TRIUMF

A novel technique for measuring ultracold neutron transmission

Sean Vanbergen – TUCAN Collaboration – WNPPC 2020

Ruediger Picker, Wolfgang Schreyer

CINP ICPN
Canadian Institute of Nuclear Physics
Institut canadien de physique nucléaire

TRIUMF UltraCold Advanced Neutron Collaboration

TUCAN Goals

1. Build a next generation ultracold neutron source at TRIUMF using a spallation neutron source and superfluid helium conversion
2. Measure the neutron electric dipole moment with an order of magnitude improved sensitivity

TRIUMF

KEK

RCNP

THE UNIVERSITY OF WINNIPEG

UNIVERSITY OF MANITOBA

UBC THE UNIVERSITY OF BRITISH COLUMBIA

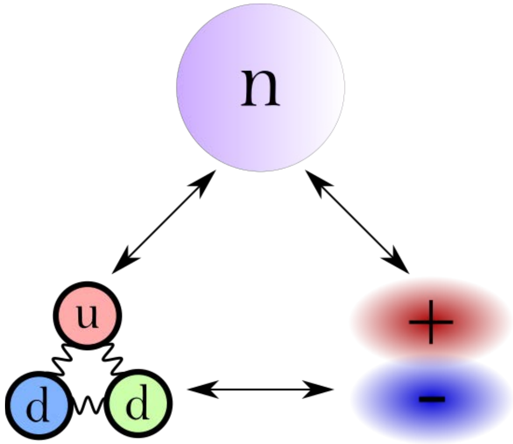
SFU SIMON FRASER UNIVERSITY ENGAGING THE WORLD

UNBC UNIVERSITY OF NORTHERN BRITISH COLUMBIA

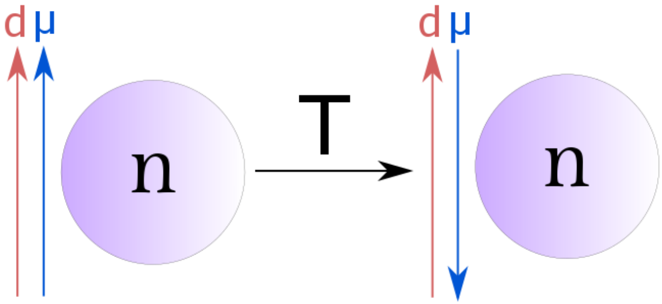
NAGOYA UNIVERSITY

Neutron Electric Dipole Moment

- The neutron consists of electrically charged quarks
- The quarks give the neutron a non-zero magnetic dipole moment μ_n
- A separation of the neutron's centres of positive and negative charge would give an electric dipole moment d_n



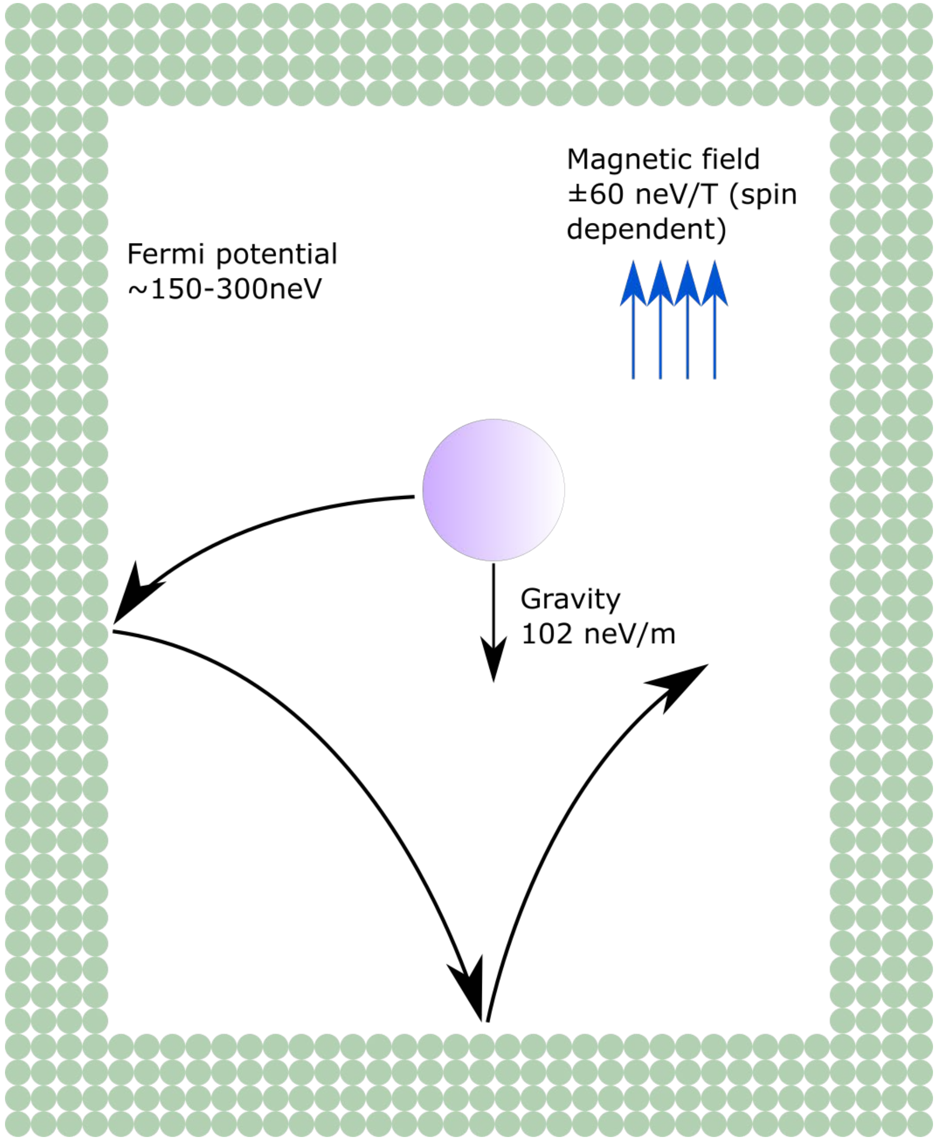
- Helps explain matter-antimatter asymmetry (Sakharov conditions)
- Under time reversal, $\boldsymbol{\mu}_n$ is reversed, but $\mathbf{d}_n$ is not.
- T violation => CP violation under CPT symmetry



