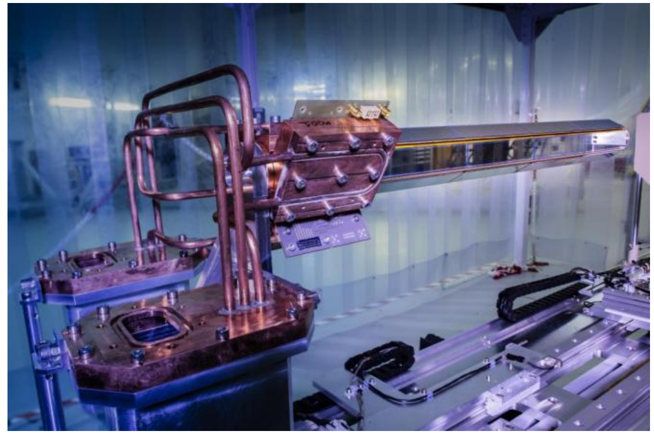



Nature of single-particle states in ^{111}Sn explored through (d,p) reaction with ISS

Joochun (Jason) Park [RIBS, SNU & CENS, IBS],

Joakim Cederkäll and Antonio Lopez [Lund U.]

for the IS686 collaboration

International Nuclear Physics Conference (INPC)

May 26, 2025

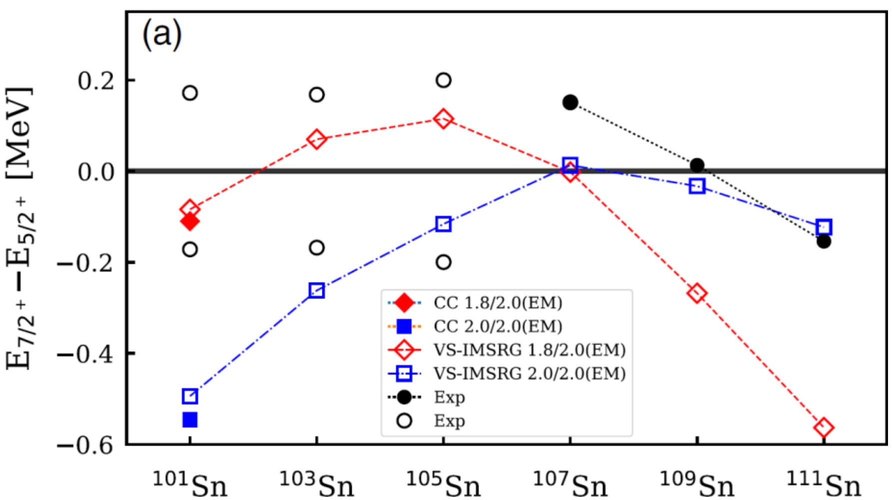
Uncovering structural evolution towards ^{100}Sn

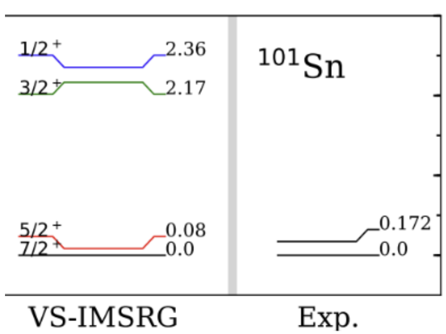
Neutron-deficient Sn isotopes:

- Doubly magic ^{100}Sn and shell evolution
- Enhanced collectivity relative to seniority scheme

Calculations with 3N forces:

- ^{100}Sn is indeed doubly magic
- Reproduce small $E(5/2^+) - E(7/2^+)$ gap in ^{101}Sn
- Significant systematic uncertainties

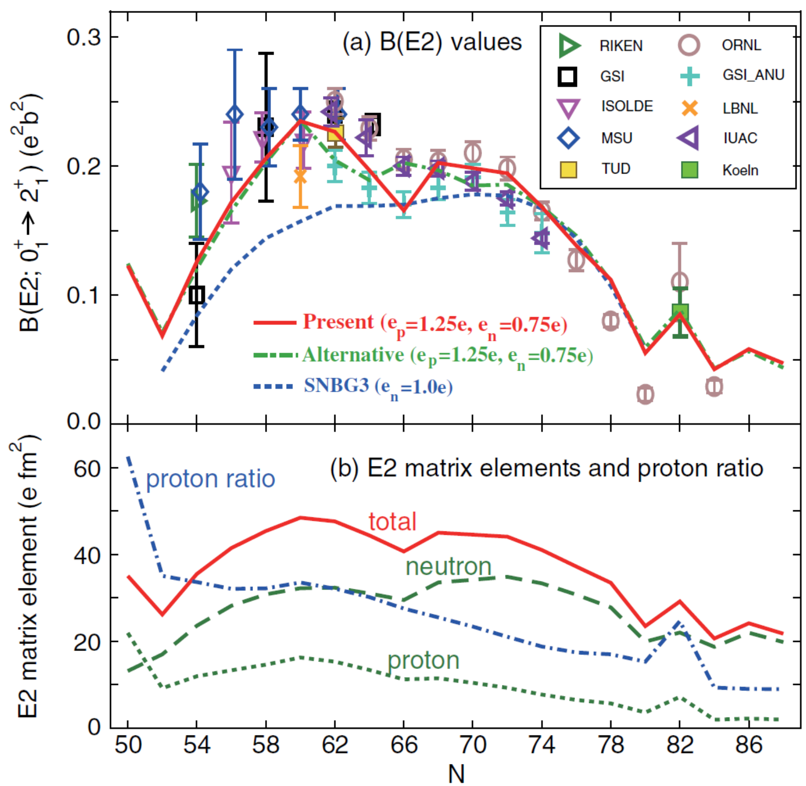




Adopted from
T. D. Morris *et al.*,
PRL 120, 152503 (2018)

Monte-Carlo Shell Model:

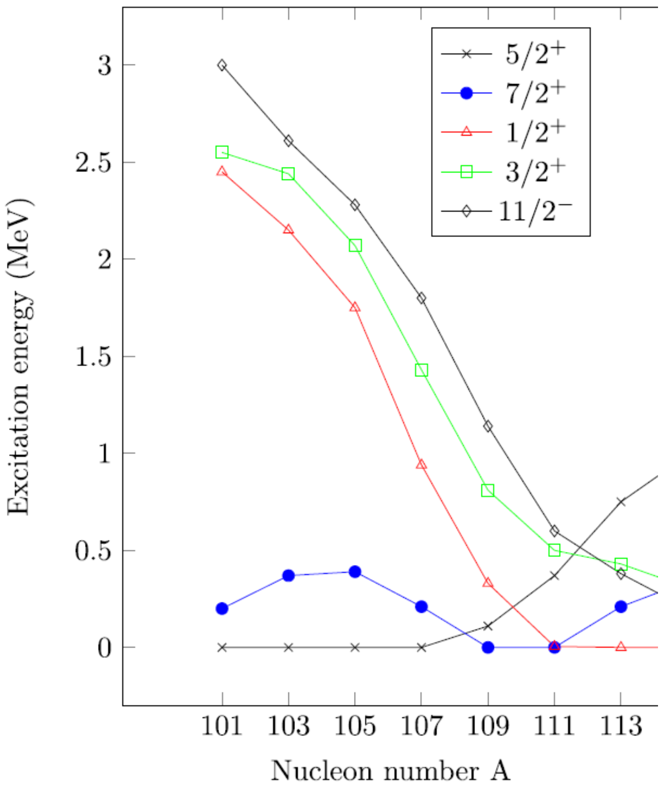
- ^{80}Zr core, up to 8 proton/neutron orbitals
- Significant proton core excitation for $B(E2)$
- Prolate 2_1^+ in ^{106,108}Sn, oblate 2_1^+ in ^{110}Sn



