

The XDK (X-ray Decay) Experiment: Upgrading KDK for General EC Measurements

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Canadian Astroparticle Physics Research Institute

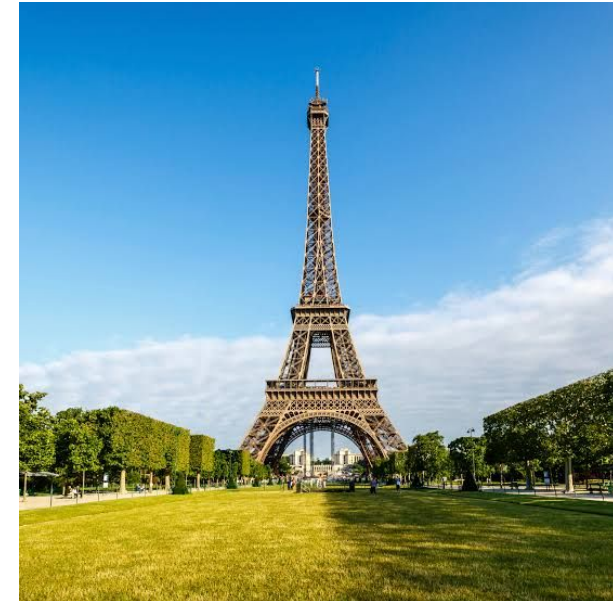
MAX PLANCK
SEMICONDUCTOR
LABORATORY



UNIVERSITY
OF WARSAW

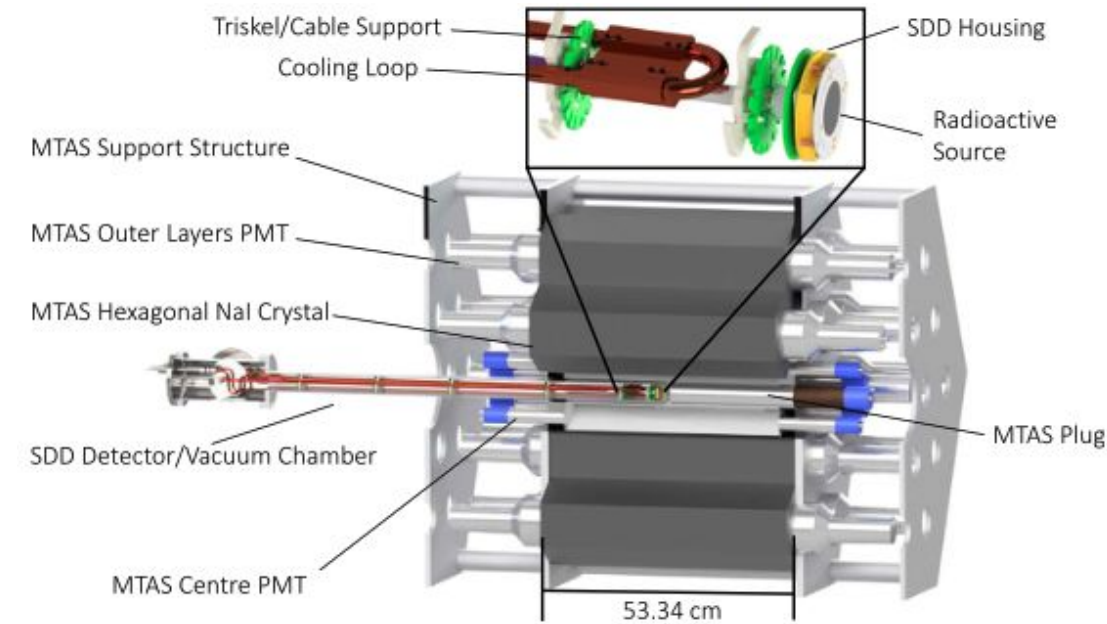
Outline

- 1) KDK Reminder
- 2) Intro to XDK
- 3) Improvements between KDK and XDK
- 4) Silicon Drift Detectors (SDDs)
- 5) Mechanical status of XDK
- 6) Commissioning XDK
- 7) Our planned first EC measurement: Ni-59
- 8) Other possible isotopes



KDK Reminder

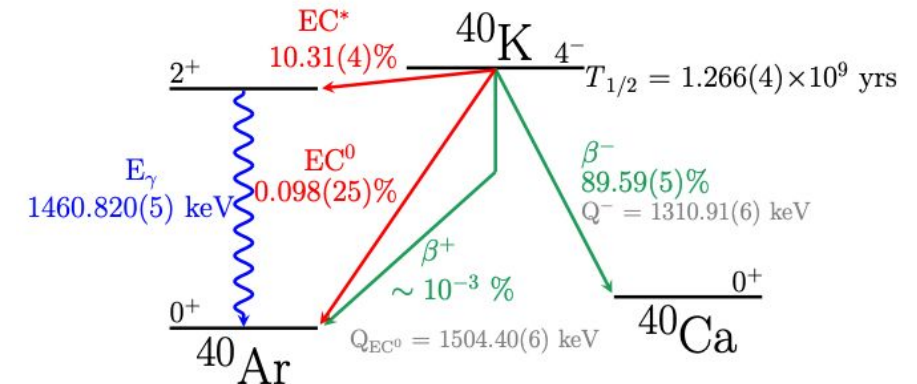
- An X-ray detector coupled with a γ -ray tagger (MTAS)
- Contained a K-40 source
- Successfully measured the EC*/EC branching ratio
- Useful technique to perform EC measurements



Stukel et al., 2021

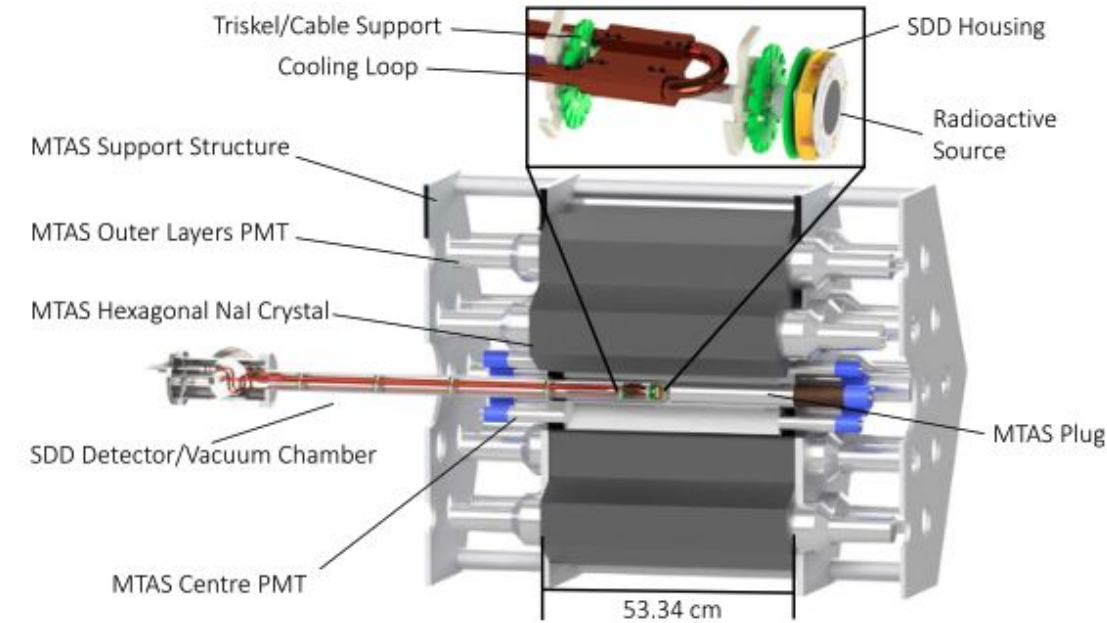
References:

<https://doi.org/10.1103/PhysRevLett.131.052503>
<https://doi.org/10.1103/PhysRevC.108.014327>
<https://doi.org/10.1016/j.nima.2021.165593>
<https://doi.org/10.1016/j.nds.2023.04.003>



