Gamma-ray spectroscopy at RIBF

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- Introduction
- Experimental technique
- Examples
  - ^{32}Ne
  - Si isotopes
- Summary

Gamma-ray spectroscopy

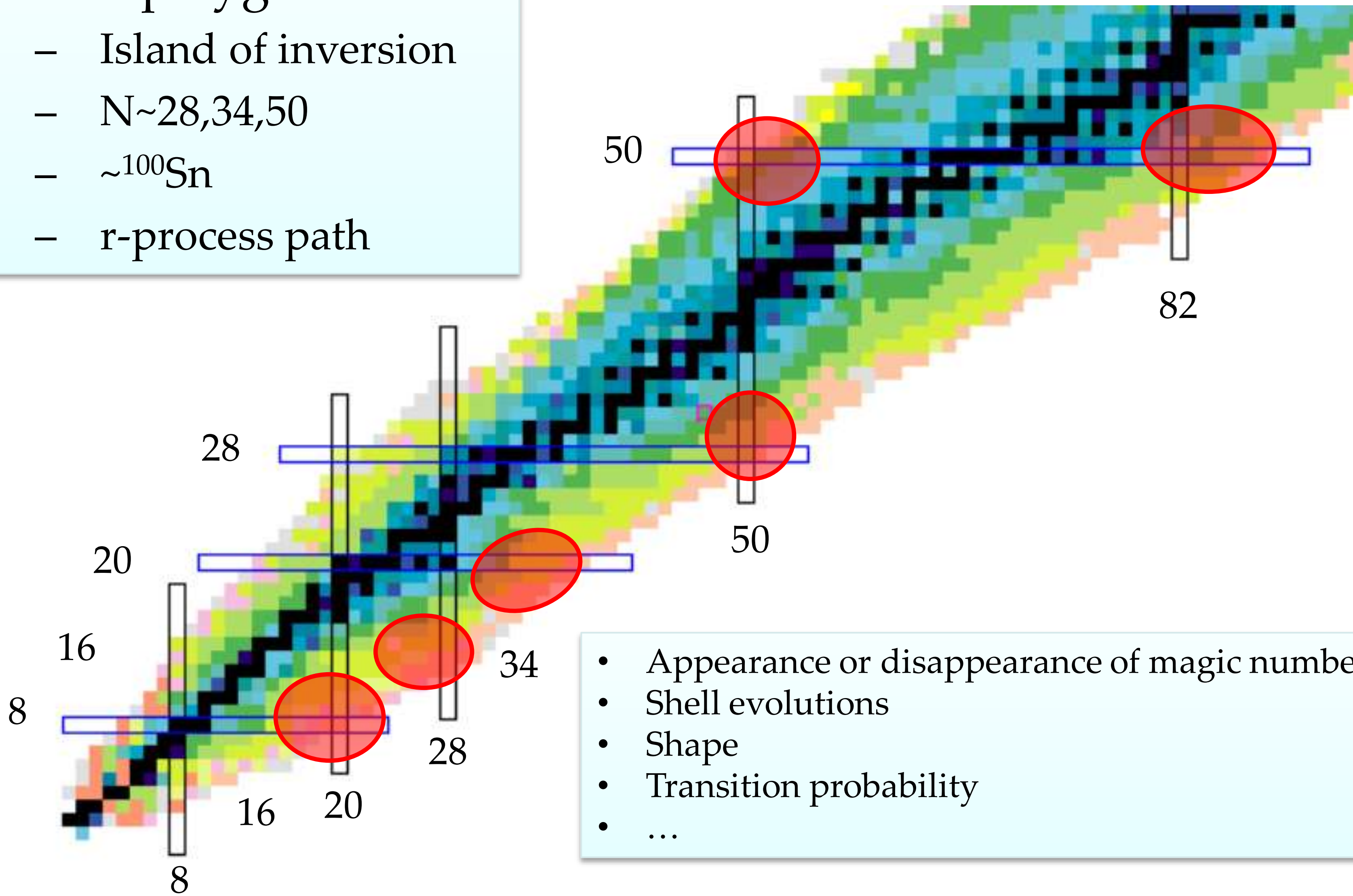
- stopped/slow beam → high spin, isomer, B(E2), …
  - GRAPE(CNS), EURICA @ RIBF
  - SeGA @ MSU
  - EXOGAM @ GANIL
  - …
    - β-γ, deep inelastic, fusion reaction, Coulomb excitation, …

- **fast beam** (v/c ~ 0.3 to 0.6) → Ex(2^+,4^+,…), cross sections, B(E2), …
  - **DALI2 @ RIBF**
  - CEASER, SeGA @ MSU
  - …
    - **inelastic scattering, removal reaction, Coulomb excitation,** …

"In-beam γ-ray spectroscopy with fast RI beams @RIBF"

In-beam γ-ray spectroscopy @ RIBF

- Our playground:
  - Island of inversion
  - N~28,34,50
  - ~^{100}Sn
  - r-process path



- Appearance or disappearance of magic number
- Shell evolutions
- Shape
- Transition probability
- …

In-beam γ-ray spectroscopy @ RIBF

- Extract physics from observation of γ rays from excited states in unstable nuclei.
  - Collectivity: B(E2)
  - Shell gap: Ex / B(E2)
  - Shape: $R(4^+/2^+)$ (energy ratio)
  - Level structure: Ex / J^π

What we do in experiments:

identifications of beam and scattered particles,

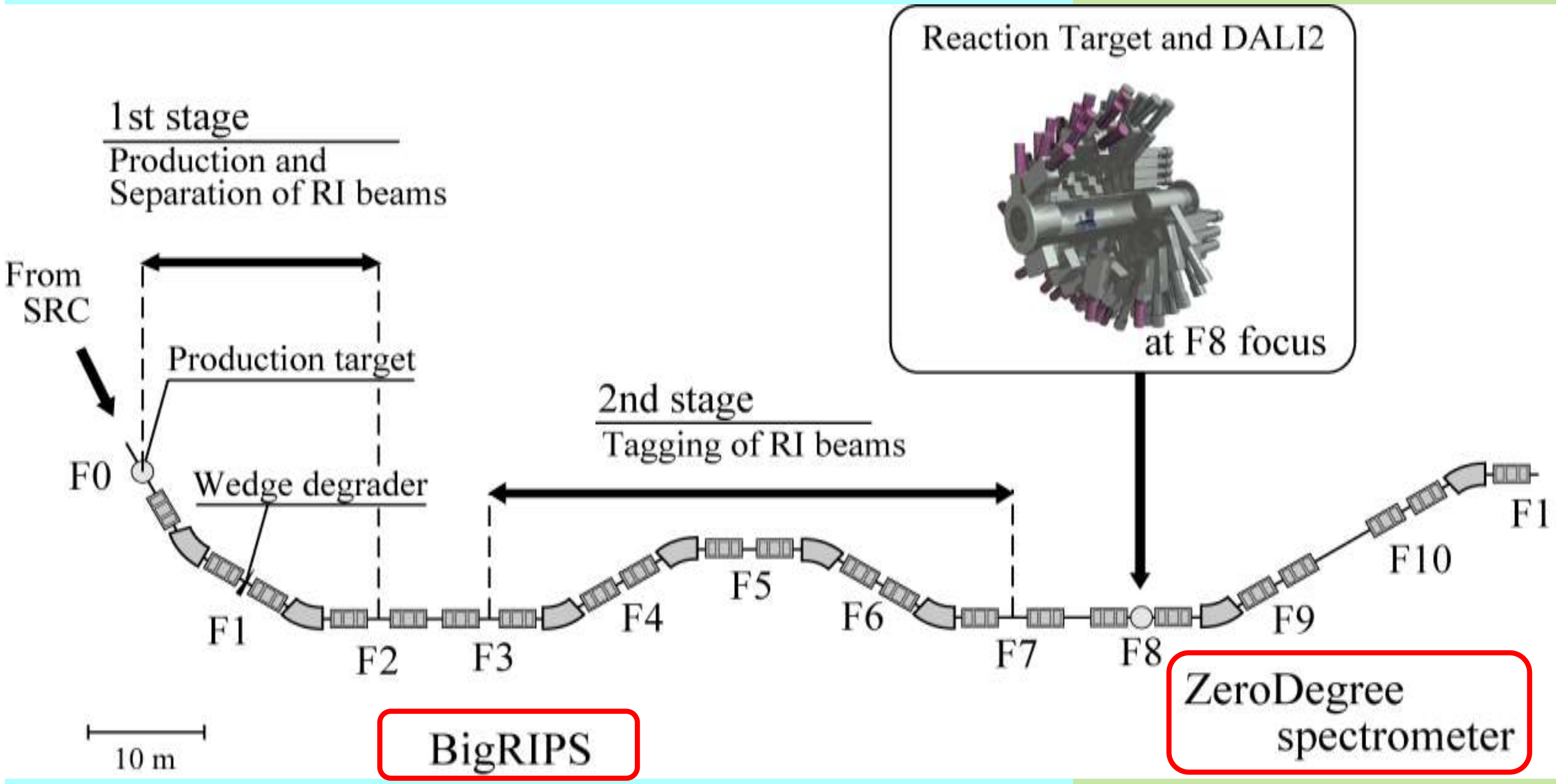
measurements of γ ray energy,

accumulation of γ ray yields,

measurements of angular distributions of γ rays or particles.

