Spectroscopy of ^{23}F Following a One-Neutron Removal Reaction

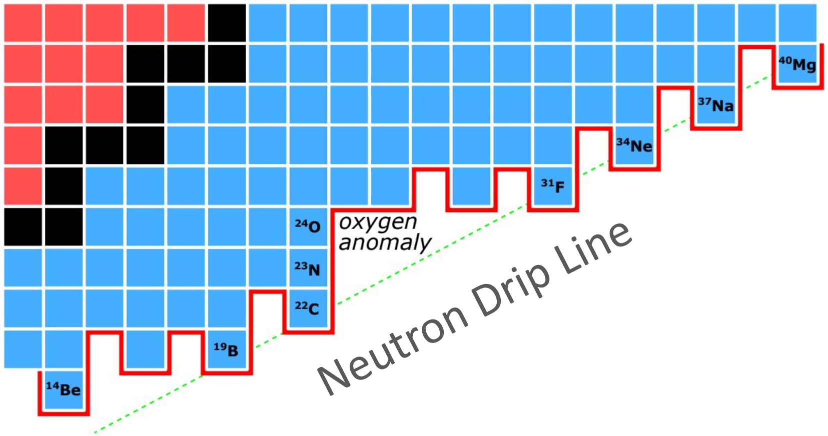
IOP Joint APP, HPP and NP Conference - 2024

Luke Tetley

10/04/2024

Light Neutron-Rich Nuclei

- Rich experimental testing grounds for nuclear models
  - Appearance of non-standard magic numbers (N=14 & N = 16)
  - Halo nuclei (^{11}Li & ^{11}Be)
  - Exotic decay modes (^{26}O 2n emission)

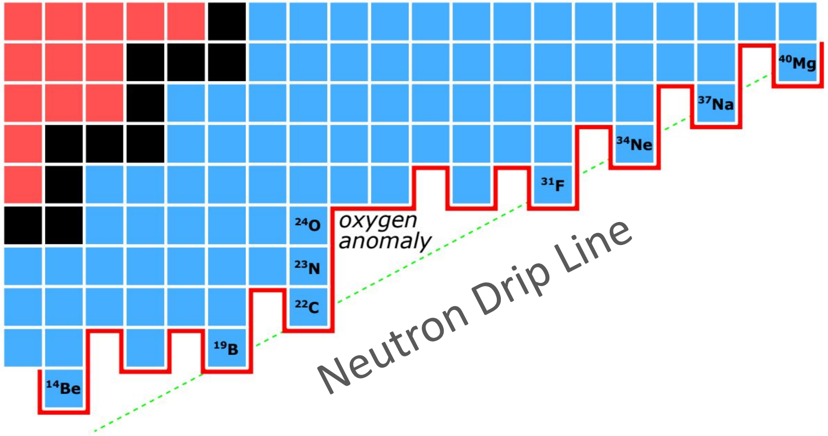


Light Neutron-Rich Nuclei

- Rich experimental testing grounds for nuclear models
  - Appearance of non-standard magic numbers (N=14 & N = 16)
  - Halo nuclei (^{11}Li & ^{11}Be)
  - Exotic decay modes (^{26}O 2n emission)

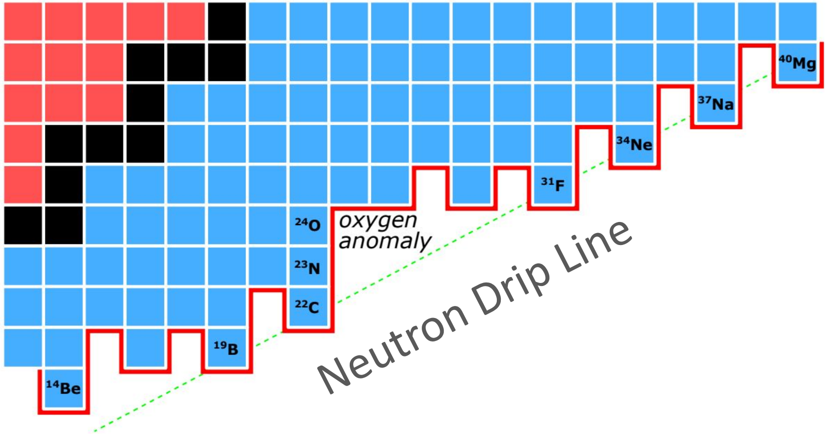
- Oxygen isotopic chain has had a notable role
  - Correct description of "oxygen anomaly" with inclusion of 3N forces

T. Otsuka *et al.* / Phys. Rev. Lett. **105** (2010)
H. Hergert *et al.* / Phys. Rev. Lett. **110** (2013)



Light Neutron-Rich Nuclei

- ➢ Rich experimental testing grounds for nuclear models
  - Appearance of non-standard magic numbers (N=14 & N = 16)
  - Halo nuclei (^{11}Li & ^{11}Be)
  - Exotic decay modes (^{26}O 2n emission)



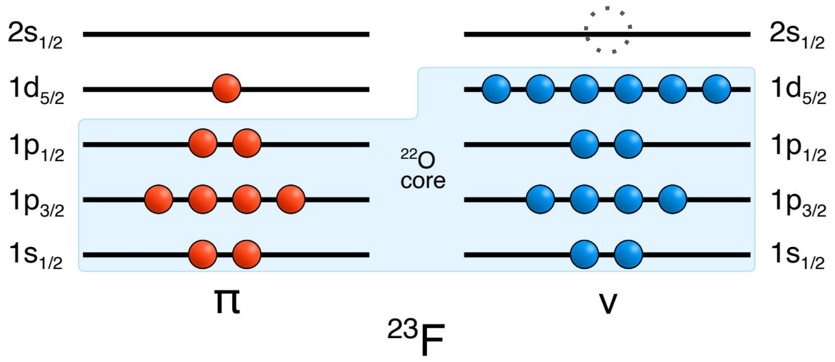
- ➢ Oxygen isotopic chain has had a notable role
  - Correct description of "oxygen anomaly" with inclusion of 3N forces

T. Otsuka *et al.* / Phys. Rev. Lett. **105** (2010)
H. Hergert *et al.* / Phys. Rev. Lett. **110** (2013)

- ➢ Region has proven critical for benchmarking nuclear interactions
  - Observables sensitive to the details of the nuclear interactions

