The (d,p) reaction on ^{206}Hg — an exploration of weak binding in heavy systems and of terra incognita

Ben Kay, Physics Division, Argonne National Laboratory
ISS meeting, Manchester 2017

The (*d*,*p*) reaction on ^{206}Hg

B. P. Kay[1], C. R. Hoffman[1], M. Avila[1], S. Bottoni[1], P. A. Butler[2], S. J. Freeman[3], L. P. Gaffney[4], R. V. F. Janssens[1], M. Labiche[5], R. D. Page[2], Zs. Podolyák[6], R. Raabe[7], P. H. Regan[6], M. Rudigier[6], D. Santiago-Gonzalez[8,1], G. Savard[1], J. P. Schiffer[1], D. K. Sharp[3], J. F. Smith[4], R. Talwar[1], and S. Zhu[1]. *(And now Francesco Recchia et al. I assume)*

[1]Argonne National Laboratory, [2]University of Liverpool, [3]University of Manchester, [4]University of the West of Scotland, [5]STFC Daresbury Laboratory, [6]University of Surrey, [7]KU Leuven, [8]Louisiana State University

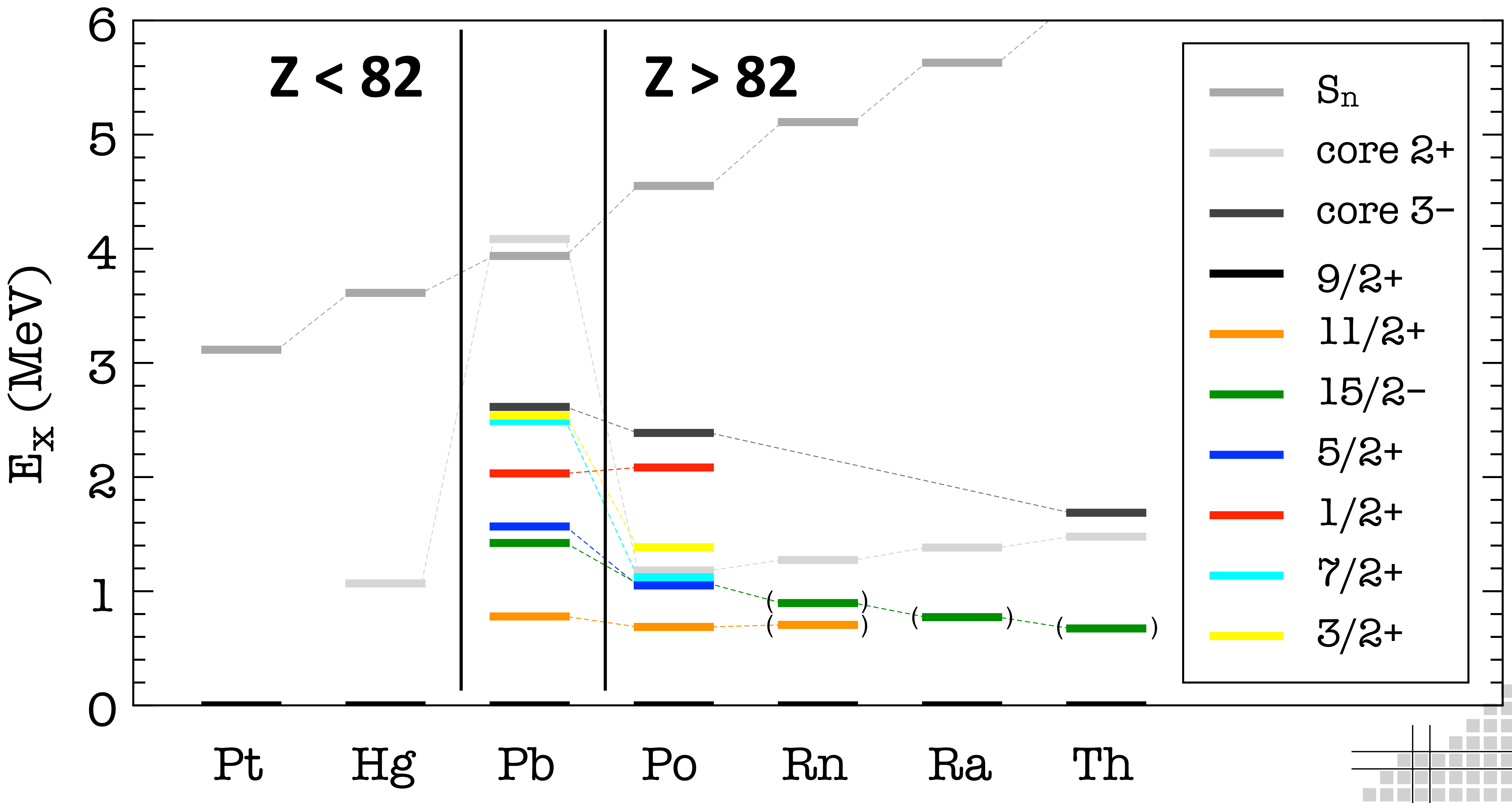
Requested shifts: 18
Beam: (ideally) 10 MeV/u ^{206}Hg, 1×10^{6} Hz, >99% purity
Target: deuterated polyethylene $(CD_2)_n$
Installation: ISOL solenoidal spectrometer

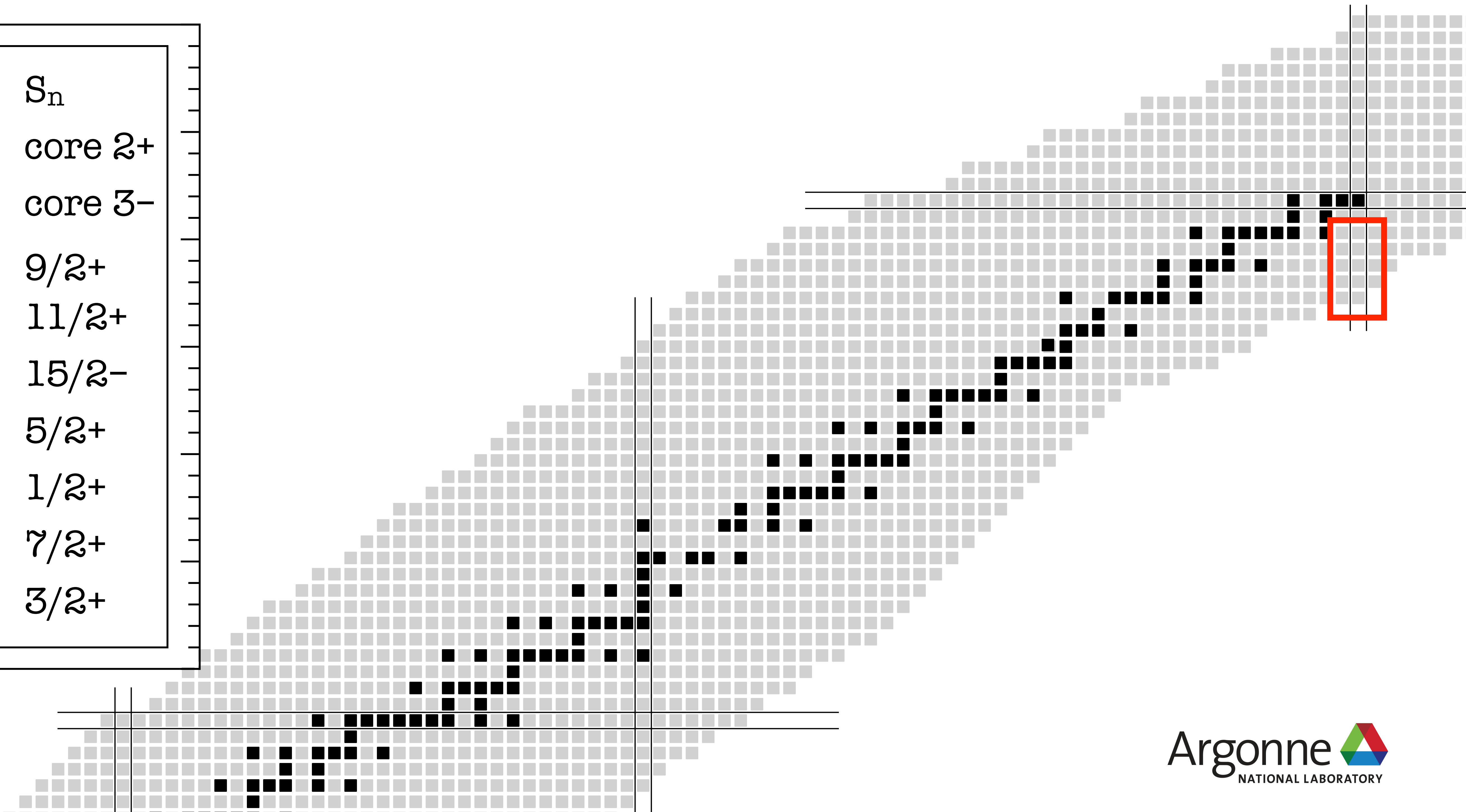
INTC meeting, June 29, 2016

Motivation — general comments

_N_ = 127 isotones below Pb

- ***Terra incognita***. Below Pb, around *N* = 126, ***very little known*** (limited knowledge on masses, decays).
- ***Evolution of single-particle states*** has ***not been explored*** in nuclei around ^{208}Pb as these require ***radioactive ion beams***.
- Data on 2^+ and 3^- in even nuclei allows us to make some assumptions.
- ***Few / no theoretical studies*** on single-particle excitations.