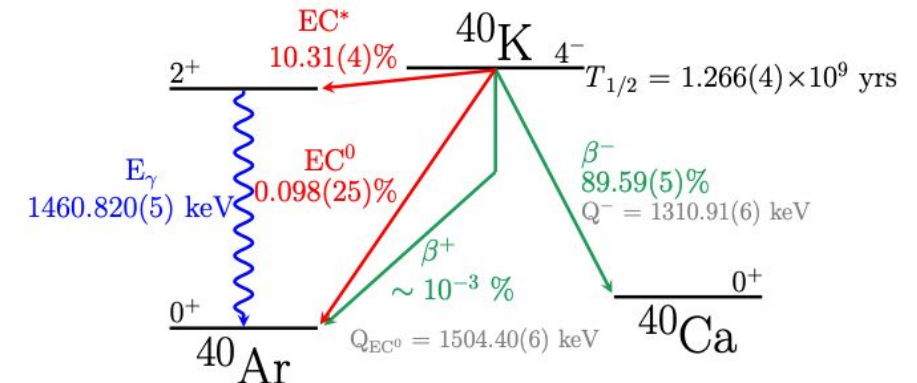
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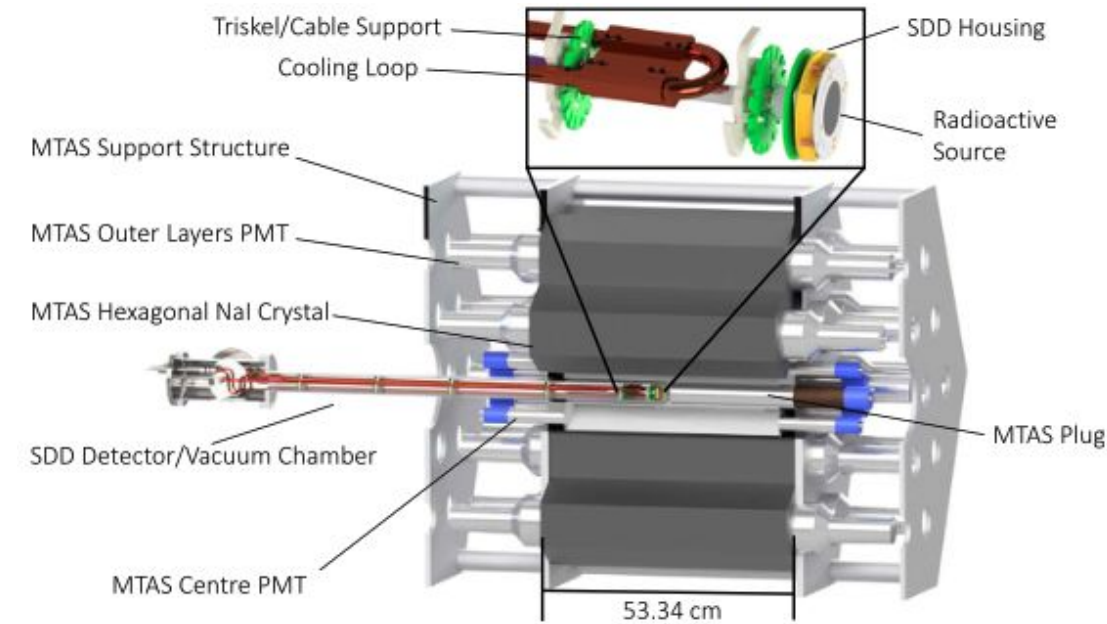
Stukel et al., 2021

Can KDK technology be used for
other isotopes of interest?



KDK Reminder

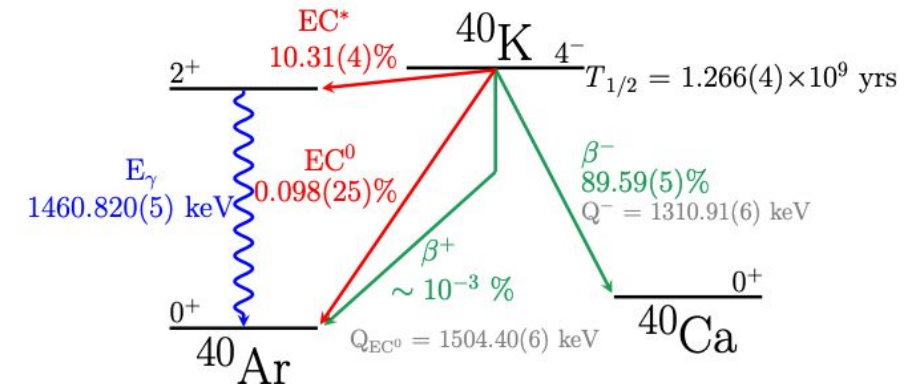
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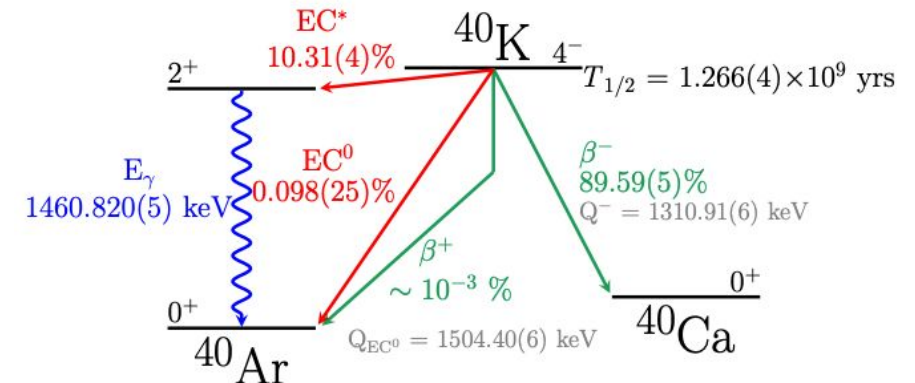
oui!



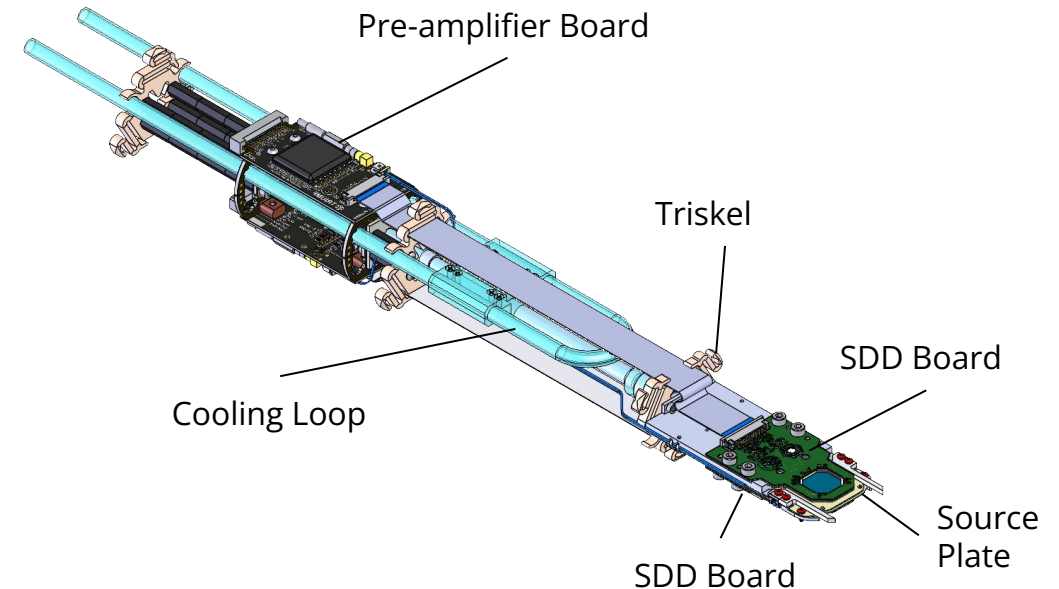
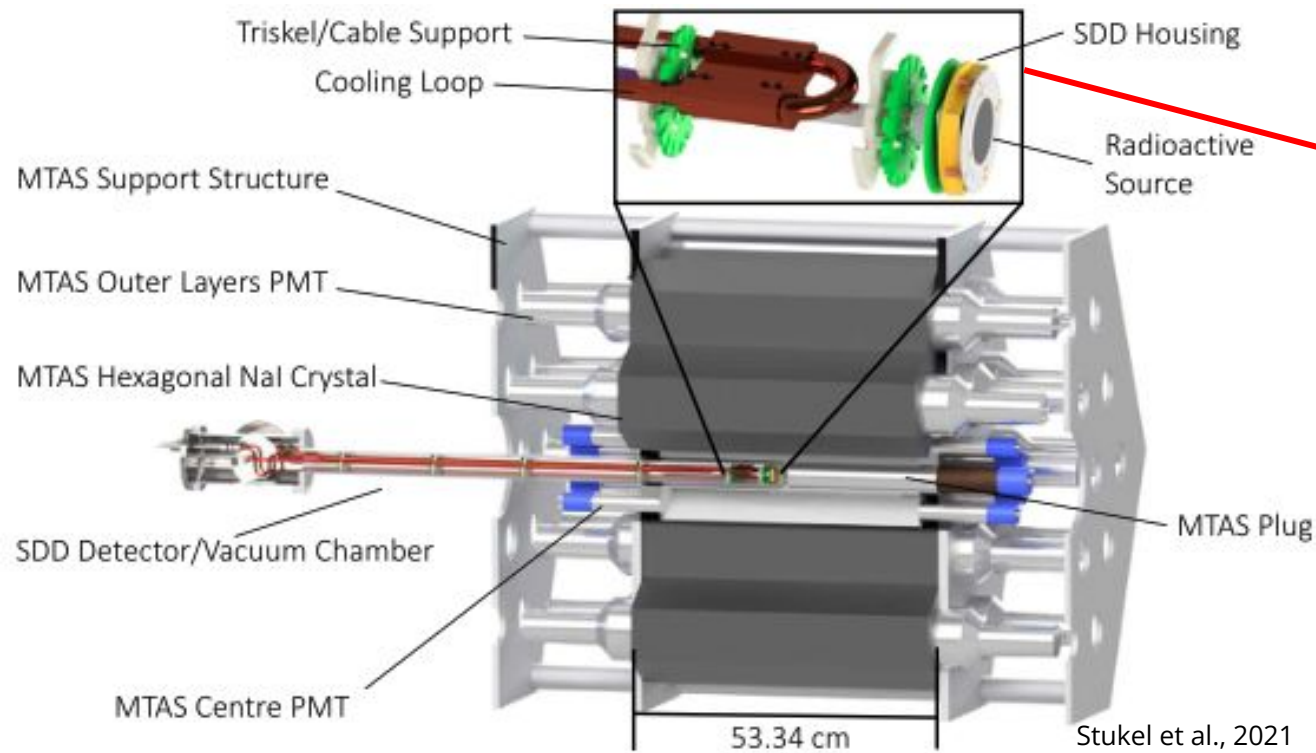
XDK (X-ray Decay)

