

Evolution of Single Particle Trends Outside the $N = 16$ Isotones $^{27}\text{Na}(\text{d},\text{p})$ Reaction at ISS

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ISOLDE WORKSHOP, MAY 2023

Overview

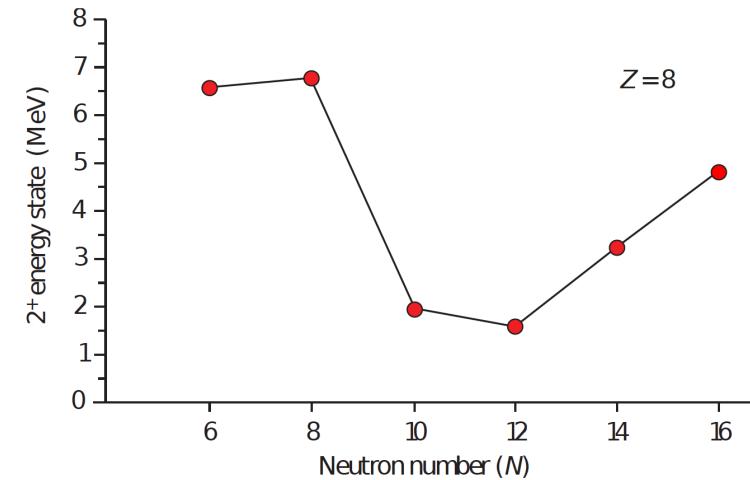


- Evolution of shell structure
- Characterising shell structure and the motivation of the measurement
- ISS: setup and analysis
- Summary and outlook

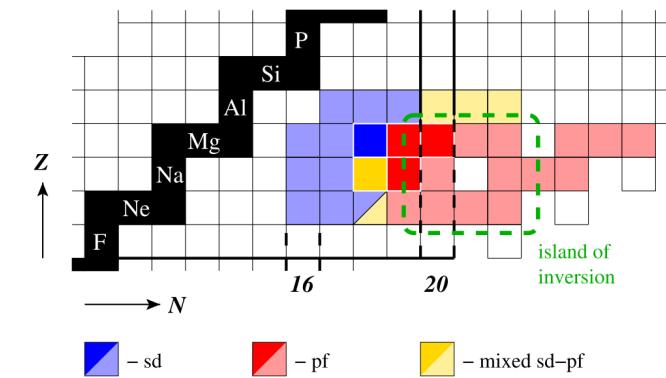
Evolution of Shell Structure

- Energy measurements of first 2^+ excited states in oxygen isotope indicate:
 - presence of a $N = 16$ shell gap
- Weakening of $N = 20$ shell gap:
 - onset of intruder configurations from upper shell
 - leads to “island of inversion”
- Evolution of shell closures:
 - due to changes in ESPE from changing **interactions** between valence protons and neutrons
- As $\pi d_{5/2}$ fills along $N = 16$, different overlaps with $\nu d_{3/2}$, $\nu p_{3/2}$ and $0f_{7/2}$ result in different **monopole shifts**

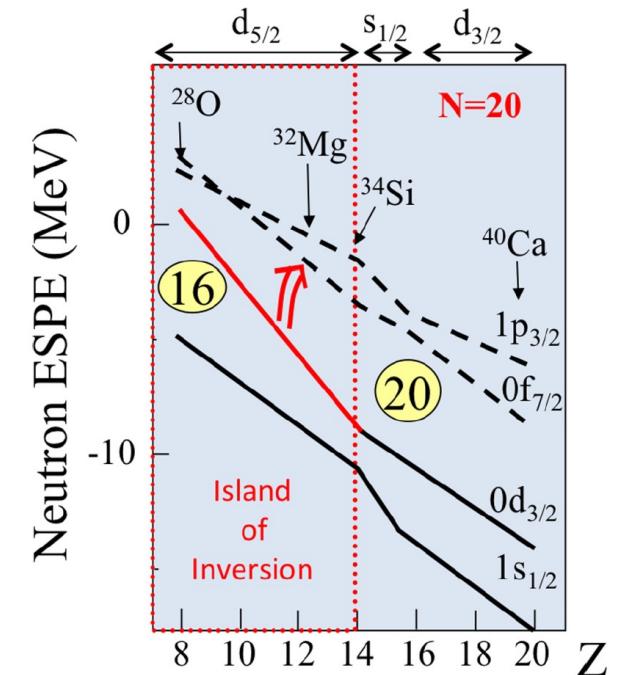
T. Otsuka et. al., Eur. Phys. J. A 15, 151–155 (2002)



R. V. F. Janssens, Nature 459, 1069 (2009)



P A Butler et al J. Phys. G: Nucl. Part. Phys. 44 044012 (2017)



A. Pepaireur, et al., PRC. 92 054309 (2015)

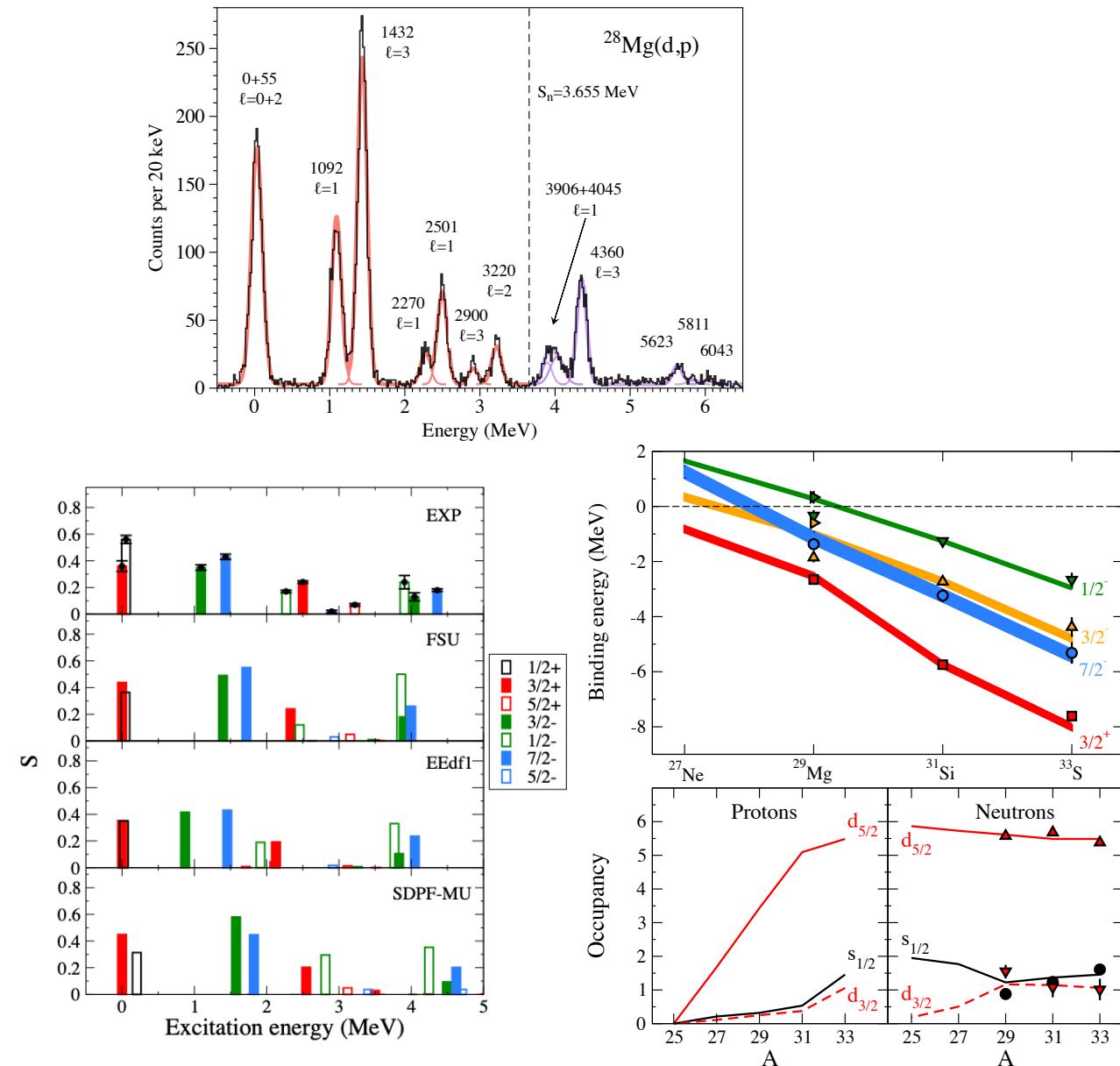
Characterising Shell Structure

- Systematic information on:
 - orbital population
 - single particle energies
- of **N = 17 isotones** can characterise shell evolution.