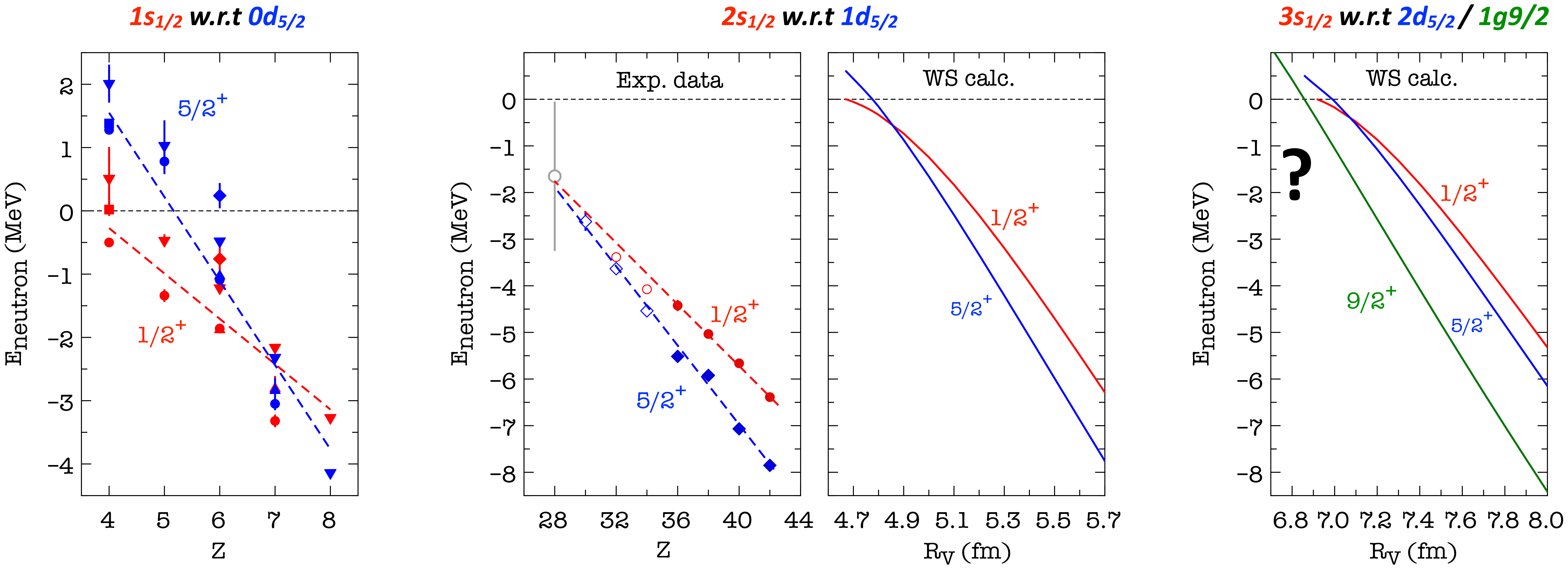




Argonne NATIONAL LABORATORY

Motivation — loosely bound systems

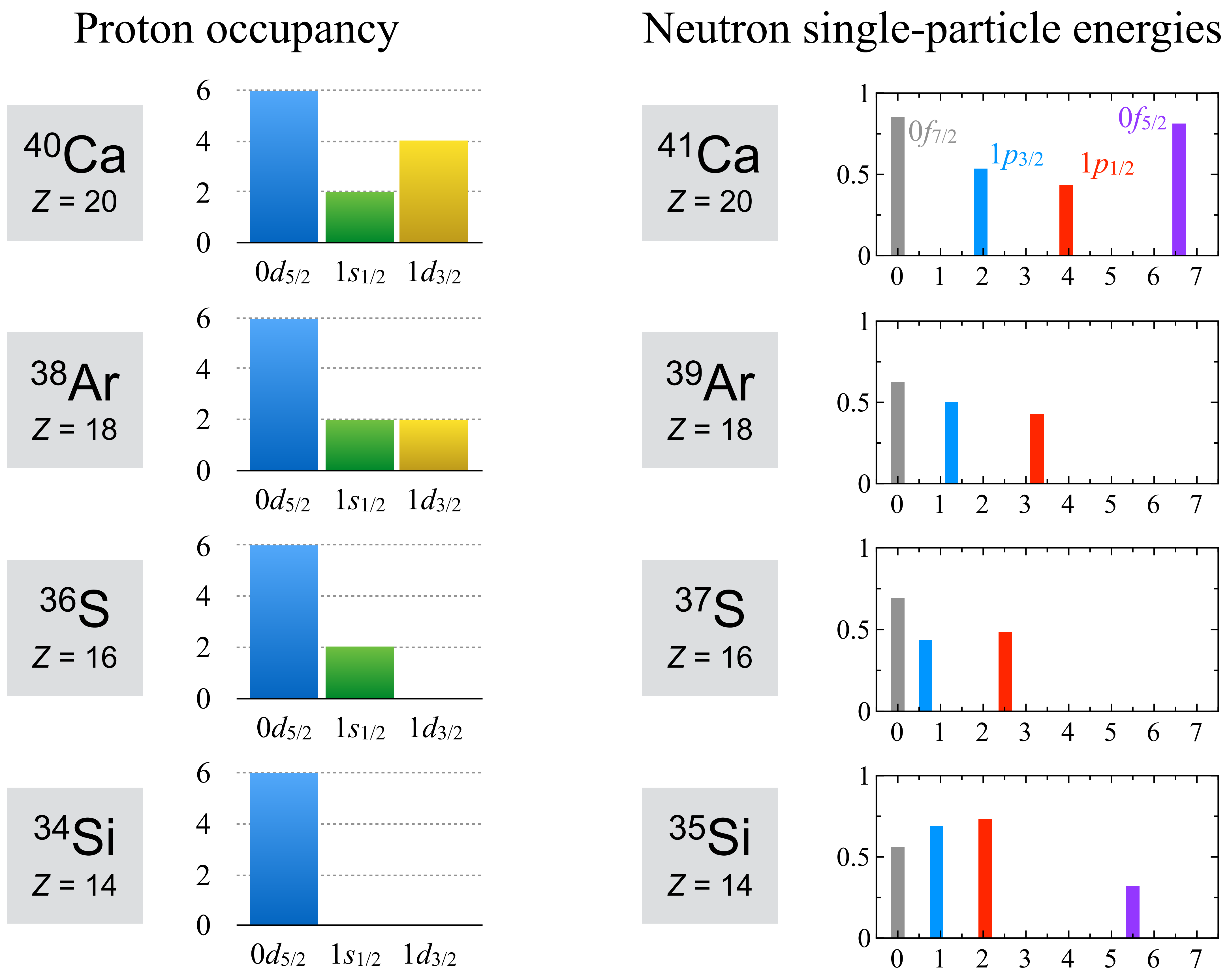
s-states in loosely bound systems tend to linger below threshold—this feature seems to ***dominate the structural changes in light nuclei***, and results in ***halo structures***. Does this characteristic of *s*-states play a role in loosely bound heavier systems?

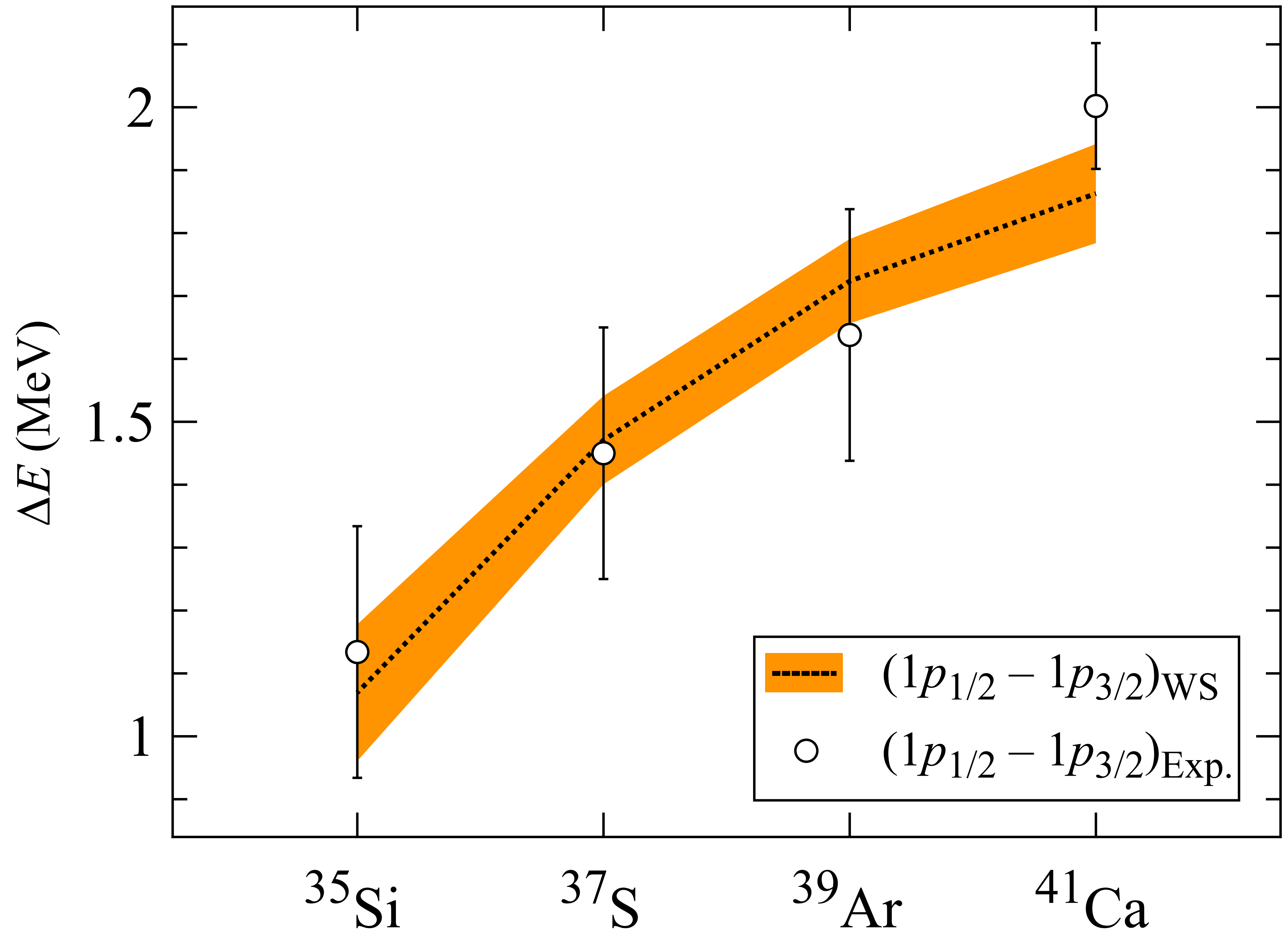


C. R. Hoffman, B. P. Kay, J. P. Schiffer, Phys Rev. C **89**, 061305(R) (2014), C. R. Hoffman, B. P. Kay, J. P .Schiffer, submitted (2016), C. R. Hoffman, and B. P. Kay, Nuclear Physics New International Oct-Dec 2015. X. F. Yang et al., Phys. Rev. Lett. **116**, 182501 (2016) [**Recent ISOLDE measurement suggests the 1/2+ isomeric state could potentially be below the 5/2+ state in the N = 49 system at Z = 30.**]

Argonne NATIONAL LABORATORY

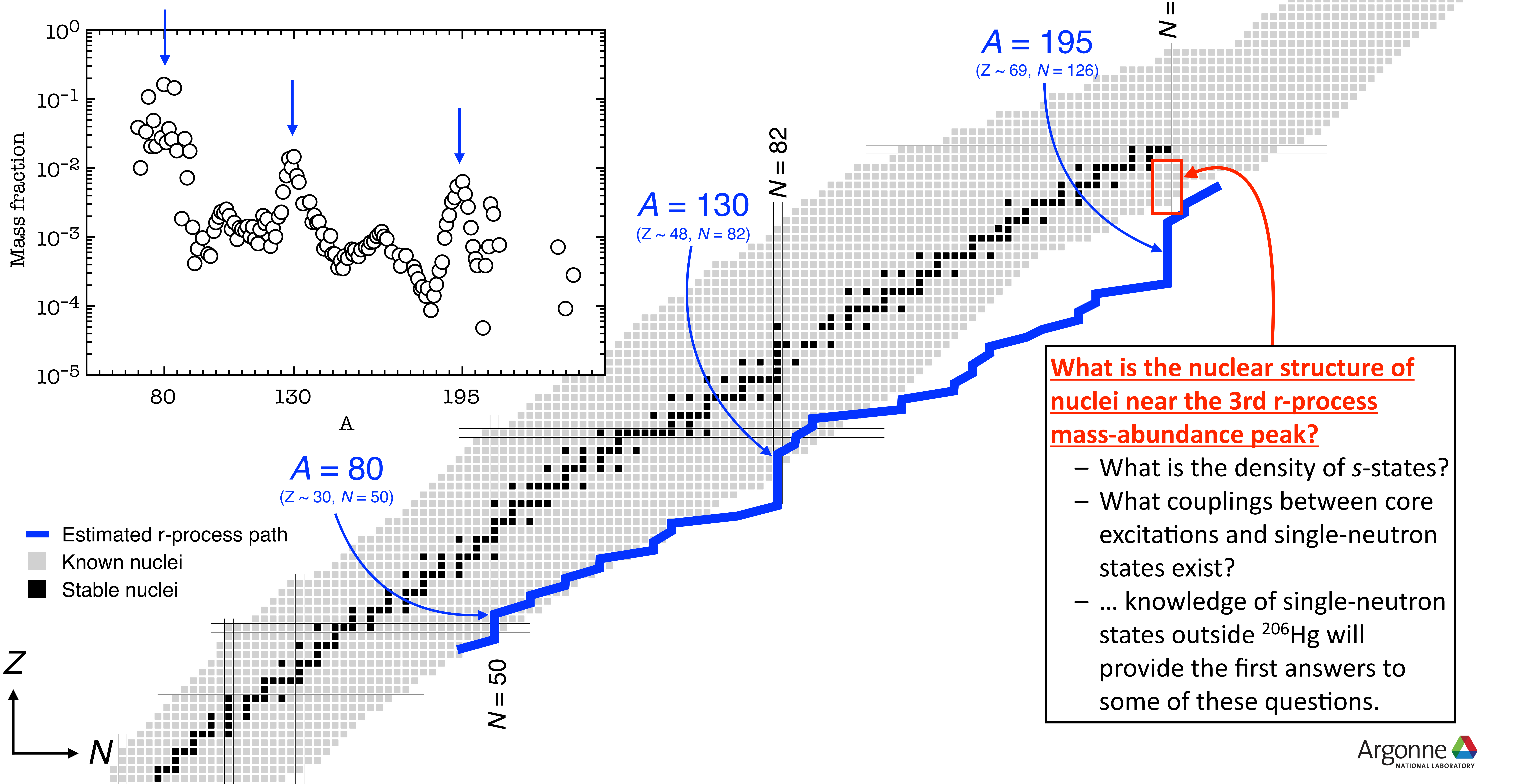
Aside — ‘bubble’ nuclei





As discussed by Calem this morning … weak binding effects often ignored in favor of ‘sensational’ explanations

Motivation — r-process physics



What is the nuclear structure of nuclei near the 3rd r-process mass-abundance peak?

- What is the density of *s*-states?
- What couplings between core excitations and single-neutron states exist?
- … knowledge of single-neutron states outside ^{206}Hg will provide the first answers to some of these questions.

Argonne NATIONAL LABORATORY

The proposed measurement

The ^{206}Hg(*d*,*p*) reaction at 10 MeV/u using the ISOL Solenoidal Spectrometer (ISS)

Why 10 MeV/u?

