Shape coexistence in ^{196}Po: An in-beam spectroscopic study

Andy Briscoe

IOP Manchester April 2025

Outline

- Introduction
  - Shape coexistence in neutron-deficient HgPbPo region
  - Evolution of excited states in Po isotopes
  - ^{196}Po Motivation
- Experimental Method
- Results
- Conclusion & Future Work

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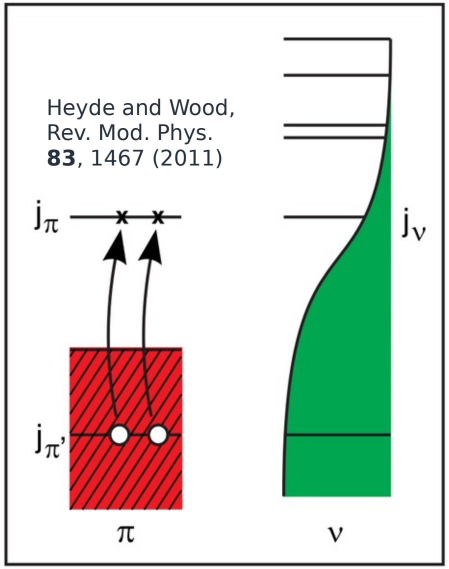
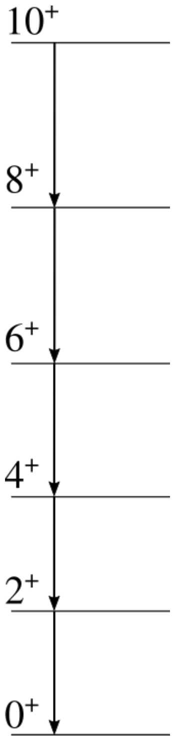
Introduction

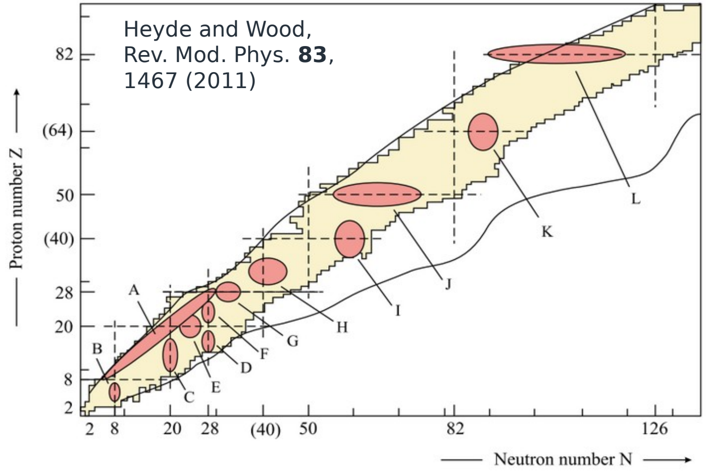
Shape coexistence, co-existing structures at low energies with distinctly different shapes.
Interplay:
i) stabilizing of closed shells
ii) residual internation of valence nucleons.

Near shell closures associated with pair excitations across shell-gap





States built on
g.s. configuration



Introduction

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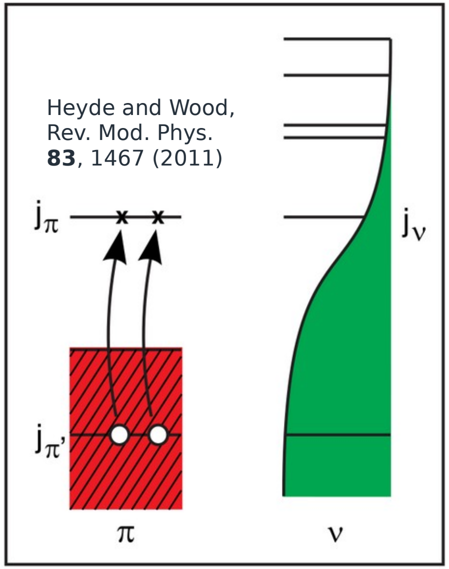
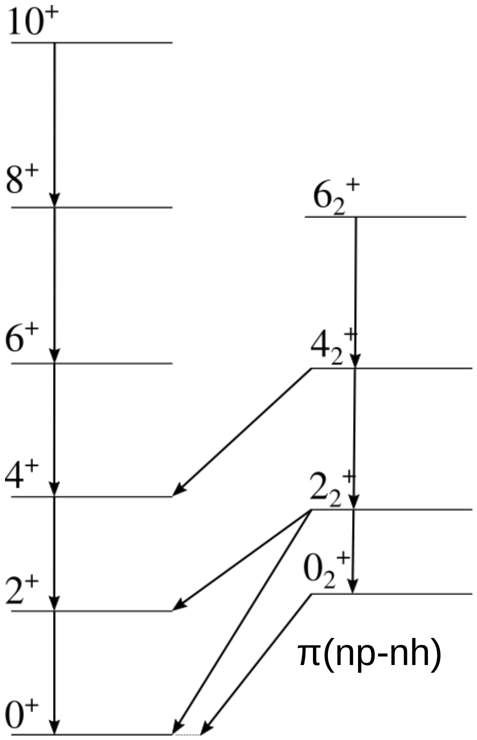
Associated with different shapes





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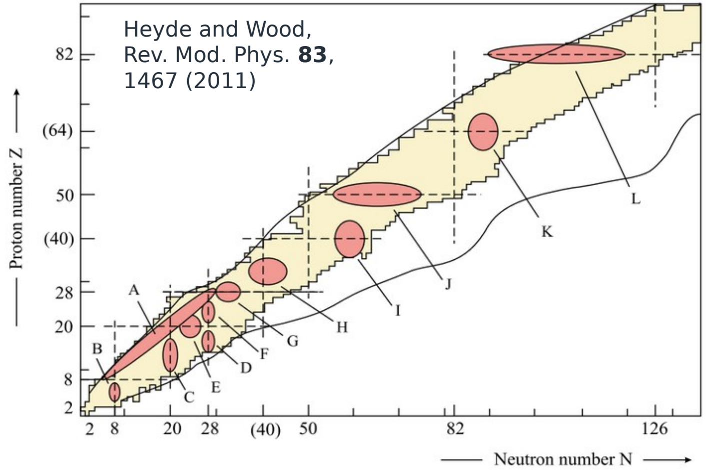


E0 transitions between (J→ J) states are are sensitive to the changes in the nuclear charge-squared radii, and their degree of mixing (α).

Enhanced conversion between these states is a fingerprint of mixed coexisting structures with different β_2 values

Measure E0 strength, assess mixing

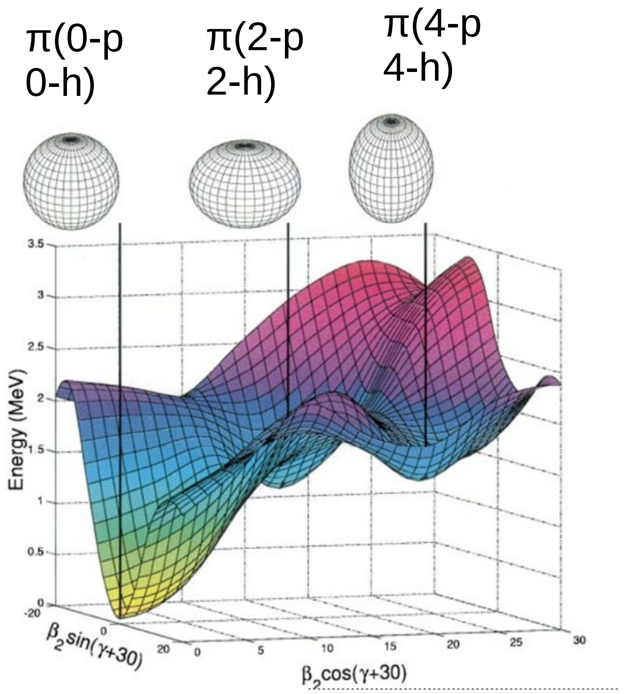
$$\rho^2\left(J_i^\pi \to J_f^\pi\right) = \left(\frac{3Z}{4\pi}\right)^2 a^2(1-a^2)\left(\beta_{2,i}^2 - \beta_{2,f}^2\right)^2$$

Shape coexistence in the neutron-deficient HgPbPo region

Famous case (Andreyev et at. 2000)
evidence of 3 different shapes probed with α-decay fine structure.

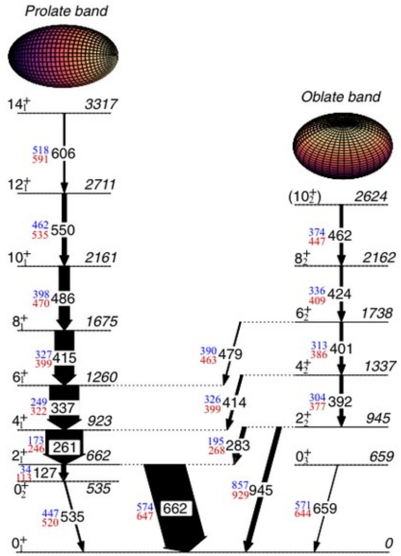
Z = 82, spherical ground state π(0p-0h) excite pairs above shell gap
oblate and prolate shapes with π(2p-2h) & π(4p-4h)

Recent work (J. Ojala et al 2023), observed band structures built on these states directly in ^{186}Pb

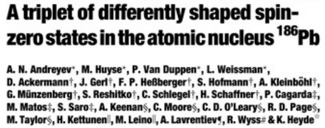



ARTICLE
https://doi.org/10.1038/s42005-022-00990-4 OPEN
Reassigning the shapes of the 0+ states in the ^{186}Pb nucleus

Joonas Ojala[1], Janne Pakarinen[1], Philippos Papadakis[1,6], Juha Sorri[1,7], Mikael Sandzelius[1], Daniel M. Cox[1,2,8], Kalle Auranen[1], Hussam Badran[1], Paul J. Davies[3], Tuomas Grahn[1], Paul T. Greenlees[1], Jack Henderson[3,9], Andrej Herzáň[1,4], Rolf-Dietmar Herzberg[2], Joshua Hilton[1,2], Ulrika Jakobsson[1], David G. Jenkins[3], David T. Joss[2], Rauno Julin[1], Sakari Juutinen[1], Tibor Kibédi[5], Joonas Konki[1], Gregory J. Lane[5], Matti Leino[1], Jarkko Liimatainen[1], Christopher G. McPeake[1,2], Olavi Neuvonen[1,7], Robert D. Page[2], Edward Parr[2], Jari Partanen[1,10], Pauli Peura[1], Panu Rahkila[1], John Revill[2], Panu Ruotsalainen[1], Jan Sarén[1], Catherine Scholey[1], Sanna Stolze[1], Juha Uusitalo[1], Andrew Ward[2] & Robert Wadsworth[3]



Deformed intruder picture firmly established in Hg & Pb isotopes, important to extend spectroscopic studies to with Z > 82, close to the neutron mid-shell


A triplet of differently shaped spin-zero states in the atomic nucleus ^{186}Pb

A. N. Andreyev*, M. Huyse*, P. Van Duppen*, L. Weissman*, D. Ackermann†, J. Gerl†, F. P. Heßberger†, S. Hofmann†, A. Kleinböhl†, G. Münzenberg†, S. Reshitko†, C. Schlegel†, H. Schaffner†, P. Cagarda‡, M. Matos‡, S. Saro‡, A. Keenan§, C. Moore§, C. D. O'Leary§, R. D. Page§, M. Taylor§, H. Kettunen‖, M. Leino‖, A. Lavrentiev¶, R. Wyss# & K. Heyde☆

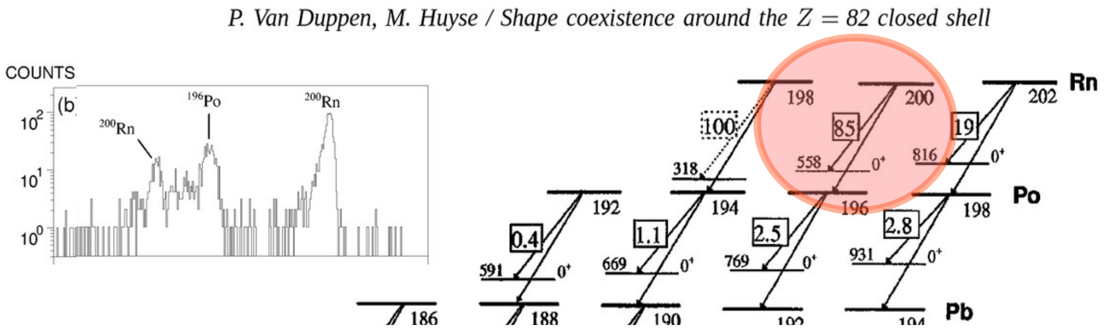
Evolution of excited states in Po isotopes

α-decay fine structure work (P. Van Duppen, M. Huyse (2000)) first revealed excited 0^+ state at 558 keV.

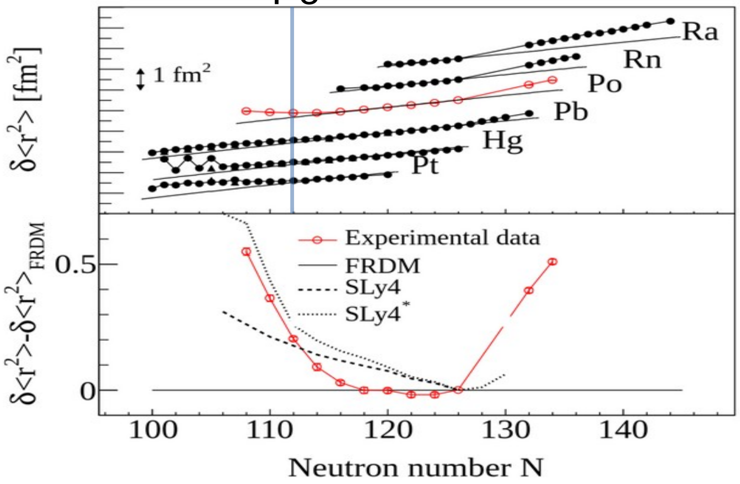
$\Delta L = 0$, Large Hindrance factor ≈ 85

$$\langle \Psi_{^{200}\mathrm{Rn}} || | \Psi_{^{196}\mathrm{Po}} \rangle \otimes | \Psi_{\alpha} \rangle \rangle$$

Significant structural change



196Po



More recent laser spectroscopy work (T. E, Cocolios 2011) has shown, mean-square charge radius displays a surprisingly large and early departure at ^{196}Po(N = 112) before mid-shell (N =104).

