Quenching Factor Measurements for Germanium Detectors at TUNL

L. Li, B. Cabrera-Palmer, C. Awe, S. Hedges and P.S. Barbeau

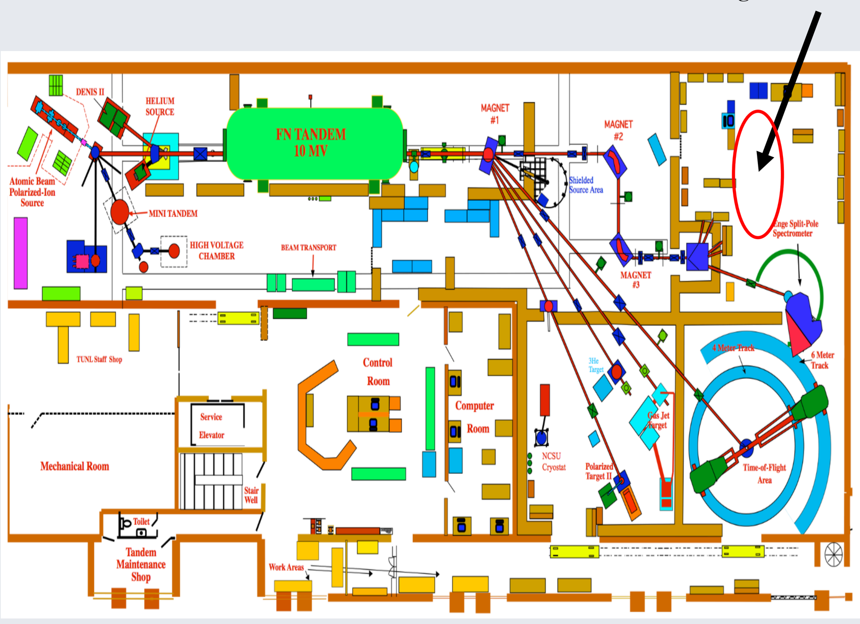
Introduction

The Coherent Elastic Neutrino-Nucleus Scattering has been observed by the COHERENT collaboration using a 14.6-kg CsI[Na] scintillator at Oak Ridge National Laboratory [5]. This indicates a new way to build a compact neutrino detector and unlocks new channels to test the Standard Model. One challenge is to understand the neutrino-induced low energy nuclear recoils. It is commonly known that the signals from nuclear recoils can be quenched in many types of detectors, resulting in less light or ionization. This phenomenon is referred to as the "quenching factor". It is defined as the ratio of the signal yield from the nuclear recoils to the signal yield from comparable electron recoils with the same energy. The quenching factor highly depends on the detector materials, so different detectors require their own quenching factor measurements. The next step for the COHERENT experiment[3] is to use different nuclear targets e.g. Ar and Ge. Aside from the COHERENT experiment, many dark matter experiments (CoGeNT[1], LUX[2], and etc.) trying to directly detect weakly interacting massive particles (WIMPs) also attempt to observe elastic scatterings between WIMPs and nuclei. In order to calibrate these detectors, a neutron beam is usually used to generate nuclear recoil signals; A new beam line has been built at TUNL in order to provide systematic and precise quenching factor measurements.

Facilities

The new beam line is located in the Target Room 4 and several experiments have be successfully done on this beam line with different neutron energies. The room has enough space for semi-permanent experiment installations.

Target Room 4



Tandem Facility

The new beam line (45° left of 70/70 magnet)

