Well-developed deformation in ^{42}Si

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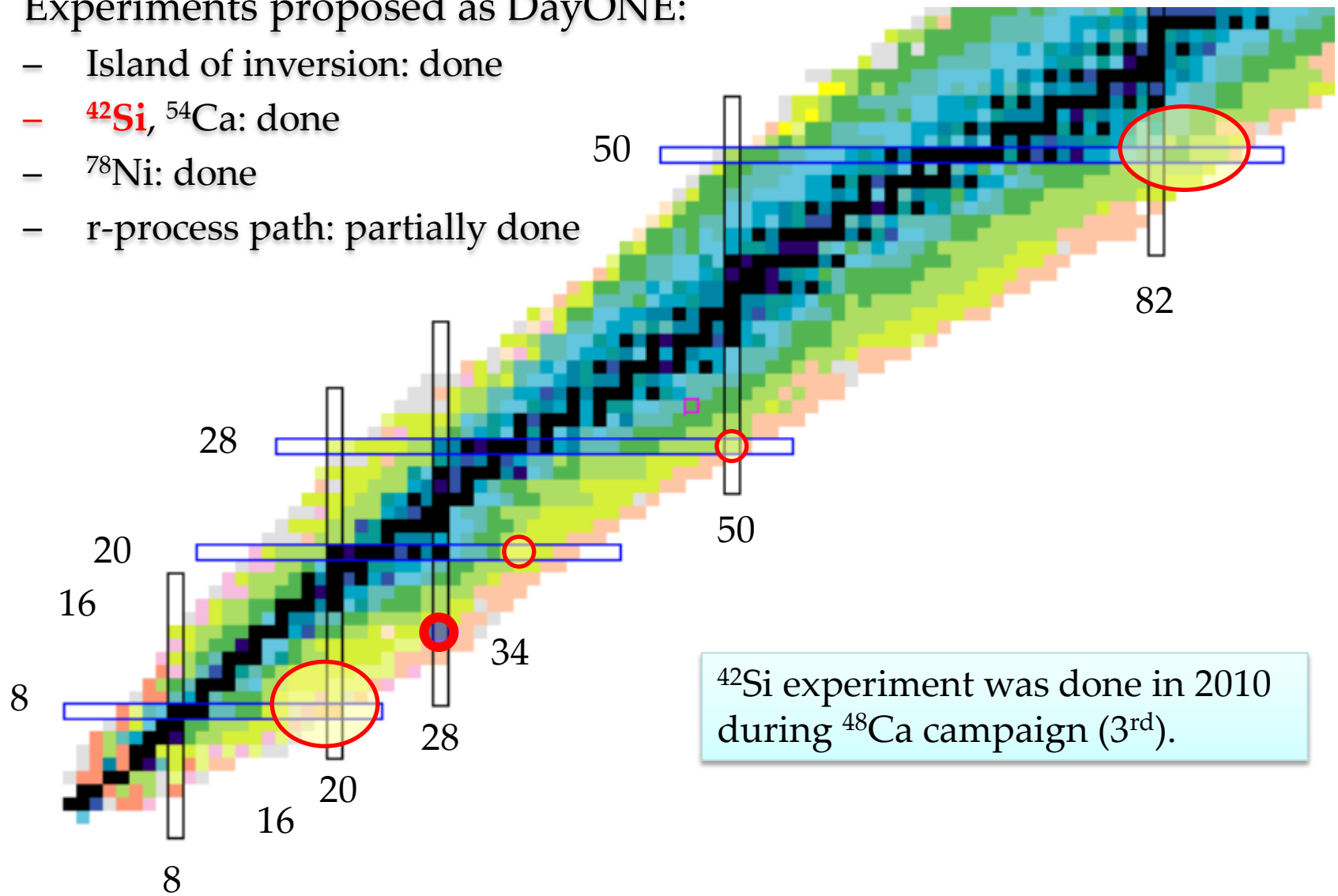
In-beam γ-ray spectroscopy @ RIBF

- Experiments proposed as DayONE:
  - Island of inversion: done
  - **^{42}Si**, ^{54}Ca: done
  - ^{78}Ni: done
  - r-process path: partially done



^{42}Si experiment was done in 2010 during ^{48}Ca campaign (3rd).

Experimental studies at shell closures

Several new phenomena are found around shell closures.

→ important properties for understanding neutron- or proton-number dependent nuclear structure.

Experiments we performed in RARF and RIBF:

N=8 light neutron rich region: disappearance of N=8

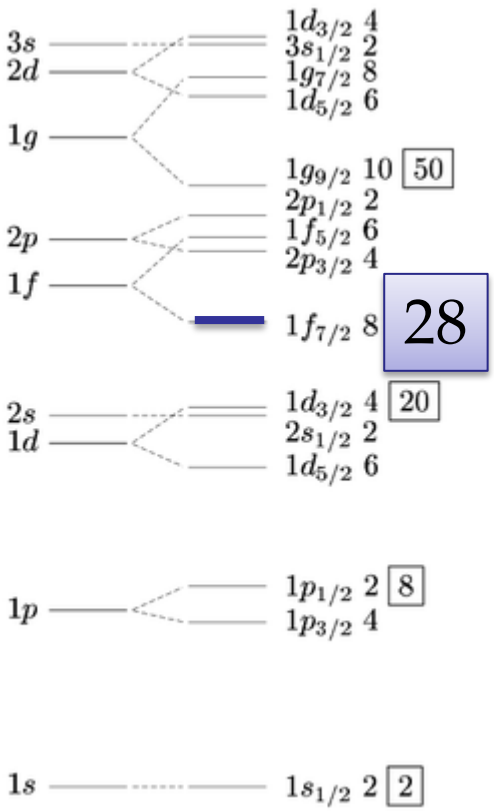
^{12}Be:	Coulex, (p,p′), isomer	H.Iwasaki et al., PLB**481**(2000)7, PLB**491**(2000)8 S.Shimoura et al., PLB**654**(2007)87

N=20 island of inversion: disappearance of N=20, boundary of IOI

^{32}Mg:	Coulex, (p,p′)	T.Motobayashi et al., PLB**346**(1995)9, S.Takeuchi et al., PRC**79**(2009)054319
^{3*}Mg:	Coulex, inelastic, removal	K.Yoneda et al., PLB**499**(2001)233, P.Doornenbal et al., in preparation
^{3*}Na:	inelastic, removal	P.Doornenbal et al., PRC**81**(2010)041305
^{30}Ne:	(p,p′)	Y.Yanagisawa et al., PLB**566**(2003)84
^{32}Ne:	inelastic, removal	P.Doornenbal et al., PRL**103**(2009)032501

