The 75th Meeting of the INTC:

Mapping single-particle neutron strength towards the mid-shell in semimagic lead isotopes Spokepersons:

Joonas Ojala, Robert Page, Janne Pakarinen

07.02.2024





YVASKYLAN YLIOPISTO

FY OF IYVÄSKYLÄ

Motivation

- Study the single-particle neutron states in neutron-deficient ^{197,199}Pb isotopes
- Understand the neutron particle occupancy development for $v1i_{13/2}$ state
- Changing neutron occupancy in v1i_{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 π(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 semimagic lead isotopic chain







Shape coexistence in Pb isotopes

- Shape coexistence in Pb nuclei has been the subject of intense study for several decades
- The π(2p-2h) and π(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





. Ojala, J. Pakarinen et al., Communications Physics 5 (2022)

JYVASKYLAN YLIOPISTO UNIVERSITY OF JYVÄSKYLÄ

Pb isotopes

Bi 193	Bi 194	Bi 195	Bi 196	Bi 197	Bi 198	Bi 199	Bi 200	Bi 201	Bi 202	Bi 203	Bi 204	Bi 205	Bi 206	Bi 207
3.12 s 63.6 s	115 s 125 s 95 s	87 s 183 s	4.00 m 0.6 s 5.13 n	n 5.15 m 9.33 m	7.7 s 11.6 m 10.3 r	n 24.70 m 27 m	31 m 36.4 m	57.5 m 103 m	1.71 h	11.76 h	11.22 h	14.91 d	6.24 d	31.55 a
$ \begin{array}{c} \epsilon \\ \gamma \ 175, \ 71 \\ 681 \\ \alpha \rightarrow g \\ \epsilon \end{array} $	$ \begin{array}{c} 1 \\ \gamma \\ 7 \\ 575 \\ 280 \\ \alpha \\ 5.599 \\ \alpha \\ \alpha \\ \gamma \\ \alpha \\ \alpha \\ \alpha \\ \gamma \\ \alpha \\ \alpha \\ \gamma \\ \alpha \\ \alpha$	$ \begin{array}{c} \epsilon, \ \beta^+ \\ \epsilon & \gamma \ 808, \ 776 \\ \alpha \ 6.106 \\ \gamma \ (341) \\ \alpha \rightarrow g \\ \alpha \rightarrow m \end{array} $	$\begin{array}{cccc} & \rho & \rho \\ \gamma & 1049 & \gamma \\ \text{IT} & (102) & \text{IT} & 1049. \\ e^- & (158) & \alpha \\ \alpha & 5.112 & e^- & 5.153 \\ \alpha & \rightarrow m & \epsilon? & \alpha \rightarrow g \end{array}$	α 5.780 ε α → g γ 855, 85 ε 867, 828 γ 1838 e [−] 1809 m, g	ε γ 1063 IT 249 198 ε e ⁻ 562 1063.	ε, p γ 842 ε 946 α 5.484 837α → g m, g	$\begin{array}{cccc} \epsilon & \epsilon \\ \beta^{+} & \beta^{+} \\ \gamma \ 1027 & \gamma \ 1027 \\ 462 & 462, \ 420 \\ 420 & 245 \end{array}$	ε, p 2.2 ε γ 629, 936 g 1014 IT 846 786 α 5.24 m, g, α?	6 ^{κ, β⁺} γ 961, 422 657, g α?	ε, β ⁺ 1.4, 2.2 γ 820, 825, 897 1848, 1034 g, m	ε γ 899, 375 984 g, m	ε, β⁺ γ 1764, 703 988	ε, β⁺ γ 803, 881, 516 1719, 537	ε, β ⁺ γ 570, 1064 1770
