

Transfer reactions with low intensity radioactive ion beams in ISS



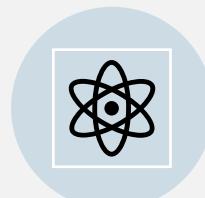
ISOLDE Solenoidal
Spectrometer

Andreas Ceulemans

HIE-ISOLDE PHYSICS WORKSHOP

24-26th May 2023

Contents



$^{68}\text{Ni}(\text{d},\text{p})$
at ISS



The ISS
detector



Preliminary
results



Transfer
reaction in Ca



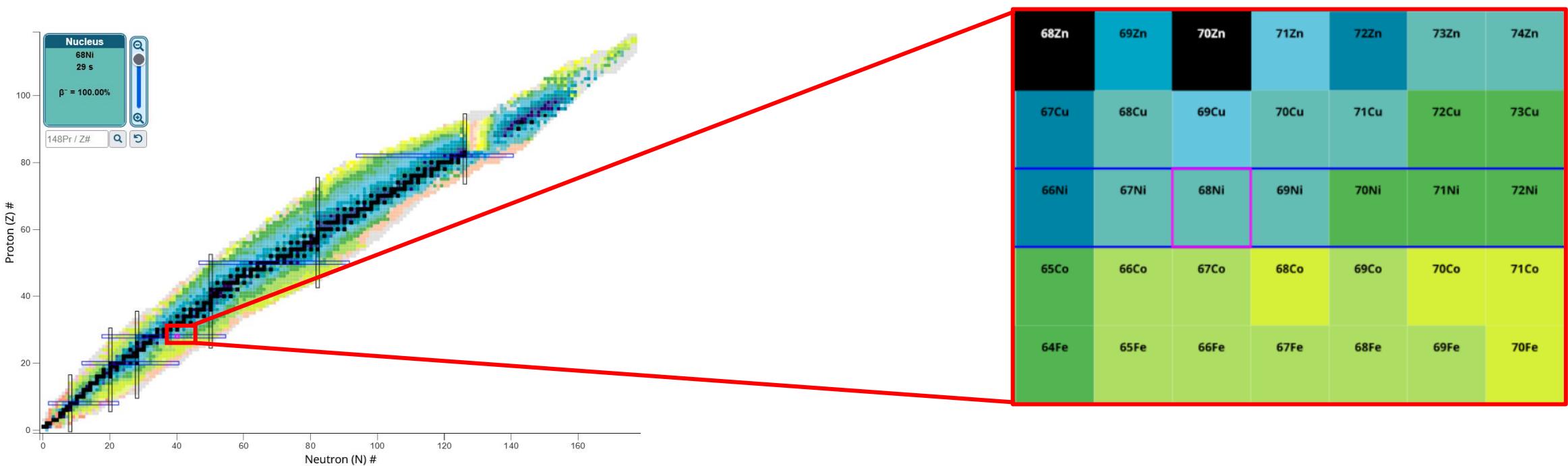
Outlook

Contents



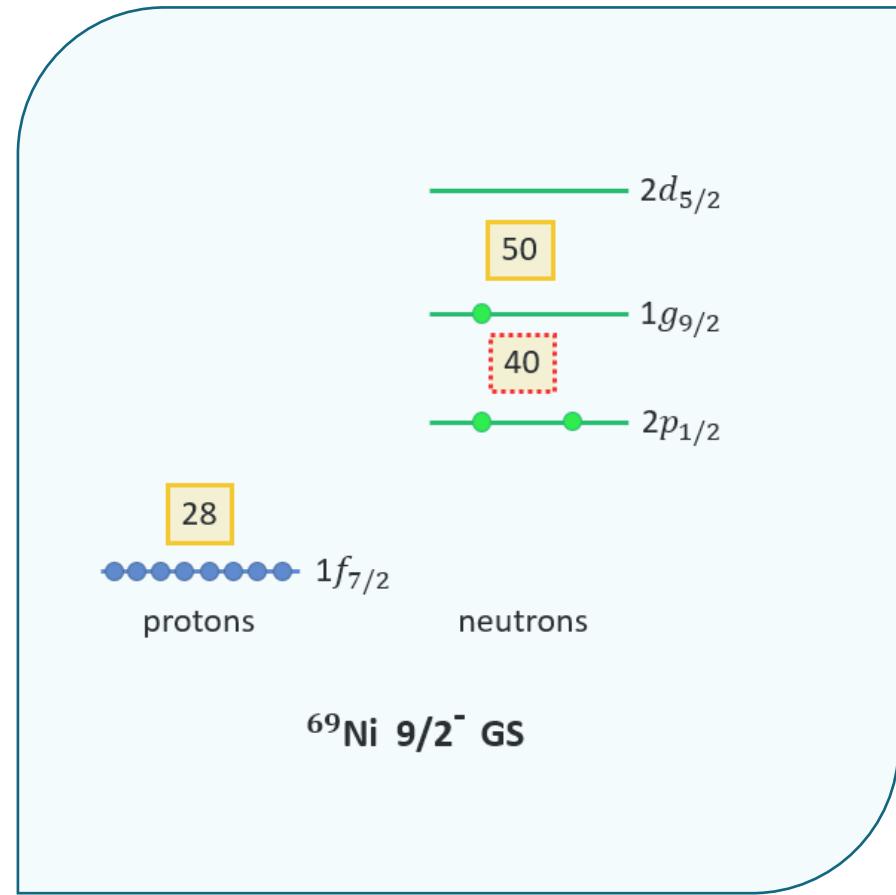
Why research nickel isotopes?

- Proton magic number $Z = 28$
- Collectivity around $N = 40$
- Doubly magic (very exotic) ^{78}Ni



The magicity of ^{68}Ni

- Magic numbers: 2, 8, 20, 28, 50, 82 & 126
- $N = 40$ subshell closure + $1g_{9/2}$ and $2d_{5/2}$
→ Quadrupole collectivity
- ^{68}Ni shows some doubly magic characteristics:
 - High 2^+ energy
 - Low $B(E2; 0_1^+ \rightarrow 2_1^+)$
 - Weak discontinuity of $2n$ separation energy
- “Island of inversion” below ^{68}Ni
 - Ground states Fe and Cr deformed



Goal

- Determination of gap between $1g_{9/2}$ and $2d_{5/2}$ orbitals
- $2d_{5/2}$ position is important input to explain the collectivity around N = 40

- Transfer reaction $^{68}\text{Ni}(\text{d},\text{p})\ ^{69}\text{Ni}$ @ 6 MeV/u
- 137 $\mu\text{g}/\text{cm}^2$ CD_2 target

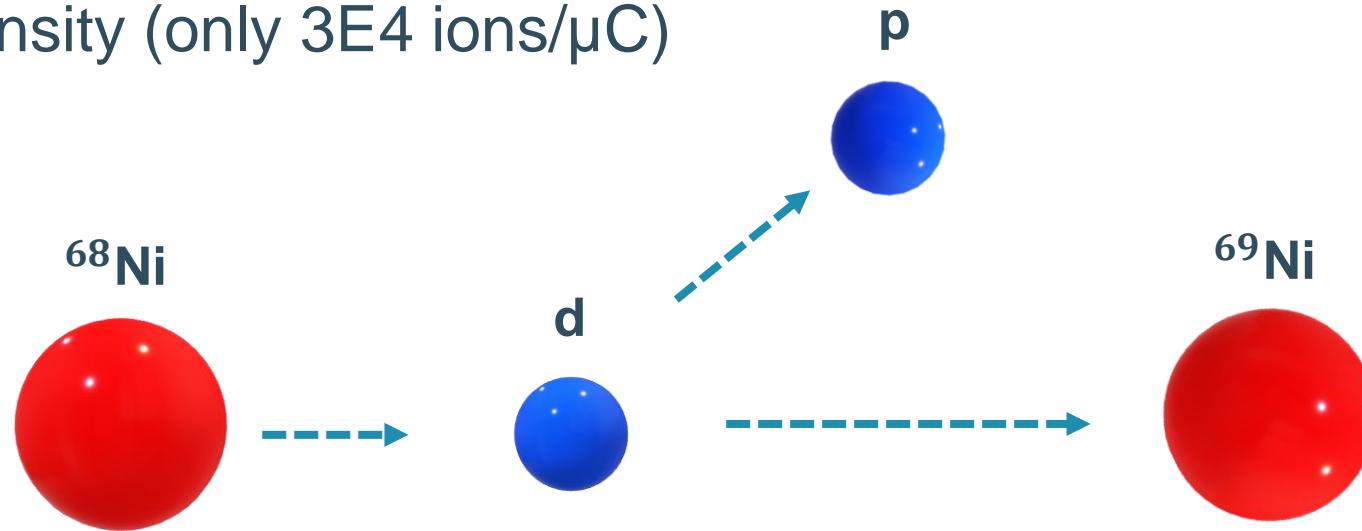


- Performed at ISOLDE, CERN in November 2022

Nuclear reactions using ISS

Inverse kinematics

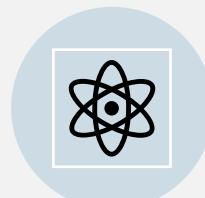
Low beam intensity (only 3E4 ions/ μC)



One-nucleon transfer reactions: e.g. $^{68}\text{Ni}(\text{d},\text{p})^{69}\text{Ni}$

- Selective population of states
- Angular distribution determined by L-transfer

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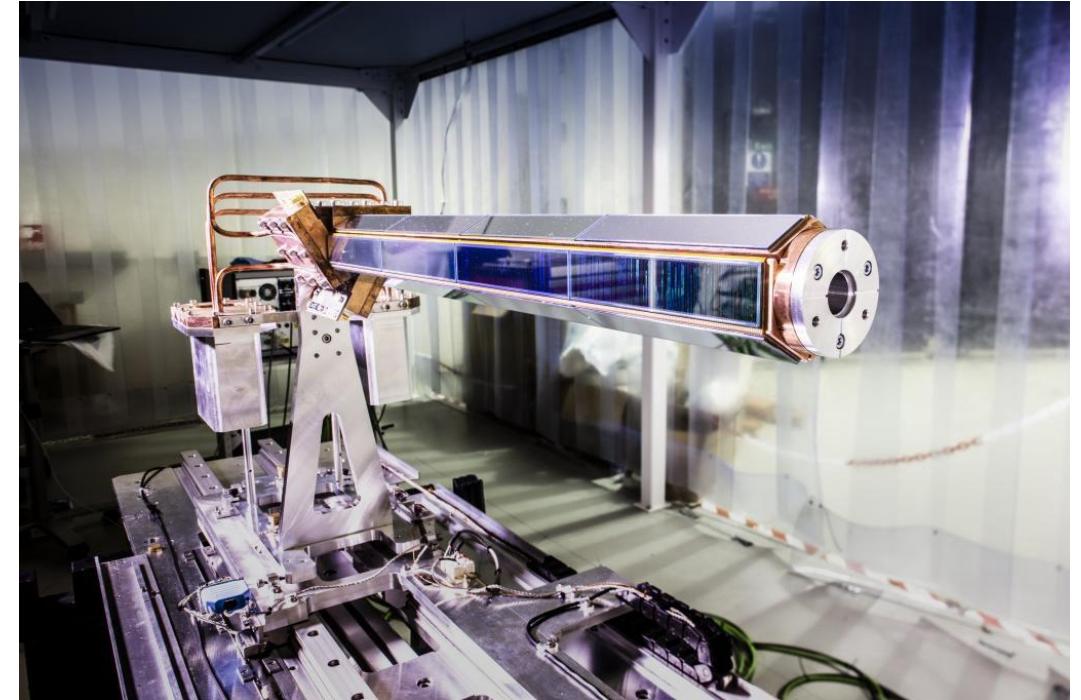
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Outlook