Interpreted as mixing with deformed intruder states.

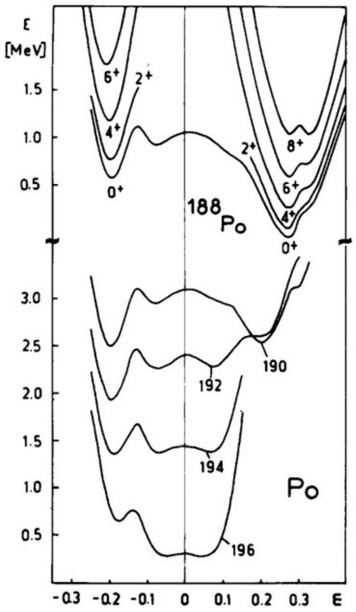
Early onset of ground-state deformation in the neutron-deficient polonium isotopes

T.E. Cocolios[1,2], W. Dexters[1], M.D. Seliverstov[1,3,4], A.N. Andreyev[1,5], S. Antalic[6], A.E. Barzakh[3], B. Bastin[1*], J. Büscher[1], I.G. Darby[1], D.V. Fedorov[3], V.N. Fedosseyev[7], K.T. Flanagan[8,9], S. Franchoo[10], S. Fritzsche[11,12], G. Huber[4], M. Huyse[1], M. Keupers[1], U. Köster[13], Yu. Kudryavtsev[1], E. Mané[8†], B.A. Marsh[7], P.L. Molkanov[3], R.D. Page[14], A.M. Sjoedin[7,15], I. Stefan[10], J. Van de Walle[1,2‡], P. Van Duppen[1], M. Venhart[1,16], S.G. Zemlyanoy[17], and M. Bender[18], P.-H. Heenen[19]

Studies restricted to ground & states populated by α decay.

Detailed spectroscopy on excited states can give further information for interpreting structure of neutron-deficient Po isotopes.

Evolution of excited states in Po isotopes



A PREDICTION ON THE SHAPE TRANSITIONS IN VERY NEUTRON-DEFICIENT EVEN-MASS ISOTOPES IN THE LEAD REGION

F.R. MAY[1], V.V. PASHKEVICH and S. FRAUENDORF[2]
Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, USSR

Received 15 December 1976

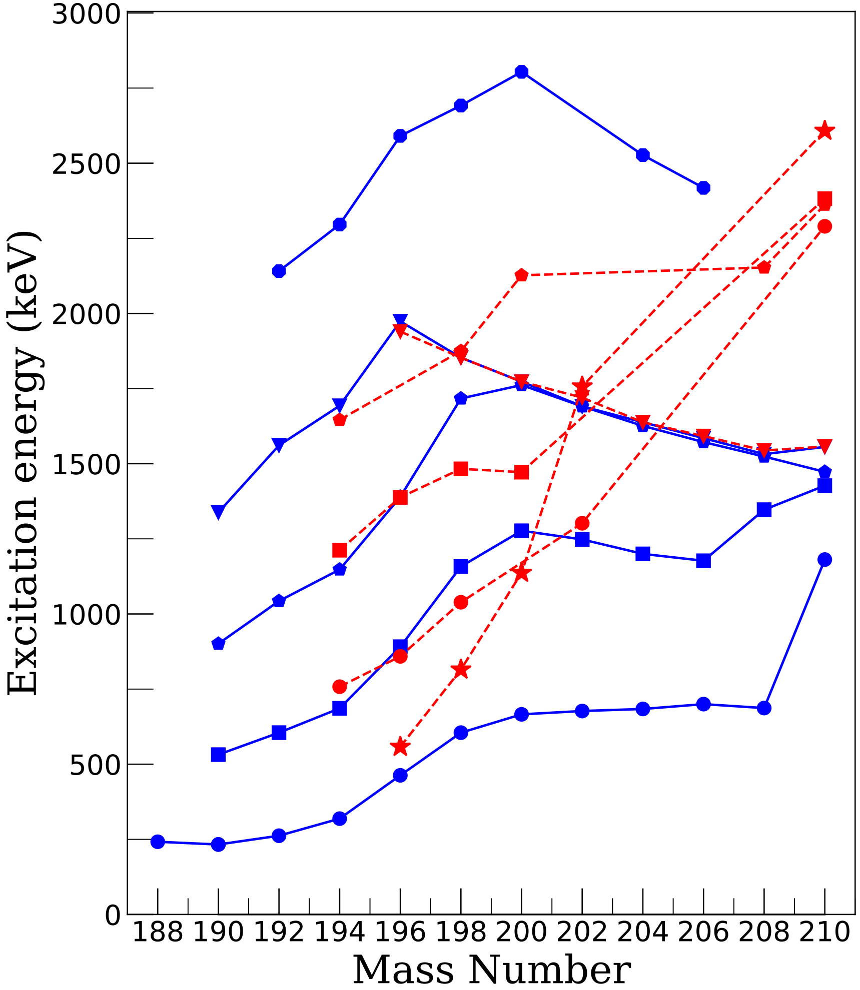
Shape transitions in neutron deficient Po isotopes first predicted May & Frauendorf 1976.

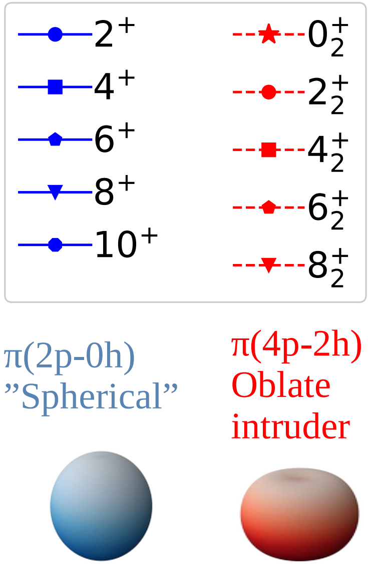
Minima in β_2 surface as a function of A. ^{196}Po spherical & oblate

Prolate minima expected to develop towards ^{188}Po

(right) excited states in even Po isotopes.

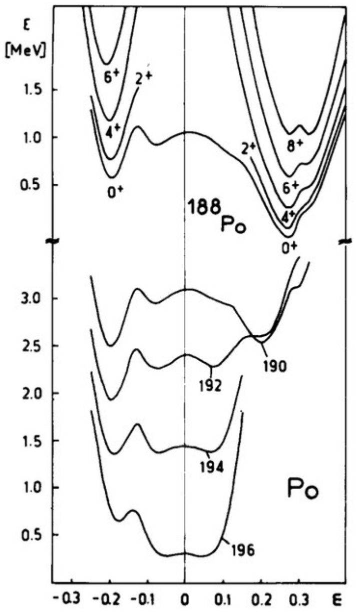
Labelled by shape at N = 126 shell closure.
Oblate π(4p-2h) intruder states comes down.
Highly mixed in the middle





Note: additional states above 2 MeV not shown.

Evolution of excited states in Po isotopes



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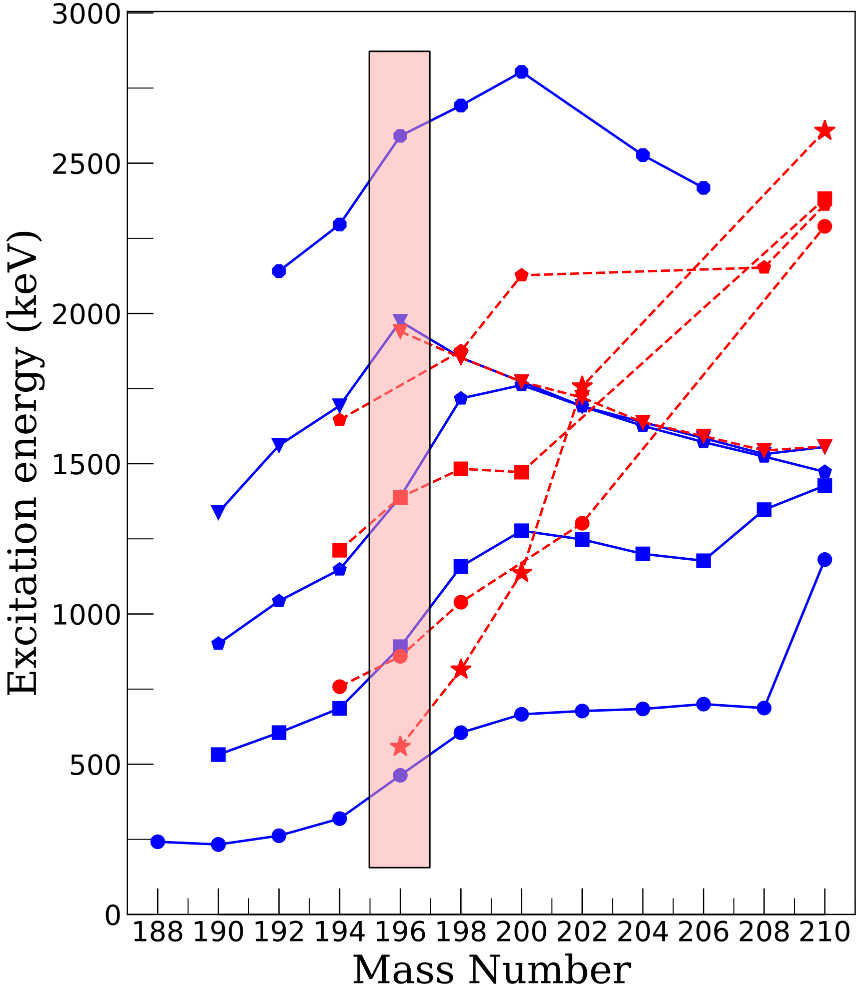
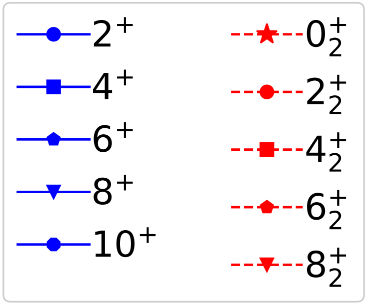
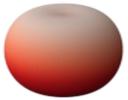
Now onto highlighted states in ^{196}Po





π(2p-0h) "Spherical"

π(4p-2h) Oblate intruder



Note: additional states above 2 MeV not shown.

^{196}Po Motivation

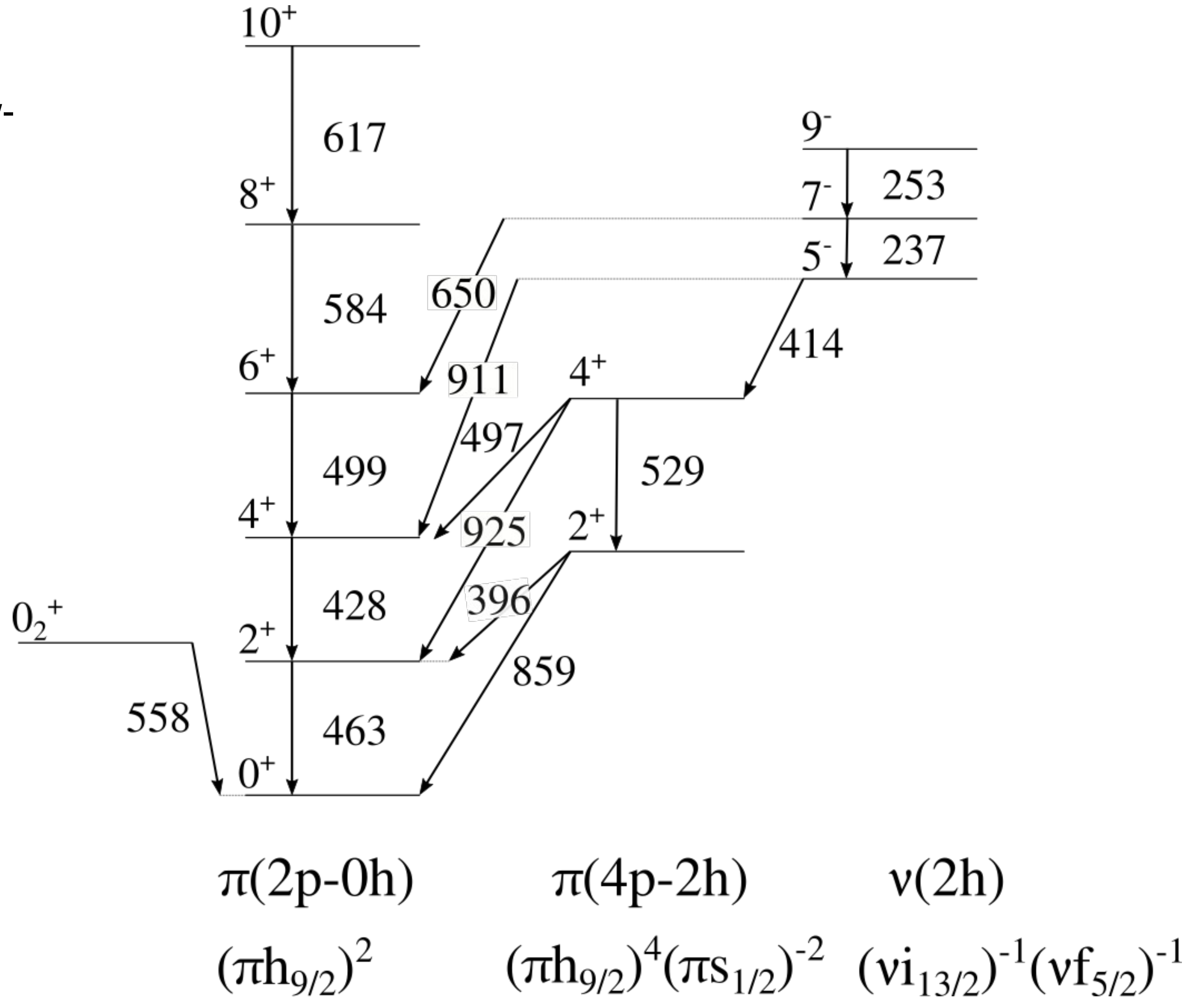
Partial level-scheme showing the known low-lying prompt structures in ^{196}Po:

i) Ground state (yrast) band

ii) Intruder oblate band

iii) negative parity neutron hole states

iv) 0_2^+ (α decay)