γ-ray spectroscopy setup @ BigRIPS/ZDS

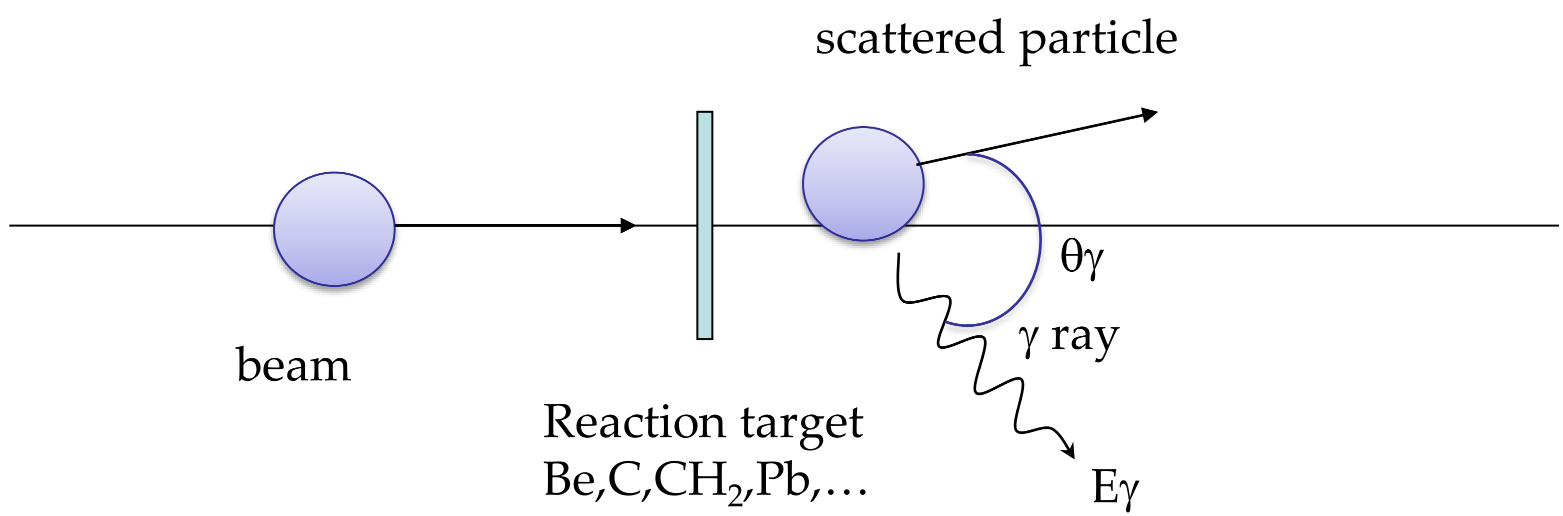
γ-ray measurements



PID of beam particles

PID of scattered particles

direct reaction in inverse kinematics



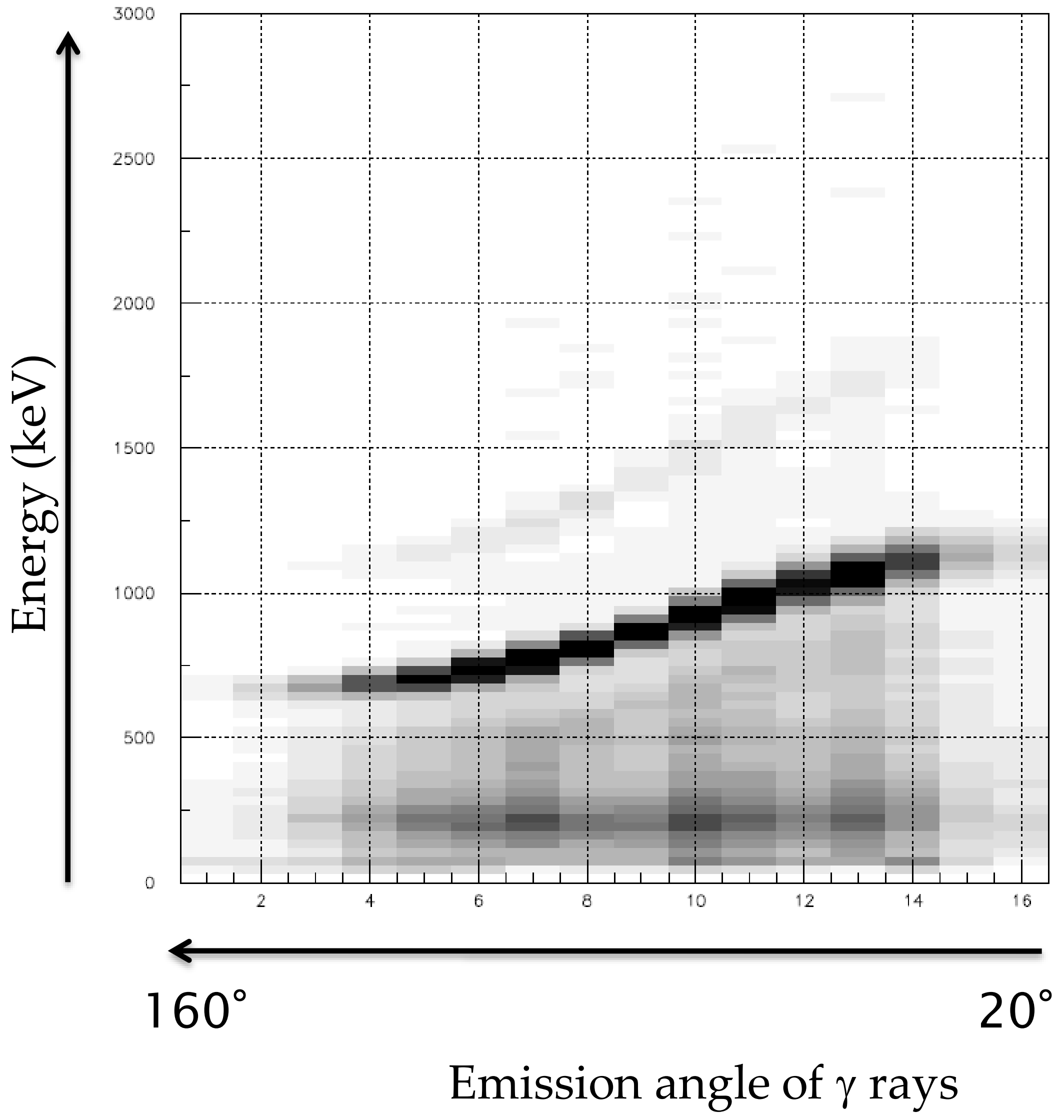
Particle Identification: beam particle → BigRIPS
scattered particle → ZeroDegree Spectrometer

Observables: velocity
emission angle of γ ray → DALI2
γ-ray energy → DALI2

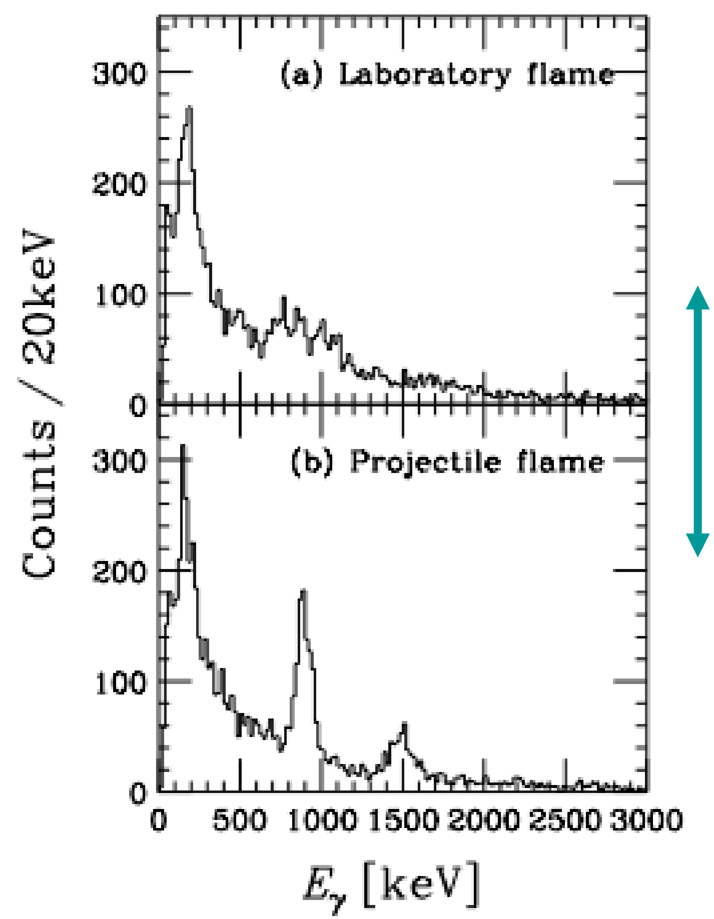
⇩

Determination of reaction channel and correct Doppler shift.

Example of Doppler shift effect



^{32}Mg(p,p′) β~0.3



Milestone of in-beam γ-ray spectroscopy at RIBF

•2008	DayOne		
	^{32}Ne, ^{31,33}Na	H. Scheit, P. Doornenbal	
		PRL 103:032501, 2009./PRC 81:041305, 2010.	
•2009	Test with U (0.3-0.6 pnA)		
	~^{132}Sn	H. Wang, N. Aoi	
•2010	^{48}Ca campaign		
	^{38,40,42}Si	S. Takeuchi, M.Matsushita	submitted to PRL
	$^{A>36}$Mg	P. Doornenbal, H. Scheit	in preparation
	~Al, P	D. Steppenbeck	in preparation
	^{33}Mg	D. Bazin	
	^{40}Mg test	P. Fallon	
•2011	U beam campaign		
	^{78}Ni	K. Yoneda, D. Steppenbeck	
	~^{132}Sn	H. Wang, N. Aoi	
•2012	^{124}Xe and ^{70}Zn beam campaign		
	^{10x}Sn	A. Obertelli, P. Doornenbal	
	^{54}Ca	D. Steppenbeck, S. Takeuchi	

Examples of in-beam γ-ray spectroscopy at RIBF

•2008	DayOne		
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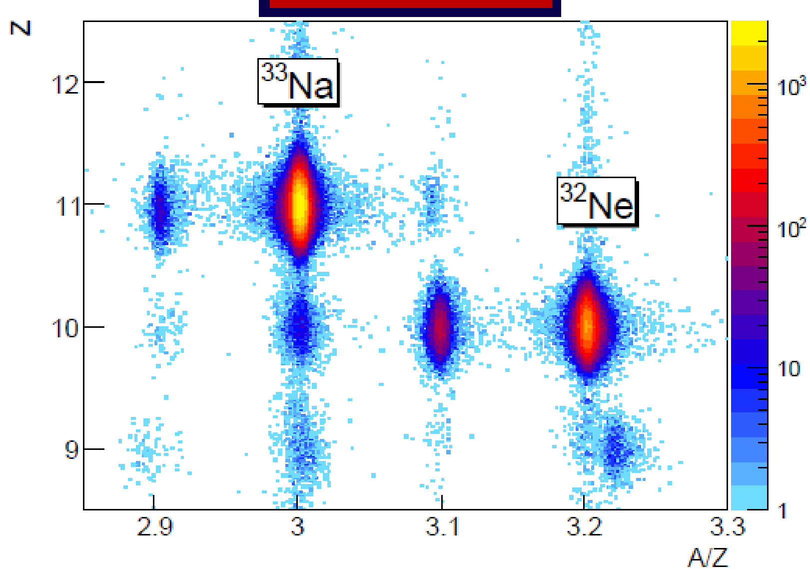
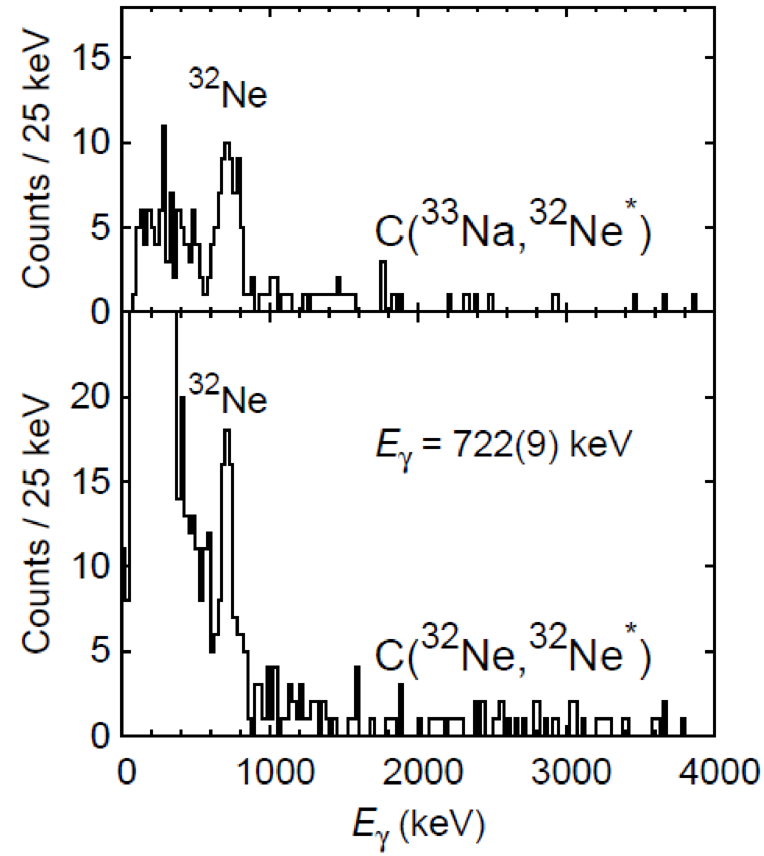
2^+ state in ^{32}Ne -DayONE experiment (2008)-

