Spectroscopy of single-particle states in ^{107}Sn through (d,p) transfer reactions
(INTC-P-589-ADD-1)

Joakim Cederkäll, Lund University, and

Joochun (Jason) Park, Seoul National University

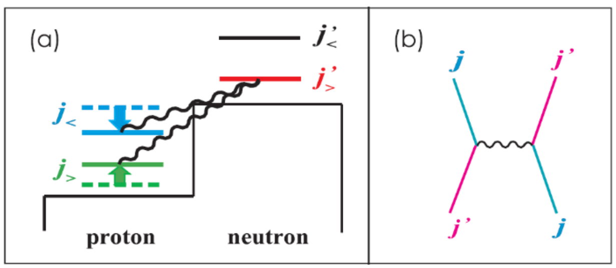
79th Meeting of the ISOLDE and Neutron Time-of-Flight Committee (INTC)

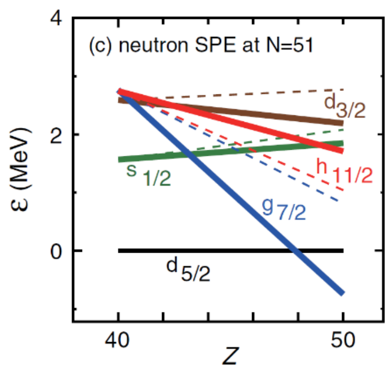
May 21, 2025

Uncovering structural evolution towards ^{100}Sn

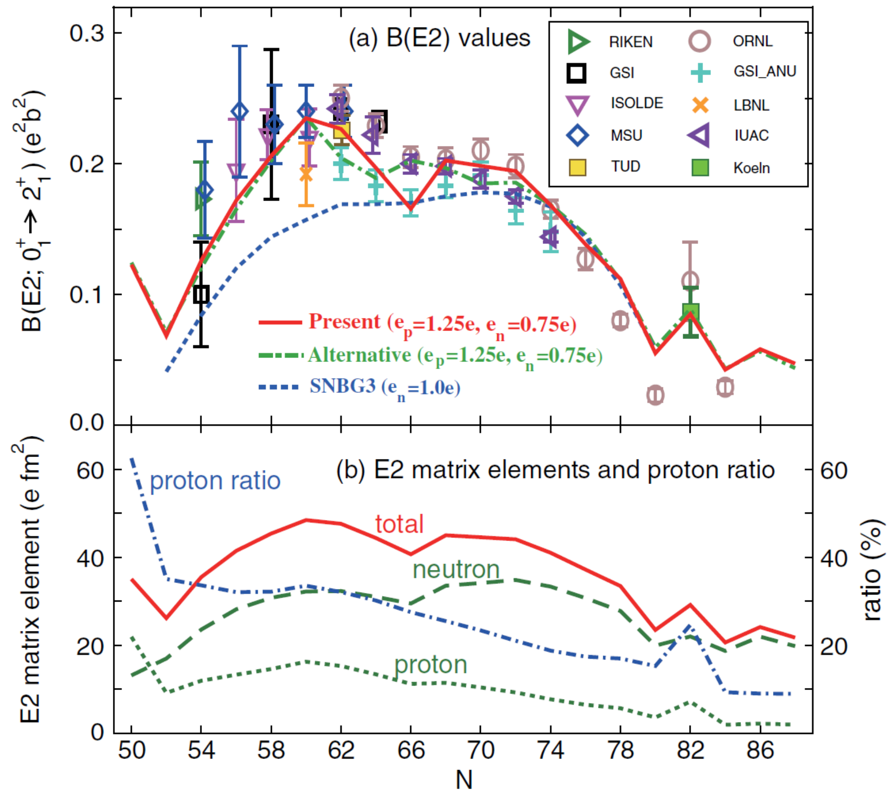
Neutron-deficient isotopes near ^{100}Sn: vicinity of double shell closures with limited/imprecise spectroscopy results

Proton-neutron tensor monopole interaction as an explanation for decreasing $E(5/2^+)$-$E(7/2^+)$ gap observed in N = 51 isotones



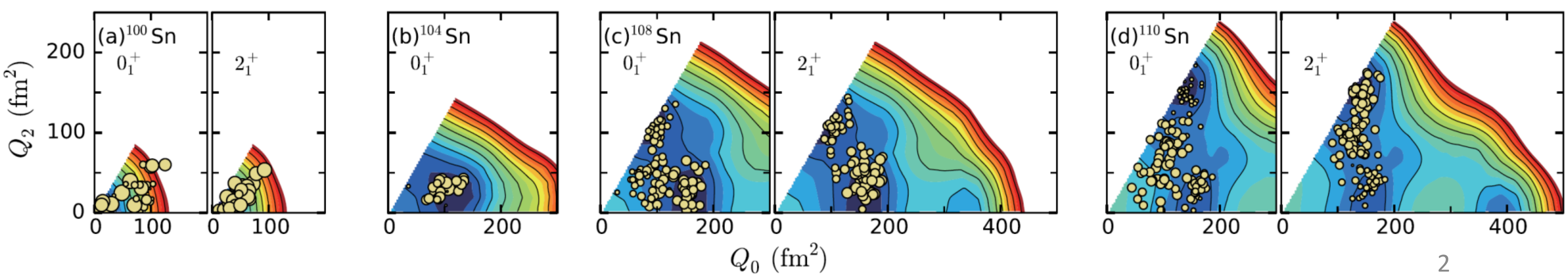


T. Otsuka *et al.*, PRL 95, 232502 (2005) and PRL 104, 012501 (2010)



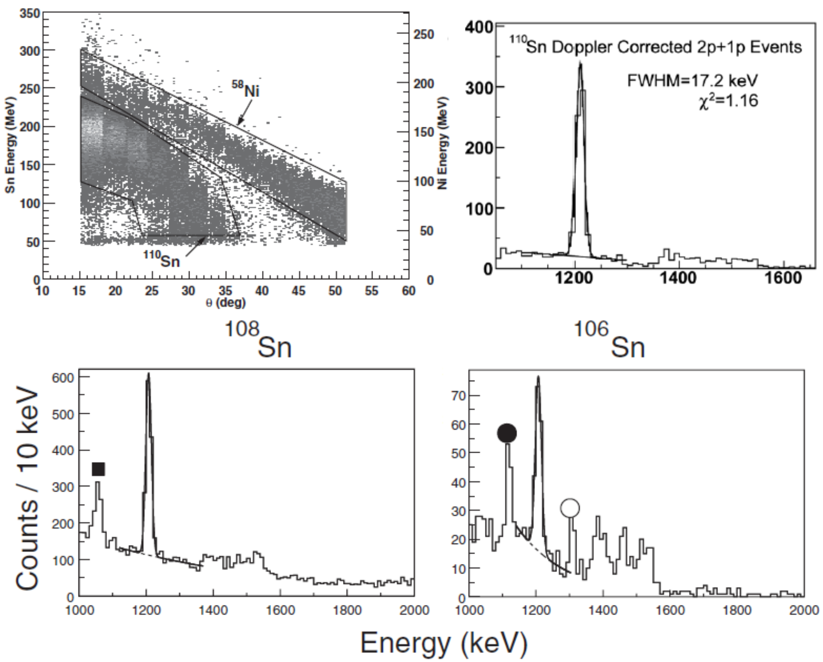
Deformation as a possible explanation for large $B(E2)$ values in light Sn isotopes, reaching maximum at ^{110}Sn (N = 60)

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



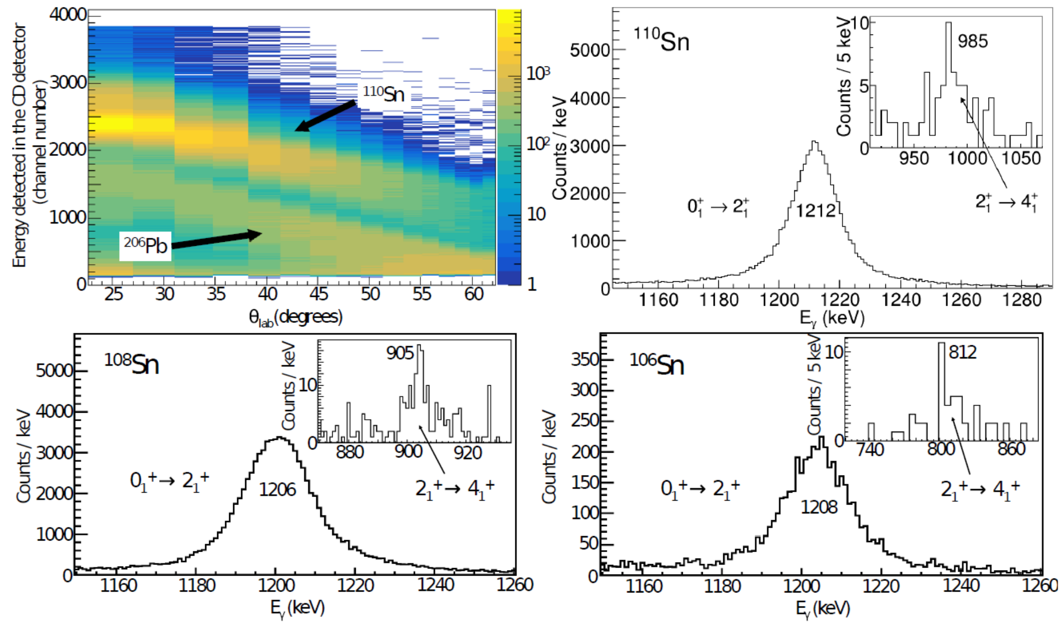
Coulex campaigns on ^{106,108,110}Sn with Miniball at ISOLDE

2.8 MeV/u on ^{58}Ni target at REX-ISOLDE



J. Cederkäll *et al.*, PRL 98 172501 (2007) and
A. Ekström *et al.*, PRL 101, 012502 (2008)

4.4 MeV/u on ^{206}Pb target at HIE-ISOLDE

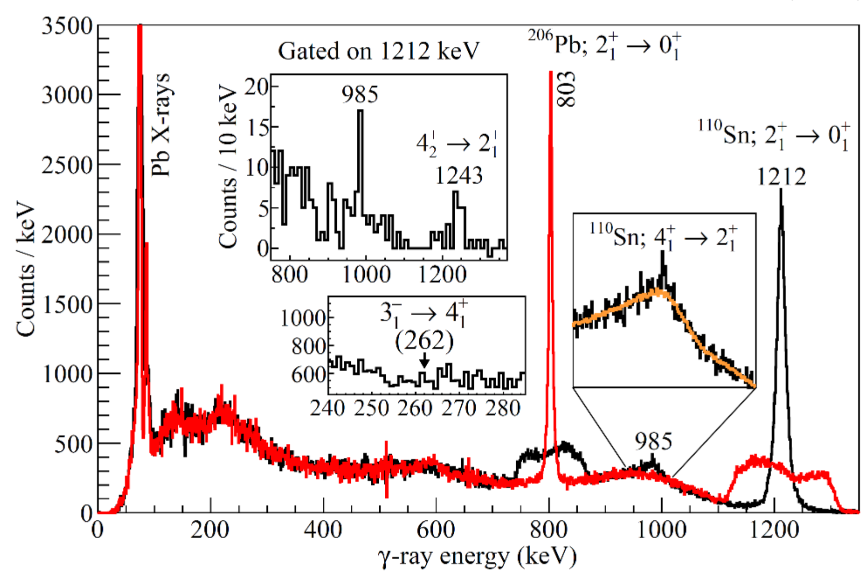


J. Park *et al.*, JPS Conf. Proc. 32, 010036 (2020)

50-100 times more statistics for the γ-ray from the 2_1^+ state in all of ^{106,108,110}Sn