- Will use and improve upon KDK technology to measure many other EC decays
- EC measurements could be useful for many different fields depending on the isotope
 - Testing nuclear structure models
 - Gain insight into effective g_A
 - Understand backgrounds in rare event searches (e.g. KDK)
 - Improving precision of decay constants
- X-ray detector setup is being upgraded
 - SDDs are the same as in KDK
 - Coupling to MTAS as done in KDK

**Great combo to
measure ECs**



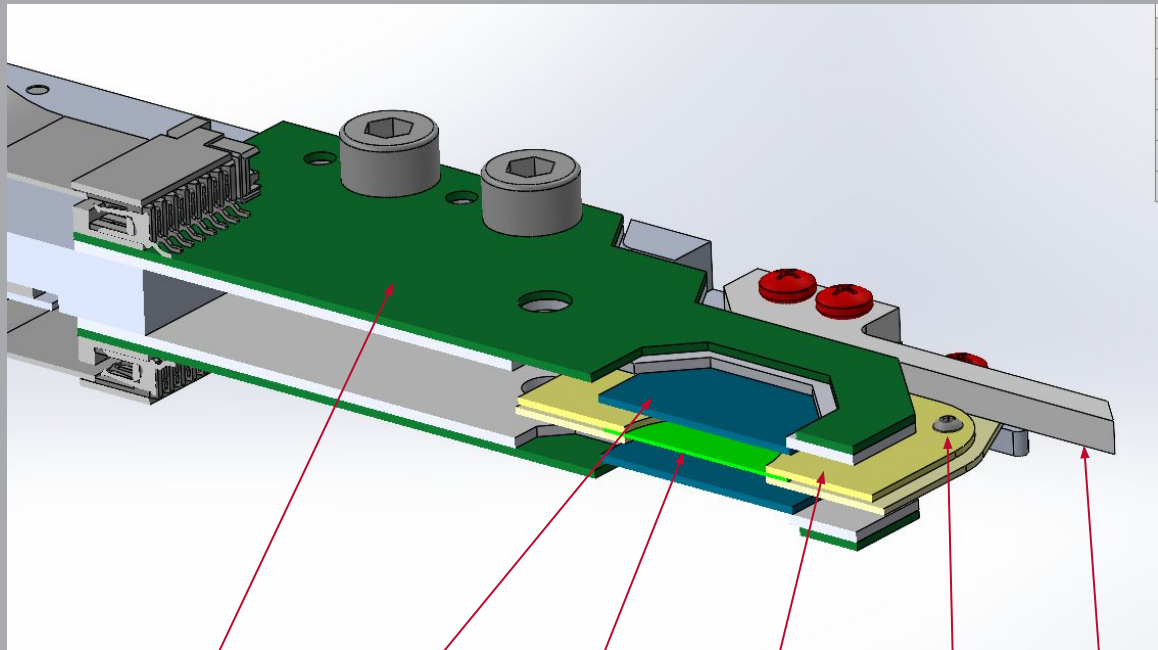
Improvements for XDK



- 1 SDD detector for $\sim 2\pi$ x-ray coverage
- Cooled with a water, ethylene mixture to a -20°C operating temperature
- “Unknown” components near source limiting background understanding

- 2 SDDs, **better coverage**
- Cooled with LN2 to lower operating temperature, **better detector resolution**
- Electronics & other components moved further from source to **improve background**

Improvements for XDK



SDD Board

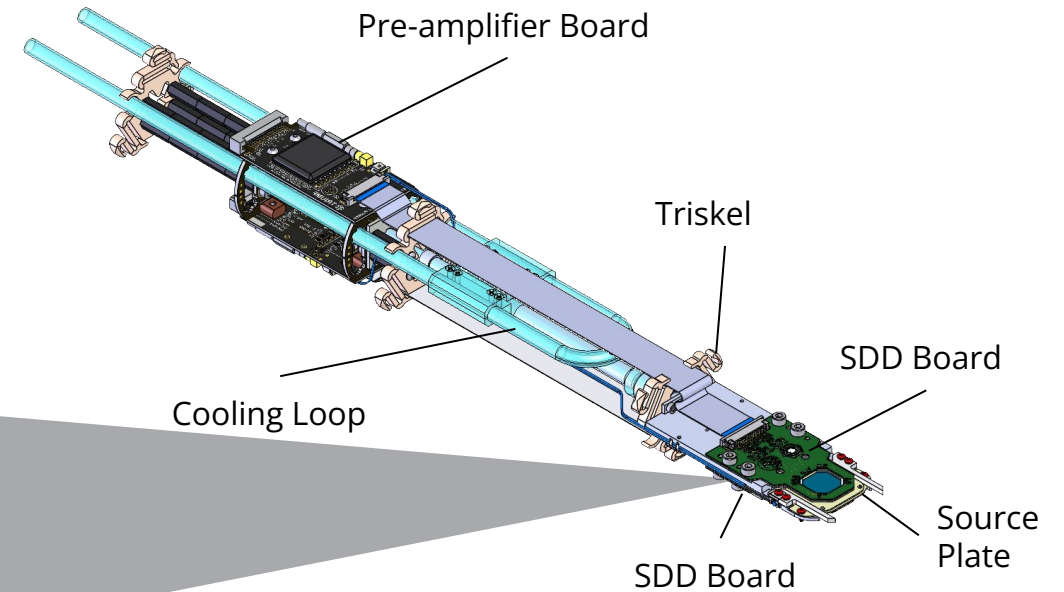
SDD

Source

Source Plate

Clamping
screws

Alignment
Bumpers



Pre-amplifier Board

Cooling Loop

Triskel

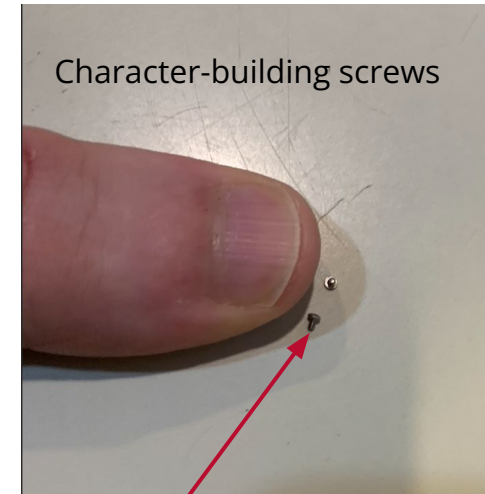
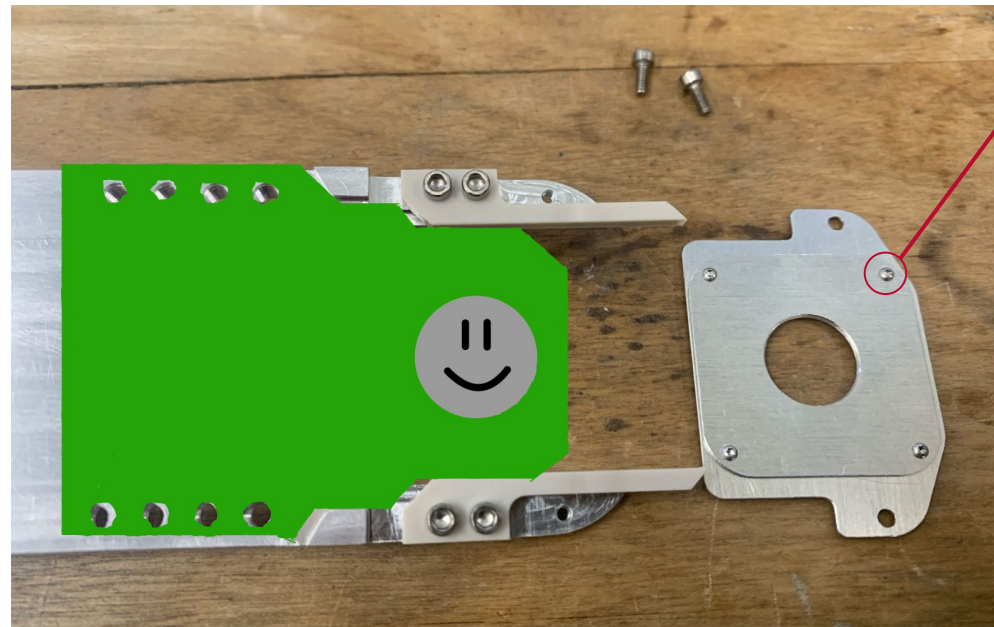
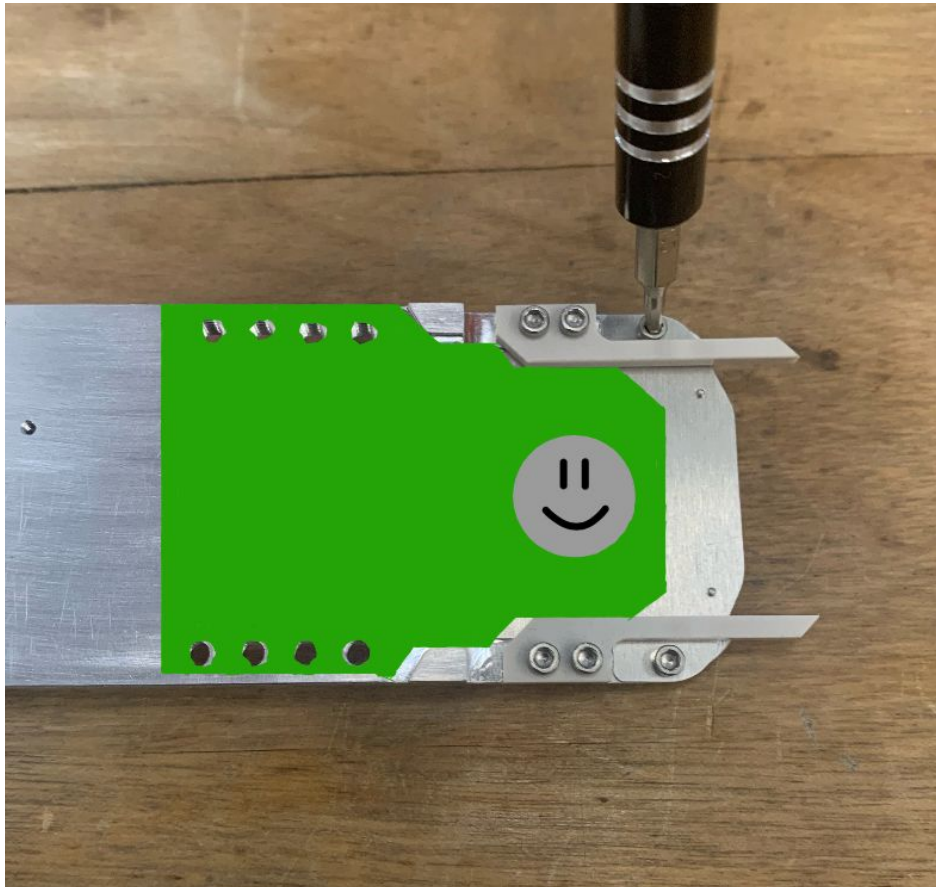
SDD Board

