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Measuring the ^{28}Mg(*d*,*p*) reaction with ISS

Patrick MacGregor
ISOLDE Solenoidal Spectrometer Workshop
27 August 2019

ISOLDE Solenoidal Spectrometer

Motivation — $N = 20$ shell gap evolution

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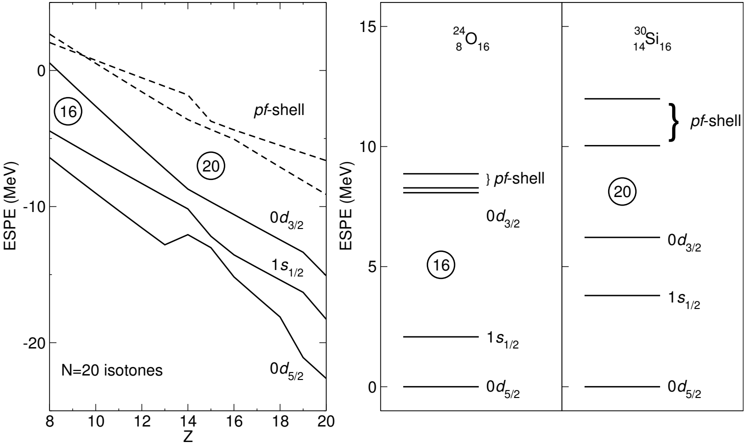
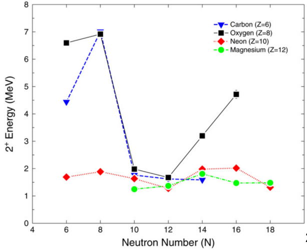


[1]

- Observed weakening in the $N = 20$ shell closure with decreasing Z.
- Weakening caused by relative strength of interaction between neutrons and protons in different orbits ($\nu d_{3/2}$ and $\pi d_{5/2}$).
- Mapping size of shell gaps crucial for understanding this region.
- Transfer reactions can be used here to map evolution of pf-states and how separation evolves.

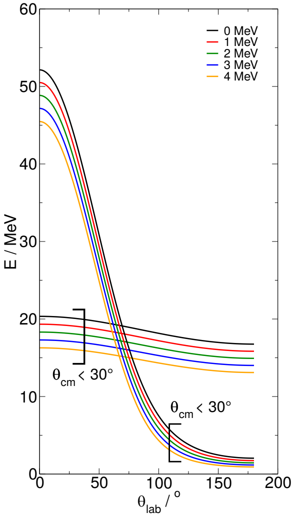


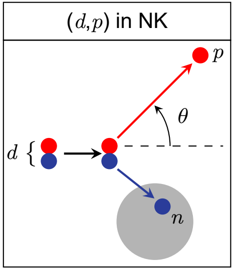
[2]

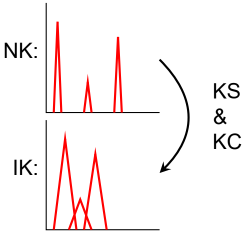
[1] Adapted from T. Otsuka et al. *Eur. Phys. J. A.* 15 (2002), pp. 151–155.

[2] C.R. Hoffman et al. *Phys. Lett. B* 672.1 (2009), pp. 17–21.

Transfer reactions in inverse kinematics







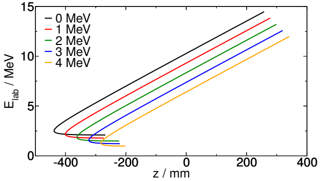
- Ejectile, p, provides information for the populated state in ^{29}Mg:
  - Yields $\rightarrow$ cross section.
  - θ $\rightarrow$ angular momentum.
  - Ejectile energy $\rightarrow$ excitation of residual nucleus.
- Single-particle strength split by correlations between nucleons.
- Deduce spectroscopic factors, $S_{j\ell}$, which measure how close each state looks like a n in IPM state:

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{EXP}} = S_{j\ell}\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{DWBA}}$$

where $\left|^{29}\mathrm{Mg}; j, \ell\right\rangle \sim \sum_{j,\ell} S_{j\ell}\left(\left|^{28}\mathrm{Mg}; 0, 0\right\rangle \otimes |n; j, \ell\rangle\right)$.

- NK works if the target is stable/long-lived BUT ^{28}Mg $\rightarrow$ ^{28}Al via β^-; $\tau_{1/2} = 21$ h.
- IK allows transfer on radioactive nuclei, but introduces some non-trivial problems:

