Nuclear structure study on iodine and tellurium isotopes using in-beam and β-delayed γ-ray spectroscopy

Byul Moon
Department of Physics, Korea University

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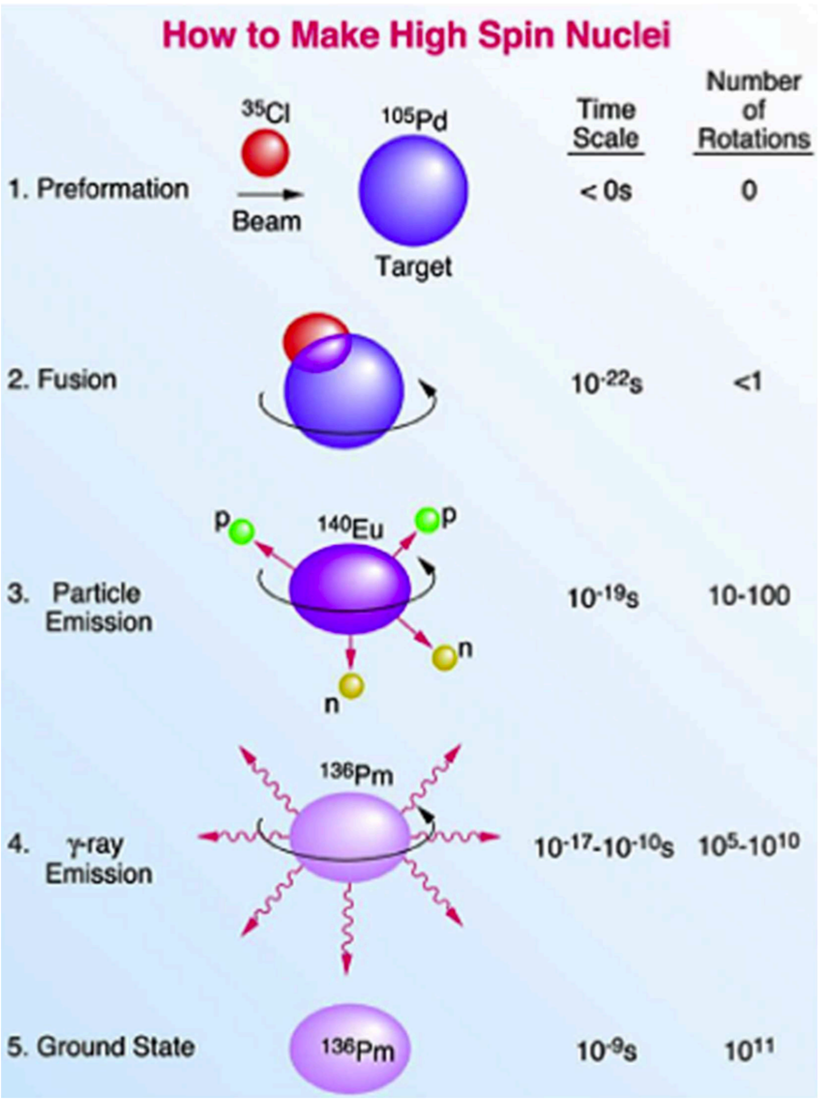
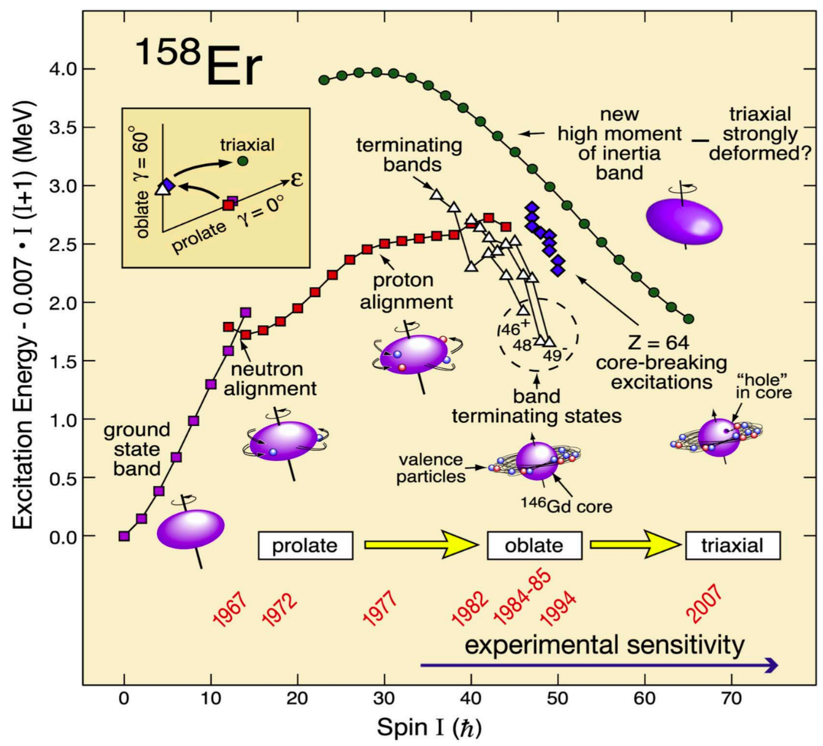
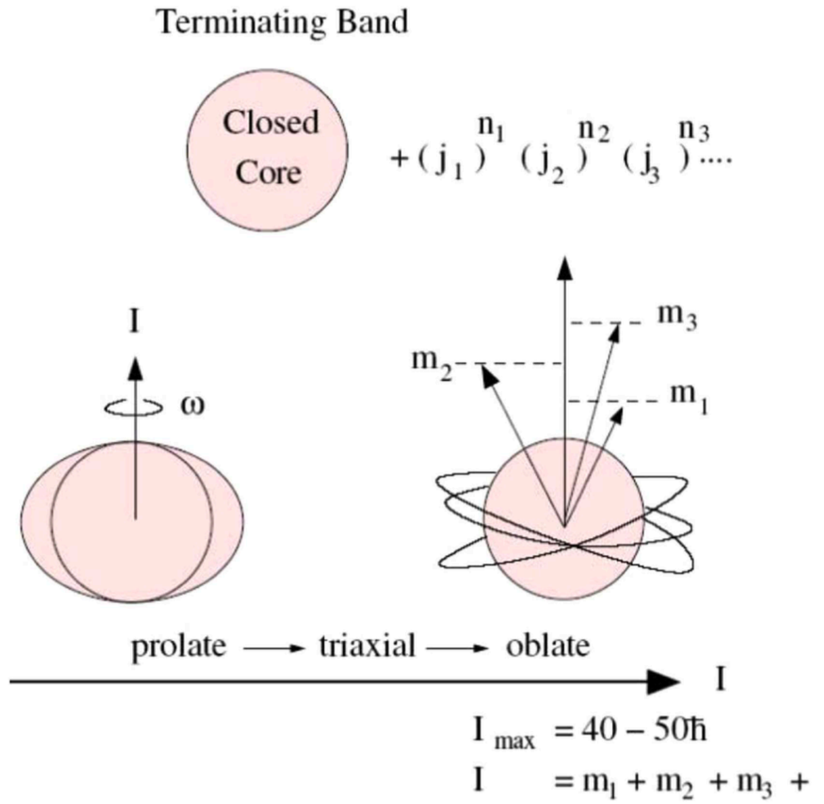


M. A. Riley et. al., Phys. Scr. **91** 123002 (2016)





In-beam γ-ray spectroscopy

1. High spin structure and rotational band structure.
2. Various phenomena related to the nuclear shape.
3. High rate and yrast line.
4. Low intrinsic energy resolution and Doppler effect.
5. Difficult if isomer exists.

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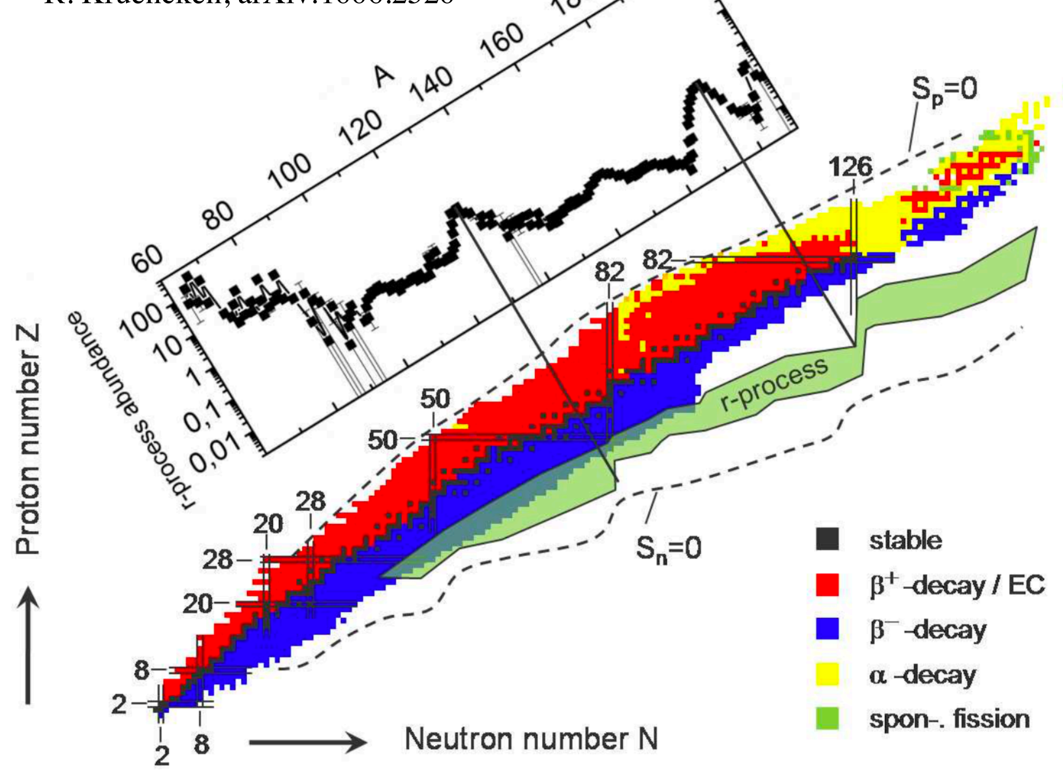
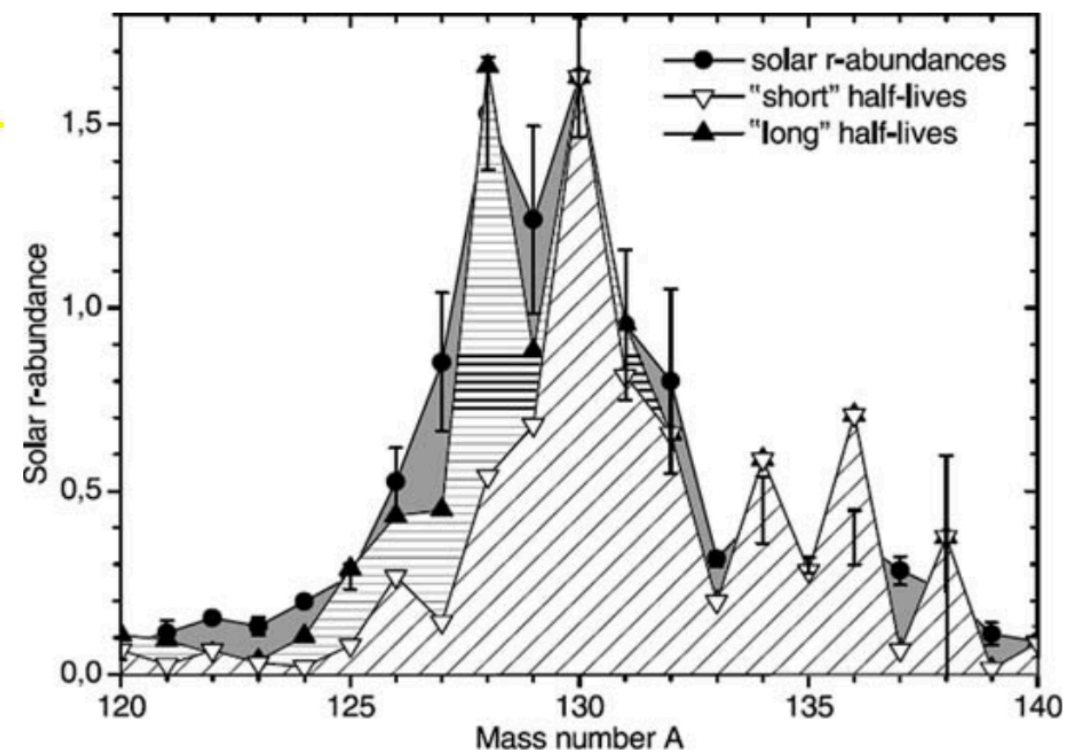
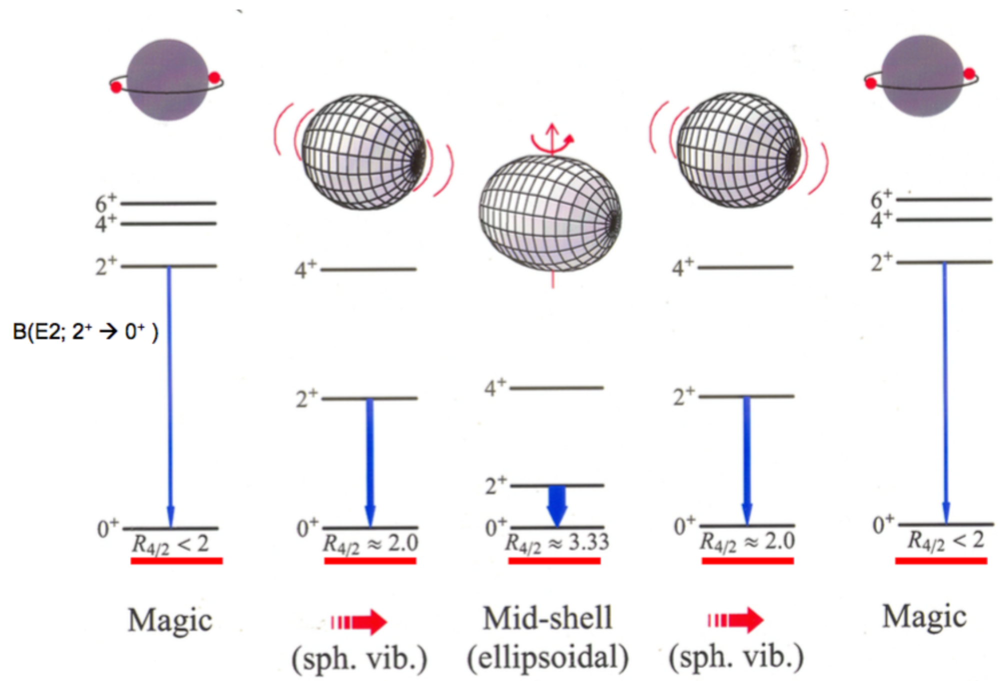
R. Kruencken, arXiv:1006.2520





