Los Alamos NATIONAL LABORATORY

Demonstration of Sub-micron UCN Position Resolution using Room Temperature CMOS Sensor

Shanny Lin, Zhehui Wang, and UCNτ Collaboration (next slide)

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UCNτ Collaboration

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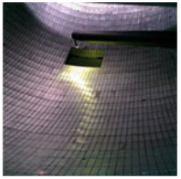
Research with Ultracold Neutrons (UCNs)

- Measurement of neutron lifetime
- Properties of neutron β-decay
- Quantum states of UCN and dark matter search
  - Increasing interest in using position sensitive measurements of UCN
  - Measurements require a spatial resolution of less than 10 μm, and 1 μm or less is highly desired
- Focus: Sub-micron position resolution in UCN detection using deep learning and a detector simulation framework Allpix Squared

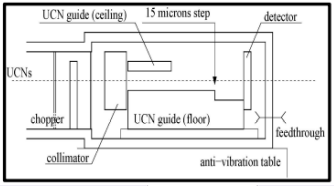
LANL Experiments

UCNB
β-decay

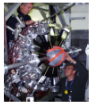
UCNtau
Neutron Lifetime

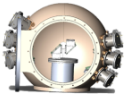


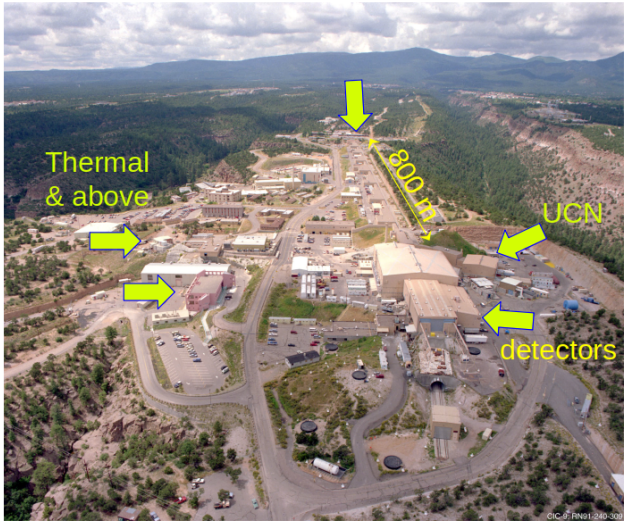
UCN-Q
Quantum Gravity



Los Alamos Neutron Science Center (LANSCE)

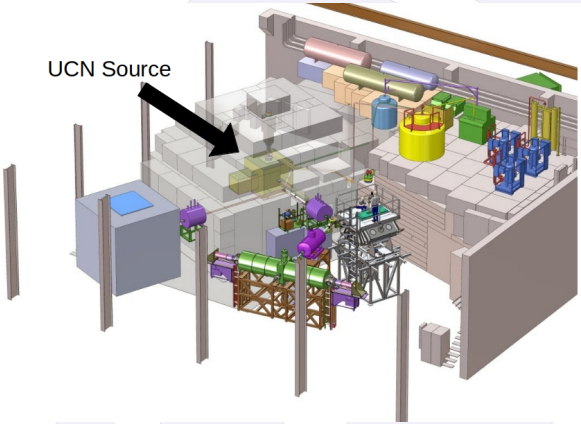




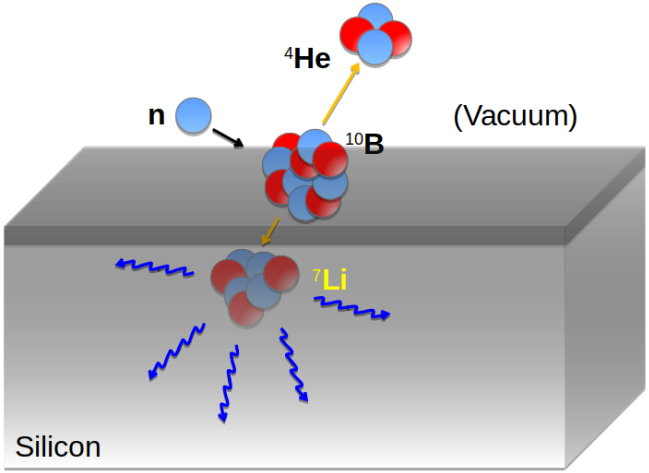


LANL UCN Science

- Neutron EDM
- Neutron β-decay
- Neutron lifetime
- Dark matter
- . . .



