# Materials Research in Canada

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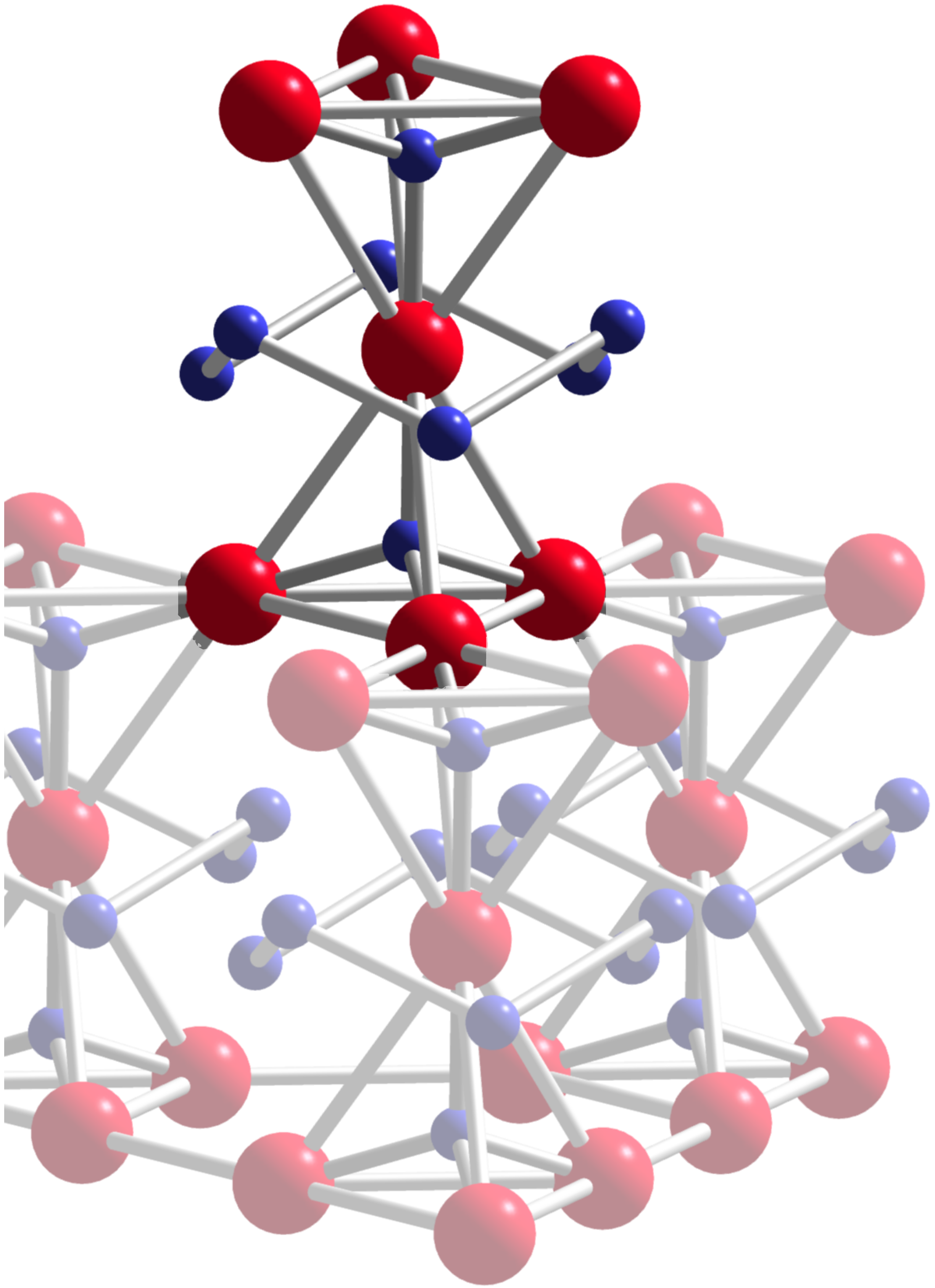
TRIUMF

NSERC CRSNG



# Materials Research in Canada

- Mobilize knowledge from physics, chemistry, biology, computer/data science, mathematics and engineering to understand, control & develop materials.
    - Highly interdisciplinary.
- From inquiry-based discovery to product development.
    - Numerous feed-back cycles.
- Scale of research: from individual researchers at lab bench to large international user facilities.

# Materials Research Topics (incomplete)

- Industrial (eg. construction- concrete), additive manufacturing.
- Metals: advanced alloys for vehicles etc.
- Energy generation & storage.
- Polymers & biomaterials
- Quantum Materials

# Advanced Materials (NRC)

- NRC Mississaugua.
- accelerate materials discovery and process development.
- computational discovery, design and simulation.
- Production scale-up & standardization.
- applied to clean energy materials, novel feedstocks for additive manufacturing, multi-functional materials and structures.

(2019)

# CanmetMATERIALS (Hamilton)

- NRC research centre dedicated to fabricating, processing and evaluating metals and other materials.

- Support industry in:

  - Transportation - vehicle, engine and component manufacturers - improve fuel efficiency, maintain safety and performance.

  - Energy - production & pipelines.

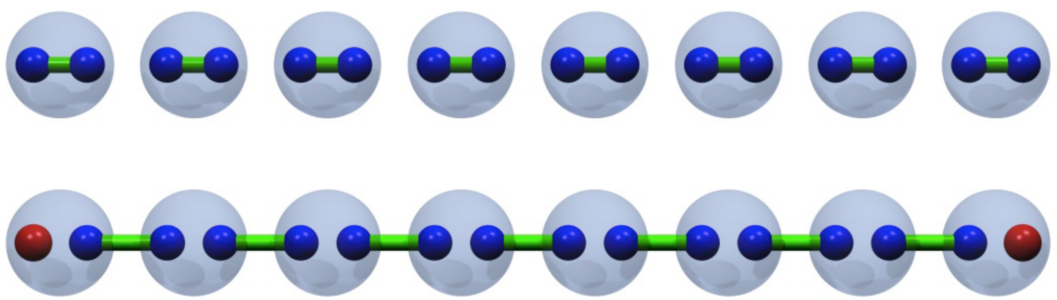
  - Manufacturing - defence, aerospace, health & construction.

# Quantum Materials

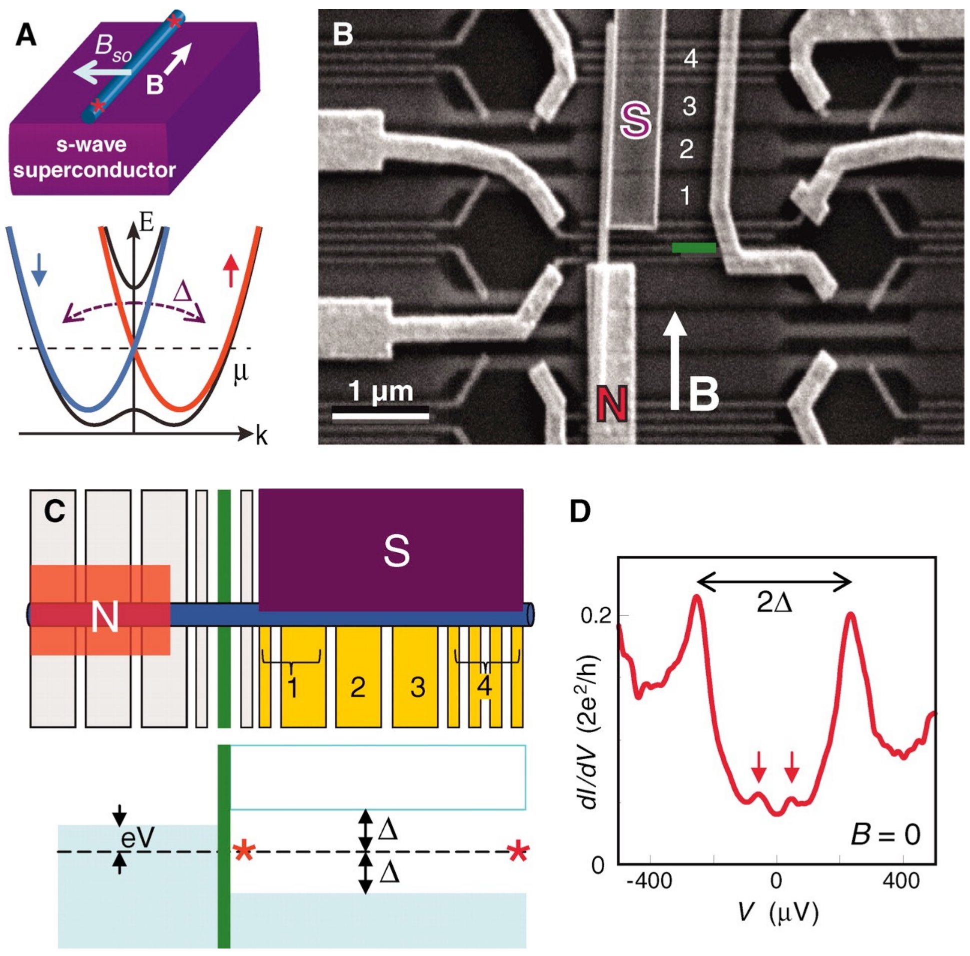
- Materials presenting strong electronic correlations and/or electronic order (superconducting, magnetic…) or whose electronic properties tied to non-generic quantum effects (topological insulators, graphene, Weyl semi-metals).
- Emergence is a unifying theme.
  - Collective excitations of condensed systems include anyons (fractional statistics), Majorana fermions, magnetic monopoles…
- Term likely coined in Canada - Tom Timusk at CIAR Superconductivity Business meeting as program proposed extension of subject areas of study.
- Potential for applications in near and far future.
  - High Tc-Cuprates - telecommunications, magnets,
  - Frustrated magnets and others - Qubits for quantum computation.

# Majorana Fermions

- Normal fermions can be represented as composed of two Majorana fermions.
- Interest comes if Majorana fermions can be separated spatially, independently probed.
    - Non-Albelian statistics.
    - immune to decoherence.
- Possible application to quantum computation.



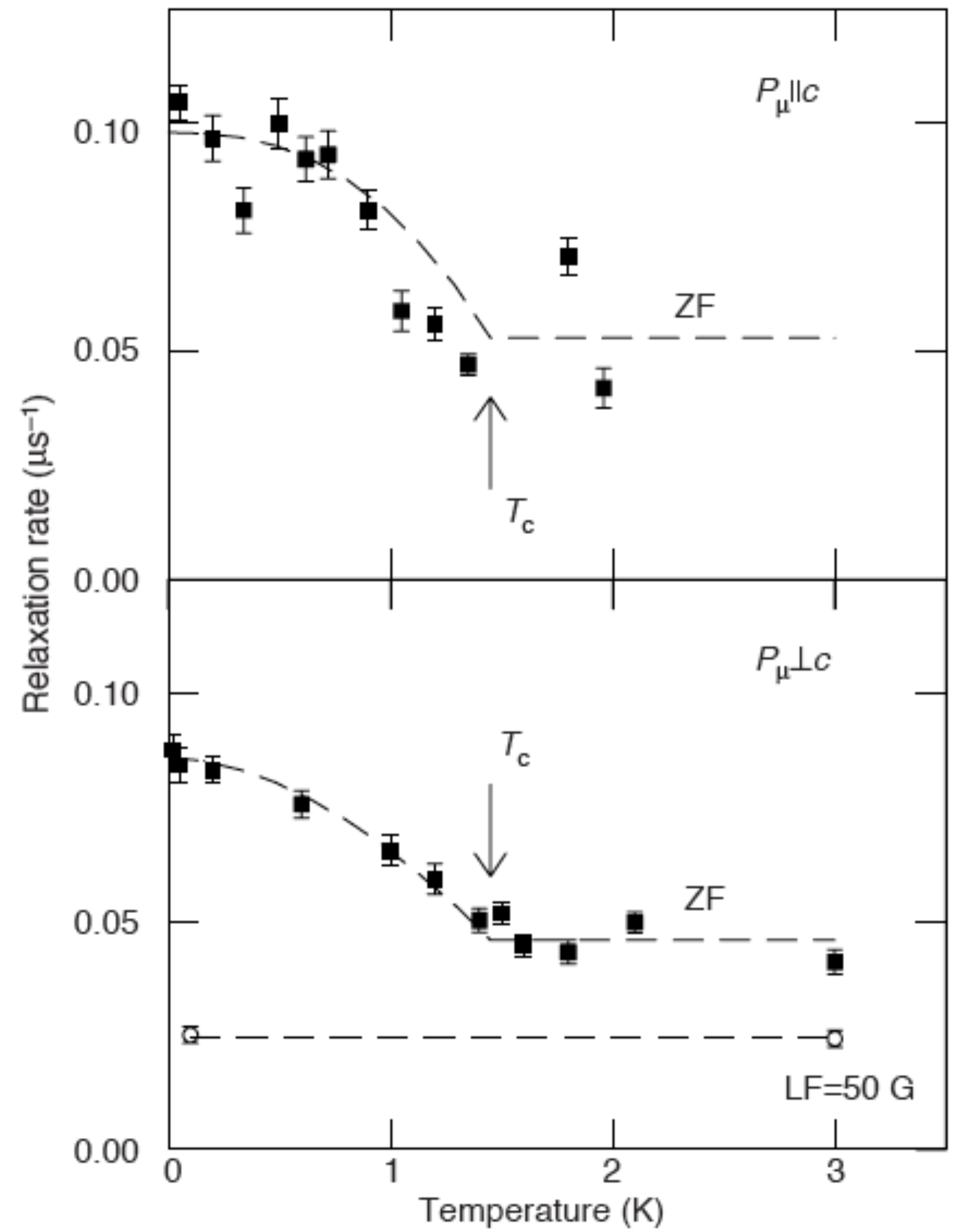
M. Franz , Nature Nanotechnology **8**, 149 (2013).




