TRIUMF Lecture, Mar 17, 2007

Using Radioactivity to Study Materials Science

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What is Materials Science?

The study of the properties of "condensed matter" – usually SOLIDS

Why is it Interesting?

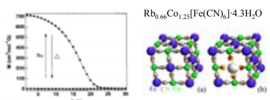
(almost) **All Technology** uses SOLIDS

New Technologies need New Materials

High Tc superconductors

Prussian Blue Analogue Photomagnets

$Rb_{0.66}Co_{1.25}[Fe(CN)_6]\cdot 4.3H_2O$



Sato et al., Inorg. Chem. **1999**, *38*, 4405-4412

The Atomic Structure of Matter

Matter is made of **ATOMS**

ATOMS are made of:
a cloud of negative **electrons** swirling around a small, heavy positive **NUCLEUS**

The **NUCLEUS** is really tiny and is made of positive **PROTONS** and uncharged **NEUTRONS**.

What is Radioactivity?

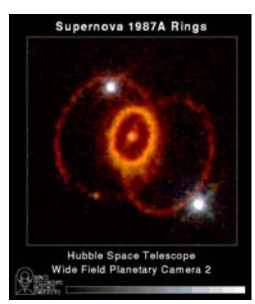
When a **NUCLEUS** has too many **PROTONS** and/or **NEUTRONS**, it is unstable and tends to fall apart.

Most matter we encounter is not radioactive.

Some types of Radiation

Alpha – heavy, positive charged, He^{++}
Beta – light, high energy electrons
Gamma – very high energy photons of light

Supernovae



Nuclear Reactions Produce Heavy Elements Including Radioactive ones

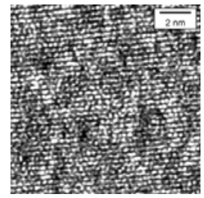
Some very nearly stable radioactive elements are still found in the earth
(billions of years after the reactions that produced them)

Crystals: The Simplest Solids

Amorphous vs. Crystalline

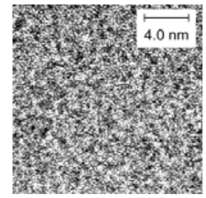
High resolution electron microscope images

Crystal

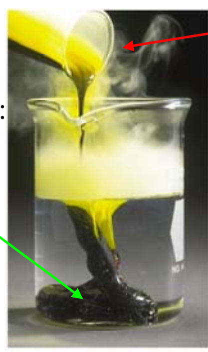


orderly rows

Glass (amorphous)



a jumble of atoms

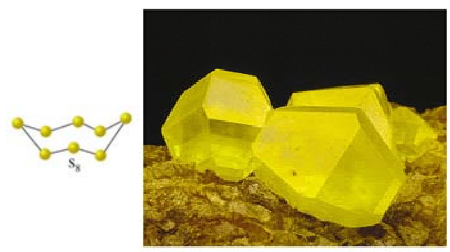


Liquid Sulphur

Plastic Sulphur: long chain molecules of sulphur **amorphous**

(d)

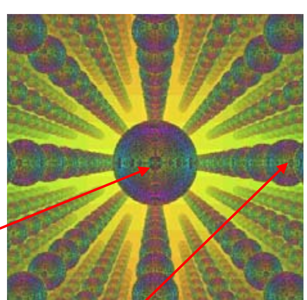
Rhombic Crystalline Sulphur



(a)

A crystal of S_8 ring shaped molecules

Crystals: a regular array of atoms

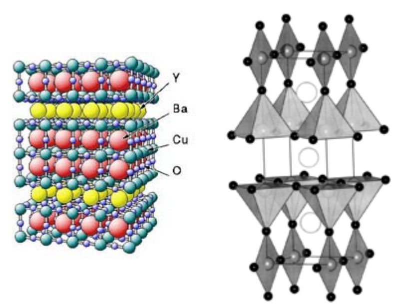


most of the atoms are far from the surface

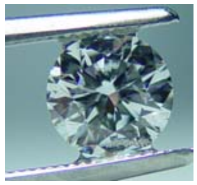
from an atom's eye view, the world of a crystal is a very **orderly** place

Moving to another atom, the view is the same... this is a kind of symmetry: **Translational Symmetry**

$YBa_2Cu_3O_7$ a cuprate high temperature superconductor



Why study crystals?