Primary aims of the experiment:

1. In-beam ɣ-e study to study J→J conversion coefficients (assess mixing)

2. Population of 0_2^+ state, measure electrons directly first time (not through α decay)

3. Identify feeding of 0_2^+, 301 keV ɣ ray.

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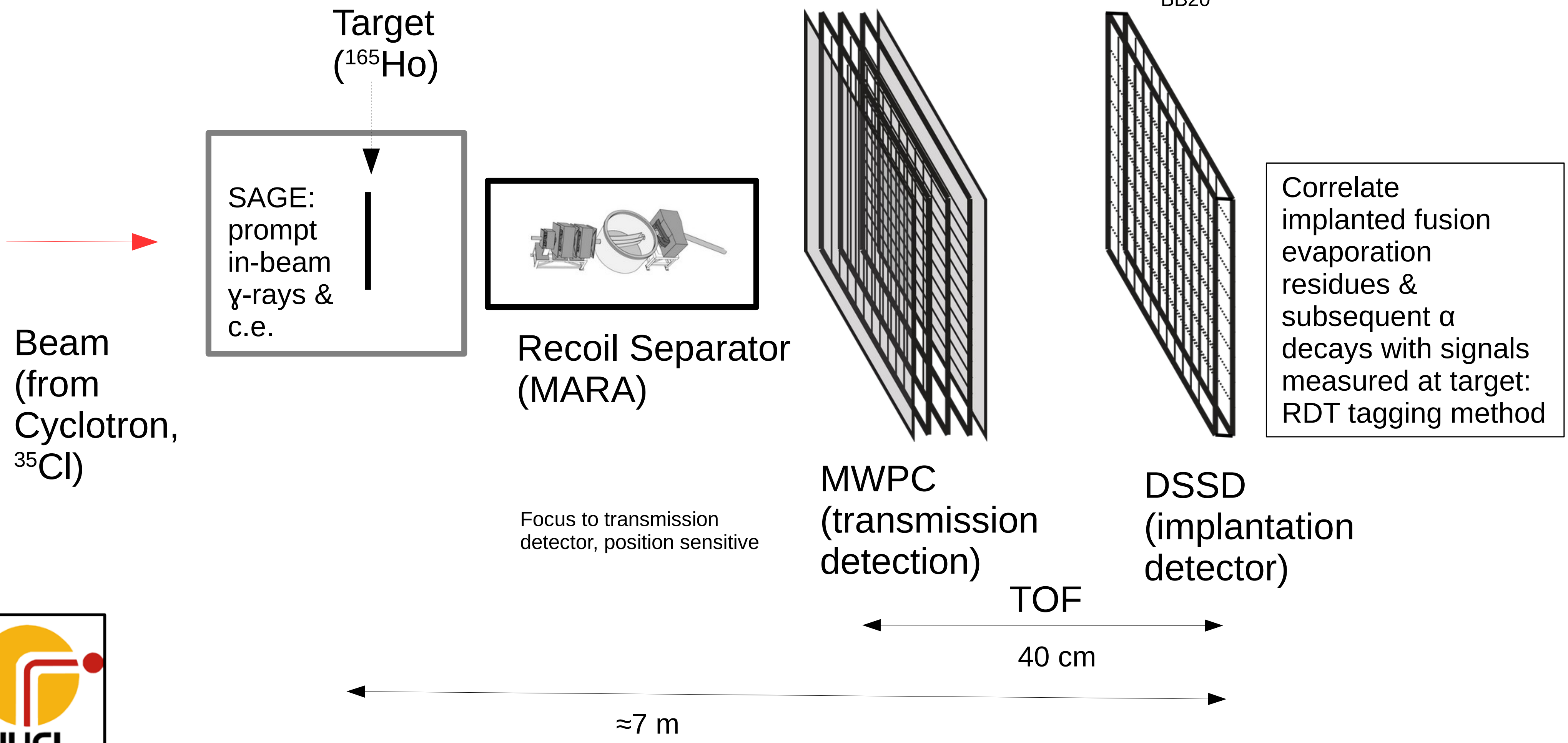
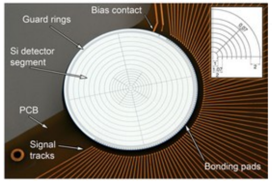
Correlation of fusion products



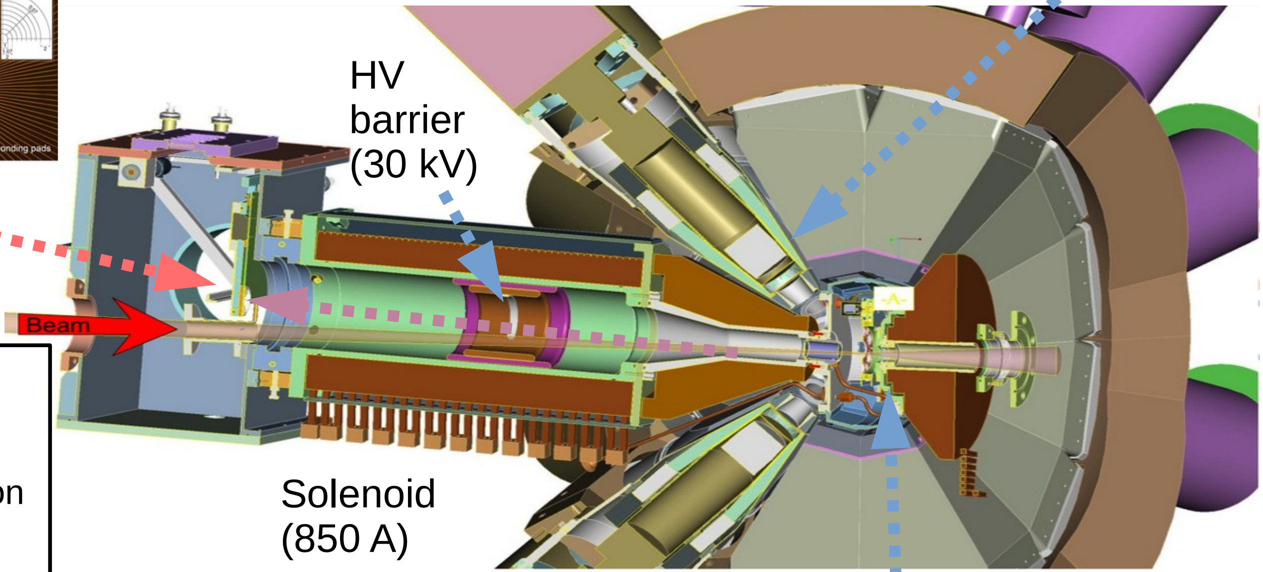
SAGE: Simultaneous in-beam-electron- and gamma-ray spectroscopy

Segmented Si detector 1.0 mm thick



Ge detectors

HV barrier (30 kV)



Solenoid (850 A)

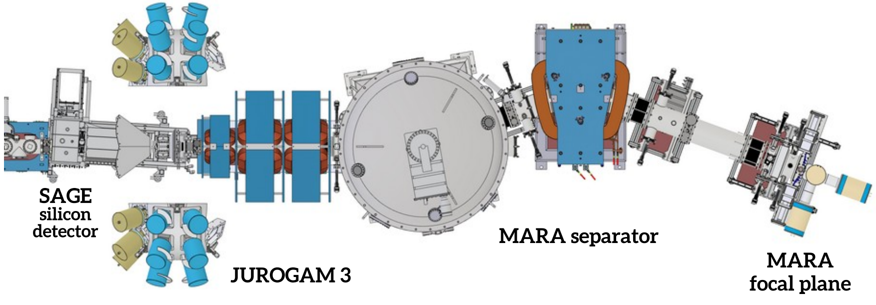
Target wheel

SAGE: simultaneous in-beam spectroscopy of electrons and ɣ rays.

Originally designed for use in superheavy region (J. Chadderton’s talk earlier today Fm region)

also finds purpose in study of low-lying 0+ states, and J→J transitions in lower mass nuclei.

Solenoid system for transport of electrons away from target to Si detector. HV barrier to suppress δ rays from atomic interaction within target. JUROGAM 3 Ge detectors for coincident ɣ rays.



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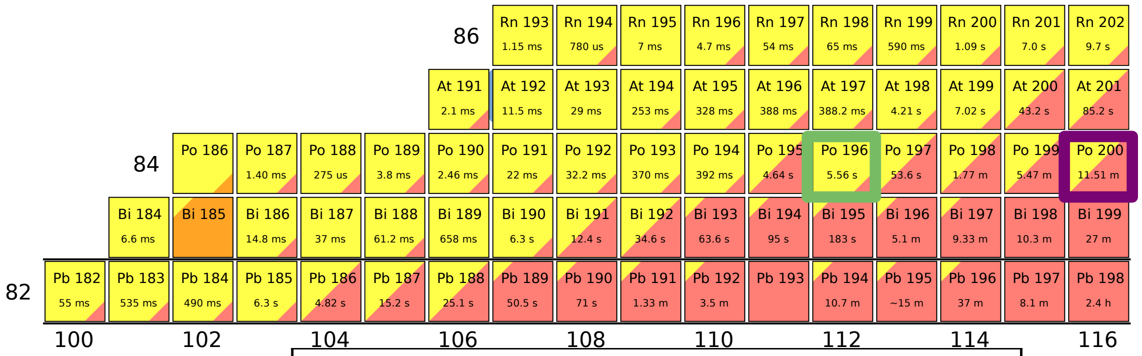
Experimental info

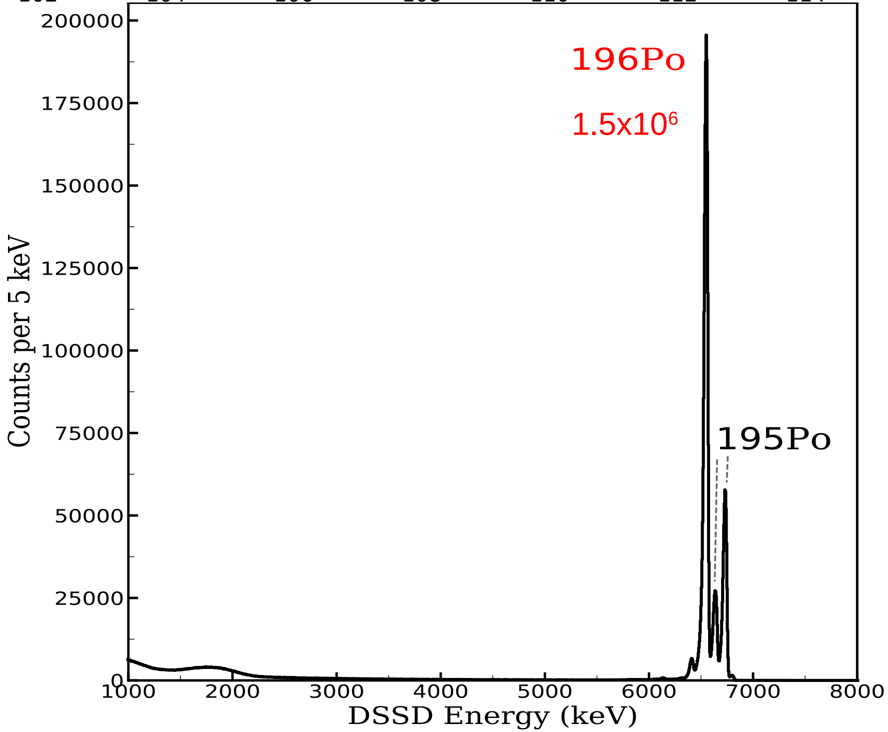
Due to increased fission probability above Pb, and distance from stability, study of exotic Po isotopes is increasingly difficult.

Reaction: ^{165}Ho(^{35}Cl, 4n)^{196}Po
Beam energy: 165 MeV
Beam intensity : 3.5 pnA
Target thickness 0.5 ug/cm^2
Cross section: ≈ 1-2 mb
Time: ≈ 7 days

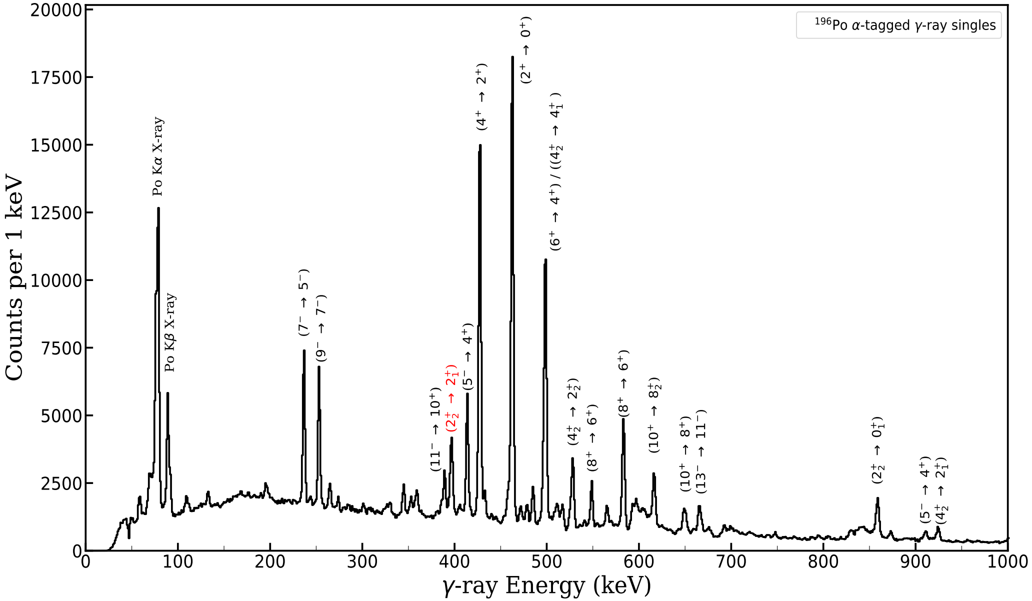
^{196}Po α decay very clean tag (MICRON BB20 DSSD 72x192, 13824 0.45 mm^2 pixels)

