## Monte Carlo Simulation of Spin Relaxation due to v × E effect in nEDM experiment

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We have simulated the precession of spin-polarized Ultra Cold Neutrons and $^3$He atoms in uniform and static $B$ and $E$ fields and calculated the spin relaxation. The spin relaxation times $T_1$ (longitudinal) and $T_2$ (transverse) of spin-polarized UCN and $^3$He atoms are important considerations in the new measurements of neutron Electric Dipole Moment in the SNS nEDM experiment. The uniform $E$ field creates a motional magnetic field due to the $\vec{v} \times \vec{E}$ effect which combines with collisions with the walls of the holding cell to produce constant variation of the total $B$ field and result in the spin relaxation of the neutron and $^3$He samples. Scattering of $^3$He atoms in $^4$He also results in spin relaxation and is highly temperature dependent. In the SNS nEDM experiment the $B$ field has magnitude of 10 mGauss. The applied $E$ field is parallel to the $B$ field and has a magnitude of 50 kV/cm. We have found the relaxation times for the neutron due to the $\vec{v} \times \vec{E}$ effect to be long with respect to the holding times and neutron lifetime. On the other hand, the $\vec{v} \times \vec{E}$ effect may have a significant influence on $^3$He relaxation times.

New Results

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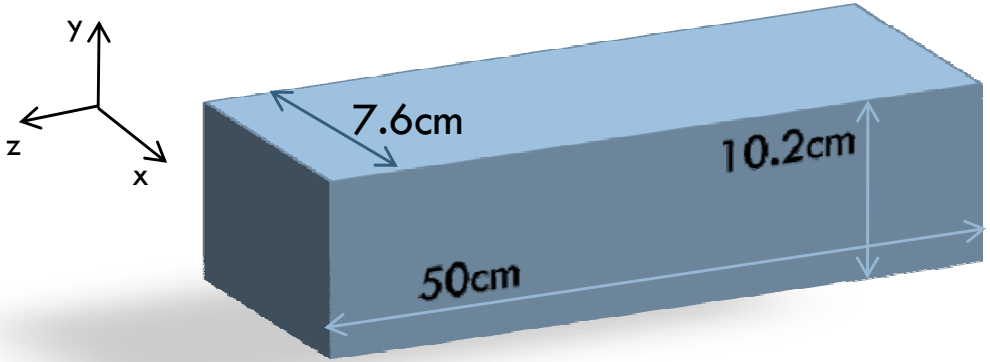
# v x E Effect



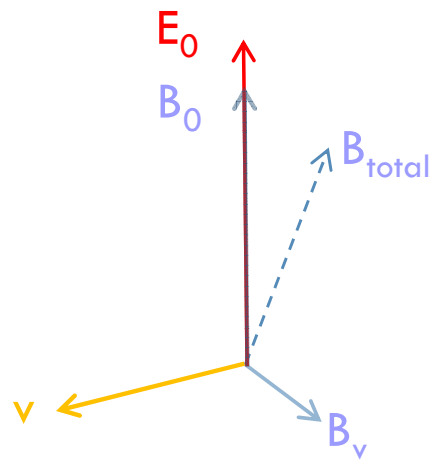
Relativistic transformation for a particle moving in an Electric Field reveals a motional magnetic field: $\vec{B}_v = \vec{E} \times \vec{v} / c^2$

Effective B field changes as velocity changes due to wall and particle collisions.




nEDM Measurement cell

$E_0$=50 kV/cm
$B_0$=10mGauss
$V_{max}$~2.5m/s (UCN)
(Bv ~ $10^{-5}$ mGauss)




For <u>uniform</u> and <u>constant</u> E and B fields:

$$\vec{E} = E_0 \hat{x} \qquad \vec{B} = B_0 \hat{x}$$

Depolarization can occur after many collisions from the sudden changes in $B_v$

# Longitudinal Spin Depolarization

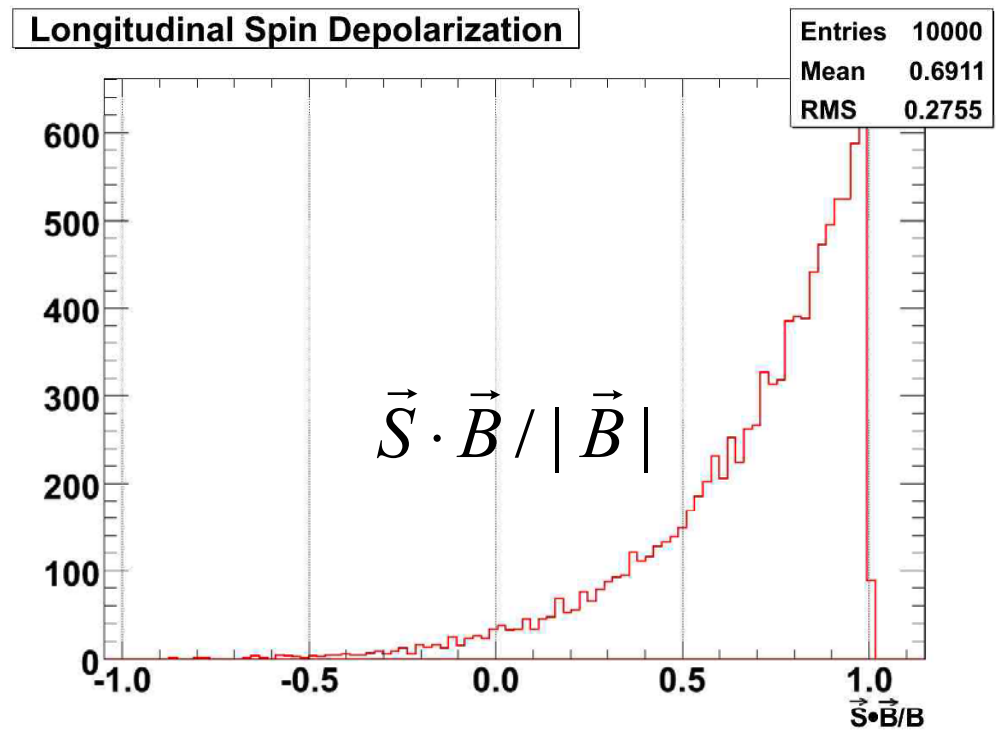


Neutrons start out with their spins aligned with the holding field $B_0$ so that $\vec{S}\cdot\vec{B}/B=1$

After some time neutron spins drift away from original orientation due to v x E effect and wall collisions

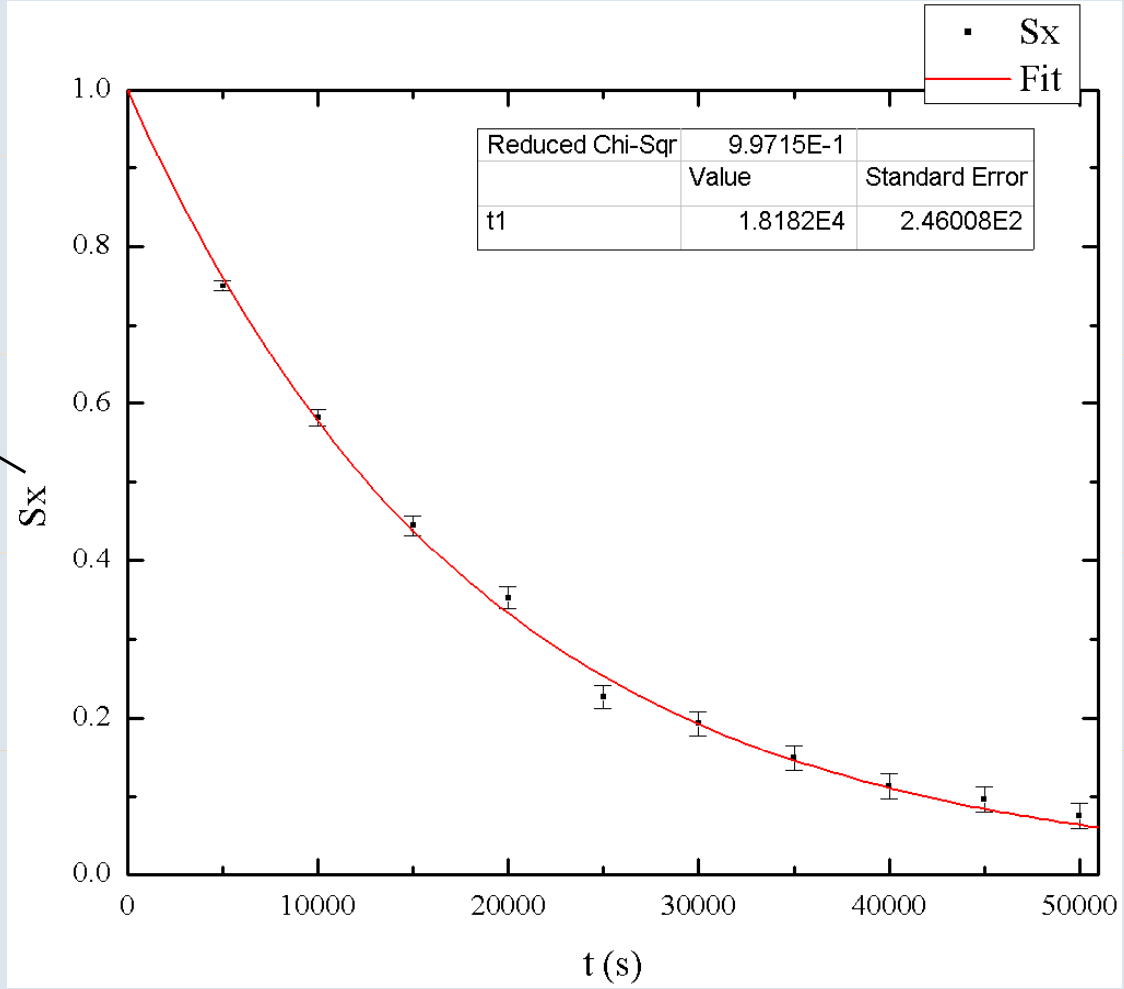
Interested in the expectation value of the component of spin aligned with the $B_0$ field $<\vec{S}\cdot\vec{B}>/B$ and its time dependence. Depolarization time $T_1$

