

# First $\beta$ -delayed spectroscopy of neutron-rich Cl isotopes with FDSi

Ian Cox

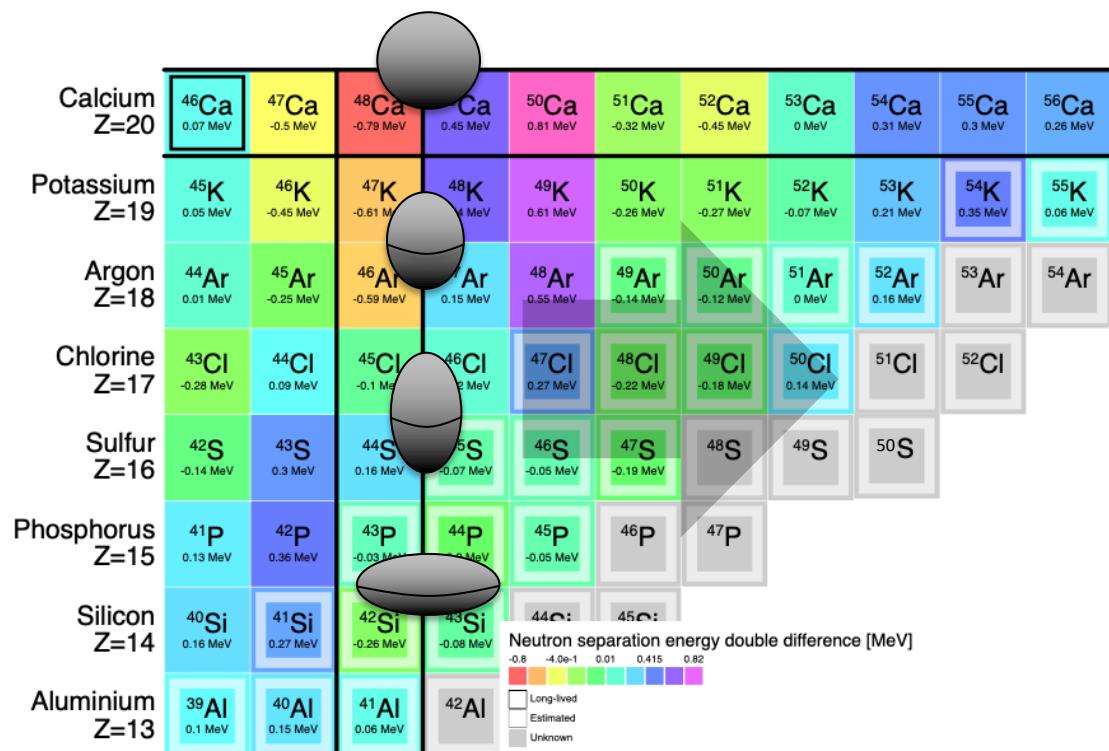
On behalf of the e21069 collaboration



THE UNIVERSITY OF  
**TENNESSEE**  
KNOXVILLE

Advances in Radioactive Isotope Science  
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# Evolving down N=28

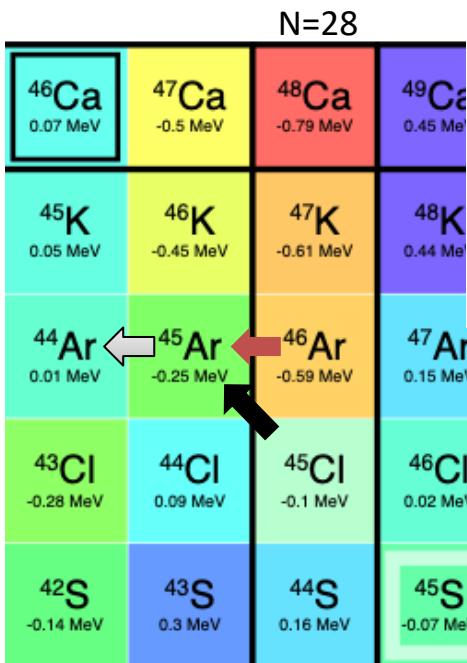


- Degeneracy of proton  $s_{1/2}$  and  $d_{3/2}$  orbitals due to addition of  $f_{7/2}$  neutrons[1]
- Going from spherical ( $Z=20$ ) to island of inversion ( $Z \approx 14$ )
- Region of rapid shape evolution [2,3]
- Testing ground for theoretical models
- Developing experimental methods for studying drip line nuclei
- $\beta^-$  decay measurements complement and expand on reaction studies

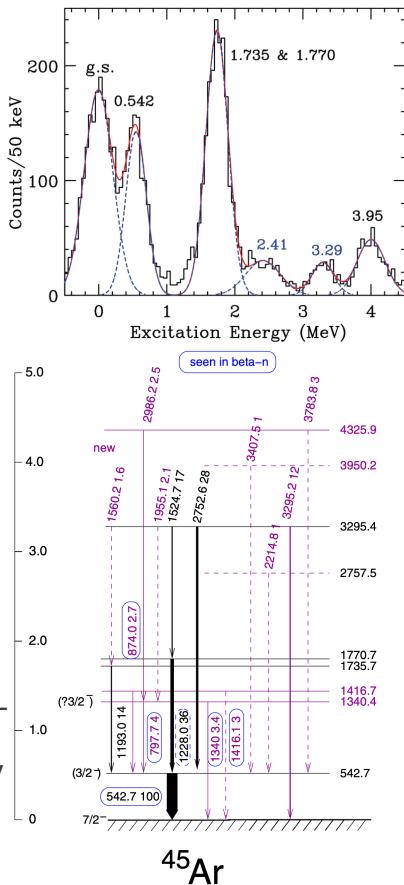
<https://people.physics.anu.edu.au/~ecs103/chart/>  
Chinese Physics C 45, 030002 (2021)

- [1] R. K. Bansal and J. B. French **Phys. Lett.** **11** (1964)  
 [2] F. Sarazin, et al. **PRL** **84** (2000)  
 [3] C. Force, et al. **PRL** **105** (2010)