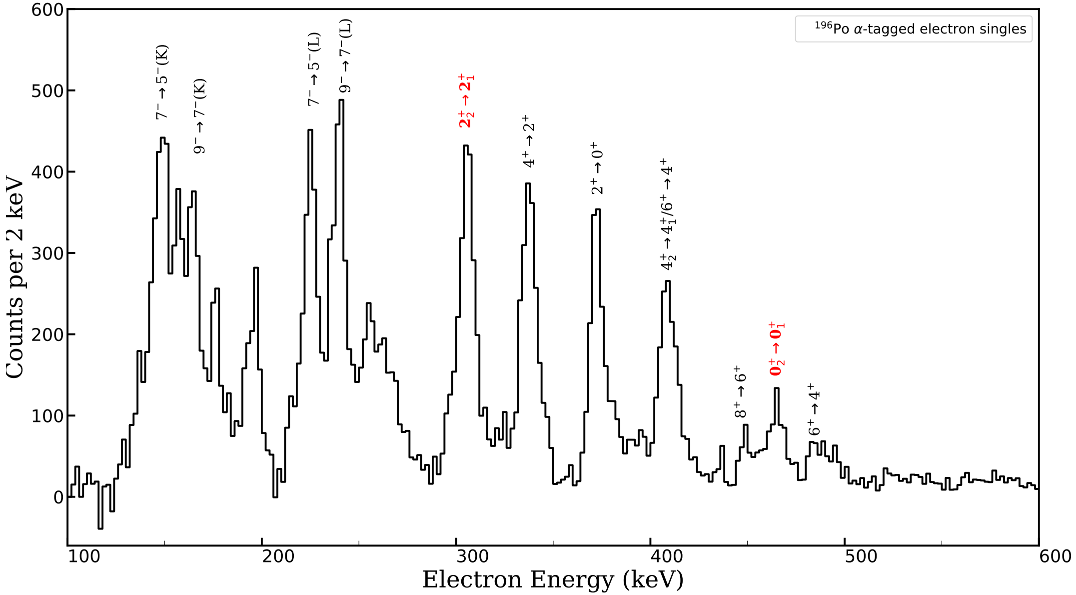
^{196}Po b_α = 98% $t_{1/2}$ = 5.8 s, E_α= 6522 keV





Results: γ ray & electron singles



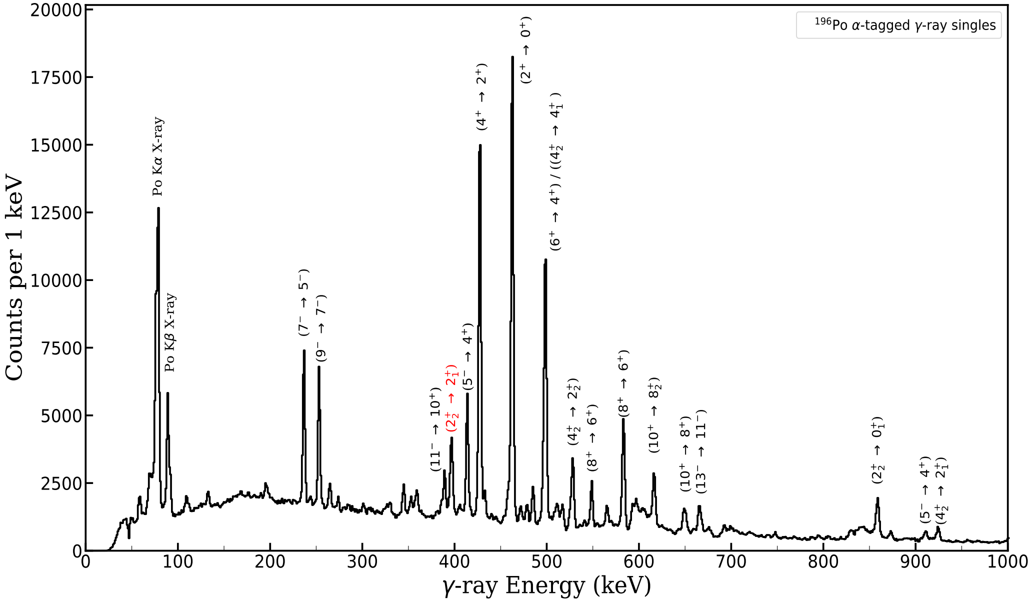


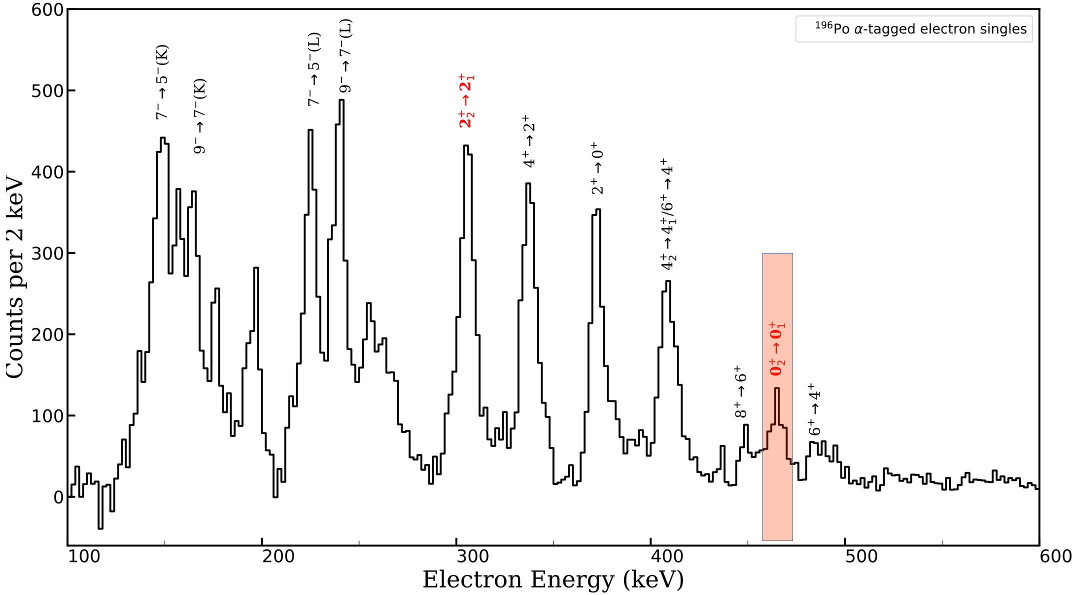
α-tagged gamma rays (left), populate all 3 structures, "normal" π(2p-0h), "intruder" π(4p-2h) & neutron hole (negative parity) states. Main peaks labelled.

α-tagged electrons measure in SAGE (right), transitions of labelled origin labelled (mostly K). E0 transitions highlighted in red. (**Note enhanced conversion of 2_2^+->2_1^+**)

Now walk through what we can learn from this.

Results: ɣ ray & electron singles





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α-tagged electrons measure in SAGE (right), transitions of labelled origin labelled (mostly K). E0 transitions highlighted in red. (**Note enhanced conversion of 2_2^+->2_1^+**)

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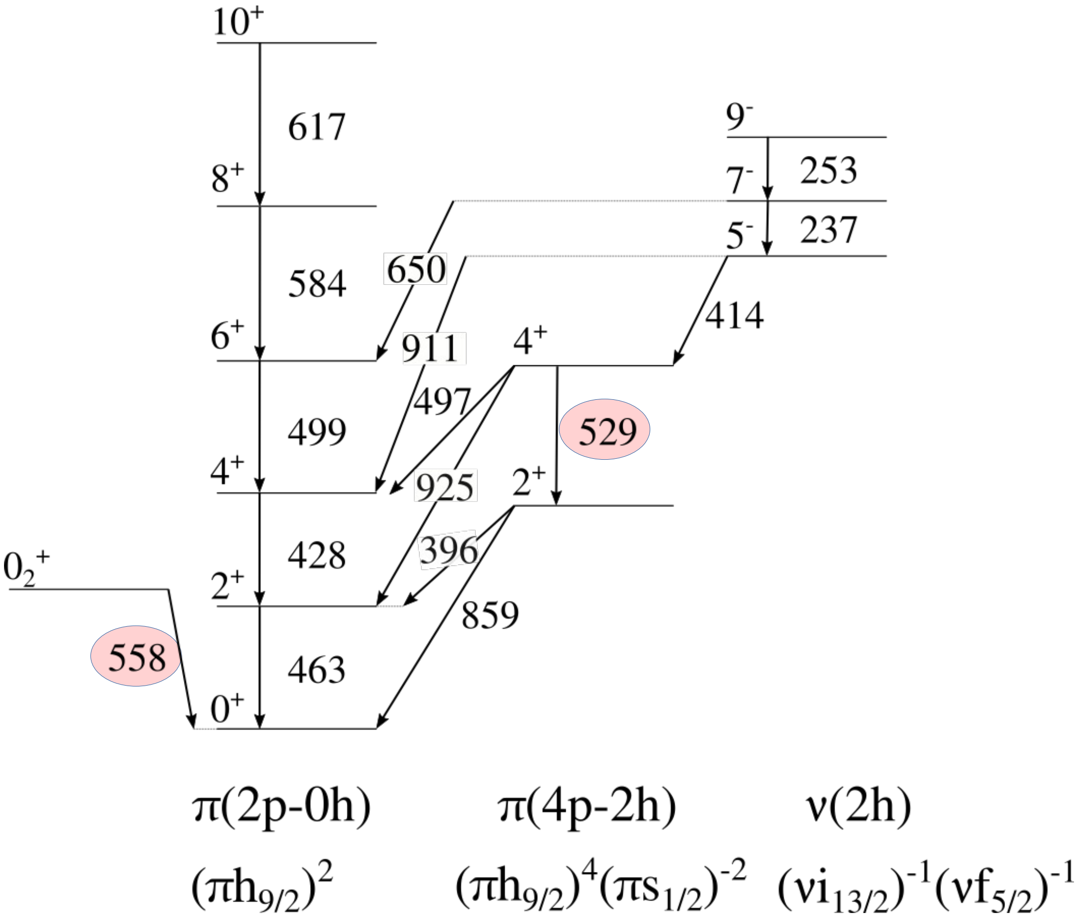
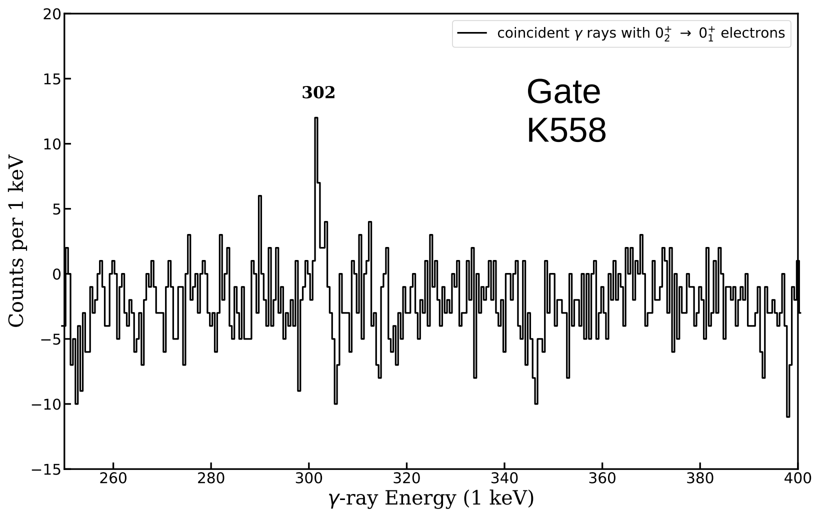
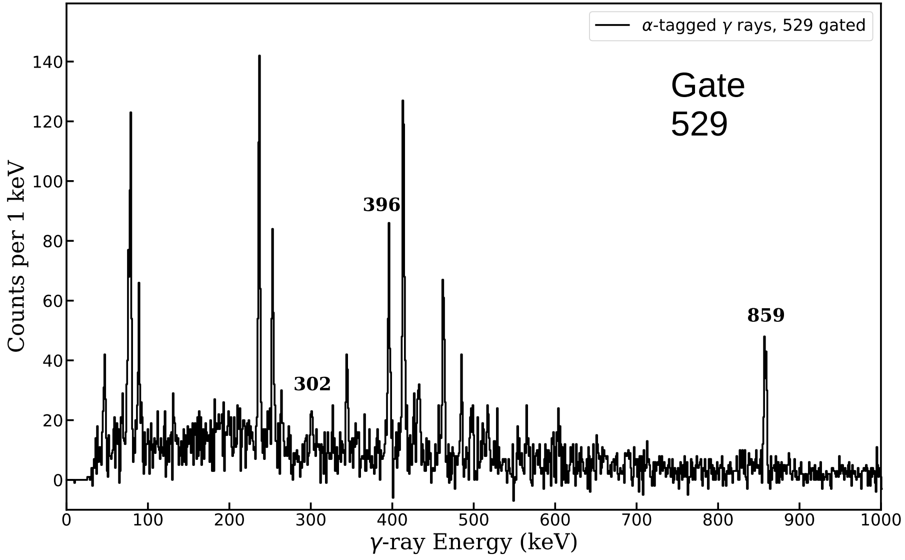
First looking at ɣ-ray feeding of 0_2^+ state