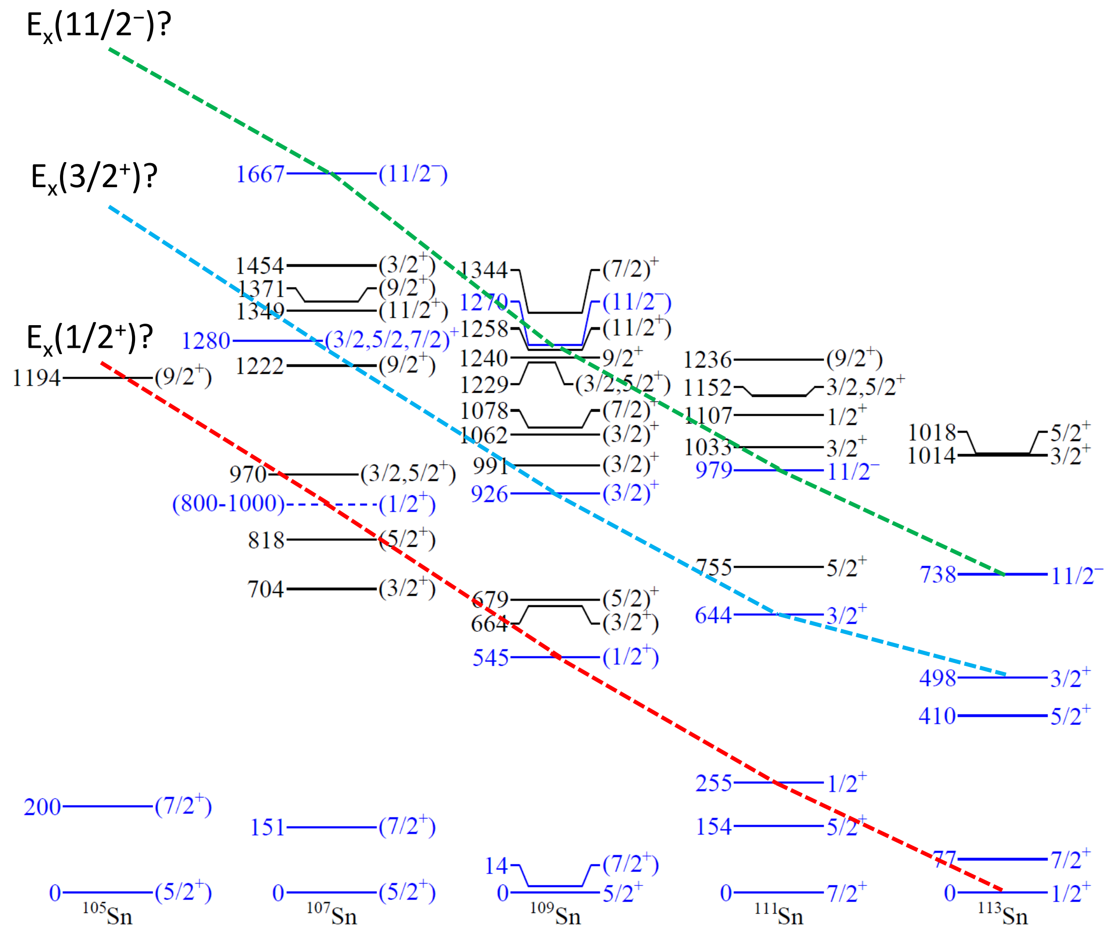
Coulex to additional excited states clearly observed, new *B(E*2*)* and *Q*(2_1^+) values determined/expected

Manuscript on ^{110}Sn submitted to PRL, results on ^{106,108}Sn being prepared



J. Park *et al.*, submitted to PRL

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



Tentative spin-parity assignments based on β-decay studies with γγ coincidences

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

Energy of the yrast **1/2⁺** state to be newly measured, and nature of the **1280-keV** state (single-particle dominated 3/2⁺?)

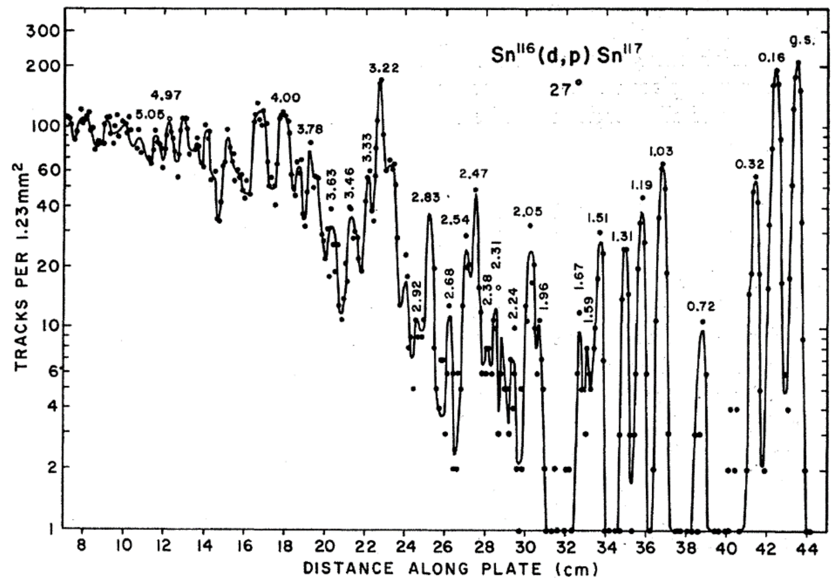
Independent check of 5/2⁺ ground state [1n knockout reactions on ^{108}Sn (G. Cerizza *et al.*, PRC 93, 021601(R) (2016)]

Transfer reactions to 11/2⁻ states (intruder orbit) are also interesting, to examine the behavior of the intruder orbital

Aim of the proposal with the ISS

Historical (d,p), (d,t) reactions on stable Sn targets in normal kinematics, E_{beam} ~ 15 MeV/u:

E. J. Schneid, A. Prakash, B. L. Cohen,
Phys. Rev. 156, 1316 (1966)



50-year hiatus since the
last measurements

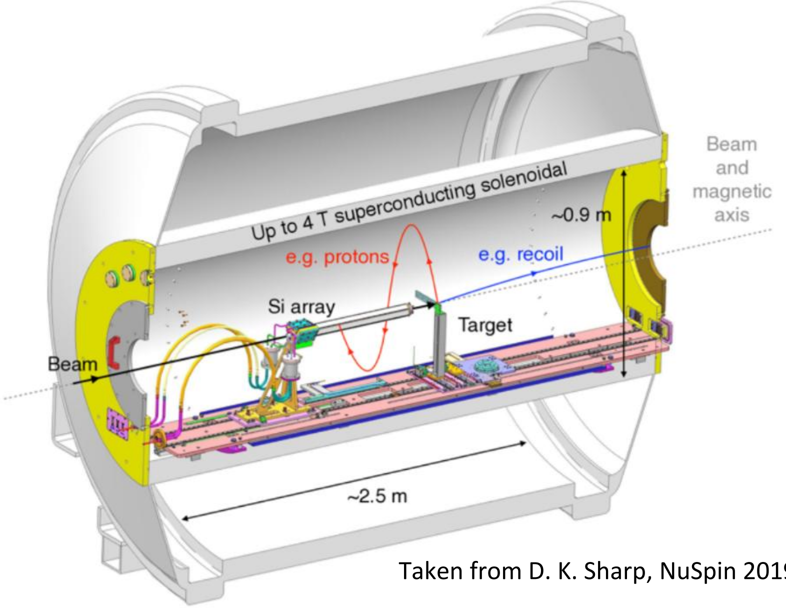
New transfer reactions in inverse kinematics with unstable Sn beams on deuterated target
Actualisation of the LOI INTC-P-362 by J. Cederkäll *et al.*

From (d,p) transfer reactions on even-mass Sn isotopes with ISS, we want to measure:

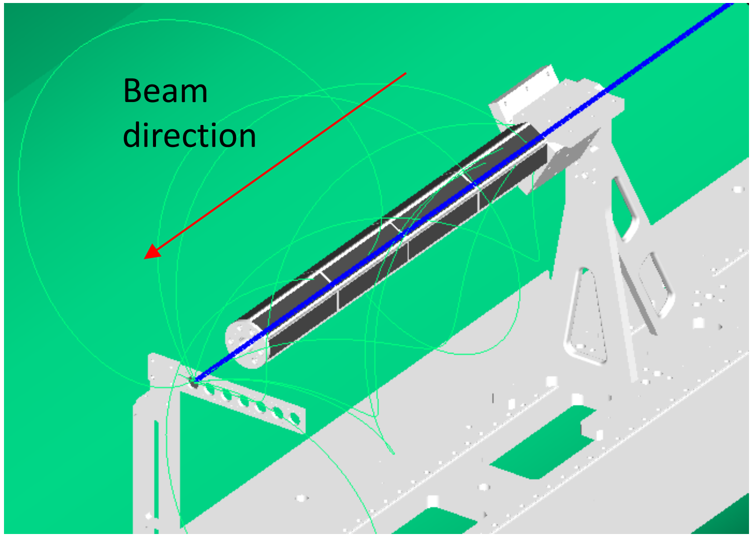
1. Energies and angular distributions of protons
→ Compare *dσ/dΩ* distributions to determine *l* for J^{π} assignments of individual excited states
→ New states for further investigation of single-particle dominated states

2. Magnitudes of (d,p) transfer cross sections
→ Spectroscopic factors (*S*) relative to DWBA, for neutron occupation in *gdsh* orbitals above *N* = 50
→ Comparisons with shell model descriptions of states and their *S*-factors

ISS spectrometer for (d,p) in inverse kinematics



Taken from D. K. Sharp, NuSpin 2019



1-mm thick DSSDs arranged in hexagonal tube
94% Si strip/70% ϕ coverage
z-coverage: (-61.05 cm, -10.0 cm) from the target
At E_{beam} = 8 MeV/u, covers $8° < \theta_{c.m.} < 49°$

Proposed B-field strength: 2.5 T
Actual B: 2.5 T for ^{110}Sn, 2.25 T for ^{108}Sn

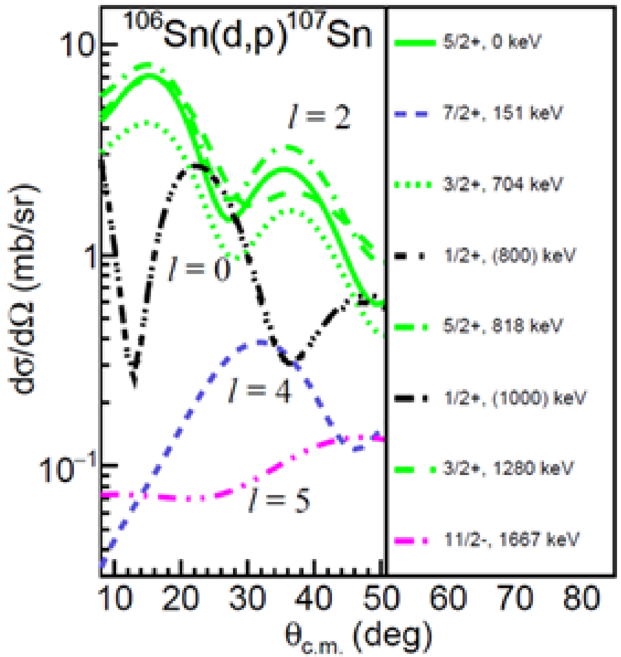
From d(^{110}Sn,p)^{111}Sn ISS data, we have ~150-keV FWHM resolution using CD_2 targets of thicknesses 100~130-μg/cm^2

