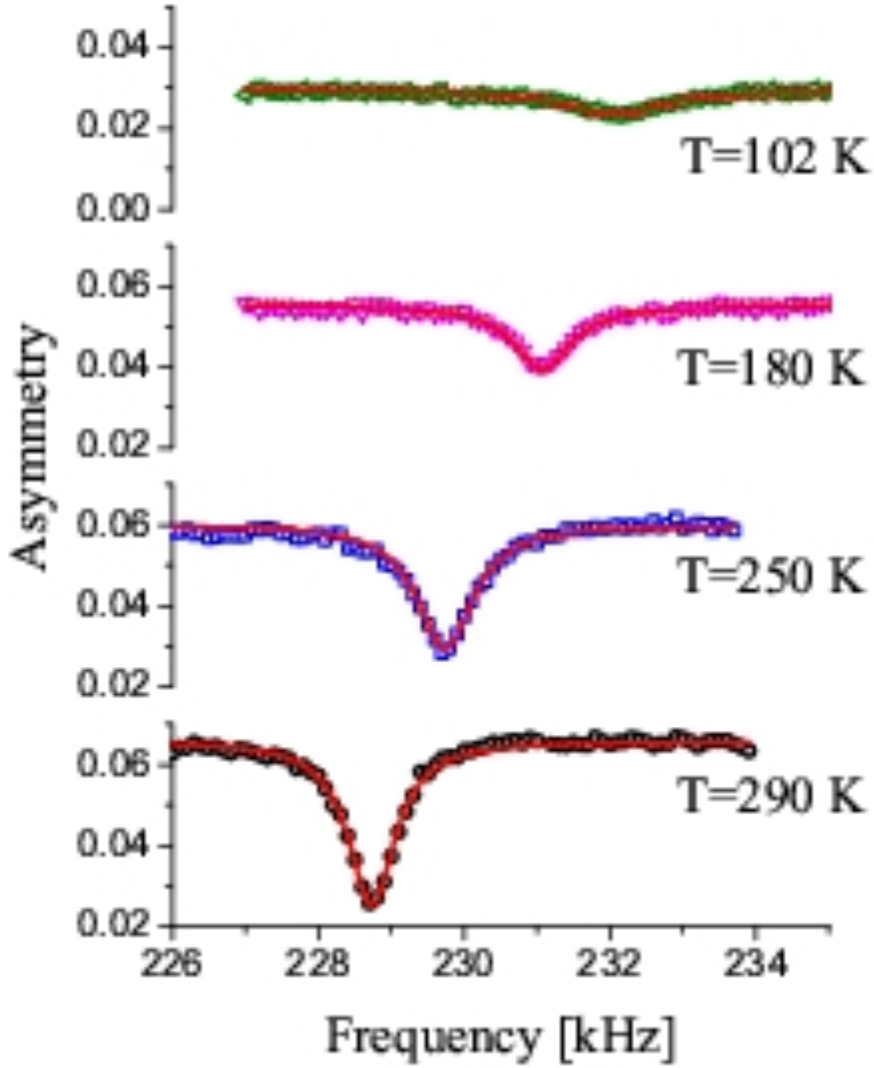
STO substrate:
transition affects overlayers



1000Å LCMO film on $SrTiO_3$
a) T > 105K   b) T < 105K

Vlasko-Vlasov et al. PRL **84**, 2239 (2000)

