Simultaneous spin measurement for ultracold neutrons at TRIUMF

Blair Jamieson <bl.jamieson@uwinnipeg.ca>

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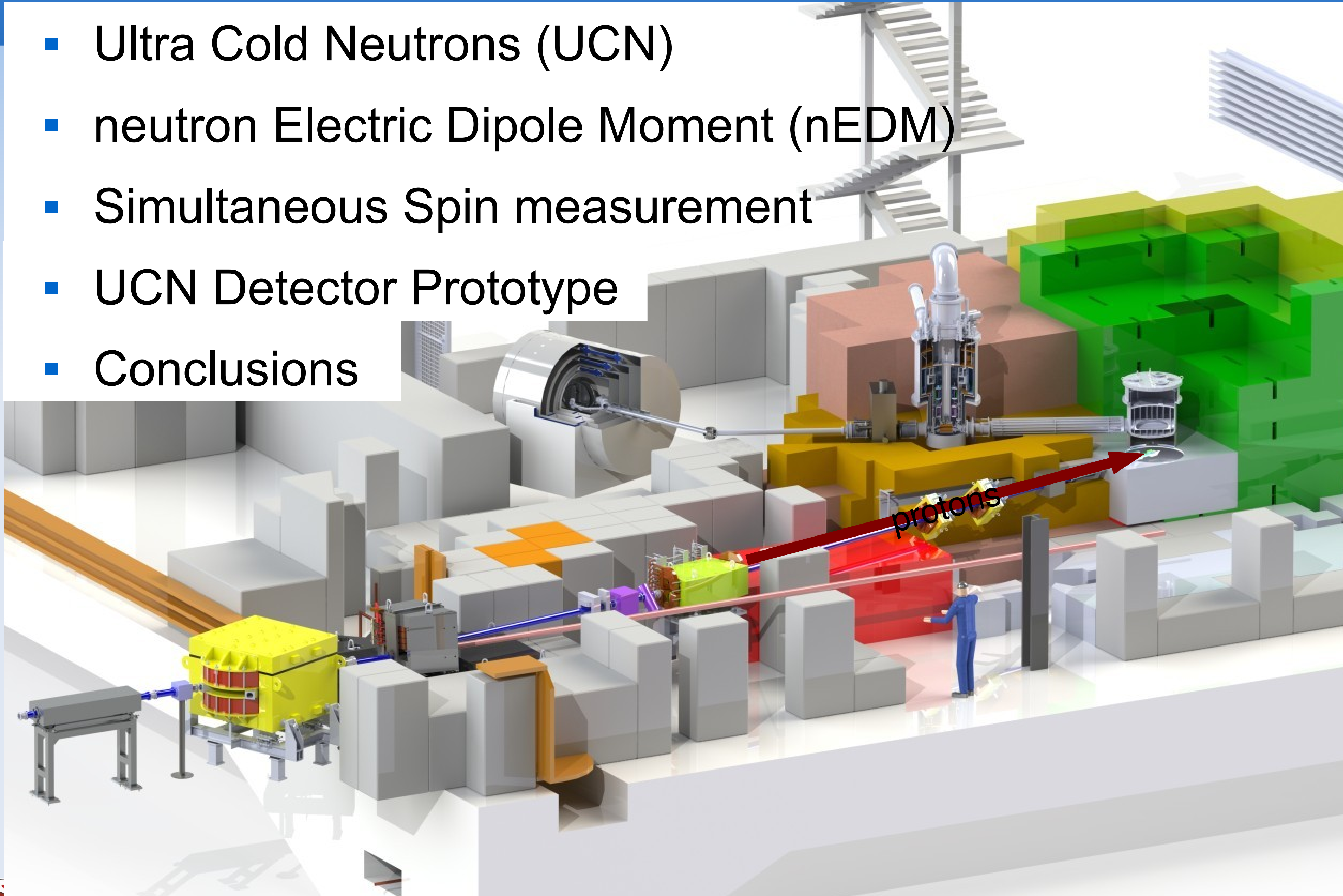
Edmonton, Alberta

Outline

- Ultra Cold Neutrons (UCN)
- neutron Electric Dipole Moment (nEDM)
- Simultaneous Spin measurement
- UCN Detector Prototype
- Conclusions



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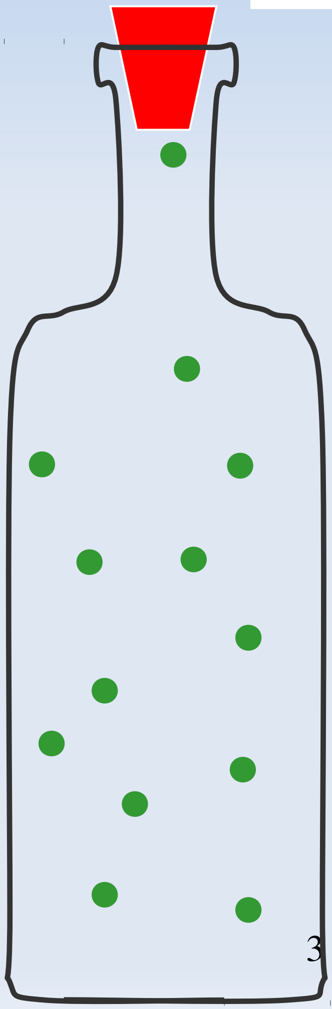
Ultracold Neutrons (UCN)

- UCN are neutrons that are moving so slowly that they are totally reflected from a variety of materials.
- Typical parameters:
  - Wavelength > 50 nm (> atomic spacing)
  - velocity < 8 m/s = 30 km/h
  - temperature < 4 mK
  - kinetic energy < 300 neV
- Interactions:
  - Gravity: $V=mgh$ $mg = 100$ neV/m
  - Magnetic: $V=-\mu\bullet B$ $\mu= 60$ neV/T
  - Strong: $V=V_{eff}$ $V_{eff} < 335$ neV
  - Weak: $\tau = 885.7$ s = 15 mins



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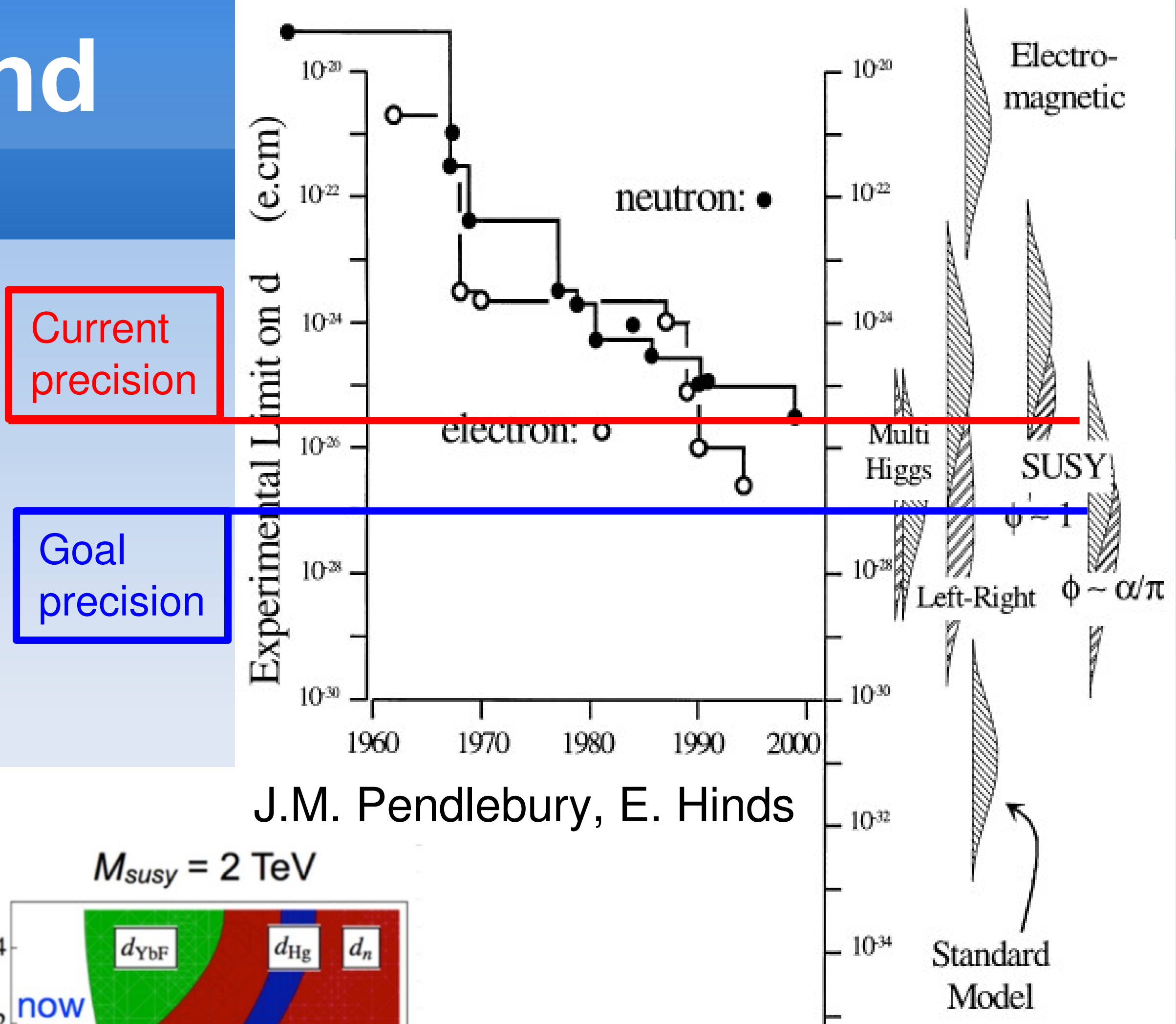
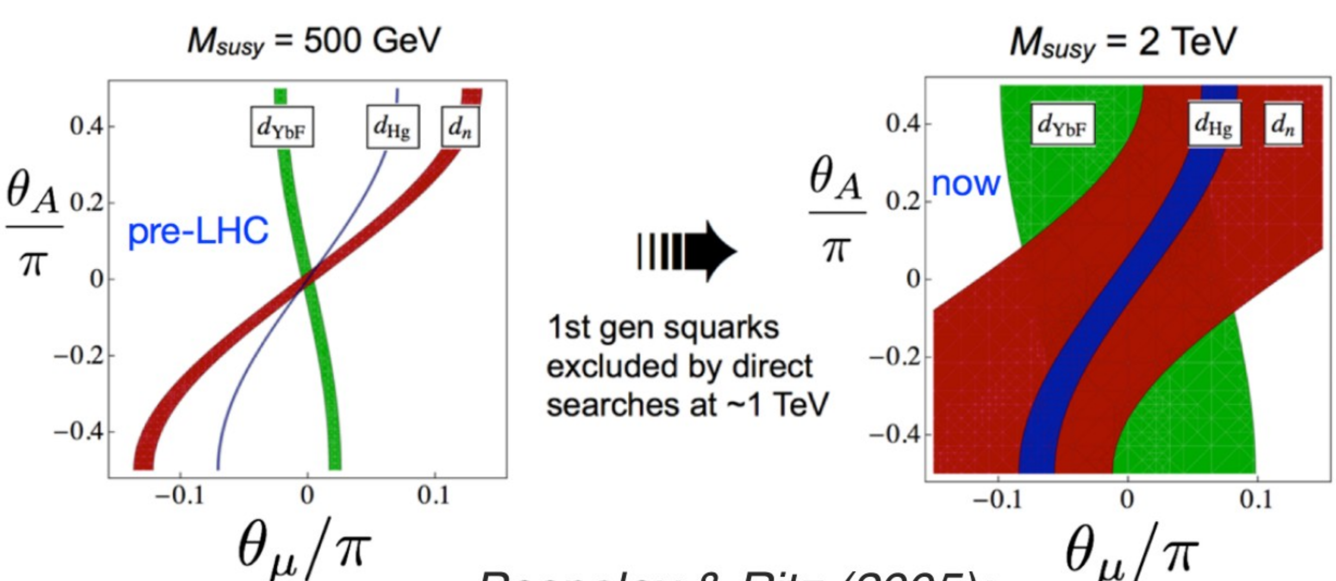
EDMs, the SM, and beyond

