Calibrating eV-Sensitive Detectors at the Université de Montréal Tandem Accelerator

Émile Michaud – François de Brienne

8 juin/june 8 2022

Ionization yield

Ionization yield (Y) : ratio of the number of electron-hole pairs produced by a nuclear recoil over an electronic recoil

$$Y = \frac{Q_{nr}}{Q_{er}}$$

For the same amount of energy deposited, a particle that hits the nucleus (E_{nr}) will excite fewer e^-h^+ pairs than if it hits the electron (E_{er})

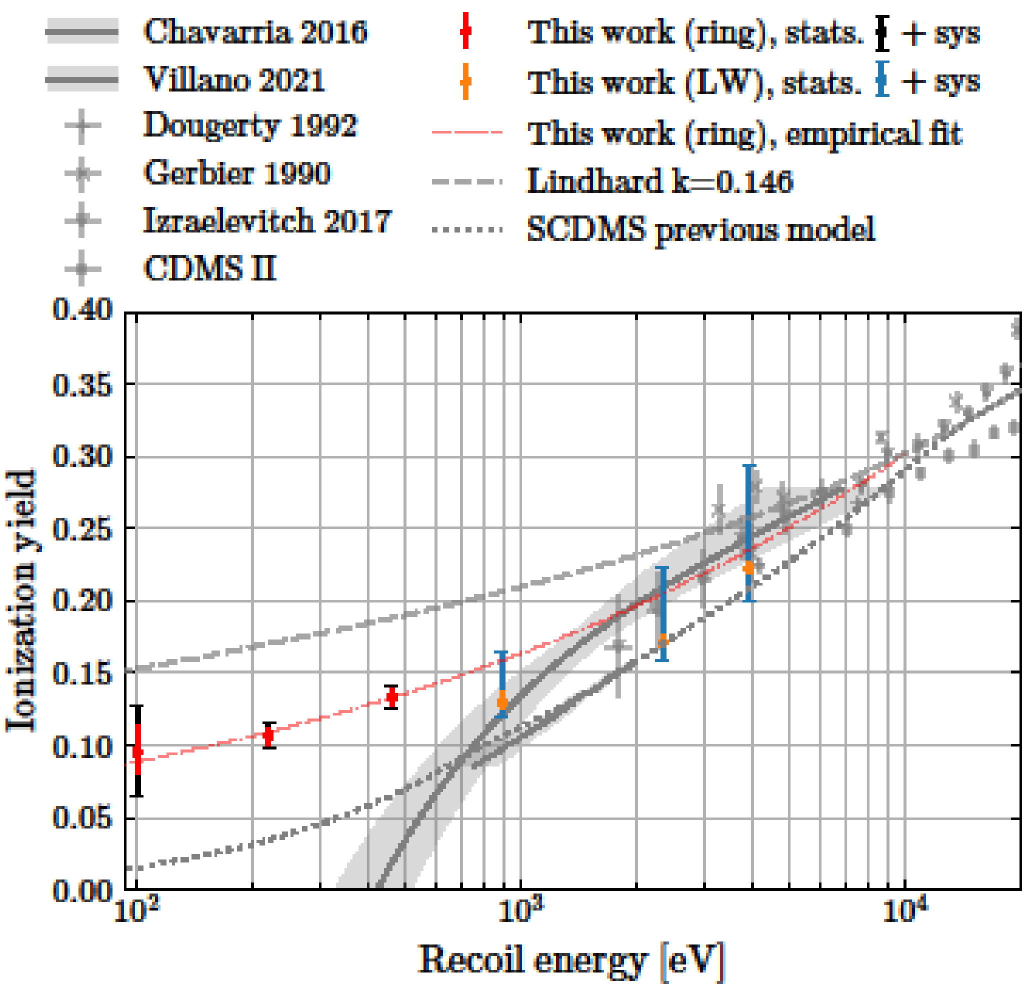
SuperCDMS (Cryogenic Dark Matter Search) detectors detect low mass WIMPS which are expected to interact via nuclear recoil and deposit $E_{nr} \leq 1$ keV

Unreliable yield (different from Lindhard) below ∼ 3 keV :

- -Is the yield speed dependent?
- -Migdal effect (Inelastic scattering on atoms)?