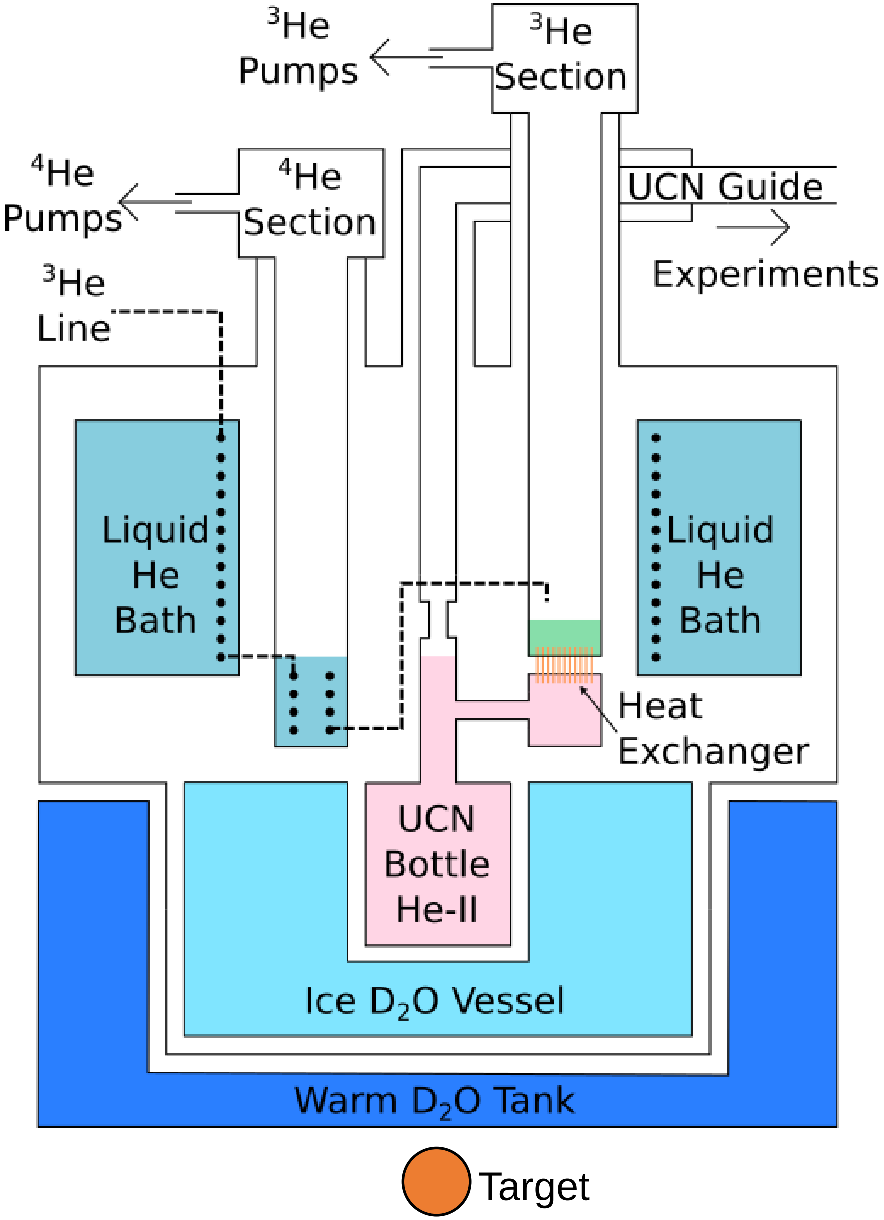
- Beyond standard model ~10^{-27} ecm
- Standard model <10^{-30} ecm
- Current limit 1.1×10^{-26} ecm **[arXiv:2001.11966]**
- TUCAN target ~10^{-27} ecm

Measuring the nEDM: Ultracold Neutrons

- Current experiments use confined neutrons
- UltraCold Neutrons (UCN) have kinetic energies <300 neV
- This corresponds to a de Broglie wavelength of ~50 nm
- UCN therefore see solids as a constant Fermi potential rather than as individual atoms
- Materials with sufficiently large potentials can be used to confine neutrons
- Energy from both gravitational and magnetic fields are also significant



UCN Production at TRIUMF



- TRIUMF main cyclotron provides 480MeV protons to a tungsten spallation target
- Neutrons are moderated in layers of warm and frozen heavy water
- A superfluid helium cryostat cools isotopically pure helium-4 to ~1K
- Remaining neutron energy is transferred to the superfluid helium through a phonon emission process
- Operation of the UCN source produces a lot of radiation, so it needs to be buried behind several meters of concrete shielding
- UCN must be transported out of the shielding to experiments

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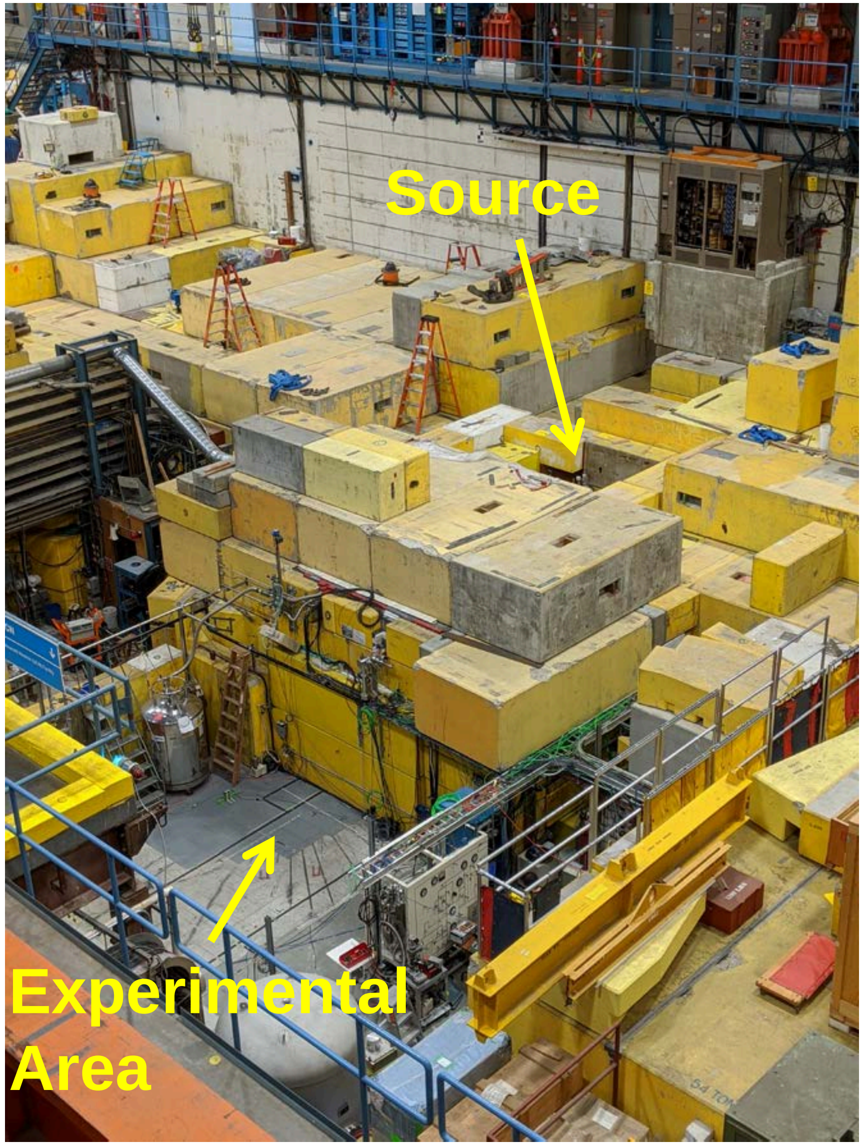

