# Probing the structure of $^{208}$Pb and $^{178}$Hf with UNILAC beams

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EMMI Workshop: New avenues for the low-energy NUSTAR program at GSI-FAIR
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# Outline

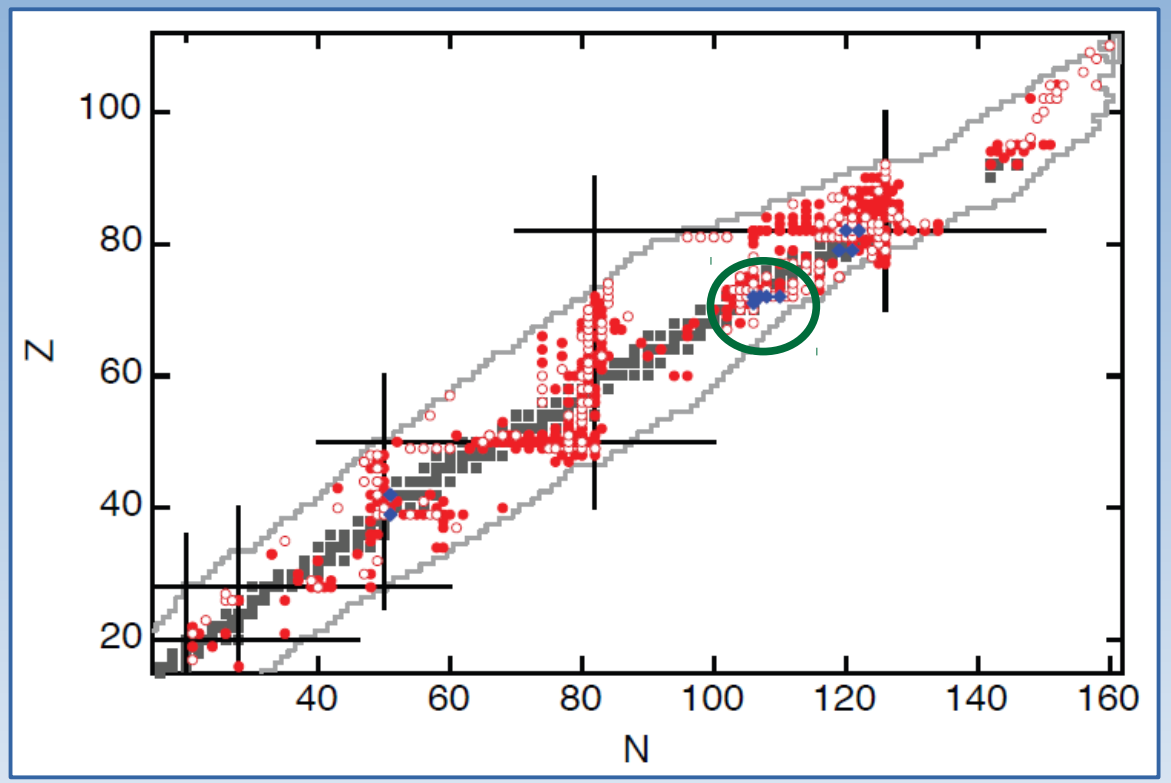
## K-isomers in $^{178}$Hf

- Nuclear isomerism in deformed nuclei
- K-isomers – What are they? Where are they found?
- Interesting case of $^{178}$Hf
- Coulex isomer population puzzle
- Possibilities at the UNILAC

## Octupole excitations in $^{208}$Pb

- Doubly-magic $^{208}$Pb
- Octupole deformation
- Searches for 2-octupole-phonon state
- $^{208}$Pb and neighbours
- Possibilities at the UNILAC

# Nuclear Isomerism

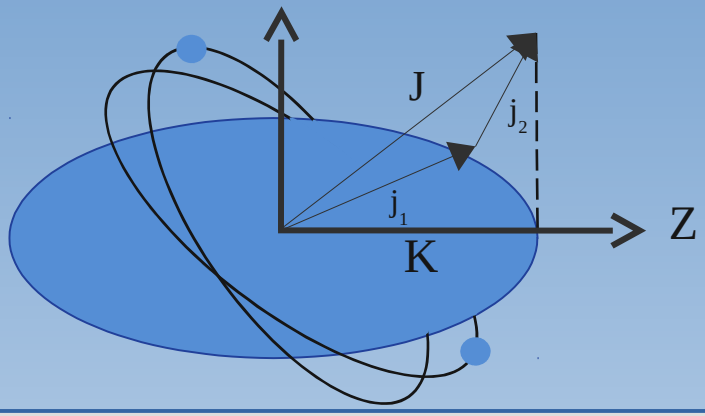



Nuclear chart showing isomers with excitation energy >600 keV. Blue diamonds indicate $T_{1/2}$ > 1 hr [1]

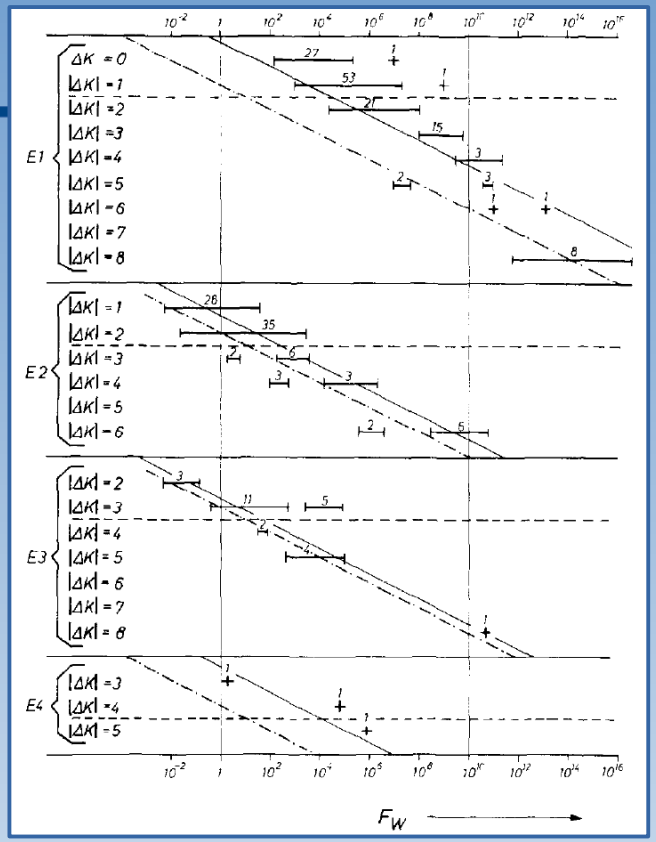
- Traditionally found in medium to heavy nuclei close to closed shells
- Valence particles can occupy **high-spin** orbitals
- For well-deformed nuclei (i.e. in-between shells): collective states dominate usually dominate yrast line
- A~180 region interesting: **high-K states** are low in energy and compete with collective excitations

[1] G.D. Dracoulis, P.M. Walker and F.G. Kondev, Rep. Prog. Phys. **79,** 076301 (2016)

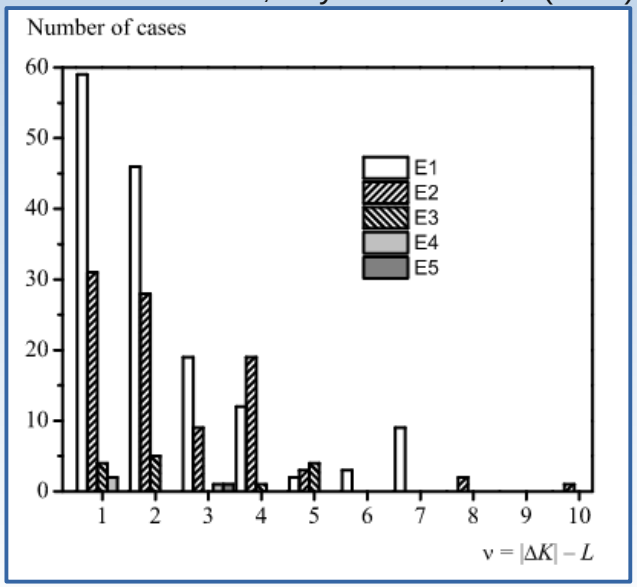
# K-isomers




- **K quantum number**: projection of nuclear angular momentum onto the symmetry axis
- "Forbidden" decay if ΔK>λ (λ = multipole order)
- Degree of forbiddenness ν = ΔK – λ
- K-mixing processes → **"hindered" transitions**
  - reduced hindrance $f_\nu = (F_W)^{1/\nu}$