I. Dillman et al., Phys. Rev. Lett. **91**, 162503 (2003)



β-delayed *γ*-ray spectroscopy

1. Non-yrast states.
2. Deduce half-life, P_n, P_{2n}, level density using log*ft*.
3. Strong relationship with nucleosynthesis.
4. Require low rate.
5. Good energy resolution.
6. More exotic if isomer exists.

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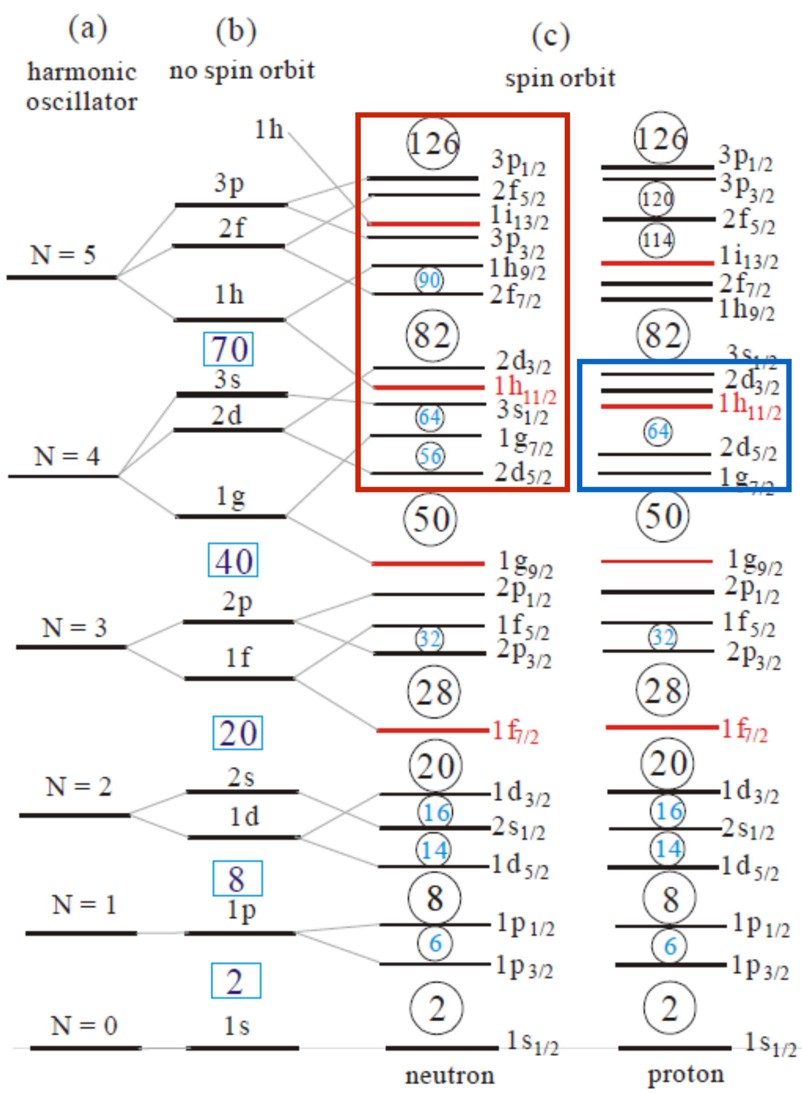

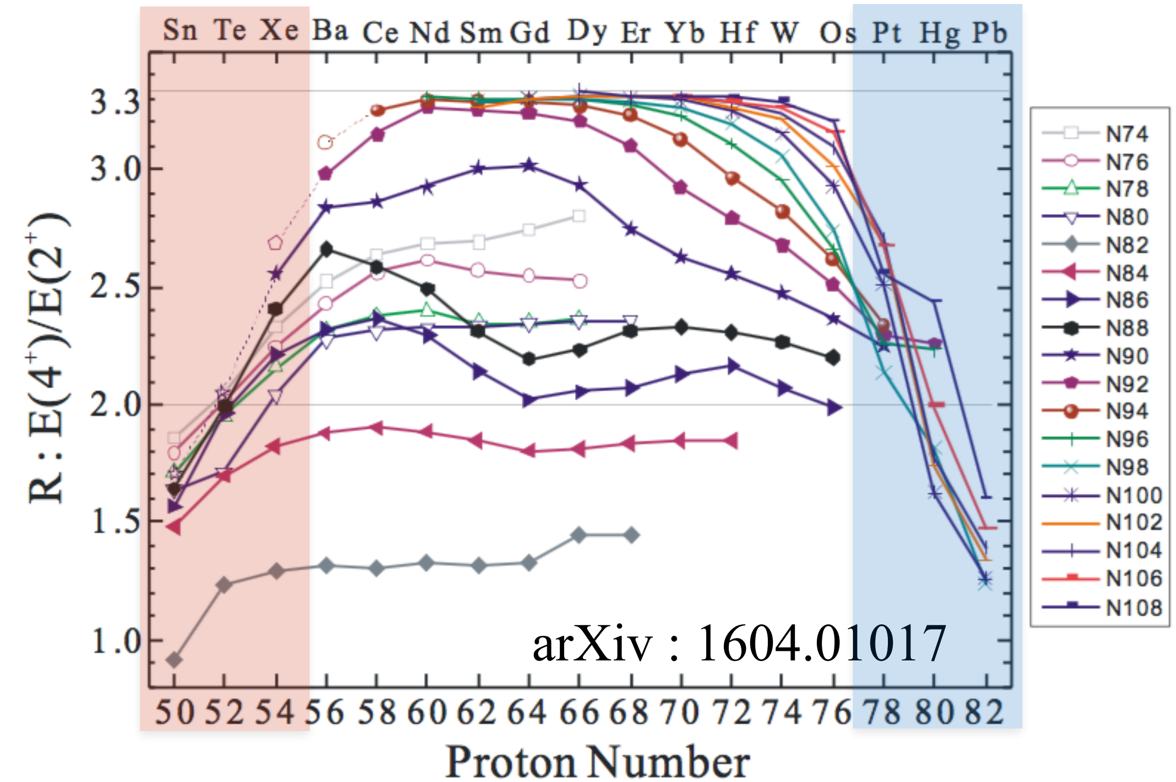

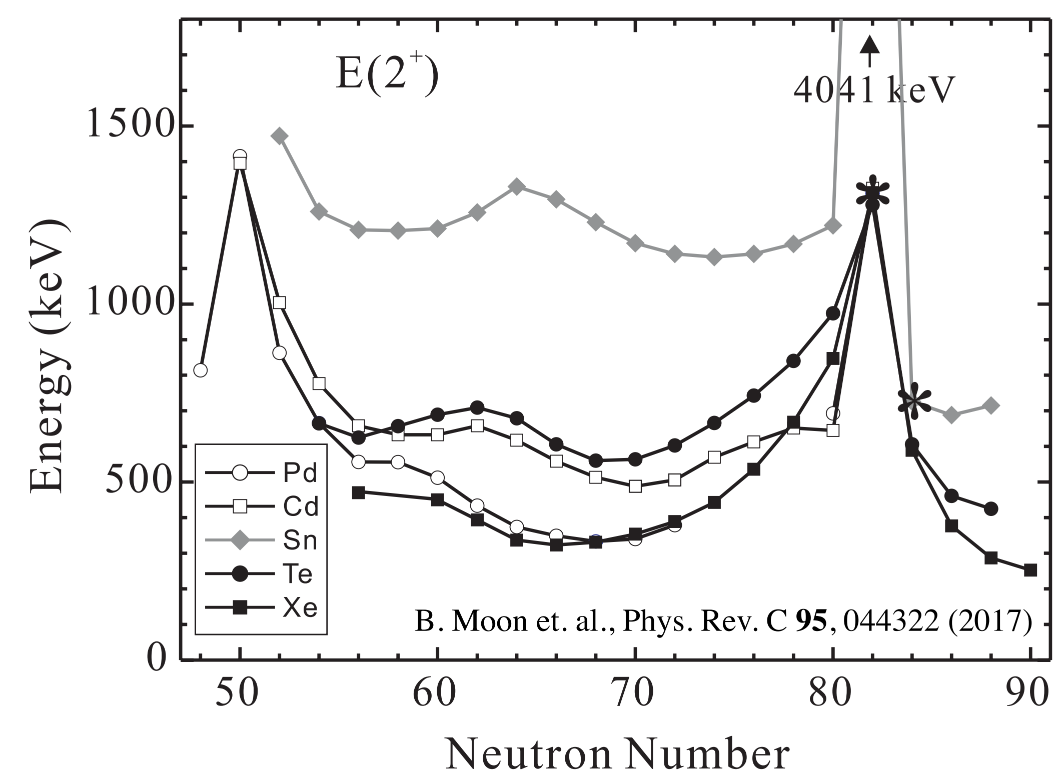

Why iodine and tellurium?

1. Near the proton magic number 50.
2. *r*-process path at neutron-rich region.
3. Unique behavior of Te : vibrator.
4. Very weak deformation.
5. Core transition in I : Xe & Te.
6. $\pi h_{11/2} \nu h_{11/2}$ around A ~ 120.
7. $\pi h_{11/2} \nu h_{9/2}$ around A ~ 140.