- Use UCN to look for an electric dipole moment (EDM) of neutron!
- nEDM rules out and constrains many BSM models



J.M. Pendlebury, E. Hinds

Complementary to LHC:



Pospelov & Ritz (2005):

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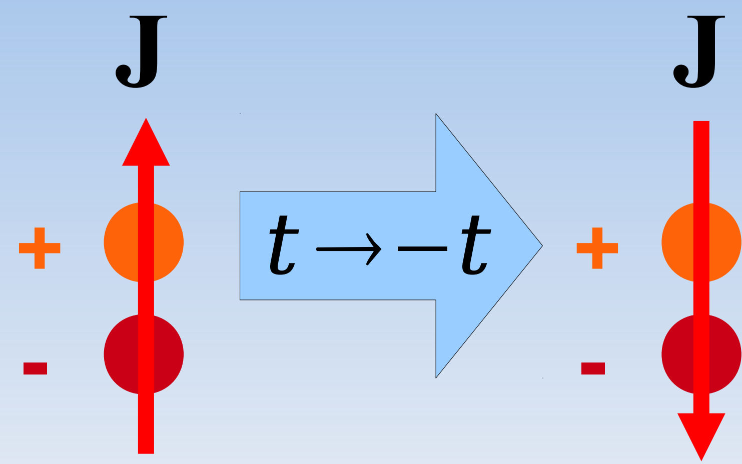
Neutron Electric Dipole Moment (n-EDM, d_n)



$$d_n \Rightarrow \not{T} \Rightarrow \not{CP}$$

New sources of CP violation are required to explain the baryon asymmetry of the universe.
(One of Sakharov's three criteria)

- Complementary to Rn-EDM, Fr-EDM @ TRIUMF.

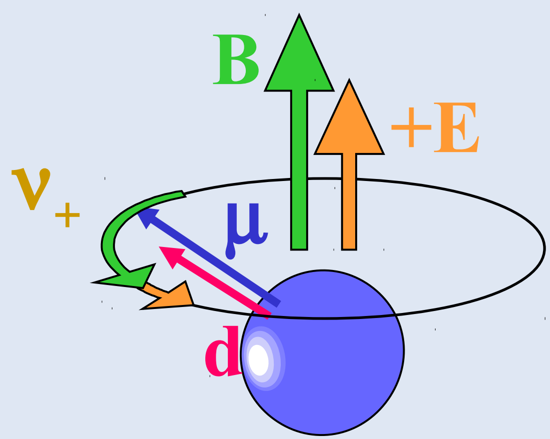
Experimental technique:

- put UCN in a bottle with *E*-, *B*-fields
- search for a change in spin precession frequency (at Larmor frequency) upon *E* reversal.

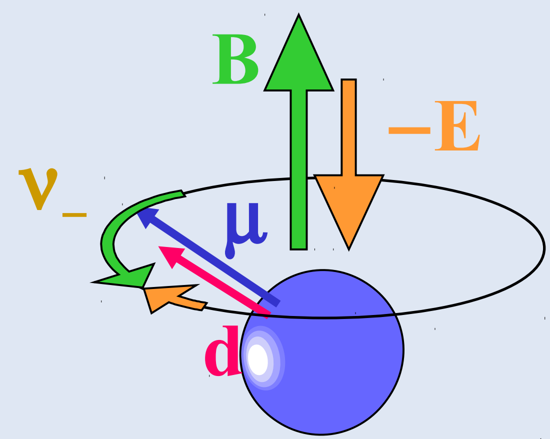
$$h\nu_{\pm} = 2\mu_n B \pm 2 d_e E$$

Electric Dipole Moment:

$$d_n = (h/2E)(\nu_+ - \nu_-)$$



Precesses Faster



Precesses Slower

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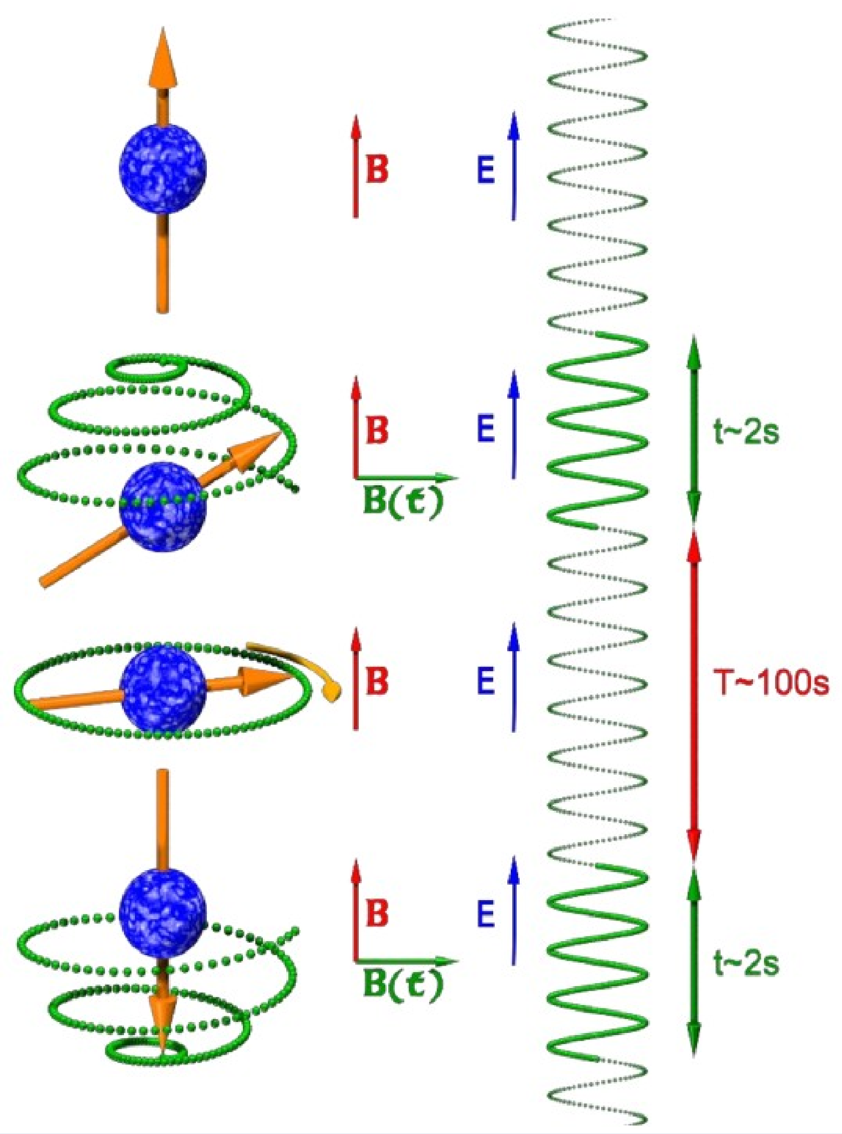
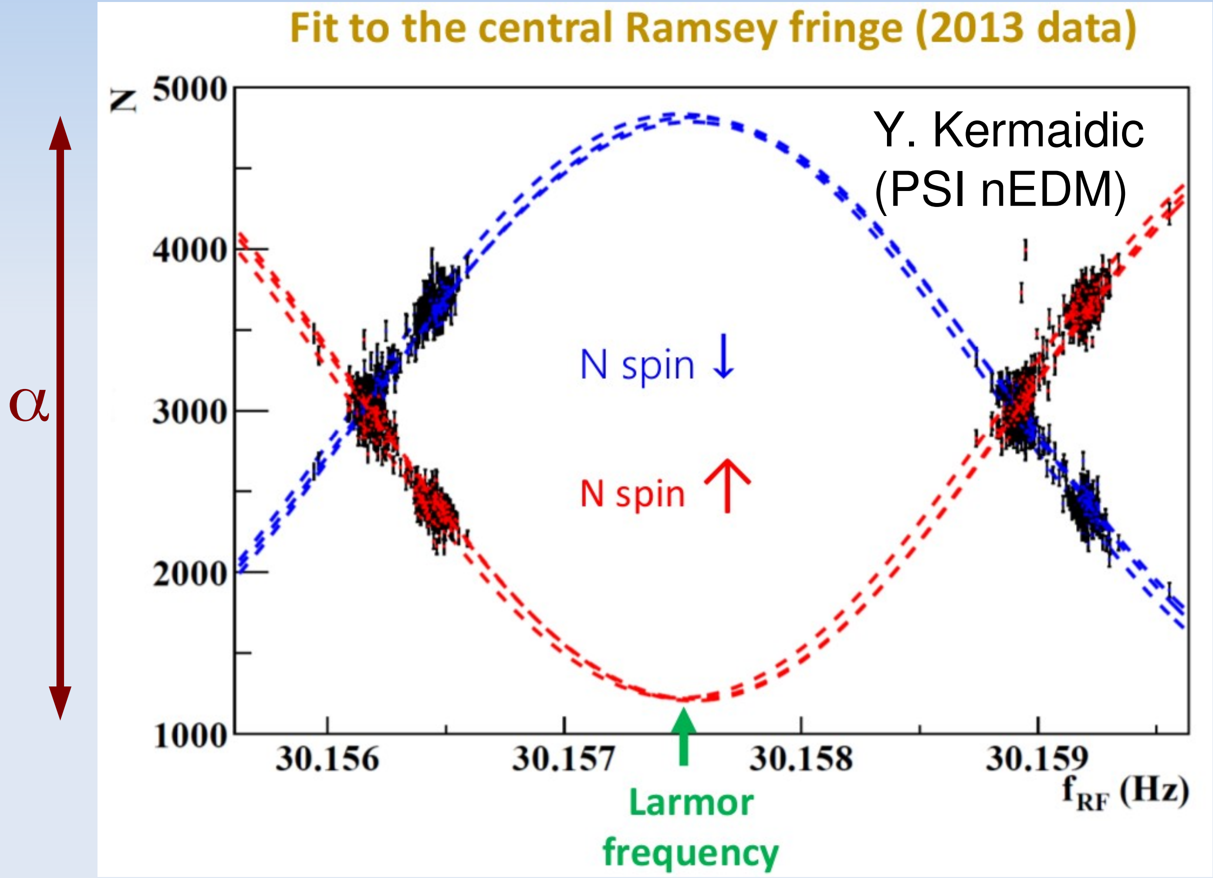
Ramsey Resonance
NMR of polarized neutrons