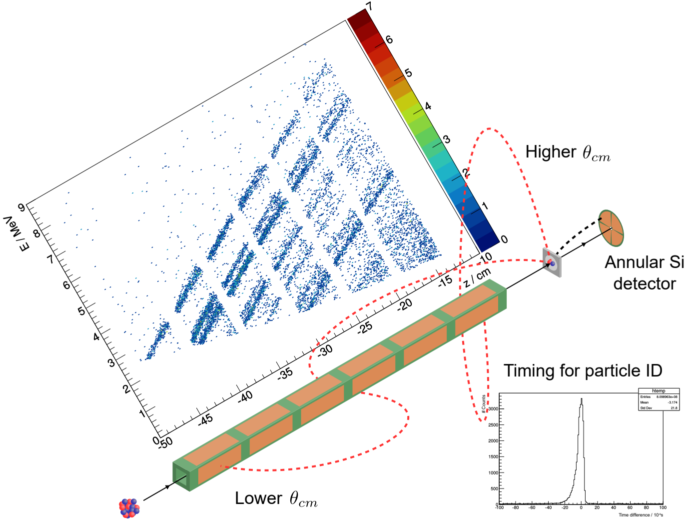
1. **Kinematic shift (KS)** - broadens peaks because of large $\frac{\mathrm{d}E}{\mathrm{d}\theta}$ for a finite angular acceptance, $\Delta\theta$.
2. **Kinematic compression (KC)** reduces energy difference between states.



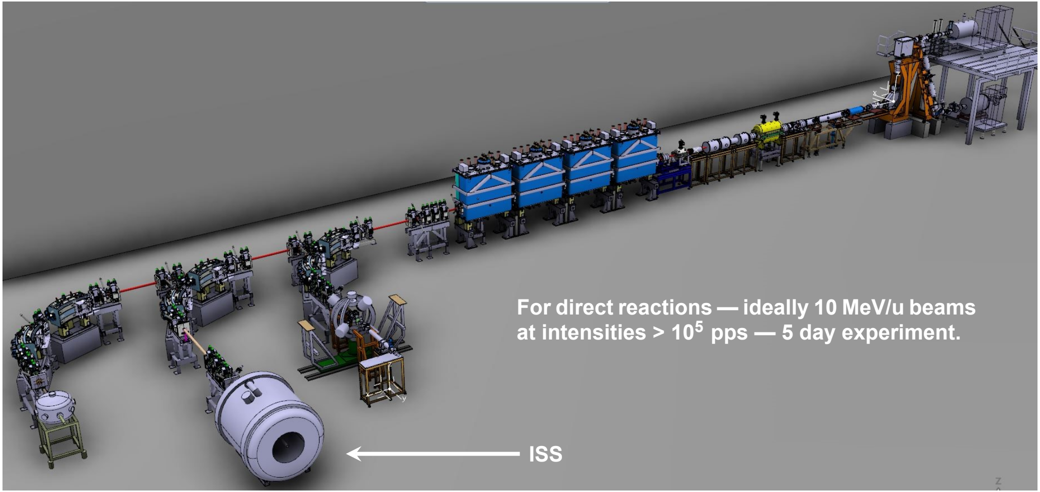
Measure z rather than θ.

For a given z, $E_{lab} \propto \Delta E_x$.
$\Rightarrow$ no compression in the solenoid.
$\Rightarrow$ better resolution.

$$E_{cm} = E_{lab} + \frac{1}{2} m V_{cm}^2 - \frac{m V_{cm} z}{T_{cyc}}$$



HIE-ISOLDE@CERN



[3]

3 URL: http://hie-isolde-project.web.cern.ch/about-hie-isolde.

ISOLDE Solenoidal Spectrometer (ISS)

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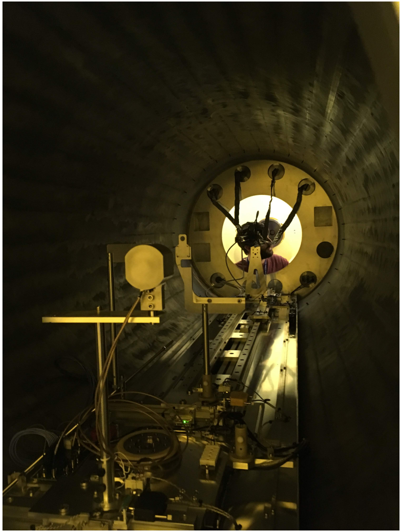

ISOLDE Solenoidal Spectrometer (ISS)

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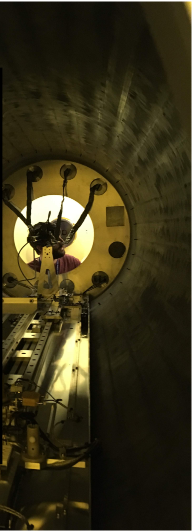
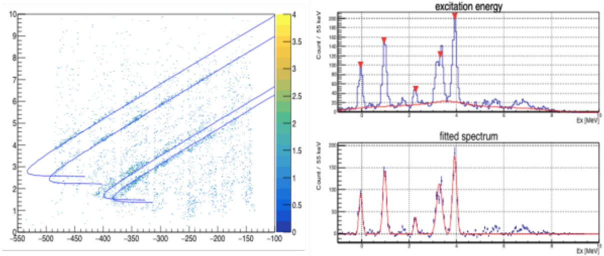
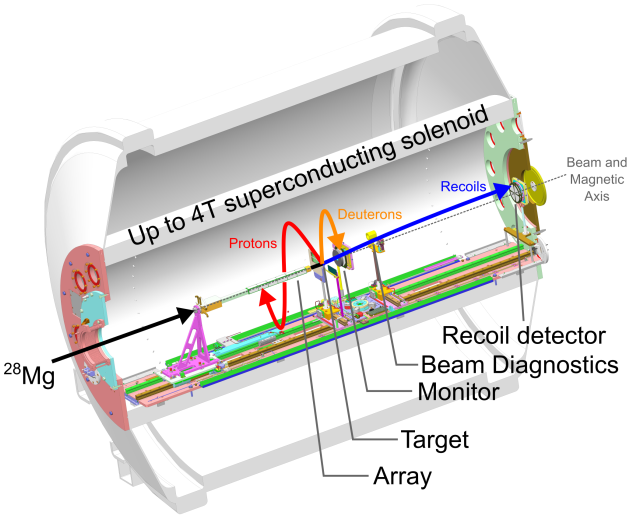