The ISS detector

Solenoid can produce magnetic field up to 2.5T



Si-array consists of DSSD's for detecting protons

Auxiliary detectors

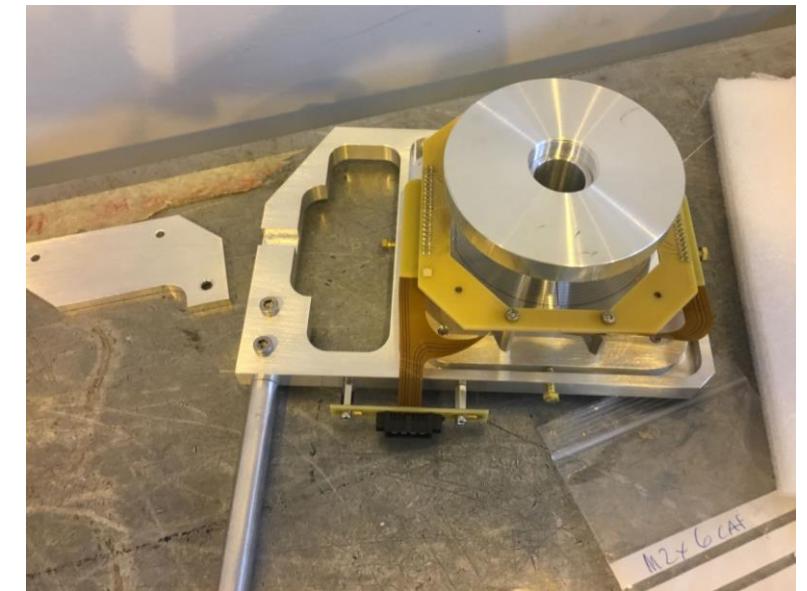
Gas filled recoil detector

- MWPC chamber
- Bragg chamber



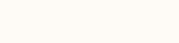
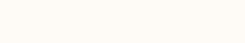
Elastic scattering detector

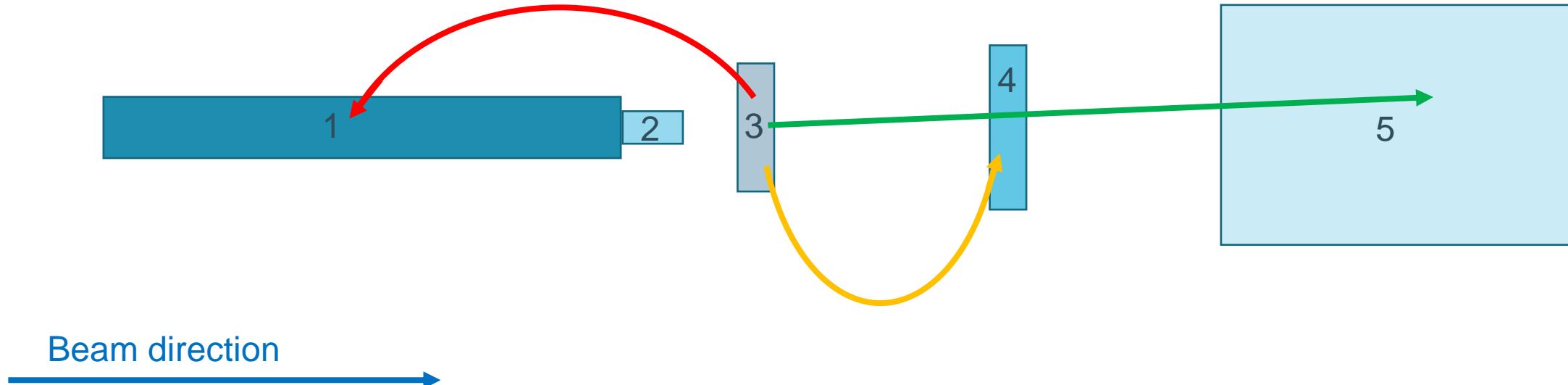
- Micron S1 double-side silicon detector
- Shielded by aluminum plate



Schematic Setup

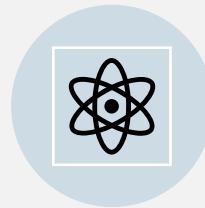
Legend

- 1) Si array 
- 2) Array blocker 
- 3) Target 
- 4) Scattering detector 
- 5) Gaseous recoil detector 



Reaction: $^{68}\text{Ni}(\text{d},\text{p})\ ^{69}\text{Ni}$

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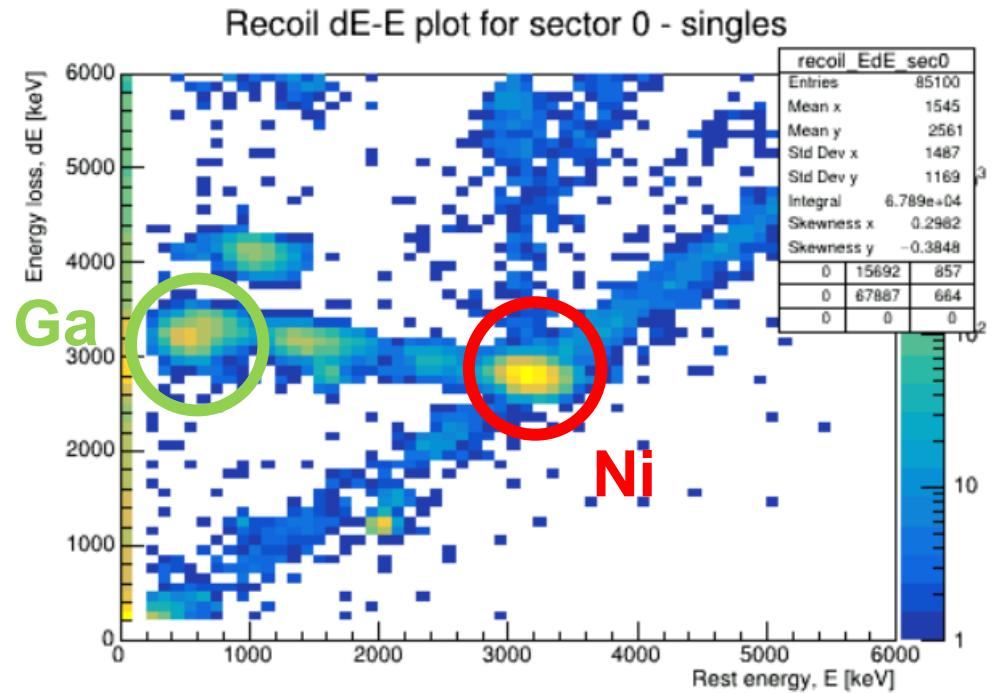


Outlook

Ga background

- Isobaric Ga contamination
- Use of 3s beam gate and consecutive proton pulses
- Laser off for Ga background

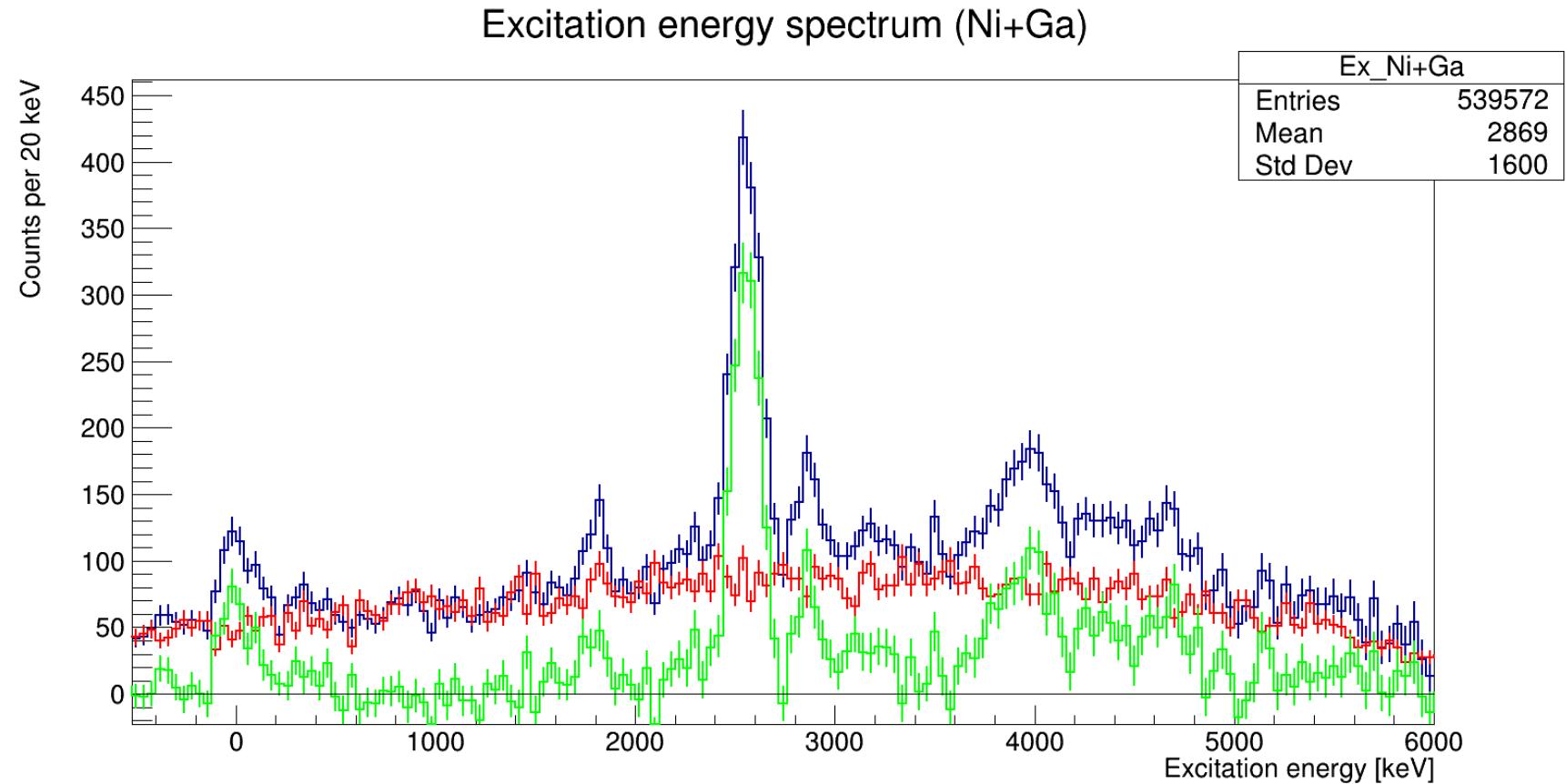
PSB Fixdisplay - W 46							15-Nov-2022 22:13:30
Comments (15-Nov-2022 20:07:44)							
Supervisor : A.Findlay 163961							
Operator : CCC: 76671							
BP	User	Pls	Inj.	Acc.	b.Ej.E10	Ej.E10	Dest.
52	ISOGPS_2022	18	●●●●	●●●●	3188	3242	ISOGPS
53	ISOGPS_2022	18	●●●●	●●●●	3201	3205	ISOGPS
54	ISOGPS_2022	18	●●●●	●●●●	3190	3145	ISOGPS
1	ISOGPS_2022	18	●●●●	●●●●	3205	3183	ISOGPS
2	ISOGPS_2022	18	●●●●	●●●●	3203	3195	ISOGPS
3	ISOGPS_2022	18	●●●●	●●●●	3207	3191	ISOGPS
4	ISOGPS_2022	18	●●●●	●●●●	3205	3213	ISOGPS
5	ISOGPS_2022	18	●●●●	●●●●	3214	3178	ISOGPS
6	ISOGPS_2022	18	●●●●	●●●●	3213	3196	ISOGPS
7	ISOGPS_2022	18	●●●●	●●●●	3197	3238	ISOGPS
8	ISOGPS_2022	18	●●●●	●●●●	3208	3193	ISOGPS
9	ISOGPS_2022	18	●●●●	●●●●	3211	3208	ISOGPS
	ISOGPS_2022						
9/54 No Message							