Next magic number …

Next magic number: N=28

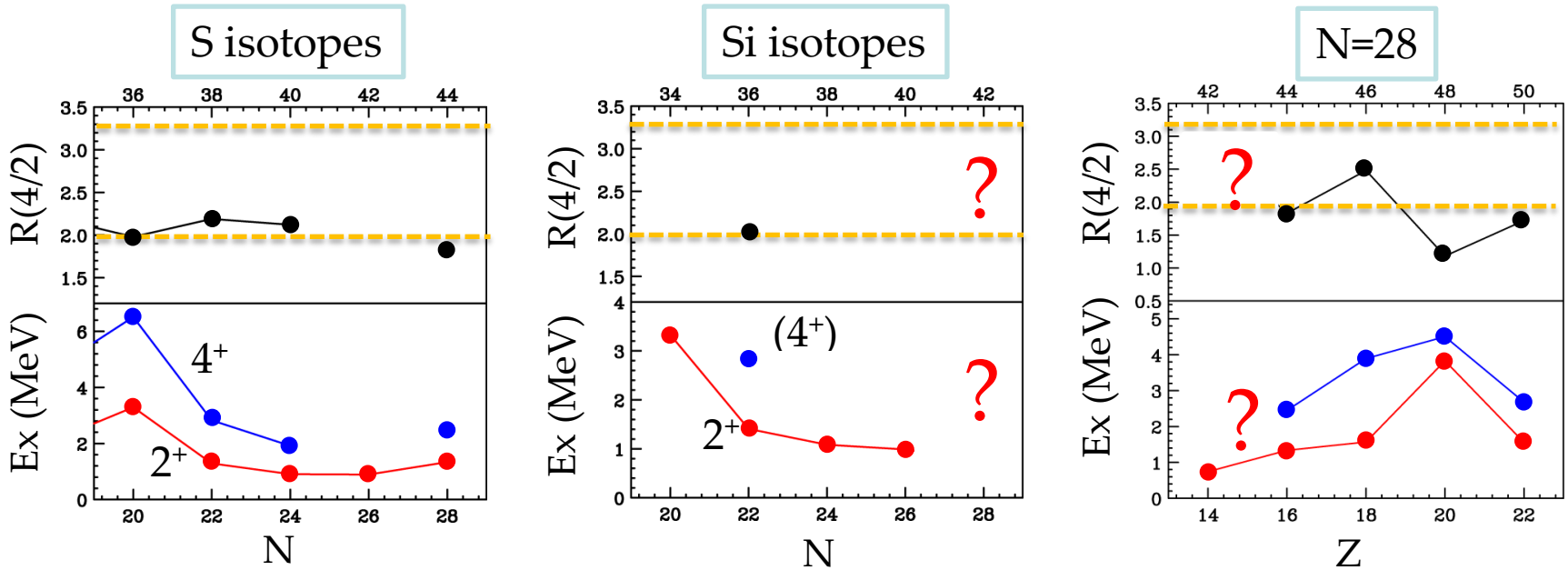


N=28 is the lightest magic number generated by the spin-orbit interaction.

Systematic studies for

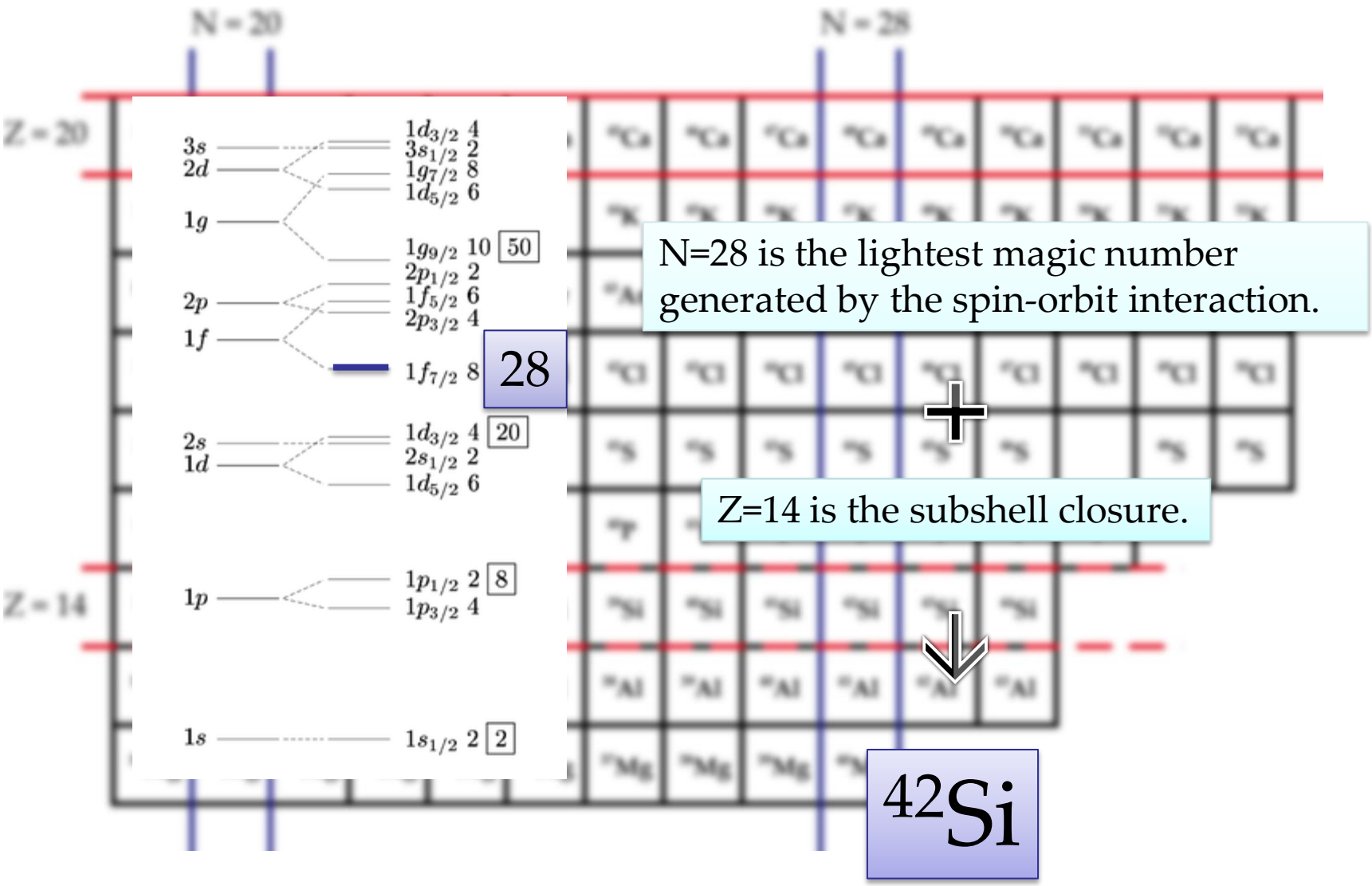
- S isotopes
  - β decay: O.Sorlin et al., PRC**47**(1993)2941.
  - Coulex: H.Scheit et al., PRL**77**(1996)3967.
    T.Glasmacher et al., PLB**395**(1997)163.
- Si isotopes
  - β decay: S.Grevy et al., PLB**594**(2004)252.
  - Coulex: R.W.Ibbotson et al., PRL**80**(1998)2081.
  - (p,p′): C.M.Campbell et al., PRL**97**(2006)112501,
    PLB**652**(2007)169.
- N=28 isotones
  - Many…

Systematics around N=28



- Spherical shapes remain toward N=28 in S isotopes.
- Lowering of $E_x(2^+)$ in Si isotopes.
- Lowering of $E_x(2^+)$ in N=28 isotones toward Z=14.

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



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

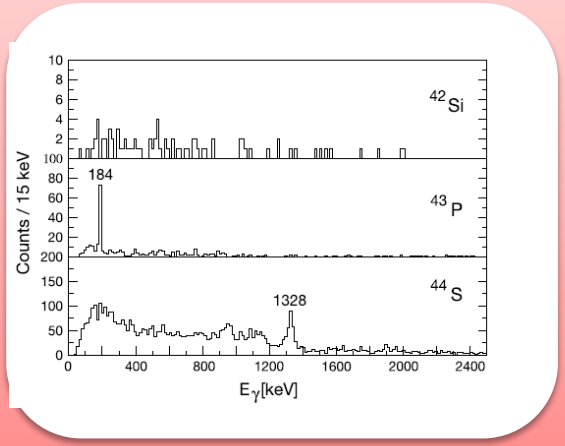
Deformed/Spherical?