^{110}Sn beam in 2022 was too intense at I_{beam} = 1.5 × 10^7 pps, puncturing all CD_2 targets
Weaker ^{108}Sn beam (~10^6 pps) during the 2024 run did not damage the targets

Slightly better resolution expected for much weaker ^{106}Sn beam, as the targets will not be degraded

(d,p) cross section calculations with DWBA

Relevant neutron orbitals above *N* = 50 and below *N* = 82: $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$



Entrance channel parameters (deutrons):

- H. An and C. Cai, PRC 73, 054605 (2006)
- Han, Shi and Shen, PRC 74, 044615 (2006)
- Daehnick, Childs and Vrcelj, PRC 21, 2253 (1980)
- Perey and Perey, Atom. Nucl. data tables 17, 1 (1976)

Exit channel parameters (protons):

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

Automatic binding potential depth adjustment in FRESCO

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

Aim to measure all *l*-transfers, including *l* = 5 to $11/2^-$ states with sufficient statistics

Angular distribution trends well separated as a function of *l* for J^π assignments

Multiple optical model parameter sets for variations in calculated *dσ/dΩ*

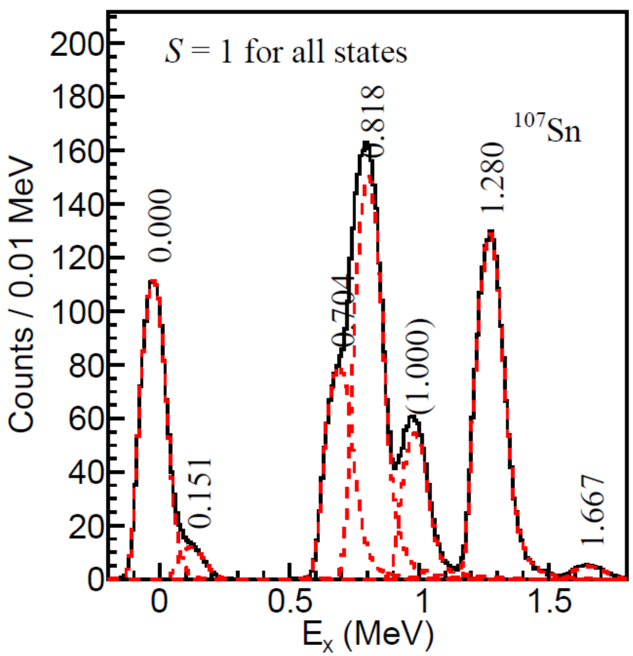
Beam time requests and expected statistics/spectra

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$_2$	1.5×10^5/s for 12 + 2 shifts (from ^{108}Sn beam time)	0	$5/2^+$	2	4.436	1170
		151	$(7/2^+)$	4	0.461	121
		704	$(3/2^+)$	2	3.444	968
		818	$(5/2^+)$	2	6.576	1725
		(1000)	$(1/2^+)$	0	2.221	568
		1280	$(3/2^+)$	2	5.641	1472
		1667	$(11/2^-)$	5	0.220	58

Transfer reaction quenching factor 0.55 applied

[B. P. Kay, J. P. Shiffer, S. J. Freeman, PRL 111, 042502 (2013)]

Simulated excitation energy spectrum of ^{107}Sn



(d,p) cross sections to non-yrast states at 704 and 818 keV may be quite small (reduced *S*-factor)
High potential for discovery of $1/2^+$ state at 800-1000 keV

The same can be said for 1280 keV for identification of $3/2^+$ state
(high-spin states exist between 1200-1400 keV)

More statistics expected for l = 5 transfer to 1667 keV
(see next slide)

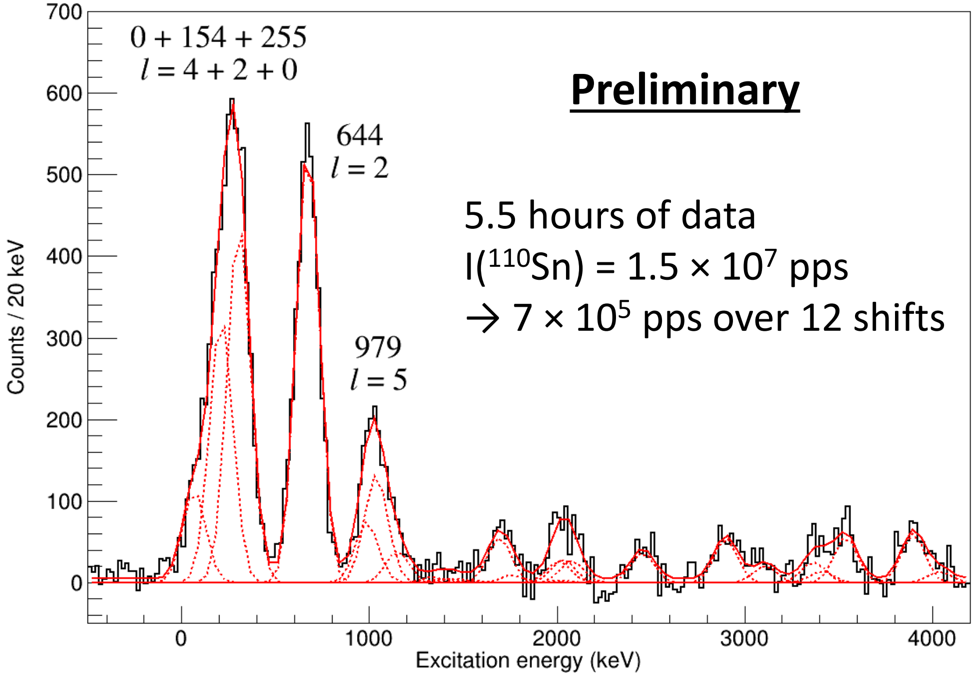
Beam time requests and expected statistics/spectra

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$_2$	1.5×10^5/s for 12 + 2 shifts (from ^{108}Sn beam time)	0	$5/2^+$	2	4.436	1170
		151	$(7/2^+)$	4	0.461	121
		704	$(3/2^+)$	2	3.444	968
		818	$(5/2^+)$	2	6.576	1725
		(1000)	$(1/2^+)$	0	2.221	568
		1280	$(3/2^+)$	2	5.641	1472
		1667	$(11/2^-)$	5	0.220	58

Transfer reaction quenching factor 0.55 applied

[B. P. Kay, J. P. Shiffer, S. J. Freeman, PRL 111, 042502 (2013)]

Excitation energy spectrum of ^{111}Sn

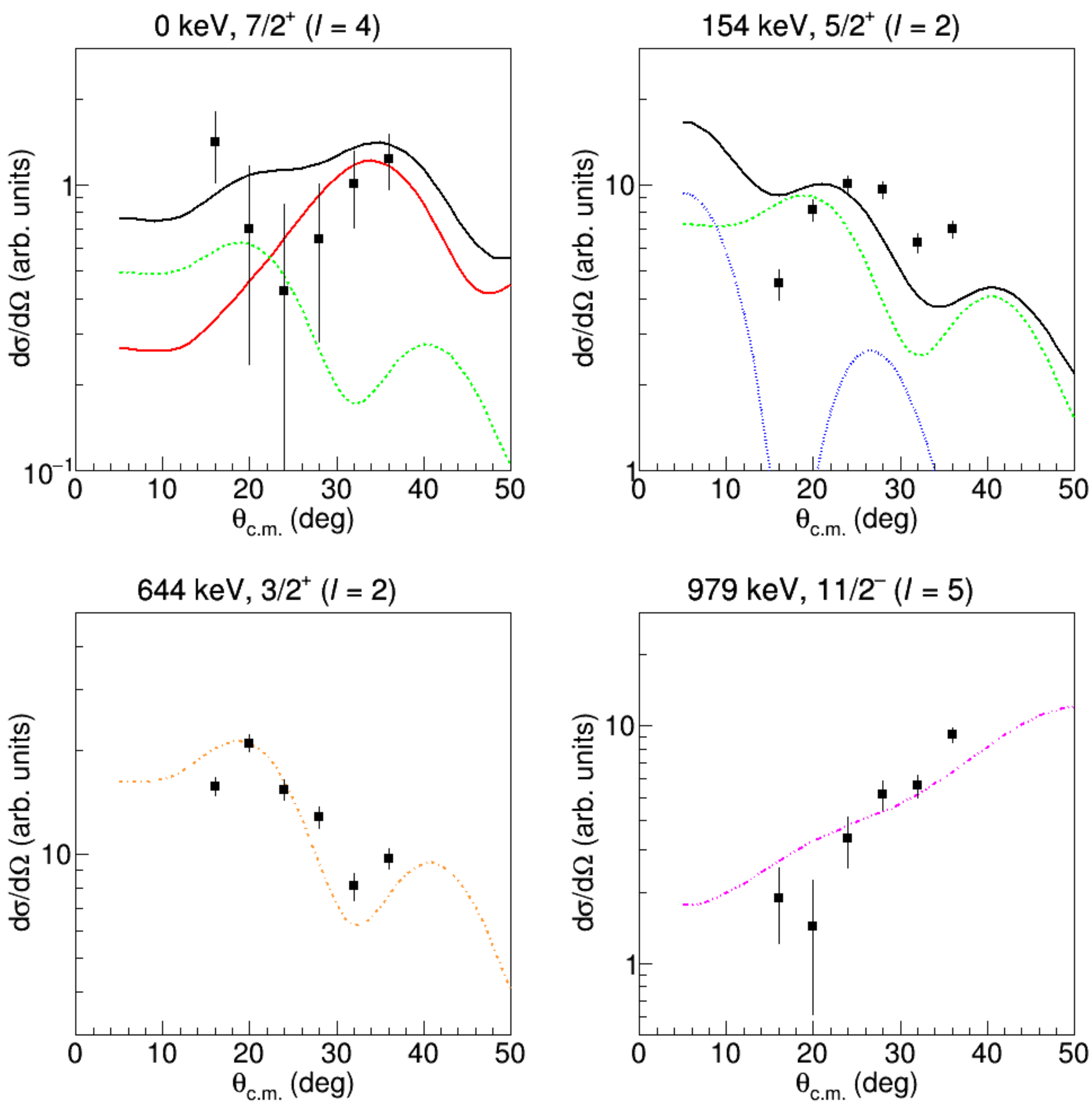


Numbers based on preliminary results from ^{111}Sn

Proton statistics exceed estimates based on DWBA cross sections by 20-100%

Required statistics for ^{107}Sn can be obtained in 12 shifts

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



Not fitted, scaling of DWBA results only (work in progress)

Mixture of components for first 3 states, different dσ/dΩ patterns

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

High intensity of *l* = 5 transfer (to be checked)

