CryoEDM: building a simulation framework for ultra-cold neutrons

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- CryoEDM
- What are UCN?
- Simulating UCN in CryoEDM

Why are we interested in EDMs anyway?

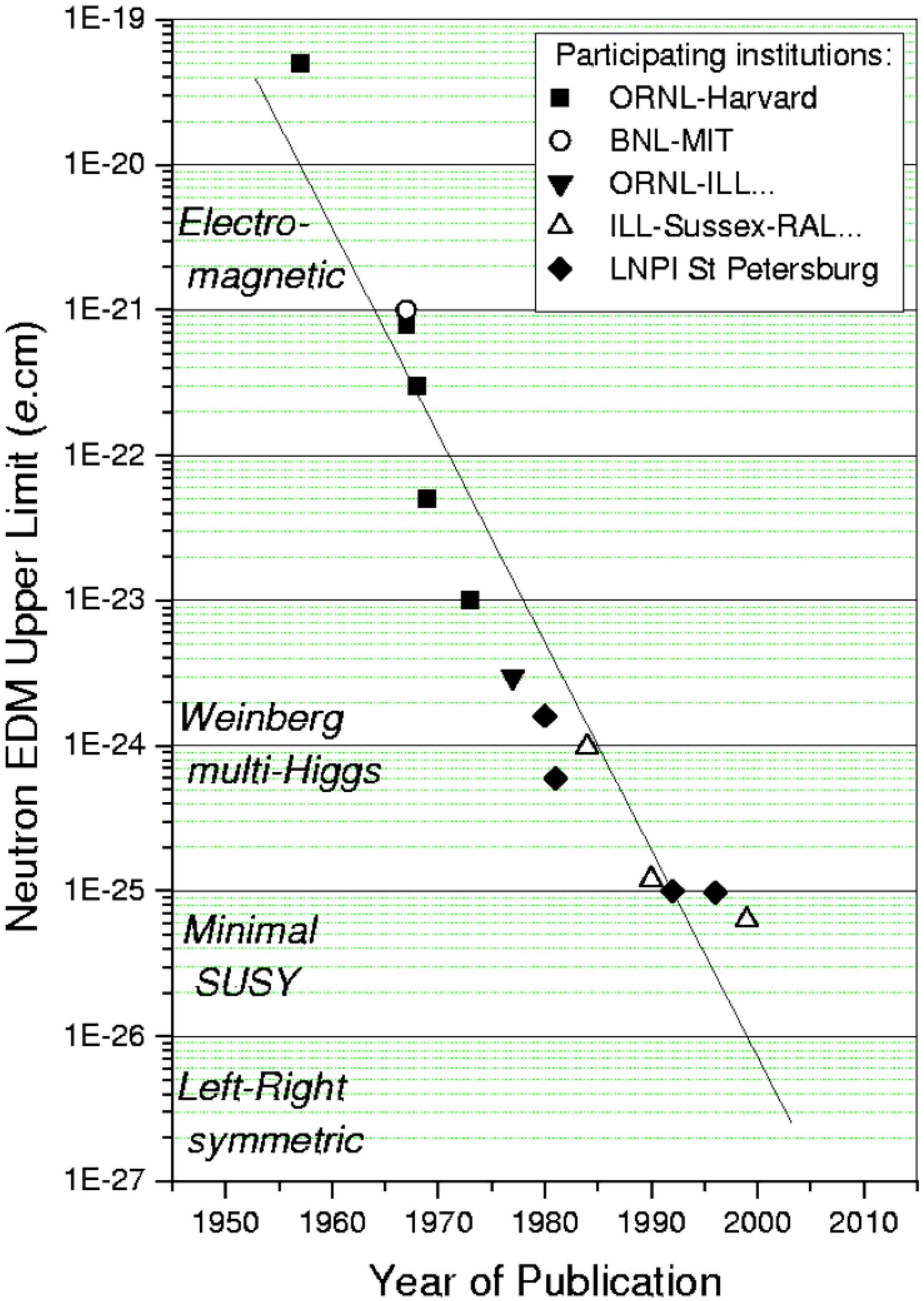
- The existence of a permanent EDM in fundamental particles would be a violation of Time reversal symmetry and therefore CP symmetry.

$$\vec{d} \quad = \quad d\vec{J} \qquad\qquad \underbrace{\hat{H} = \vec{d} \cdot \vec{E}}_{\text{Asymmetric under } T,\ P \text{ and } CP}$$

- *CP* violation is thought to be one of the key ingredients necessary for the predominance of matter over anti-matter in the universe.
  - ➡ Sakharov's necessary conditions for Baryogenesis

- However, sources of CP-violation in the standard model are generally thought to be **insufficient to generate presently observed baryon asymmetry**.

Neutron EDM Measurements



- Many different theoretical models predict new sources of CP-violation (such as the many from super-symmetry) and therefore **give predictions for the size of the nEDM**.
- *Thus, searches for a nEDM place experimental limits on many theories of beyond-standard-model physics*

Sussex-RAL 2006 Best Limit:

$$d_n < 2.9 \times 10^{-26} e\mathrm{cm}$$

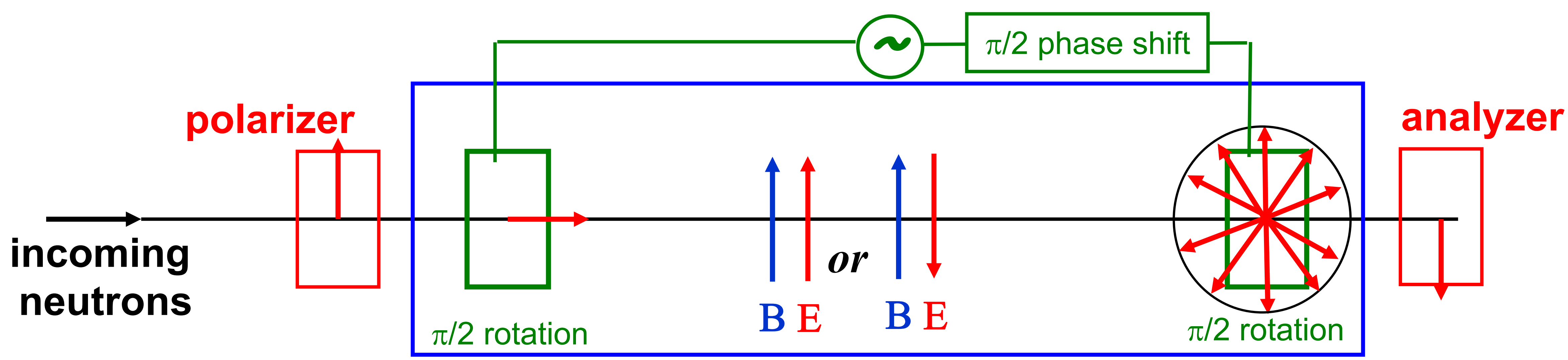
Measurement Principle

- Measure changes in neutron's Larmor precession frequency due to a potential EDM's interaction with an applied Electric field.