- Cross sections
- Angular momentum matching
- Angular distributions

Why ISS?

Resolution

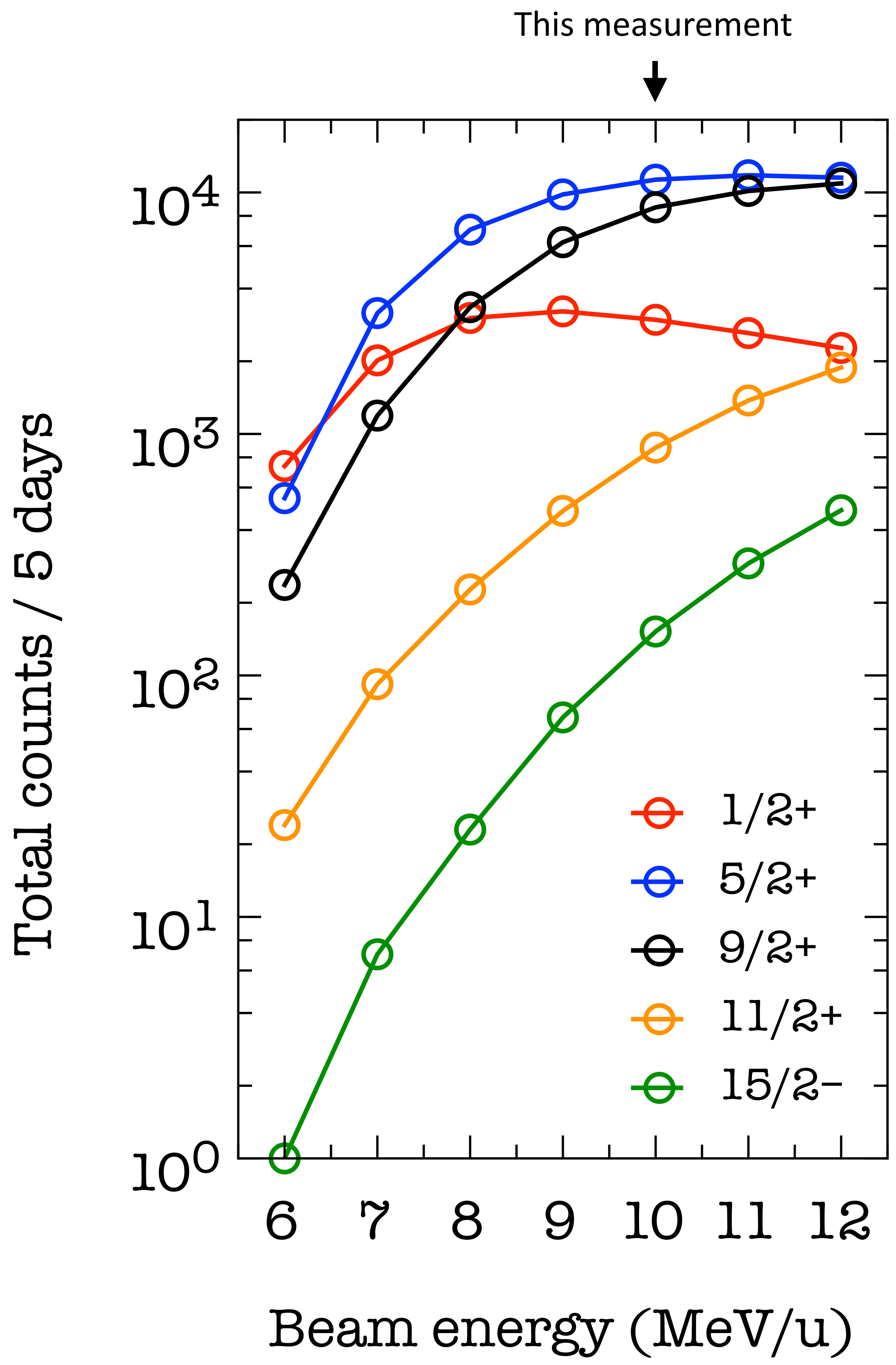
- Charged-particle spectroscopy with ***<100-keV Q-value resolution*** using thin targets

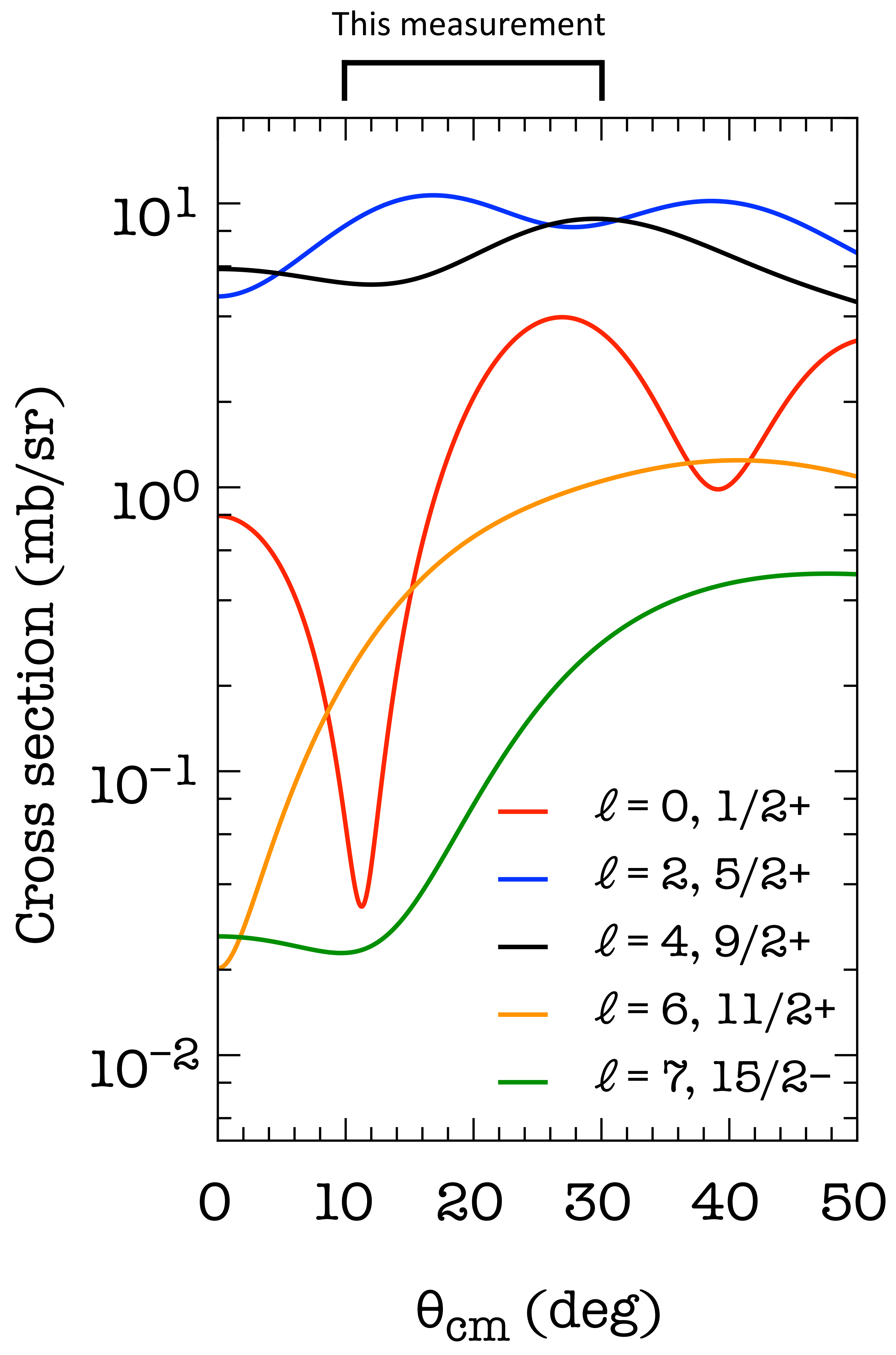
Efficiency

- Limited only by geometrical acceptance, not intrinsic efficiency of the detectors.

Direct probe of excited states

- ***Does not*** require coincident γ-rays de-exciting the states ($\therefore$ no concerns with isomers*, ground state, states not connected by γ-ray decay, etc).

