SAND2021-14882C

Polarization in Noble Gases workshop 2021 (PiNG 2021)

Abstract for an invited talk

Title: **^{3}He NSFs for sensitive neutron polarimetry and neutron E-field imaging**

Speaker: Yuan-Yu Jau, Sandia National Laboratories (USA)

With the mature spin-exchange optical pumping (SEOP) technique, high-pressure (≥ 1 atm), hyperpolarized ^{3}He cells have been widely used as neutron spin filters (NSFs) to polarize cold-to-thermal neutrons and to analyze neutron polarization for various neuron science applications. Compared to other neutron polarizing and analyzing technologies, ^{3}He NSF has several advantages including relatively high polarizing and analyzing power (> 90%), capable of flipping the polarizing and analyzing direction via adiabatic fast passage (AFP) of the ^{3}He spins, long ^{3}He spin relaxation time (hundreds of hours), small size and low weight that enable various orientations of a ^{3}He NSF, etc. By taking advantage of ^{3}He NSFs, we demonstrated simple experimental implementation that is capable of detecting a small angular change ($\ll 10^{-3}$ rad) in neutron spin orientation. Using a high-flux neutron beam, 10^{-6} rad angular sensitivity is in-principle feasible within a day. With this sensitive neutron polarimetry capability, we further demonstrated electric-field (E-field) imaging using polarized neutrons for first time in the world.

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^{3}He NSFs for sensitive neutron polarimetry and neutron E-field imaging

Yuan-Yu Jau

Sandia National Laboratories

Polarization in Noble Gases workshop 2021

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Scientific motivation

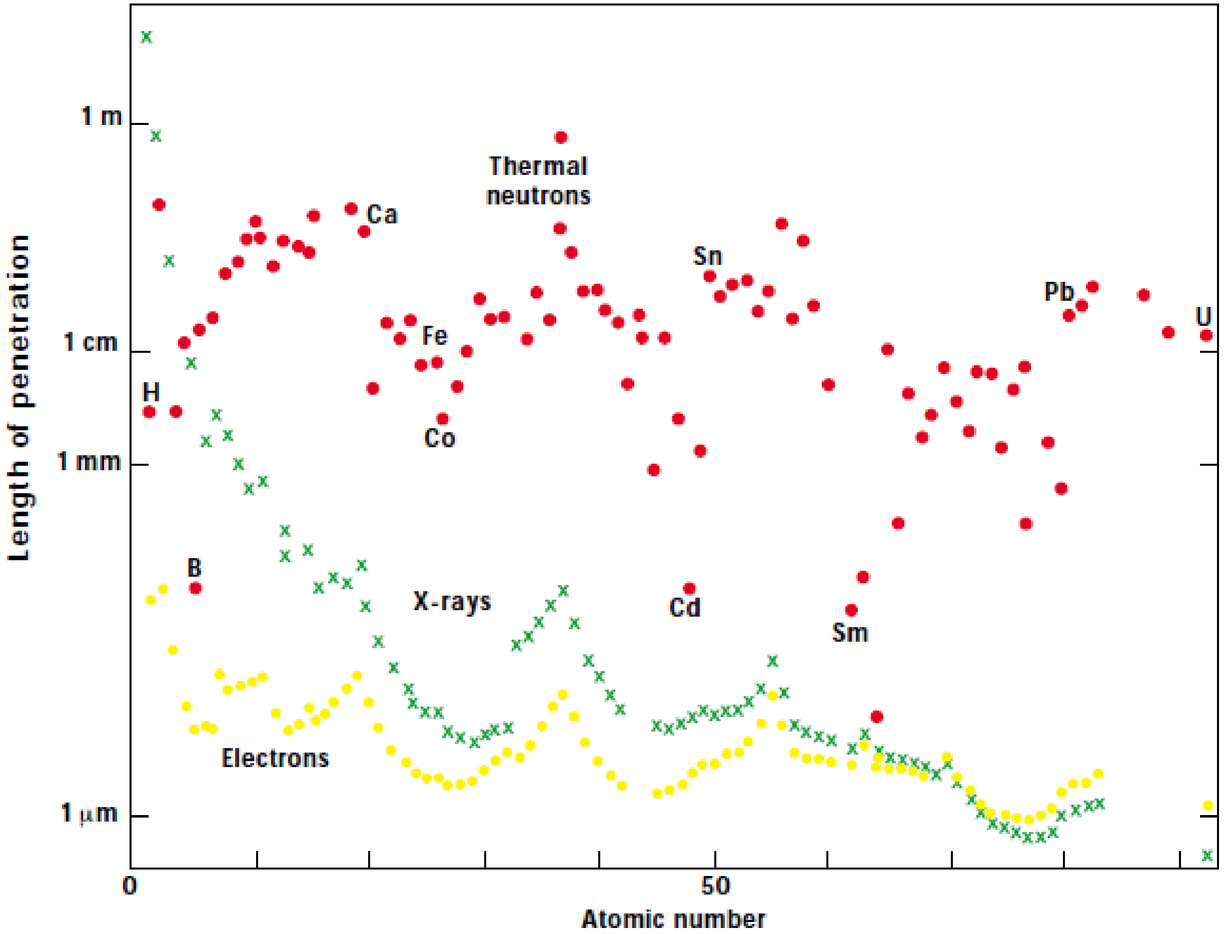
Nondestructive but penetrative electric-field (E-field) imaging can be highly valuable for studying material property and structure regarding electric potential, electric polarization, charge distribution, and dielectric constant behind physical barriers.

Possible probe candidates:

- ➢Charge particles, such as **electrons or alpha particles**: Can directly interact with electric fields but cannot travel far in a space filled with matters.
- ➢High-energy photons, such as **hard X-ray or gamma-ray**: Can in-principle go through metals but its interaction strength with electric field is too small to be useful based on quantum electrodynamics (QED).

How about neutrons?

❖Neutrons are highly penetrative through many elements!



Penetration depth of a beam of thermal neutrons (red, 25 meV), of X-rays (green, 12.4 keV) or of electrons (yellow, 94 keV) as a function of the atomic number. Note the logarithmic scale along the vertical axis.

But neutrons are electrically neutral! Can we really utilize them to probe electric fields?