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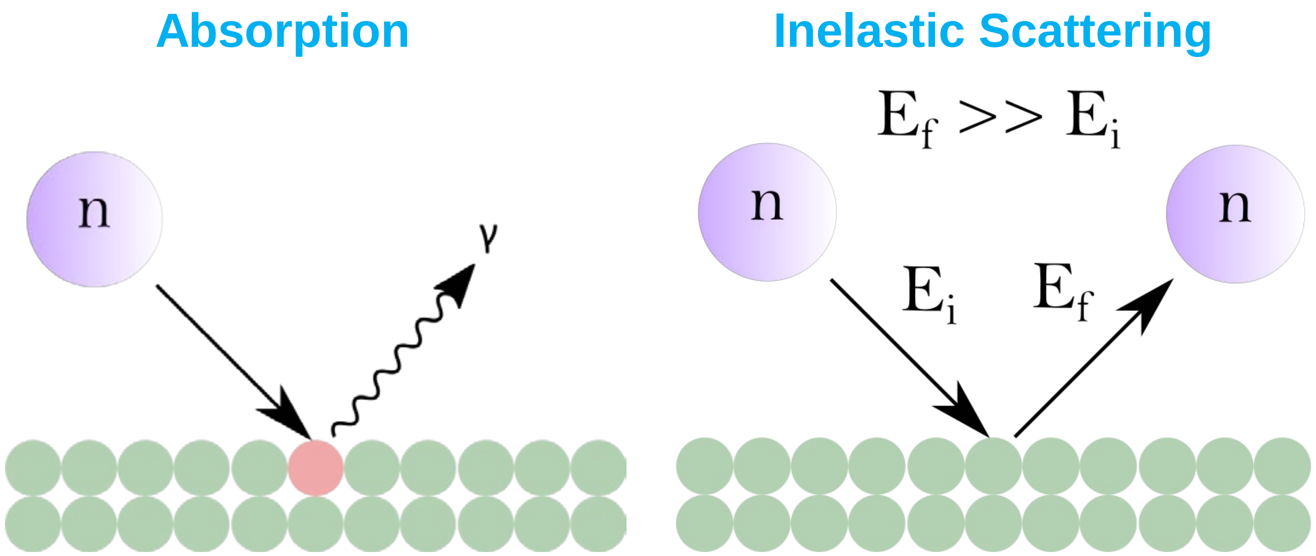
Transporting Neutrons: UCN Guides

- UCN are “transported” by propagating down guides (pipes of suitable material)
- The transmission through a guide is determined by two properties:
    1. Loss of neutrons at the guide walls (~10^{-4} loss per bounce), represented as an imaginary component of the Fermi potential W
    2. Diffuse reflection at the guide walls (instead of specular reflection), with some probability P_L, which deflects the neutrons backwards

$$W = \sum n_i(\sigma_{i,abs} + \sigma_{i,scatter})v$$


Absorption

Inelastic Scattering

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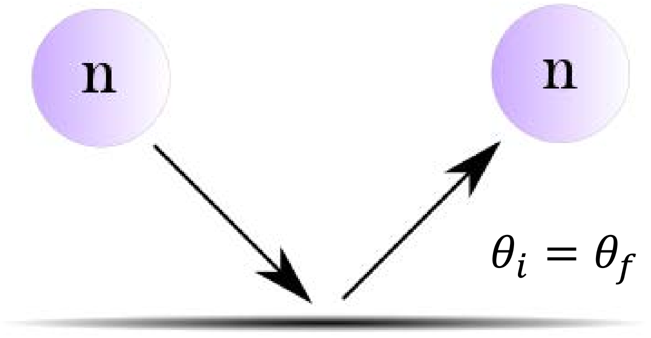
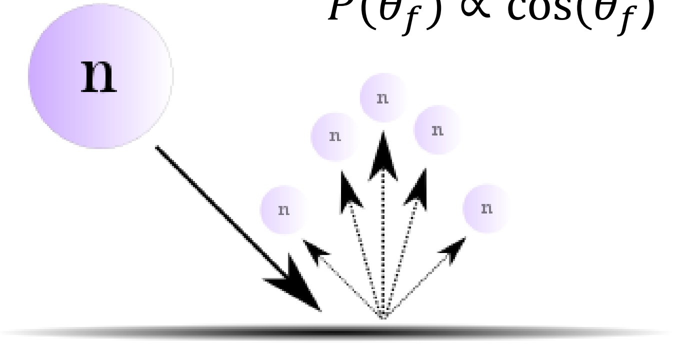
Specular Reflection



$\theta_i = \theta_f$

Diffuse Reflection

$P(\theta_f) \propto \cos(\theta_f)$



Aside: UCN Storage Lifetime

- UCN stored in a volume are lost over time.
- Roughly exponential with lifetime τ:

$$N(t) = N_0 e^{-t/\tau}$$

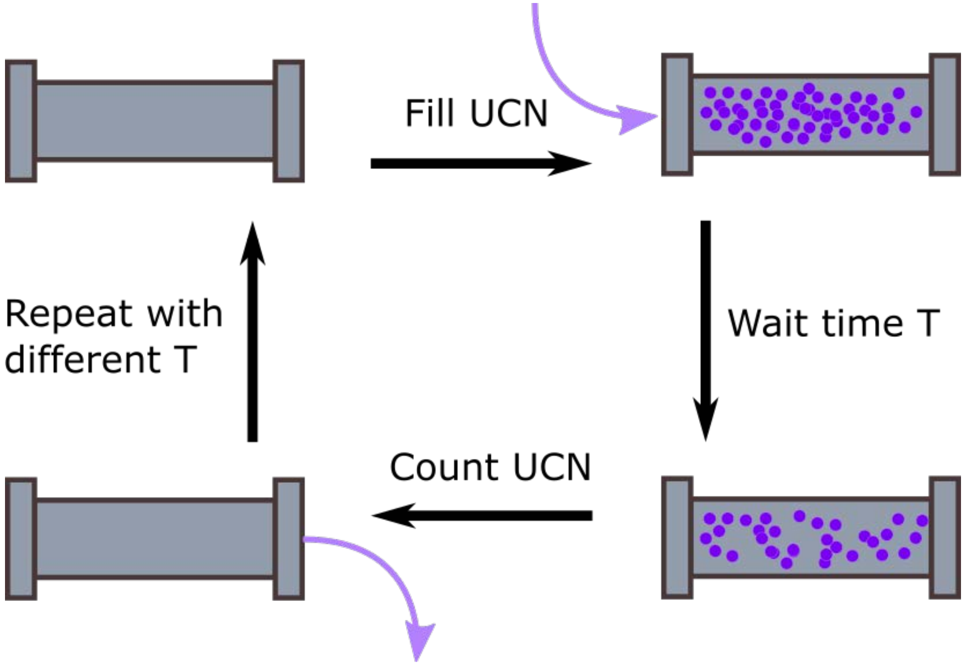
- The lifetime is the combined neutron decay and wall loss lifetime from W

$$\frac{1}{\tau} = \frac{1}{\tau_W} + \frac{1}{\tau_\beta}$$

$$\tau_W \ll \tau_\beta$$

- Dominated by W, low sensitivity to P_L
- Important because:

1. We have two parameters, W and P_L, so we need two measurements to fit them accurately
2. Lifetime affects other measurement techniques