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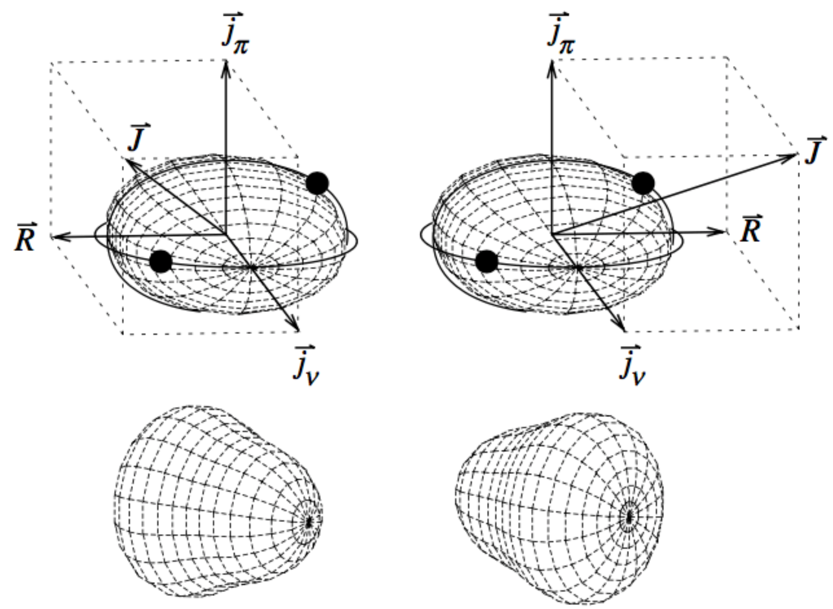
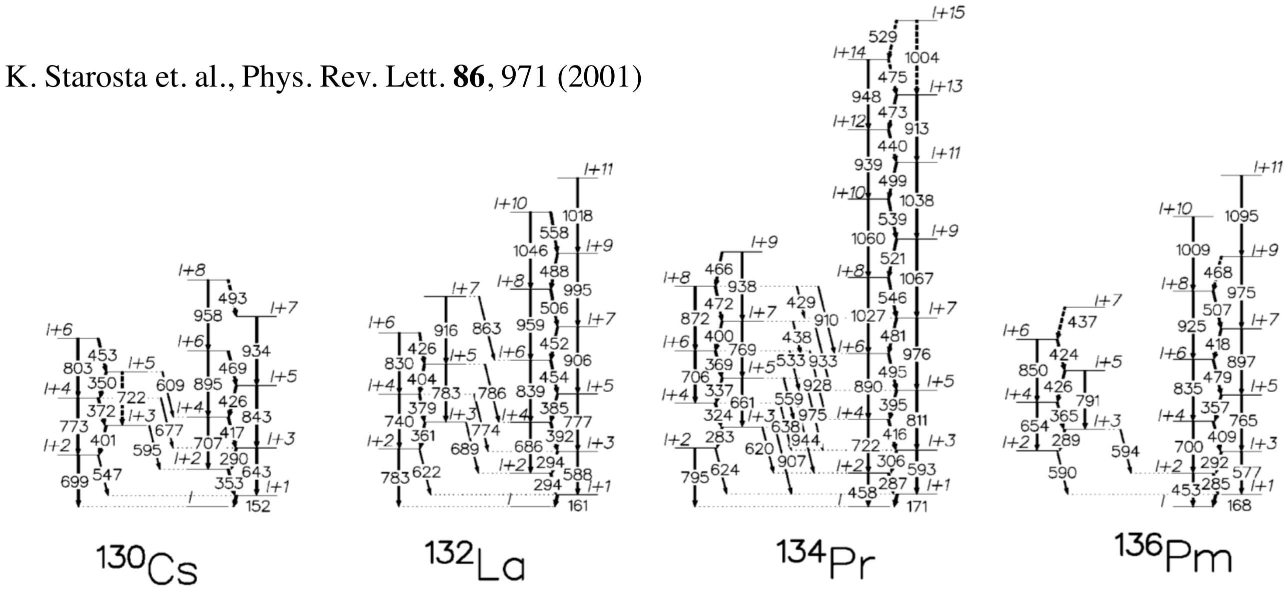
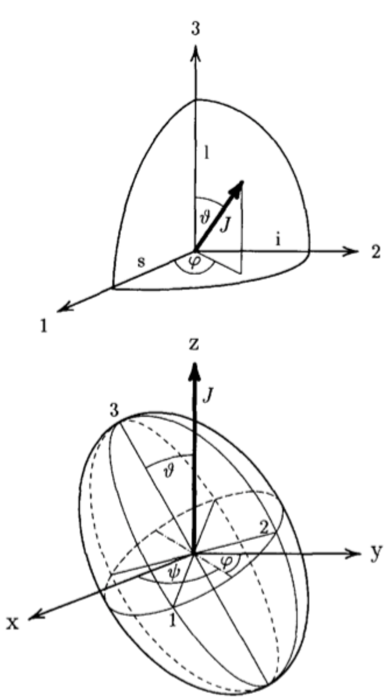


K. Starosta et. al., Phys. Rev. Lett. **86**, 971 (2001)





S. Frauendorf et. al., Nucl. Phys. A **617**, 131 (1997)

Chiral doublet structure (twin band)

1. Associated with spontaneous chiral symmetry breaking. [1, 2]
2. Fermi level, lower par of a valence proton high-j subshell. [1, 3]
3. Require aplanar solution, which means $\boldsymbol{J}$ does not lie on any principle plane. [1]
4. Best at $\gamma = -30^\circ$, or $25^\circ < -\gamma < 40^\circ$, triaxial shape. [1]

[1] S. Frauendorf et. al., Nucl. Phys. A **617**, 131 (1997)

[2] S. Frauendorf, Rev. Mod. Phys. **73**, 463 (2001)

[3] K. Starosta et. al., Phys. Rev. Lett. **86**, 971 (2001)

Results on A ~ 120

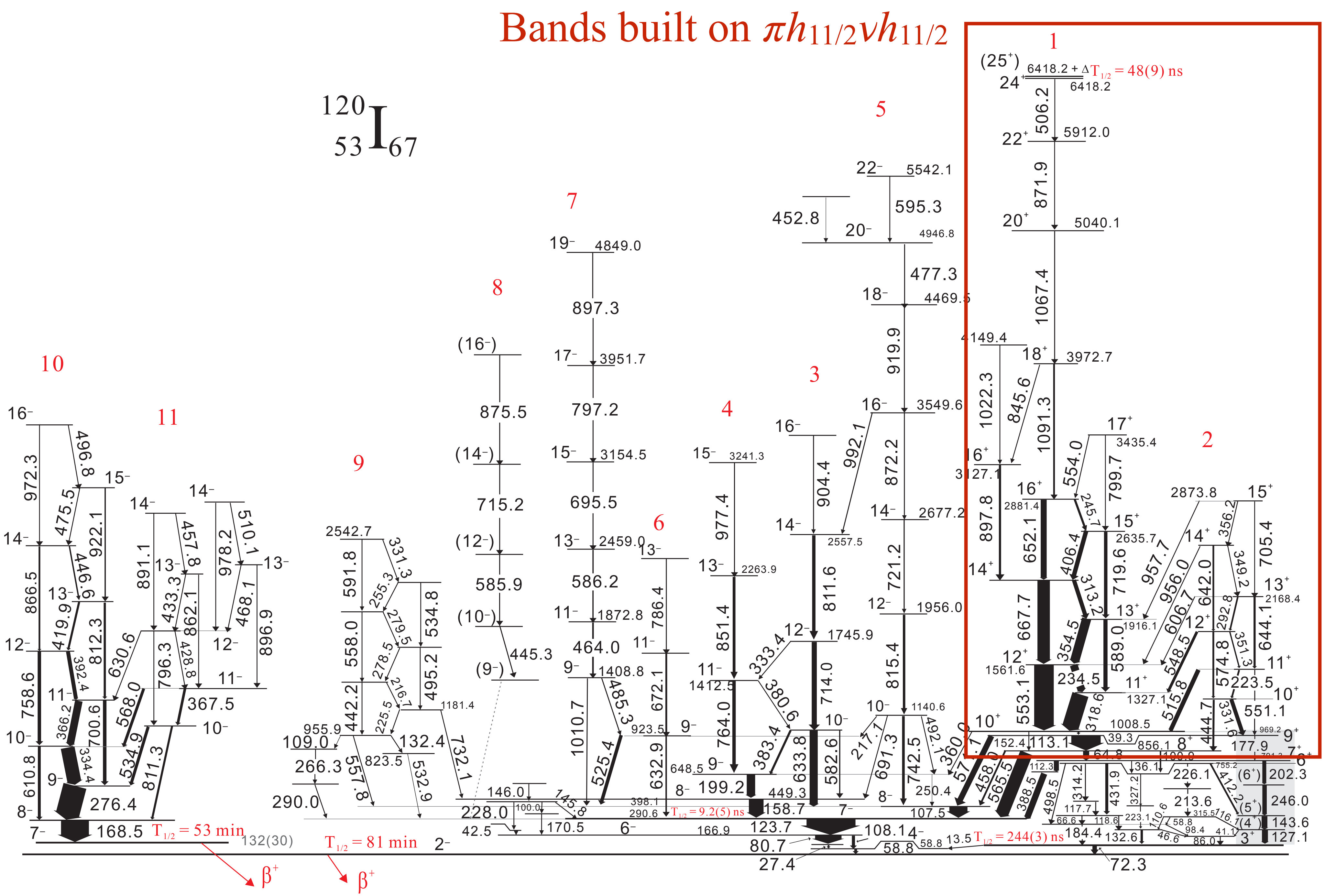
- Experiment

ANU HIAF
(Australia National University Heavy Ion Accelerator Facility)

1. 14UD tandem accelerator with chopped beams.
2. Exp. beam & reaction setup
   beam period : 1 ns online beam / 1.7 μs total period
   reaction : ^{118}Sn(^{6}Li, 4n)^{120}I
   beam energy : 48 MeV
   target thickness : 3.6 mg/cm^{2} ^{118}Sn foil
3. CAESAR array :
   6 Compton suppressed HPGe detectors
   2 LEPS detectors
   Two at 97˚, two at 48˚, two at 145˚ for DCO analysis

Results on A ~ 120

- ^{120}I, Occurrence of twin band and oblate isomer



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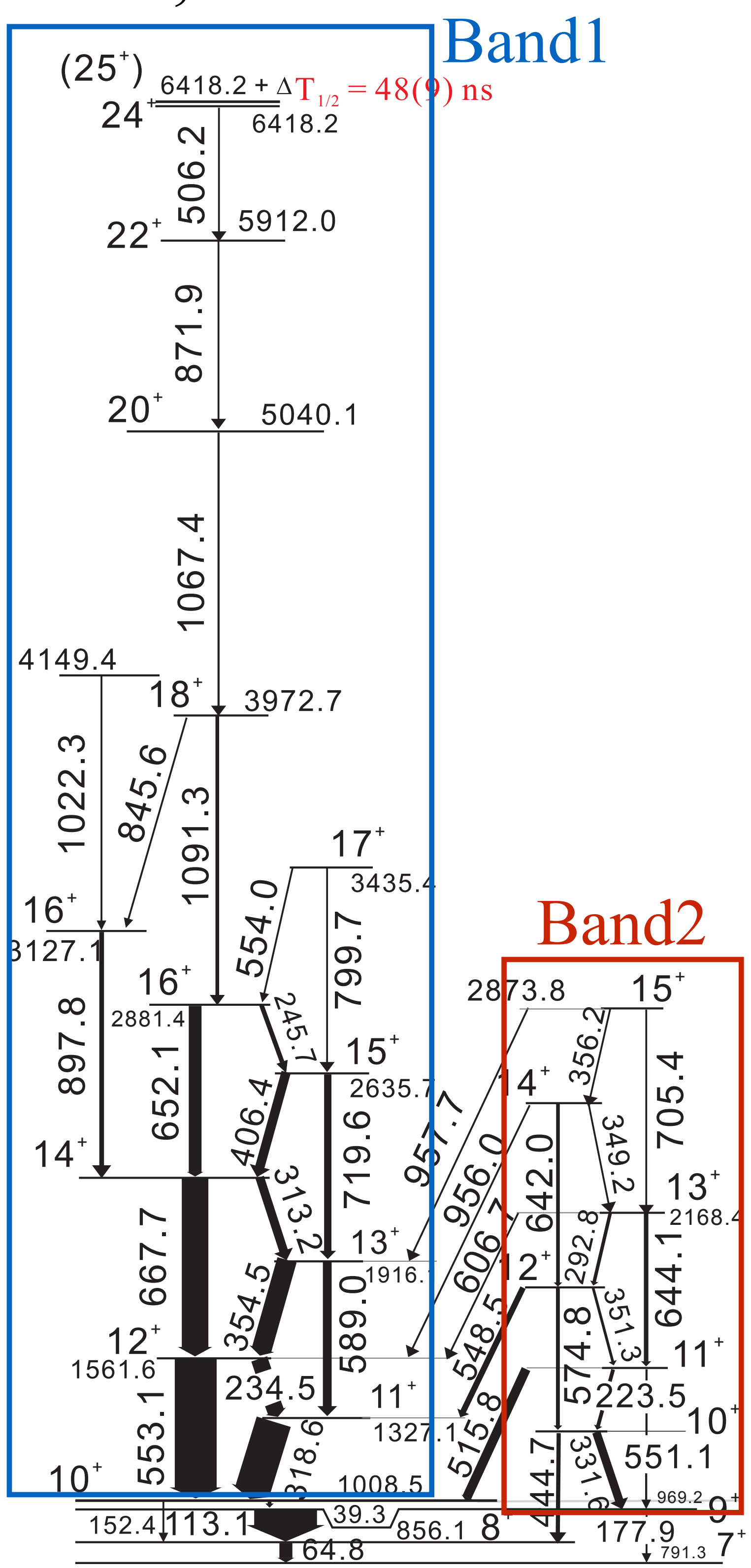
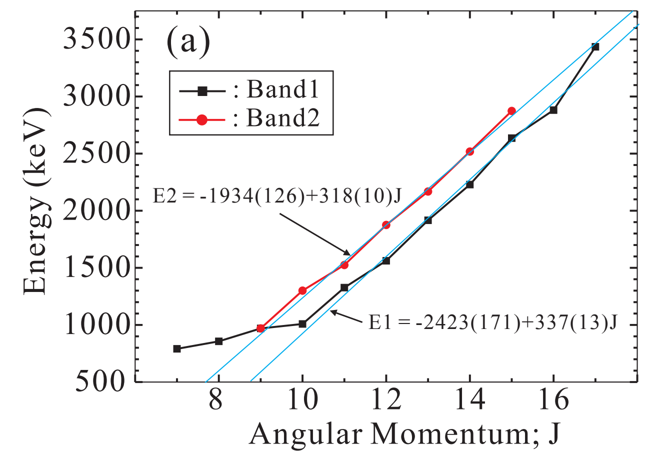
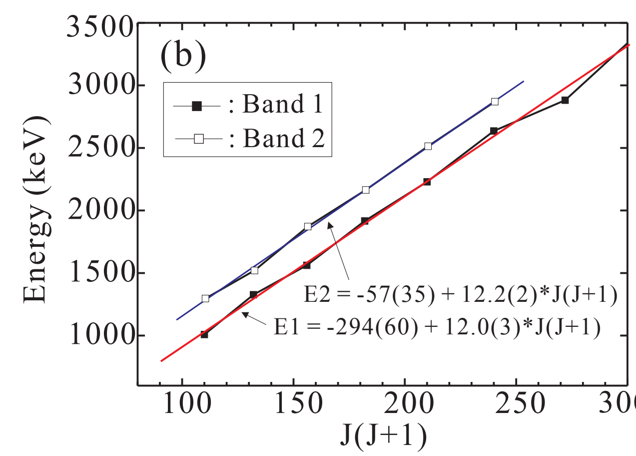


