

The 75th Meeting of the INTC:

Mapping single-particle
neutron strength towards
the mid-shell in semi-
magic lead isotopes

Spokepersons:

Joonas Ojala, Robert Page, Janne Pakarinen

07.02.2024



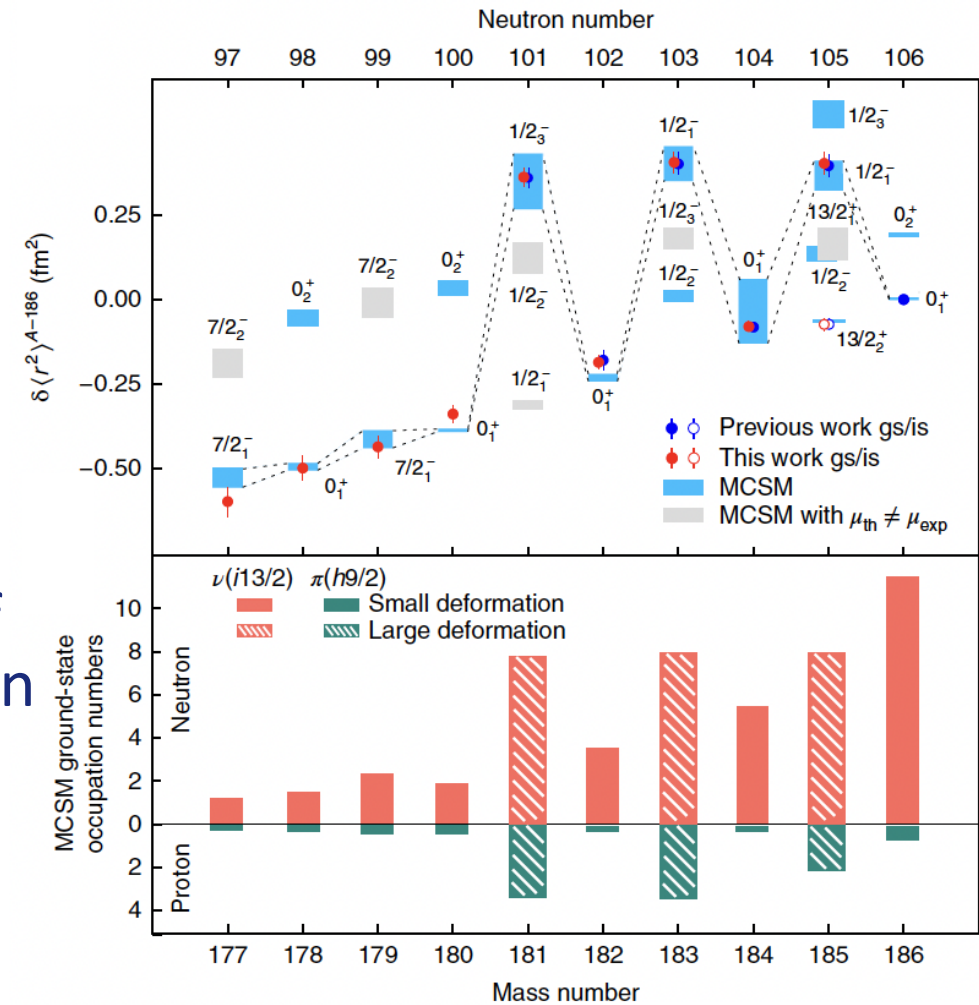
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LIVERPOOL