- Previous measurements by collaboration:
 - $^{28}\text{Mg}(\text{d},\text{p})^{29}\text{Mg}$ – *ISS*
 - $^{29}\text{Al}(\text{d},\text{p})^{30}\text{Al}$ – *HELIOS* (undergoing analysis)
- with existing transfer data for ^{33}S , ^{31}Si , ^{27}Ne .

- A **reduction** in the N = 20 shell gap is observed between ^{29}Mg and ^{31}Si , and **reproduced** by shell-model calculations.

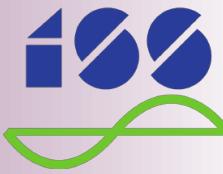
- Shell-model calculations indicate ^{29}Mg at a **transitional point** in $d_{3/2}$ and $s_{1/2}$ occupancies.



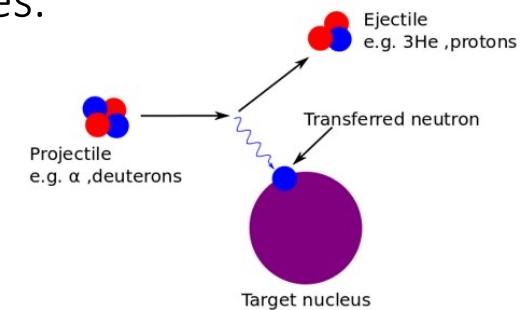
PT. MacGregor et al., PRC 104, L051301 (2021)

Measurement:

$^{27}\text{Na}(\text{d},\text{p})^{28}\text{Na}$ reaction in inverse kinematics at ISS



- Neutron-adding reactions ideal probe to study single particle properties.



- Beam intensities and energies at HIE-ISOLDE sufficient to probe the **distribution of single particle strength** in ^{28}Na .

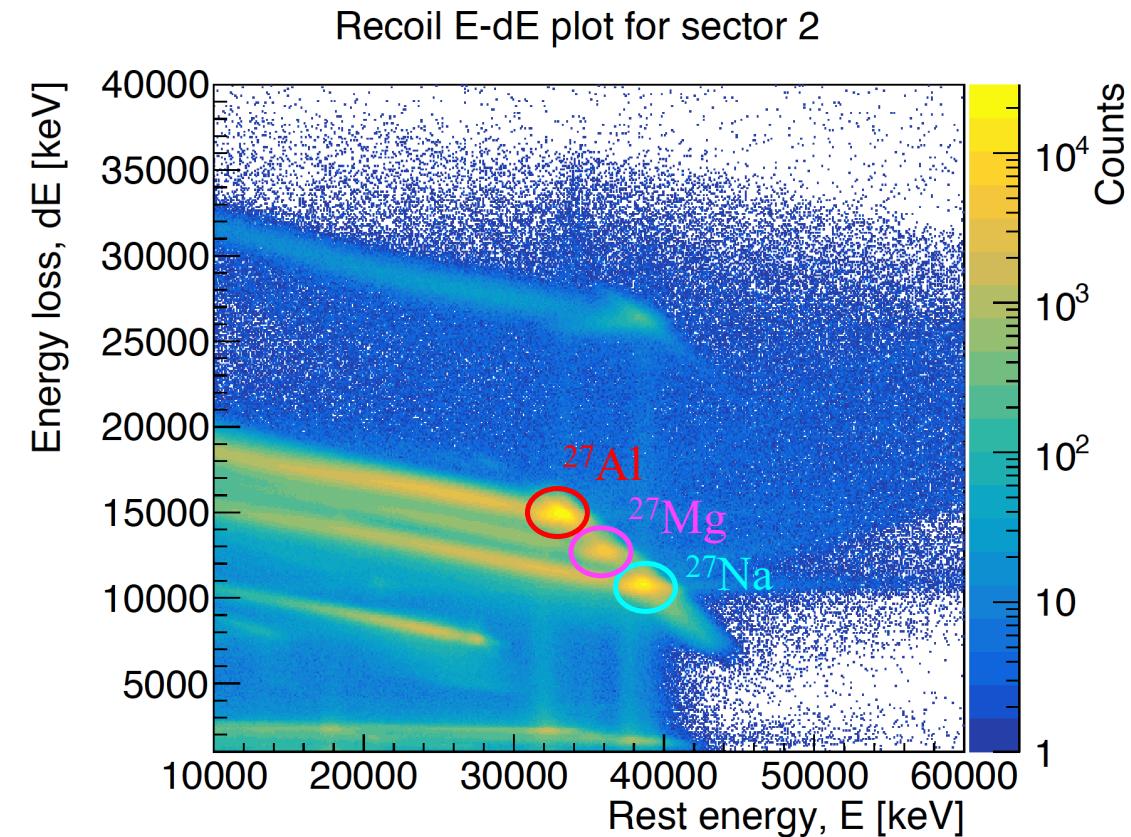
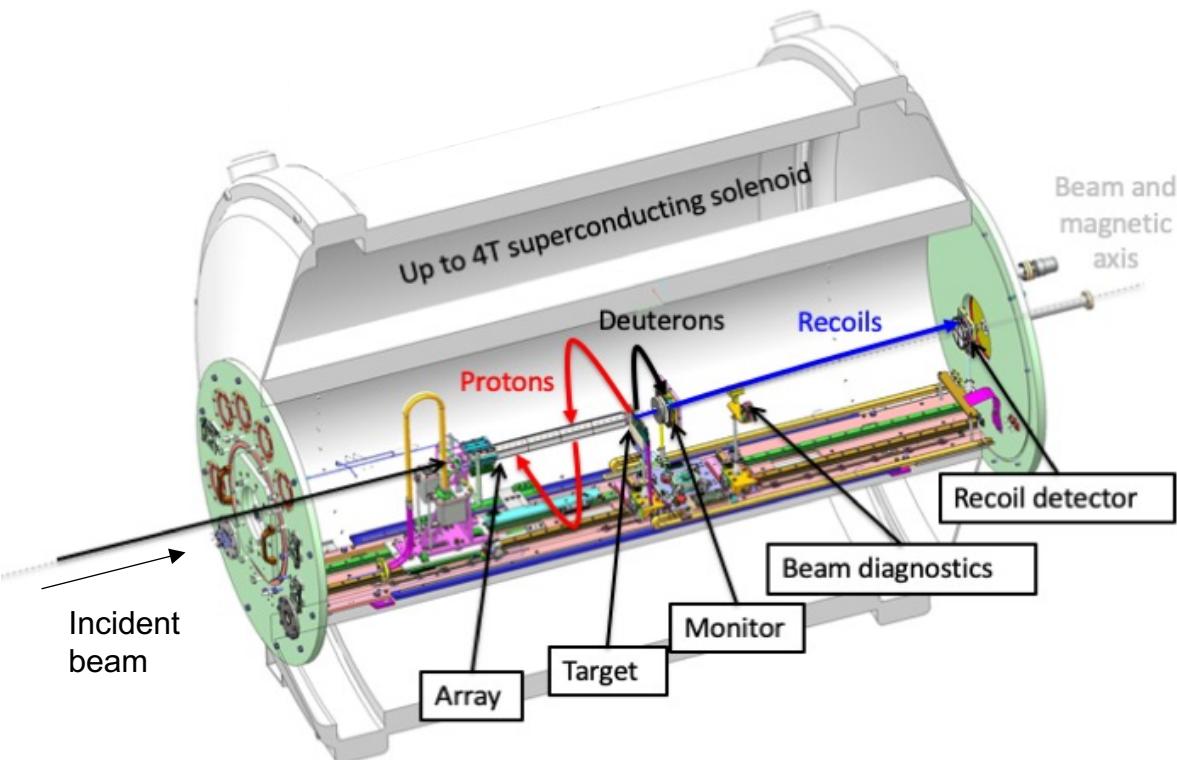
- Solenoidal technique: gives sufficient identification of populated states **up to** and **beyond S_n** .