Configuration	Ratio Ni:Ga
No beam gate	1:7
With beam gate	4:1

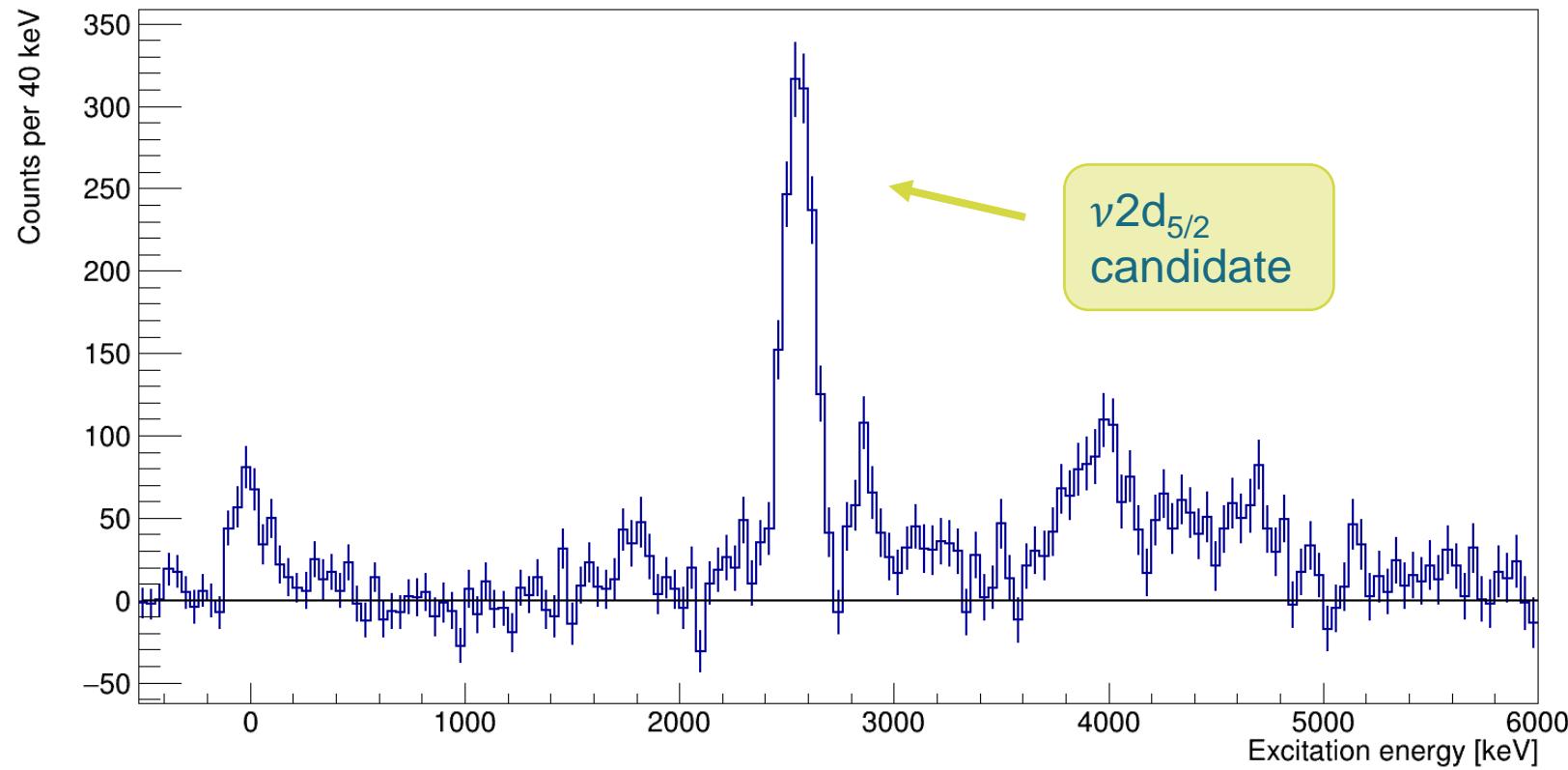
Background subtraction

- Ni + Ga
- Ga bg (scaled)
- Ni bg subtracted

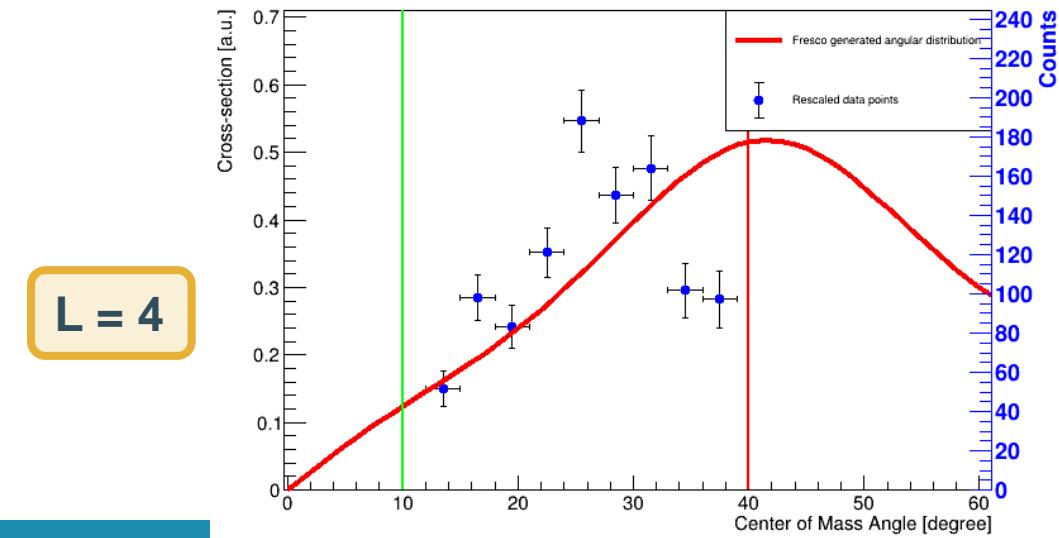
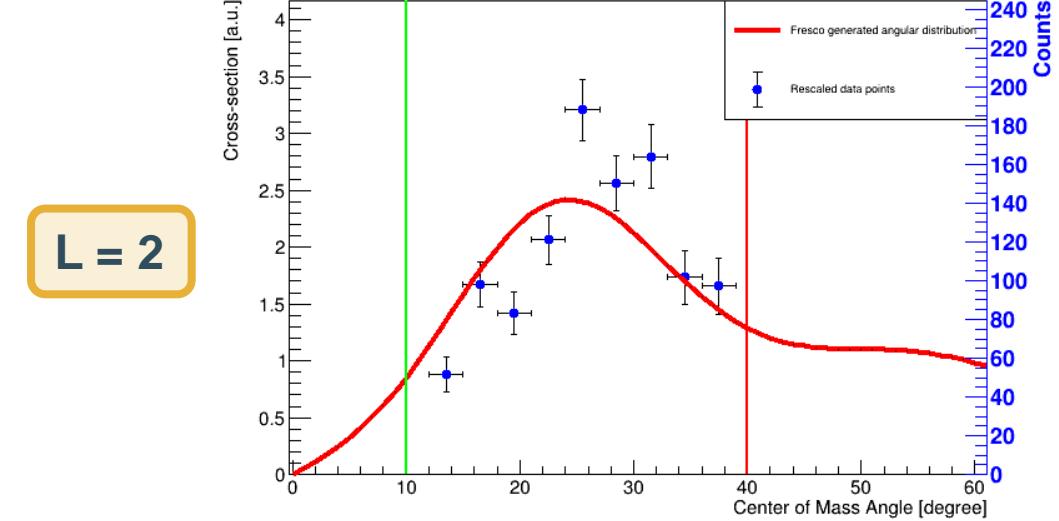
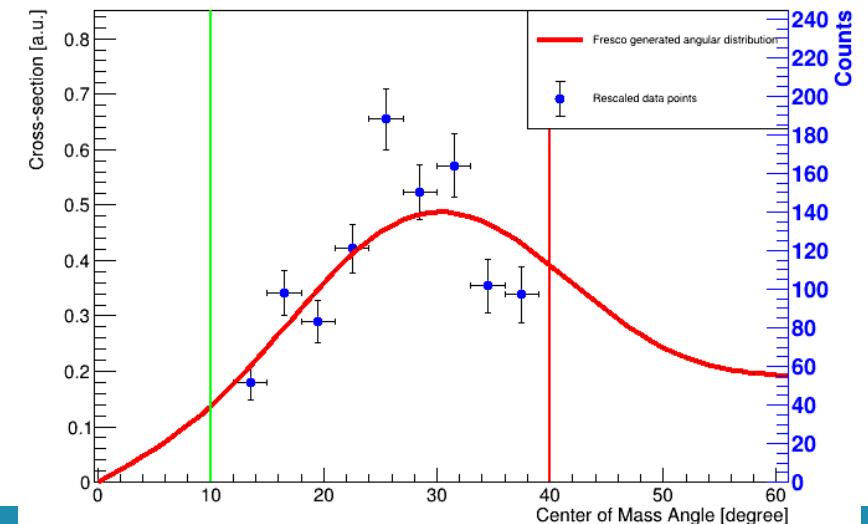
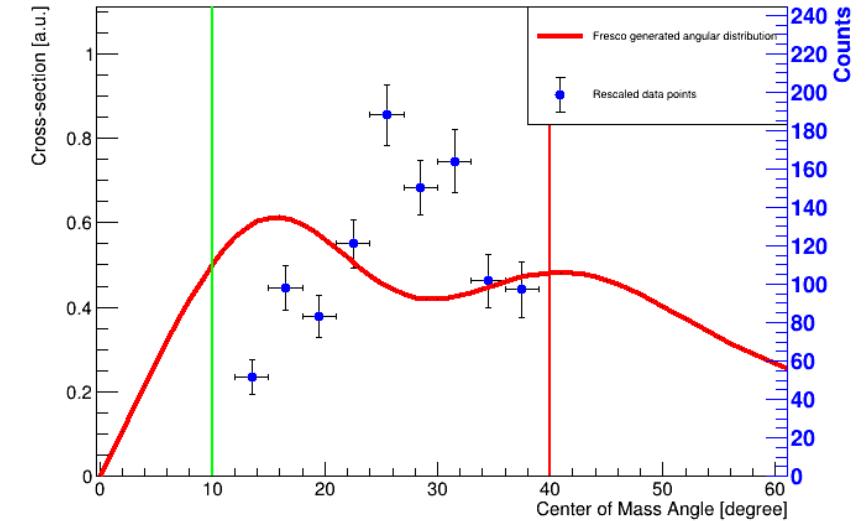


Preliminary energy spectrum

Excitation energy Nickel background subtracted



Angular Distributions (2.5 MeV state)



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IS587
experiment



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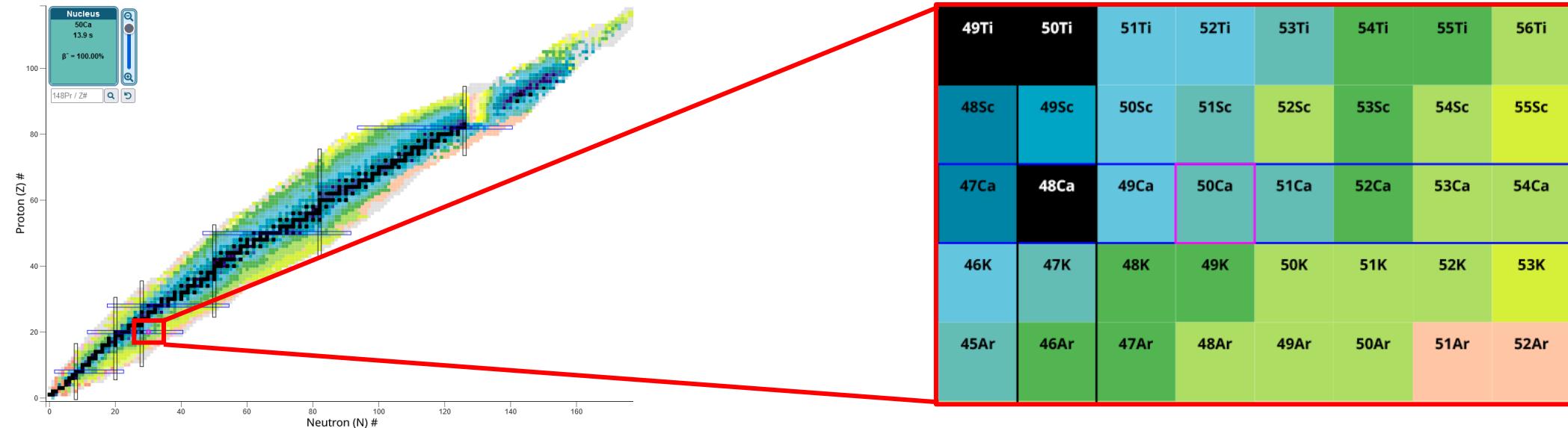
Physics case

Single-particle structure study in neutron-rich Ca through $^{50}\text{Ca}(\text{d},\text{p})$

February 28, 2023

- ^{40}Ca and ^{48}Ca : stable doubly magic isotopes
- Evidence for new neutron magic numbers $N = 32, 34$
by measurements of mass, 2^+ energy, charge radius

A. Ceulemans¹, R. Raabe¹, Y. Ayyad², F. Browne³, A. Camaini¹, Z. Eleme⁴, S. Fracassetti¹, S.J. Freeman^{3,5}, L. Gaffney⁶, S. Goula⁴, A.M. Heinz⁷, B.R. Jones⁶, A. Kawecka⁷, T. Kröll⁸, P.T. MacGregor³, M.V. Managlia⁷, A. Mitchell⁹, J. Ojala⁶, N. Patronis⁴, O. Poleshchuk¹, A.M. Sanchez-Benitez¹⁰, D.K. Sharp⁵, M.E. Stamat⁴, A. Youssef⁴ and the ISS collaboration