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

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

NSCL case

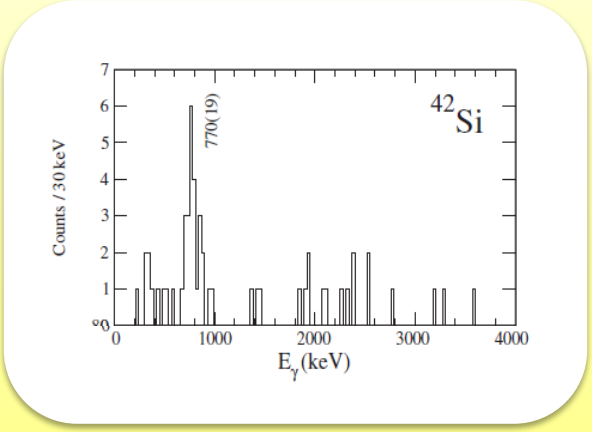
→ A **substantial Z=14 subshell closure**



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

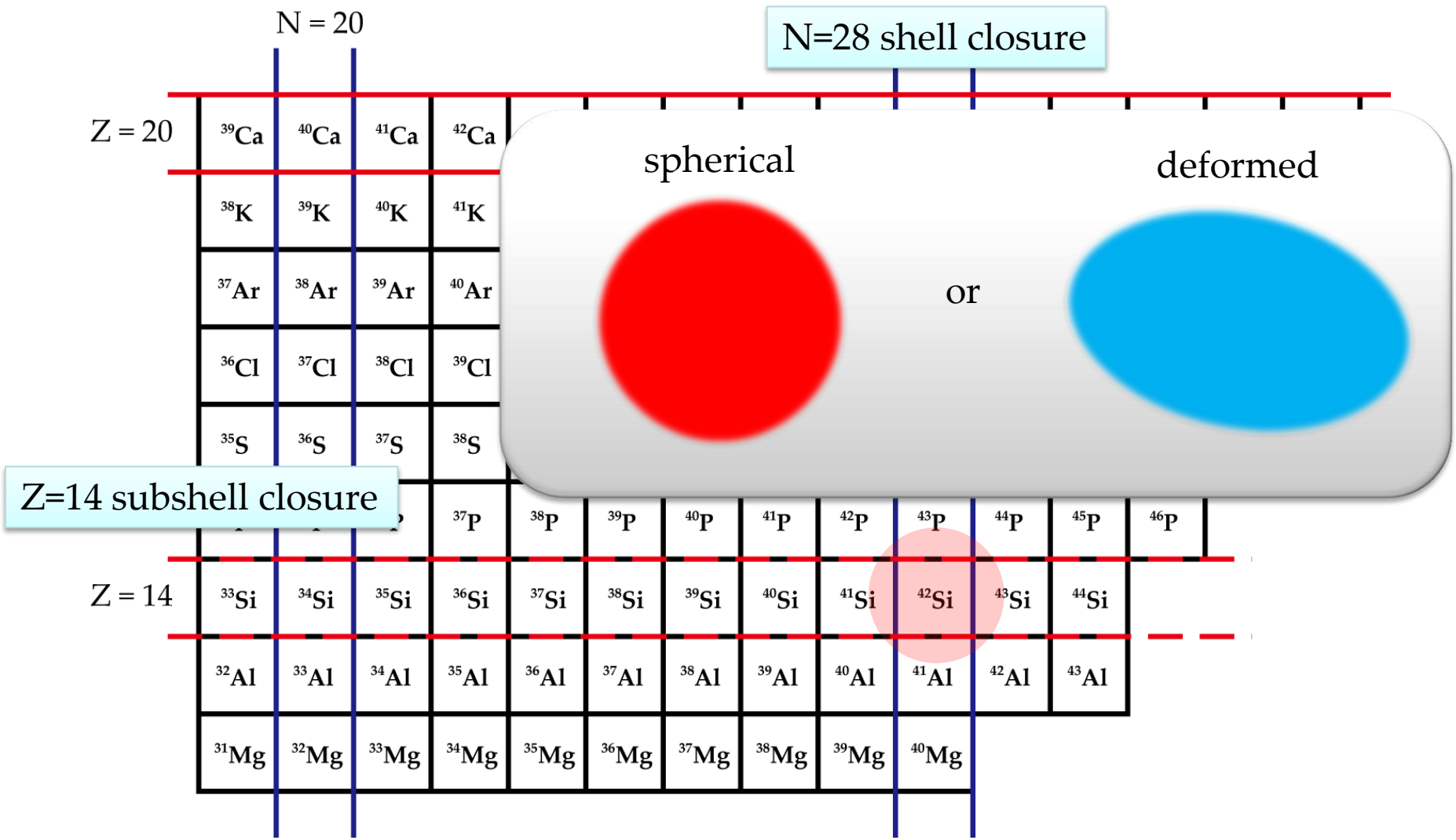
GANIL case

→ **Well-deformed oblate rotor**



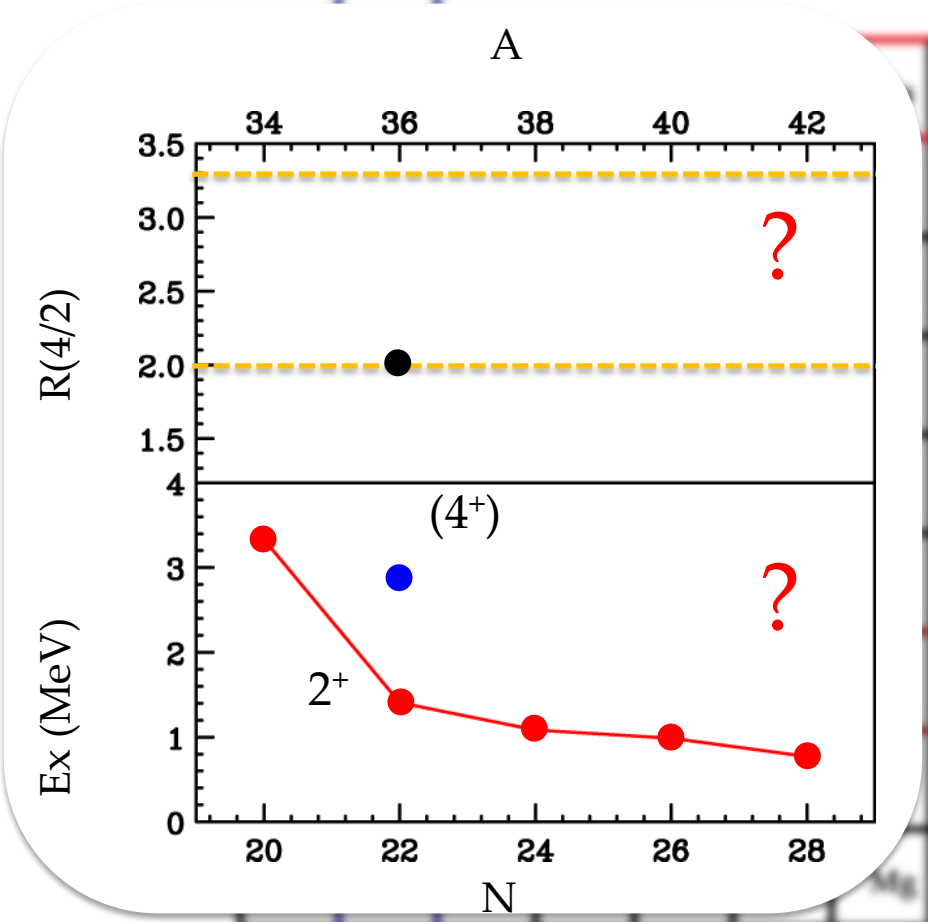
B.Bastin *et al.*, Phys. Rev. Lett. 99, 022503 (2007).

^{42}Si: spherical or deformed?



One can extract information on shape from Ex of 2^+ and 4^+.