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UNIVERSITY OF JYVÄSKYLÄ

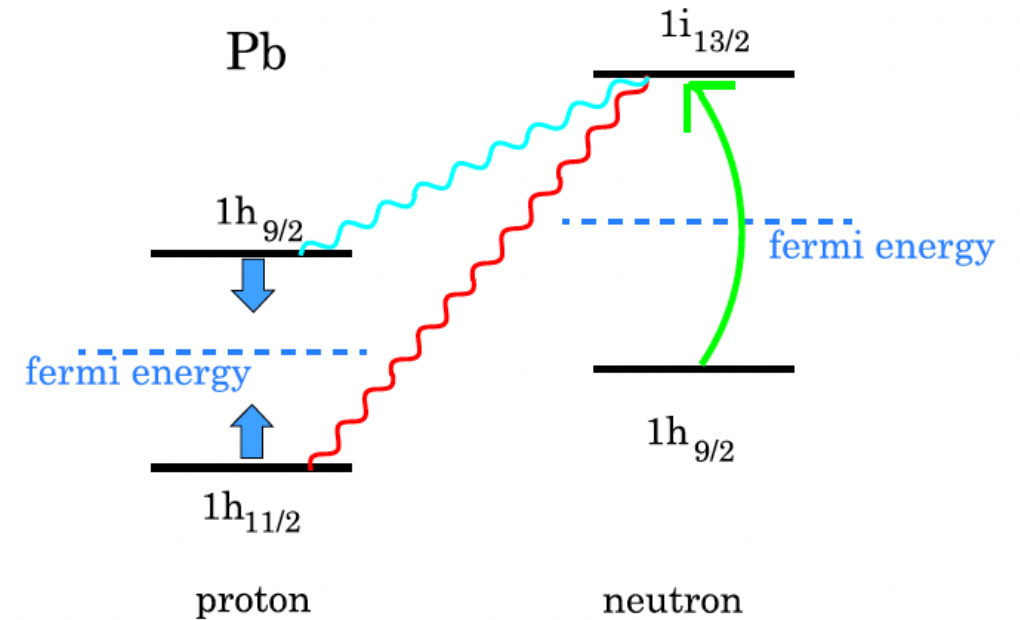
Motivation

- Study the single-particle neutron states in neutron-deficient $^{197,199}\text{Pb}$ isotopes
- Understand the neutron particle occupancy development for $\nu 1i_{13/2}$ state
- Changing neutron occupancy in $\nu 1i_{13/2}$ orbital has been identified as driving the evolution of deformed intruder configurations in this region
- In Monte Carlo Shell Model calculations performed by Otsuka et al. to Hg isotopes, is shown



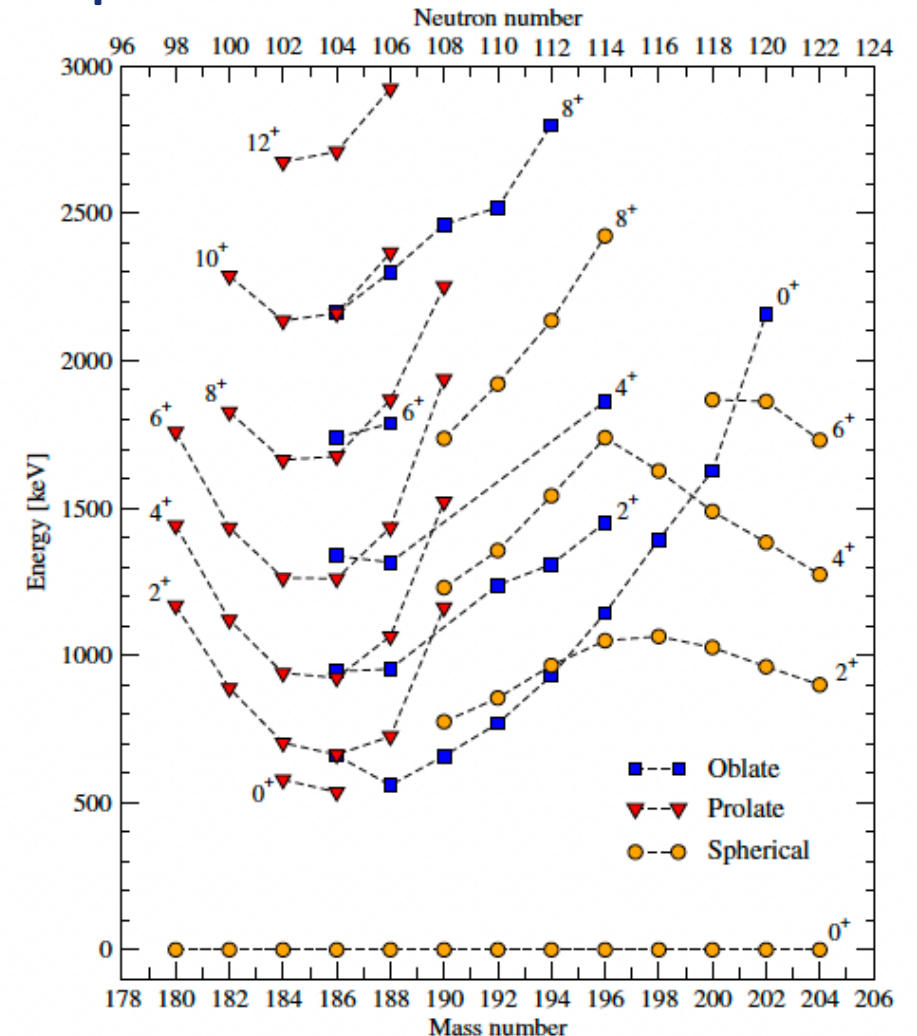
Motivation

- Data on single-particle states strongly coupled to the $\pi(0p-0h)$ band configuration are currently lacking neutron-deficient Pb isotopes
- There is no information on how the single-particle strength is distributed
- This experiment would be the first step towards systematic studies of evolving single-particle strength along the semi-magic lead isotopic chain



Shape coexistence in Pb isotopes

- Shape coexistence in Pb nuclei has been the subject of intense study for several decades
- The $\pi(2p-2h)$ and $\pi(4p-4h)$ intruder configurations are associated with oblate and prolate deformed structures, respectively
- The minima of these can be found in the neutron mid-shell



