

The single-neutron excitation of ^{207}Hg

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Collaborators:

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|-------------------------------|------------------------------|-------------------------------------|-------------------------------------|-----------------------------------|--------------------------------------|-------------------------------|------------------------------------|-----------------------------------|-------------------------------------|----------------------------------|-------------------------------|------------------------------|-------------------------------|------------------------------|------------------------------|----------------------------|----------------------------|----------------------------|----------------------------|
| ²⁰⁶ At 30.6 m | ²⁰⁷ At 108.6 m | ²⁰⁸ At 97.8 m | ²⁰⁹ At 5.42 h | ²¹⁰ At 8.1 h | ²¹¹ At 7.214 h | ²¹² At 314 ms | ²¹³ At 125 ns | ²¹⁴ At 558 ns | ²¹⁵ At 100 μ s | ²¹⁶ At 300 μ s | ²¹⁷ At 32.62 ms | ²¹⁸ At 1.5 s | ²¹⁹ At 56 s | ²²⁰ At 222.5 s | ²²¹ At 138 s | ²²² At 54 s | ²²³ At 50 s | ²²⁴ At 150 s | |
| ²⁰⁵ Po 104.4 m | ²⁰⁶ Po 8.8 d | ²⁰⁷ Po 5.8 h | ²⁰⁸ Po 2.898 γ | ²⁰⁹ Po 124 γ | ²¹⁰ Po 138.376 d | ²¹¹ Po 516 ms | ²¹² Po 294.7 ns | ²¹³ Po 3708 μ s | ²¹⁴ Po 183.72 μ s | ²¹⁵ Po 1.781 ms | ²¹⁶ Po 145 ms | ²¹⁷ Po 1.514 s | ²¹⁸ Po 185.88 s | ²¹⁹ Po 10.3 m | ²²⁰ Po 221.5 s | ²²¹ Po 132 s | ²²² Po 9.1 m | | |
| ²⁰⁴ Bi 11.22 h | ²⁰⁵ Bi 15.31 d | ²⁰⁶ Bi 6.243 d | ²⁰⁷ Bi 31.2 γ | ²⁰⁸ Bi 368 ky | ²⁰⁹ Bi 20.1 E γ | ²¹⁰ Bi 5.012 d | ²¹¹ Bi 128.4 s | ²¹² Bi 60.55 m | ²¹³ Bi 45.61 m | ²¹⁴ Bi 19.9 m | ²¹⁵ Bi 1.33 s | ²¹⁶ Bi 98.5 s | ²¹⁷ Bi 33 s | ²¹⁸ Bi 8.7 s | ²¹⁹ Bi 2.19 s | ²²⁰ Bi 9.5 s | | | |
| ²⁰³ Pb 51.916 h | ²⁰⁴ Pb | ²⁰⁵ Pb 17.3 My | ²⁰⁶ Pb | ²⁰⁷ Pb | ²⁰⁸ Pb | ²⁰⁹ Pb 194.04 m | ²¹⁰ Pb 22.2 γ | ²¹¹ Pb 36.164 m | ²¹² Pb 10.6 m | ²¹³ Pb 1.06 s | ²¹⁴ Pb 15 s | ²¹⁵ Pb 1.5 s | ²¹⁶ Pb 1.5 s | ²¹⁷ Pb 1.5 s | ²¹⁸ Pb 1.5 s | ²¹⁹ Pb 1.5 s | ²²⁰ Pb 1.5 s | | |
| ²⁰² Tl 12.31 d | ²⁰³ Tl | ²⁰⁴ Tl 3.783 γ | ²⁰⁵ Tl | ²⁰⁶ Tl 4.202 m | ²⁰⁷ Tl 4.77 m | ²⁰⁸ Tl 183.18 s | ²⁰⁹ Tl 129.72 s | ²¹⁰ Tl 78 s | ²¹¹ Tl 78 s | ²¹² Tl 78 s | ²¹³ Tl 78 s | ²¹⁴ Tl 78 s | ²¹⁵ Tl 78 s | ²¹⁶ Tl 78 s | ²¹⁷ Tl 78 s | ²¹⁸ Tl 78 s | ²¹⁹ Tl 78 s | ²²⁰ Tl 78 s | |
| ²⁰¹ Hg | ²⁰² Hg | ²⁰³ Hg 46.613 d | ²⁰⁴ Hg | ²⁰⁵ Hg 5.14 m | ²⁰⁶ Hg 8.32 m | ²⁰⁷ Hg 174 s | ²⁰⁸ Hg 42 m | ²⁰⁹ Hg 38 s | ²¹⁰ Hg 32 s | ²¹¹ Hg 28 s | ²¹² Hg 24 s | ²¹³ Hg 20 s | ²¹⁴ Hg 16 s | ²¹⁵ Hg 12 s | ²¹⁶ Hg 8 s | ²¹⁷ Hg 5 s | ²¹⁸ Hg 3 s | ²¹⁹ Hg 2 s | ²²⁰ Hg 1.5 s |
| ²⁰⁰ Au -30 | ²⁰¹ Au -14.55 | ²⁰² Au 0.9 | ²⁰³ Au 16.35 | ²⁰⁴ Au 31.8 | ²⁰⁵ Au 32.5 s | ²⁰⁶ Au 47 s | ²⁰⁷ Pt 10.3 s | | | | | | | | | | | | |
| ¹⁹⁸ Ir 8 s | ¹⁹⁹ Ir 7 s | ²⁰⁰ Ir 43 s | ²⁰¹ Ir 21 s | ²⁰² Ir 11 s | | | | | | | | | | | | | | | |

Log of Half-life [s]

- 30 -14.55 0.9 16.35 31.8
- Stable ■ Unknown

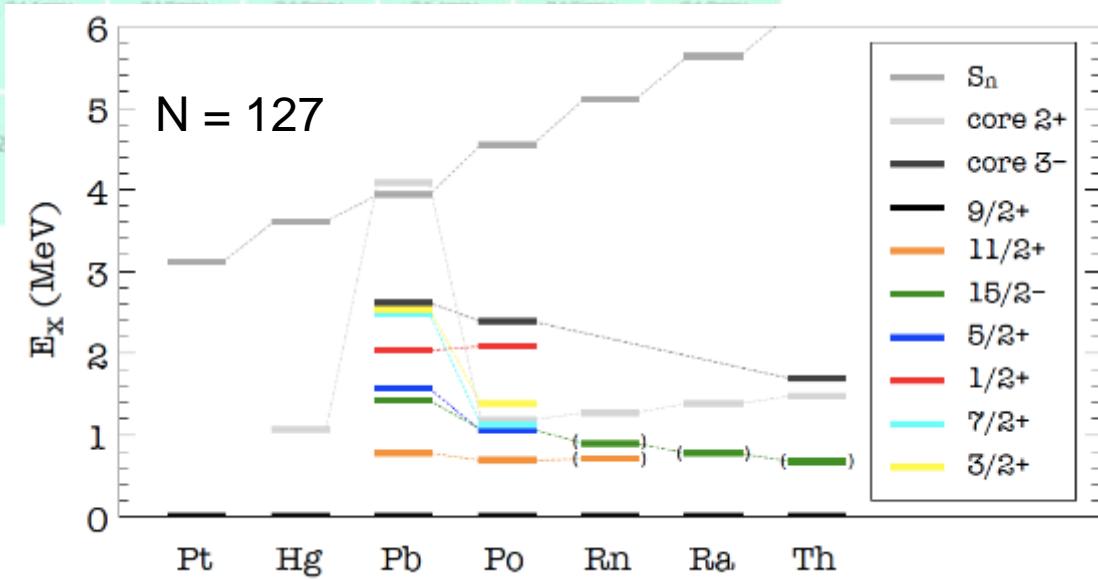
1st step!

- ²⁰⁸Pb is a cornerstone to our understanding of the single-particle structure of heavy nuclei.