Nuclear Structure of ^{23}F

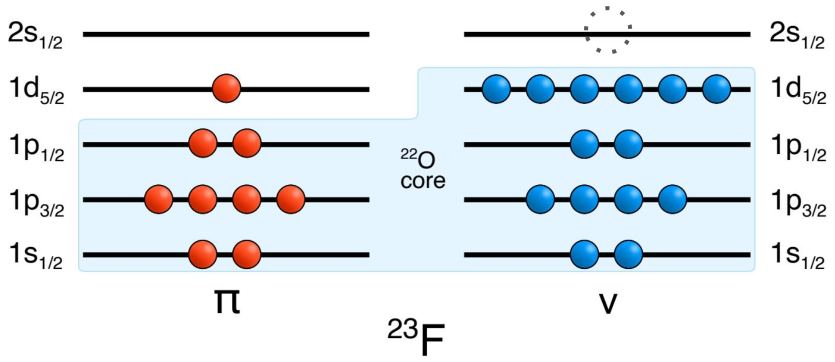
- Structure of a single valence proton outside of ^{22}O core (Z=8, N=14)
  - Study of S.P. degrees of freedom on top of closed shell

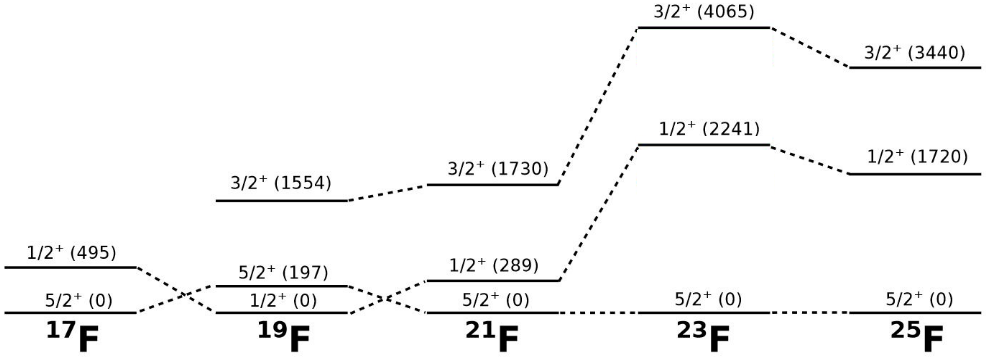


Nuclear Structure of ^{23}F

- Structure of a single valence proton outside of ^{22}O core (Z=8, N=14)
  - Study of S.P. degrees of freedom on top of closed shell

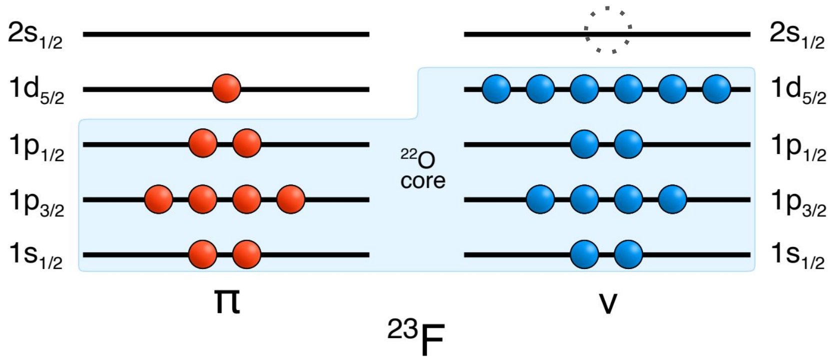
- Probe the role of the tensor force
  - Splitting the $\pi 1d_{5/2}$ - $\pi 2s_{1/2}$ via occupancy of neutron shells
  - Changes in S.P. structure linked to tensor force

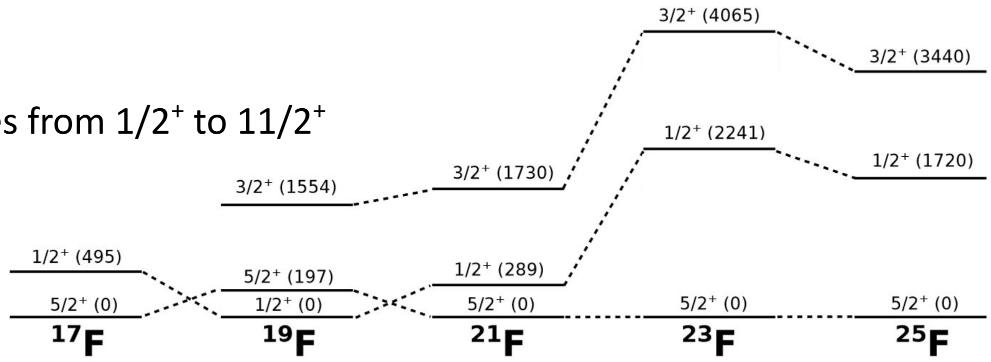




Nuclear Structure of ^{23}F

- Structure of a single valence proton outside of ^{22}O core (Z=8, N=14)
  - Study of S.P. degrees of freedom on top of closed shell
- Probe the role of the tensor force
  - Splitting the $\pi 1d_{5/2}$ - $\pi 2s_{1/2}$ via occupancy of neutron shells
  - Changes in S.P. structure linked to tensor force
- One-neutron KO of ^{24}F should populate states from $1/2^+$ to $11/2^+$
  - From ^{24}F g.s. 3^+ coupled to $\nu 1d_{5/2}$

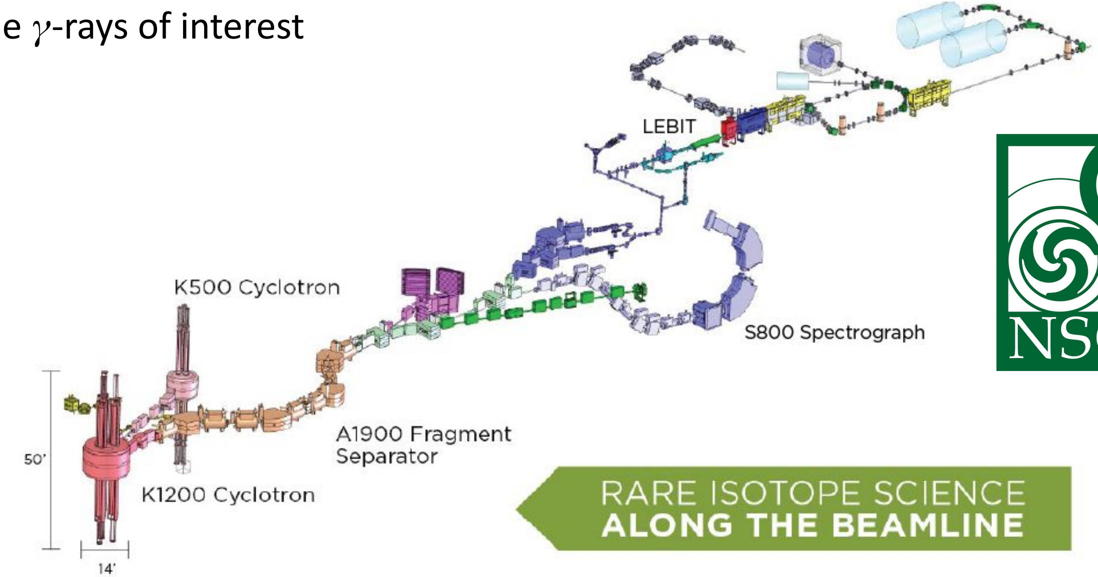




Experiment Overview

- Nuclear excited states of ^{23}F investigated via in-beam γ-ray spectroscopy following 1n removal of a ^{24}F beam