A. Huck et al. Phys. Rev. C, 31:2226–2237, 1985

D. Stepenbeck et al. Nature (London), 502(7470):207–210, 2013.

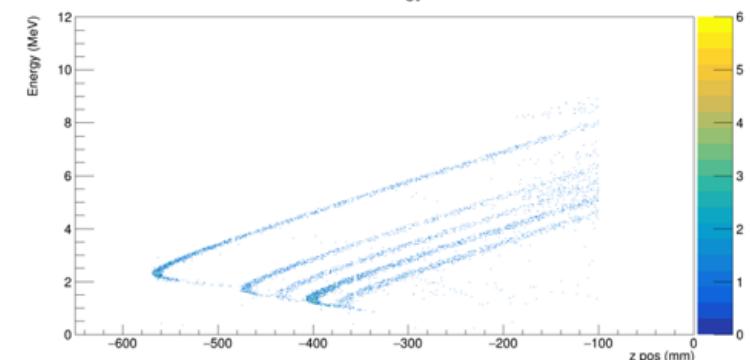
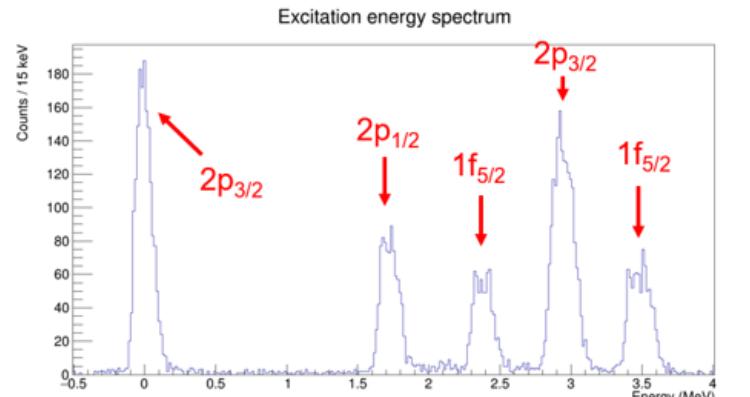
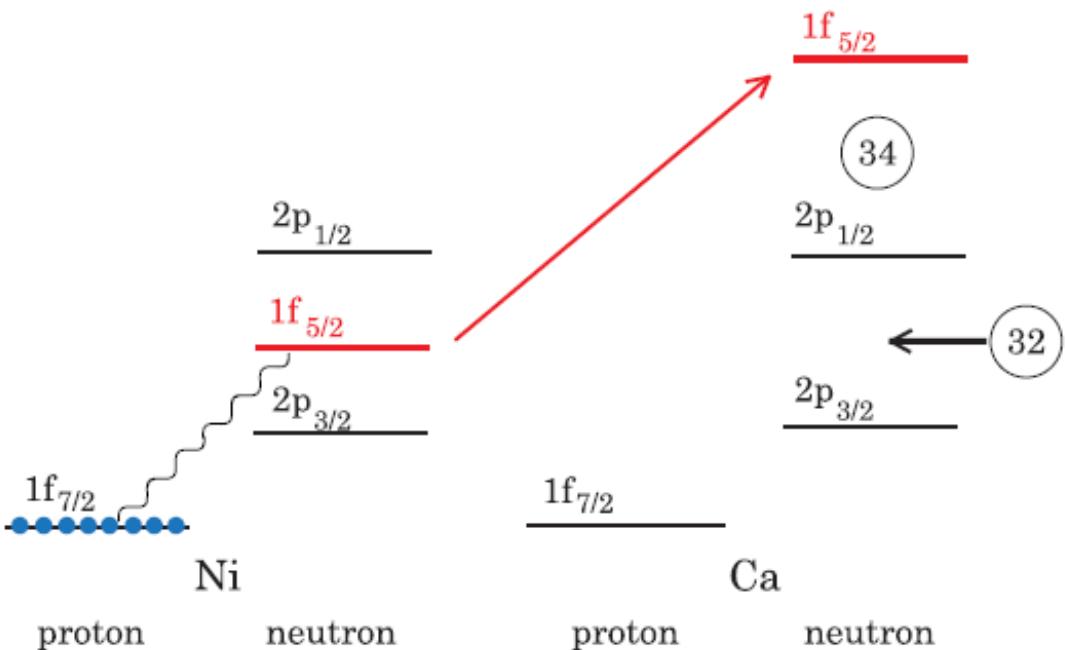
R. F. Garcia Ruiz, et al. Phys. Rev. C, 91:041304, 2015

Figures from: National nuclear data center, NuDat 3 ,<https://www.nndc.bnl.gov/nudat3/>, retrieved 30/01/2023

T. Otsuka, et al. Phys. Rev. Lett., 87:082502, 2001

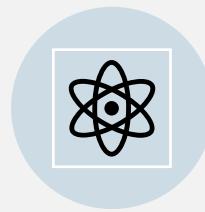
F. Wienholtz, et al. Nature (London), 498(7454):346–349, 2013

New magic numbers



- attractive interaction between $\pi 1f_{7/2}$ and $\nu 1f_{5/2}$
- Ca has full $\pi 1d_{3/2}$ but empty $\pi 1f_{7/2}$
- Single neutron transfer can be used to investigate N=32,34 gaps

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Conclusion

- Data analysis for $^{68}\text{Ni}(\text{d},\text{p})$ is nearly finished and article in preparation
- Experiment IS727 $^{50}\text{Ca}(\text{d},\text{p})$ (and also $^{49}\text{Ca}(\text{d},\text{p})$ by F. Browne) will be scheduled this summer (end of July)

Acknowledgements



- This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511

A. Ceulemans¹, L. P. Gaffney², F. Flavigny³, A. Alharbi², H. Ayatollahzadeh⁴, Y. Ayyad⁵, F. Browne⁶, A. Camaiani¹, D. Clarke⁷, A. Dolan², Z. Eleme⁸, S. Fracassetti¹, S. J. Freeman⁶, G. Georgiev^{6,9}, S. Goula⁸, A. Heinz¹⁰, B.R. Jones², A. Kawęcka¹⁰, J. Keatings⁴, T. Kröll¹¹, P. MacGregor⁶, M.V. Managlia¹⁰, A. Mitchell¹², J. Ojala², B. Olaizola⁶, N. Patronis⁸, O. Poleshchuk¹, R. Raabe¹, A.M. Sánchez-Benítez¹³, D. K. Sharp⁷, M.E. Stamati⁸, H. Törnqvist¹⁰, A. Youssef¹ and the ISS collaboration

¹KU Leuven, Belgium; ²University of Liverpool, U.K.; ³LPC Caen, France; ⁴University of the West of Scotland, U.K.;

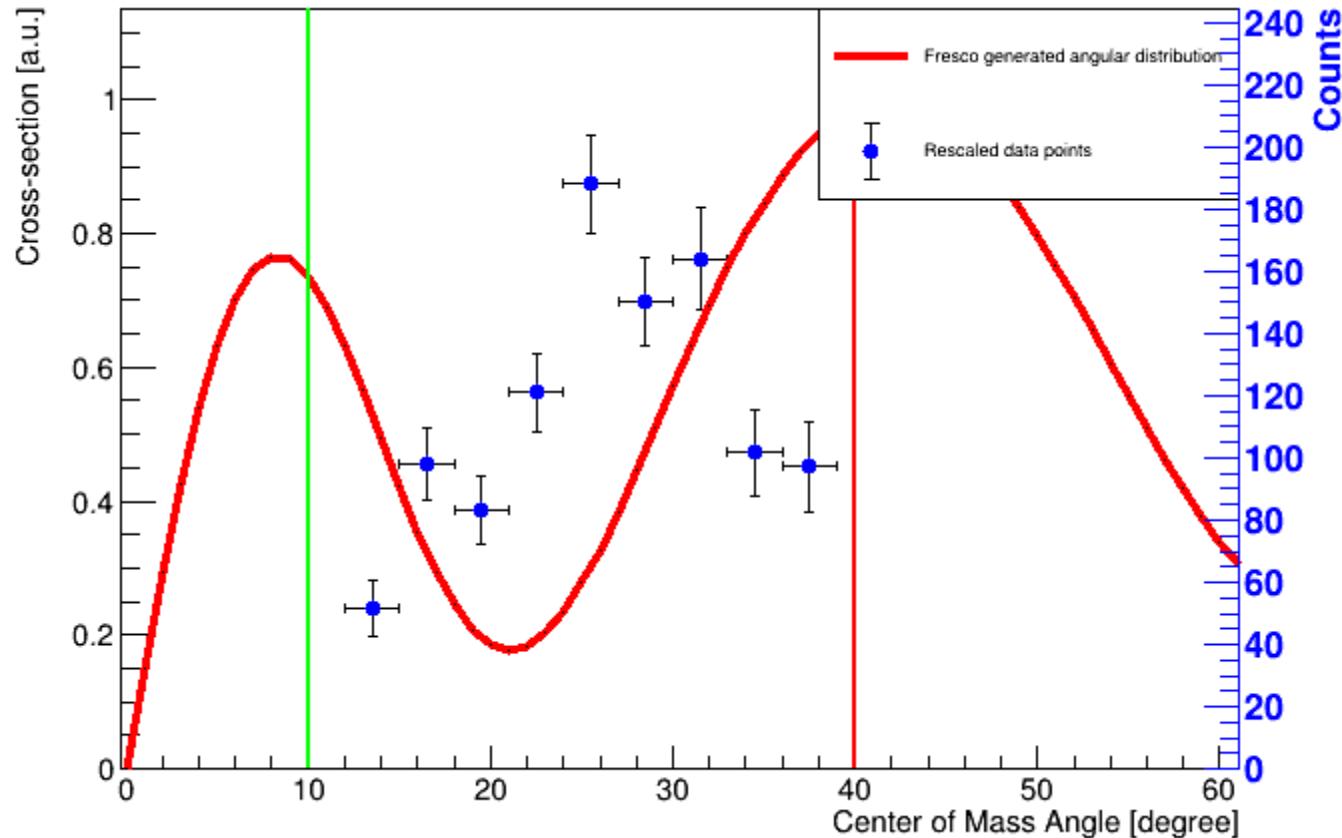
⁵Universidade de Santiago de Compostela, ⁶CERN-ISOLDE, Switzerland; ⁷University of Manchester, U.K.; ⁸University Of Ioannina, Greece.; ⁹IJCLab, France; ¹⁰Chalmers university of Technology, Sweden; ¹¹Technische Universität Darmstadt, Germany, ¹²Australian National University, ¹³University of Huelva, Spain

Thanks for listening

Backup slides

Angular Distributions (2.5 MeV state)

L = 0



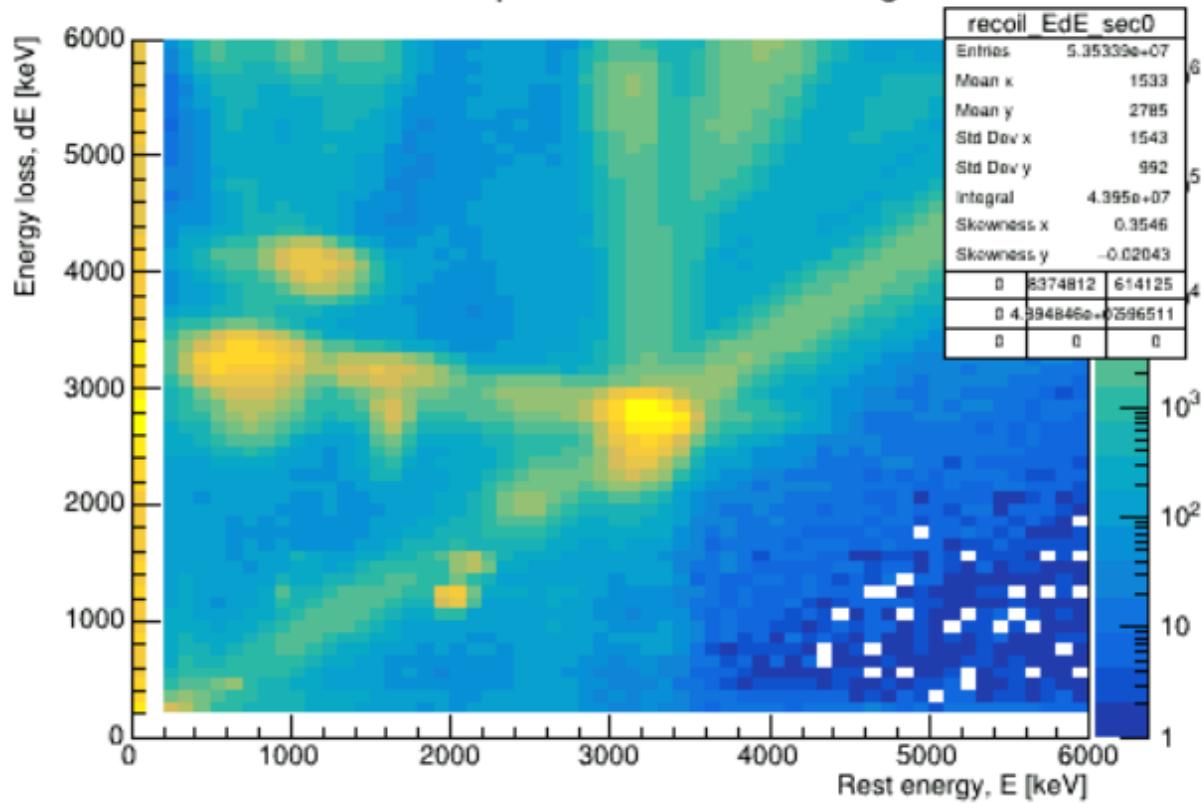
Reaction Info

- Transfer reaction $^{68}\text{Ni}(\text{d},\text{p})^{69}\text{Ni}$
- At beam energy of 6 MeV/u
- Using 137 $\mu\text{g}/\text{cm}^2$ CD_2 target
- Estimated beam intensity 3×10^4 ions/ μC