- Evolution of shell-structure along N=127

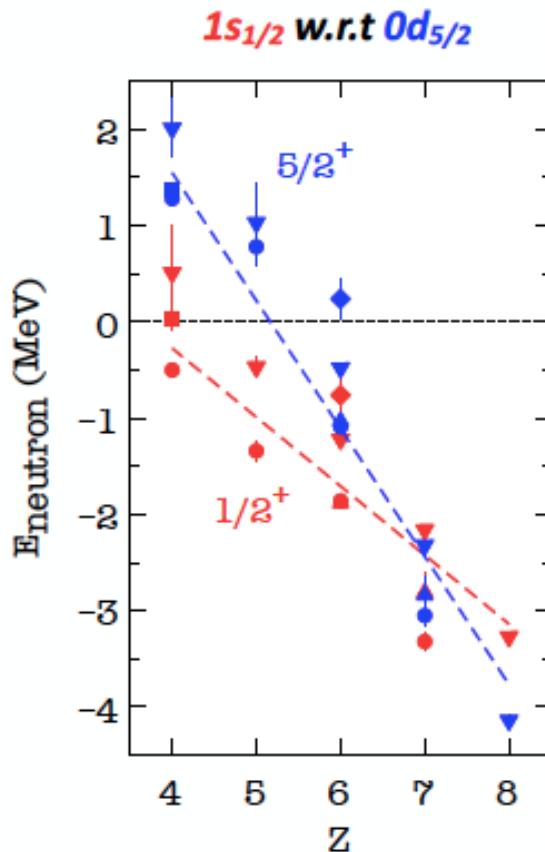
- Toward r-process for heavy elements
 - S-orbital energy level

- Few/no theoretical and NO experimental study
 - No single particle structure is known

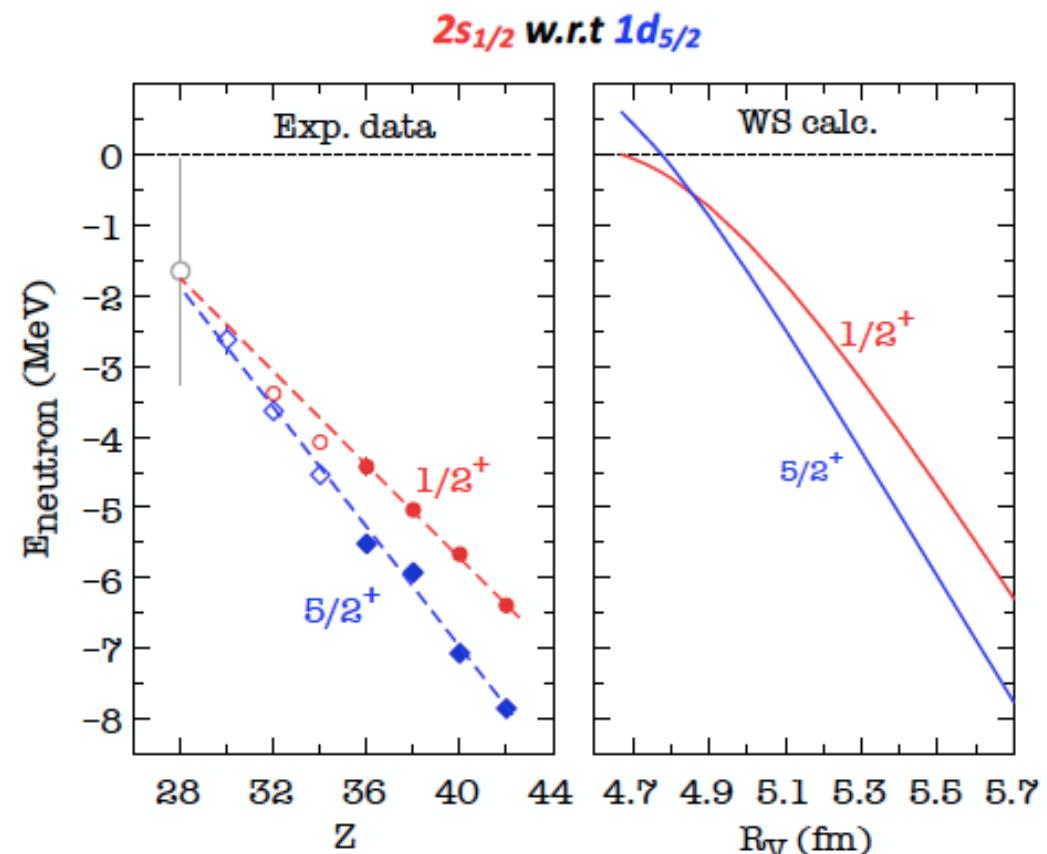


Weak binding and nuclear structure

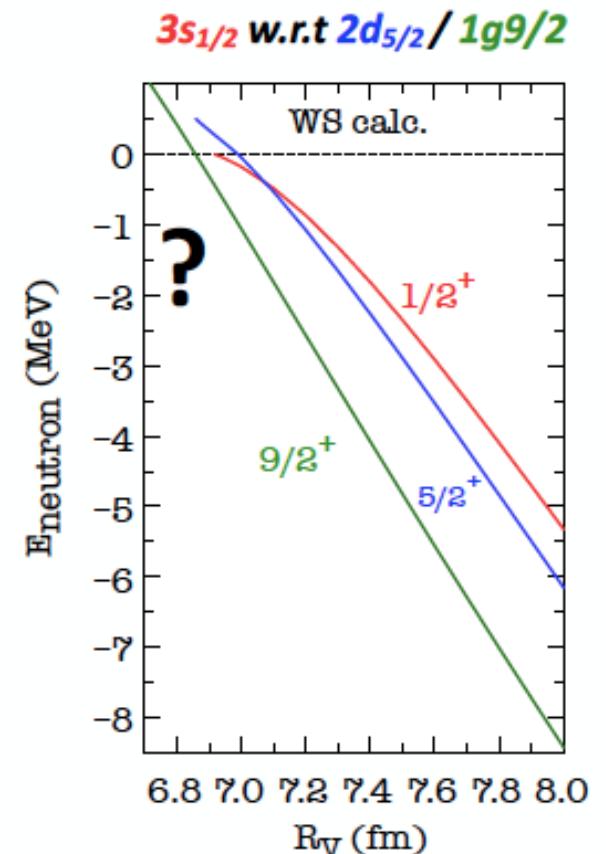
$A \sim 7 - 15$



$A \sim 90$



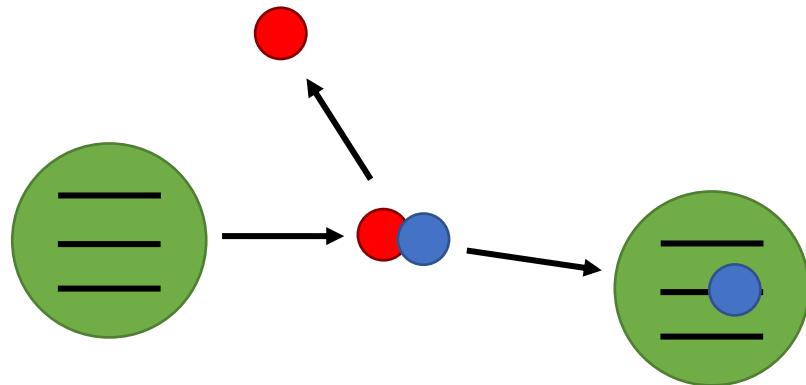
$A \sim 200$



C. R. Hoffman et al., PRC89(2014)061305

^{207}Hg is a more weak bound system than ^{209}Pb

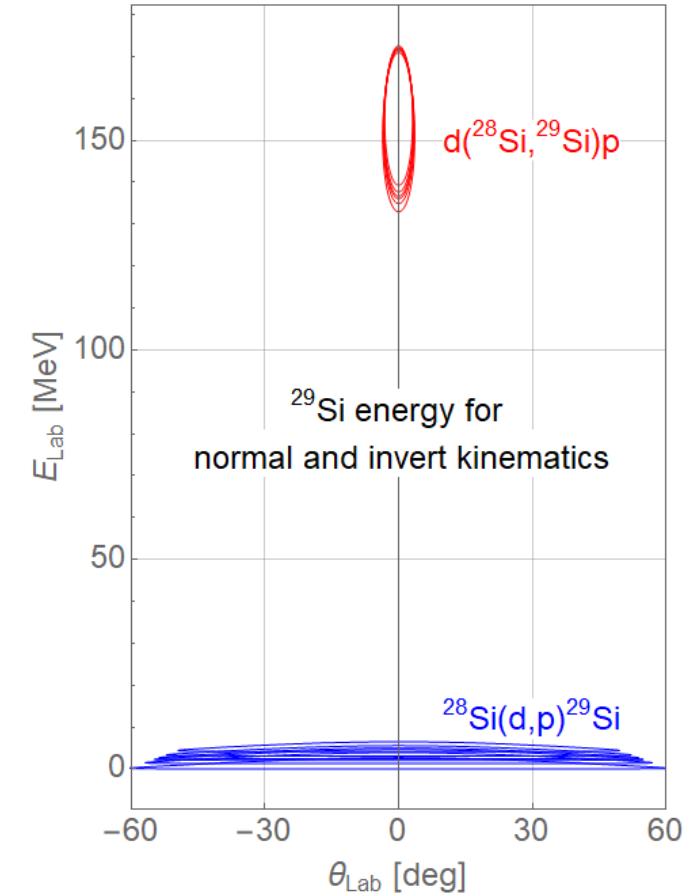
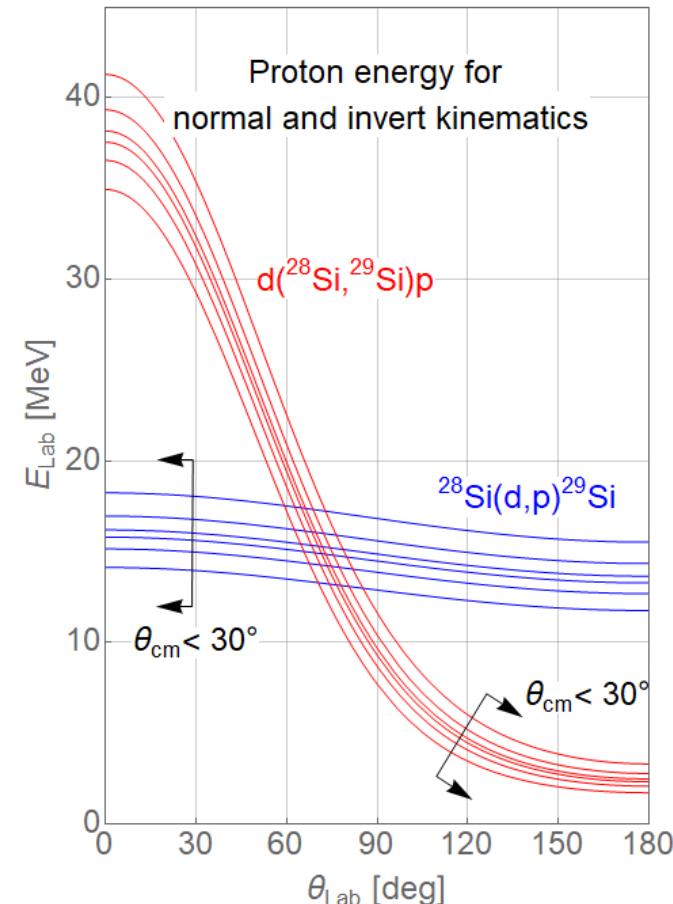
Using the (d,p) neutron transfer reaction in inverse kinematics