Distribution of spin alignment with $B_0$ field after some time




Similarly, in Transverse Spin Depolarization, spins start out perpendicular to the holding field $\vec{S}\cdot\vec{B}=0$ and have a depolarization time $T_2$

$$< \vec{S} \cdot \vec{B}_0 > / B_0$$




4

# Time evolution example

T1 is extracted from the fit to a single parameter exponential

# $T_1$ from vxE effect (diffusive wall collisions)

**[following McGregor, Phys. Rev. A 41, 2631 (1990)]**



$$\frac{1}{T_1} = \frac{\gamma^2}{2}[S_{Hx}(\omega_0) + S_{Hy}(\omega_0)]$$

and $T_2 \cong 2T_1$

where $S_{Hx}(\omega) = \int_{-\infty}^{\infty} \langle H_x(t) H_x(t+\tau) \rangle e^{-i\omega\tau} d\tau$ is the FT of the field correlation function

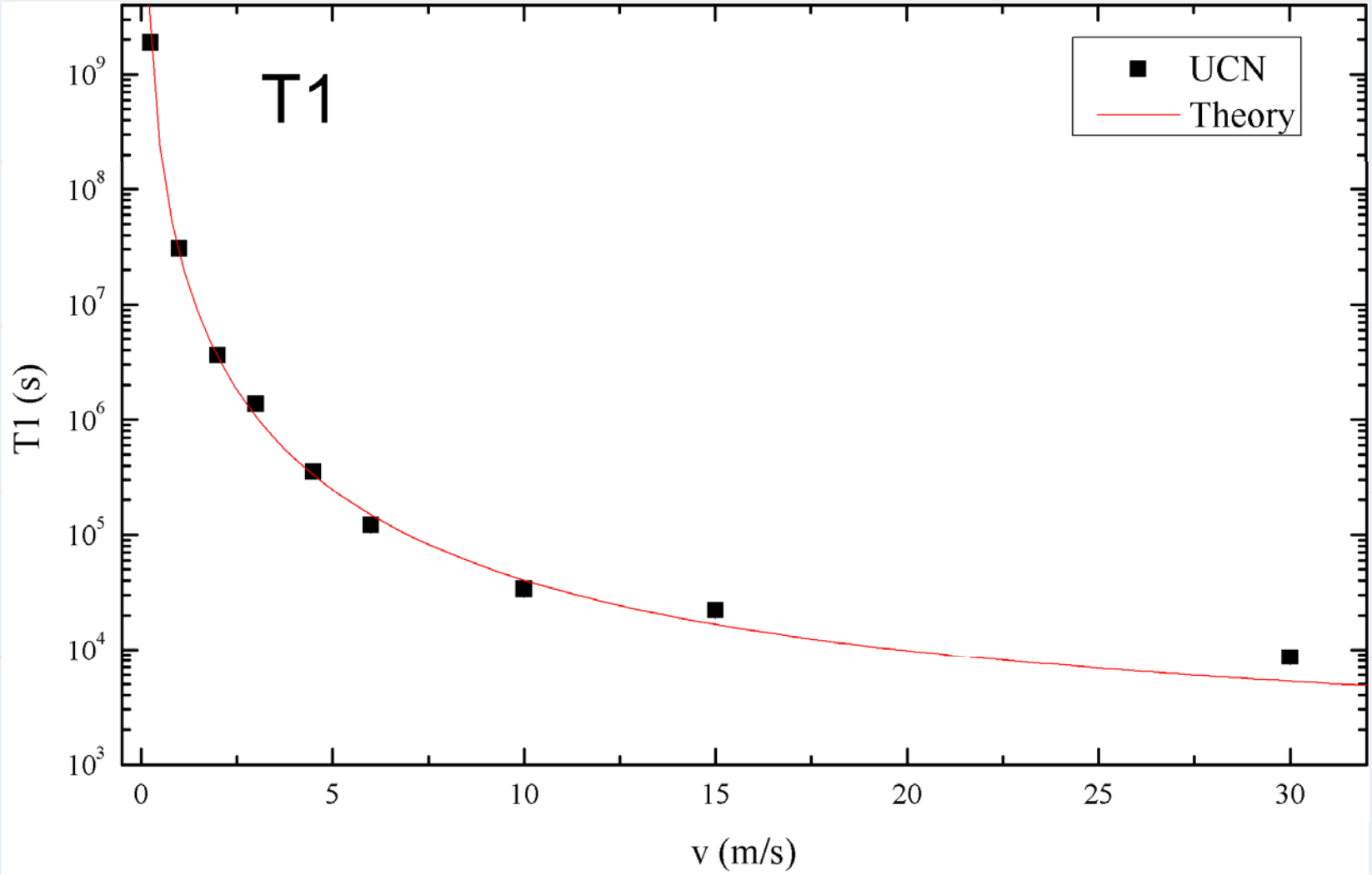
The motional *vxE* field depends on velocity. Using $\langle u_x(t) u_x(t+\tau) \rangle = \langle u_x^2 \rangle e^{-\frac{\tau}{\tau_C}}$

