The VIEnna Workshop on Simulations 2024

Simulations of low energy events for DAMIC-M

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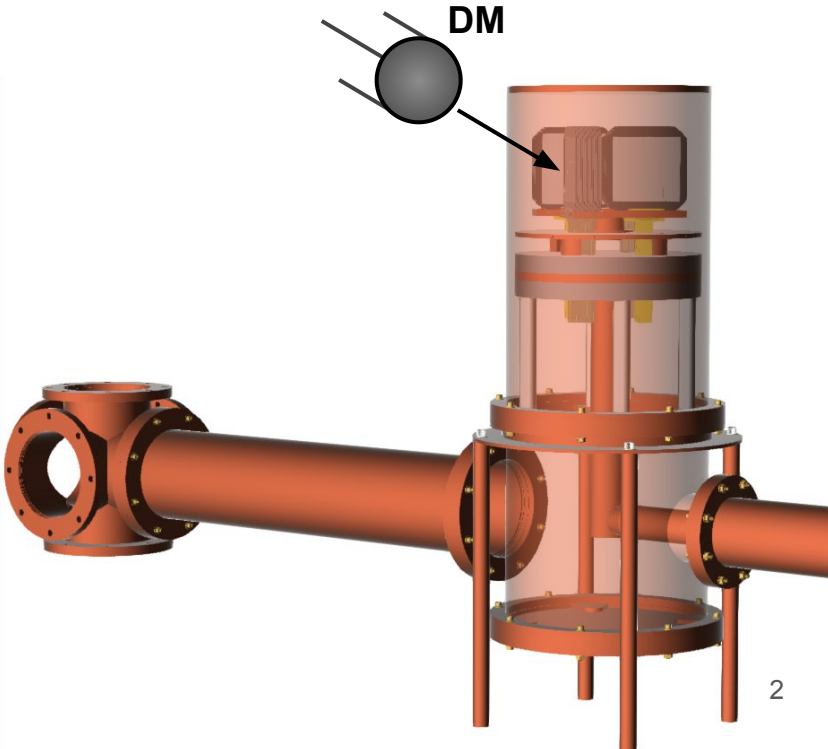
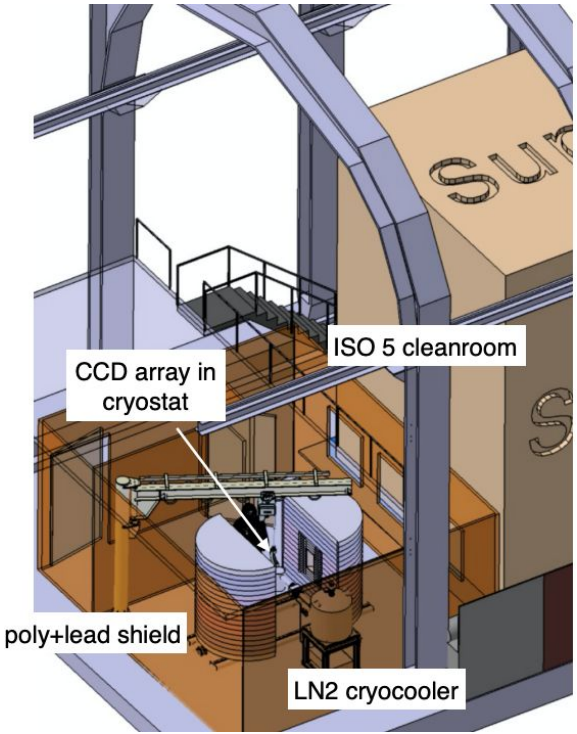
Outline

- The DAMIC-M experiment:
  - Working principle
  - Status of the experiment
- DAMIC-M simulation software
- Calibration measurements & comparison with simulations:
  - the Compton measurement
  - the Photo-neutron measurement



DArk Matter In CCDs at Modane



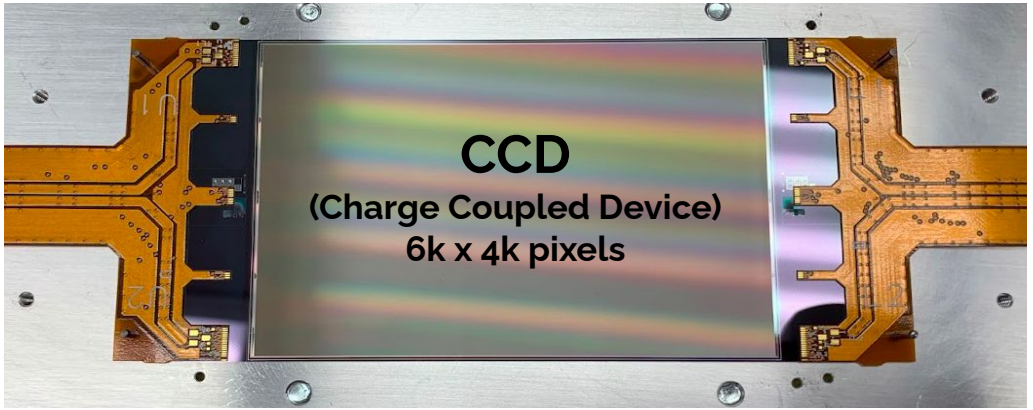
DAMIC-M@LSM
(conceptual design)