Pb isotopes

Bi 193 3.12 s 63.6 s ε γ 175, 711 α 6.475 α → g ε	Bi 194 115 s 125 s 95 s ε γ 965 575 280... α 5.599... α → m α?	Bi 195 87 s 183 s ε, β ⁺ γ 808, 776 α 6.106... 134..., e ⁻ , g γ (341) α 5.420... α → m	Bi 196 4.00 m 0.6 s 5.13 m ε, β ⁺ γ 1049... IT (102) e ⁻ (158...) α γ 1049... 5.153 α → g 1809...	Bi 197 5.15 m 9.33 m α 5.780 α → g γ 855, 85 867, 828... e ⁻	Bi 198 7.7 s 11.6 m 10.3 m ε γ 1063 198 ε 562... 1063...	Bi 199 24.70 m 27 m ε, β ⁺ ... γ 842 946 γ 1027 462 420...	Bi 200 31 m 36.4 m ε β ⁺ γ 1027 462 420...	Bi 201 57.5 m 103 m ε, β ⁺ 2.2... γ 629, 936 1014 786... IT 846 α 5.24 m, g, α?	Bi 202 1.71 h ε, β ⁺ ... γ 961, 422 657..., g α?	Bi 203 11.76 h ε, β ⁺ 1.4, 2.2... γ 820, 825, 897 1848, 1034... g, m	Bi 204 11.22 h ε γ 899, 375 984... g, m	Bi 205 14.91 d ε, β ⁺ ... γ 1764, 703 988...	Bi 206 6.24 d ε, β ⁺ ... γ 803, 881, 516 1719, 537...	Bi 207 31.55 a ε, β ⁺ ... γ 570, 1064 1770...
Pb 192 3.5 m ε, β ⁺ 2.1, 2.3... 3.9... γ 1195, 608, 168... e ⁻ , g α 5.112	Pb 193 5.8 m ~5 m ε, β ⁺ 3.3 3.9... γ 392 716... m ε	Pb 194 10.7 m ε, β ⁺ ... γ 582, 1519 204..., e ⁻ , g α 4.64	Pb 195 15.0 m ~15 m ε β ⁺ γ 394, 878 708... m g	Pb 196 36.4 m ε γ 253, 502, 367 192... g	Pb 197 42.9 m 8.1 m ε γ 386, 388 223... IT 234, e ⁻ γ 85, e ⁻ 375...	Pb 198 2.4 h ε γ 290, 365 173... g	Pb 199 12.2 m 90 m IT 424, e ⁻ γ? ε γ 145 - 2613	Pb 200 21.5 h 12.2 m 90 m IT 424, e ⁻ γ? ε γ 145 - 2613	Pb 201 60.8 s 9.33 h ε β ⁺ γ 331, 361 946... IT 629	Pb 202 3.54 h 5.25·10 ⁴ a IT 787... γ 422 961... ε, γ 490 460, 390... α?	Pb 203 6.21 s 51.92 h IT 825 γ 820, (5) e ⁻ γ 279 401...	Pb 204 66.93 m 1.4 IT 912... γ 899 375... σ 0.703	Pb 205 1.70·10 ⁷ a ε no γ σ ~5	Pb 206 24.1 σ 0.027
Tl 191 5.22 m 20 m? ε β ⁺ γ 216, 326 265, 336... g β?	Tl 192 10.8 m 9.6 m ε β ⁺ γ 423, 635 787... 1113...	Tl 193 2.11 m 21.6 m IT (<13), e ⁻ γ 365 1580... g	Tl 194 32.8 m 33.0 m ε β ⁺ γ 428, 636 749... γ 428...	Tl 195 3.6 s 1.16 h ε β ⁺ 1.8... γ 564, 884 1364... IT (99), e ⁻ γ 384	Tl 196 1.41 h 1.84 h ε γ 426, 635 695... IT (120), e ⁻ γ 426, 611 635...	Tl 197 2.84 h ε β ⁺ ... γ 426, 152... g	Tl 198 1.87 h 5.3 h ε, β ⁺ ... γ 637, 412 587... IT 261, e ⁻ γ 283..., e ⁻ 637...	Tl 199 7.42 h ε γ 455, 208, 247 158... g	Tl 200 26.1 h ε β ⁺ ... γ 368, 1206, 579 828... ε	Tl 201 3.0422 d ε γ 167, 135... γ 440, (520...)	Tl 202 12.23 d ε γ 440, (520...)	Tl 203 29.52 σ 11.4 σ _{n,α} < 0.0003	Tl 204 3.78 a β ⁻ 0.8 ε no γ, g σ 21.6	Tl 205 70.48 σ 0.104
Hg 190 20.0 m ε γ 143, 172, 155... α?	Hg 191 50.8 m ~50 m ε β ⁺ γ 420 579... m, g	Hg 192 4.85 h ε γ 253 196... g, m	Hg 193 11.8 h 3.80 h ε, β ⁺ γ 408 573... IT (101), e ⁻ γ (40), e ⁻ g	Hg 194 447 a ε no γ	Hg 195 41.6 h 10.53 h IT (123), e ⁻ γ 37... ε, β ⁺ ... γ 780 61... e ⁻ 388... m g	Hg 196 0.15 σ 107 + 2973	Hg 197 23.8 h 64.14 h IT (165) e ⁻ γ 134, e ⁻ γ 77 191... e ⁻	Hg 198 10.04 σ 0.018 + 2.0	Hg 199 42.67 m 16.94 IT 374... e ⁻ γ 158... σ 2150	Hg 200 23.14 σ 15.0	Hg 201 13.17 σ 4.9	Hg 202 29.74 σ 4.91	Hg 203 46.59 d β ⁻ 0.2 γ 279	Hg 204 6.82 σ 0.43