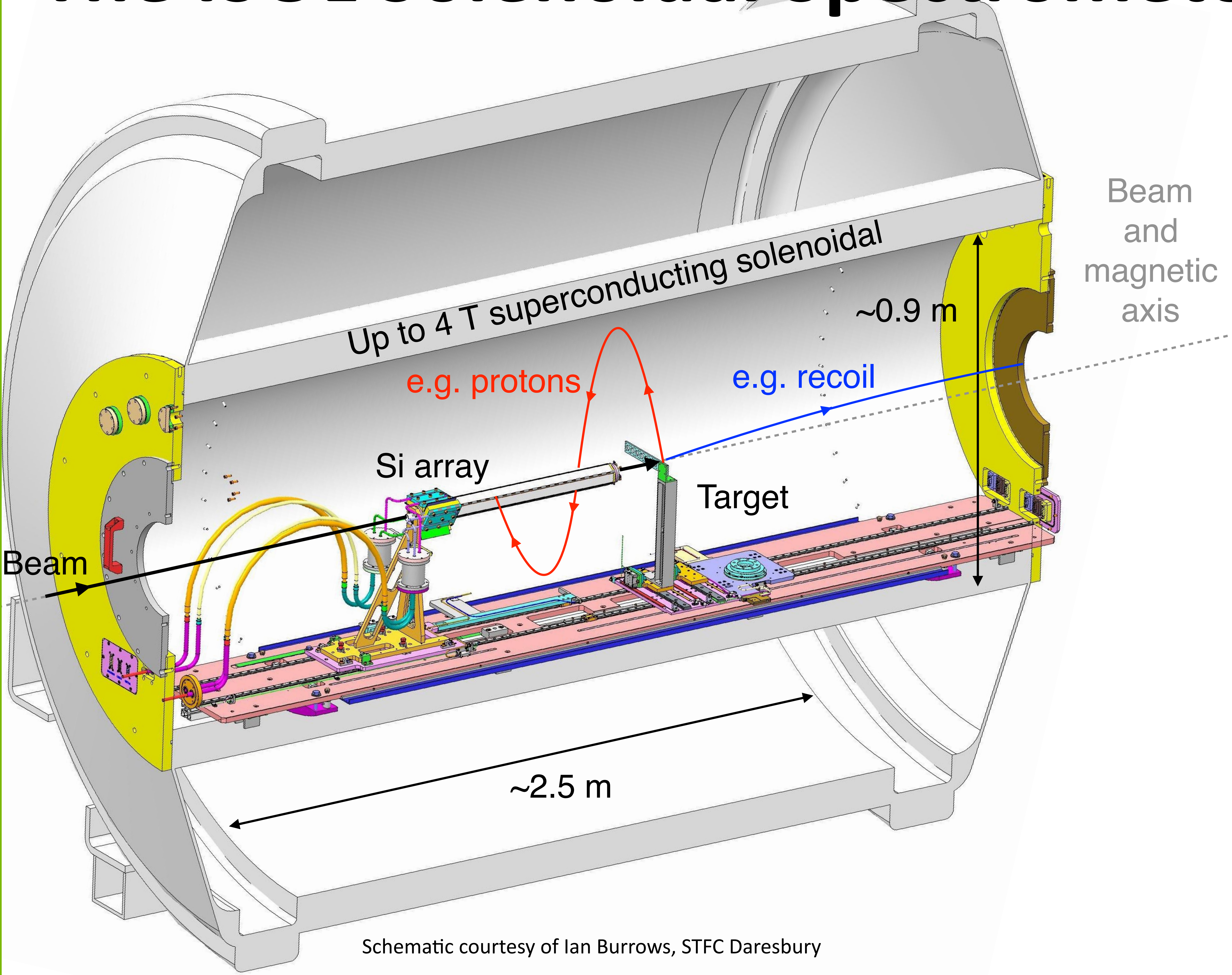




*Isomers prevalent in the region around Pb

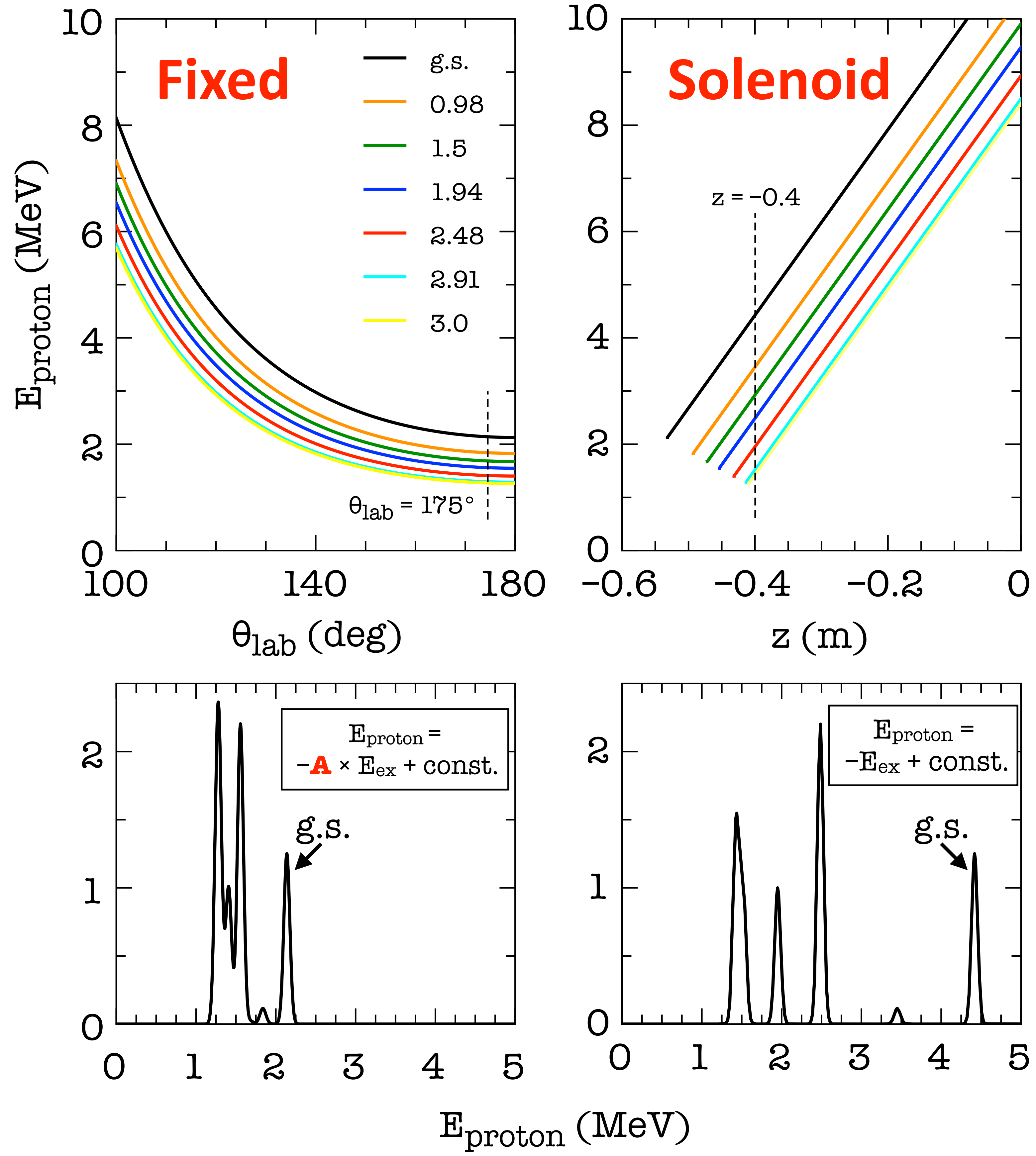
Cross sections estimated using DWBA code Ptolemy using standard parameterizations.

The ISOL Solenoidal Spectrometer (ISS)



Schematic courtesy of Ian Burrows, STFC Daresbury

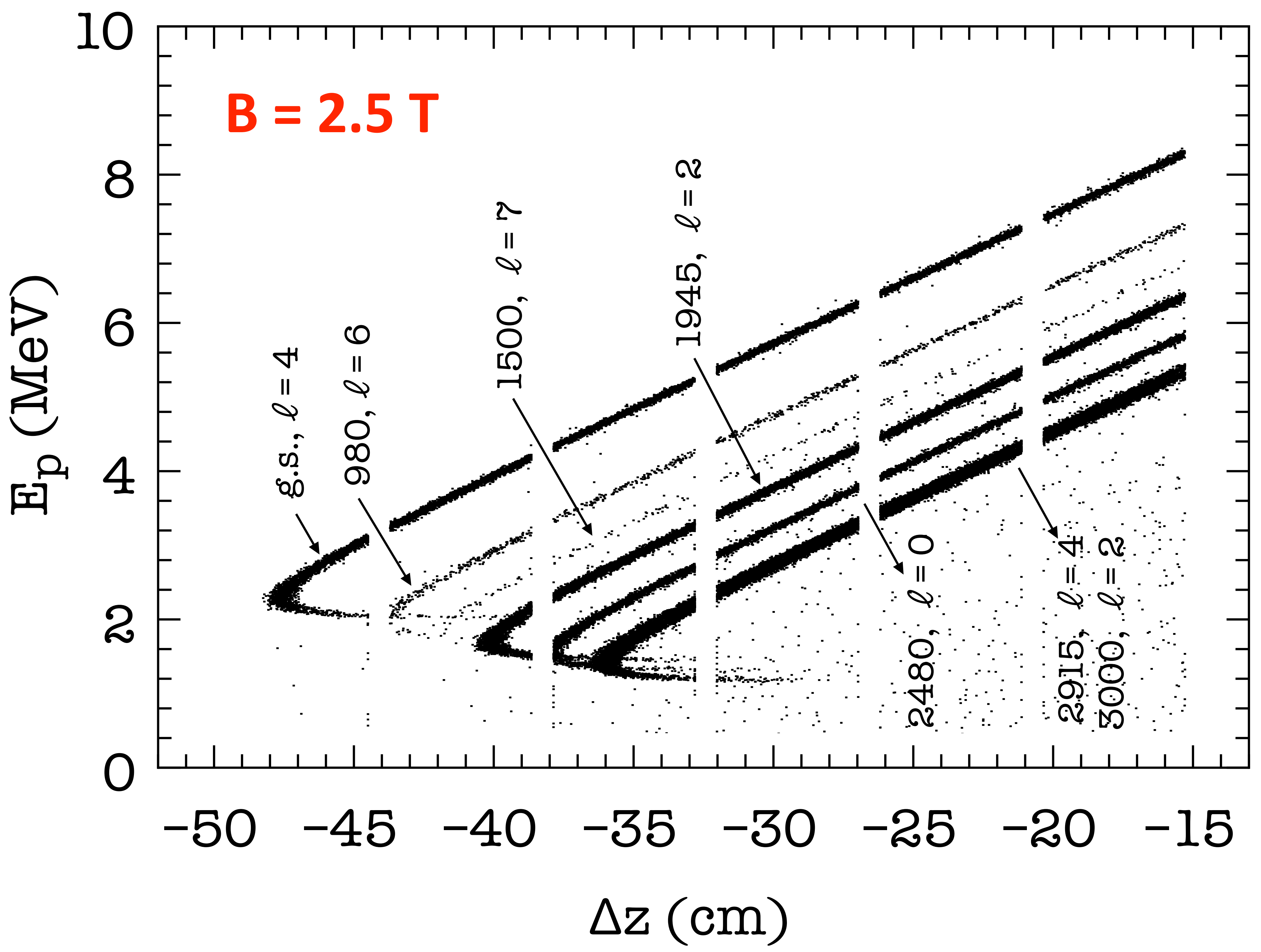
Kinematics: ^{206}Hg(d,p), 10 MeV/u

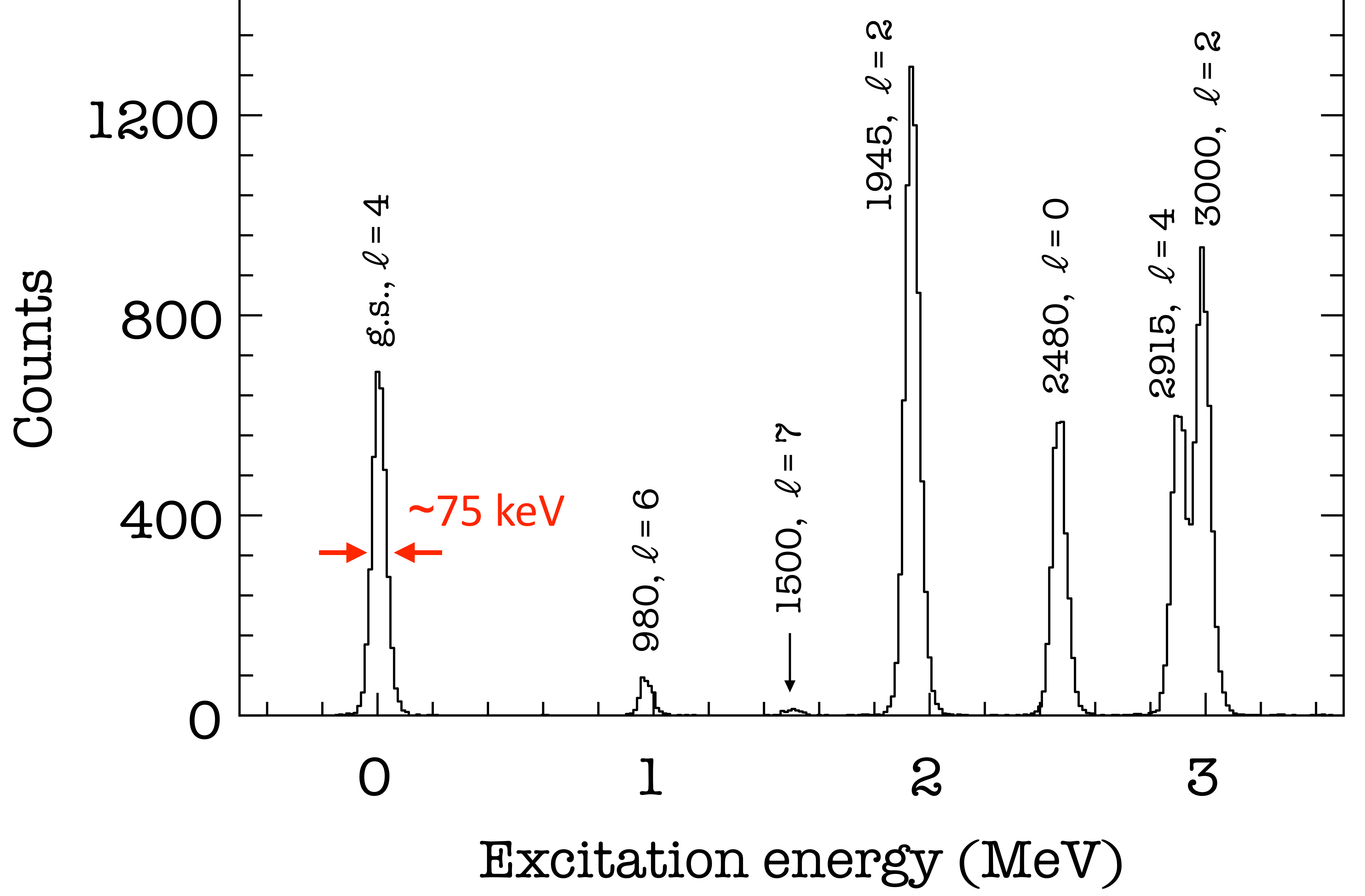


No kinematic compression (**A = 0.31**), only **modest** kinematic shift (~17 keV/mm) *cf.* other techniques.

For this measurement the Si array used in the comparable HELIOS spectrometer at Argonne National Laboratory will be used in place of the one shown in this schematic.

The solenoidal-spectrometer technique





Simulation:

Marc Labiche, STFC Daresbury, using NPTool, assuming 40-keV intrinsic Si resolution[1] and the geometry of the ANL array, beam properties of the linac[2]. Comparable to actual performance of the HELIOS spectrometer at ANL. Location of states states in ^{207}Hg estimated from Woods-Saxon calculations[3].

