Fundamental Research
Lowest Attainable Temperatures

Unique: High $B$ and Ultra-Low $T$
Part of National High Magnetic Field Laboratory

Create new states of matter

- Superfluids
- Superconductors
- Magnetic ordering

Explore new phenomena

- Highly correlated electron systems
- Quantum criticality
- 2G Electron gases

Supported by the National Science Foundation
Coldest Temperature in Nature? $T = 2.725$ K

WMAP Resolves the Universe
Credit: WMAP Science Team, NASA
Microkelvin Laboratory has 3 bays:

Each: electromagnetic shield, vibration isolation mounts, nuclear refrigerator
High B/T Bay

- heat switch
- 5 T magnet (to be developed)
- top loading access (2.54 cm diam.)
- 5 mole Pr Ni$_5$
- 8 T magnet
- bottom loading connection
- 15/17 T magnet
- $1 \times 10^{-4}$/1 cm dsv
UF-NHMFL High B/T Facility

Available to users worldwide
T < 1mK, B up to 16 T

Research
Superfluid $^3$He
Nuclear ordering
2D Electron gas
Quantum Transport
Nuclear Refrigerator

Relies on fact that B/T for a ‘good’ magnet remains constant if perfectly isolated.

\[ M = F(B/T) \]

(1) Cu: Precool to ~ 10mK in B = 10 T

   Isolate (open superconductor switch)

(2) Demagnetize to 0.03 T (very carefully)

   T drops from 10 mK to 30 microK)

Good design
   -- stay cold for several weeks

Cu or PrNi5 demagnetization

e.g. PrNi5:
   cool from 30mK to 0.03mK

Fig. 10.13. Nuclear spin entropy of PrNi5 as a function of temperature in the indicated fields [10.55] F. Pobell: Ultra-Low Temperatures
Comparison International Facilities
Quantum Fluids & Solids: \(^3\text{He}, \(^4\text{He}, \text{H}_2, \text{HD}\ldots\)

**Ideal prototypes** for testing fundamental phenomena

♦ *Interactions known from first principles*
♦ *Effect of disorder accurately controllable*

**Quantum Transport**
Highly polarized dilute Fermi liquids
dé Broglie wavelength > scattering length
→ quantum exchange dominated transport

**Nuclear Magnetism** --- Solid \(^3\text{He}\)
competing interactions
(anti-ferromagnetic and ferromagnetic)
Superfluid transition in $^4$He

$T < T_\lambda$

$T > T_\lambda$

Courtesy: S. Balibar, *History of Superfluidity*

arXiv:cond-mat/0303561
Peter Kapitza, (Institute of Phys. Problems, Moscow) and John Allen (Mond Lab., Cambridge Univ.) discovered superflow 1937-39.

Helium 4: boson $s=0$

Superfluid $T < 2.17 \text{K}$

Supersolid $T < 0.2 \text{K}$

Helium 3: fermion $s=1/2$

Superfluid $T < 0.0022 \text{K}$ (spins pair up $\rightarrow$ bosons)

Solid: Nuclear magnet $T < 0.0009 \text{mK}$
Superconductivity

Kamerlingh-Onnes (1911)

\[ \Delta T < 10^{-3} \text{ K.} \]

Resistivity \( R \) at \( T < T_c \) is zero, unless \( H > H_c \)

\( T < T_c: \) no dissipation

Temperature \( T \)

Resistivity \( R \)

Kamerlingh-Onnes (1911)
Type 1 Superconductors
(Cooper pairs of e’s)
Low \(T_c\), Low \(H_c\):
Pb 7.2K, 803 G; Al 1.2K, 105 G
Not very practical

New high temperature
Superconductors ceramics: YBCO...

Complex interplay between
lattice symmetry and interactions

High field magnets, MRI, MagLev

\(\text{YBa}_2\text{Cu}_3\text{O}_{7-x}\)

\(T_c\) 93K
\(H_{c2}\) > 100T
\(J \sim 1\text{MA/cm}^2\)

N. Miura et al.
JLTP (2003)
Effect of strong magnetic field on superfluid $^3$He in 98% porosity aerogel

The normal-A and A-B transitions suppressed due to the scattering of $^3$He quasiparticles (fermions)
Ideal Fermi Liquid: 150 ppm $^3$He in $^4$He
Very dilute, weakly interacting $^3$He atoms

Quantum Transport: viscosity increase rapidly with B

Spins align in strong B

↑↑ high scattering interaction

↑↓ low scattering interaction

Measure spin diffusion directly with NMR (15 T)

D. Candela et al.
Nuclear Magnetic Order in Solid $^3$He

High B/T experiments
D. Adams, Y. Takano

High Field Phase ??

Low B phase
Anti-ferromagnetic

Ultra-low T

Magnets

World records

900 MHz NMR quality high homogeneity persistent superconductor (22 tesla)

45 Tesla; Hybrid superconductor outer DC power (25 MW) inner
Resistive Magnets

35 T, 32mm bore, 20MW

Florida-Bitter Magnet Plates
Heavily elongated holes

Four of the five largest magnet labs use Florida-Bitter plates.

Current Density = 700 A/mm²
Power Density = 13 W/mm³
Heat Flux = 7 W/mm²
Destructive Quench

If exceed maximum field, superconductor “quenches”… goes normal.

Releases enormous energy

If protection inadequate

“quench” is destructive.
1. Quantum Phase Transitions

YbRh$_2$Si$_2$

Non-Fermi liquid

AFM

Fermi liquid

Abrupt change in ground state as tune across transition due to quantum fluctuations e.g. sweep B, concentration....
2. "Supersolid" $^4$He

Sharp drop in rotational inertia

"supersolid fraction" = 2%

*M. Chan et al.* Penn. State U.

\[ \tau_o = 2\pi \sqrt{\frac{I}{K}} \]
“Supersolid” $^4$He: Effect of $^3$He Impurities? M. Chan et al.

Need to study quantum behavior of defects.
First experiment to probe microscopic dynamics of proposed supersolid helium

NMR relaxation times measure atom-atom exchange rates: sensitive to changes in ground state and transition to supersolid

Dramatic change in $T_1$ for low $^3$He at supersolid transition: mimics change in elastic modulus

S. S. Kim et al.
JLTP 158, 584 (2010)
Ni S=1 spins: 3D XY anti-ferromagnet
--- critical fields: $H_{c_1} \sim 2$ T, $H_{c_2} \sim 12$ T.

Expect power-law $T$ dependence:

$H_{c1}(T) \sim H_{c1}(0) = aT^{\alpha}$ with $\alpha = 1.5$

Confirmed at mK temperatures with $\alpha = 1.47 \pm 0.01$

AC susceptibility measurements, NHMFL
High B/T facility

Ultrasound Measurements

Effect of strong magnetic field superfluid $^3$He in 98% porosity aerogel

The normal-A and A-B transitions suppressed due to the scattering of $^3$He quasiparticles (fermions)

Y. Lee et al.
Pulsed NMR studies:
- Determine diffusion and interactions of H$_2$ in mesoporous structures (zeolites and MOFs)

Spin-lattice rates give interaction energies.

Spin-spin relaxation rates measure diffusion.

NMR: can determine intercage diffusion: rates surprisingly high at low temperatures.
Comparison: High B/T Facilities

- Gainesville (High B/T)
- 2009
- 20 + T Upgrade