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



- Confirm **Ex(2^+)**
- Determine **Ex(4^+)** for ^{42}Si (^{38,40}Si)
- Obtain **R($4^+/2^+$)**

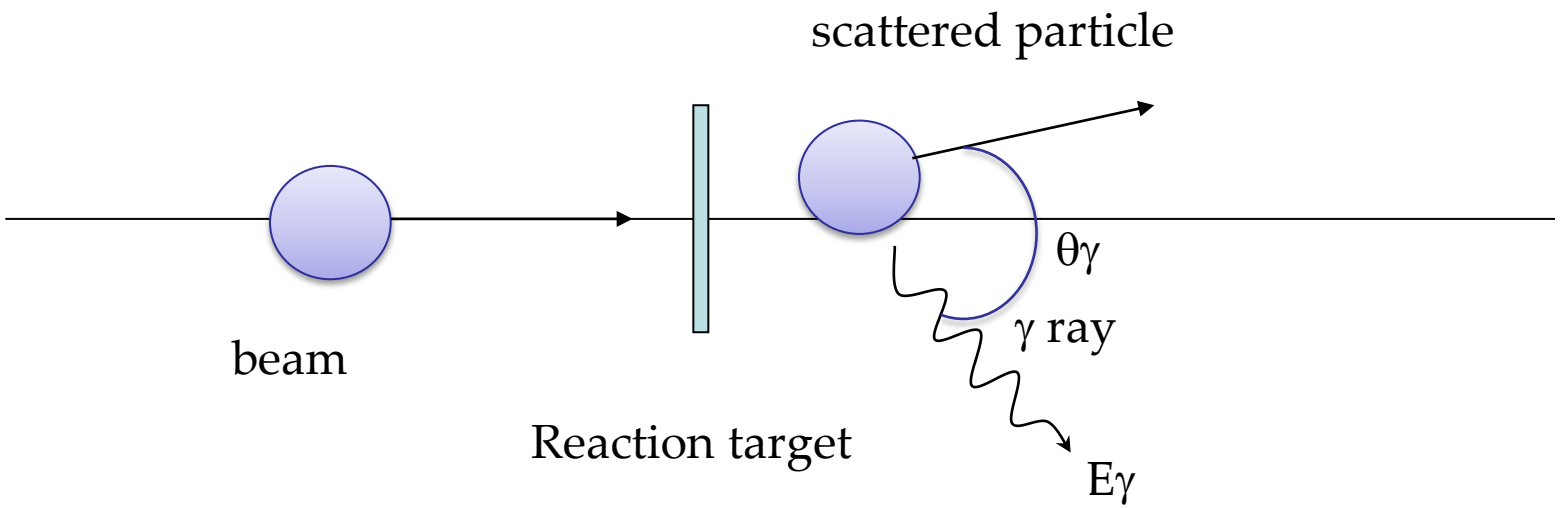
How ?

two proton removal reactions

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

- high intensity beams
- a thick target
- high efficiency detector array.

Two proton removal reaction ($^{44}S \rightarrow {}^{42}Si$) in inverse kinematics



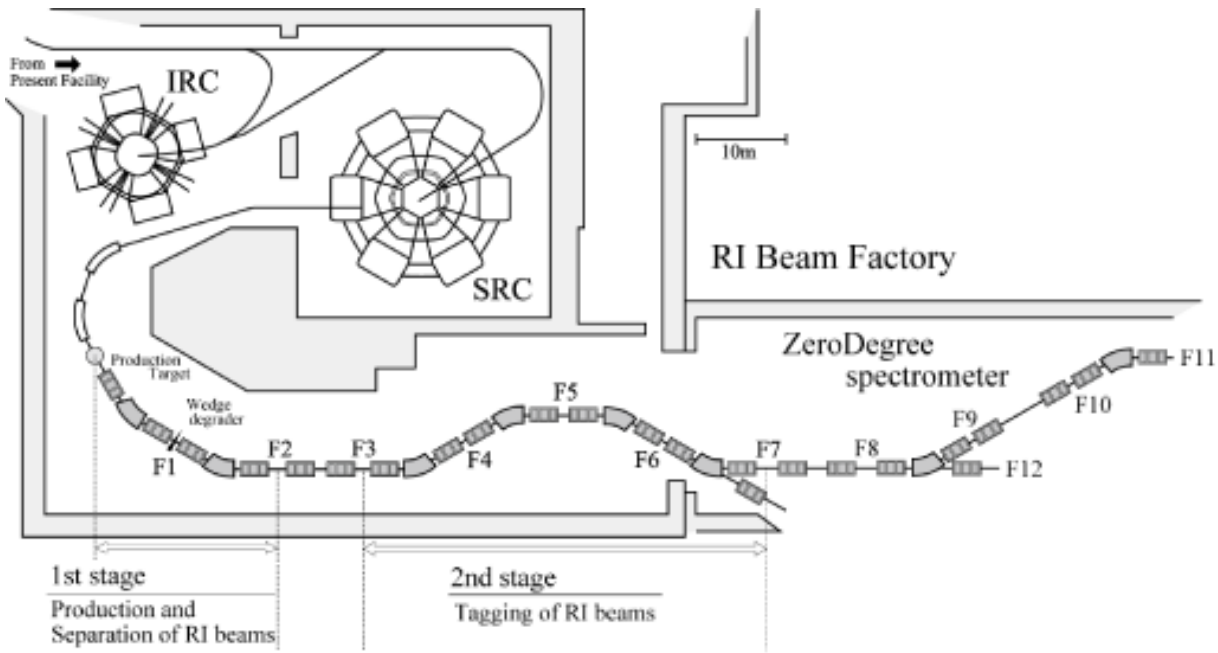
Particle Identification:	beam particle	→ BigRIPS
	scattered particle	→ ZeroDegree Spectrometer
Observables:	velocity	
	emission angle of γ ray	→ DALI2
	γ-ray energy	→ DALI2

⇩

Determination of reaction channel and correct Doppler shift.