Pb 192	Pb 193	Pb 194	Pb 195	Pb 196	Pb 197	Pb 198	Pb 199	Pb 200	Pb 201	Pb 202	Pb 203	Pb 204	Pb 205	Pb 206
3.5 m	5.8 m ~5 m	10.7 m	15.0 m ~15 m	36.4 m	42.9 m 8.1 m	2.4 h	12.2 m 90 m	21.5 h	60.8 s 9.33 h	3.54 h 5.25-10 ⁴ a	6.21 s 51.92 h	66.93 m 1.4	1.70·10 ⁷ a	24.1
ε, β⁺ 2.1, 2.3 γ 1195, 608, 168. e⁻, g α 5.112	ε, p 3.3 3.9 γ 392 716 m ε	ε, β⁺ γ 582, 1519 204, e⁻, g α 4.64	ε β ⁺ ε γ 394, 878 γ 384 708 883 m g	ε γ 253, 502, 367 192 g	ε γ 386, 388 223 IT 234, e [−] γ 85, e [−] γ 386, 76 375	ε γ 290, 365 ₁ 173 g	$\begin{array}{lll} \text{IT } 424, e^- & \epsilon \\ \gamma? & \beta^+ \\ \epsilon & \gamma \ 367, \ 353 \\ \gamma \ 145 \ - & 1135 \\ 2613 & 720 \end{array}$	ε γ 148, 257, 236 268	ε β ⁺ γ 331, 36 ⁻ IT 629 946	IT 787 γ 422 961 ε 1 ε, γ 490 no γ 460, 390 α?	IT 825 ε γ 820, (5) γ 279 e⁻ 401	IT 912 γ 899 375 σ 0.703	ε no γ σ ~5	σ 0.027
TI 191	TI 102	TI 402												
	92	11 193	11194	11195	11 196	TI 197	TI 198	TI 199	TI 200	TI 201	TI 202	TI 203	TI 204	TI 205
5.22 m 20 m?	10.8 m 9.6 m	2.11 m 21.6 m	194 32.8 m 33.0 m	11 195 3.6 s 1.16 h	196 1.41 h 1.84 h	TI 197 2.84 h	TI 198	TI 199 7.42 h	TI 200 26.1 h	TI 201 3.0422 d	TI 202 12.23 d	TI 203 29.52	TI 204 3.78 a	TI 205 70.48
5.22 m 20 m? δ γ 216, 326 265, 336 β*?	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	II 93 2.11 m 21.6 m ε, β ⁺ γ 324 IT (<13), e ¹ 1045, 676 γ 365 1580 ε g	11 194 32.8 m 33.0 m γ 428, 636 β* γ428, - γ428 γ 428	II 195 3.6 s 1.16 h β ⁺ 1.8 γ 564, 884 IT (99), e ⁻ 1364 9	II 1.96 1.41 h 1.84 h ε ε γ426, 635 ε ε 695 β* IT (120), e [±] γ 426, 611 γ275 635 635	11 197 2.84 h ε β ⁺ γ 426, 152 g	$\begin{array}{c c} TI 198 \\ \hline 1.87 h & 5.3 h \\ \hline \epsilon, \beta^* & \rho^* \\ \gamma 637, 412 \\ \epsilon \\ 587 & \beta^* \\ TI 261, e^- & \gamma 412, 676 \\ \gamma 283 & e^- 637 \end{array}$	Π 199 7.42 h ε γ 455, 208, 247 158 g	Π 200 26.1 h ε β* γ 368, 1206, 579 828	TI 201 3.0422 d γ 167, 135	τι 202 12.23 d γ 440, (520)	TI 203 29.52 σ 11.4 σ _{n,α} < 0.0003	Γ TI 204 3.78 a β ⁻ 0.8 ε no γ, g σ 21.6	TI 205 70.48 <u>σ 0.104</u>