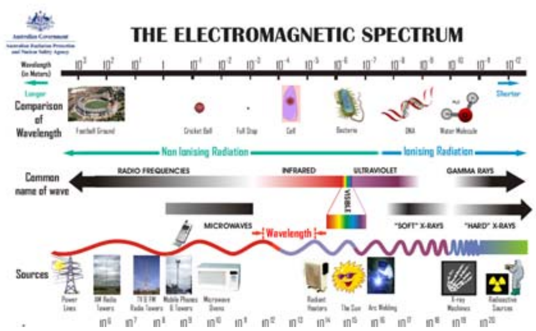


Structural Complexity
Variability

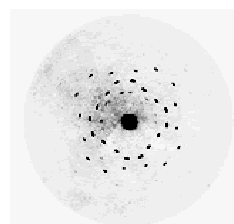
Structural Simplicity
Minimal variability (purity/perfection)
Unlikely to poop in your eye!

apologies to B. Ahlborn

Using Radiation to Study Solids



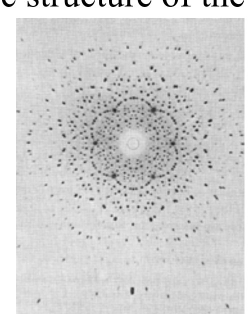
Xray Diffraction by Crystals



ZnS diffraction pattern

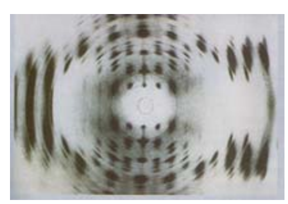
Max von Laue
Nobel (1914)

Diffraction Pattern reflects atomic structure of the crystal



Diffraction Pattern of Beryl Crystal

Xray Diffraction from a **Crystal of DNA**
established double helix



Watson, Crick, Rosalind Franklin and Maurice Wilkins

Modern Xray Source

Canadian Light Source
Centre canadien de rayonnement synchrotron

Saskatoon

Electron synchrotron (accelerator)

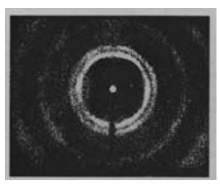
Very high ***intensity*** of xray photons

More Diffraction Patterns from Crystals

Aluminum (polycrystalline)

Xray Diffraction

Electron Diffraction



neutron diffraction (Cu)

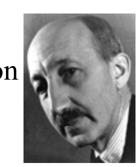
Neutrons from radioactive decay (reactors), e.g. AECL Chalk River, Ont.

or particle accelerators, e.g. Spallation Neutron Source, Oakridge, Tennessee

Radiotracers to Study Solids

Radiotracers

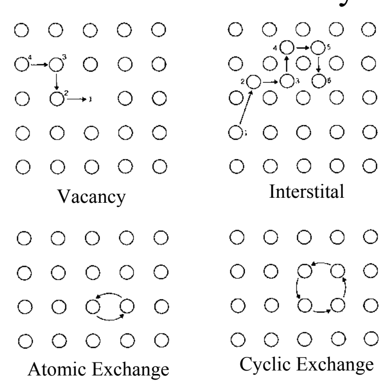
The idea: high energy radiation is *easy to detect*



George de Hevesy
Nobel 1943

use radioactive tracer atoms to study:
physical, chemical and biological processes