^{22}Ne$(d,p)^{23}$Ne (May 2018)



Success!

ISS Setup



HELIOS

Argonne NATIONAL LABORATORY

- Based on HELIOS spectrometer at Argonne National Laboratory.
- Uses HELIOS array on loan from Argonne to allow for experiments before LS2.
- Detectors:
  - HELIOS array — backwards scattered p.
  - S1 detector — elastically scattered d.
  - $E\Delta E$ recoil detector — scattered beam.
- Measure energies, position, and times on each detector.
- Beam energy: 9.473 MeV/u ($\mathrm{d}E/E = 0.3\%$).
- Maximum 10^6 pps.

Extracting *E* and *z*

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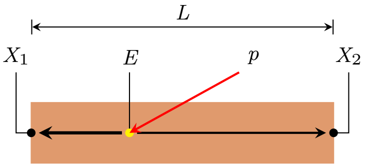
Positions:



$$\text{Position on strip} = X = \begin{cases} \frac{X_1}{E}, & X_1 > 0.5E \\ \frac{X_2}{E}, & X_2 > 0.5E \end{cases}$$

- Calculate position on strip using gain-matched X_1, X_2, and E.
- Use laser alignment from CERN team to calculate distance from target:

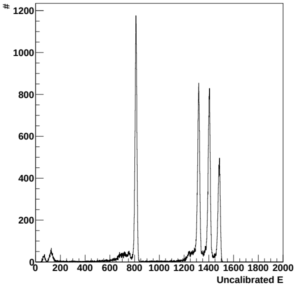
$$z = L\left(X - \frac{1}{2}\right) - z_{\mathrm{off}} - d_i,$$

z is the distance along the beam axis from the target.

d_i is the distance along the array to the centre of strip i.

z_{off} is the distance from the target to the array.

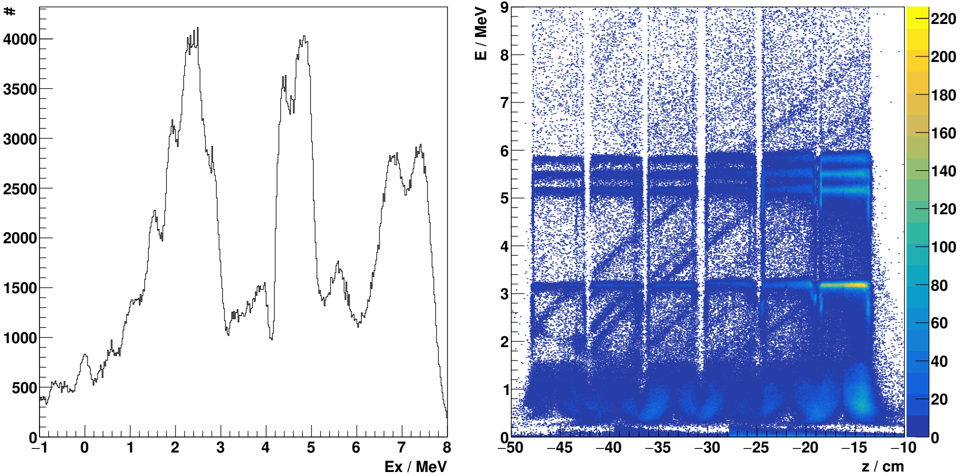
Energies:



- Rough energy calibration with quadruple α-source.
- Gain match X_1 and X_2 to each other.
- Match X_1 and X_2 to E.
- α-source not sufficient, as α's lose energy in the target.
- α-source calibration improved by calibrating to known states in ^{29}Mg.