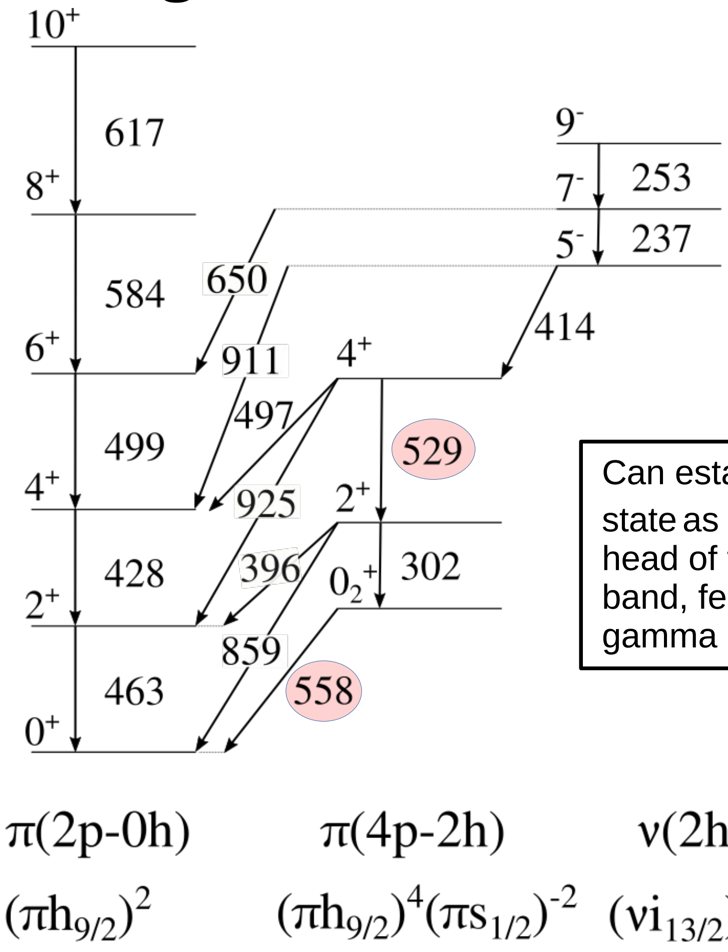
0_2^+ feeding


10+
617
8+
584
6+
499
4+
428
2+
463
0+
0₂+
558
650
911
497
925
396
859
4+
529
2+
9-
7-
5-
253
237
414
π(2p-0h)
(πh9/2)2
π(4p-2h)
(πh9/2)4(πs1/2)-2
ν(2h)
(νi13/2)-1(νf5/2)-1

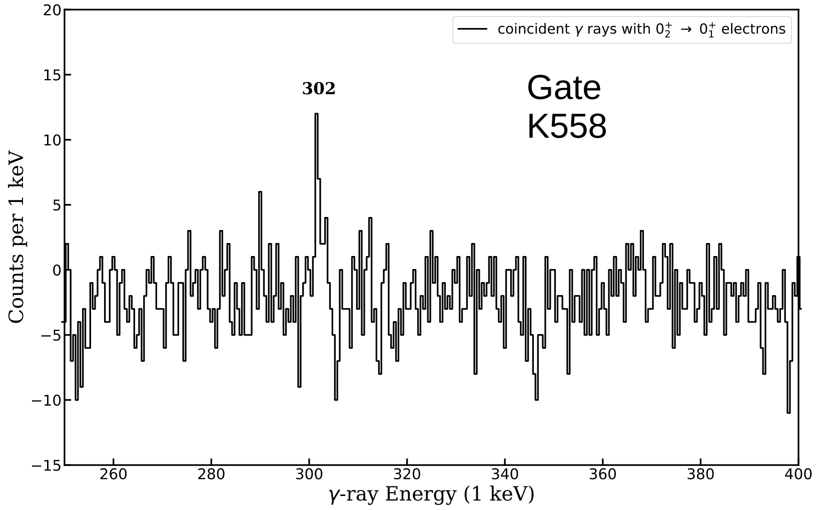

coincident γ rays with 0₂+ → 0₁+ electrons
Gate
K558
302
Counts per 1 keV
γ-ray Energy (1 keV)

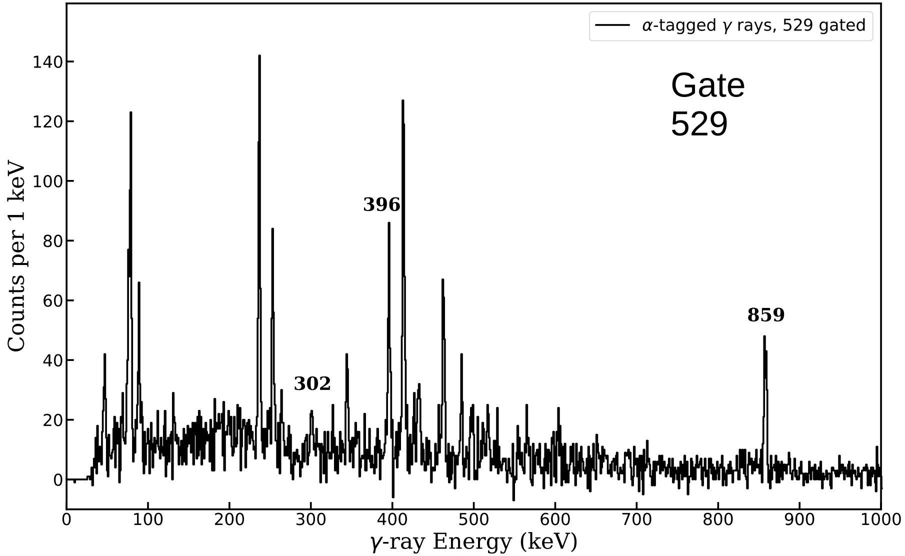

α-tagged γ rays, 529 gated
Gate
529
396
302
859
Counts per 1 keV
γ-ray Energy (keV)

0_2^+ feeding: oblate band via 302



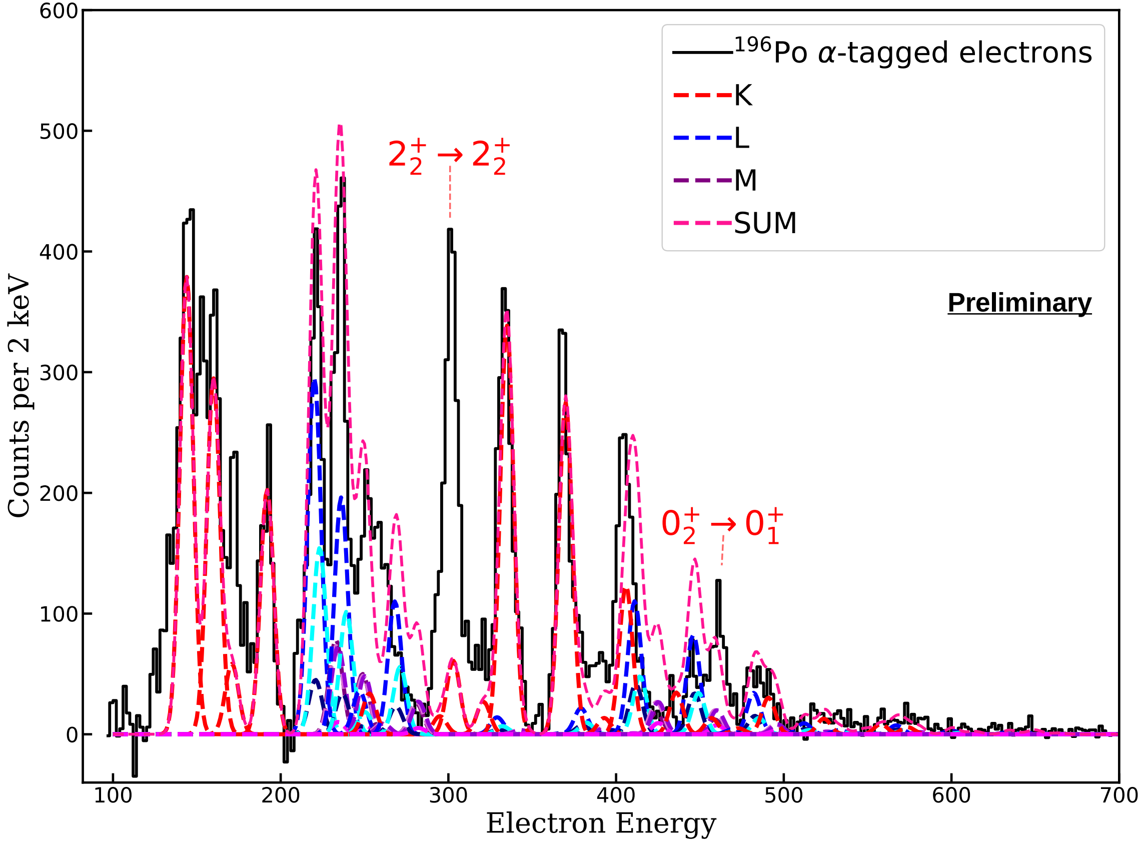
Can establish the 0_2^+ state as the band head of the oblate band, fed by 302 keV gamma ray

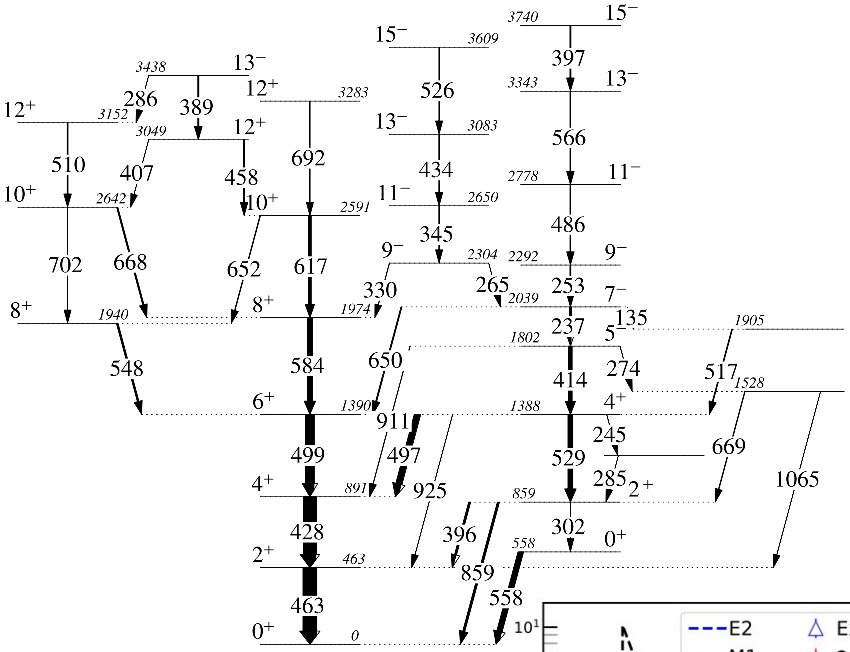


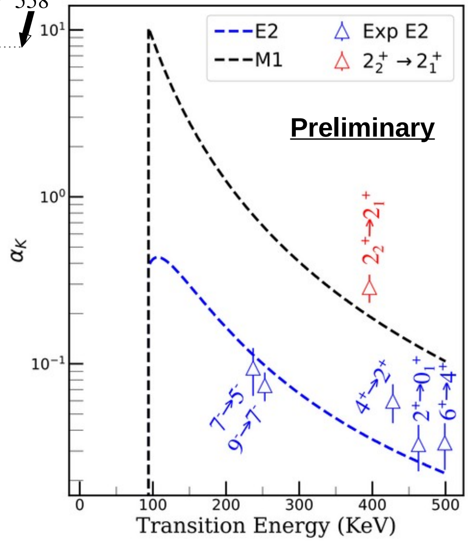


What about the rest of the electron spectrum and $2_2^+ \rightarrow 2_1^+$?

Conversion coefficients & mixing







Measure ɣ-ray intensities. Overlay deconvolution of calculated electron using BRICC and efficiencies.

Most of the electron described well. E0 transitions (2+→2+) and (0+→0+)

Alternatively, can fit electron spectrum for conversion coefficients. Ongoing to extract these, many components..

$2_2^+ \rightarrow 2_1^+$ α_k (E0 + E2) = 0.287(55),

396 keV ɣ ray R_{DCO} = 0.97(17)

BRICC: E2 3.623E-02

(M1 1.937E-01)

α_k(E0) = 0.251(55)

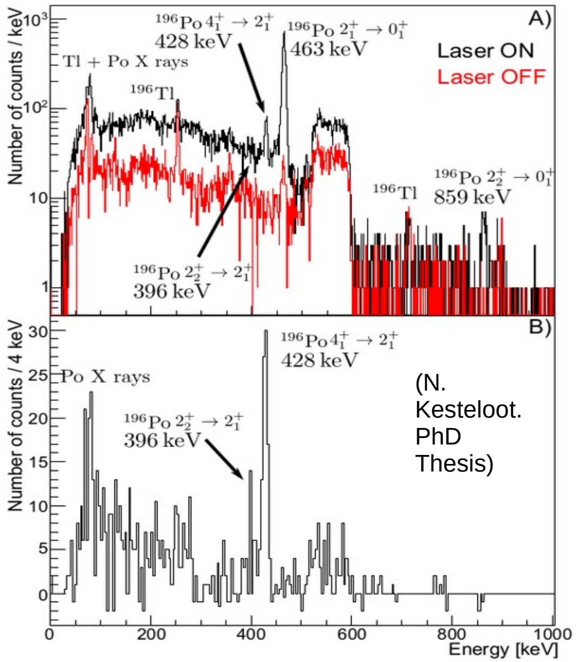
Conversion coefficients & mixing

The electric monopole strength for the $2^+ \rightarrow 2^+$ transition can be calculate from the E0 component of $\alpha_k(E0)$ = 0.251(55)

$$\rho^2 = \frac{I_K(E0)}{I_\gamma(E2)\,\Omega_K(E0)\,\tau_\gamma(E2)}$$

τ_γ = 7(1) ps, measured Coulex (N. Kesteloot PRC 2015)

$\rho^2 =$ 48(13) x 10^{-3}



(N. Kesteloot. PhD Thesis)

$$\rho^2\,(J_i^\pi \rightarrow J_f^\pi) = \left(\frac{3Z}{4\pi}\right)^2 a^2(1-a^2)\,\left(\beta_{2,i}^2 - \beta_{2,f}^2\right)^2 \,,$$

$\beta_{2,i\text{-}f}$ can be estimated from measured transition strengths, used to calculate mixing

$\beta_{2,i}$= (-)0.18 (130 W.u. N. Kesteloot PRC 2015), $\beta_{2,f}$= 0.10 (47 W.u. T. Grahn PRC 2009)

α^2 = 0.55(15) ≈45% spherical – oblate mixing can be expected at low-spin in ^{196}Po