Source
Plate

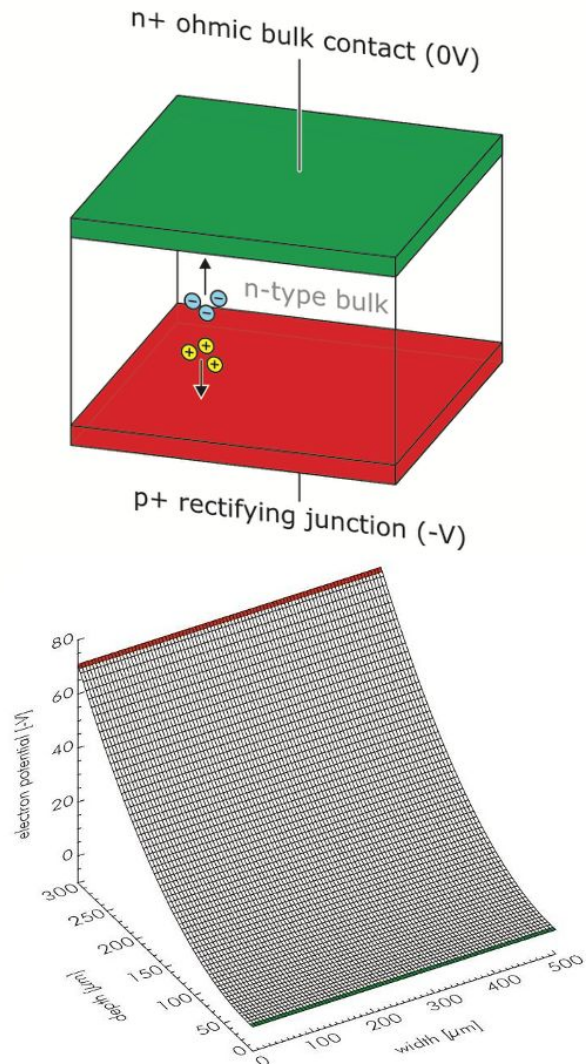
SDD Board

Improvements for XDK

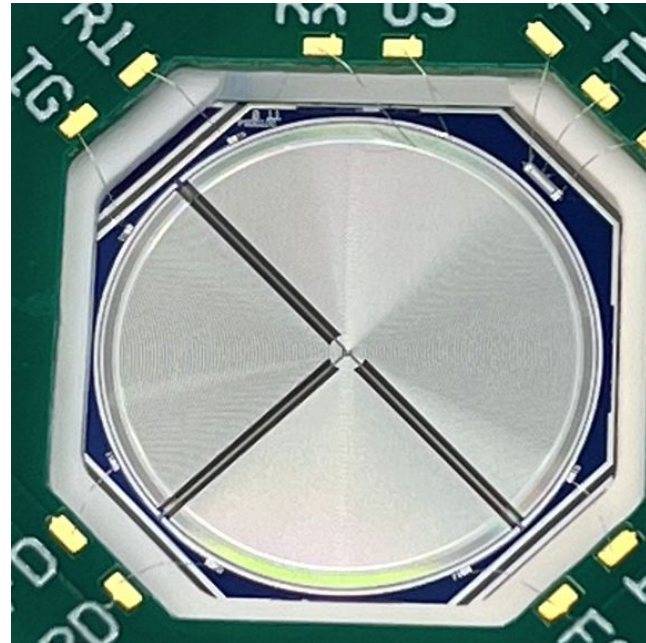
- Undo 6 screws to replace the source
- Undo 8 screws to replace the SDDs



Silicon Drift Detectors

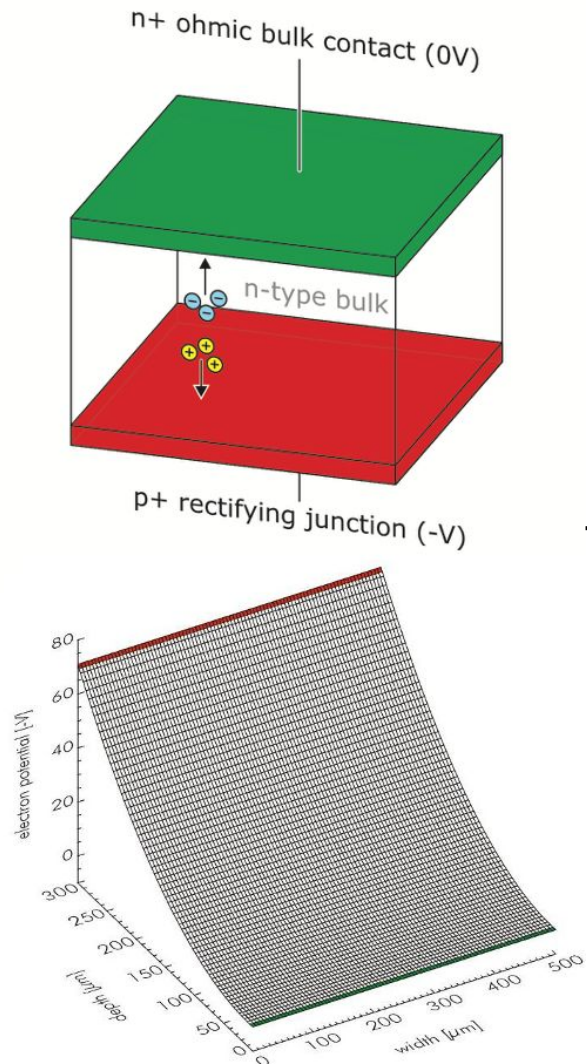


- Si-based semiconductors made by HLL (Max Planck Semiconductor Lab)
- X-rays interacting in the Si create electron-hole pairs
- Signal electrons drift to the anode (n+), are collected and readout
- A smaller anode minimizes noise from capacitance

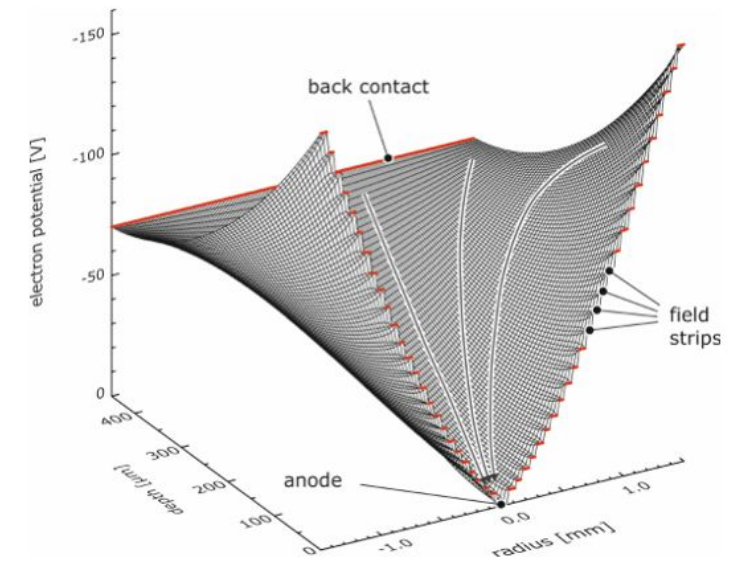
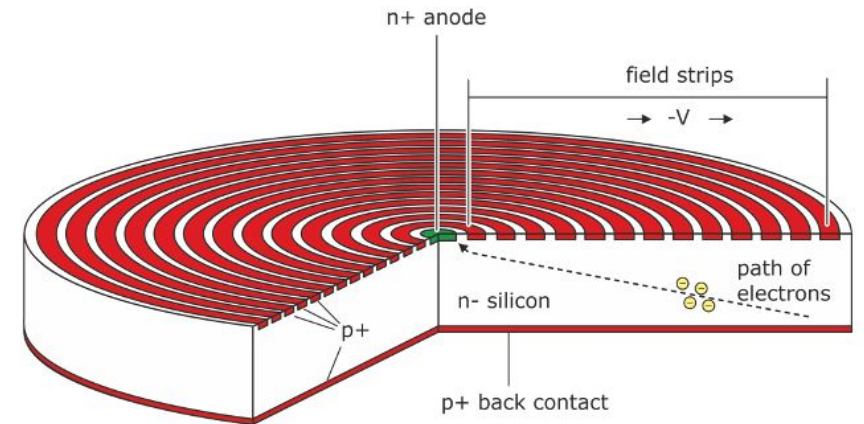