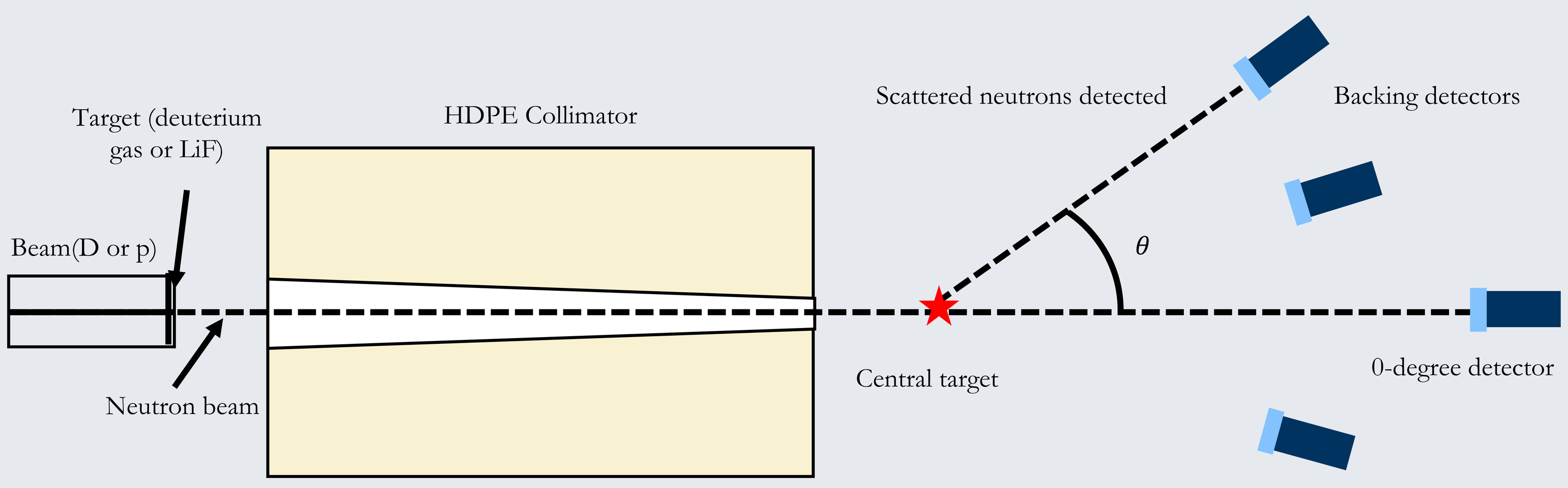
Beam: The tandem van de Graaff accelerator is capable of accelerating different particles (proton, deuteron, triton, helium and heavier ions) up to 10 MV. It can run in DC mode or pulsed mode. In pulsed mode, the period can be simply adjusted to 400 ns, 800 ns or even 1600 ns. The current can go as high as 800 nA in pulsed mode.
Neutron Production: Depending on the energy scale expected to see in the actual experiments, $D + D \rightarrow {}^3He + n$ reaction can produce few MeV neutrons. ${}^7Li(p,n)\ {}^7Be$ reaction can produce few hundred keV neutrons. Switching between the deuterium gas cell and LiF target is straightforward.
Neutron Collimation: The neutron beam is square collimated and is about 3.2 cm x 3.2 cm.
Neutron Energy and Flux: The neutron energy is calculated from the time of flight between gammas and neutrons. The flux is estimated from the fast neutron capture in the ${}^3He$ gas detector and is about $122\ cm^{-2}s^{-1}$ (500 nA on target with 5 um LiF target). The flux can be increased by a factor of 100 if using the deuterium gas cell.

Experimental Set Up

Low energy nuclear recoils can be mimicked by elastic scatterings with neutrons. The recoil energy is determined once the incident neutron energy and the scattering angle of the outgoing neutron are known [4]:

$$E_{recoil} = 2E_n \frac{M_n^2}{(M_n + M_T)^2} \left(\frac{M_T}{M_n} + \sin^2\theta - cos\theta \sqrt{\left(\frac{M_T}{M_n}\right)^2 - \sin^2\theta} \right)$$

Here E_n is the incident neutron energy, M_n and M_T are the neutron mass and target nucleus mass, and θ is the scattering angle of the outgoing neutron.