5.22 m 20 m? ^β / _{β⁺ ^γ/_{216, 326} ^{265, 336} ^g/_{β⁺?} Hg 190}	$\begin{array}{c c} 11 & 1.52 \\ \hline 10.8 \text{ m} & 9.6 \text{ m} \\ \hline \beta^{+} \\ \gamma & 423, 635 \\ \gamma & 423, 635 \\ \gamma & 423, 691 \\ \hline 787 & 1113 \\ \hline Hg & 191 \end{array}$	II I93 2.11 m 21.6 m ε, β ⁺ 324 IT (<13), e ⁻ 1045, 676 γ 365 g Hg 192	11 194 32.8 m 33.0 m ^ε γ 428, 636 β* 749 γ 428 Hg 193	II 195 3.6 s 1.16 h β ⁺ 1.8 γ 564, 884 IT (99), e ⁻ 1364 γ 384 g Hg 194	II 196 1.41 h 1.84 h γ 426, 635 ε β 695 β* IT (120), σ* γ 426, 611 γ 275 635 Hg 195	11 197 2.84 h ^ε β ⁺ γ 426, 152 g Hg 196	TI 198 1.87 h 5.3 h γ 637,412 ε 587 587 β* 11261, e ⁻ γ 412,676 γ 283, e ⁻ 637 Hg	11 199 7.42 h ^ε γ 455, 208, 247 158 g Hg 198	TI 200 26.1 h ^ε ^{β⁺ γ 368, 1206, 579 828 Hg 199}	Π 201 3.0422 d γ 167, 135 Hg 200	TI 202 12.23 d ^ε γ 440, (520) Hg 201	TI 203 29.52 σ _{11.4} σ _{n,α} < 0.0003 Hg 202	7 TI 204 3.78 a β ⁻ 0.8 ε σ 21.6 Hg 203	TI 205 ^{70.48} <u>∝ 0.104</u> Hg 204
5.22 m 20 m? ^β , ^γ 216, 326 265, 336 g Hg 190 20.0 m	$\begin{array}{c c} 11 & 152 \\ \hline 10.8 \text{ m} & 9.6 \text{ m} \\ \hline \beta^{+} & \beta^{+} \\ \gamma & 423, 635 \\ \gamma & 423, 635 \\ \gamma & 423, 691 \\ 787 & 1113 \\ \hline Hg & 191 \\ \hline 50.8 \text{ m} & -50 \text{ m} \end{array}$	$\begin{array}{c c} II & I93\\ \hline 2.11 m & 21.6 m\\ \hline \epsilon, \beta^*\\ \gamma 365\\ \epsilon & 365\\ \hline g\\ \hline Hg & 192\\ \hline 4.85 h \end{array}$	11 194 32.8 m 33.0 m γ 428, 636 β* γ428, 100 γ γ428 Hg 193 11.8 h 3.80 h	$\begin{array}{c c} II 195\\ \hline 3.6 \text{ s} & 1.16 \text{ h}\\ & & & \\ & & & \\ & & & \\ \hline \gamma 564, 86'\\ & & & \\ \gamma 384' & & \\ \hline Hg 194\\ & & \\ & & \\ 447 \text{ a} \end{array}$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	11 197 2.84 h ^ε γ 426, 152 9 Hg 196 0.15	TI 198 1.87 h 5.3 h ε, β* γ γ 637,412 ε β* 587 β* T261, e ⁻ γ 412, 676 γ 233 e ⁻ 637 Hg 197 23.8 h 64.14 h	H 199 7.42 h ^ε γ 455, 208, 247 158 g Hg 198 10.04	Π 200 26.1 h ε β* γ 368, 1206, 579 828 Hg 199 42.67 m 16.94	TI 201 3.0422 d γ 167, 135 Hg 200 23.14	^ε ^γ 440, (520) Hg 201 13.17	σ 11.4 σ _{n,α} < 0.0003 Hg 202 29.74	TI 204 3.78 a β ⁻ 0.8 ε πο γ, g σ 21.6 Hg 203 46.59 d	TI 205 70.48 <u>∝ 0.104</u> Hg 204 6.82