Taking advantage of electromagnetism with special relativity

Neutron spin seems to be able to interact only with magnetic field. So how about the electric field?

Neutrons, however, do see an effective magnetic field when they are moving through a space with electric field $\mathbf{E}$ due to the relativistic effect, and from Lorentz transformation, we find the effective magnetic field $\mathbf{B}_{\text{eff}}$ to be:

$$\mathbf{B}_{\text{eff}} = \frac{1}{\sqrt{1 - v^2/c^2}} \frac{-\mathbf{v} \times \mathbf{E}}{c^2}.$$

Since neutron is kind a heavy particle, its speed $|\mathbf{v}|$ is usually way less than speed of light c. We then find the total effective magnetic field to be (including the ambient magnetic field $\mathbf{B}_{\text{lab}}$):

$$\mathbf{B}_{\text{eff}} = \mathbf{B}_{\text{lab}} - \frac{\mathbf{v} \times \mathbf{E}}{c^2}, \text{ for } |\mathbf{v}| \ll c.$$

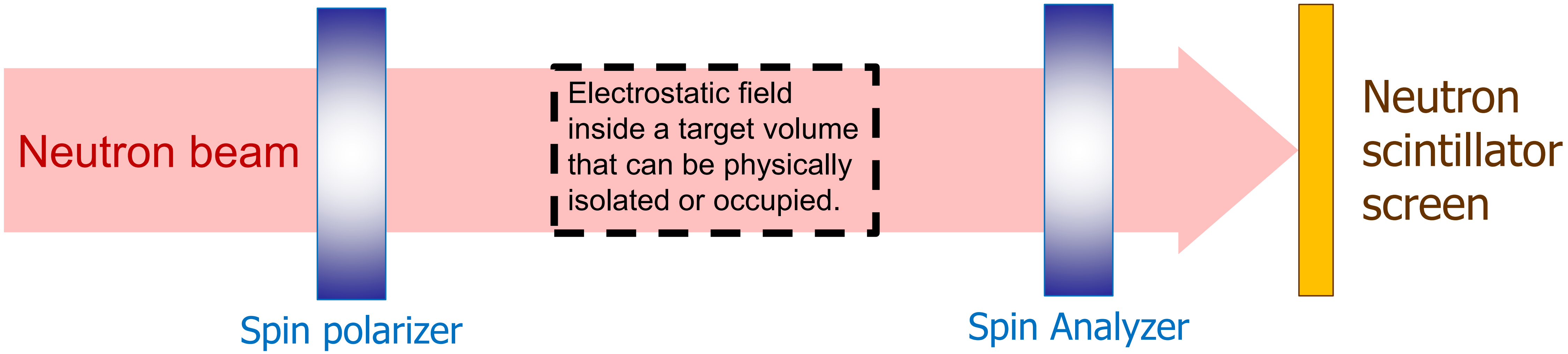
We find a net change in the angle vector $\boldsymbol{\theta}$ of a neutron spin due to field-induced precession from its trajectory l to be:

$$\boldsymbol{\theta} = \int_l \frac{d\langle \mathbf{I} \rangle}{|\langle \mathbf{I} \rangle|} = \int_l \gamma_{\text{n}} \left[\mathbf{e}_{\text{I}} \times \frac{\mathbf{B}_{\text{lab}}}{|\mathbf{v}|} - \mathbf{e}_{\text{I}} \times \frac{(\mathbf{e}_v \times \mathbf{E})}{c^2} \right] dl, \text{ where } \mathbf{e}_{\text{I}} = \langle \mathbf{I} \rangle / |\langle \mathbf{I} \rangle|, \text{ and } \mathbf{e}_v = \mathbf{v}/|\mathbf{v}|.$$

One unique feature we can see from the equation above is that the spin rotation angle $\boldsymbol{\theta}$ due to electric field is independent of the neutron velocity.

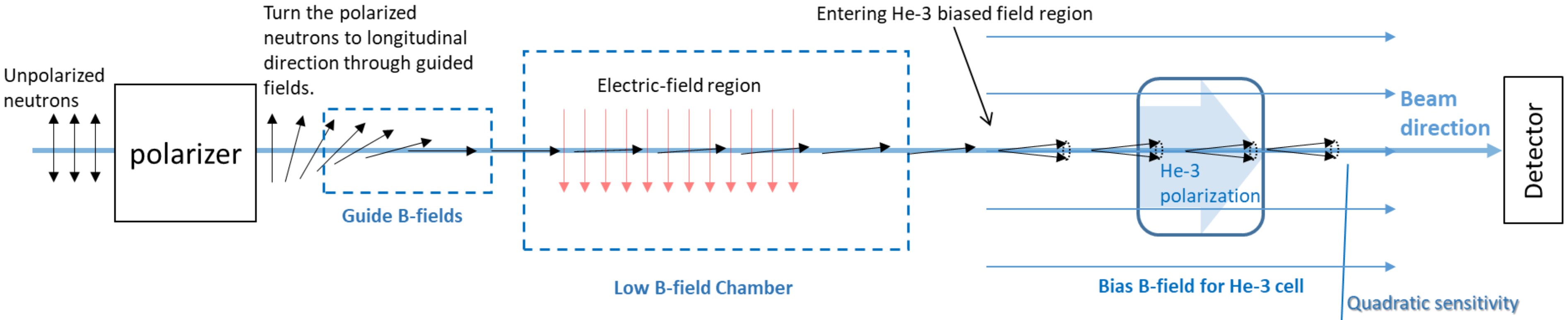
Thus, we can determine electric-field vector by measuring the neutron spin rotation with different probing parameters!