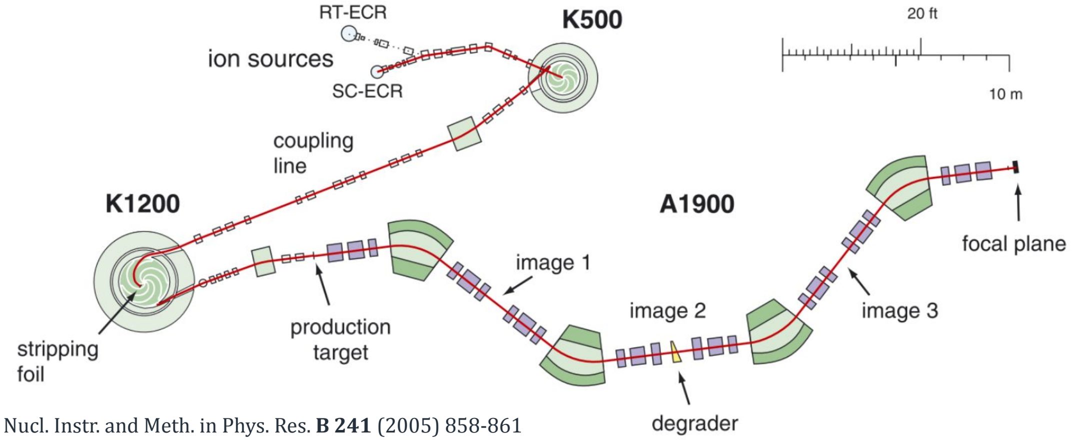
- Measurement was carried out at NSCL, using GRETINA coupled to the S800 spectrograph to measure the γ-rays of interest



Experiment Details - Beam Delivery

- 95 AMeV ^{24}F beam (95% purity) delivered by A1900
  - Via ^{48}Ca primary beam fragmentation on a 893 mg/cm^2 ^{9}Be primary target
  - Accelerated by K500 and K1200 coupled cyclotrons

- ^{24}F fragments directed at 370 mg/cm^2 ^{9}Be secondary target
  - Wherein the 1 neutron removal reactions took place
  - Target shifted 13 cm upstream from nominal position

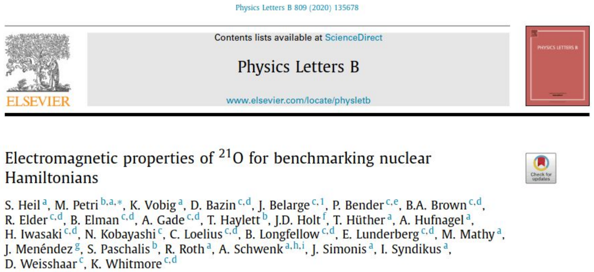


A. Stolz *et al.* / Nucl. Instr. and Meth. in Phys. Res. **B 241** (2005) 858-861

To the secondary ^{9}Be target and GRETINA and the S800

Experiment Details - Beam Delivery

- ➢ 95 AMeV ^{24}F beam (95% purity) delivered by A1900
  - Via ^{48}Ca primary beam fragmentation on a 893 mg/cm^2 ^{9}Be primary target
  - Accelerated by K500 and K1200 coupled cyclotrons


Physics Letters B 809 (2020) 135678

Contents lists available at ScienceDirect

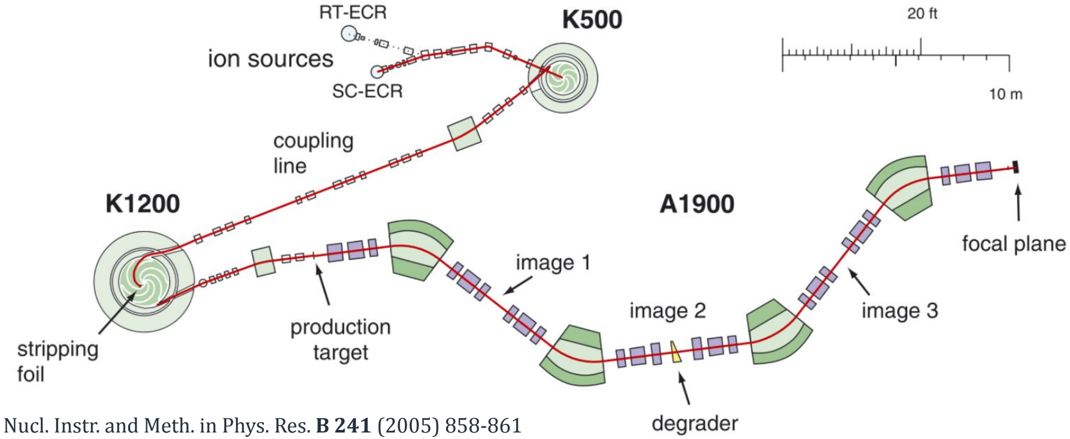
Physics Letters B

www.elsevier.com/locate/physletb

Electromagnetic properties of ^{21}O for benchmarking nuclear Hamiltonians

S. Heil[a], M. Petri[b,a,*], K. Vobig[a], D. Bazin[c,d], J. Belarge[c,1], P. Bender[c,e], B.A. Brown[c,d], R. Elder[c,d], B. Elman[c,d], A. Gade[c,d], T. Haylett[b], J.D. Holt[f], T. Hüther[a], A. Hufnagel[a], H. Iwasaki[c,d], N. Kobayashi[c], C. Loelius[c,d], B. Longfellow[c,d], E. Lunderberg[c,d], M. Mathy[a], J. Menéndez[g], S. Paschalis[b], R. Roth[a], A. Schwenk[a,h,i], J. Simonis[a], I. Syndikus[a], D. Weisshaar[c], K. Whitmore[c,d]

- ➢ ^{24}F fragments directed at 370 mg/cm^2 ^{9}Be secondary target
  - Wherein the 1 neutron removal reactions took place
  - Target shifted 13 cm upstream from nominal position