Mourik et al., Science **336**, 1003 (2012).

# Majorana Fermions

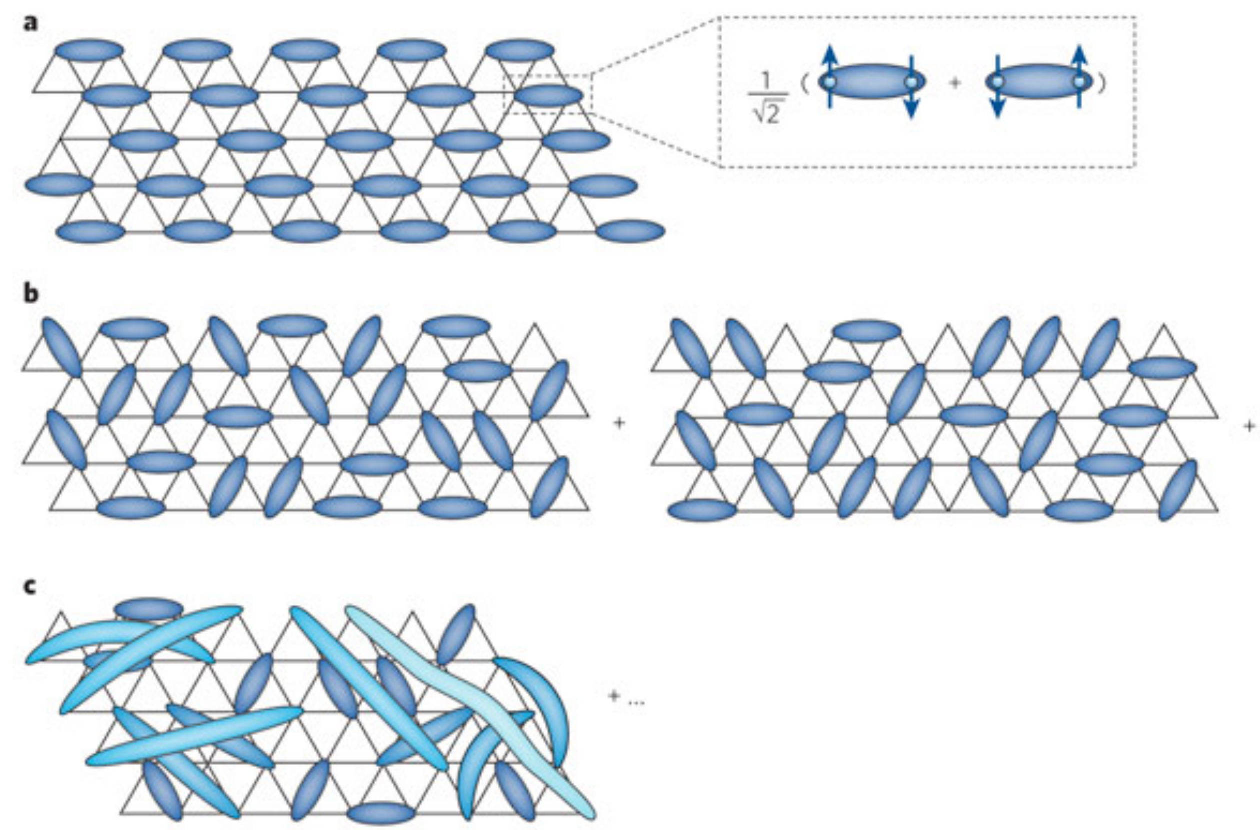
- Active particle physics searches. Neutrino?
- Theoretically predicted to exist in topological superconductors.
  - $Sr_2RuO_4$ $p_x \pm ip_y$
  - $Cu_xBi_2Se_3$
  - $(Ir,Pt)Te_2$




Luke *et al.*, Nature **394**, 558 (1998).

# Quantum Spin Systems

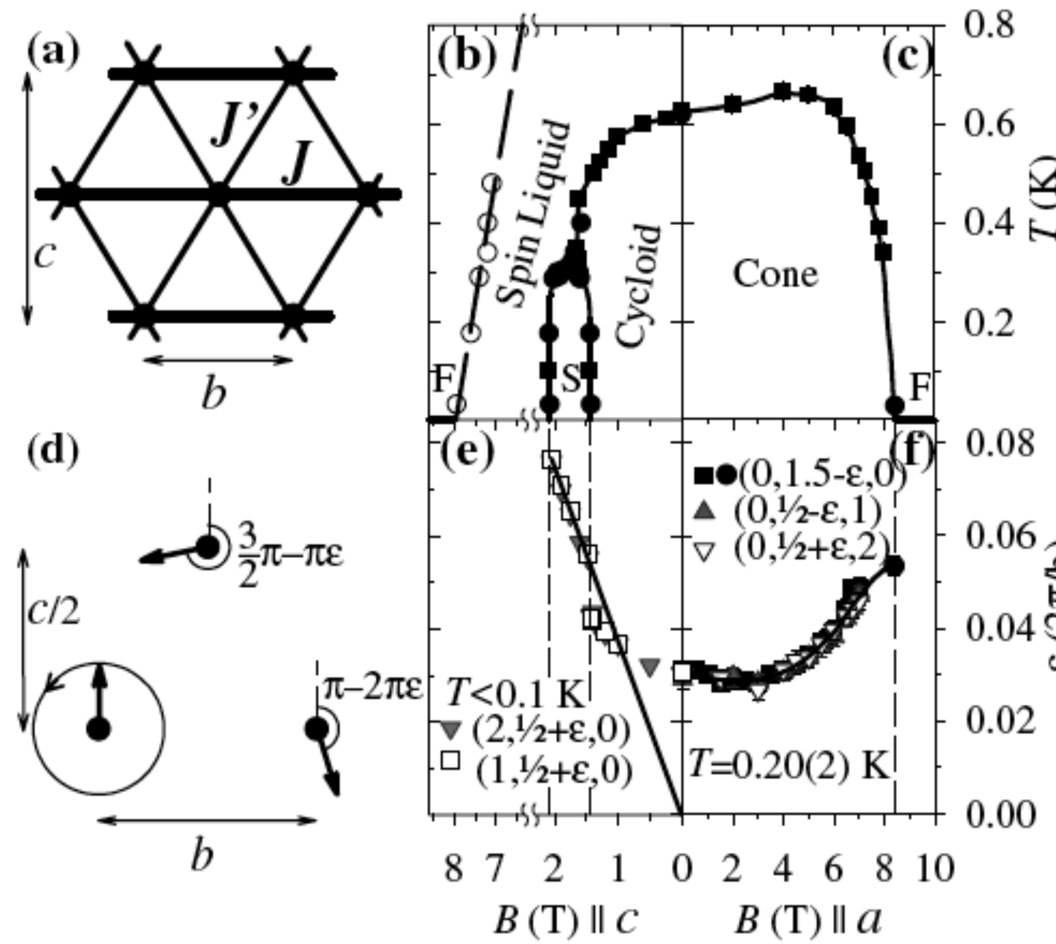
- Role of quantum fluctuations in Quantum spin systems (eg. spin 1/2).
  - Neel state not an eigenstate of Heisenberg Hamiltonian.
  - increasingly bad for low-d, low spin.
- Quantum spin liquid: originally suggested by Anderson for 2-D spin 1/2 -RVB.
- Tsvelik suggested Majorana approach to Kondo system, finding singlet ground state with Majorana excitations.
- extended to spin liquids, spin chains, Heisenberg AFM's...




Balents, Nature **464**, 199 (2010).

# Quantum Spin Liquids

- Interacting spin systems, mostly characterized by "What they are not": not magnetically ordered.
- Entanglement entropy...



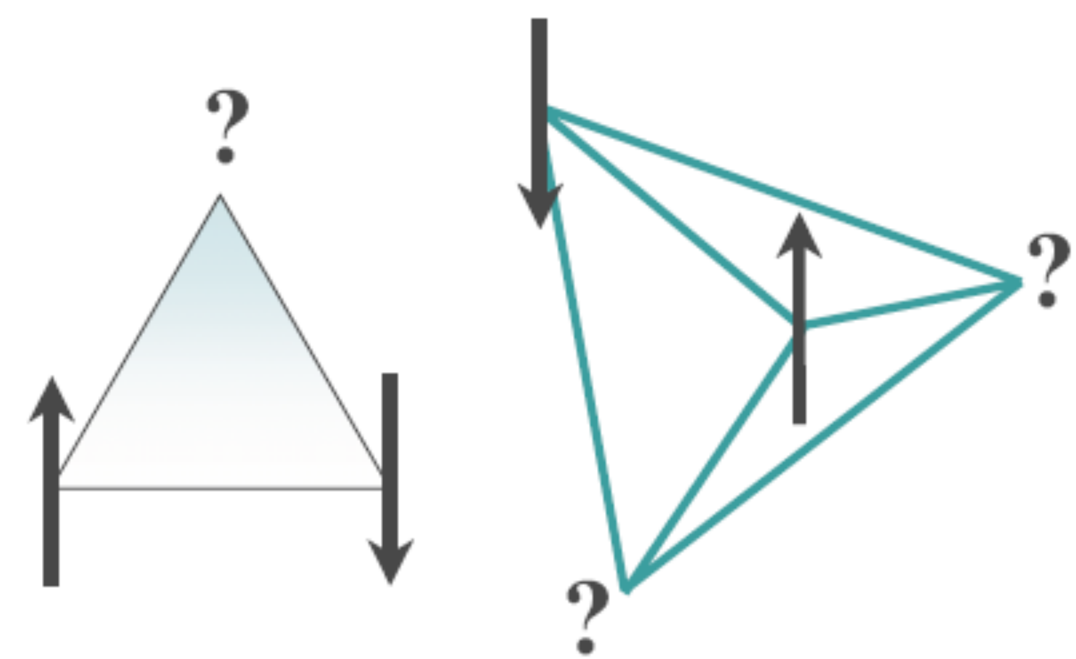

Coldea *et al*., Phys. Rev. Lett **86**, 1335, (2001).

## $Cs_2CuCl_4$

- 1-d - dimensional reduction (domain walls), likely not 2-d QSL.