Diffusion Processes in Crystals



Complementarity

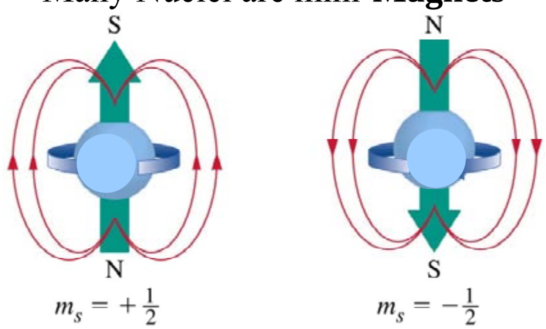
xrays and neutrons are characterized by a **WAVELENGTH**

radiotracers are characterized by their atomic **POSITION**

yield very different types of information

Nuclear Magnetism

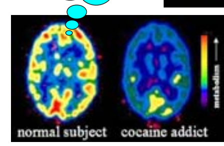
Many Nuclei are mini-**Magnets**

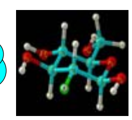


"Spinning" Charged particles

Nuclear Magnetic Resonance

Magnetic Resonance Imaging

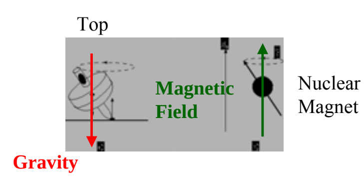




Positron Emission Tomography

Radioactive Spin Probes

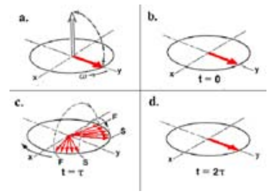
Spin Precession

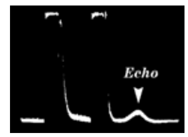


Manipulating Nuclear Spins

Spin Echos

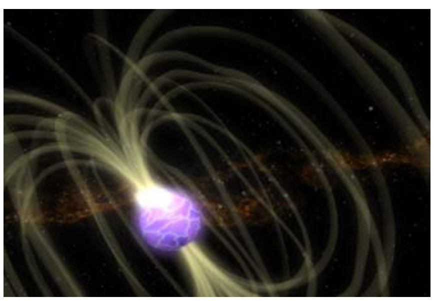
a big magnetic field polarizes the nuclear spins



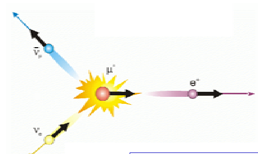


Hahn's Spin Echo

Radioactive Spin Probes



Muon Decay: $\mu^+ \rightarrow \nu_e + \bar{\nu}_\mu + e^+$; τ_μ = 2.2 μs



We can only detect e^+

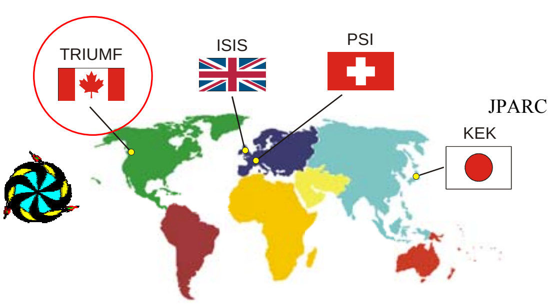
e^+ emitted PREFERENTIALLY along *instantaneous* spin direction

Basis of *μSR*

Can detect signal from a small number of probe particles!

The Production of Short-Lived Radioactive Particles

***μSR* Laboratories:**

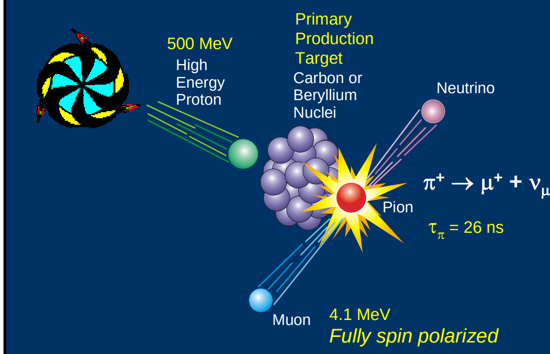


Lower half of TRIUMF cyclotron magnet

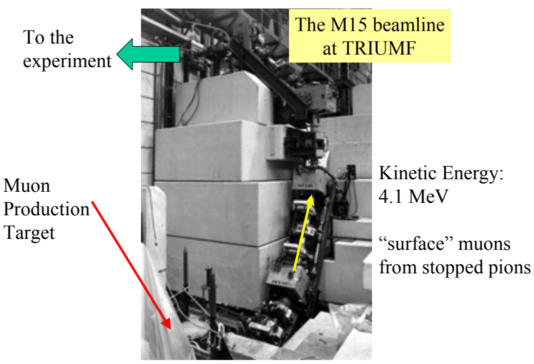
1972

Logo:

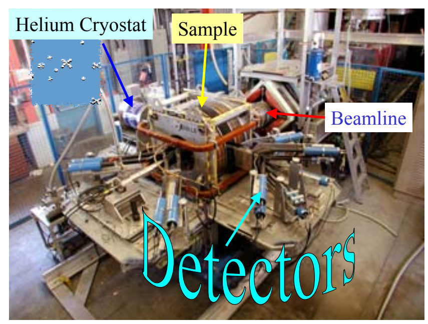
Muon Production by Nuclear Reactions



Transport Muons as a Beam

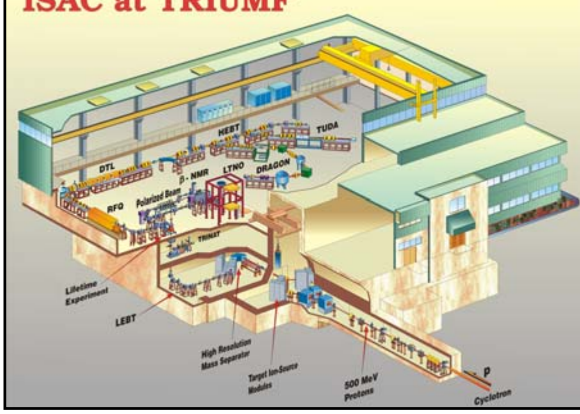


A Real μSR Spectrometer



Other beta decay probes

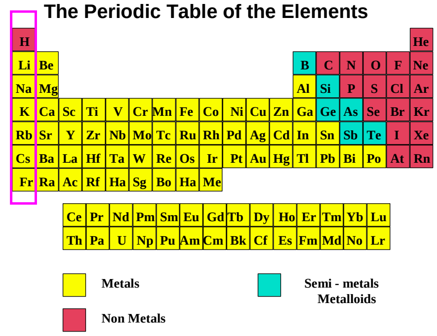
ISAC at TRIUMF



Some Suitable Isotopes for βNMR at ISAC

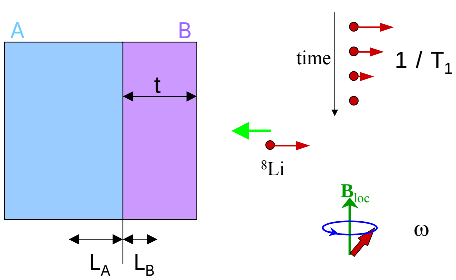
Isotope	Spin	$\tau_{1/2}$	γ (MHz/T)	β-Decay Asymmetry	Estimated Rate (s^{-1})
^{8}Li	2	0.8	6.3	0.33	10^{8}
^{11}Be	1/2	13.8	22	~0.3	10^{7}
^{15}O	1/2	122	10.8	0.66	10^{8}
^{19}O	5/2	26.9	4.6	0.71	10^{8}
^{17}Ne	1/2	0.1		0.33	10^{6}

What is Lithium?