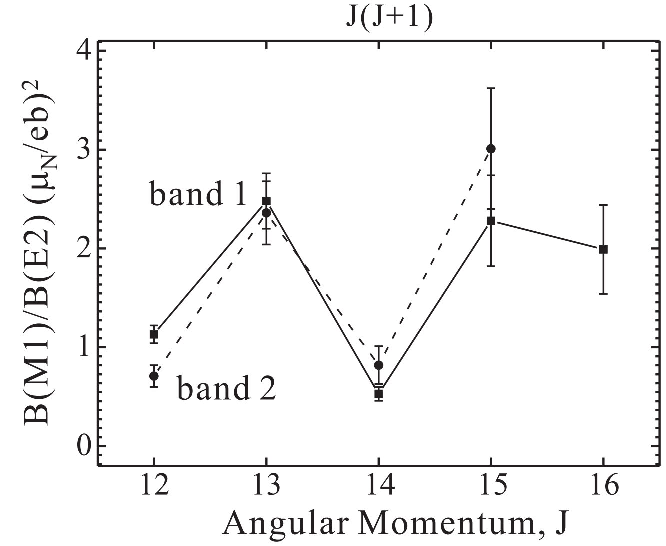


Angular freq.
$\omega \approx 330$ keV/$\hbar$

Constant E difference
$\Delta E \approx 250$ keV



Moment of inertia,
$\mathfrak{I}_0 \approx 42\ \hbar^2$/MeV



Similar B(M1)/B(E2) ratio

Shape coexistence?
Chiral doublet band?

Results on A ~ 120

- ^{120}I, Occurrence of twin band and oblate isomer

6qp

$\pi(g_{7/2})^1(d_{5/2})^1(h_{11/2})^1\nu(h_{11/2})^3$

$_{50}$Sn Core

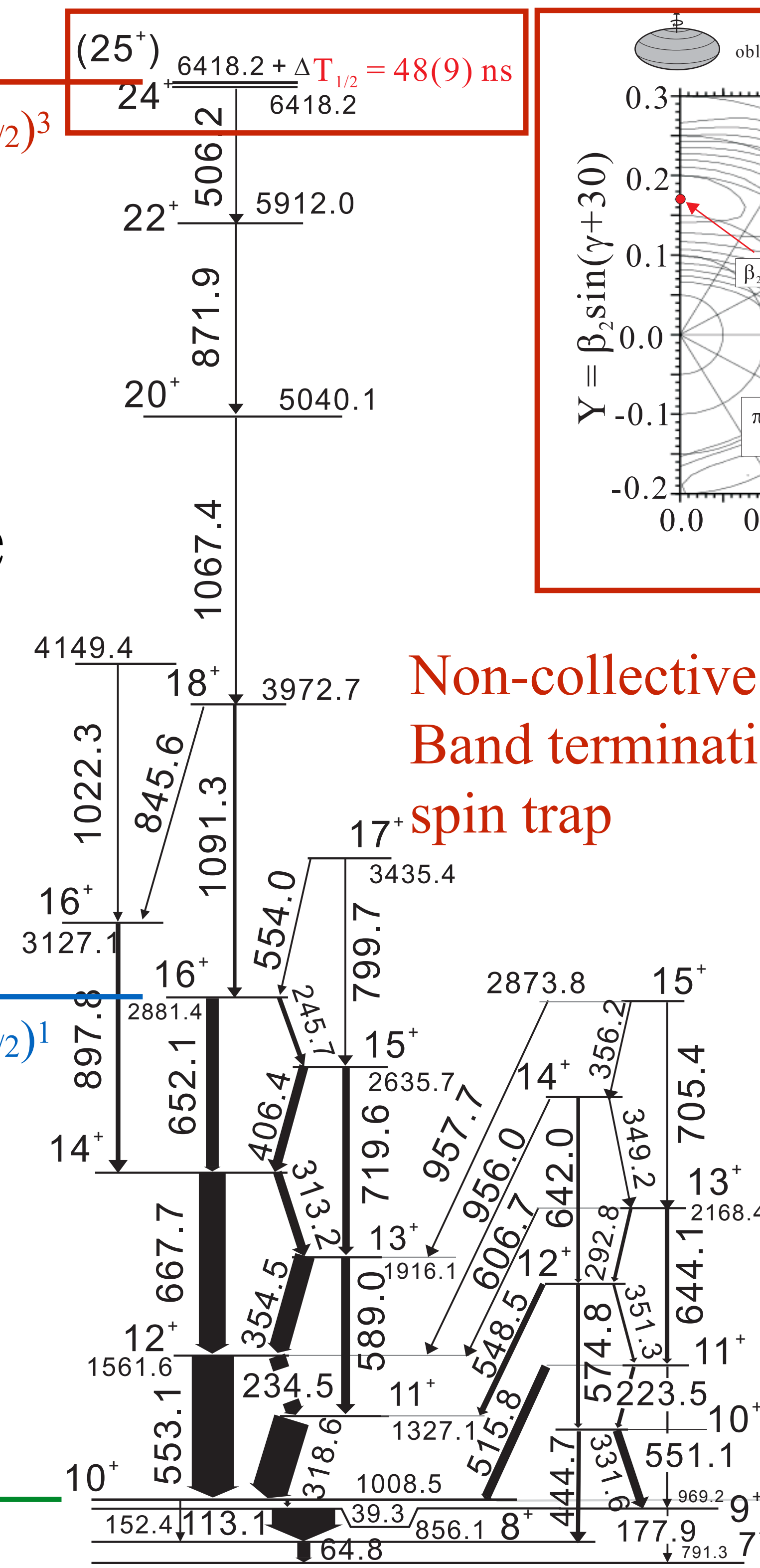
4qp

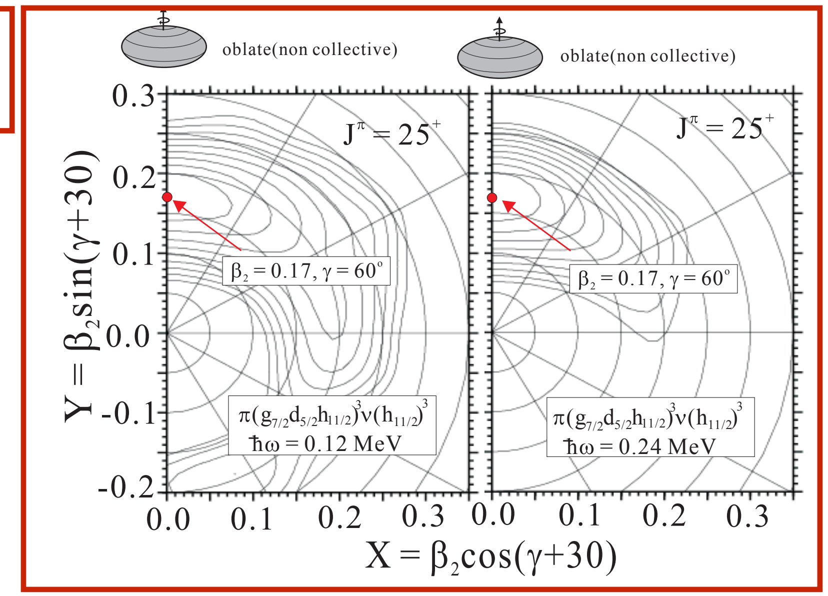
$\pi(g_{7/2})^1(d_{5/2})^1(h_{11/2})^1\nu(h_{11/2})^1$