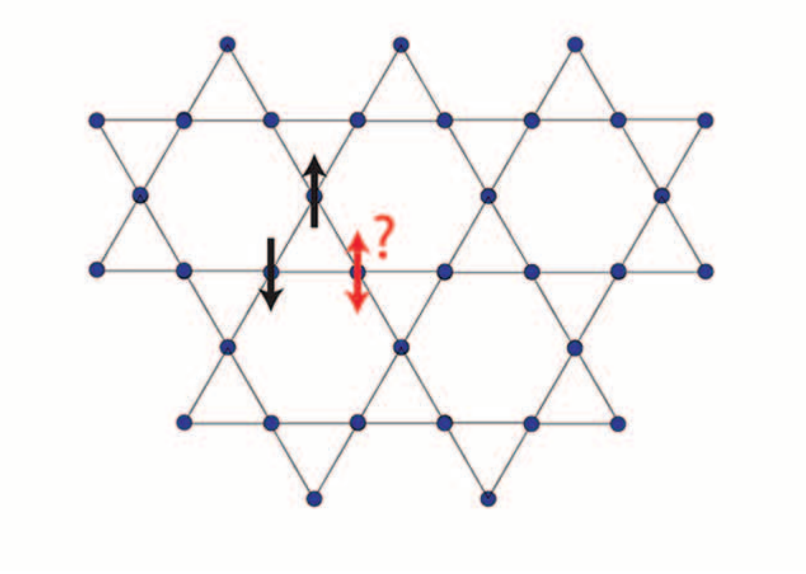
# Geometrical Frustration

- No periodic arrangements of moments which can simultaneously minimize energy.
- Can have large number of classically degenerate ground states.
- Leads to competing low temperature phases and enhanced quantum mechanical spin dynamics.
- Possible emergent phenomena, quasiparticles.

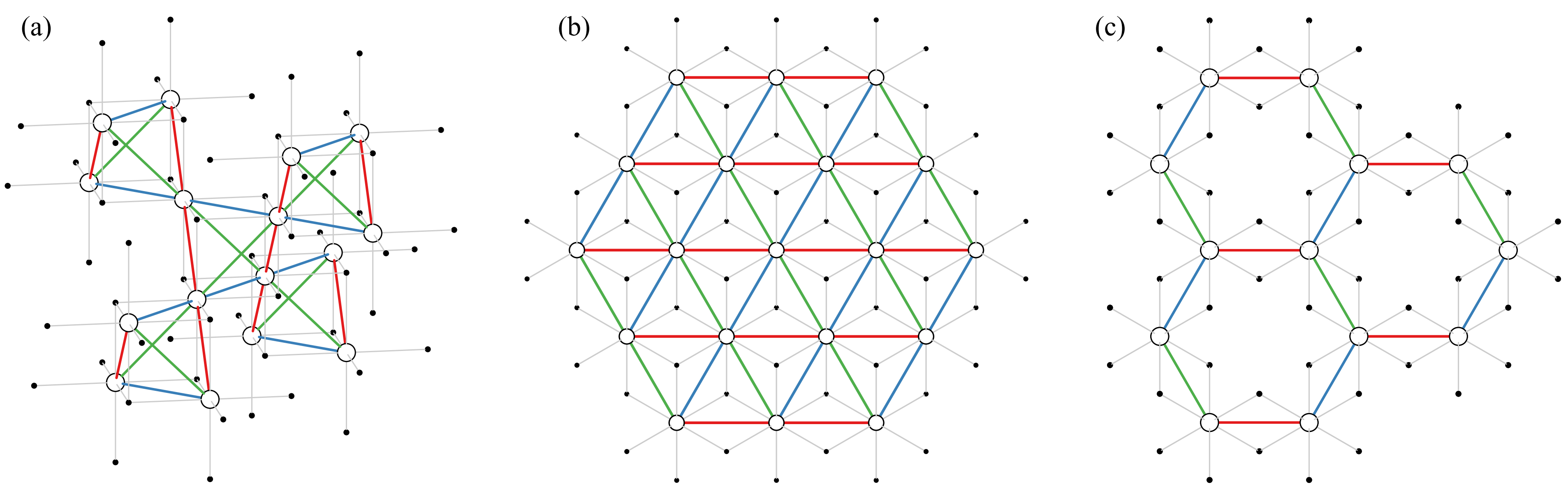


# Frustrated Lattices

- Triangular motifs
  - pyrochlore, spinel
  - Kagome
    - breathing Kagome
  - Kitaev (honeycomb)
  - stacked triangular



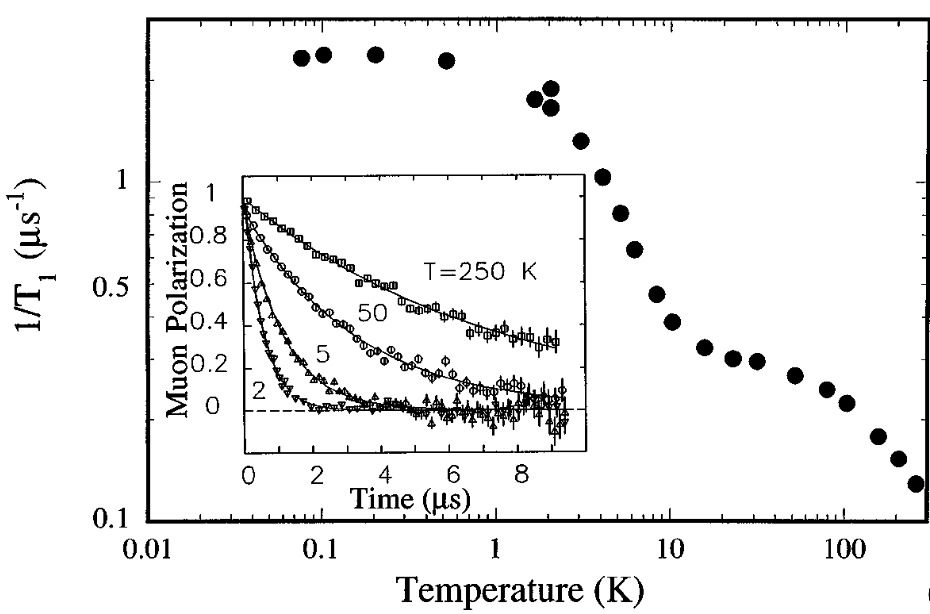

Fu et al., Science **350**, 655 (2015)

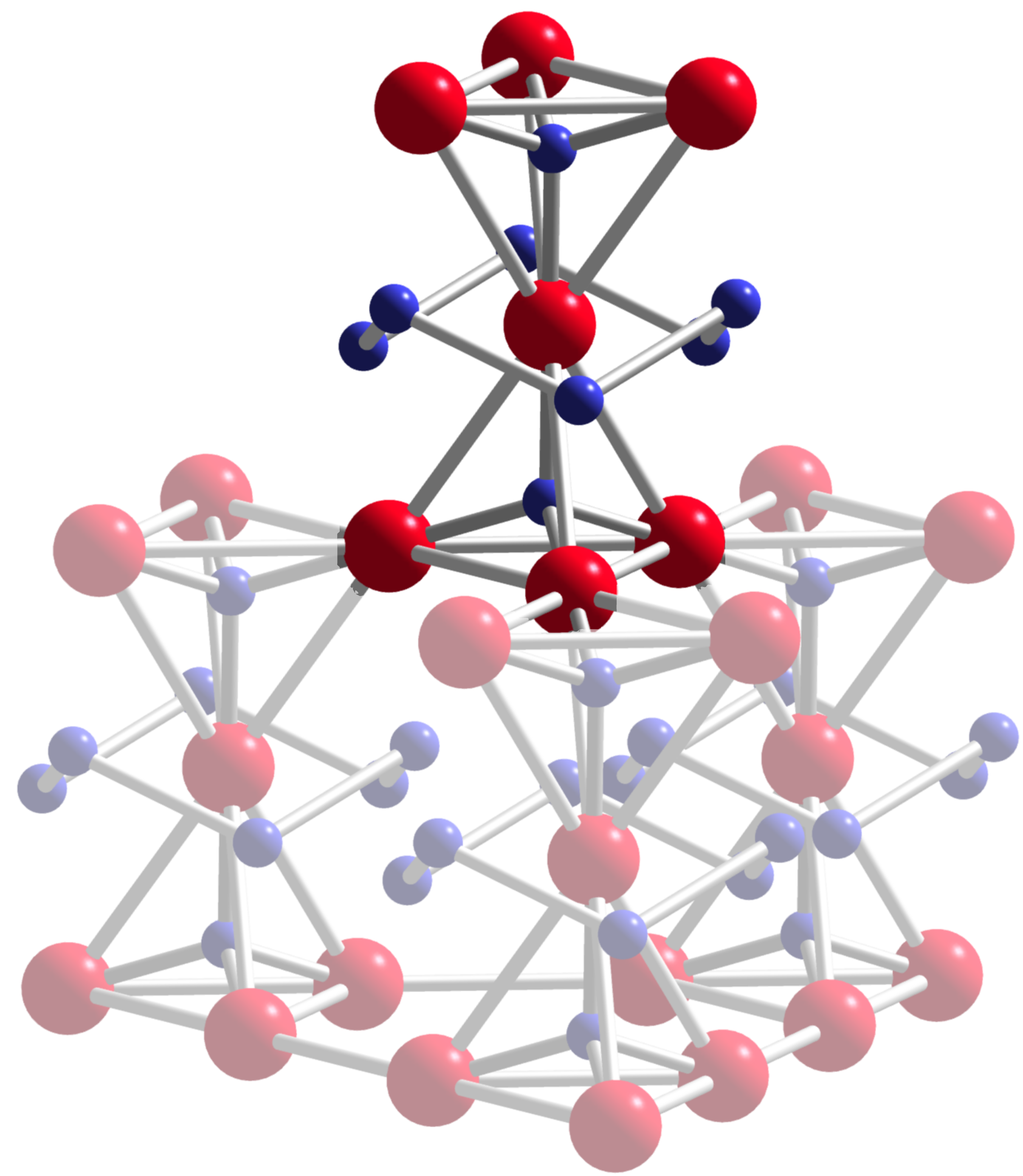



Rau & Gingras, PRB **98**, 054408 (2018)

# Pyrochlore Lattice $A_2Ti_2O_7$

- Spin Ice: $Ho_2Ti_2O_7$, $Dy_2Ti_2O_7$,
- Quantum Spin Ice: $Yb_2Ti_2O_7$
- Moment fragmentation $Sm_2Ti_2O_7$
- XY antiferromagnet: $Er_2Ti_2O_7$
- Multiple transitions AFM $Gd_2Ti_2O_7$
- Spin Liquid $Tb_2Ti_2O_7$