$$\sigma_{d_n} = \frac{\hbar}{2 \alpha T E \sqrt{N_{tot}}}$$

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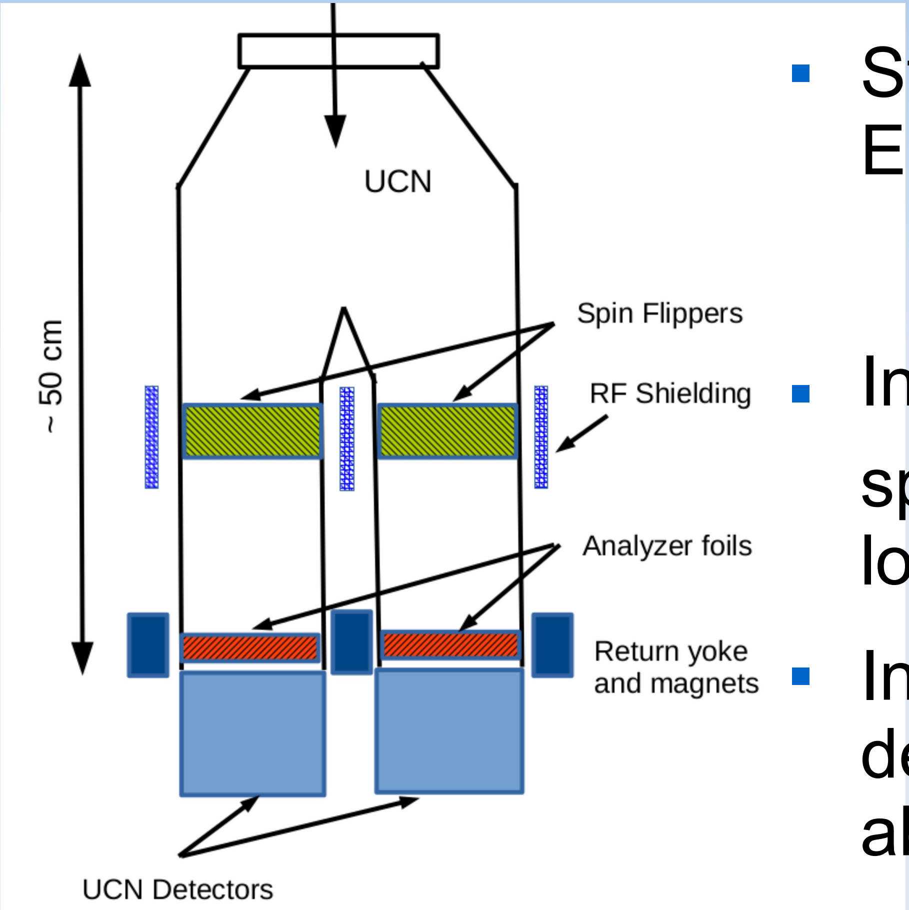
Simultaneous Spin Analysis (SSA) Concept



Such a system is described in:
V.Helaine's thesis, and
ArXiv:1502.06876

- Stat. Uncertainty in measured EDM is given by:

$$\sigma_{d_n} = \frac{\hbar}{2 \alpha T E \sqrt{N_{tot}}}$$

- Increase N_{tot} by measuring both spin states simultaneously (less loss due to storage time)
- Increase alpha due to less depolarization while storing above analyzer foil
- Multiple spin flippers to study systematic uncertainties (in principle only one is needed)

bl.jamieson@uwinnipeg.ca

UCN Detector Requirements

- diameter of 85 mm to cover the entrance pipe (based on expected UCN in the experiment cell, and draining simulations)
- Rate ~1.5 MHz and ability to handle any effects of pile-up
- Ability to account for backgrounds (gamma, beta, thermal neutron)
- A variation in efficiency better than 0.03% over an hour (based on 1/sqrt(N) statistical uncertainty, $N=10^7$)
- Ability to normalize for changes in UCN density

(ie. Due to drifts in detector efficiency, changes in number of UCN produced, etc.)

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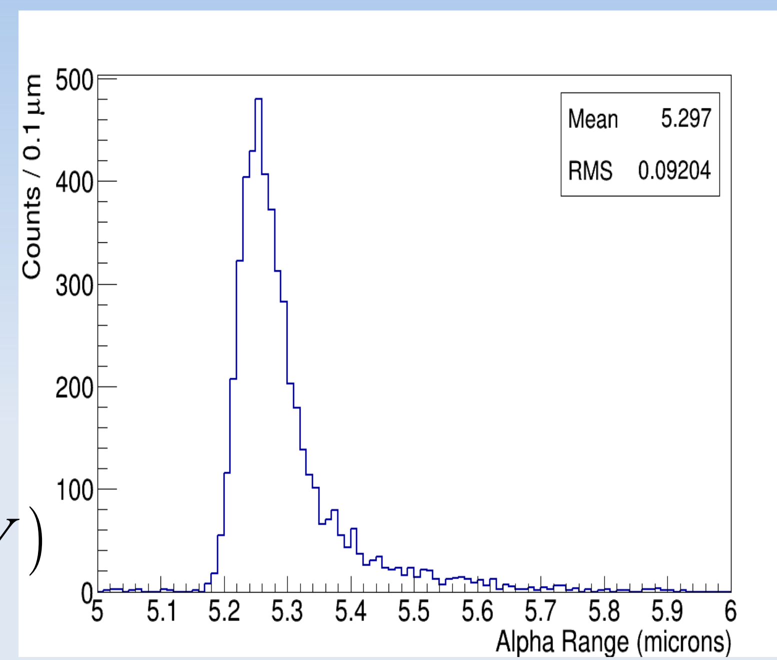
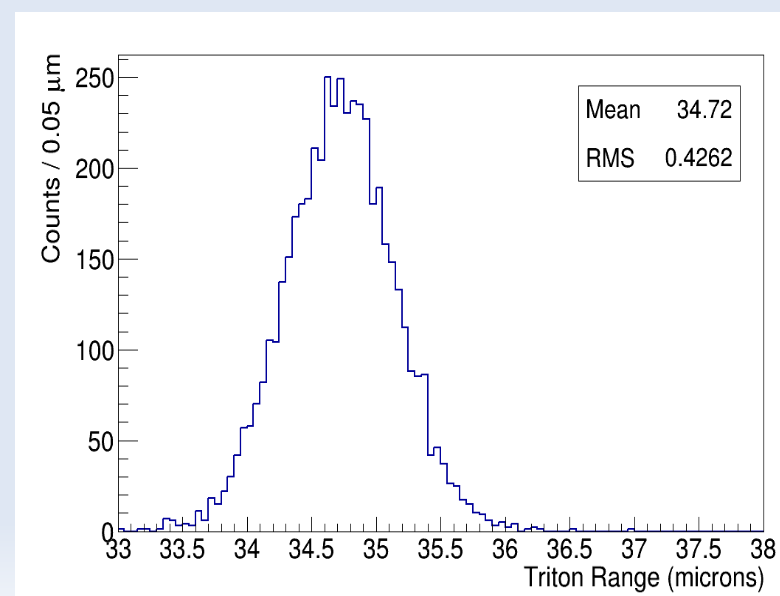
Li glass scintillator detector chosen

Based on Ban et. al. NIM A611 (2009) 280

Ce doped glass scintillators



- Use Li-6 depleted glass on top (GS30) of Li-6 enriched glass (GS20)
- UCNs go through GS30 and capture within 1-2 microns of the surface of the GS20 via: $n + {}^{6}Li \rightarrow t(2.73\,\mathrm{MeV}) + \alpha(2.05\,MeV)$
- Full energy of triton and alpha produce scintillation light in the glass scintillator (very little edge effect)
  - Only need < 50 microns thick for each of scintillators to capture full energy
  - Have 100 um thick GS20 and 60 um thick GS30 optically contacted set