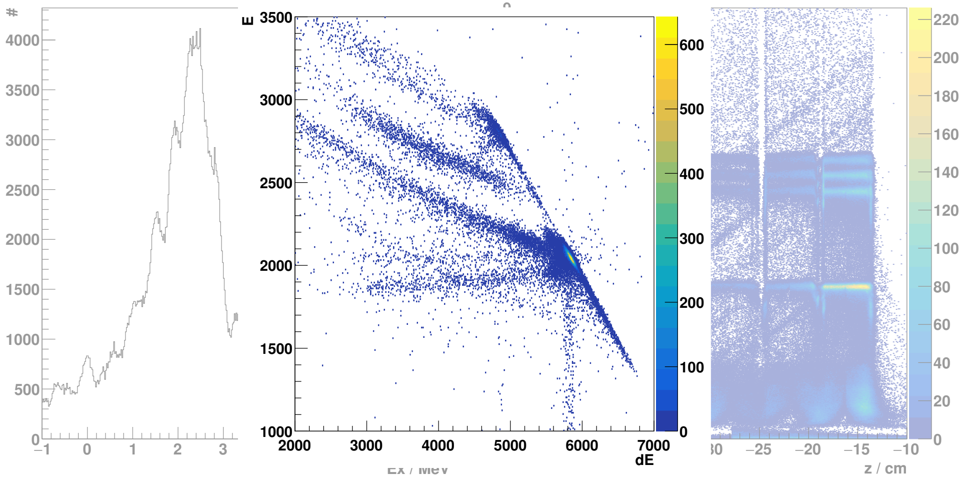
Analysis methodology

Raw Data



Analysis methodology

Raw Data



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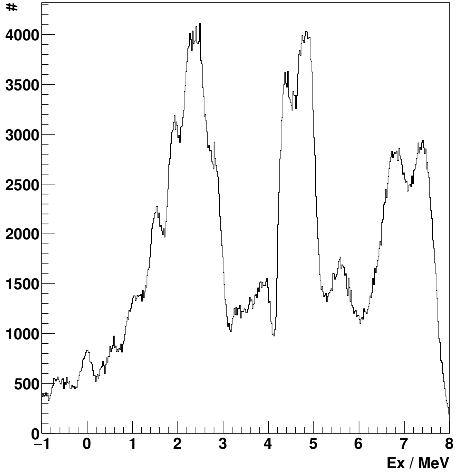
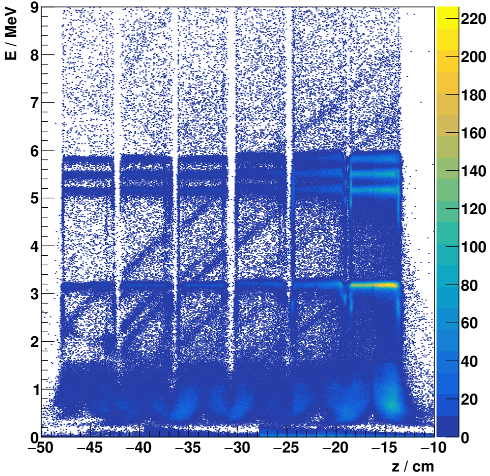
Raw Data





Analysis methodology

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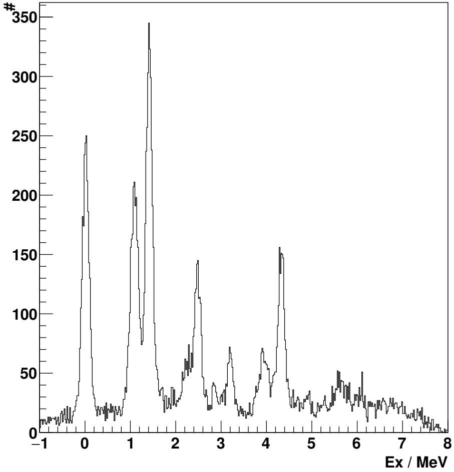
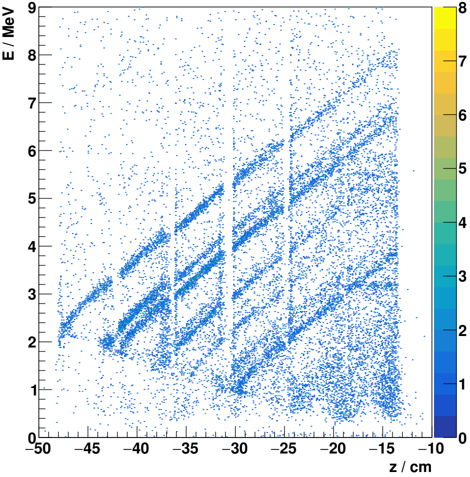
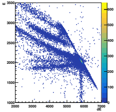
RDT Cuts