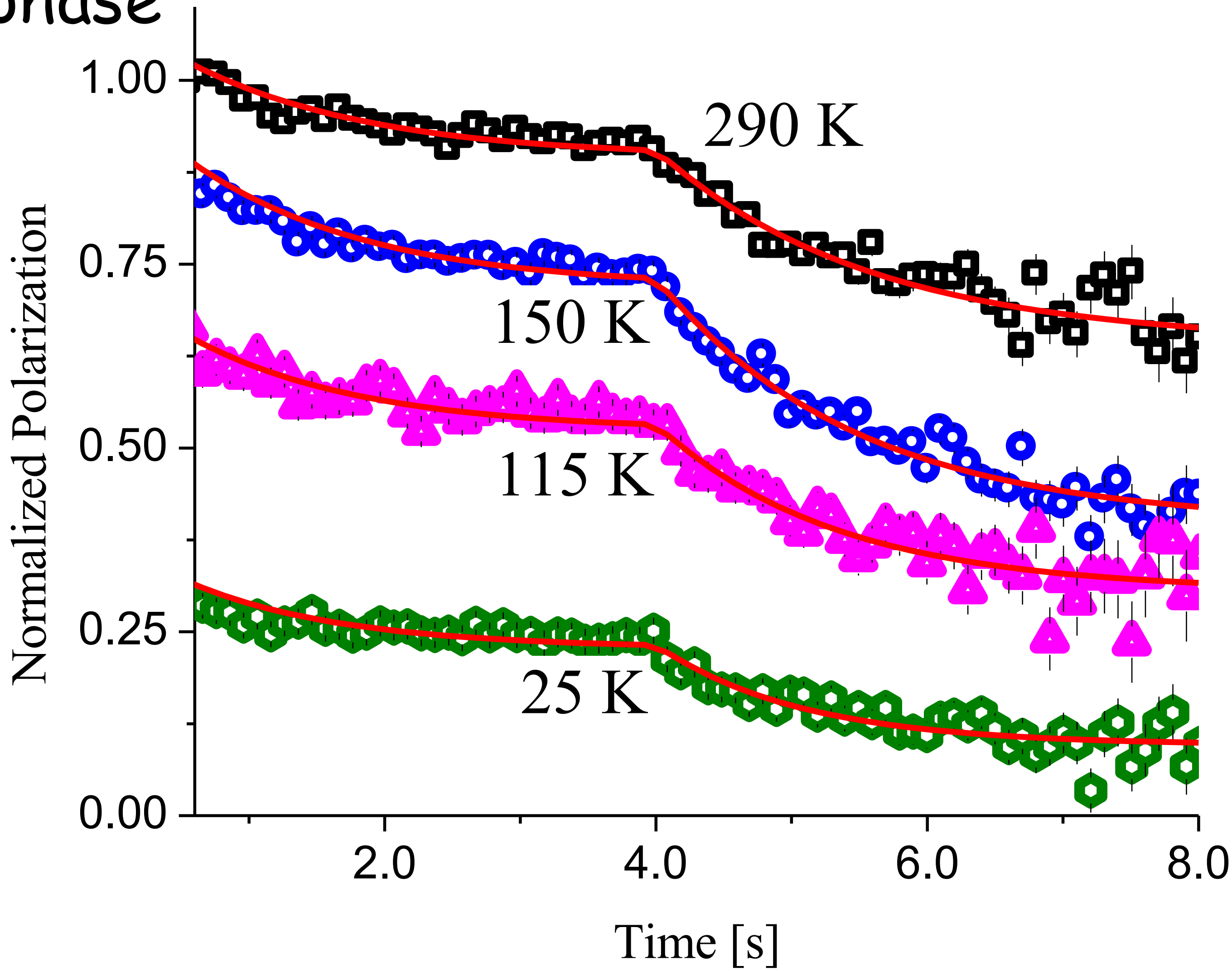
Temperature Dependence of the βNQR



