Neutron Physics at NIST and ILL and Prospects for the SNS

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1. Facilities
2. Experiments
3. Development of instrumentation
NIST Center for Neutron Research

- 20 MW split-core research reactor
- peak core neutron flux = $4 \times 10^{14} \text{ /cm}^2\text{s}$
- cold source: 5 liters liquid hydrogen at 20 K
- 7 straight, 1 curved $^{58}\text{Ni}$-coated neutron guides

Activities:

- neutron scattering
- neutron activation analysis
- neutron radiography/tomography
- fundamental neutron physics
ILL Research Reactor

- 58 MW research reactor
- peak core neutron flux = $1.5 \times 10^{15}$/$\text{cm}^2\text{s}$
- vertical cold source: 20 L of liquid D$_2$ at 25 K
- horizontal cold source: 6 L of liquid D$_2$ at 25 K
- 6 horizontal and 1 vertical neutron guides

Activities:

- neutron scattering
- neutron activation analysis
- neutron radiography/tomography
1. NG-6 cold neutron beam:
   • capture flux: $1.4 \times 10^9$ /cm$^2$s
   • peak wavelength = 5 Å (3 meV)
   • unpolarized beam area = 28 cm$^2$
   • polarized beam: 96 % polarization
     - capture flux = $3.3 \times 10^8$ /cm$^2$s

2. NG-6 M1 monochromatic beam:
   • wavelength = 5 Å (3 meV)
   • beam intensity = $3 \times 10^5$ n/cm$^2$s

3. NG-6 M2 monochromatic beam:
   • wavelength = 8.9 Å (1 meV)
   • beam intensity = $10^7$ n/cm$^2$s

4. NG-7 Neutron Interferometer:
   • fringe contrast > 90 % (at 2.7 Å)
   • phase stability < 5 mrad/day
1. PF1B cold neutron beam:
   - capture flux: $1.6 \times 10^{10}$ /cm$^2$s (120 cm$^2$ beam area)
   - mean wavelength = 4.5 Å (4 meV)
   - polarized beam: 94–99% polarization
     - capture flux = $3 \times 10^9$ /cm$^2$s

2. PF2 ultracold neutron beams:
   - total flux: $2 \times 10^4$ n/cm$^2$s ($v < 6.2$ m/s)
   - mean wavelength = 1000 Å (100 neV)

3. PN1 fission product spectrometer
   - beam intensity = $5 \times 10^{14}$ n/cm$^2$s

4. PN3 gamma-spectrometers:
   - beam intensity = $3–5 \times 10^{14}$ n/cm$^2$s

5. S18: thermal neutron interferometer:
   - fringe contrast > 73% (at 1.84 Å)
Upcoming Fundamental Cold Neutron Experiments at NIST

- Neutron lifetime measurement using helium superthermal UCN production and magnetic trapping
- Improvement of T-violation D-coefficient search (emiT II)
- New measurement of the e-ν correlation ("a" coefficient)
- Improved measurement of parity-violating neutron spin rotation in liquid helium
- Neutron-electron scattering length
Upcoming Fundamental Cold and Ultracold Neutron Experiments at the ILL

- Neutron lifetime measurement using bottled UCN (MAMBO II)
- An improved measurement of the neutron EDM using UCN produced via superthermal helium production
- Neutron lifetime with trap door or RF spin-flip loading into a magnetic trap
- Trine - D coefficient time-reversal invariance test
- Measurement of $g_a/g_v$ by measuring $\lambda = (A-B)/(A+B)$
Importance of Neutron Decay Parameters

\( \tau_n: \) Big Bang Nucleosynthesis - determines primordial helium abundance

\( g_v: \) determines \( V_{ud} \), test of CKM unitarity

\( g_a: \) axial vector coupling in weak decays

D: search for new CP violation

a, A, B: precise comparison is sensitive to non-SM physics:

- right handed currents
- scalar and tensor forces
- CVC violation
- second class currents
MAMBO II

- $\tau_n = 881 \pm 3$ (Pichlmaier et al., 2000)
- Systematic limitations due to neutron loss
- Possible next generation using "Low Temperature Fomblin"