Pb isotopes

Bi 193	Bi 194	Bi 195	Bi 196	Bi 197	Bi 198	Bi 199	Bi 200	Bi 201	Bi 202	Bi 203	Bi 204	Bi 205	Bi 206	Bi 207
3.12 s 63.6 s	115 s 125 s 95 s	87 s 183 s	4.00 m 0.6 s 5.13 m	n 5.15 m 9.33 m	7.7 s 11.6 m 10.3 m	24.70 m 27 m	31 m 36.4 m	57.5 m 103 m	1.71 h	11.76 h	11.22 h	14.91 d	6.24 d	31.55 a
$ \begin{array}{c} \epsilon \\ \gamma \ 175, \ 71 \\ 681 \\ \alpha \rightarrow g \\ \epsilon \end{array} \\ \begin{array}{c} \epsilon \\ \alpha \rightarrow m \end{array} $	$ \begin{array}{cccc} & & & & \\ \gamma & 965 & & & \epsilon & \\ 1 & 575 & \gamma & 965 & \gamma & 672 \\ 280 & 575 & \alpha & \\ \alpha & 5.599 & 280 & 5.645 \\ \alpha \rightarrow m & \alpha? & \alpha \rightarrow g \end{array} $	$ \begin{array}{c} \epsilon, \ \beta^+ \\ \gamma \ 808, \ 776 \\ \alpha \ 6.106 \\ \gamma \ (341) \\ \alpha \rightarrow g \\ \alpha \rightarrow m \end{array} $	$ \begin{array}{cccc} & \rho & \rho \\ \gamma & 1049 & \gamma \\ \text{IT} & (102) & \text{IT} & 1049. \\ e^- & (158) & \alpha \\ \alpha & 5.112 & e^- & 5.153 \\ \alpha & \rightarrow m & \epsilon? & \alpha \rightarrow g \end{array} $	α 5.780 ε α→g γ 855, 85 ε 867, 828 γ 1838 e [−] 1809 m, g	ε γ 1063 IT 249 198 ε e ⁻ 562 1063	$\begin{array}{c} \epsilon, \ p \ \dots \\ \gamma \ 842 \\ \epsilon \qquad 946 \\ \alpha \ 5.484 \qquad 837 \dots \\ \alpha \ \rightarrow g \qquad m, g \end{array}$	$ \begin{array}{cccc} \epsilon & \epsilon \\ \beta^{+} & \beta^{+} \\ \gamma \ 1027 & \gamma \ 1027 \\ 462 & 462, \ 420 \\ 420 & 245 \end{array} $	ε, p 2.2 ε γ 629, 936 g 1014 IT 846 786 α 5.24 m, g, α?	^δ ^{ε, β⁺} γ 961, 422 657, g α?	ε, β ⁺ 1.4, 2.2 γ 820, 825, 897 1848, 1034 g, m	ε γ 899, 375 984 g, m	ε, β ⁺ γ 1764, 703 988	ε, β⁺ γ 803, 881, 516 1719, 537	ε, β⁺ γ 570, 1064 1770
Pb 192	Pb 193	Pb 194	Pb 195	Pb 196	Pb 197	Pb 198	Pb 199	Pb 200	Pb 201	Pb 202	Pb 203	Pb 204	Pb 205	Pb 206
3.5 m	5.8 m ~5 m	10.7 m	15.0 m ~15 m	36.4 m	42.9 m 8.1 m	2.4 h	12.2 m 90 m	21.5 h	60.8 s 9.33 h	3.54 h 5.25-10 ⁴ a	6.21 s 51.92 h	66.93 m 1.4	1.70·10 ⁷ a	24.1
ε, β ⁺ 2.1, 2.3 γ 1195, 608, 168 e [−] , g α 5.112	ε, p 3.3 3.9 γ 392 716 m ε	ε, β⁺ γ 582, 1519 204, e⁻, g α 4.64	ε β ⁺ ε γ 394, 878 γ 384 708 883 m g	ε γ 253, 502, 367 192 g	ε γ 386, 388 223 IT 234, e ⁻ γ 85, e ⁻ 375	ε γ 290, 365 173 g	$\begin{array}{ccc} \text{IT } 424, e^- & \epsilon \\ \gamma? & \beta^+ \\ \epsilon & \gamma \ 367, \ 353 \\ \gamma \ 145 \ - & 1135 \\ 2613 & 720 \end{array}$	ε γ 148, 257, 236 268	ε β ⁺ γ 331, 36 ⁻ IT 629 946	IT 787 γ 422 961 ε 1 ε, γ 490 no γ 460, 390 α?	IT 825 γ 820, (5) γ 279 e⁻ 401	IT 912 γ 899 375 σ 0.703	ε no γ σ ~5	ş 0.027
TI 101														
11191	11/192	11 193	TI 194	TI 195	TI 196	TI 197	TI 198	TI 199	TI 200	TI 201	TI 202	TI 203	TI 204	TI 205
5.22 m 20 m?	11 192 10.8 m 9.6 m	2.11 m 21.6 m	TI 194 32.8 m 33.0 m	TI 195 3.6 s 1.16 h	TI 196	TI 197 2.84 h	TI 198	TI 199 7.42 h	TI 200 26.1 h	TI 201 3.0422 d	TI 202 12.23 d	TI 203 29.52	TI 204 3.78 a	TI 205 70.48