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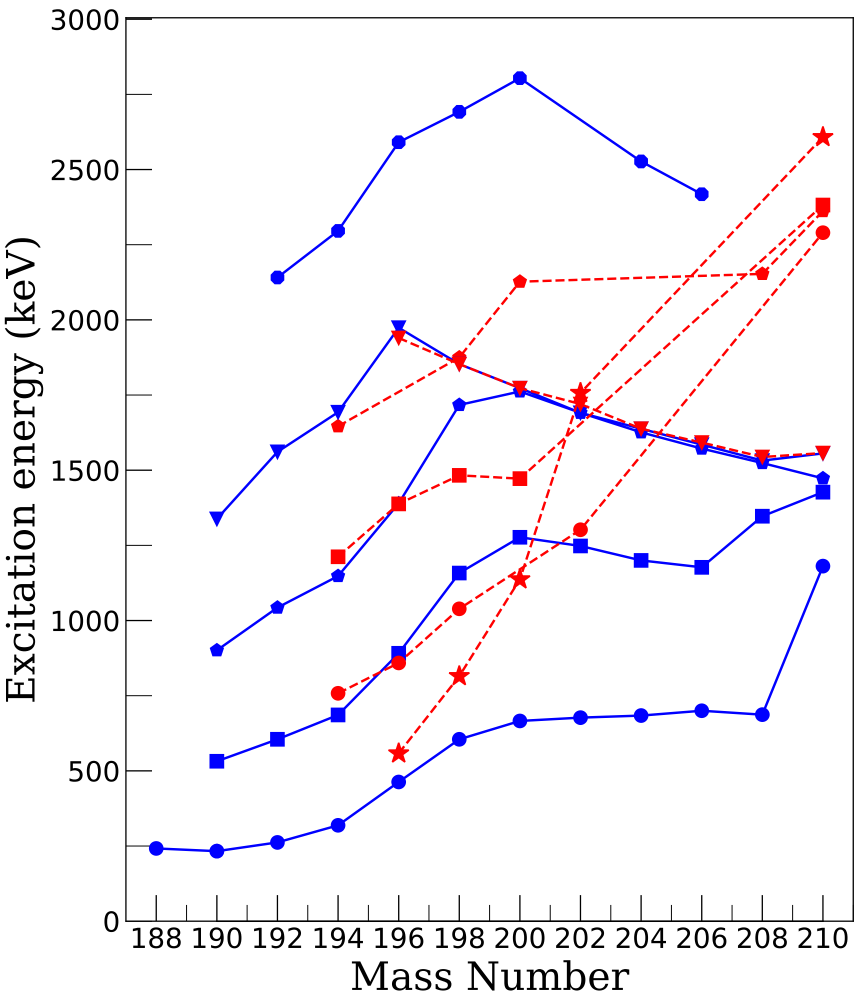
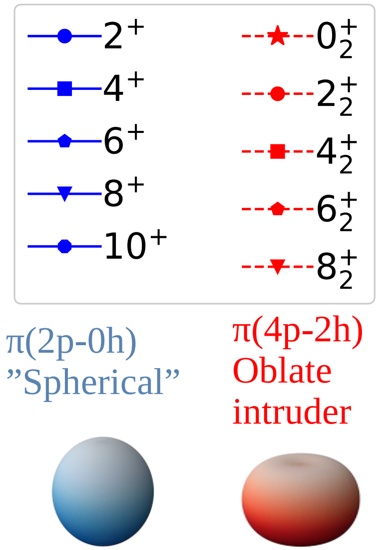
<u>Conclusions & Future Work</u>

In-beam ɣ-e spectroscopy experiment on ^{196}Po performed.

i) Population of 0_2^+ state, established as the band head of oblate band, via 302 keV ɣ ray.

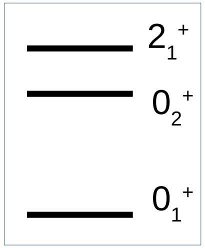
ii) Enhanced conversion of the $2^+ \rightarrow 2^+$ interpreted as significant E0 strength – ρ^2= 48(13) x 10^{-3} (preliminary), large amount of mixing.





Evidence in support the extension of the deformed intruder model above Z = 82.

Future: tracking intruding 0_2^+ band to lighter Po isotopes. Example of 1st excited State 0^+ (190-194) ?

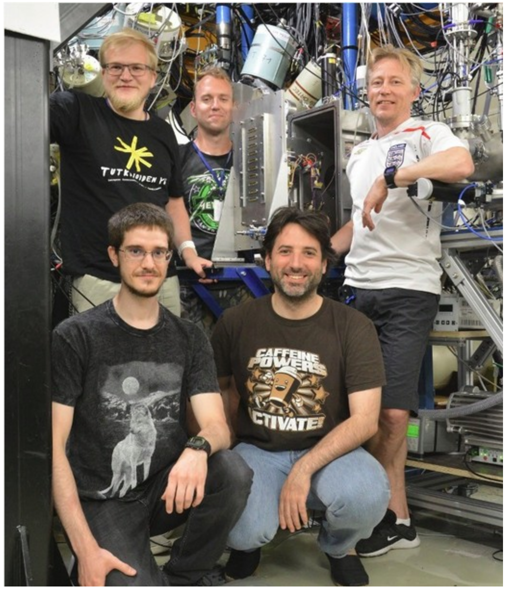


thanks for listening!

And to my collaborators:

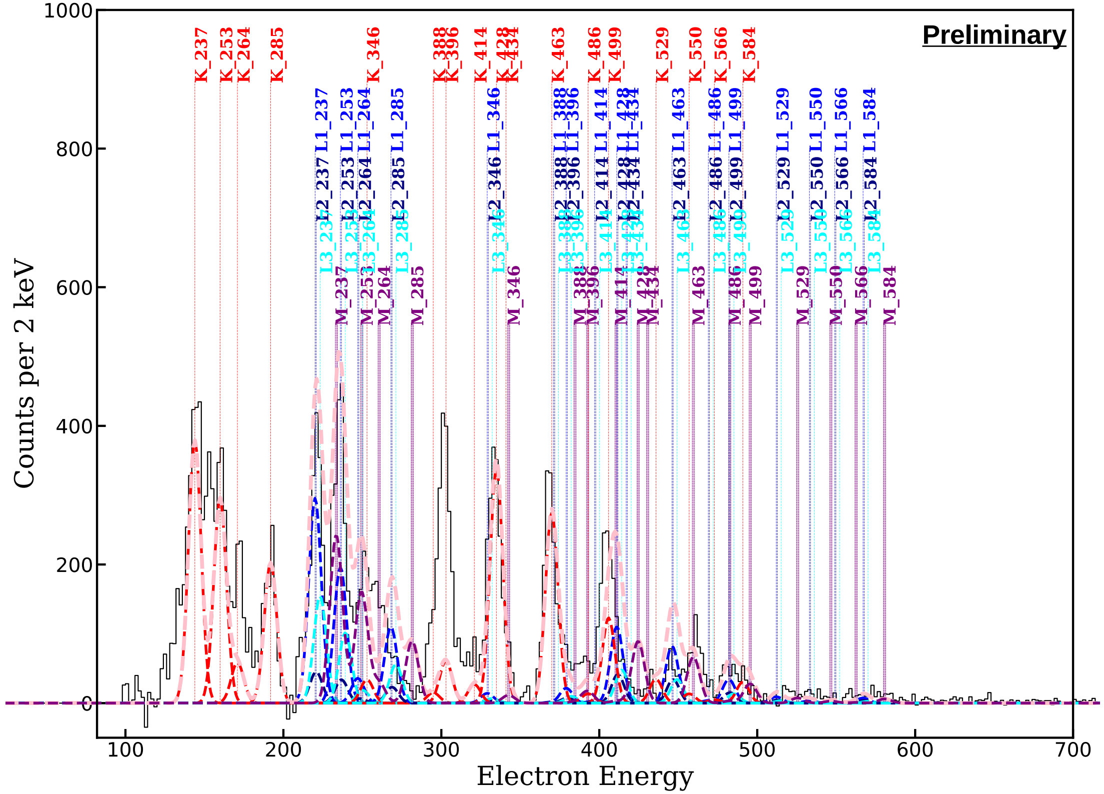
A. D. Briscoe, J. Pakarinen, A. Illana, J. Ojala , A.M. Plaza

Nuclear Spectroscopy Group JYFL
Nuclear Physics Group University of Liverpool

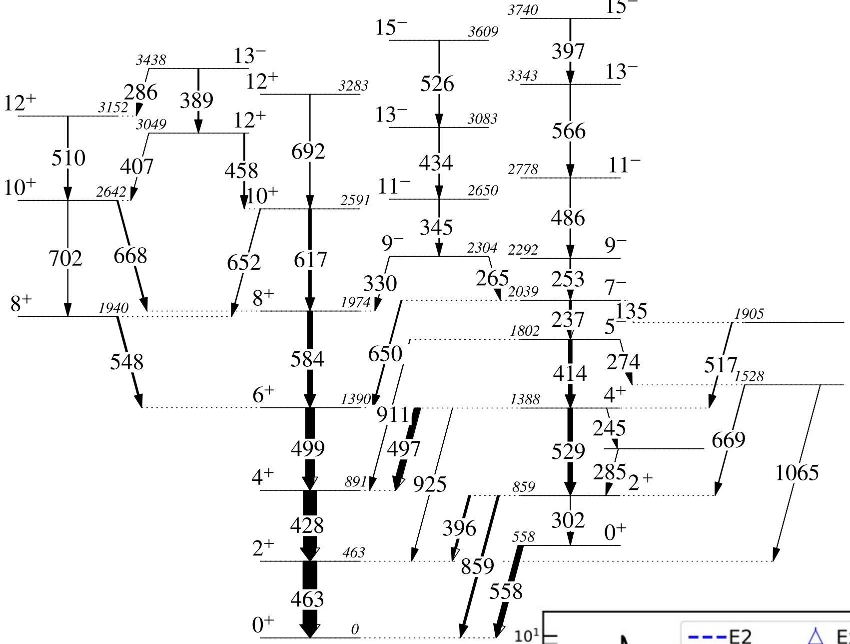


Back up slides next

Conversion coefficients & mixing



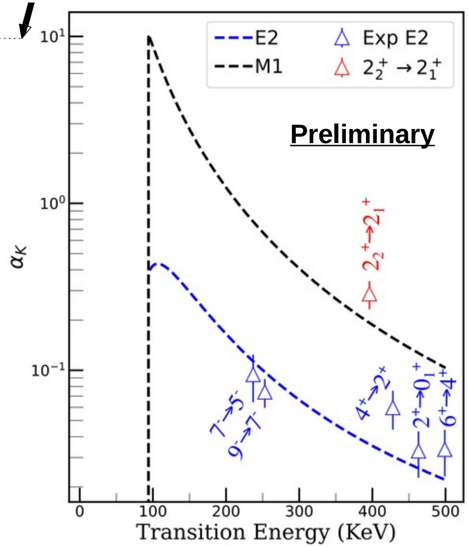
Work ongoing to extract remaining conversion coefficients.



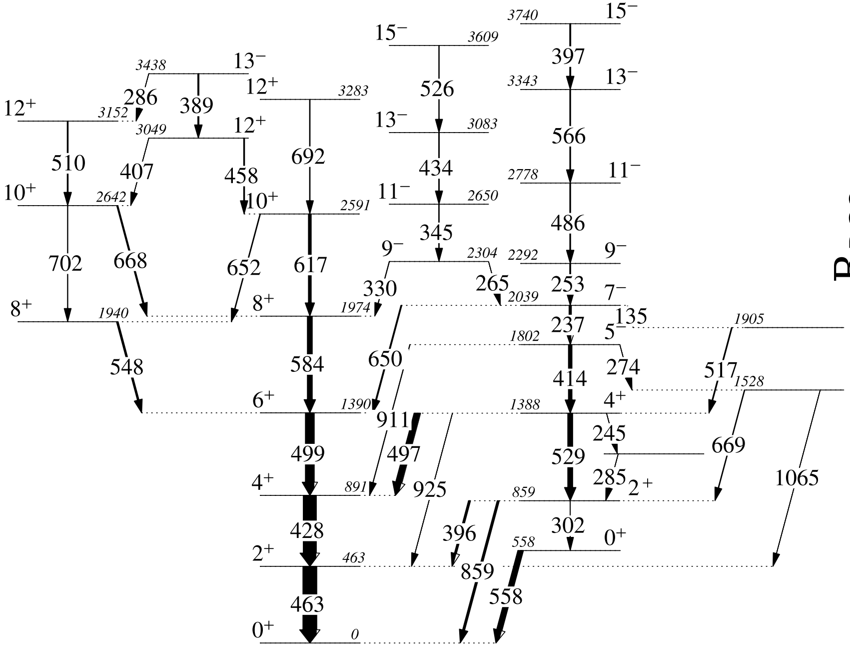
Measure γ-ray intensities. Overlay deconvolution of calculated electron using BRICC and efficiencies.