T. Togashi *et al.*, PRL 121, 062501 (2018)

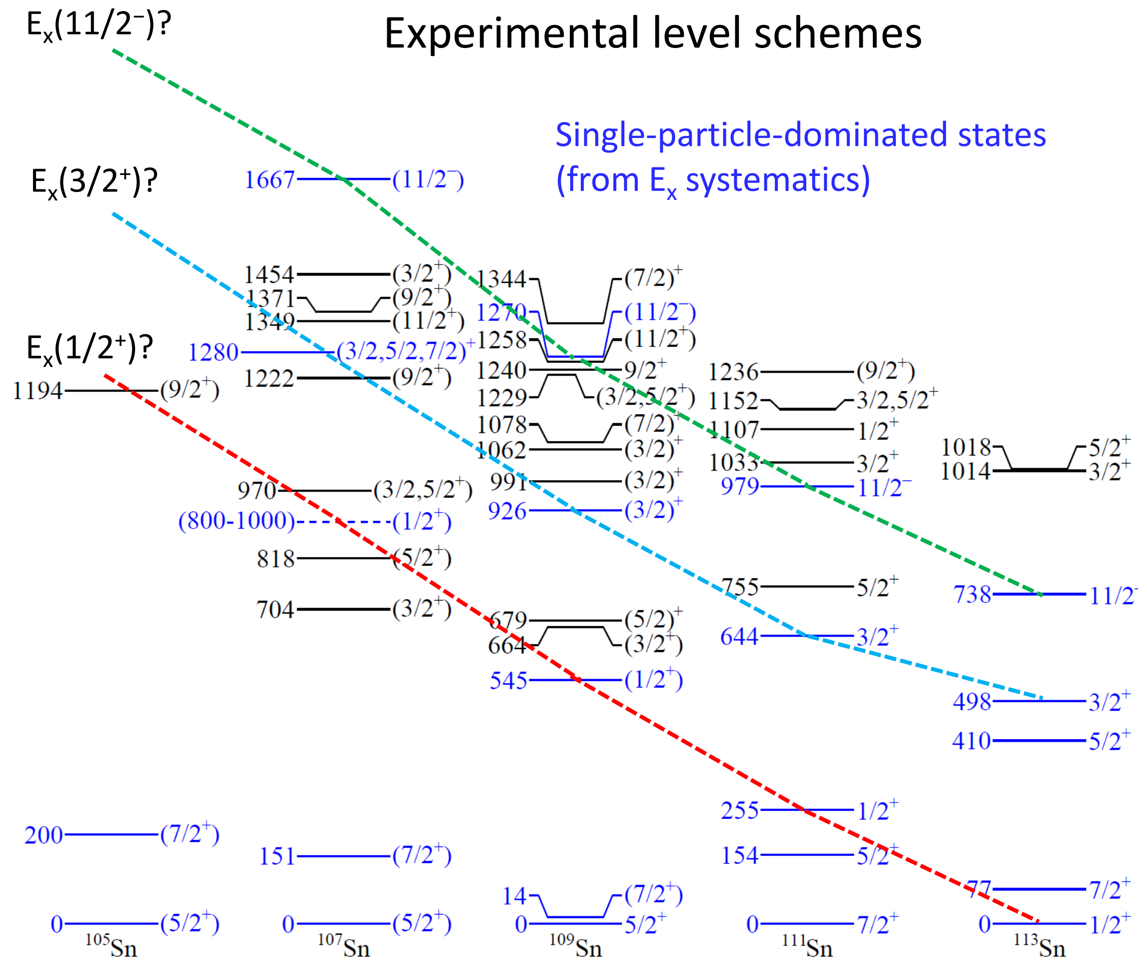
Single-particle state candidates and energy trends in $^{105-113}$Sn

LSSM, N3LO *G*-matrix



Adopted from T. Engeland, M. Hjorth-Jensen, M. Kartamyshev and E. Osnes, NPA 928, 51 (2014)

Experimental level schemes



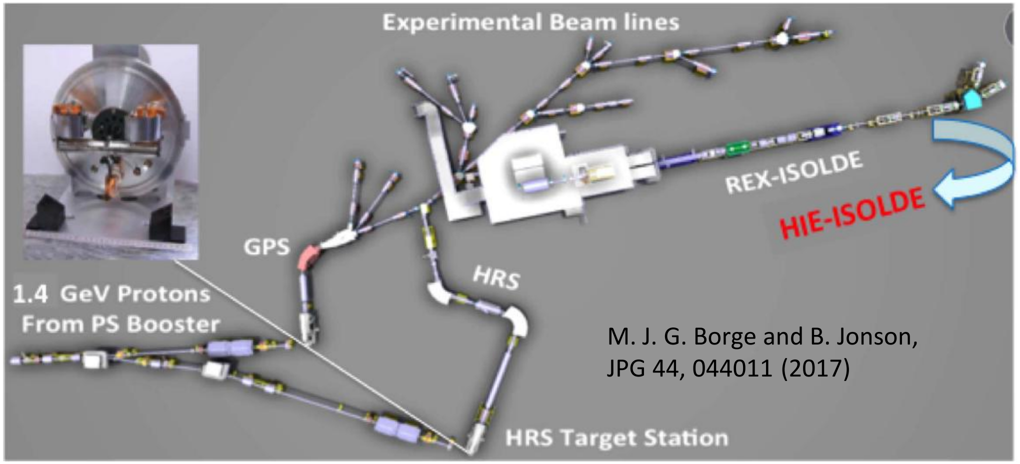
Previously suggested single-particle states in blue, J^{π} to be firmly determined through (d,p)

Limited spectroscopic factors for *A* < 111, first (d,p) study for ^{111}Sn

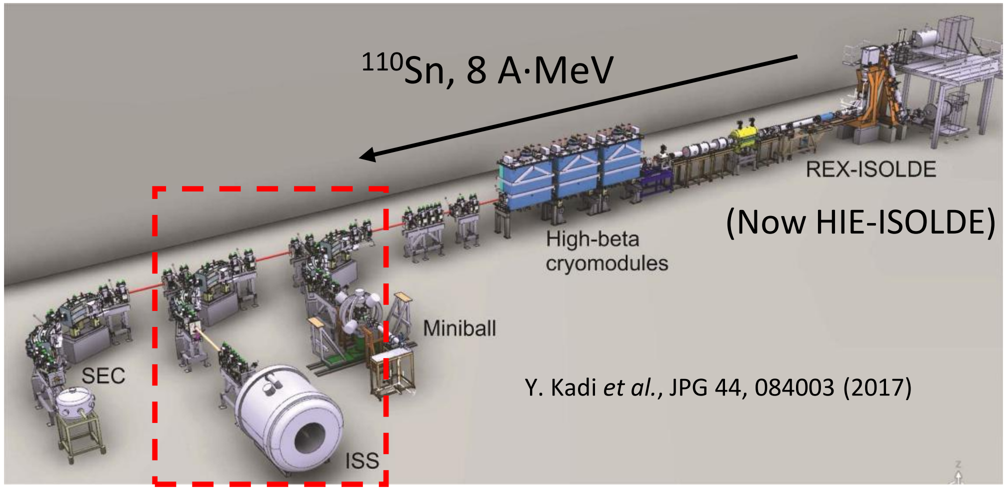
[*S*-factors for 5/2$^+$ and 7/2$^+$ in ^{107}Sn from ^{9}Be + ^{108}Sn reaction; G. Cerizza *et al.*, PRC 93, 021601(R) (2016)]

Radioactive ^{110}Sn beam production at CERN HIE-ISOLDE

1.4-GeV protons from CERN PS booster on LaC_x target, ISOL method
^{110}In isobaric contamination suppressed with Resonance Ionization Laser Ion Source (RILIS)