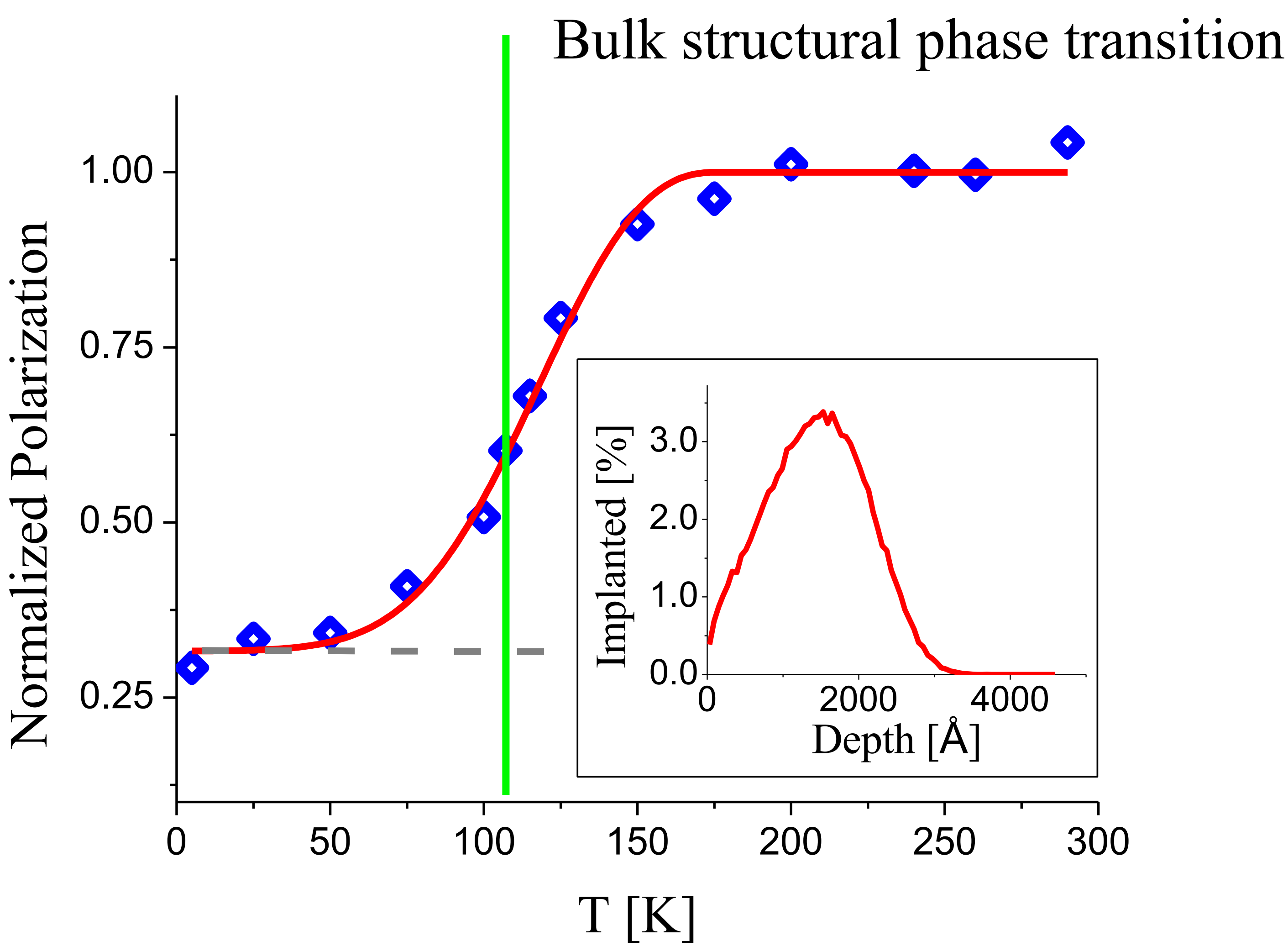
Z. Salman et al. PRL **96**, 147601 (2006)

Spin Relaxation "T_1"