In the future, we want to measure the yield at lower energies (< 100 eV) and with slower neutrons (4.8 keV instead of 56 keV) in Si and Ge

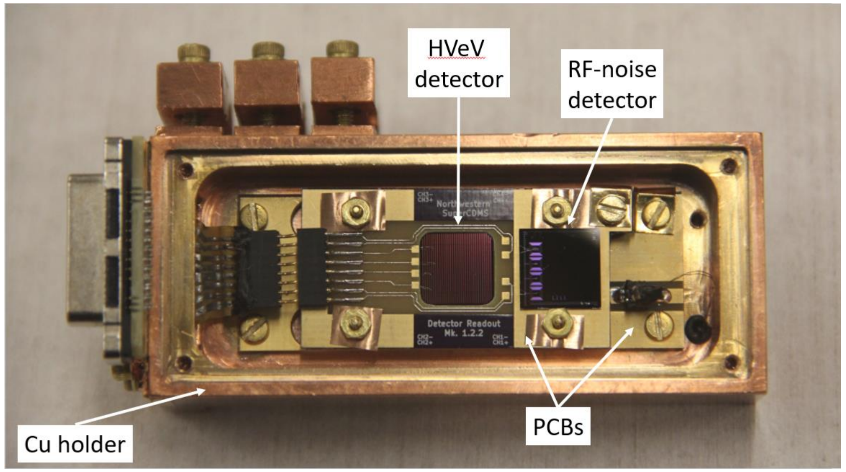
Ionization yield in silicon for energies between 100 eV and 11 keV



See Tyler Reynolds' talk for more details (Monday 6th, June 11h45 : Technical Sessions / Particle Physics)

J. Lindhard, et al., *Integral equations governing radiation effects (notes on atomic collisions, III)*. Mat. Fys. Medd. Dan. Vid. Sels., 33, 10 (1963).

SuperCDMS detectors (HVeV)



Incoming particles hit the detector which produces electron-hole pairs and recoil phonons

Drifting charge carriers produce additional phonons via the Neganov-Trofimov-Luke (NTL) effect because of the applied voltage (~ 100 V)

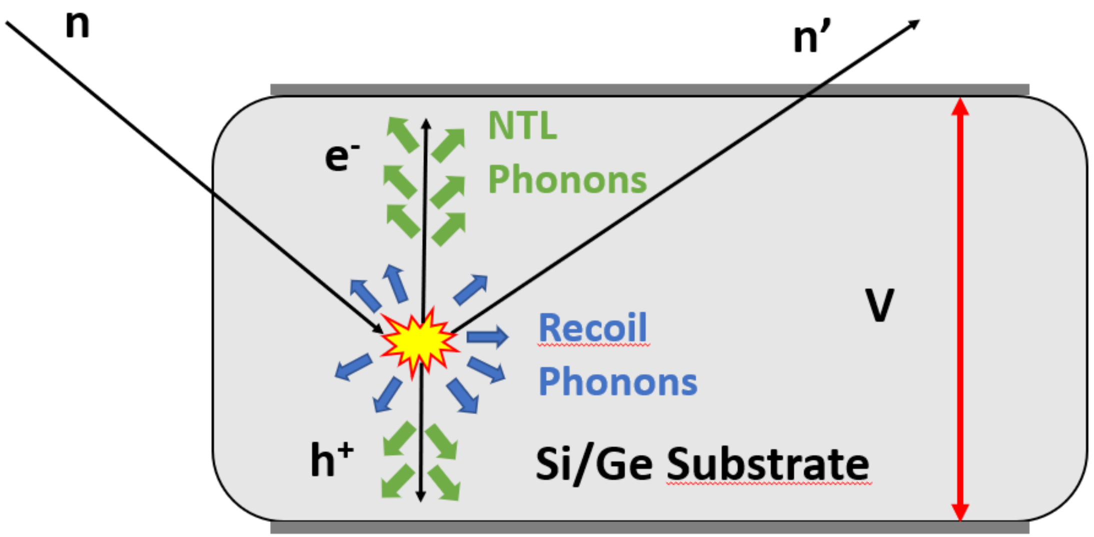
Total phonon energy : $E_{ph} = E_r + n_{eh} \cdot e \cdot V$

where E_r is recoil energy, n_{eh} the number of electron-hole pairs produced, e the electric charge and V the voltage.

$$n_{eh} = Y \frac{E_r}{\epsilon_{eh}}$$

ε_{eh} is the average energy needed to excite one electron-hole pair (3.8 eV in Si at mK temperature)

R. Agnese et al. : *First dark matter constraints from a SuperCDMS single-charge sensitive detector*. Phys. Rev. Lett.,121:051301, Aug 2018.