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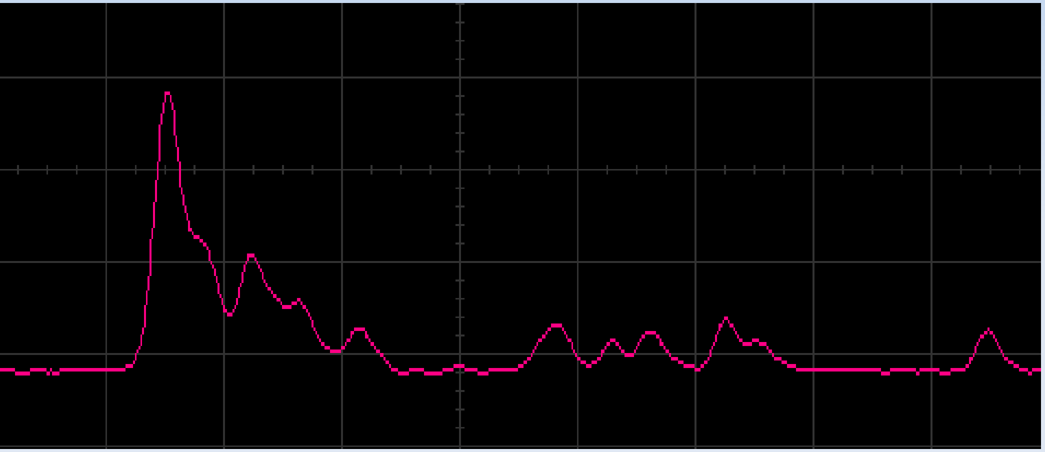
Waveforms from test setup

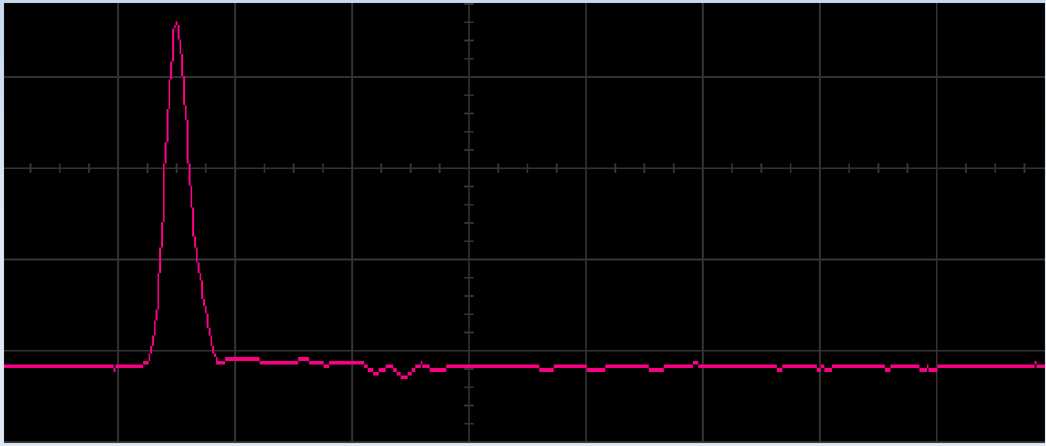
20 ns x 100 mV per division

Scintillator / Alpha Event



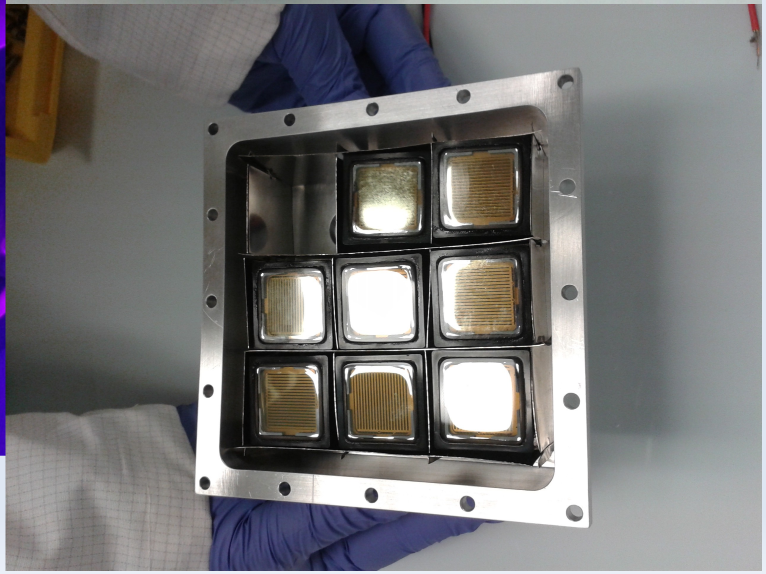
- Scintillation has a fast and short component
- Fast component ~50ns,
- Long component ~1us.
- UCN should look similar to alpha event

Cerenkov Event



- Cerenkov may have a large pulse, but short duration, ~ 20 ns.
- Notable pulse shape difference

Photos from detector assembly



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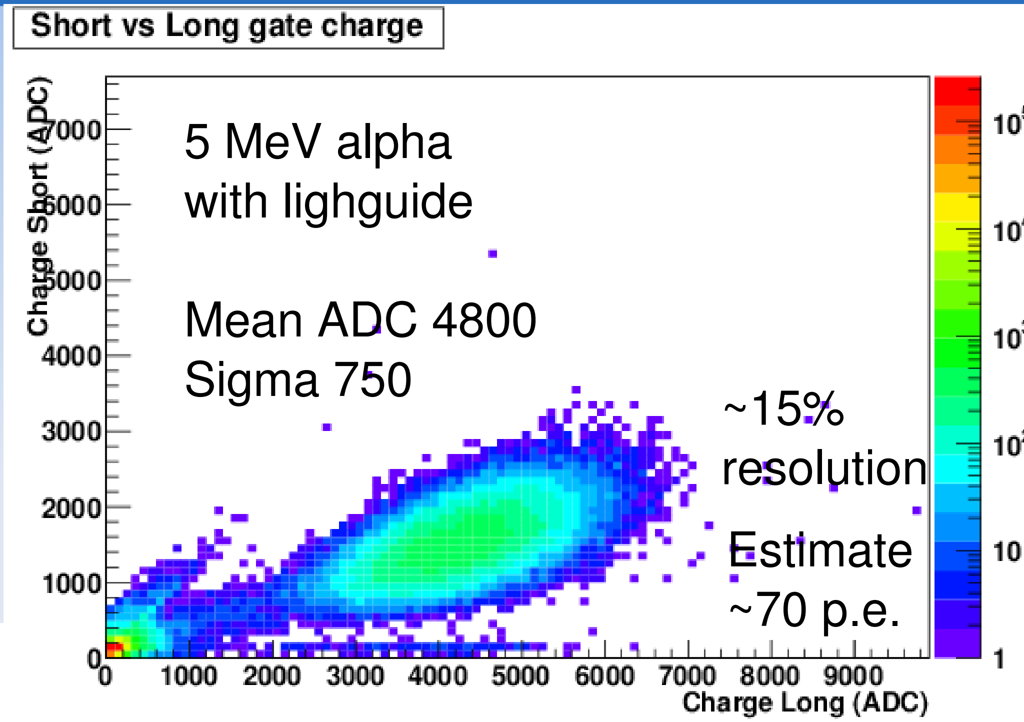
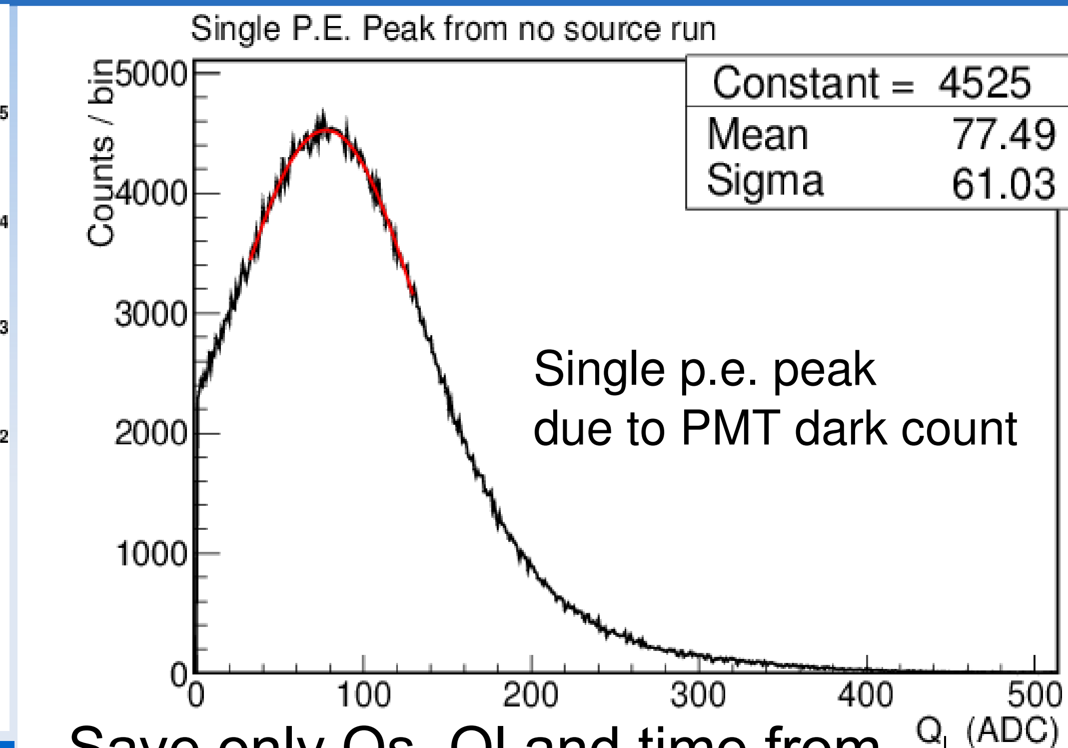
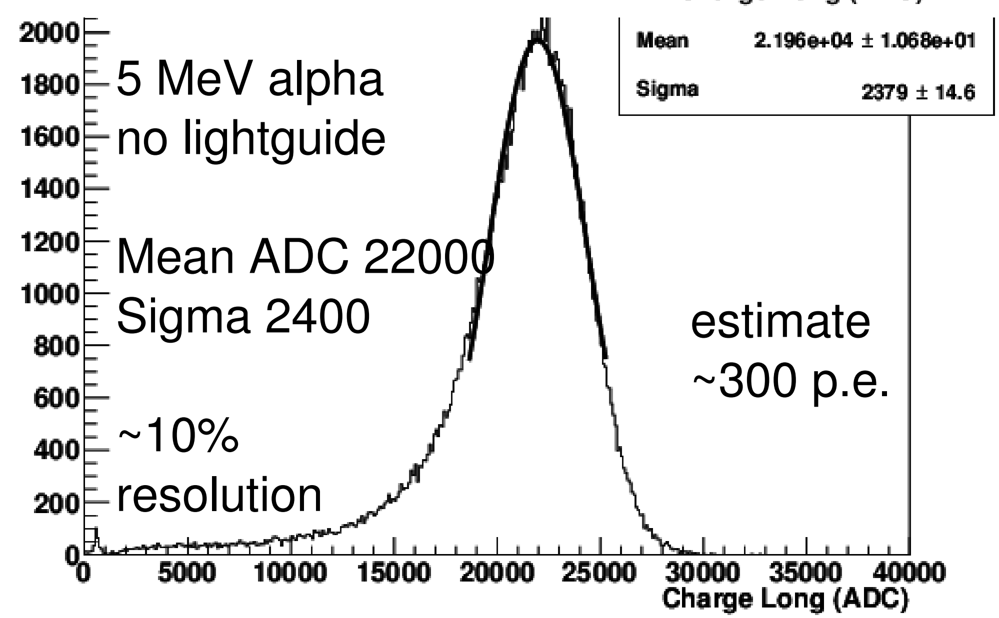
Long and Short Charge for Alpha Source