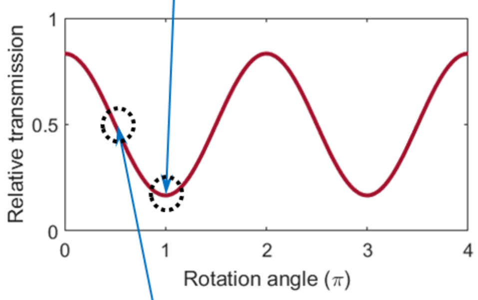
Conceptual diagram of E-field imaging with polarized neutrons



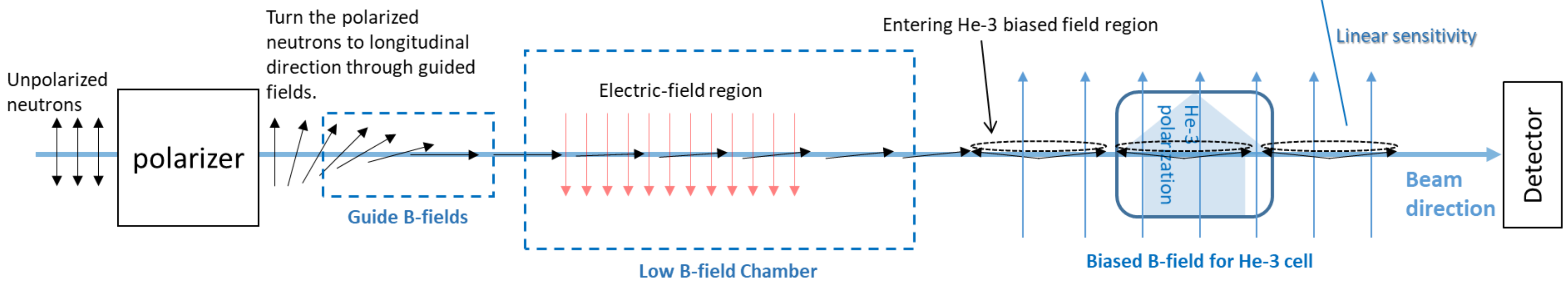
Methods of neutron polarization analysis

Conventional neutron polarization analysis configuration





Preferred configuration for neutron polarization analysis

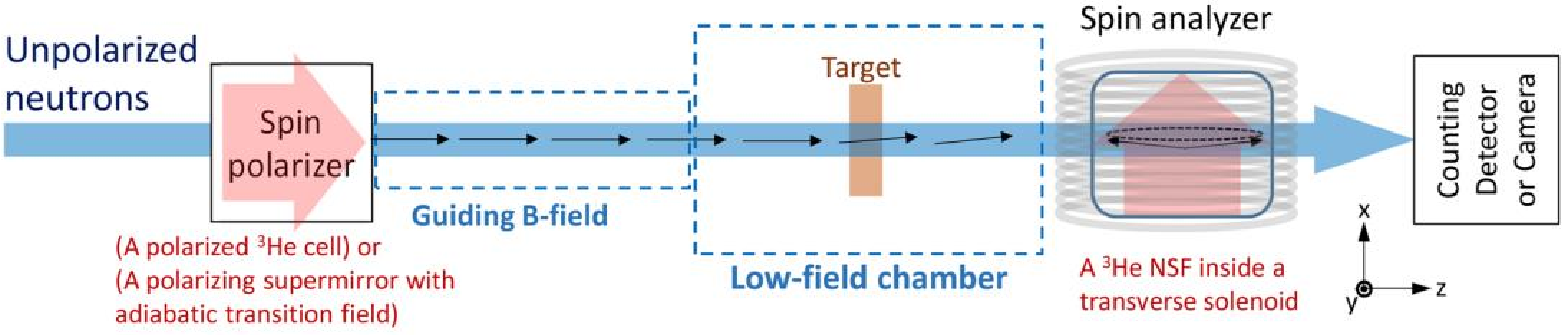


$$\delta\theta(\text{parallel}) = \sqrt{\frac{2\sqrt{N_0(1-P_nA)+1/4}+1}{N_0P_nA}} \approx \frac{\sqrt{2}(1-P_nA)^{1/4}}{\sqrt{P_nAN_0^{1/4}}}$$

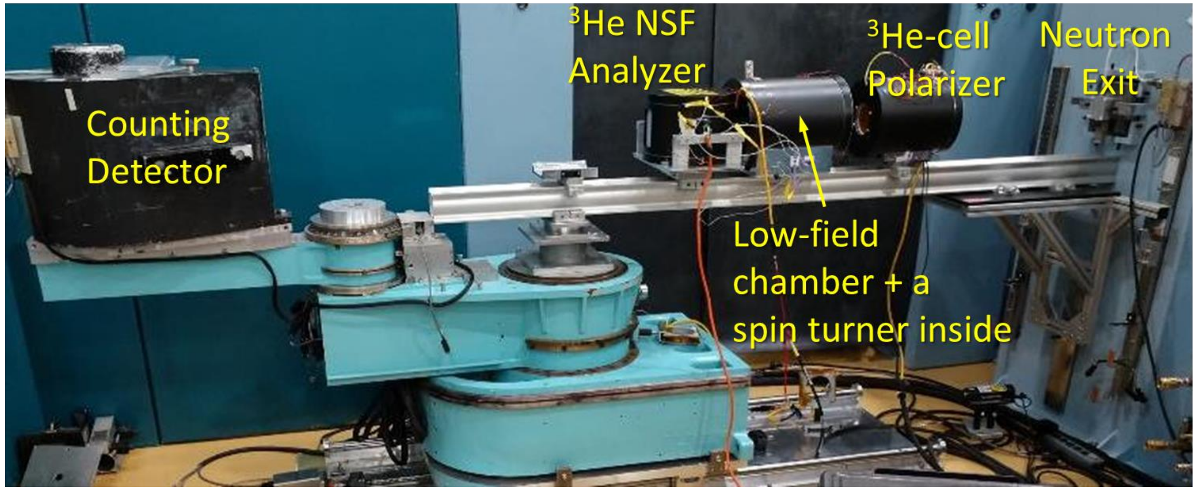
Here, P_n is the neutron polarization, A is the analyzing power, and N_0 is the detected neutron number.