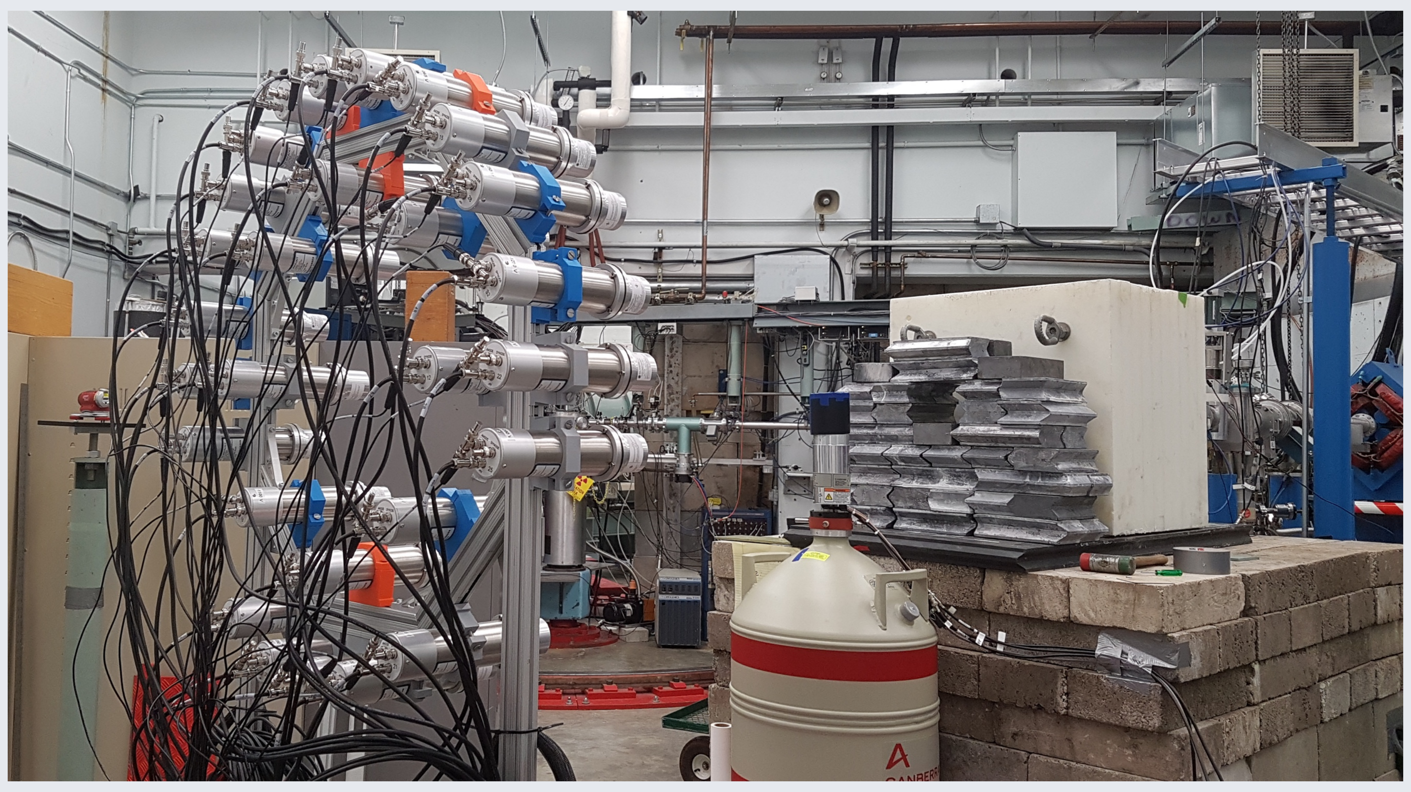


A schematic diagram of QF experiments (beam direction: left to right)

The central target is the detector to be calibrated. Because fast neutrons incident into the germanium crystal can cause radiation damage, a ring like configuration was set up to achieve enough statistics for one scattering angle in a safe time period (~20 hours). 19 detectors were mounted outside the octagon (outer ring) and 8 were mounted inside the octagon (inner ring). This allowed us to tag neutrons being scattered at two different angles at the same time. The octagon frame can be moved forward and backward. Therefore, we have the ability to further change the nuclear recoil energy to be calibrated. Furthermore, the backing detectors are liquid scintillators which are capable of both fast timing and pulse shape discrimination. This can significantly reduce the room background and the beam related background.