[1]Mean value for ANL Si array, J. C. Lighthall *et al*., Nucl. Instrum. Methods Phys. Res. A 622, **97** (2010).
[2]Beam spot: 2.3 mm FWHM, Beam divergence: 1.8 mrad, Beam energy spread: 0.26%
[3]http://www.volya.net

Argonne NATIONAL LABORATORY

Beam time request — 18 shifts

Assume:

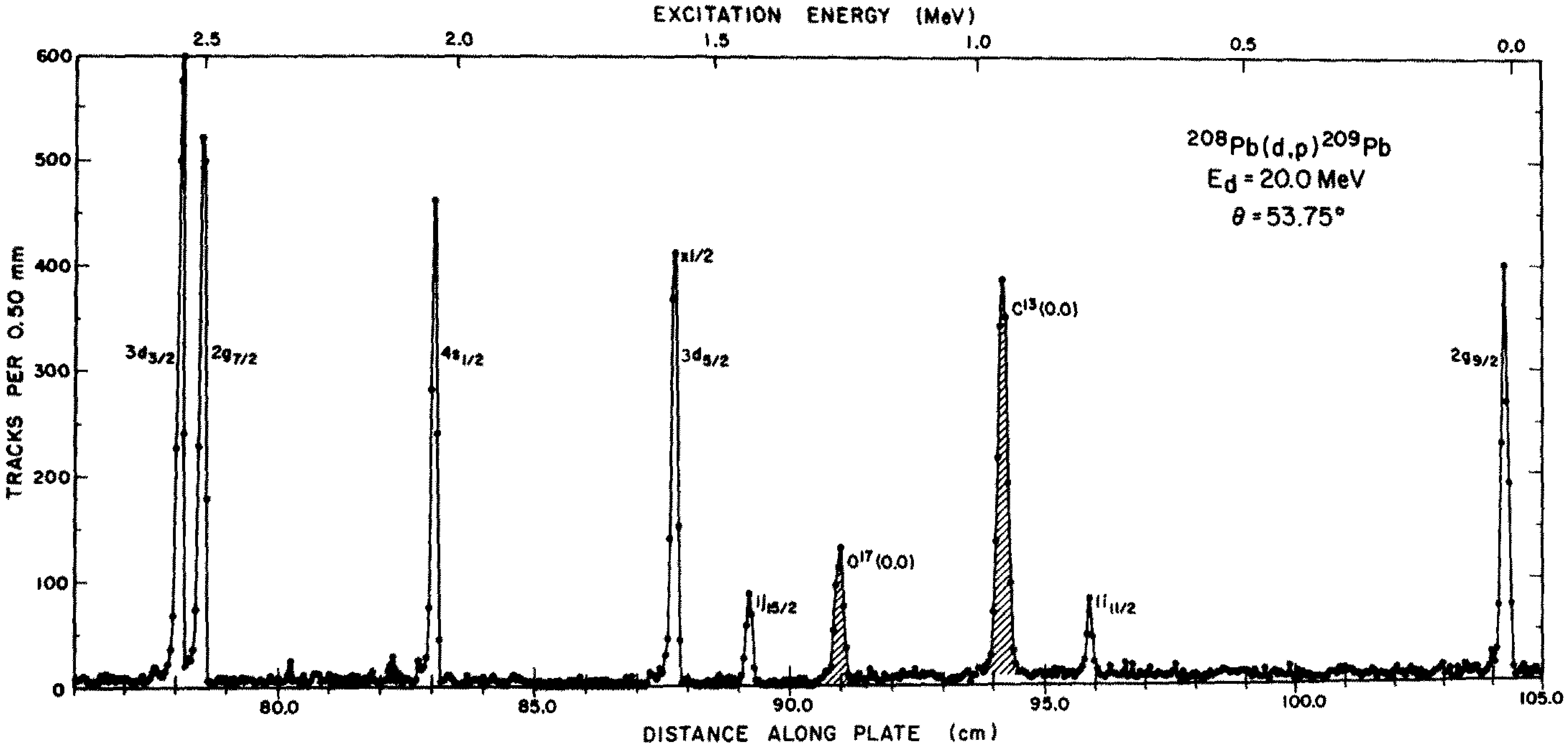
1×10^6 Hz of ^{206}Hg, **>99%** purity desired, **10 MeV/u** desired, **75 μg/cm^2** CD_2 target, cross sections from DWBA calculations using standard parameterizations, **40%** solid angle for Si array over angular range 10° ≲ θ_{cm} ≲ 30°.

5 days (**18 shifts**) of beam on target yields **3000**, **11300**, **8700**, **900**, and **150** counts in single-particle states populated in **ℓ = 0, 2, 4, 6, and 7** transfer.

1 additional day is requested for the optimization and calibration of the set up (1 shift), target changes (1 shift), and to record background events (1 shift).

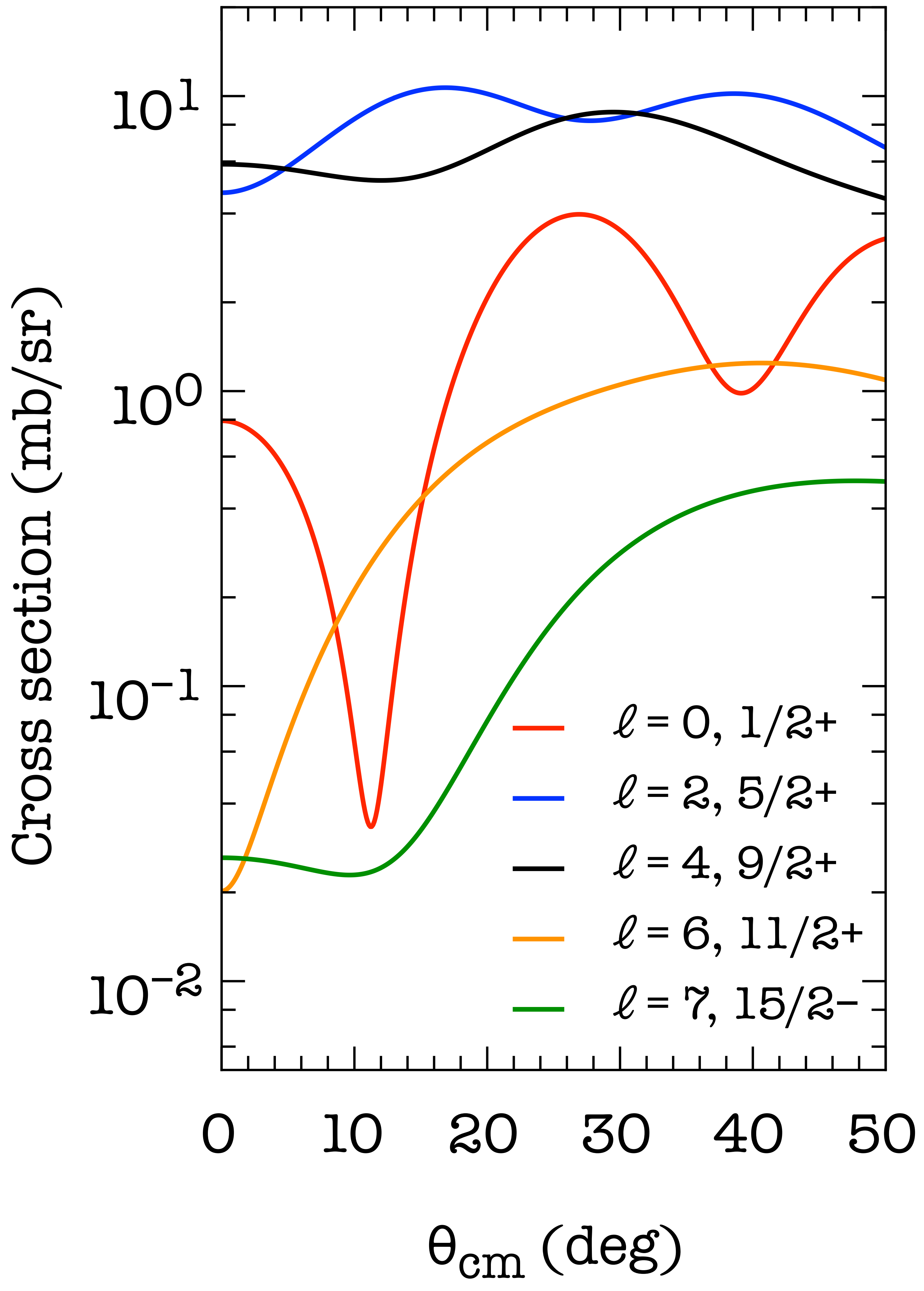
We hope to run ^{208}Pb(d,p) prior to this run (maybe some people would like to join?)

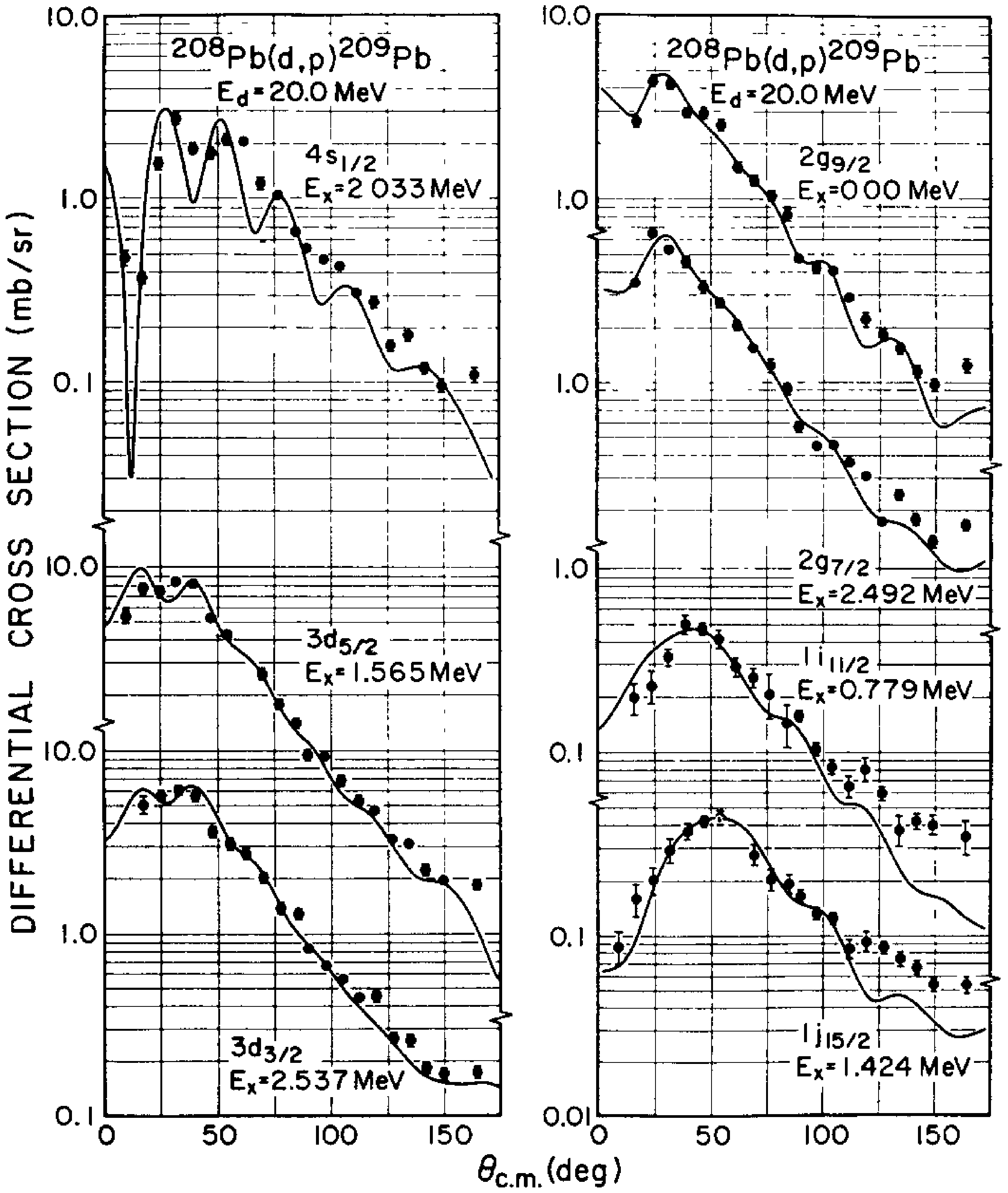
Benchmark with $^{208}Pb(d,p)$



Kovar *et al.*, Nucl. Phys. **A231**, 266 (1974): Yale tandem and Yale multigap spectrometer, 100 µg/cm2 foils, 10-15 keV resolution

Benchmark with $^{208}Pb(d,p)$





Kovar *et al.*, Nucl. Phys. **A231**, 266 (1974): DWBA agrees very well — reassuring.

Summary

- A study of the ^{206}Hg(*d*,*p*) reaction will be a flagship measurement—not possible at any other facility in the foreseeable future, particularly at this ideal energy for transfer.

- ***First ever exploration*** of single-particle structure of this region of the chart—terra incognita.

- Impact on nuclear structure — evolution of single-neutron states along *N*=126 — and on nuclear astrophysics, offering a first look at ***s-states below Pb*** on approach to the ***3rd r-process peak*** *(poorly understood in astrophysical models due to lack of data constraining them)*.