$$\hbar\omega_0 = -2\mu_n|\mathbf{B}_0| \mp 2d_n|\mathbf{E}_0|$$

- Changing **B** field and **E** field from parallel to anti-parallel results in,

$$\delta\omega_0 = -\frac{4d_n E_0}{\hbar}$$



Dewey, FNPSS 09

EDM Statistical sensitivity

$$\sigma_{edm} \propto \frac{\hbar}{\alpha E T \sqrt{N_n}}$$

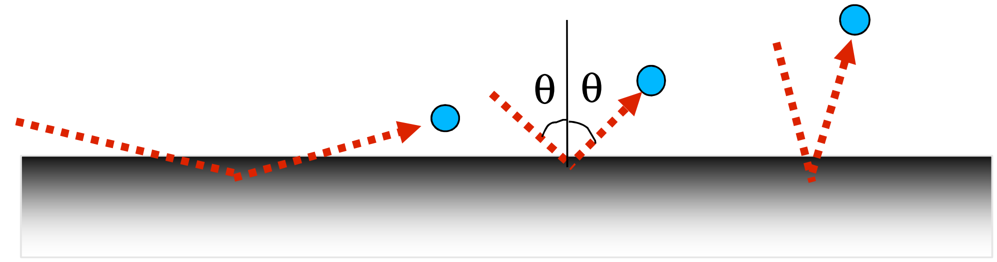
$$\begin{aligned} \alpha &= \text{polarisation efficiency} \\ E &= \text{applied E field} \\ T &= \text{observation time} \\ N &= \text{total number of neutrons detected} \end{aligned}$$

- Previous Sussex/RAL nEDM experiment was eventually limited by systematics - (Geometric phase effect)

- Measurement is highly dependent on a highly uniform magnetic field with variations of order $\approx 1\,\mathrm{nT/m}$ (Earth's field $\approx 30\,\mu\mathrm{T}$)

Ultra-Cold Neutrons

- Ultra-cold neutrons are typically of energy: $E \lesssim 200 \times 10^{-9} eV$
  - Typical UCN velocity: $v \leq 5 \text{ ms}^{-1}$
  - Wavelength: $\lambda \geq 400 \text{ Å}$



- Defining feature - **reflects from material boundary at all angles**
- UCN can be stored in material bottles for **hundreds of seconds**, limited by:
  - Capture by material's nuclei
  - Inelastic up-scattering by thermal vibrations.
- UCN are also heavily restricted by gravity!

$$V_g = m_n g h = (939 \text{ MeV/c}^2 * 9.81 \text{m/s}^2) h \approx (100 \text{neV/m}) * h$$

Simulating Ultra-Cold Neutrons

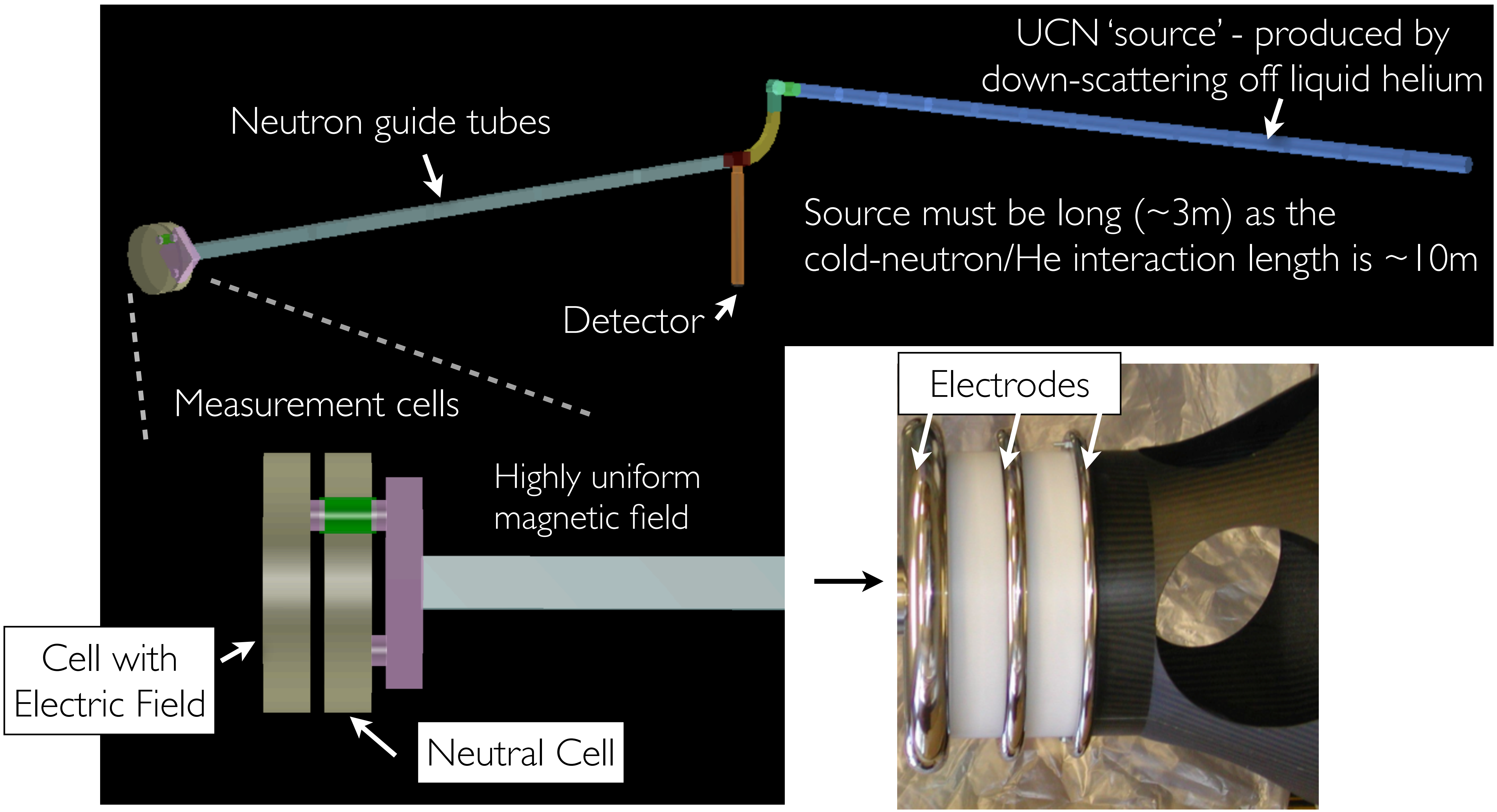
- UCN are very different to typical particle physics simulations (more akin to a ideal Gas + Quantum Mechanics)