DAMIC experiment
at SNOLAB (Canada)

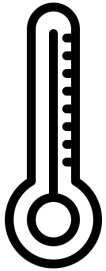
DAMIC-M experiment
at LSM (France)

2017 → 2025

Aim: detect **Light DM** (WIMP, Hidden Sector) signals via interaction with Si nucleus or e- in the bulk of **CCDs**

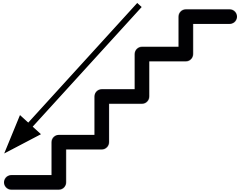


DAMIC-M detector features



~100 K

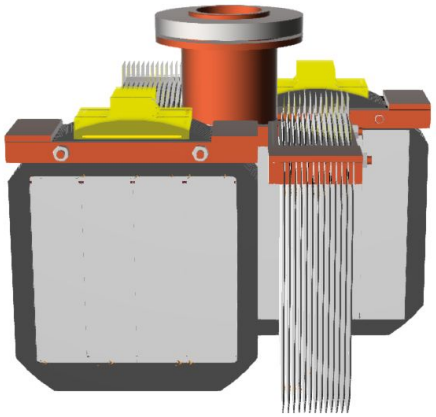
Temperature



1 d.r.u*

Background Level
< 1 d.r.u

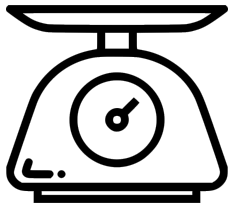
DAMIC-M CCD stack



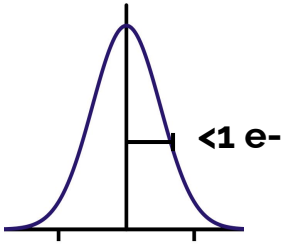
~200 SKIPPER CCDs

6000 pix x 1500 pix

~1 kg



Sensitive Mass



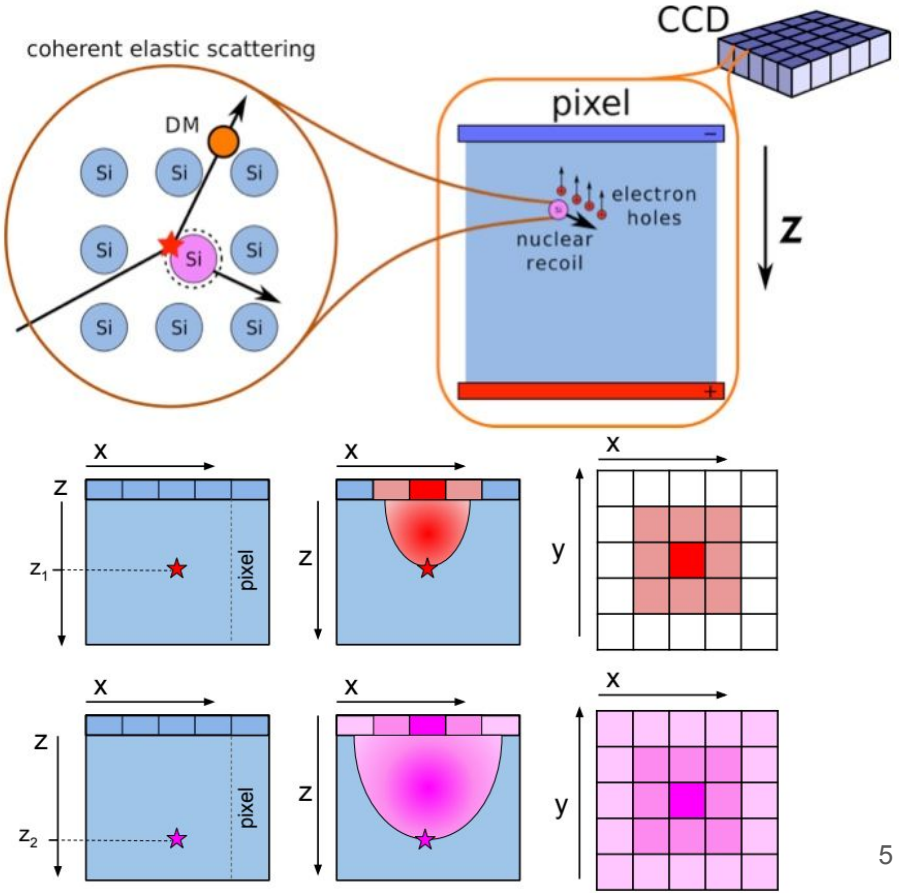
<1 e-

Resolution (readout noise)
< 1 e-

(*) 1 d.r.u = 1 decay/kg/day/keV

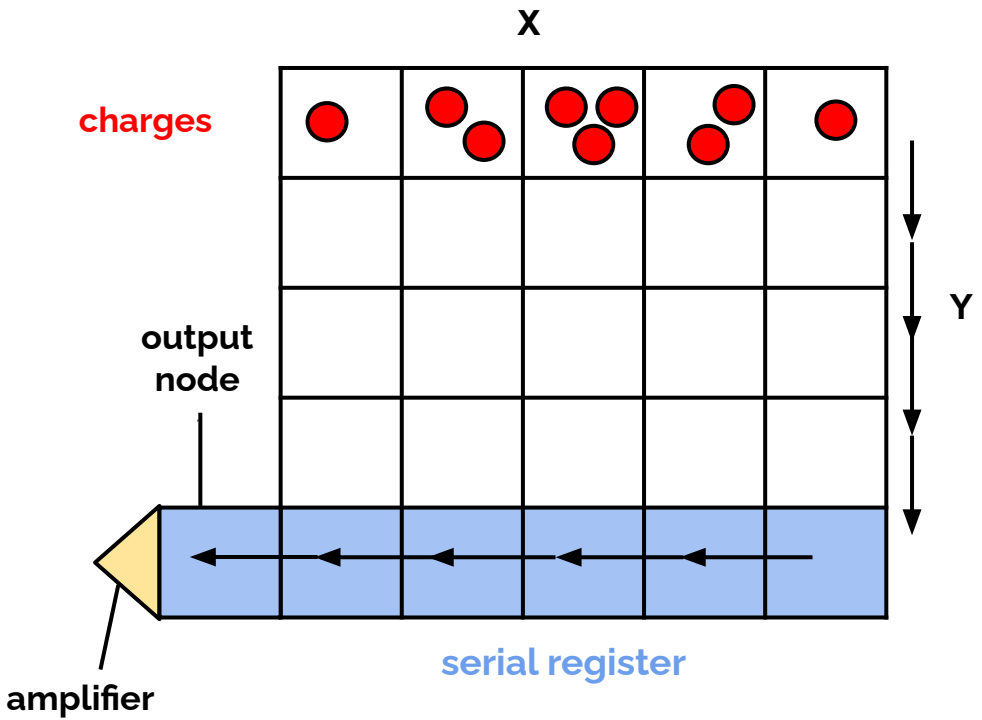
CCDs operation and 3D reconstruction