Only way to probe exotic nuclei

Features of inverse kinematics:

- Detection of the residual nucleus
- Smaller KE for the light particle
- Larger spread of θ_{Lab} for $\theta_{cm} \in (0^\circ, \sim 30^\circ)$



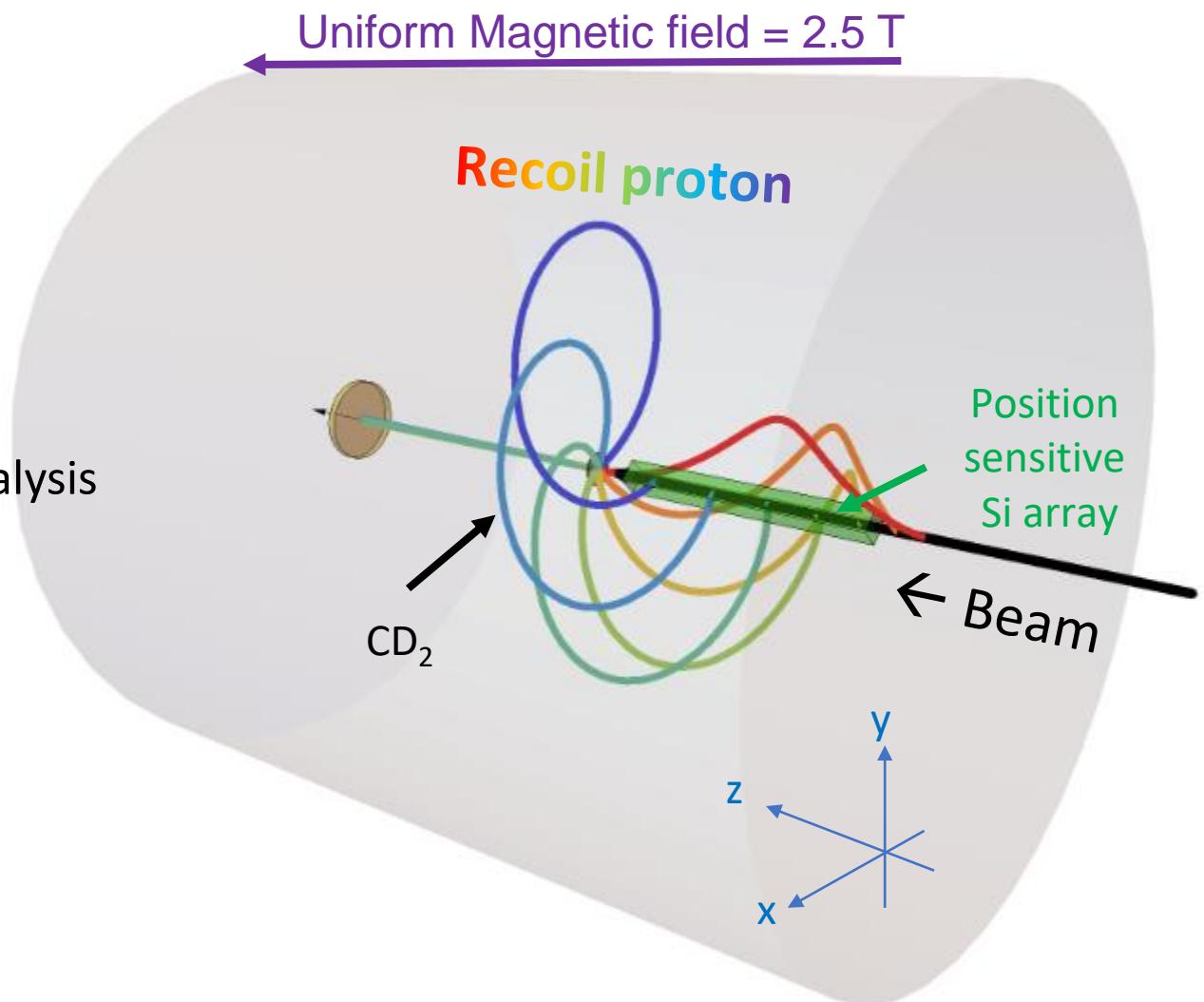


The HELIOS concept

1. Q-value resolution **~ 100 keV FWHM for (d,p)**
2. Large acceptance
3. Good angular resolution
4. Identification of residual nuclei
5. Background free spectrum for (d,p)
6. Simple analysis
 - hard to make mistake, and consistency of analysis

$$E_p = \frac{1}{\gamma} E_{cm}(E_x) + \frac{cQB}{2\pi} \beta z$$

ISS is an excellent spectrometer for (d,p) reaction.
It can be extended to (d,t) (d,³He)



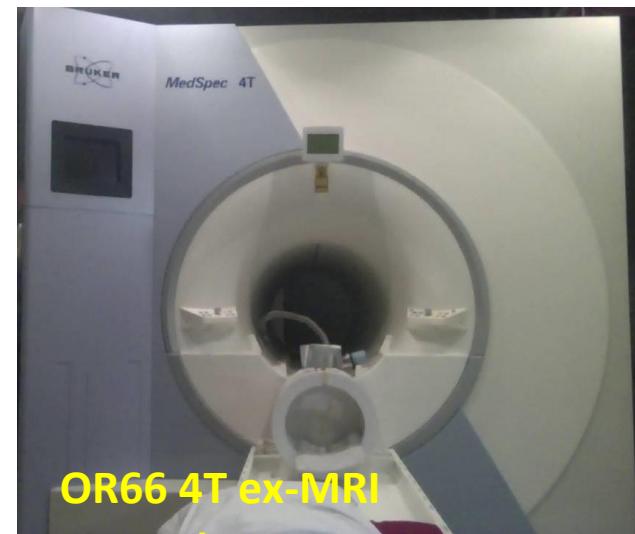
The birth of the ISOLDE Solenoidal Spectrometer



lead by R. Page from the University of Liverpool

- Vacuum testing
- Cooling
- Field-up test
- Stray-Field shielding

Magnet in Wesley Hospital, Brisbane, September 2015

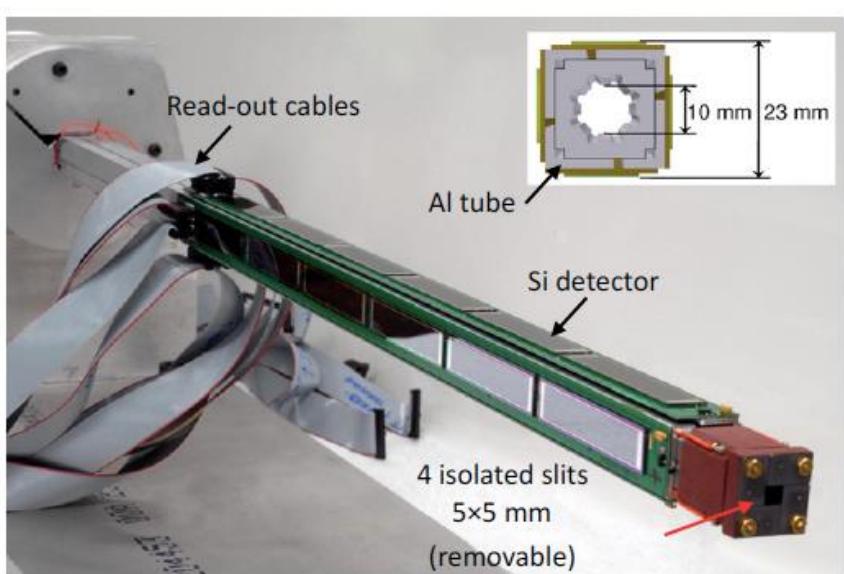


Commissioning of the ISS @ Sept, 2018

$^{28}\text{Mg}(d,p)$ – Next talk by Patrick MacGregor

$^{206}\text{Hg}(d,p)$ – This talk!