PID after F8



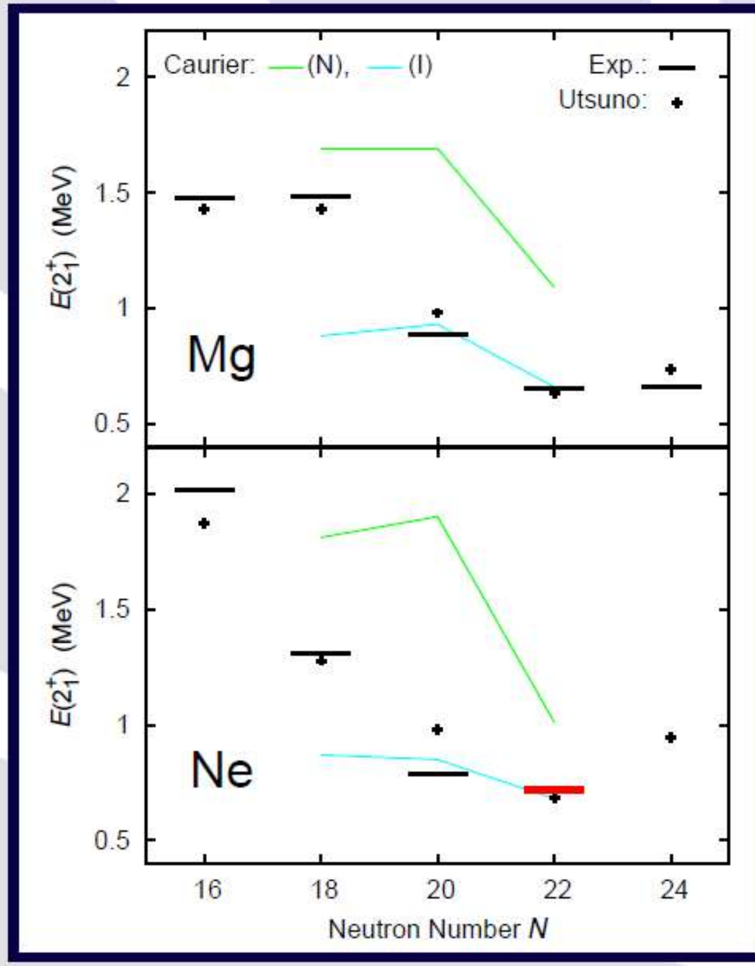
- C(^{32}Ne,^{32}Ne*), C(^{33}Na,^{32}Ne*)
- ^{32}Ne: 6 pps, 230 MeV/u
- F8 target: $^{nat.}$C (2.54 g/cm^2) for Day-One
- DALI2 array: 180 NaI(Tl) detectors
- total data taking: **8 hours**

Doppler corrected γ-ray energy



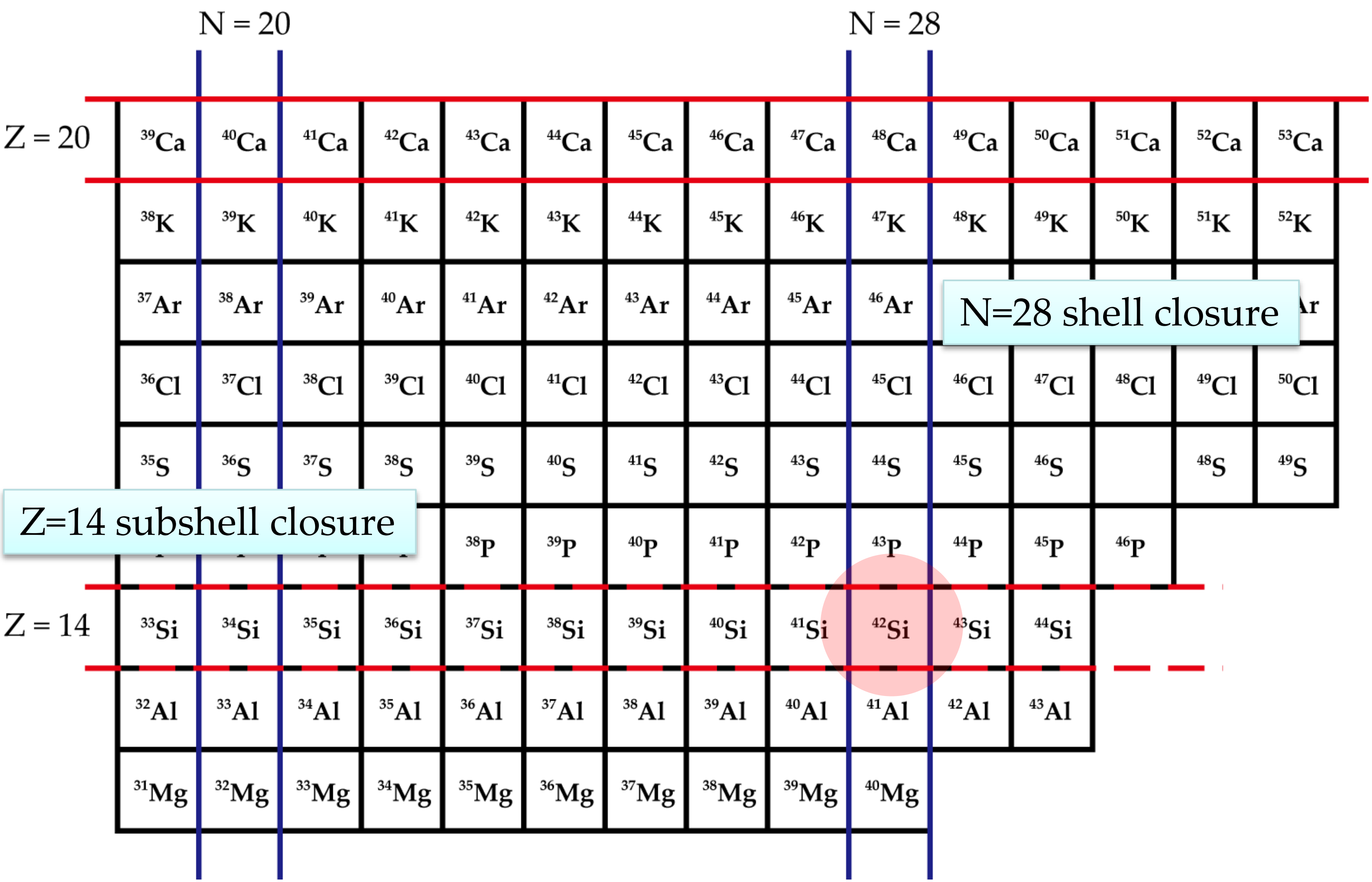
2^+ state in ^{32}Ne -DayONE experiment (2008)-

- lowest $E(2^+)$ of Ne isotopes
- very good agreement with Utsuno *et al.*, PRC 60, 054315 (1999)
- very good agreement with Intruder calculation of Caurier *et al.*, NPA 693, 374 (2001)
- ^{32}Ne belongs to the "Island of Inversion"



P. Doornenbal, H. Scheit *et al.*
Phys. Rev. Lett. 103, 032501 (2009)
arXiv:0906.3775

^{42}Si: N=28 and Z=14 → doubly magic?



Ref.: arXiv:1207.6191

What we know about ^{42}Si.

β-decay experiment

Short half-life → **Large deformation** (possibly oblate), comparing with QRPA calculation.

S.Grevy *et al*., Phys. Lett. B 594, 252 (2004).

Mass measurement

Deformed/Spherical?

B.Jurado *et al*., Phys. Lett. B 694, 43 (2007).

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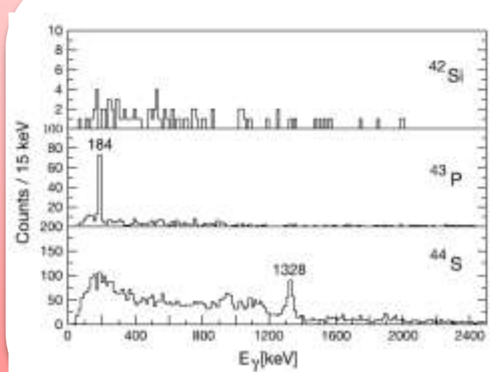
Two-proton removal reactions, ^{44}S → ^{42}Si

NSCL case

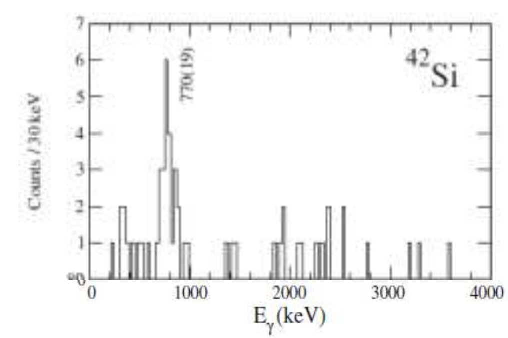
→ A **substantial Z=14 subshell closure**



J.Fridmann *et al.*, Phys. Rev. C 74, 034313 (2006)

