NEUTRON SOURCES

- Types of Sources
- U.S. Sources Available for Users
- Plans for the Future
- The Neutron Scattering Society of America (NSSA)

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SNS/ANL School on Neutron and x-Ray Scattering, June 2010
What do we need to do neutron scattering?

- **Neutron Source** – produces neutrons
- **Diffractometer or Spectrometer**
  - Allows neutrons to interact with sample
  - Sorts out discrete wavelengths by monochromator (reactor) or by time of flight (pulse source)
  - Detectors pick up neutrons scattered from sample
- **Analysis methods to determine material properties**
- **Brain power to interpret results**
Sources of neutrons for scattering

- **Nuclear Reactor**
  - Neutrons produced from fission of $^{235}\text{U}$
  - Fission spectrum neutrons moderated to thermal energies (e.g. with $\text{D}_2\text{O}$)
  - Continuous source – no time structure
  - Common neutron energies -- $3.5 \text{ meV} < E < 200 \text{ meV}$
Pulse sources – time structure and wide energy spectrum

• Proton accelerator and heavy metal target (e.g., W or U)
  – Neutrons produced by spallation
  – Higher energy neutrons moderated to thermal energies
  – Neutrons come in pulses (e.g. 20 Hz at LANSCE)
  – Wider range of incident neutron energies
Neutron sources – steady state (Reactors) and pulsed (Spallation)

- **Reactor**
  - Fission of $^{235}\text{U}$ produces neutrons
  - Fission spectrum moderated (slowed down) by either $\text{D}_2\text{O}$ or $\text{H}_2\text{O}$ (less good moderator) and neutrons are extracted through beam tubes for spectrometers – fixed wavelength used

- **Spallation source**
  - High E protons (e.g., 800 MeV) impinge on target ($\text{W}$, $\text{Hg}$ or $\text{U}$)
  - Nucleus of target is raised to excited state and subsequent decay produces neutrons ($+\gamma$s, nucleons and neutrinos) – 15 – 25 neutrons produced per proton with average $E = 55$ MeV
  - Neutrons moderated by liquid $\text{H}$, $\text{H}_2\text{O}$ or methane
  - Spallation sources generally operate in pulse mode – 20 Hz at LANSCE, 60 Hz at new SNS

Time of flight is used to sort out wavelengths
What Can Neutrons Do?

Neutrons measure the space and time-dependent correlation function of atoms and spins – *All the Physics!*

- **Diffraction (the momentum [direction] change of the neutron is measured)**
  - Thermal neutron wavelength well-matched to interatomic spacings
  - Atomic Structure via nuclear positions
  - Magnetic Structure (neutron magnetic moment interacts with internal fields)
  - Disordered systems - Fourier transform techniques provide local atomic order
  - Depth profile of order parameters from neutron reflectivity
  - Macro-scale structures from Small Angle Scattering (1 nm to 100 nm)

- **Inelastic Scattering (the momentum and energy change of the neutron is measured)**
  - Dispersive and non-dispersive phonon and magnon excitations
  - Density of states
  - Quasi-elastic scattering

- **Neutral charge of neutron provides unique 3-D information** (generally low absorption, ex. Gd, B, Cd, etc.)
Neutron Scattering’s Moment in the Limelight

The Royal Swedish Academy of Sciences has awarded the 1994 Nobel Prize in Physics for pioneering contributions to the development of neutron scattering techniques for studies of condensed matter.

Neutrons reveal structure and dynamics

Neutrons show where atoms are

Neutrons show what atoms do

Neutrons bounce against atomic nuclei. They also react to the magnetism of the atoms.

Bertram N. Brockhouse, McMaster University, Hamilton, Ontario, Canada, received one half of the 1994 Nobel Prize in Physics for the development of neutron spectrometry.

Brockhouse made use of inelastic scattering i.e. of neutrons, which change both direction and energy when they collide with atoms. They then start or cancel atomic oscillations in crystals and record movements in liquids and solids. Neutrons can also interact with spin waves in magnets.

With his 3-axis spectrometer Brockhouse measured energies of phonons (atomic vibrations) and magnons (magnetic waves). He also studied how atomic structures in liquids change with time.