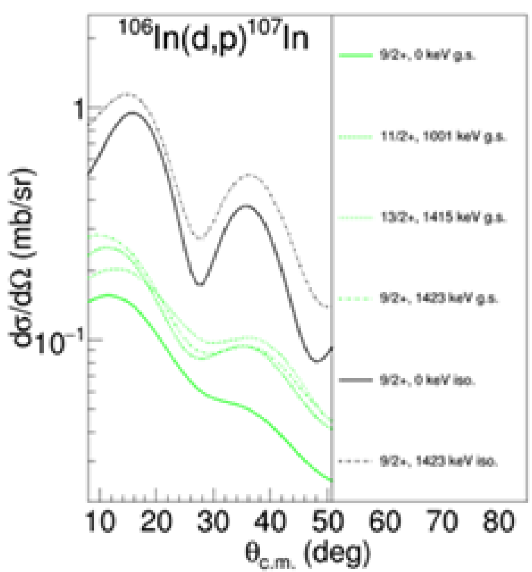
Background contaminants

Isobaric ^{106}In and their isomers are the leading contaminants
Z-selective RILIS effectiveness: expecting In/Sn ratio to 1:1 for ^{106}Sn

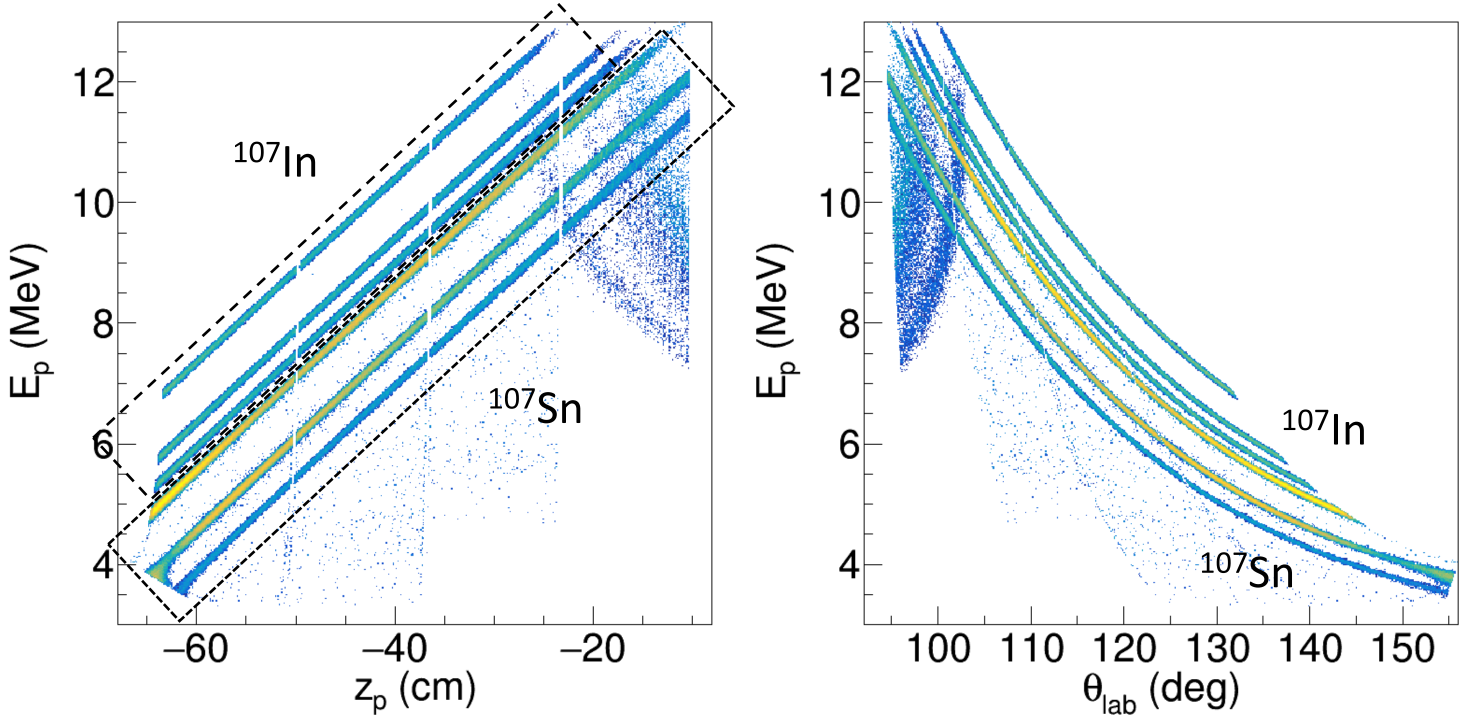
Methods to characterise and minimize background:

- Gas ionisation recoil detector for selecting Sn can be deployed for I_{beam} ~ 10^5 pps
- Laser on/off technique to profile ISS spectrum with enhanced background, later used in offline analysis
- Pure carbon target to determine contributions from fusion evaporation as backup

Calculated transfer cross sections on In isobars at 8 MeV/u, from 7$^+$ ground states and low-energy 2$^+$ isomers:



ISS spectra from potential In contaminant



Reaction kinematics governed by $Q_x = Q_{g.s.} - E_x$

A_{beam}	$Q_{g.s.}$(Sn), MeV	$Q_{g.s.}$(In), MeV	ΔQ(In-Sn)
106	7.00	8.80	1.80

No excited states in range of 0-1000 keV, low $d\sigma/d\Omega$ at higher excitation energies
Cross sections from ground state lower by an order of magnitude compared to Sn, higher from isomer
50% isomeric ratio inferred for ^{108}In [A. Ekström *et al.*, EPJA 44, 355 (2010)]
Transfers on ^{106}In to excited states where E_x > 1.8 MeV potentially cause overlaps, but unlikely as they are not single-particle dominated; recoil detector and RILIS-off data for separation

Summary

Spectroscopy of single-particle states in ^{107}Sn through (d,p) in inverse kinematics

- Structure evolution towards ^{100}Sn: testing the role of tensor force and deformation
- First (d,p) transfer reaction to determine ground-state spin of ^{107}Sn isotopes and $E(1/2^+)$
- Completion of ISS campaign, from ^{110}Sn (preliminary results) to more exotic ^{106}Sn
- Complementing previously successful Coulomb excitation experiments on ^{106,108,110}Sn with Miniball

ISOLDE Solenoidal Spectrometer and setup

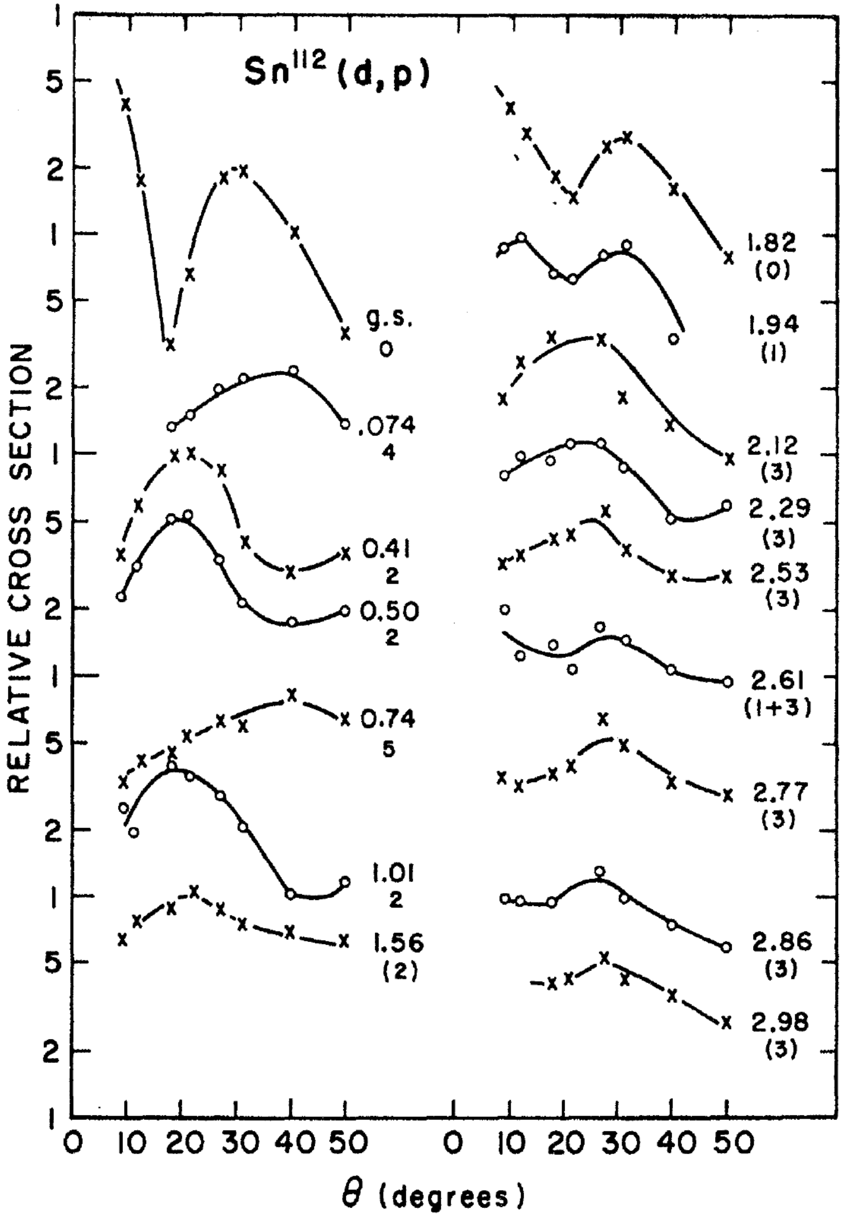
- 100-keV FWHM energy resolution to distinguish states of interest
- Angular coverage of $8° < \theta_{c.m.} < 49°$ at E_{beam} = 8 MeV/u
- 100-130-μg/cm^2 CD_2 targets, B = 2.5 T
- RILIS, recoil detector and carbon target for possible C, ^{106}In background events

Requested beams and shifts:

Isotope	Intensity (pps)	Energy (MeV/u)	Shifts requested
^{106}Sn	1.5×10^5	8.0	12

Thank you!