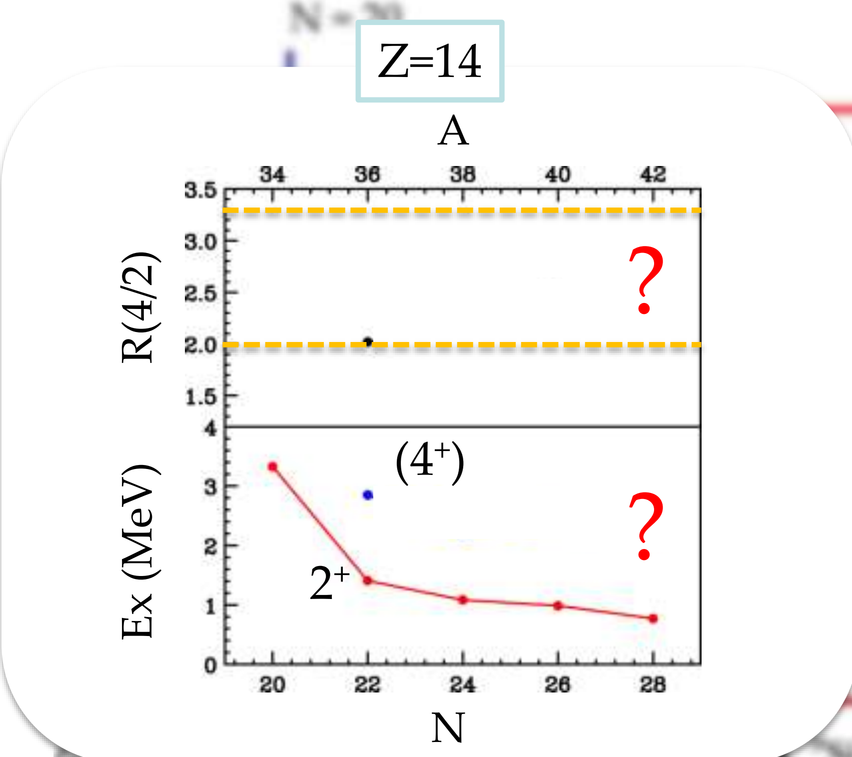
GANIL case

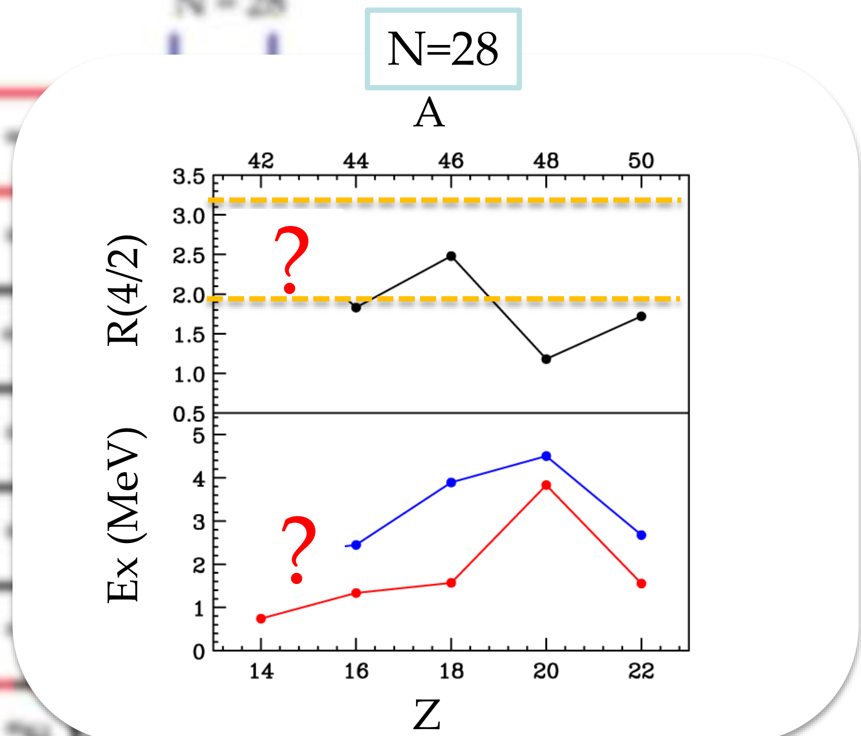
→ **Well-deformed oblate rotor**



B.Bastin *et al.*, Phys. Rev. Lett. 99, 022503 (2007).

^{42}Si: low Ex(2^+). R(4/2) = ?





Re-visit ^{42}Si to confirm the 2^+ excitation energy

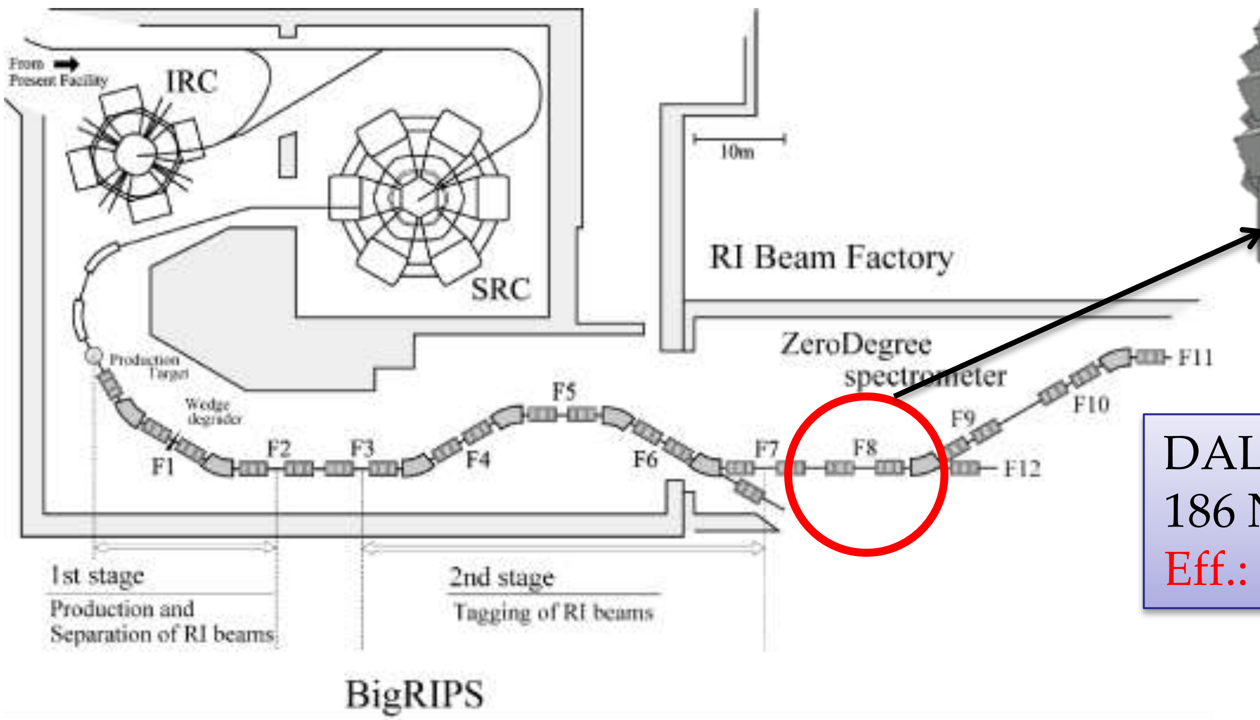
Determine **the location of the 4^+ state in ^{42}Si (and other Si isotopes)**

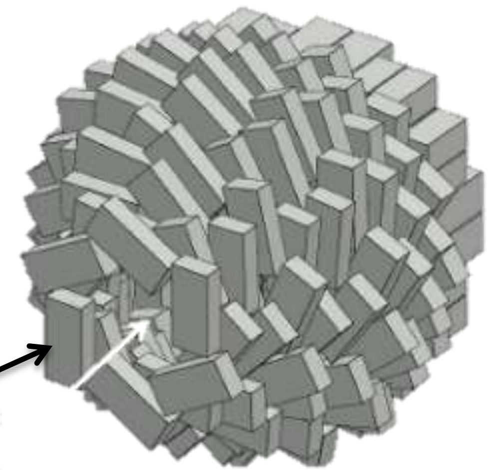
→ two proton removal reactions, $^{44}S + C \rightarrow {}^{42}Si + \gamma + X$,

with high intensity beams, a thick target, and high efficiency detector array.

RIBF: BigRIPS + DALI2 + ZeroDegree

Primary beam:	^{48}Ca 345*A* MeV
Primary beam intensity:	~70 pnA (average)
Primary target:	Be 15mmt





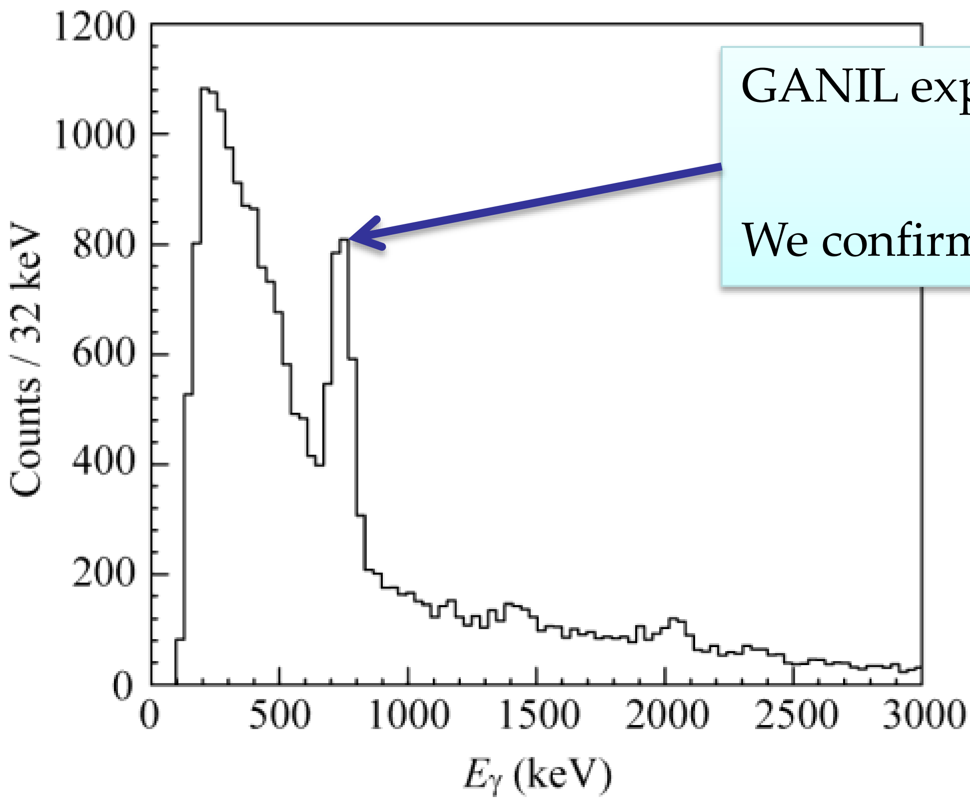
DALI2
186 NaI(Tl) crystals
Eff.: ~20% for 1 MeV (β~0.6)

Secondary beam:	^{44}S 200*A* MeV
Beam intensity:	40k pps (average)
Reaction targets:	C 2.54g/cm^2

BigRIPS&ZDS
T. Kubo *et al.*, IEEE Trans. Appl. Supercond. **17**, 1069 (2007)
Y. Mizoi *et al.*, RIKEN Accel. Prog. Rep. 38, 297 (2005)
DALI2
S. Takeuchi *et al.*, RIKEN Accel. Prog. Rep. 36, 148 (2003)
S. Takeuchi *et al.*, Phys.Rev. C, 79:054319, 2009.

2^+ peak with high statistics.