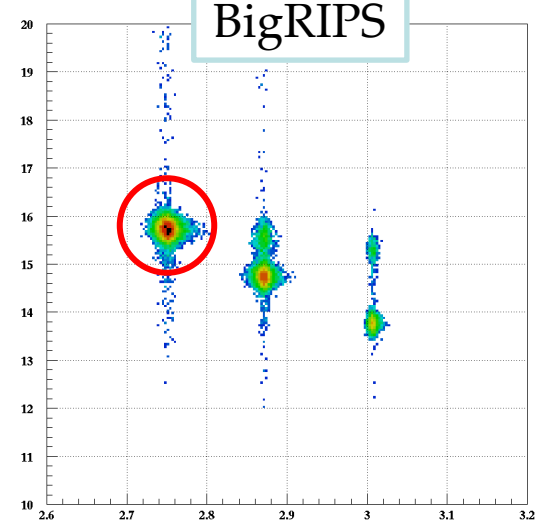
Particle Identifications

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

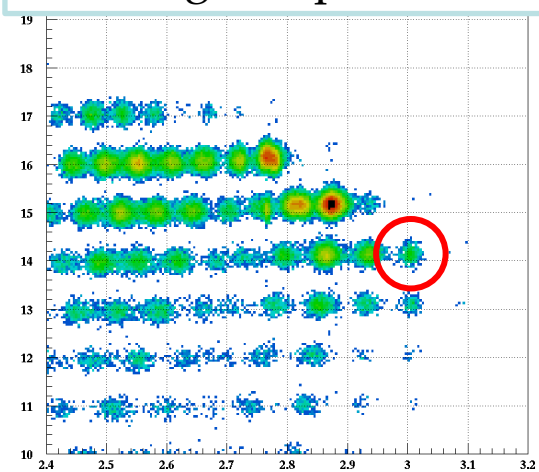


BigRIPS

BigRIPS



ZeroDegree Spectrometer

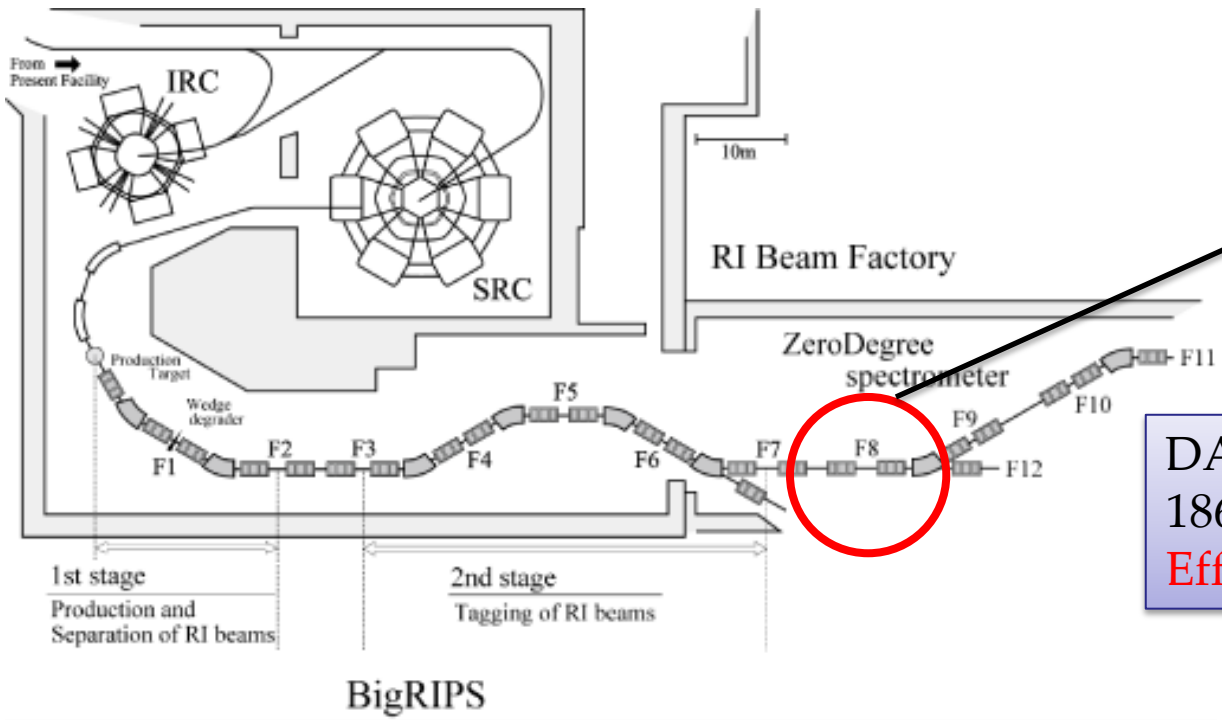


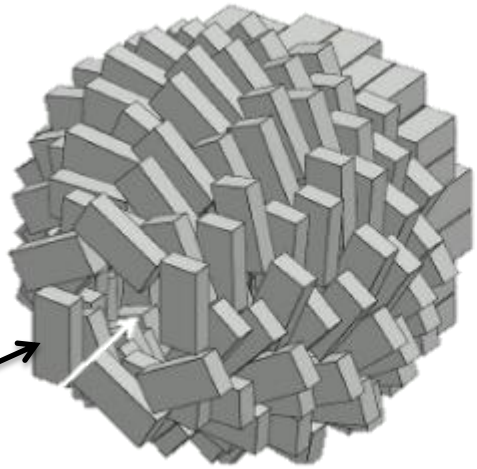
Secondary beam:	^{44}S 200*A* MeV
Beam intensity:	40k pps (average)
Reaction targets:	C 2.54g/cm^2

BigRIPS&ZDS
T. Kubo *et al.*, IEEE Trans. Appl. Supercond. **17**, 1069 (2007)
Y. Mizoi *et al.*, RIKEN Accel. Prog. Rep. 38, 297 (2005)

RIBF: BigRIPS + DALI2 + ZeroDegree

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





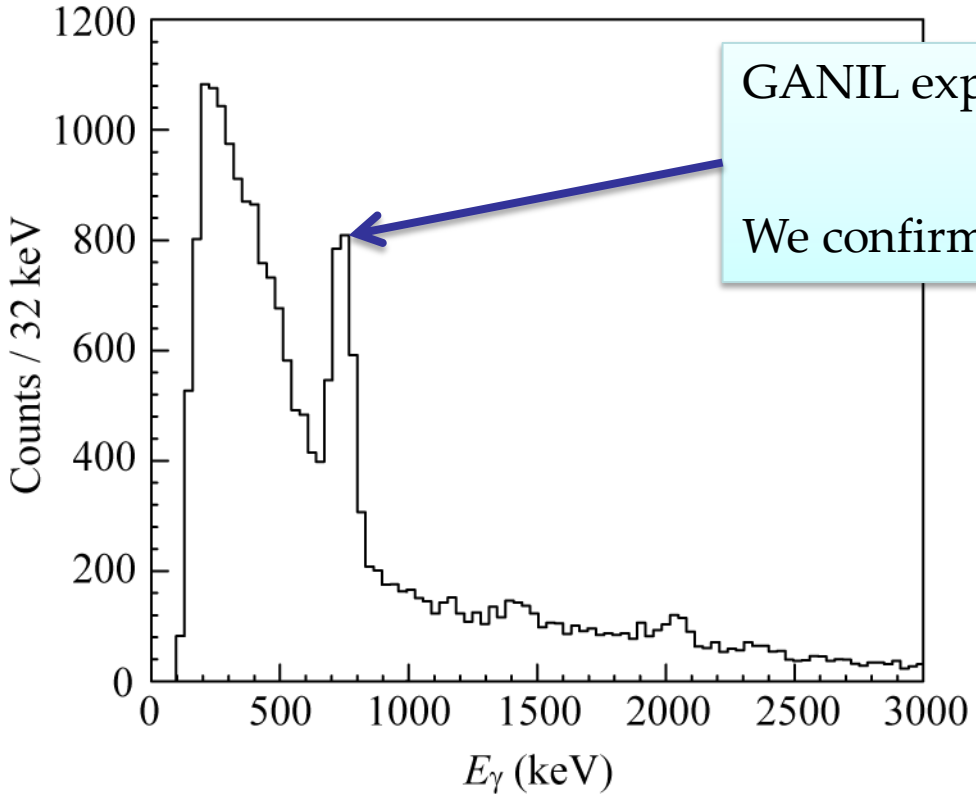
DALI2
186 NaI(Tl) crystals
Eff.: ~20% for 1 MeV (β~0.6)

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.

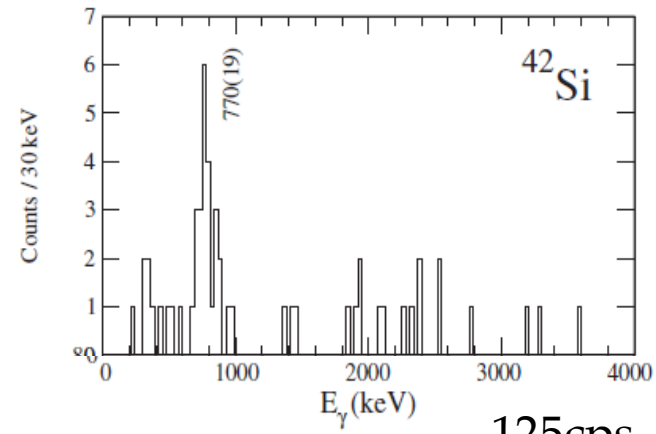
$^{44}S + C \rightarrow {}^{42}Si + \gamma + X$



GANIL exp. : 770(19) keV

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

We confirmed γ line observed at GANIL.