- They also require their own special treatment when it comes to simulating them.
    - Highly gravitationally bound (parabolic trajectories)
    - UCN wall interactions (reflection, absorption, up-scattering, diffuse reflection)
    - Magnetic field interactions (neutron magnetic moment, spin-polarisation)
    - Electric field interactions ($\vec{B}' = \frac{1}{\gamma}\frac{\vec{v} \times \vec{E}}{c^2}$ relativistic motion-induced magnetic field)

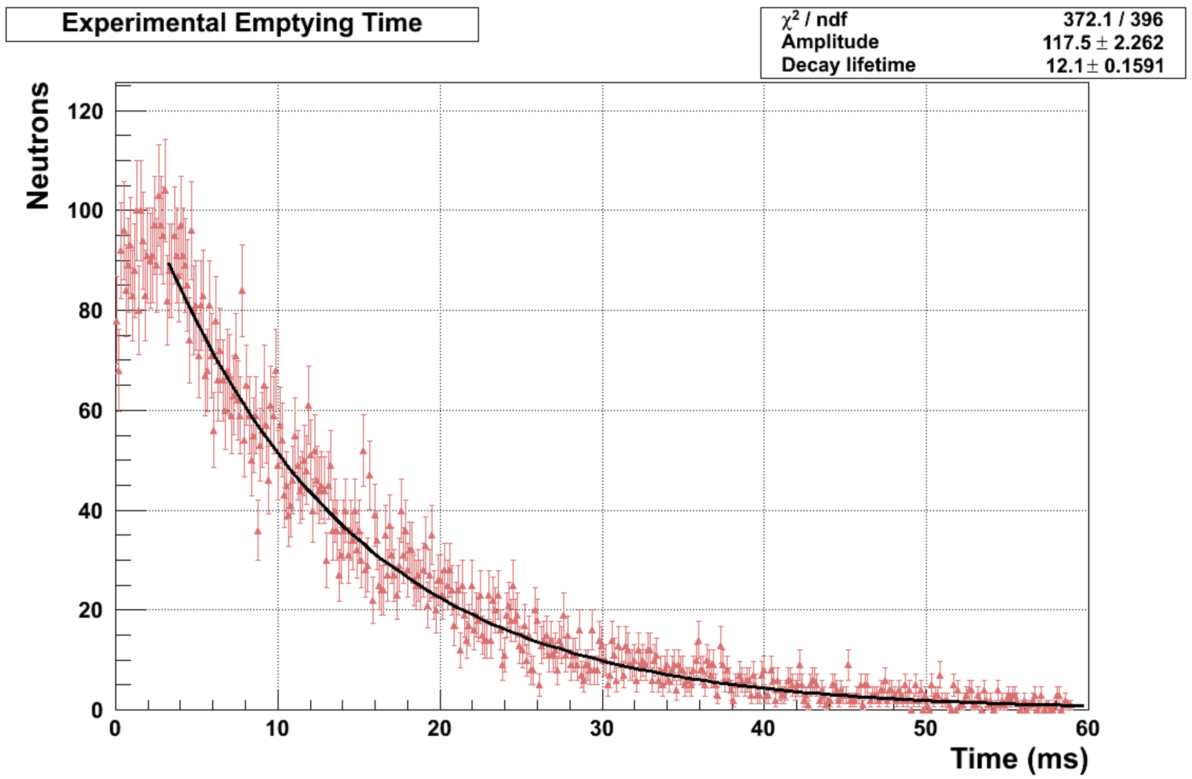
- No 'off-the-shelf' simulation package in this area, so started from ground up, designed specifically for UCN physics.