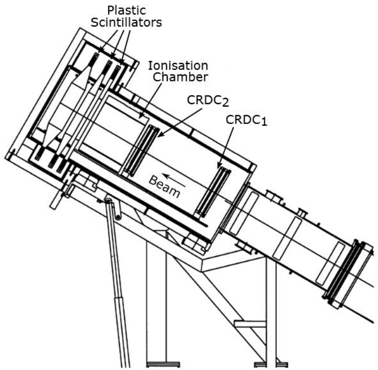


To the secondary ^{9}Be target and GRETINA and the S800

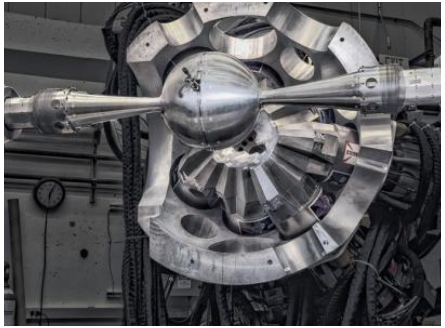
A. Stolz *et al.* / Nucl. Instr. and Meth. in Phys. Res. **B 241** (2005) 858-861

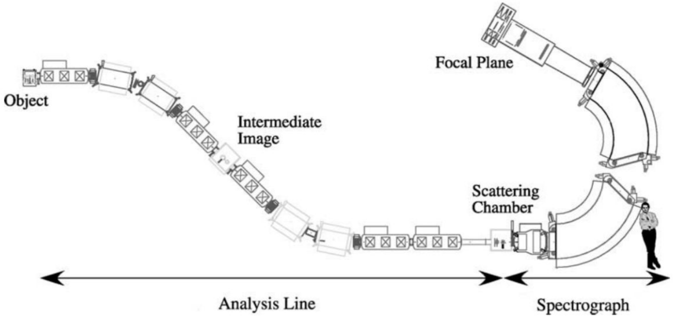
Experiment Details - GRETINA & S800

- γ-rays emitted in flight were detected by GRETINA
  - 9 modules available for this experiment, 1.2π solid angle coverage
  - Covering ~25^{o} to ~80^{o} w.r.t. target position
  - State-of-the-art tracking, enables good Doppler reconstruction



- The S800 used for the identification and tracking of outgoing fragments
  - Timing scintillators, CRDCs and IC at the focal plane

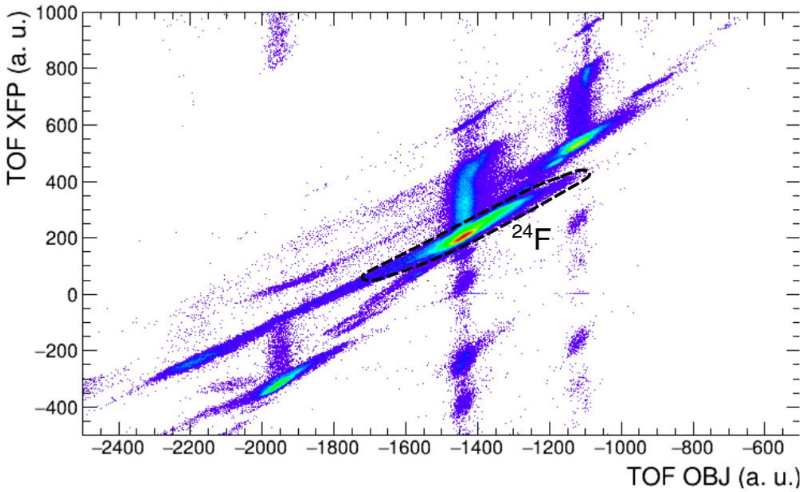


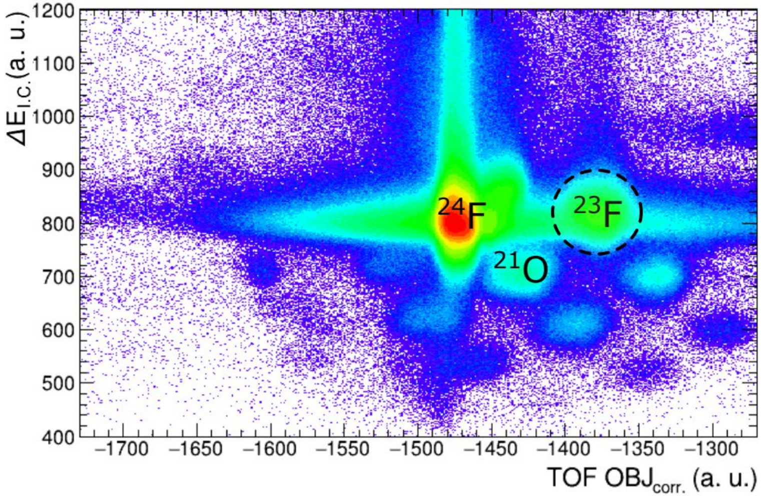


Particle Identification (PID)

- Incoming PID, TOFs between timing scintillators
  - Plastic scintillators at (OBJ) station, A1900 (Xfp) and S800 (E1) focal planes
  - Diagonal lines denote incoming fragments with same velocities

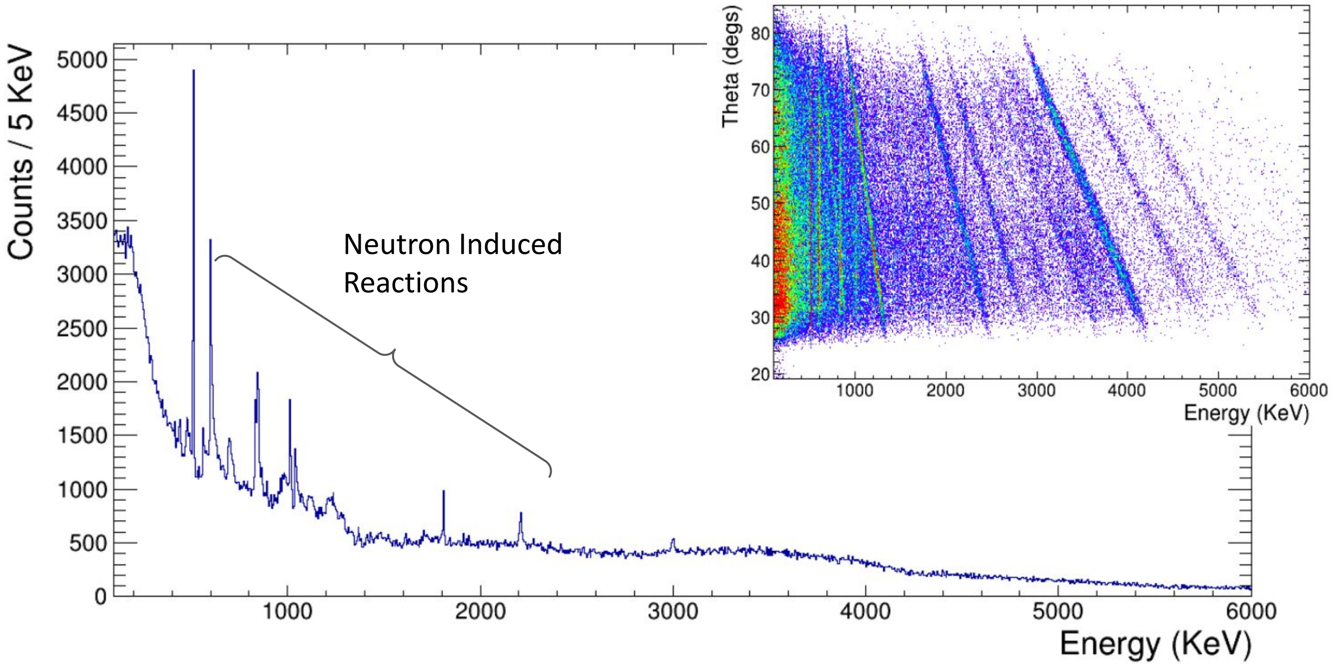
- Outgoing PID, energy loss in IC against TOF between OBJ and E1
  - TOF corrected for fragment trajectories through S800