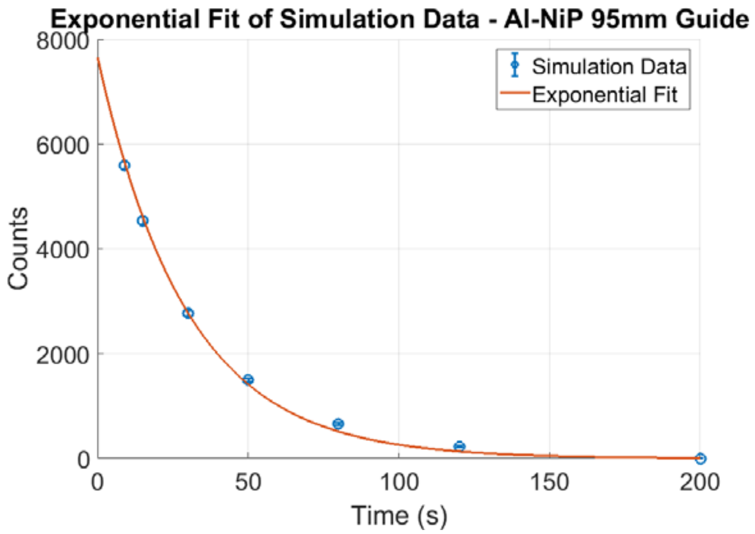


Fill UCN

Wait time T

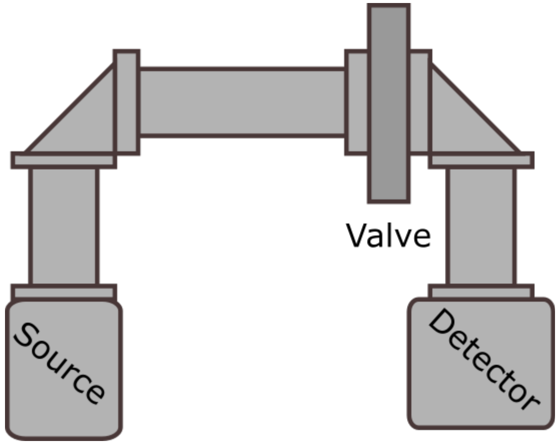
Count UCN

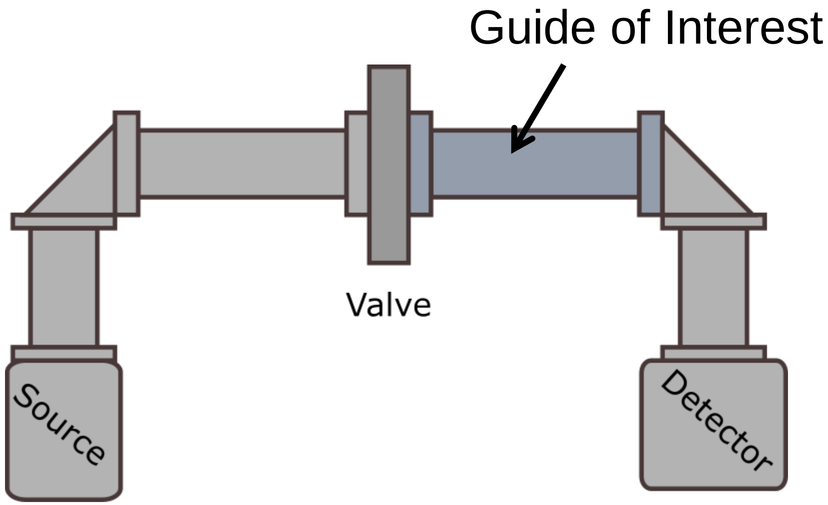
Repeat with different T



Measuring Neutron Transmission

- Could we not simply do this?



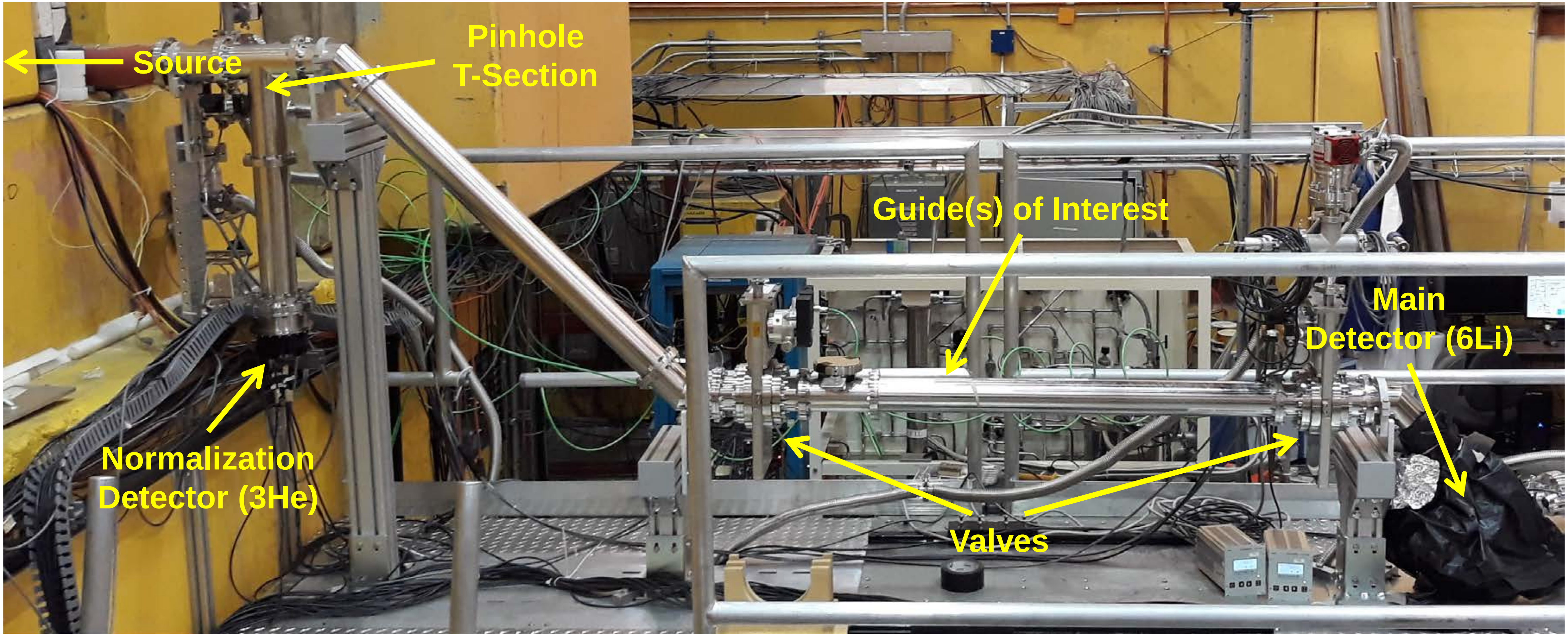


- Measure of transmission is:

$$T = \frac{\#\text{UCN detected with guide}}{\#\text{UCN detected without guide}}$$

- Problem is that we cannot confirm that the number of UCN delivered is always the same
- The TUCAN source uses a spallation neutron source, which has relatively low stability (compared to a reactor neutron source), due to fluctuating beam currents, temperatures, etc.
- Solution: use a secondary normalization detector to measure (proportionally) how many neutrons produced

Normalization Detector



Sean Vanbergen

Normalization Detector: When to Count?

$$T = \frac{N_{Li}}{N_{He}} = \frac{\text{\#UCN detected in main detector}}{\text{\#UCN detected in normalization detector}}$$