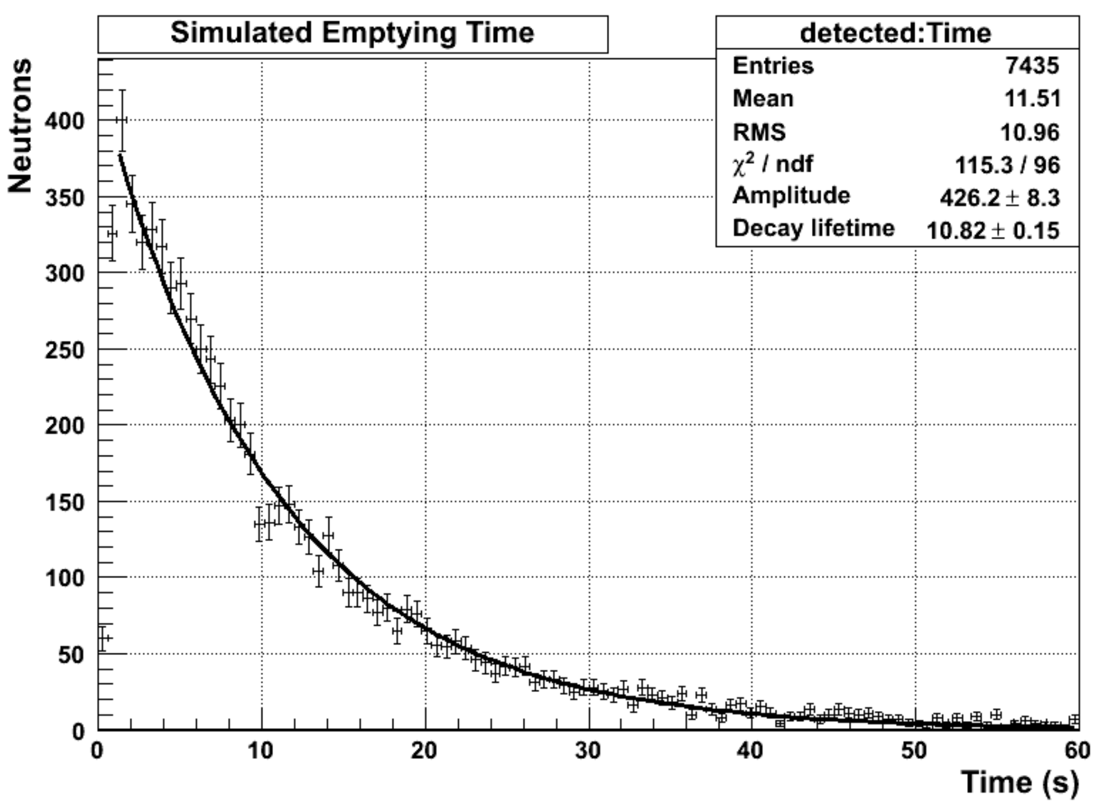
Simulating Ultra-Cold Neutrons

- Have developed a complete model of the neutron-facing parts of CryoEDM apparatus.



Simulating Ultra-Cold Neutrons

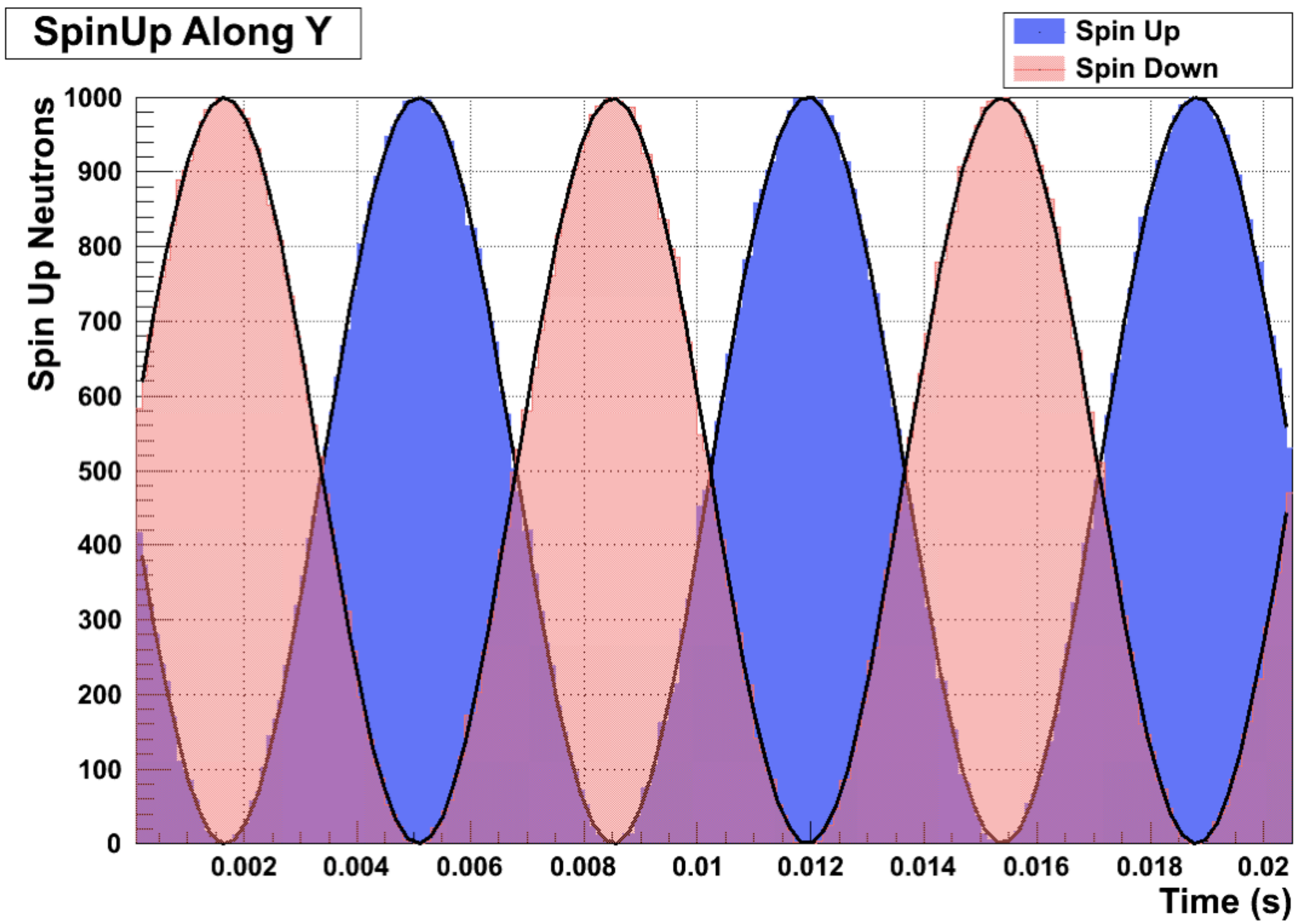




- Simulation has been tested, and is now in use on CryoEDM
  - Used to understand flow of UCN 'gas' through apparatus
  - Modelling factors that affect storage lifetime of UCN
- Able to show agreement with CryoEDM data on UCN flow through experiment