# Studying Neutron Hole States $^{45}\text{Ar}$



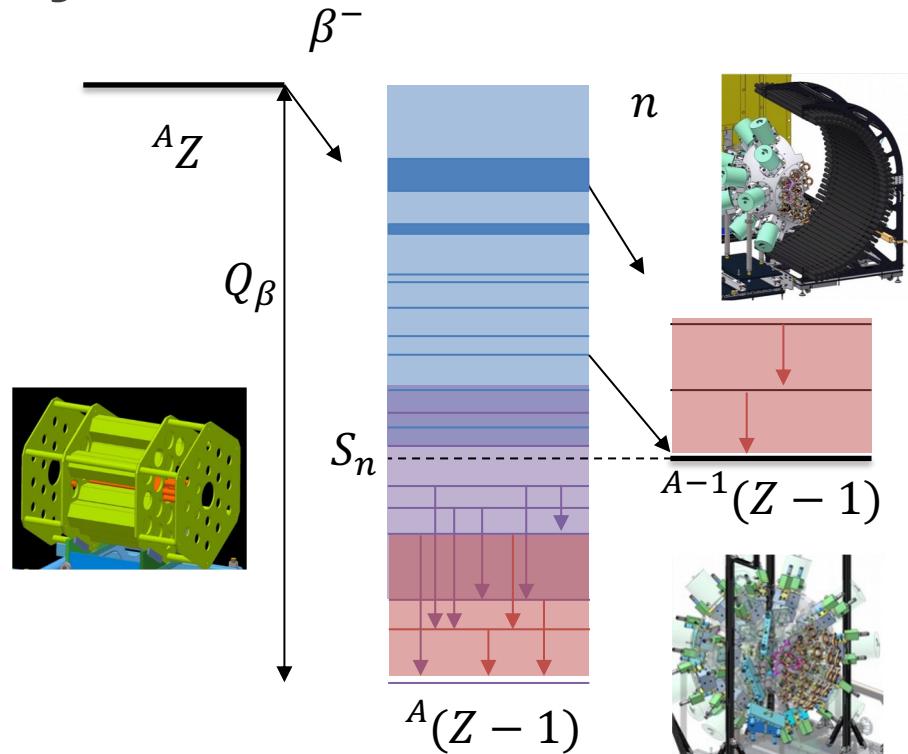
- $^{45}\text{Cl}$   $\beta^-$  decay



- $^{46}\text{Ar}(p, d) ^{45}\text{Ar}$  [4] (Red arrow)
  - Overlap between  $^{46}\text{Ar}$  GS to 1.735 and 1.770 MeV states, assigned  $3/2^+$  and  $1/2^+$  respectively
  - Indicates reduction of neutron shell gaps
  - Previous  $\beta^-$  decay measurements at GANIL:
    - O. Sorlin, et al. **PRC 47**, 6 (1993)
    - S. Grévy, et al. **Phys. Lett. B 594** (2004)
    - J. Mrázek, et al. **Nuc. Phys. A 734** (2004)
  - Level energy,  $I_\gamma$  in  $^{45}\text{Ar}$
  - $t_{1/2}$ ,  $P_n$  of  $^{45}\text{Cl}$ , compared with QRPA
  - Need to measure  $\beta$  intensity + states above  $S_n$

# FDSi Two Focal Plane System

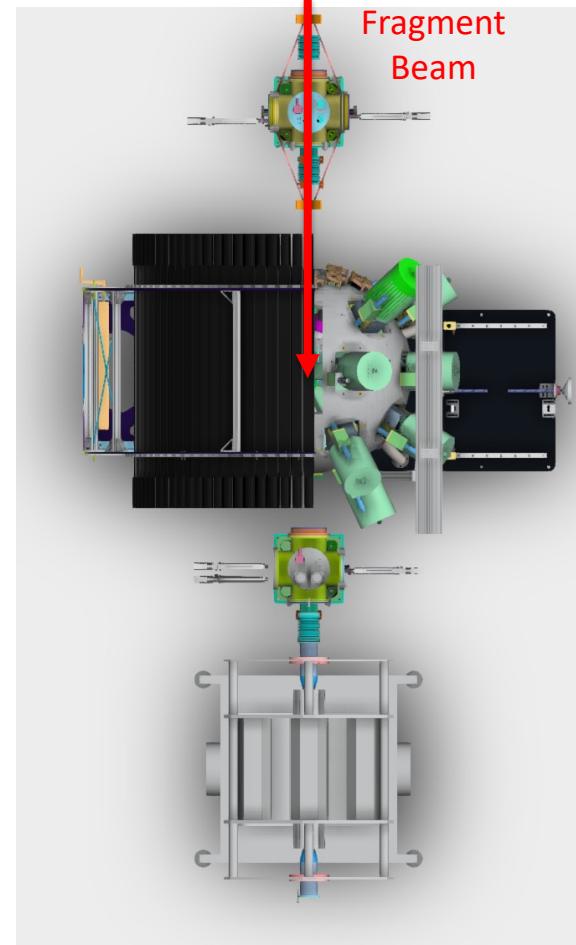
- FRIB Decay Station Initiator (FDSi)
- High resolution  $\gamma$ -spectroscopy needed for precise energy measurements (**Red region**)
- Neutron spectroscopy allows for discrete state measurement above  $S_n$  (**Blue region**)
- Total absorption best at determining ground and excited state feeding, while also able to measure  $S_n$  threshold neutrons (**Purple region**)



<https://fdsi.ornl.gov>

# FRIB Decay Station Initiator

- $\text{Y}_2\text{SiO}_5$  (YSO) based implant detectors [5,6]
- 88 time-of-flight neutron detector modules (VANDLE)[7,8], arranged into double layers
- 13 HPGe clover  $\gamma$ -ray detectors
- 15  $\text{LaBr}_3$  scintillator  $\gamma$ -ray detectors [9]
- 2 Si “pin” detectors for particle identification
- Fast scintillating plastic for particle identification



[5] Yokoyama et al. **NIM A, 937** 93-97 (2019)

[6] H.L. Crawford, et al. **PRL 129** 212501 (2022)

[7] S. Paulauskas, et al. **NIM A, 737** (2014)

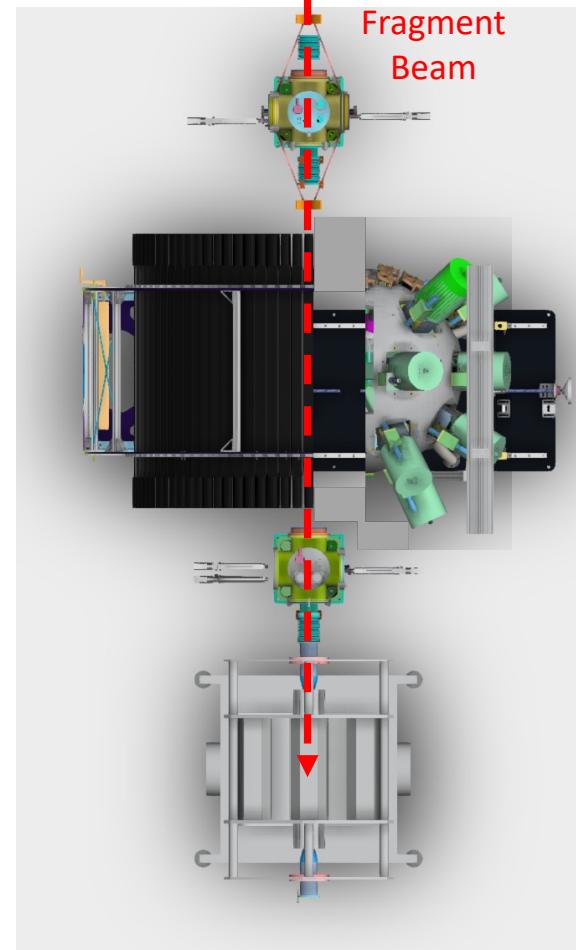
[8] W. Peters, et al. **NIM A, 836** (2016)

[9] K. Smith, et al. **NIM B, 414** (2018)

[10] M. Karny, et al. **NIM A, 836** (2016)

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- **2 Si “pin” detectors for particle identification**
- **Fast scintillating plastic for particle identification**
- **2<sup>nd</sup> focal plane: Modular Total Absorption Spectrometer (MTAS) [10]**
  - **New segmented central module**
  - **Implantation detector inside MTAS**



[5] Yokoyama et al. **NIM A, 937** 93-97 (2019)

[6] H.L. Crawford, et al. **PRL 129** 212501 (2022)