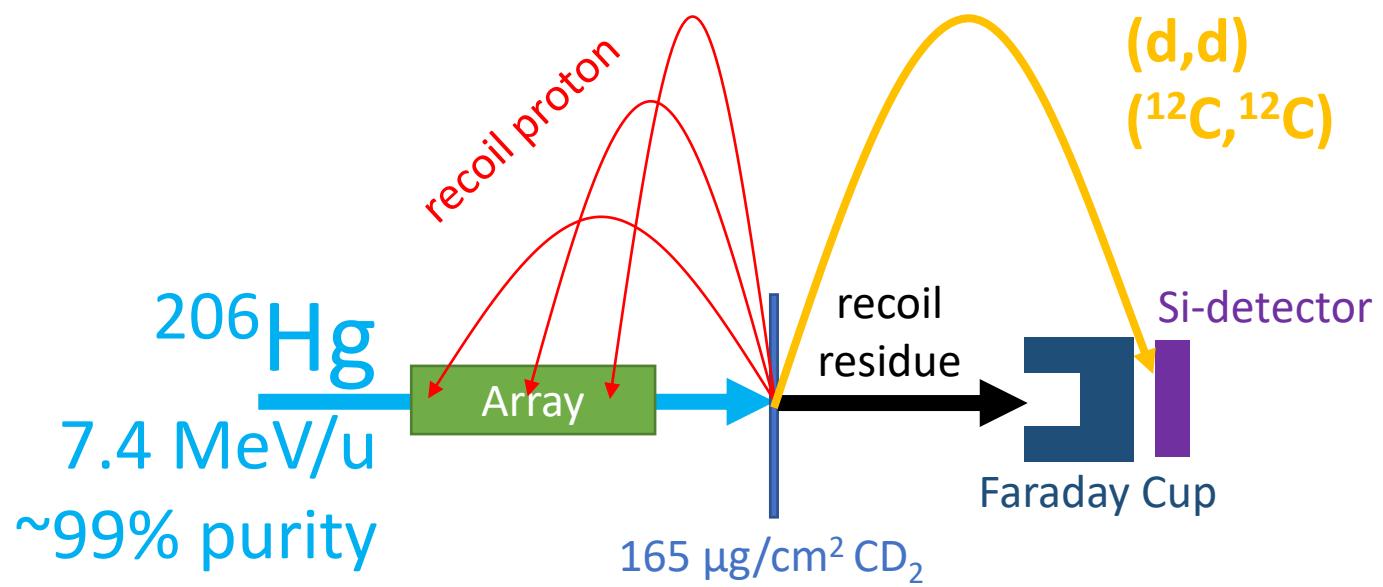
Berkeley designed
Digitizer



Array and the DAQ system are From ANL.



The Experimental Setup

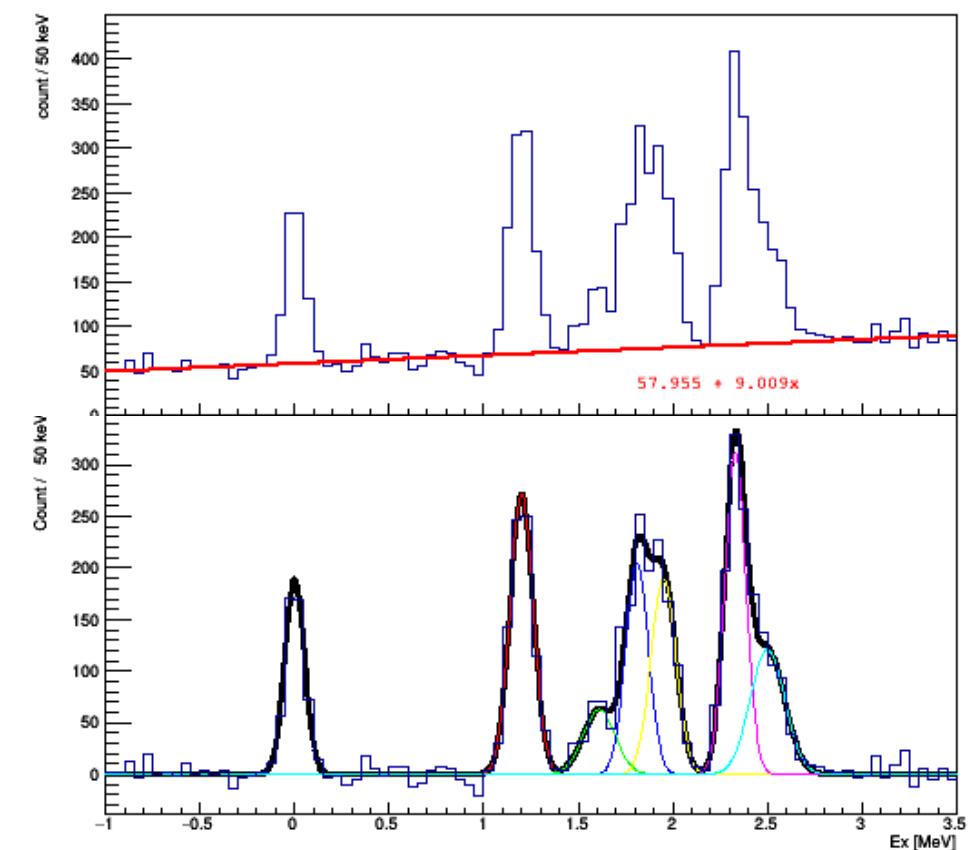
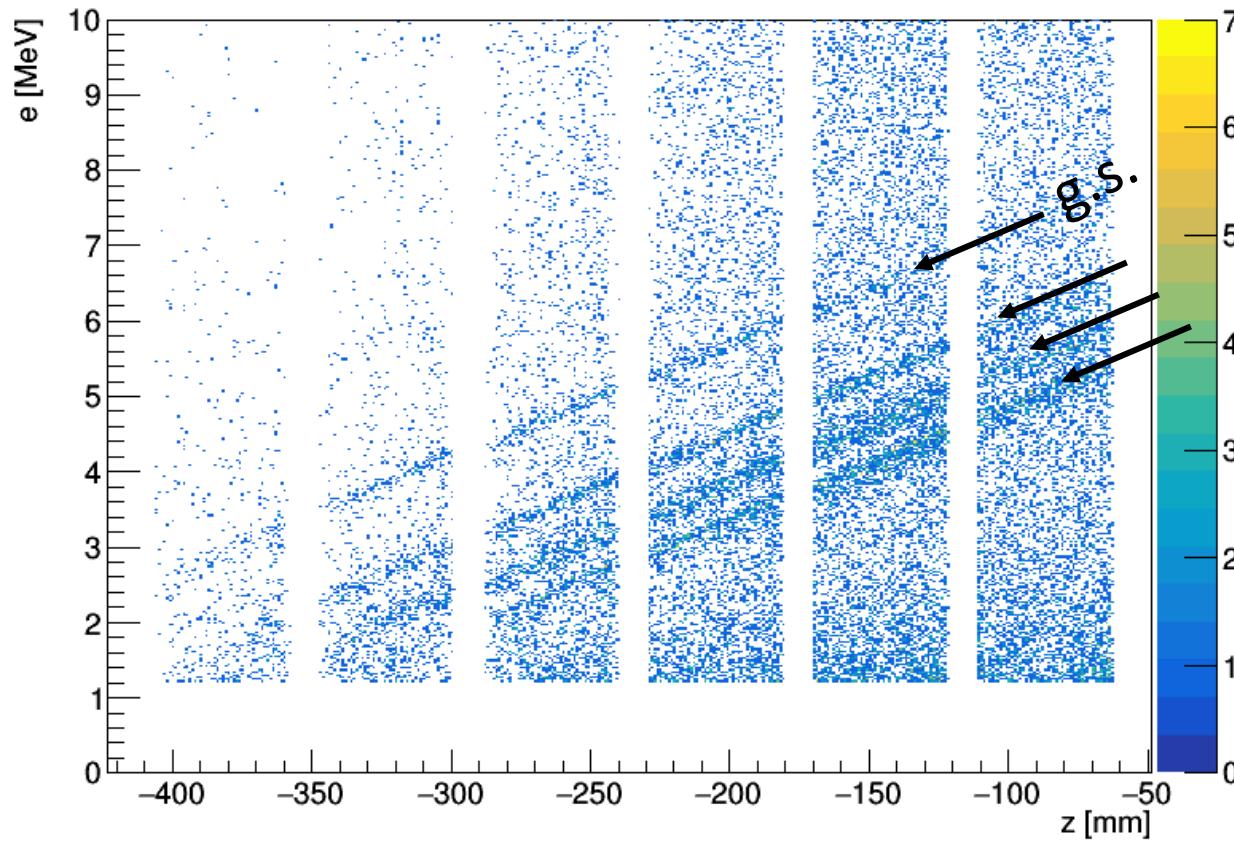


heavy beam is used,
radiation damage is large
→ target degradation,
→ A dedicated **8 × 8** type-writer target
ladder is used.