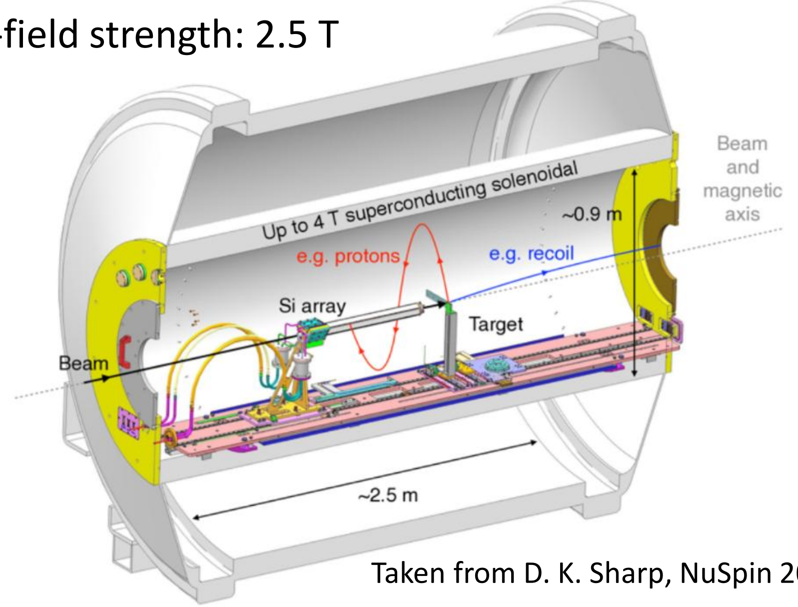


Post-accelerated beam through GPS to HIE-ISOLDE, sent towards ISS

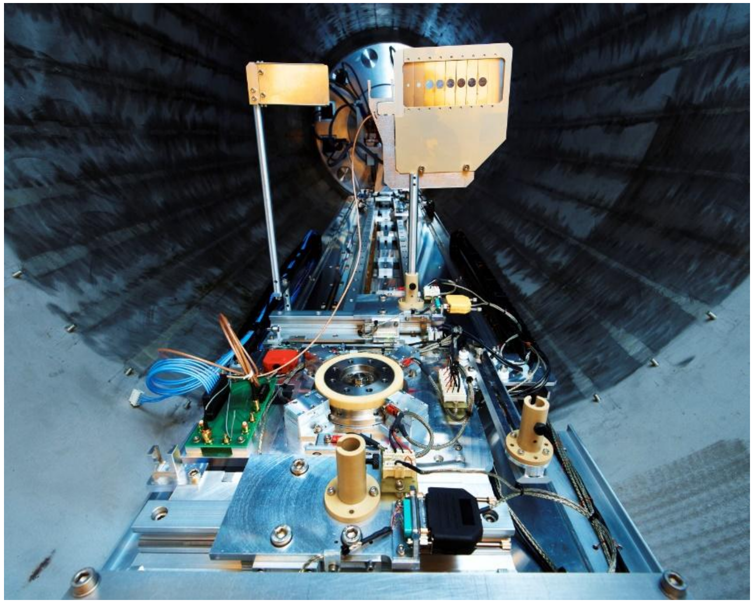


ISS spectrometer for (d,p) in inverse kinematics

B-field strength: 2.5 T

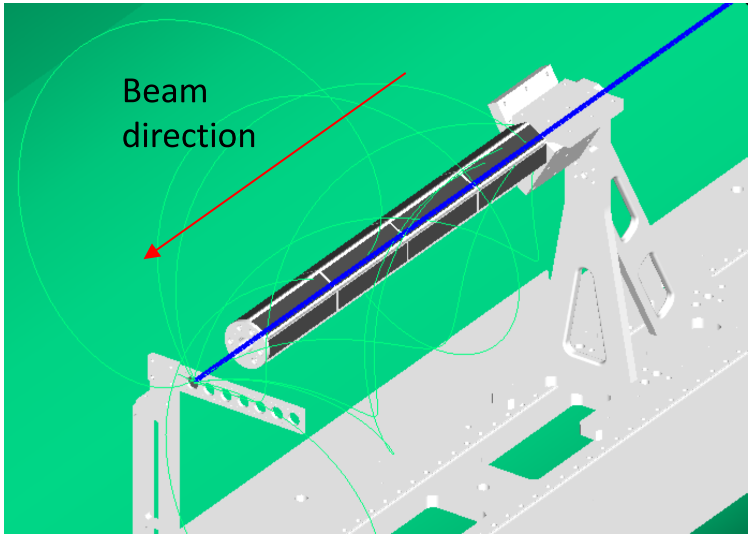


Taken from D. K. Sharp, NuSpin 2019



Geant4/NPTool simulation of ISS

A. Matta *et al.*, JPG 43, 045113 (2016) and M. Labiche, priv. comm.



Particle kinematics in solenoidal magnetic field

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

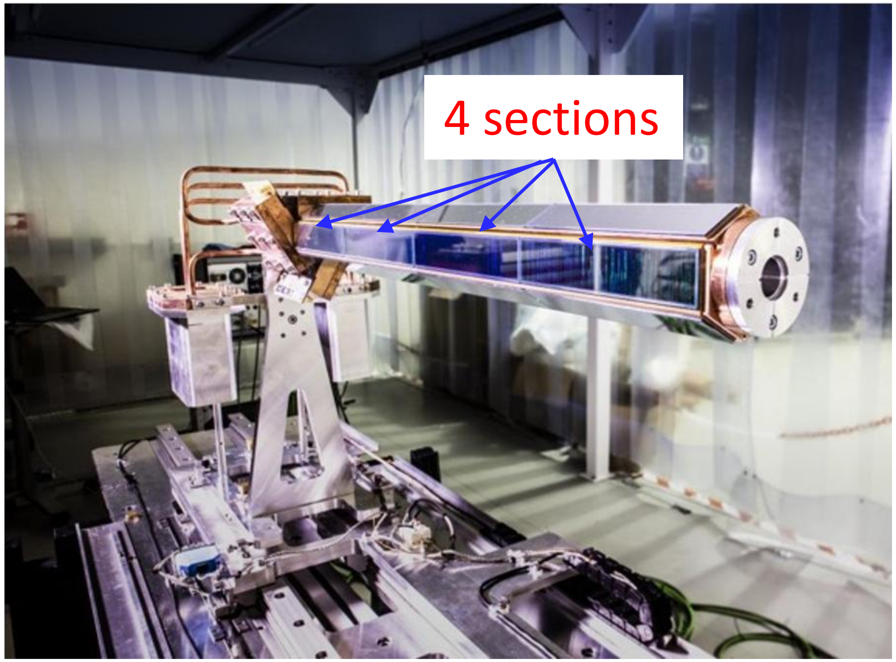
$$T_{cyc} = (2\pi/B)(m/qe)$$

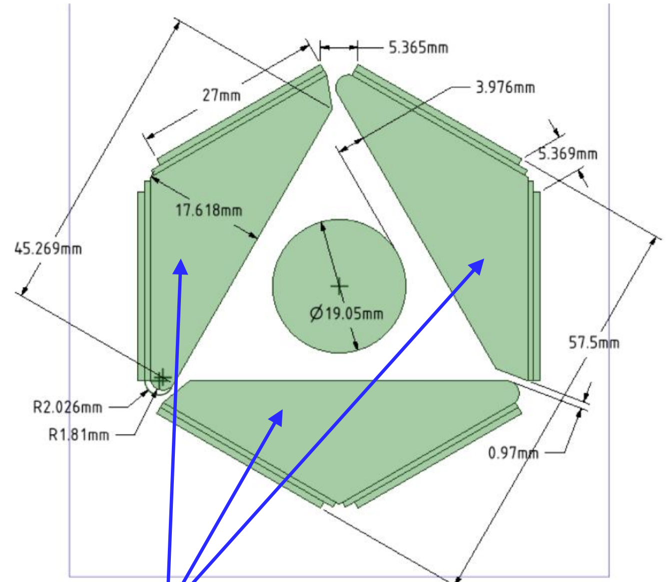
V_{cm} = velocity of center-of-mass frame in laboratory

[See J. C. Lighthall *et al.*, NIM A 622, 97 (2010)]

Linear relationship between E_{cm}, E_{lab} and z, no kinematic quenching at $\theta_{lab} > 90°$