Recoil detector spectra

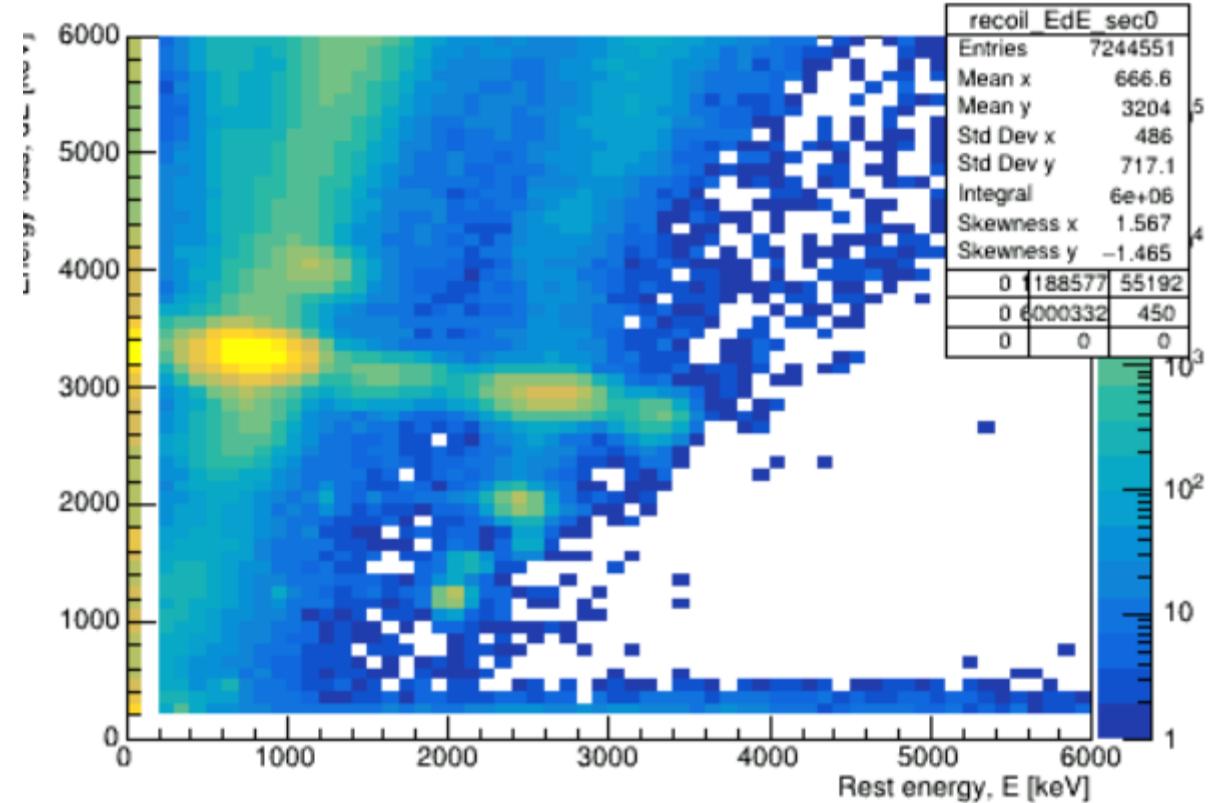
- All Ni+Ga runs

Recoil dE-E plot for sector 0 - singles



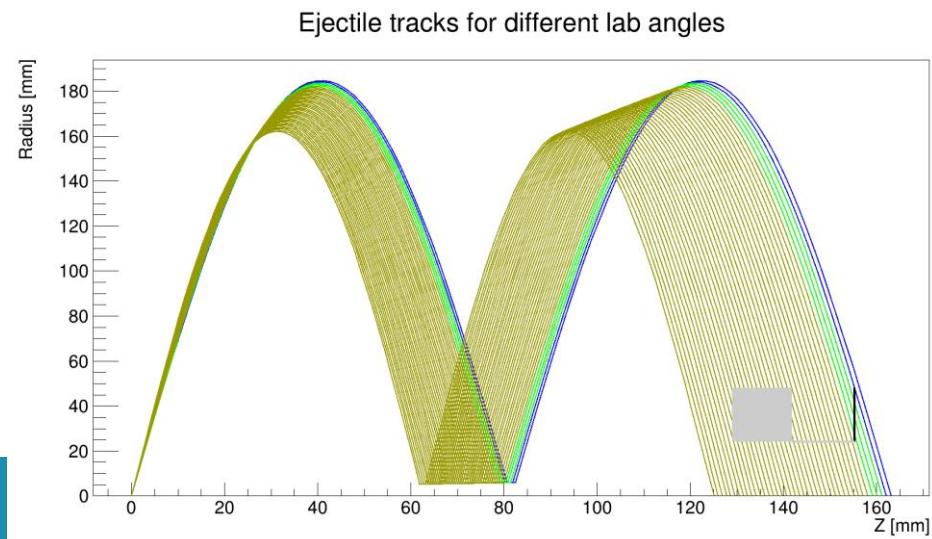
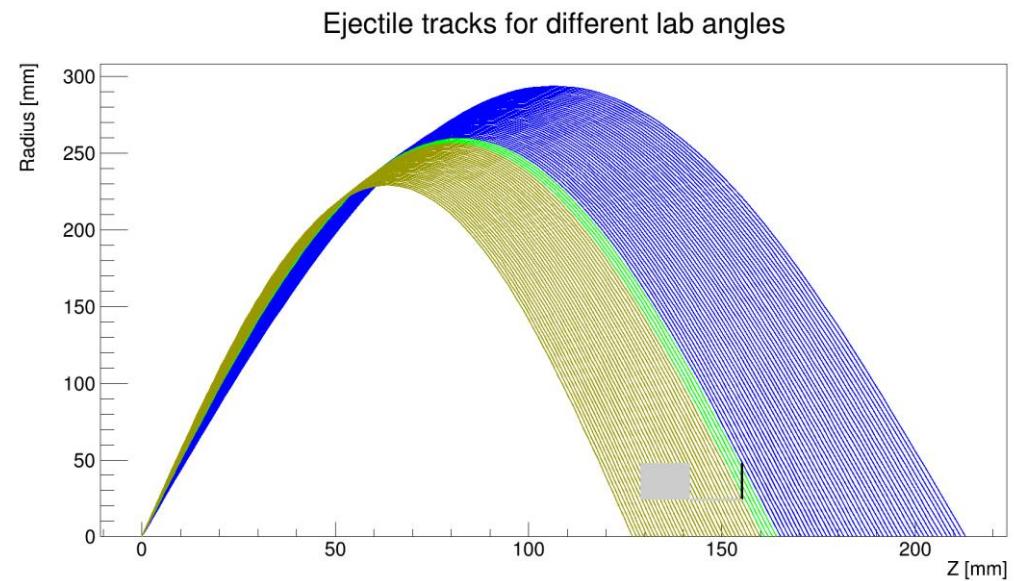
- All Ga runs

Recoil dE-E plot for sector 0 - singles



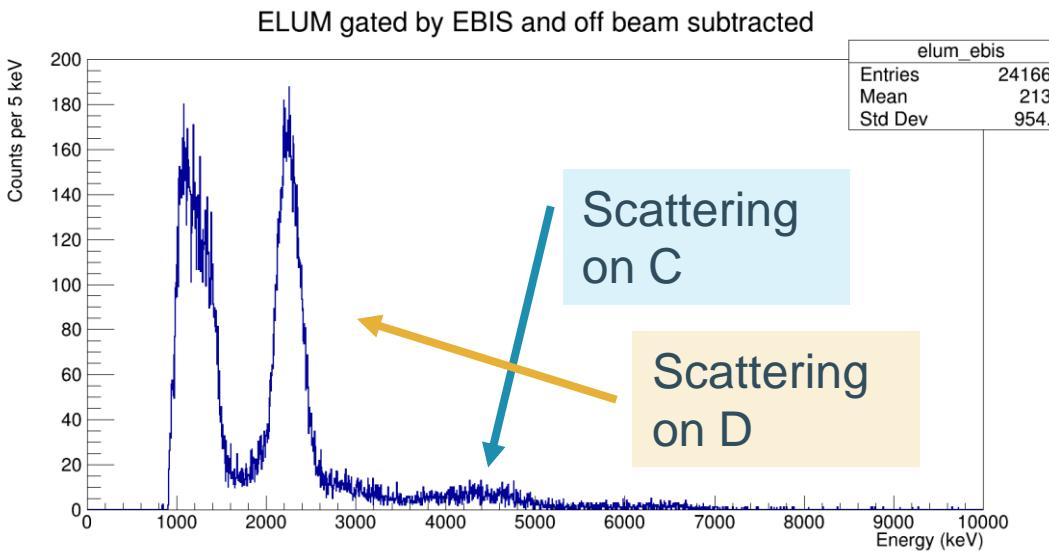
^{68}Ni scattering on d

- Single turns
- $\theta_{lab} \in [78.59^\circ, 78.74^\circ]$
- $E_{kin} \in [1.769, 1.724] \text{ MeV}$
- Double turns
- $\theta_{lab} \in [82.04^\circ, 82.11^\circ]$
- $E_{kin} \in [0.868, 0.852] \text{ MeV}$