Literature review: $^{112}Sn(d,p)^{113}Sn$



$$\frac{d\sigma}{d\Omega} = \frac{2J+1}{2I+1}\sigma(l,\theta,Q)S$$

Single-particle C.S. from DWBA

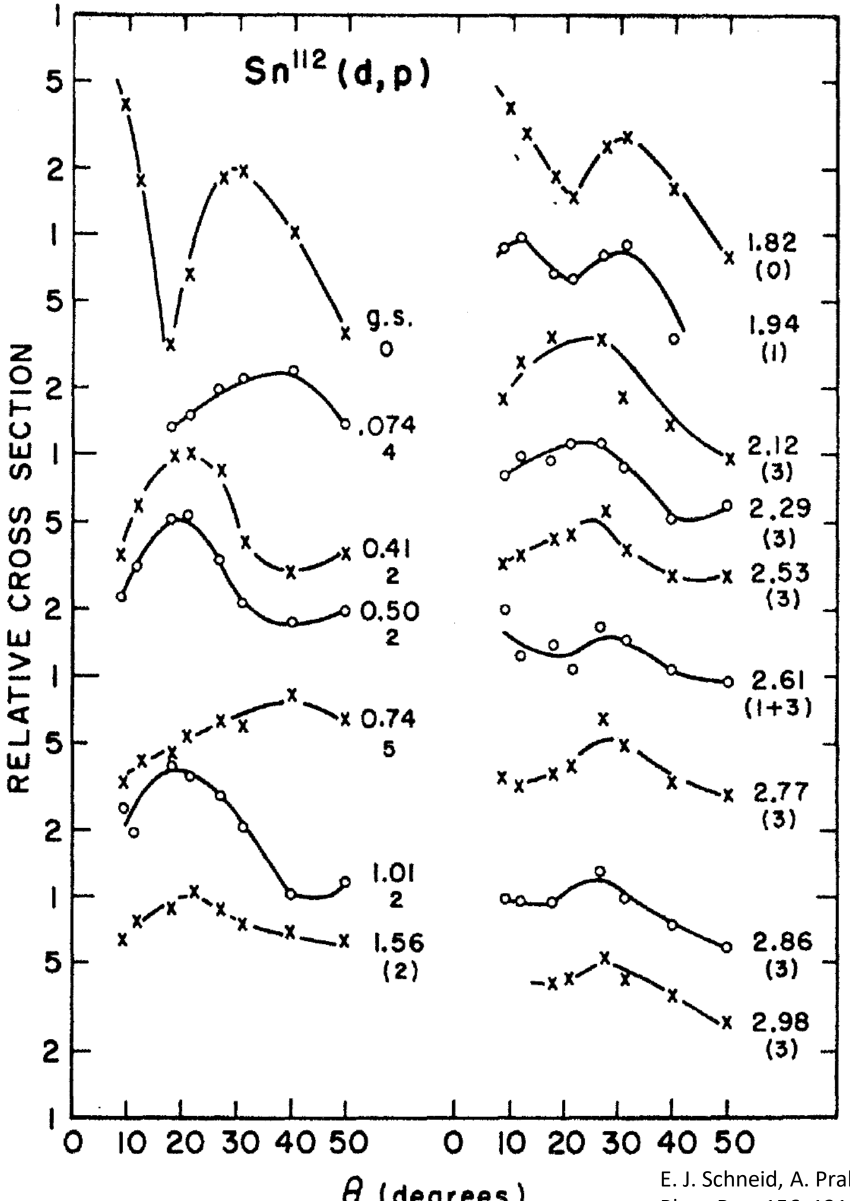
^{113}Sn

E^* (MeV)	l_n	(d,p) J^π	$(d\sigma/d\Omega)_{max}$ (mb/sr)	$S_{d,p}$
0	0	$\frac{1}{2}^+$	4.23	1.16
0.07	4	$\frac{7}{2}^+$	0.263	0.31
0.41	2	$\frac{5}{2}^+$	1.76	0.15
0.50	2	$\frac{3}{2}^+$	4.75	0.75
0.74	5	$11/2^-$	1.20	1.30
1.01	2	$(\frac{5}{2}^+)$	0.216	0.017
1.56	2	$(\frac{5}{2}^+)$	0.730	0.053
1.82	0	$\frac{1}{2}^+$	0.423	0.090
1.94	1	$(\frac{3}{2}^-)$	0.222	0.011
2.12	3	$(\frac{7}{2}^-)$	0.437	0.056
2.29	3	$(\frac{7}{2}^-)$	0.332	0.041
2.53	3	$(\frac{7}{2}^-)$	0.460	0.055
2.61	3	$(\frac{7}{2}^-)$	0.397	0.047
2.77	3	$(\frac{7}{2}^-)$	0.326	0.037
2.86	3	$(\frac{7}{2}^-)$	0.676	0.078
2.98	3	$(\frac{7}{2}^-)$	0.344	0.038

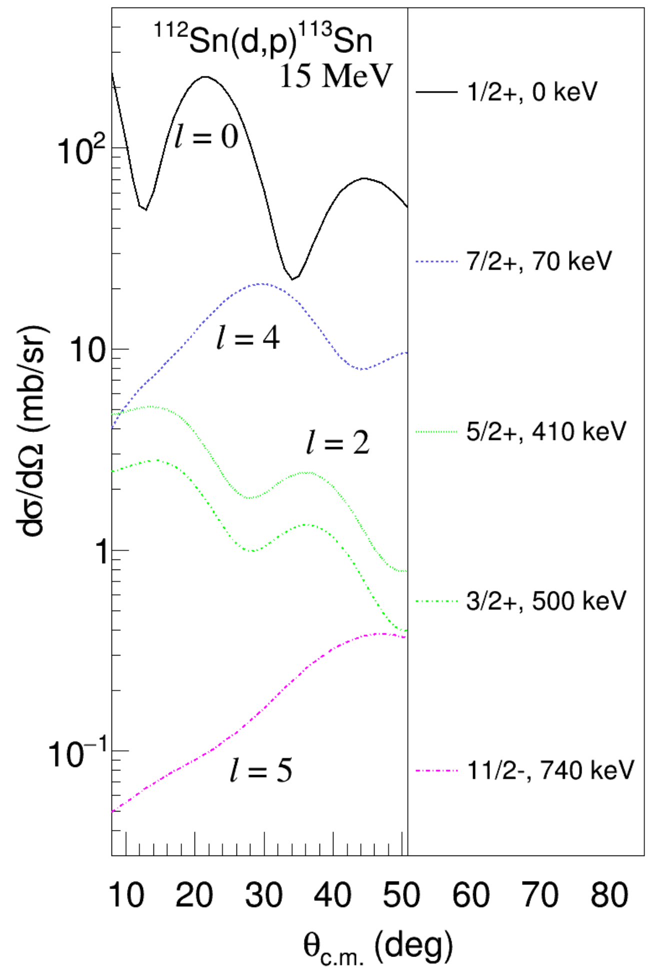
E. J. Schneid, A. Prakash, B. L. Cohen, Phys. Rev. 156, 1316 (1967)

Comparisons with DWBA used in the proposal

15-MeV deuterons (~7.5 MeV/u) on stable Sn



E. J. Schneid, A. Prakash, B. L. Cohen, Phys. Rev. 156, 1316 (1967)



Cross sections arbitrarily scaled for separation and ordering

Literature dσ/dΩ in Sn isotopes

TABLE I. The energy levels of Sn^{113} from the (d,p) and (d,t) reactions. Listed are the energies, the values of angular momentum transfer, the assigned spins and parity, the absolute cross section for (d,p) taken at the first maximum beyong 9°, the spectroscopic factors and the absolute cross section for (d,t) taken at 45°.

E^* (MeV)	l_n	(d,p) J^π	$(d\sigma/d\Omega)_{max}$ (mb/sr)	$S_{d,p}$	(d,t) E	$d\sigma/d\Omega(45°)$ (mb/sr)
0	0	$\frac{1}{2}^+$	4.23	1.16	0	0.699
0.07	4	$\frac{7}{2}^+$	0.263	0.31	0.07	0.371
0.41	2	$\frac{5}{2}^+$	1.76	0.15	0.39	1.304
0.50	2	$\frac{3}{2}^+$	4.75	0.75	0.49	0.314
0.74	5	$11/2^-$	1.20	1.30		
1.01	2	$(\frac{5}{2}^+)$	0.216	0.017		
1.56	2	$(\frac{5}{2}^+)$	0.730	0.053		
1.82	0	$\frac{1}{2}^+$	0.423	0.090		
1.94	1	$(\frac{3}{2}^-)$	0.222	0.011		
2.12	3	$(\frac{7}{2}^-)$	0.437	0.056		
2.29	3	$(\frac{7}{2}^-)$	0.332	0.041		
2.53	3	$(\frac{7}{2}^-)$	0.460	0.055		
2.61	3	$(\frac{7}{2}^-)$	0.397	0.047		
2.77	3	$(\frac{7}{2}^-)$	0.326	0.037		
2.86	3	$(\frac{7}{2}^-)$	0.676	0.078		
2.98	3	$(\frac{7}{2}^-)$	0.344	0.038		

TABLE II. Energy levels of Sn^{115} from the (d,p) and (d,t) reactions. (See also caption for Table I.)

E^* (MeV)	l_n	(d,p) J^π	$(d\sigma/d\Omega)_{max}$ (mb/sr)	$S_{d,p}$	(d,t) E^* (MeV)	$d\sigma/d\Omega(45°)$ (mb/sr)
0	0	$\frac{1}{2}^+$	3.67	0.960	0	1.61
0.49	2	$\frac{3}{2}^+$	3.96	0.62	0.48	0.314
0.60	4	$\frac{7}{2}^+$	0.209	0.19	0.61	0.368
0.73	5	$\frac{11}{2}^-$	0.741	0.77	0.72	0.112
0.98	2	$\frac{5}{2}^+$	1.52	0.12	0.98	1.43
1.28	2	$(\frac{5}{2}^+)$	0.40	0.029	1.25	0.053
					1.30	0.080
1.63	(2)	$(\frac{5}{2}^+)$	0.63	0.044		
1.97	(0)	$\frac{1}{2}^+$	0.41	0.082		
2.07	(0)	$\frac{1}{2}^+$	0.23	0.045		
2.17	(2)	$(\frac{5}{2}^+)$	0.33	0.021		
2.49	(2)	$(\frac{5}{2}^+)$	0.35	0.021		
2.77	(1)	$(\frac{3}{2}^-)$	0.89	0.050		
2.95	(3)	$(\frac{7}{2}^-)$	0.56	0.064		

E. J. Schneid, A. Prakash and B. L. Cohen, Phys. Rev. 156, 1316 (1967)

15-MeV deuterons (~7.5 MeV/u) on stable Sn

Magnitude of dσ/dΩ similar to predictions on lighter isotopes at 8 MeV/u

TABLE III. The energy levels of Sn^{117} from the (d,p) and (d,t) reactions. (See also caption for Table I.)