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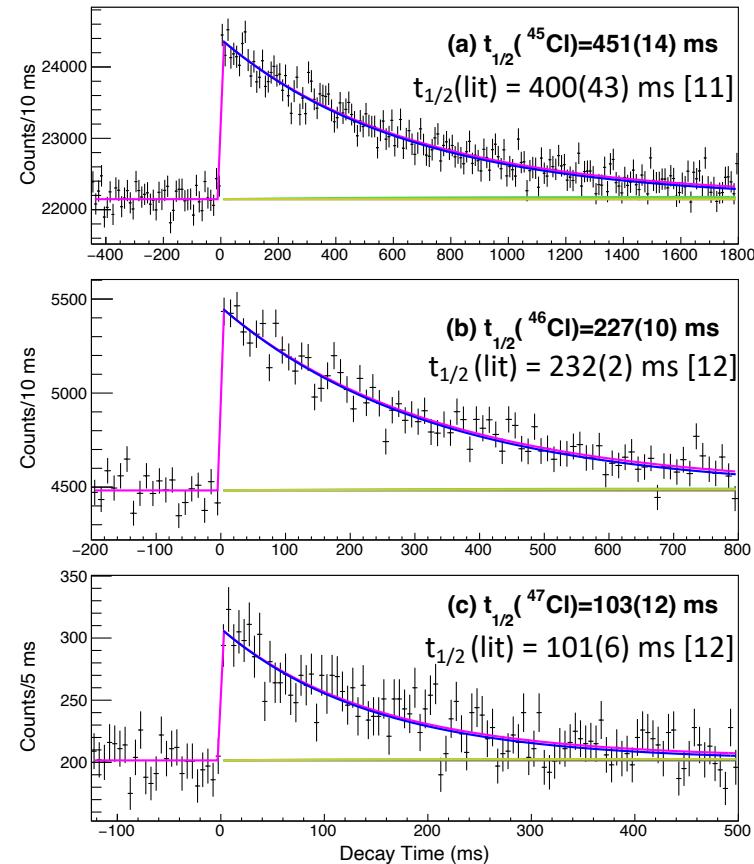
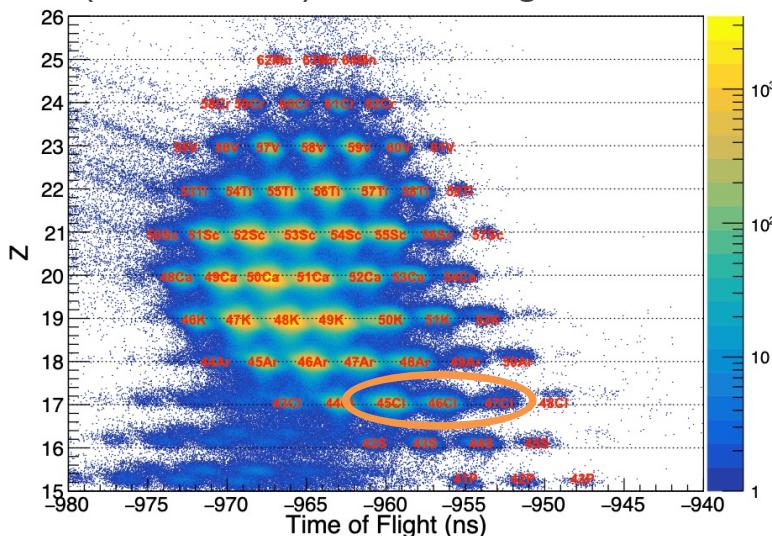
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[10] M. Karny, et al. **NIM A, 836** (2016)

# Experiment

- FRIB e21069 PI: Wei Jia Ong (LLNL)
- Beam setting focused on K isotopes allowed for the implantation of  $^{45-47}\text{Cl}$
- Beamtime of 7.5 days with 1kW  $^{82}\text{Se}$  beam (165 MeV/u) on  $^9\text{Be}$  target

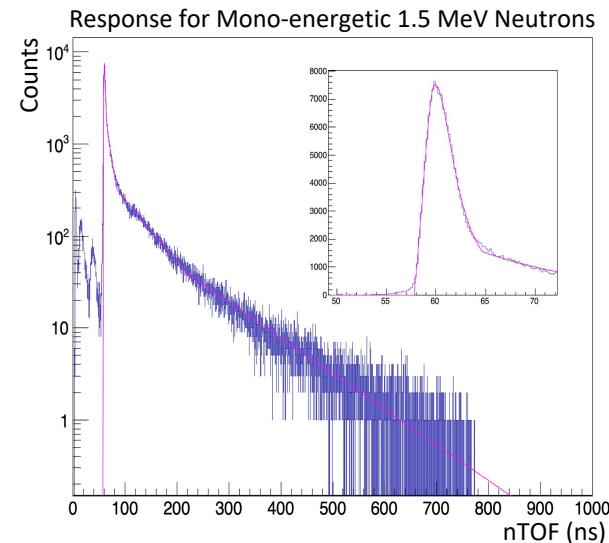
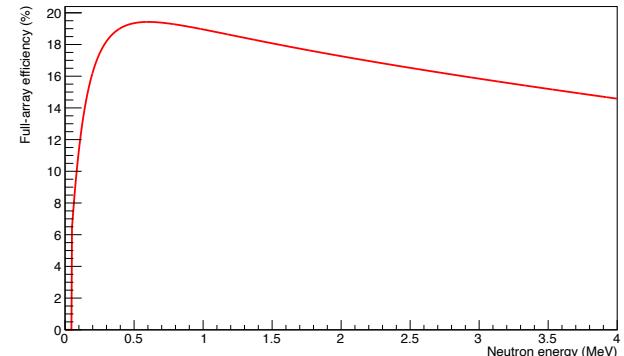
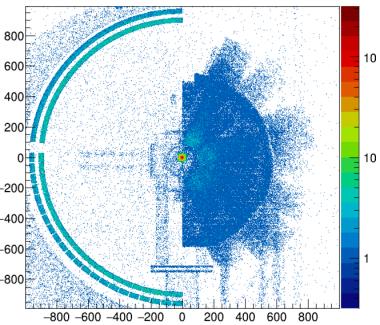
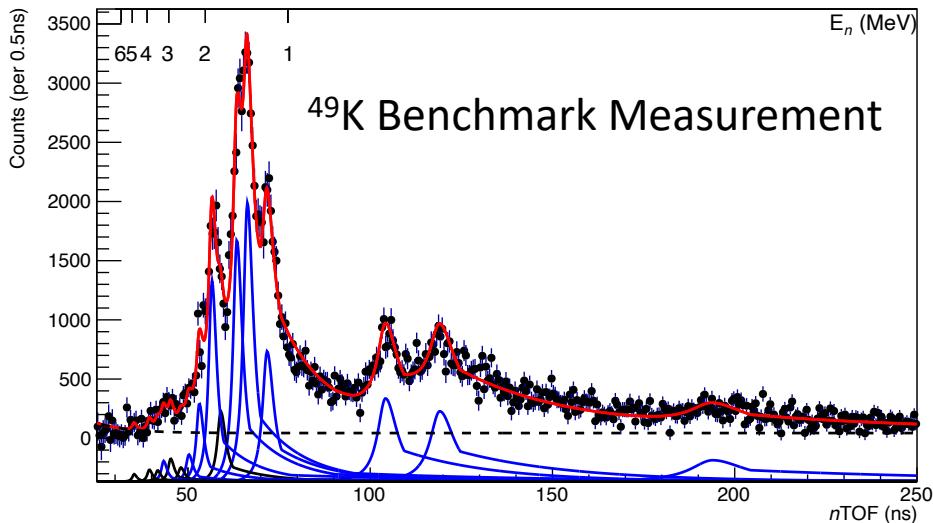


[11] O. Sorlin, et al. *Nuc. Phys. A* 583 (1995)

[12] S. Grévy, et al. *Phys. Lett. B* 594 (2004)