$_{52}$Te Core

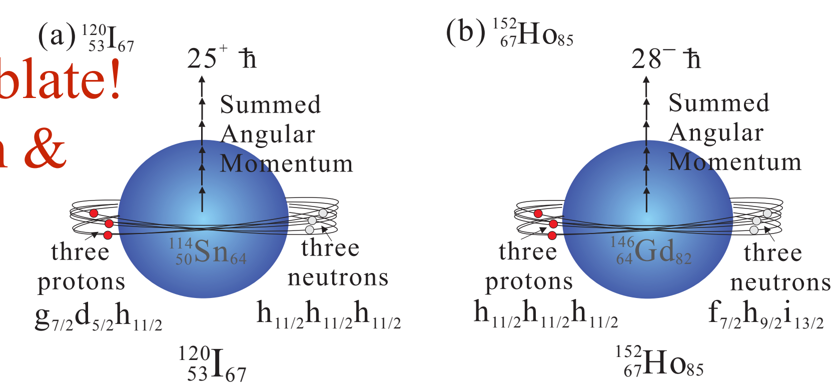
2qp

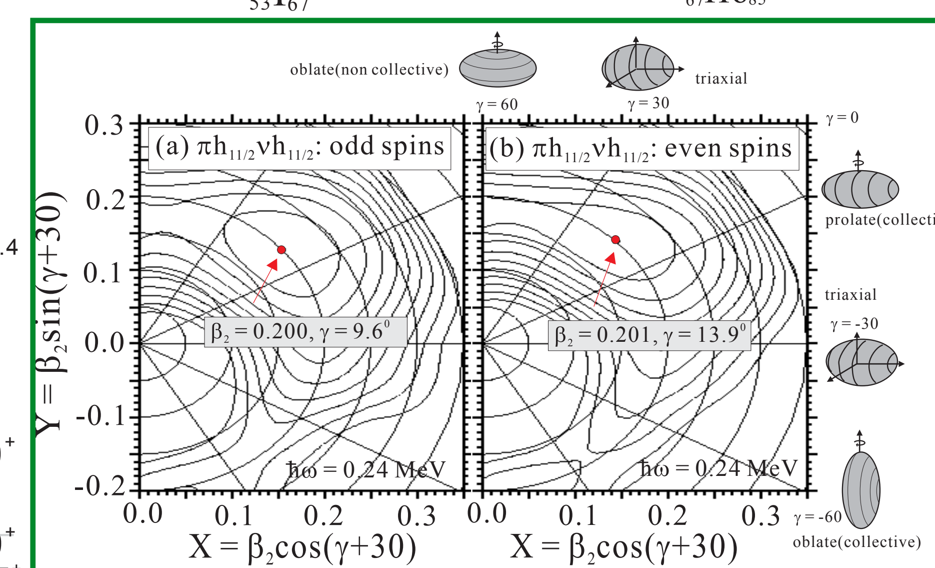
$\pi(h_{11/2})^1\nu(h_{11/2})^1$





Non-collective oblate!
Band termination & spin trap





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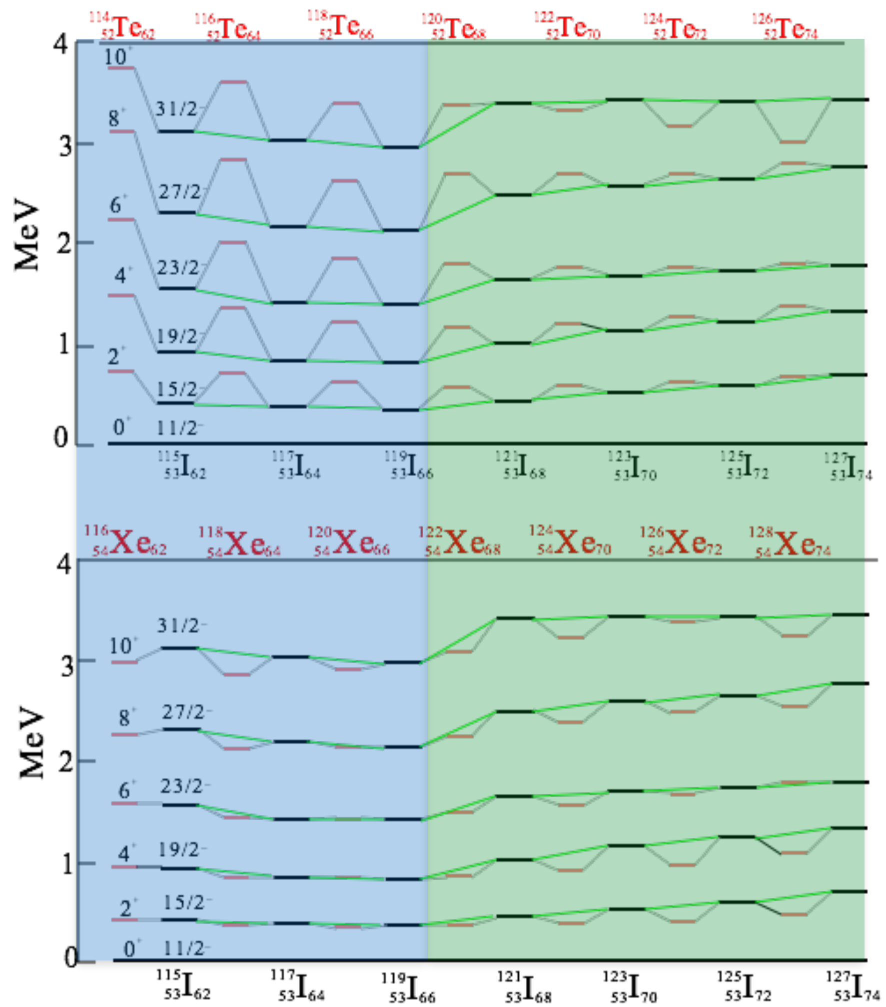
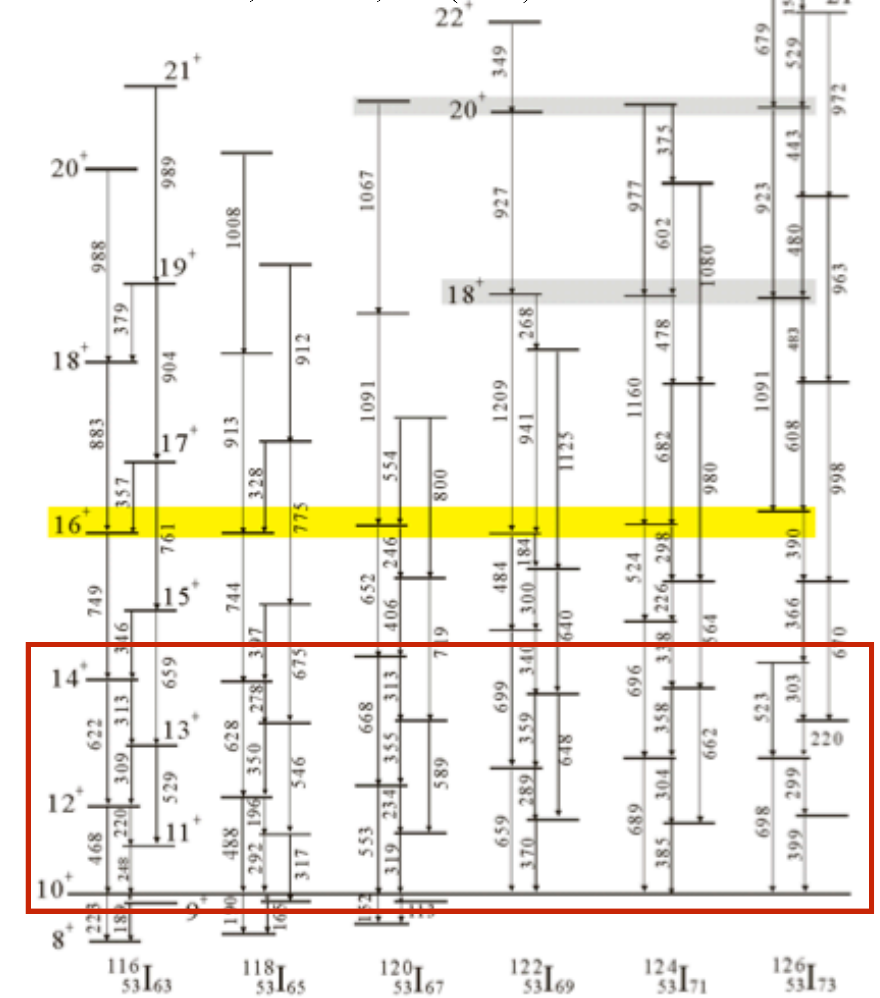
- Systematic approach on iodines isotopes



$_{54}$Xe core　　$_{52}$Te core

C.-B. Moon, JKPS **44**, 244 (2004)



$_{54}$Xe core ⇒ $_{52}$Te core

1. Xe core to Te core transition trend. Soft rotator to vibrator.
2. 16^+ states in the rotational band on $\pi h_{11/2}\nu h_{11/2}$ are constant. Two additional proton quasiparticle configuration, $\pi(g_{7/2})^1(d_{5/2})^1(h_{11/2})^1\nu(h_{11/2})^1$.
3. TRS : Weak triaxial shape near collective prolate for A = 116, 118, 120. γ-soft non-collective oblate shape for A = 122, 124. γ-soft triaxial shape for A = 126.
4. Iodine isotopes are good playgrounds for investigating the shell evolution.

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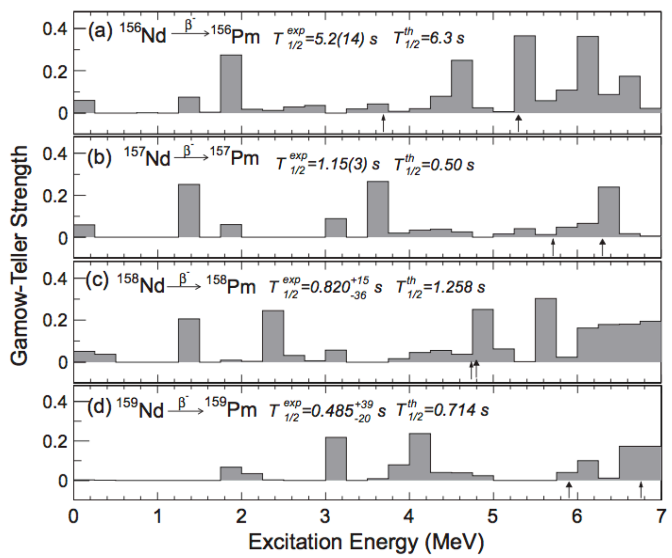
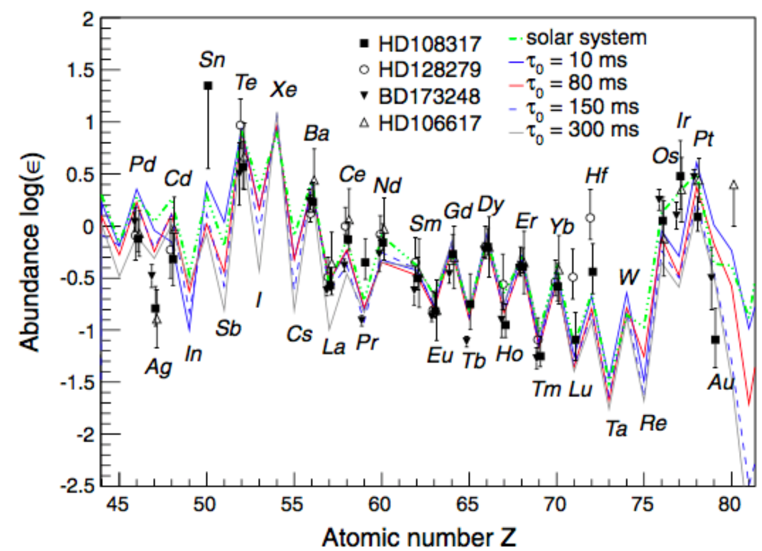
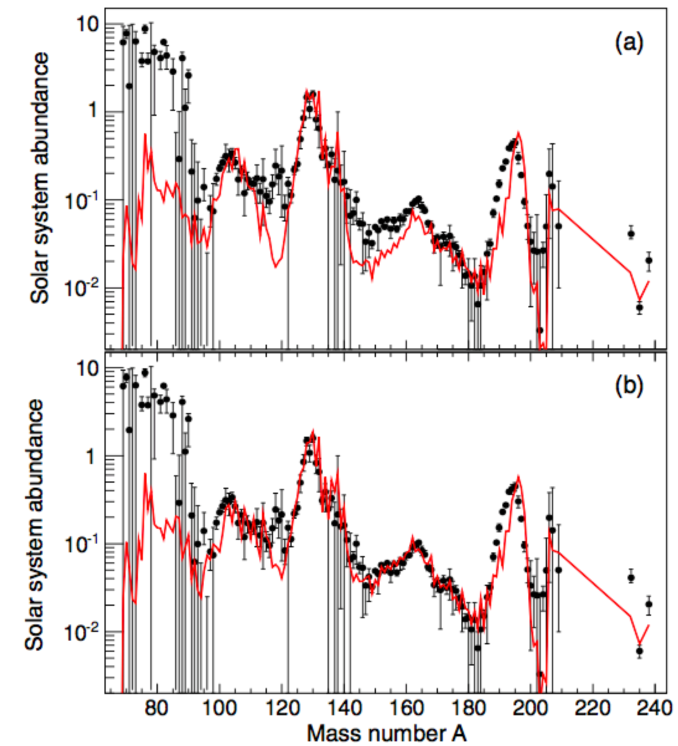
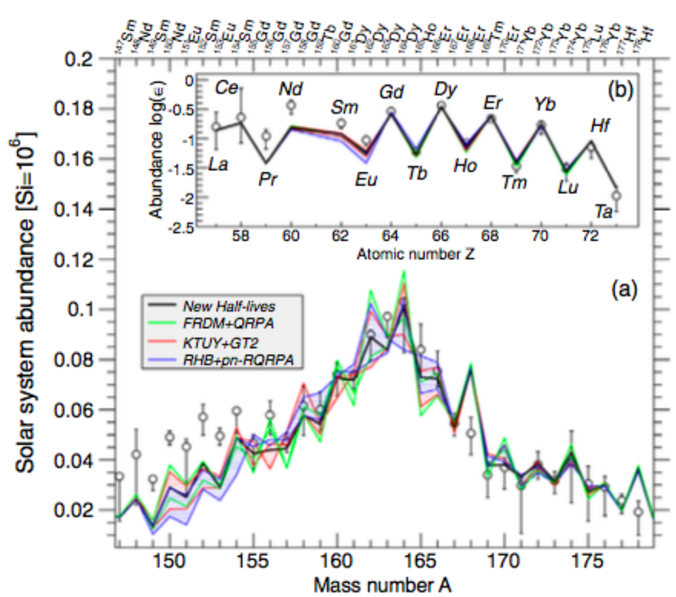


FRDM+QRPA model



G. Lorusso et. al., Phys. Rev. Lett. **114**, 192501 (2015)





The *r*-process abundances pattern.

J. Wu et. al., Phys. Rev. Lett. **118**, 072701 (2017)

1. $T_{1/2}$, S_n, S_{2n}, B(GT), G-T resonance, $Q_{\beta-}$: significant observables for the r-process path and solar element abundances. [1]
2. B(GT), G-T resonance : crucial evidence for shell evolution, and shell structure. [2, 3]

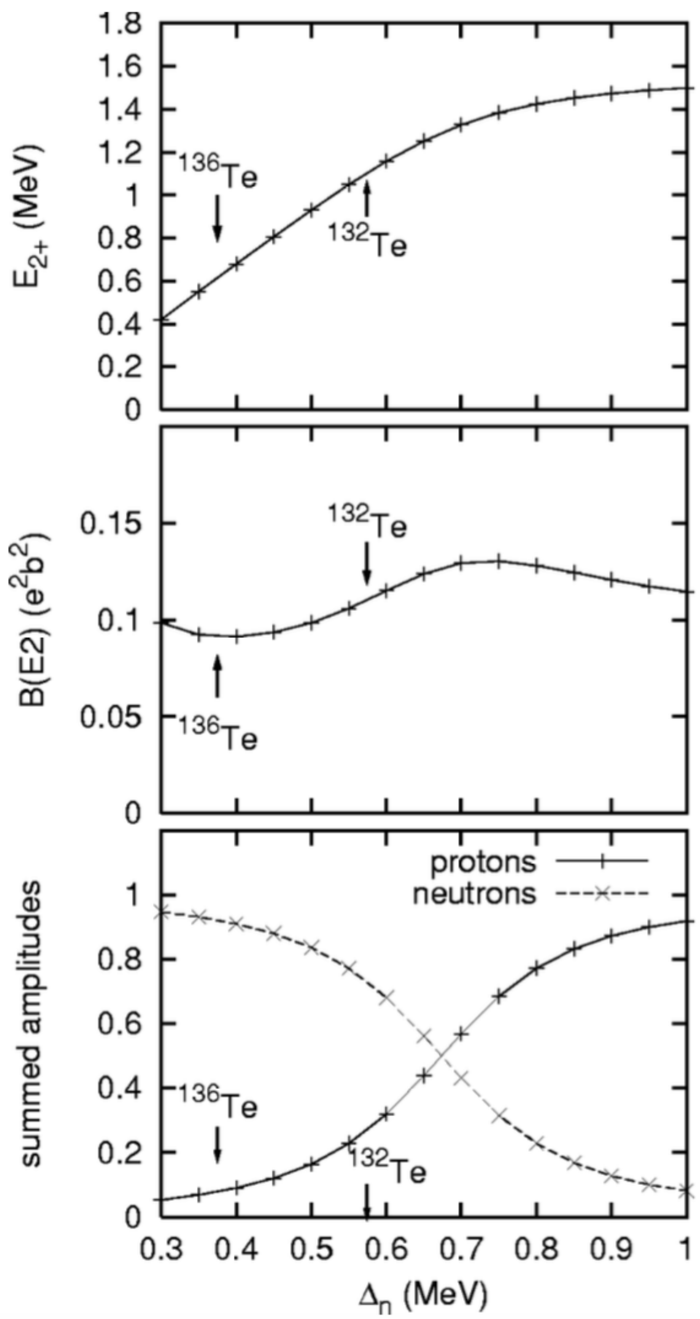
[1] K.-L. Kratz et. al., Nucl. Phys. A **630**, 352c (1998).