Drift Detectors designed to reduce the anode area

Silicon Drift Detectors

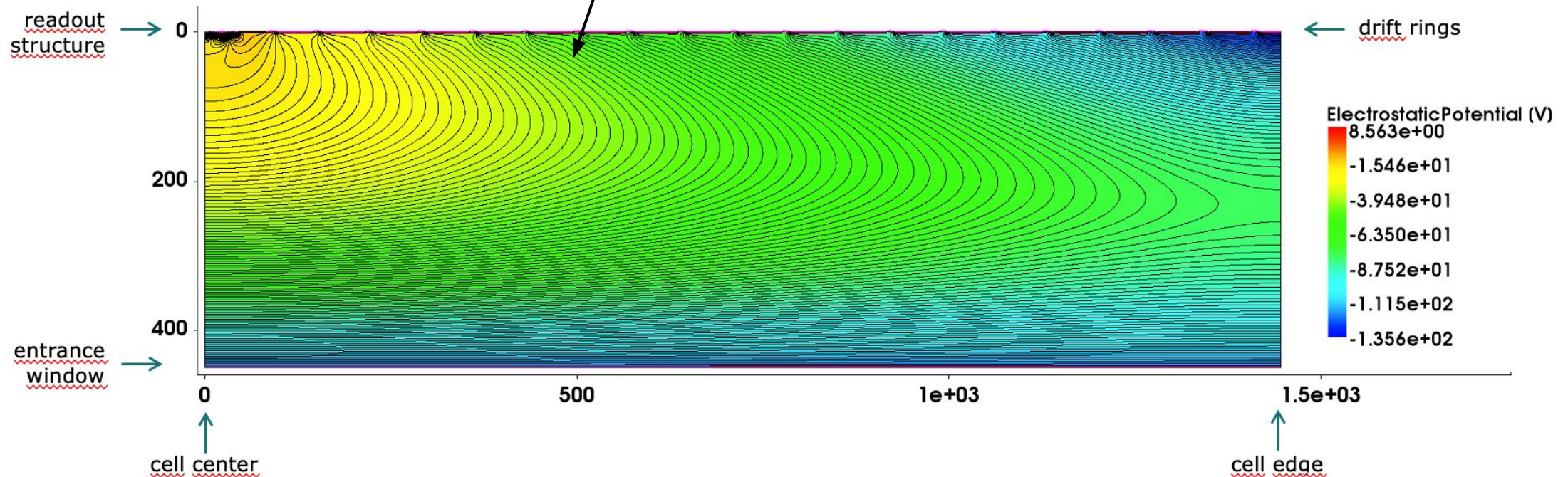
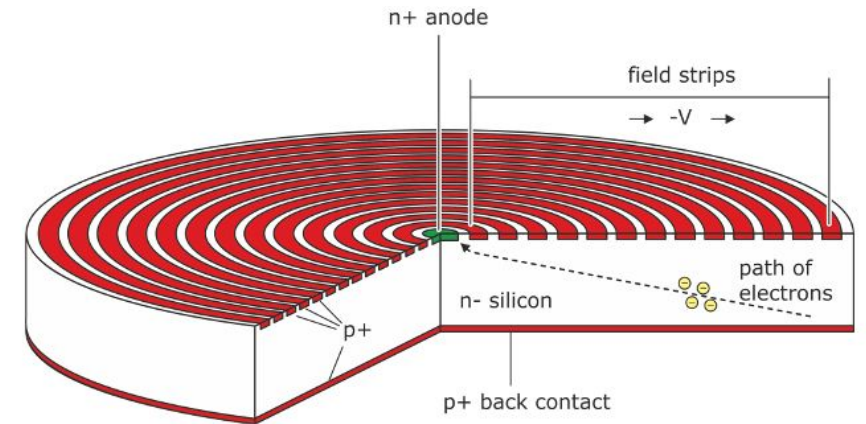


Drift Detectors use
sideward depletion to
minimize anode area

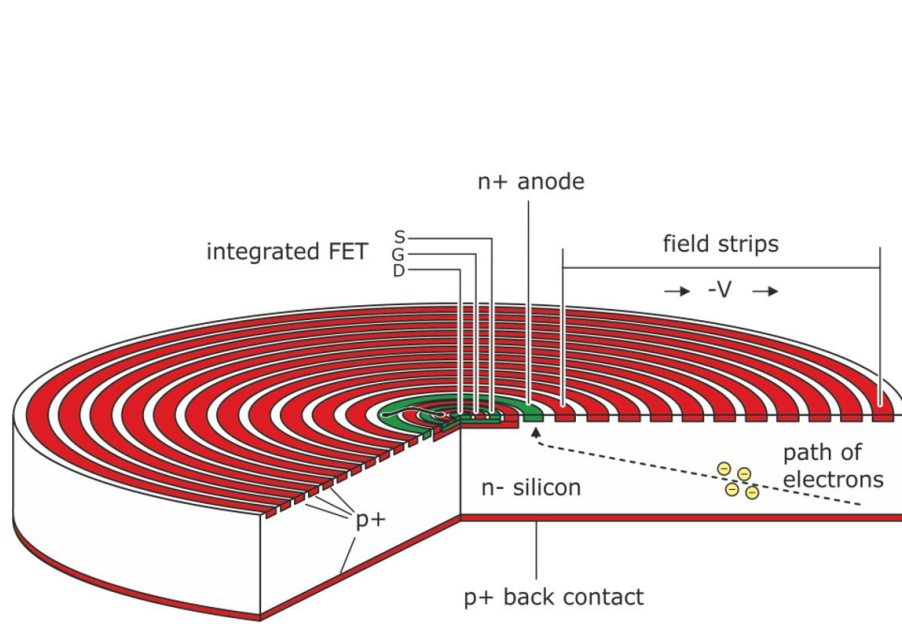


Silicon Drift Detectors

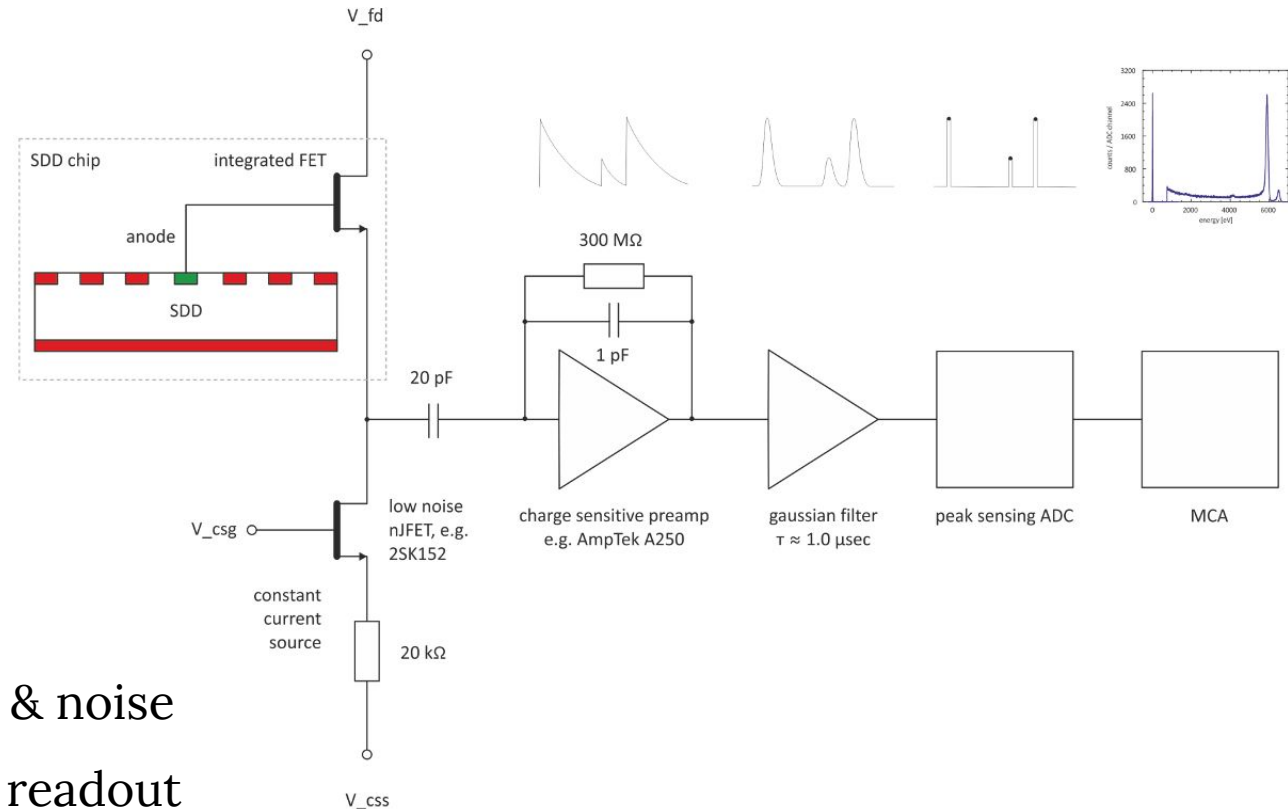
- Potentials applied between the inner and outer p+ ring such that electrons drift toward the anode
- Electrons travel perpendicular to equipotential lines