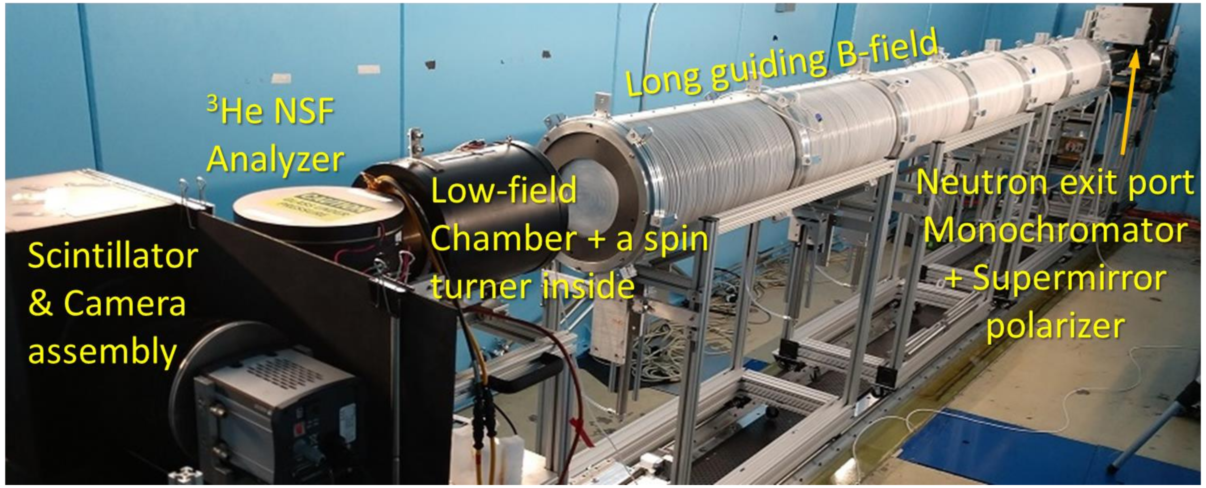
$$\delta\theta(\text{Transverse}) = \frac{1}{P_nAN_0^{1/2}}$$

Realizing neutron transverse polarization analysis



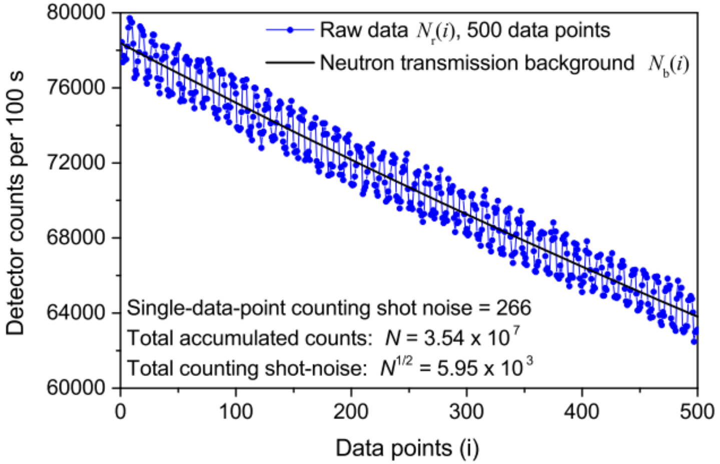
We used the PHADES beamline and NG6e at NIST Center for Neutron Research (NCNR) for experimental verifications.