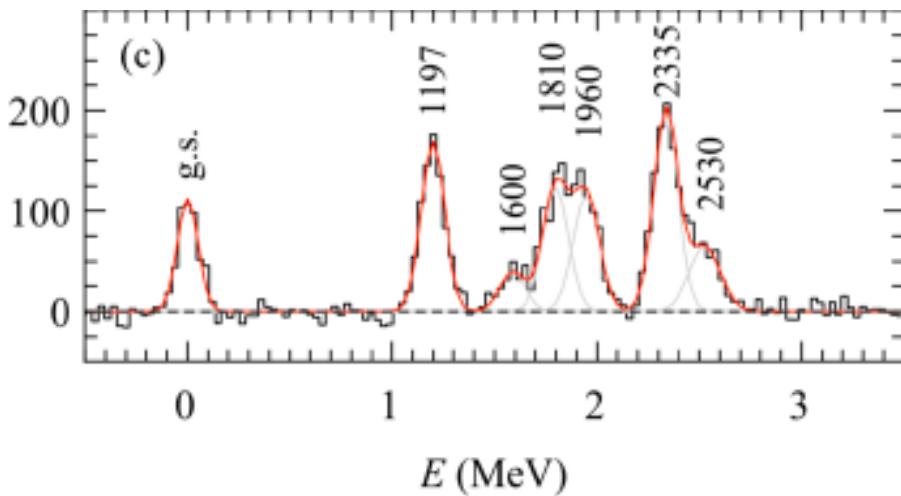
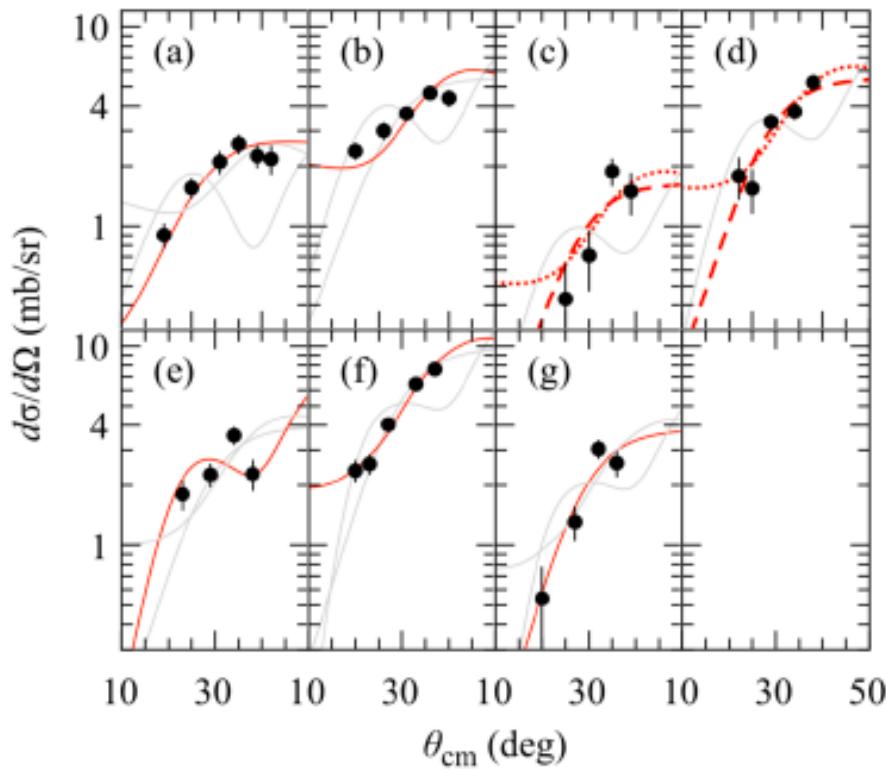


$$E_p = \frac{1}{\gamma} E_{cm}(E_x) + \frac{cB}{2\pi} \beta z$$

$$z = \frac{2\pi}{cB} (\gamma \beta E_{cm}(E_x) + \gamma \beta p \cos \theta_{cm})$$



Resol. = 55 keV (σ) = 130 keV (FWHM)



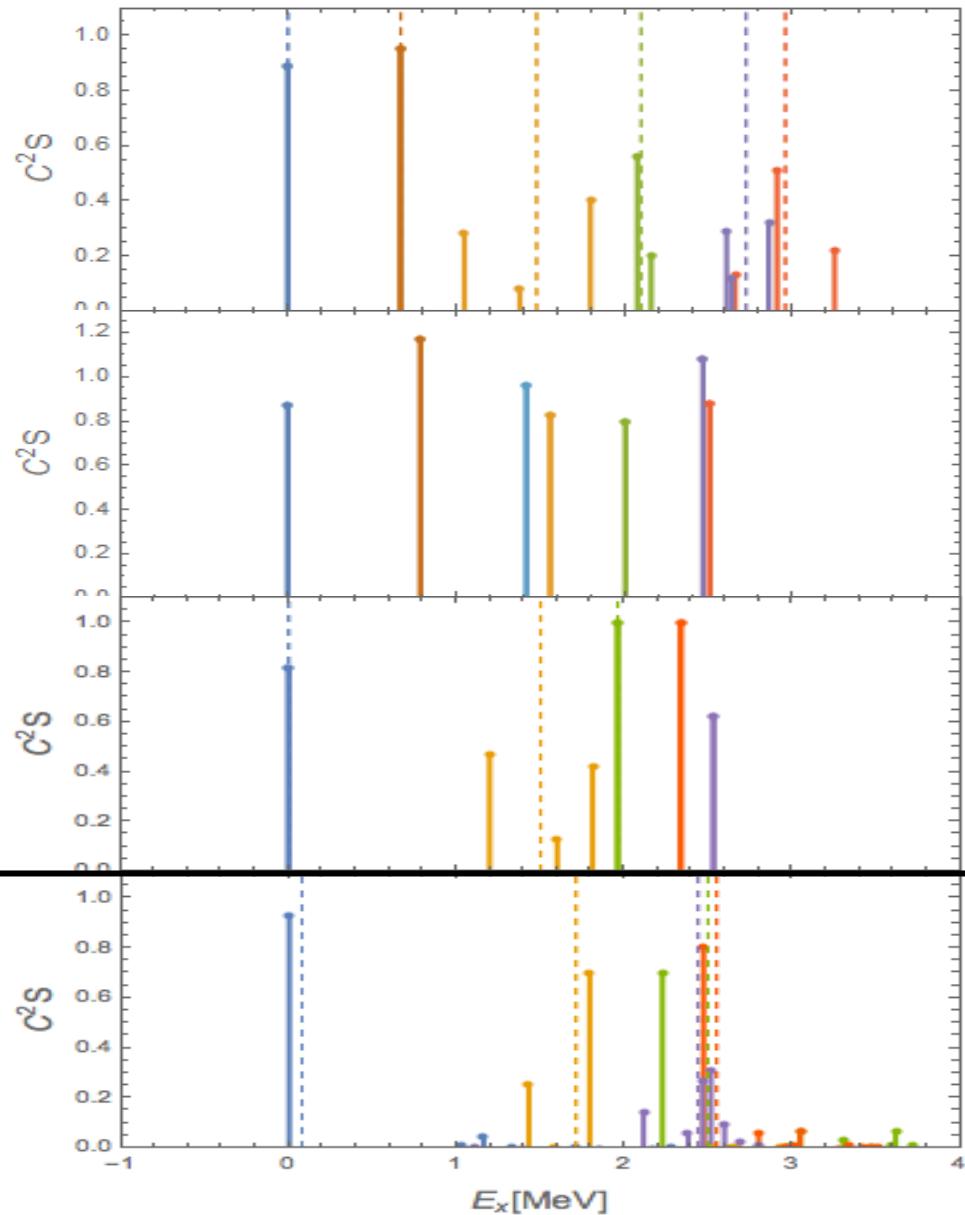
Measured Angular Distributions

DWBA calculation: Ptolemy

Spin-parity assignment and Spectroscopic factors

* Normalized to $3s_{1/2}$ state.