[2] P. Urkedal et. al., Phys. Rev. C **64**, 054304 (2001).

[3] B. Rubio et. al., Lecture Notes in Physics **764**, 99 (2009).

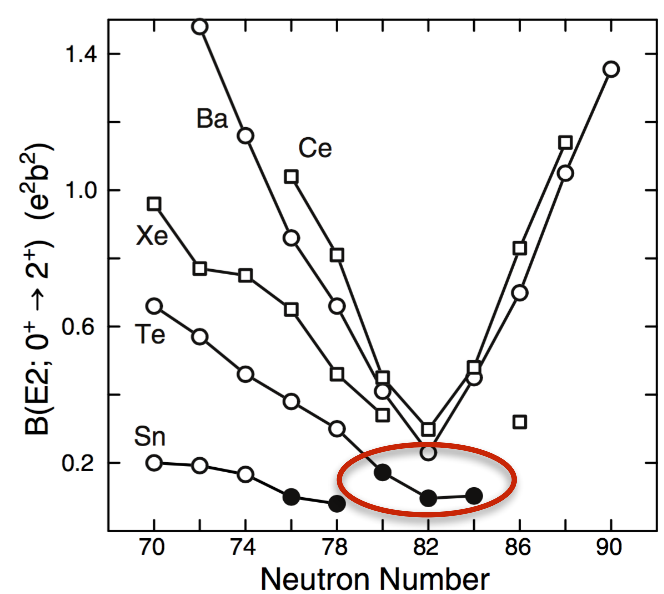
Results on A ~ 140

- Motivation



J. Terasaki et. al., Phys. Rev. C **66**, 054313 (2002)

D. C. Radford et. al., Phys. Rev. Lett. **88**, 222501 (2002)



N. Shimizu et. al., Phys. Rev. C **70**, 054313 (2004)

$$|0_1^+\rangle = 0.91 \times |S_\nu \times S_\pi\rangle + \cdots,$$

$$|2_1^+\rangle = 0.82 \times |D_\nu \times S_\pi\rangle + 0.45 \times |S_\nu \times D_\pi\rangle + \cdots$$

$$|2_2^+\rangle = 0.38 \times |D_\nu \times S_\pi\rangle - 0.76 \times |S_\nu \times D_\pi\rangle + \cdots$$

S_ν : ground state of ^{134}Sn deduced by a neutron pair
S_π : ground state of ^{134}Te deduced by a proton pair
D_ν : first 2^+ state of ^{134}Sn deduced by a neutron pair
D_π : first 2^+ state of ^{134}Te deduced by a proton pair

$$|2^+; {}^{132}\mathrm{Te}\rangle = 0.74|\nu^{-2}\rangle \pm 0.67|\pi^2\rangle$$

$$|2^+; {}^{136}\mathrm{Te}\rangle = 0.92|\nu^{2}\rangle \pm 0.39|\pi^2\rangle$$

Simplistic seniority-two empirical model. [1]

1. ^{136}Te has lower B(E2) value than expected. [1]
2. Explains by the neutron dominance using the simplistic seniority-two empirical model. [1]
3. Theoretical shell model calculations show the 2^+_1 has strong neutron pair effects. [2]
4. QRPA calculations show this effect is deduced by the small value of the neutron pair gap. [3]

[1] D. C. Radford et. al., Phy. Rev. Lett. **88**, 222501 (2002)
[2] N. Shimizu et. al., Phy. Rev. C **70**, 054313 (2004)
[3] J. Terasaki et. al., Phy. Rev. C **66**, 054313 (2002)

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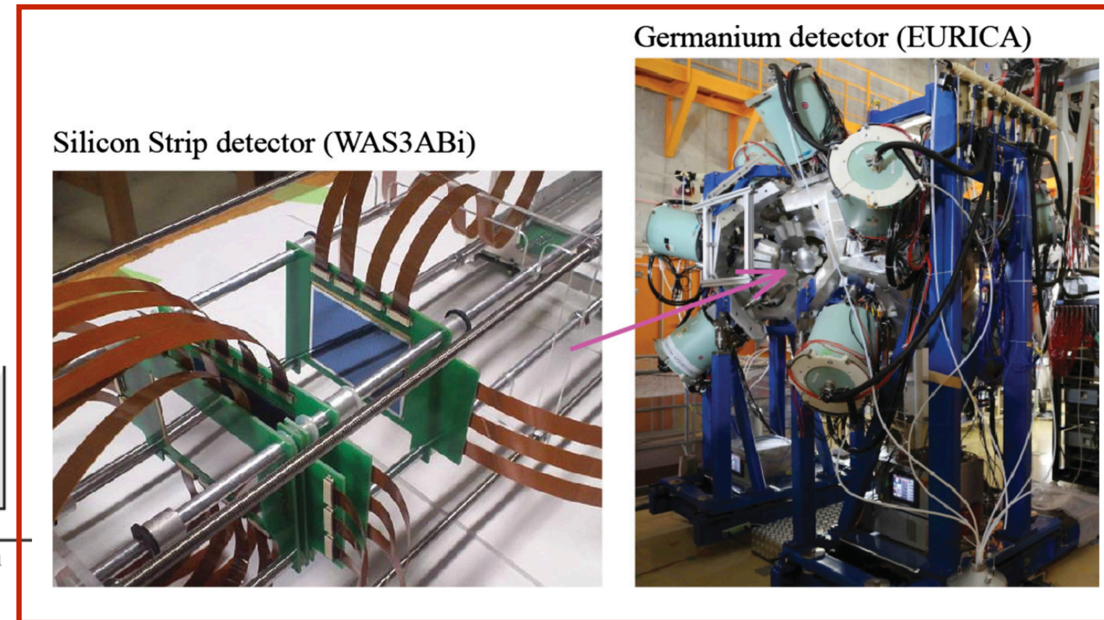
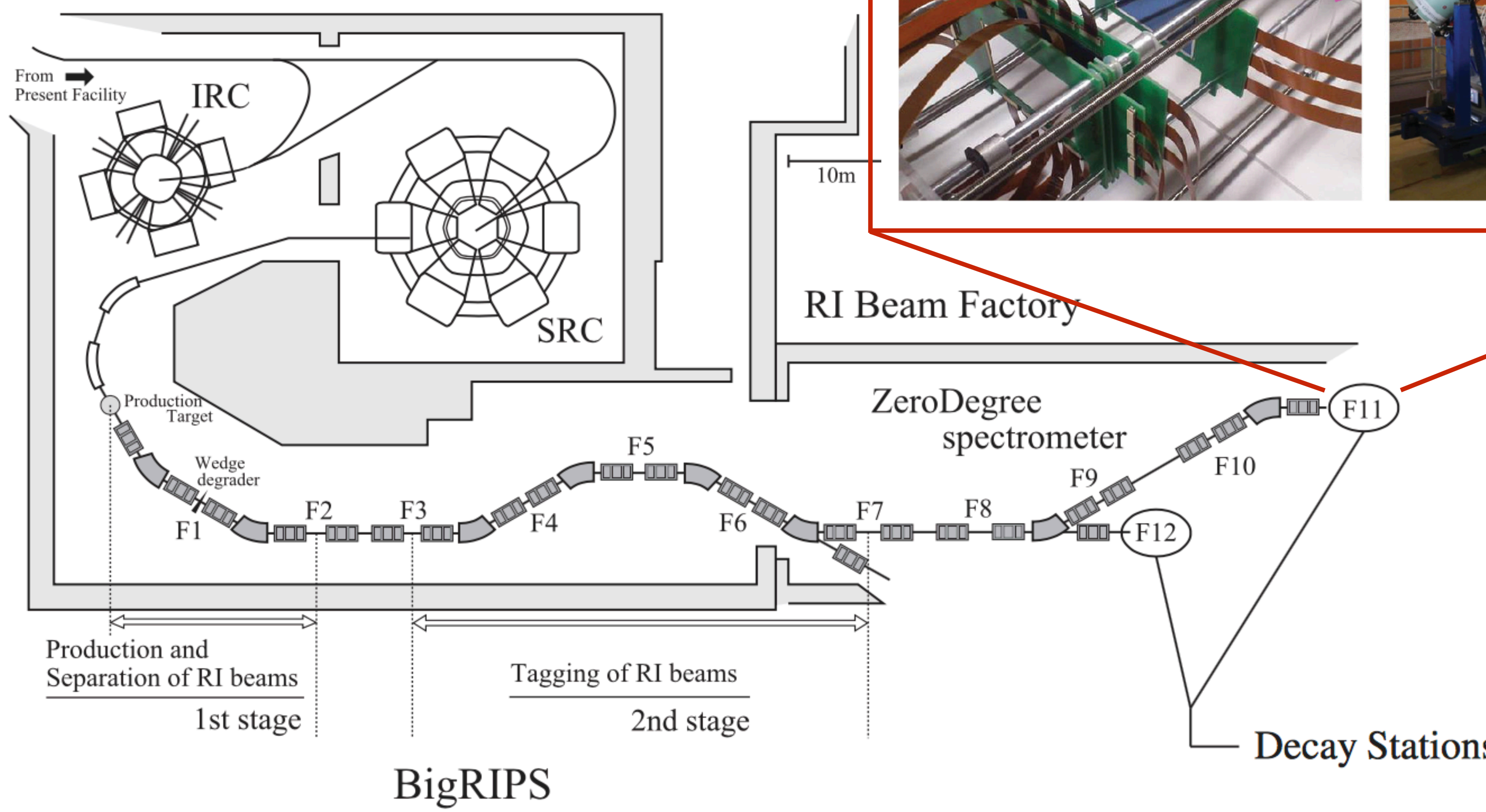


S. Nishimura, Prog. Theor. Exp. Phys. **2012**, 03C006



1. RIKEN Nishina Center (RNC), RIBF (Radioactive Isotope Beam Factory).
2. EURICA Campaign, locate at F11 experimental hall.
3. NP1112-RIBF87 “Shape evolution in neutron-rich A~140 nuclei beyond the doubly-magic nucleus ^{132}Sn”

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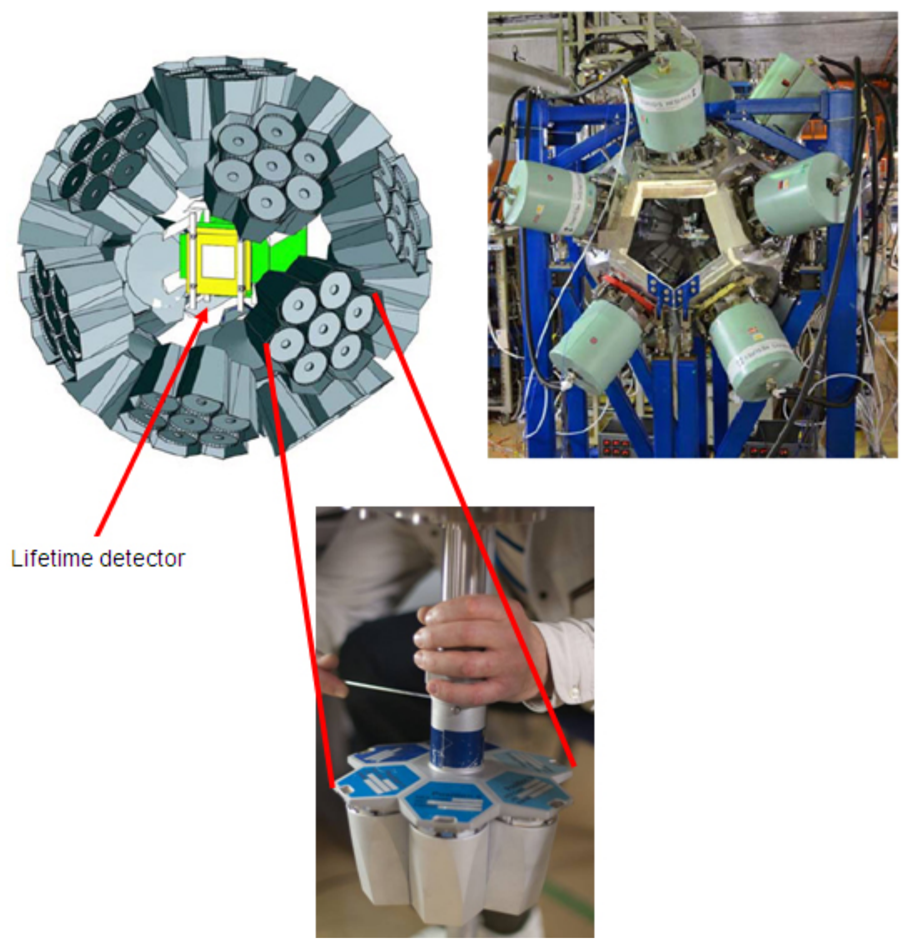
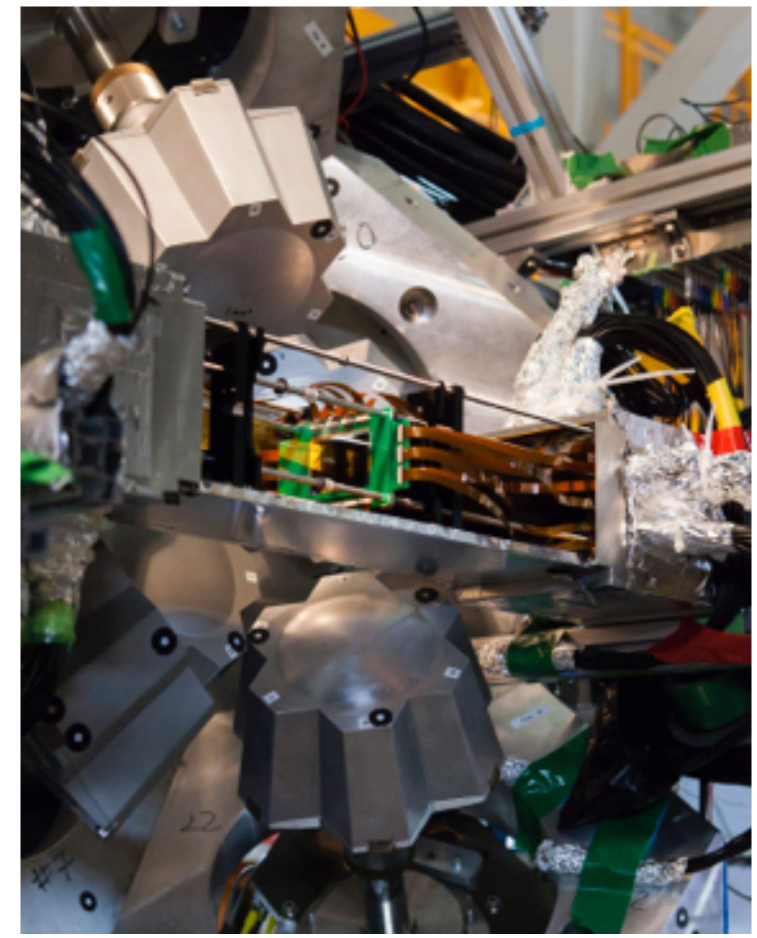