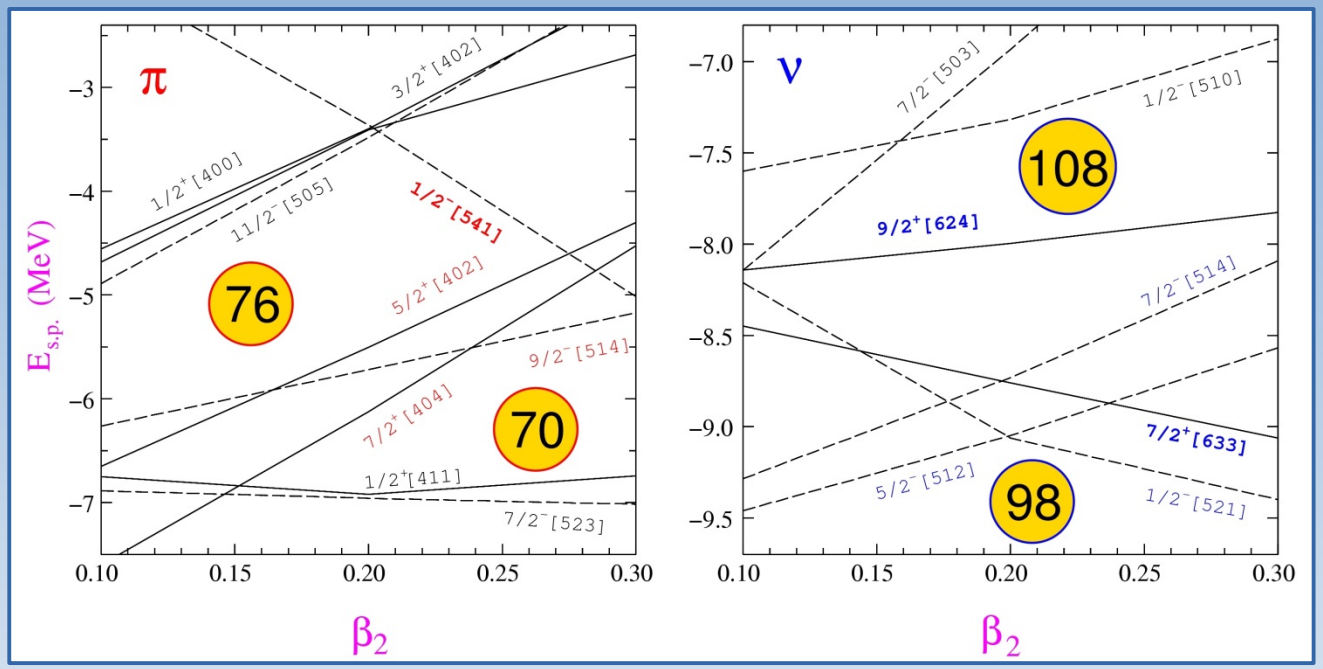

K. E. G. Löbner, Phys. Lett. 26B, 6 (1968)




A.P. Lashko and T.N. Lashko, Prob. At. Sci. Tech. N5 (105) (2016)

- $F_W = T_{1/2\gamma}$ (experiment) / $T_{1/2\gamma}$ (Weisskopf estimate)
- For rare-earth region 89 ≤ N ≤ 114, 62 ≤ Z ≤ 78, and actinides with N ≥ 134