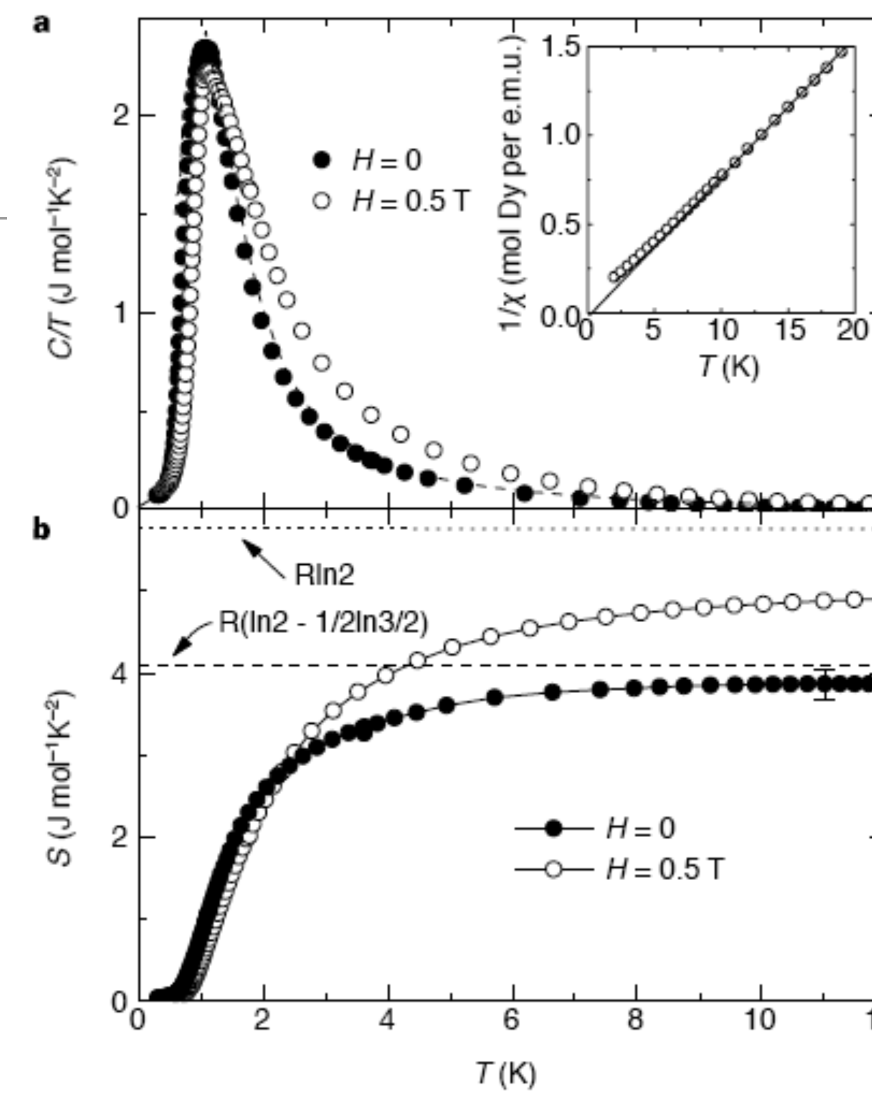


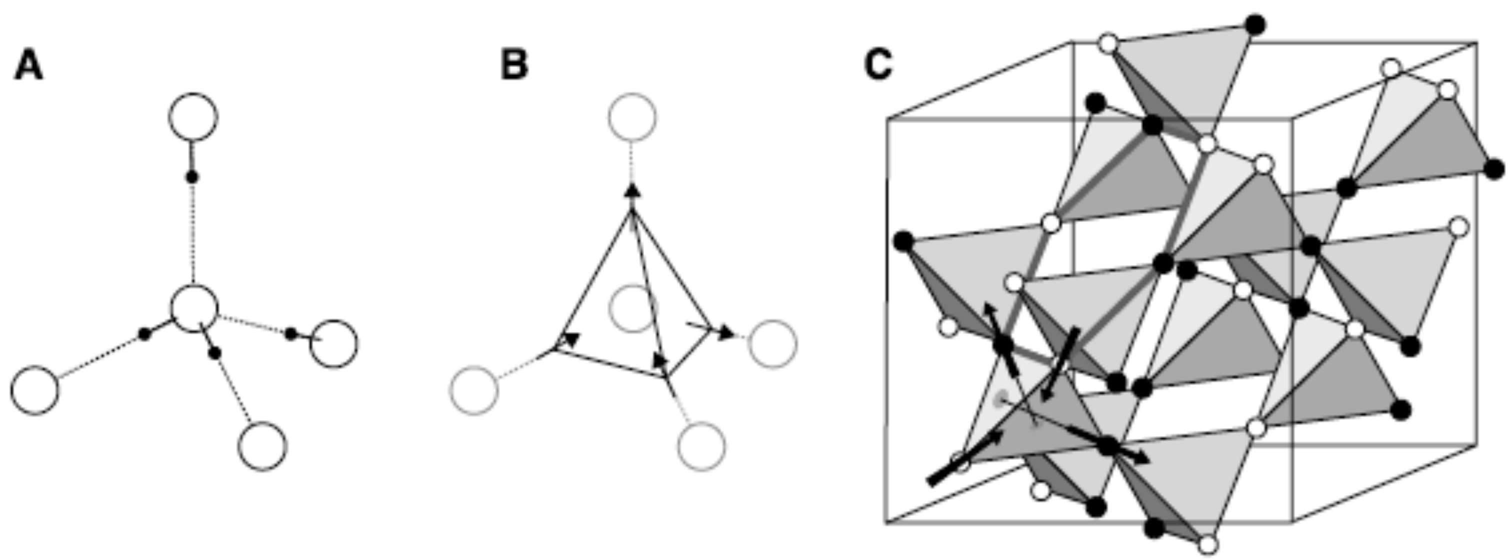
Gardner, Dunsiger *et al*., Phys. Rev. Lett. **82**, 1012 (1999)

# Spin Ice

- $Ho_2Ti_2O_7$, $Dy_2Ti_2O_7$, $Ho^{3+}/Dy^{3+}$ occupy vertices of corner-sharing tetrahedra in pyrochlore lattice.
- Strong crystal field anisotropy results in “Ising”-spins, either in or out along local <111>.
- Ferromagnetic interactions give “ice-rules” - 2 in / 2 out. 6-fold degeneracy for each tetrahedron.
- macroscopic degeneracy, corresponding to water ice.



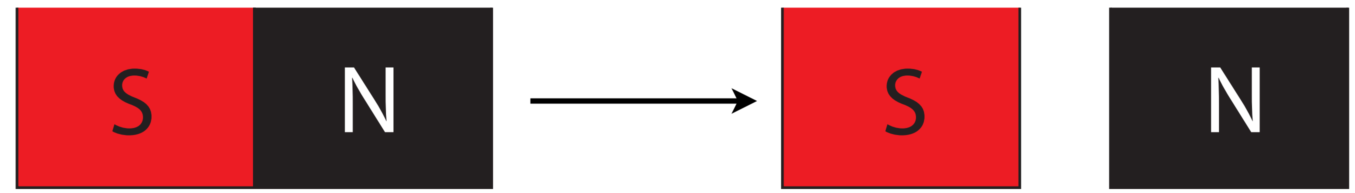

Ramirez et al., Nature 399, 333 (1999).

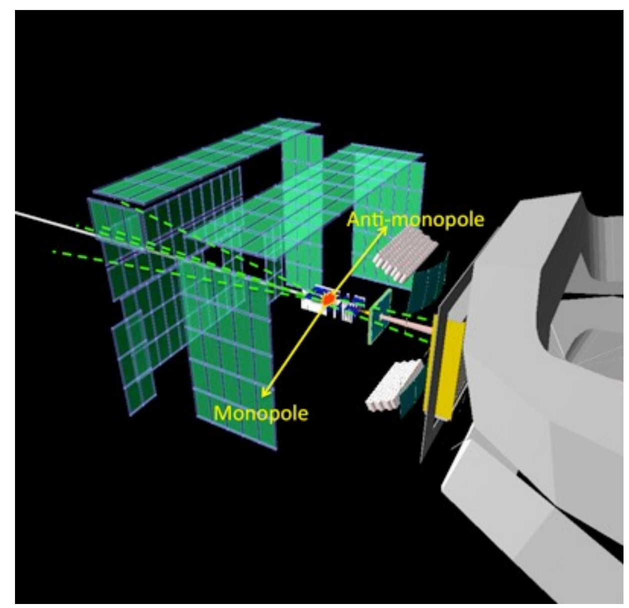



Bramwell & Gingras, Science 294, 1495 (2001).

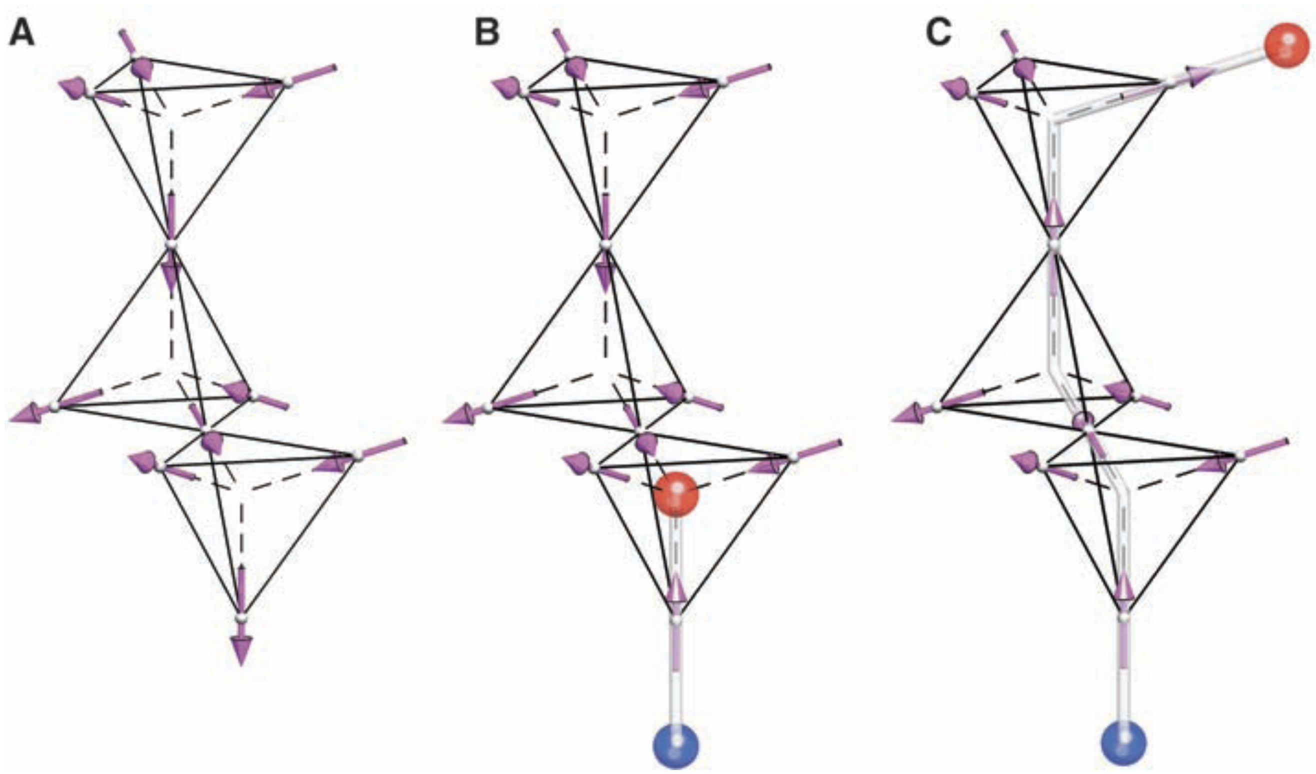
# Magnetic Monopoles

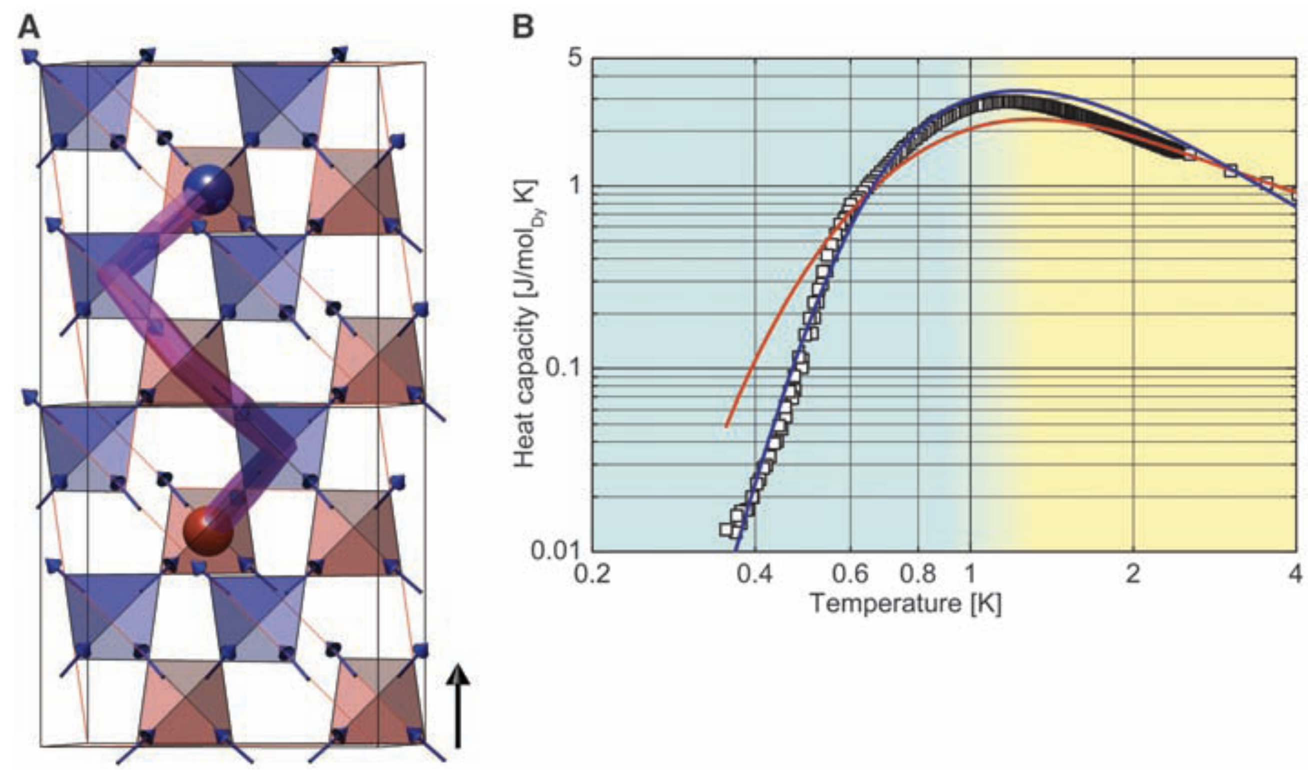
- Hypothetical particle, predicted in grand unified and superstring theories.
- Not observed (yet)
- MOEDEL (CERN)
- Searches in polar volcanic rock (eg. PRL **110**, 121803 (2013)).