- **Relative changes** in strength distribution compared to other isotones provide details on:

1. relative strengths of **monopole interactions** between $\pi d_{5/2}$ and neutron orbitals (so far poorly constrained by experimental data)
2. benchmarking **shell-model** calculations
3. behaviour of **negative-parity** (intruder) states

ISS Setup

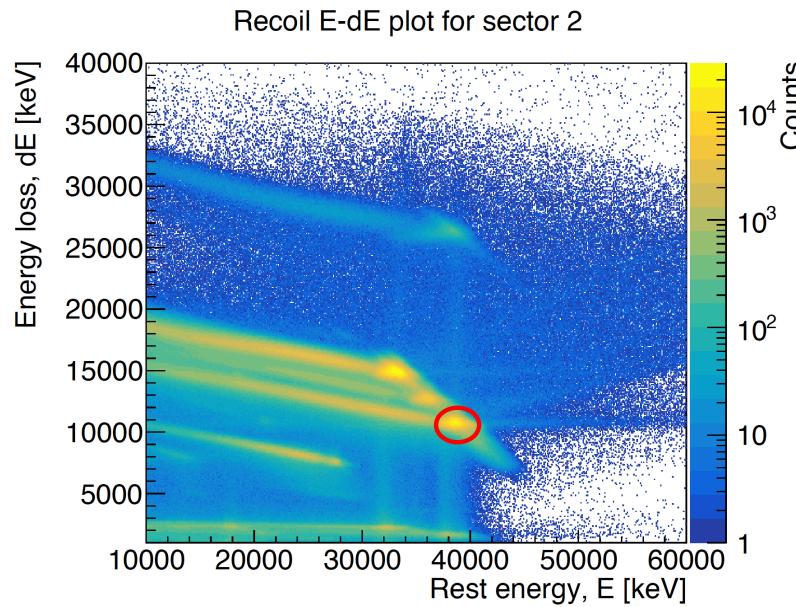
- B-field: **2.1 T**
- Array-to-target: **10 cm**
- Annular silicon detector – monitor for **absolute normalisation**
- **Silicon recoil** detectors at rear of magnet
- Beam diagnostics – FC and zero-degree detector



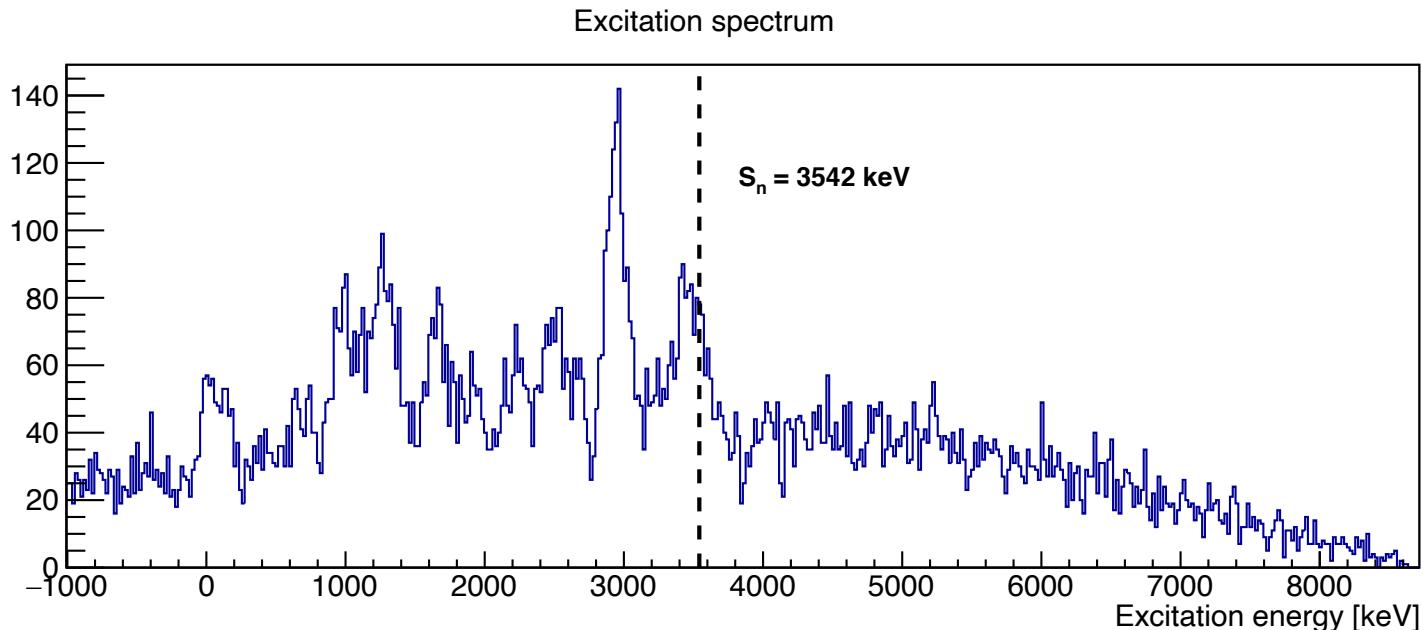
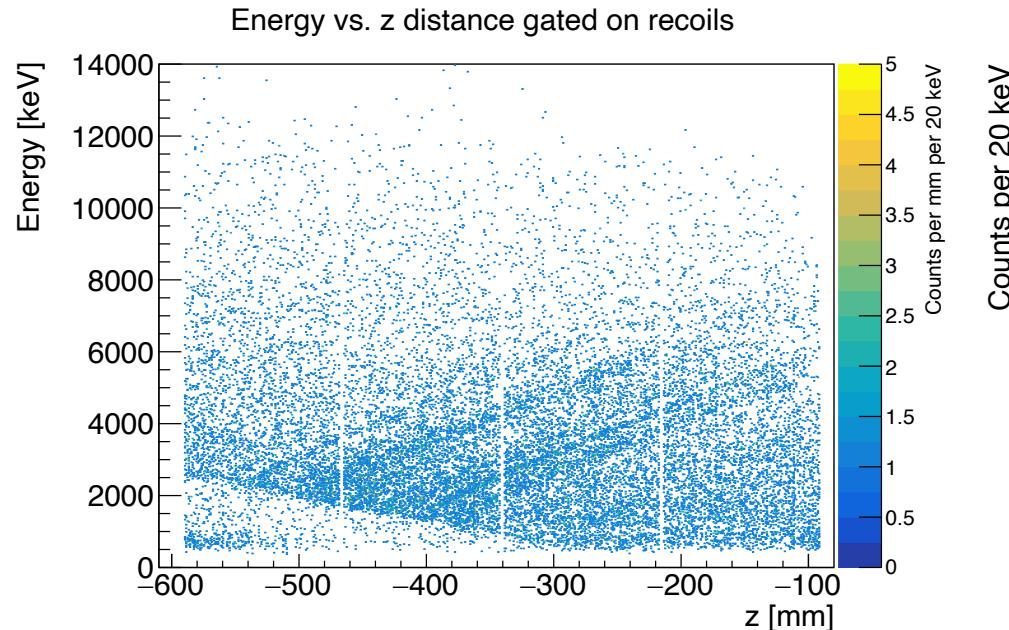
- Beam energy: **9.77 MeV/u**
- CofM angular coverage for protons: **10 - 40 degrees**
- < 50% ^{27}Al and 13% ^{27}Mg contamination – the reaction of interest selected using **recoil detectors**

ISS Analysis:

Reducing Noise



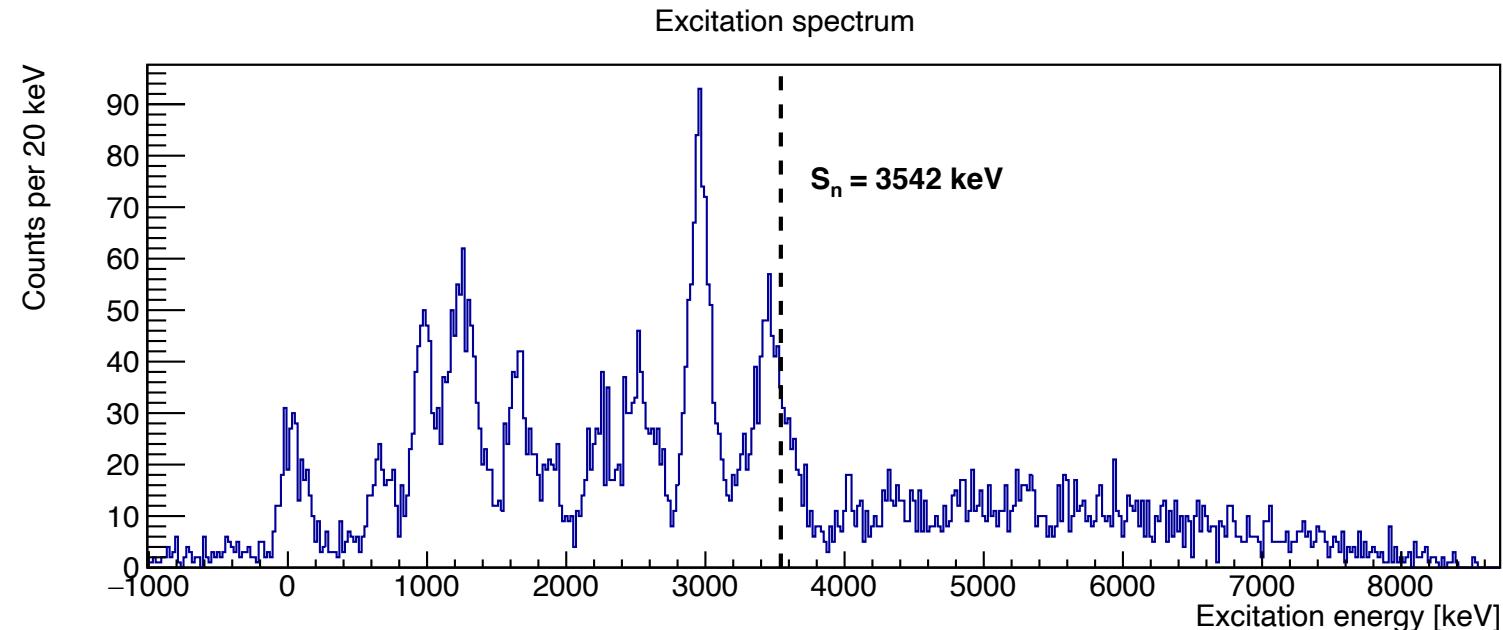
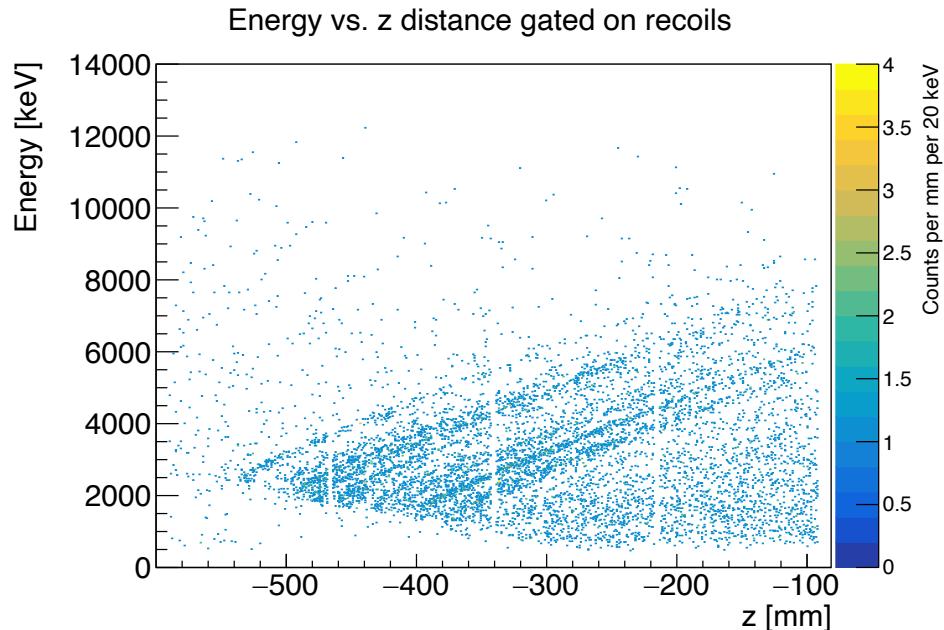
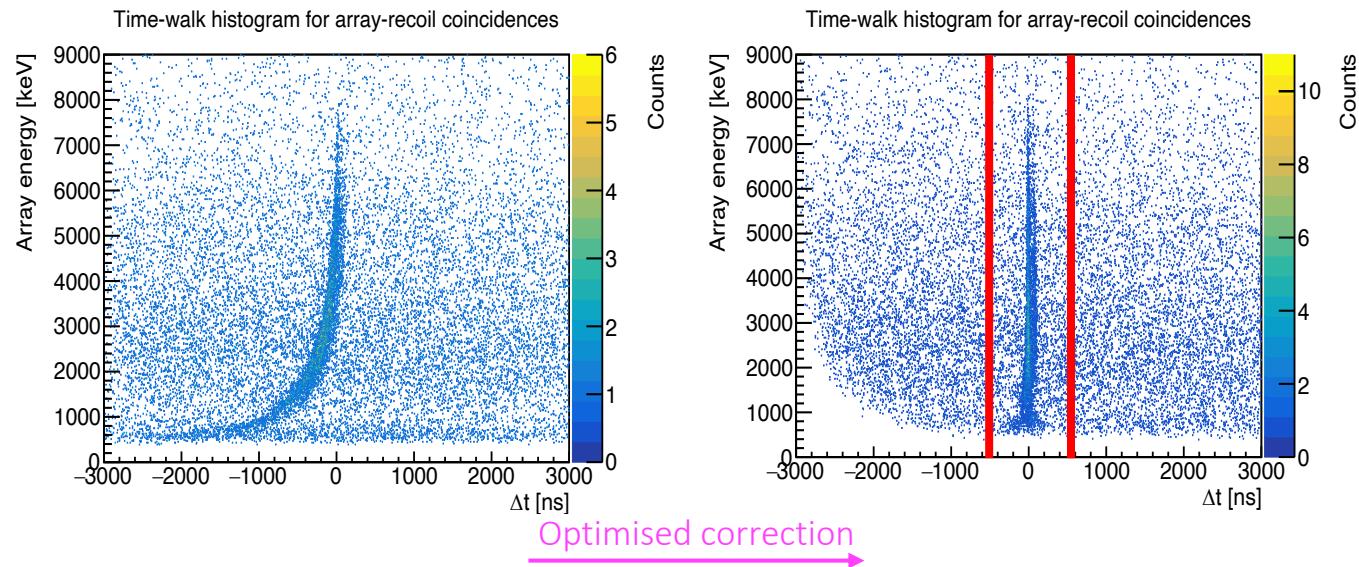
- Energy vs array position (z) and excitation energy spectra from selected region of interest
- Initial problems:
 - Considerable background
 - Low density of counts in kinematic lines (combination results in difficulties when extracting angular distributions)



ISS Analysis:

Reducing Noise

- ▶ **Array-recoil** coincidences are used to filter random coincidence
- ▶ Problem: leading edge trigger in array timing gives rise to **time-walk**
- ▶ Optimised correction of curve enabled **constriction** of array-recoil coincidence window filtering maximal noise