N_{He} is counted at the same time as N_{Li}

- Problem: most UCN go to the main detector, so we get low counts in the normalization detector
- Assuming $\sqrt{N}$ statistics, uncertainty in T is:

$$\frac{\sigma_T}{T} = \sqrt{\frac{1}{N_{Li}} + \frac{1}{N_{He}}}$$

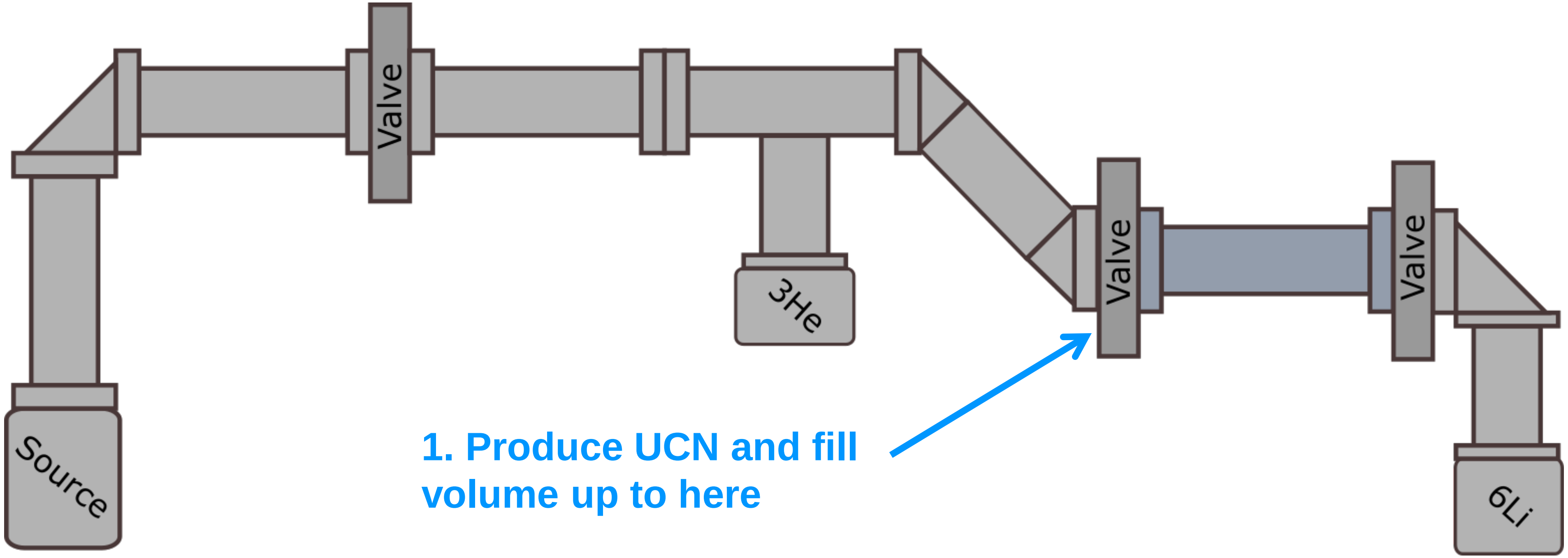
- The lowest count dominates the uncertainty

N_{He} is counted during UCN production

- Gives much higher 3He counts
- Problem: because the detector is “connected” to the source during this period, these counts are very sensitive to the source conditions
- This turns out to introduce some significant systematics
- Measurements stop being replicable

Transmission Measurement with Prestorage

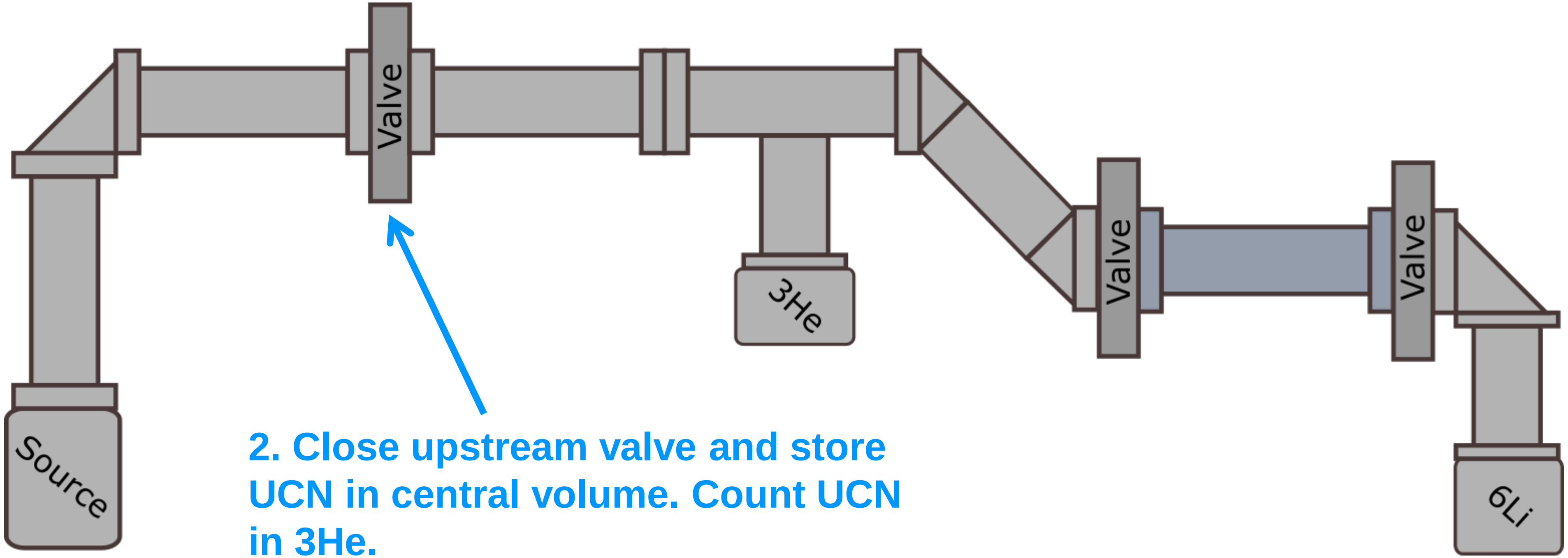
Phase	Production	Prestorage	Transmission
Timing	t_i	t_p	t_c



1. Produce UCN and fill volume up to here

Transmission Measurement with Prestorage

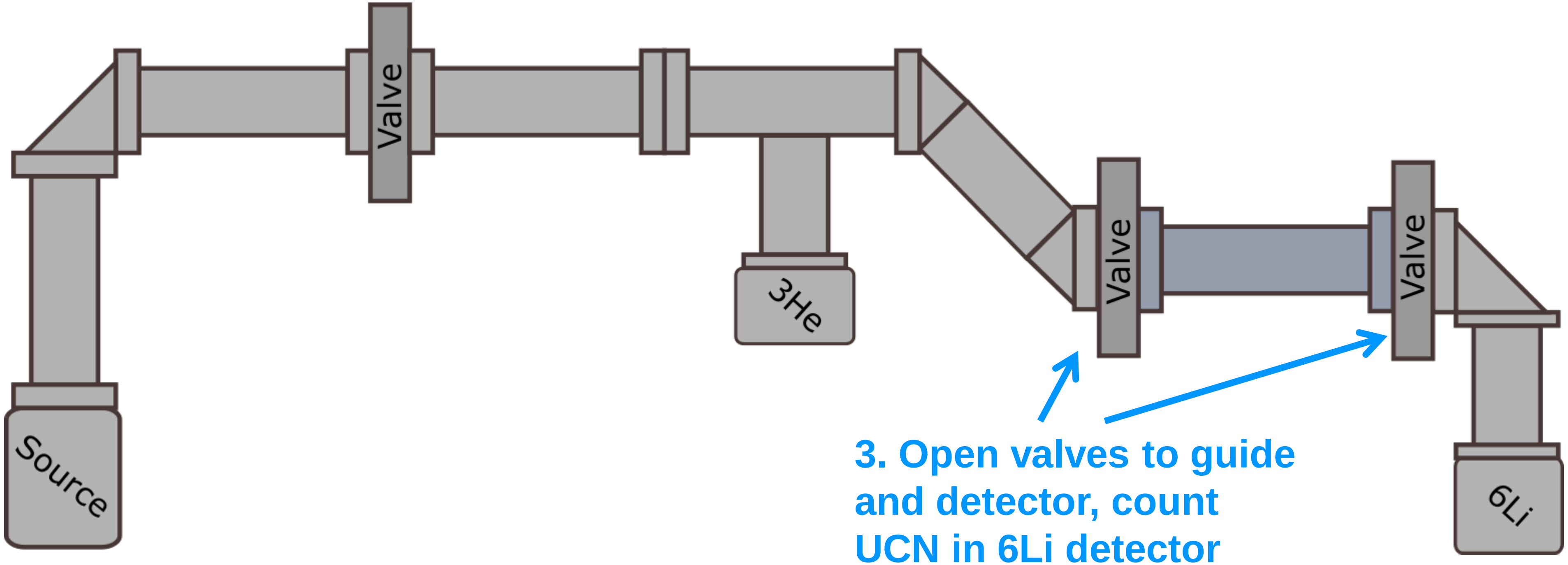
Phase	Production	Prestorage	Transmission
Timing	t_i	t_p	t_c