- CCD: n-type silicon with buried p-channel, thickness = 0.675 mm, 6k x 1.5k pixels, pixel: 15 um x 15 um
- Creation of a depletion region (active volume) in the CCD (full depletion)
- DM interaction causes creation of e-/h pair (3.77 eV required on average) in depletion region
- **3D reconstruction:**
  - z position: diffusion of charges during drift
  - x-y position: Precise spatial resolution (0.015 mm x 0.015 mm pixels)



CCD readout

- charges in a row moved in the following row
- charges in serial register moved pixels by pixels in X direction
- charges in output node read by amplifier
- In DAMIC-M: Skipper Amplifier for sub-electron readout noise (single e- resolution)



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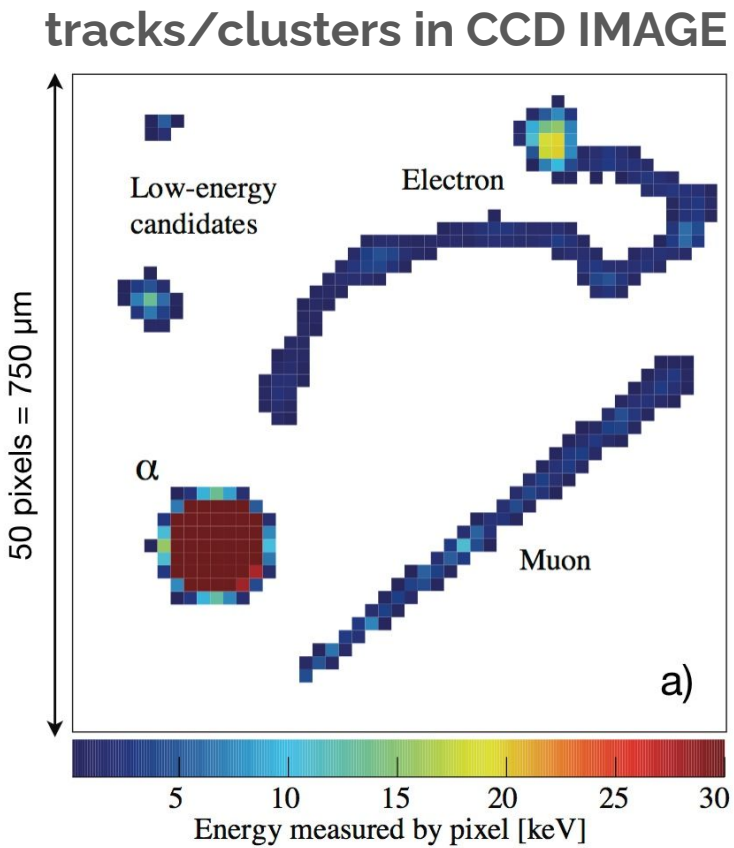
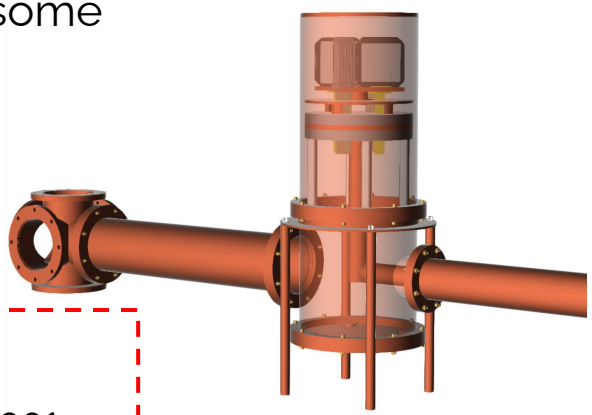