Simulating Ultra-Cold Neutrons

- We also model the interaction of neutron spin with the various static and time-varying magnetic fields present



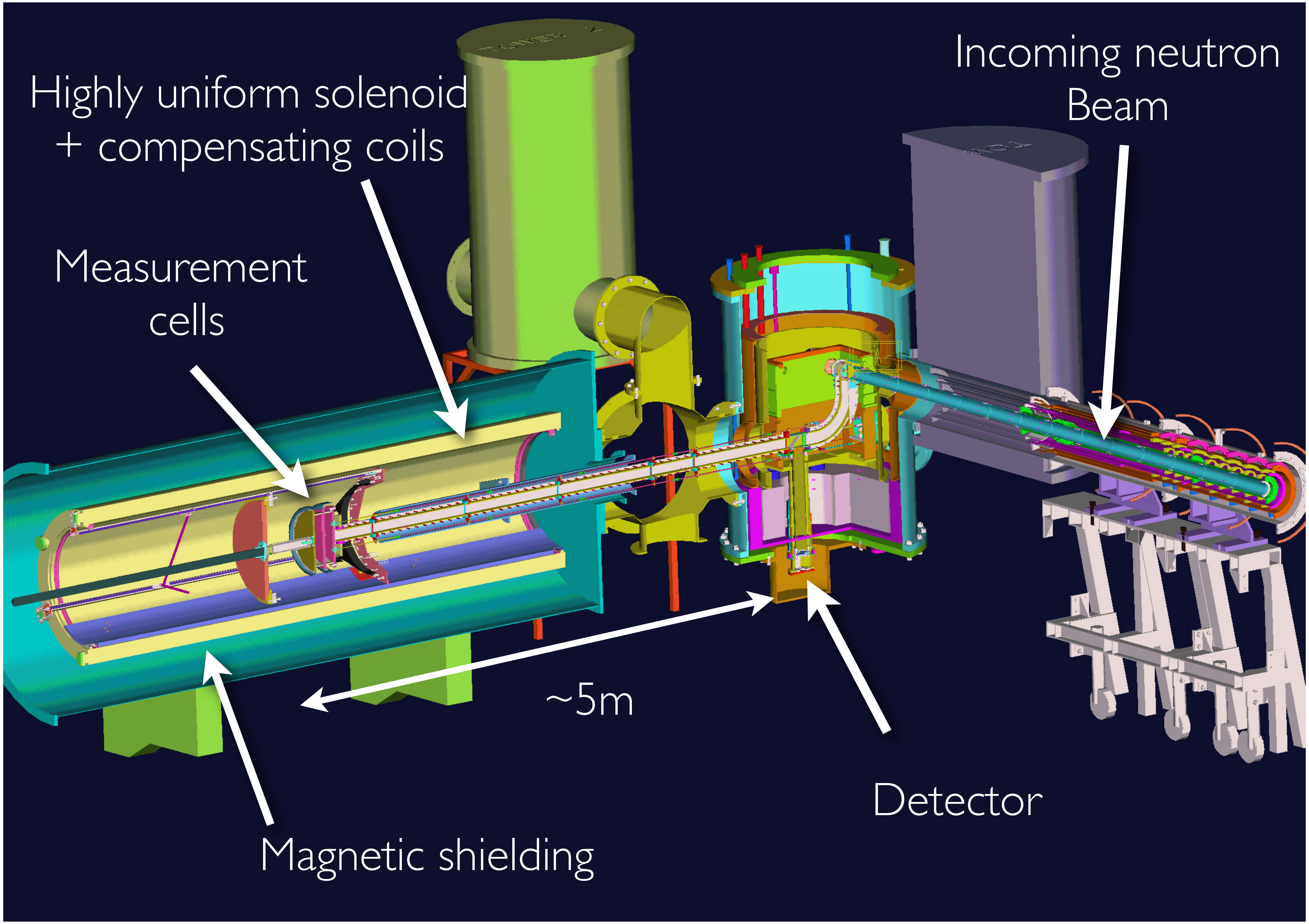
- Simulation is used to model effect of measured magnetic inhomogeneities on the characteristic depolarisation time.

- Also models systematics like $v \times E$ effect.

Summary

- Have created and tested a completely new monte-carlo simulation package for the physics of ultra cold neutrons.
- Models particle motion under gravity, utilising a new parabolic-path-finding algorithm, that supports arbitrary, complex geometries.
- We simulate neutron spin interaction under any kind of static or time-varying magnetic field (including the relativistically induced '$v \times E$' magnetic field)
- Simulation shows good agreement with initial experimental data and is now used by CryoEDM in understanding the physics.

CryoEDM


Highly uniform solenoid
+ compensating coils
Measurement
cells
Incoming neutron
Beam
~5m
Detector
Magnetic shielding

1.4 Generating Matter-Antimatter Asymmetry

A.D. Sakharov, JETP Lett. 5, 24, (1967)

1. Just after the Big Bang, ($t < 10^{-6}$s), matter and antimatter were in thermal equilibrium (T >> 1GeV) - balance between baryons and anti-baryons.

2. At some point, a symmetry-breaking process caused a slight imbalance between baryons and anti-baryons.

3. When the universe cooled to somewhere below (T ~ 1GeV), all the anti-baryons annihilated leaving a few baryons and lots of photons.

4. The photons are now microwaves in the CMB from subsequent expansion.

In this scenario the actual matter-antimatter asymmetry is really small, given by the ratio of baryons to CMB photons:

$$\frac{n_{baryon}}{n_{\gamma}} \approx 10^{-10}$$

1.5 Sakharov Conditions

- Sakharov identified three requirements for a process to generate the observed baryon asymmetry.