Most of the electron described well. E0 transitions (2+→2+) and (0+→0+)

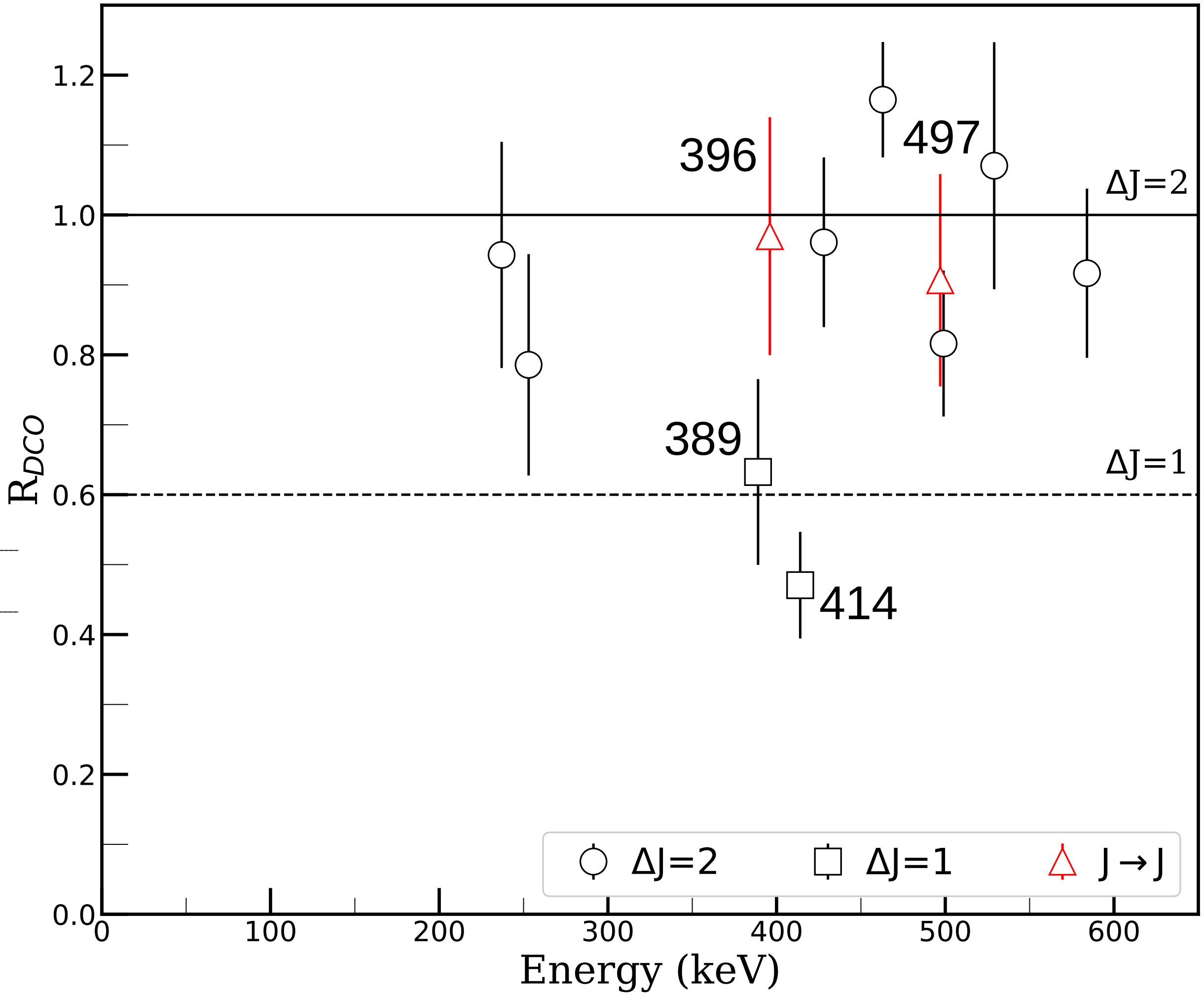
Alternatively, can fit electron spectrum for conversion coefficients. Ongoing to extract these, many components..



R_{DCO}

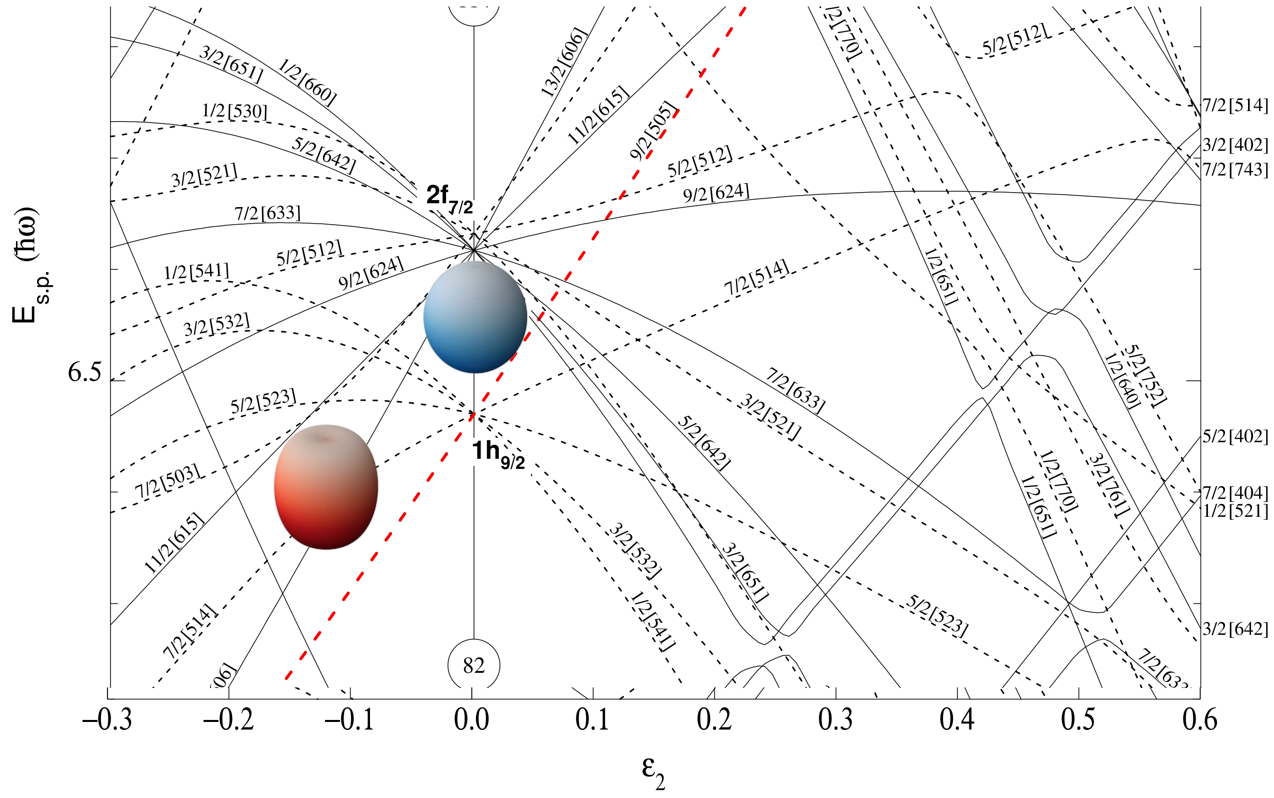


15⁻
3740
3609
397
526
13⁻
3438
3343
12⁺
3283
286
389
12⁺
3152
3049
13⁻
3083
566
510
407
458
692
434
2778
11⁻
2650
10⁺
2642
10⁺
2591
345
486
9⁻
2304
2292
702
668
652
617
330
265
253
8⁺
1940
1974
2039
7⁻
237
135
1905
1802
5⁻
548
584
650
414
274
517
1528
6⁺
1390
1388
911
4⁺
245
669
499
497
529
1065
4⁺
891
925
285
2⁺
859
428
396
302
0⁺
2⁺
463
558
859
463
558
0⁺
0



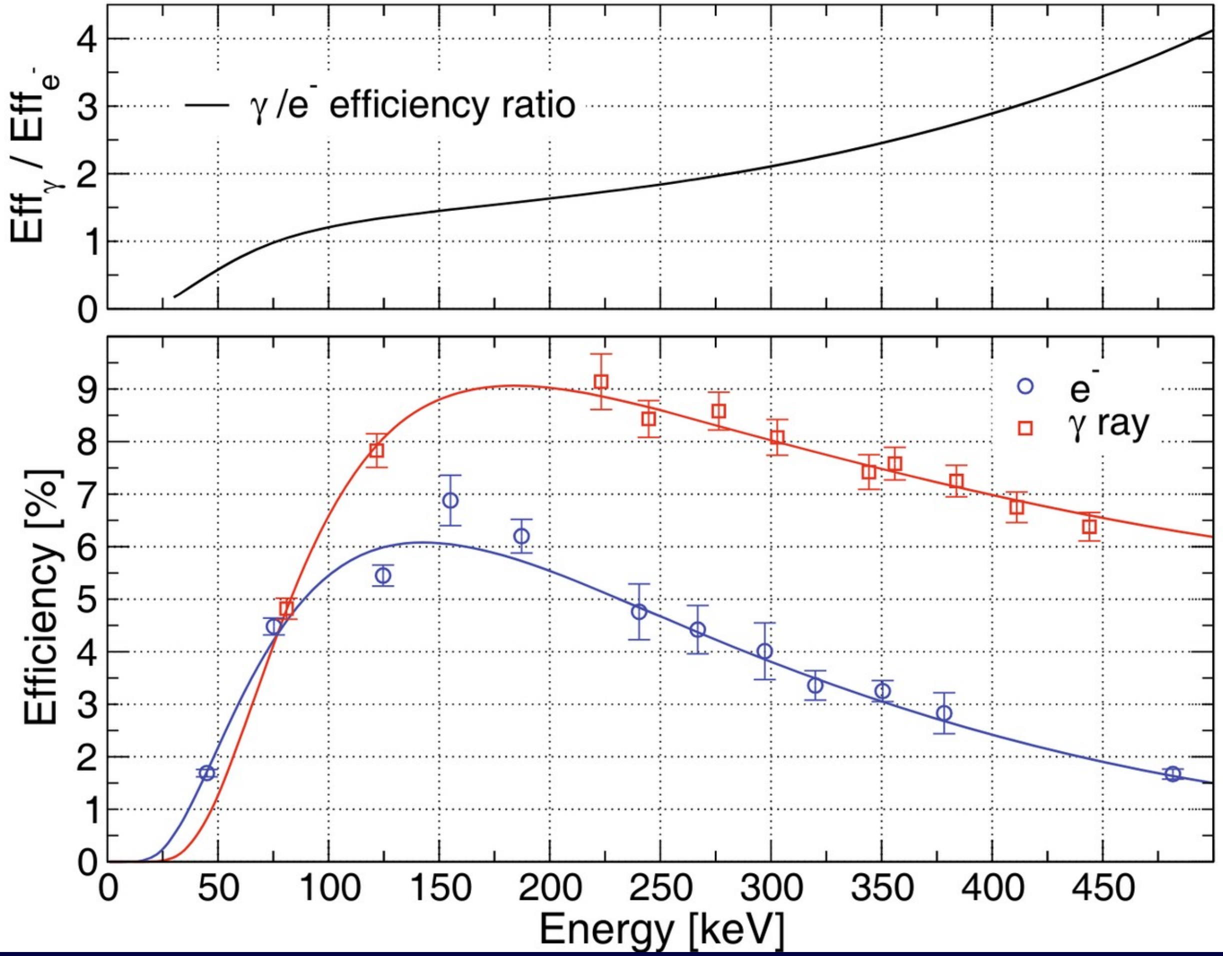
396
497
389
414
ΔJ=2
ΔJ=1
R_{DCO}
Energy (keV)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
600
ΔJ=2
ΔJ=1
J→J

Nilsson Back up

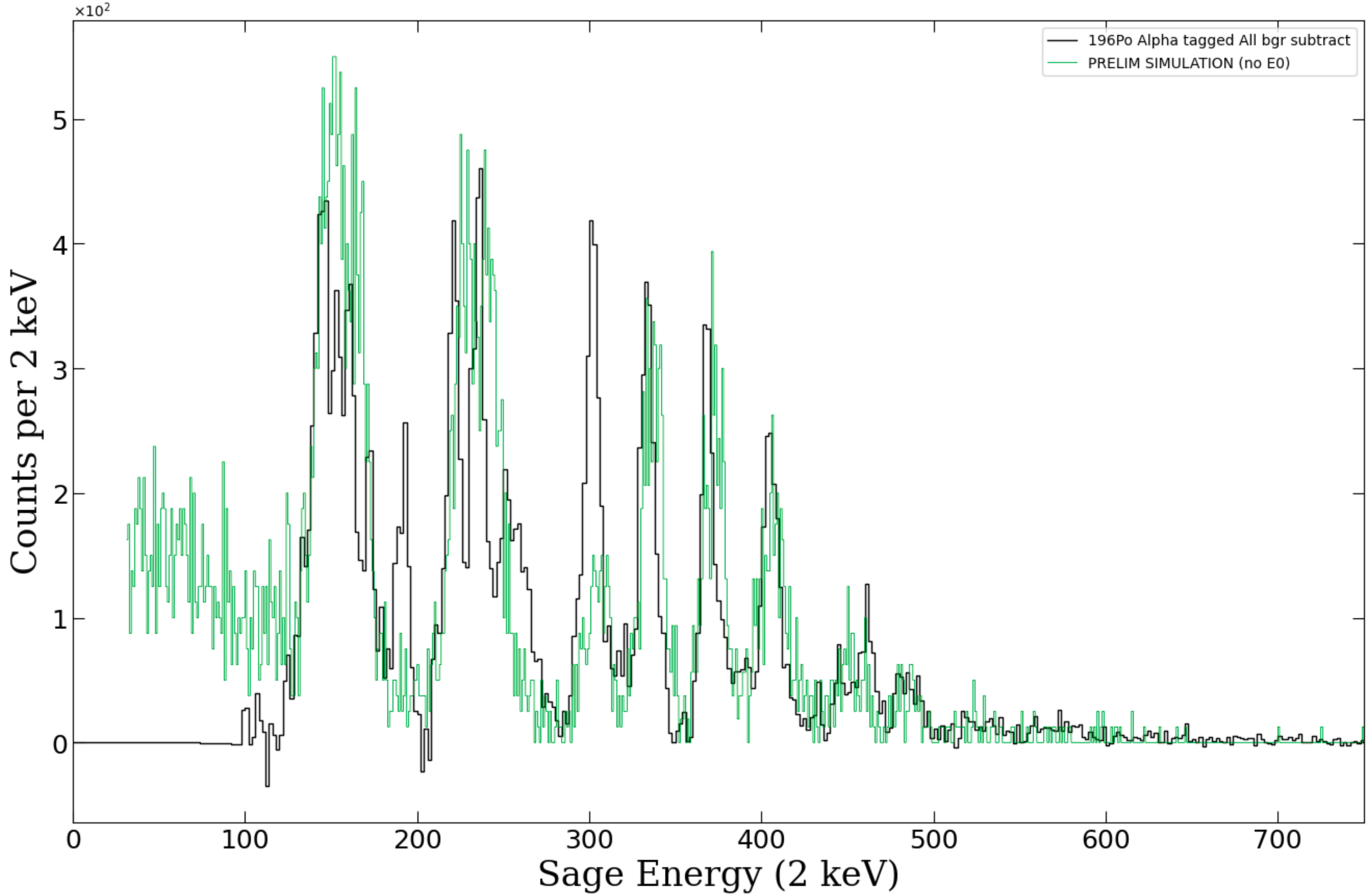


SAGE: Efficiciency

Energy & Efficiency Calibrations with ^{133}Ba ^{207}Bi source.