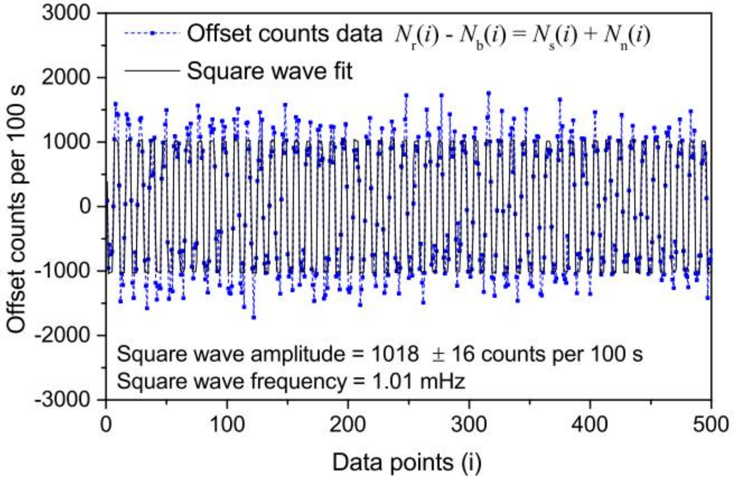


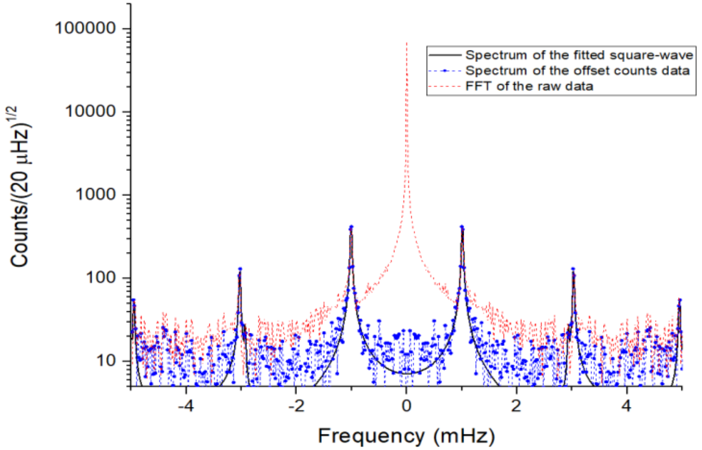


Data of transverse polarization analysis

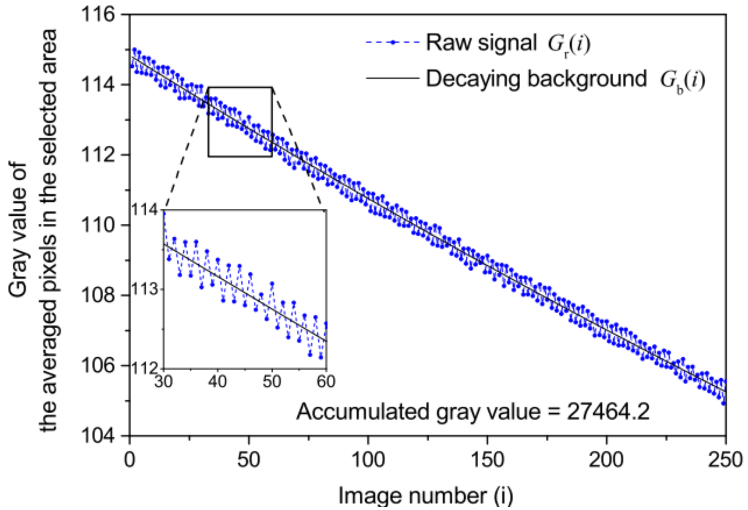
On PHADES beamline

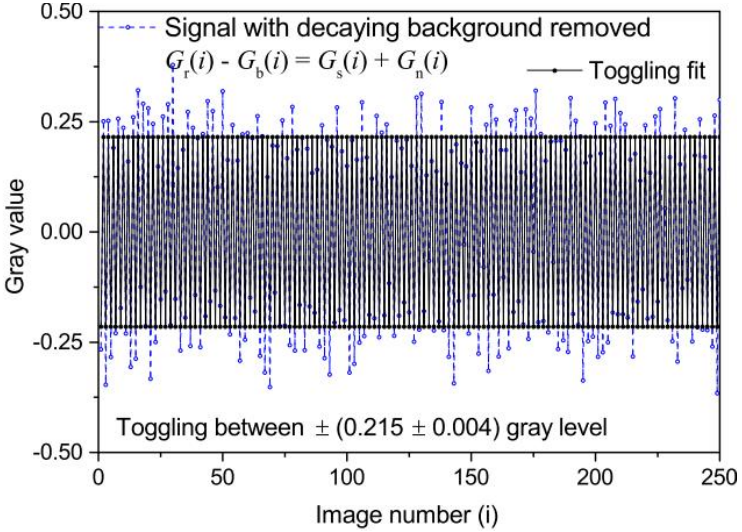


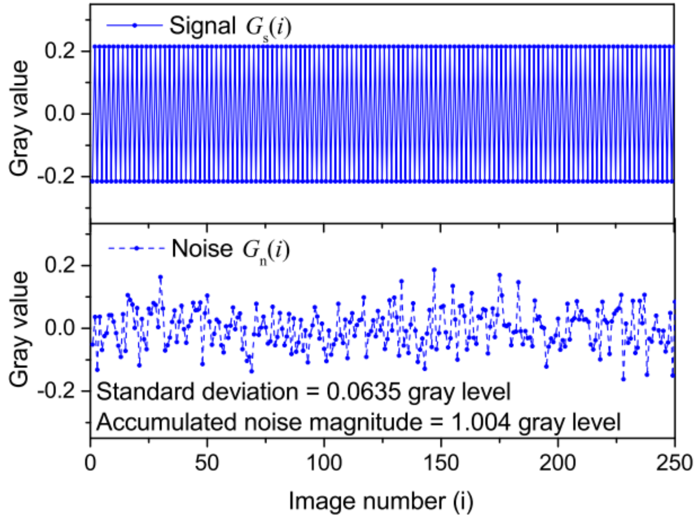




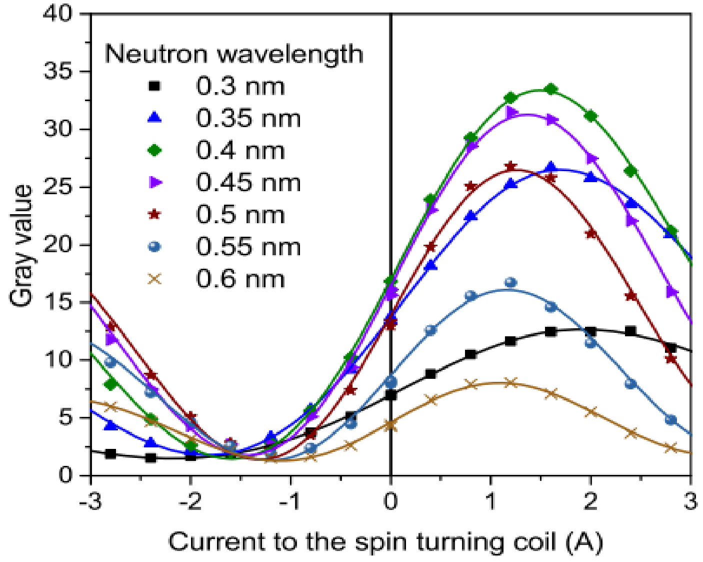
On NG6e beamline with a tunable monochromator