Schematic of the phonon production in the HVeV detectors

Single $e^- h^+$ pair sensitivity

Calibration data with 1.95 eV photons (635 nm laser pulsed) and 100 V bias

1 g silicon detector

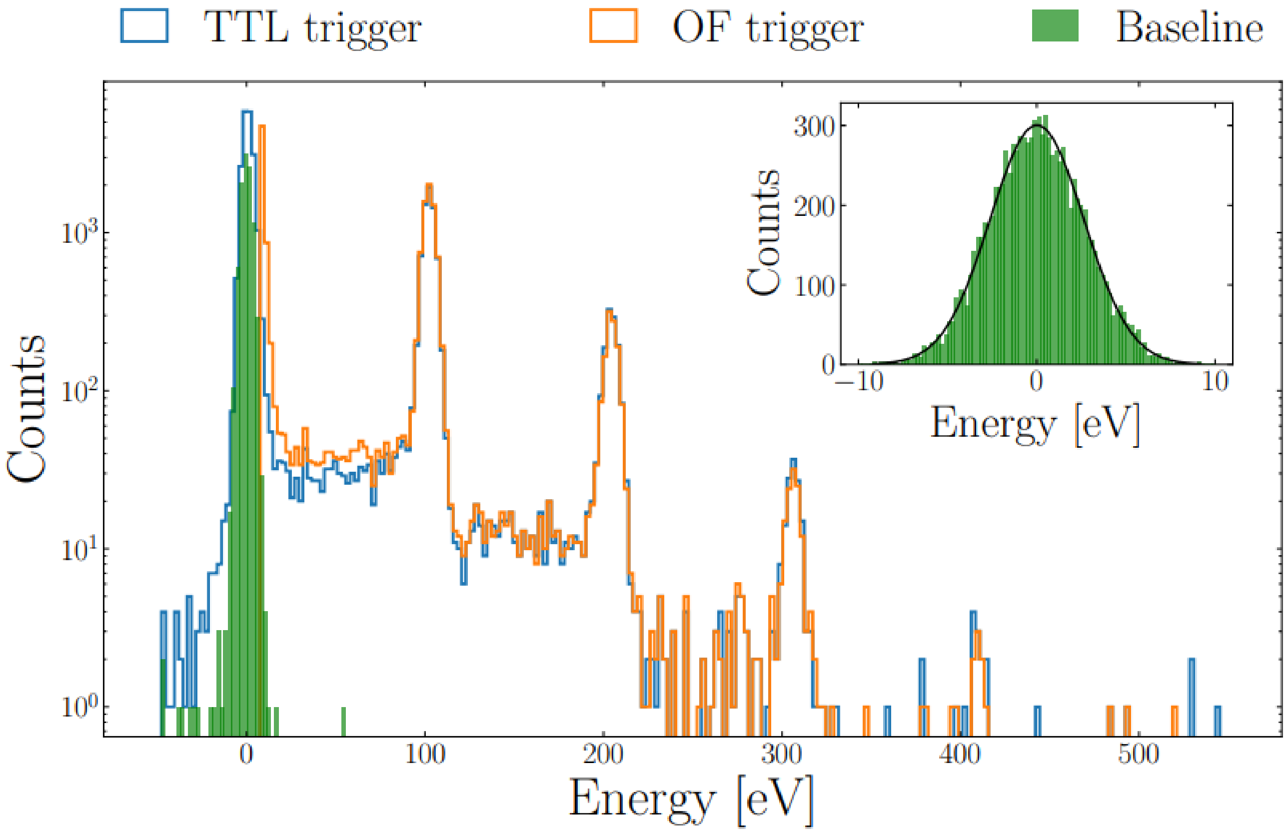
Crystal dimensions : 1 cm x 1 cm x 4 mm

Detector cooled down to ~ 50 mK

Able to measure 1 e-h+ pair in Si crystal

By applying high voltage we can obtain eV resolution thus the name : High Voltage eV (HVeV)

$$E_{ph} = E_r + n_{eh} \cdot e \cdot V$$



R.Ren et al. : *Design and characterization of a phonon-mediated cryogenic particle detector with an eV-scale threshold and 100 keV-scale dynamic range*. Phys. Rev. D 104, 032010 (2021).