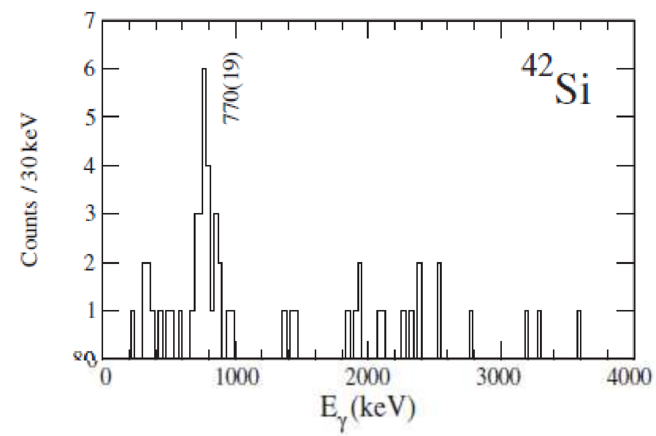
$^{44}S + C \rightarrow {}^{42}Si + \gamma + X$



GANIL exp. : 770(19) keV

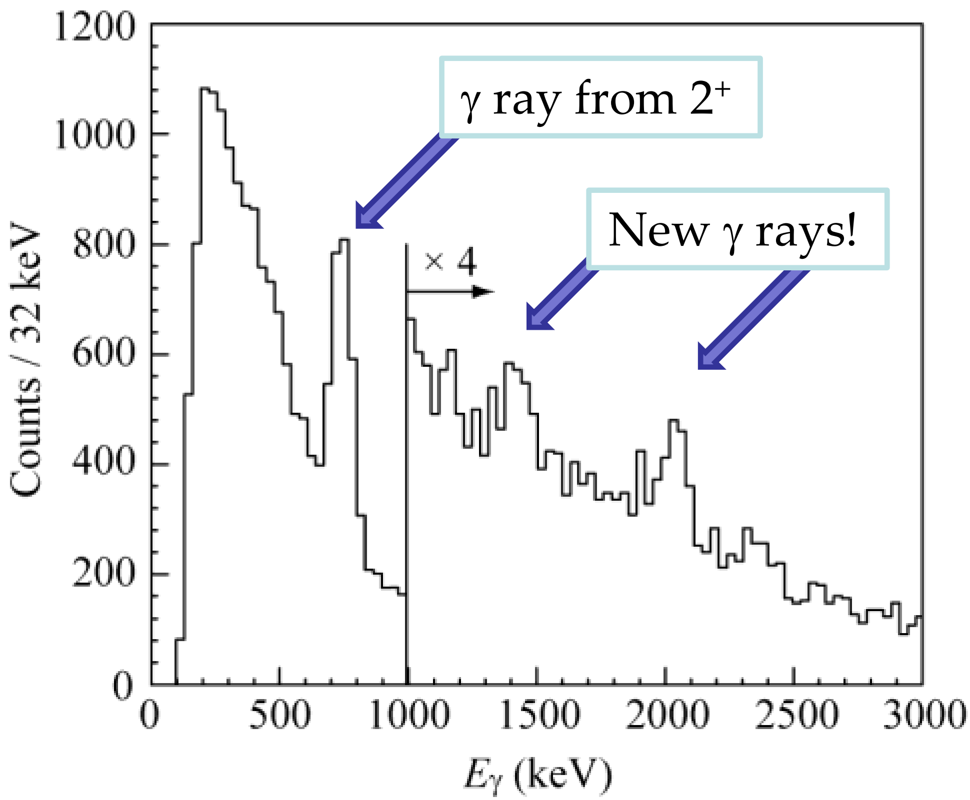
B.Bastin *et al.*, Phys. Rev. Lett. 99, 022503 (2007).

We confirmed γ line observed at GANIL.



Additional peaks.

$^{44}S + C \rightarrow {}^{42}Si + \gamma + X$



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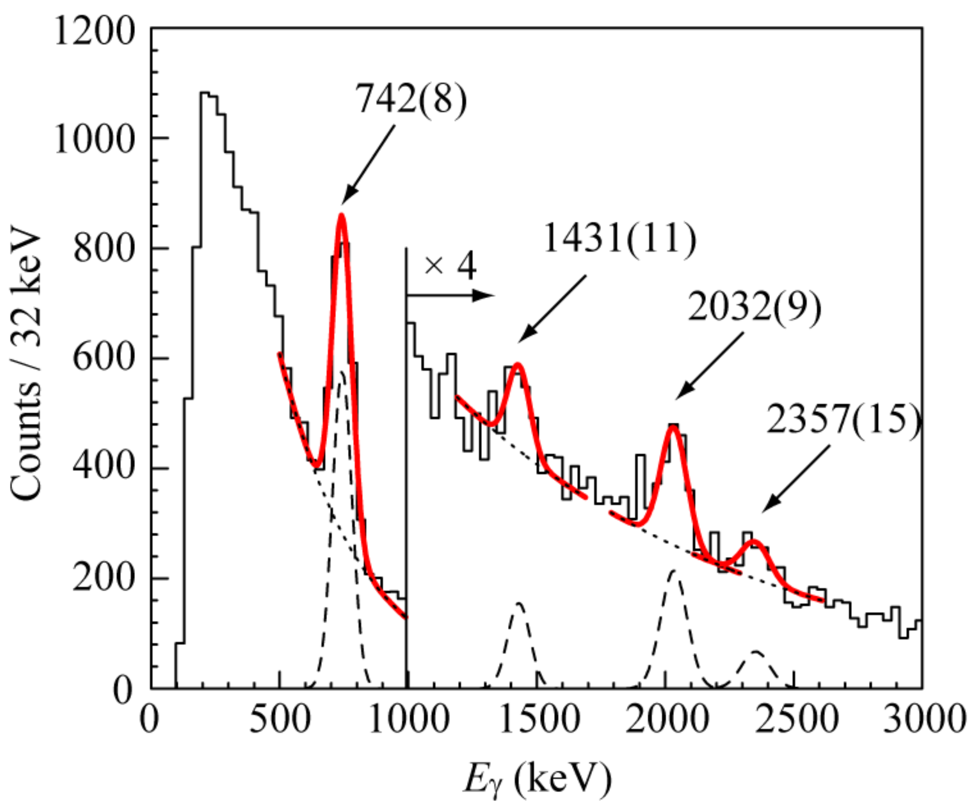


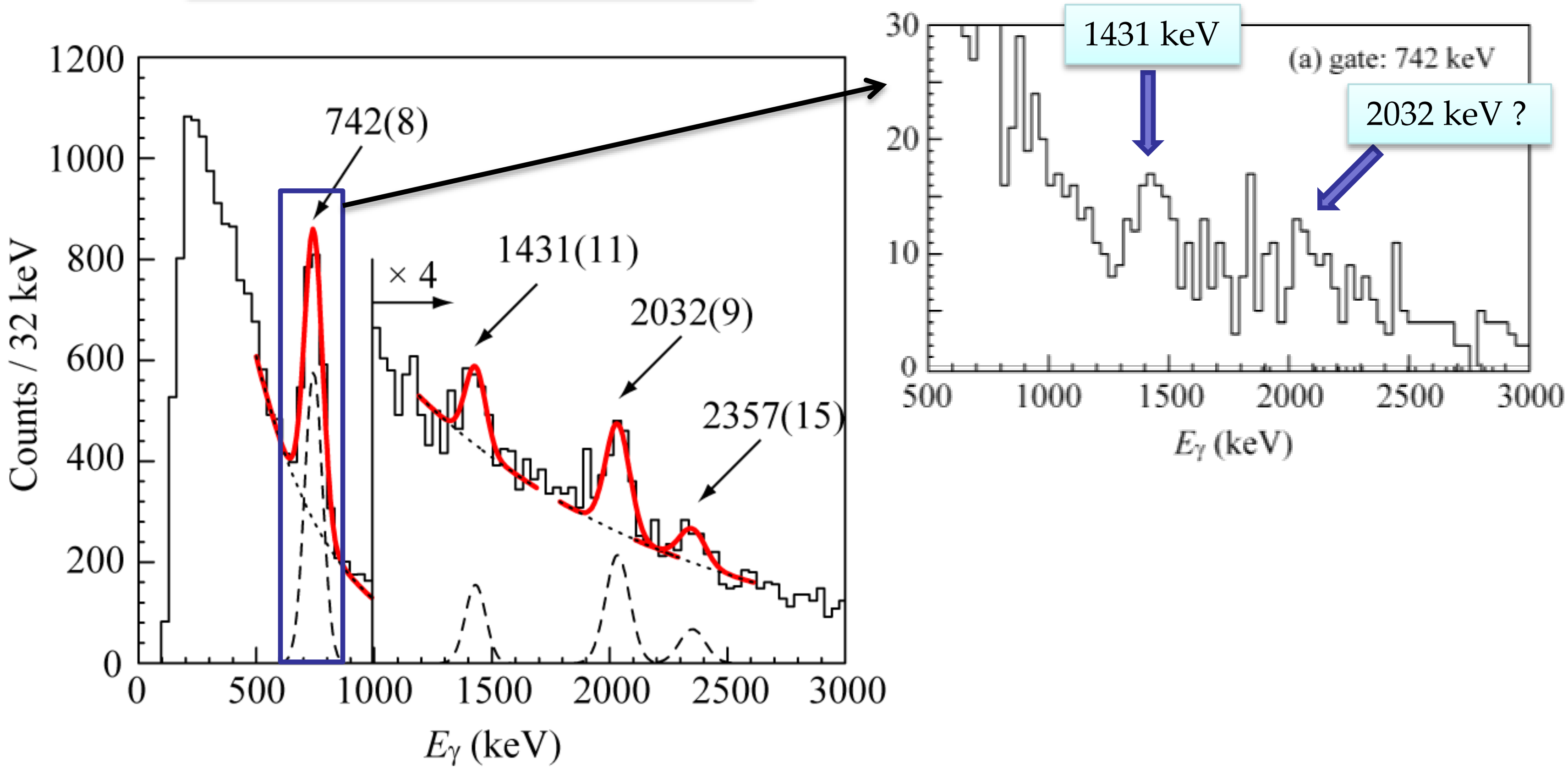
*Widths are fixed to simulated values.

γ ray ($2^+ \rightarrow 0^+$): 742(8) keV
new lines:
1431(11) keV
2032(9) keV
2357(15) keV

γ-γ coincidence

$^{44}S + C \rightarrow {}^{42}Si + \gamma + X$

1431 keV and 742 keV: cascade?



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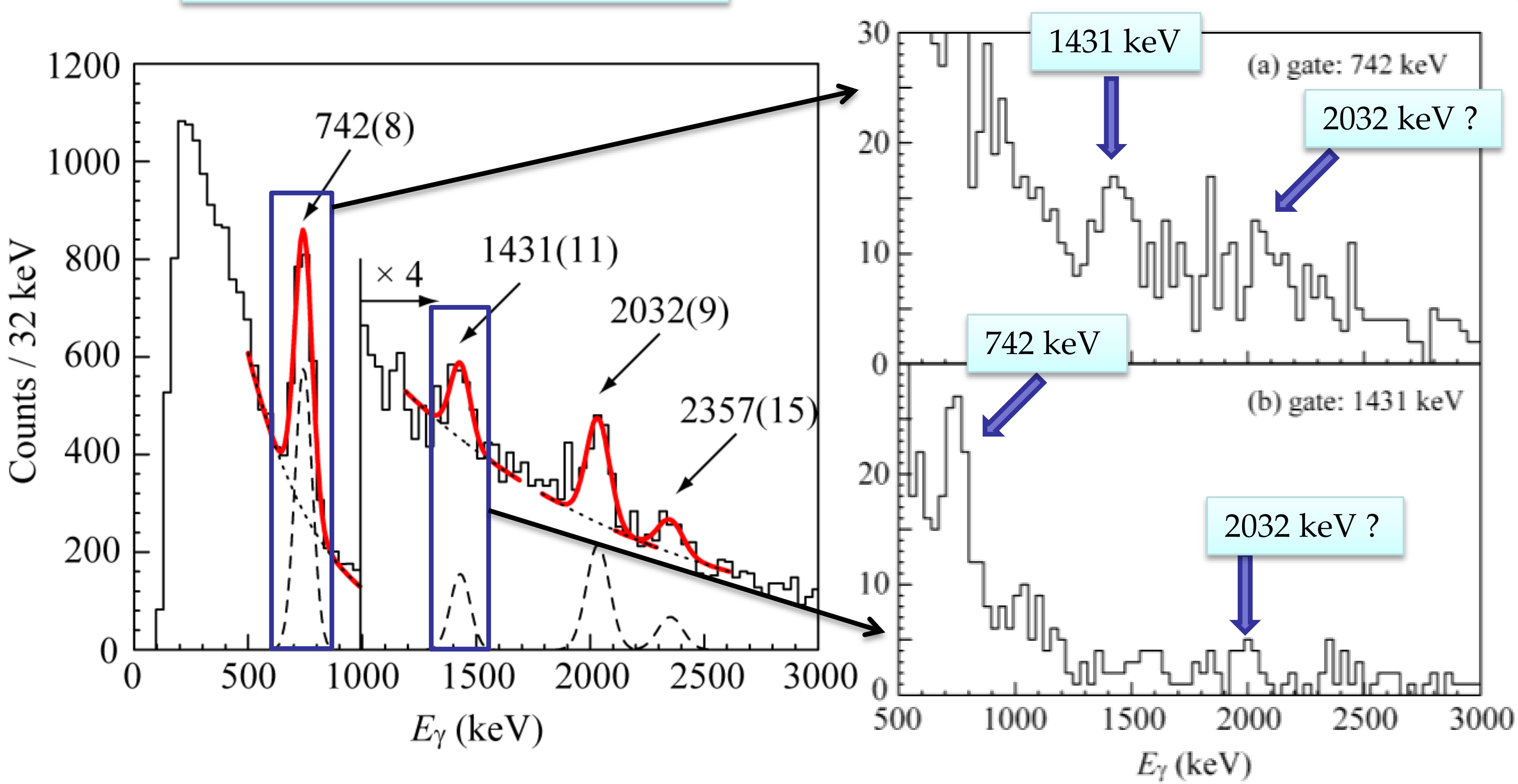