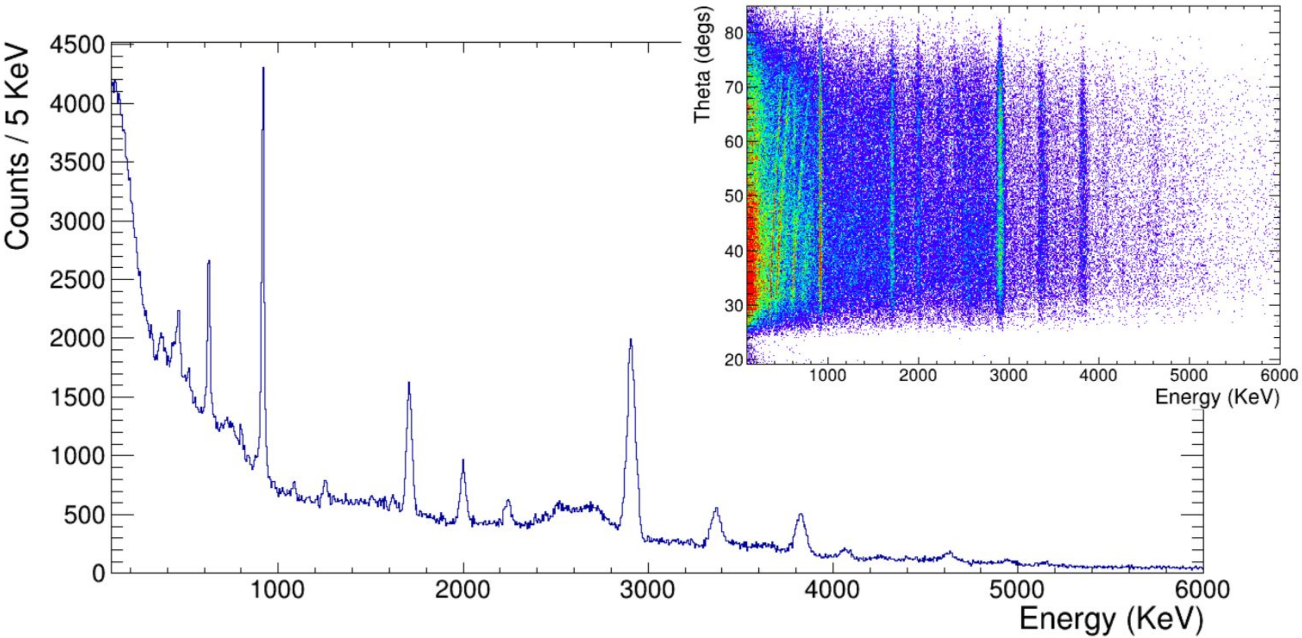
γ-ray Spectrum

- ➢ γ-rays decay in-flight at significant fraction of the speed of light
  - Angular dependence on γ-ray energy smears peaks



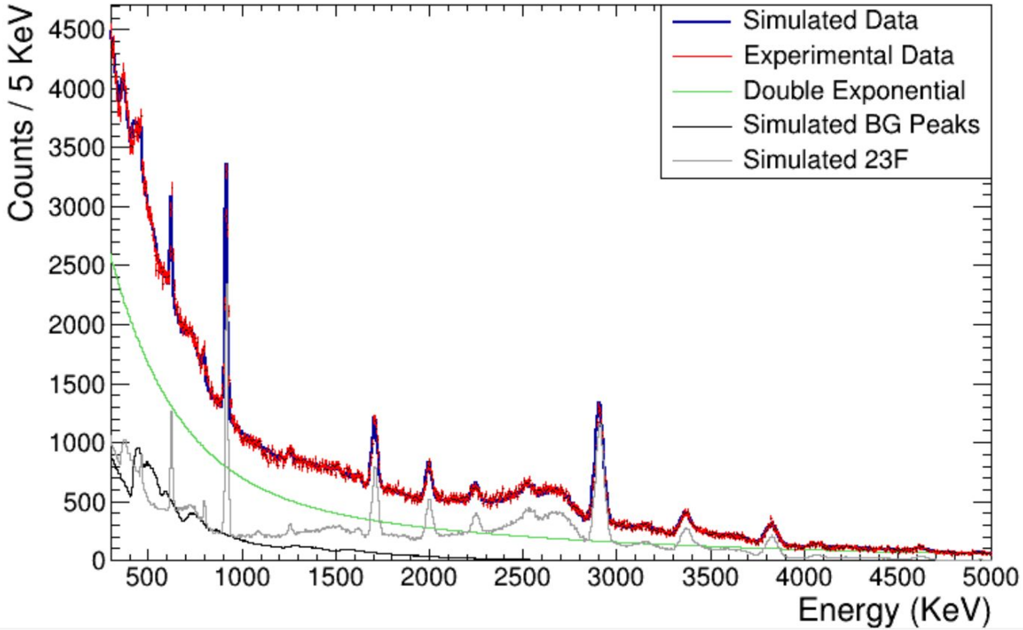
Doppler Corrected γ-ray Spectrum

➢ Doppler correction performed event-by-event
  - Average Doppler correction β = 0.4175, to remove energy-angle correlation
  - Beam direction from CRDCs at the S800 focal plane