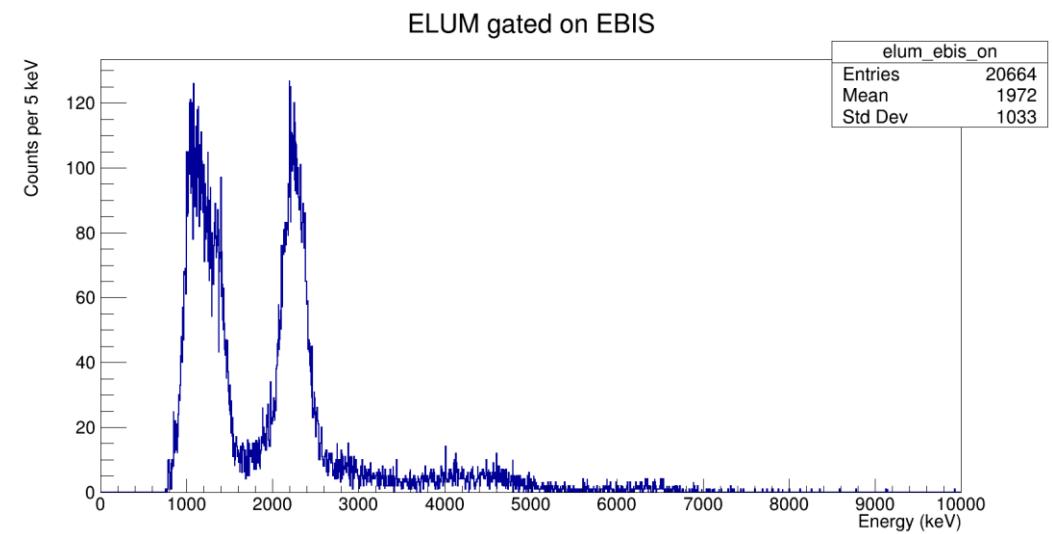


ELUM detector

- Ni + Ga



- Ga



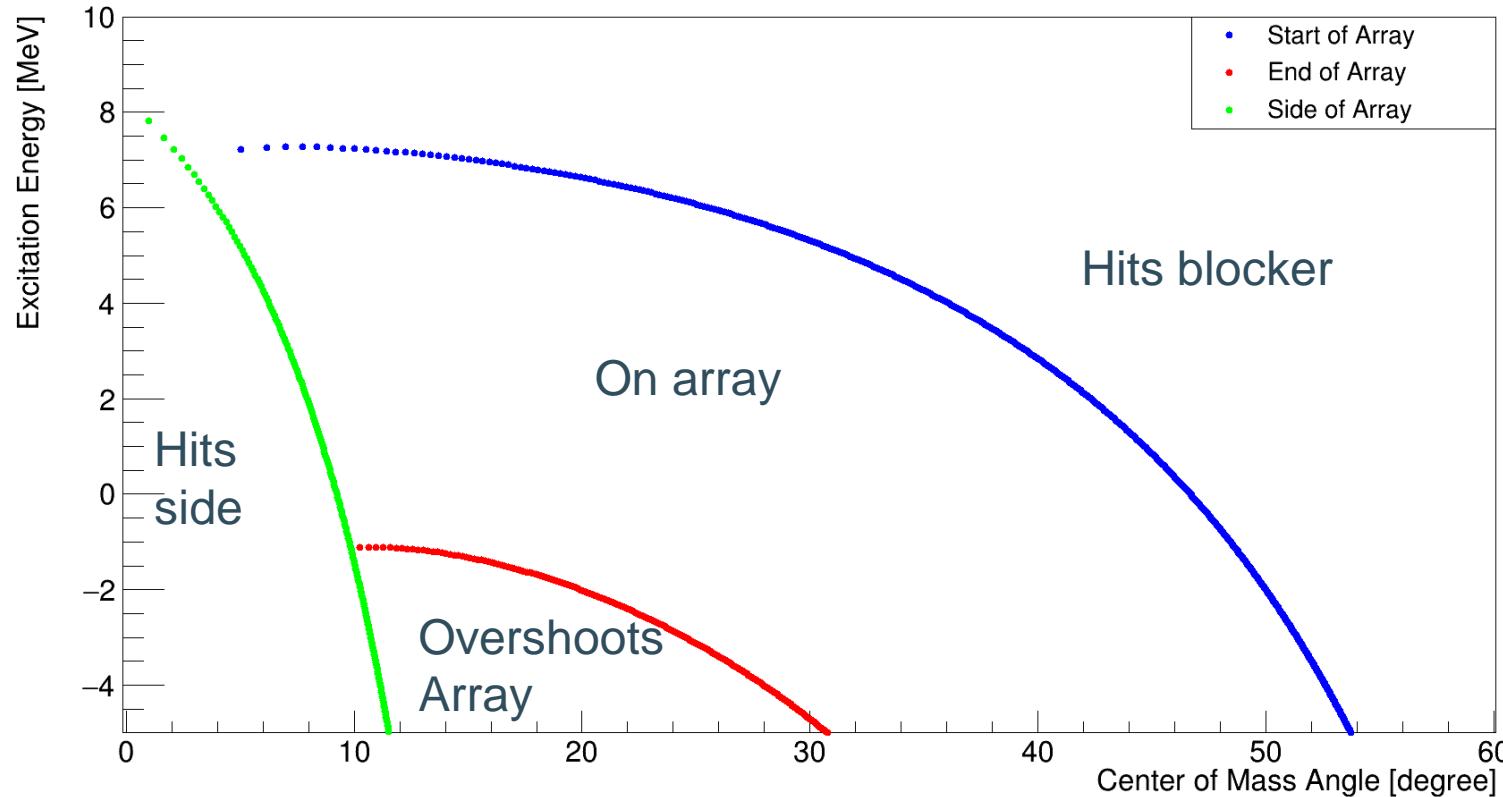
ELUM detector

Shape coexistence

- Ground state deformations for ^{66}Fe and ^{64}Cr
- Low lying isomeric states
- ^{68}Ni has multiple 0^+ states

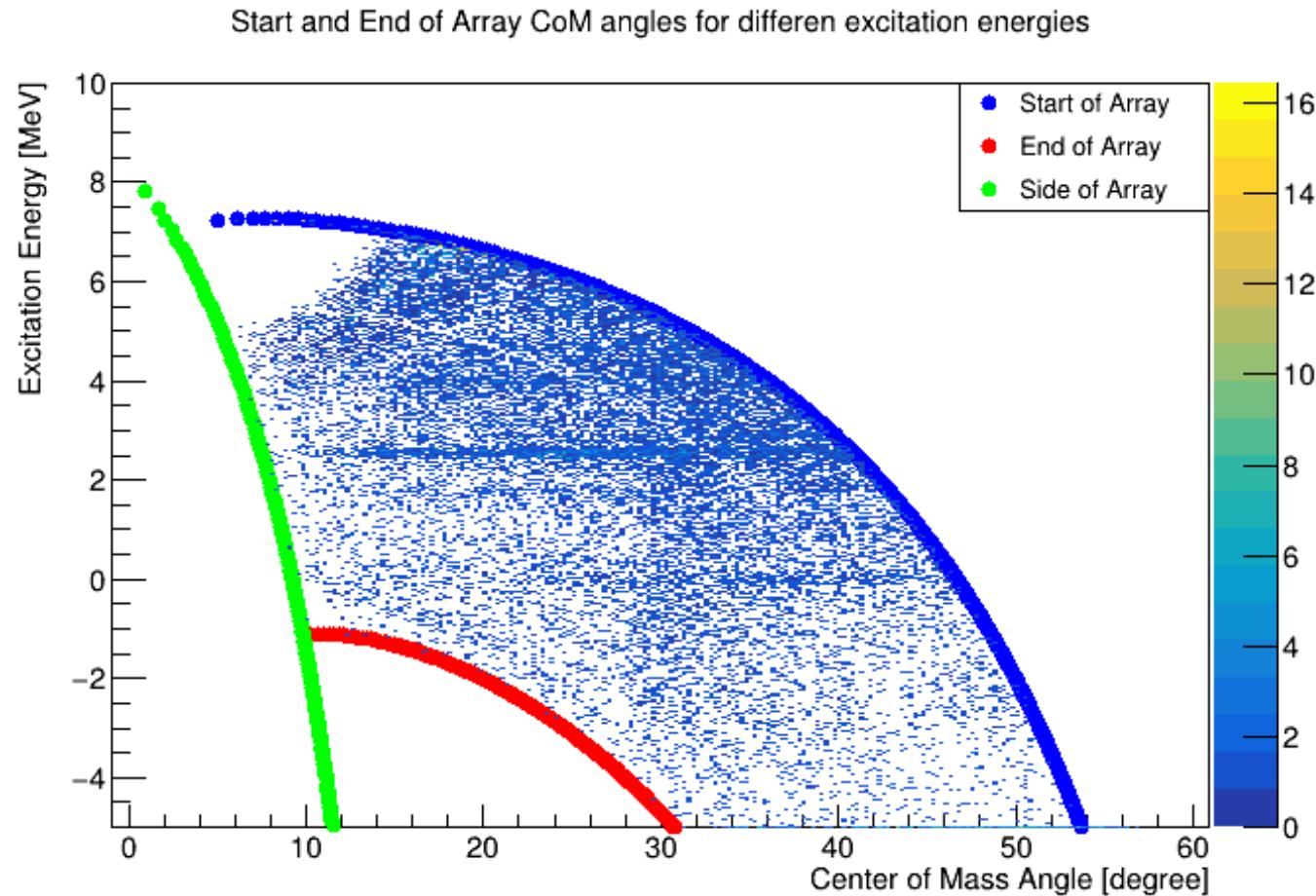
Detection Limits

Start and End of Array CoM angles for differen excitation energies



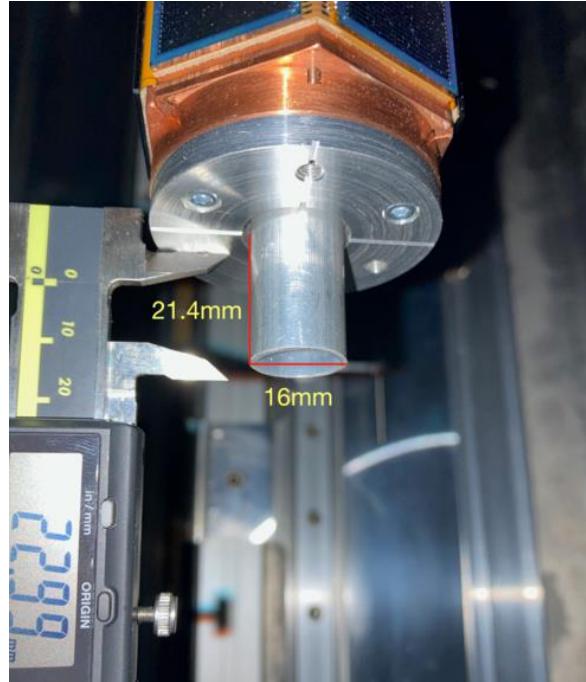
Excitation Energy [MeV]	Angular Range [°]
0	9,2 – 46,7
0,3	9,1 – 46,1
1,77	8,1 – 42,9
2,5	7,6 – 41,0
2,8	7,3 – 40,1
3,1	7,1 – 39,2
4	6,2 – 36,1
4,35	5,9 – 34,7
4,7	5,6 – 33,1