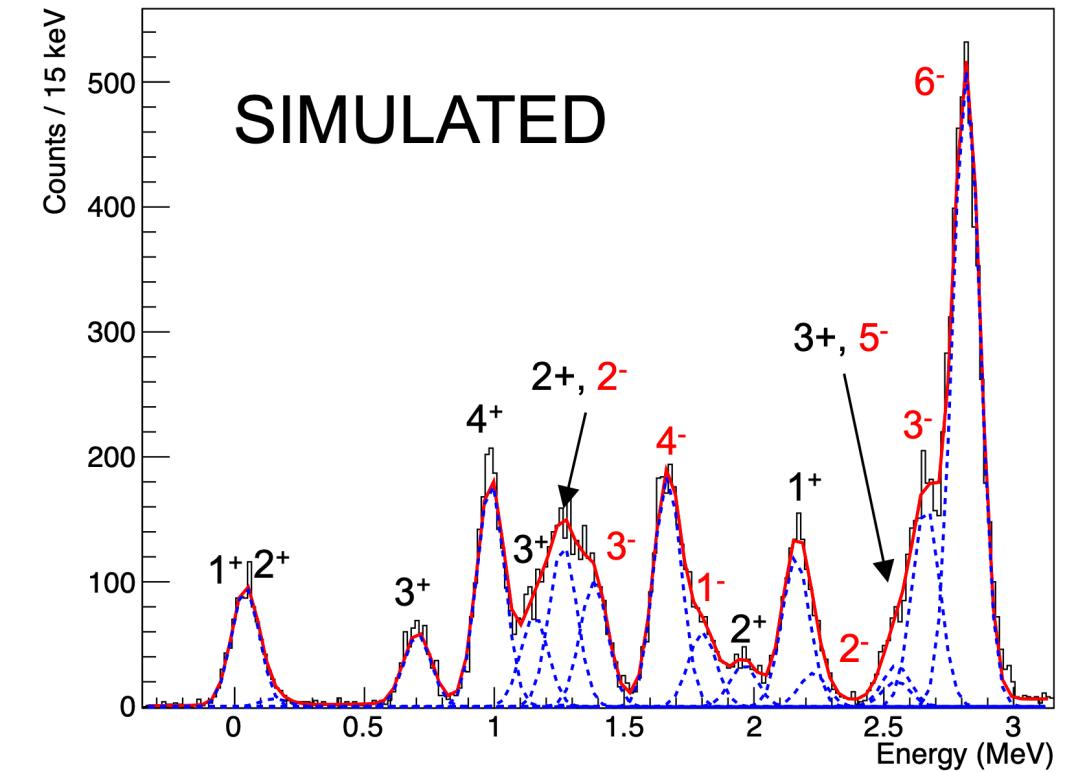
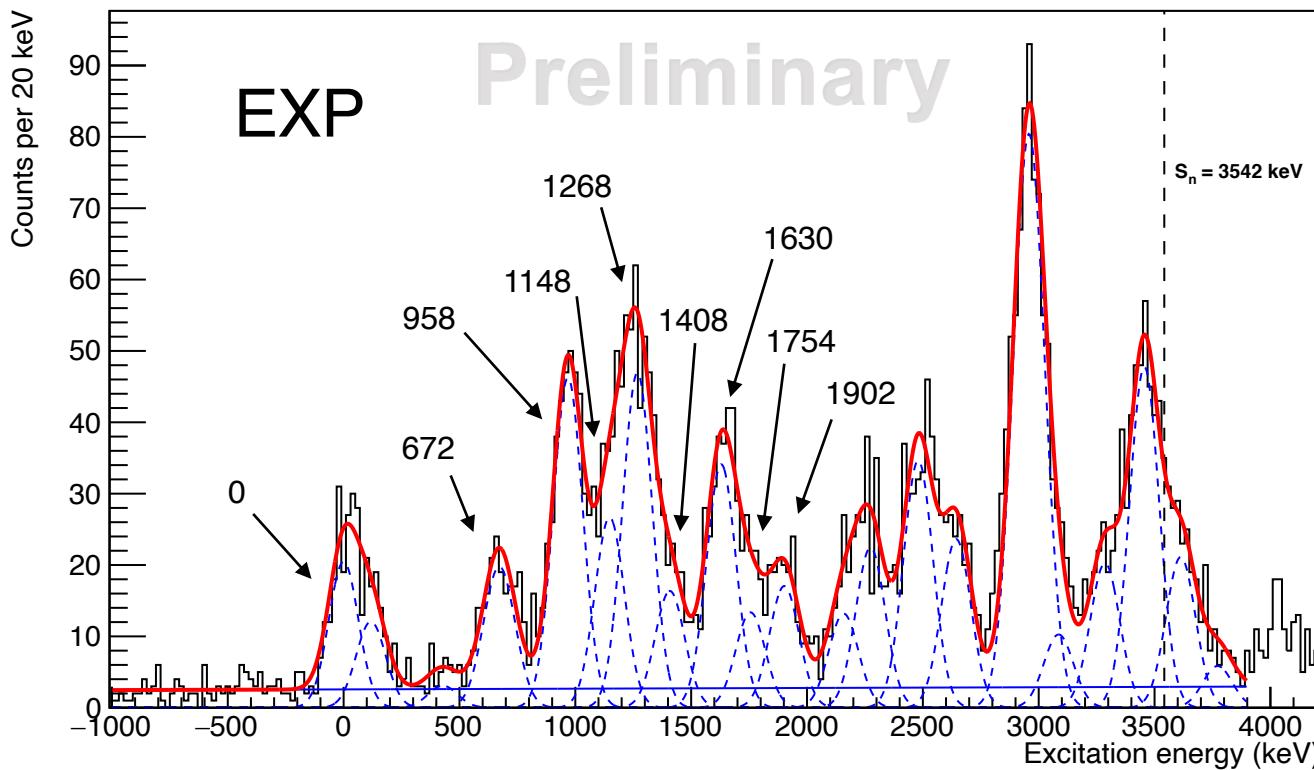


Excitation Spectrum:

Identifying populated states

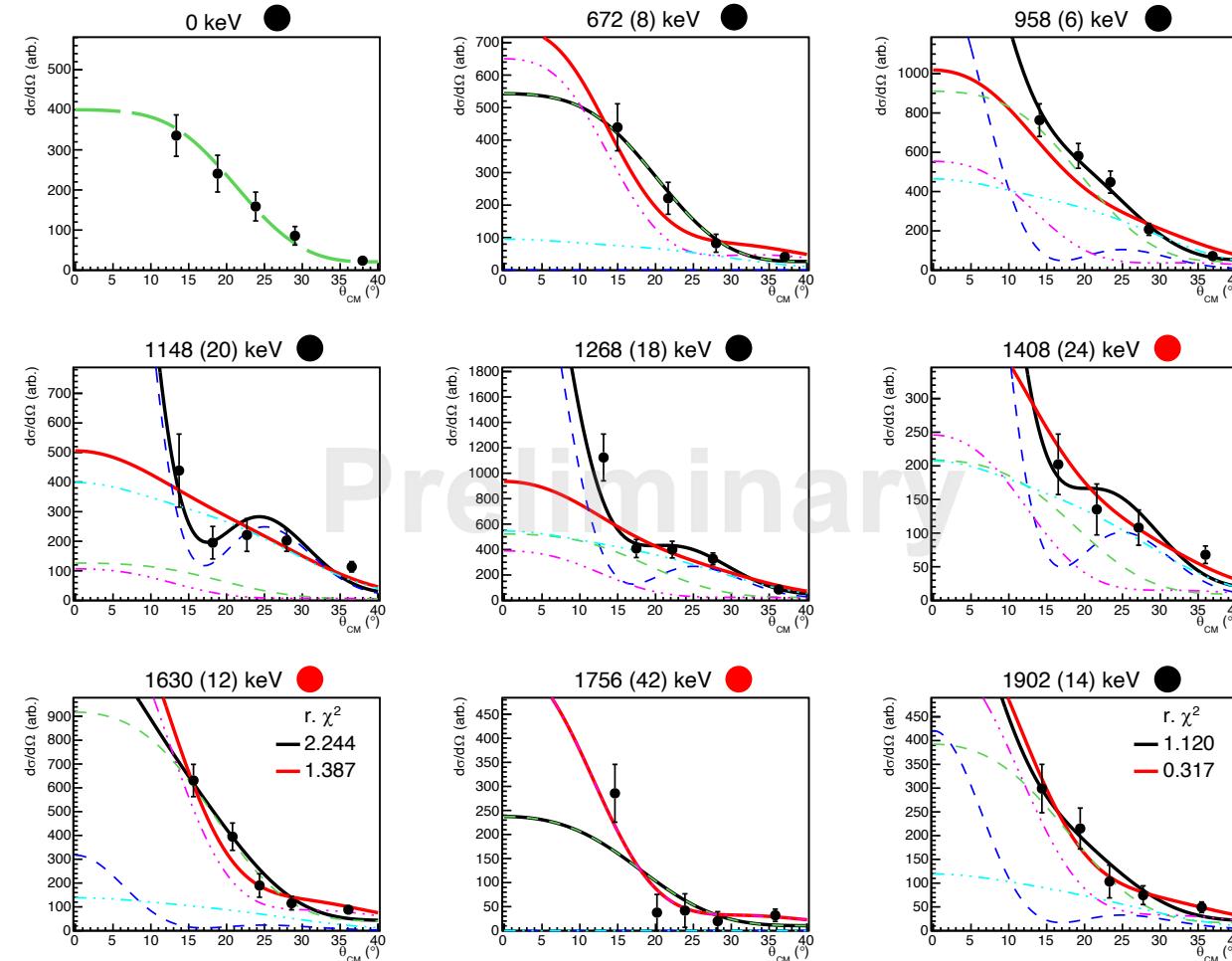


- Preliminary identification of **bound states**
(select number of energies shown)
- **Peak widths** fixed on the basis of those from prominent singlet states
- FWHM 150 keV
- Simulated expected excitation energy from **Shell Model** calculations using FSU interaction
[R. S. Lubna, et al., Phys. Rev. C. 100 034308 \(2019\)](#)
- Simulated spectrum: proton current 1.3 μ A,
FWHM 120 keV