Si barrel array for ISS





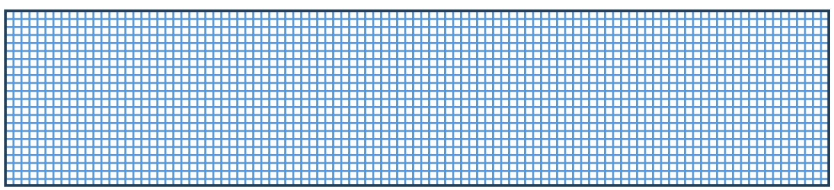
3 modules, ~70% coverage in φ

<u>DSSSD:</u>

<u>Micron BB21</u>

1-mm thick

← 128 p-side strips, 121.5 mm →

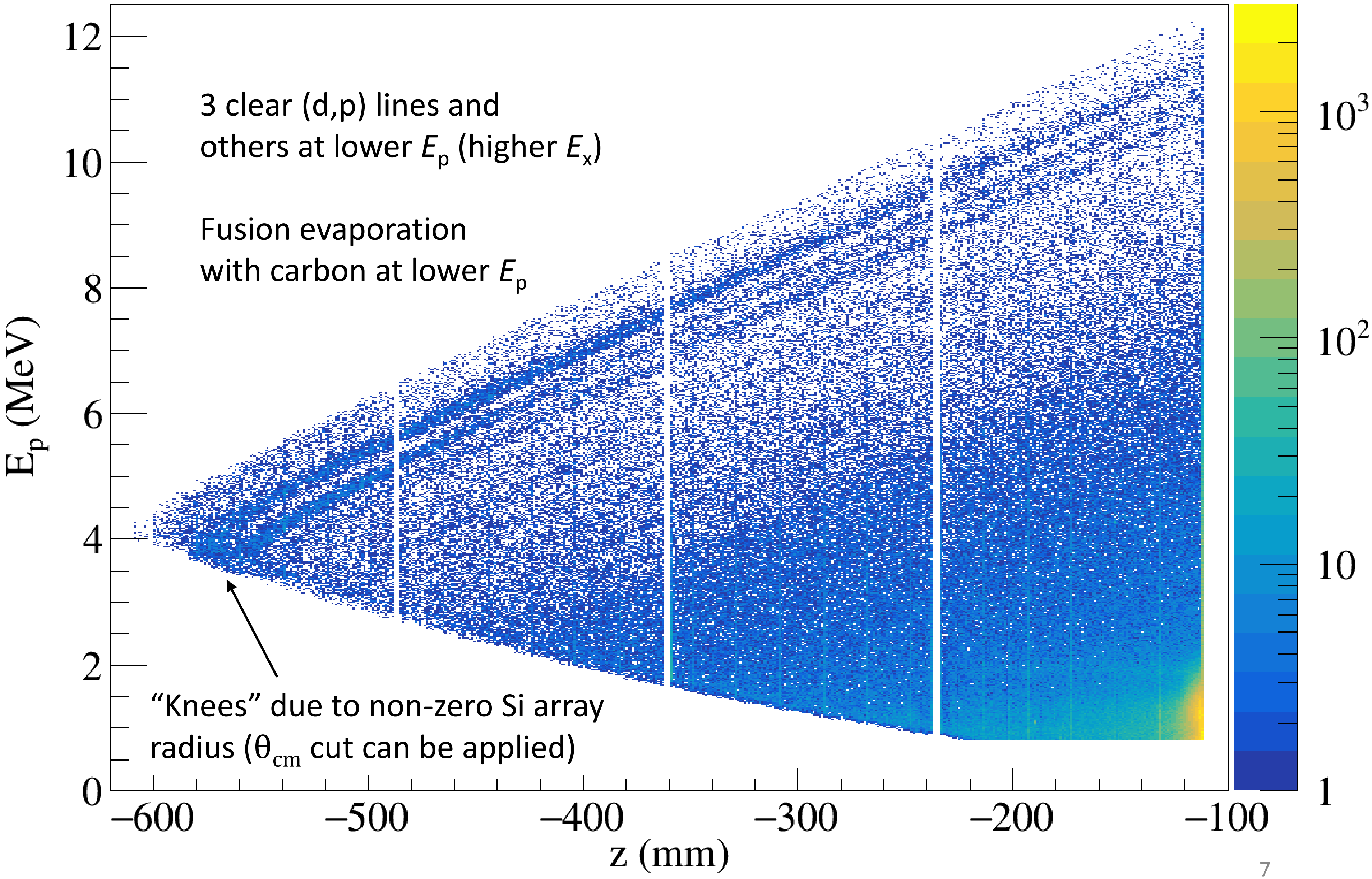


11 n-side strips, 21.9 mm

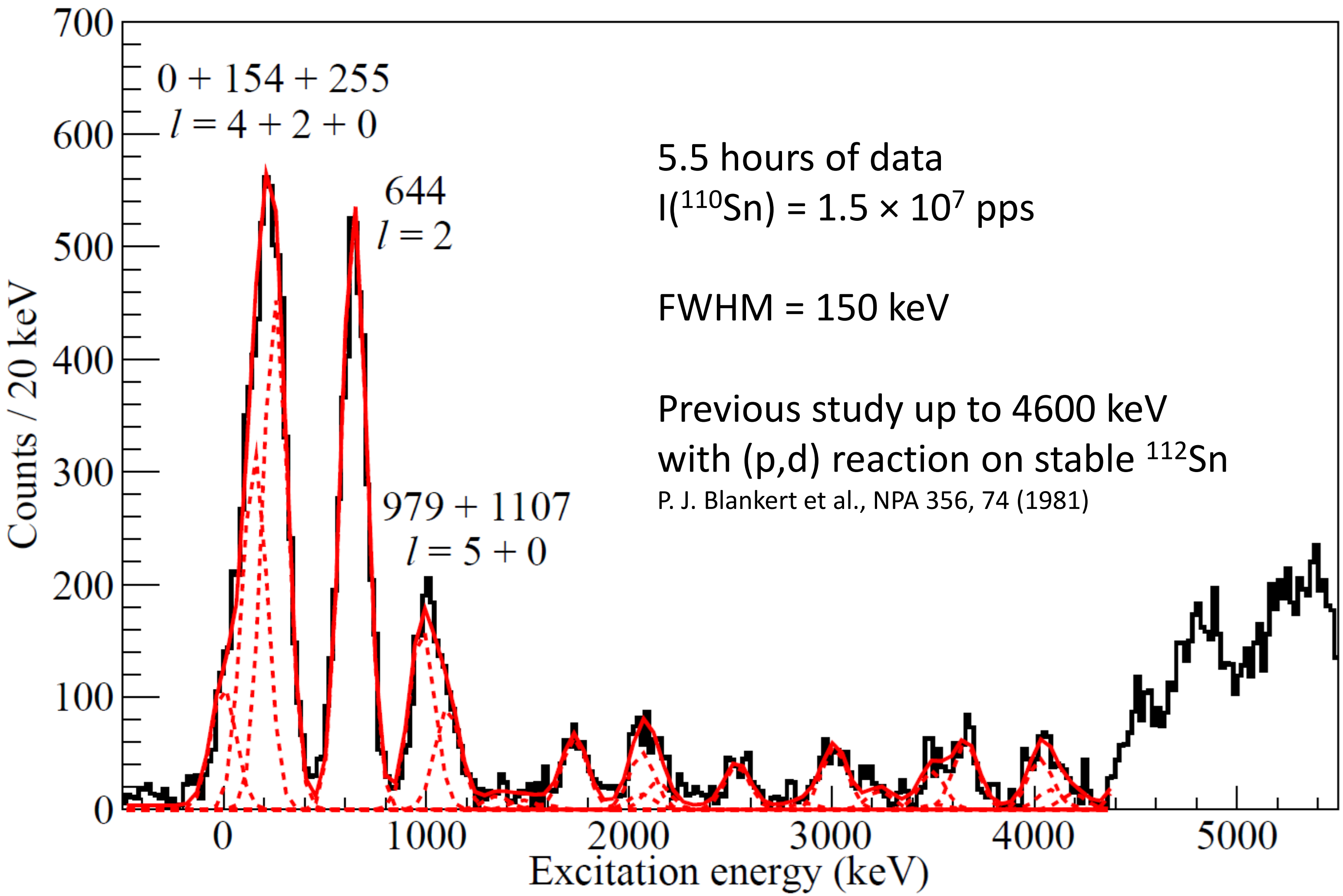
z-coverage: (-61 cm, -11 cm) from the target, 94%

→ At E_{beam} = 8 A·MeV, ISS array covers $10° < \theta_{cm} < 45°$

E_p vs z matrix from ISS data



Preliminary excitation energy spectrum of $d(^{110}Sn,p)^{111}Sn$



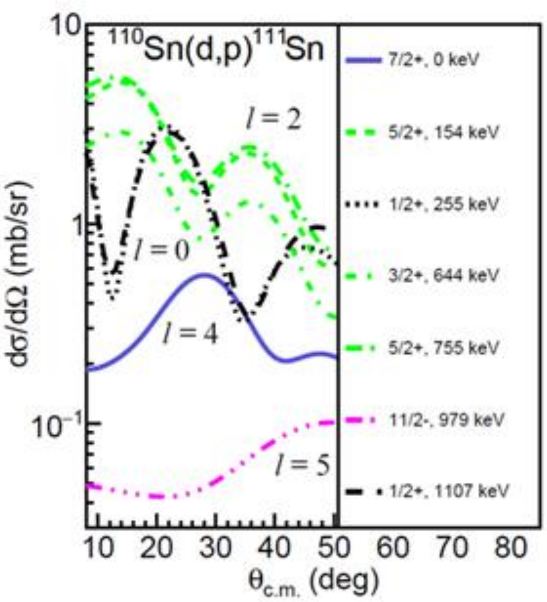
Higher-energy peaks seen up to 4000 keV

Fusion evaporation with carbon in CD_2 target dominates beyond E_x = 4300 keV

(d,p) cross section calculations with DWBA

Relevant neutron orbitals above N = 50: $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$

Choice of optical model parameters (OMP) for DWBA calculations



Results from one pair of OMP sets

Entrance channel (d) parameters:

H. An and C. Cai, PRC 73, 054605 (2006)
Y. Han, Y. Shi and Q. Shen, PRC 74, 044615 (2006)
W. W. Daehnick, J. D. Childs and Z. Vrcelj, PRC 21, 2253 (1980)
C. M. Perey and F. G. Perey, Atom. Nucl. data tables 17, 1 (1976)

Exit channel (p) OMP:

A. J. Koning and J. P. Delaroche, NPA 713, 231 (2003)
F. D. Becchetti, Jr. and G. W. Greenlees, PR 182, 1190 (1969)
F. G. Perey, PR 131, 745 (1963)

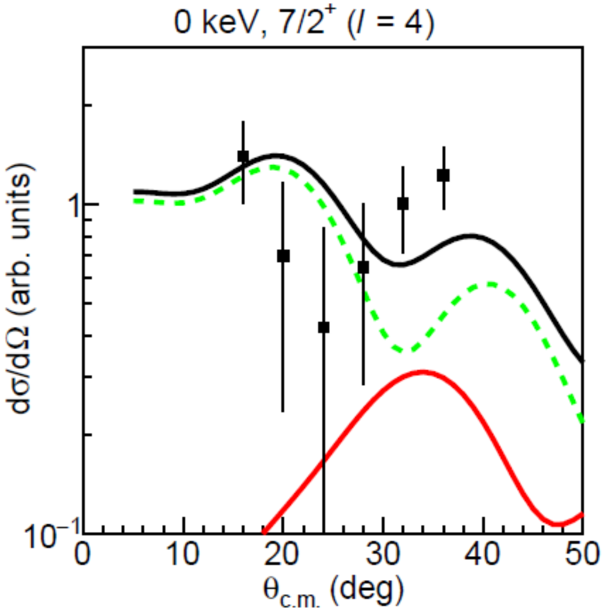
Automatic binding potential depth adjustment in FRESCO

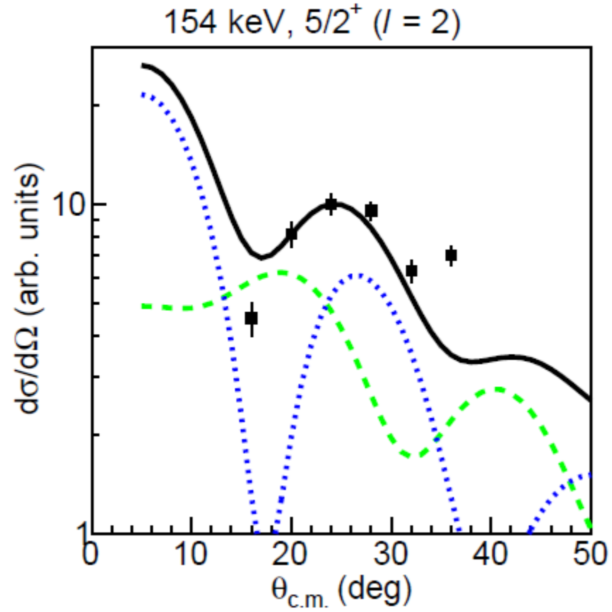
I. Thompson, Compt. Phys. Rep. 7, 167 (1988)