| E (keV) | ℓ | j^π | $n\ell s$ | S | χ^2/dof |
|-----------|--------|---------|------------|----------|---------------------|
| 0 | 4 | $9/2^+$ | $1g_{9/2}$ | 0.82(5) | 1.3(8) |
| 1197(5) | 2 | $5/2^+$ | $2d_{5/2}$ | 0.47(6) | 2.9(1.1) |
| 1600(45) | —4 | $9/2^+$ | $1g_{9/2}$ | 0.30(4) | 1.5(2) |
| | 2 | $5/2^+$ | $2d_{5/2}$ | 0.13(1) | 1.4(3) |
| 1810(20) | —4 | $9/2^+$ | $1g_{9/2}$ | 0.93(12) | 1.1(1) |
| | 2 | $5/2^+$ | $2d_{5/2}$ | 0.42(3) | 1.3(3) |
| 1960(30) | 0 | $1/2^+$ | $3s_{1/2}$ | 1.00(13) | 4.4(2.7) |
| 2335(6) | 2 | $3/2^+$ | $2d_{3/2}$ | 1.00(7) | 1.1(9) |
| 2530(20) | 4 | $7/2^+$ | $1g_{7/2}$ | 0.62(6) | 1.4(2) |



^{211}Po , 8.5 MeV/u [NPA314(1979)101-114]

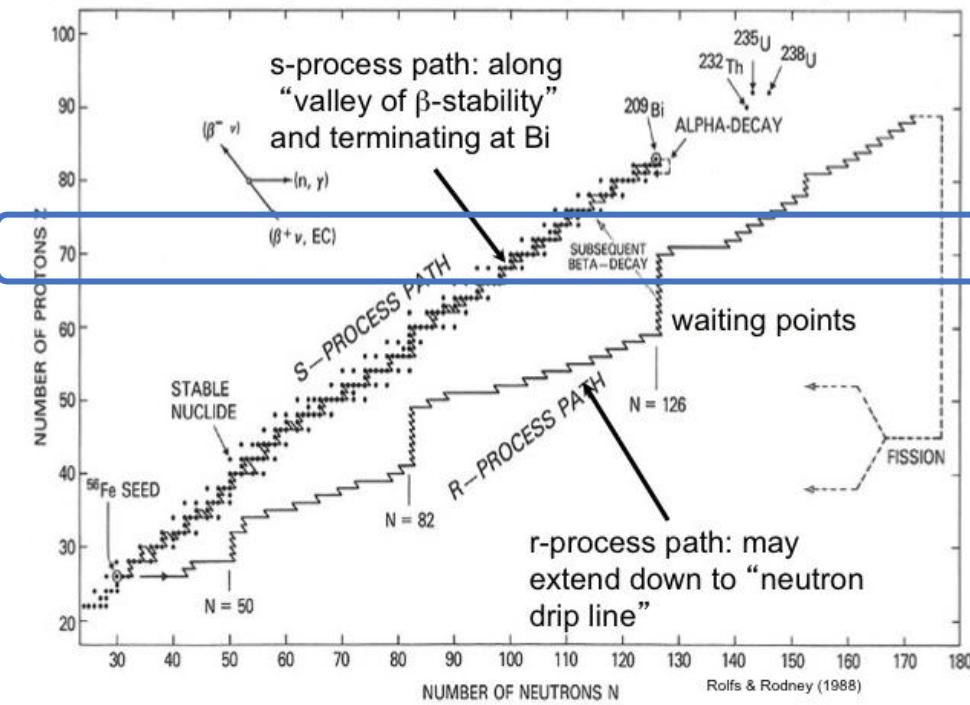
^{209}Pb , 7.5 MeV/u [Phys. Rev. 159(1967)1039]

^{207}Hg , 7.39 MeV/u

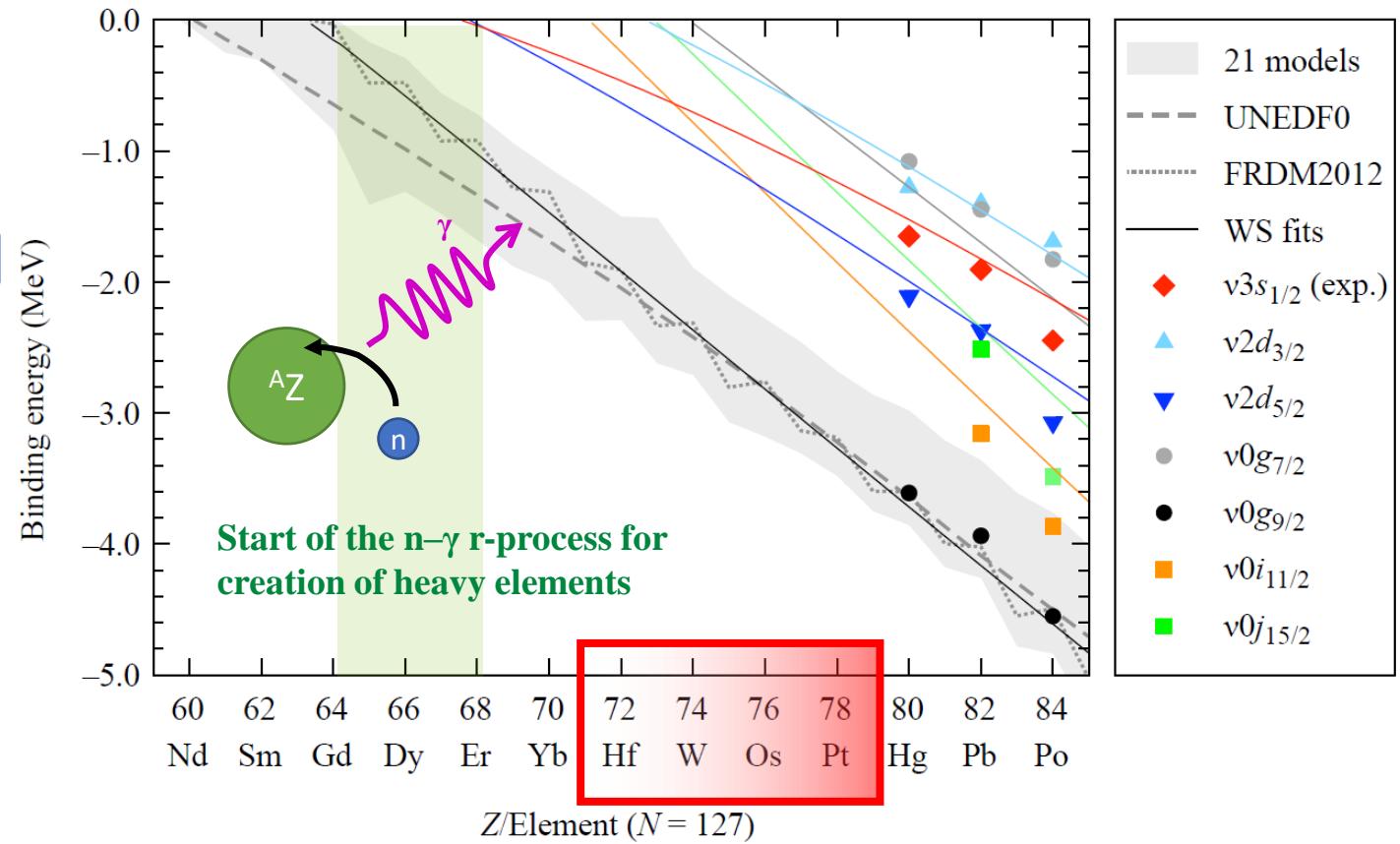
| orbital | Sum(SF) | Centroid [MeV] |
|---------|----------|----------------|
| $1g9/2$ | 0.82(5) | 0.000 |
| $2d5/2$ | 1.02(7) | 1.501 |
| $3s1/2$ | 1.00(13) | 1.960 |
| $2d3/2$ | 1.00(7) | 2.335 |
| $1g7/2$ | 0.62(6) | 2.530 |

Shell Model (^{207}Hg) [Alex Brown, priv. comm.]

Connection to r-process



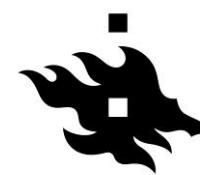
Woods-Saxon calculations fitted to experimental binding energies of the neutron orbitals at $N = 127$ (^{207}Hg , ^{209}Pb , and ^{211}Po).



Those isotopes could be produced in HIE-ISODLE and FRIB.