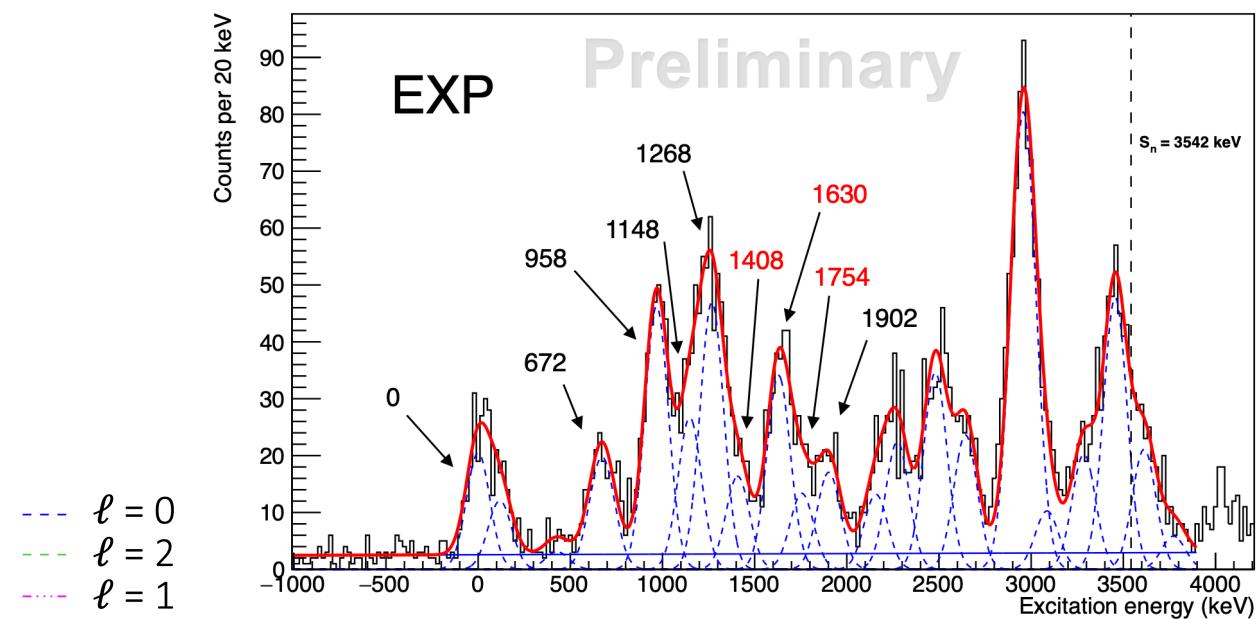


Angular Distributions:

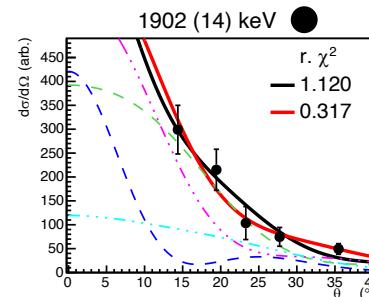
Assigning Parity



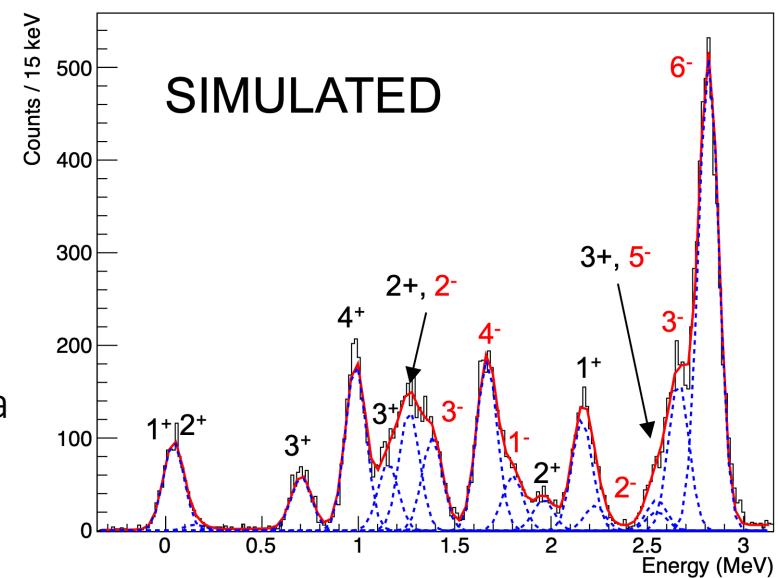
- Preliminary angular distributions of a select number of states (data compared with DWBA calculations)
- Evidence of both **positive-** and **negative-parity** states



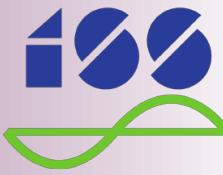
$\ell = 0$
 $\ell = 2$
 $\ell = 1$
 $\ell = 3$
 — +ve Parity ($\ell = 0 + \ell = 2$)
 — -ve Parity ($\ell = 1 + \ell = 3$)



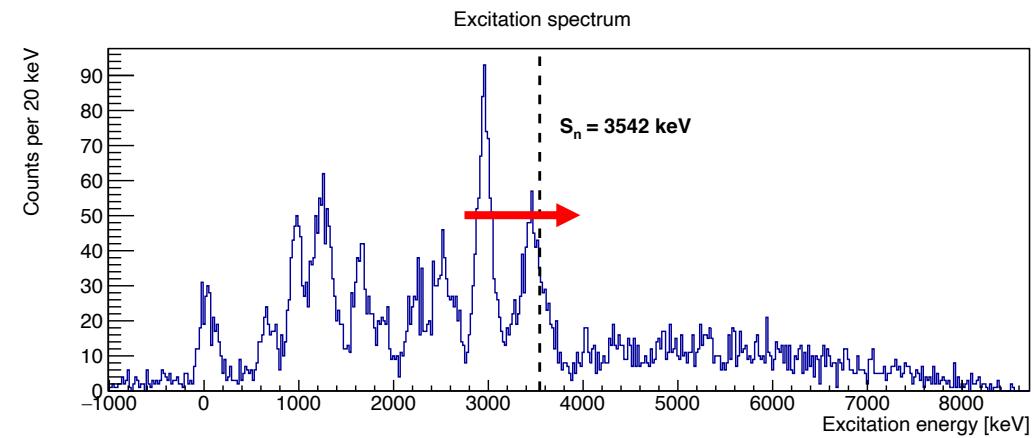
- Initial assignments show correspondence with existing data
- use known states to constrain ambiguous distributions



Summary & Outlook



- Physics motivation: characterise **evolution** of shell structure and **weakening** of $N = 20$ shell closure
- Preliminary angular distributions show **agreement** thus far with existing data, and show **low-energy** negative-parity strengths
- Identify all states and calculate the **strength distribution**, compare with ^{30}Al and ^{29}Mg
- Potential of extracting states **beyond** neutron separation energy



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The University of Manchester