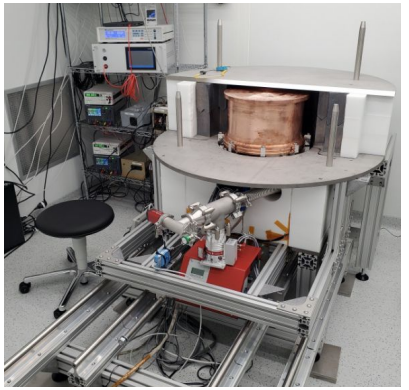
Status of DAMIC-M

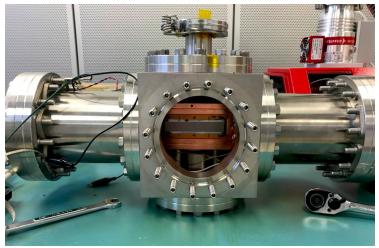
- Detector design almost finalized and some part prototypes are tested
- CCD production done
- Electronics designed, under test
- Calibration with radioactive sources:
  - gamma source: Phys. Rev. D 106, 092001
  - neutron source: data acquired, analysis ongoing
- Low Background chamber operating at LSM
- Installation in 2025

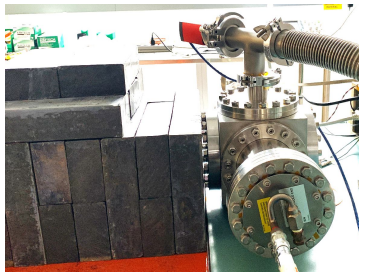
Preliminary design DAMIC-M



LBC @LSM







Compton measurement & photo-neutron measurement setup @UChicago

DAMIC-M simulation software

Geant4: simulate the passage of particle via the geometry setup

- version: 10.4.p02, **10.6.p03**
- Livermore physics list, low energy cut at 20 eV + hadron (e.g. neutrons and protons) processes and radioactive decay
- obtain energy deposits in CCD sensitive part

WADERS: python based code to simulate the response of the detector

- processes: electron/hole pair production, diffusion process, dark current, pixelization, clusterization, electronic saturation, and readout noise.

The Compton measurement

Aim:

- Parametrize Compton spectrum at low energy (main source of background for DM search)
- Provide detector calibration

Setup:

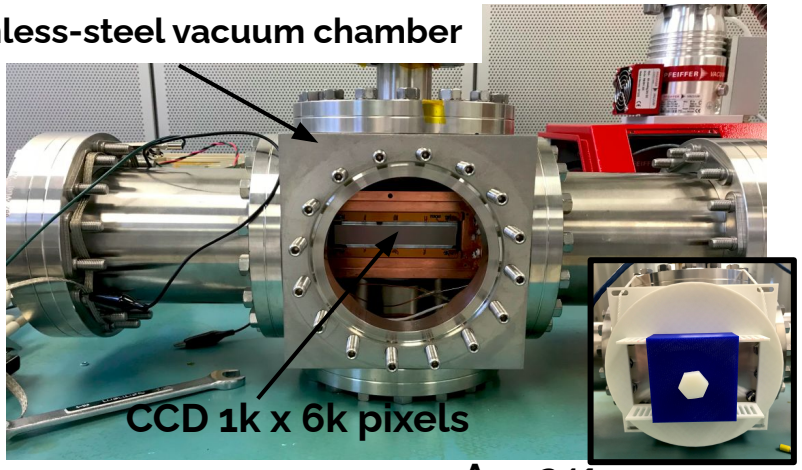
- Temperature: 126 K
- γ source: Am241 (γ Energy: 26.3 keV & **59.5 keV)**
- 1 skipper CCD (1k x 6k pixels)