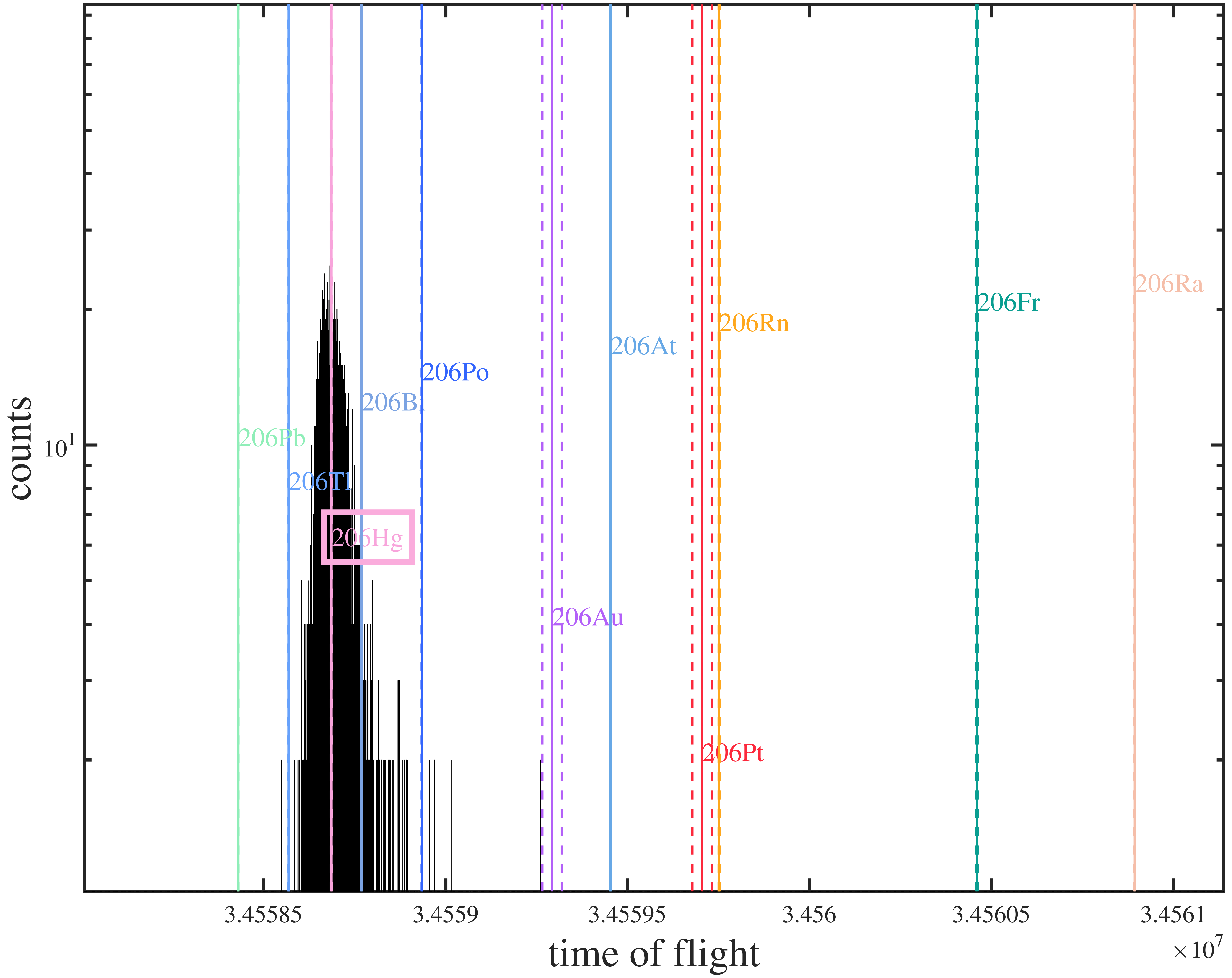
- Solenoidal spectrometer technique ***well proven***, removing many complications plaguing other techniques. Ideal for ***extracting reliable spectroscopic factors*** from the data.

- Collaboration with the Argonne group—use of Si array, etc.

Supplemental material — beam purity

Use of VADLIS source

No evidence of ^{206}Tl or ^{206}Pb in the time of flight spectrum

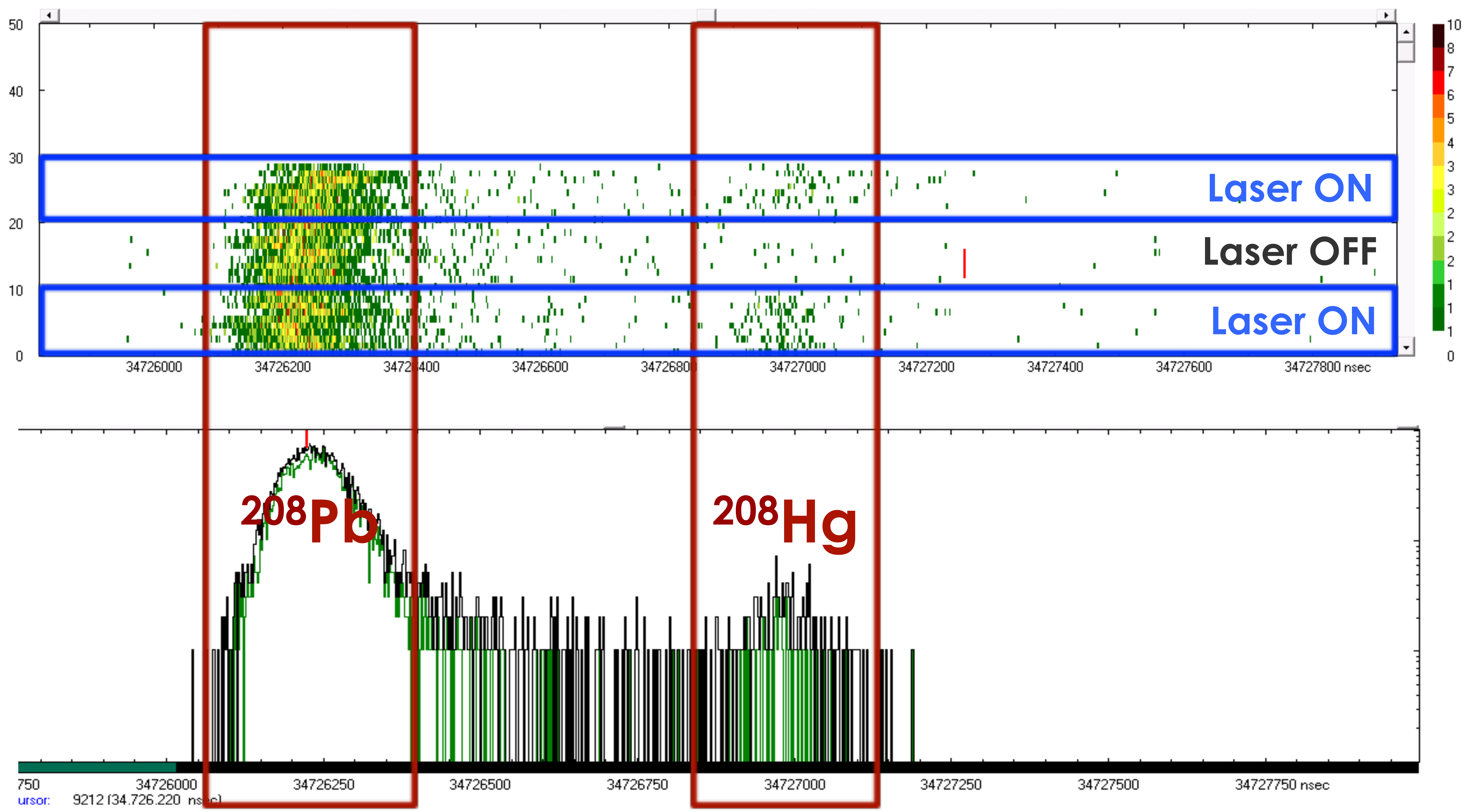


Private communication (Liam Gaffney, Frank Wienholtz), data from the IS598 experiment at MR-TOF.
T. Day Goodacre *et al.*, Nucl. Instrum. Methods Phys. Res. B **376**, 39 (2016).

Supplemental material — beam purity

Use of VADLIS source

From ^{208}Hg measurements, some small amount of Pb expected, though predicted to be about <600 ions/s cf. >10^6 ions/s of Hg.



Private communication (Liam Gaffney, Frank Wienholtz), data from the IS598 experiment at MR-TOF.
T. Day Goodacre *et al*., Nucl. Instrum. Methods Phys. Res. B **376**, 39 (2016).

Argonne NATIONAL LABORATORY

Supplemental material — time lines

Ordering of events prior to experimental campaign

2016:

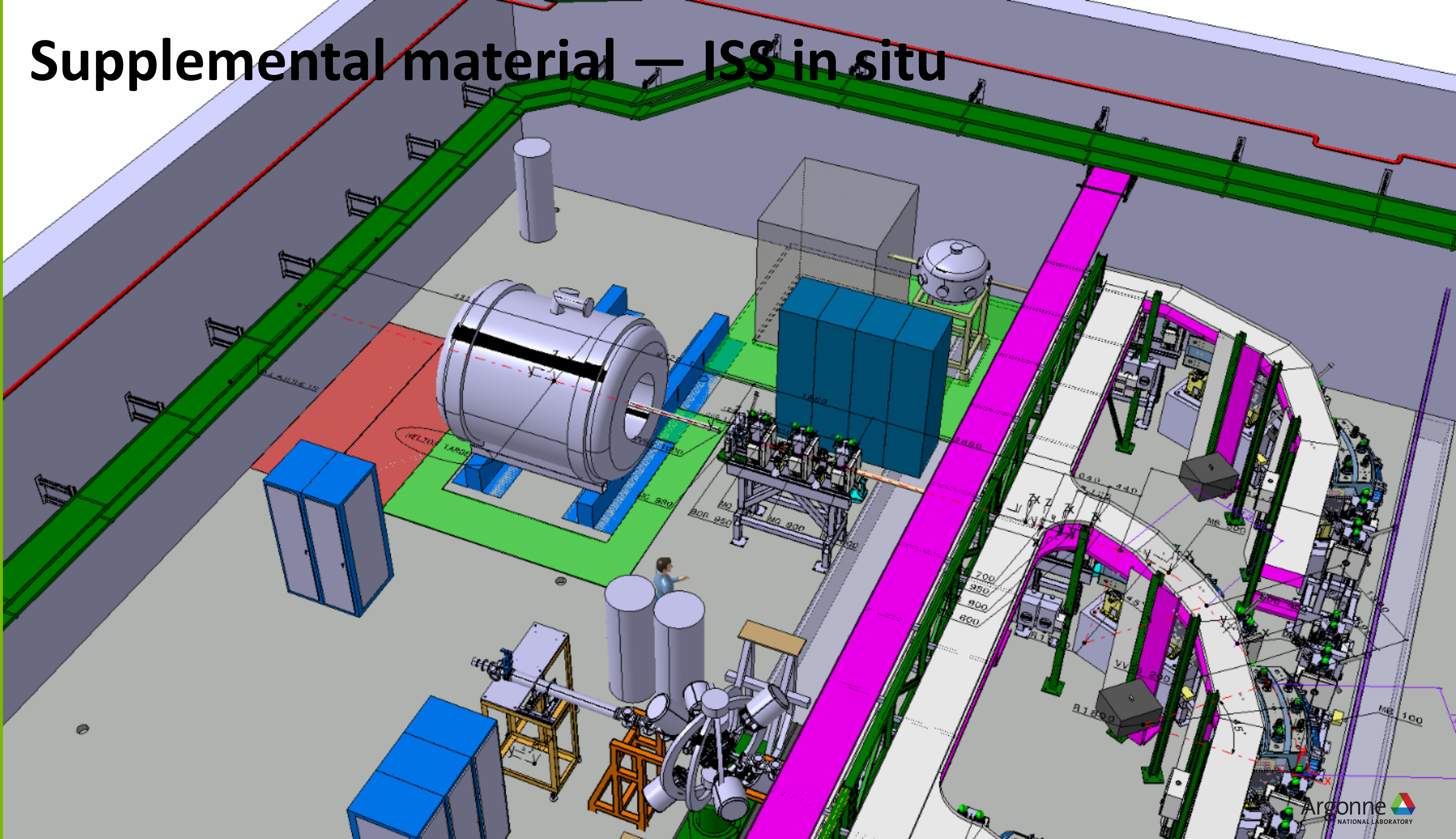
- ***Cool down*** the solenoid
- ***Energize*** and ***verify the field***

2017:

- ***Locate*** in ISOLDE hall
- ***Shield***
- Install various ***mechanical components***
- Install ***ANL Si array, electronics, DAQ***
- **Sources tests & take data with test beams for the beam line commissioning**