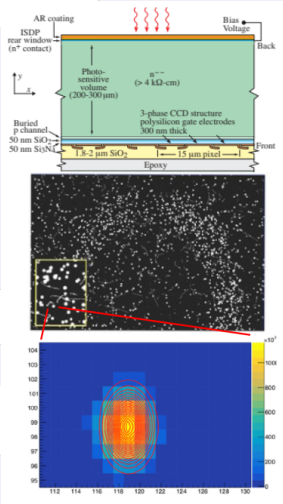
Solid State Detector using ^{10}B



Towards Sub-micron Position Resolution

Detection using bCCDs[1]

- Scientific grade boron-coated CCD (bCCD) back-illuminated sensor
- 250 μm thick, fully depleted, high-resistivity silicon
- 15 μm $\times$ 15 μm pixel size
- Cooled to 140 K to suppress dark current
- Built by Lawrence Berkeley National Laboratory and *extensively characterized* by FermiLab for Dark Energy Camera (DECam) project



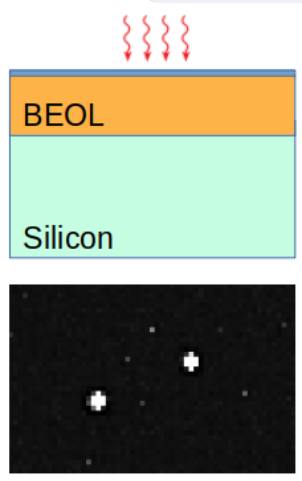
[1] K. Kuk et al. "Projection imaging with ultracold neutrons". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1003 (2021), p. 165306. ISSN: 0168-9002.

UCN Detection using CMOS

- Less costly than scientific grade CCDs
- Can be operated at room temperature
- Smaller pixel size

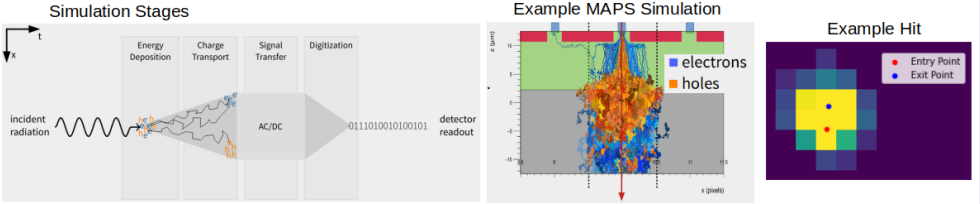
DMM 27UJ003-ML, The Imaging Source

- Front-illuminated camera
- 1.67 μm $\times$ 1.67 μm pixel size
- Known detector parameters are extracted from the datasheet



Synthetic Data Generation using Allpix Squared[3]

- An open source framework for particle detection in silicon sensors
- Implements end-to-end Monte Carlo simulations and stores the Monte Carlo truth information from initial particle hit to generated image



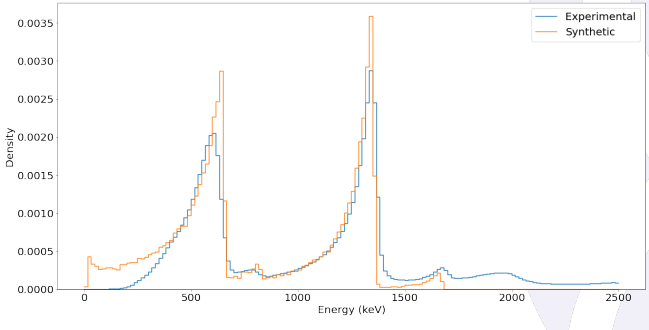
[Source: Indico CERN[2]]

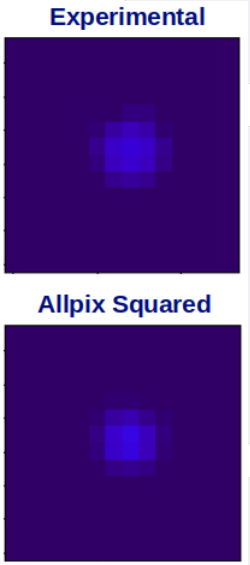
[2] URL: https://indico.cern.ch/event/829863/contributions/5054267/attachments/2567656/4429767/2022-12-15-PIXEL-APSQ.pdf.

[3] S. Spannagel et al. "Allpix2: A modular simulation framework for silicon detectors". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 901 (2018), pp. 164–172. DOI: 10.1016/j.nima.2018.06.020. URL: https://doi.org/10.1016%2Fj.nima.2018.06.020.

Experimental vs. Synthetic: bCCD

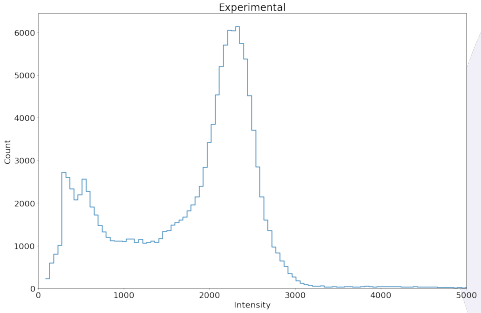
- Fully characterized by FermiLab

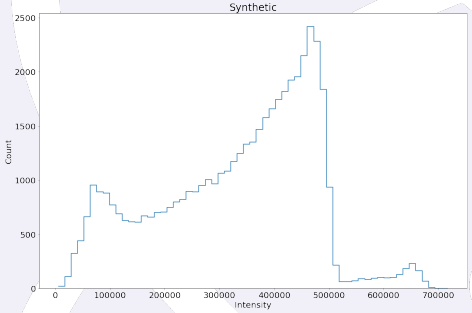




Experimental vs. Synthetic: DMM CMOS

- Not fully characterized. Known detector parameters are extracted from the sensor datasheet, while unknown parameters need to be tuned.





