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

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, \( \text{He}^+ \)
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 vs. Glass (amorphous)
    - Orderly rows vs. a jumble of atoms

- **Plastic Sulphur**
  - Long chain molecules of sulphur amorphous

- **Liquid Sulphur**

- **Rhombic Crystalline Sulphur**
  - A crystal of S₄ 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

- **YBa₂Cu₃O₇ 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

X-ray Diffraction by Crystals

ZnS diffraction pattern
Max von Laue Nobel (1914)

Diffraction Pattern reflects atomic structure of the crystal

Diffraction Pattern of Beryl Crystal

Watson, Crick, Rosalind Franklin and Maurice Wilkins
Modern Xray Source

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

The idea: high energy radiation is easy to detect

use radioactive tracer atoms to study:

physical, chemical and biological processes

Radiotracers

George de Hevesy
Nobel 1943

Diffusion Processes in Crystals

Vacancy

Interstitial

Atomic Exchange

Cyclic Exchange
Complementarity

X-rays 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**

\[ m_s = \pm \frac{1}{2} \]

"Spinning" Charged particles

**Nuclear Magnetic Resonance**

Magnetic Resonance Imaging

Positron Emission Tomography

**Spin Precession**

Radioactive Spin Probes
Manipulating Nuclear Spins

A big magnetic field polarizes the nuclear spins.

Radioactive Spin Probes

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

We can only detect $e^+$ emitted PREFERENTIALLY along instantaneous spin direction.

Basis of $\mu$SR

Can detect signal from a small number of probe particles!

The Production of Short-Lived Radioactive Particles

$\mu$SR Laboratories:
Transport Muons as a Beam

To the experiment

The M15 beamline at TRIUMF

Muon Production Target

Kinetic Energy: 4.1 MeV

“surface” muons from stopped pions

A Real $\mu$SR Spectrometer

Helium Cryostat

Sample

Beamline

Detectors

Other beta decay probes
Some Suitable Isotopes for $\beta$NMR at ISAC

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Spin</th>
<th>$\tau_{1/2}$ (MHz/T)</th>
<th>$\gamma$</th>
<th>$\beta$-Decay Asymmetry</th>
<th>Estimated Rate (s$^{-1}$)</th>
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</thead>
<tbody>
<tr>
<td>$^8$Li</td>
<td>2</td>
<td>0.8</td>
<td>6.3</td>
<td>0.33</td>
<td>$10^9$</td>
</tr>
<tr>
<td>$^{11}$Be</td>
<td>1/2</td>
<td>13.8</td>
<td>22</td>
<td>-0.3</td>
<td>$10^7$</td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>1/2</td>
<td>122</td>
<td>10.8</td>
<td>0.66</td>
<td>$10^8$</td>
</tr>
<tr>
<td>$^{19}$O</td>
<td>5/2</td>
<td>26.9</td>
<td>4.6</td>
<td>0.71</td>
<td>$10^8$</td>
</tr>
<tr>
<td>$^{17}$Ne</td>
<td>1/2</td>
<td>0.1</td>
<td></td>
<td></td>
<td>$10^6$</td>
</tr>
</tbody>
</table>

What is Lithium?

The Periodic Table of the Elements

- Metals
- Non Metals
- Semi-metals
- Metalloids

Magnetic Properties of Interfaces

Optical Polarizer

Deceleration of Ion Beam

- Sample at high voltage

Can’t do this with standard muon beams, since they are moving too fast.
Loading a sample into the high-field $\beta$NMR spectrometer

Load Lock

$10^{-9}$ torr

Gold Foil

Beamspot

$^8$Li at 5 keV

8 mm

Some Examples

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

Some Examples

1. Magnetic Heterostructures
2. Thin Palladium Films
3. Lithium Battery Materials
4. High Spin Molecules
Pauli Susceptibility: Pd is almost Ferromagnetic

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

What happens when the film gets thinner?

Stay tuned…

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

Solid State Battery Schematic
Thin Film Batteries

Power source on a chip, in a satellite etc.

LiCoO₂
A Battery Cathode Material

Lithium Batteries

Lithium Battery Explosion Hazard

Some Examples

1. Magnetic Heterostructures
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4. High Spin Molecules

subMonoLayers of Mn₁₂ on Si

average distance

Si with Mn₁₂

Si without Mn₁₂
Materials Science is interesting!

Radioactivity provides may useful ways to study materials

Many nuclci 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

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

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DAQ: S. David, R. Pouliou, D. Areneau
Beam Transport: R. Baartman, M. Olivo
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