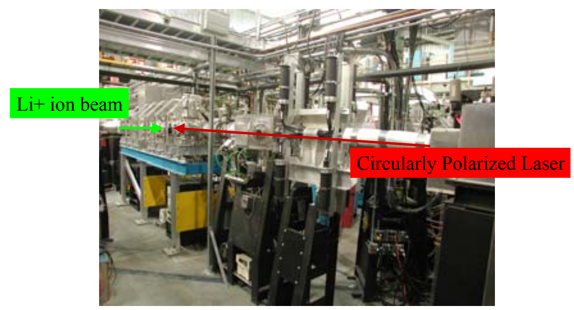


video

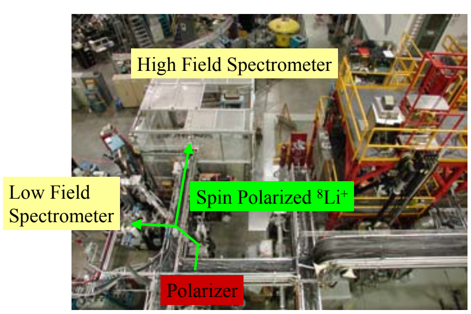
Magnetic Properties of Interfaces



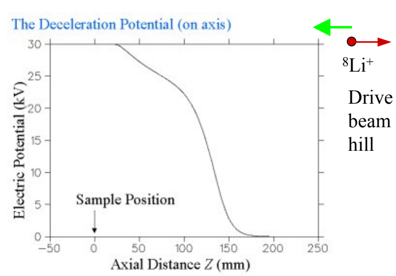
Optical Polarizer



βNMR at ISAC



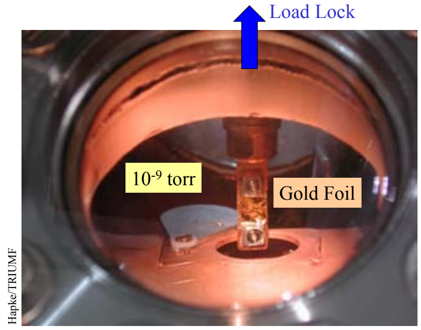
Deceleration of Ion Beam -sample at high voltage



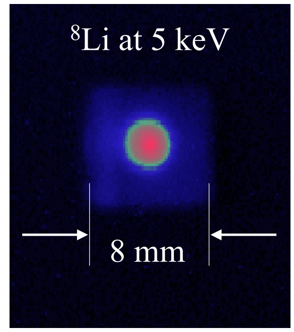
Drive the beam up the hill

Can't do this with standard muon beams, since they are moving too fast

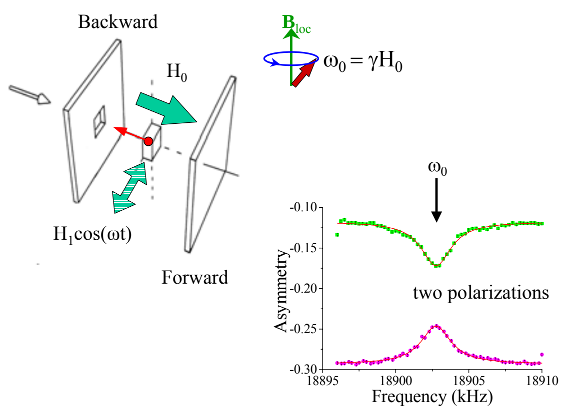
Loading a sample into the high-field βNMR spectrometer