# Emergent Magnetic Monopoles?



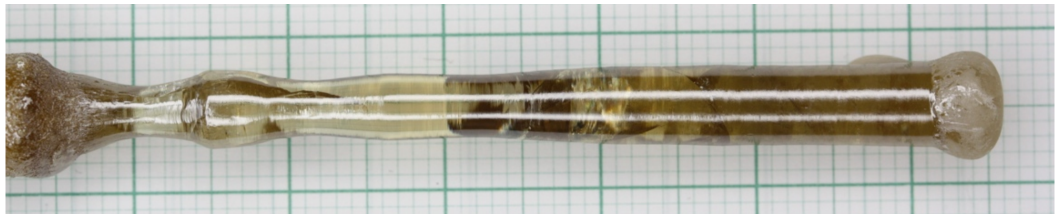



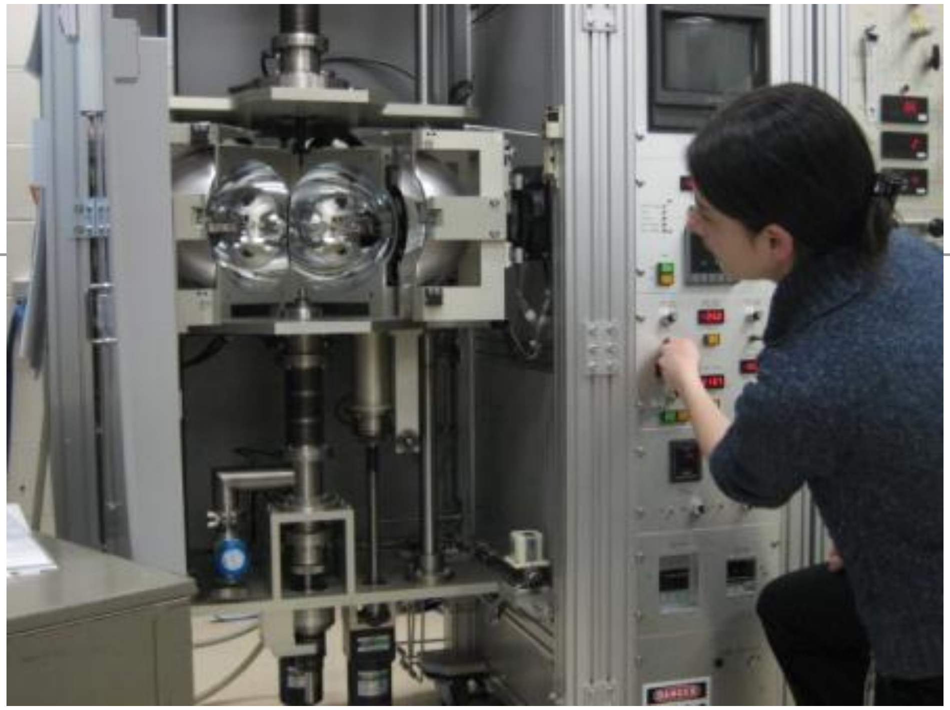

- Spin flip excitations from ground state create magnetic dipoles which can separate with minimal energy cost.
- Separated excitations correspond to magnetic monopoles.
    - Interact via Coulomb potential

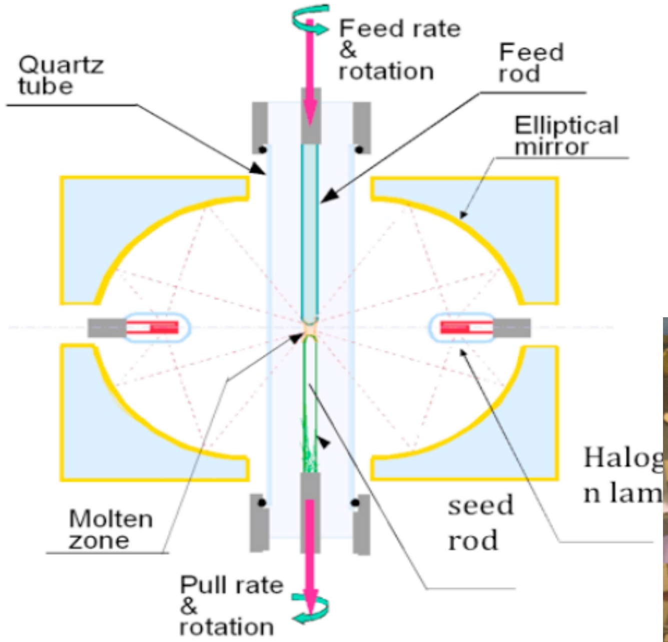
# Tools for Materials Science (in Canada)

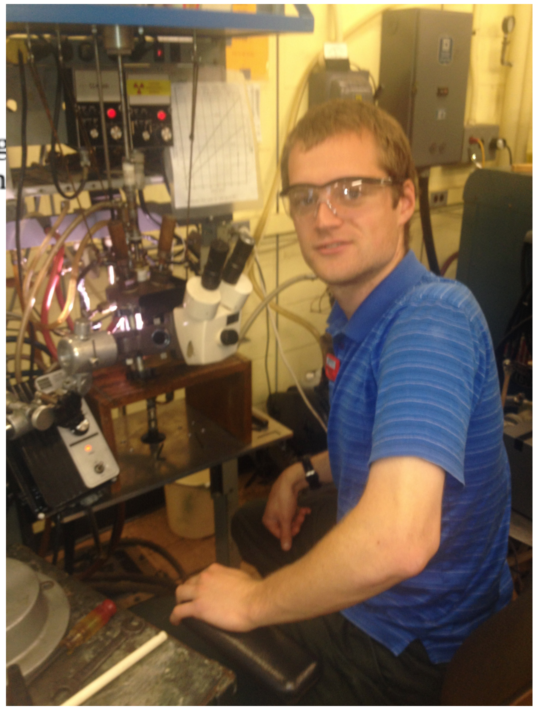
- Individual investigator (lab bench).
  - Sample growth / characterization
- Intermediate (regional facilities).
  - Electron microscopy, sample characterization (shared facilities).
- National/International facilities.
  - TRIUMF (muons, $\beta$-NMR).
  - Neutrons (Chalk River, MNR)
  - Synchrotron X-Ray (CLS)
  - Electron Microscopy (CCEM)
  - High Magnetic Fields

# Crystal Growth







# Mid-Size Facilities

- Brockhouse Institute for Materials Science
- Formerly had ~20 staff, now reduced to ~2, CCEM now independent.
- Maintained common infrastructure such as He liquifier, materials synthesis, characterization (optical microscopy, TGA, DTA, SQUID magnetometry).
- Seminar Series.
- Loss of government funding, reliance on user fees in environment of declining grant funding leads to loss of user support,

[4] Their arguments are as follows: From the $He^6$ recoil experiment and from Eq. (A-4) of reference 1 one concludes that $(|C_A|^2+|C_A'|^2)/(|C_T|^2+|C_T'|^2)\lesssim\frac{1}{3}$. Hence, by comparing Eq. (16) of reference 3 [see also Eq. (A-6) of reference 1], one concludes that the present large asymmetry is possible only if both conservation of parity and invariance under charge conjugation are violated.

## Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

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*Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York*

(Received January 15, 1957)

LEE and Yang[1-3] have proposed that the long held space-time principles of invariance under charge conjugation, time reversal, and space reflection (parity) are violated by the "weak" interactions responsible for decay of nuclei, mesons, and strange particles. Their hypothesis, born out of the $\tau-\theta$ puzzle,[4] was accompanied by the suggestion that confirmation should be sought (among other places) in the study of the successive reactions

$$\pi^+\rightarrow\mu^++\nu, \tag{1}$$

$$\mu^+\rightarrow e^++2\nu. \tag{2}$$

They have pointed out that parity nonconservation implies a polarization of the spin of the muon emitted from stopped pions in (1) along the direction of motion and that furthermore, the angular distribution of electrons in (2) should serve as an analyzer for the muon polarization. They also point out that the longitudinal polarization of the muons offers a natural way of determining the magnetic moment.[5] Confirmation of this proposal in the form of preliminary results on $\beta$ decay of oriented nuclei by Wu *et al.* reached us before this experiment was begun.[6]

By stopping, in carbon, the $\mu^+$ beam formed by forward decay in flight of $\pi^+$ mesons inside the cyclotron, we have performed the meson experiment, which establishes the following facts:

I. A large asymmetry is found for the electrons in (2), establishing that our $\mu^+$ beam is strongly polarized.

II. The angular distribution of the electrons is given by $1+a\cos\theta$, where $\theta$ is measured from the velocity vector of the incident $\mu$'s. We find $a=-\frac{1}{3}$ with an estimated error of 10%.

III. In reactions (1) and (2), parity is not conserved.

IV. By a theorem of Lee, Oehne, and Yang,[2] the observed asymmetry proves that invariance under charge conjugation is violated.

V. The $g$ value (ratio of magnetic moment to spin) for the (free) $\mu^+$ particle is found to be $+2.00\pm0.10$.

VI. The measured $g$ value and the angular distribution in (2) lead to the very strong probability that the spin of the $\mu^+$ is $\frac{1}{2}$.[7]

VII. The energy dependence of the observed asymmetry is not strong.

VIII. Negative muons stopped in carbon show an asymmetry (also leaked backwards) of $a\sim-1/20$, i.e., about 15% of that for $\mu^+$.

IX. The magnetic moment of the $\mu^-$, bound in carbon, is found to be negative and agrees within limited accuracy with that of the $\mu^+$.[8]

X. Large asymmetries are found for the $e^+$ from polarized $\mu^+$ beams stopped in polyethylene and calcium. Nuclear emulsion (as a target in Fig. 1) yields an asymmetry of about half that observed in carbon.

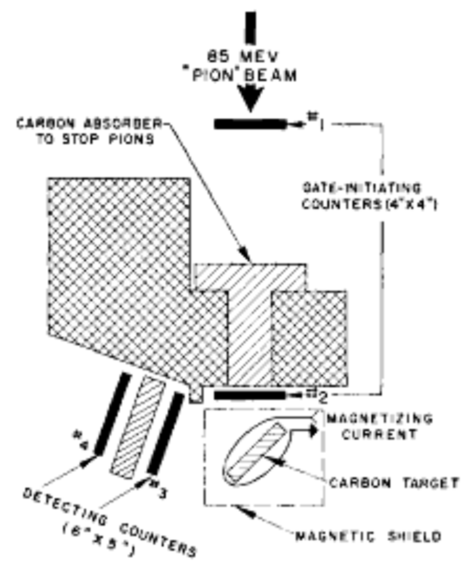


FIG. 1. Experimental arrangement. The magnetizing coil was close wound directly on the carbon to provide a uniform vertical field of 79 gauss per ampere.