Silicon Drift Detectors: Typical Readout Scheme

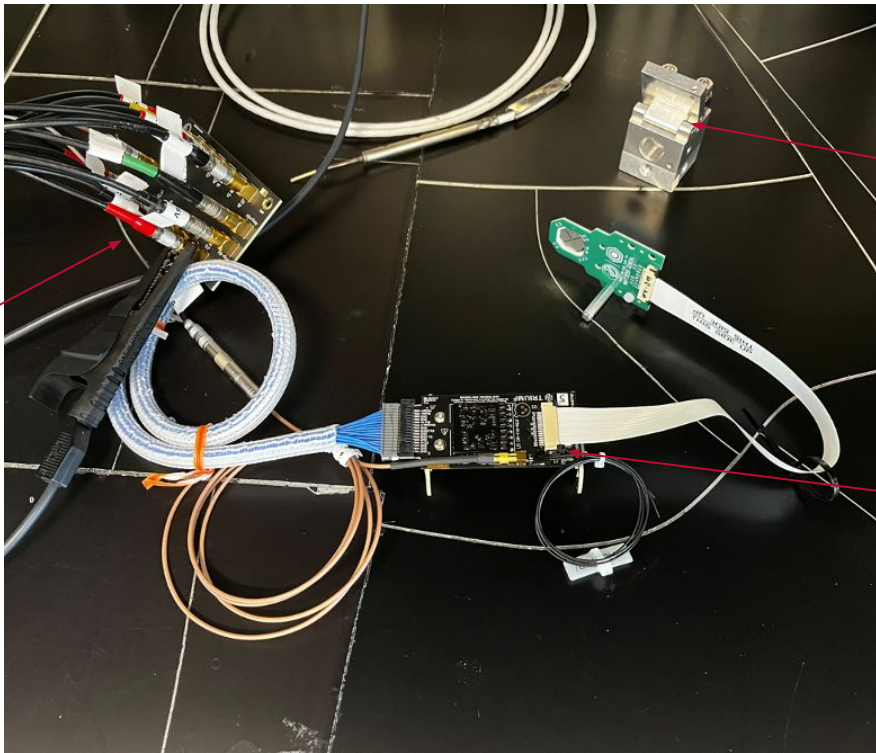


- Integrating first FET minimizes capacitance & noise
- More electrically robust, allows for a longer readout cable



SDD Testing

- SDDs are from the same batch of detectors produced for KDK
- Circuit board is different than KDK
- Tested at HLL in a climate chamber at -40 C
- Have 10 detectors with promising Fe-55 spectra & resolution

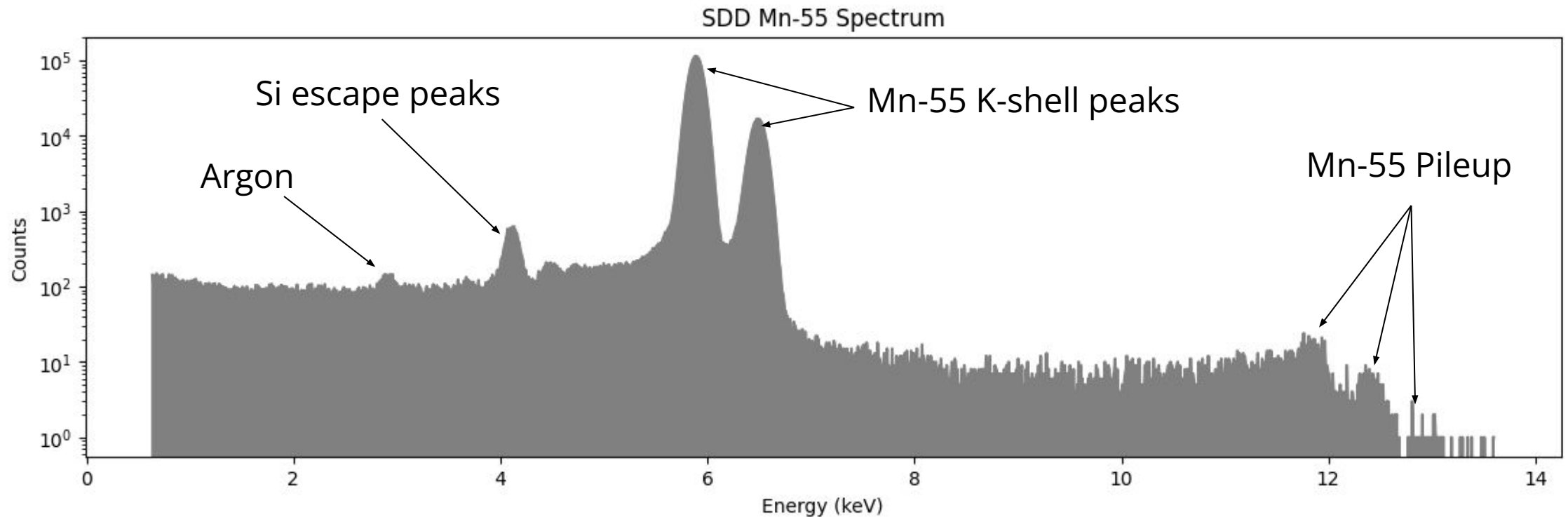


Fe-55 source: EC to Mn-55 produces
5.89 keV & 6.49 keV x-rays

Pre-amplifier board

Breakout board

SDD Energy Spectrum



- Spectra from testing at HLL
- FWHM values are 151 eV and 161 eV for the Mn-55 peaks
 - KDK had ~200 eV for 8 keV peaks from Zn-65
- Will test again in the XDK setup @ Queen's

Mechanical Status of XDK

- Most parts have been produced or procured so far
- A few still to be produced/procured (custom LN2 dewar, RTDs, etc.)
- Meanwhile commissioning has started @ Queen's



XDK Commissioning

1. Vacuum/Leak testing the setup
 - Outer tubing
 - Cooling loop
2. Cryogenic test
 - Circulating LN2
 - Testing heater
3. Electronics test
 - with SDDs



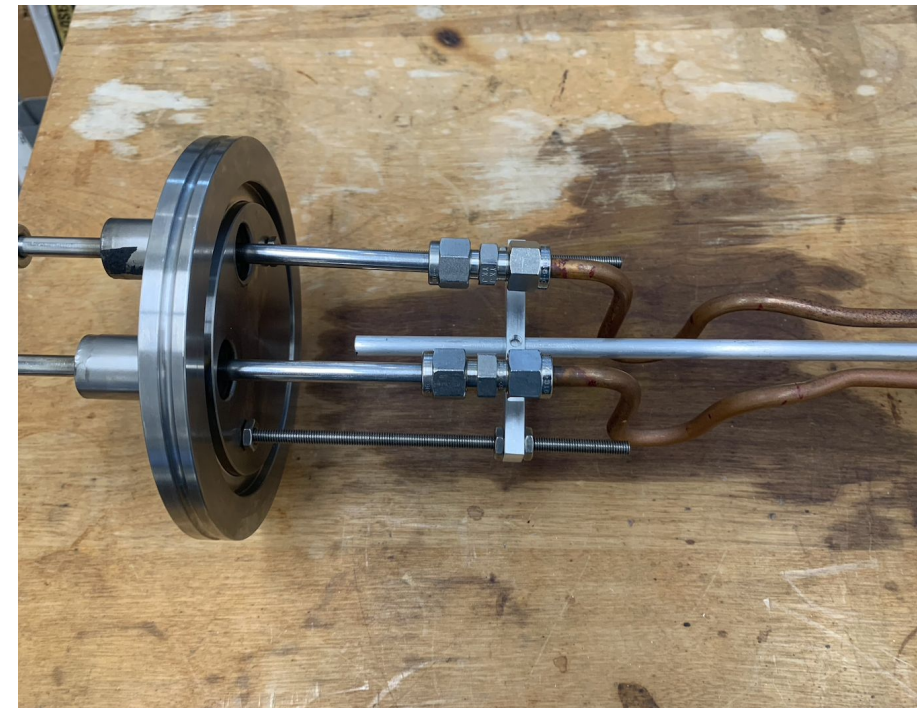
Leak Tests (at 300K)

- Outer vacuum tubing successfully leak tested
 - Inlet leak detector pressure = 8×10^{-3} mbar
 - Largest possible leak on the order of 5×10^{-10} mbar L/s



Cooling Loop production

- LN2 cooling loop made from copper tubes
 - Bent in house (Jeff Kingma)
- Used swage connections to put together and attach to top flange



Cooling Loop production

- Leak testing the cooling loop was successful!
 - Inlet leak detector pressure = $3\text{e-}3$ mbar
 - Tight to $2\text{e-}9$ mbar L/s



XDK Commissioning

1. Vacuum/Leak testing the setup

- Outer tubing
- Cooling loop



(at 300K)