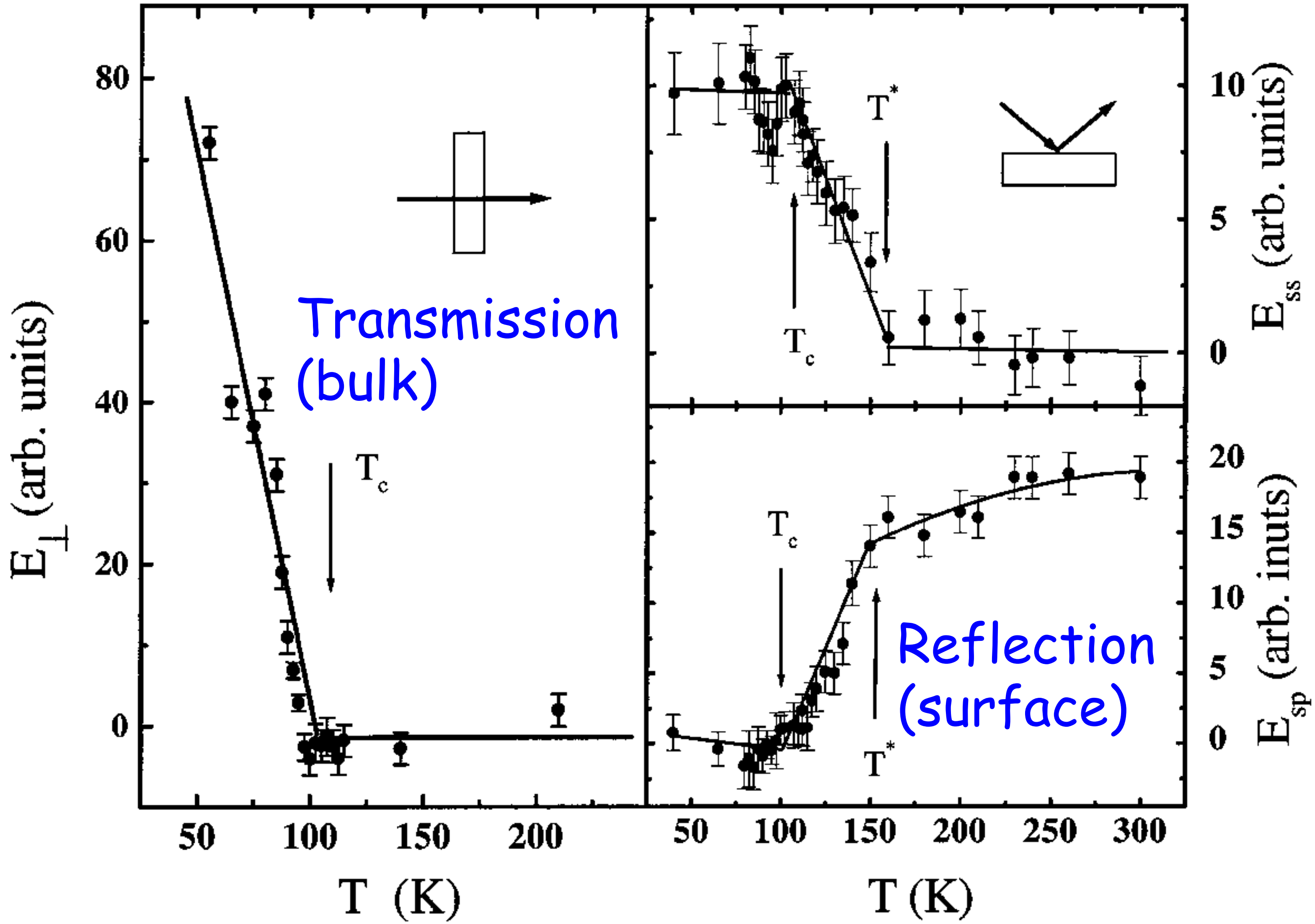
Cubic phase



Temperature Dependence of the Amplitude



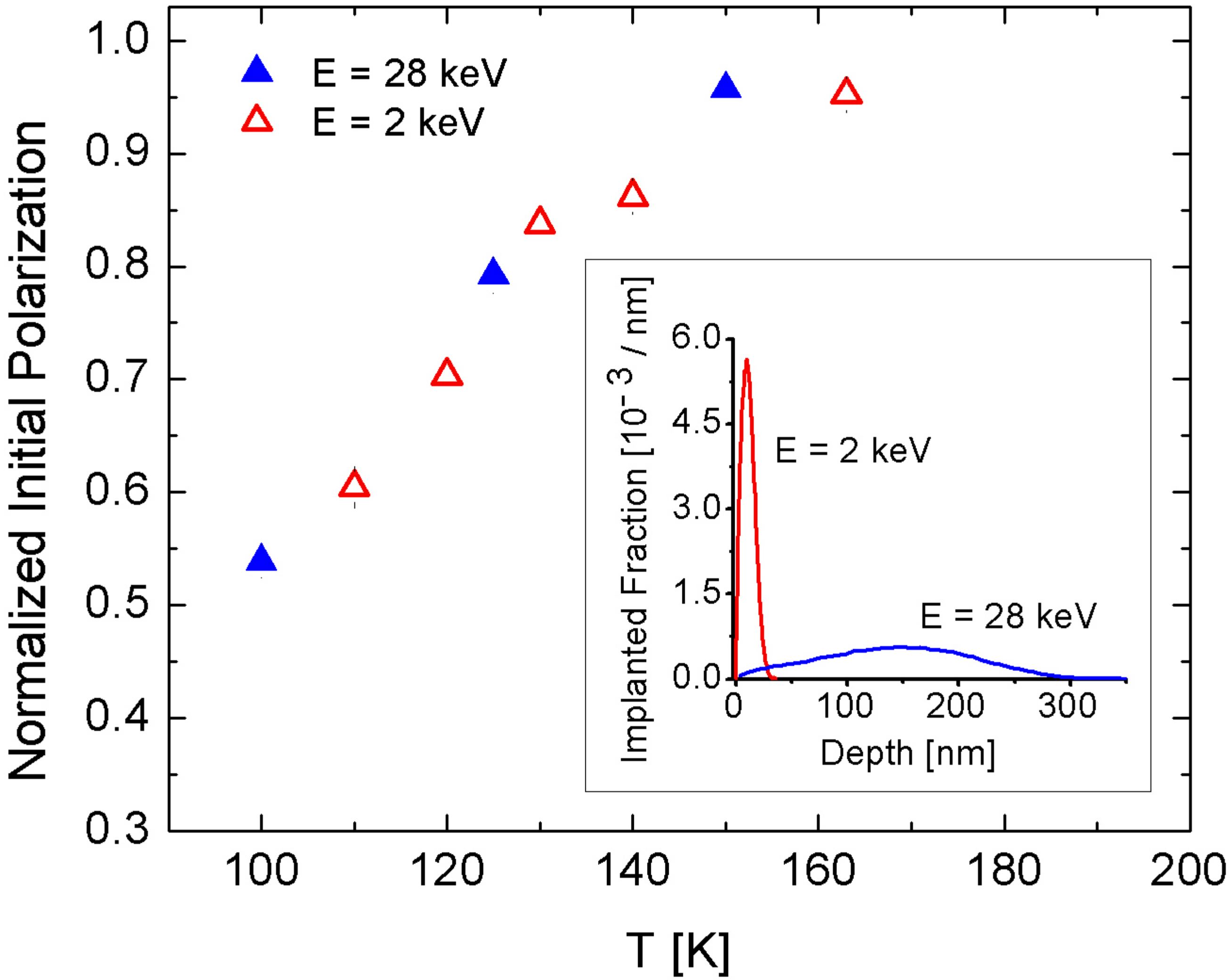
Surface SHG



Depth sampling ~ exp(-z/40 nm)

Mishina et al. Phys. Rev. Lett. 85, 3664–3667 (2000)

Depth Independence below 200 nm



Phys. Rev. B **83**, 224112 (2011)