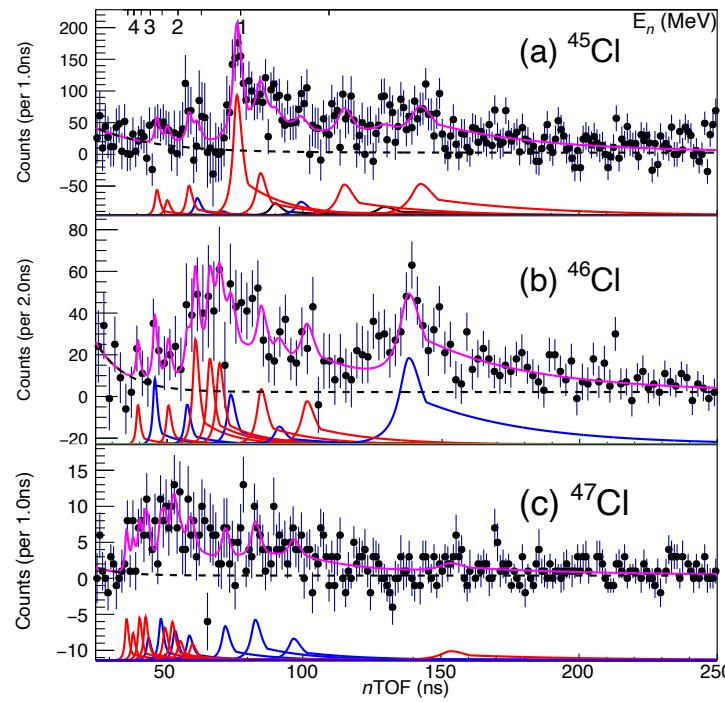
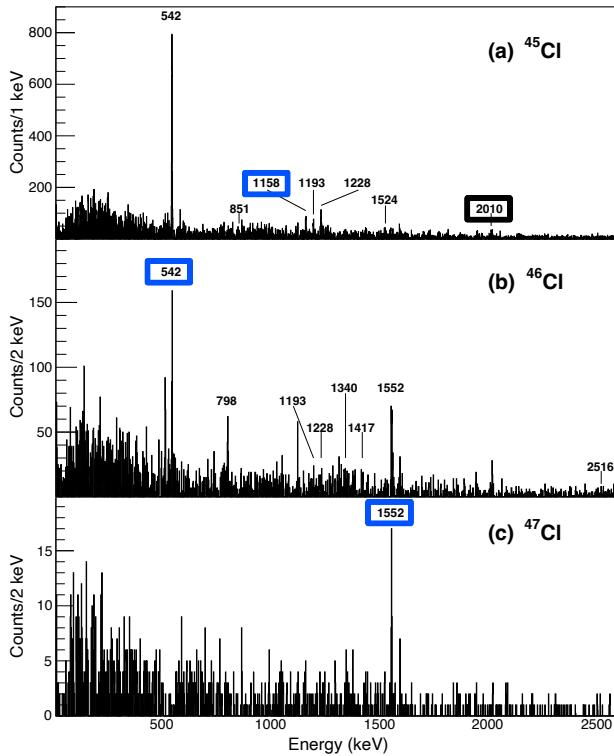
# Neutron Time-of-Flight Detector

- Geant4 simulations used to parametrize response function
- Calibrated Neutron detector array using  $^{49}\text{K}$  decay

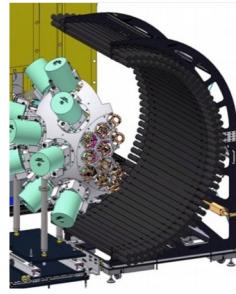


# Discrete Neutron and $\gamma$ -Spectroscopy

## First Focal Plane



Red – neutrons to GS  
Blue – neutrons to 1<sup>st</sup>  
Ex. State  
Black – neutrons to 2<sup>nd</sup>  
Ex. State  
Magenta - total fit

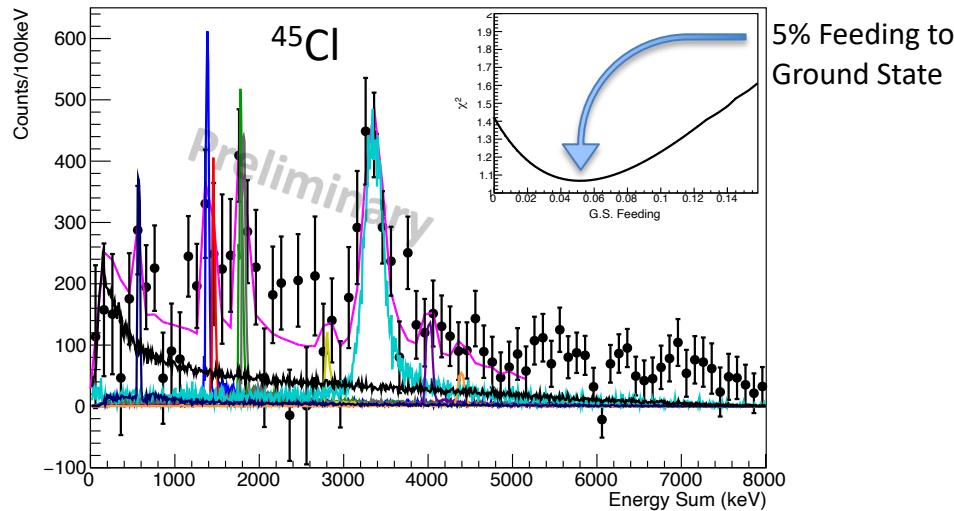
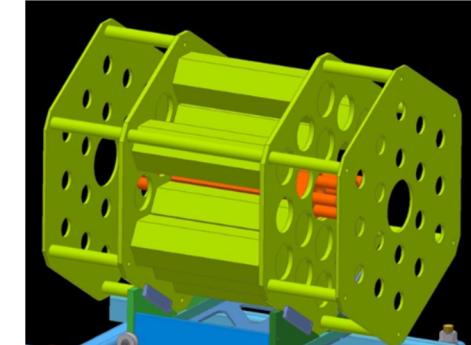


\*  $\gamma$ -rays agree with those reported in Grévy 2003 and Mrázek 2004

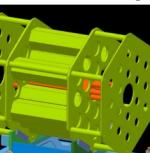
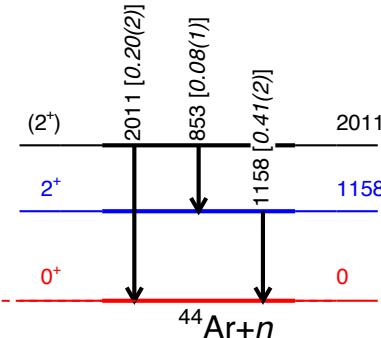
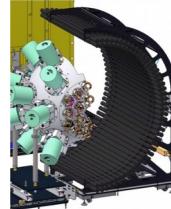
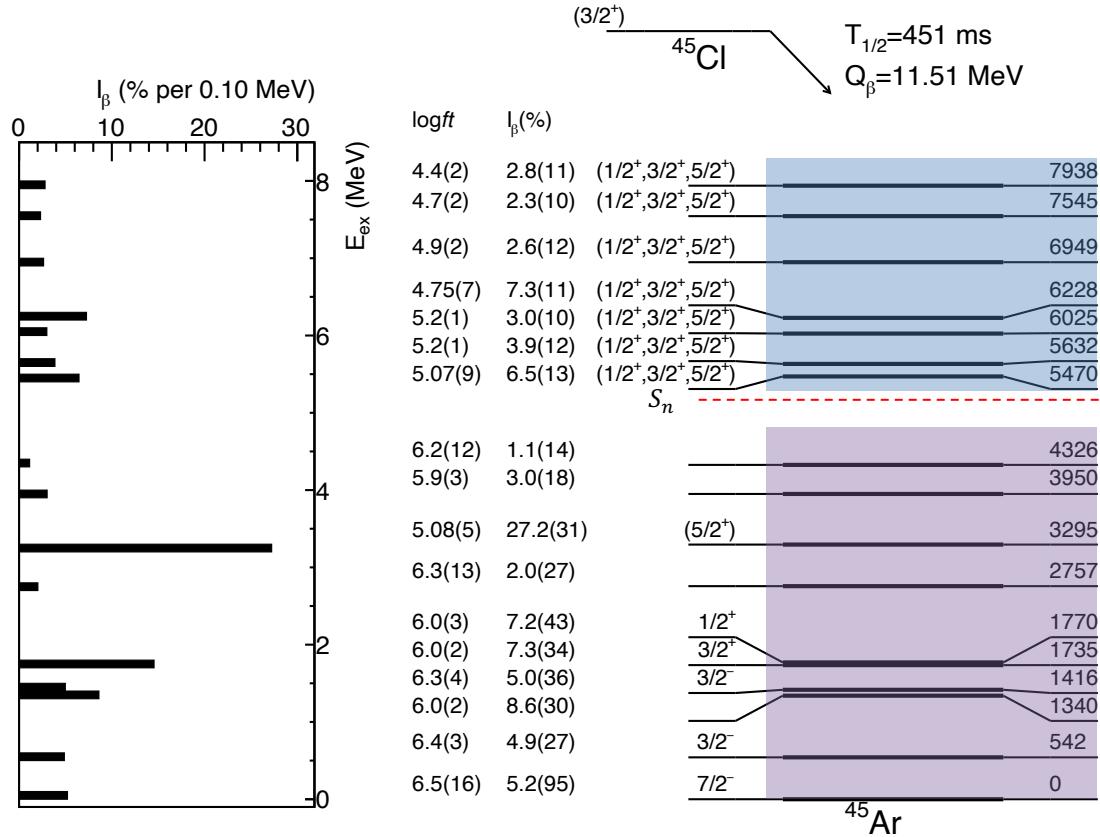
# Total Absorption Spectroscopy