2. Cryogenic test

- Circulating LN2
- Testing heater

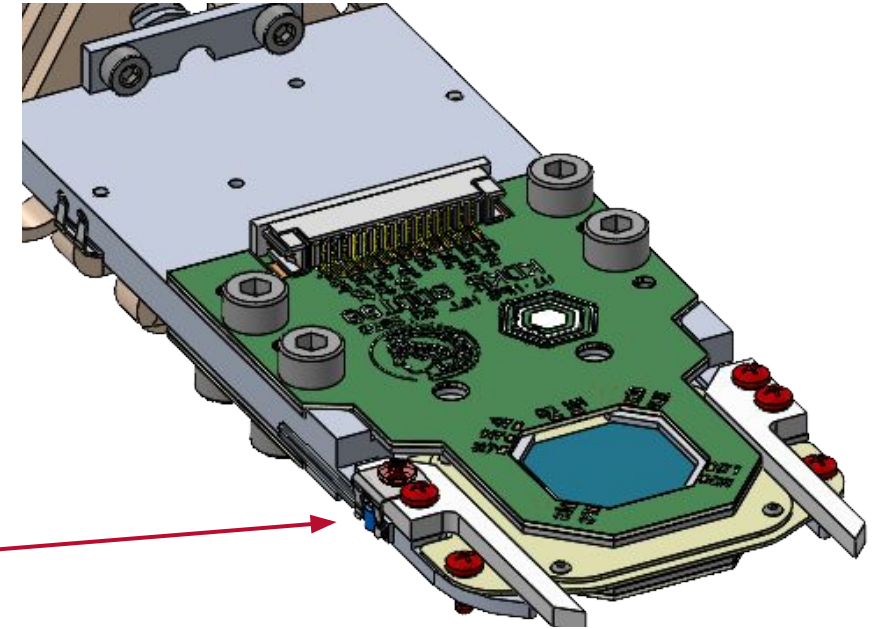
3. Electronics test

- with SDDs



Cryogenic Tests

- Using a custom gravity assisted LN2 dewar
 - Should keep liquid at detector end of the setup
 - Arriving in November
- RTDs will be used in the main experiment
 - Clipped near detectors
 - Wiring goes through same filter board as other electronics
- Planning on doing the following tests
 - Cold leak tests & vacuum holds
 - Circulating LN2 with RTDs attached
 - Install heater & repeat



**Requires temporary RTD setup
& possibly LN2 circulation**

XDK Commissioning

1. Vacuum/Leak testing the setup

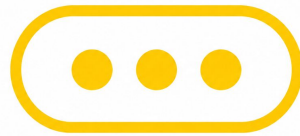
- Outer tubing
- Cooling loop



(at 300K)

2. Cryogenic test

- Circulating LN2
- Testing heater



3. Electronics test

- with SDDs



XDK Commissioning

1. Vacuum/Leak testing the setup

- Outer tubing
- Cooling loop



(at 300K)

2. Cryogenic test

End of October

- Circulating LN2
- Testing heater

3. Electronics test

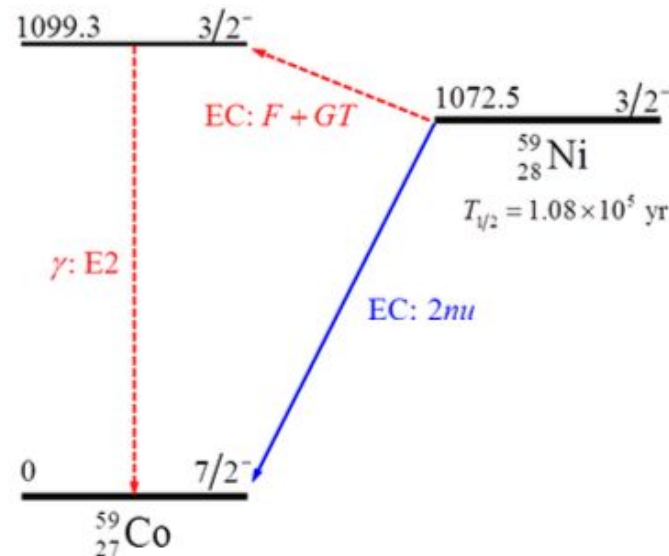
November

- with SDDs



The First Measurement: Ni-59

- Decays nearly 100% of the time through a 2nd forbidden non-unique transition to the ground state of Co-59
- The first excited state of Co-59 (Co-59*) is only ~27 keV higher than Ni-59
- Of interest for a couple reasons:
 - Testing radiative electron capture (REC) models and **verifying virtual β - γ transitions**
 - Can estimate the effective value g_A , useful for $0\nu\beta\beta$

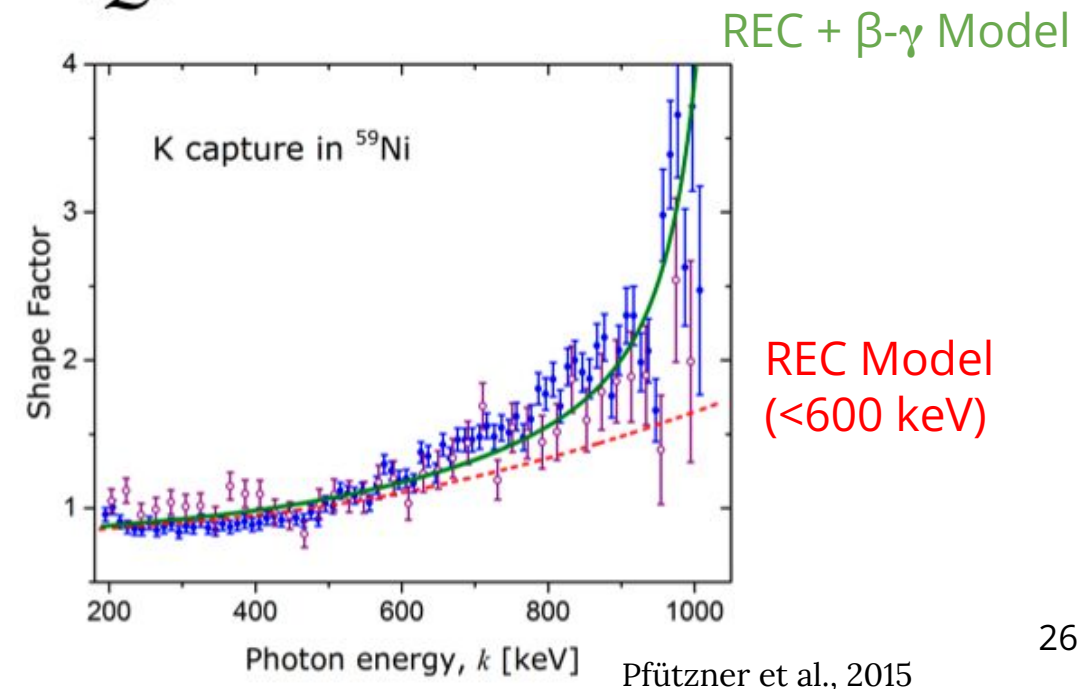


Radiative Electron Captures

- Currently accepted REC model done by Pachucki (2007)
 - Calculated in the length gauge rather than the coulomb gauge
- Extended to 2nu transitions in 2015, applicable to Ni-59

$$\mathcal{R}_{2\nu} = \left(1 - \frac{k}{Q}\right)^2 \mathcal{R}^{(1)}(k) + \Lambda \left(\frac{k}{Q}\right)^2 \mathcal{R}^{(2)}(k)$$

- Ni-59 data from the late 80s was used to help verify this REC theory
 - Showed evidence for virtual β - γ transitions



Verifying REC & β - γ transitions with Ni-59

$$\mathcal{R}_{2\nu} = \left(1 - \frac{k}{Q}\right)^2 \mathcal{R}^{(1)}(k) + \Lambda \left(\frac{k}{Q}\right)^2 \mathcal{R}^{(2)}(k)$$

$$\Lambda \equiv \frac{|\mathcal{M}_{2\nu}^{(4)}|^2}{|\mathcal{M}_{2\nu}^{(2)}|^2}$$

$$\chi \equiv \frac{\mathcal{M}_{E2} \mathcal{M}_{GT}}{\mathcal{M}_{2\nu}^{(2)} \lambda}$$

- Pfützner et al., 2015 treated Λ as a free parameter
- Included terms for the virtual transition dependent on χ
- Fitted using 80s data

REC:

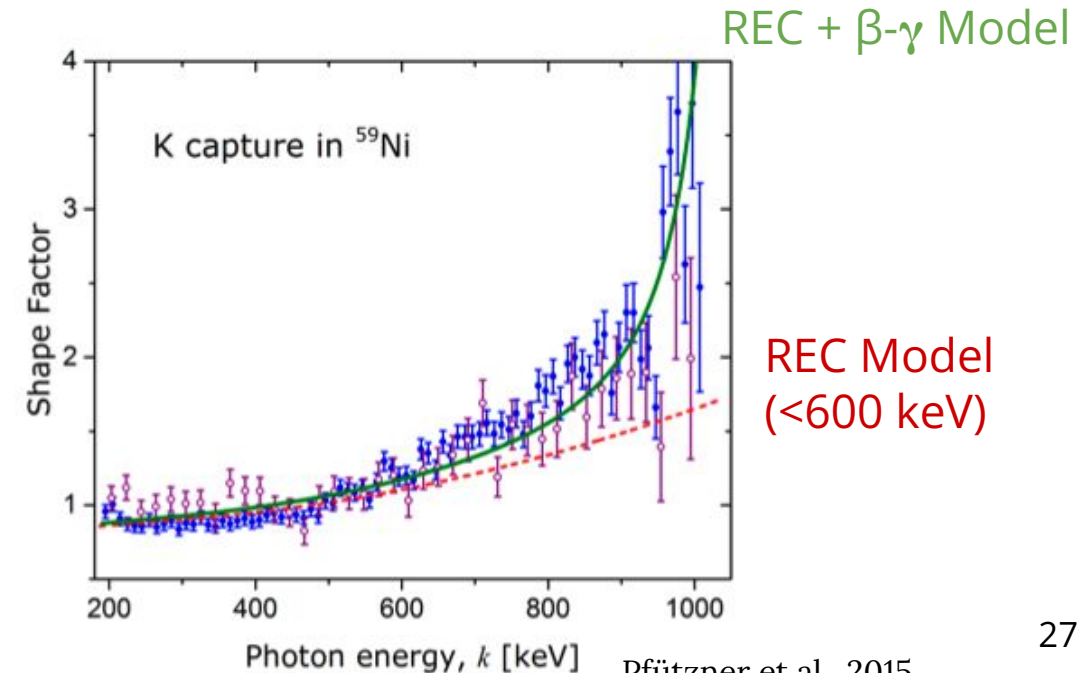
$$\Lambda = 1.47 \pm 0.15$$

REC + β - γ :

$$\Lambda = 1.52 \pm 0.18$$

$$\chi = 0.31^{+0.17}_{-0.34}$$

- Comparable Λ implies REC works alone at low energy
- Virtual transitions distort the spectrum at high energy