# Interesting case: $^{178}$Hf

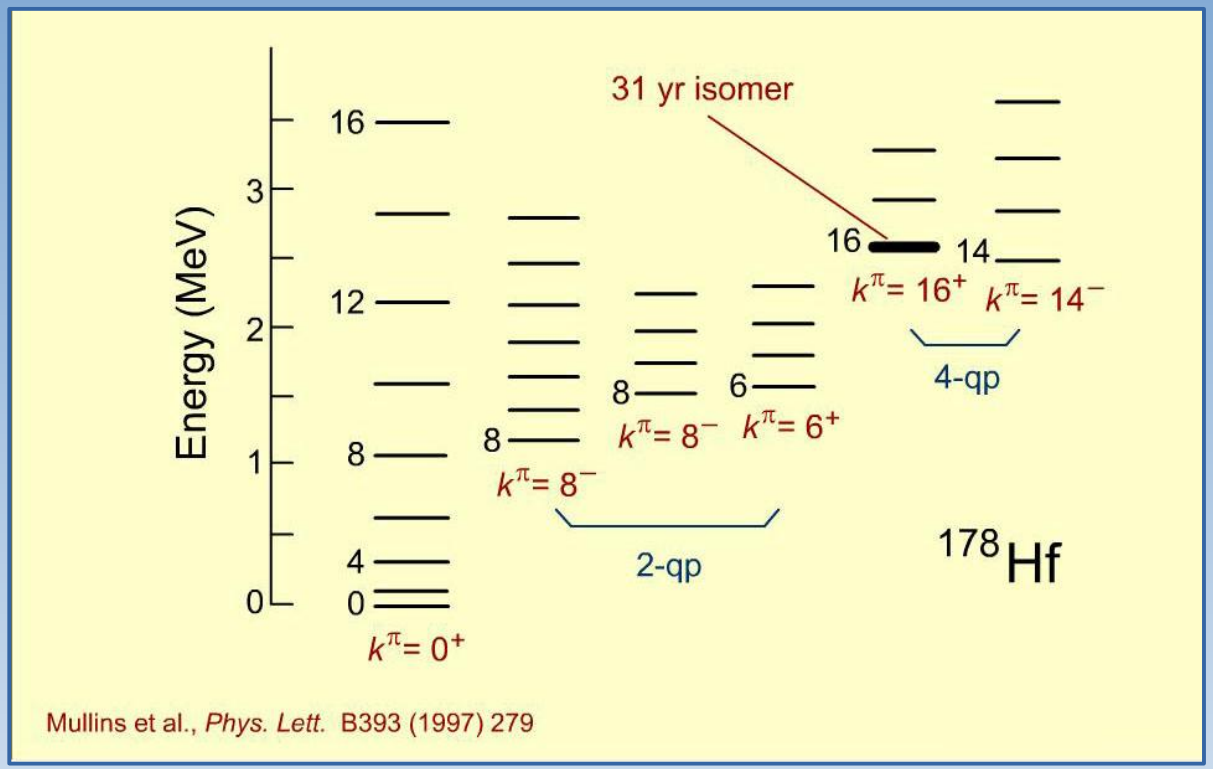


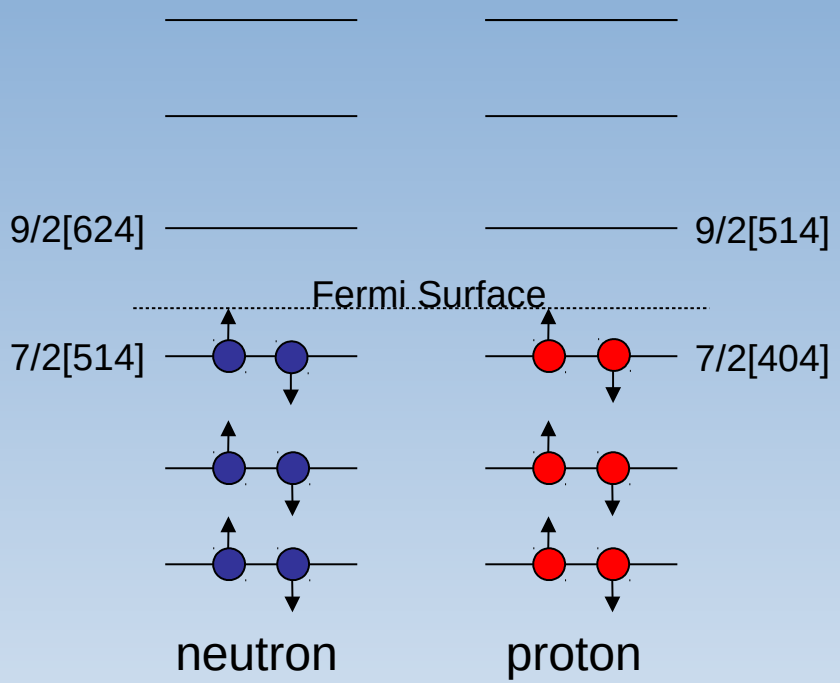

- If protons and neutrons occupy high-Ω states close to Fermi surface → large total projection
- High-Ω states located in upper half of shell, but too-high Fermi level weakens deformation

Nilsson diagrams for A~180, Z = 70 (Yb) to Z = 77 (Ir)

| protons | neutrons |
|---|---|
| $5/2^+[402]$ | $9/2^+[624]$ |
| $9/2^-[514]$ | $7/2^-[514]$ |
| $7/2^+[404]$ | $7/2^+[663]$ |
| | $5/2^-[512]$ |

# Interesting case: $^{178}$Hf




- High-Ω orbital combinations near Fermi surface

neutrons

$K^\pi = 6^-$ $\nu^2(5/2^-[512] \otimes 7/2^+[633])$

$K^\pi = 6^+$ $\nu^2(5/2^-[512] \otimes 7/2^-[514])$

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protons

$K^\pi = 6^+$ $\pi^2(5/2^+[402] \otimes 7/2^+[404])$

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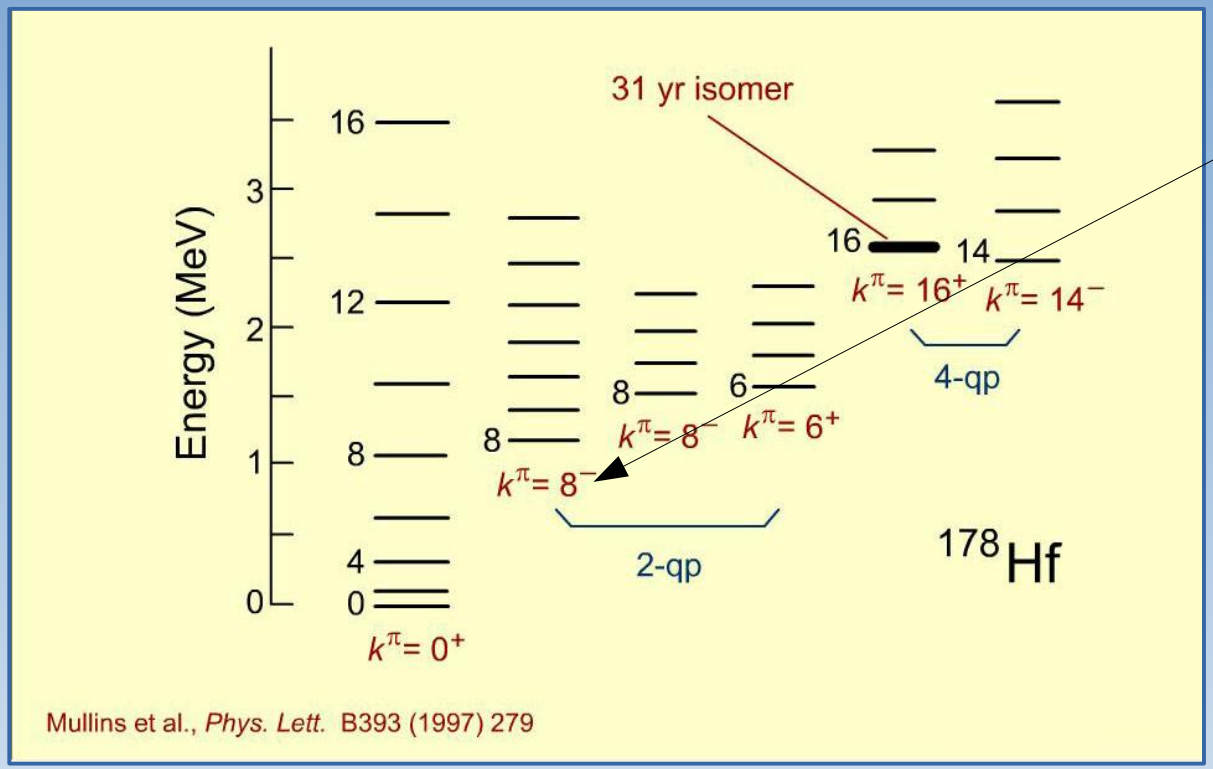
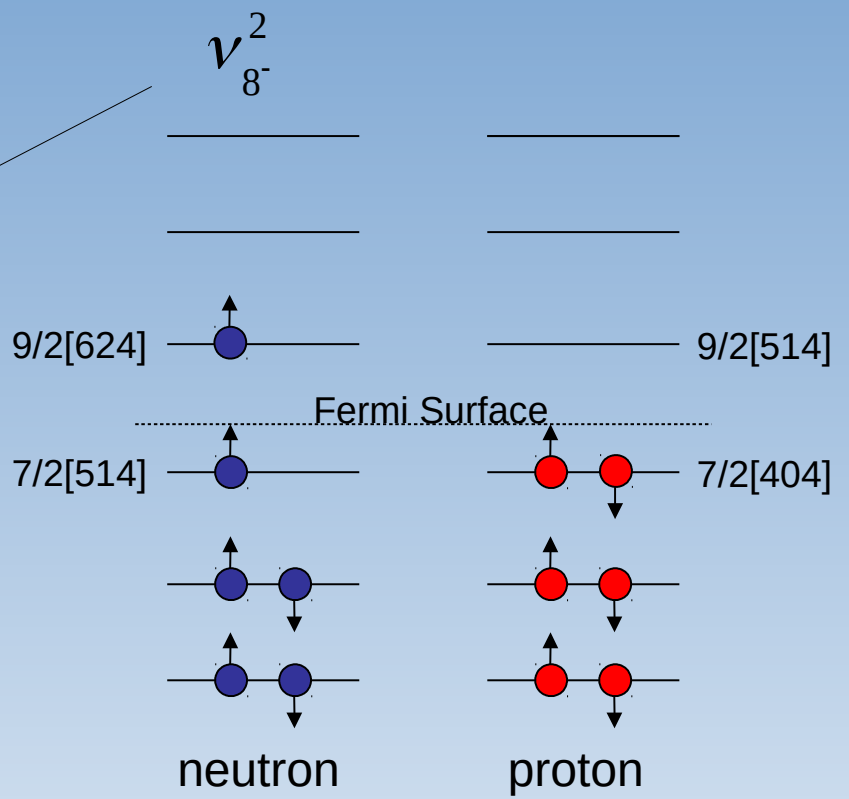
# Interesting case: $^{178}$Hf