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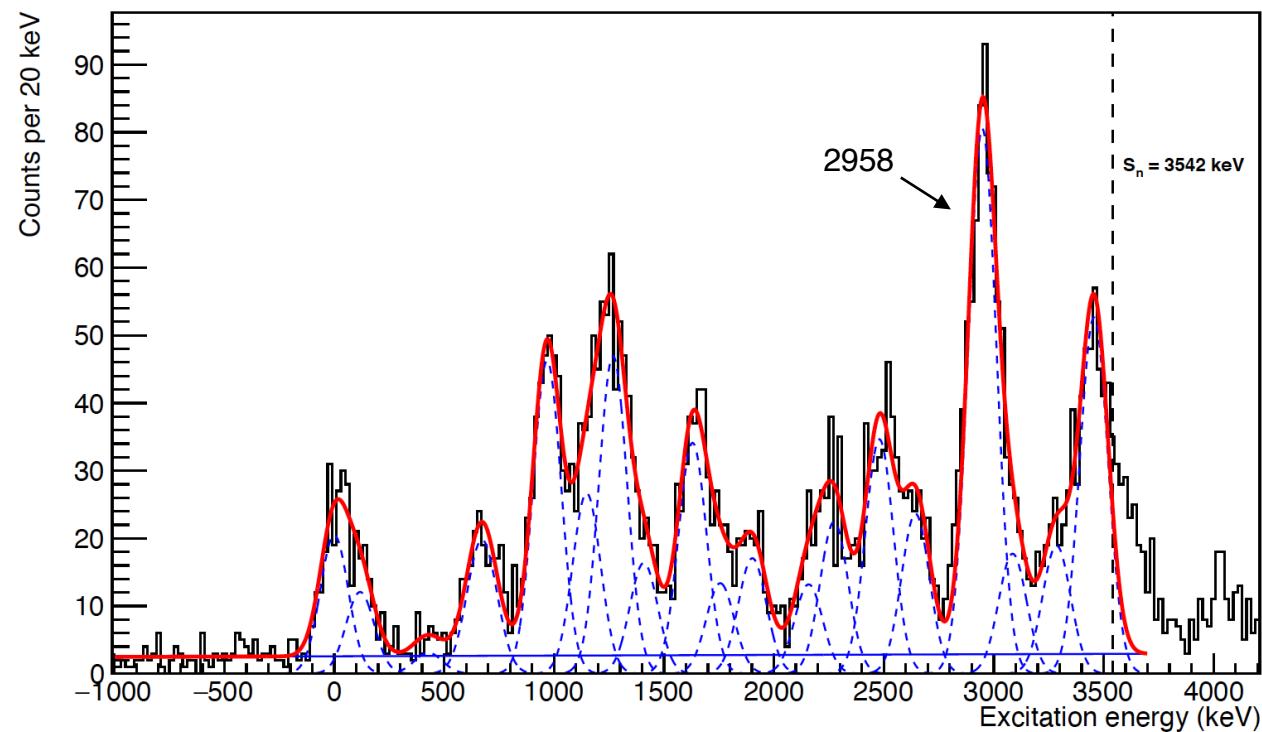


Determining Number of States

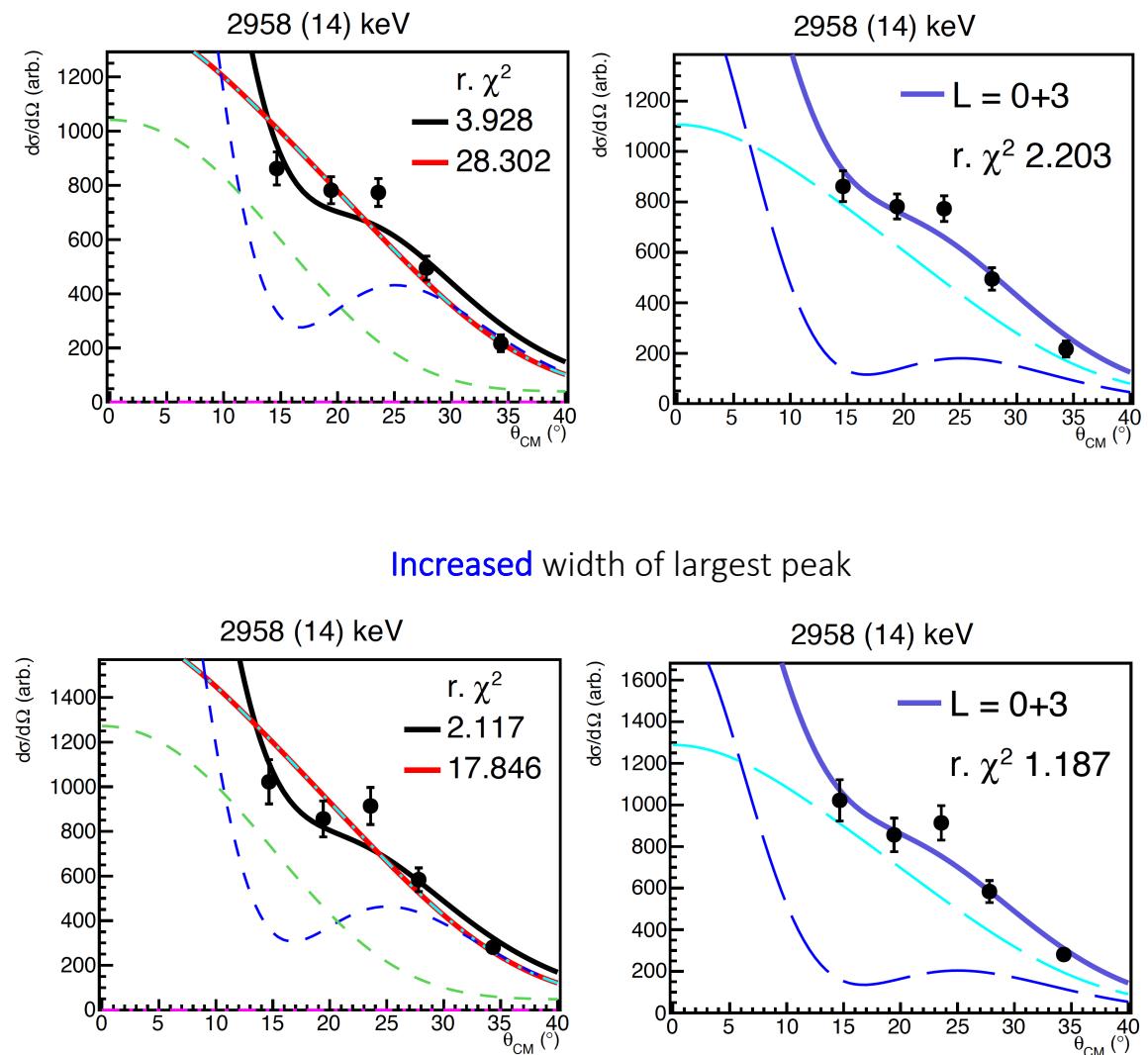
(Back up)

► Challenges in determining number of states:

- no isolated single peak
- high density of states
- largest peak maybe a doublet, difficult to resolve