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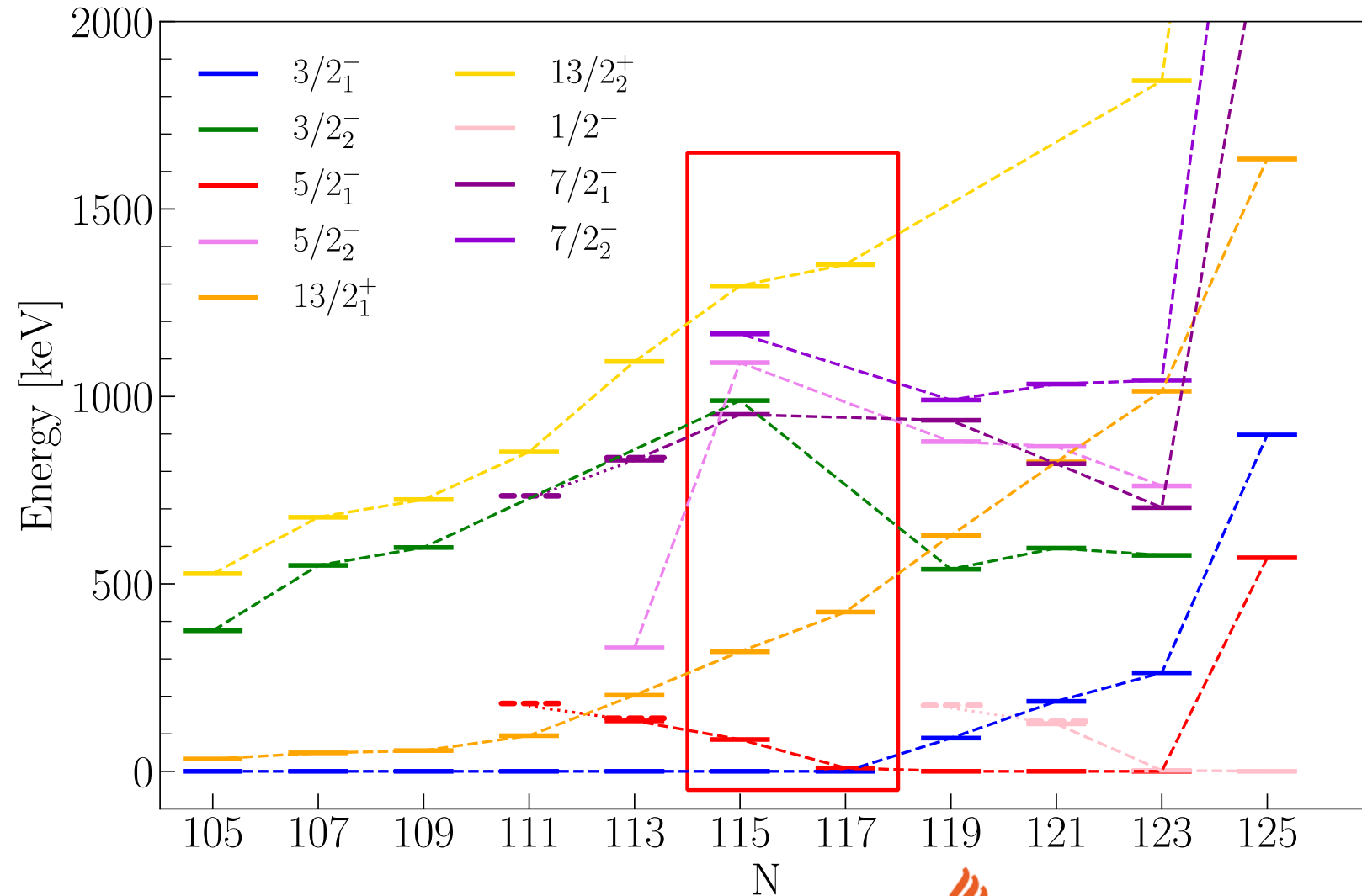
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Systematics

- Assumed single-particle states are shown in the figure
- The level energies are based on the α - and β -decay studies
- Is the first excited $13/2^+$ state coupled with the $\pi(0p-0h)$ spherical configuration?