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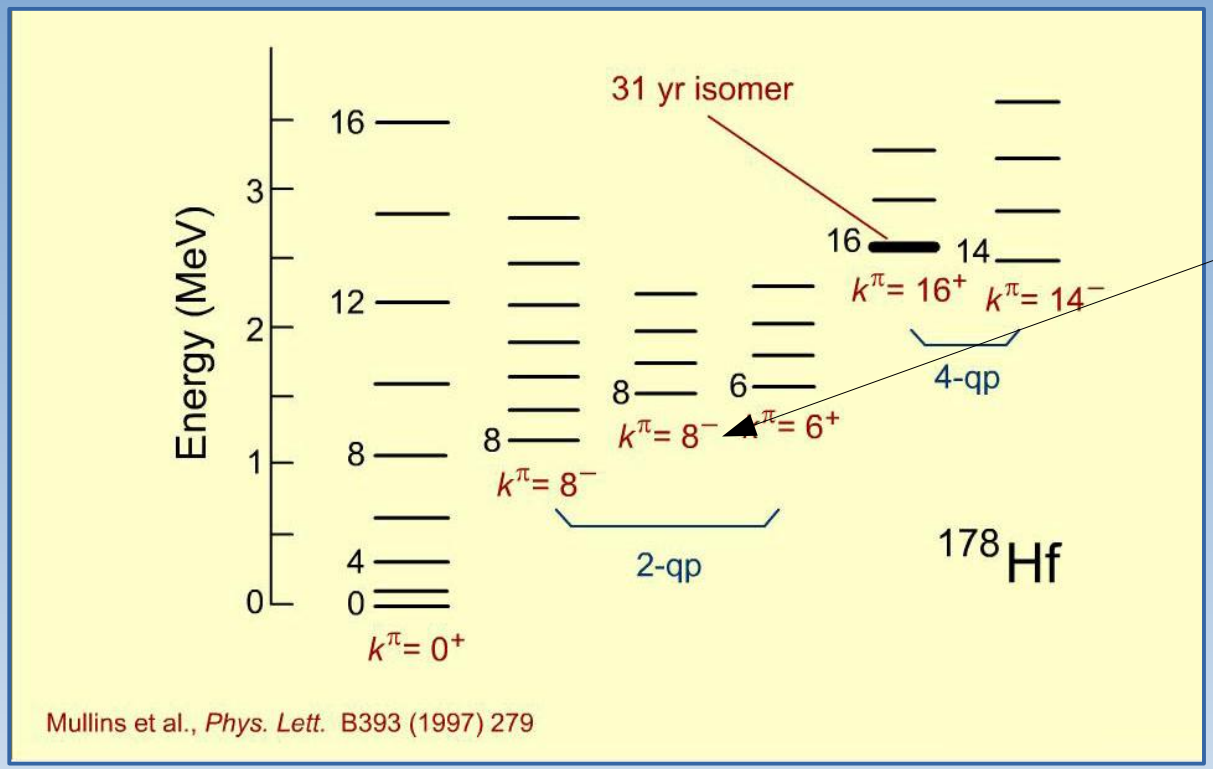


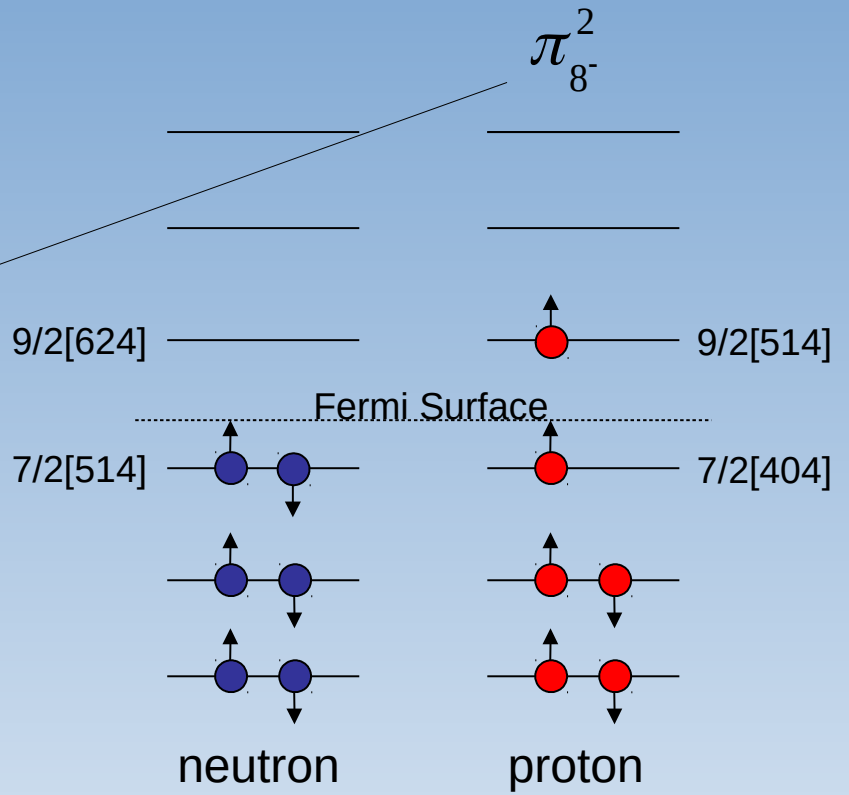


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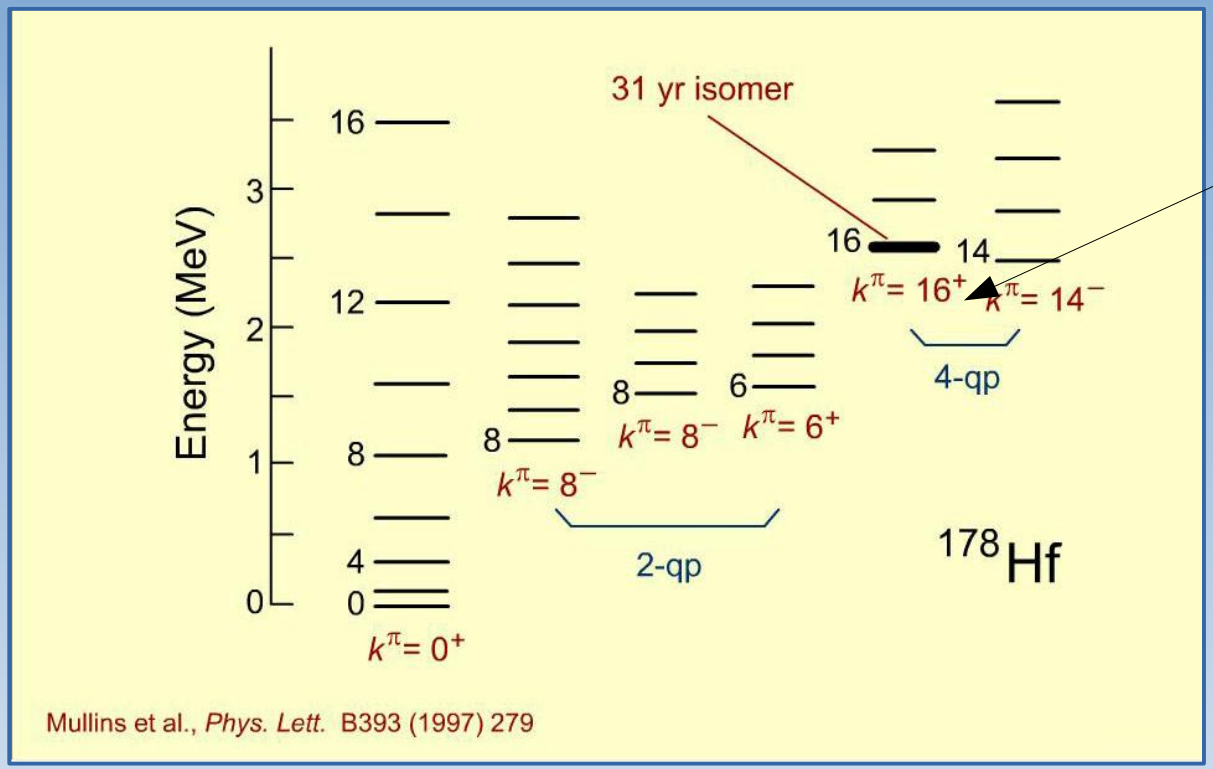