$$S_{Hx}(\omega) = \frac{E^2}{c^4} \cdot S_{uy}(\omega) = \frac{E^2}{c^4} \cdot \frac{2\langle v_y^2 \rangle \tau_C}{1 + \omega^2 \tau_C^2}$$

$$\langle v_x^2 \rangle + \langle v_y^2 \rangle = \frac{2}{3} \langle v^2 \rangle$$

$$T_1 = \frac{3}{2} \frac{B^2 c^4 \lambda}{E^2 \bar{v}^3} \left( \frac{1 + (\omega_0 \tau_c)^2}{(\omega_0 \tau_c)^2} \right)$$

$$\omega_0 = \gamma B_0$$

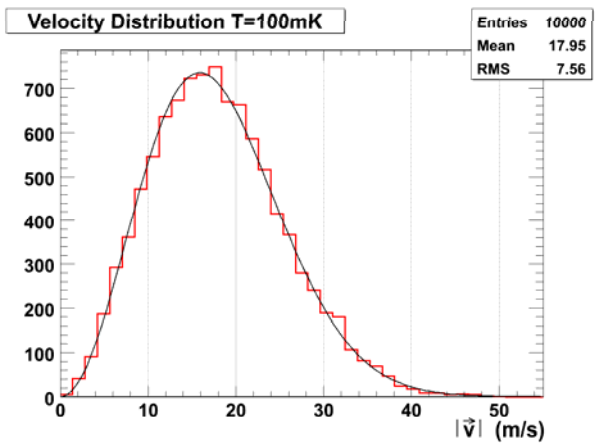





# UCN $T_1$ dependence on velocity

# $^3$He Simulations






Maxwell Velocity Distribution with much higher velocities

$$P(v) = 4\pi(M/2\pi\tau)^{3/2} v^2 e^{-Mv^2/2\tau}$$

$M$ = effective mass in $^4$He

Introduce Mean Free Path from collisions with He4 atoms

$$\lambda \cong 3D/\langle v \rangle$$

$$\langle v \rangle = \sqrt{8\tau/\pi M}$$

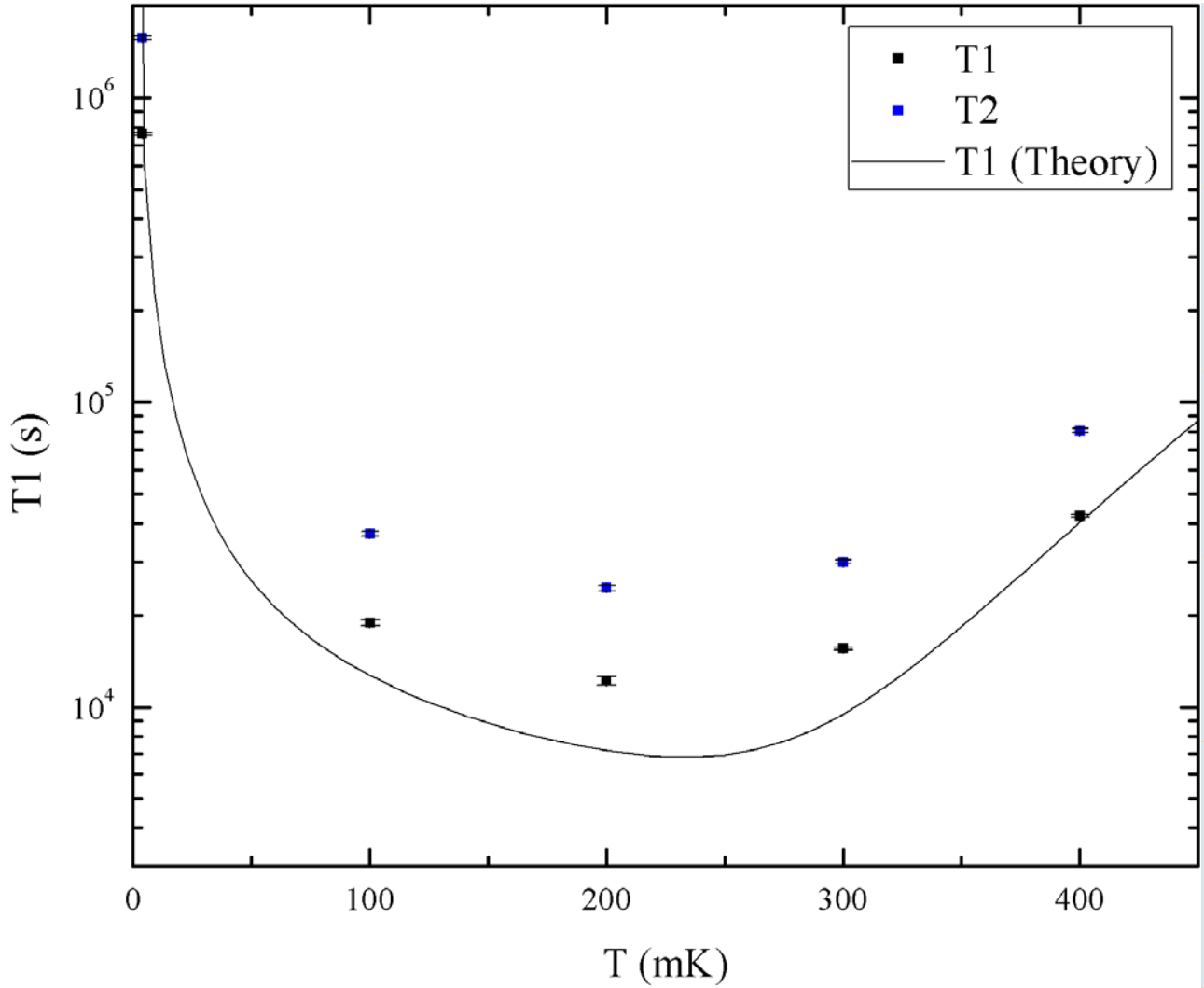
Diffusivity* $D = \dfrac{1.6 cm^2/s}{(T[K])^7}$

Mean free path in the cell $\lambda \approx 4V/A \approx 8\text{cm}$ (diffusive collisions)

| T (mK) | <v> (m/s) | λ (cm) | |
|---|---|---|---|
| 100 | 17.86 | 2.69e+4 | >> nEDM wall boundary (8cm) |
| 200 | 25.26 | 148 | |
| 300 | 30.94 | 7.09 | ~ wall boundary |
| 400 | 35.73 | 0.82 | < wall boundary |

Great Temperature dependence of Mean Free path

$T_2 \cong 2T_1$




8

# $^3$He Depolarization T1 and T2

The lowest depolarization times for $^3$He due to vxE fields can affect the nEDM experiment for temperatures T < 400 mK

# Conclusions and Future



- v x E effect as testing framework for future simulations (Uniform fields, no way around it)
- Depolarization due to gradients in the *B* fields
- Geometric phase simulations
  - Test the effect on $^3$He and UCNs
  - Simulations specific to nEDM *B* field profile

# Simulation Software (past, present, future)



- Using C++ and ROOT framework
- Implement modularized spin precession calculations
  - Exact calculation for vxE effect
  - More than one numerical method for GeoPhase
  - Gravity effects for UCNs
- Use parameter files for simulation settings and field maps