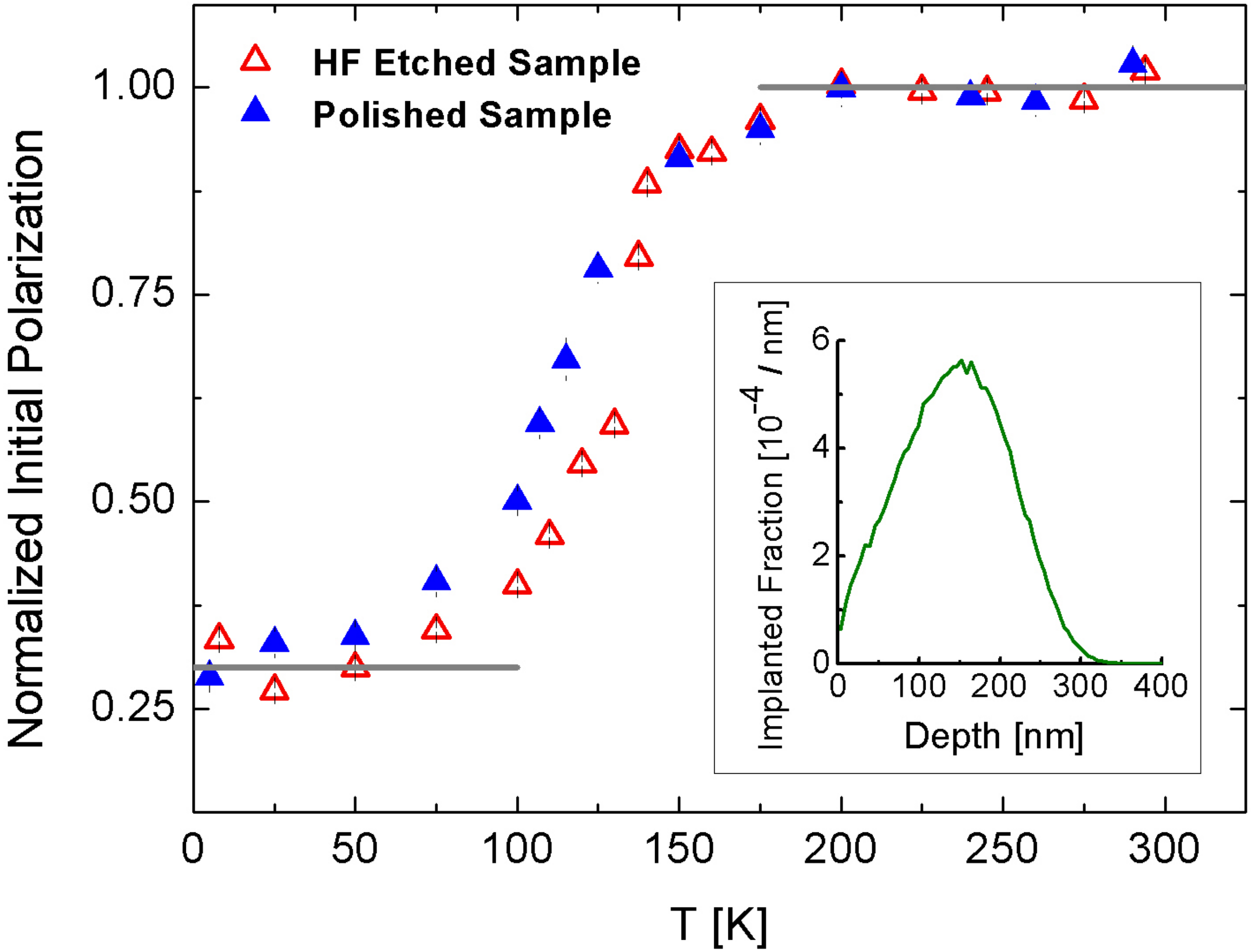
STO Transition at the Surface

Surface transition onset at ~ 150 K

50 μm (XRD) > crossover depth > 200 nm (βNMR)

Sharp bulk phase transition at 105 K

The Effect of Surface Preparation



Phys. Rev. B **83**, 224112 (2011)