The experimental arrangement is shown in Fig. 1. The meson beam is extracted from the Nevis cyclotron in the conventional manner, undergoing about 120° of magnetic deflection in the cyclotron fringing field and about −30° of deflection and mild focusing upon emerging from the 8-ft shielding wall. The positive beam contains about 10% of muons which originate principally in the vicinity of the cyclotron target by pion decay-in-flight. Eight inches of carbon are used in the entrance telescope to separate the muons, the mean range of the "85-"Mev pions being ~5 in. of carbon. This arrangement brings a maximum number of muons to rest in the carbon target. The stopping of a muon is signalled by a fast 1–2 coincidence count. The subsequent beta decay of the muon is detected by the electron telescope 3–4 which normally requires a particle of range >8 g/cm²(~25-Mev electrons) to register. This arrangement has been used to measure the lifetimes of $\mu^+$ and $\mu^-$ mesons in a vast number of elements.[9] Counting rates are normally ~20 electrons/



## Nuclear Emulsion Evidence for Parity Nonconservation in the Decay Chain $\pi^+-\mu^+-e^+$*†

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*Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois*

(Received January 17, 1957)

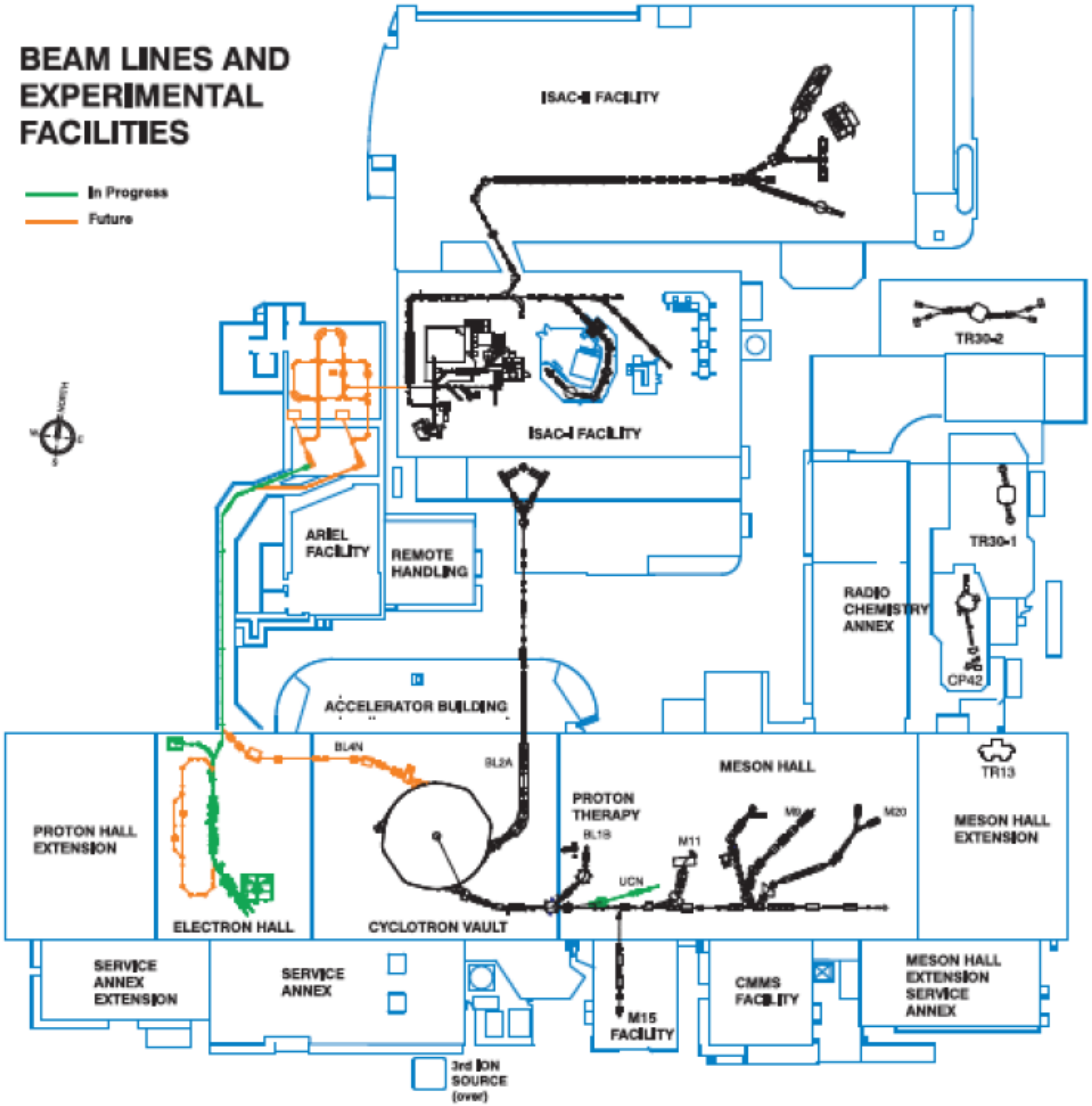
LEE and Yang[1] recently re-examined the problem as to whether parity is conserved in nature and emphasized the fact that one actually lacks experimental evidence in support of this most natural hypothesis in the case of weak interactions (such as $\beta$ decay). Violation of parity conservation can be inferred essentially only by measuring the probability distribution of some *pseudoscalar* quantity, e.g., of the projection of a polar vector along an axial vector, and measurements of this kind had not been reported. Lee and Yang suggested several experiments in which a spin direction is available as a suitable axial vector; in particular, they pointed out that the initial direction of motion of the muon in the process $\pi\rightarrow\mu+\nu$ can serve for this purpose, as the muon will be produced with its spin axis along its initial line of motion if the Hamiltonian responsible for this process does not have the customary invariance properties. If parity is further not conserved in the process $\mu\rightarrow e+2\nu$, then a forward-backward asymmetry in the distribution of angles $W(\theta)$ between this initial direction of motion and the momentum, $\mathbf{p}_e$, of the decay electron is predicted.

It is easy to observe the pertinent correlation by bringing $\pi^+$ mesons to rest in a nuclear emulsion in which the $\mu^+$ meson also stops. One has only to bear in mind two facts: (1) even weak magnetic fields, such as the fringing field of a cyclotron, can obliterate a real effect, as the precession frequency of a Dirac $\mu$ meson is $(2.8/207)\times10^6$ sec⁻¹/gauss; (2) $\mu^+$ can form "muonium," i.e., $(\mu^+e^-)$, and the formation of this atom can be an additional source of depolarization, both through its internal hyperfine splitting and the precession of its total magnetic moment around the external field. In the absence of specific experiments on muonium formation, one can perhaps be guided by analogous data on positronium in solids.[2,3]

With these facts in mind, we exposed (in early October, 1956) nuclear emulsion pellicles (1 mm thick) to a $\pi^+$ beam of the University of Chicago synchrocyclotron. The pellicles were contained inside three concentric tubular magnetic shields and subject to $\leq4\times10^{-3}$ gauss. Over 1300 complete $\pi-\mu-e$ decays have been recorded to date, and the space angle $\theta$ defined above has been calculated for each. From these preliminary data we find[4]

$$\left\{\int_{90^\circ}^{180^\circ}|W(\theta)|d\Omega-\int_0^{90^\circ}|W(\theta)|d\Omega\right\}\bigg/\int_0^{180^\circ}W(\theta)d\Omega=0.062\pm0.027,$$

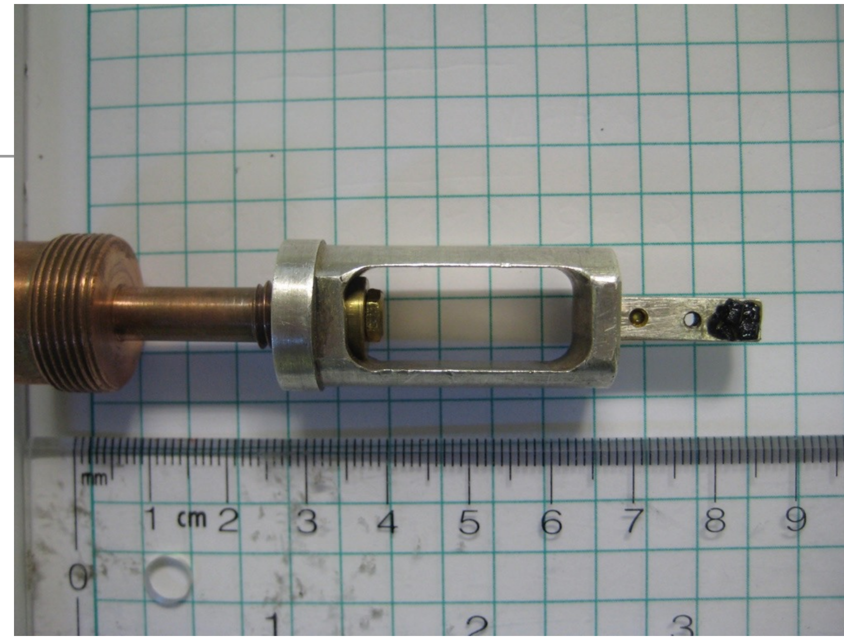
# TRIUMF

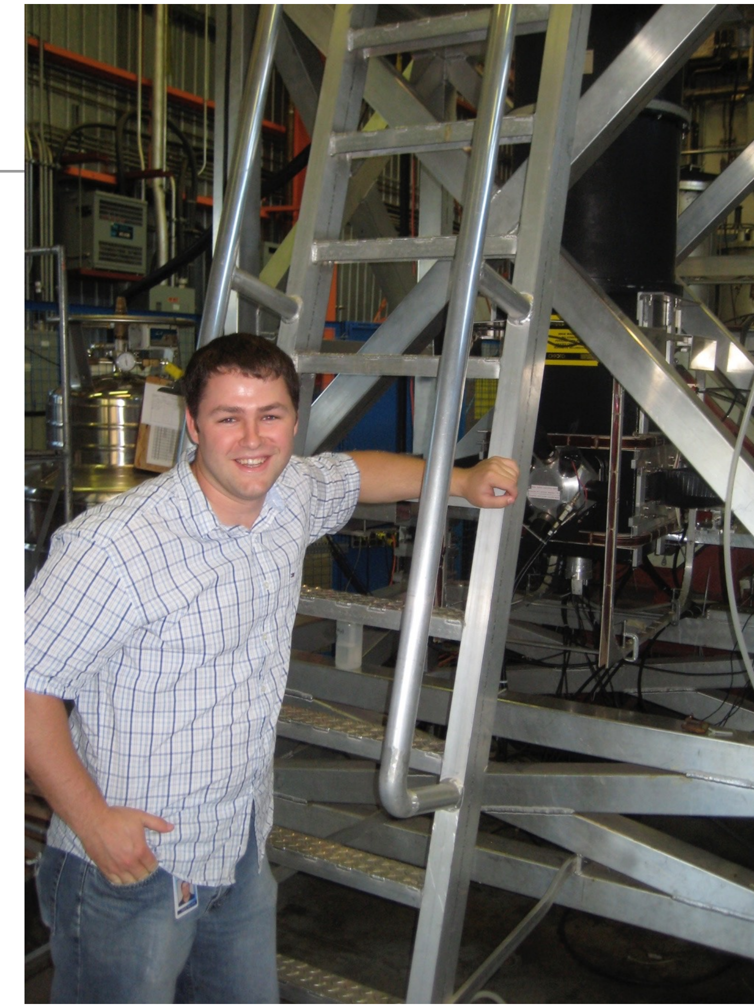


BEAM LINES AND EXPERIMENTAL FACILITIES
In Progress
Future
ISAC-II FACILITY
ISAC-I FACILITY
TR30-2
TR30-1
ARIEL FACILITY
REMOTE HANDLING
RADIO CHEMISTRY ANNEX
CP42
ACCELERATOR BUILDING
TR13
PROTON HALL EXTENSION
ELECTRON HALL
BL4N
BL2A
CYCLOTRON VAULT
MESON HALL
PROTON THERAPY
BL1B
M11
M9
M20
UCN
MESON HALL EXTENSION
SERVICE ANNEX EXTENSION
SERVICE ANNEX
M15 FACILITY
CMMS FACILITY
MESON HALL EXTENSION SERVICE ANNEX
3rd ION SOURCE (over)