Overlay angular ranges

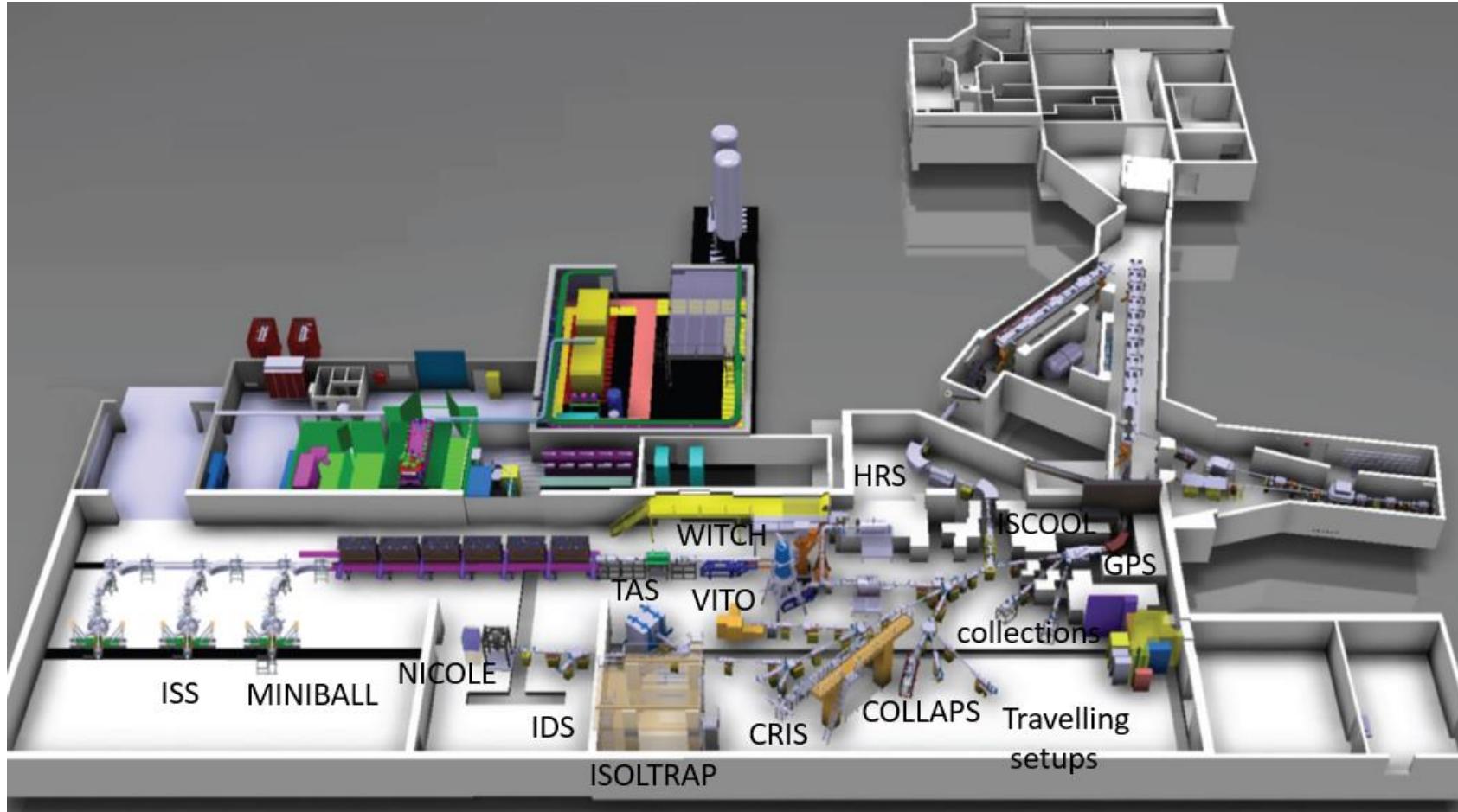


Array blocker

- Avoids protons making multiple loops

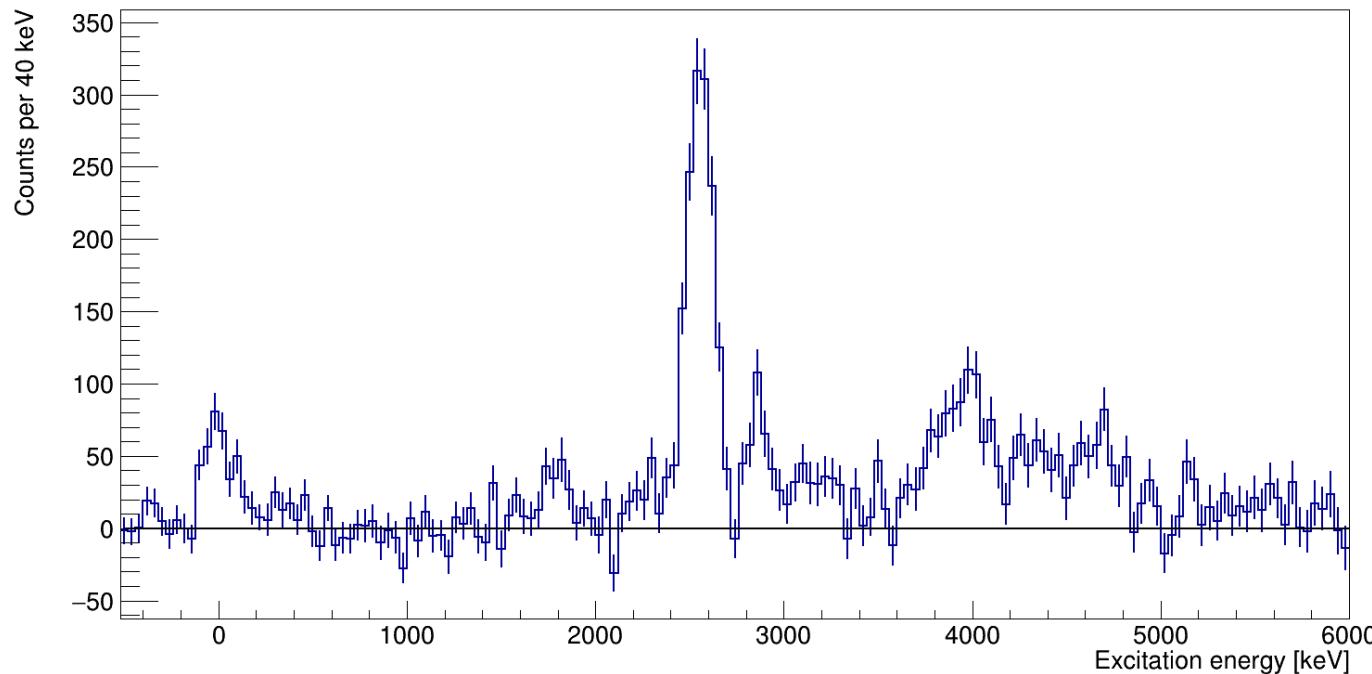


ISOLDE layout



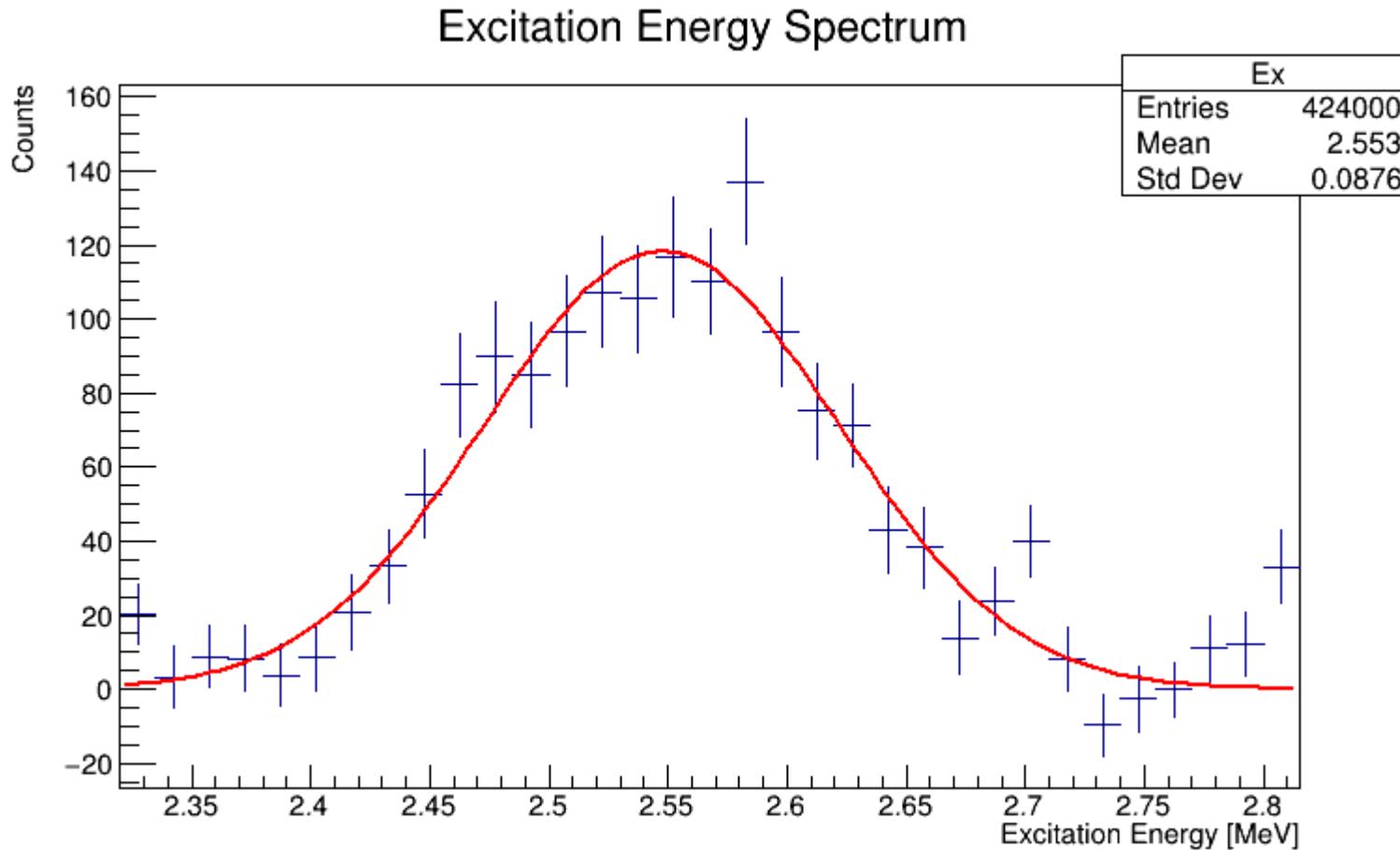
Known energy levels

Excitation energy Nickel background substracted



E (level) (keV)	XREF	J ^π (level)	T _{1/2} (level)	E (γ) (keV)	I (γ)	M (γ)	Final Levels
0.0	ABC	(9/2+)	11.4 s 3 % β ⁻ = 100 % β ⁻ n = ?				
321.2	AB	(1/2-)	3.5 s 4 % β ⁻ ≈ 100 % IT < 0.01				
915.3	AB	(5/2-)	120 ps 34	594.3		[E2]	321 (1/2-)
1517.4	A	(5/2-)		602.4 1196.5	79 9 100 11		915.3 (5/2-) 321 (1/2-)
1821.0	A			303.6			1517.4 (5/2-)
1959	B	(9/2-)		1044 1959			915.3 (5/2-) 0.0 (9/2+)
2241	B	(13/2+)		2241			0.0 (9/2+)
2552	BC	(13/2-)	519 ps 24	311 593	39 100	[E1] [E2]	2241 (13/2+) 1959 (9/2-)
2700	B	(17/2-)	0.439 ps 3 % IT = 100	148		[E2]	2552 (13/2-)

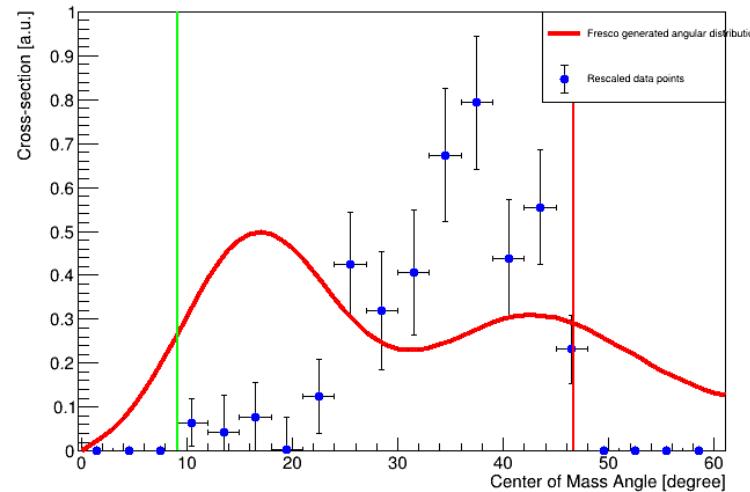
2,5MeV peak



$\text{FWHM} = 175 \pm 8 \text{ keV}$
 $\text{Integral} = 1467 \text{ counts}$
 $\text{Center} = 2,547 \pm 0,003 \text{ MeV}$

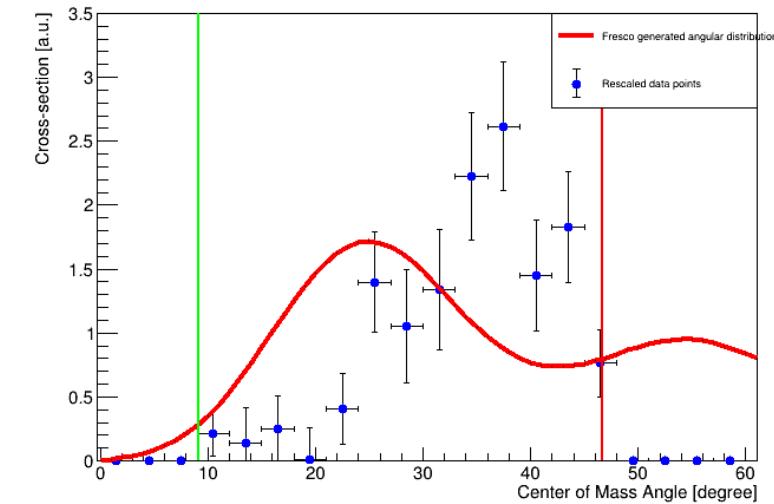
Angular Distributions (GS)