ε 20 m? γ 216, 326 265, 336 g β*?	$\begin{array}{c c} & 1 & 1 & 9 \\ \hline 10.8 & m & 9.6 & m \\ \hline & & & & \\ \beta^{+} & & & & \\ \gamma & 423, 635 & \gamma & 423, 69' \\ \gamma & 787 & & 1113 \end{array}$	II 193 2.11 m 21.6 m ε, β ⁺ γ 324 IT (<13), e ⁻ 1045, 676 γ 365 1580 g 9	11 194 32.8 m 33.0 m γ 428, 636 β ⁺ γ428, - γ428 γ 428	TI 195 3.6 s 1.16 h β ⁺ 1.8 γ 564, 884 IT (99), e ⁻ 1364 γ 384	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	TI 197 2.84 h ^ε β ⁺ γ 426, 152 g	$\begin{array}{c c} TI 198 \\ \hline 1.87 h & 5.3 h \\ \hline \epsilon, \beta^* & \\ \gamma 637, 412 \epsilon \\ \hline 587 & \beta^* \\ TI 261, e^- \gamma 412, 676 \\ \gamma 283 & e^- 637 \end{array}$	TI 199 7.42 h ^ε γ 455, 208, 247 158 g	TI 200 26.1 h ε β ⁺ γ 368, 1206, 579 828	TI 201 3.0422 d γ 167, 135	TI 202 12.23 d γ 440, (520)	TI 203 29.52 σ 11.4 σ _{n,α} < 0.0003	ΓΙ 204 3.78 a β [−] 0.8 ε no γ, g σ 21.6	TI 205 70.48 σ 0.104
5.22 m 20 m? ^β / _{β⁺} ^γ 216, 326 265, 336 ^g β ⁺ ? Hg 190	11 192 10.8 m 9.6 m β ⁺ β ⁺ γ423, 635 γ423, 69 ⁻ 787 11113 Hg 191	$\begin{array}{c c} II 193\\ 2.11 m & 21.6 m\\ \epsilon, \beta^+\\ \gamma 355\\ \epsilon & 355\\ \epsilon & g\\ Hg 192 \end{array}$	II 194 32.8 m 33.0 m ^ε γ428, 636 β* 749 γ 428 Hg 193	TI 195 3.6 s 1.16 h ^{β+} 1.8 γ 564, 884 γ 384 g Hg 194	TI 196 1.41 h 1.84 h γ 426, 635 ε β 695 β* IT (120), σ'' γ 426, 611 γ 275 635 Hg 195	TI 197 2.84 h ^ε β ⁺ γ 426, 152 g Hg 196	$\begin{array}{c c} TI 198 \\ 1.87 h & 5.3 h \\ \hline \epsilon, \beta^* & \\ 587 & \beta^* \\ 17 261e^- \gamma 412, 676 \\ \hline \gamma 283, e^- 637 \\ \hline Hg 197 \end{array}$	TI 199 7.42 h ^ε 455, 208, 247 158 g Hg 198	TI 200 26.1 h ^ε ^{β⁺ γ 368, 1206, 579 828 Hg 199}	TI 201 3.0422 d γ 167, 135 Hg 200	TI 202 12.23 d ^ε γ 440, (520) Hg 201	TI 203 29.52 σ11.4 σ _{n.a} < 0.0003 Hg 202	7 TI 204 3.78 a ^{β[−] 0.8 ε ^{no γ, g} σ 21.6 Hg 203}	TI 205 _{70.48} <u>• 0.104</u> Hg 204
5.22 m 20 m? ^β [†] ^γ 216, 326 ^{265, 336} ^g ^{β*?} Hg 190 20.0 m	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	$\begin{array}{c c} II 193\\ 2.11 m & 21.6 m\\ \epsilon, \beta^+\\ \gamma 365\\ \epsilon & g\\ IT (<13), e^-\\ 1045, 676\\ 1580\\ g\\ Hg 192\\ 4.85 h\end{array}$	II 194 32.8 m 33.0 m ^ε γ γ428, 636 β ⁺ γ428 γ Hg 193 11.8 h 3.80 h	$\begin{array}{c c} TI 195\\ \hline 3.6 \text{ s} & 1.16 \text{ h}\\ \hline \beta^+ 1.8\\ \gamma 564, 884\\ 1364\\ g\\ \hline Hg 194\\ 447 \text{ a} \end{array}$	$\begin{array}{c c c c c c c c c c c c c c c c c c c $	TI 197 2.84 h ^ε ^{β+} γ 426, 152 9 Hg 196 0.15	$\begin{array}{c c} TI 198 \\ 1.87 h & 5.3 h \\ \epsilon, \beta^* \\ \gamma 637,412 \\ \epsilon \\ 587 & \beta^* \\ 17261, e^- \gamma 412, 676 \\ \gamma 283 e^- 637 \\ Hg 197 \\ 23.8 h & 64.14 h \\ r \\ \gamma 495 & 64.14 h \\ \end{array}$	TI 199 7.42 h ^ε γ 455, 208, 247 158 9 Hg 198 10.04	TI 200 26.1 h ^ε ^{β⁺ γ 368, 1206, 579 828 Hg 199 42.67 m 16.94}	TI 201 3.0422 d γ 167, 135 Hg 200 23.14	TI 202 12.23 d ^ε γ 440, (520) Hg 201 13.17	TI 203 29.52 σ _{π,α} < 0.0003 Hg 202 29.74	^{β[−]} TI 204 3.78 a ^{β[−] 0.8 ^ε σ 21.6 Hg 203 46.59 d}	TI 205 ^{70.48} <u>∝ 0.104</u> Hg 204 6.82