Experimental Setup

Measurement performed with the UdeM (Université de Montréal)'s Tandem accelerator.

We produced and selected 1.566 MeV protons (~ 1 keV energy resolution)

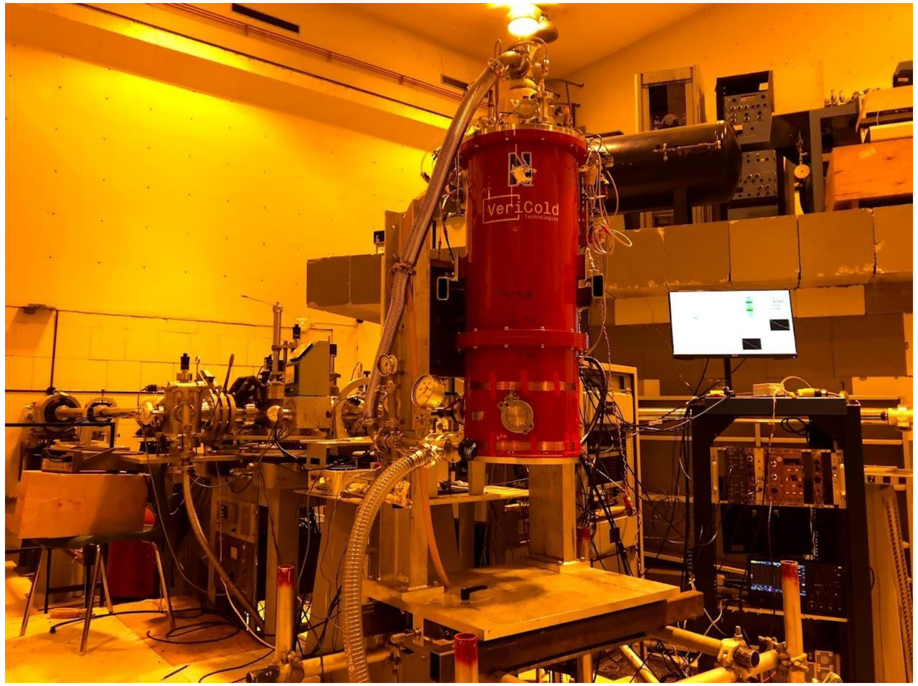
beam current of ~ 1.7 μA

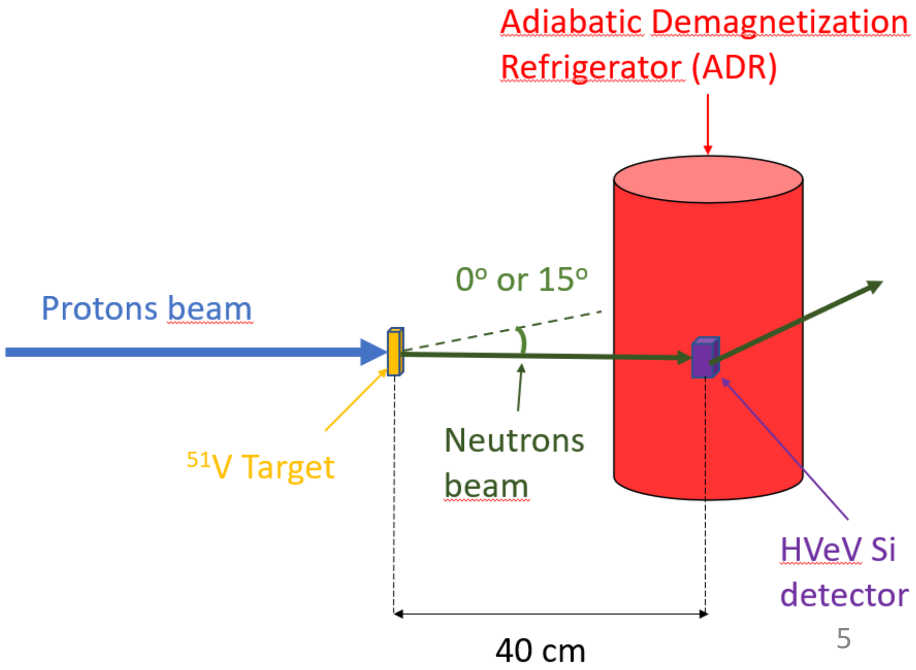
Proton beam directed to a ^{51}V target → monoenergetic 4.8 keV neutrons via the reaction ^{51}V(p,n)^{51}Cr [1] (≤ 1 keV energy resolution)