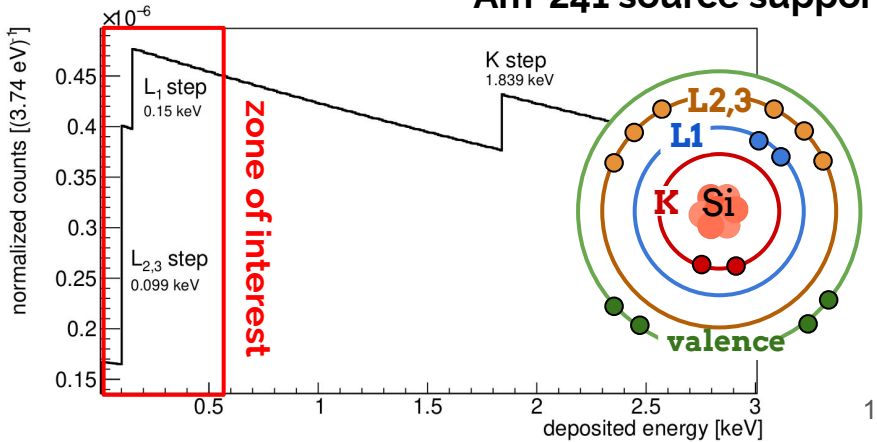
Readout:

- 64 skips
- 0.7 e- readout noise (~2.6 eV)
- binning: 4 pixels x 4 pixels

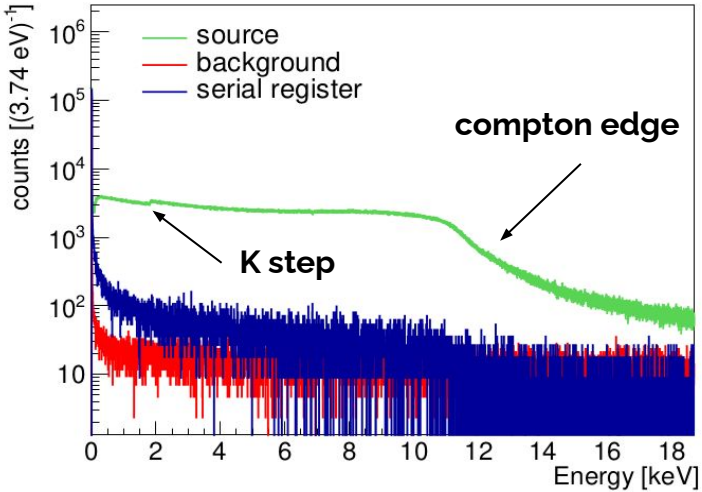
Publication: Phys. Rev. D 106, 092001

Stainless-steel vacuum chamber

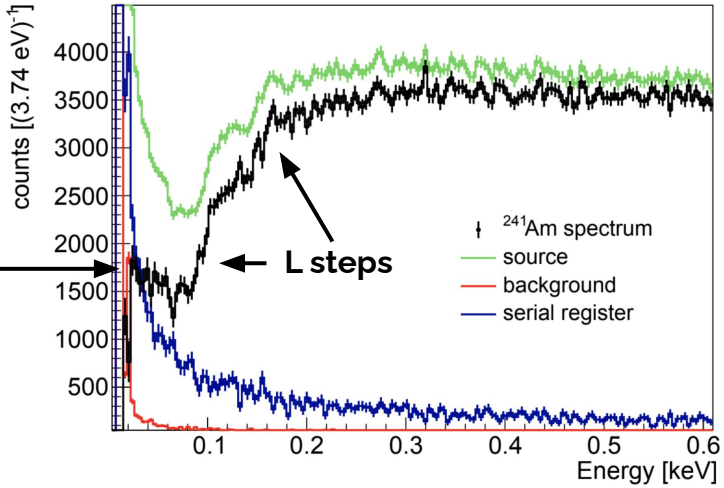




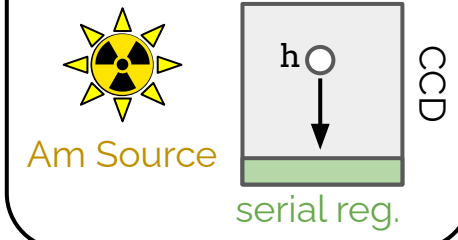
Compton measurement - Data taking



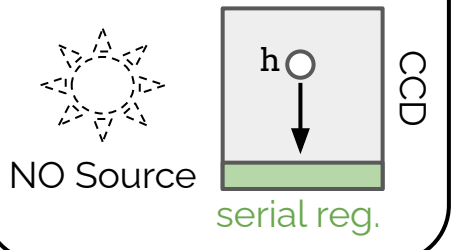
Compton spectrum measured down to 23 eV!