Pb isotopes

Bi 193	Bi 194	Bi 195	Bi 196	Bi 197	Bi 198	Bi 199	Bi 200	Bi 201	Bi 202	Bi 203	Bi 204	Bi 205	Bi 206	Bi 207
3.12 s 63.6 s	115 s 125 s 95 s	87 s 183 s	4.00 m 0.6 s 5.13 n	m 5.15 m 9.33 m	7.7 s 11.6 m 10.3 m	24.70 m 27 m	31 m 36.4 m	57.5 m 103 m	1.71 h	11.76 h	11.22 h	14.91 d	6.24 d	31.55 a
$ \begin{array}{c} \epsilon \\ \gamma \ 175, \ 711 \\ 681 \\ \alpha \rightarrow g \\ \epsilon \end{array} $	$ \begin{array}{cccc} \gamma & 965 & \epsilon & \epsilon \\ 575 & \gamma & 965 & \gamma & 672 \\ 280 & 575 & \alpha \\ \alpha & 5.599 & 280 & 5.645 \\ \alpha \rightarrow m & \alpha? & \alpha \rightarrow g \end{array} $	$ \begin{array}{c} \epsilon, \ \beta^{+} \\ \gamma \ 808, \ 776 \\ \alpha \ 6.106 \ 134, \ e^{-}, \ g \\ \gamma \ (341) \\ \alpha \rightarrow g \\ \alpha \rightarrow m \end{array} $	$\begin{array}{cccc} \gamma & 1049 & \gamma \\ \gamma & 1049 & \gamma \\ \text{IT} & (102) & \text{IT} & 1049. \\ \text{e}^- & (158) & \alpha \\ \alpha & 5.112 & \text{e}^- & 5.153 \\ \alpha \rightarrow m & \epsilon? & \alpha \rightarrow g \end{array}$	α 5.780 ε α → g γ 855, 85 ε 867, 828. γ 1838 e [−] 1809 m, g	 γ 1063 μT 249 198 ε ε [−] 562 1063	$\begin{array}{c} \epsilon, p & \dots \\ \gamma & 842 \\ \epsilon & 946 \\ \alpha & 5.484 & 837 \dots \\ \alpha \rightarrow g & m, g \end{array}$	$\begin{array}{ccc} \beta^{+} & \beta^{+} \\ \gamma \ 1027 & \gamma \ 1027 \\ 462 & 462, \ 420 \\ 420 \\ \end{array}$	$\begin{array}{c} \epsilon, p \ 2.2\\ \epsilon & \gamma \ 629, 930\\ g & 1014\\ \text{IT} \ 846 & 786\\ \alpha \ 5.24 & \text{m}, \text{g}, \alpha? \end{array}$	^δ γ 961, 422 657, g α?	ε, β ⁺ 1.4, 2.2 γ 820, 825, 897 1848, 1034 g, m	ε γ 899, 375 984 g, m	ε, β ⁺ γ 1764, 703 988	ε, β ⁺ γ 803, 881, 516 1719, 537	ε, β ⁺ γ 570, 1064 1770
Pb 192	Pb 193	Pb 194	Pb 195	Pb 196	Pb 197	Pb 198	Pb 199	Pb 200	Pb 201	Pb 202	Pb 203	Pb 204	Pb 205	Pb 206
3.5 m	5.8 m ~5 m	10.7 m	15.0 m ~15 m	36.4 m	42.9 m 8.1 m	2.4 h	12.2 m 90 m	21.5 h	60.8 s 9.33 h	3.54 h 5.25-10 ⁴ a	6.21 s 51.92 h	66.93 m 1.4	1.70·10 ⁷ a	24.1
ε, β⁺ 2.1, 2.3 γ 1195, 608, 168 e⁻, g α 5.112	3.9 γ 392 716 m ε	ε, β⁺ γ 582, 1519 204, e⁻, g α 4.64		ε γ 253, 502, 367 192 g	ε γ 386, 388 ε 223 ΙΤ 234, e [−] γ 386, 761 γ 85, e [−] 375	: 7 290, 365 173	11 424, e ⁻ ε γ? β ⁺ ε γ 367, 353 γ 145 - 1135 2613 720	2 148, 257, 236 268	ε β ⁺ γ 331, 36 IT 629 946	11 787 γ 422 961 ε 1 ε, γ 490 no γ 460, 390 α?	IT 825 ε γ 820, (5) γ 279 e⁻ 401	IT 912 γ 899 375 σ 0.703	ε no γ σ ~5	; 0.027
TI 191	TI 192	TI 193	TI 194	TI 195	TI 196	TI 197	TI 198	TI 199	TI 200	TI 201	TI 202	TI 203	🖊 TI 204	TI 205
5.22 m 20 m?	10.8 m 9.6 m	2.11 m 21.6 m	32.8 m 33.0 m	3.6 s 1.16 h	1.41 h 1.84 h	2.84 h	1.87 h 5.3 h	7.42 h	26.1 h	3.0422 d	12.23 d	29.52	3.78 a	70.48
ε β ⁺ γ 216, 326 265, 336 g	ε β ⁺ γ 423, 635 787 ε β ⁺ γ 423, 691 1113	ε, β ⁺ γ 324 ΙΤ (<13), e [−] 1045, 676 γ 365 1580 ε g	ε γ 428, 636 β ⁺ 749 γ 428	IT (99), e ⁻ β ⁺ 1.8 γ 564, 88 γ 384 g	$ \begin{array}{c} \epsilon \\ \gamma \ 426, \ 635 \\ 695 \\ IT \ (120), \ e^{-} \\ \gamma \ 426, \ 611 \\ 635 \end{array} $	ε β⁺ γ 426, 152 g	ε, β ⁺ γ 637, 412 ε 587 β ⁺ ΙΤ 261, e [−] γ 412, 676 γ 283, e [−] 637	ε γ 455, 208, 247 158 g	ε β ⁺ γ 368, 1206, 579 828	9 ε γ 167, 135	ε γ 440, (520)	σ 11.4 σ _{n,α} < 0.0003	β⁻ 0.8 ε no γ, g σ 21.6	σ 0.104
Hg 190	Hg 191	Hg 192	Hg 193	Hg 194	Hg 195	Hg 196	Hg 197	Hg 198	<u>Hg</u> 199	Hg 200	Hg 201	Hg 202	Hg 203	Hg 204
20.0 m	50.8 m ~50 m	4.85 h	11.8 h 3.80 h	447 a	41.6 h 10.53 h	0.15	23.8 h 64.14 h	10.04	42.67 m 16.94	23.14	13.17	29.74	46.59 d	6.82
	lot		ε, β΄		11 (123), e									