2. Close upstream valve and store UCN in central volume. Count UCN in 3He.

Transmission Measurement with Prestorage

Phase	Production	Prestorage	Transmission
Timing	t_i	t_p	t_c



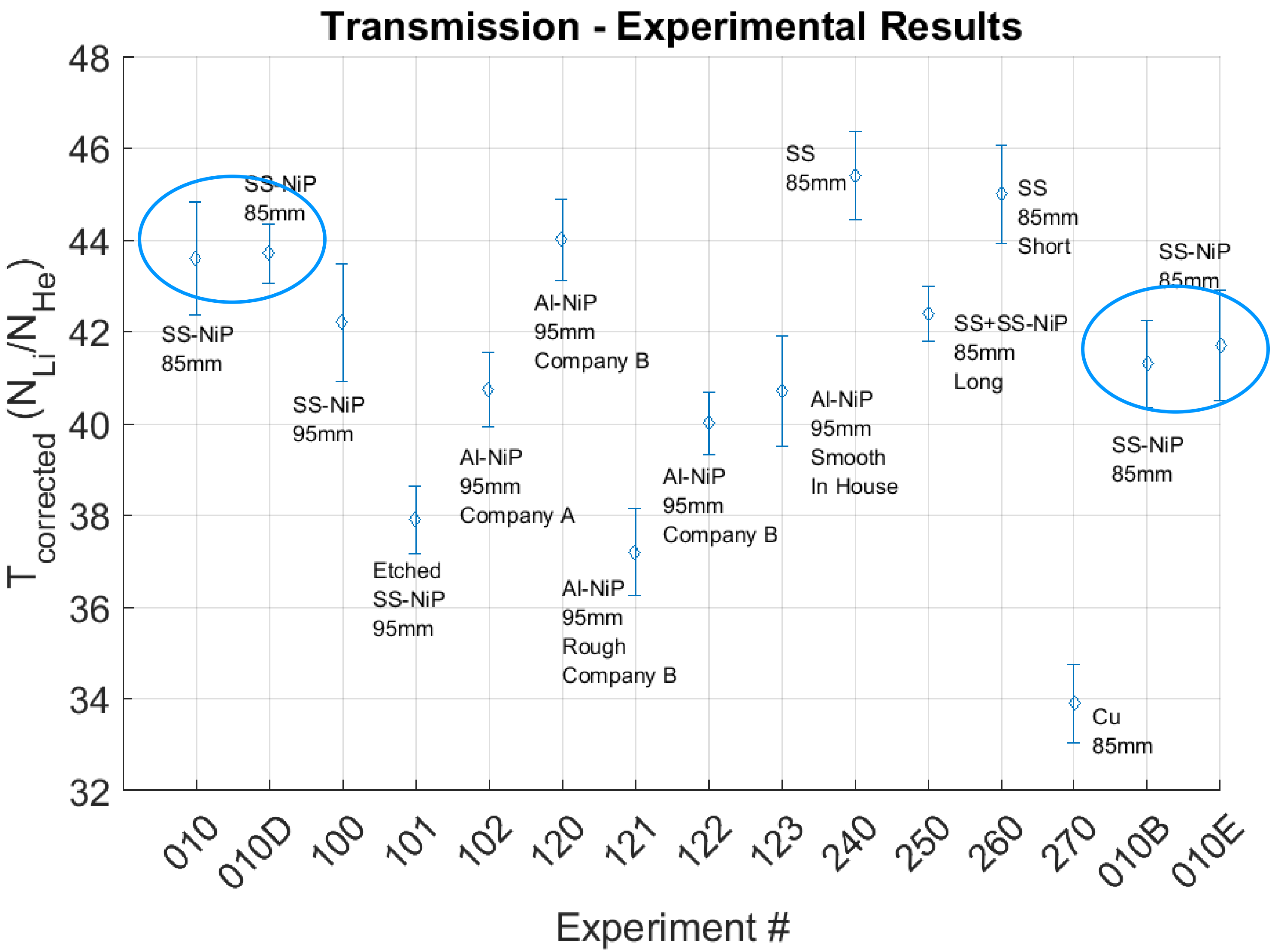
3. Open valves to guide and detector, count UCN in 6Li detector

Prestorage Transmission Measurement: 2019 Results

- Measured a number of different guides in November
  - Different materials
  - Different surface preparation
  - 85mm and 95mm diameter

- Repeated measurements showed that the prestorage method gives consistent results

- How do we go from these numbers to W and P_L?