Analysis methodology

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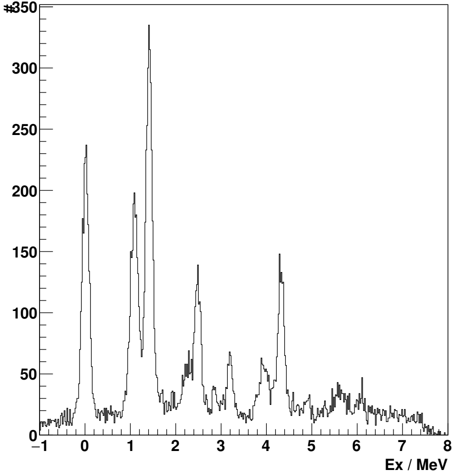
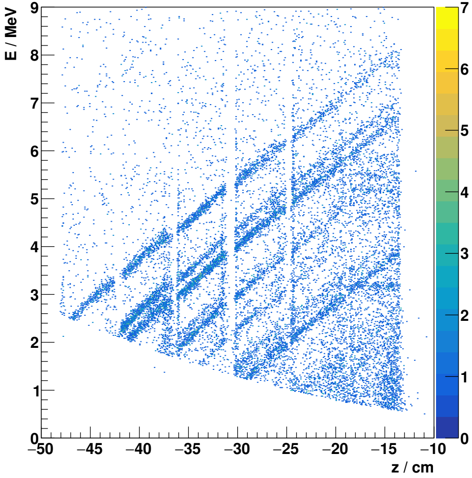
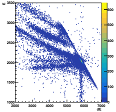
RDT + CM Angle Cuts







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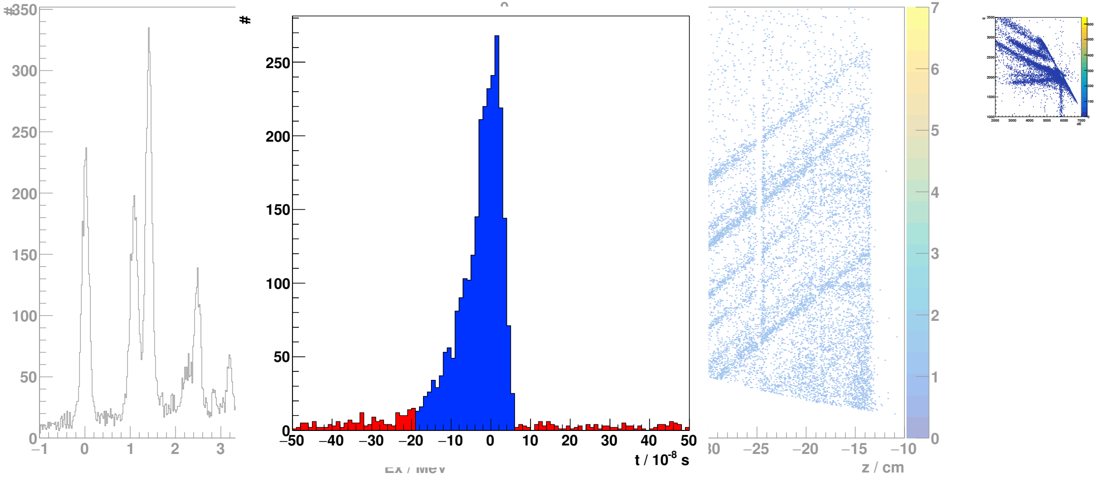
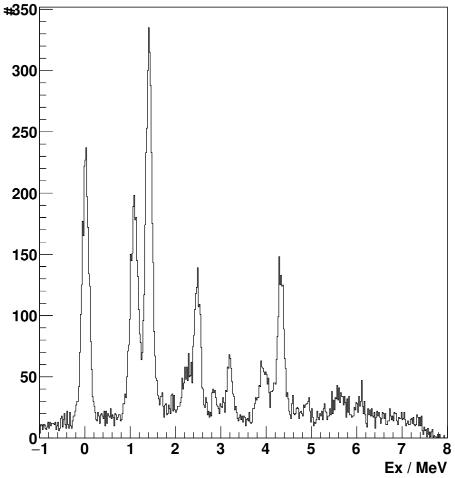
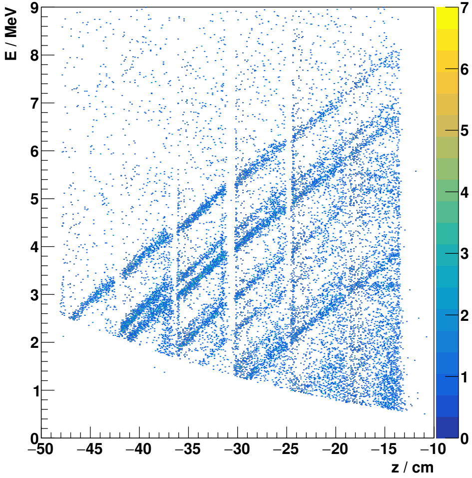
RDT + CM Angle Cuts