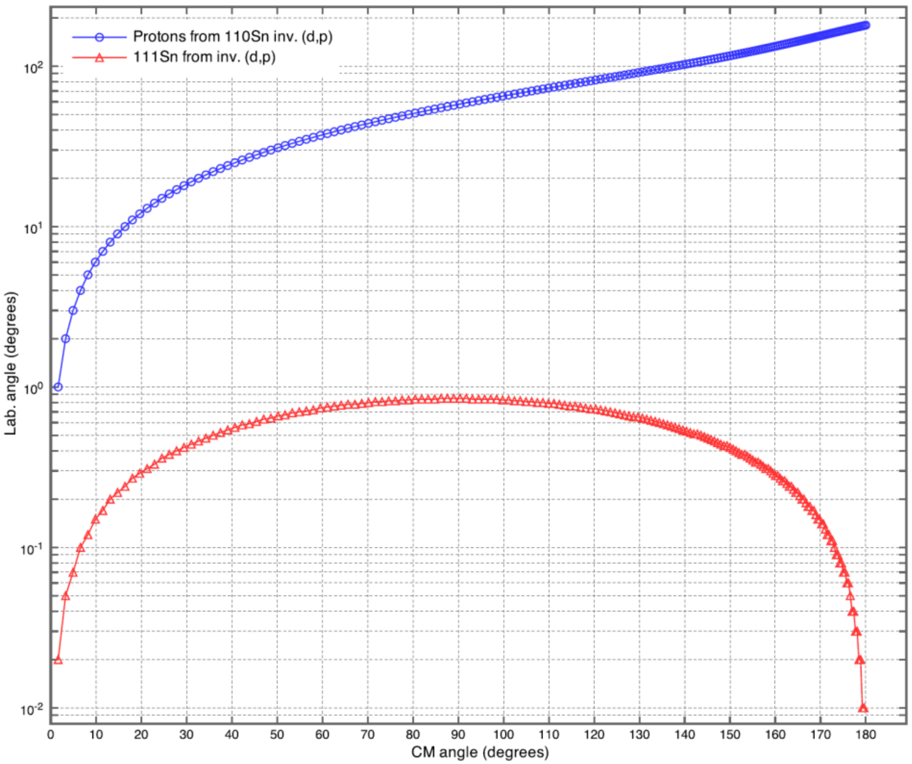
E^* (MeV)	l_n	(d,p) J^π	$(d\sigma/d\Omega)_{max}$ (mb/sr)	$S_{d,p}$	(d,t) E^* (MeV)	$d\sigma/d\Omega(45°)$ (mb/sr)
0	0	$\frac{1}{2}^+$	2.74	0.65	0	2.26
0.16	2	$\frac{3}{2}^+$	3.72	0.55	0.16	0.695
0.32	5	$11/2^-$	0.800	0.81	0.31	0.212
0.72	4	$\frac{7}{2}^+$	0.166	0.13	0.71	0.306
1.03	2	$\frac{5}{2}^+$	0.875	0.061	1.01	1.15
1.19	2	$\frac{5}{2}^+$	0.490	0.033	1.18	0.526
1.31	(3)	$(\frac{7}{2}^-)$	0.226	0.029		
1.51	(2)	$(\frac{5}{2}^+)$	0.315	0.020	1.50	0.173
1.59	(2)	$(\frac{5}{2}^+)$	0.098	0.006		
1.67	(2)	$(\frac{5}{2}^+)$	0.106	0.007		
1.96	(1+3)	$(\frac{3}{2}^-)$	0.040	0.003		
		$(\frac{7}{2}^-)$	0.020	0.002		

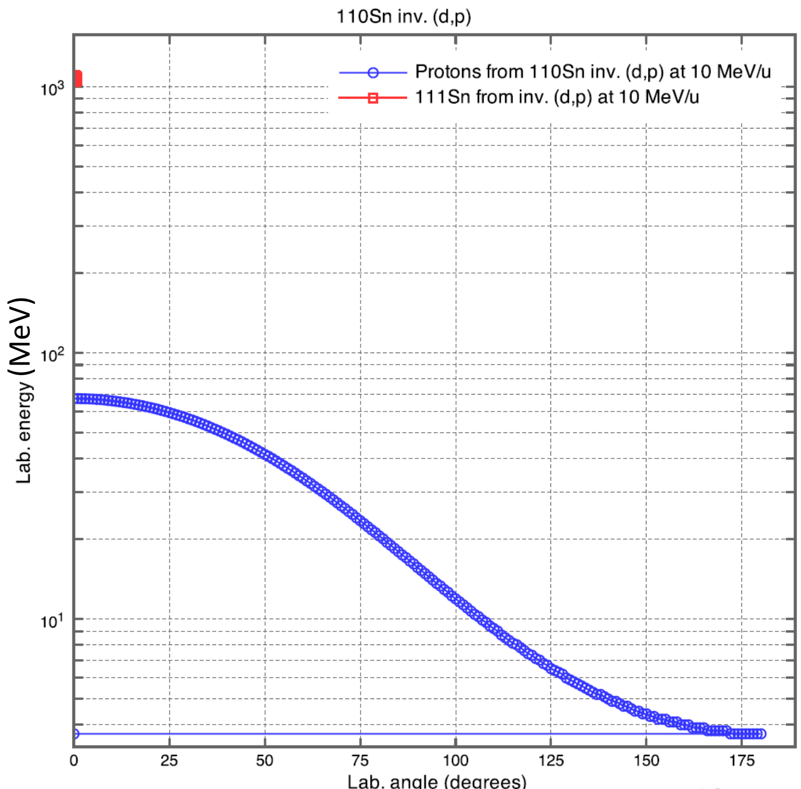
Technical considerations for ISS proposal

Isotope	Half life	Driver	Yield / uC	Target
^{105}Sn	31 s 6	PSB	8.00e+4	U Carbide
^{106}Sn	115 s 5	PSB	1.60e+6	La Carbide
^{107}Sn	2.90 m 5	PSB	6.00e+6	La Carbide
^{108}Sn	10.30 m 8	PSB	1.40e+8	La Carbide
^{109}Sn	18.0 m 2	PSB	1.00e+9	La Carbide
^{110}Sn	4.11 h 10	PSB	1.80e+9	La Carbide

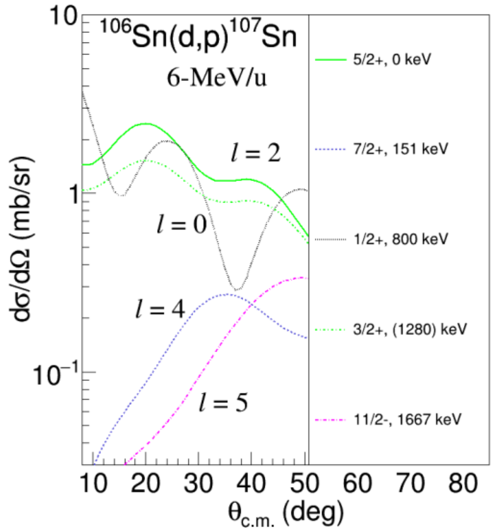
ISOLDE Yield Database, development version

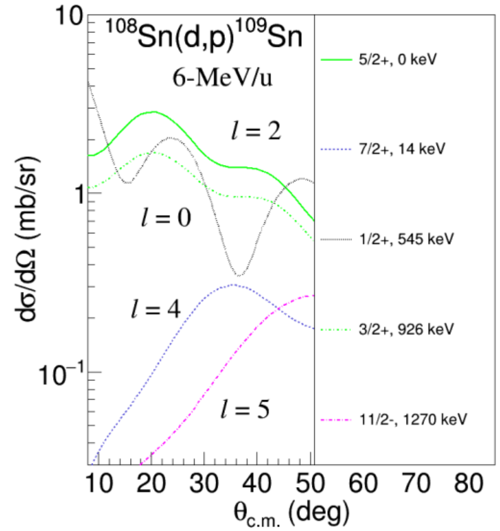
Approximate beam energy: 6-10 MeV/u
CD_2 target with thickness 0.165 mg/cm^2
Typical ISS magnetic field: 2.5 T
Energy resolution: 100 keV
Expected θ_{cm} coverage: 8-49°
Maximal cross section ~5 mb/sr
(d,p) Q-value: 6-7 MeV

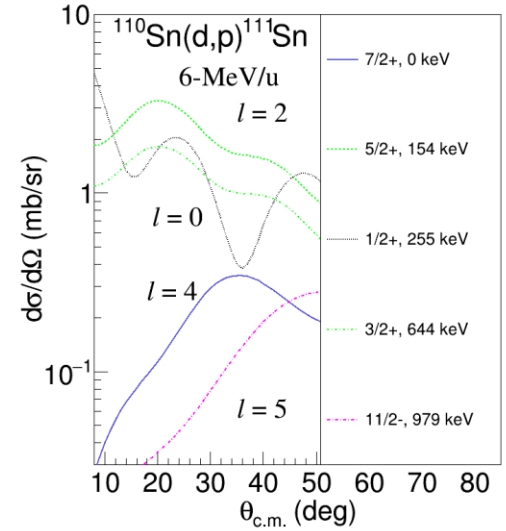


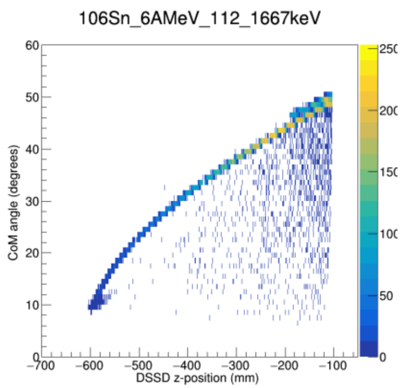


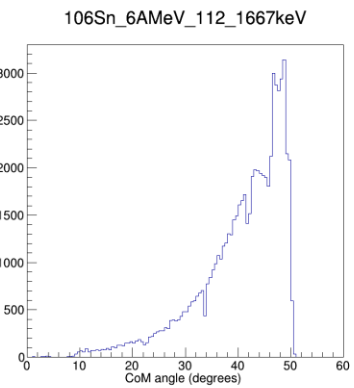
Cross sections and ISS coverage at 6 MeV/u