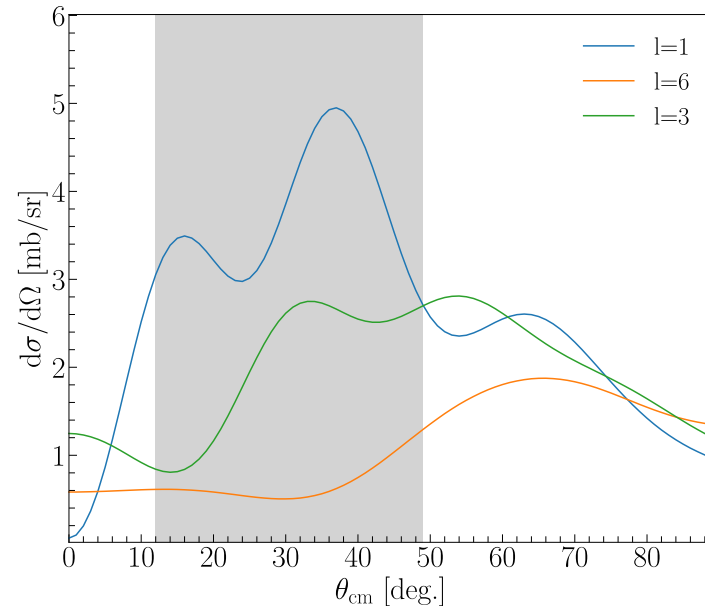
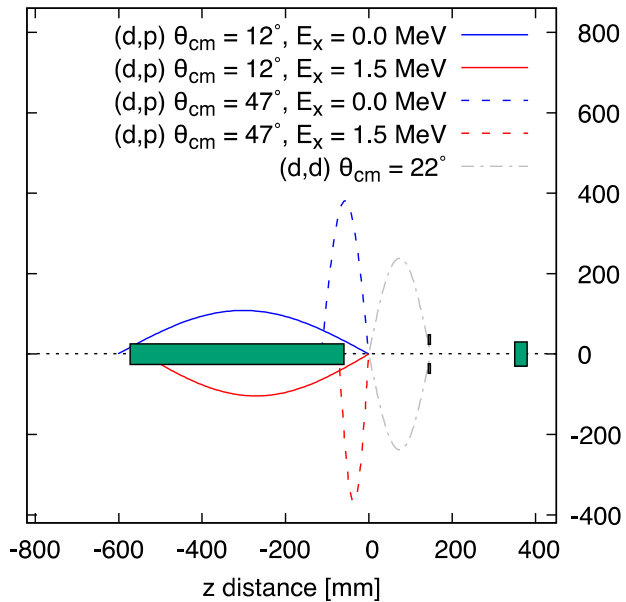
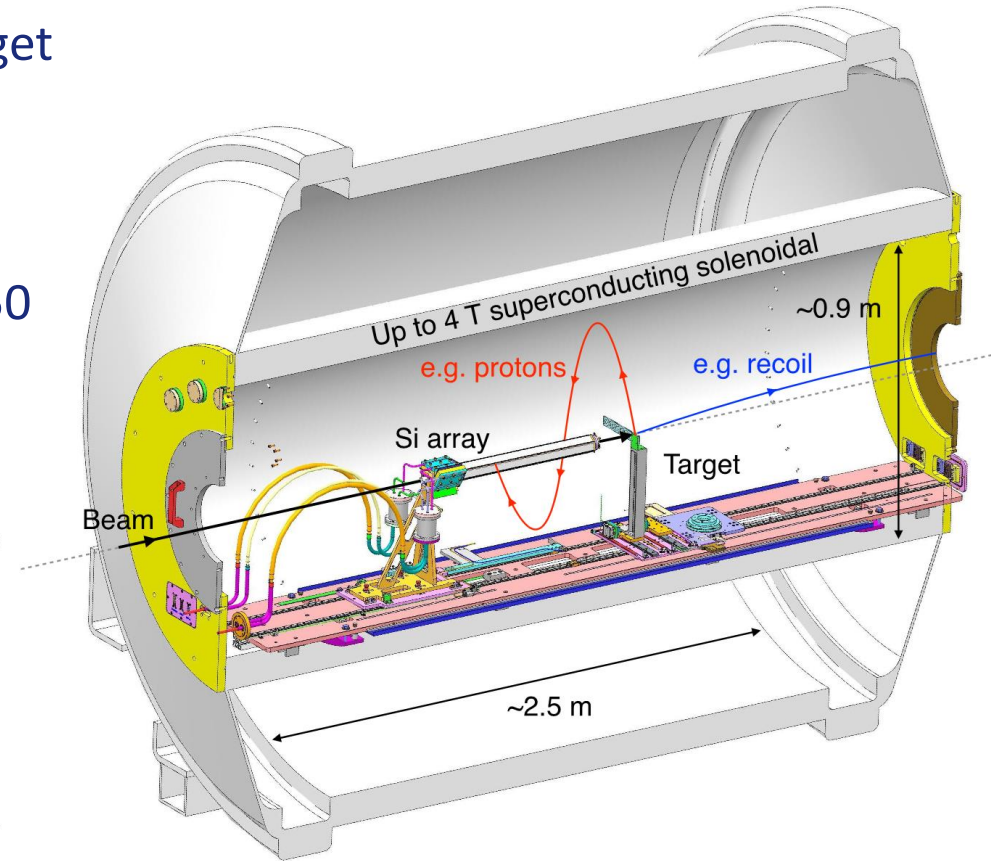