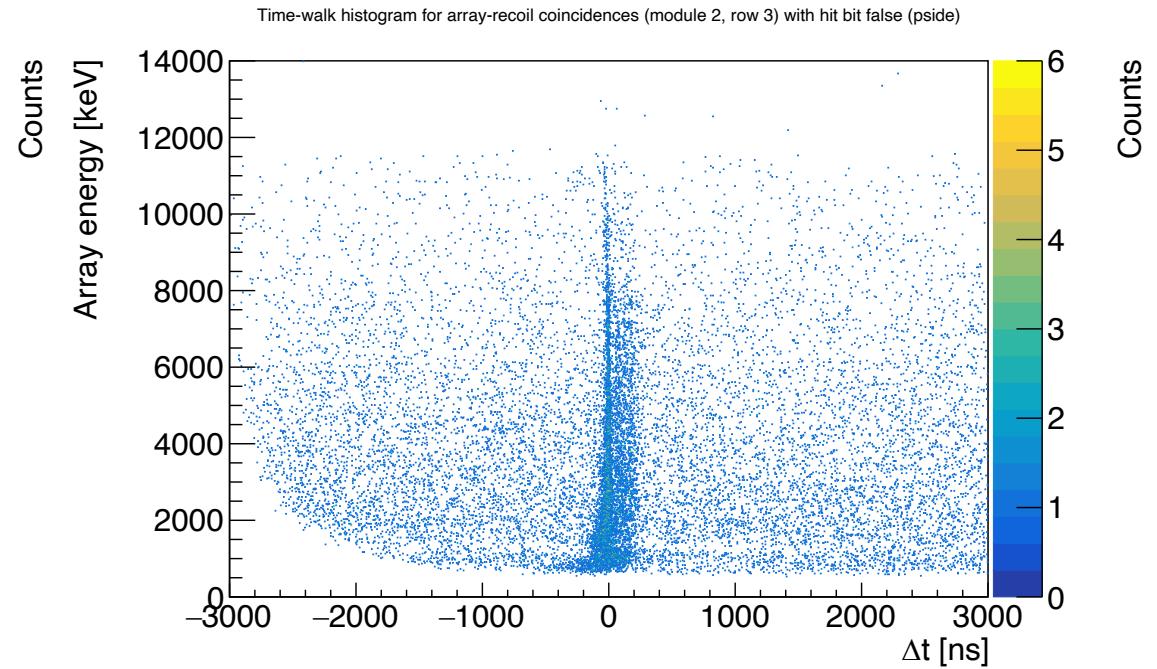
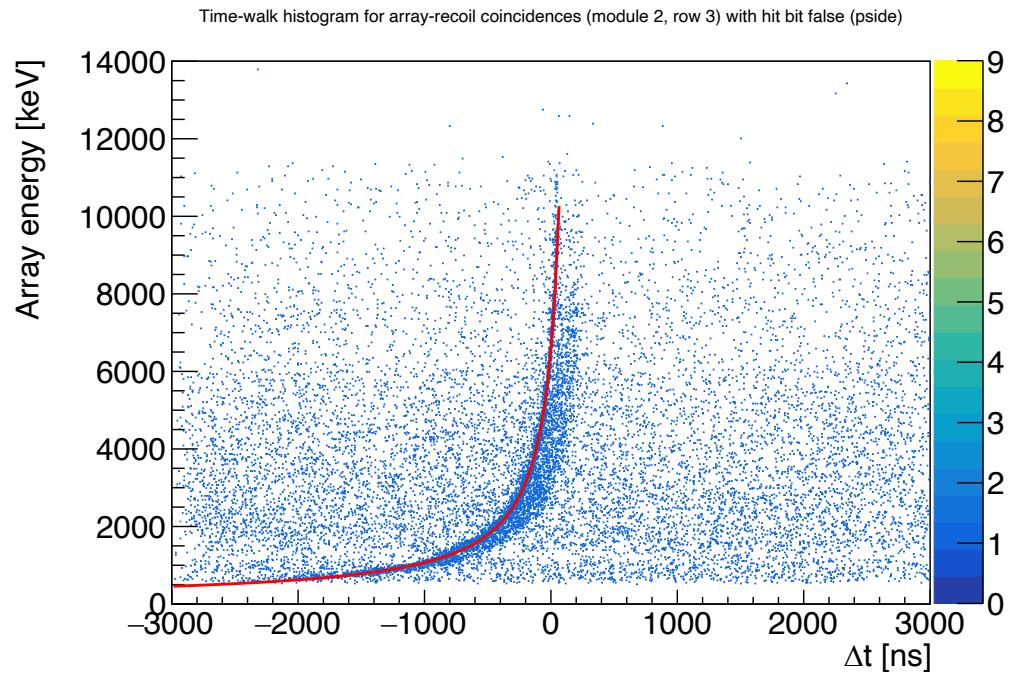


Fitting peaks left and right of largest with relative widths



Time-walk Correction

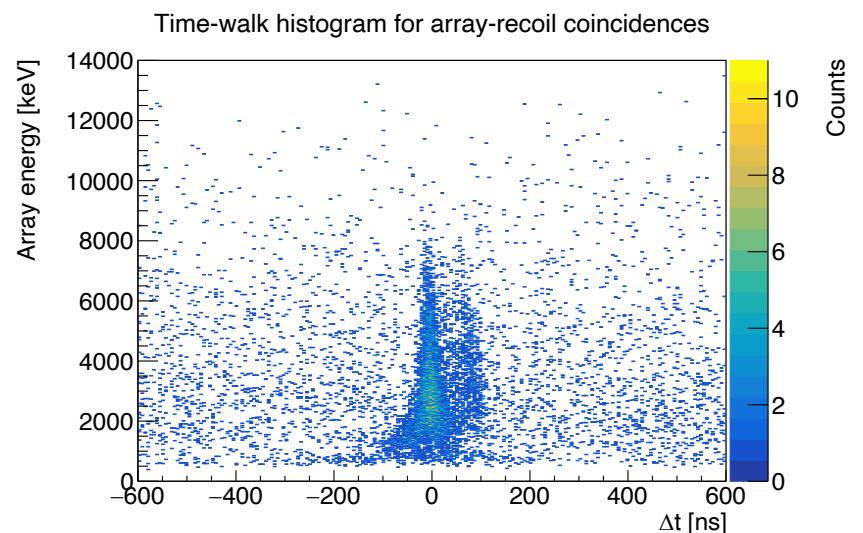
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- Curve fitted with function:

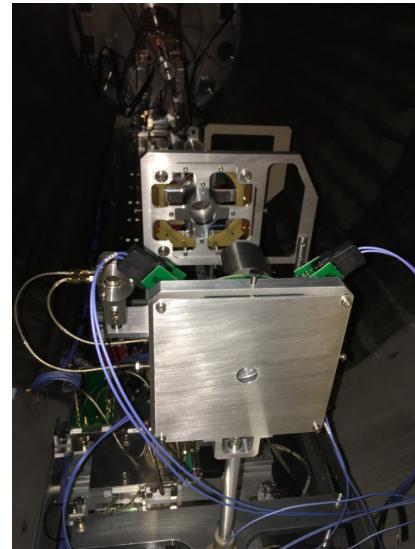
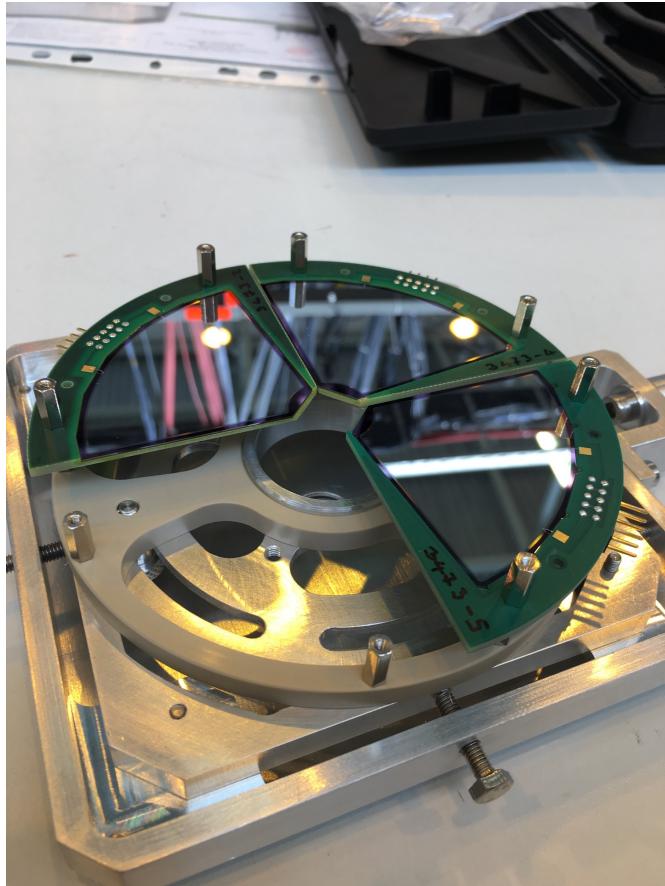
$$f(x) = A + \frac{B}{C - Dx}$$

- Function solved, giving each energy a **correction parameter**
- Correction done for each **row** (segment) of each array **module**, and for both n-side and p-side signals
- Origin of “shadow” unknown: possibly recoil **pile up**



Silicon Recoil Detector

(Back up)



- dE-E arrangement
- 2 sets of **Micron Semiconductor QQQ1** quadrant detectors
- Thickness:
 - dE = 50 μm
 - E = 500 μm
- For **light** recoils: $A < 30$
- Has a **rate limit** of $\sim 10 \text{ kHz}$