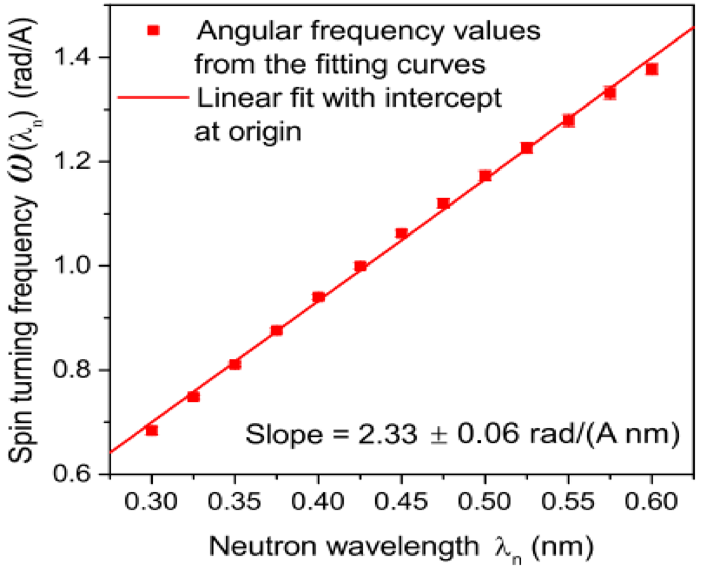






Results of transverse polarization analysis





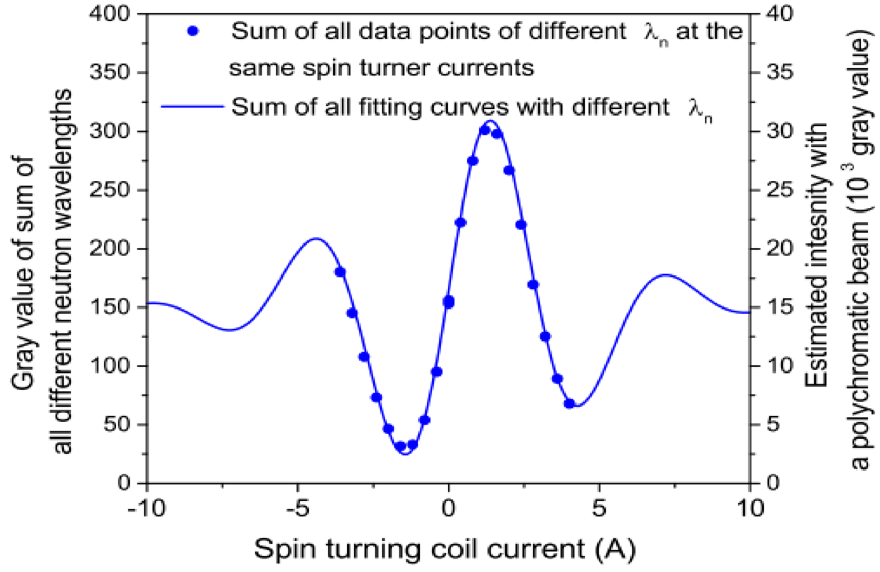


TABLE I. Comparison of experimental (PHADES) and theoretical values with 3.54 × 10^7 total detection counts.

	Experiment	Theory
Noise of single data point	273	266
Total measurement noise	6.1 × 10^3	5.95 × 10^3
Angular resolution $\delta\theta$ (mrad)	0.24 ± 0.01	0.25 ± 0.01

TABLE II. Comparison of experimental and theoretical values of angular resolution with 5.9 × 10^{10} photoelectrons in detection using a monochromatic neutron beam at 0.425 nm on the NG6e beamline.

	Angular resolution (μrad)
Experimental result	37 ± 5
Theoretical result	43 ± 4

For the best estimated performance on NG6e with similar experimental apparatus, we find the available area of the 3He cell to be 55.4 cm^2, and use a polychromatic beam. We find the expected accumulated N_{pe} for one day to be 5.9 × 10^{10} × (area ratio) × (polychromatic enhancement) × (duration ratio) ≈ 5.9 × 10^{10} × 55.4/31.7 × 1000 × 24/12.5 = 2 × 10^{14}. Hence, the calculated daily dependent angular resolution is $\delta\theta \approx [(0.87 \pm 0.02) \times \sqrt{2 \times 10^{14}/(82 \pm 8)/d}]^{-1} = (0.70 \pm 0.07) \times 10^{-6}$ rad/ √ d.

Sensitive neutron transverse polarization analysis using a ^{3}He spin filter

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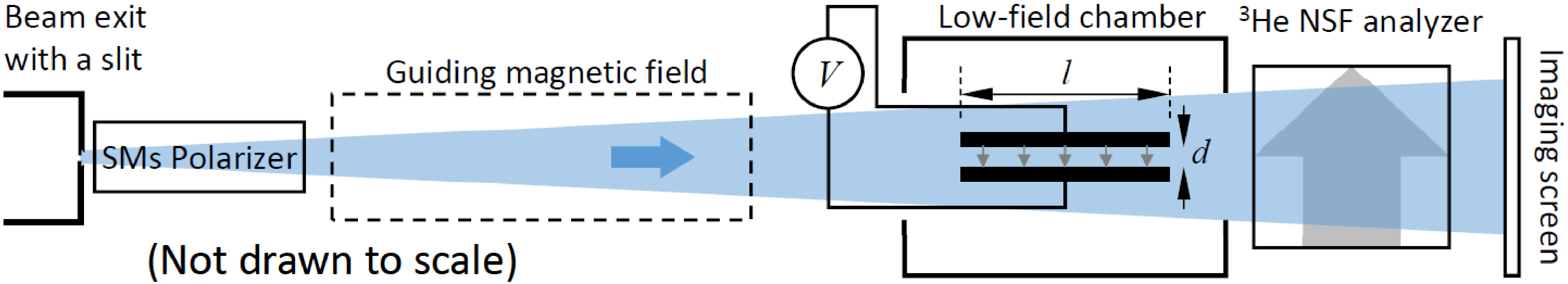
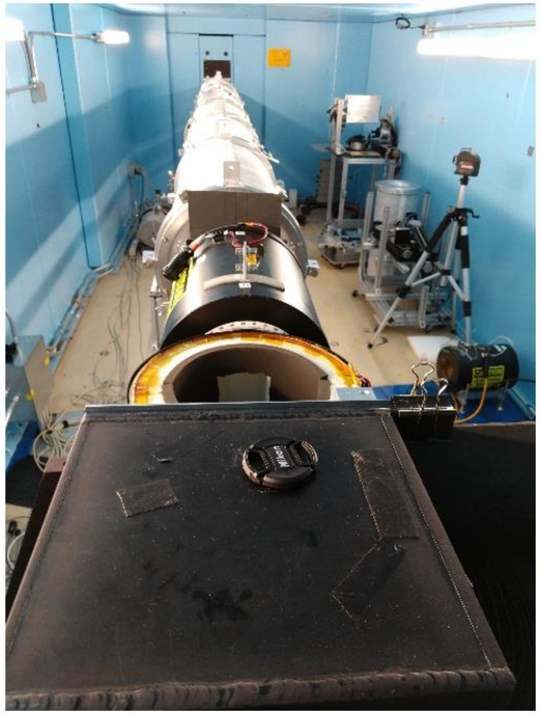
ABSTRACT

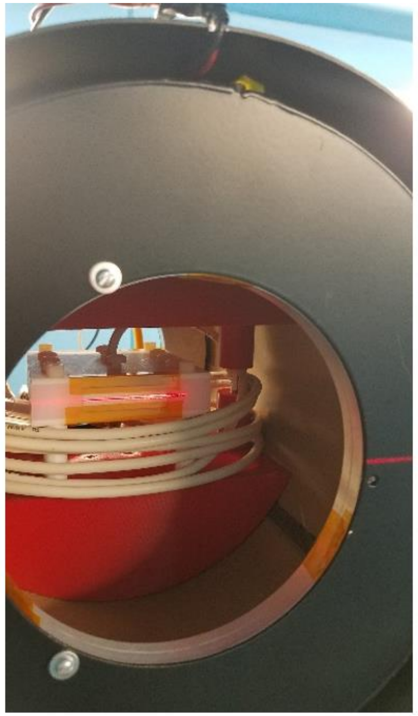
We report an experimental implementation for neutron transverse polarization analysis that is capable of detecting a small angular change ($\ll 10^{-3}$ rad) in neutron spin orientation. This approach is demonstrated for monochromatic beams, and we show that it could be extended to polychromatic neutron beams. Our approach employs a ^{3}He spin filter inside a solenoid with an analyzing direction perpendicular to the incident neutron polarization direction. The method was tested with polarized neutron beams and a spin rotator placed inside a μ-metal shield just upstream of the analyzer. No cryogenic superconducting shields or additional neutron spin manipulations are needed. With a counting detector, we experimentally show that the angular resolution $\delta\theta = 1/(P_n A \sqrt{N})$ rad is only determined by the counting statistics for the total counts N and the product of the neutron polarization P_n and the analyzing power A. With a high-flux neutron beam, 10^{-6} rad angular sensitivity is feasible within a day. This simple, classical-quantum-limited transverse polarization analysis scheme may reduce the overall complexity of experimental implementation for applications requiring sensitive neutron polarimetry and improve the precision in fundamental science studies and polarized neutron imaging.