- Save only Qs, Ql and time from digitizer
- Able to collect data up to 500kHz per channel
- Will need to do some online analysis to reduce data size!

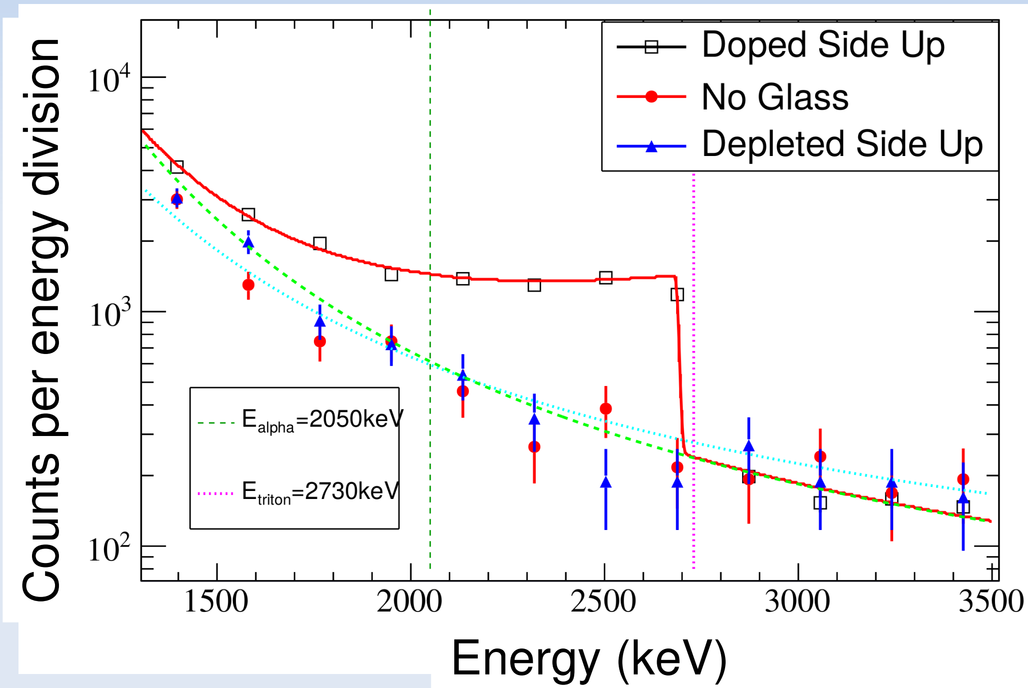
Note: 70/300~0.23,
expect ~0.3 from area change alone

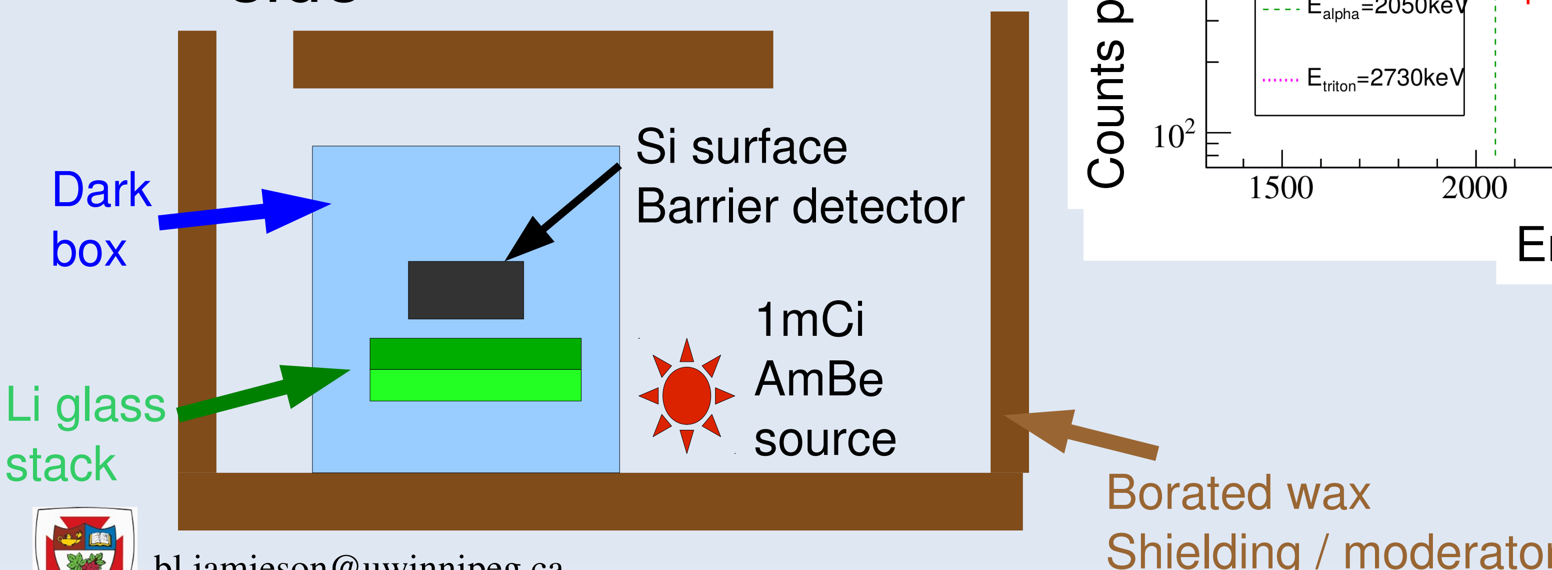
Which side of Li glass stack is GS20

Published as NIM A 740 (2015) 6-9 -- arXiv:1502.01392

- Want to glue the scintillator stacks the right way up!
  - Look for alpha/tritium from n(6Li,t)alpha
  - Only from 6Li enriched side

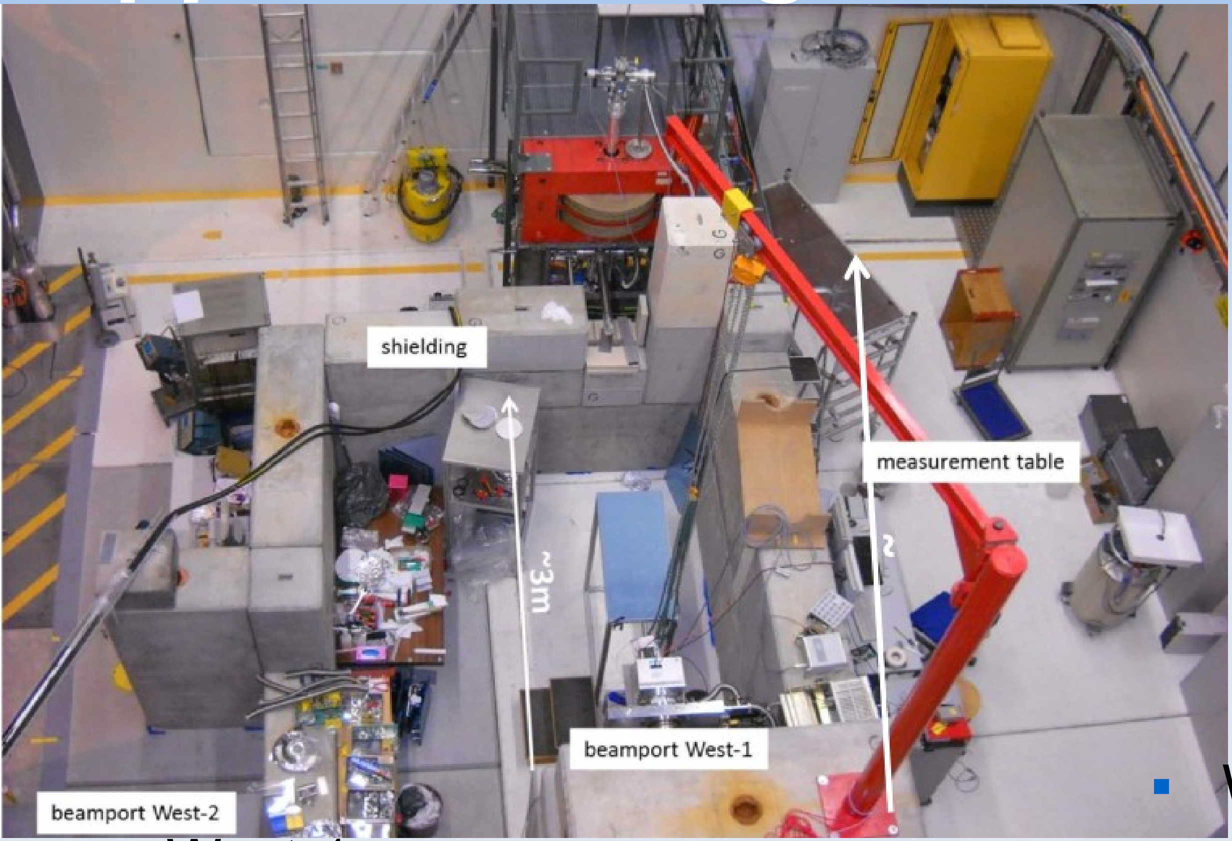
Have tested all 10 samples this way and glued them to lightguides