Los Alamos National Laboratory

EST.1943
Golden Rule of Neutron Scattering

- We don’t take pictures of atoms!
- Job security for neutron scatterers – we live in reciprocal space
Neutron scattering machines

- **Spectrometers or diffractometers**
  - typically live in a beam room or guide hall
  - are heavily shielded to keep background low and protect us
  - Receive the neutrons from the target (or reactor)
  - Correlate data with specific neutron wavelengths by time of flight
  - Accommodate sample environments (high/low temperature, magnetic fields, pressure apparatus)
User instruments span general purpose and specialized categories

- **Diffraction instruments**
  - Atomic and magnetic structures – polycrystalline and single crystal form

- **Inelastic instruments**
  - Dispersive and non-dispersive excitations
  - Magnetic modes (magnons or crystal field excitations)
  - Phonon modes and density of states

- **Special purpose instruments**
  - Neutron reflectivity (depth profile of order parameters)
  - Small angle scattering (bridge between atomic and macro-dimensional structures)
  - Neutron applications to engineering problems

- **Sample environments enable science**
Sample environments – key to modern experiments

- **Extremes of temperature**
  - Low (cryostats)
    - conventional closed cycle refrigerators [Joule expansion cycles] (4K and up)
    - He cryostats (1.2 K [pumped] and up)
    - He³-He⁴ dilution refrigerators (20 mK and up)
  - High (furnaces)
    - Conventional (up to 1200 °C)
    - Special purpose (up to 3000 °C)

- **Magnetic fields on samples**
  - Fe-core magnets (up to about 3T)
  - Superconducting magnets (typical – 9T; special [finicky] – 18T)

- **High Pressure**
  - Fluid cells (He or liquid) [up to 1.4 GPA (14 kbar)]
  - Anvil presses (up to 40 GPa)

- **Other specialized environments** – sheer cells, Langmuir troughs, etc.
National User Facilities

Have sample, will travel
Where do I go to get neutrons?
There are five National User Facilities for neutron scattering in the US:

- **INTENSE PULSED NEUTRON SOURCE** (7 kW)
- **HIGH-FLUX ISOPTOE REACTOR** (100 kW)
- **DIVERSE MATERIALS SUPPLY INC.** (1400 kW)
- **MANUEL LUJAN JR. NEUTRON SCATTERING CENTER**
- **NIST CENTER FOR NEUTRON RESEARCH**

Local/Regional Facilities (University Reactors):
- MIT
- Missouri
- ...
US Neutron Source Support

- DOE operates 3 out of 4 of the Major Neutron Sources (and supports fuel for university reactors)
- DOC/NIST operates the only fully internationally competitive neutron facility (NCNR) with the largest user base (cold neutrons)
- NSF, NIH, and DOD support current neutron beam research mostly by supporting university research
  - EXCEPTIONS: NSF funds the Center for High Resolution Neutron Scattering (CHRNS) at NIST, and has supported some construction of instruments at LANSCE, HFIR, IPNS and MURR)
  - NIH has funded a reflectometer at NCNR.
World View of Neutron Scattering Facilities

The number of neutron scattering instruments available in the U.S. now and in the future will be less than half that available in Western Europe and less than available in Japan. On a per capita basis the United States has half the neutron scattering capacity of either Western Europe or Japan – and this shortfall is unlikely to change for the foreseeable future.

NIST Center for Neutron Research (NCNR)

A Comprehensive Neutron User Facility

• 20 MW Heavy-Water-Moderated REACTOR
• A Cold Neutron Source and Guide Hall
• Current Total -- 17 Thermal and Cold Neutron Instruments
• Developing 2nd guide hall – Amer. Competes Act
• Installation of 2nd guide hall components begins March 2011 – approx. 11 months
Reactor Hall Instruments
NCNR Guide Hall Instruments

10 Cold-Neutron Scattering Instruments
New Guide Hall Initiative
5 additional instruments

Red: new

Blue: relocated
High Flux Isotope Reactor

- Oak Ridge, Tennessee
- BES, Department of Energy
- Started Operation: 1966
- 85 MW Light Water Reactor
- Peak Core Neutron Flux
  \[ 12 \times 10^{14} \text{ /cm}^2\text{s} \]
SPALLATION NEUTRON SOURCE

- First neutron production scheduled for June 2006
  April 28, 2006
  2:04 p.m.
- Started with 3 (soon to be 8) instruments
- Capacity for a total of 24 instruments – plan for second target
- Accommodate 2000 users/year at full operation
HFIR Neutron Scattering Upgrade