  1. *The process must violate baryon number conservation.*

  2. *There must be a period of non-thermal equilibrium*

  3. *There must be a process that violates CP symmetry.*

- ***Can this CP/T-violation needed in the very early universe be understood better through an observable quantity today?***

2.2 Scattering From Fixed Nucleus

- At low energies can represent nuclear potential as a spherical square well.
- In this case, the solution for the scattered wave function may be expanded in eigenfunction of angular momentum:

$$\begin{aligned} \psi_s(\vec{r}) &= \frac{f(\theta)}{r} e^{i\vec{k}\vec{r}} \\ f(\theta) &= \frac{1}{2ik} \sum_l (2l+1)[e^{2i\delta_l(k)} - 1] P_l(\cos\theta) \end{aligned}$$

- Since the cold neutron de Broglie wavelength is much larger than the range of the nuclear force, the scattering is predominantly s-wave, and

$$f(\theta) \simeq \text{constant} \equiv -a$$

which is known as the scattering length

2.3 Scattering Length

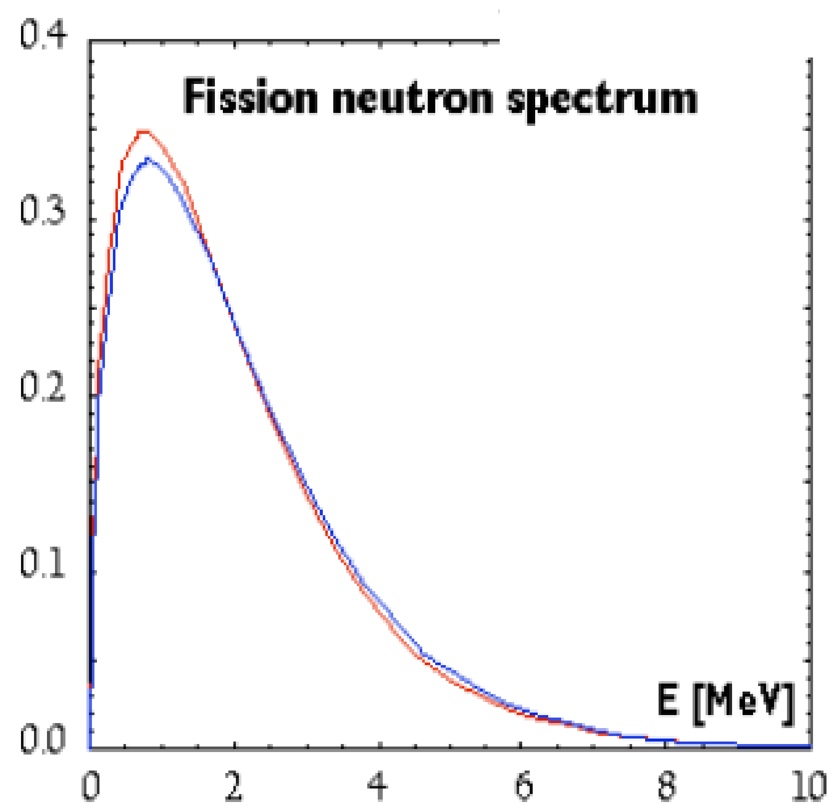
- The scattering length is actually determined experimentally and characterises the scattering cross section.

element	b (fm)
H	-3.74
Be	7.79
C	6.65
Al	3.45
Si	4.15
Ti	-3.44
Fe	9.45
Co	2.49
Ni/^{58}Ni	10.3/14.4
Cu/^{65}Cu	7.72/10.6
Cd	4.87-0.7i

- Can be imaginary - implies strongly absorbing material. Real part can be positive or negative, with negative scattering length is also often absorbing.

2.6 UCN Production

- Basic challenge for Experiments using UCN:



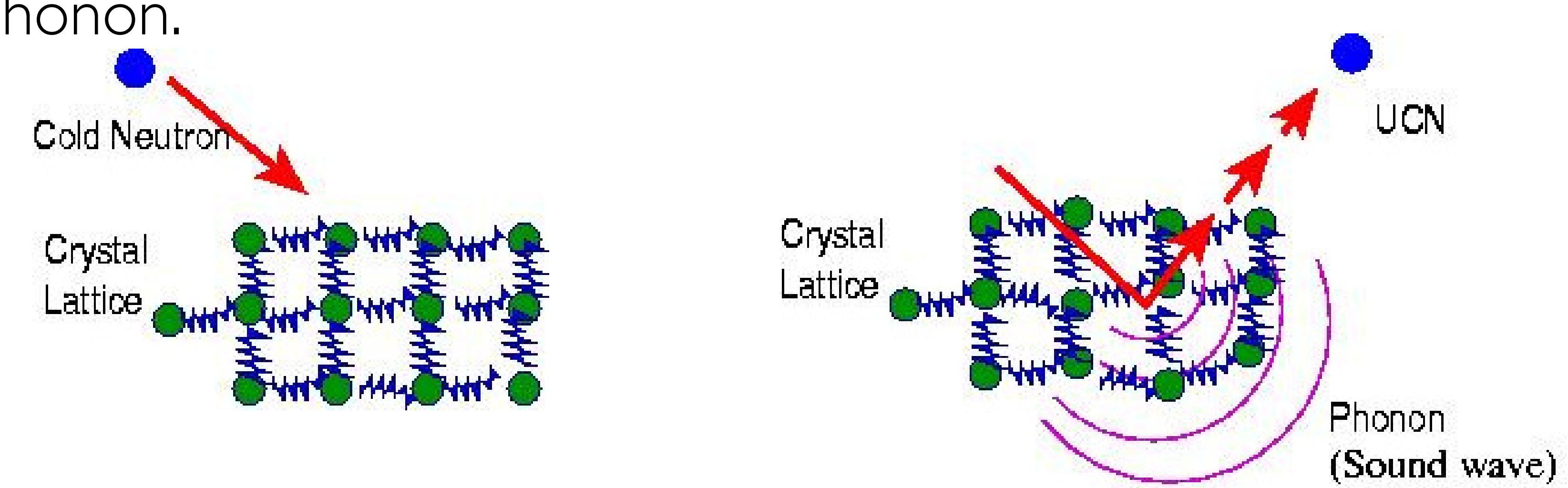
Typical UCN density in previous nEDM experiment $\sim 25\ \mathrm{UCN\ cm^{-3}}$

How do we increase the proportion of UCN?