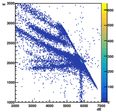


Analysis methodology

RDT + CM Angle Cuts







Analysis methodology

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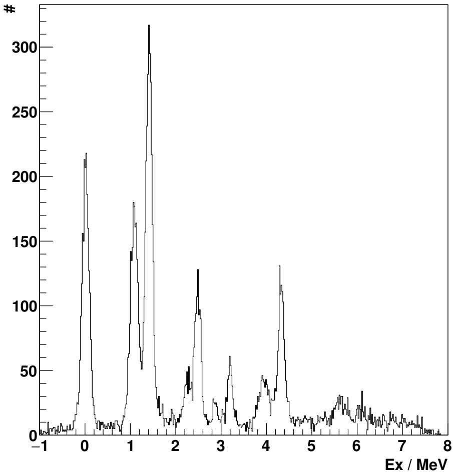
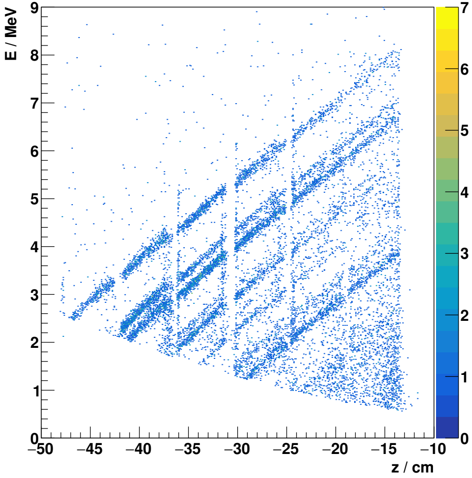
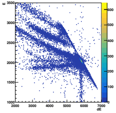
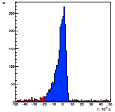
RDT + CM Angle + Timing Cuts









Analysis methodology

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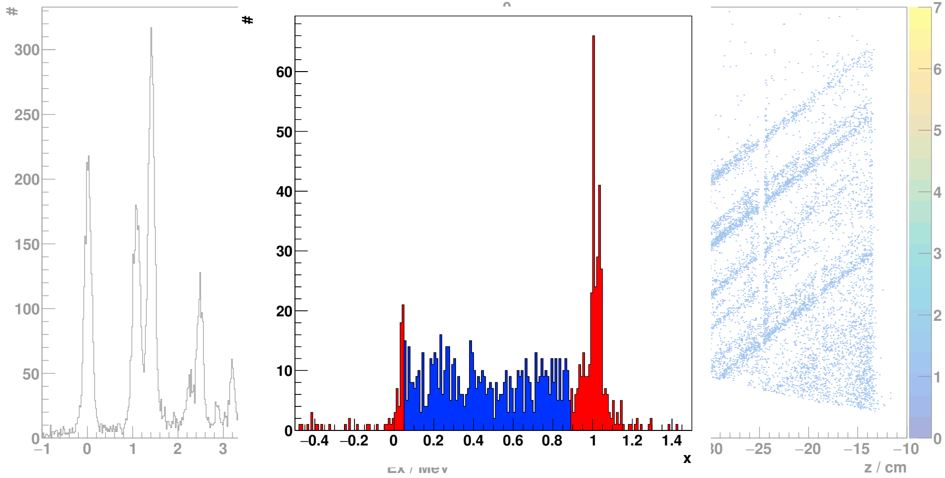
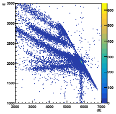
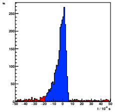
RDT + CM Angle + Timing Cuts







Analysis methodology

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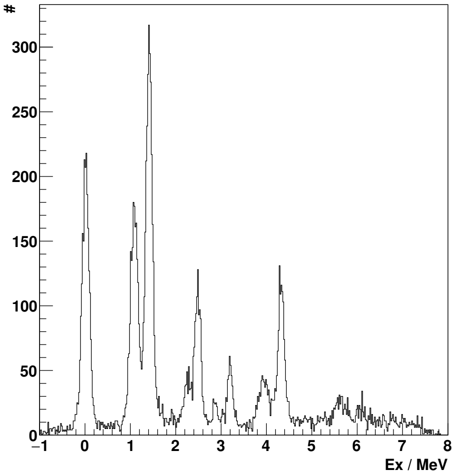
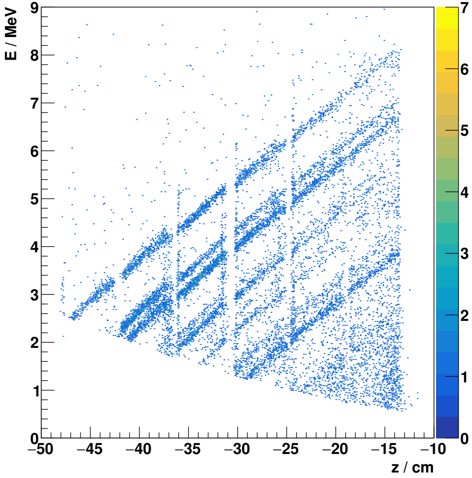
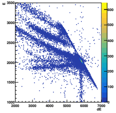
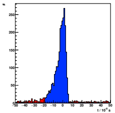