1. 84 hexaconical HPGe crystals from GSI
2. A cluster consists of 7 crystals, 12 clusters
3. Spherical structure surrounding WAS3ABi
4. 1.99 keV at 1.3 MeV energy resolution
5. 51°, 129° : 5 clusters for each / 90° : 2 clusters



1. Up to 8 DSSD layers, generally 5 DSSD layers
2. 1mm thickness and 60X40 strips
3. 20 keV threshold
4. 20 keV energy resolution
5. 100-200 pps maximum count rate
6. Ion implantation and β-ray detect(β-ray tracking)

P.-A. Söderström et. al., Nucl. Inst. Meth. B **317**, 649 (2013)

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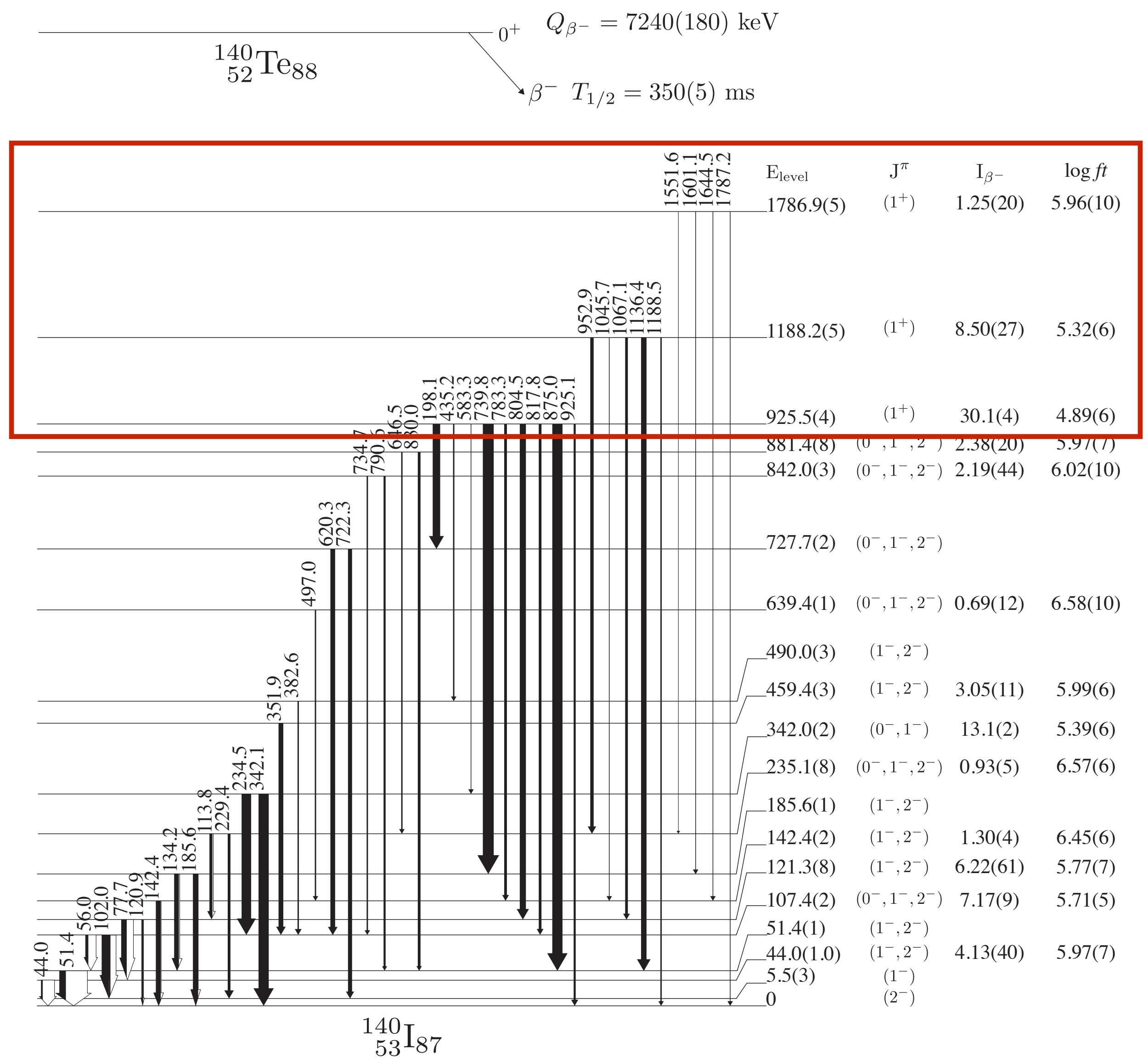

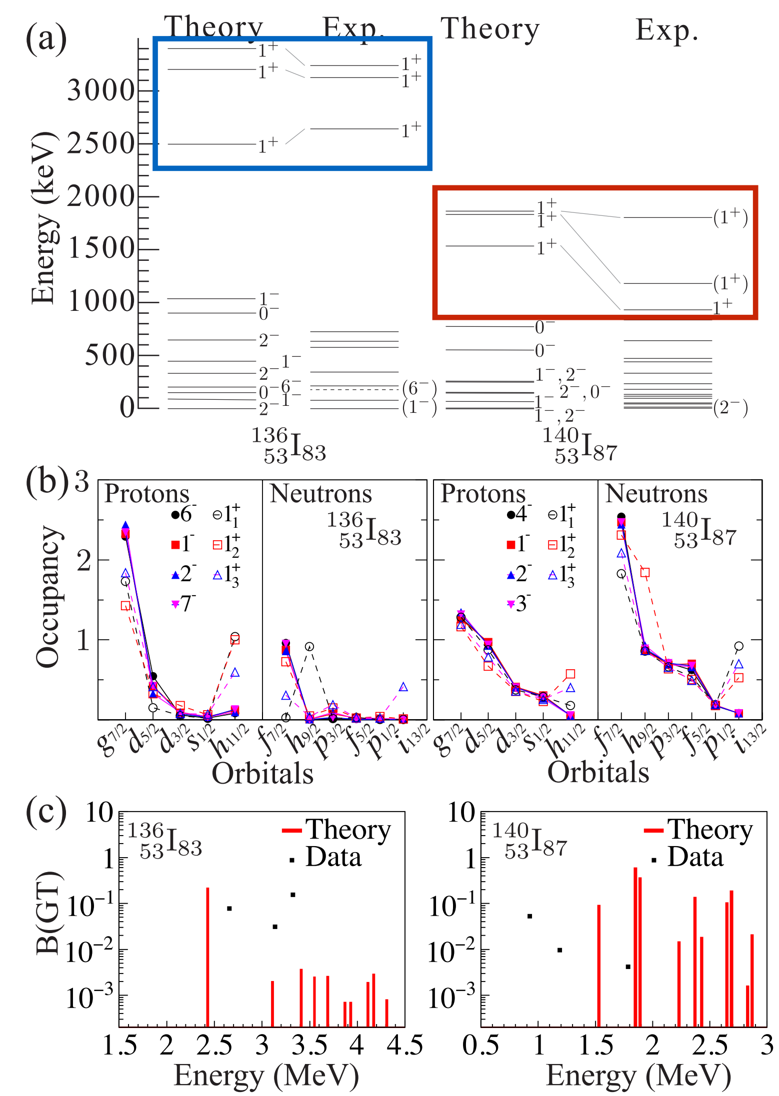

B. Moon et. al., Phys. Rev. C **96**, 014325 (2017)

1. Energy suppression of 1$^+$ states in ^{140}I compared to ^{136}I and SM calculations.
2. Opposite tendency and suppression of B(GT) of 1$^+$ states in ^{140}I compared to SM calculations.

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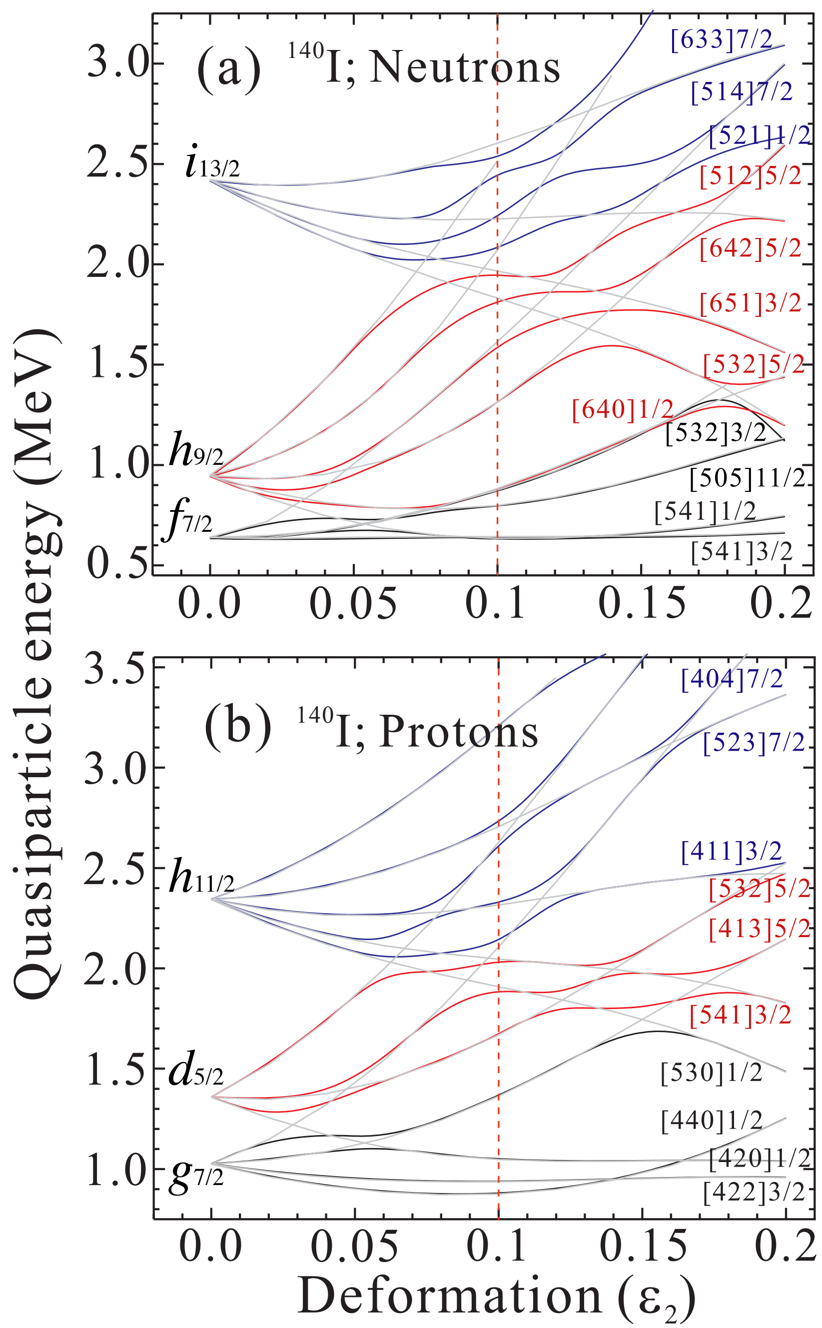
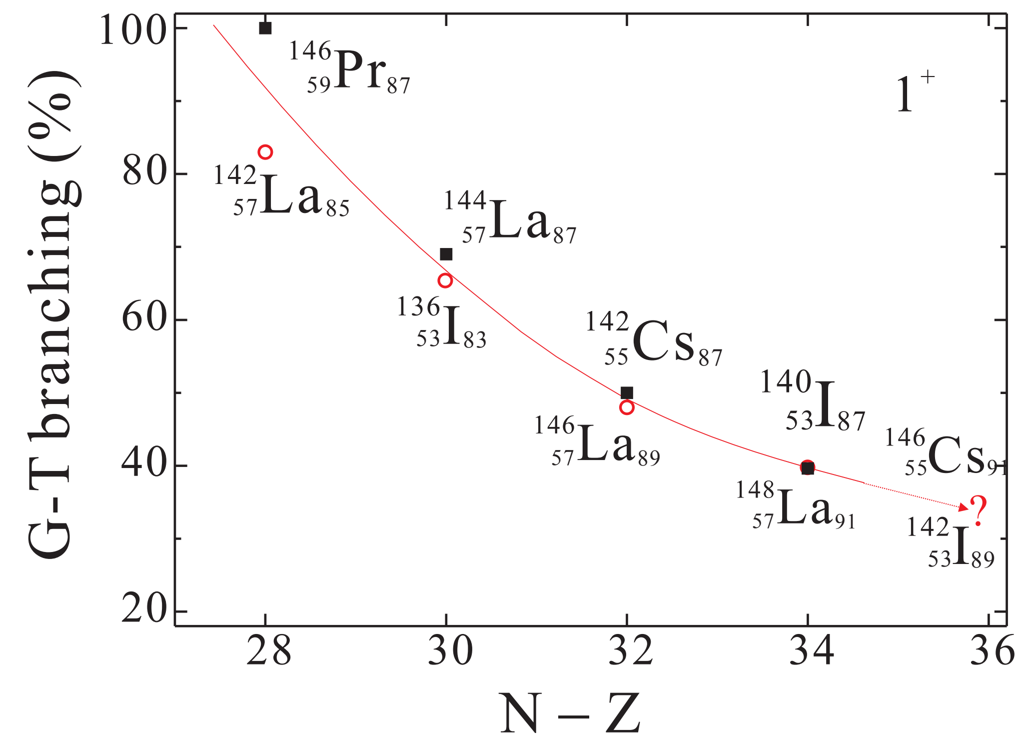
B. Moon et. al., Phys. Rev. C **96**, 014325 (2017)