## Second Focal Plane

- MTAS is 90% efficient detector
- First MTAS fragmentation experiment
- Geant4 simulations are used to deconvolute spectrum
- Provides pivotal insight into  $\beta$ -feeding below  $S_n$
- $\beta$ -particles measured in central module for GS-feeding
- New Implantation detector



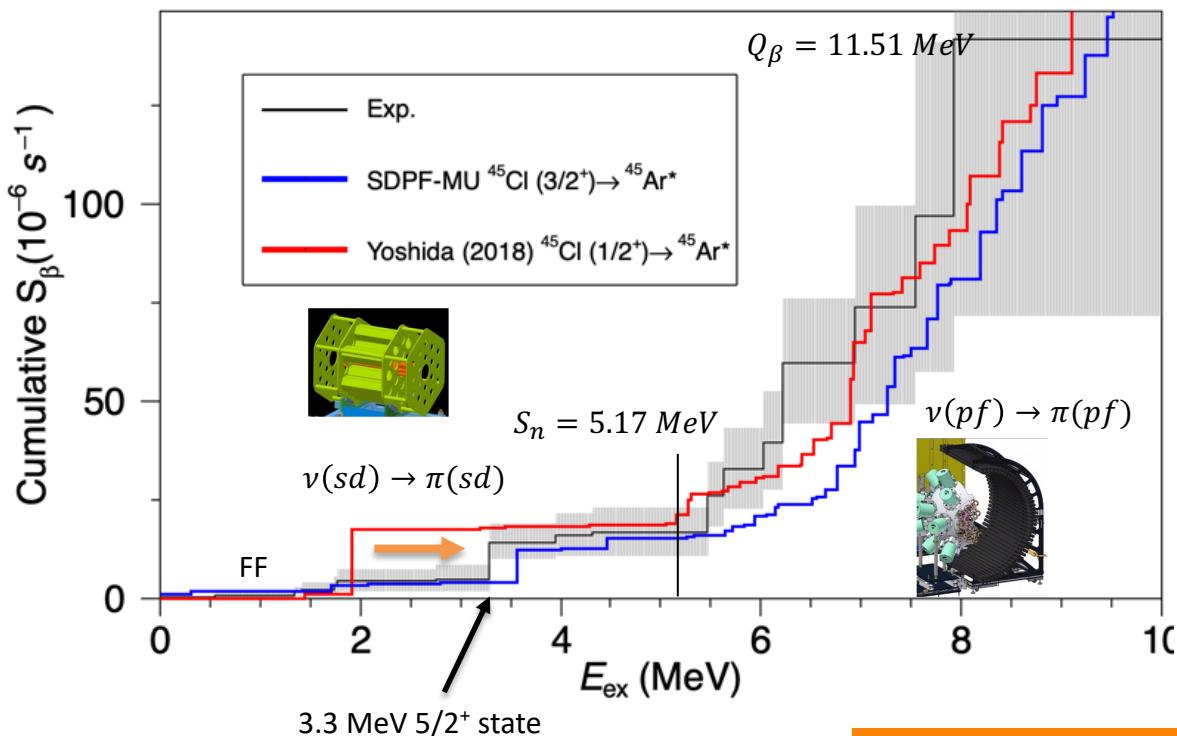
# Populating $^{45}\text{Ar}$ Excited States



- New measurement above  $S_n$
- First measurement of  $\beta$  intensity above and below  $S_n$  in single experiment

# $\beta$ Strength ( $S_\beta$ ) Distribution

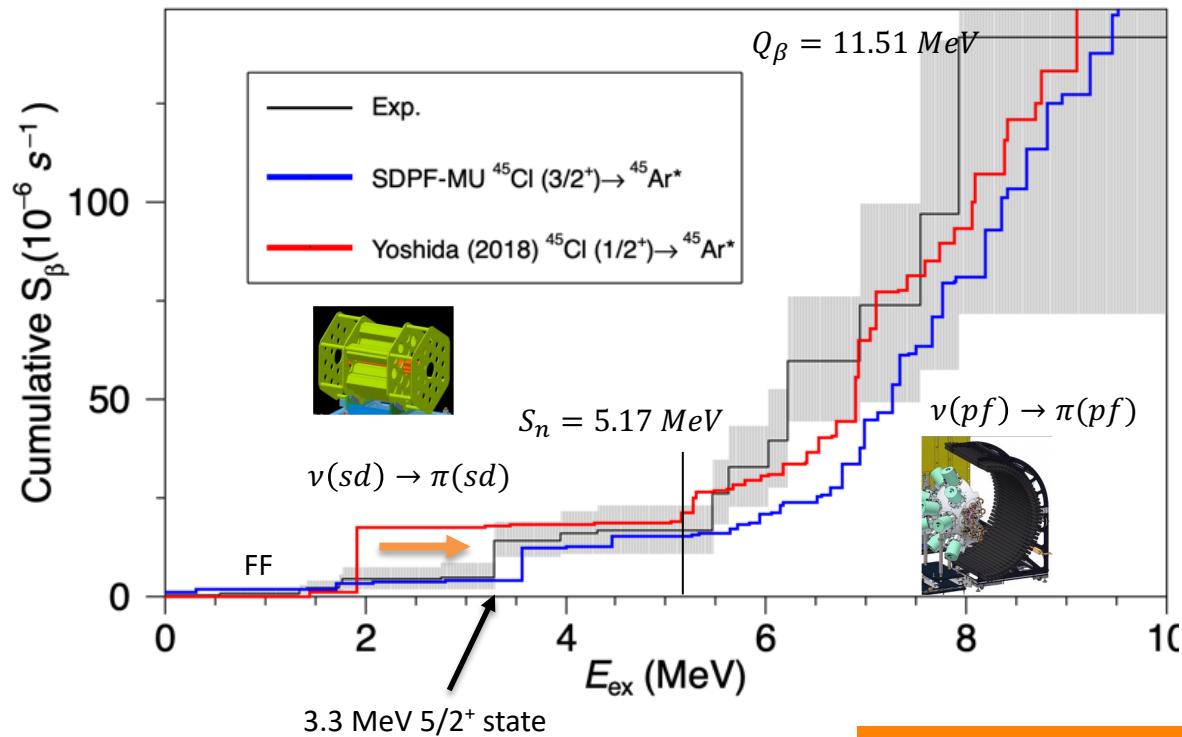
- Red – GT calculations from Yoshida, PRC (2018)
- Blue – SDPF-MU calculations with FF decays
- Measured both GT and FF decays
- Experiment agrees with  $3/2^+$  GS in  $^{45}\text{Cl}$ , proposed by [13]
- Strong feeding from  $^{45}\text{Cl}$   $3/2^+$  GS to  $5/2^+$  excited state in  $^{45}\text{Ar}$  near 3.5 MeV