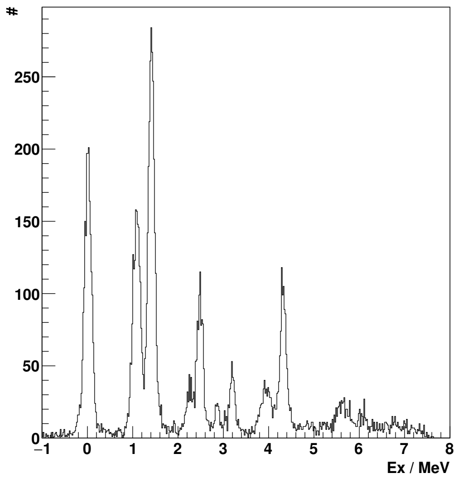


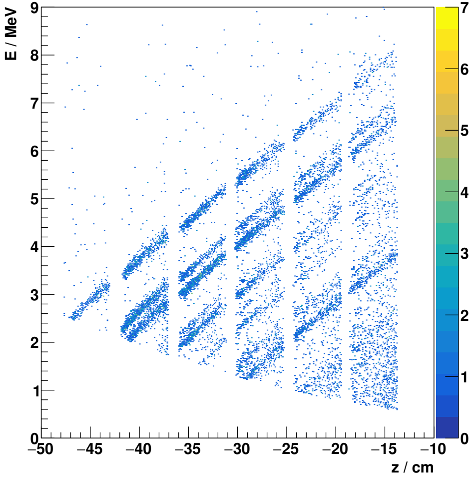


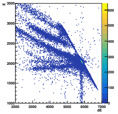


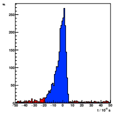
Analysis methodology

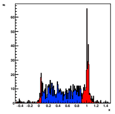
RDT + CM Angle + Timing + Si Cuts



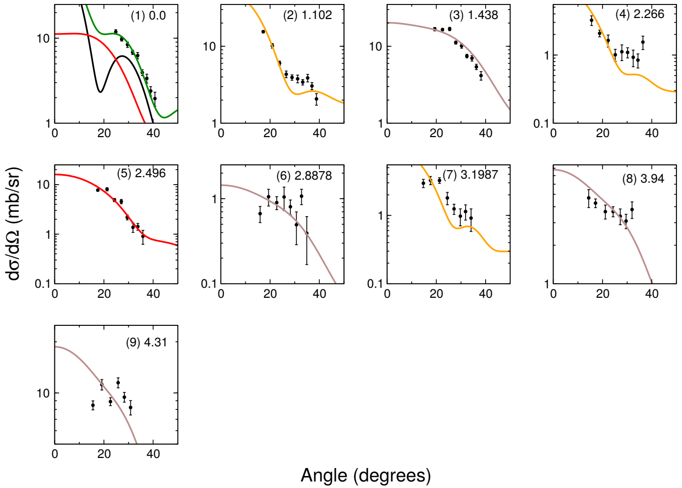






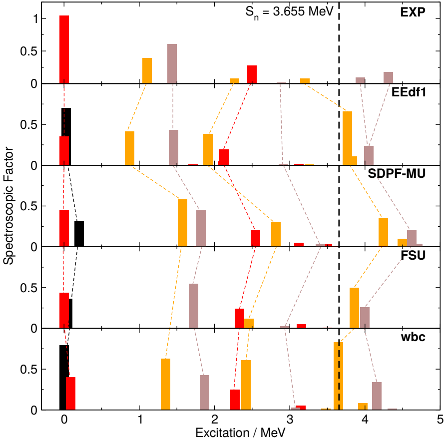


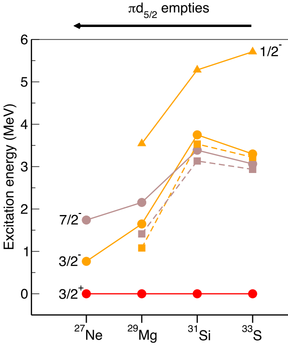
Results



- Angular distributions fitted for all states.
- Assigned angular momenta using DWBA calculations.
- Ground state is a ℓ = 0,2 doublet (total shown in green).
- Unbound states (S_n = 3.655 MeV) not fitting well with chosen optical potentials for DWBA.
- Spectroscopic factors extracted.

Results





Drop in energies relative to $\nu d_{3/2}$ as $\pi d_{5/2}$ empties.

- Compared to different shell-model calculations[4,5,6].
- Experimental states have clear analogues in theoretical models.
- Modern calculations reproduce ordering of doublet ($\ell = 2$ g.s.)
- Generally good calculations overall.
- Seen some unbound states.

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4 A. Matta et al. *Phys. Rev. C* 99 (4 2019), p. 044320.
5 R. Lubna. Priv. communication.
6 Y. Otsuna. Priv. communication.