- Similar energy spectrums. Further parameter tuning needed for more accurate modeling.

What is Deep Learning?

Artificial Intelligence:

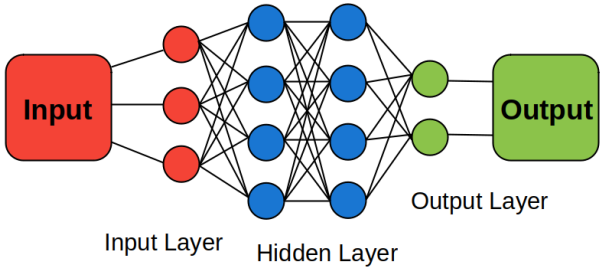
Engineering intelligent machines/programs that aims to mimic human behavior.

Machine Learning:

Algorithms that learn and make predictions using pattern recognition.

Deep Learning:

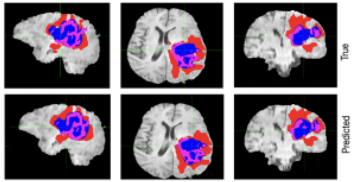
Subfield of machine learning that utilizes multilayered neural networks.



Deep Learning Applications

Virtual Assistants

Robotics



Medical Imaging[4]

Deep Learning for UCN Position Resolution

- Learn underlying detector physics by learning a mapping from input hit images to ground-truth labels such as hit position

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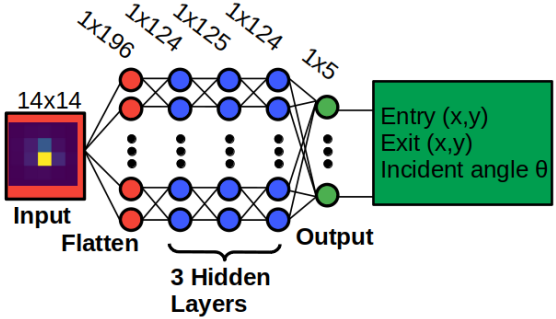
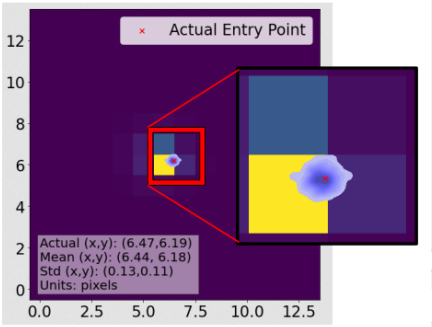
[4] Mehmet Akif Cifci, Sadiq Hussain, and Peren Jerfi Canatalay. "Hybrid Deep Learning Approach for Accurate Tumor Detection in Medical Imaging Data". In: *Diagnostics* 13.6 (2023), p. 1025

Predicting UCN Hit Position[5]

- Generated synthetic dataset consisting of ∼50,000 hit images and corresponding ground-truth labels. Split into 60% training, 20% validation, and 20% testing.
- *Note:* 1 pixel = 1.67 μm





[5] Xin Yue et al. "Ultrafast CMOS image sensors and data-enabled super-resolution for multimodal radiographic imaging and tomography". In: *arXiv preprint arXiv:2301.11865* (2023).

Overall Model Performance

- Kernel density estimate mean and standard deviation computed for each test sample. Used to compute deviation between predicted and true values.
- Achieved *sub-micron* position resolution in predicting UCN hit position on the synthetic dataset
- *Note:* 1 pixel = 1.67 μm

Output Label	$\frac{1}{N}\sum_N \lvert\hat{x}_n - x_n\rvert$	$\frac{1}{N}\sum_N \hat{\sigma}_n$
Entry x (pixels)	0.13	0.12
Entry y (pixels)	0.13	0.11
Exit x (pixels)	0.17	0.11
Exit y (pixels)	0.18	0.10
θ (degrees)	4.48	3.21

Summary

- UCN detection method using solid state detectors, i.e., boron-coated CCD and CMOS detectors
- Experimental hit images are readily available, while the ground-truth hit position is unknown
- Allpix Squared leveraged to generate synthetic hit images with corresponding ground-truth labels
- Deep learning is used to learn underlying detector physics by learning a mapping from input images to ground-truth labels
- FCNN prediction achieved *sub-micron* position resolution

Thank you!

Questions?