The neutrons then scattered on the HVeV Si detector, which was aligned inside an Adiabatic Demagnetization Refrigerator (ADR)

We took background and beam data at both 0 V and 100 V

Goal : measure the background/neutron rate for upcoming ionization yield measurements (Is UdeM a good facility?)





Event rate

We applied some cuts :

- at 0V : χ^2 time domain vs energy cut (to remove events with pulse shape too different from expected signal)
- at 100 V : dt > 0.004 s (dt is time difference between two closest pulses) to remove short burst events
- Energy range cut (we select events between 250 eV and 600 eV at 0 V and between 900 eV and 2 keV at 100 V)

The lower limit is to remove events with lot of noise. The upper limit is ~ endpoint of 4.8 keV neutrons on ^{28}Si at 0 V and 100 V respectively

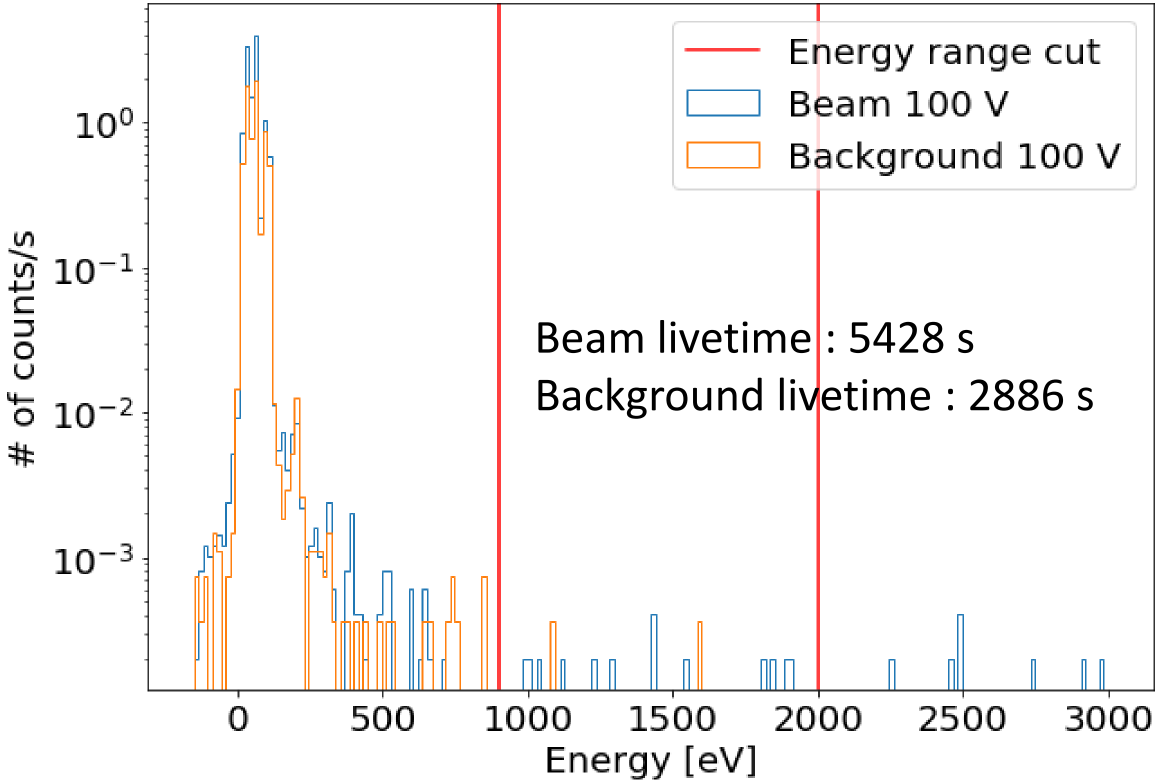
We measured the event rate with the beam on and subtracted the background rate to get the excess rate