2.7 Super-Thermal UCN Production

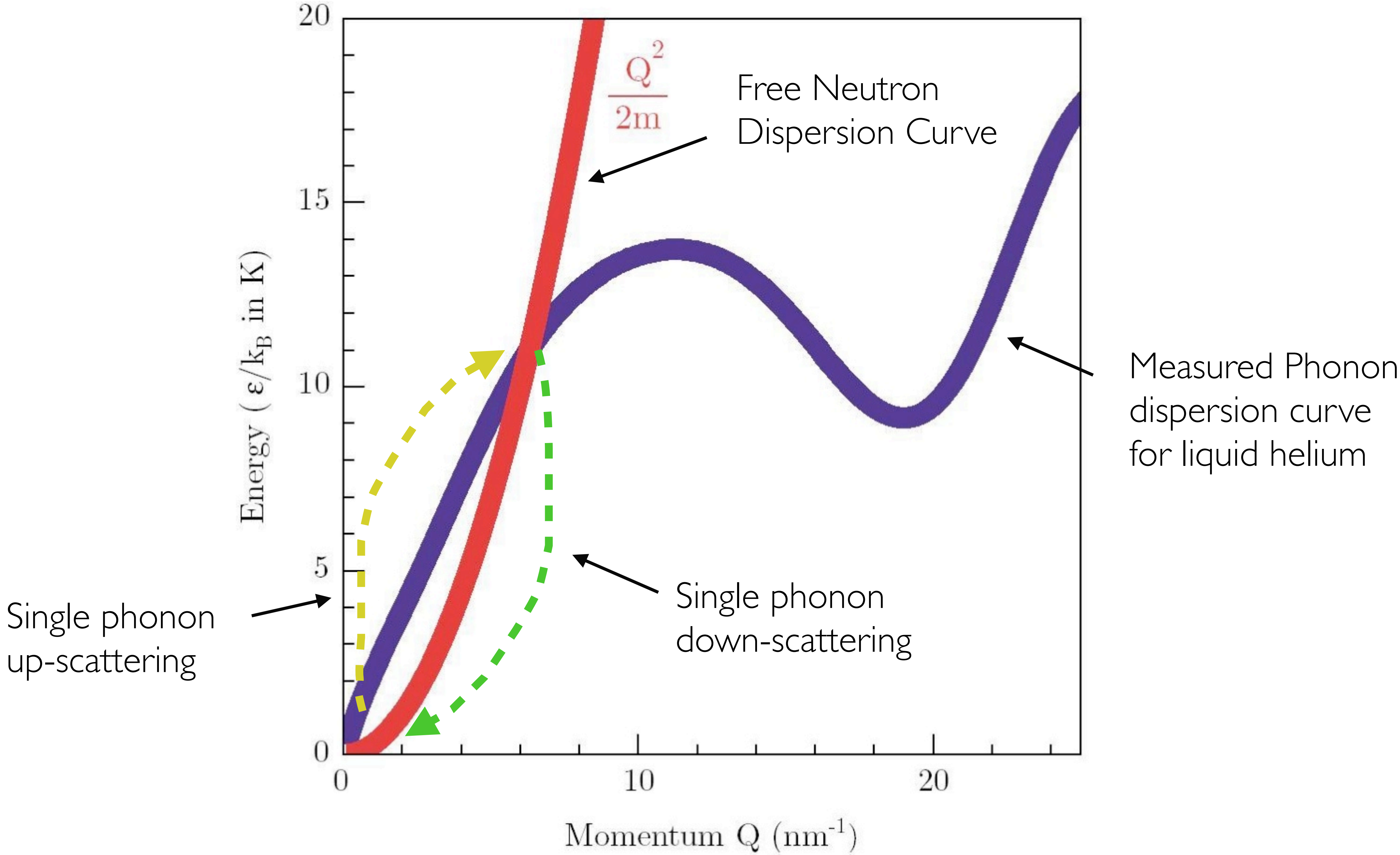
- Pendlebury and Golub (Phys. Lett., 53,1975) showed that a system such as superfluid Liquid ^{4}He can significantly increase the proportion of UCN, since it is an entirely coherent scatterer and has a zero neutron absorption cross-section.

- Cold neutrons, $\lambda \sim 9\text{Å}$ can down-scatter into the UCN energy regime by emission of a single phonon.



- Super-fluid liquid helium, cooled to temperatures such as $\sim 0.5\text{K}$ will therefore have very few 9Å phonons available to facilitate the reverse process - single phonon UCN up-scattering.

2.8 UCN Production in Liquid Helium



2.9 UCN Production in Liquid Helium

- Measurements of super-thermal production of UCN by neutron EDM group at Sussex/RAL found:

$$\begin{array}{rll} \text{Measured UCN Production rate:} & (0.91 \pm 0.13) & \mathrm{cm^{-3}s^{-1}} \\ \text{Theoretical single-phonon UCN production rate:} & (1.19 \pm 0.18) & \mathrm{cm^{-3}s^{-1}} \end{array}$$

C.A.Baker et al., Phys.Lett. A308 67-74 (2002)

- Other modes of down/up-scattering, involving multiple-phonon emission/absorption, and can be particular significant in relation to UCN up-scattering.

3.0 Experiments using UCN

- Many other research areas with an impact into BSM physics, are using UCN to increase their precision:
    - Neutron Lifetime (P. Huffman; FNSS 09)
    - Neutron Beta-decay correlations (S. Baessler; FNSS 09)
    - 'Exotic' neutron decay - $n \rightarrow \bar{n}$ oscillations
    - Tests of quantisation of gravity with UCN (H. Abele; FNSS 09)

2.2 Fermi Potential

- This potential in fact, **defines**, the UCN energy regime, since at this energy the neutrons will be totally internally reflected:

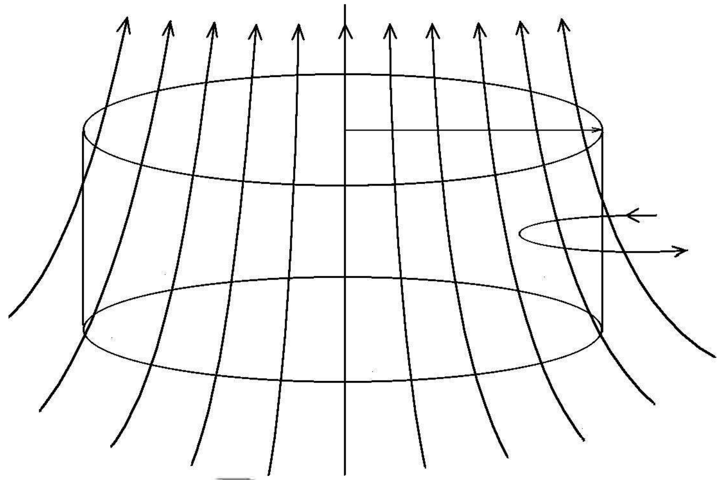
$$E_{\mathrm{UCN}} < V_{\mathrm{Boundary}}$$

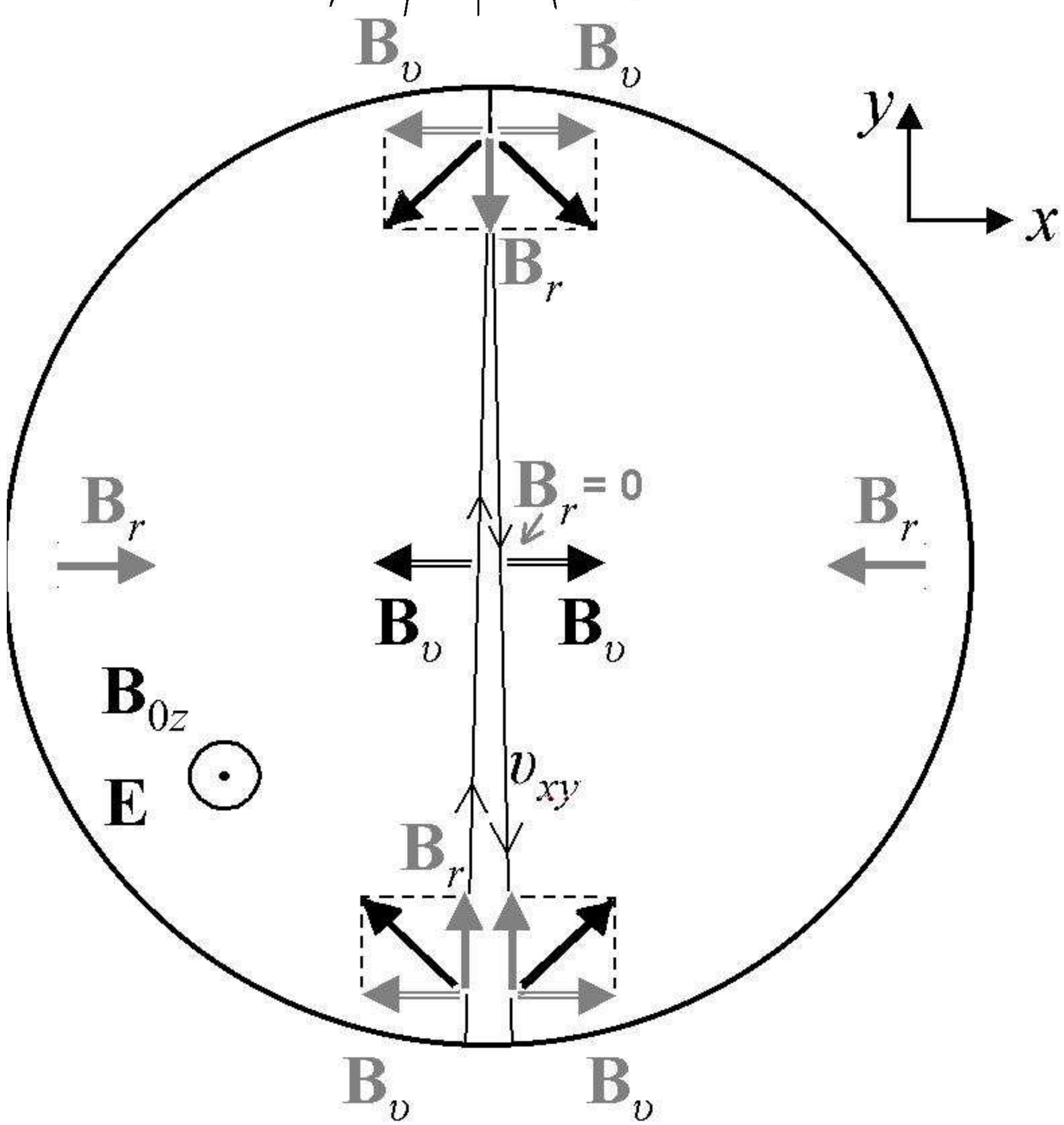
- Potential can be positive or negative, with negative signifying an absorbing material

Material	Effective potential (units of 10^{-8} eV) (equation (2.12))	Theoretical loss factor, $f = W/V \times 10^{4}$ (equation (3.8))
Ni (spin up)	27	2·5
Ni (spin down)	21	
Be	25	0·1 (300 K)
C	18	0·1
Cu	17	3·1
SiO_2	11	—
Mg	6·1	0·2
Al	5·6	0·5
Perspex	3·3	—
Polyethylene	−1·1	—
H_2O	−1·7	—

Geometric Phase

* J.M.Pendlebury et al. Phys. Rev. A 70, (2004)





- Combination of two factors:
  - Small inhomogeneities in the magnetic field

$$\partial B_{0_z}/\partial z \Rightarrow B_r \propto r$$

  - *Relativistic* motion-induced field,

$$\vec{B}' = \frac{1}{\gamma}\frac{\vec{v}\times\vec{E}}{c^2}$$

- Two effects combine to produce an additional rotating magnetic field in x-y plane, shifting the neutron precession frequency.
- Shift is proportional to $\vec{E}$, just like a neutron EDM.
- Contribution to neutron EDM is roughly,

$$d_n \propto \frac{v_\perp |\partial B/\partial z|}{B_0^2}$$

Ultra-Cold Neutrons

- UCN wavelength is large compared to the atomic spacing in a solid and therefore interact macroscopically with the medium.
- The surface of a material can be approximated as a potential step.
- UCN can be considered as 1-D wave mechanics coming to life