Ongoing work

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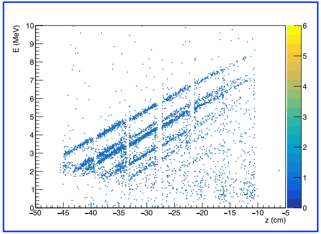

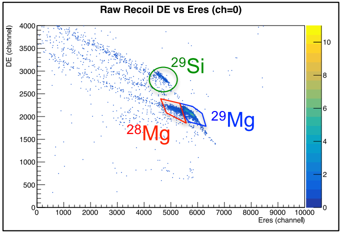

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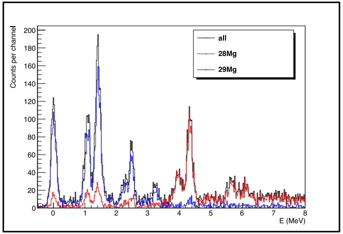

- Recoil detector able to distinguish ^{28}Mg/^{29}Mg.
- Look at the difference between bound and unbound states in ^{29}Mg - is there a γ-branch (unbound state decaying to bound state before neutron emitted)?
- Work ongoing…

7 D. K. Sharp. Private Communication.

Conclusions

- First experiment of ISS in early implementation stage.
- Comparable resolution to HELIOS.
- More beam than expected - requested 6×10^5 pps and got 1×10^6 pps. Allowed measurements at two array positions.
- Energy resolution of excitation not as good as hoped. Many possible reasons for this, e.g. beam properties, alignment etc. $\rightarrow$ this helps us learn about beam delivery into ISS for future runs.
- Highest energy per nucleon in a HIE-ISOLDE radioactive beam experiment.
- Data looks promising - in final stages of analysis before publication.
- A successful experiment!

Acknowledgements

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Manchester Group

David Sharp	Sean Freeman
Benjamin Cropper	

Additional Collaborators

Liam Gaffney	Joonas Konki
Calem Hoffman	Ryan Tang
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Thorsten Kröll	Marc Labiche
Peter Butler	Francesco Recchia
Riccardo Raabe	Oleksii Poleshchuk
Jiecheng Yang	Giacomo de Angelis
Ismael Martel	

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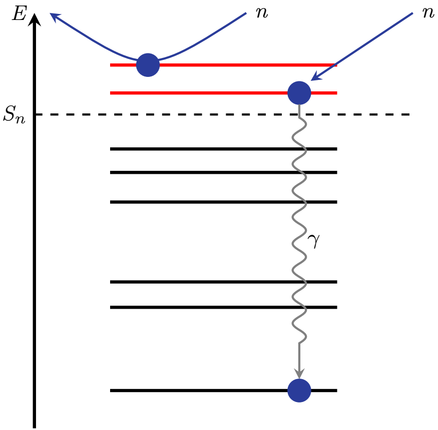
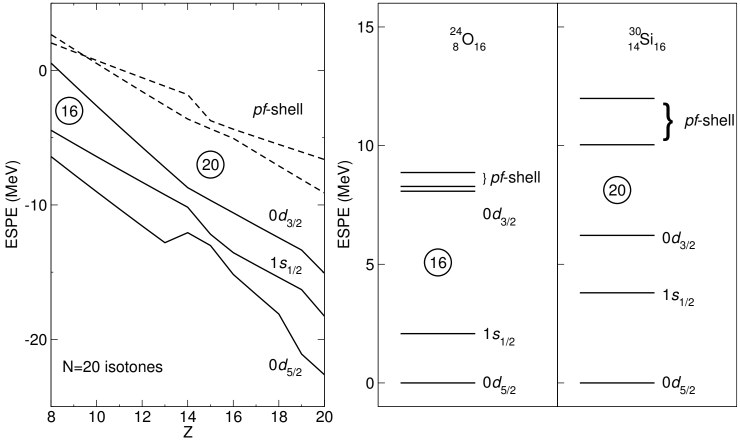
γ-branch



- Neutrons above separation energy form unbound states.
- Neutrons forming unbound states close to S_n have *potential* to γ-decay to a bound state — is called a γ-branch.
- No direct measure of γ-rays in ISS.
- This information can be extracted using Si recoil and array: detect protons corresponding to states above S_n, and detect recoiling ^{29}Mg.

Mechanism



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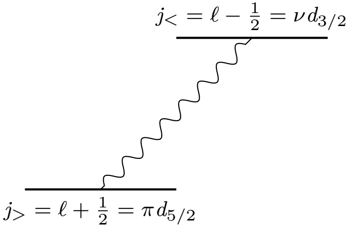
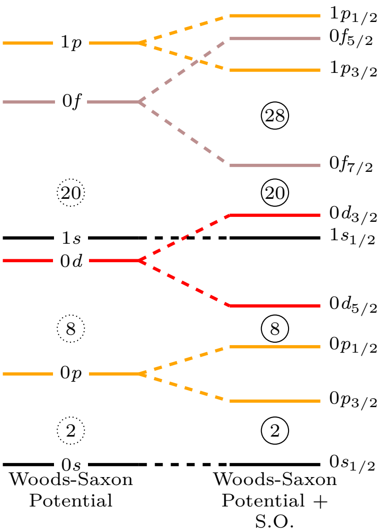


8 Adapted from Otsuka,

Shell Model



$1p_{1/2}$
$0f_{5/2}$
$1p_{3/2}$
$1p$
$0f$
28
$0f_{7/2}$
20
20
$0d_{3/2}$
$1s_{1/2}$
$1s$
$0d$
$0d_{5/2}$
8
8
$0p_{1/2}$
$0p$
$0p_{3/2}$
2
2
$0s$
$0s_{1/2}$
Woods-Saxon Potential
Woods-Saxon Potential + S.O.