We expect 13 neutrons/h (or 0.0036 neutrons/s) in the energy range based on previous run, beam current, distance between detector and target and simulations

Excess at :

- 0 V : 0.0041 ± 0.0016 events/s
- 100 V : 0.0027 ± 0.0009 events/s

Measured excess rate is consistent with the expected neutron rate. Excess events probably neutrons. For our yield measurement, neutrons will deposit energy well above peak at ~ 100 eV



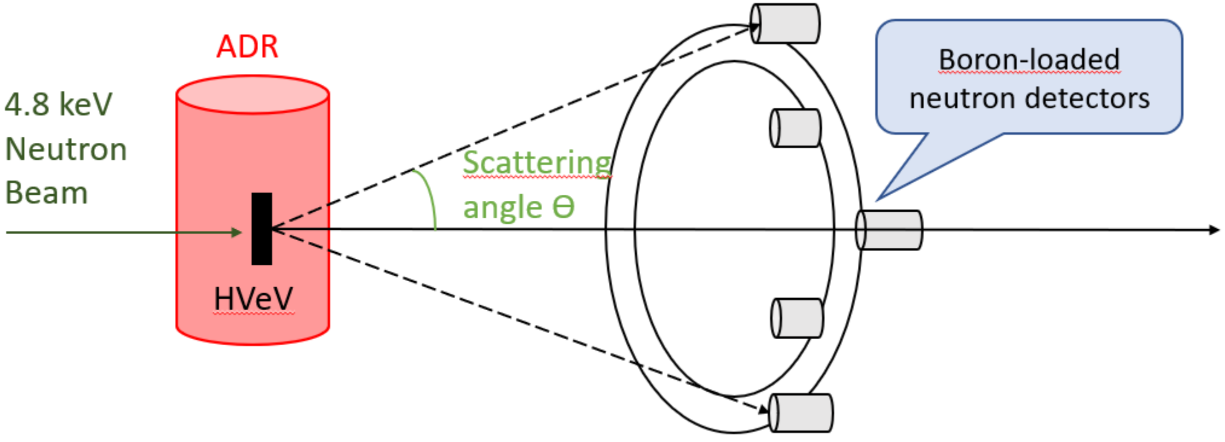
100 V background and beam energy spectra after the cuts

Next Steps

In the future, we want to measure the ioniziation yield for recoils below 100 eV in Ge and Si with 4.8 keV neutrons. Neutron rate high enough at UdeM to do so when combined with long exposure

Boron-loaded liquid scintillators with pulse shape discrimination for thermal neutrons under construction

Boron-loaded scintillators are able to detect low energy neutrons by measuring the high energy alpha particle from the reaction $^{10}B(n,\alpha)^{7}Li$



$$E_R = 2E_n \frac{m_n m_T}{(m_n + m_T)^2}(1 - \cos\theta)$$

E_n : neutron energy
m_n : neutron mass
m_T : target mass (Si)

The incoming neutrons scatter on the HVeV detector and are then captured by the neutron detectors backing array

We then compare the energy measured by the HVeV detector (E_{ph}) to the expected recoil energy (E_r) given by the scattering angle ϴ to extract the yield

Summary

We used a neutron beam of 4.8 keV at Université de Montréal on our HVeV superCDMS detector with single electron-hole pair sensitivity as a test run to measure the neutron and background rate.

We plan on upgrading the facility with boron-loaded liquid scintillators + PMTs able to measure neutron recoil energies below 100 eV.

Once we upgrade the laboratory, we plan on measuring the ionization yield in silicon and germanium for recoil energies below 100 eV

Merci / Thank you!