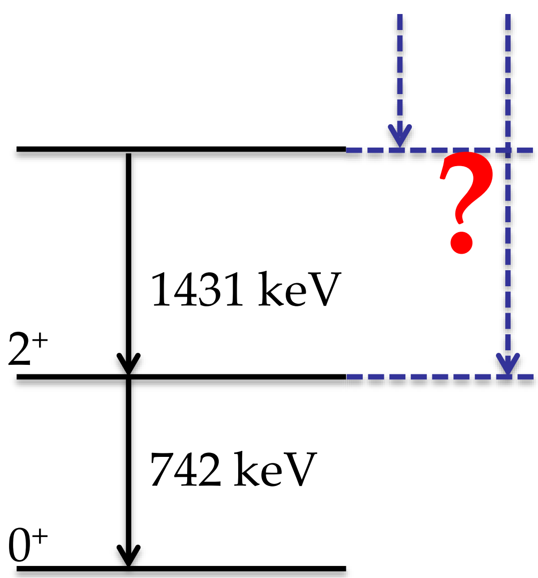
*Widths are fixed to simulated values.

γ_{1431}: transition to 2^+ state

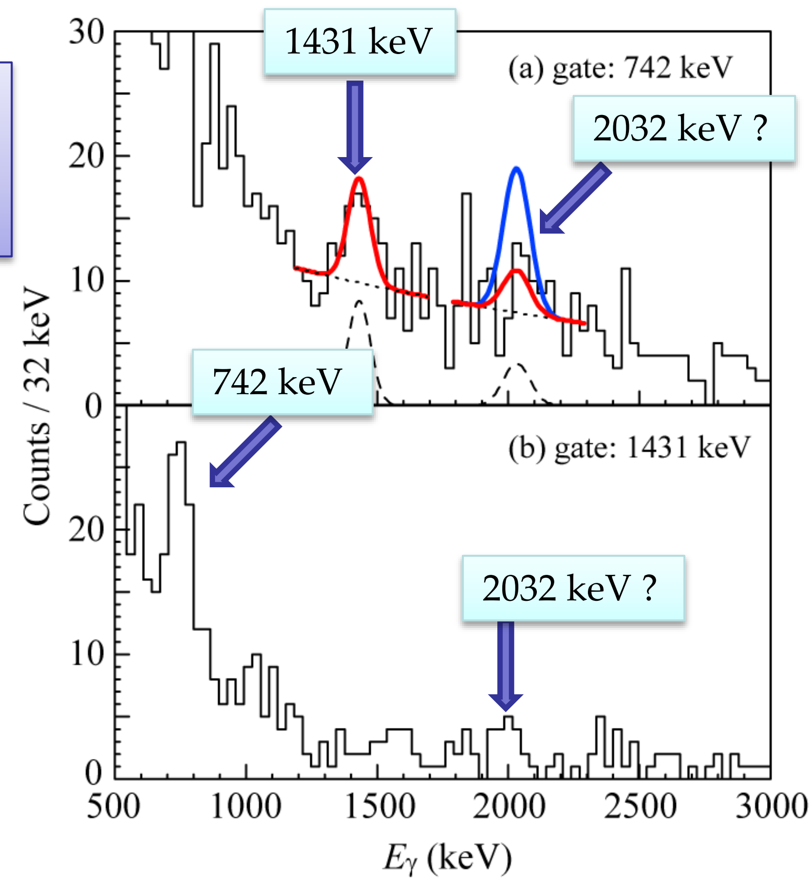
$^{44}S + C \rightarrow {}^{42}Si + \gamma + X$

Partner of 742 keV
1431 keV
~~2032 keV?~~

Partner of 1431 keV
742 keV
~~2032 keV?~~



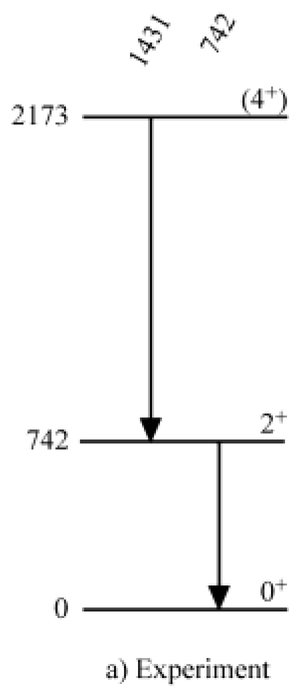
1431 keV and 742 keV: cascade



*Widths are fixed to simulated values.

4^+ at 2173 keV

Excited state at **2173(14) keV** has been tentatively assigned to **the 4^+ state** from present study.



$E_x(4^+)/E_x(2^+) = 2.93$
→ well-deformed shape

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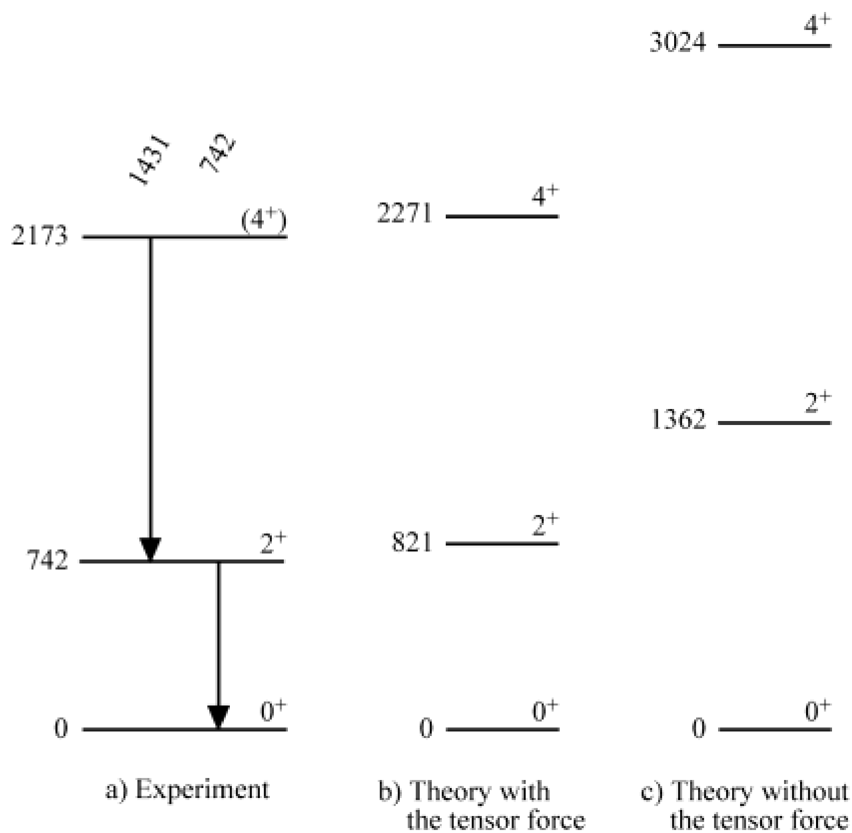


$E_x(4^+)/E_x(2^+) = 2.93$
→ well-deformed shape

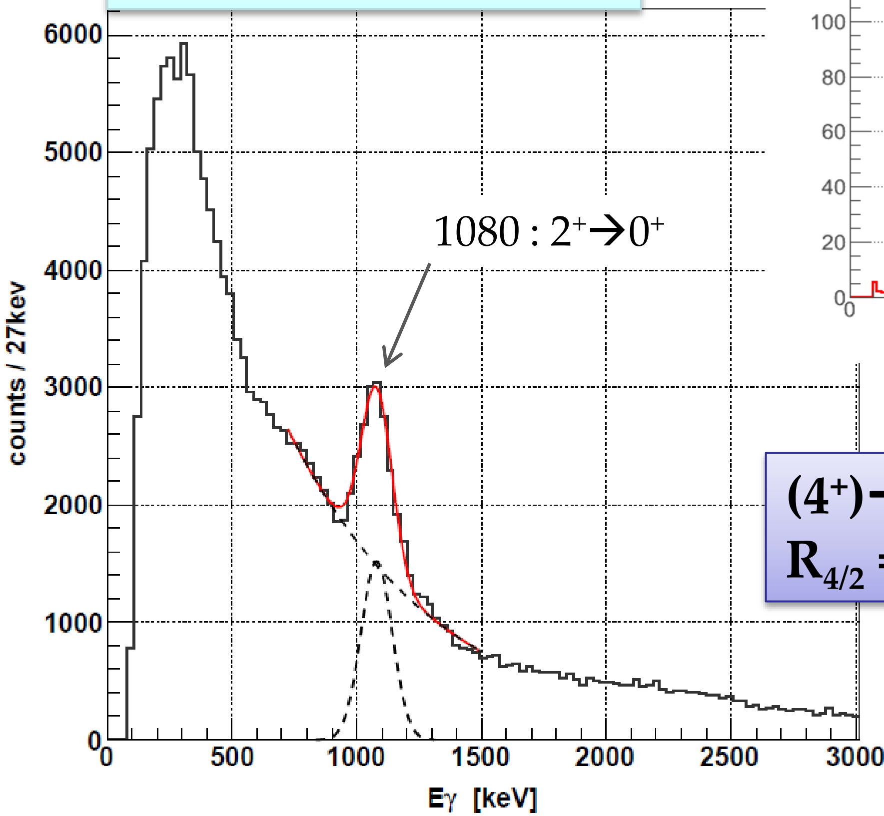
The results from the shell model calculations with the tensor force are in good agreement with experimental data.