Beamspot



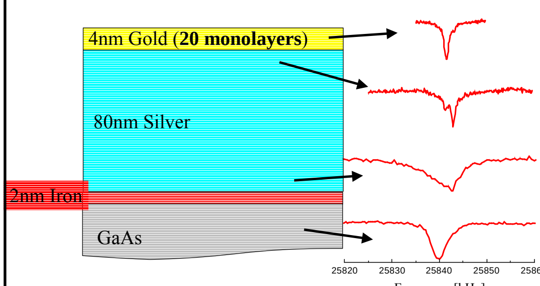
βNMResonance



Some Examples

1. Magnetic Heterostructures
2. Thin Palladium Films
3. Lithium Battery Materials
4. High Spin Molecules

Depth Resolved βNMR in Magnetic Multilayers



Some Examples

1. Magnetic Heterostructures
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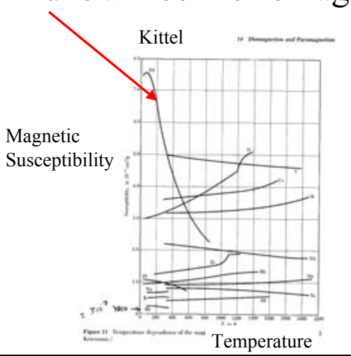
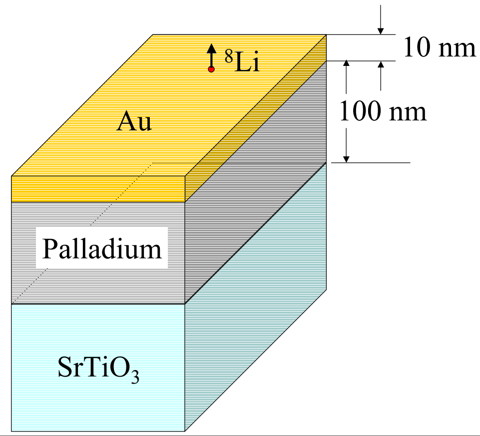
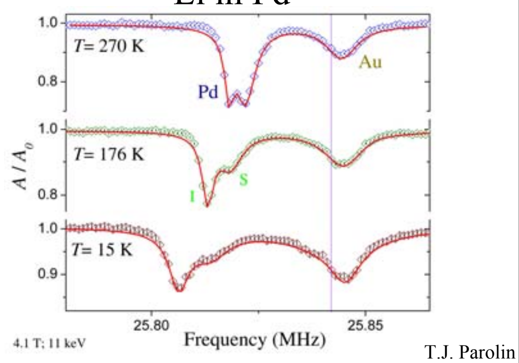
Pauli Susceptibility: Pd is almost Ferromagnetic





Giant Negative Knight Shift of ^{8}Li in Pd



What happens when the film gets thinner?

Stay tuned…

Some Examples

1. Magnetic Heterostructures
2. Thin Palladium Films
3. Lithium Battery Materials
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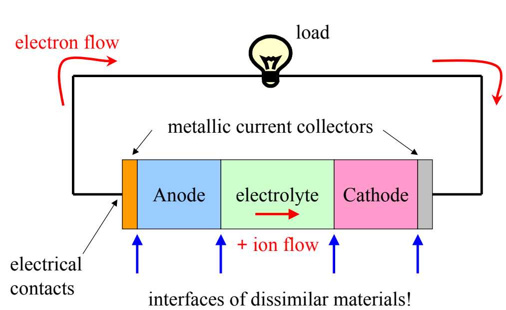
Solid State Battery Schematic



Thin Film Batteries

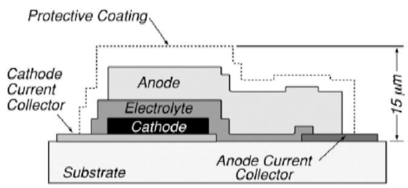
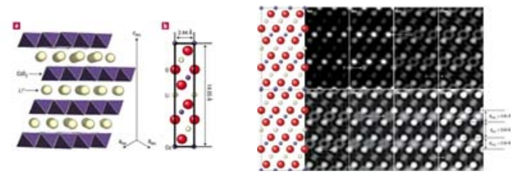


Fig. 1. Schematic cross-section of a thin-film lithium battery.

Power source on a chip, in a satellite etc.

Current Opinion in Solid State and Materials Science **4** (1999) 479–482

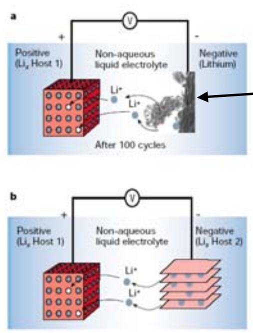
$LiCoO_2$
A Battery Cathode Material



Special TEM techniques

Nature Materials **2**, 464 (2003)

Lithium Batteries



Lithium Metal

"Rocking Chair"
Li Ion battery

Lithium Battery Explosion Hazard

overcharge or shorting

video

Numbers swell in Sony battery recall

Last Updated: Friday, September 29, 2006 | 10:51 AM ET
CBC News

Toshiba, Fujitsu and Dell recalled more Sony-made laptop batteries Friday, swelling the number of units involved in the massive global recall to more than seven million.