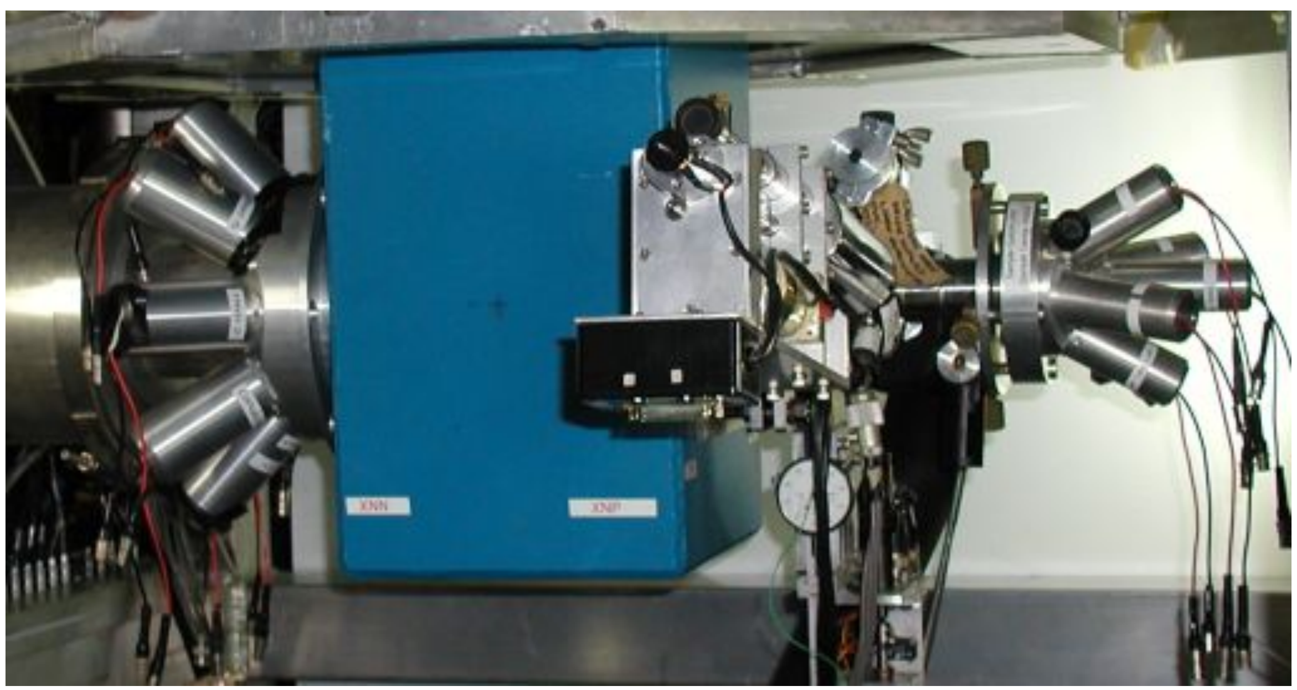
# Capabilities at TCMMS

Low Background

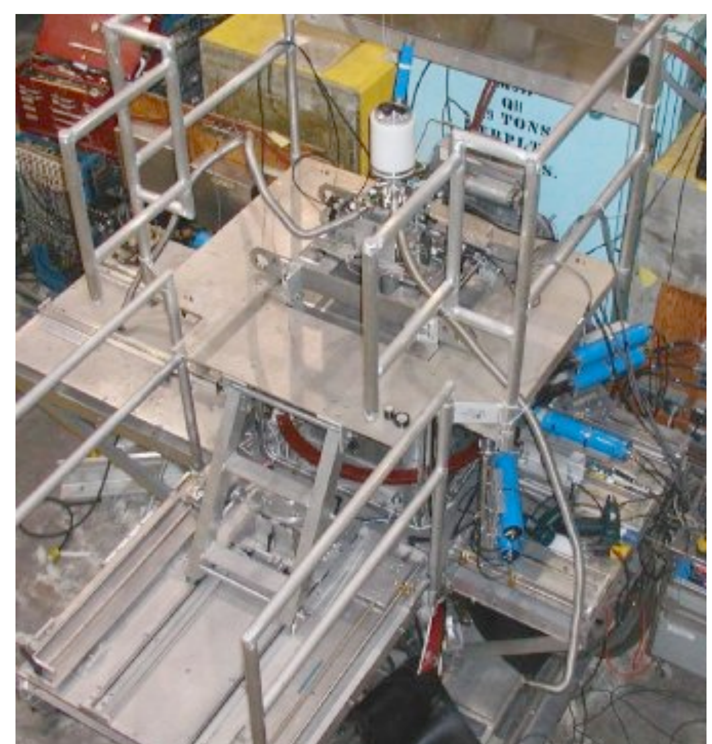




DR: 20mK, 5T



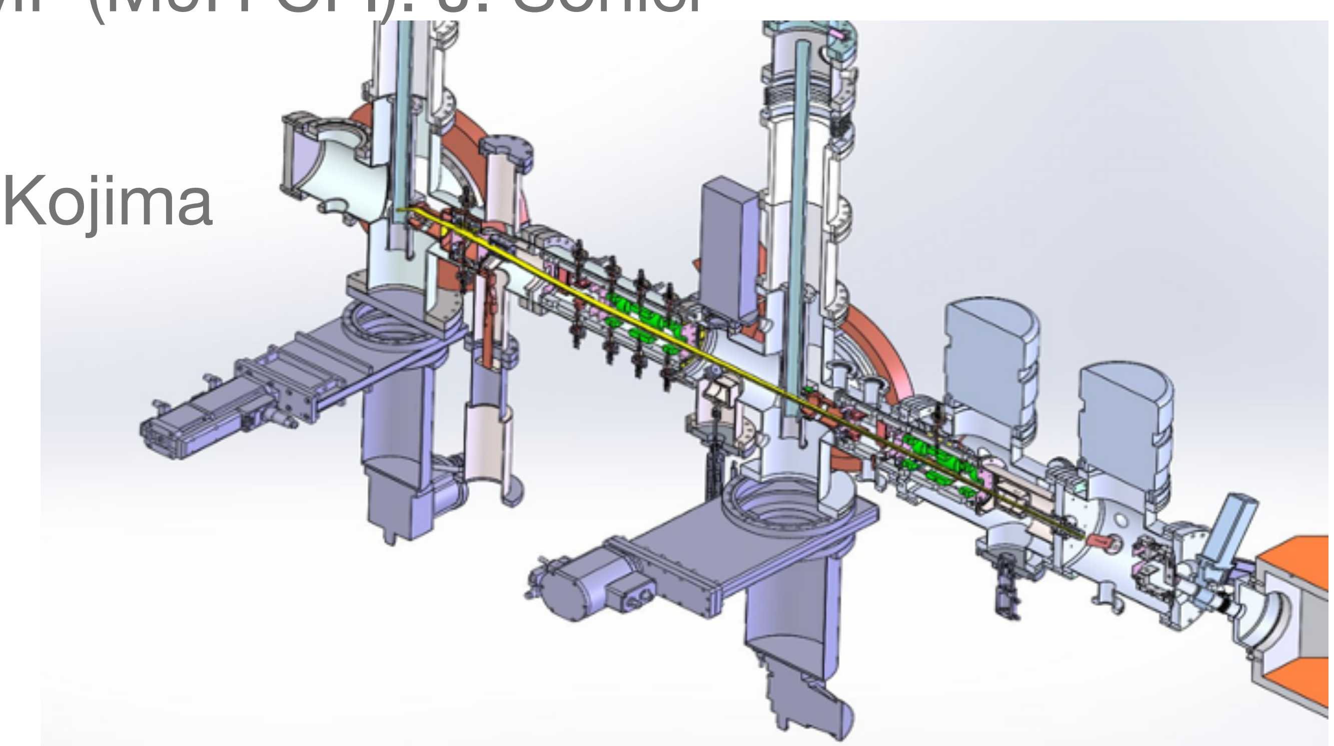
HiTime: 7.5T, 1GHz, 2K



High Pressure:
22kbar, 2.5K,
55% sample

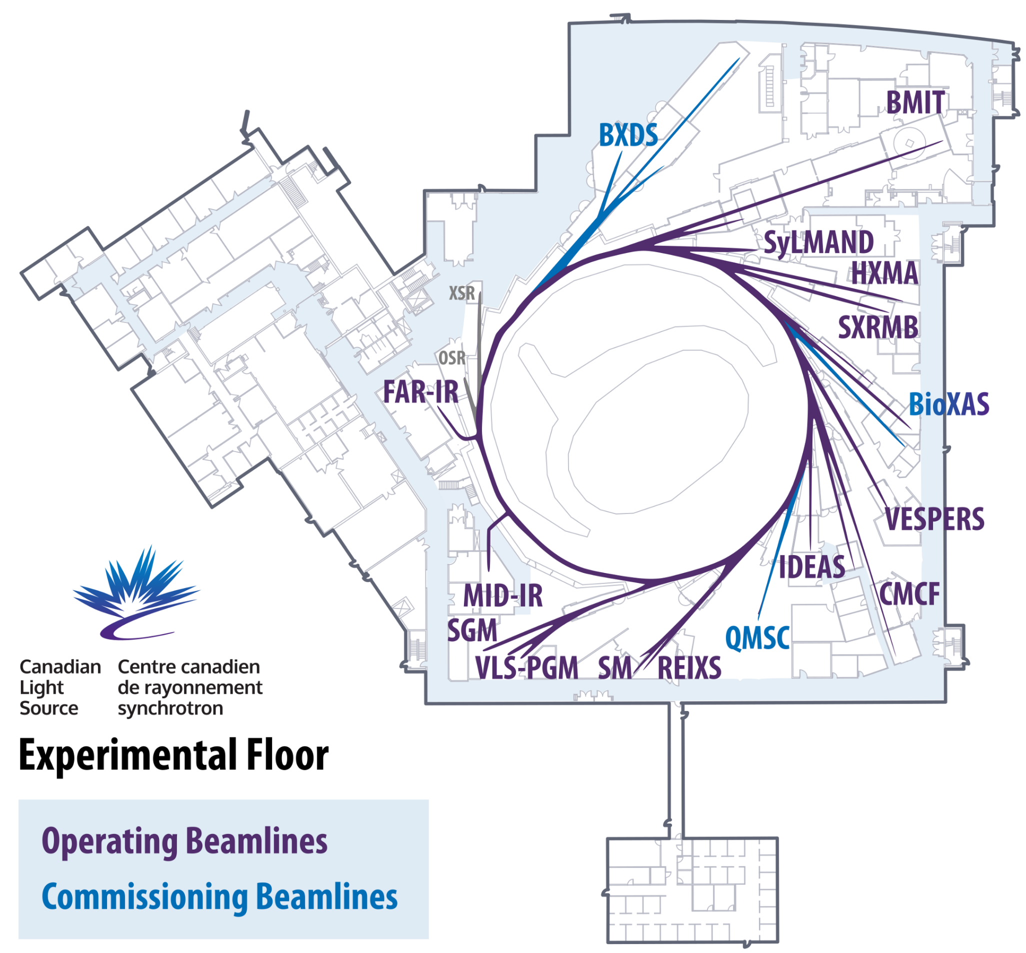
# 5 Year Plan CMMS Initiatives

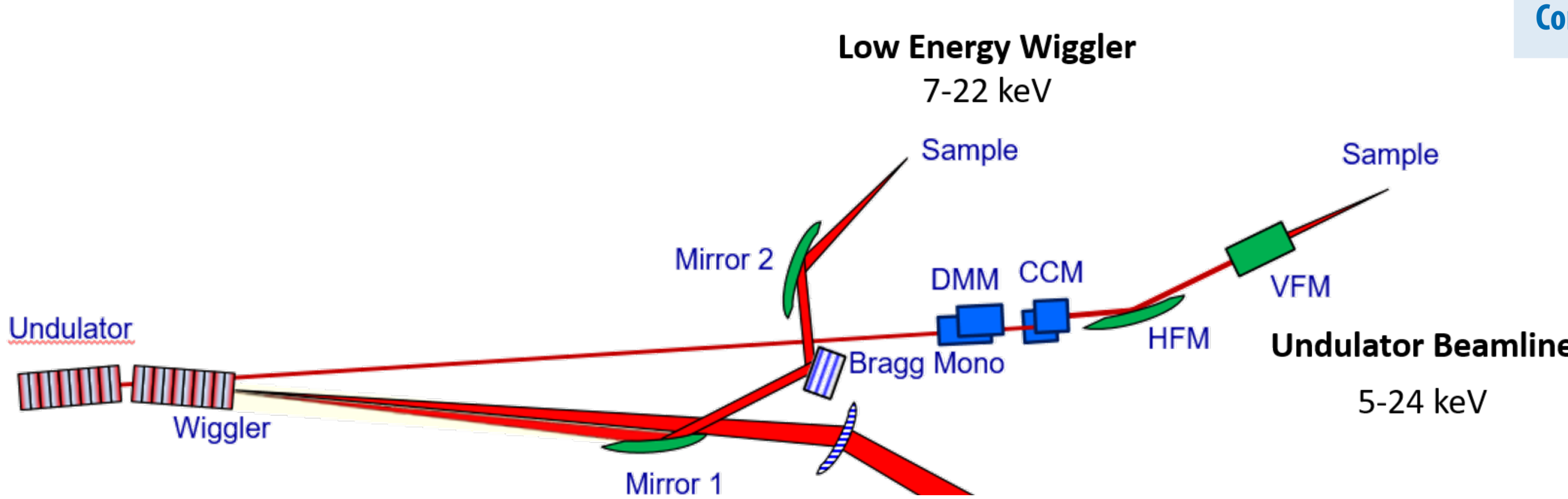
- Polaris: Spin echo techniques using $\beta$ detected NMR and expanded access to Polarized Ion Beams: S. Dunsiger.
- Muonic X-Ray spectrometer for elemental analysis of energy storage devices and objects of cultural heritage: Iain McKenzie.
- Expanding Muon Beam Lines at TRIUMF (M9H CFI): J. Sonier
- SiPM, spectrometer developments: K. Kojima
- Revitalizing M15
- Healthy state of affairs.