GEANT4 Simulation Analysis

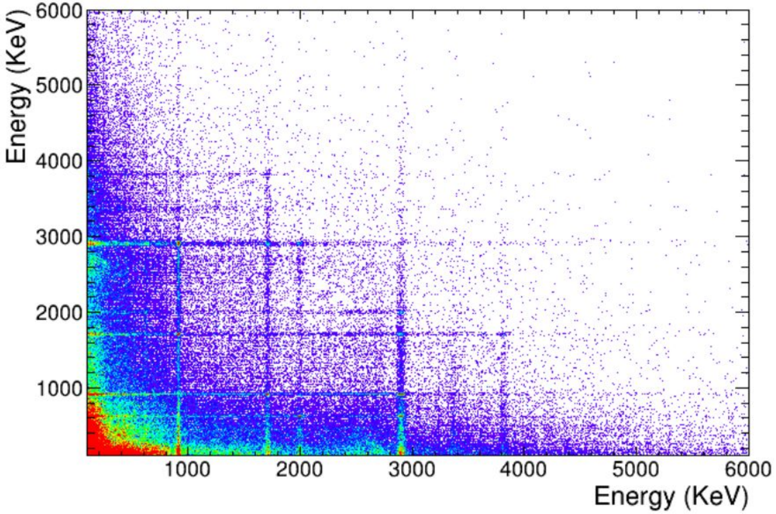
- Utilized detailed GEANT4 simulations to fully describe the spectrum
  - Correct detector response functions, materials and geometries
  - Simulated several background components, i.e neutron inelastic peaks, and a double exponential background function

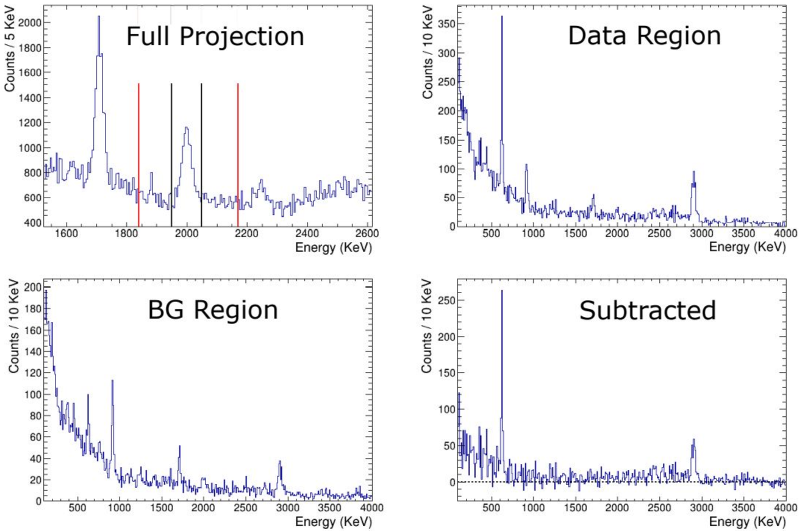


γ-γ Coincidence Analysis

- γ - γ coincidence matrix constructed to analyse the cascades
  - Background subtraction taken from gates adjacent to data gates

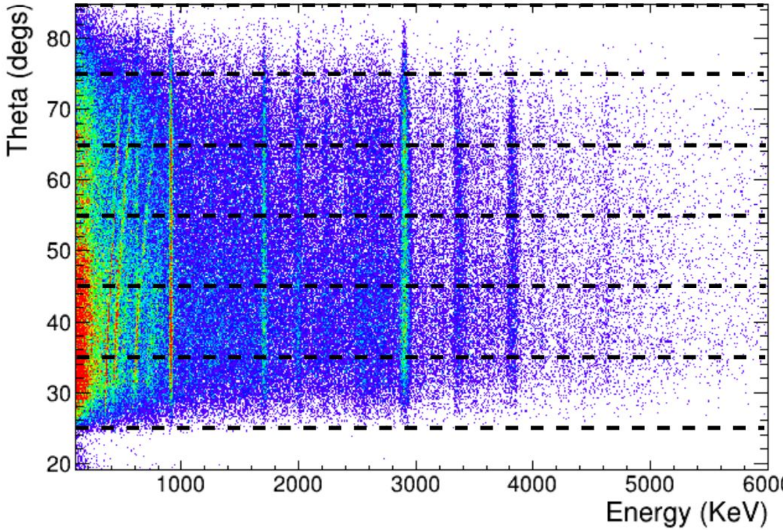
- Limited angular coverage of GRETINA (1.2π) impacts γ - γ efficiency
  - Only applicable to the most intense transitions

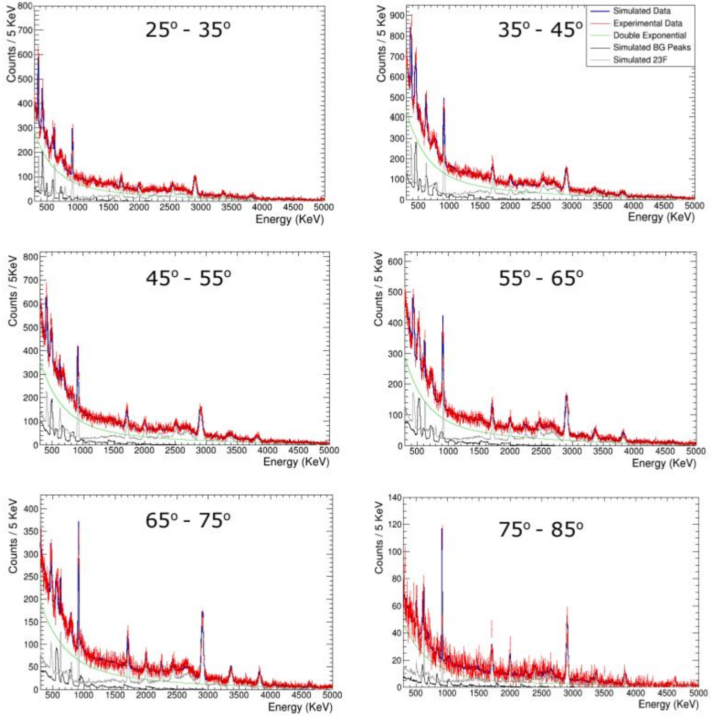




γ-ray Angular Distributions

- ➢ Slicing angular detection range and fitting spectra
  - Extraction of the experimental γ-ray angular distributions, in lab frame