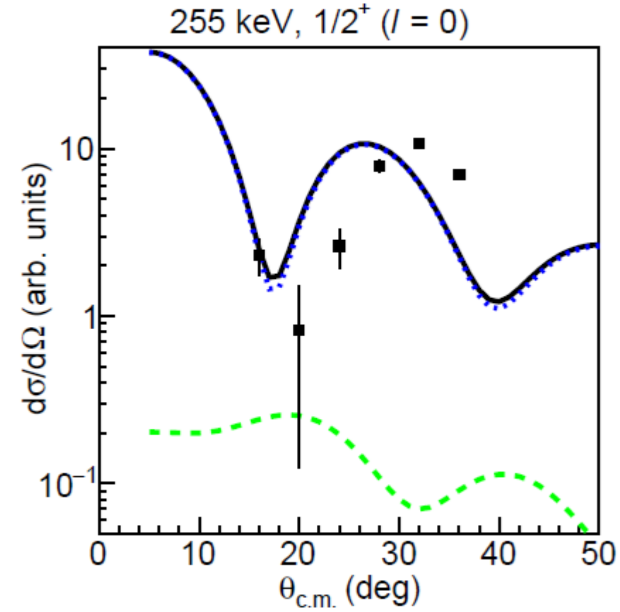
Priority on measuring l = 5 transfers to $11/2^-$ states with sufficient statistics

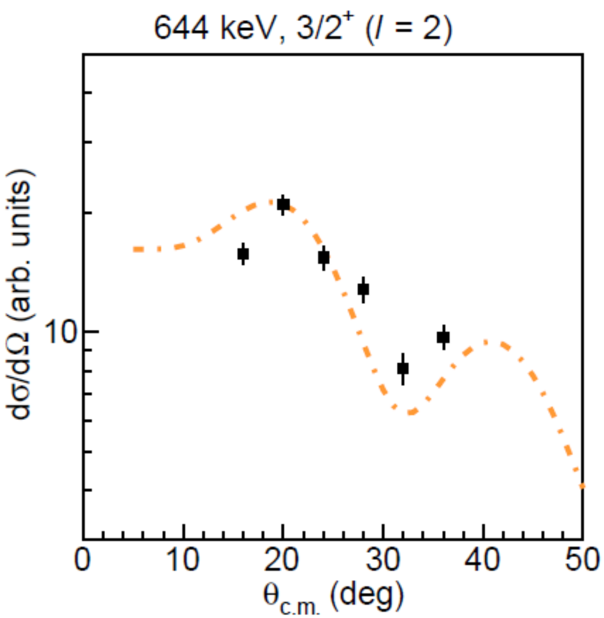
Calculated $d\sigma/d\Omega$ trends as a function of l well distinguished for J^π assignments

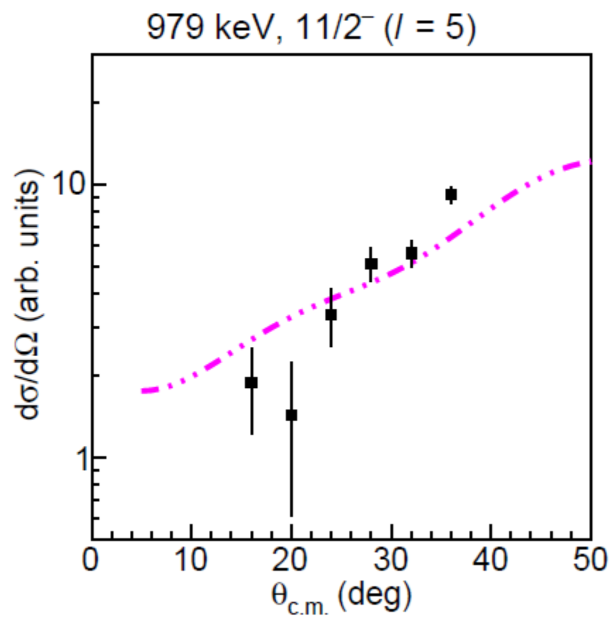
Preliminary $d\sigma/d\Omega$ on d(^{110}Sn,p)^{111}Sn











<u>Not fitted</u>, scaling of DWBA only (work in progress)

Mixture of components for first 3 states, different $d\sigma/d\Omega$ patterns reflect different *l*-transfers

$3/2^+$ and $11/2^-$ state consistent with expected *l*-transfers

Summary and acknowledgements

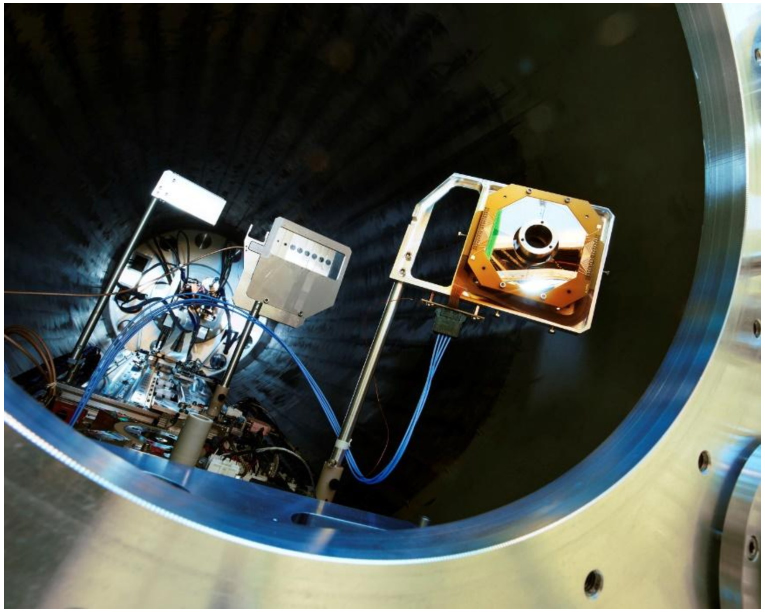
- d(^{110}Sn,p)^{111}Sn experiment with ISS successful, excitations up to 4 MeV observed
- Analysis of differential cross sections and spectroscopic factors underway
- Beam time for ^{108}Sn (d,p) planned this year, proposal for ^{106}Sn beam presented 5/21

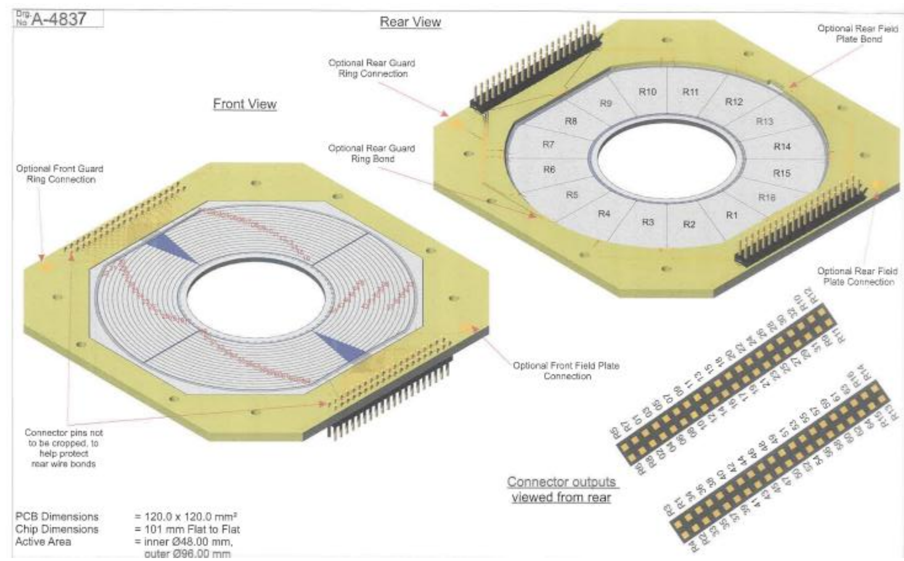
IS686 collaborators for ^{110}Sn (d,p)

Name	Institution
Sean Freeman	CERN
Daniel Clarke	University of Manchester
Sam Bennett	University of Manchester
Sam Reeve	University of Manchester
Joakim Cederkäll	Lund university
Majid Chishti	Lund university
Claes Fahlander	Lund university
Jedrek Iwanicki	University of Warsaw
Chris Page	University of York
Maria Vittoria Managlia	Chalmers University of Technology
Anna Kawecka	Chalmers University of Technology
Ben Kim	Sungkyunkwan University
Andy Chae	Sungkyunkwan University
Minju Kim	Sungkyunkwan University
Suso Pereira Lopez	CENS, IBS
Sunji Kim	CENS, IBS
Jason Park	CENS, IBS
Ismael Martel	University of Huelva
Annie Dolan	University of Liverpool
Liam Gaffney	University of Liverpool
Joonas Ojala	University of Liverpool
Andreas Ceulemans	KU Leuven
Oleksii Poleshchuk	KU Leuven