Why to perform this experiment

- This experiment would allow us to obtain single-particle strength for the $i_{13/2}$ state, which is possible with ISS, unlike with MINIBALL as it is an isomeric state
- The needed beam is feasible only in ISOLDE (FRIB beam intensity is one order of magnitude lower)
- The experiment would provide a testing ground for theory calculations, which suffer from lack of the spectroscopic information in neutron-deficient Pb nuclei

Transfer reaction at ISS - $d(^{196,198}\text{Pb}, p) ^{197,199}\text{Pb}$

- The Si array will be located as close as possible to the target
- The luminosity detector will be used to detect elastically scattered deuteron
- Magnetic field: 2.5 T
- A new 2-dimensional target ladder will allow more than 50 targets to be used
- Polyethylene target thickness: $150 \mu\text{g}/\text{cm}^2$



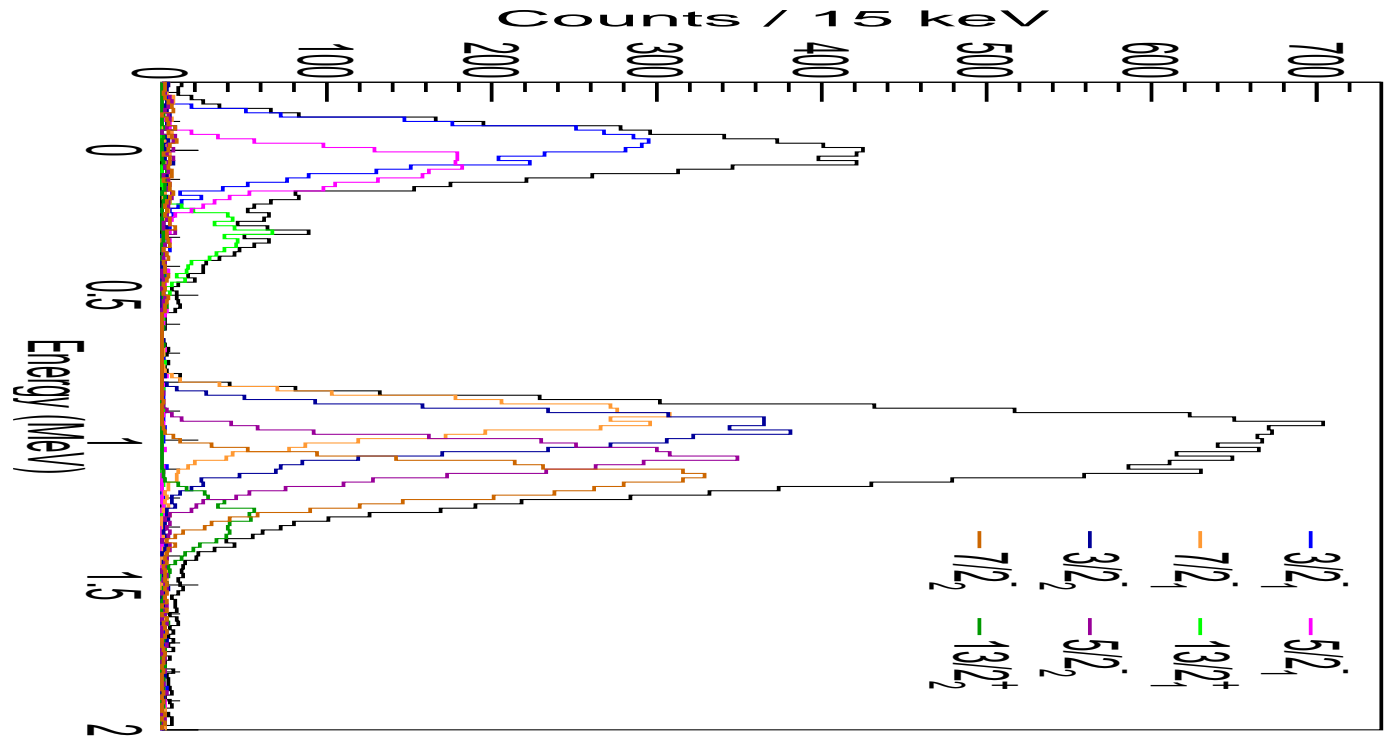
Proton yields for different states

- Calculated with an assumption $C^2S=0.2$
- DWBA calculations were performed with Ptolemy
- The requested 10 shifts would allow to have large enough statistics for $i13/2$ state
- Similar yields are expected for ^{199}Pb

Energy (keV)	I^π	σ_{DWBA}	Counts per shift
0	$3/2_1^-$	7.8	350
85	$5/2_1^-$	4.5	203
319	$13/2_1^+$	1.4	65
952	$7/2_1^-$	7.7	346
989	$3/2_2^-$	9.4	423
1089	$5/2_2^-$	5.4	243
1167	$7/2_2^-$	8.0	361
1295	$13/2_2^+$	1.6	71

Simulation of $d(^{196}\text{Pb},p)^{197}\text{Pb}$

- Simulation performed with NPTool
- Aim to be sensitive to $C^2S \geq 0.2$ for $13/2^+$ state
- Some fragmentation of the low- l strength is expected.
- A similar excitation spectrum is expected for ^{199}Pb