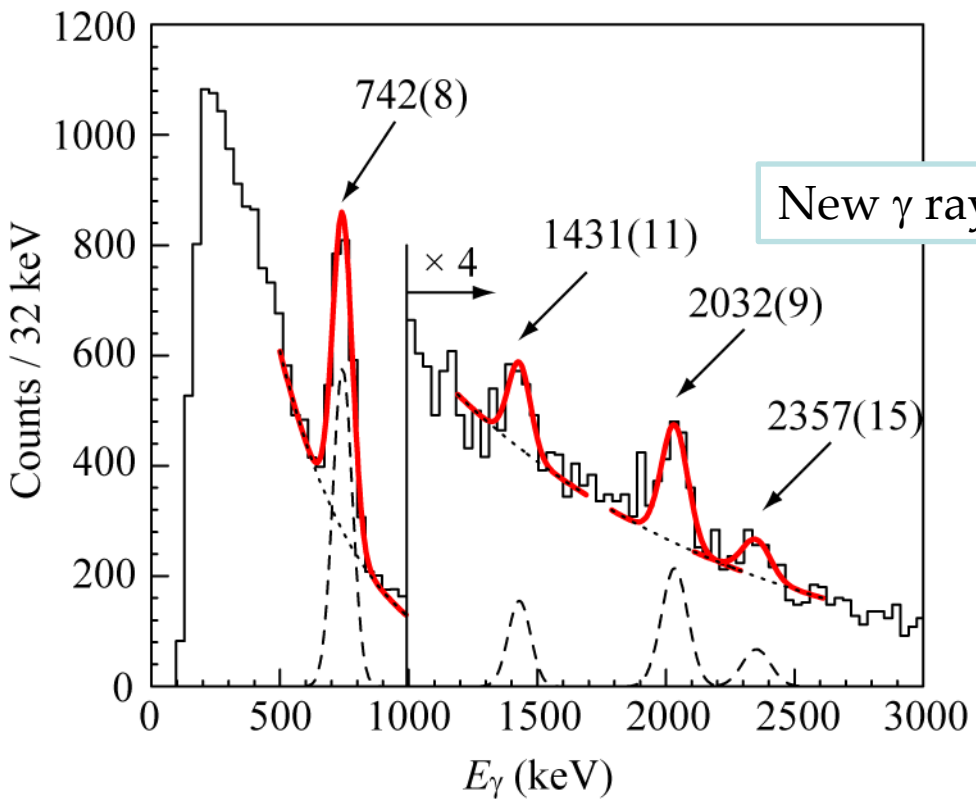


125cps

^{44}S beam with 40kcps

Additional peaks.

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



New γ rays!

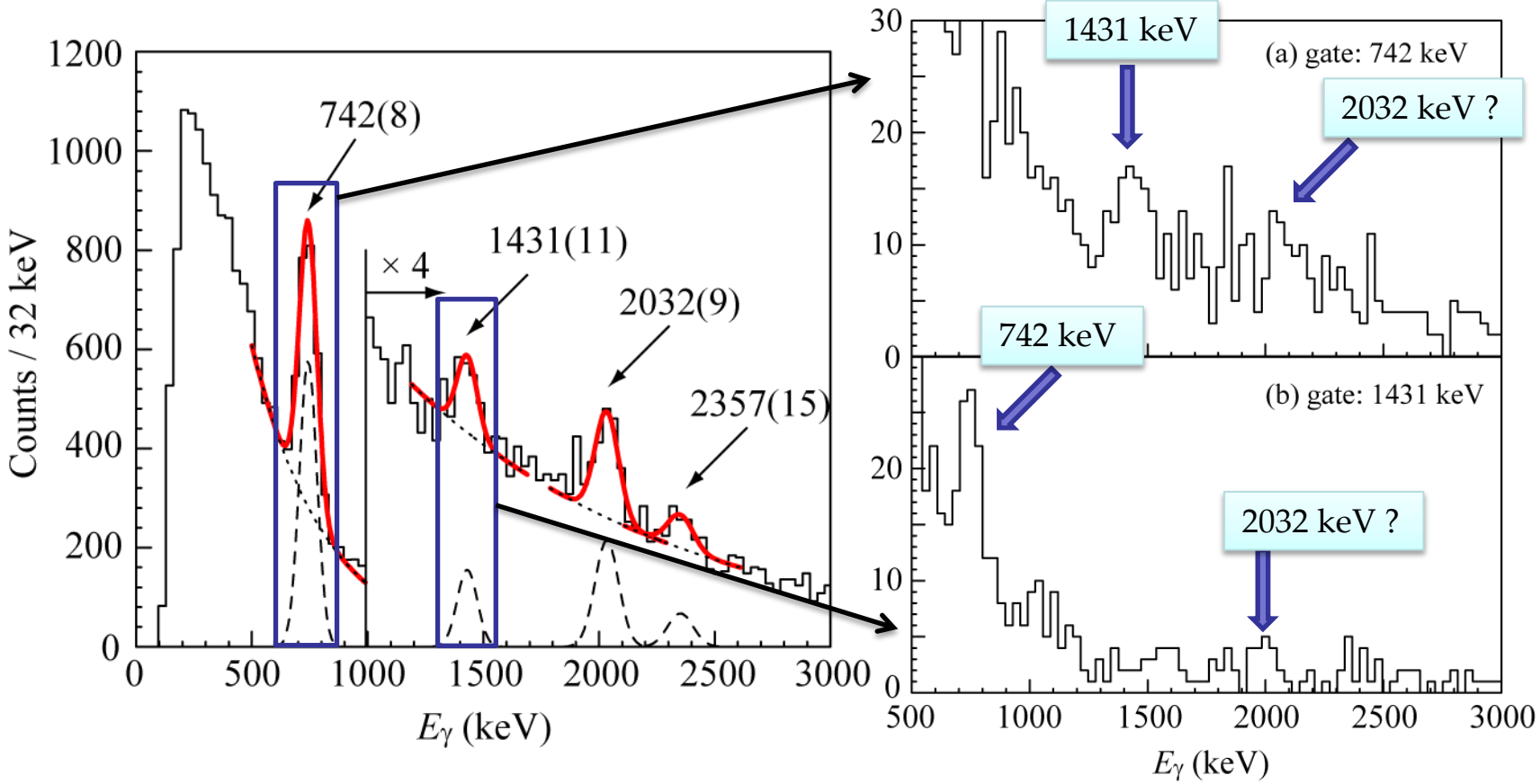
γ ray ($2^+ \rightarrow 0^+$): 742(8) keV
new lines:
1431(11) keV
2032(9) keV
2357(15) keV

*Widths are fixed to simulated values.

γ-γ coincidence

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

1431 keV and 742 keV: cascade?



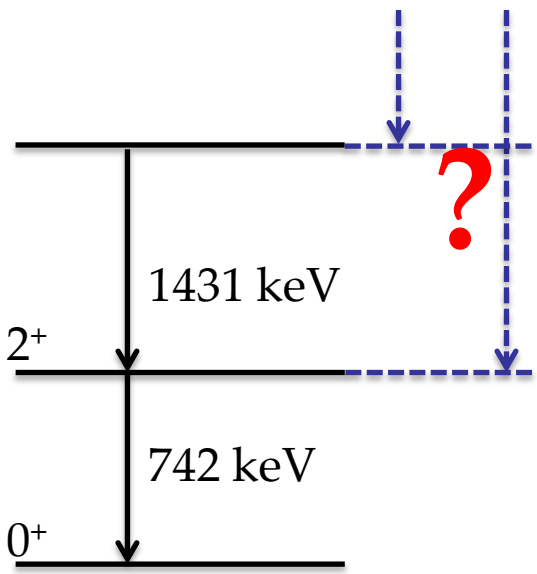
*Widths are fixed to simulated values.

γ_{1431}: transition to 2^+ state

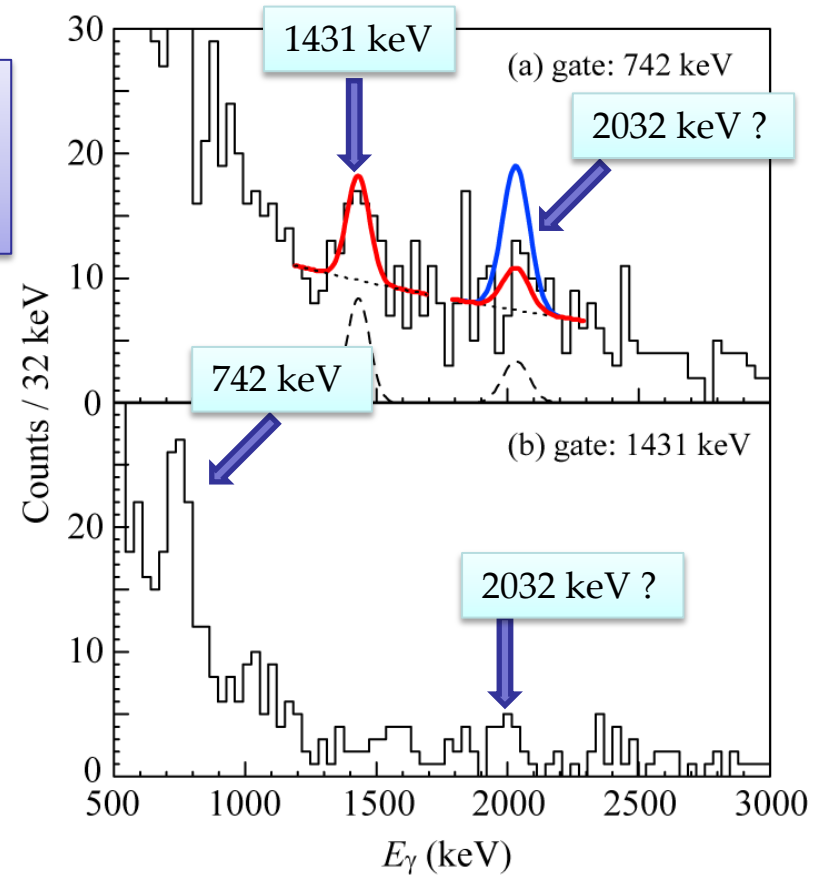
$$^{44}S + C \rightarrow {}^{42}Si + \gamma + X$$