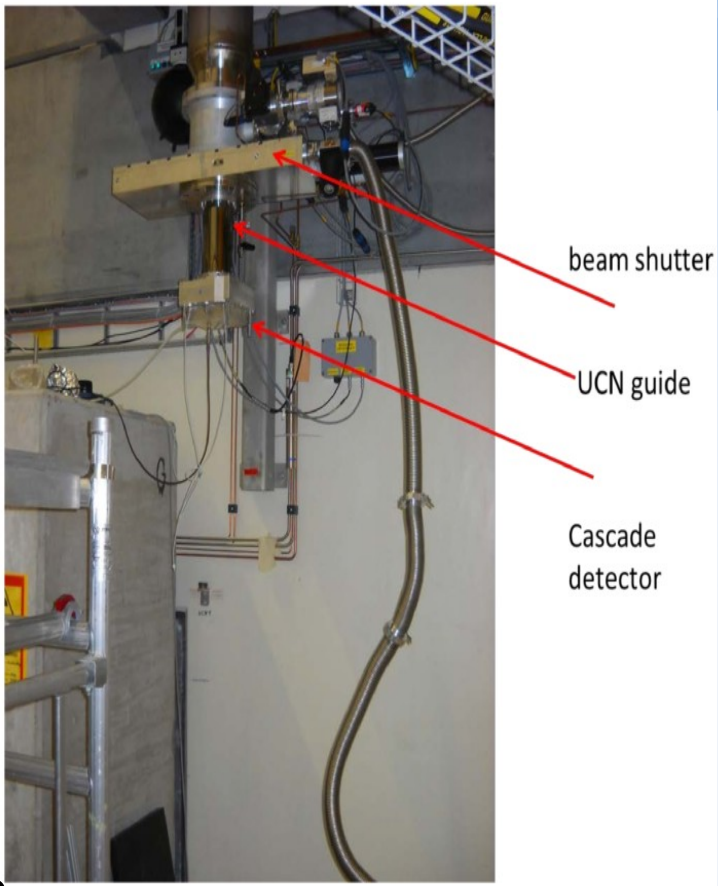




bl.jamieson@uwinnipeg.ca

UCN Detector Tests at PSI
Approved : Aug. 5-19, 2015





- West-1
  - 10x higher rate when nEDM expt not running
  - Will use for chopper tests and high rate tests
- West-2
  - Few x 10^4 Hz of UCN
  - 100 neV minimum
  - Different dropping heights
  - Compare to 3He and Cascade (borated gem detector)

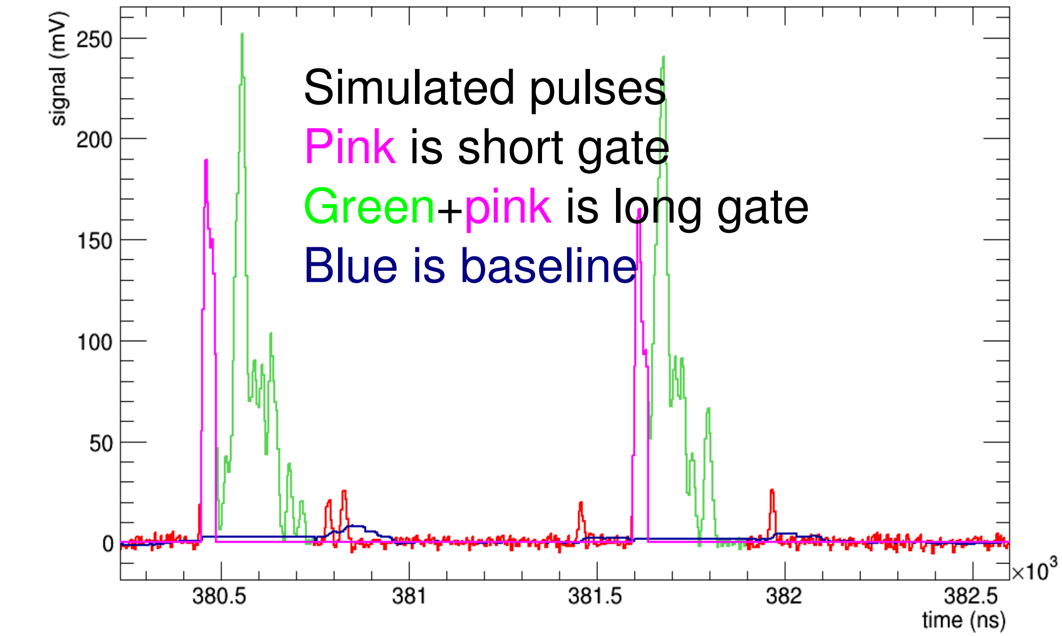
bl.jamieson@uwinnipeg.ca

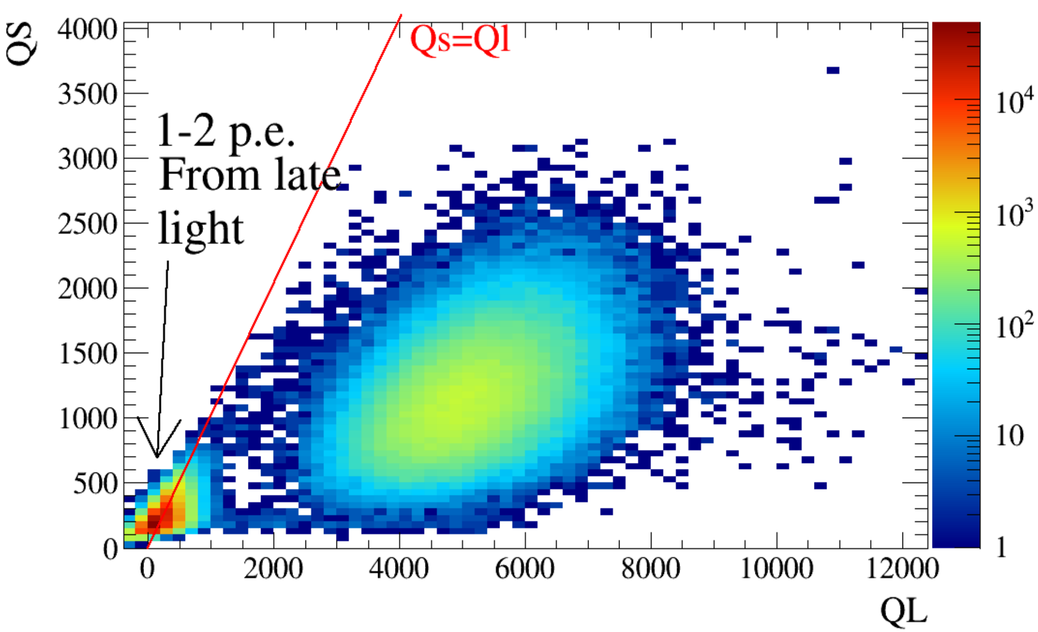
UCN Summary

- Neutron EDM experiments are being prepared, ultimately to improve precision to the 10^{-27} e-cm level.
- UCN sources are popping up all over the world, with vibrant fundamental physics programs: Neutron lifetime, Neutron Gravity levels experiment, Neutron beta-decay, $n\bar{n}$ oscillation search, neutron-ion interactions.
- As part of this effort we are designing a suite of detectors to perform a simultaneous spin measurement

Fin.