Beam request

- There is experience in producing these beams
- Beam energy: 7.5 MeV/u (as high as possible)
- Beam purity: 98.7%
- Beam intensity and target condition can be evaluated in combination with a FC and luminosity monitor

Isotope	E_{Beam} [MeV/u]	Average yield [pps]	Purity [%]
^{188}Pb	2.82	3.2E+05	55.1±5.5
^{190}Pb	2.82	2.2E+05	86.3±2.0
^{192}Pb	2.84	5.0E+05	96.9±0.8
^{194}Pb	2.82	7.8E+05	97.0±0.7
^{196}Pb	2.82	5.0E+05	98.7±0.5
^{198}Pb	2.82	2.5E+05	98.6±0.7

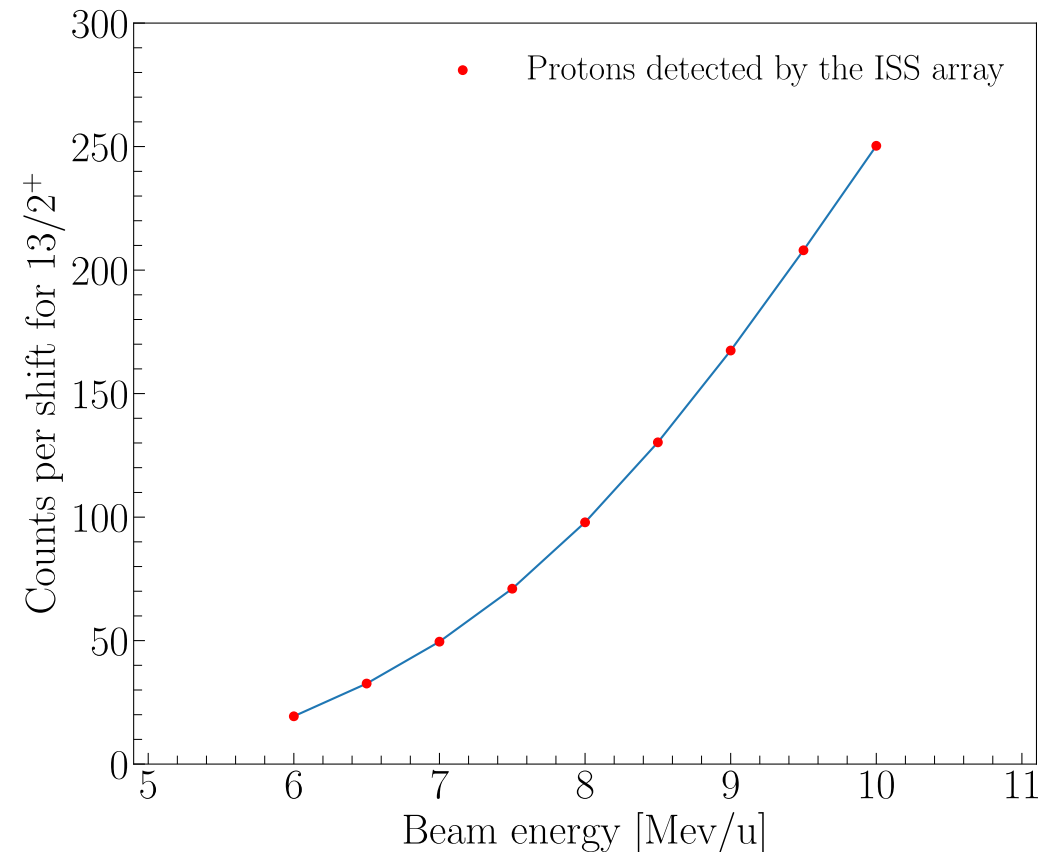


TAC Recommendation

TAC
recommendation

The TAC notes that the requested energy is at the edge of the feasibility and that the rate at the experiment might be 50% lower than requested.

- The energy will have an effect on transferring cross-sections. The higher beam energy is preferred as the $13/2^+$ state would have a higher cross-section
- The effect of beam energy is low for statistics.
- A thicker target can be used to recover some loss of beam intensity, with a compromise on energy resolution



Summary and beam time request

- 10 shifts for both $^{197,199}\text{Pb}$
- 3 shift C-foil to assess fusion-evaporation background
- 1 shift each isotope for laser on/off running
- 1 shift is required for beam tuning and preparation of the experimental setup
- **Total 26 shifts**

Energy (keV)	I^π	σ_{DWBA}	Counts per shift
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Thank you!