[13] L. A. Riley, et al. PRC 86 (2012)

# $^{45}\text{Cl}$ Ground State

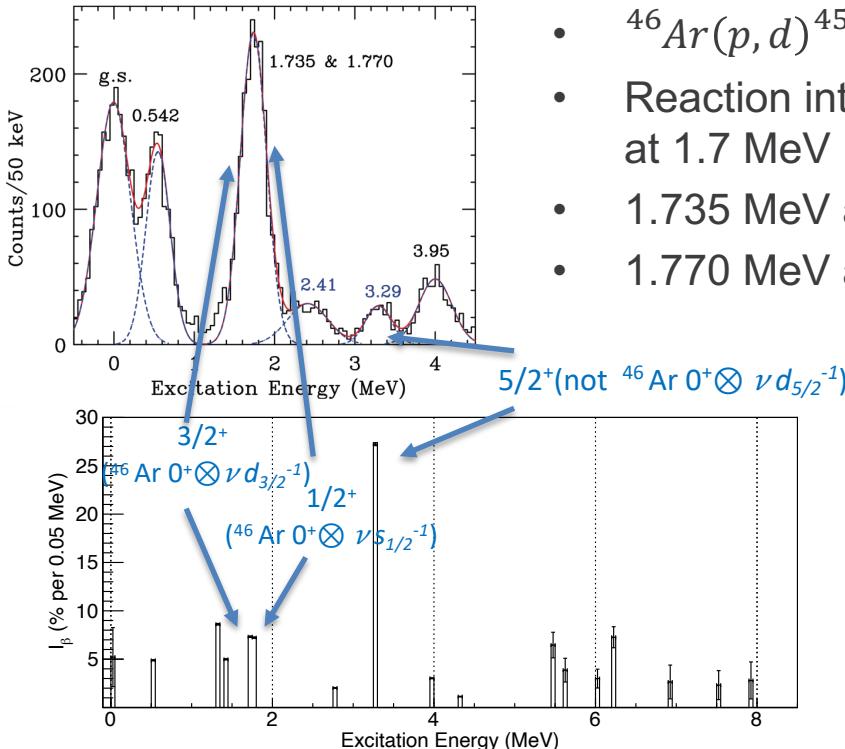
- Gade measured 127 keV 1<sup>st</sup> excited state in  $^{45}\text{Cl}$  [14]
- $^{45}\text{Cl}$  ground state (GS) of 1/2<sup>+</sup> based on Shell Model (SDPF-NR) predictions
- Experiments show inversion of 1/2<sup>+</sup> and 3/2<sup>+</sup> states in  $^{45}\text{Cl}$  [This work, 13]



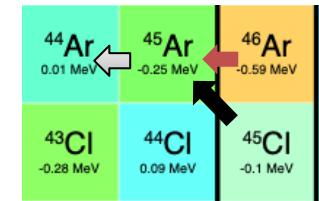
[13] L. A. Riley, et al. **PRC 86** (2012)

[14] A. Gade, et al. **PRC 74** (2006)

# Beta Decay and Direct Reactions to $^{45}\text{Ar}$



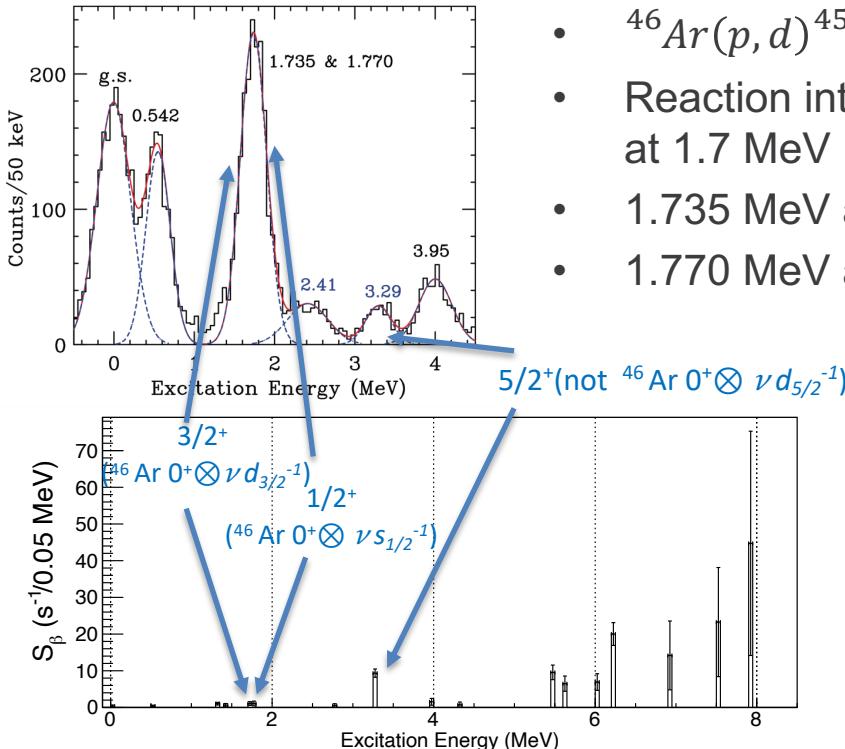
- $^{46}\text{Ar}(p, d)^{45}\text{Ar}$  [4] (Red arrow)
- Reaction intensity to lower states at 1.7 MeV [4]
- 1.735 MeV assigned to be  $3/2^+$
- 1.770 MeV assigned to be  $1/2^+$



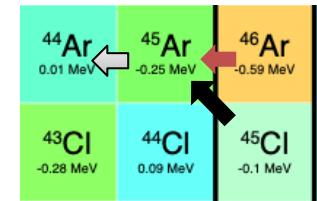
- $\beta^-$  decay to study  $^{45}\text{Ar}$
- Strong  $\beta^-$  intensity to the  $5/2^+$  3.3 MeV state instead of 1.7 MeV states
- Measured states above  $S_n$ 
  - Proton excitations above Z=20 shell
- Probing differences between  $^{45}\text{Cl}$  and  $^{46}\text{Ar}$

[4] F. Lu, et al. PRC 88 (2013)

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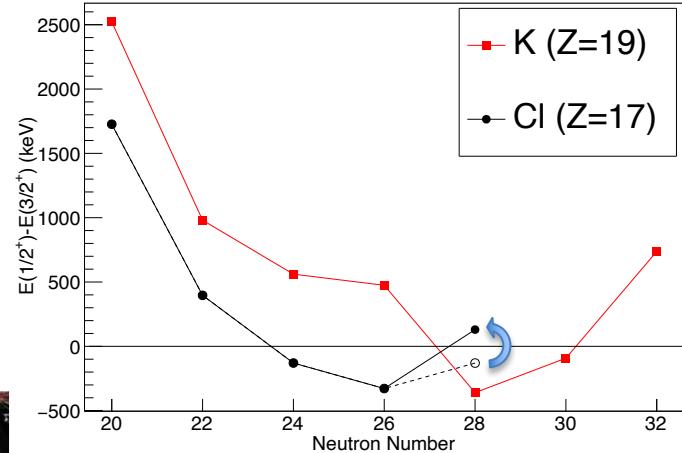
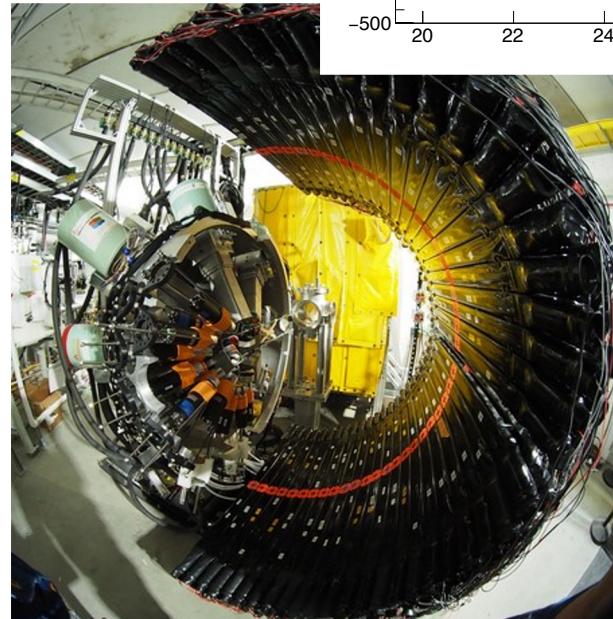