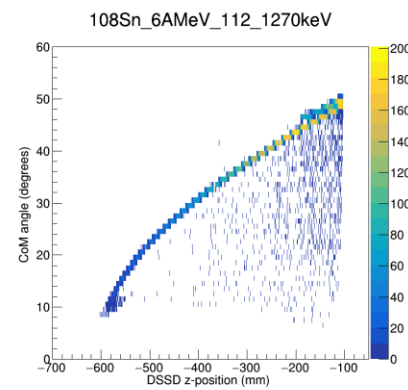


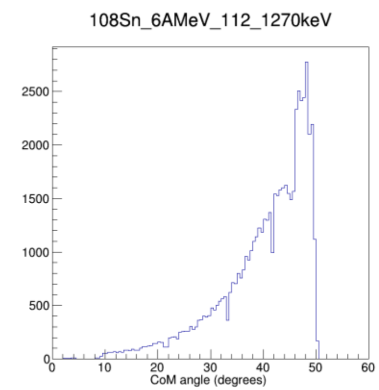


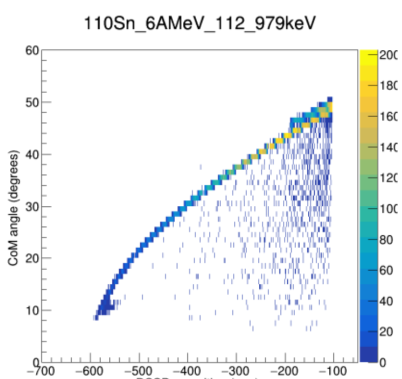


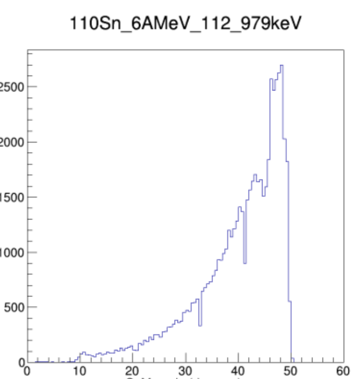






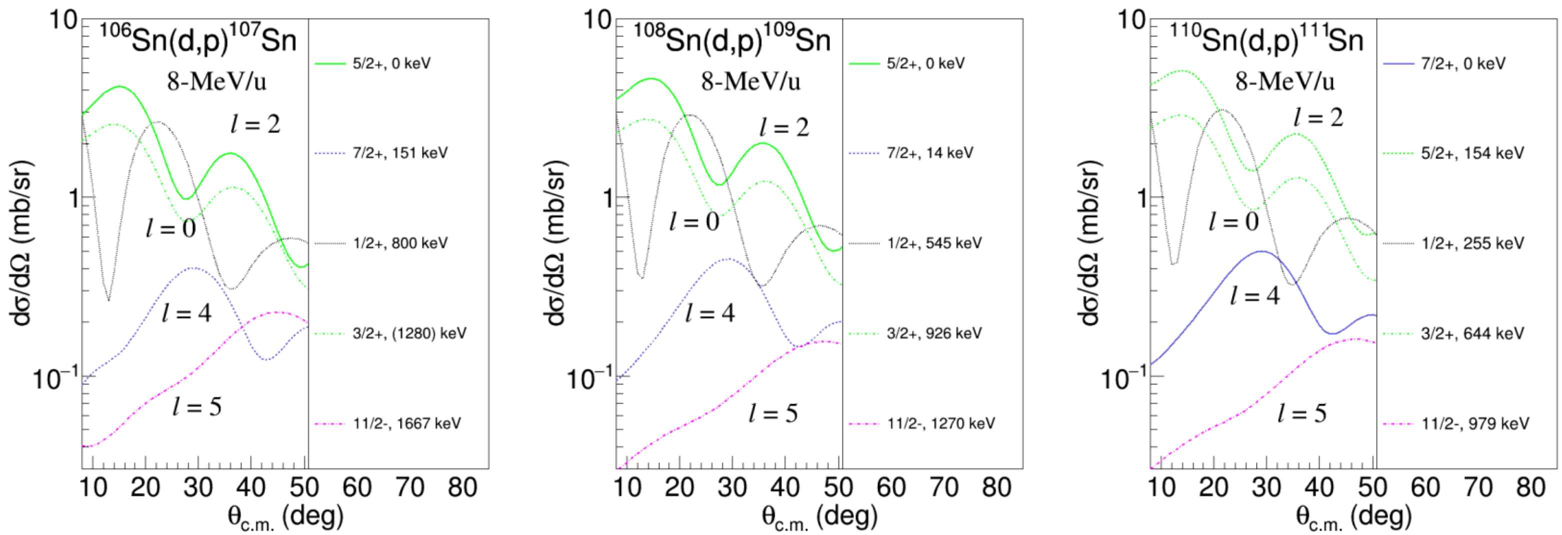


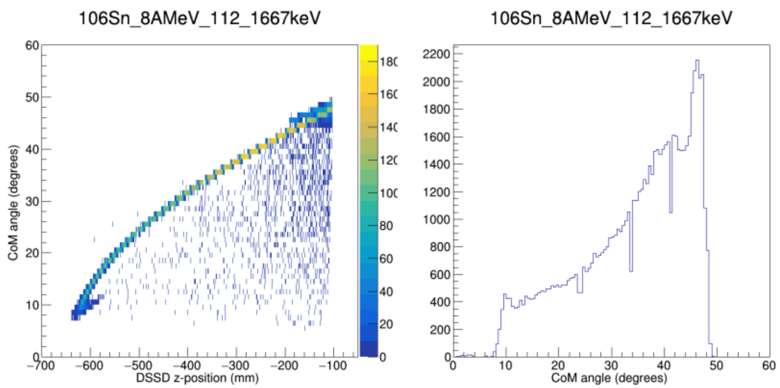


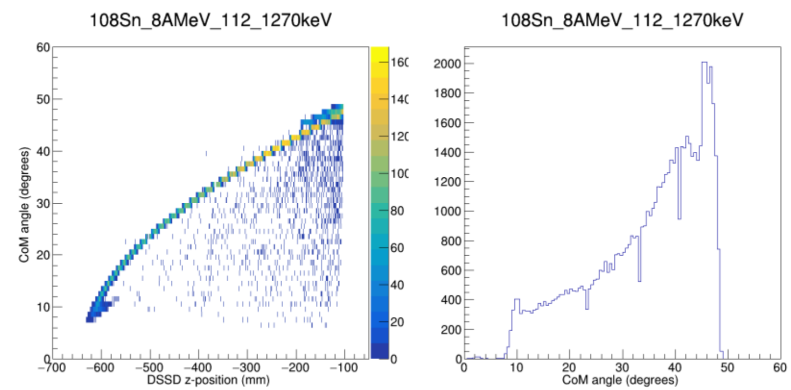


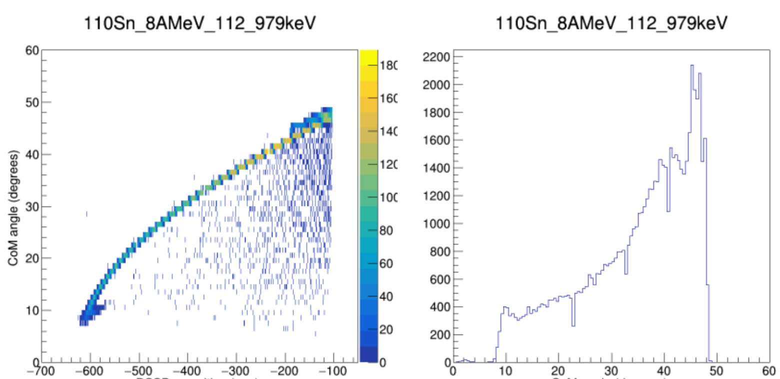
Coverage for (d,p) to $11/2^-$ state
Counts not normalised to cross section

Cross sections and ISS coverage at 8 MeV/u



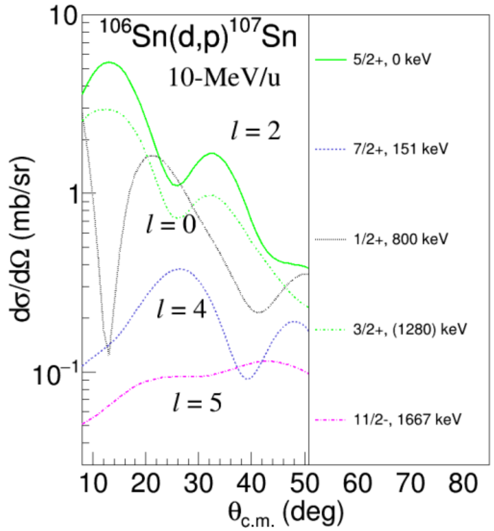


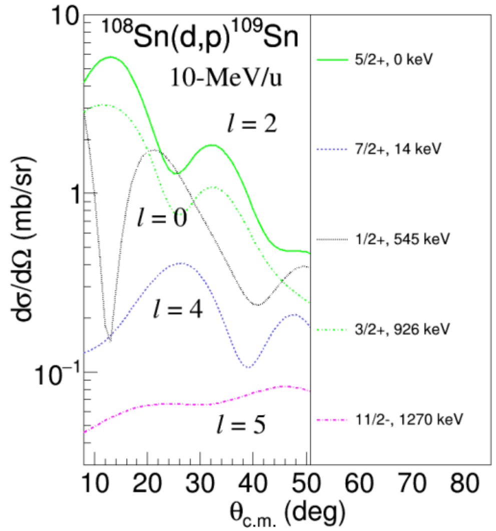


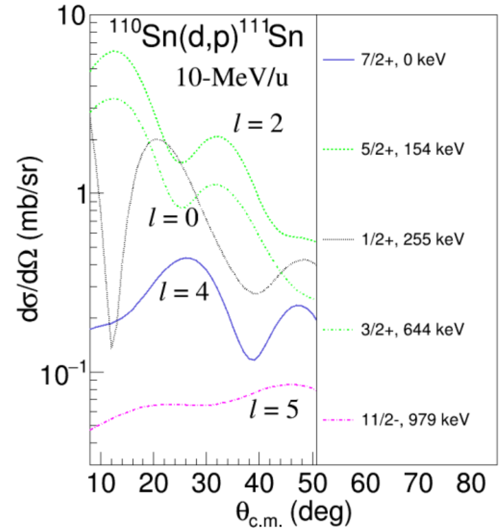


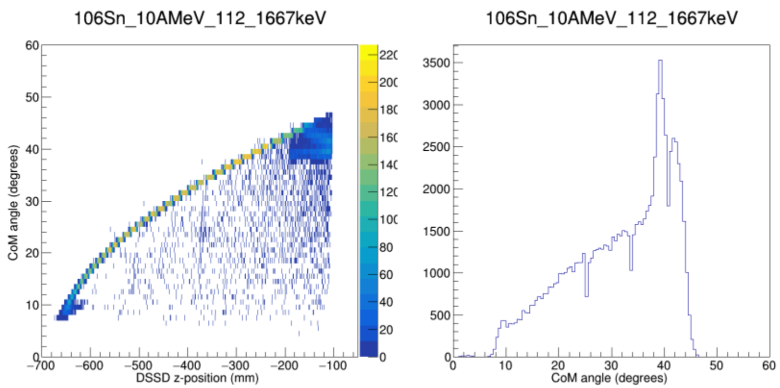
Coverage for (d,p) to $11/2^-$ state
Counts not normalised to cross section

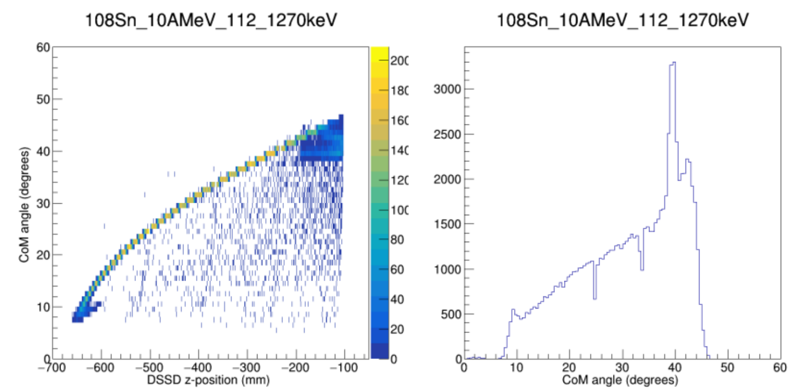
Cross sections and ISS coverage at 10 MeV/u

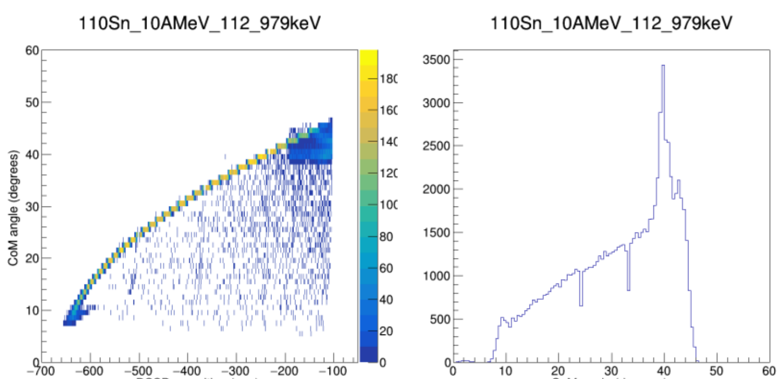












Coverage for (d,p) to $11/2^-$ state
Counts not normalised to cross section

TAC feedback and response

"8 MeV/u is feasible, there is the possibility of perhaps going slightly higher depending on the performance of the accelerator. Would there be a benefit in aiming to deliver higher energy beams?"