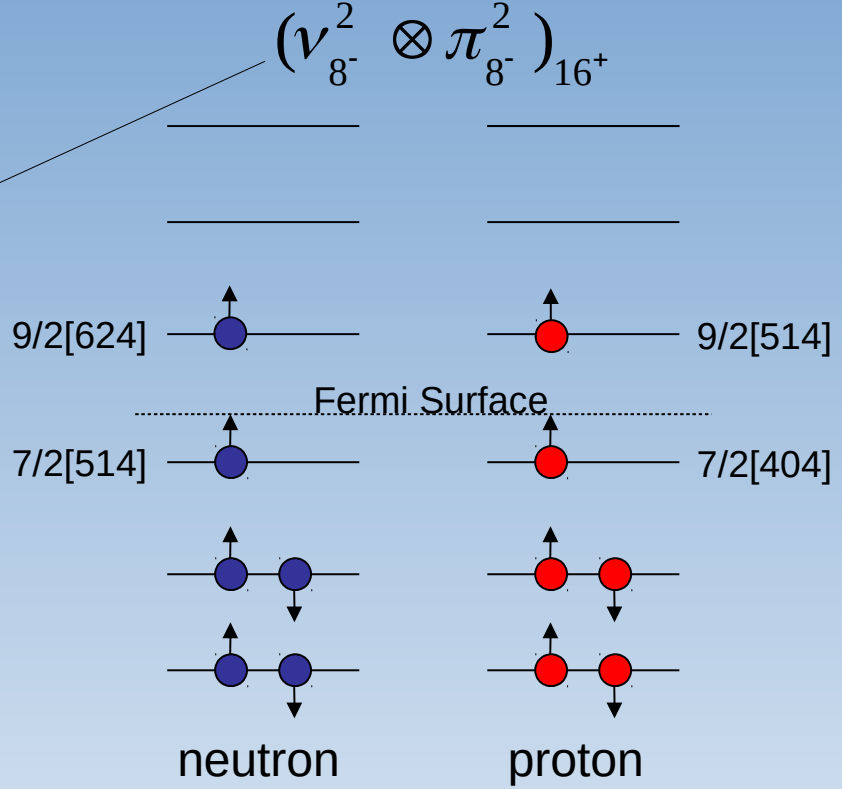


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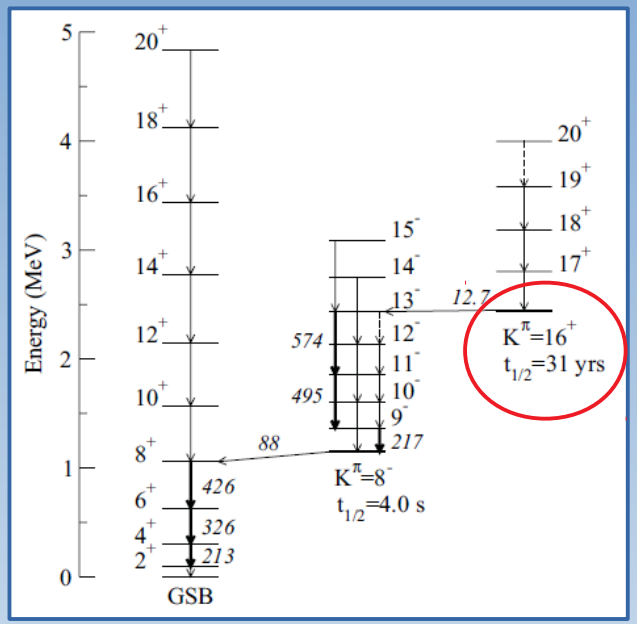
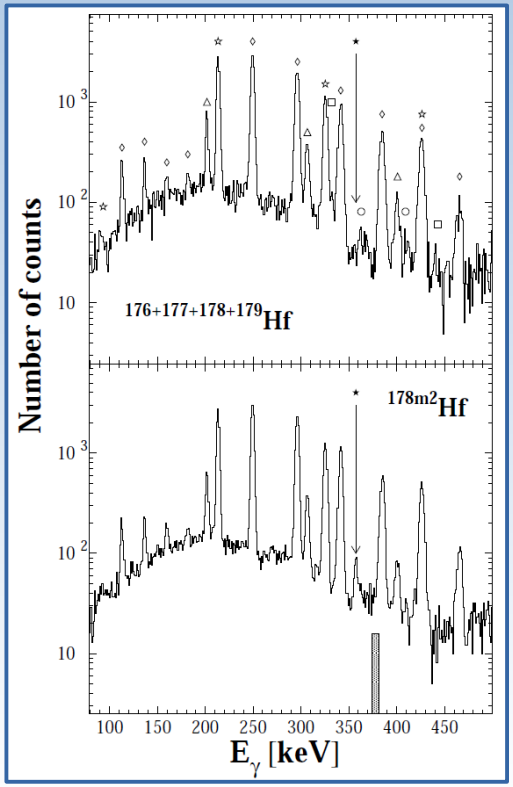
# Aside: $16^+$ isomer in $^{178}$Hf




Partial level diagram for $^{178}$Hf [1]

- $K^\pi = 16^+$ isomer, $\mathbf{T_{1/2}}$ **~ 31 years**, excitation energy 2.447 MeV of particular interest
- Relatively high excitation energy → **high energy storage**
- Goal: release of isomer energy via e.g. photo-induced triggering
- Mechanism of triggering 12.7-keV E3 transition through higher-lying levels? e.g. [2]
- As yet, cross sections appear low
- Triggering mechanism not yet understood: **topic remains active** e.g. [3]

- $^{178m2}$Hf excellent candidate for target material
- Example: Coulomb excitation of $K^\pi = 16^+$ isomer using $^{178m2}$Hf, E. Lubkiewicz *et al.* [4]
- Target produced via $^{176}$Yb(α,2n) (originally T.K. Khoo *et al.*)
- Right: 'artificial' spectrum with $^{176\text{-}179}$Hf targets (top), spectrum measured with $^{178m2}$Hf target (bottom)
- Observation of $17^+ \rightarrow 16^+$, 357-keV transition above $16^+$ isomer



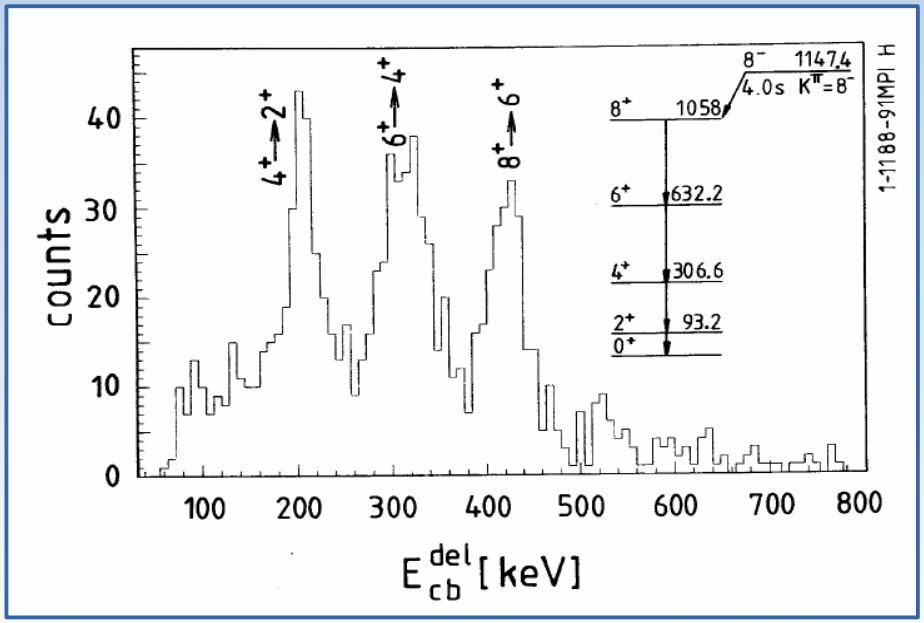


[1] A.B. Hayes *et al.*, Phys. Rev. C **75**, 034308 (2007)
[2] F.F. Karpeshin *et al.*, Eur. Phys. J. A **39**, 341–348 (2009)
[3] V.I. Kirischuk *et al.*, Phys. Lett. B **750**, p89-94 (2015)
[4] E. Lubkiewicz *et al.*, Z. Phys. A **355**, 377 (1996)