Simulated ^{196}Po, no E0, basic level scheme input

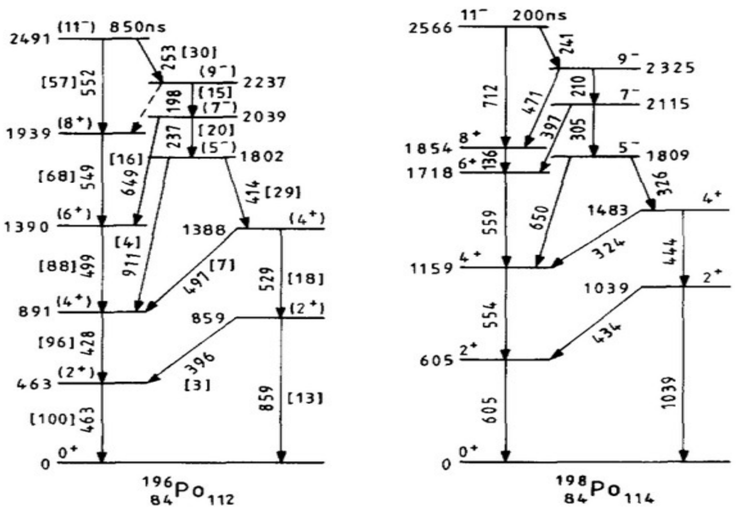


^{196}Po previous studies in beam, conflicting results?

Quadrupole and octupole collectivity in light Po Isotopes

D. Alber[1], R. Alfier[1], C.E. Bach[1], D.B. Fossan[1*], H. Grawe[1], H. Kluge[1], M. Lach[1**], K.H. Maier[1], M. Schramm[1], R. Schubart[1], M.P. Waring[1***], L. Wood[1], H. Hübel[2], and Jing-ye Zhang[3****]

[1] Hahn-Meitner-Institut, Glienickerstrasse 100, W-1000 Berlin 39, Federal Republic of Germany
[2] Institut für Strahlen- und Kernphysik, Universität Bonn, Nussallee 14-16, W-5300 Bonn, Federal Republic of Germany
[3] State University of New York at Stony Brook, NY 11794, USA

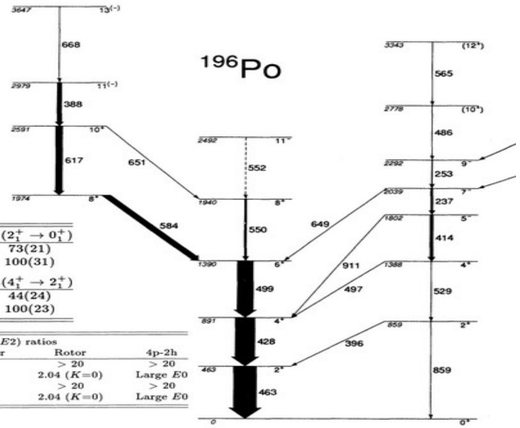


Support 4p-2h interpretation of intruding states

Change in levels 196-198, and missing intensities 4^+_2 and 2^+_2 ,

Onset of collectivity in neutron deficient ^{196,198}Po

L. A. Bernstein,[1] J. A. Cizewski,[1] H.-Q. Jin,[1,*] W. Younes,[1] R. G. Henry,[1,2,†] L. P. Farris,[1,3] A. Charos,[1] M. P. Carpenter,[2] R. V. F. Janssens,[2] T. L. Khoo,[2] T. Lauritsen,[2] I. G. Bearden,[2,5,‡] D. Ye,[2,6,§] J. A. Becker,[3] E. A. Henry,[3] M. J. Brinkman,[3,∥] J. R. Hughes,[3] A. Kuhnert,[3,¶] T. F. Wang,[3] M. A. Stoyer,[3,4] R. M. Diamond,[4] F. S. Stephens,[4] M. A. Deleplanque,[4] A. O. Macchiavelli,[4] I. Y. Lee,[4] B. Cederwall,[4] J. R. B. Oliveira,[4,∥] J. Burde,[4] P. Fallon,[4] C. Duyar,[7] J. E. Draper,[7] E. Rubel,[7] and D. T. Vo[8]



Nucleus	Gate	$I_\gamma(2_2^+ \to 2_1^+)$	$I_\gamma(2_1^+ \to 0_1^+)$
^{196}Po	529 keV	91(21)	73(21)
^{198}Po	444 keV	89(31)	100(31)

Nucleus	Gate	$I_\gamma(4_2^+ \to 4_1^+)$	$I_\gamma(4_1^+ \to 2_1^+)$
^{196}Po	414 keV	59(22)	44(24)
^{198}Po	391 keV	51(26)	100(23)

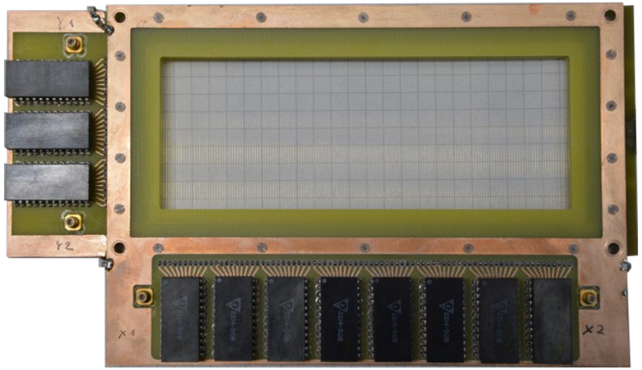
		$B(E2)$ ratios			
Nucleus	Transition	Experiment	Vibrator	Rotor	4p-2h
^{196}Po	$4_2^+ \to 2_2^+ / 4_2^+ \to 4_1^+$	1.0(5)	1.10	> 20	> 20
^{196}Po	$2_2^+ \to 2_1^+ / 2_2^+ \to 0_1^+$	64(14)	∞	2.04 (K=0)	Large $E0$
^{198}Po	$4_2^+ \to 2_2^+ / 4_2^+ \to 4_1^+$	2.0(5)	1.10	> 20	> 20
^{198}Po	$2_2^+ \to 2_1^+ / 2_2^+ \to 0_1^+$	158(6)	∞	2.04 (K=0)	Large $E0$

Disagree with 4p-2h inpretation of intruding states - instead support η $i_{13/2}$ orbital, interaction with π $h_{9/2}$ in vibrational picture.

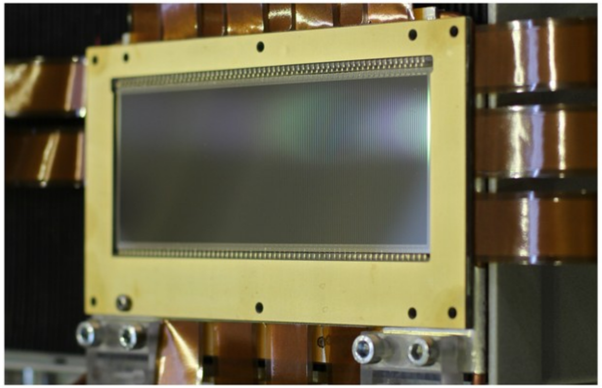
No missing intensity of 4^+_2 and 2^+_2

Experimental techniques and apparatus: Focal-plane detectors

Multi-wire proportional counter (MWPC)



Grid of 20 µm diameter gold-coated tungsten wires, provides (x,y) position of recoils



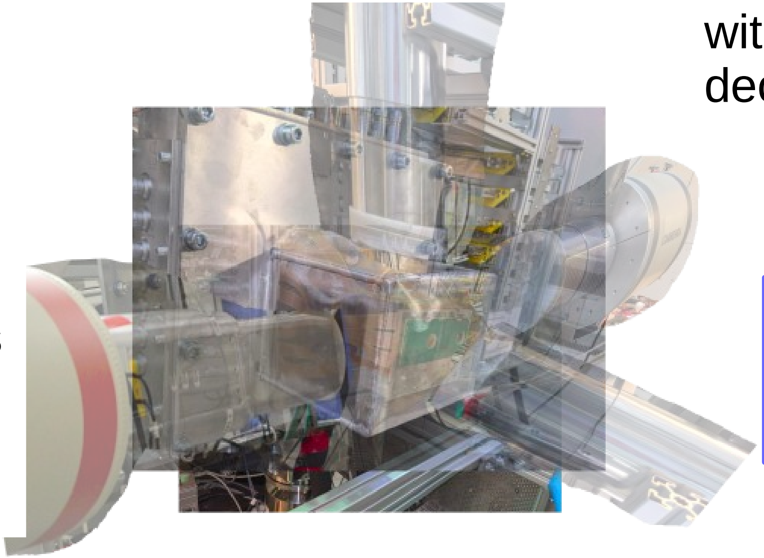
Micron BB20 DSSD

72 x 192 strips,
13,824 0.45 mm^2 pixels
300 um thick Si

Correlations of ɣ rays with implanted recoils or decays for around 50 us

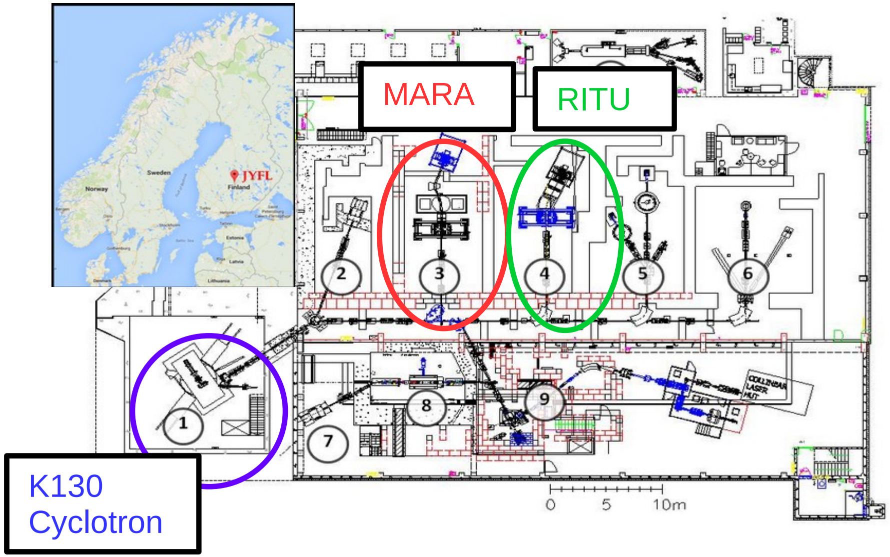
Ge detectors

3 BEGe & 1 Clover detectors outside chamber surrounding DSSD in close geometry.



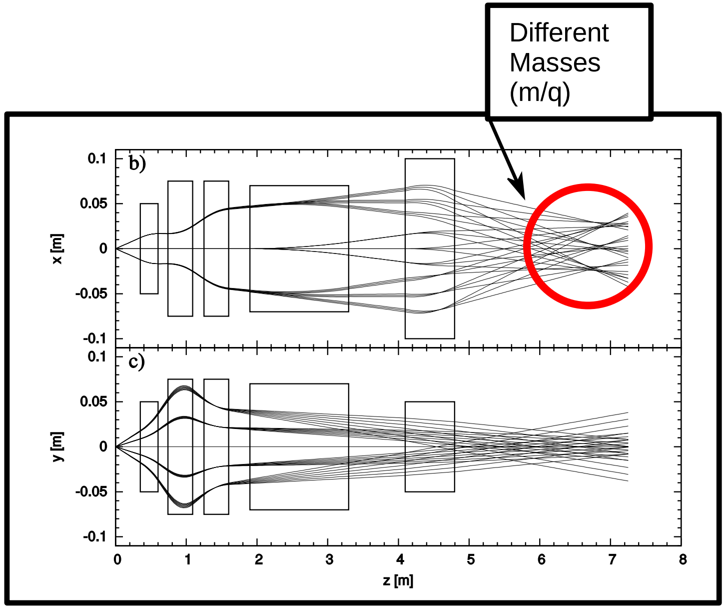
All signals time stamped by a 100 MHz clock,
read out individually for correlation analysis

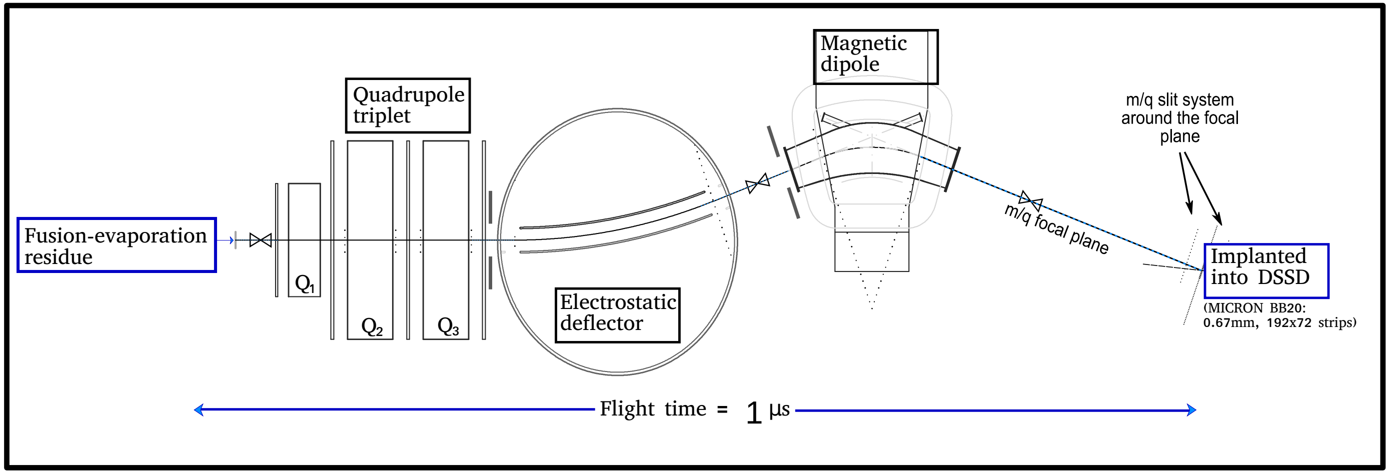
Experimental with recoil separators at JYFL



$$E\rho_E = \frac{pv}{q} \approx \frac{2E_k}{q}$$

$$B\rho_B = \frac{p}{q} \approx \frac{\sqrt{2E_k m}}{q}$$





30 MeV Recoil => v/c = 0.02

Fusion-evaporation residues transported to focal plane for spectroscopy