Tables of integrated cross sections in the range 8° < $\theta_{c.m.}$ < 49° for different E_{beam}; lower E_{beam} likely better due to high Q-value (see backup slides for updated differential cross sections and DSSD coverages)

^{106}Sn (in mb)	3s1/2	2d3/2	2d5/2	1g7/2	1h11/2
6 MeV/u	2.214	2.167	2.767	0.387	0.362
8 MeV/u	2.031	2.323	2.906	0.467	0.319
10 MeV/u	1.343	2.039	2.546	0.418	0.212

Q(g.s.) = 7.00 MeV

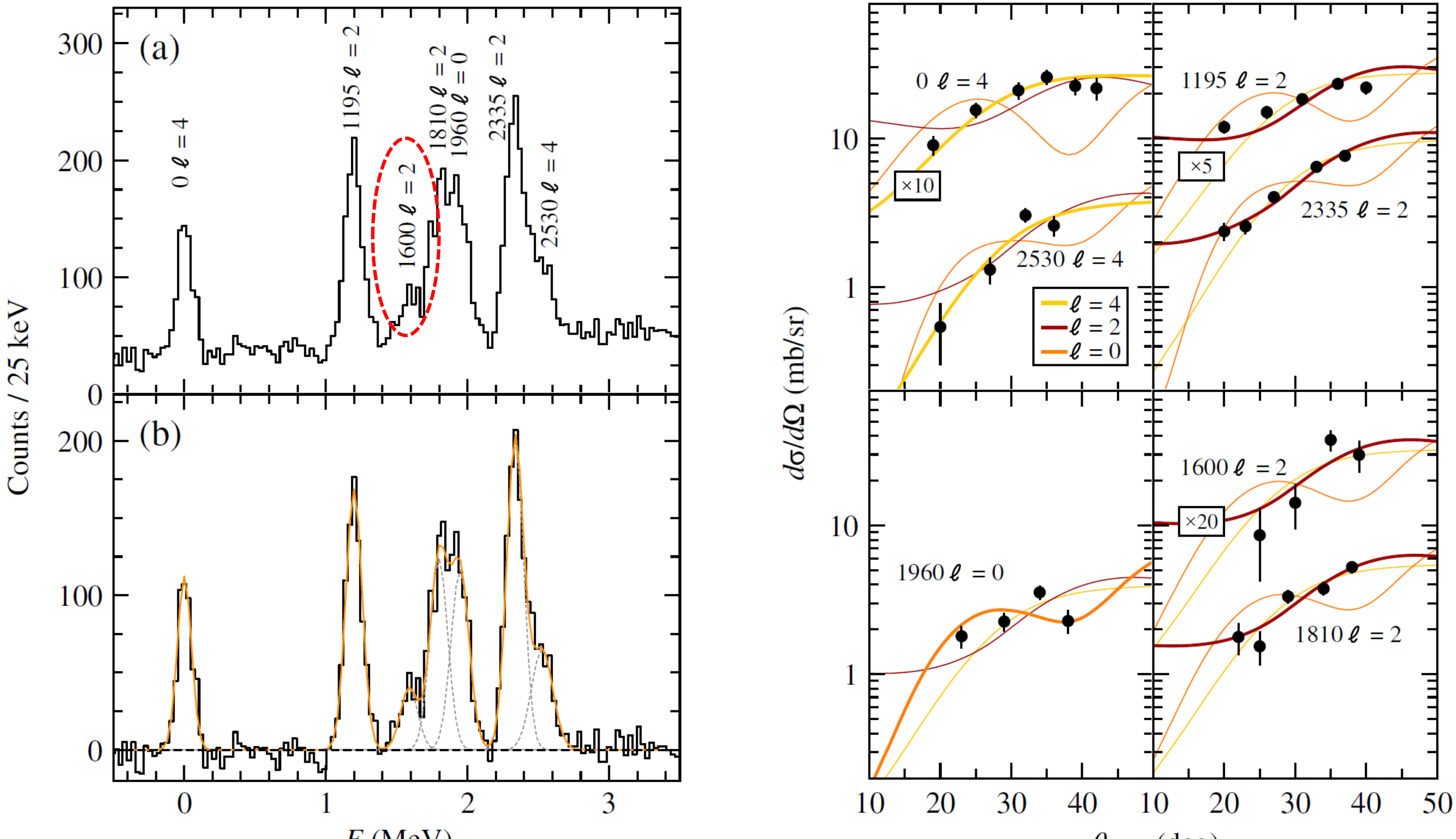
^{108}Sn (in mb)	3s1/2	2d3/2	2d5/2	1g7/2	1h11/2
6 MeV/u	2.449	2.322	3.521	0.445	0.279
8 MeV/u	2.220	2.464	3.893	0.547	0.218
10 MeV/u	1.438	2.155	3.625	0.483	0.152

Q(g.s.) = 6.41 MeV

^{110}Sn (in mb)	3s1/2	2d3/2	2d5/2	1g7/2	1h11/2
6 MeV/u	2.591	2.439	4.117	0.506	0.294
8 MeV/u	2.346	2.553	4.378	0.618	0.225
10 MeV/u	1.538	2.225	3.991	0.528	0.154

Q(g.s.) = 5.94 MeV

Requirement of ≥100 counts for peak identification



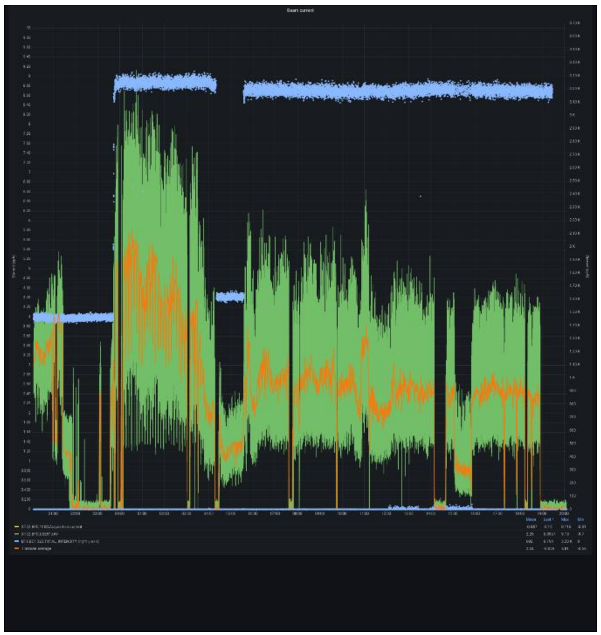
T. L. Tang et al., PRL 124, 062502 (2020)

1600-keV state in ^{207}Hg identified and *S* measured with ca 100 counts, given good energy separation

^{108}Sn run summary (2024)

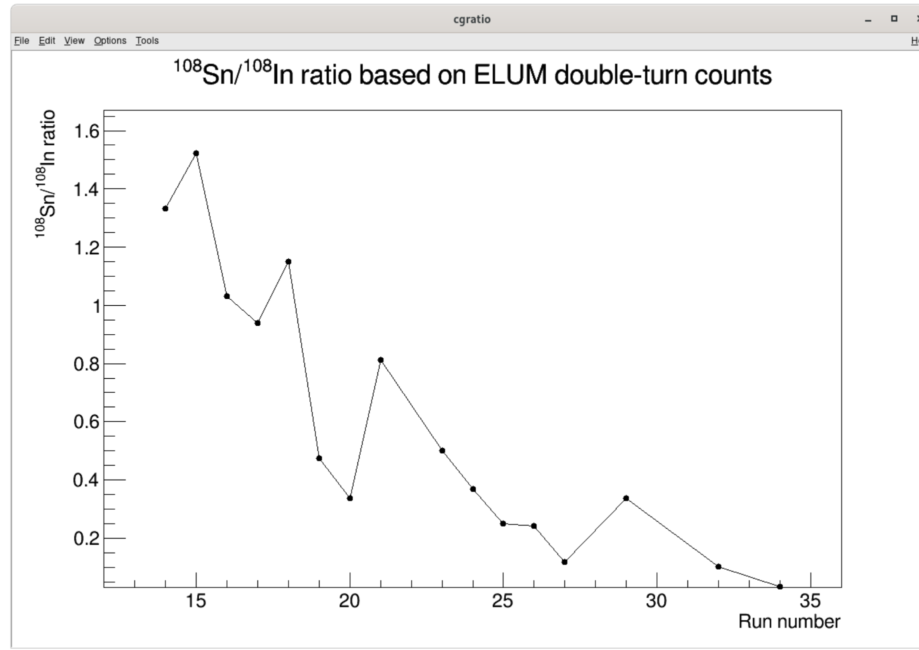
RILIS laser <u>on</u>: ^{108}Sn extracted efficiently from ISOL target
RILIS laser <u>off</u>: no ^{108}Sn and mostly ^{108}In isobaric contaminant

Current readings (first night)



Proton current

FC behind ISS
(and average)



^{108}Sn/^{108}In ratio not great to begin with

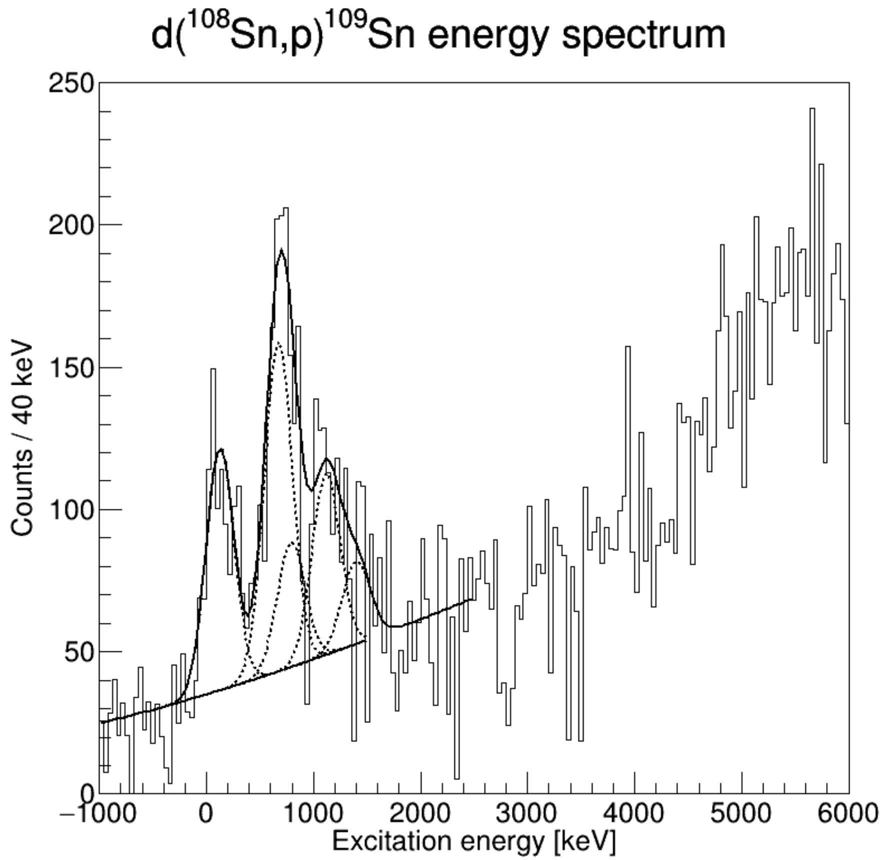
^{108}Sn beam intensity dropped over weekend

Gradual, significant loss of ^{108}Sn relative to ^{108}In

Site-wide fire alarm caused further delays with beam recovery

Prospects for remaining ^{108}Sn shifts

On the last day of beam time, efficient extraction of ^{108}Sn beam was recovered
10-15% of total expected statistics gathered in the last 12 hours



Rough peak fitting on 12-hour data
~7 times more statistics expected after 10 successful shifts