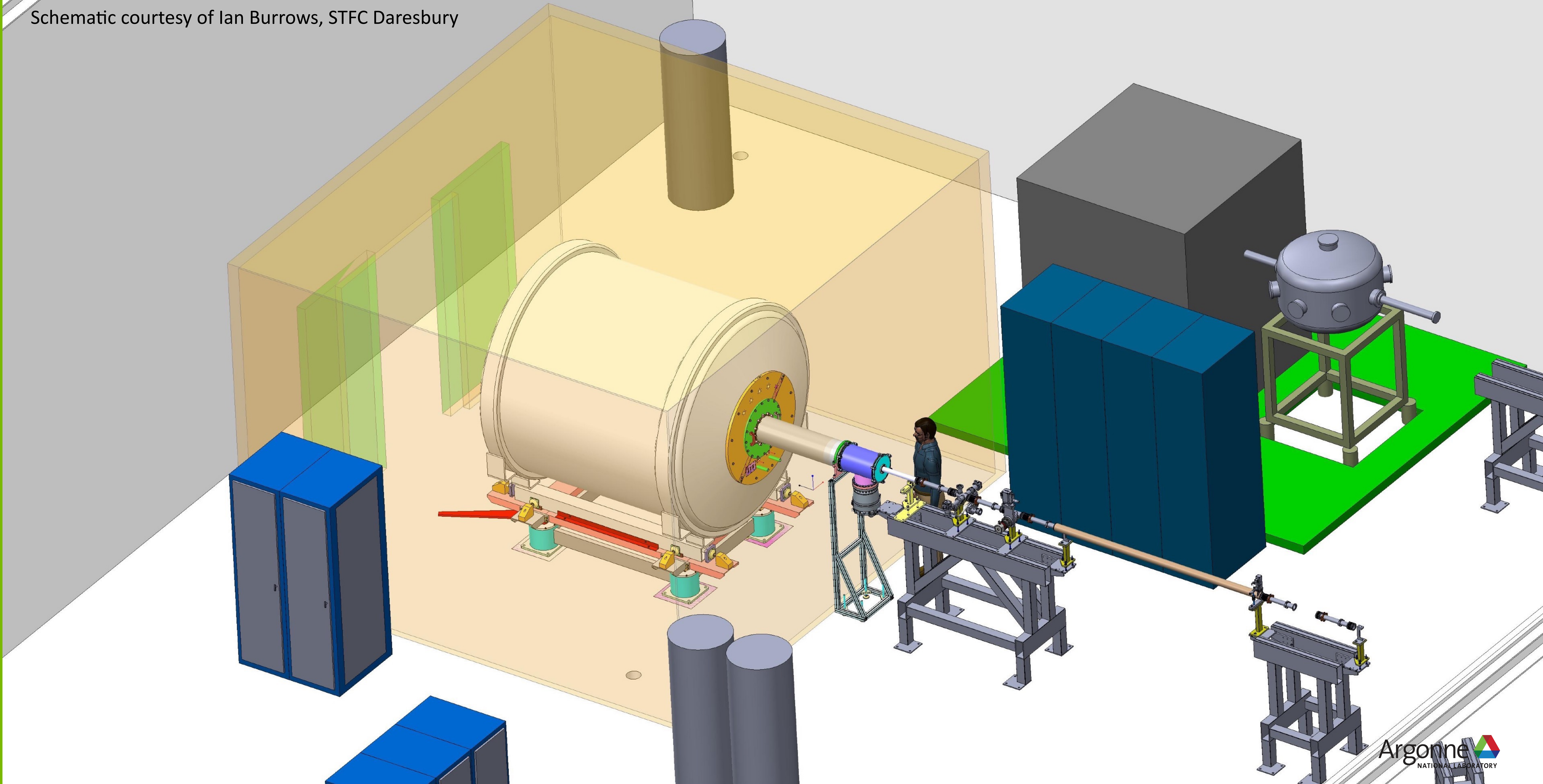
Further details given in Appendix common to proposals P-467 and P-470.