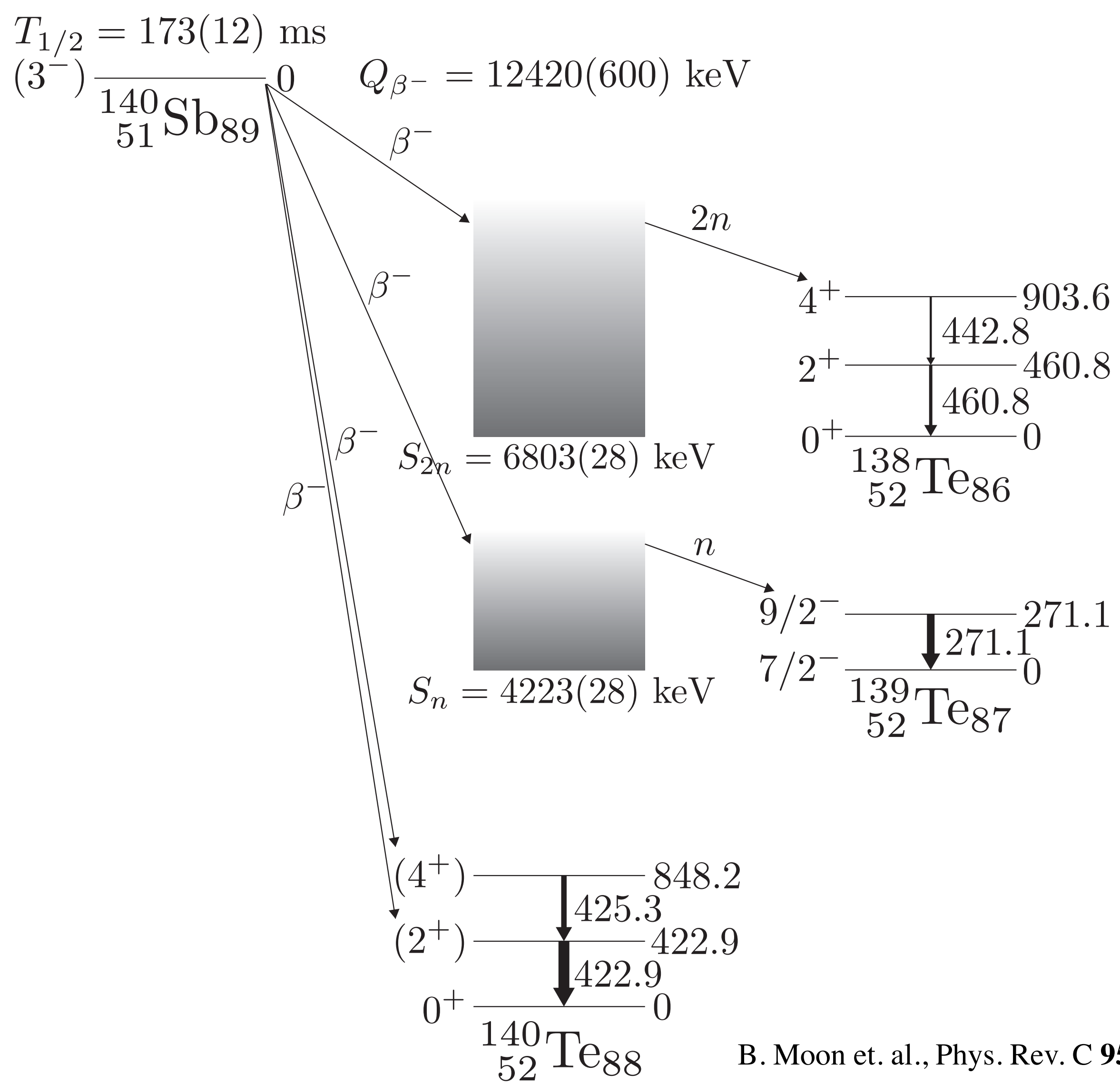




1. According to Nilsson model calculations, the $\pi[541]3/2\nu[541]1/2$ forms the first 1+ state at $\boldsymbol{\varepsilon}_2 \sim 0.1$.
2. The sum of branching ratio induced by the G-T transition drastically decreases as a function of *N*-*Z*, the isospin quantum number.
3. The strong suppression of B(GT) and energy of 1$^+$ state may be induced by the neutron dominance such as a neutron skin effect.

Results on A ~ 140

- ^{140}Te, Vibrator induced by neutron dominance



B. Moon et. al., Phys. Rev. C **95**, 044322 (2017)

1. First measured half-life.
2. $R = 2.00$, typical vibrator.
3. S_n, S_{2n} probabilities.

Nuclides	Level	log(ft)[a]	I_{β^-}[a]	Observed γ rays; I_γ[b]	Spin-parity
^{140}Te	422.9(3)	6.03(13)	17(3)%	422.9(3); 100(16)	$2^+ \rightarrow 0^+$
	848.2(3)	6.02(16)	14(4)%	425.3(3); 45(12)	$4^+ \rightarrow 2^+$
^{139}Te	271.1(2)		23(4)%	271.1(2); 74(13)	$9/2^- \rightarrow 7/2^-$
^{138}Te	460.8(5)		2.0(8)%	460.8(5); 24(11)	$2^+ \rightarrow 0^+$
	903.6(5)		5.6(2.3)%	442.8(5); 17(12)	$4^+ \rightarrow 2^+$

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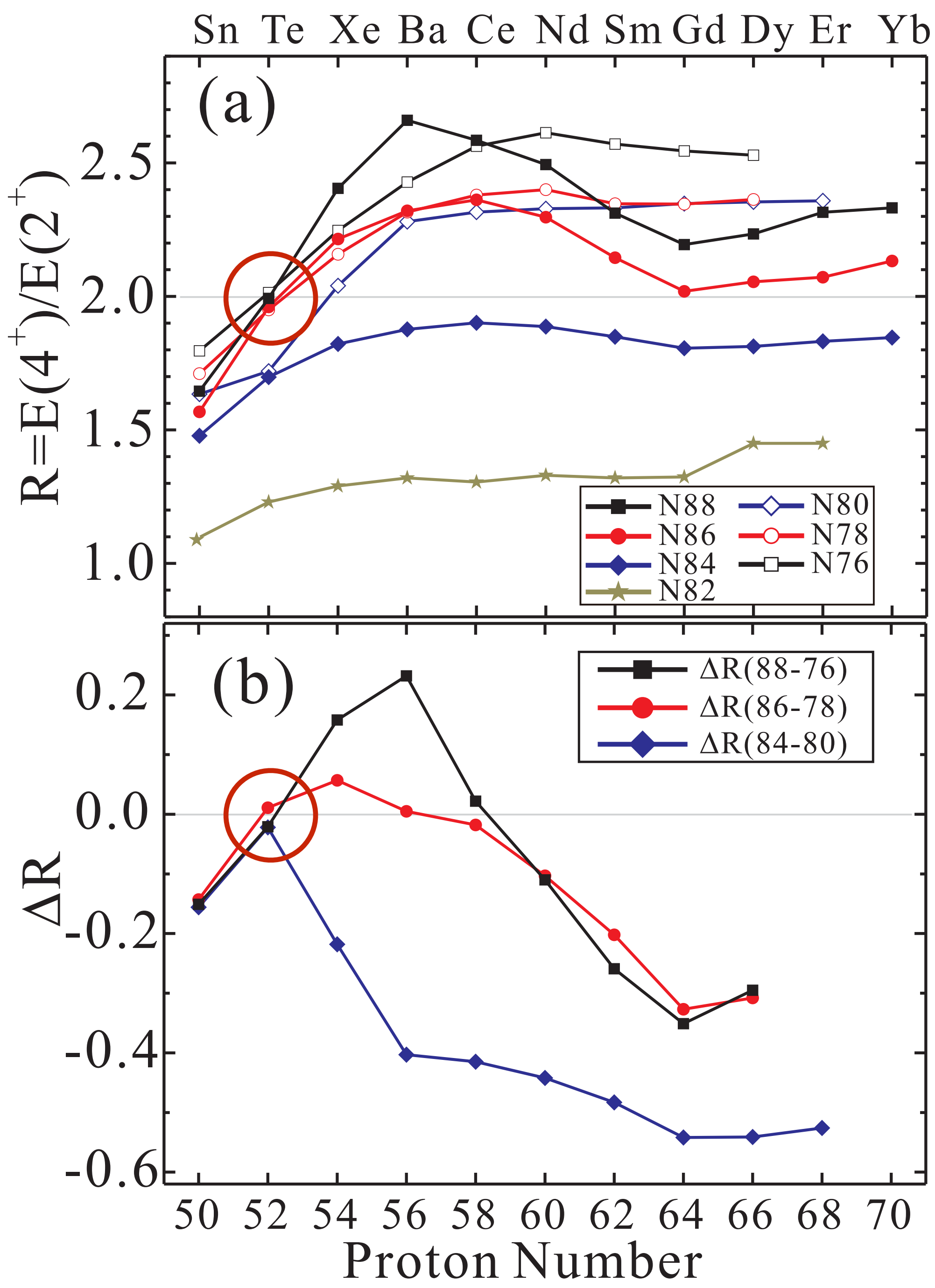
Results on A ~ 140

- ^{140}Te, Vibrator induced by neutron dominance



B. Moon et. al., Phys. Rev. C **95**, 044322 (2017)

1. Te isotopes have *R* value with 2.0, the vibrator.
2. *ΔR* : *R* value difference between two isotopes with same number of neutron particles and holes based on *N* = 82.
3. Only Te converges this value to 0.
4. Neutron dominance effect : Core strongly bounds two valence protons of Te.
5. Dominant effect induced by neutrons.

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^{140}I
^{140}Te
Summary

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- Iodine and tellurium isotopes are important for not only the nuclear structure but also the astrophysics.
- In-beam experiment at ANU HIAF.
- ^{120}I forms unique chiral doublet bands on $\pi h_{11/2}\nu h_{11/2}$ configuration and the non-collective oblate spin-trap isomer at the 25^{+} state.
- Iodine isotopes near A = 120 show dynamic changes of their shapes and core characteristics.
- Decay experiment at RIBF, RIKEN.
- ^{140}I shows the suppression of energies and B(GT) values of 1^{+} states caused by the neutron dominance effect.
- ^{140}Te confirms that Te isotopes behave as strong vibrators induced by the neutron dominance effect.

Thank you!