Systematics

- Assumed single-particle states are shown in the figure
- The level energies are based on the α- and βdecay studies
- Is the first excited 13/2⁺ state coupled with the π(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}Pb,p) ^{197,199}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 $\mu g/cm^2$





Proton yields for different states

- Calculated with an assumption C²S=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 ¹⁹⁹Pb



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(¹⁹⁶Pb,p)¹⁹⁷Pb

- Simulation performed with NPTool
- Aim to be sensitive to C²S≥0.2 for 13/2⁺ state
- Some fragmentation of the low-*l* strength is expected.
- A similar excitation spectrum is expected for ¹⁹⁹Pb





NPTool: A. Matta et al. J. Phys. G **43**, 045113 (2016)



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 evaluated in combination with a FC and luminosity monitor

Isotope	E _{Beam}	Average yield	Purity
	[MeV/u]	[pps]	[%]
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



J. Pakarinen et al JPS Conf. Proc. 6 02001 (2015)



TAC Recommendation

TACThe TAC notes that the requested energy is at the edge of the feasibility and that the
recommendationrecommendationrate 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}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

En	ergy (keV)	I^{π}	σ_{DWBA}	Counts per shift
2	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



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

J. Ojala¹, R. D. Page¹, J. Pakarinen^{2,3}, M. Alaqeel^{4,1}, A. N. Andreyev⁵, J. Benito⁶,
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

1 ~ - - - -







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







Level schemes ^{197,199}Pb

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