First Exploration of Neutron Shell Structure below Lead and beyond $N=126$

T. L. Tang,¹ B. P. Kay^{1,*} C. R. Hoffman,¹ J. P. Schiffer,¹ D. K. Sharp,² L. P. Gaffney,³ S. J. Freeman,² M. R. Mumpower,^{4,5} A. Arokiaraj,⁶ E. F. Baader,³ P. A. Butler,⁷ W. N. Catford,⁸ G. de Angelis,⁹ F. Flavigny,^{10,11} M. D. Gott,¹ E. T. Gregor,⁹ J. Konki,³ M. Labiche,¹² I. H. Lazarus,¹² P. T. MacGregor,² I. Martel,⁷ R. D. Page,⁷ Zs. Podolyák,⁸ O. Poleshchuk,⁶ R. Raabe,⁶ F. Recchia,^{13,14} J. F. Smith,¹⁵ S. V. Szwec,^{16,17} and J. Yang⁶



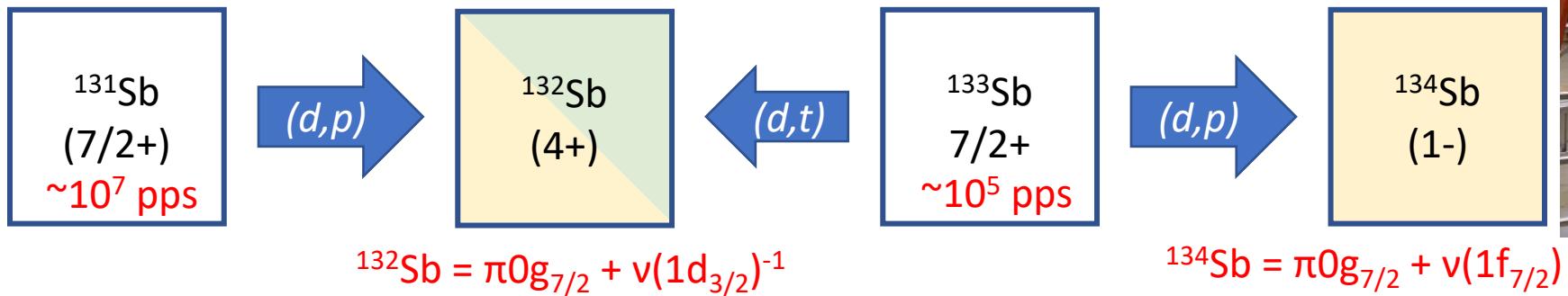
Outlook

Next logical step is going down to lower Z nuclei

- Like Pt, Os, etc... That would be challenging in beam production.
- Within few years, FRIB may able to product
- SOLARIS is an other solenoidal spectrometer at FRIB.

Transfer reaction is feasible on heavy nuclei.

- Medium mass nuclei should be OK too.
- We will propose the $^{133}\text{Sb}(d,p)$ reaction

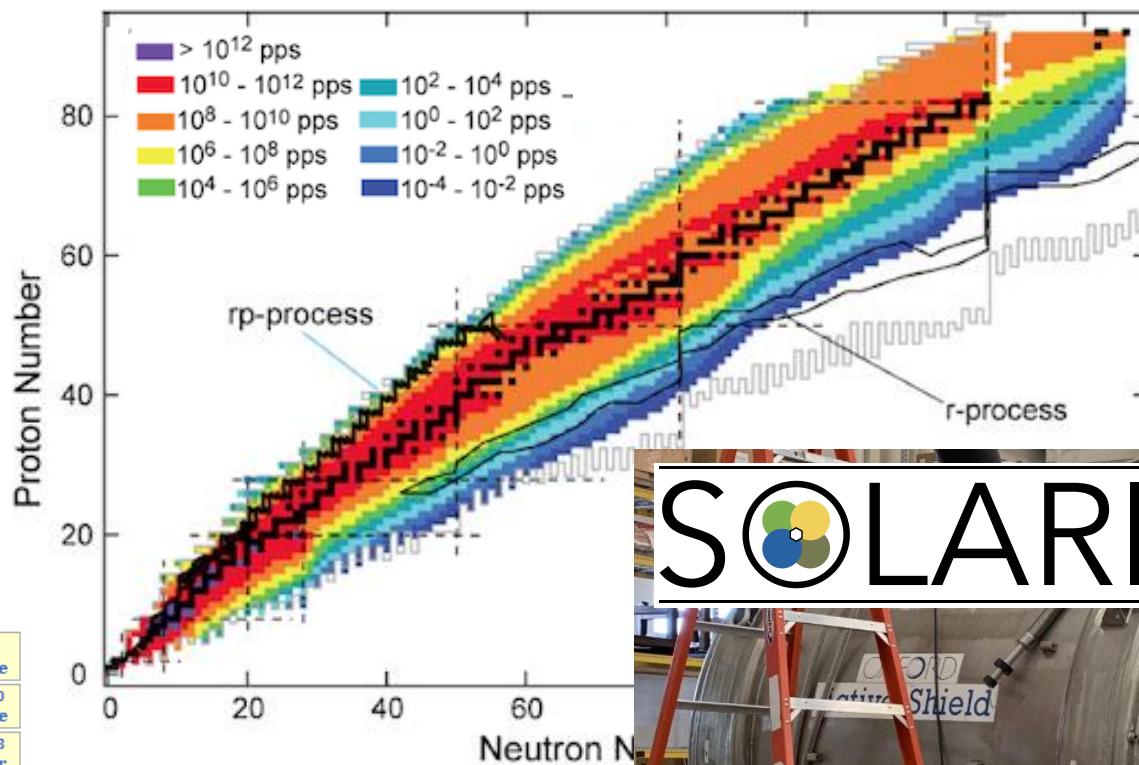


Back up

Outlook



| ICOCDE Colloidal Spectrometer | | | | | | | | | | | | | | | | | | 2 He |
|-------------------------------|-------|-------|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|-------|-------|--------|--------|--------|---------|
| 2 | 3 Li | 4 Be | | | | | | Laser | | | | 5 B | 6 C | 7 N | 8 O | 9 F | 10 Ne | |
| 3 | 11 Na | 12 Mg | | | | | | | | | | 13 Al | 14 Si | 15 P | 16 S | 17 Cl | 18 Ar | |
| 4 | 19 K | 20 Ca | 21 Sc | 22 Ti | 23 V | 24 Cr | 25 Mn | 26 Fe | 27 Co | 28 Ni | 29 Cu | 30 Zn | 31 Ga | 32 Ge | 33 As | 34 Se | 35 Br | |
| 5 | 37 Rb | 38 Sr | 39 Y | 40 Zr | 41 Nb | 42 Mo | 43 Tc | 44 Ru | 45 Rh | 46 Pd | 47 Ag | 48 Cd | 49 In | 50 Sn | 51 Sb | 52 Te | 53 I | |
| 6 | 55 Cs | 56 Ba | * | 71 Hf | 72 Ta | 73 W | 74 Re | 75 Os | 76 Ir | 78 Pt | 79 Au | 80 Hg | 81 Tl | 82 Pb | 83 Bi | 84 Po | 85 At | |
| 7 | 87 Fr | 88 Ra | ** | 103 Lr | 104 Rf | 105 Db | 106 Sg | 107 Bh | 108 Hs | 109 Mt | 110 Ds | 111 Rg | | | | | | 86 Rb |
| * Lanthanides | | | * | 57 La | 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb | 66 Dy | 67 Ho | 68 Er | 69 Tm | 70 Yb | |
| ** Actinides | | | ** | 89 Ac | 90 Th | 91 Pa | 92 U | 93 Np | 94 Pu | 95 Am | 96 Cm | 97 Bk | 98 Cf | 99 Es | 100 Fm | 101 Md | 102 No | |



Compare with Woods-Saxon

- 1) Fit ^{209}Pb centroid with all 6 Woods-Saxon parameters

- RMS of the fit is 98 keV

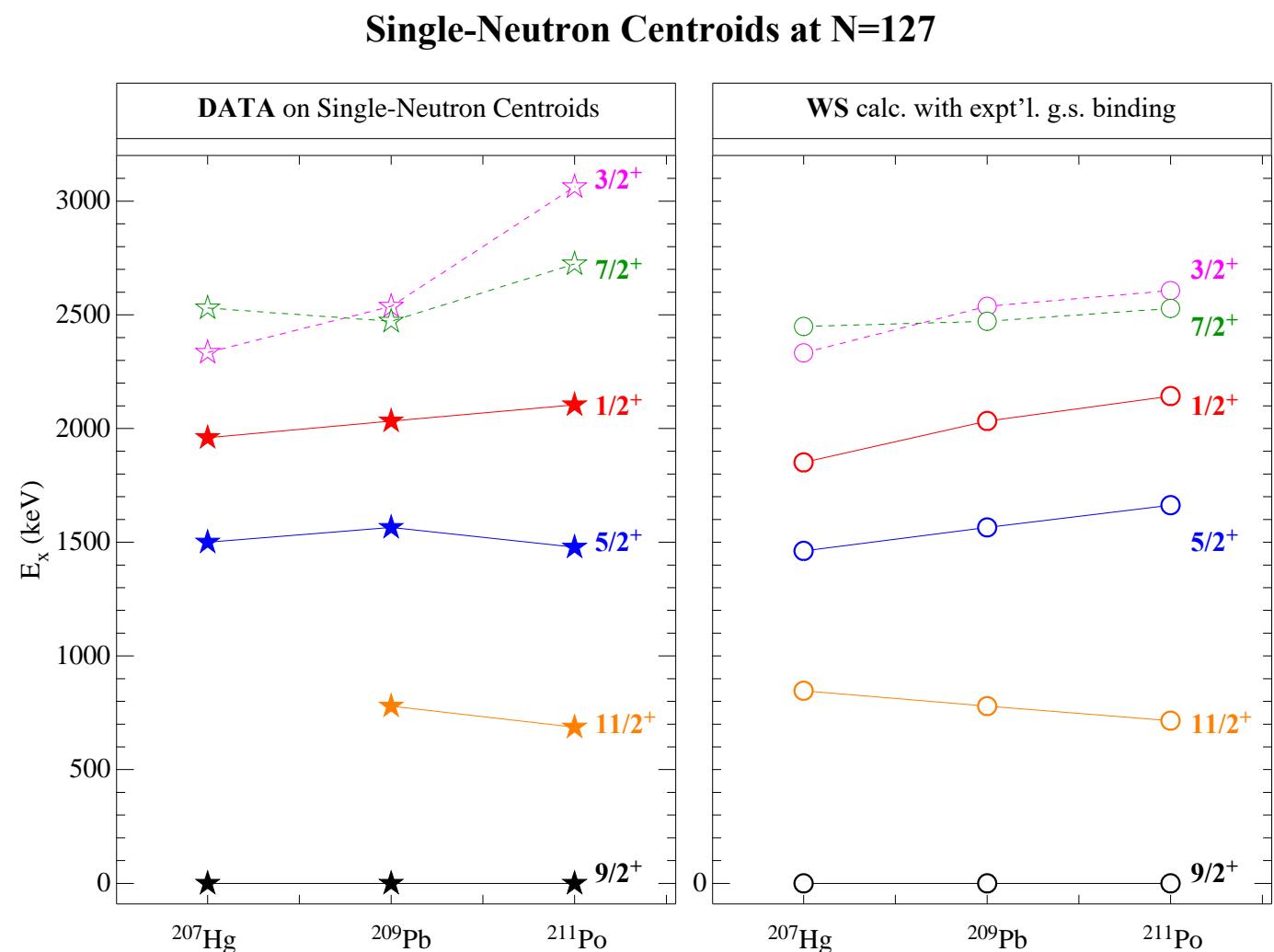
$$H = \frac{P^2}{2m} + V(r) + \langle L \cdot S \rangle \frac{1}{r} \frac{d}{dr} V_{SO}(r)$$