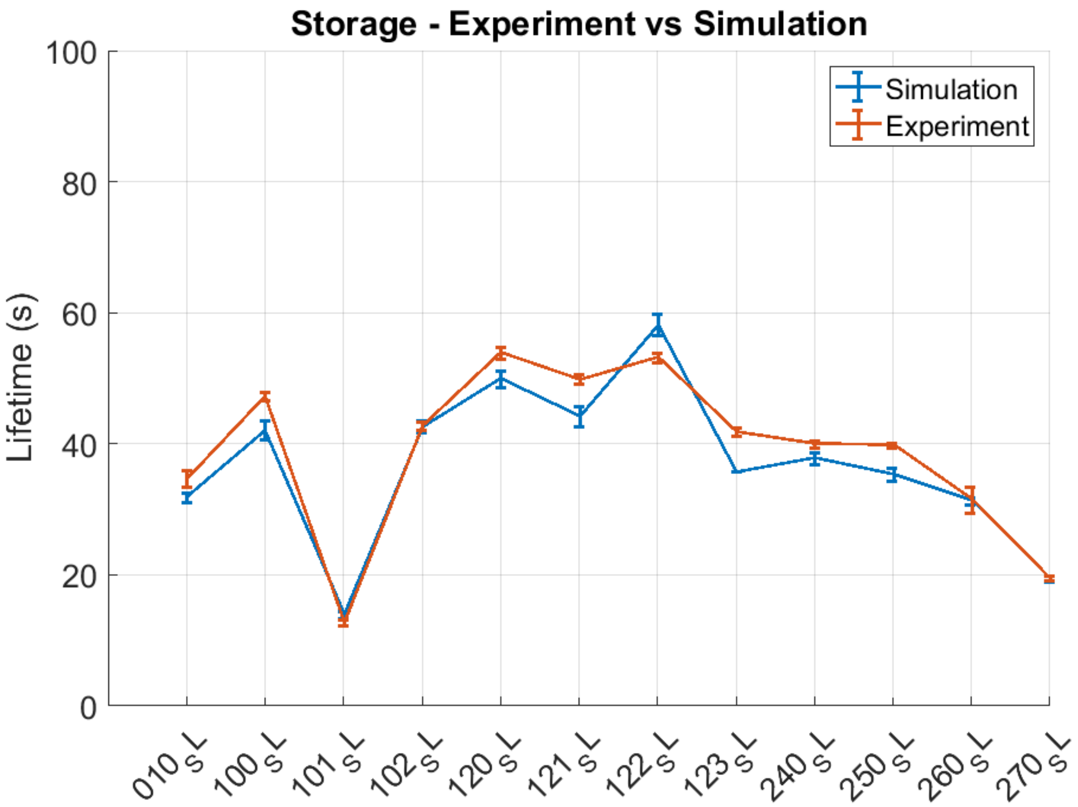


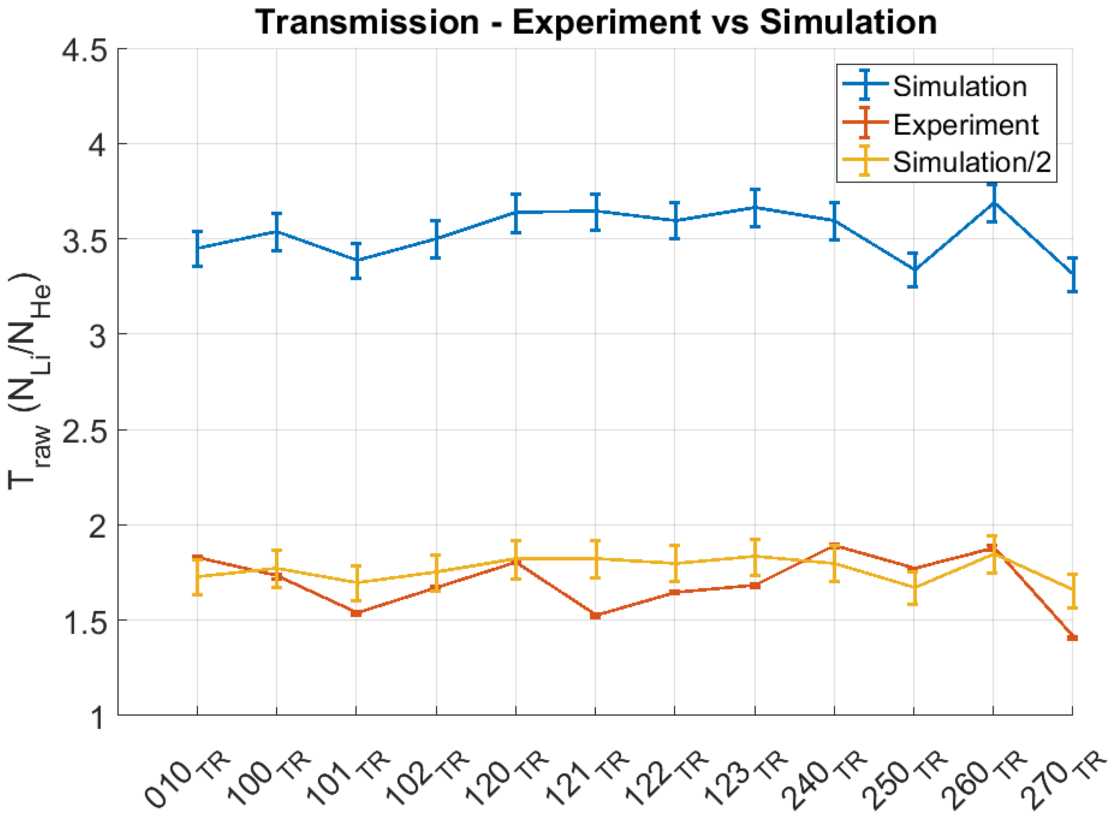
Finding W and P_L Using T: Simulations

- PENTrack: Monte Carlo simulations for UCN
- Fully implemented as-built geometry to simulate each experiment exactly as it was performed
- Fit parameters to match the experimental results (transmission and storage lifetime measurements)
- Using the Compute Canada clusters to simulate many millions of neutrons over 24 measurements (+39 measurements from 2018)

Simulation Results

- Fitting one experiment is easy, but a simultaneous fit of everything is hard
- Success in modelling lifetime → good determination of W





- Ongoing challenge with transmissions
- Mysterious factor of 2 difference… could be an unaccounted-for systematic effect

Summary

- Achieving high statistics in UCN experiments requires the study of guide properties
- At TRIUMF we have developed techniques for measuring transmission through a guide with good accuracy and precision
- We can use simulations to take our experimental results to quantitative guide properties
- But such simulations can be quite challenging, and potentially reveal problems of which we are not otherwise aware

Thank you!

Backup Slides

Systematics in the Irradiation Period Measurement

- Define the detection rate in the 3He detector as r_{He}.
- The counts in the detector at a time t_i are given by the integral:

$$N_{He}(t_i) = \int_{t_i-\Delta t}^{t_i} r_{He}(t)dt$$

- Where Δt defines the period over which we are integrating.
- The rate is proportional to the number of UCN in the source, which we can model as a saturating exponential defined by the source storage lifetime τ.