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

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



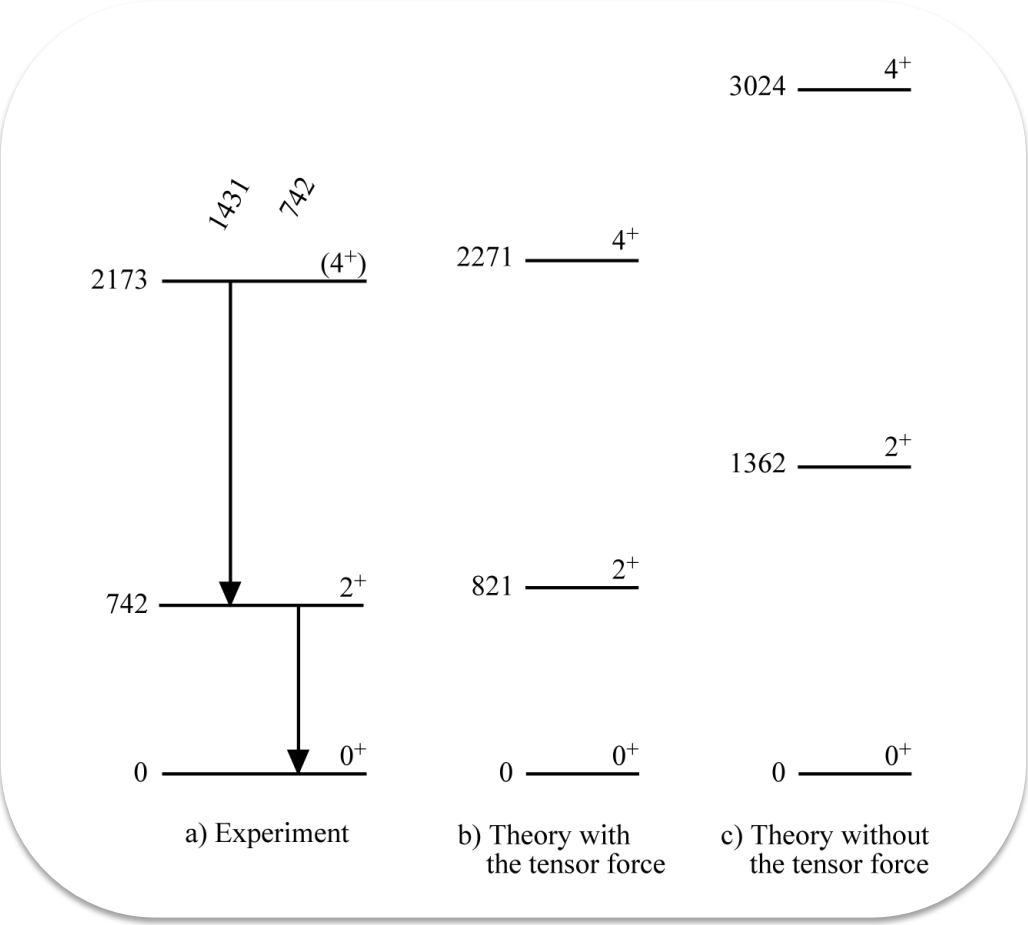
1431 keV and 742 keV: cascade



*Widths are fixed to simulated values.

4^+ at 2173 keV

Excited state at **2173(19) keV** has been tentatively assigned to **the 4^+ state** from present study.



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

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

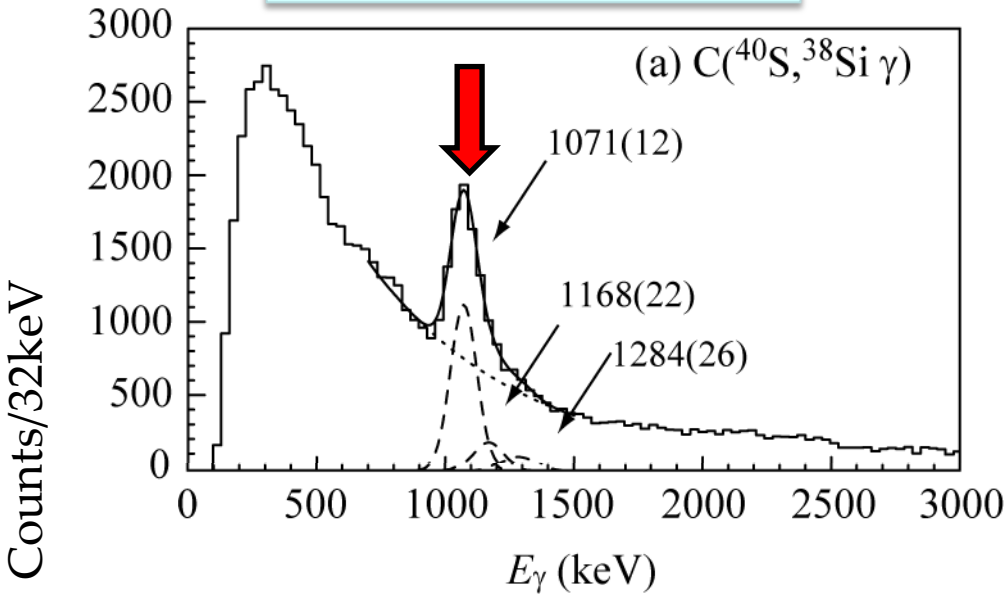
→ oblate shape

Ref. Otsuka et al., NPA**805**(2008)127c
Utsuno et al., to be published in PRC.