• Beam tubes enlarged to 6”
  – New monochromator dums
  – Focussing optics
• Cluster of 4 instruments at HB-2
  – Powder diffractometer
  – Wide angle diffractometer
  – Residual stress spectrometer
  – Future instrument
• High-brightness cold source installed at HB-4 (guide hall)
  – 2 SANS (40m, 35m; flux gain x 100)
  – Cold triple axis spectrometer
• Schedule
  – Rx restarted May 2007 following cold source installation
  – Cold guide hall instruments – currently being completed
User Facilities at LANSCE: Los Alamos Neutron Science Center

- Visitor Center
- H+/H- Sources
- 800 MeV Linac
- Proton Rad.
- WNR
- Proton Storage Ring
- Lujan Center

Lujan Center
- BES/NNSA, Department of Energy
- Started Operation: 1985
- 85 kW Spallation Source (LANSCE)
- Peak Flux – $30 \times 10^{14} /\text{cm}^2\text{s}$
- Cold Source
- 11 Instruments
Lujan has 17 flight paths, 11 of which have neutron scattering instruments.

Moderators (FPs)

- H$_2$O decoupled high resolution (1, 2, 16)
- H$_2$O decoupled high intensity (3-8)
- liq-H$_2$ partially coupled (9-11)
- liq-H$_2$ coupled (12-13)
- H$_2$O coupled (14-15)

Rapid growth in number and versatility of instruments has occurred in the last decade.
Instruments by functional categories

- High Pressure Environ.
- High Intensity Powder
- Residual Stress
- Pair Distribution Function
- Inelastic Scattering
- Protein Crystallography
- Single Crystal
- Vibrational Spectroscopy
- Reflectometers Soft Matter Polarized Beam
- Small Angle
- Future High Resolution Inelastic
NRU Reactor – Chalk River, CA

• 125 MW heavy water reactor – Large Core, peak thermal flux of $3 \times 10^{14}$, initial operation in 1957 – currently down because of D$_2$O leak – expected restart summer 2010

• Seven beam tubes dedicated to neutron instruments
  – DualSpec
    • C2, High Resolution Powder Diffractometer
    • C5, Polarized Beam Triple-Axis Spectrometer /Reflectometer
  – D3 – Reflectometer
  – E3 – Materials Science Diffractometer
  – L3 – Strain-Scanning Spectrometer
  – N5 – Triple-axis Spectrometer
  – T3 – Bioscience Diffractometer

• Neutron Scattering Program Funded/Operated by National Research Council of Canada
Procedure for Obtaining Time on Spectrometers

- Make contact with and discuss proposed experiments with instrument scientist at facility
- Go to facility web site and access proposal form – complete by deadline (caution: usually only 2 per year!)
- Approval (declination) received within about 6 weeks
- Fine tune schedule with instrument scientist (if necessary)
- Complete radiation training module and access approvals in advance of visit (each lab has different procedures).
- If using ancillary equipment, make sure sample dimensions are correct, etc.
- Arrange travel and housing for visit (partial travel assistance may be available for first-time visitors or students.)
- Arrive at facility in advance of allocated time to set up experiment
- Apply for more time for next series of experiments (max. about 2 – 3 visits/year)
Reports

- **Neutron Source Upgrades and Specifications for SNS (1996)**
  - Research Reactor Upgrades, Robert Birgeneau, Chair
  - Spallation Neutron Source Upgrades, Gabriel Aeppli, Chair
  - Technical Specifications for the Next Generation Spallation Source, Thomas Russell, Chair

- **Review of the High Flux Isotope Reactor Upgrade and User Program** (October, 1998; Jack Crow, Chair)

- **Neutron Scattering** (February, 2000; Martin Blume, Chair)

- **Review of IPNS/LANSCE** (March, 2001; Ward Plummer, Chair)

Information on North American National Neutron Scattering Facilities

• **Neutron Scattering Society of America (NSSA)** [on-line or mail-in membership form]
  – http://www.neutronscattering.org
  – Announcements of meetings, workshops, etc.
  – Links to major neutron facilities

• **Oak Ridge Spallation Neutron Source (SNS) and High Flux Isotope Reactor (HFIR)**
  – http://neutrons.ornl.gov/

• **NIST Center for Neutron Research (NCNR)**
  – http://www.ncnr.nist.gov/

• **Los Alamos Lujan Neutron Scattering Center (LANSCE)**
  – http://lansce.lanl.gov/

• **NRU Chalk River**
  – http://neutron.nrc.ca/intro.html