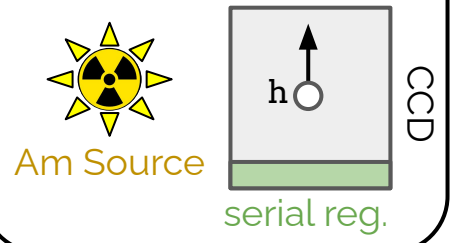
Source: 113.5 days



Background: 48.2 days



Serial register: 12.7 days



Am241 spectrum

=

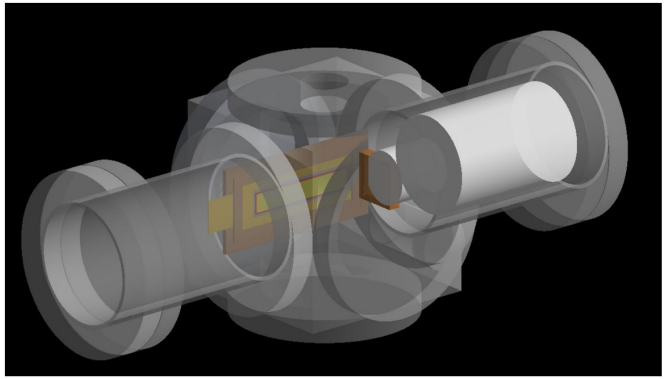
Source - Bkg - Serial register

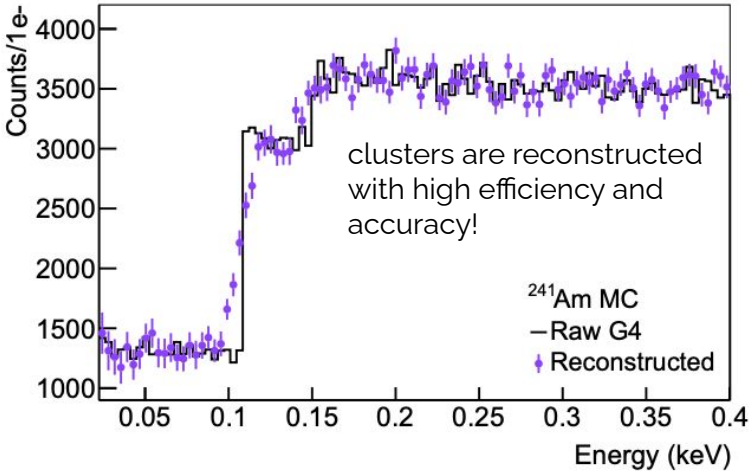
Compton measurement - Simulations

- Geant4 simulations of the experiment (10.6.p03)

- Edep in CCDs transformed in e/h pairs [Phys. Rev. D 102, 063026], diffused and clusterized with WADERS

- simulated cluster on bkg images (to properly include the pixel readout noise, the dark current, and the presence of cosmic rays and other tracks) with same spatial distribution and with same number/image of real data



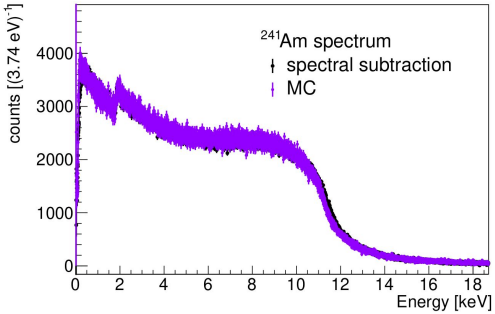


Compton measurement - Data vs model

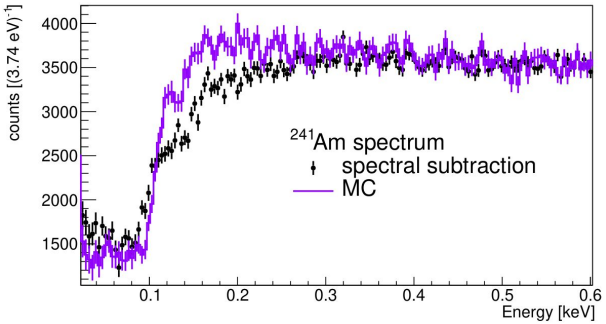
FREE ELECTRON APPROXIMATION

RIA MODEL

Relativistic Impulse Approximation model



MC
=
Geant4
+
WADERS



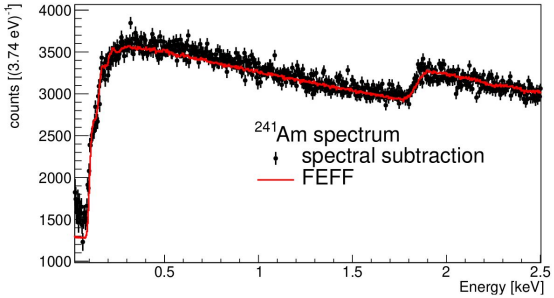
FEFF spectrum reproduce better data below 0.3 keV

to be confirmed using a different source!

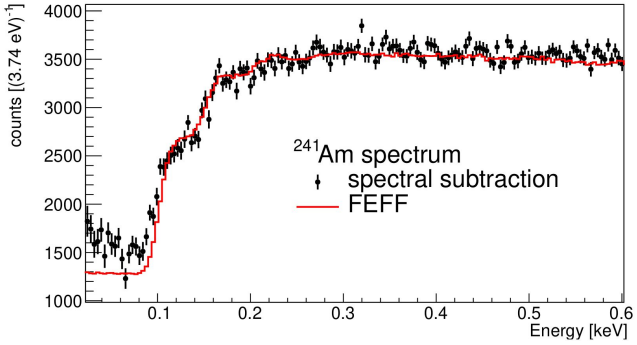
FULL QUANTUM TREATMENT

FEFF MODEL

Ab-initio calculation



FEFF spectrum
=
FEFF code
+
detector resolution



The Photo-neutron measurement

Measurement of nuclear recoil ionization efficiency in silicon:

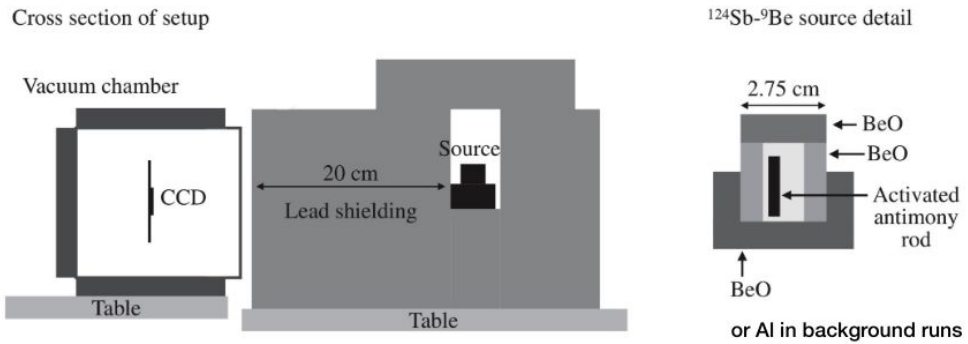
- Similar setup as in the Compton measurement and Phys. Rev. D 94, 082007 (2016),
- Monochromatic ~23 keV neutrons from Sb124-Be9 source ($T_{1/2}$ = 60.2 days), moderation in various materials before reaching the CCD

Steps:

1. Measure nuclear recoil and background spectra,

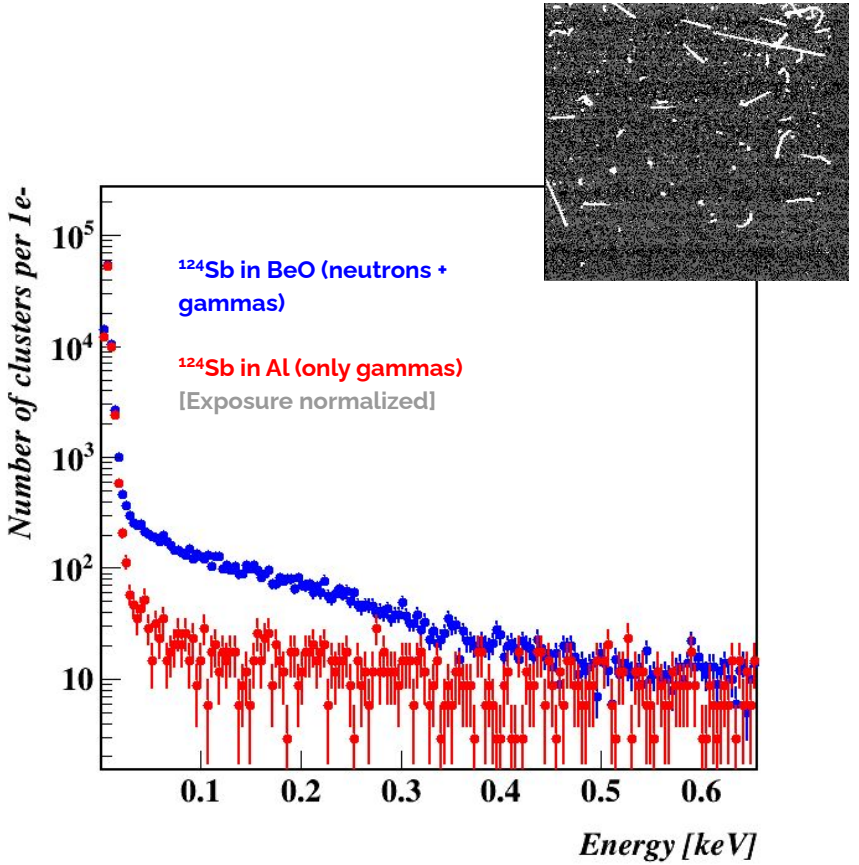
2. Expected recoil spectrum from simulation,

3. Extraction of ionization efficiency.



The Photo-neutron measurement: Data taking

- 1600 skips
- 4x4 Binning
- Image size : 250 rows, 275 columns
- Resolution : ~0.15 e-
- ^{124}Sb in BeO (neutrons + gammas): exposure = 35.84 days
- ^{124}Sb in Al (only gammas): exposure = 13.10 days
- Ambient background with no ^{124}Sb source was also collected



The Photo-neutron measurement: GEANT4 vs MCNP

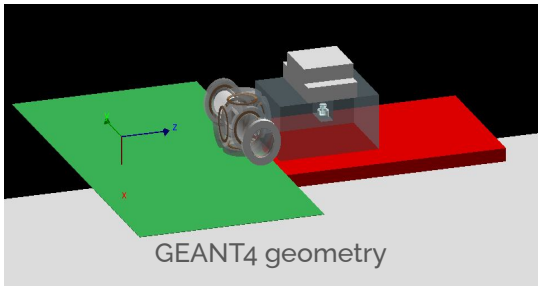
Comparison between Geant 4 v.10.6 and MCNPx v.2.7.0