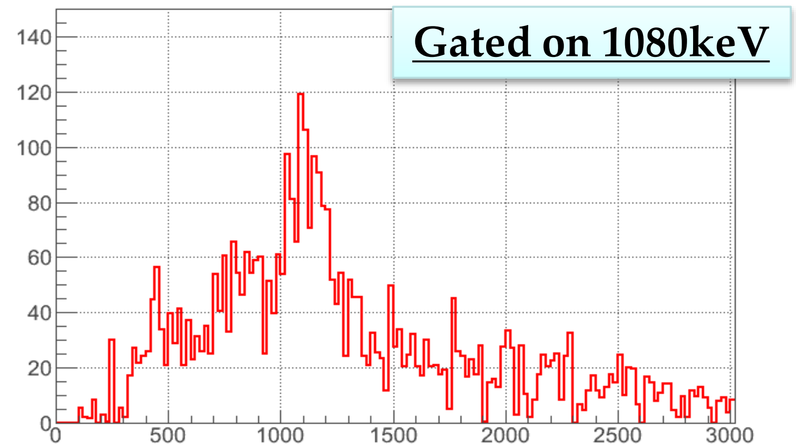
→ oblate shape

Ref. Utsuno and Otsuka, private comm.

Other isotopes 1: ^{38}Si

$^{40}S + C \rightarrow {}^{38}Si + \gamma + X$



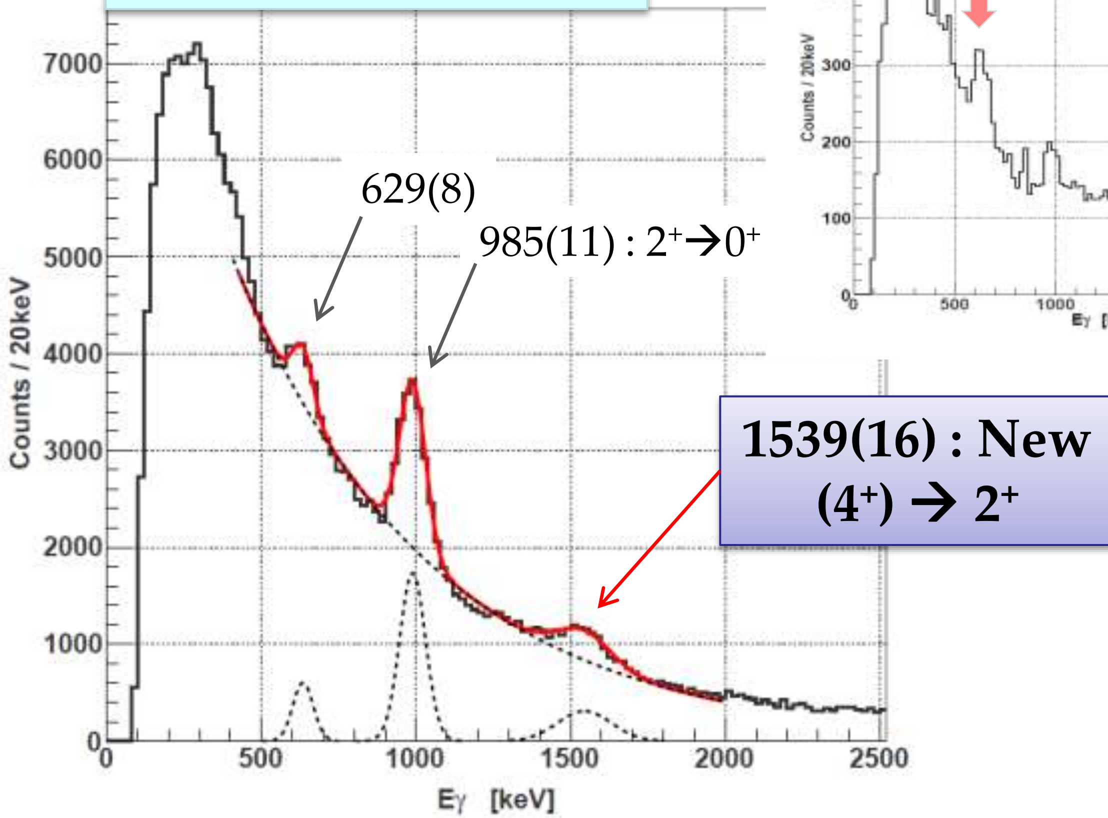


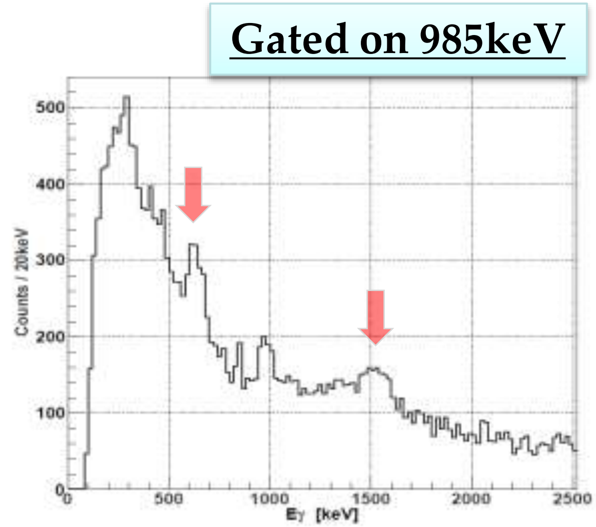
$(4^+) \rightarrow 2^+$: New transition around 1080 keV
$R_{4/2} = Ex(4^+)/Ex(2^+) \sim 2$