# Synchrotron X-Ray (CLS)

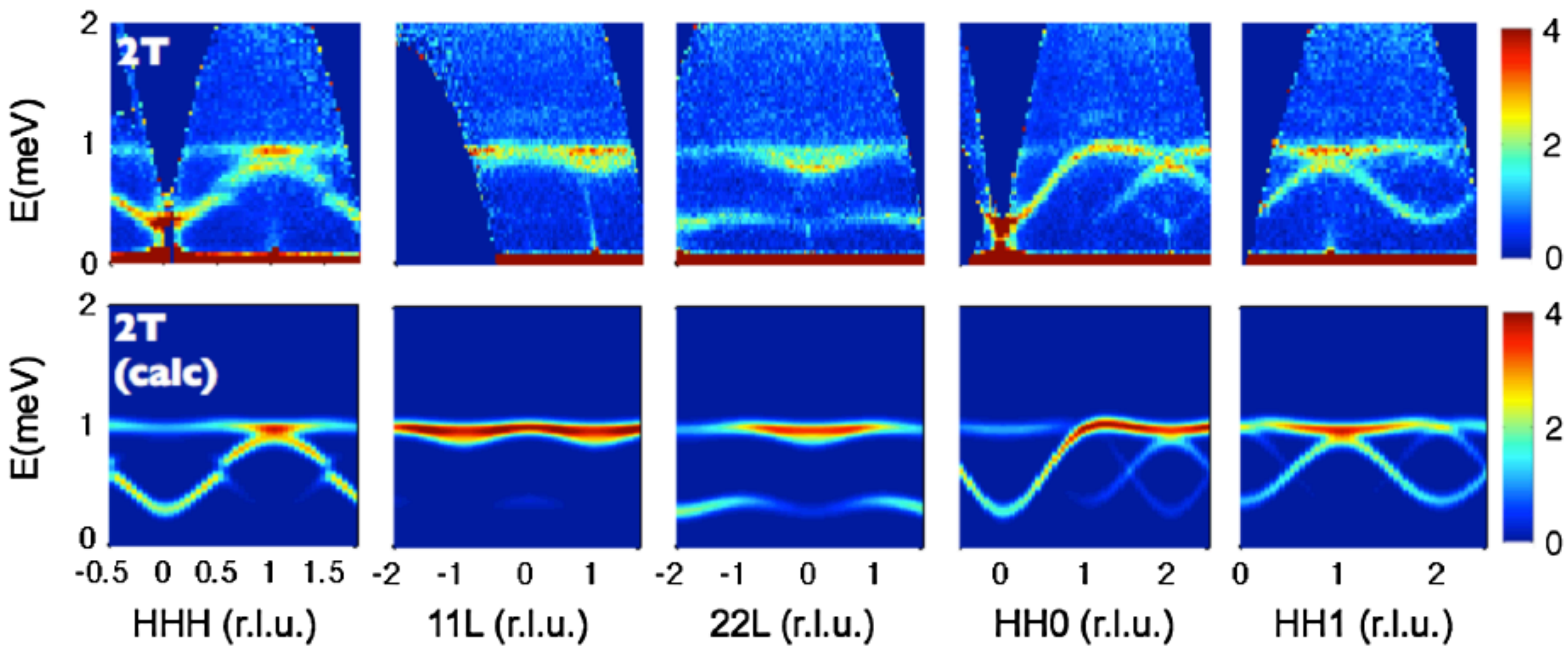
- Brockhouse Sector at CLS
- X-ray diffraction, resonant/magnetic diffraction, reflectivity.
- 0.1mm beamspot dimension (typical).
- Resonant Inelastic X-Ray Scattering, X-ray Absorption Fine Structure (XAFS)…
- Macromolecular crystallography…




# Neutron Scattering

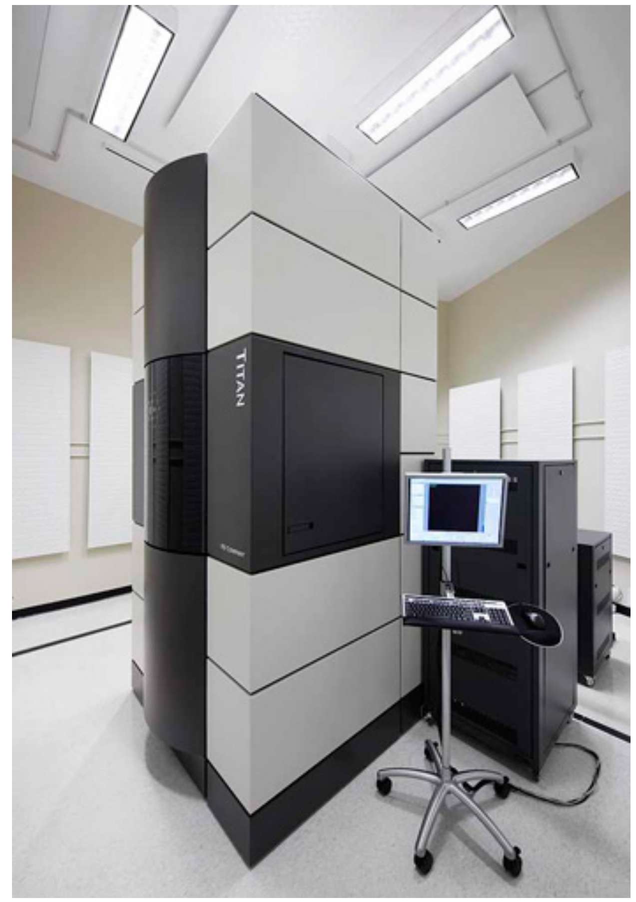
- Loss of Chalk River.
- McMaster Nuclear Reactor
- CINS
- Use of international facilities: ORNL, NIST, ILL, ISIS, JPARC, ESS (future).
- Development of new sources.

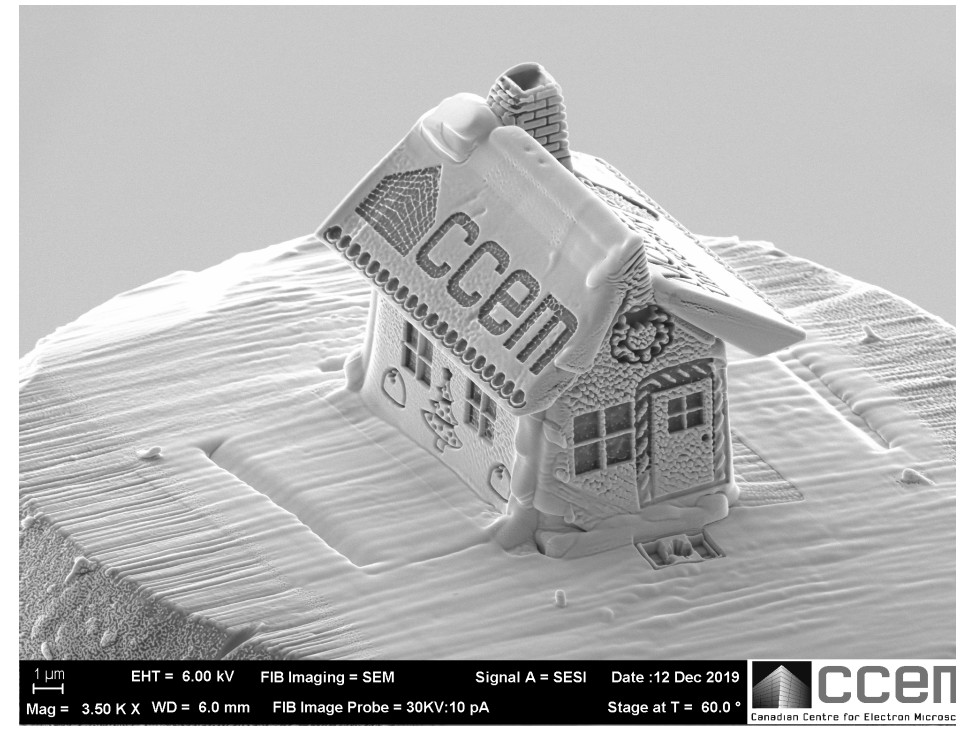


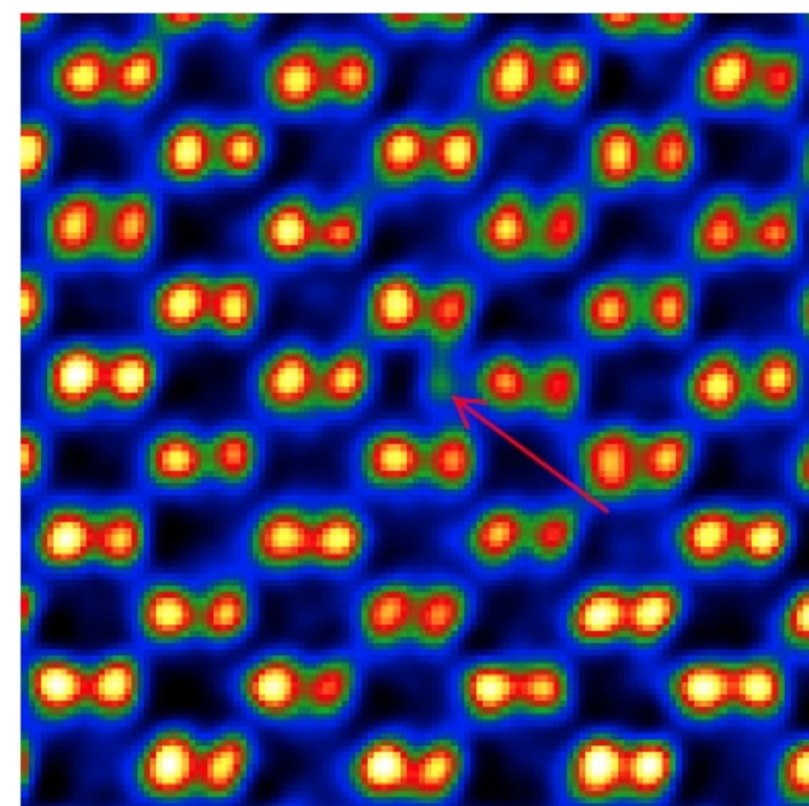

Ross *et al.*, Phys. Rev. X **1**, 021002 (2011)

# Canadian Centre for Electron Microscopy

- User facility: 11 staff, plus affiliated faculty members.
- Atomic resolution.
- Ability to manipulate materials.
- Mail-in of samples possible.
- User Fees (barrier).



# CIFAR - Quantum Materials Program

- Began as Superconductivity, following discovery of cuprates (Bednorz & Muller, 1986.
- Institute without walls- highly effective.
- Support for interactions, summer school, biannual program meetings.
- Multiple renewals (5 year cycle). Most recent with a much more narrow membership, 50% international membership.
- Ongoing QM community, organizing meetings, online seminar series.
- Model for interactions portion of EPiQS program (Moore Foundation).
- Seeded 2 successful CFREF's (UBC, Sherbrooke).
- National Quantum Initiative?

# Materials Science in Canada

- Canada lacks a coherent program in Materials Science.
- Some bright spots
  - muons, $\beta$-NMR/NQR
  - Energy materials - batteries @ Dalhousie
  - Soft & Biomaterials
- CLS Materials program relatively new (Brockhouse sector just starting now).
- Largely out of Neutron Scattering, $8B investment elsewhere.
- Funding for mid-size facilities largely eliminated (MRS program).
- Need to organize communities to develop a Platform to support Materials facilities supporting research, develop and address Grand Challenges for Materials Research.