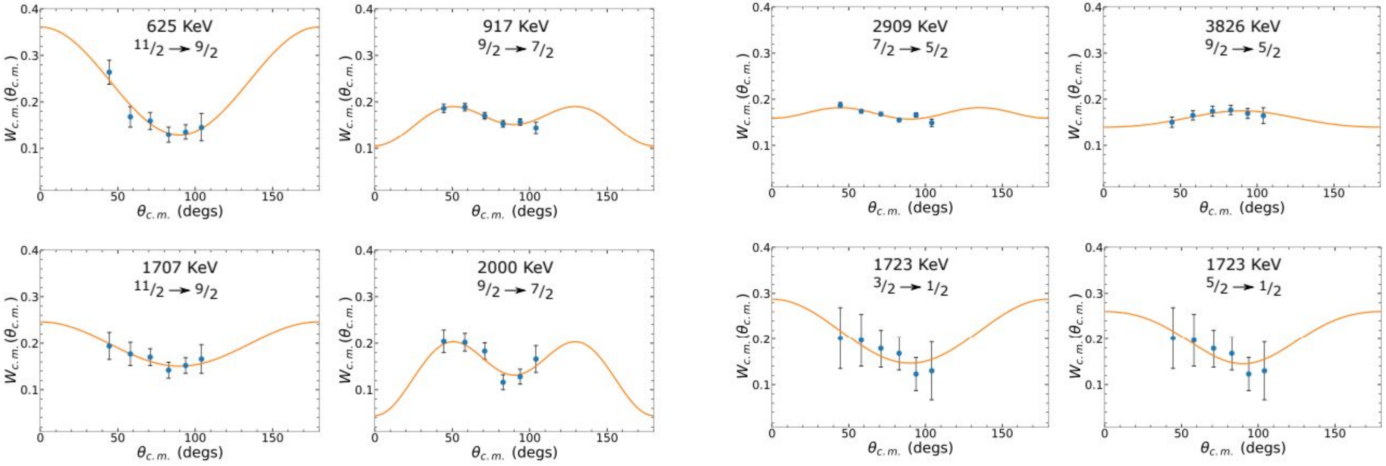




γ-ray Angular Distributions

- ➢ Calculated γ-ray angular distributions were fitted to the data
  - Converted to the C.M. frame
  - A range of distributions for M1 and E2 transition between spins of 1/2 and 11/2

- ➢ Enabled spin assignments to the states
  - Only for the most intense transitions

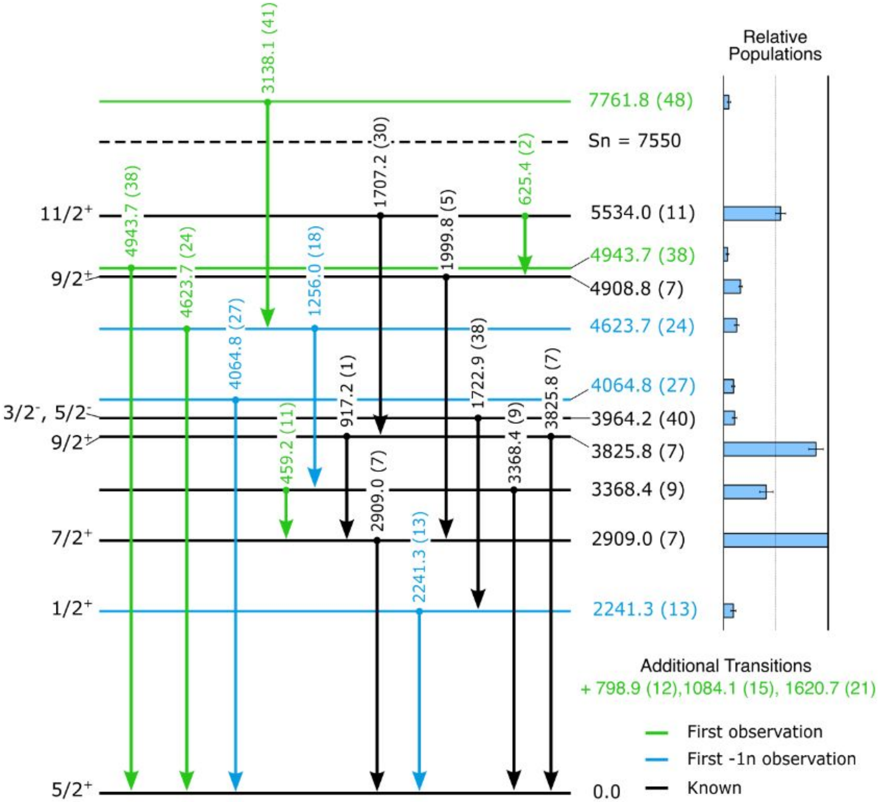


Thank you to Jeff Tostevin for the Angular Distribution calculations

Results

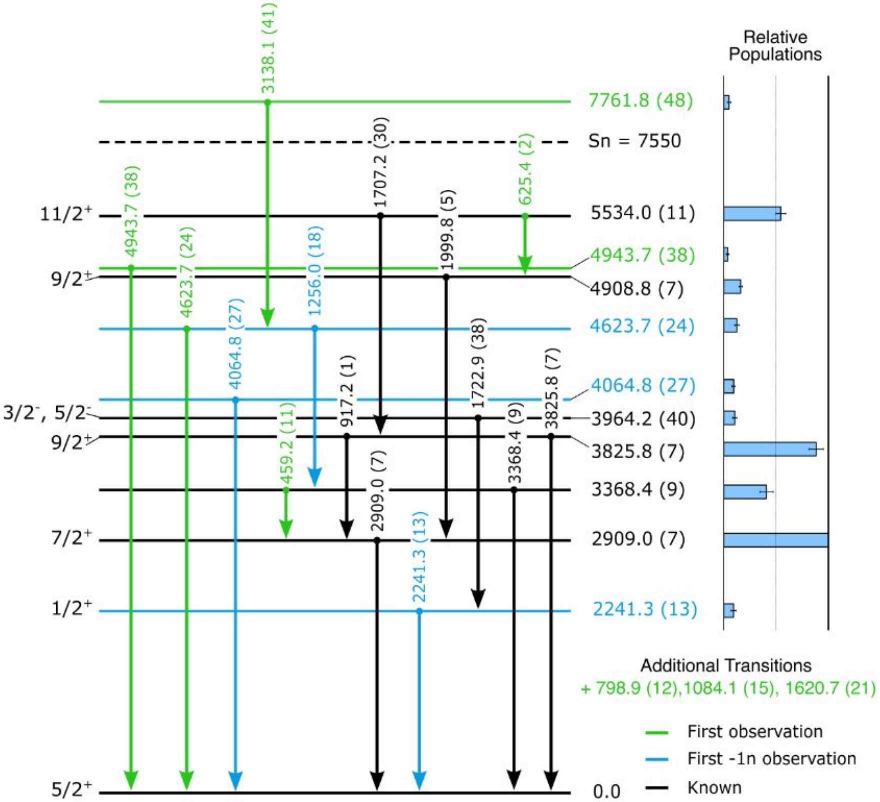
- First observation of several transitions predicted by theory
  - New BR data

- γ-ray angular distribution confirms spin assignments from;
  - Shell model (USD-type)
  - Previous assignments from fragment ang. dist.