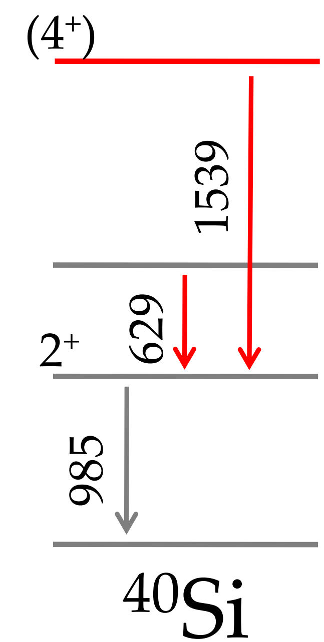
By M.Matsushita

Other isotopes 2: ^{40}Si

$^{44}S + C \rightarrow {}^{40}Si + \gamma + X$

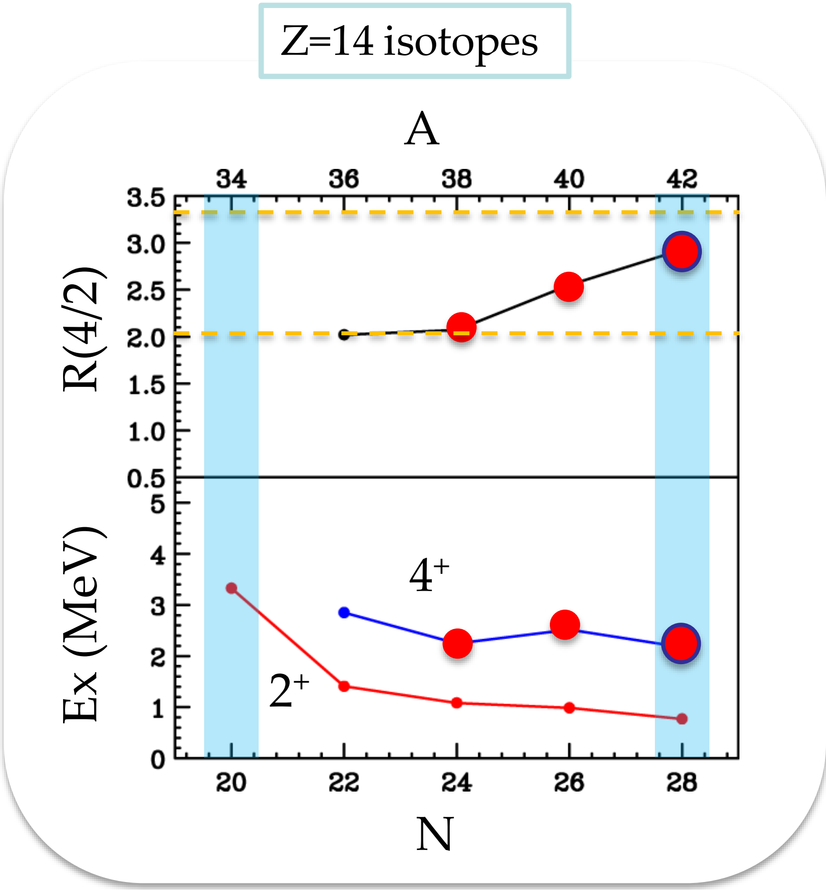


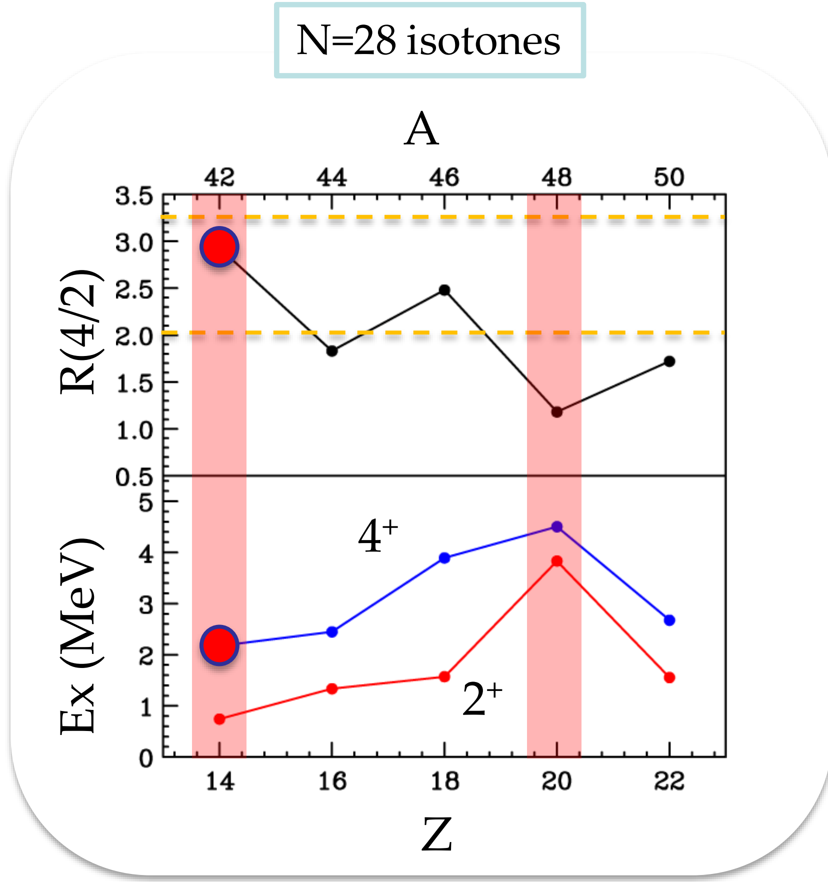




By M.Matsushita

2^+ and 4^+ states in $^{38-42}$Si

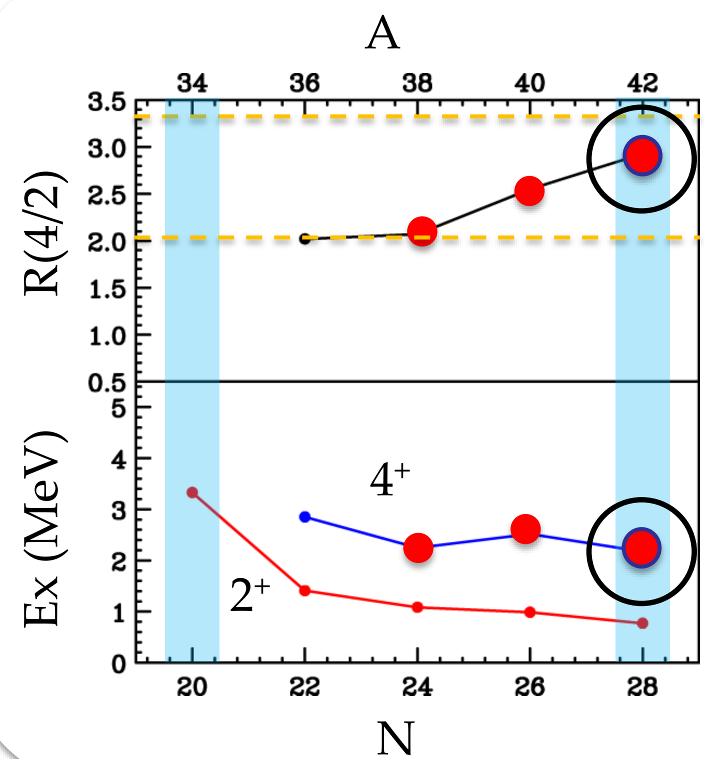




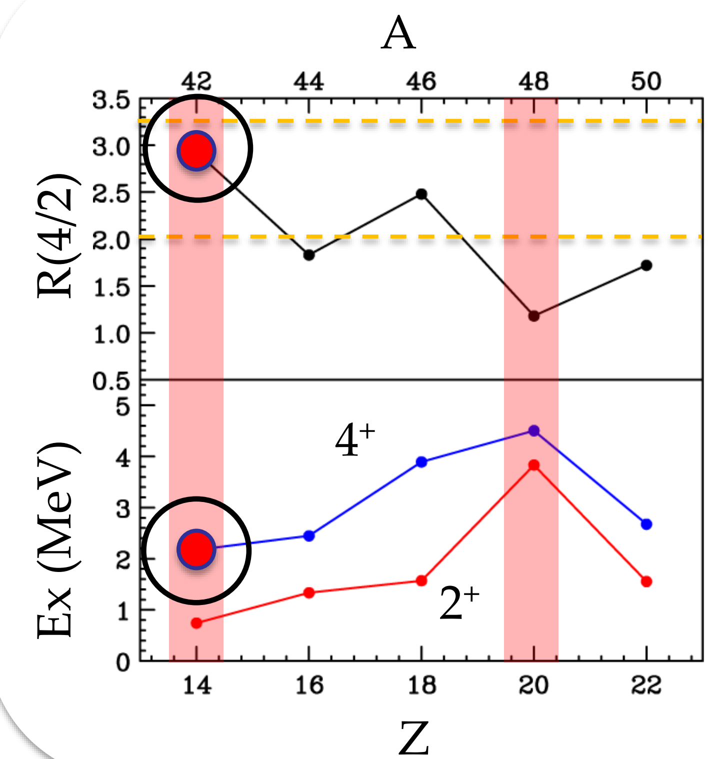
^{36}Si: ref: X.Liang et al., PRC74,014311(2006)
^{46}Ar: ref: Zs.Dombradi *et al.*, NPA 727(2003)195
^{44}S: ref: D.Santiago-Gonzalez *et al.*, PRC 83,061305R(2011)

^{42}Si: well deformed

Z=14 isotopes

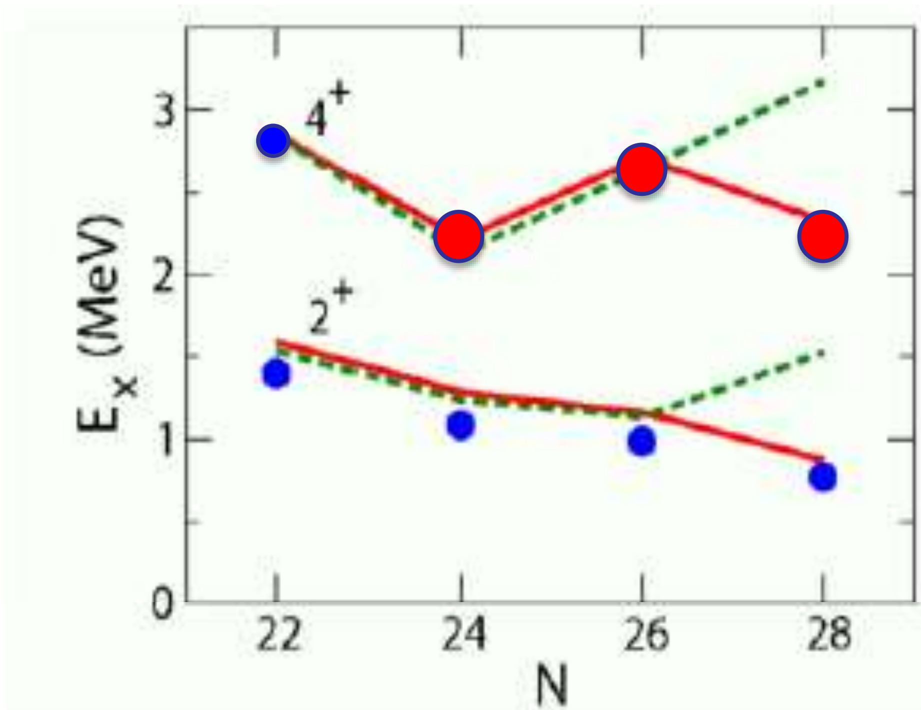


N=28 isotones



R(4/2) = 2.93 → well deformed like rigid rotor.

Comparison with calculations



Present exp.

-- without tensor force → spherical min.

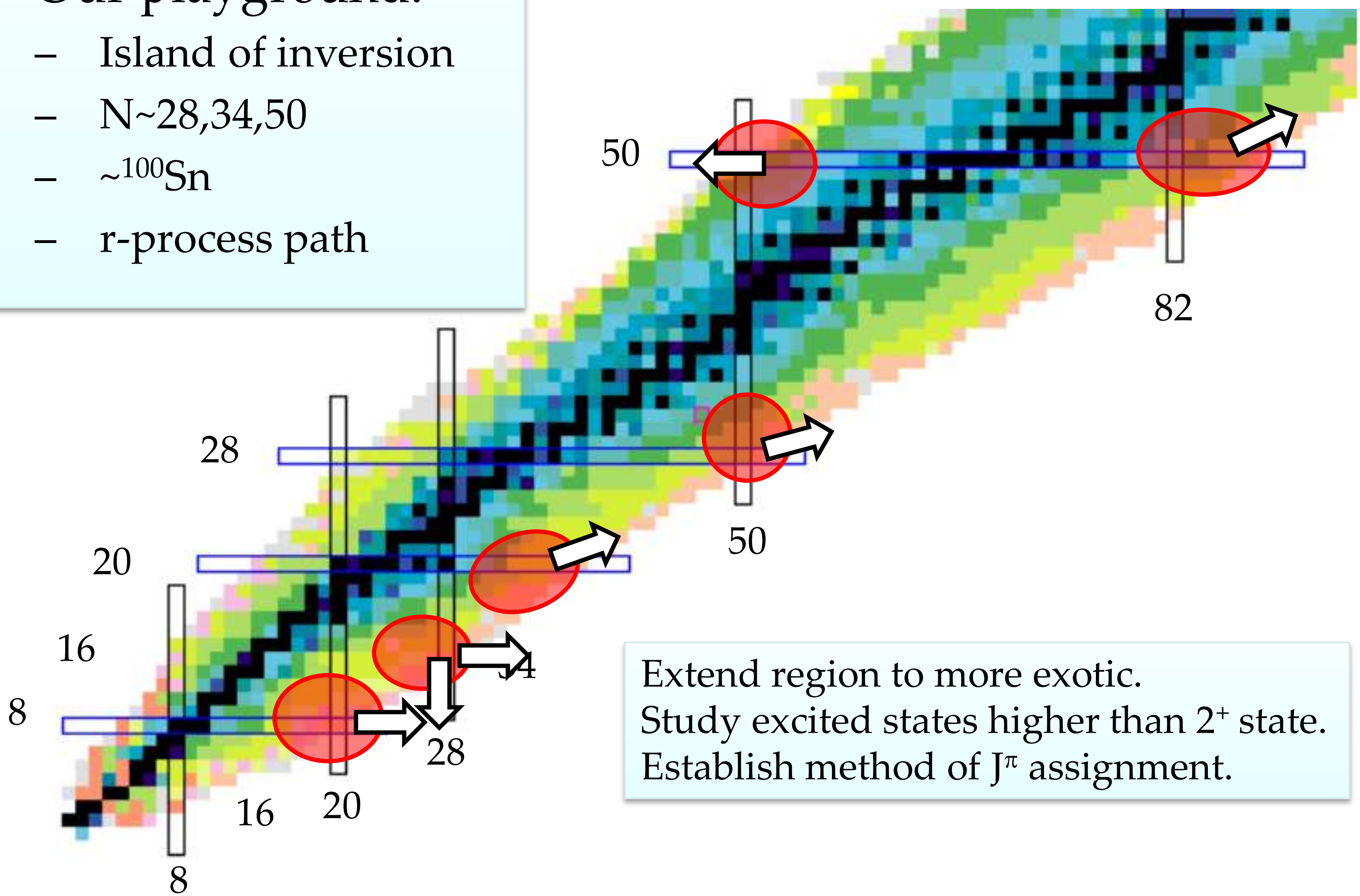
— with tensor force → oblate min.

T.Otsuka et al., NPA 805 (2008) 127c

Y.Utsuno et al., arXiv/1201.4077 (2012)

Summary

- Our playground:
  - Island of inversion
  - N~28,34,50
  - ~^{100}Sn
  - r-process path



Extend region to more exotic.
Study excited states higher than 2^{+} state.
Establish method of J^{π} assignment.

Summary & questions

RIBF provides various RI beams with high intensity.
Detectors will be improved.
Experimental technique may be improved.

In-beam γ-ray spectroscopy group continues to perform experiments for more exotic nuclei.

- What observables do we need to measure for understanding 'tensor force effects'?
  - Second $0^+/2^+$ state?
  - Systematic study of 2^+ state? (such as Si and Mg isotopes?)
- Which nuclei or region are important for understanding 'tensor force effects'?
  - More exotic?
  - Revisit lighter nuclei?

Members of In-beam γ-ray spectroscopy group

RIKEN:	P.DOORNENBAL, H.WANG, J.LEE, T.MOTOBAYASHI, H.SAKURAI, K.YONEDA, S.T
RCNP:	N.AOI, E.IDEGUCHI
CNS:	D.STEPPENBECK, M.MATSUSHITA
TU Darmstadt:	H.SCHEIT
Peking Univ:	L.KUOANG

THANK YOU FOR YOUR ATTENTION ☺