# Coulomb excitation of $^{178}$Hf – Isomer population puzzle

- Structure of $^{178}$Hf extensively studied (e.g. via β decay [1], particle spectroscopy [2],…)
- Lowest $K^{\pi} = 8^-$ isomer in $^{178}$Hf first populated by Coulex in early 80s with Kr and Xe ions [3], and later with $^{130}$Te [4]
- **Isomer population "Puzzle"**:
  (i) EM excitation probabilities **decrease dramatically** with increasing λ
  (ii) probability of multiple-step Coulex **drops ~exponentially** with number of steps
  → Can the population mechanism be *quantitatively* explained?
  → How "good" is the K quantum number?

- $K^{\pi} = 8^-$ isomer at 1147.4 keV in $^{178}$Hf populated via Coulex with $^{130}$Te beam [4]
- Goal: to investigate reaction mechanism for isomer population
- Darmstadt-Heidelberg Crystal Ball at MPI

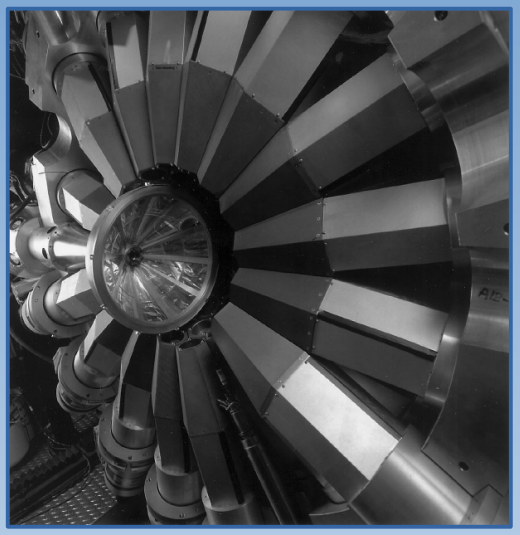


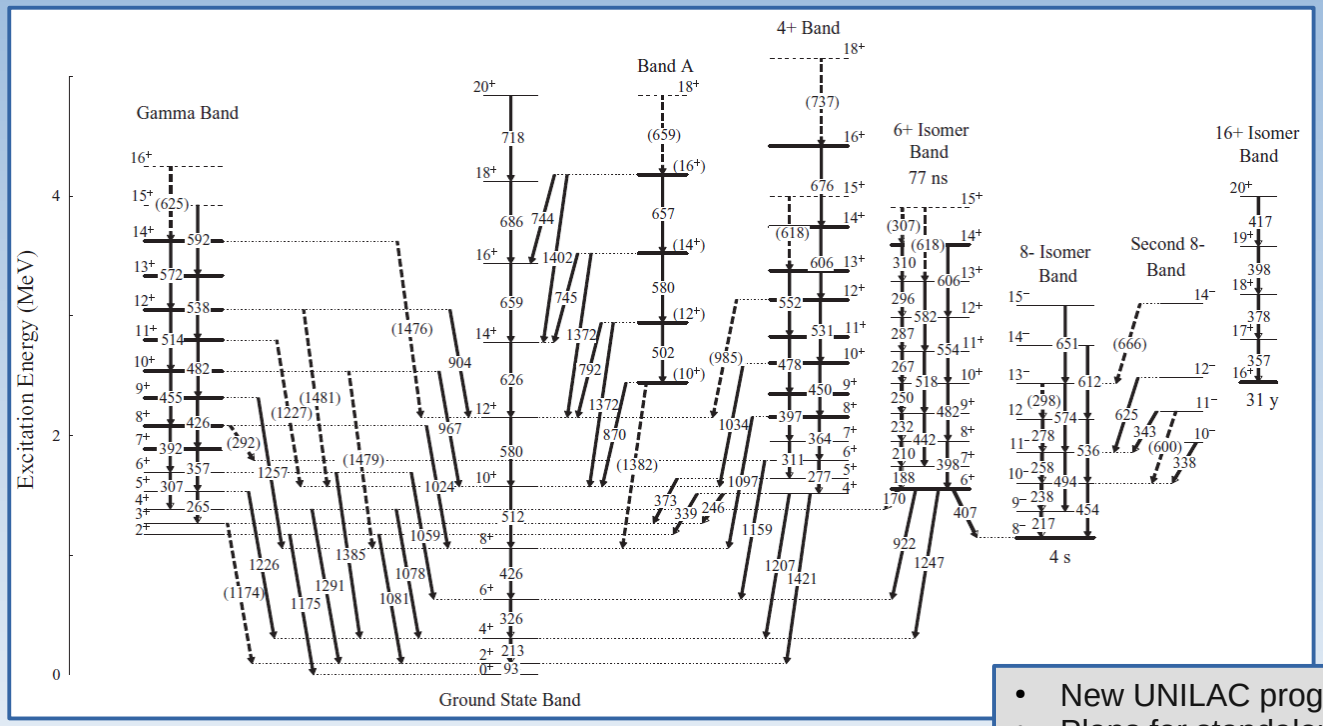

Delayed gamma spectrum [4]


[1] J. Wiederhold *et al.*, Phys. Rev. C **99**, 024316 (2019)
[2] D.G. Burke *et al.*, Nucl. Phys. A **569**, 523 (1994)
[3] J.H. Hamilton *et al.*, Phys. Lett. **122B**, 327 (1982)
[4] H. Xie *et al.*, Phys. Rev. C **48**, 2517 (1993)

# Coulomb excitation of $^{178}$Hf – Isomer population puzzle

- K isomers populated via Coulex with Xe and Ta at ANL [1,2]
  - Gammasphere and CHICO [3]
- Extensive level scheme known
- Surprisingly high $19^+ \rightarrow 18^+$ yields in $K^\pi = 16^+$ isomer






- Three different mechanisms for population of $6^+$, $8^-$ and $16^+$ isomers
- For $K^\pi = 8^-$, $B(E3; K^\pi = 0^+ \rightarrow 8^-)$ values fitted using spin-dependent mixing model
- No direct evidence of GSB decays into $K^\pi = 16^+$
- New band stuctures tentatively seen in later measurements [4]

- New UNILAC program at GSI
- Plans for standalone CW linac (W. Barth et al., EPJ Web Conf. 138, 01026 (2017))
- State-of-the-art detector hardware and DAQs
- $^{178}$Hf UNILAC beams? → different targets for activation measurement, Coulex with heavy ions
- High-precision HPGe array, large solid angle


[1] P.J. Napiorkowski *et al.*, Acta Phys. Pol. **B32**, 861 (2001)
[2] A.B. Hayes *et al.*, Phys. Rev. Lett. **89**, 242501 (2002), PRL **96**, 042505 (2006), Phys. Rev. C **75**, 034308 (2007)
[3] M.W. Simon *et al.*, NIM A **452**, 205-222 (2000)
[4] A.B. Hayes *et al.*, Int. J. of Mod. Phys E. **20**, No. 2, p474-481 (2011)