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- Probing differences between  $^{45}\text{Cl}$  and  $^{46}\text{Ar}$

[4] F. Lu, et al. PRC 88 (2013)

# Summary

- First implementation of two focal plane system at FDSi
- First measurements with MTAS at fragmentation facility
- Complete decay strength measurement up to 8 MeV in  $^{45}\text{Ar}$
- Full strength measurement allows for understanding of physics
- Theoretical predictions for  $3/2^+$  GS in  $^{45}\text{Cl}$  agree with strength better than  $1/2^+$  GS
- Future analysis of  $^{46,47}\text{Cl}$  decays and future experiments in Cl region



# Thank you

- FDSi Collaboration
- UTK – R. Grzywacz, Z. Xu, D. Hoskins, K. Siegl
- ORNL – B. Rasco, K. Rykaczewski, J. M. Allmond, T. King
- LLNL – W. J. Ong, S. Neupane, K. Kolos
- University of Tokyo (CNS) – R. Yokoyama, N. Kitamura
- FRIB – O. Tarasov, B. Sherrill, H. Schatz, R. Lubna
- U. of Warsaw – M. Karny, A. Fijalkowska
- This work is supported by:  
NNSA DOE DE-NA0003899 and DOE DE-FG02-96ER40983



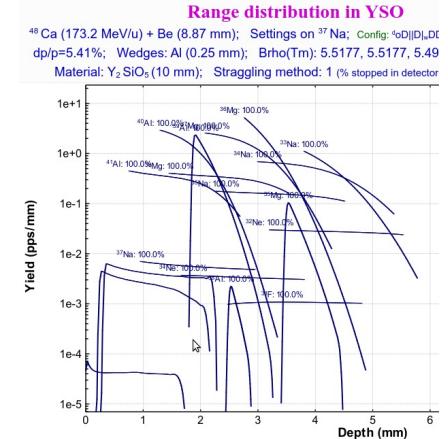
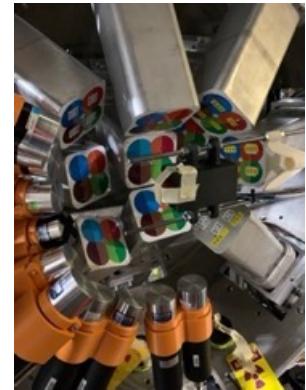
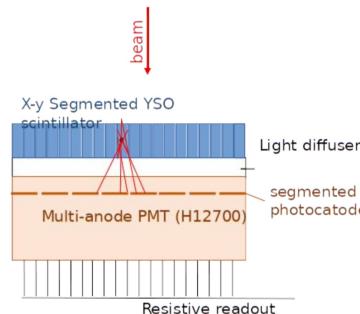
<https://fds.ornl.gov>



# Backup Slides

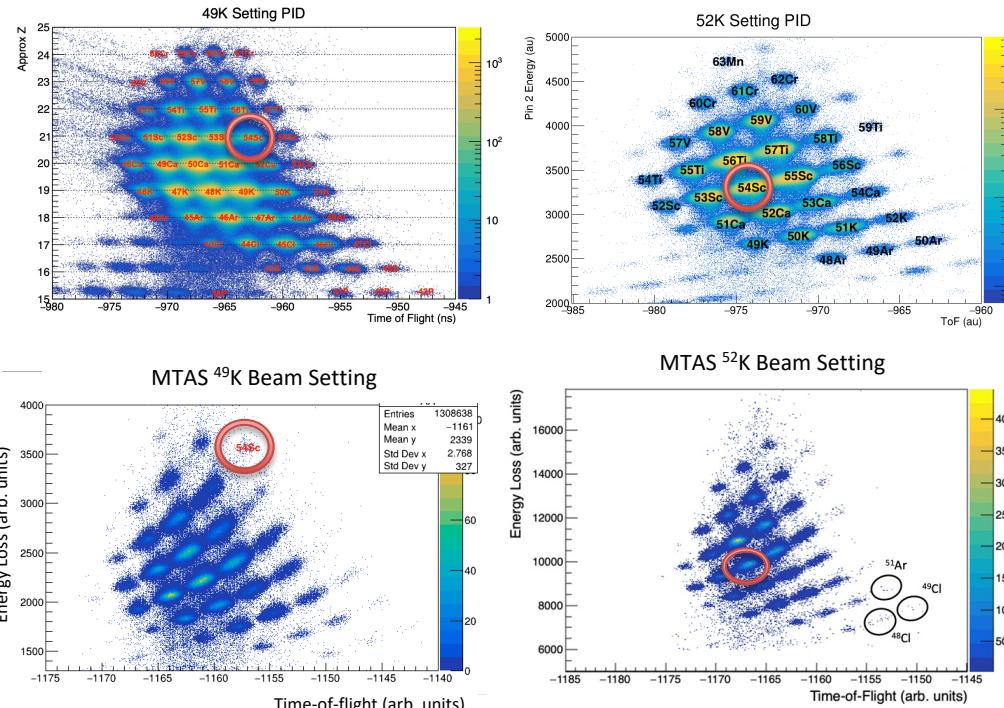
# Scintillator based implant detector

- Need good time and spatial correlations between implant and decay events
- Segmented scintillators enable small pixel size (1-2mm) for high position resolution [2,3]
- Fast timing (~500ps) allows for neutron time-of-flight measurements or fast beta-gamma correlation
- High stopping power of inorganic scintillators ( $Z_{eff} \sim 30$ ,  $\rho \approx 5 \text{ g/cm}^3$ ) enables implantation of wide range of isotopes in a single detector