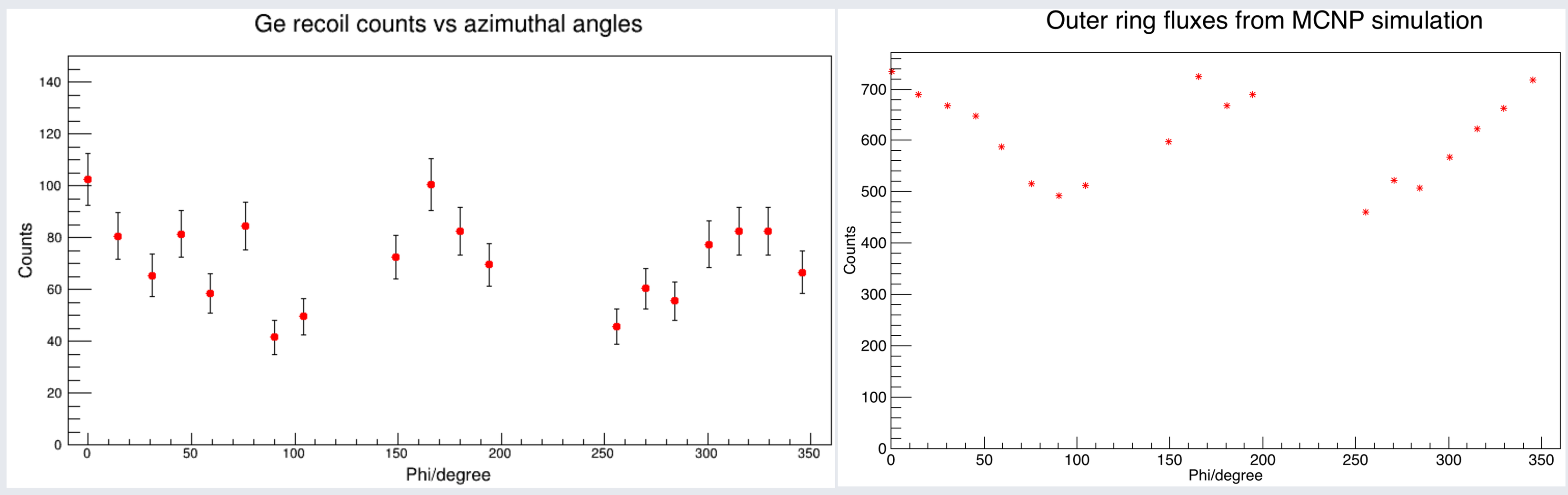
References

[1] C.E. Aalseth, et al., CoGeNT: A Search for Low-Mass Dark Matter using p-type Point Contact Germanium Detectors, arXiv:1208.5737 [astro-ph.CO]



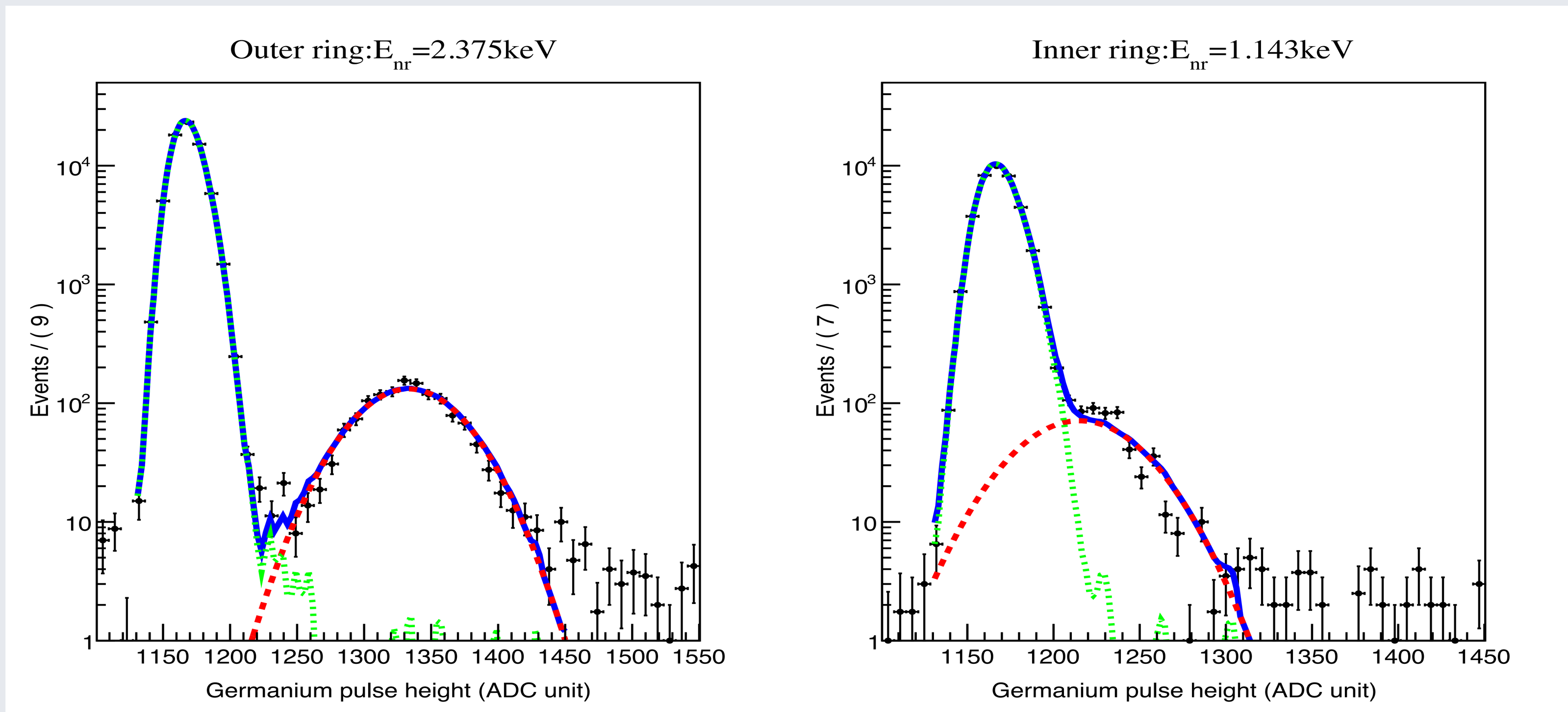
The actual set up (germanium QF)