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

(Following HIE-ISOLDE Letter of Intent I-110)

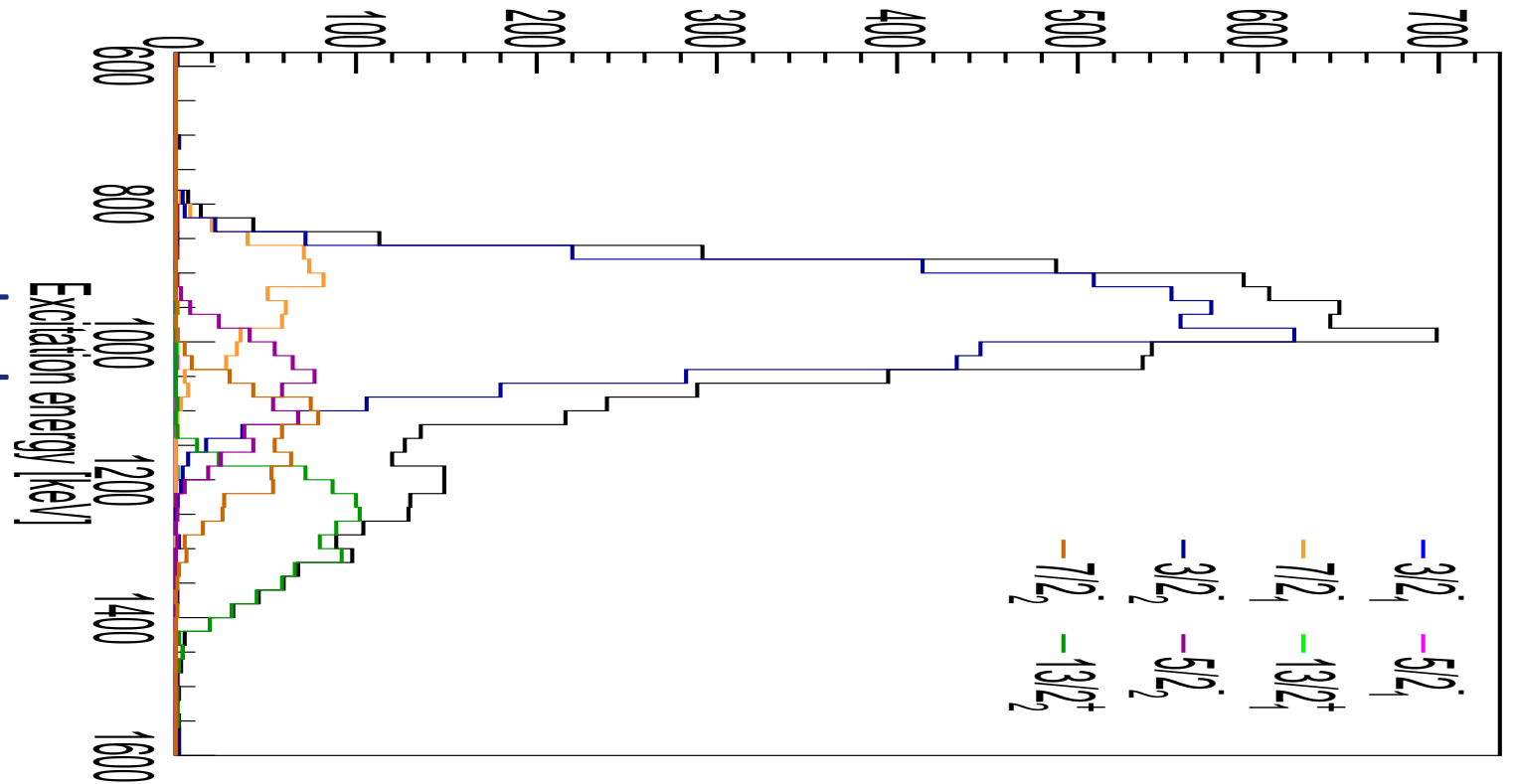
**Mapping single-particle neutron strength towards the mid-shell
in semi-magic lead isotopes**

February 6, 2024

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P. A. Butler¹, D. J. Clarke⁷, J. G. Cubiss⁵, A. J. Dolan¹, L. M. Fraile⁶, S. J. Freeman^{7,8},
L. P. Gaffney¹, A. Heinz⁹, C. R. Hoffman¹⁰, A. Illana⁶, B. R. Jones¹, D. T. Joss¹,
B. P. Kay¹⁰, Th. Kröll¹¹, M. Labiche¹², I. Lazarus¹², P. T. MacGregor⁸,
A. Montes Plaza^{1,2,3}, B. S. Nara Singh¹³, P. Papadakis¹², R. Raabe¹⁴, S. Reeve⁷,
F. A. Rowntree¹, M. Scheck¹³, D. K. Sharp⁷, J. F. Smith¹³, K. Wrzosek-Lipska¹⁵

Excitation spectrum for identification $13/2_2^+$

- $I=3$ @ 952 keV; $C^2S = 0.2$ +
- $I=1$ @ 989 keV; $C^2S = 0.8$ +
- $I=3$ @ 1089 keV; $C^2S = 0.2$ +
- $I=3$ @ 1167 keV; $C^2S = 0.2$ +
- $I=6$ @ 1295 keV; $C^2S = 0.8$



Level schemes $^{197,199}\text{Pb}$

- Based on EC-decay of $^{197,199}\text{Bi}$ spectroscopy
- The spins of the ^{199}Pb are not well-known