Backup slides

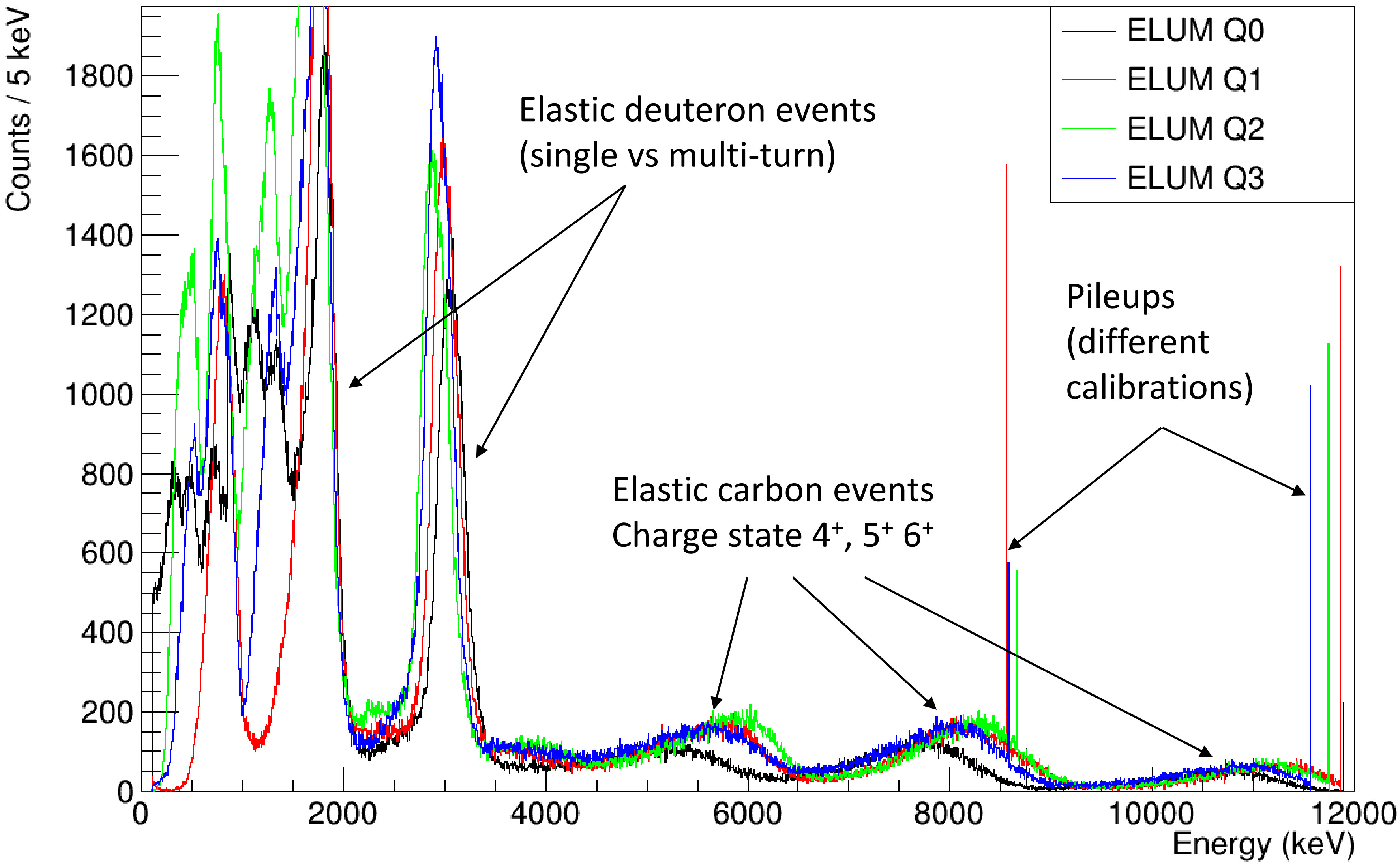
Elastic Luminosity (ELUM) detector



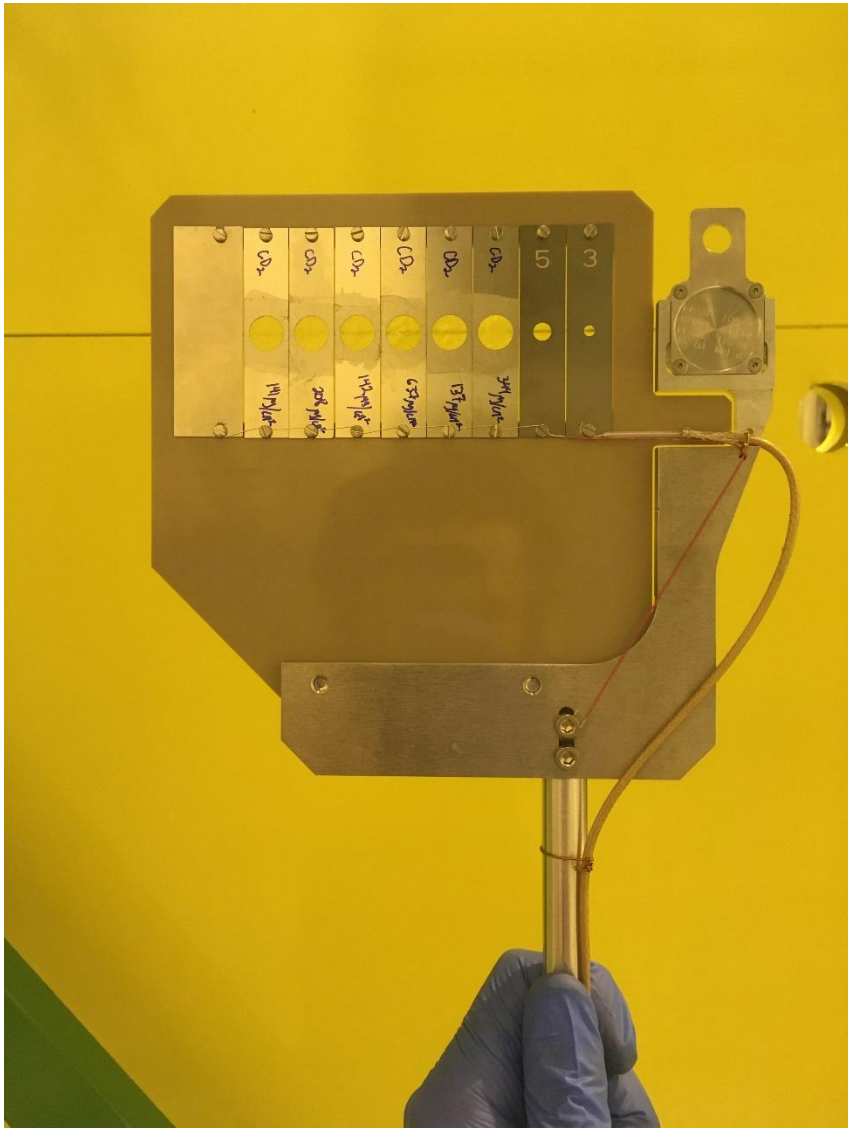


- Detect elastically scattered particles for beam intensity normalization
- Micron S1 DSSSD
- Signals summed together for each quadrant, data from 4 quadrants
- Blocker to control event rate (only a fraction of θ_{lab} accepted)

Preliminary spectra



Target ladder + alpha source holder



- 6 targets + 2 apertures for beam tuning
- Reversible alpha source holder
- Connected to drive motor that is turned on only when switching targets (eliminate noise)

- CD_2 targets used (not same as photo):
    - 97 μg/cm^2
    - 103 μg/cm^2
    - 108 μg/cm^2
    - 117 μg/cm^2
    - 129 μm^2
    - 209 μg/cm^2

5/6 targets thinner than the proposed thickness of 165 μg/cm^2 for better ΔE/E

Beam time requests and expected statistics/spectra

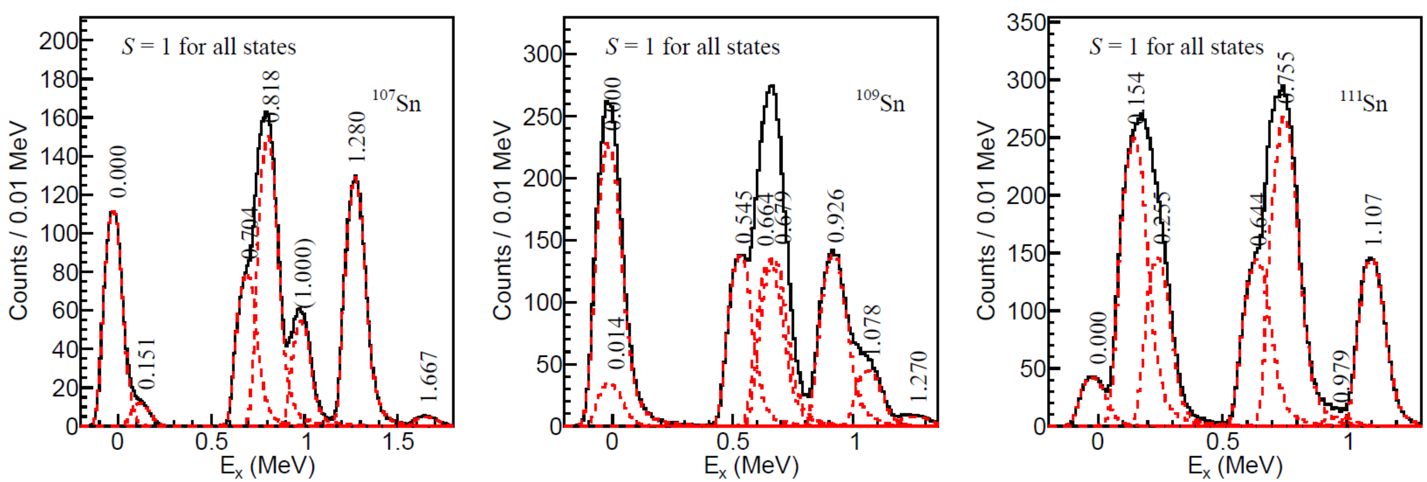
Reaction/ target	Intensity and beam time	E_x (keV)	J^π	ΔL	σ (mb)	Proton counts
^{106}Sn$(d,p)^{107}$Sn at 8 MeV/u on 165-μg/cm^2 CD_2	1×10^5/s for 24 shifts	0	$5/2^+$	2	4.436	1378
		151	$(7/2^+)$	4	0.461	143
		704	$(3/2^+)$	2	3.444	1070
		818	$(5/2^+)$	2	6.576	2043
		(800-1000)	$(1/2^+)$	0	2.031-2.072	631-644
		1280	$(3/2^+)$	2	5.641	1753
		1667	$(11/2^-)$	5	0.220	68
^{108}Sn$(d,p)^{109}$Sn at 8 MeV/u on 165-μg/cm^2 CD_2	5×10^5/s for 12 shifts	0	$5/2^+$	2	3.893	3018
		14	$(7/2^+)$	4	0.547	424
		545	$(1/2^+)$	0	2.220	1722
		664	$(3/2^+)$	2	2.357	1828
		679	$(5/2^+)$	2	2.411	1869
		926	$(3/2^+)$	2	2.463	1910
		1078	$(7/2^+)$	4	0.750	581
		1270	$(11/2^-)$	5	0.141	109
^{110}Sn$(d,p)^{111}$Sn at 8 MeV/u on 165-μg/cm^2 CD_2	5×10^5/s for 12 shifts	0	$7/2^+$	4	0.685	532
		154	$5/2^+$	2	4.378	3401
		255	$1/2^+$	0	2.346	1822
		644	$3/2^+$	2	2.553	1983
		755	$5/2^+$	2	4.813	3738
		979	$11/2^-$	5	0.147	114
		1107	$1/2^+$	0	2.458	1909