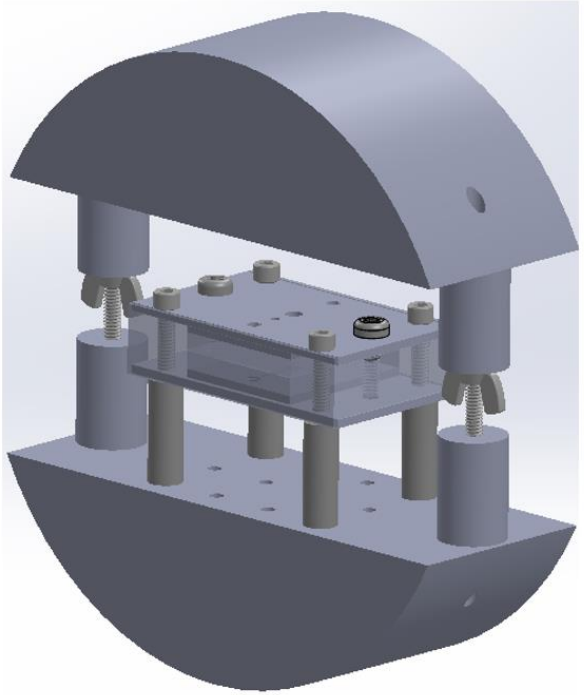
Direct electric field imaging using polarized neutrons



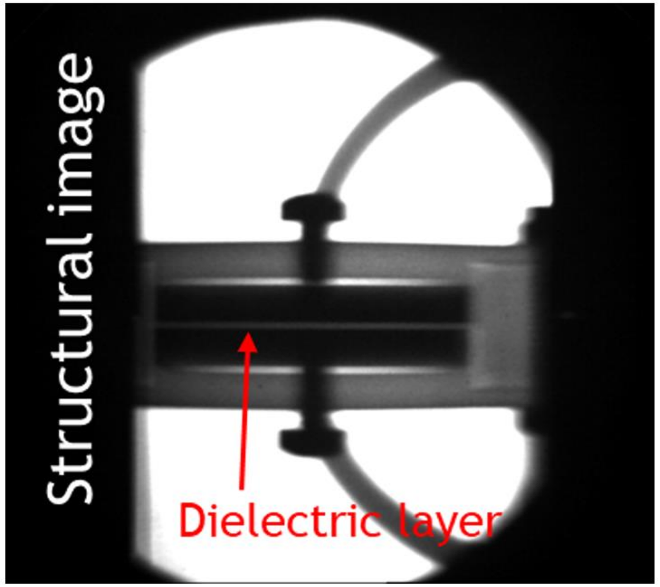
(Not drawn to scale)