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- K-isomers – What are they? Where are they found?
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- Doubly-magic $^{208}$Pb
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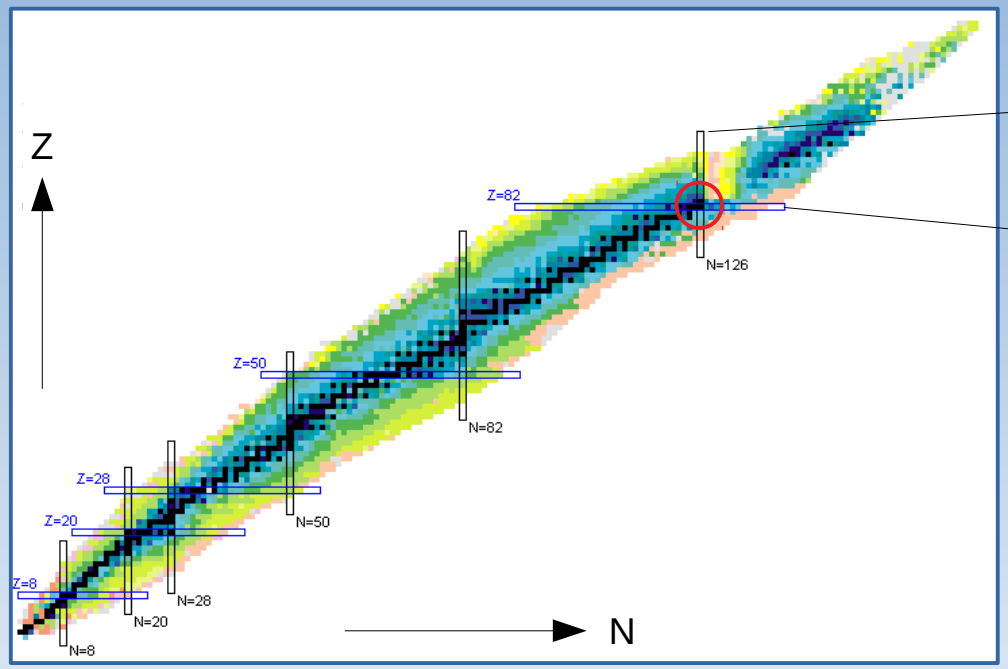
# Doubly-magic $^{208}$Pb

- Heaviest known doubly-magic nucleus; (Z,N) = (82,126)
- Spherical in GS, **octupole vibration** in $^{208}$Pb is **lowest in energy**




- Shell closure energies large (several MeV) for both protons and neutrons

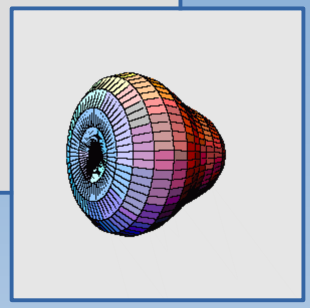
**Table 1 -- Nuclear Shell Structure** (from *Elementary Theory of Nuclear Shell Structure*, Maria Goeppert Mayer & J. Hans D. Jensen, John Wiley & Sons, Inc., New York, 1955.)

| Angular Momentum ($\hbar\Omega/2\pi$) | | Spin-Orbit Coupling (1/2, 3/2, 5/2, 7/2...) | Number of Nucleons Shell | Total | Magic Number |
|---|---|---|---|---|---|
| 7 | 1j | 1j 15/2 | 16 | [184] | {184} |
| | | 3d 3/2 | 4 | [168] | |
| 6 | 4s | 4s 1/2 | 2 | [164] | |
| 6 | 3d | 2g 7/2 | 8 | [162] | |
| | | 1i 11/2 | 12 | [154] | |
| 6 | 2g | 3d 5/2 | 6 | [142] | |
| | | 2g 9/2 | 10 | [136] | |
| 6 | 1i | 1i 13/2 | 14 | [126] | {126} |
| | | 3p 1/2 | 2 | [112] | |
| 5 | 3p | 3p 3/2 | 4 | [110] | |
| | | 2f 5/2 | 6 | [106] | |
| 5 | 2f | 2f 7/2 | 8 | [100] | |
| | | 1h 9/2 | 10 | [92] | |
| 5 | 1h | 1h 11/2 | 12 | [82] | {82} |
| 4 | 3s | 3s 1/2 | 2 | [70] | |
| | | 2d 3/2 | 4 | [68] | |
| 4 | 2d | 2d 5/2 | 6 | [64] | |
| | | 1g 7/2 | 8 | [58] | |
| 4 | 1g | 1g 9/2 | 10 | [50] | {50} |
| | | 2p 1/2 | 2 | [40] | {40} |
| 3 | 2p | 1f 5/2 | 6 | [38] | |
| | | 2p 3/2 | 4 | [32] | |
| 3 | 1f | 1f 7/2 | 8 | [28] | {28} |
| | | 1d 3/2 | 4 | [20] | {20} |
| 2 | 2s | 2s 1/2 | 2 | [16] | |
| 2 | 1d | 1d 5/2 | 6 | [14] | |
| | | 1p 1/2 | 2 | [8] | {8} |
| 1 | 1p | 1p 3/2 | 4 | [6] | |
| 0 | 1s | 1s 1/2 | 2 | [2] | {2} |

Spherical single-particle levels

# Octupole phonon excitations near $^{208}$Pb

- First excited state is a natural-parity $3^-$ octupole state (one phonon octupole vibration) at 2615 keV
- Occurs due to many $\Delta l = \Delta j = 3$ orbital couplings around the shell closures
- Decay to GS via **collective E3 octupole transition**
- $B(E3; 3^- \rightarrow 0^+)$ = 33.8(6) W.u. [2]



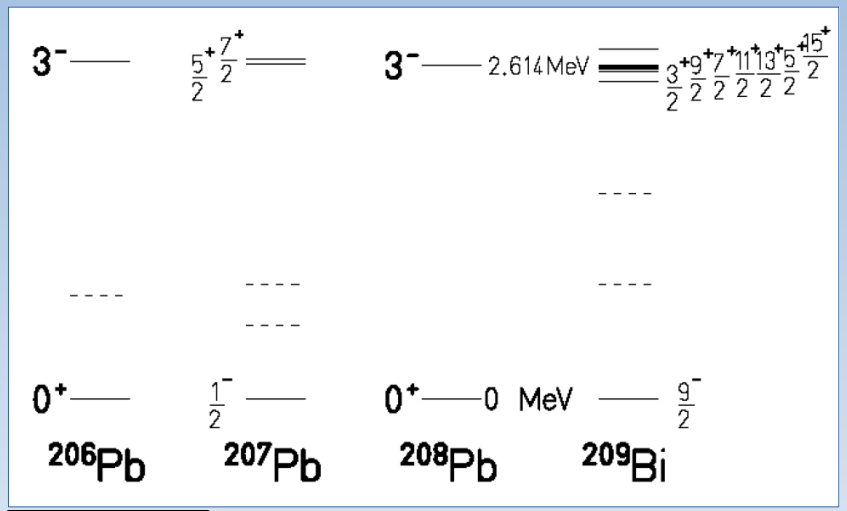



Fig. from [1]

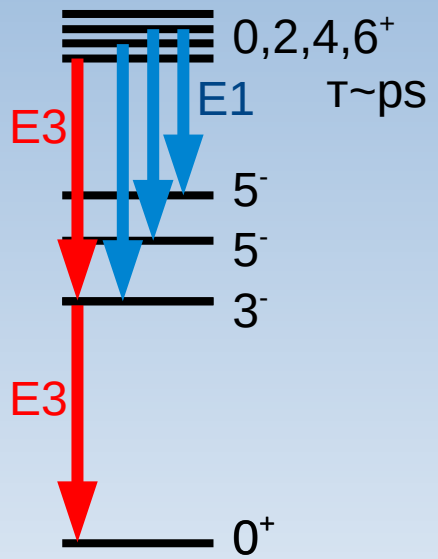
- Particle-phonon structures evident in neighbouring nuclei
- $5/2^+$ $7/2^+$ doublet at similar energy in $^{207}$Pb ($p_{1/2}$,$3^-$ coupling), septuplet in $^{209}$Bi ($h_{9/2}$, $3^-$ coupling)
- Collective octupole states close to $^{208}$Pb recently studied via deep-inelastic / multi-nucleon transfer reactions e.g. [3,4]