![Mambo II Diagram]
• $\tau_n = 885.3 \pm 4$ s – Preliminary value
• Error dominated by the uncertainty in the neutron count rate
• Calorimetric measurements underway to reduce this uncertainty.
• Expect final error of $\pm 2$ s with calorimetric data.
NIST Beam Lifetime

Proton Counts/Neutron Monitor Counts

Trap Length (number of electrodes)

Residuals

Individual Trap Lengths
Linear Fit
Fit Residuals

Neutron Lifetime (s)
Extrapolated Neutron Lifetime
(statistical uncertainty only)
Linear Fit

Backscattering Fraction
Magnetic Trapping of Ultracold Neutrons

Trap Depth of 1 Tesla (0.7 mK)

Neutrons Scatter in Liquid Helium

Loading 500-600 UCN into trap

Trapping Signal

$^3$He Non-Trapping Signal
• Measurement of the 'D' coefficient in neutron decay.

\[ dW \propto (g^2_V + 3g^2_A)F(E) \left[ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \vec{\sigma} \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right] \]

• Search for extensions to the Standard Model:
  – Left-Right symmetric models
  – Exotic Fermions
  – Lepto-Quarks
  – Super Symmetry

• Requires a polarized neutron beam.

• One must detect both the electron and proton in coincidence in order to obtain both \( \vec{p}_e \) and \( \vec{p}_\nu \) (indirectly)
emiT (NIST)/TRINE(ILL)

- **emiT:**
  \[ D = [-0.6 \pm 1.2\text{(stat)} \pm 0.5\text{(syst)}] \times 10^{-3} \]
  (PRC 62, 055501, 2000)

- **TRINE:**
  \[ D = [-3.1 \pm 6.2\text{(stat)} \pm 4.7\text{(syst)} \pm 4.7\text{(statsys)}] \times 10^{-4} \]
  (Torsten Soldner, thesis, T.U. München, 2001)

- emiT - scheduled to run at NIST, early 2002
- TRINE - no future plans at present
Electron-Antineutrino Coefficient

• Measurement of the 'a' coefficient in neutron decay.

\[ dW \propto (g_V^2 + 3g_A^2)F(E) \left[ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \vec{\sigma} \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right] \]

• Current accuracy \( \sim 5\% \), new goal is 1\%.
Phase shift is given by:

\[ \Delta \phi = N b \ell D \]

where

- \( N \) = atomic density
- \( b \) = scattering length
- \( \ell \) = wavelength
- \( D \) = thickness of sample
Deuterium Scattering Length

\[ b = 6.674 \pm 0.008 \text{ fm (Koester)} \]
\[ b = 6.55 \pm 0.08 \text{ fm (Kaiser)} \]
• Fundamental physics experiments:
  – npdγ
  – Asymmetry coefficient measurements (A, B, D)
  – Neutron spin rotation

• Why use $^3$He?
  – large area polarizer
  – accurate measurement of neutron polarization
  – undeflected beam
  – easy to flip spin
  – low gamma background
NIST Polarized $^3$He Program

![Graph showing neutron polarization, transmission, or figure of merit against $^3$He pressure × cell length (bar–cm).]

- Neutron polarization
- Neutron transmission
- Figure of merit ($P^2T$)

0.50 nm (5.0 Å) neutrons, 45% $^3$He Polarization

- Spin exchange
- Metastability exchange
Neutron Radiometer

- Operated as a power substitution device
  - $T_{\text{Target}} > T_{\text{Heatsink}}$
  - $\Delta T = T_{\text{Target}} - T_{\text{Heatsink}} = \text{constant}$
  - $\dot{Q} = C \Delta T = \text{constant}$
  - Temperature control at the $\mu$K level

- Flux measurement to 0.1 %
Conclusions

• Reactors have - and continue to have - a long history of carrying out fundamental physics experiments

• We have or are in the process of developing many of the tools required and experiments planned for the SNS:
  – All five of the experiments have NIST/ILL collaborators, two presently based at NIST
  – npdγ and Asymmetry Coefficient measurements will require large area $^3$He polarizers
  – Expertise in absolute flux measurements
  – Expertise in development of monochromators and multi-layer depositions

• Large existing knowledge base to draw upon

• We have neutrons!