Early Friday, Sony Corp. formally asked manufacturers using its problem batteries to carry out a recall.
Sony has said the batteries could pose a risk of fire in rare cases when microscopic metal particles generated during manufacturing come into contact with other parts of the battery cell, leading to a short circuit.

Typically a battery pack will power off when there is a short circuit, but on **occasion the battery can catch fire**.

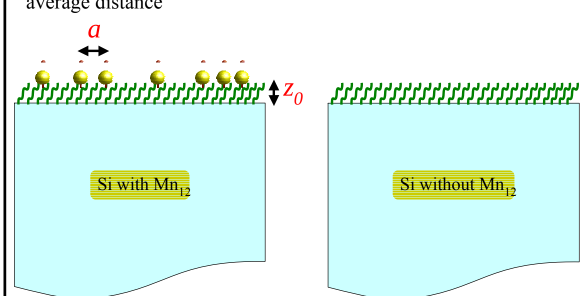
Chem. Mater. **2003,** *15*, 3190-3193

Some Examples

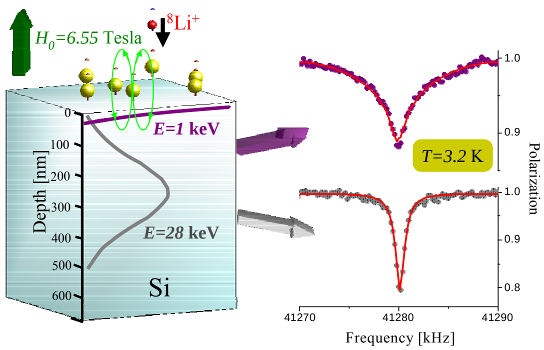
1. Magnetic Heterostructures
2. Thin Palladium Films
3. Lithium Battery Materials
4. High Spin Molecules

subMonoLayers of Mn_{12} on Si

average distance



β-*NMR in* Mn_{12} *on Si*



Materials Science is interesting!

Radioactivity provides may useful ways to study materials

Many nulcei are **mini-Magnets**

Nuclear magnets can say a lot about their local environment

In *very small numbers*, **radioactive nuclear magnets** can say a lot about their local environment, e.g. in thin films

bnmr.triumf.ca

No – Not Biology! well if you must ...

Acknowledgments

R.F. Kiefl, J.H. Brewer, E.P. Reynard, T.R. Beals, K.M. Nichol, **T. Keeler**, M.D. Hossain, W. Dong, H. Saadaoui, A. Morello, M. Smadella, J. Schultz (UBC Physics)
T.J. Parolin, Q. Song, J. Shi, J. Valiani (UBC Chemistry)
Z. Salman*, G.D. Morris, R.I. Miller (TRIUMF), Z. Yamani (Chalk River)
K.H. Chow (Alberta, Physics)
S.R. Dunsiger (McMaster), R.H. Heffner (LANL)

SAMPLES:

L.H. Greene (Urbana), T. Hibma, S. Hak (Groningen), B. Heinrich (SFU), Y. Maeno (Kyoto), J. Buriak (Alberta) P. Fournier (Sherbrooke), J. Wei (Toronto), J.W. Brill (Kentucky), J. Chakhalian (MPI-Stuttgart, Arkansas), G. Condorelli, R. Sessoli (Florence), A. Mar, A.V. Tkaczuk (Alberta)

At TRIUMF:
Polarizer: C.D.P. Levy, M. Pearson, A. Hatakeyama (Tokyo)
DAQ: S. Daviel, R. Poutissou, D. Arseneau
Beam Transport: R. Baartman, M. Olivo
RF: S.R. Kreitzman

***now at RAL**

G.D. Wight, C. Bommas (Bonn)