Supplemental material — ISS in situ

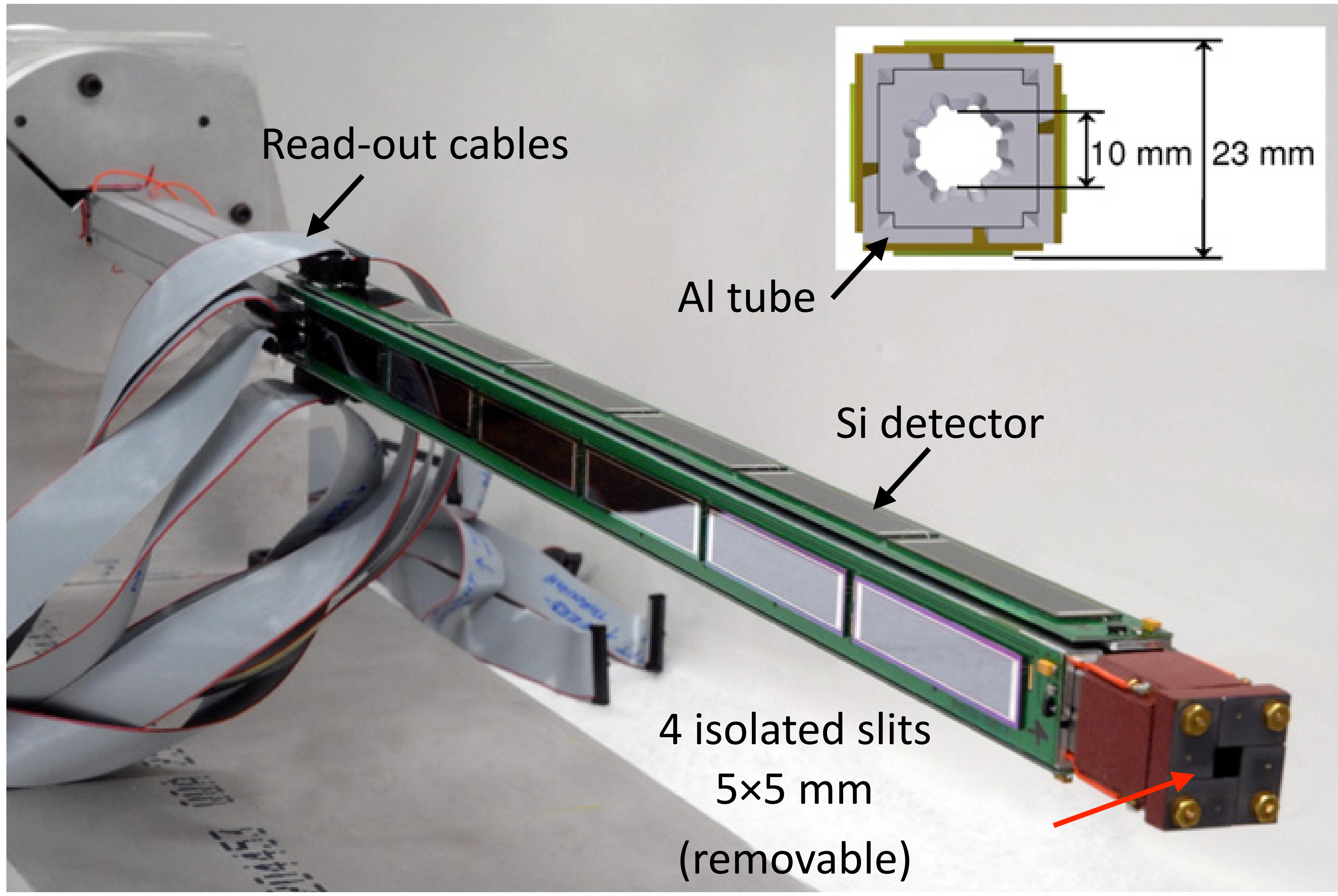


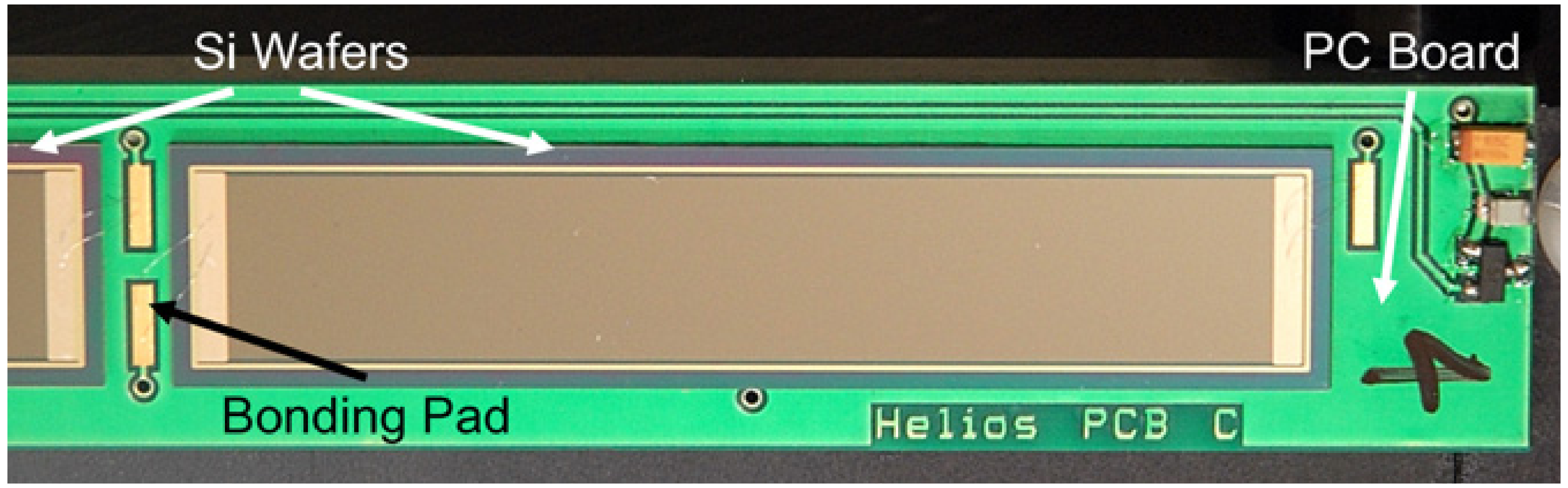
Supplemental material — ISS in situ

Schematic courtesy of Ian Burrows, STFC Daresbury

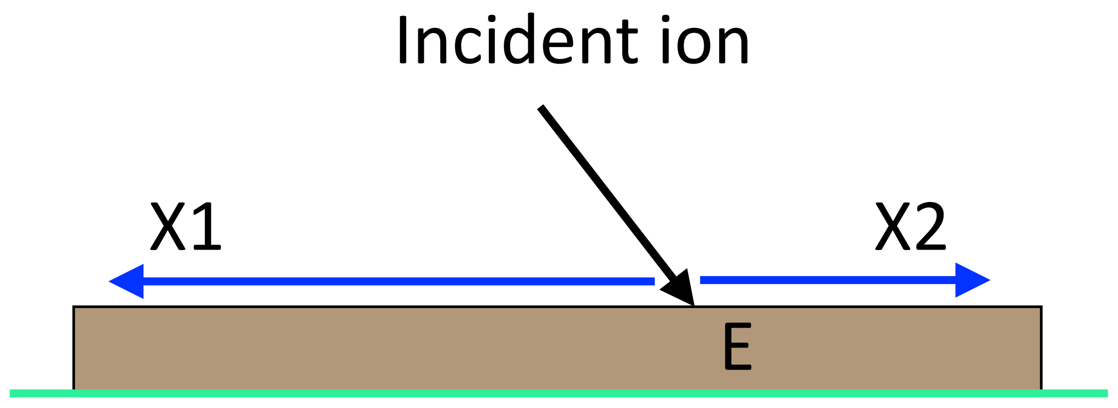


Supplemental material — ANL Si array





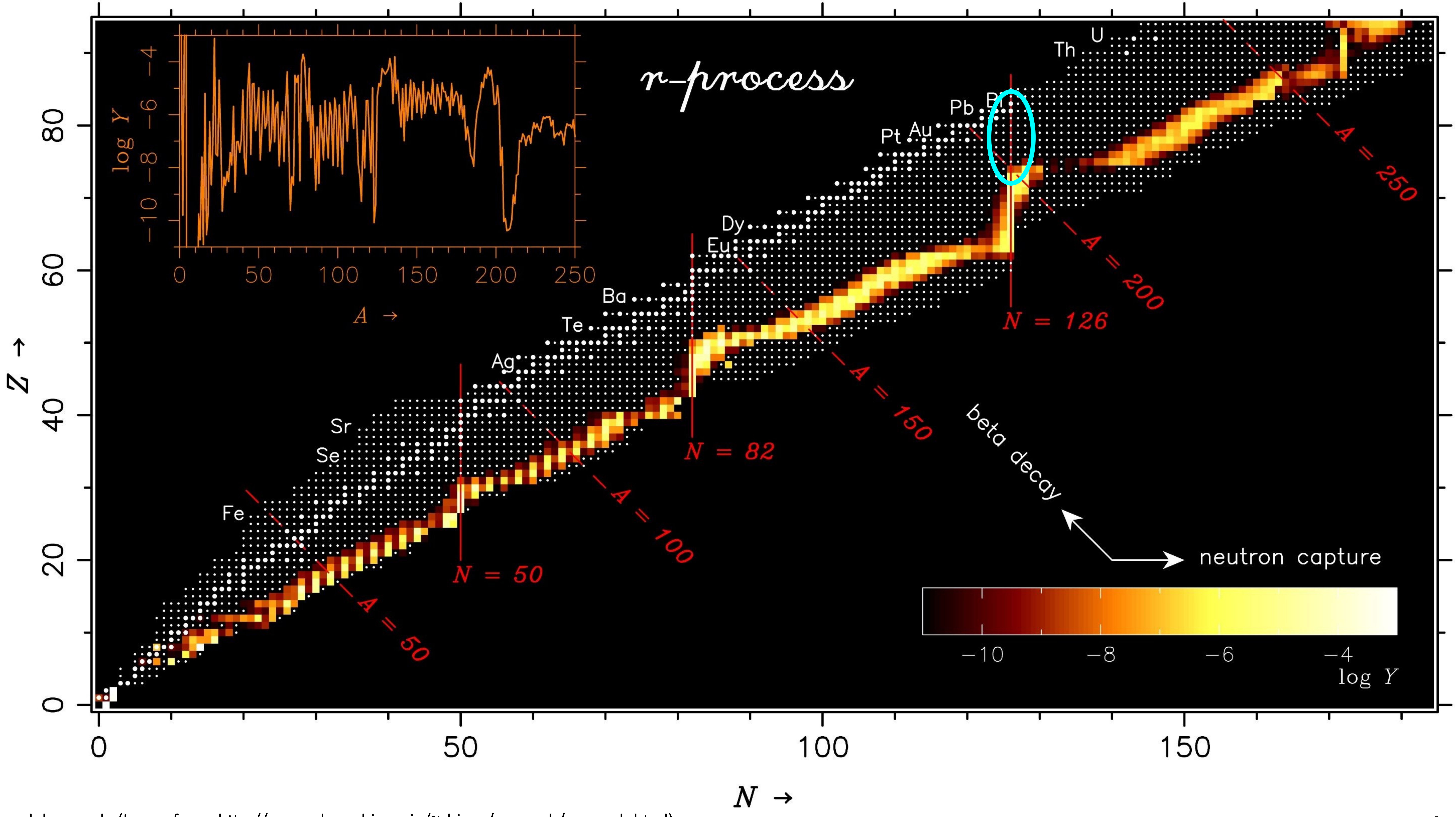
- 4 sides, 6 elements long
- Detector size, 9×50 mm
- 700-µm thick (e.g. ~10 MeV protons)
- Φ coverage, ***0.48 of 2π***
- $\Omega_{element}$ = ***~21 msr*** (depending on kinematics, field, etc)
- Ω_{array} = ***~500 msr***



Position ≈ (X1–X2)/E

(about ~0.5 mm)

Supplemental material — r-process path

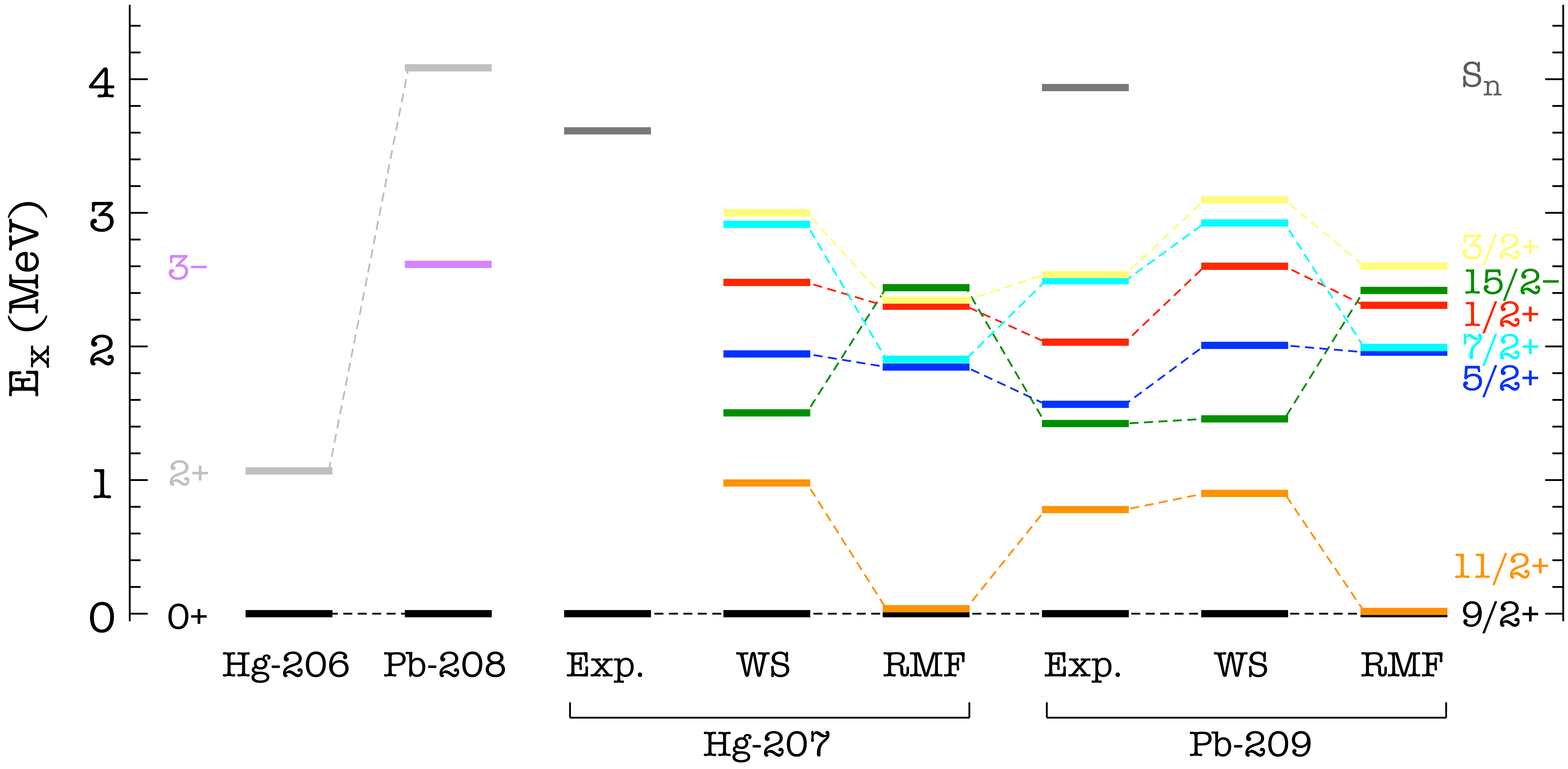


r-process model example (Image from: http://www.ph.sophia.ac.jp/~shinya/research/research.html)
From study described in S. Wanajo, S. Goriely, M. Samyn, and N. Itoh, ApJ 606, 1057 (2004)

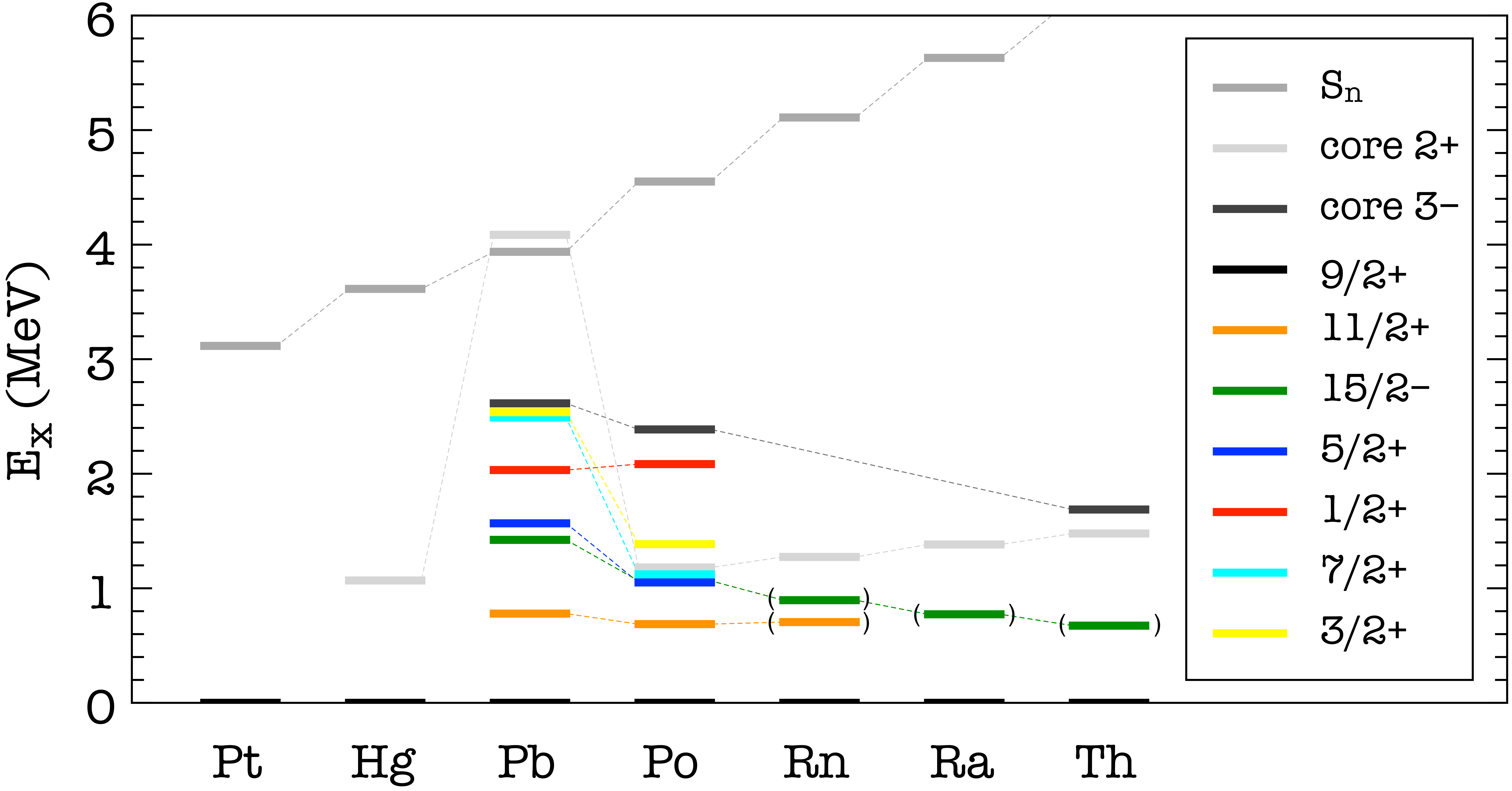
Supplemental material — ^{208}Pb (*d*,*p*) at 10 MeV/u

Supplemental material — ^{208}Pb (*d*,*p*) at 10 MeV/u

Supplemental material — level structure



Supplemental material — N = 127 isotones



Compilation of data from ENSDF, XUNDL, and AME12—no information on excited states in ^{207}Hg

Supplemental material — fragmentation

Fragmentation of the $s_{1/2}$ strength

Fragmentation of the neutron *s*-state strength would be valuable data for **estimations of neutron-capture cross sections**.

In ^{207}Pb, below N = 126, the *s*-state strength appears at relatively high excitation energy, around 4.5-5 MeV in ***at least 3 fragments***.

In ^{211}Po, one neutron outside 126, but above Z = 82, ***two strong fragments*** of the *s*-state strength are seen.

In ^{207}Hg, the $3s_{1/2}$ state could lie around 1.7 MeV in excitation energy (1.9 MeV below threshold like in ^{209}Pb), but could mix with the nearby core 2^+ (1.1 MeV) resulting in fragments lying closer to threshold.

A measurement of the (d,p) reaction on ^{206}Hg would provide a clear assessment of the fragmentation.