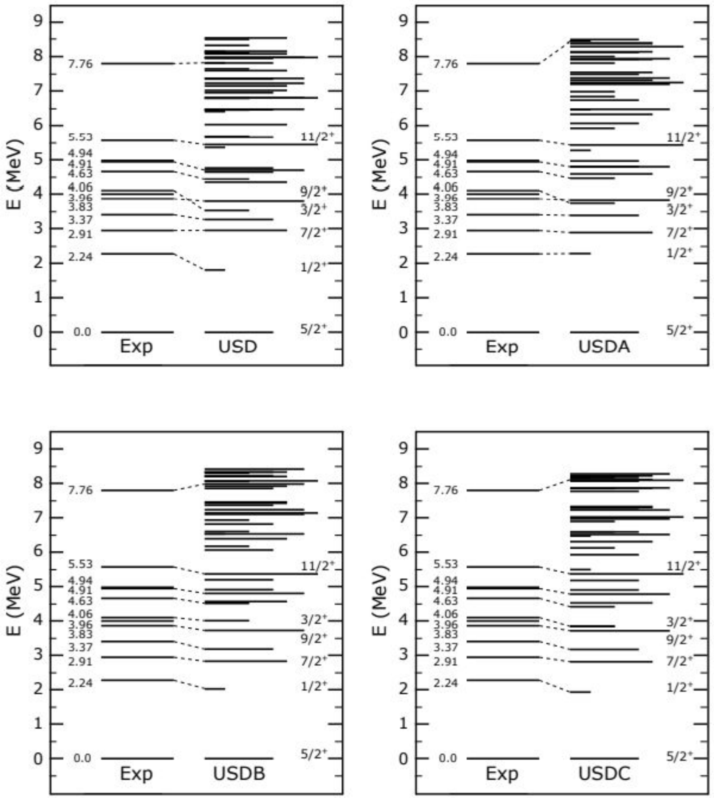
Results

- ➢ First observation of several transitions predicted by theory
  - New BR data
- ➢ γ-ray angular distribution confirms spin assignments from;
  - Shell model (USD-type)
  - Previous assignments from fragment ang. dist.
- ➢ Apparent direct population to s.p proton states
  - 2241 keV ($\pi 2s_{1/2}$) and 4065 KeV ($\pi 1d_{5/2}$)
  - Observed feeding can't account for measured intensities
  - Mixed nature or unobserved feeding?



Shell-Model Calculations

- ➢ Compared data to phenomenological USD-type calculations
- ➢ Associated experimental levels via energies, spins, BRs
- ➢ USDA and USDB calculations are in best agreement with data
    - Not particularly surprising since they are fit with neutron-rich data



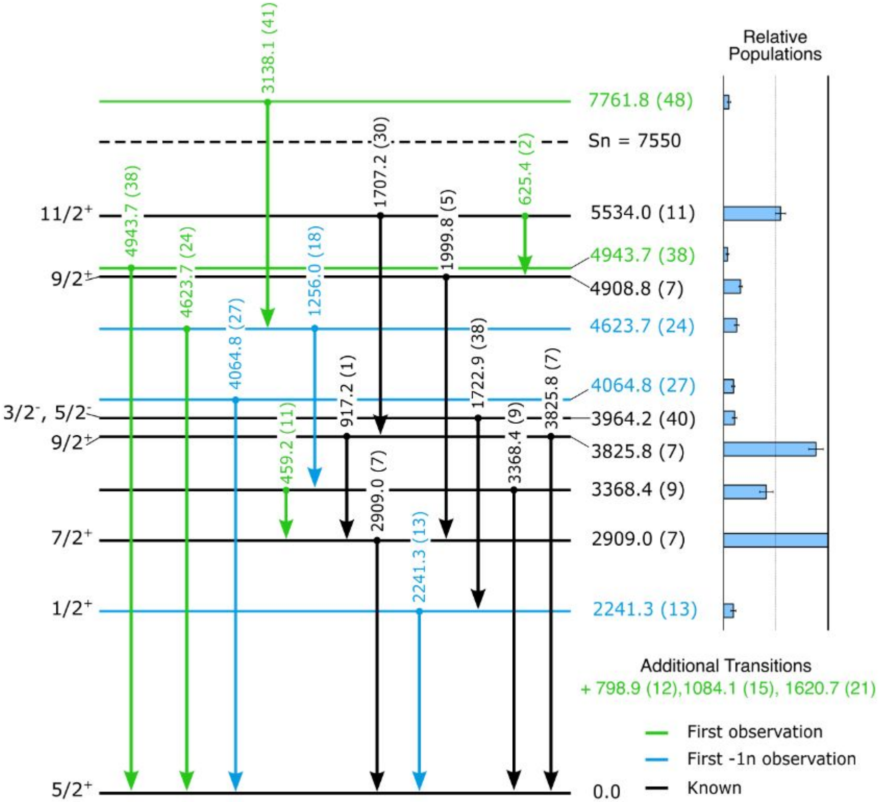
Thank you to Alex Brown for the Shell Model calculations

Summary

- ➢ In-beam γ-ray spectroscopy measurement on ^{23}F following 1n removal reactions

- ➢ First observation of several transitions and excited states predicted by theory

- ➢ Observed an apparent direct population to what was previous assigned S.P. proton states



Collaboration

Deutsche Forschungsgemeinschaft

THE ROYAL SOCIETY

SFB 1245

U.S. DEPARTMENT OF ENERGY | Office of Science

TECHNISCHE UNIVERSITÄT DARMSTADT

Sebastian Heil
Ina Syndikus
Alexander Hufnagel
Michael Mathy

UNIVERSITY of York

Marina Petri
Stefanos Paschalis
Ryo Taniuchi
Luke Tetley
Thoryn Haylett

NSCL
MICHIGAN STATE UNIVERSITY

Hiro Iwasaki
Charles Loelius
Kenneth Whitmore
Robert Elder
Nobuyuki Kobayashi
Daniel Bazin
Alexandra Gade
Dirk Weisshaar
Peter Bender
Joe Belarge
Eric Lunderberg
Brandon Elman
Brenden Longfellow

Achim Schwenk
Johannes Simonis
Javier Menendez
Jason Holt

TECHNISCHE UNIVERSITÄT DARMSTADT
THE UNIVERSITY OF TOKYO
TRIUMF

Robert Roth
Klaus Vobig
Thomas Huether

TECHNISCHE UNIVERSITÄT DARMSTADT

Alex Brown

NSCL