Verifying REC & β - γ transitions with Ni-59

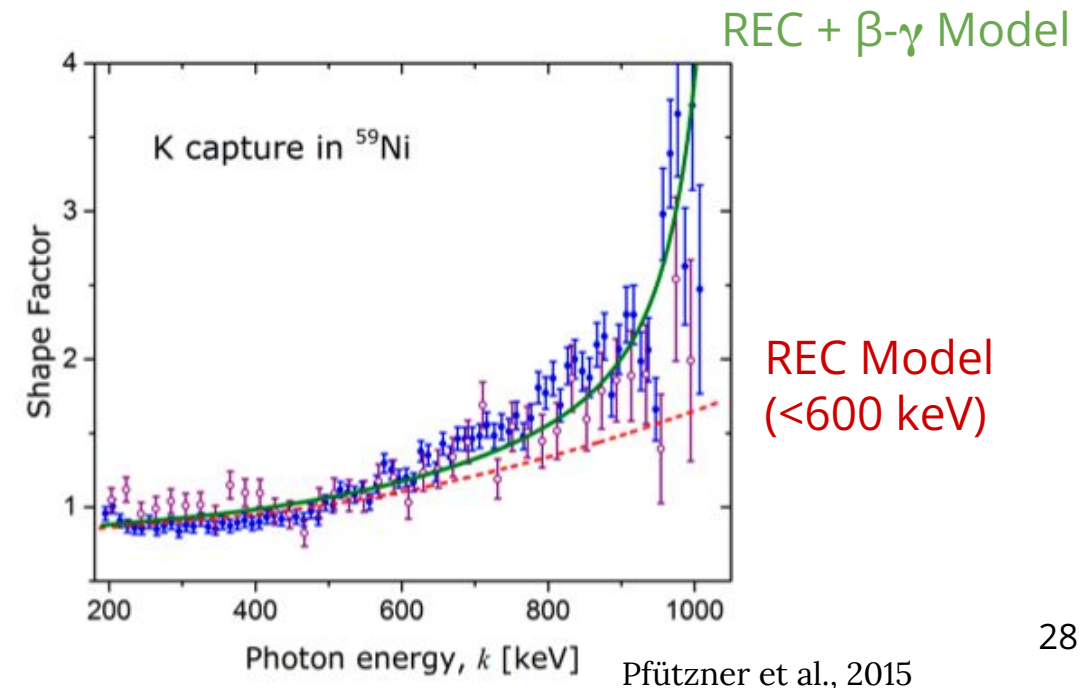
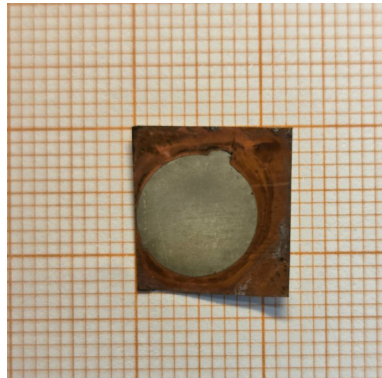
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$$\chi \equiv \frac{\mathcal{M}_{E2} \mathcal{M}_{GT}}{\mathcal{M}_{2\nu}^{(2)} \lambda}$$

- **XDK will be able to improve upon this Ni-59 study**
 - Technology ~40 years newer
- Hope to further constrain parameters & provide a stronger verification of the virtual β - γ transition
- Could also remeasure β^+ /K
 - Janas (1991) result is far from theory

Using the same Ni-59 source from the 80s!
(~100 Bq)



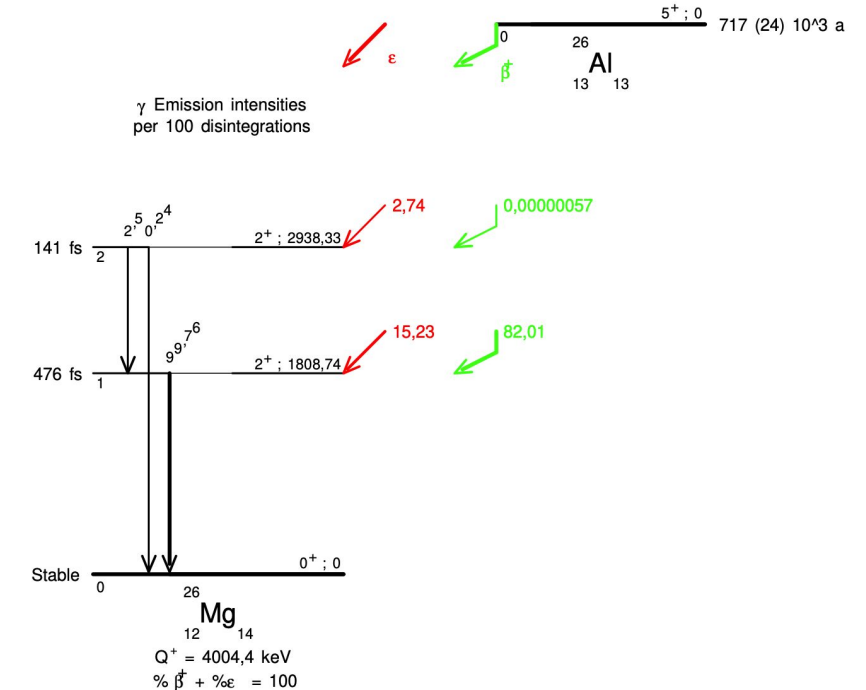
Other Isotopes of Interest

Mn-53:

- Mn-53 was abundant in the early solar system
- Decays to Cr-53, used as a stellar chronometer
- More precise half-life measurement improves timelines for stellar and planetary formation
- Half-life: $3.7 (6) 10^6$ yrs

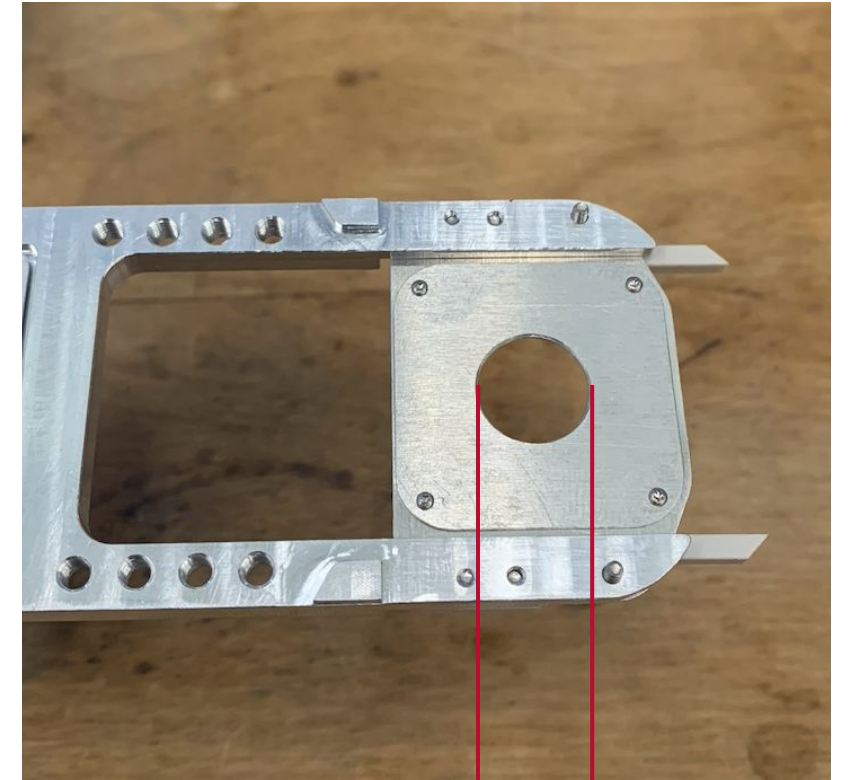
Al-26:

- Also a stellar chronometer
- Shorter half-life than Mn-53, better probe for early stellar formation
- Half-life: $7.17 (24) 10^5$ yrs



Call for Sources

- Open to collaborations or suggestions on other sources
- Criteria for testing a source in XDK are:
 - Fits in the source holder
 - Or another source holder we could design & produce
 - Ideally transparent (so both SDDs see the source)
 - Doesn't harm the SDDs (~1 kBq is ideal)
 - Doesn't harm the student handling them



1 cm

Summary & Outlook

- XDK is improving upon KDK to be able to measure ECs from various isotopes
- Most mechanical parts have been produced/procured
- SDDs have been tested and some brought back to Queen's
- Currently commissioning the experiment @ Queen's
- Once complete, we transport to Argonne National Lab for the first measurement with Ni-59!

Thanks for listening!



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