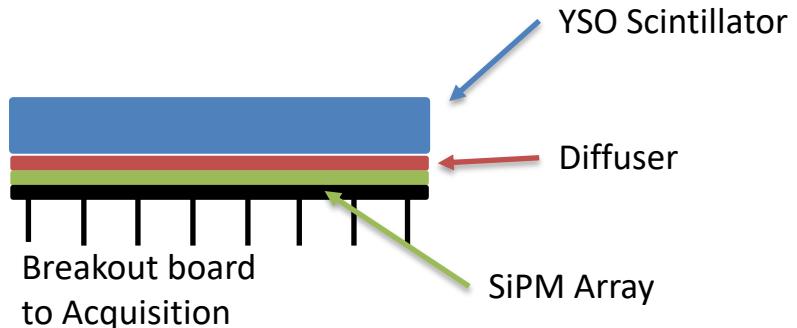
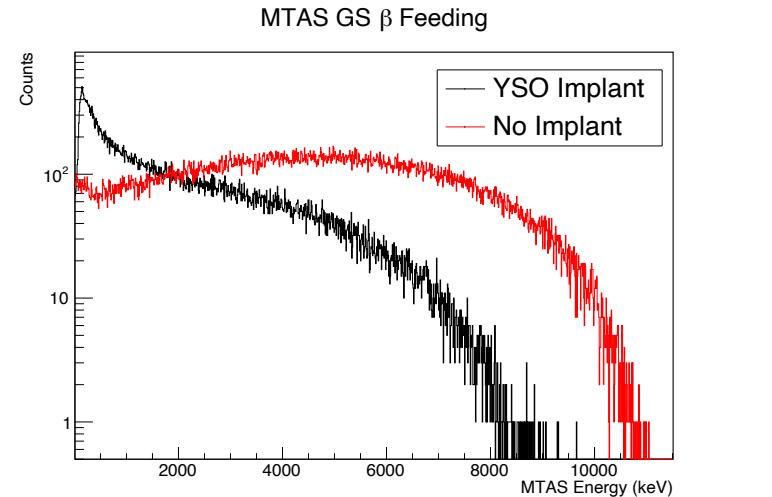
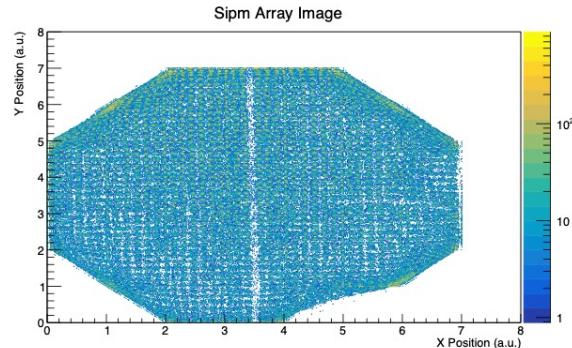
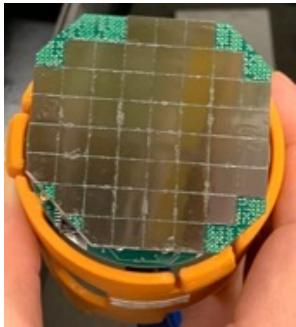
# Beamtime

- 7 days 9 hours total time
- 4 days 9 hours production beam
- $^{49}\text{K}$  Setting (Includes  $^{45-47}\text{Cl}$ )
  - 18 hours high resolution focal plane
  - 18 hours MTAS focal plane
- $^{52}\text{K}$  Setting (includes  $^{47,48}\text{Cl}$ )
  - 21 hours high resolution focal plane
  - 48 hours MTAS focal plane
- $^{54}\text{Sc}$  circled in each setting
- 140,000  $^{45}\text{Cl}$  beta-decays
- 30,000  $^{46}\text{Cl}$  beta-decays
- 3,000  $^{47}\text{Cl}$  beta-decays

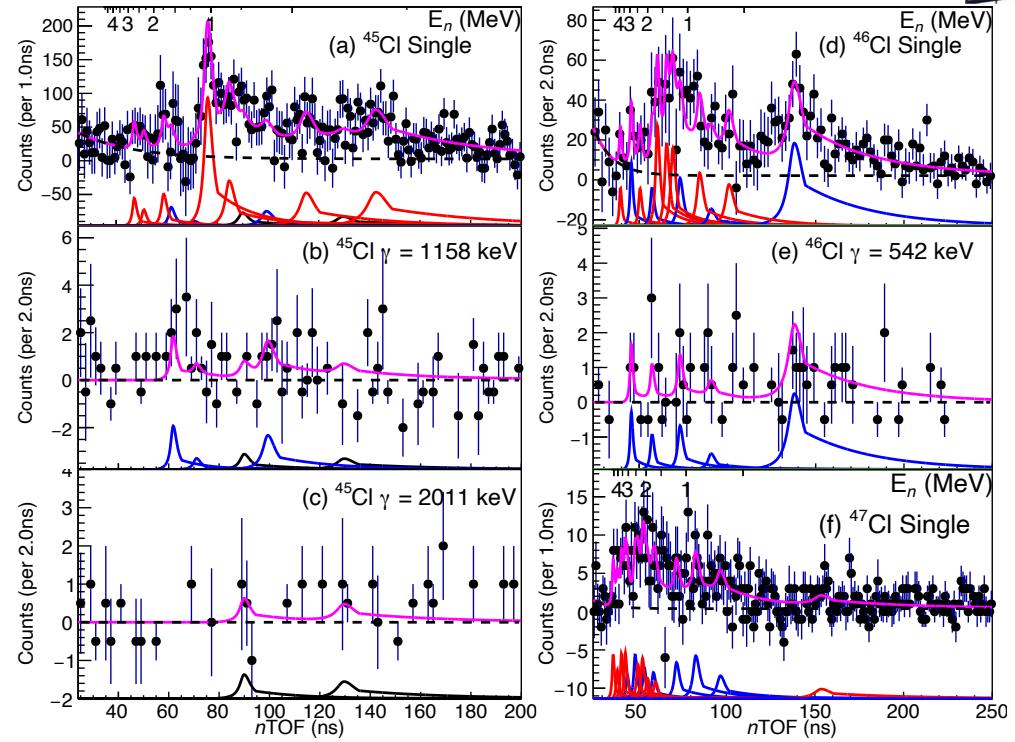
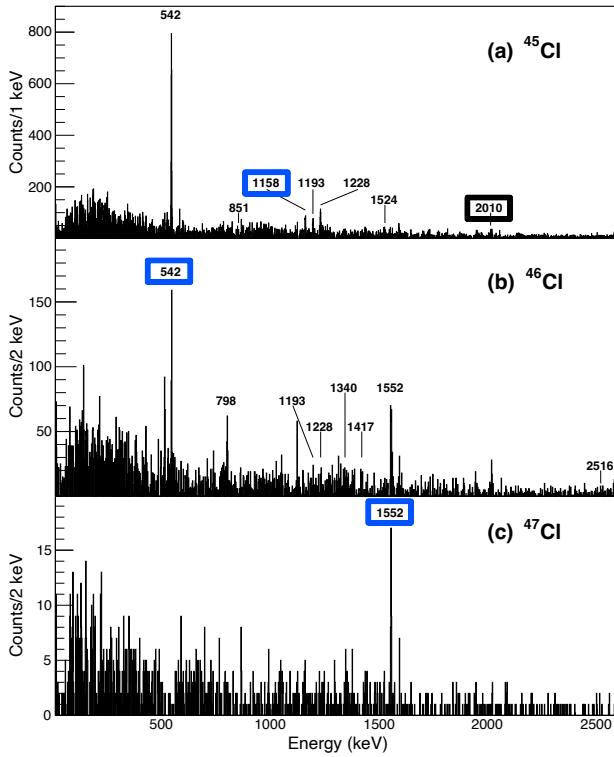
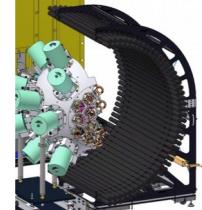


# MTAS Implant Detector

- Modified 8x8 Sensl SiPM array
- Vertilon breakout board
- 5mm thick YSO scintillator coupled to diffusers and SiPM array
- Diffusers allow for light sharing between pixels allowing for higher position resolution



# Discrete Neutron and $\gamma$ -Spectroscopy



\*  $\gamma$ -rays agree with those reported in Grévy 2003 and Mrázek 2004

# Gamma Transitions

# **45Cl 1/2+ GS**

- GT transition to  $1/2^+$  or  $3/2^+$
  - Unlikely transitions from  $1/2^+$ ,  $3/2^+$  to  $7/2^-$  GS

# **45Cl 3/2<sup>+</sup> GS**

- GT transition to  $1/2^+$ ,  $3/2^+$ , or  $5/2^+$
  - $5/2^+$  to  $7/2^-$  E1 transition
  - Seen by 3.3 MeV  $\gamma$ -ray