Pulse and Digitizer Simulation

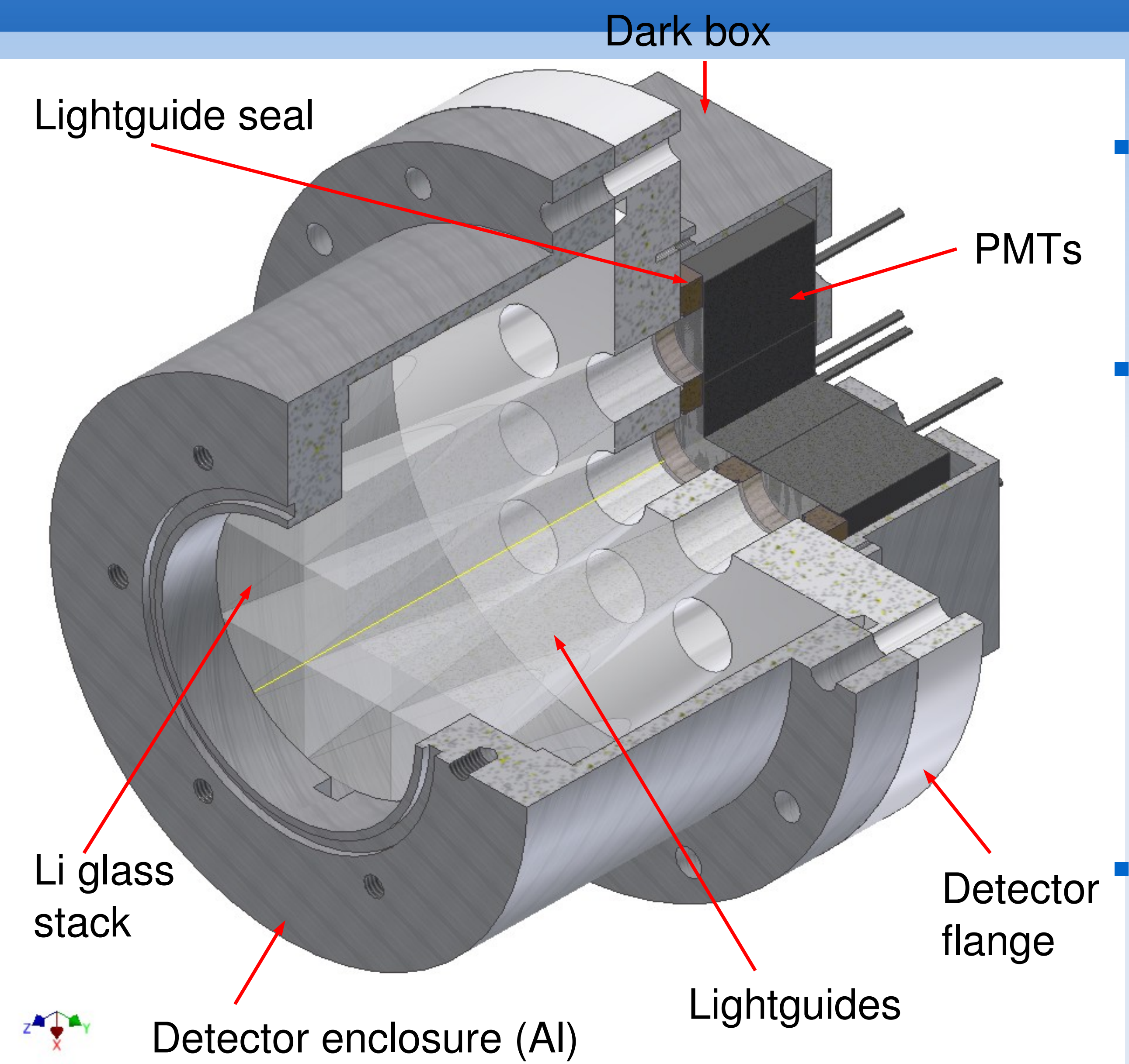




- Scintillation+PMT pulse simulation based on summing multiple gaussian single pe pulses
  - Model includes a short and long rate scintillation
- Can set pulse rate
- Add some gaussian white noise
- Digitizer simulation

Need to tune simulation of Cerenkov light

Li glass prototype detector design



- Make enclosure with low density non-magnetic material (Al)
- Lightguides are Ultra-violet transmitting acrylic
  - Use white o-rings around lightguides to make vacuum seal
- PMTs are in air, with darkbox holding them in place

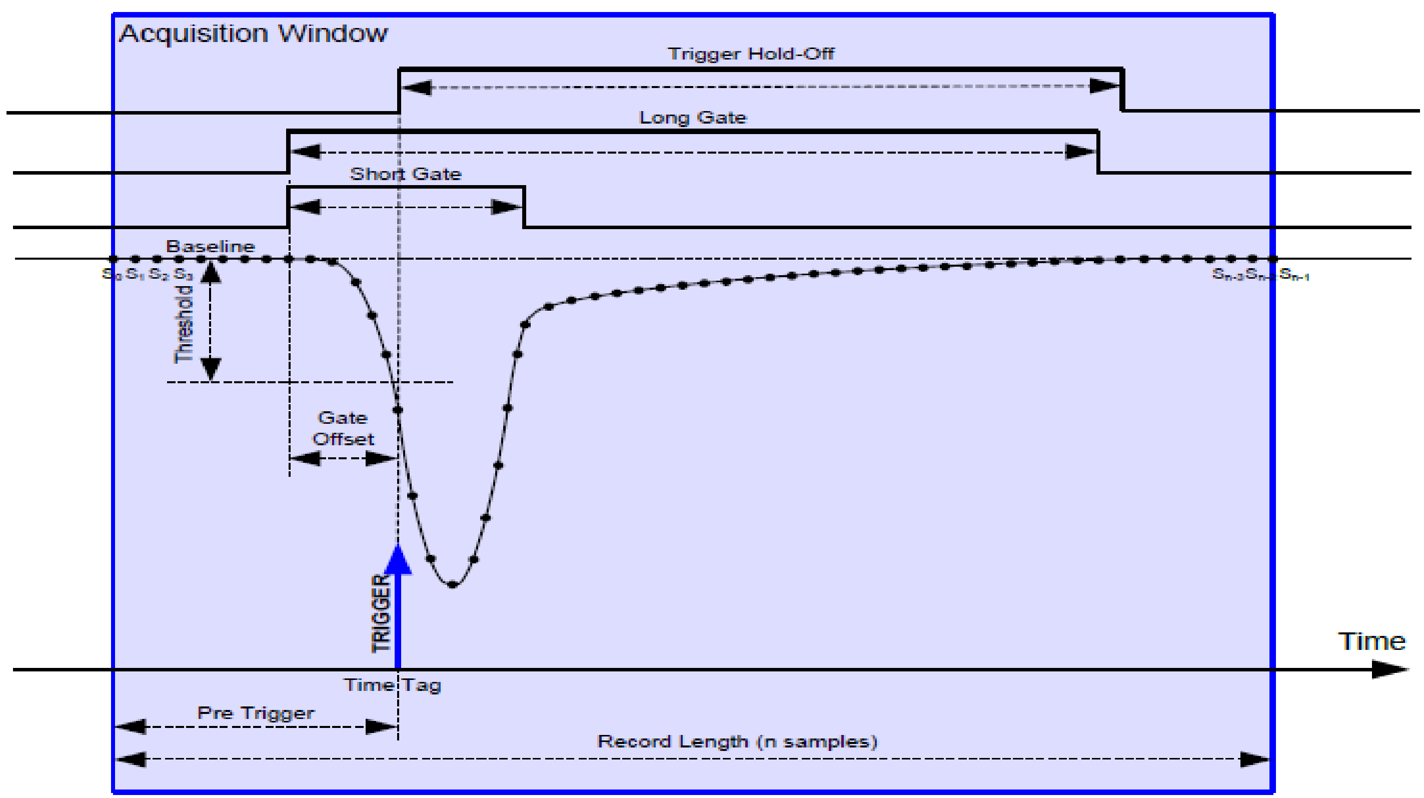
For now opening and bolt pattern match RCNP guides, may want to go to a square Opening to match the “pixels” (better distribute the rate).

bjamieson@uwinnipeg.ca

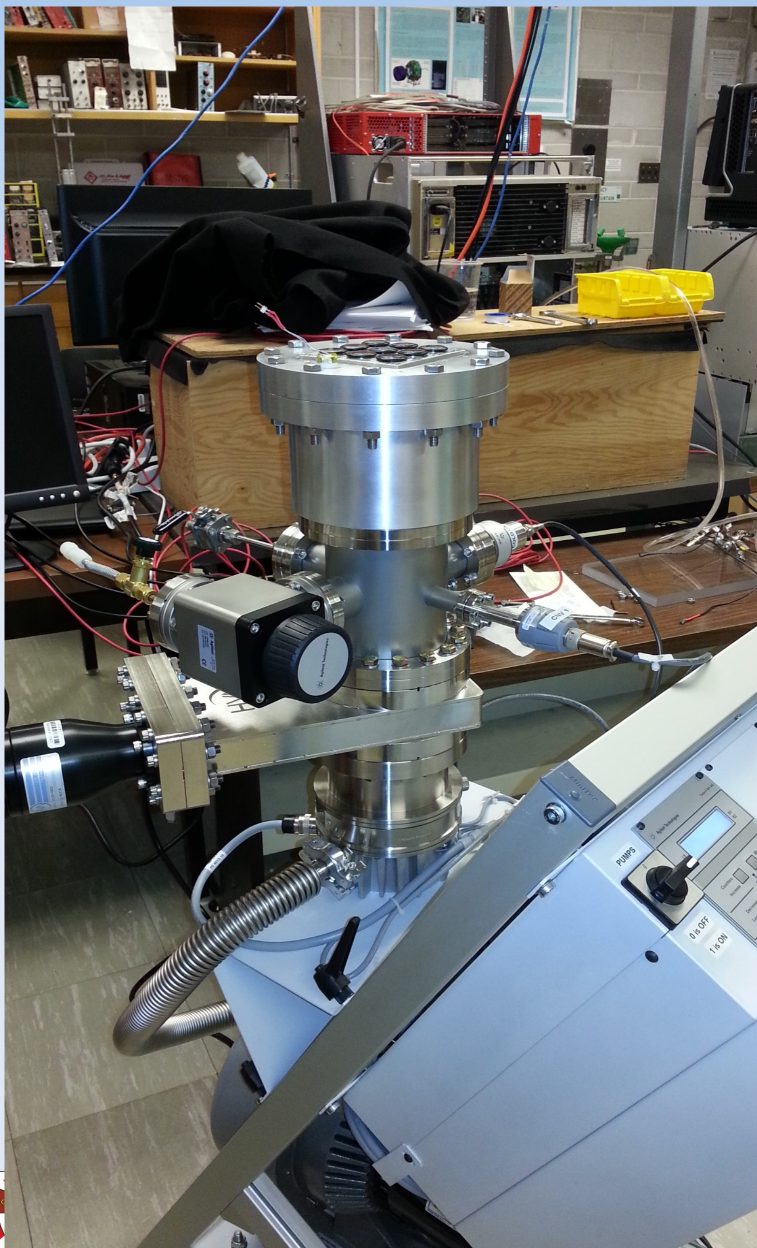
Figures from CAEN manuals.