Preliminary Results



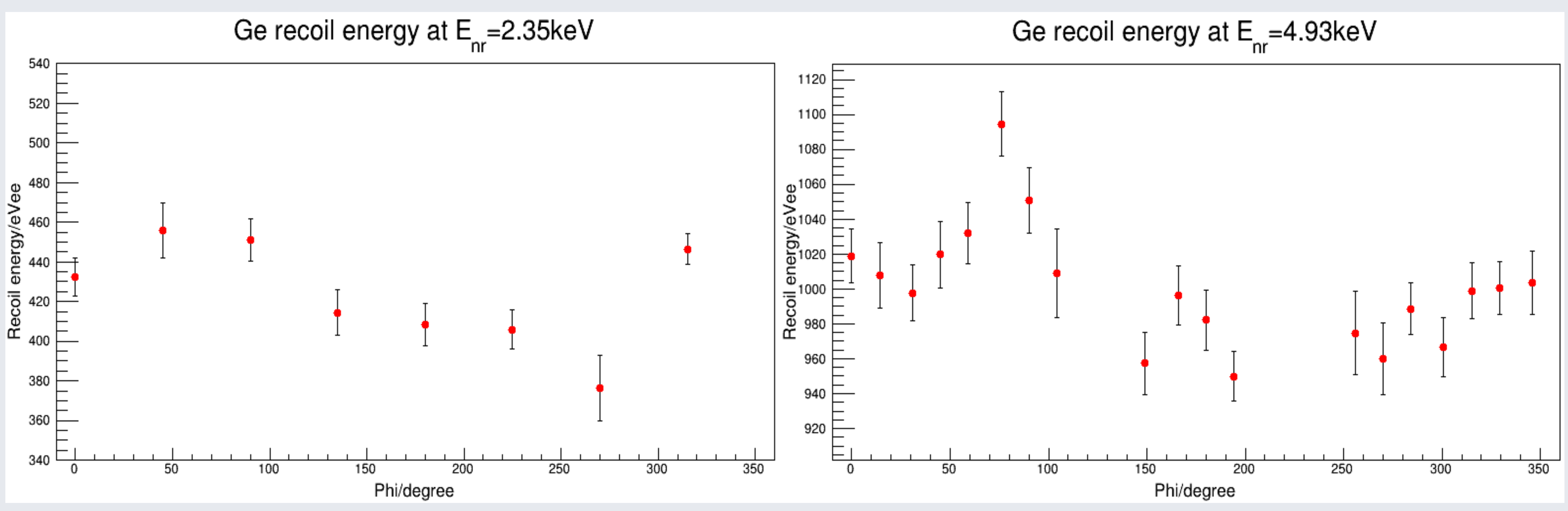
Left: nuclear recoil events seen in the data. Right: a MCNP simulation of the setup.

Due to the aluminum housing around the Ge, the Ge nuclear recoil counts depends on the azimuthal angle where the backing detector is at. The MCNP simulation shows the agreement with data.



The combined energy spectrum of the germanium detector (black dots) when observing a neutron in the outer ring (left) or in the inner ring (right). Green dashed line: background fit. Red dashed line: Gaussian signal fit. Blue solid line: overall fit.

We managed to isolate the Ge signals from the random coincidence. The width of the noise pedestal (greed dashed line) highly depends on the intrinsic electronic noise of the Ge detector. This limits the lowest nuclear recoil energy we can probe.



At higher recoil energies, the nuclear recoil energy from each backing detector is able to be shown. On average, the inner ring detectors saw 424 eV and outer ring detectors saw 1001 eV. This translates to a quenching factor of 18.0% and 20.3% for 2.35 keVnr and 4.93 keVnr. A total of five measurements covered 10 points in the range from 0.8 keVnr to 5 keVnr. The analysis is undergoing, and the result will help future COHERENT and dark matter experiments using Ge detectors.

Acknowledgements

I would like to thank Ron Malone of Duke University providing the beam scanner to measure the neutron collimation and Jonathan Mueller of NC State University providing the liquid scintillators and the high voltage power supply.

References

[2] Akerib, D.; et al. (March 2013). "The Large Underground Xenon (LUX) experiment". Nuclear Instruments and Methods in Physics Research A. 704: 111–126.
[3] COHERENT Collaboration, The COHERENT Experiment at the Spallation Neutron Source, arXiv:1509.08702 [physics.ins-det]
[4] G.C. Rich et al., High-precision measurements of quenching factors for low-energy nuclear recoils at TUNL.
[5] D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

Duke UNIVERSITY