Transfer reaction quenching by 0.55 applied
[B. P. Kay, J. P. Shiffer, S. J. Freeman, PRL 111, 042502 (2013)]

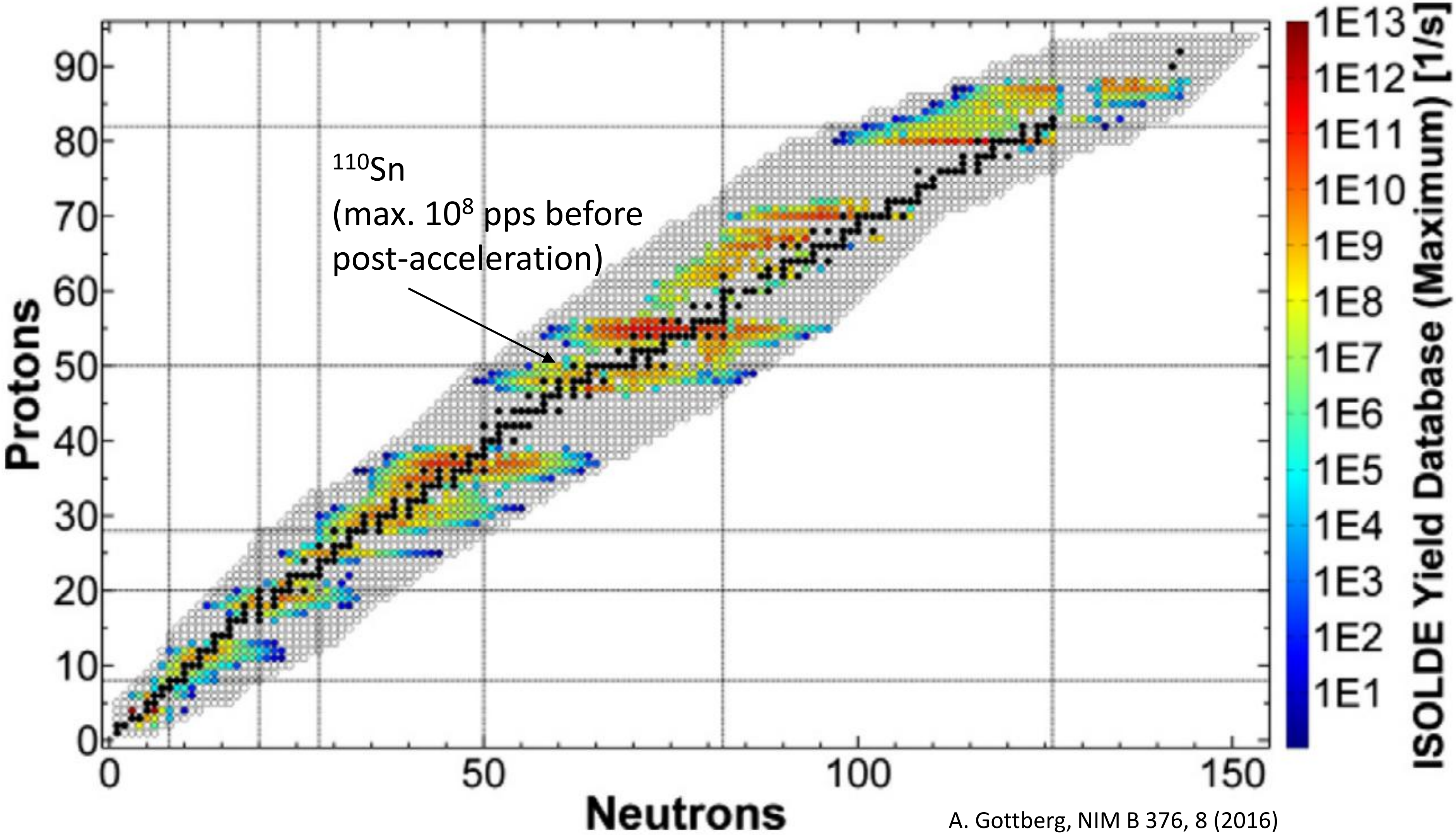
Statistics comparable to d(^{206}Hg,p)^{207}Hg results

Beam time set to measure transfers to $11/2^-$ states with ~10^2 counts at nominal RIB intensities, updated cross sections and lower E_{beam} can improve these numbers by 70-100%

Search for $1/2^+$ single-particle state in ^{107}Sn in E_x range 800-1000 keV with little dependence on cross section



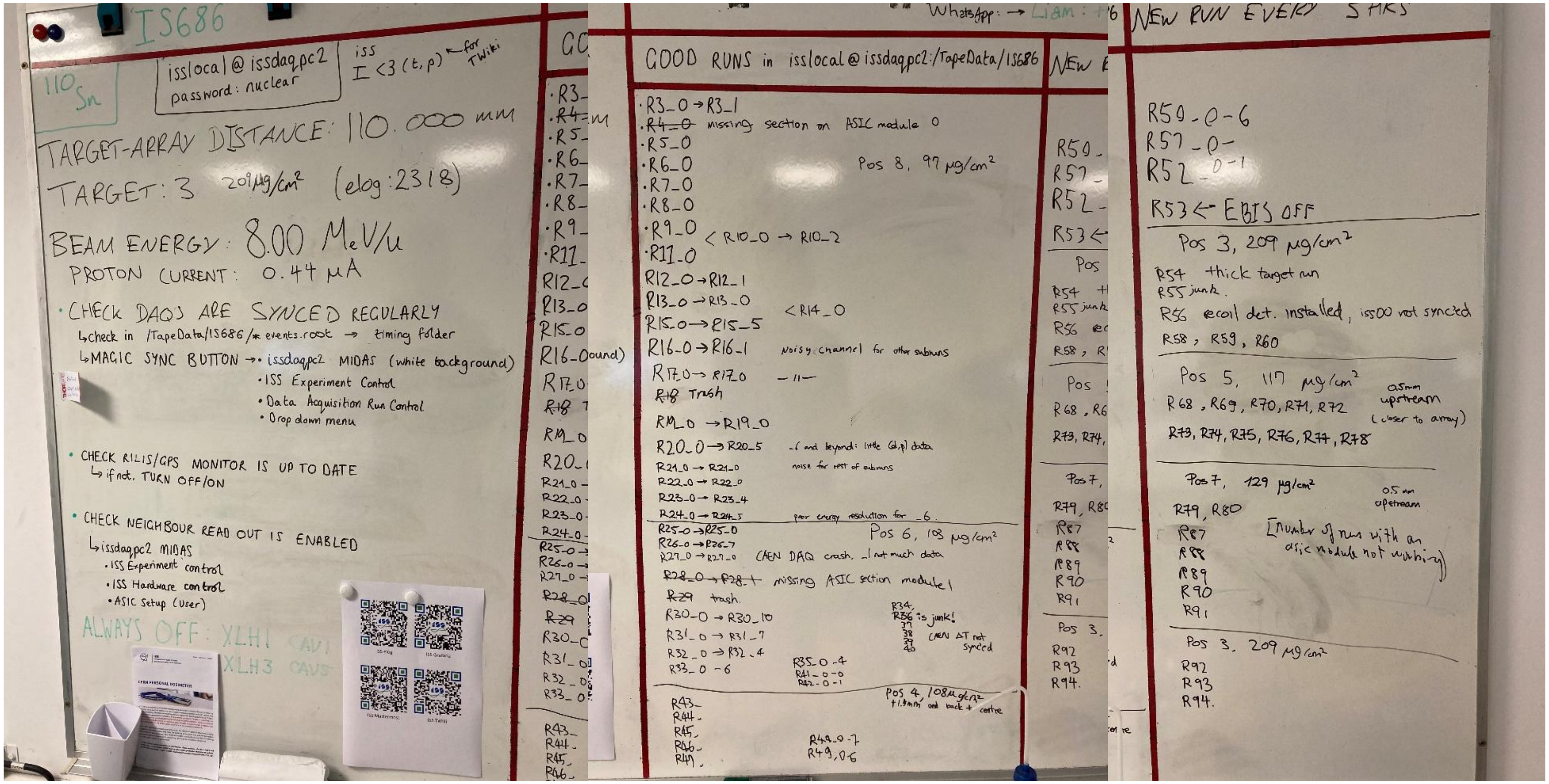
CERN-ISOLDE yields



A. Gottberg, NIM B 376, 8 (2016)

1.4-GeV proton synchrotron booster (PSB) for RIB production through spallation
Various primary targets with elements' atomic number from 6 (C) to 92 (U)