Digitizer used for fast DAQ

- V1720 Digitizer from CAEN
  - 8-channel waveform digitizer with pulse shape analysis on FPGA

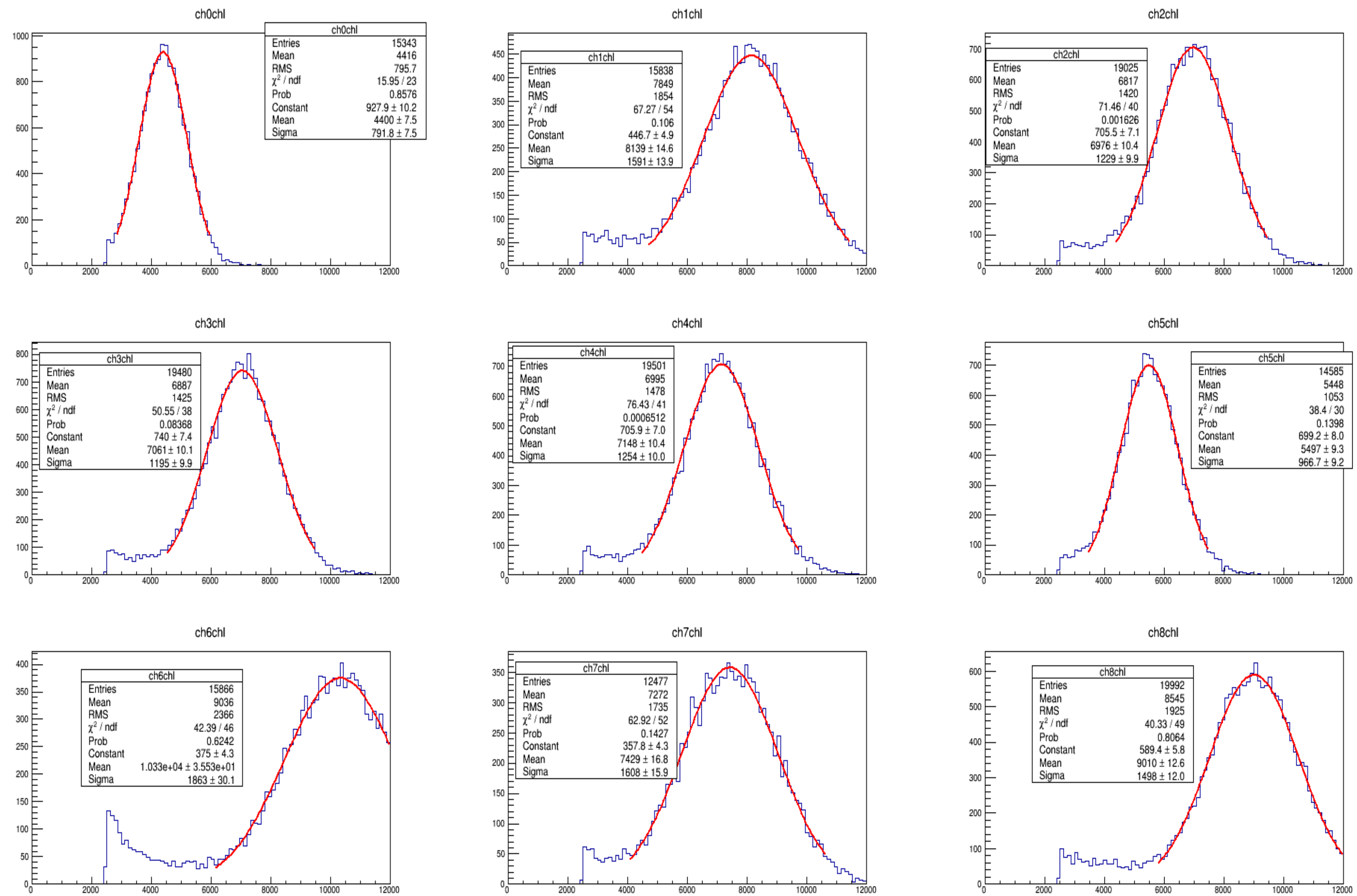


Detector leak tests with vacuum and ready for UCN

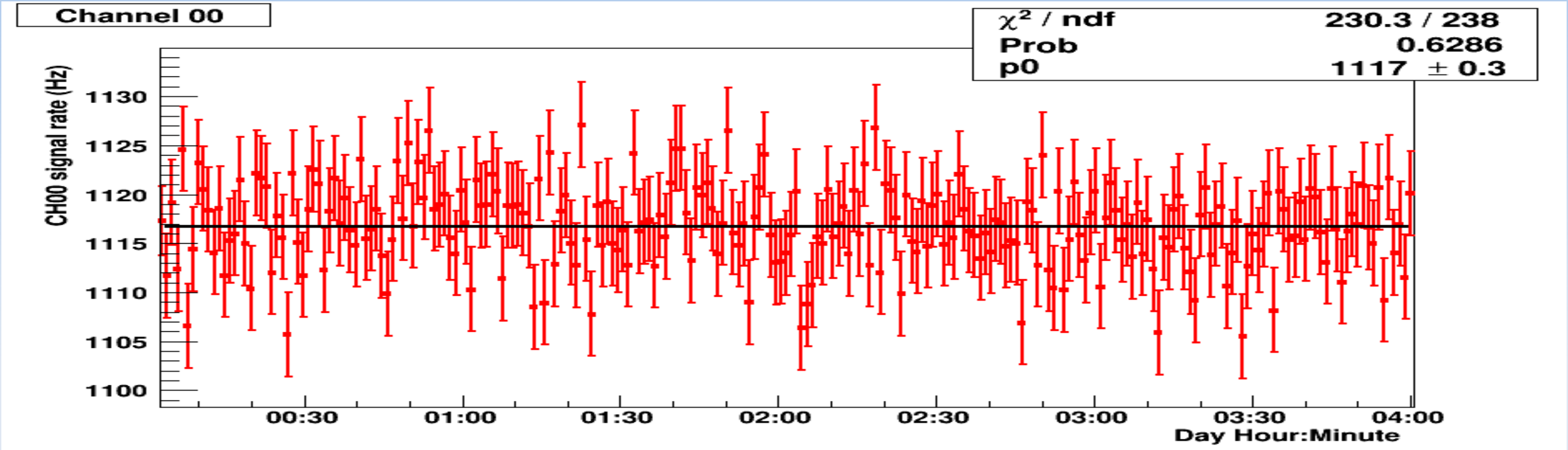


- Gets to 1.6×10^{-6} Torr after one day of pumping with vacuum as pictured at left
- Leak rate of a few $\times 10^{-8}$ atm cc/min measured with He leak detector
- Ready for tests with UCN
  - Proposal to do detector tests in PSI West-1 and West-2 beamlines was approved by PSI beam PAC

Detecting thermal neutrons
Charge after rejecting Cerenkov events



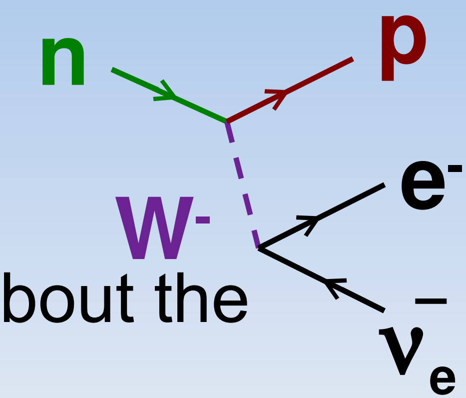
Detector Stability Tests



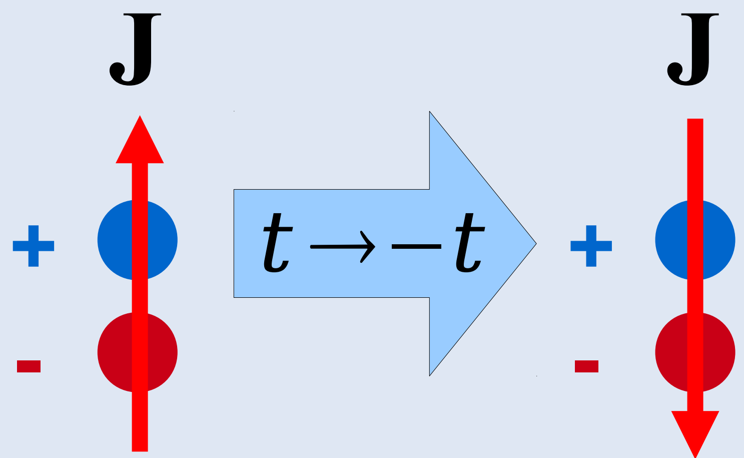
- Have done some initial studies of the rate stability at low rate
- Above is rate measured for an alpha source over a four hour period
- Still developing method to handle high rates with some pile-up

Fundamental Physics with UCN

- How fast do neutrons decay? BBN.



- Details about how neutrons decay tell us about the weak nuclear force. (V_{ud})
- Does the neutron possess an electric dipole moment? The predominance of matter over antimatter in the universe.



- Interactions of neutrons with gravity and are there extra dimensions?

bl.jamieson@uwinnipeg.ca

UCN Facilities

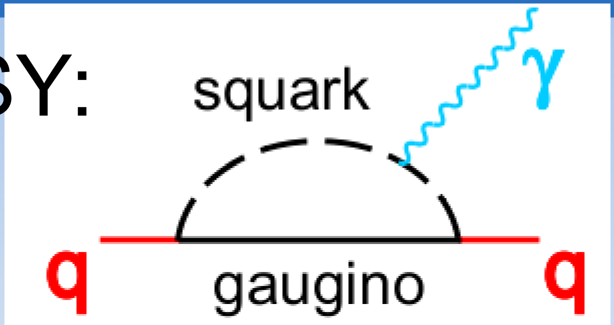
- Reactor sources:
  - ILL, Mainz, Munich, NCSU, PNPI
- Spallation sources:
  - LANL, KEK-RCNP-TRIUMF, PSI, J-PARC
- And dedicated UCN experiments installed in Cold Neutron beamlines:
  - ILL, NIST, SNS

bl.jamieson@uwinnipeg.ca

EDM's and Supersymmetry (SUSY)

- Scale of EDM's for quarks in SUSY:

$$d_q \sim \frac{\alpha}{\pi} \times \frac{m_q}{\Lambda_{SUSY}^2} \times \sin\theta_{CP}$$



from P. Harris, Sussex

- For “reasonable” values of new parameters:

$$d_q \sim 3 \times 10^{-24} e \cdot cm$$

- According to neutron EDM measurements:

$$d_u < 2 \times 10^{-25} e \cdot cm \qquad d_d < 5 \times 10^{-26} e \cdot cm$$

- Unattractive solution (“SUSY CP problem”):
  - Λ_{SUSY} > 2 TeV and/or θ_{CP} < 0.01

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