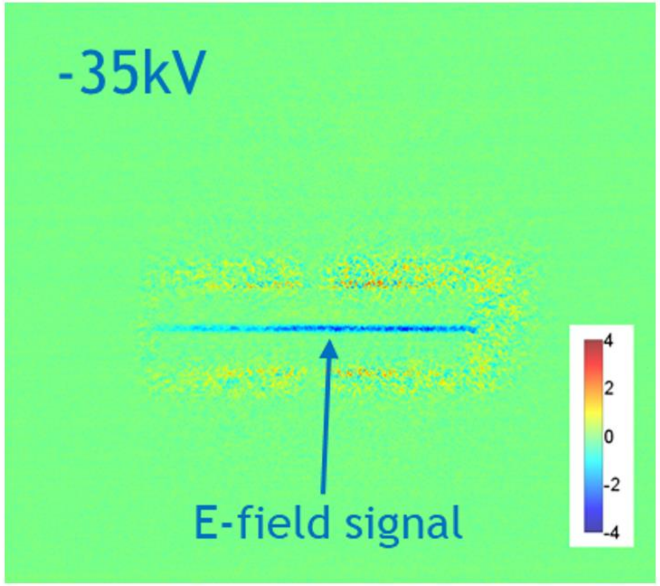


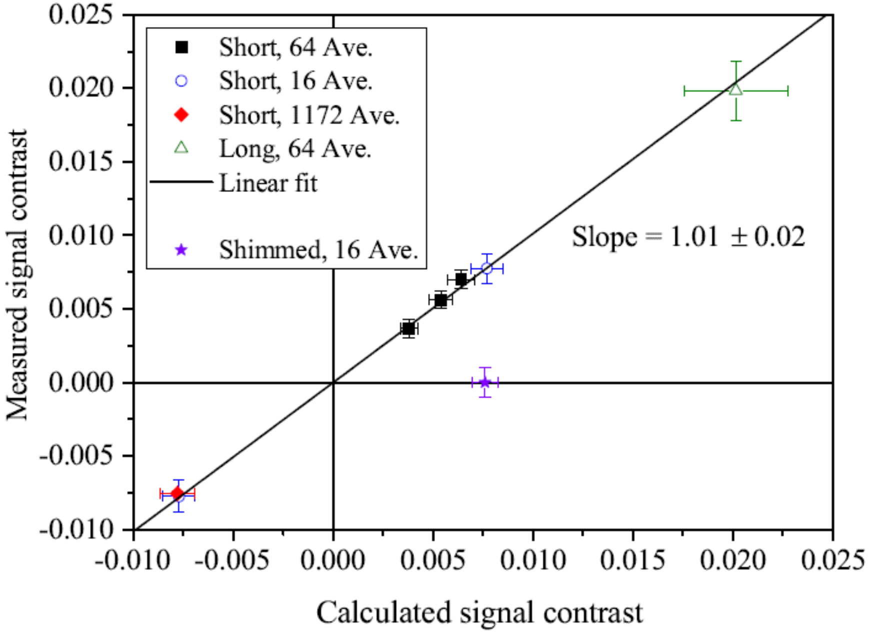


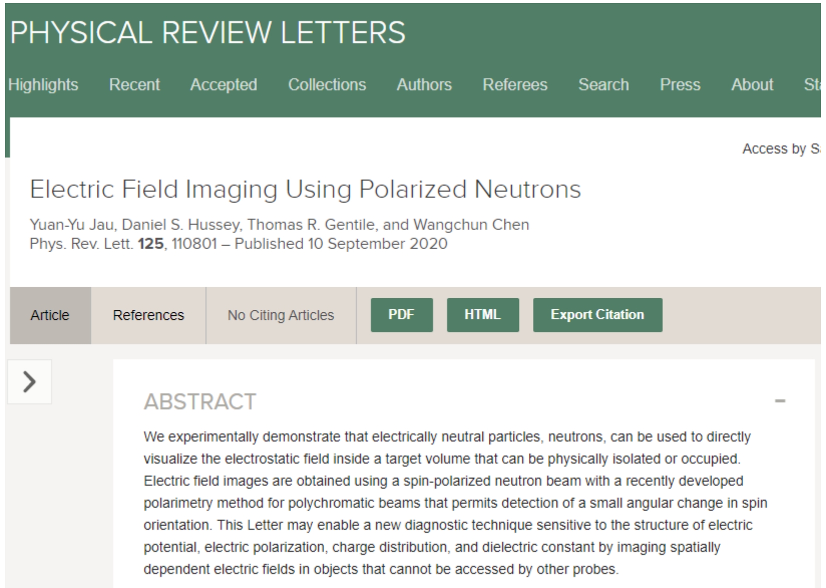


E-field imaging data





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Electric Field Imaging Using Polarized Neutrons

Yuan-Yu Jau, Daniel S. Hussey, Thomas R. Gentile, and Wangchun Chen

Phys. Rev. Lett. **125**, 110801 – Published 10 September 2020

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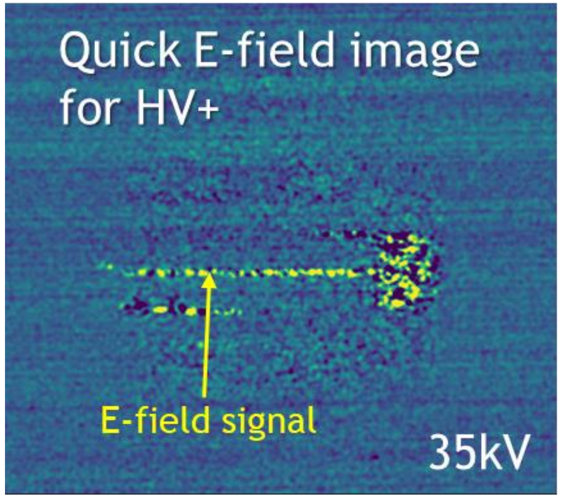
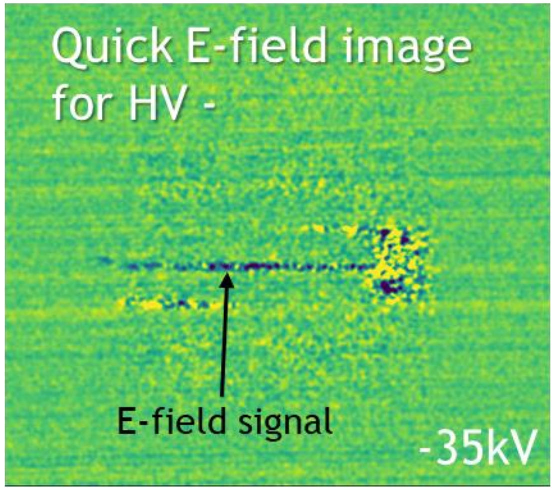
ABSTRACT

We experimentally demonstrate that electrically neutral particles, neutrons, can be used to directly visualize the electrostatic field inside a target volume that can be physically isolated or occupied. Electric field images are obtained using a spin-polarized neutron beam with a recently developed polarimetry method for polychromatic beams that permits detection of a small angular change in spin orientation. This Letter may enable a new diagnostic technique sensitive to the structure of electric potential, electric polarization, charge distribution, and dielectric constant by imaging spatially dependent electric fields in objects that cannot be accessed by other probes.





Summary and outlook

- We have demonstrated a simple experimental implementation using ^{3}He NSFs and spin-polarized neutrons for transverse polarization analysis with counting detection and imaging detection. For the future, this 3He NSF-based transverse polarization analysis may reduce the overall complexity of experimental implementation for applications requiring sensitive neutron polarimetry and improve the precision in fundamental science studies and polarized neutron imaging.
- We have demonstrated direct images of an electrostatic field in parallel plate capacitors using a polarized, polychromatic neutron beam. Our work may enable new diagnostic power of the structure of electric potential, electric polarization, charge distribution, and dielectric constant inside an investigated target by visualizing spatially dependent electric field from a distance.

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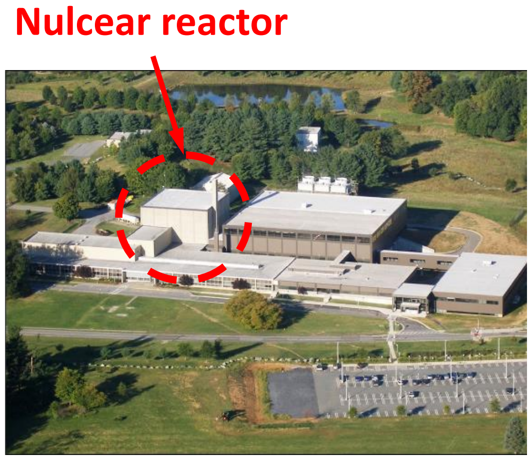

NCNR building @ NIST