Angular distribution comparison



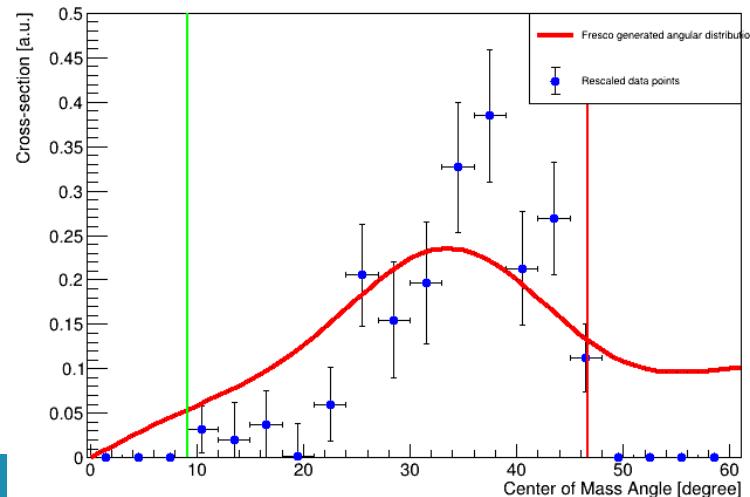
$L = 1$

Angular distribution comparison



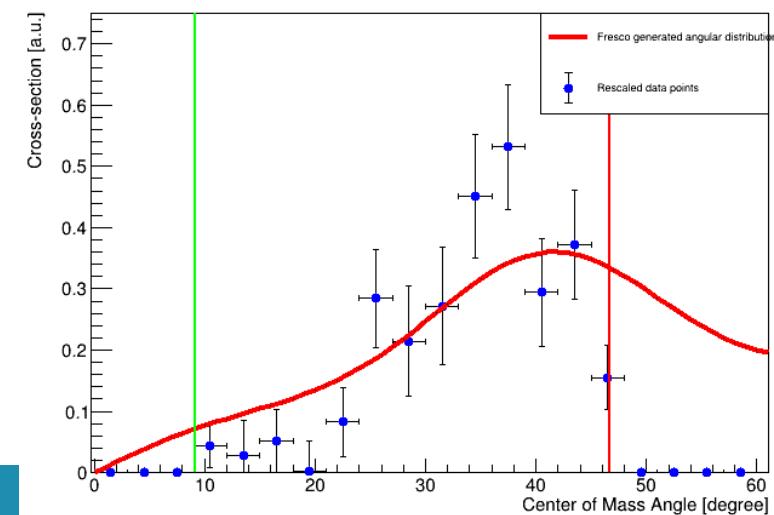
$L = 2$

Angular distribution comparison



$L = 3$

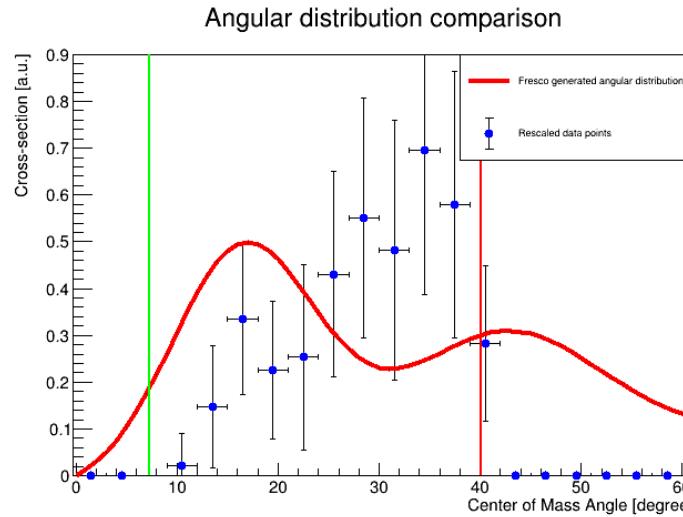
Angular distribution comparison



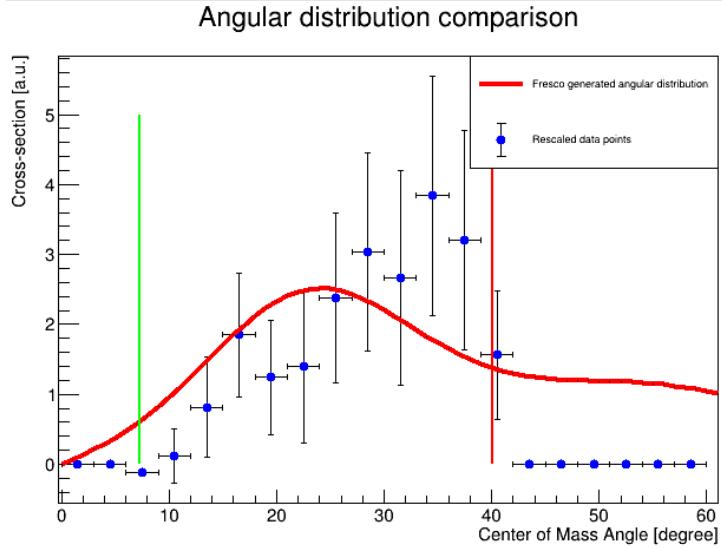
$L = 4$

Angular Distributions (2,8 MeV)

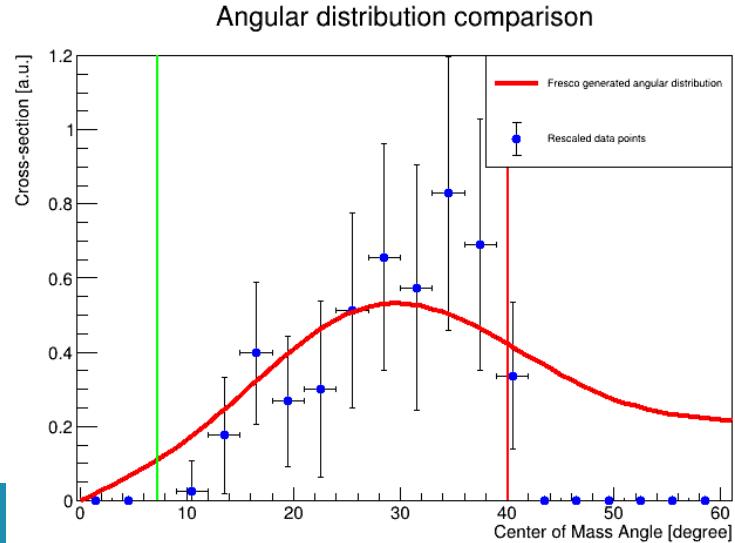
L = 1



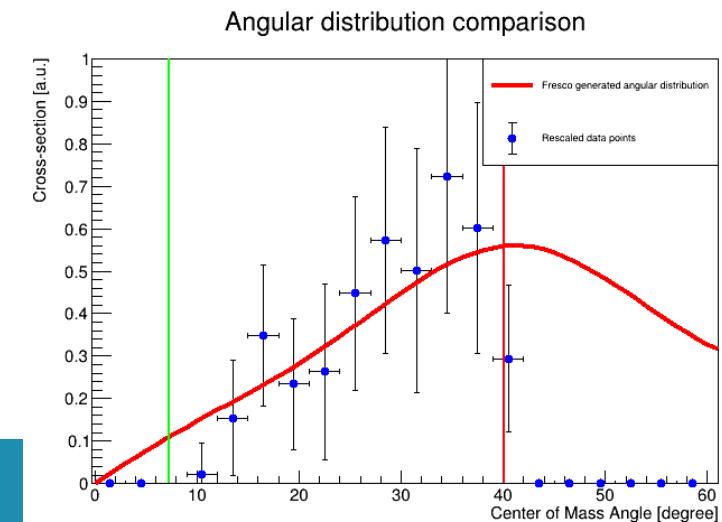
L = 2



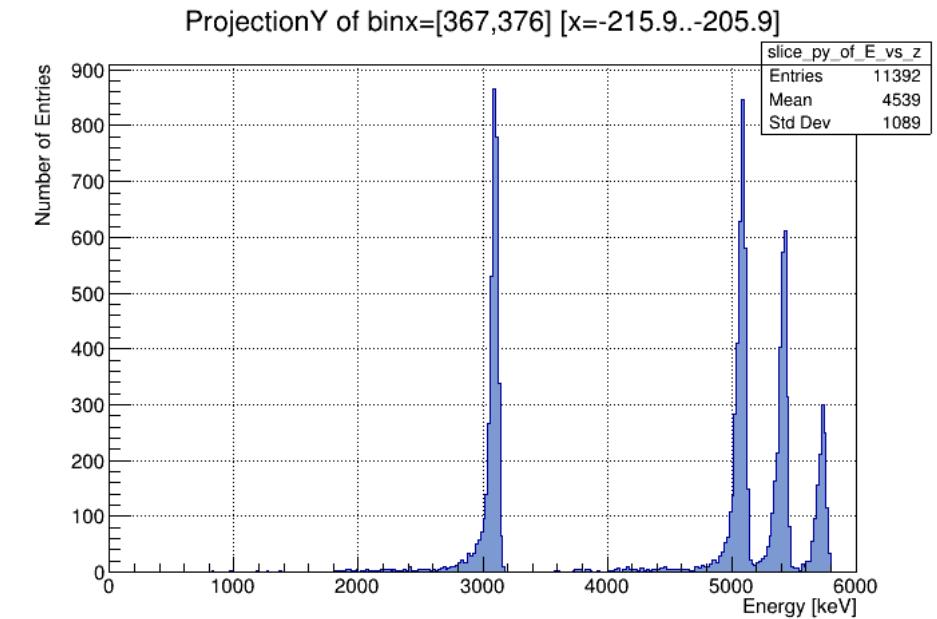
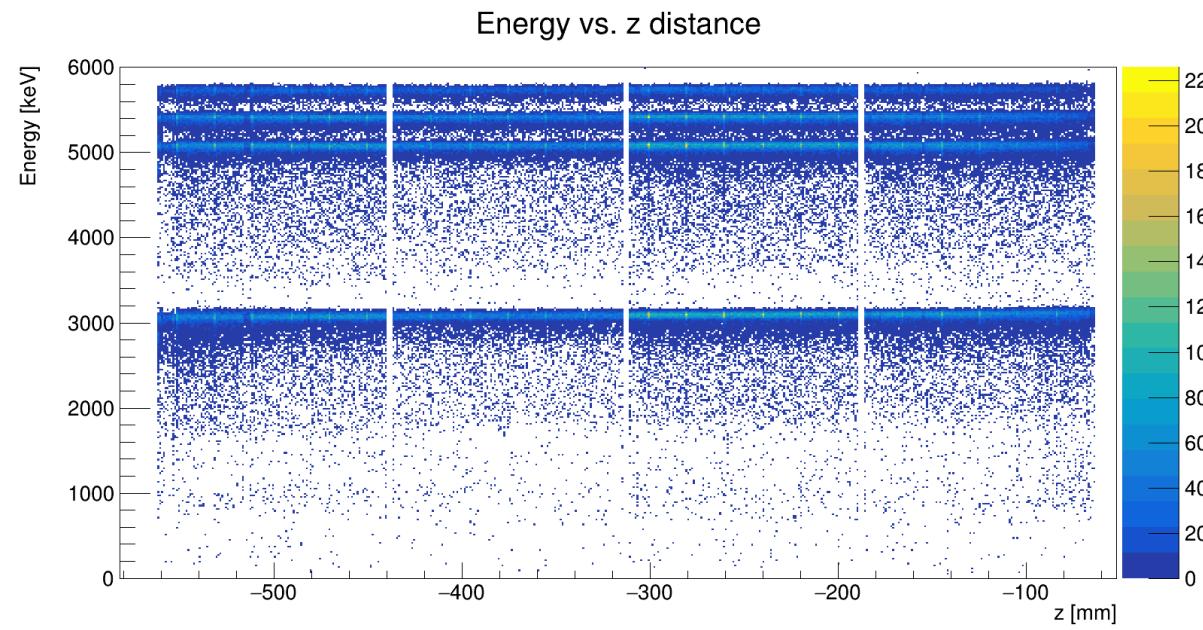
L = 3



L = 4



Alpha calibration (single subrun R121_30)



A. Ceulemans¹, L. P. Gaffney², F. Flavigny³, A. Alharbi², H. Ayatollahzadeh⁴, Y. Ayyad⁵, F. Browne⁶, A. Camaiani¹, D. Clarke⁷, A. Dolan², Z. Eleme⁸, S. Fracassetti¹, S. J. Freeman⁶, G. Georgiev^{6,9}, S. Goula⁸, A. Heinz¹⁰, B.R. Jones², A. Kawęcka¹⁰, J. Keatings⁴, T. Kröll¹¹, P. MacGregor⁶, M.V. Managlia¹⁰, A. Mitchell¹², J. Ojala², B. Olaizola⁶, N. Patronis⁸, O. Poleshchuk¹, R. Raabe¹, A.M. Sánchez-Benítez¹³, D. K. Sharp⁷, M.E. Stamati⁸, H. Törnqvist¹⁰, A. Youssef¹ and the ISS collaboration

¹KU Leuven, Belgium; ²University of Liverpool, U.K.; ³LPC Caen, France; ⁴University of the West of Scotland, U.K.; ⁵Universidade de Santiago de Compostela, ⁶CERN-ISOLDE, Switzerland; ⁷University of Manchester, U.K.; ⁸University Of Ioannina, Greece.; ⁹IJCLab, France; ¹⁰Chalmers university of Technology, Sweden; ¹¹Technische Universität Darmstadt, Germany, ¹²Australian National University, ¹³University of Huelva, Spain