- Expected that a double-octupole phonon quartet ($0^+$, $2^+$, $4^+$, $6^+$) exists at roughly twice E($3^-$), i.e. ~ 5.2 MeV
- $^{208}$Pb excellent candidate to find those states due to the low excitation energy (and therefore low level density)

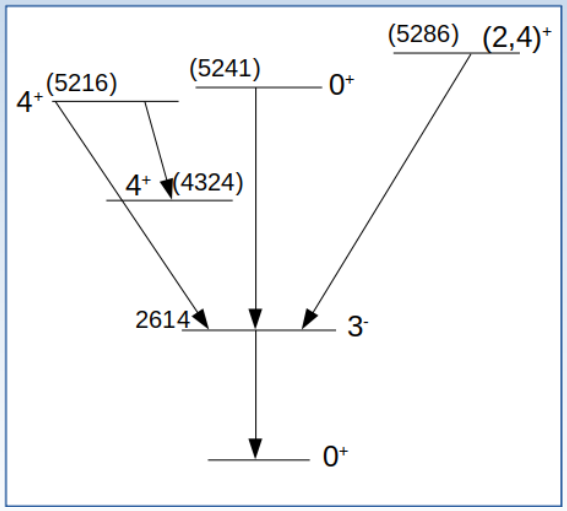

[1] H.J. Wollersheim, Il Nuovo Cimento A **111**, 691-696 (1998)
[2] M.J. Martin, Nucl. Data Sheets **108**, 1583 (2007)
[3] Zs. Podolyak *et al.*, J. Phys.: Conf. Ser. **580**, 012010 (2015)
[4] D. Ralet *et al.*, Phys. Lett. B **797**, 134797 (2019)

# Searches for 2-phonon octupole excitations in $^{208}$Pb

- Signatures of 2-phonon excitation:
  - energies ~double E($3^-$) (i.e. ~5.2 MeV)
  - cascade of two E3 transitions from $0^+$ and $6^+$ members
  - enhanced E1 transitions from $(2^+,4^+) \rightarrow 3^-$ or $(6^+,4^+) \rightarrow 5^-$
  - τ~ps lifetimes




- Many attempts to search for the 2-phonon octupole quartet members carried out (e.g. [1-3])
- Candidates for lower-spin members proposed [4]
  - Evidence for $0^+$ at 5.251 MeV: cascade of two E3 transitions, produced via (n,n'γ)
  - $2^+$ and $4^+$ proposed at 5.288 and 5.216 MeV, respectively
- Calculations suggest fragmentation of $6^+$ member [5], later seen via Coulex that lowest $6^+$ state carries ~20% of E3 strength



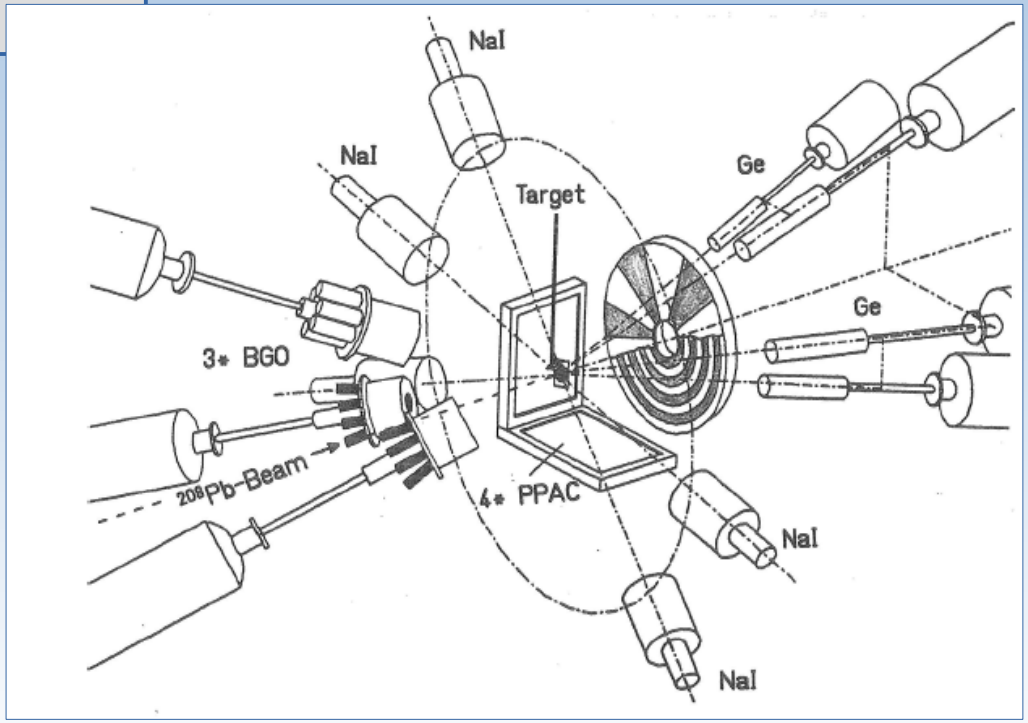


[1] M.A.J. Mariscotti *et al.*, Nucl. Phys. A **407** (1) 98-126 (1983)
[2] H.J. Wollersheim *et al.*, Z. Phys. A **341** (2) 137-144 (1992)
[3] E.F. Moore *et al.*, NIM Phys. Res. Sect. B **99** (1) 308-311 (1995)
[4] M. Yeh *et al.*, Phys. Rev. Lett. **76** (8) 1208-1211 (1996), Phys. Rev. C **57** (5) R2085-R2089 (1998)
[5] B.A. Brown, Phys. Rev. Lett. **85** (25) 5300-5303 (2000)
[6] K. Vetter *et al.*, Phys. Rev. C **58** (5) R2631-R2635 (1998)

# Searches for 2-phonon octupole excitations in $^{208}$Pb

- Recent lifetime measurement of $19/2^+$ state in $^{207}$Pb [1]
- MNT reactions with $^{208}$Pb beam on $^{100}$Mo target
- In $^{208}$Pb's neighbours, strong couplings between orbitals $j_1$ and $j_2$ if $|j_1 - j_2| = 3$
- States built by particles/holes coupled to octupole phonon should mix → enhanced $B(E3)$ from $6^+$ quartet member in $^{208}$Pb should be observable as enhanced $B(E3)$ values in $^{207}$Pb
- $B(E3, 19/2^+ \rightarrow 13/2^+)$ of 40(8) W.u. measured, but uncertainties too large to disentangle particle-octupole and two-phonon contributions...

- Low-energy UNILAC program at GSI
- Previous experiments suffered from
  (i) low cross sections (too high energy)
  (ii) high background (insufficient Compton supression)
- Coulex using very heavy beams (max. Z1Z2)
  - e.g. $^{206}$Pb on $^{208}$Pb
- High-efficiency array (FATIMA), state-of-the-art DAQ




Experimental setup at UNILAC, Coulex $^{208}$Pb+$^{208}$Pb @ 6.2 MeV/u

[1] D. Ralet et al., Phys. Lett. B 797, 134797 (2019)

# Summary

- Two interesting cases for new experiments at the UNILAC:
  - K-isomers in $^{178}$Hf and puzzle of isomer population
  - Multi-phonon octupole excitation in $^{208}$Pb
- Suitable detector configurations required: high efficiency, large solid angles, state-of-art Data Acquisition,...
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- Experiments could be done simulateously

Thank you!

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