Good agreement between the two simulation codes

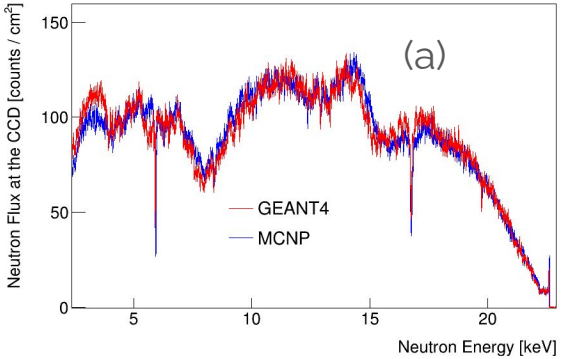
ENDF VII model for neutron scattering was used in both G4 and MCNP

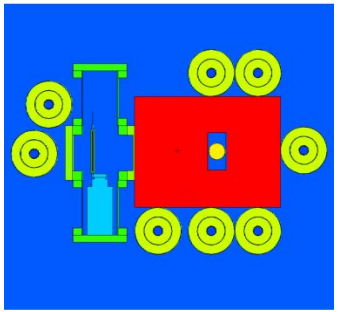
GEANT4 fails to implement the photodisintegration process $^{9}Be + \gamma$ (1.69 MeV) $\rightarrow$ $^{8}Be + n$ (~23 keV) . Hence we just resort to simulating an isotropic mono-energetic flux of 22.6 keV neutrons starting from the BeO volume.

Isotropic mono-energetic neutrons of energy 22.6 keV were simulated at the BeO volume and its flux was recorded at the CCD surface (a) and outside the lead castle (b)

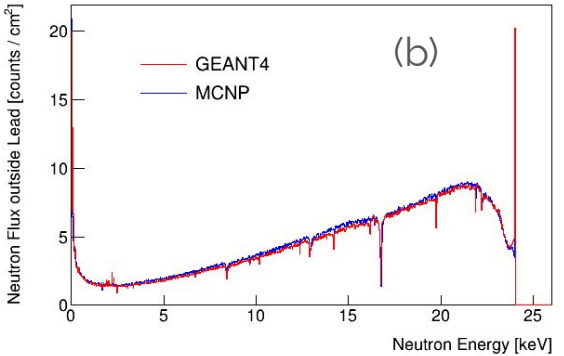


GEANT4 geometry

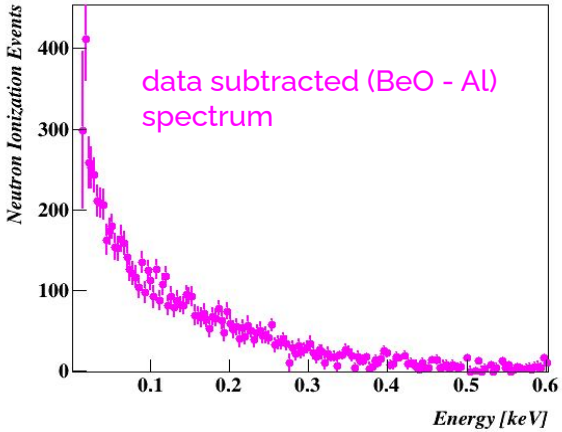


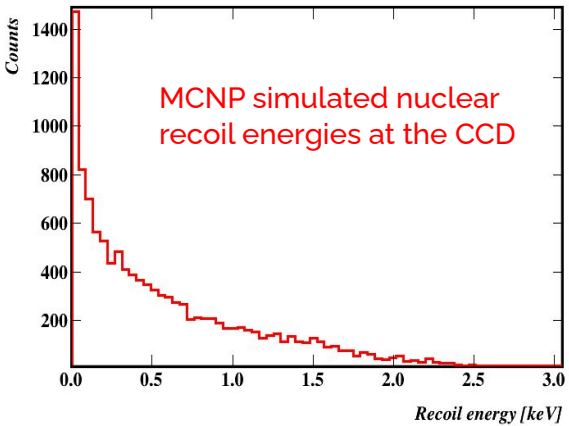


MCNP geometry



The Photo-neutron measurement: neutron ionization efficiency





- Data-driven iterative procedure to map the subtracted ionization spectrum to the simulated recoil energies. Preliminary result is almost in line with the previous measurement by Chavarria et al. and extends the measurement to 18 eV_{ee}

- Final results will be published soon

Conclusions

Calibration measurements & comparison with simulations:

- the Compton measurement:
  - good agreement data-G4 sims > 0.3 keV
  - G4 sims fail to reproduce data < 0.3 keV
  - data agree better with FEFF code < 0.3 keV (when properly tuned)
  - agreement of data with FEFF code to be tested with other measurement with different gamma source (Co57)

- the Photo-neutron measurement:
  - good agreement between MCNP & G4 simulations