$$V(r) = \frac{V_0}{1 + \exp\left(\frac{r - R_0}{a_0}\right)}$$

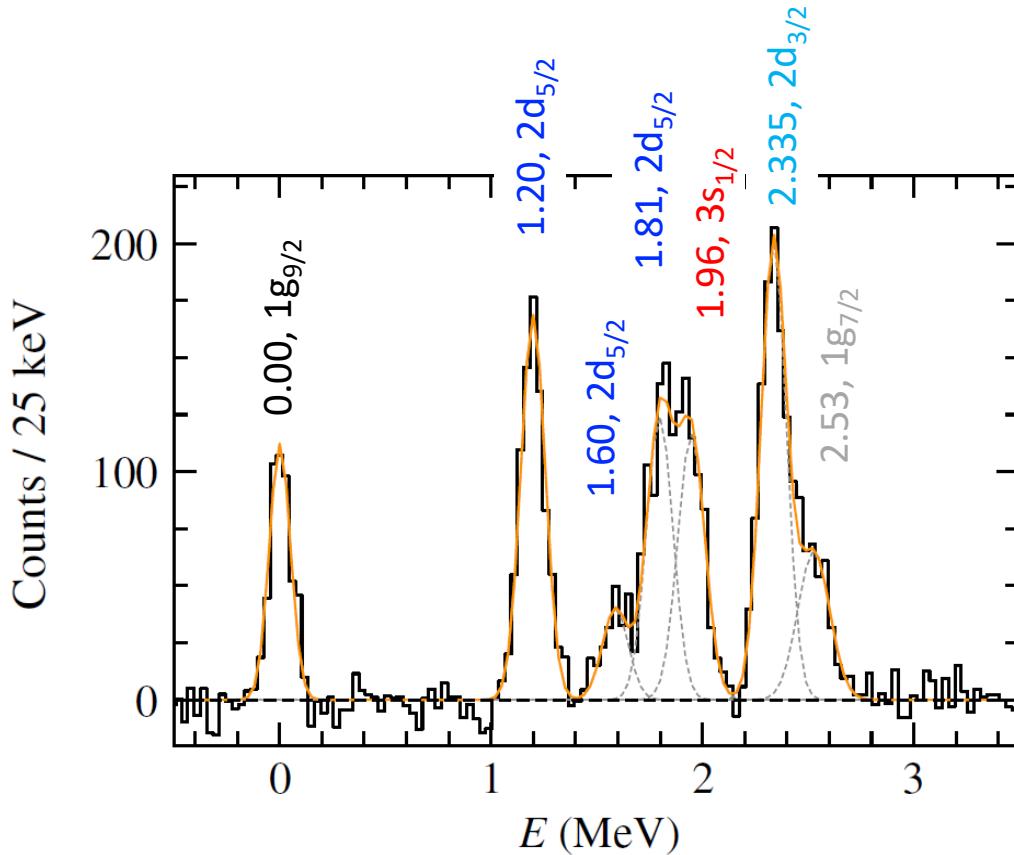
$$V_{SO}(r) = \frac{V_{SO}}{1 + \exp\left(\frac{r - R_{SO}}{a_{SO}}\right)}$$

- 2) Fixed the r_0 , a_0 , V_{SO} , r_{SO} , a_{SO} , fit ^{207}Hg and ^{211}Po centroids with V_0

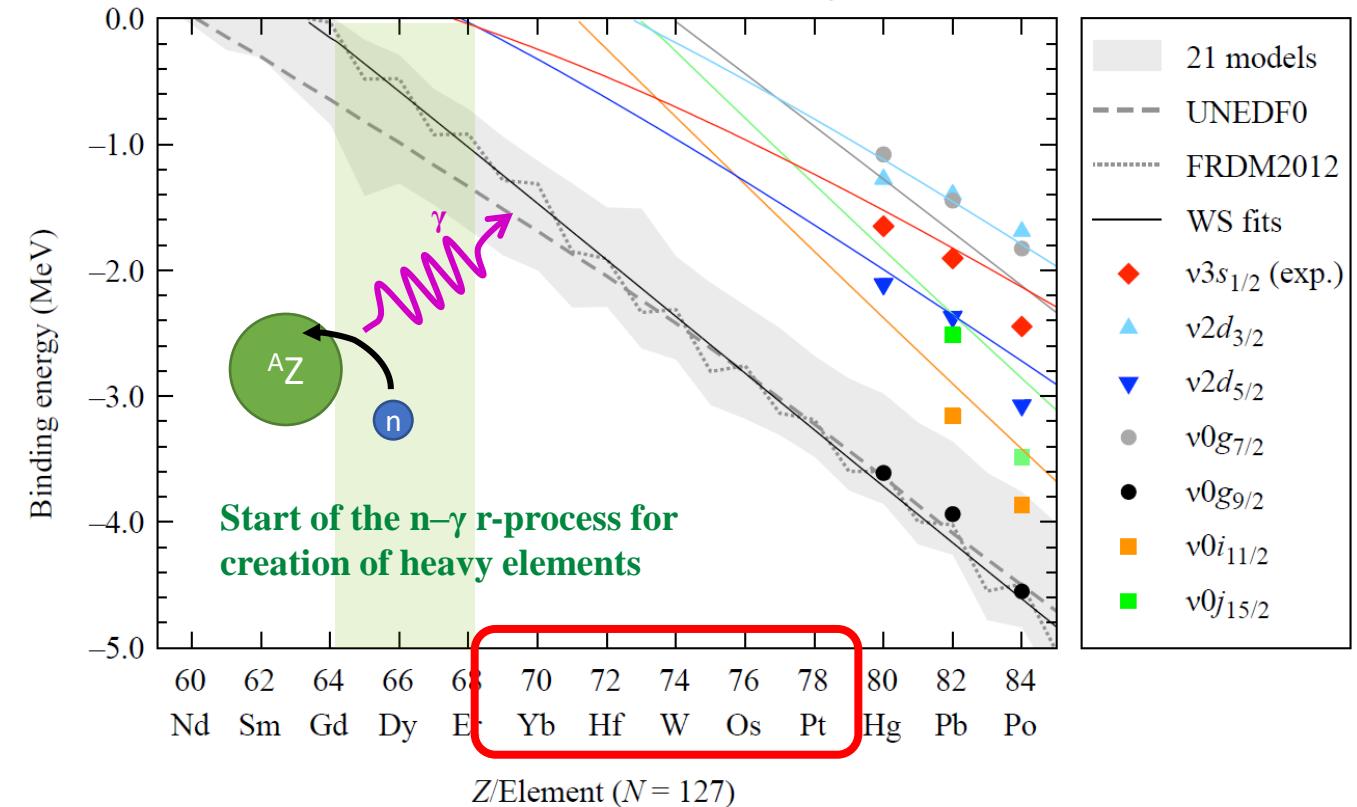
- RMS for ^{207}Hg is 137 keV
- RMS for ^{211}Po is 246 keV



Connection to r-process



Woods-Saxon calculations fitted to experimental binding energies of the neutron orbitals at $N = 127$ (^{207}Hg , ^{209}Pb , and ^{211}Po).



Those isotopes could be produced in FRIB era.