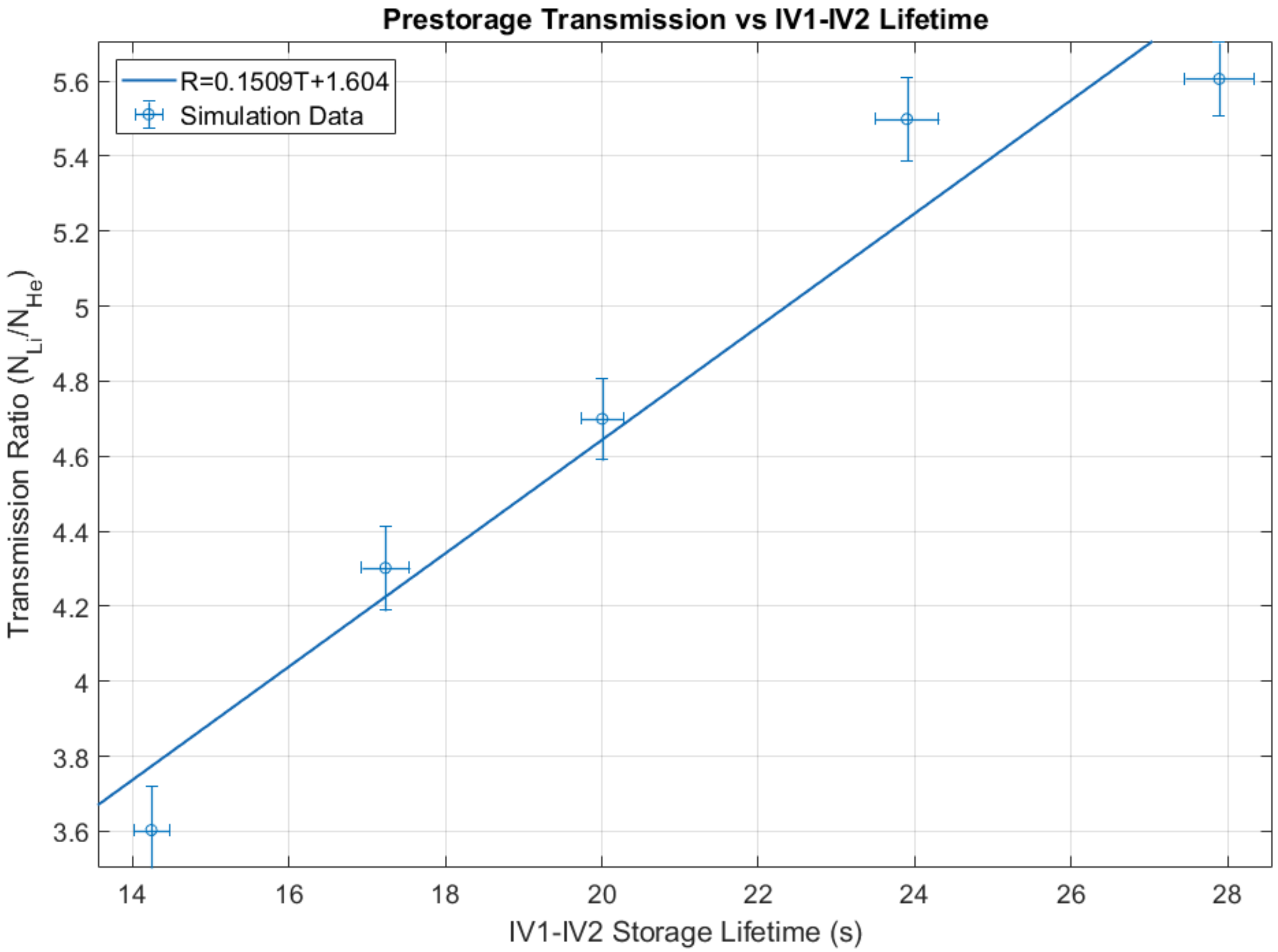
$$r_{He}(t) \propto N_{src}(t) = N_0\left(1 - e^{-t/\tau}\right)$$

- Then, the proportionality constant between the rate and the UCN in the source is:

$$\frac{N_{He}(t_i)}{N_{src}(t_i)} = \frac{\int_{t_i-\Delta t}^{t_i}\left(1 - e^{-t/\tau}\right)dt}{\left(1 - e^{-t_i/\tau}\right)}$$

- If τ changes, this proportionality changes. This is worse if window Δt is large.
- Can introduce big systematic differences between measurements of different guides.
- Unfortunately τ does change – the superfluid helium in the source introduces a big temperature dependence, and the source conditions can be very dynamic.

Prestorage Volume Lifetime Sensitivity



- The prestorage counting is sensitive to the prestorage volume lifetime.
- The adjustment is:

$$\frac{N_{Li}}{N_{He}} = T_{corr} \frac{e^{-t_p/\tau_p}}{\tau_p\left(1 - e^{-t_p/\tau_p}\right)}$$

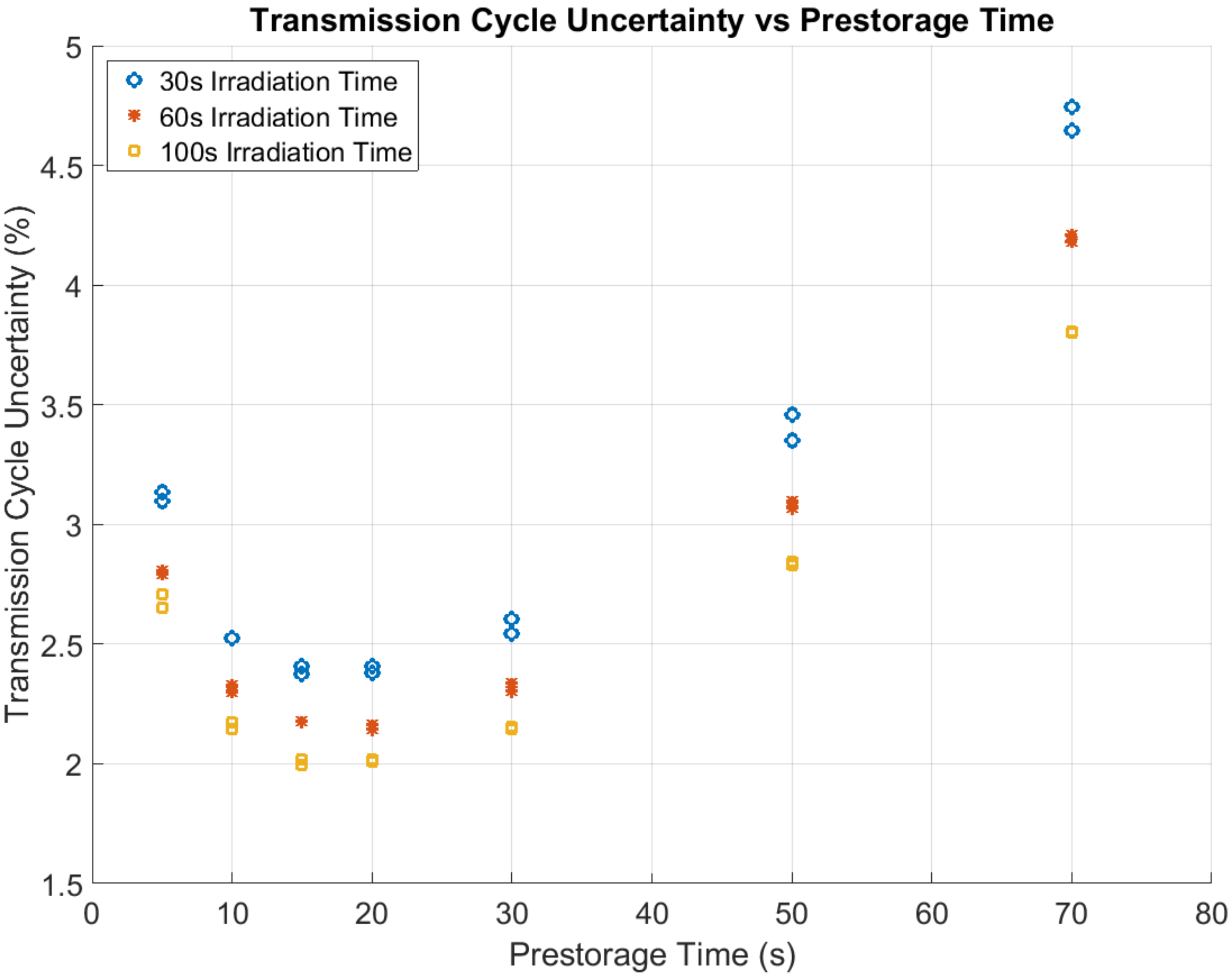
- In theory, τ_p should be constant between measurements
- In practice it fluctuated by a small amount (16.2s to 17.2s)
- We can measure τ_p from the 3He detector rates, since the rate is proportional to the number of UCN available.

Prestorage Transmission Measurement: Optimization

- Optimize the production time and prestorage time to give minimal uncertainty

$$\frac{\sigma_T}{T} = \sqrt{\frac{1}{N_{Li}} + \frac{1}{N_{He}}}$$

- Carried out optimization measurements on an expected “typical” guide
- At long prestorage time, 6Li become low, at short prestorage time, 3He become low
- The sweet spot is around where the counts are equal



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