Run summary

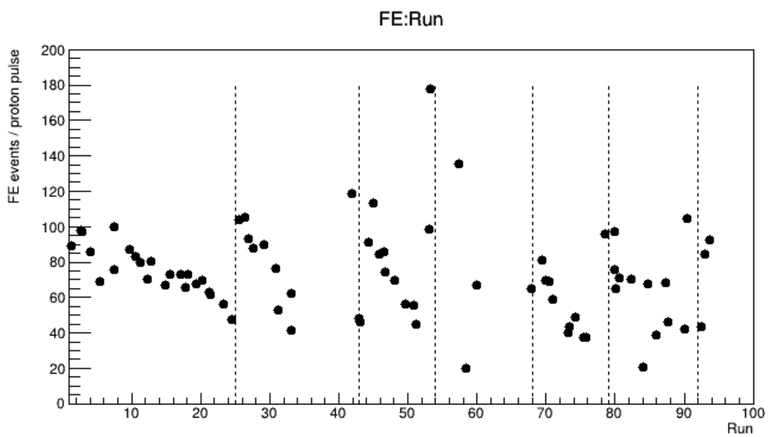


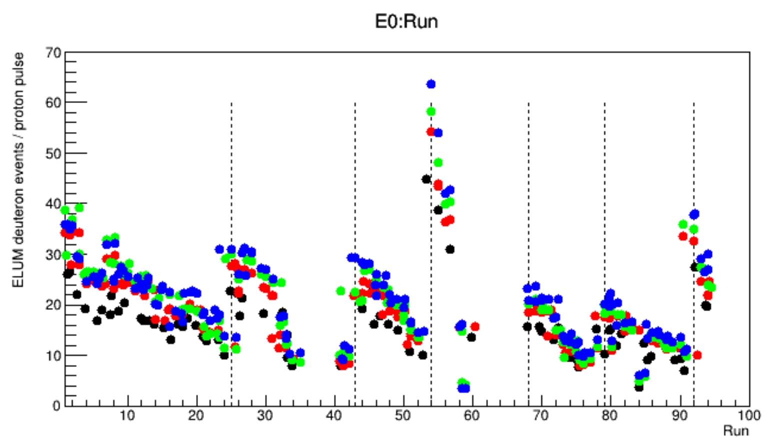
- E(^{110}Sn) = 8.00 A·MeV (±0.3%), very pure – R(^{110}In/^{110}Sn) ~ 0.1%
- Beam start/end: Sep. 29, 13:00 – Oct. 5 07:30
  ~6 days > 4 days assigned!
- Beam intensities: 0.30-0.5 μA protons, ~10^7 ^{110}Sn pps
  [0.03 μA protons during recoil detector test, down to ~5 × 10^5 pps]

Decreasing event rates

Counts divided by proton pulse → normalized event rate (intensity not considered)

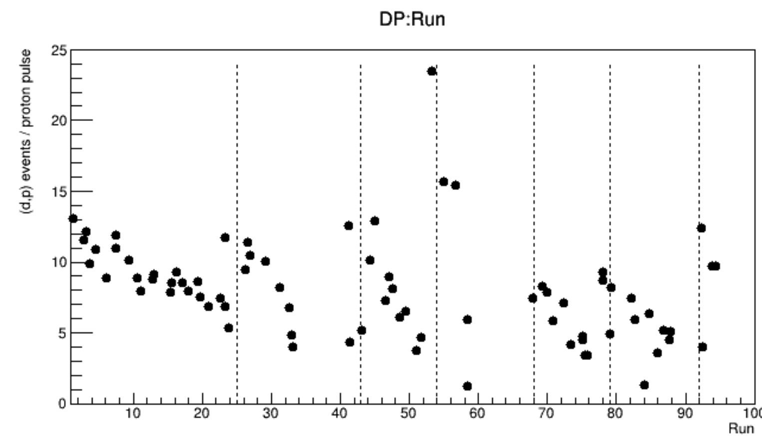
Gated on high-excitation energy bump

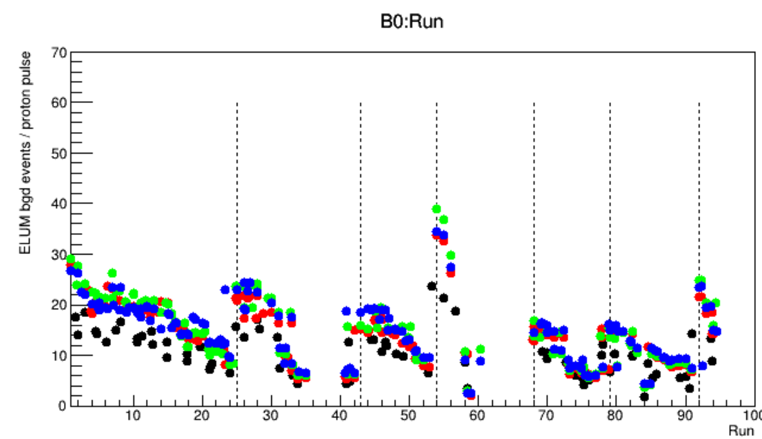




ELUM deuteron signal

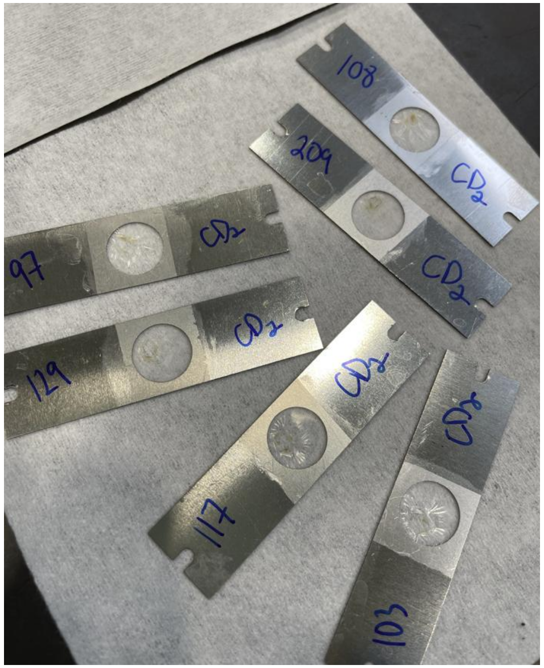
Counts under expected (d,p) peaks



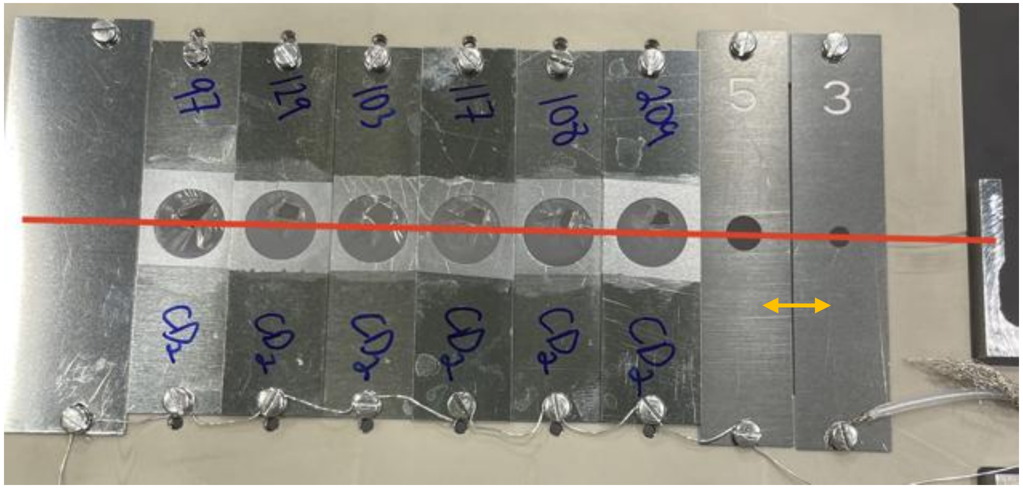


ELUM carbon signal

Postmortem analysis



All 6 CD_2 targets with holes!



- Hole shapes are irregular
- Hole positions rather consistent; little beam drift
- Small gap between 3-mm/5-mm apertures
  → To be considered in beam offset calculations
- Pure carbon target unavailable then

Cross section should be analyzed carefully with ELUM data