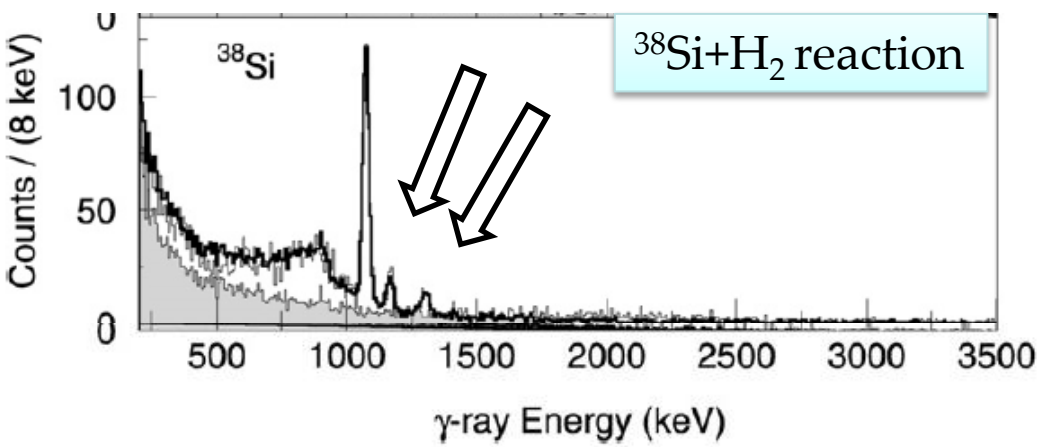
Other isotopes 1: ^{38}Si

By M.Matsushita

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

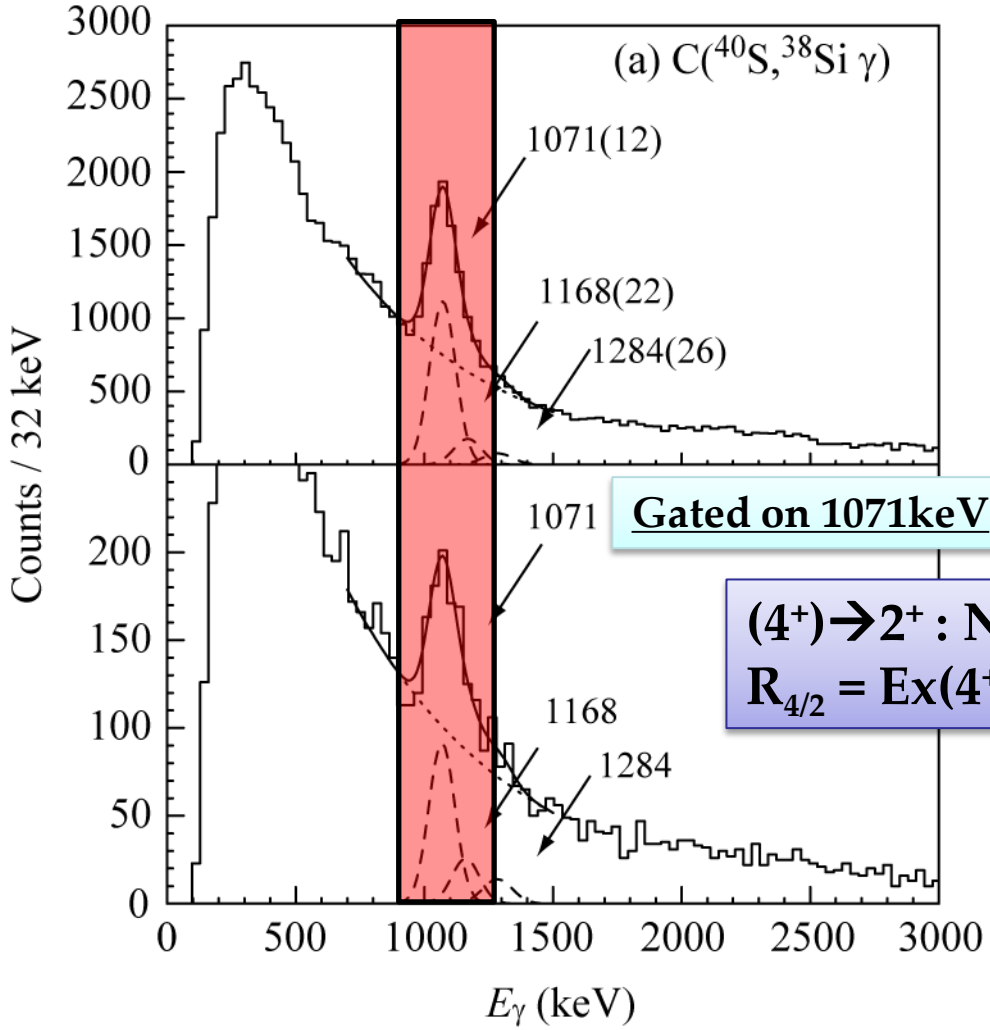


Ref. C.M.Campbell et al., PLB652(2007)169

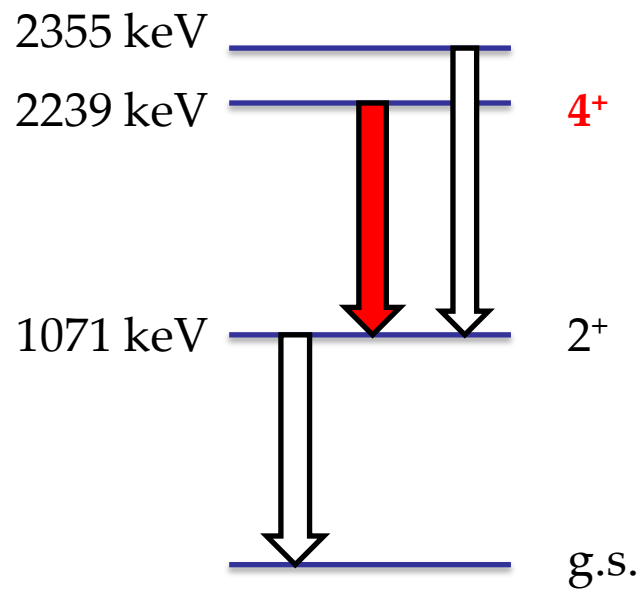


Other isotopes 1: ^{38}Si

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



Gated on 1071keV



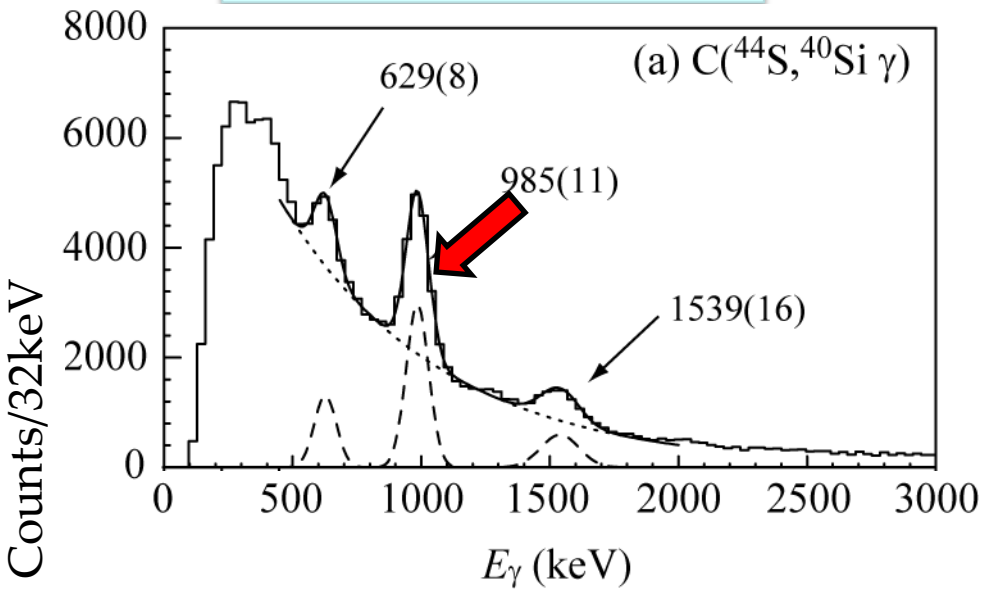
$(4^+) \rightarrow 2^+$: New transition around 1080 keV

$R_{4/2} = Ex(4^+)/Ex(2^+) \sim 2$

Other isotopes 2: ^{40}Si

By M.Matsushita

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



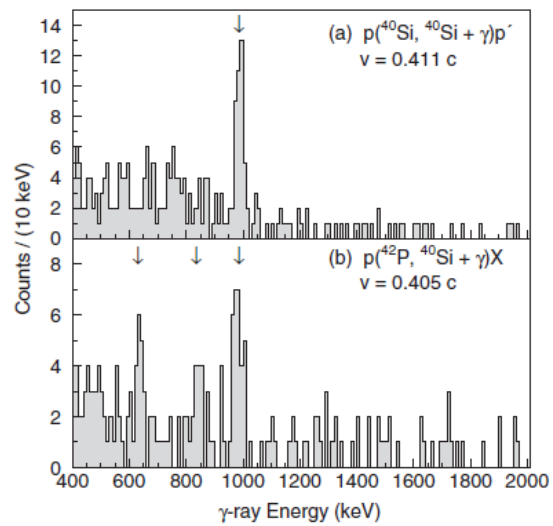


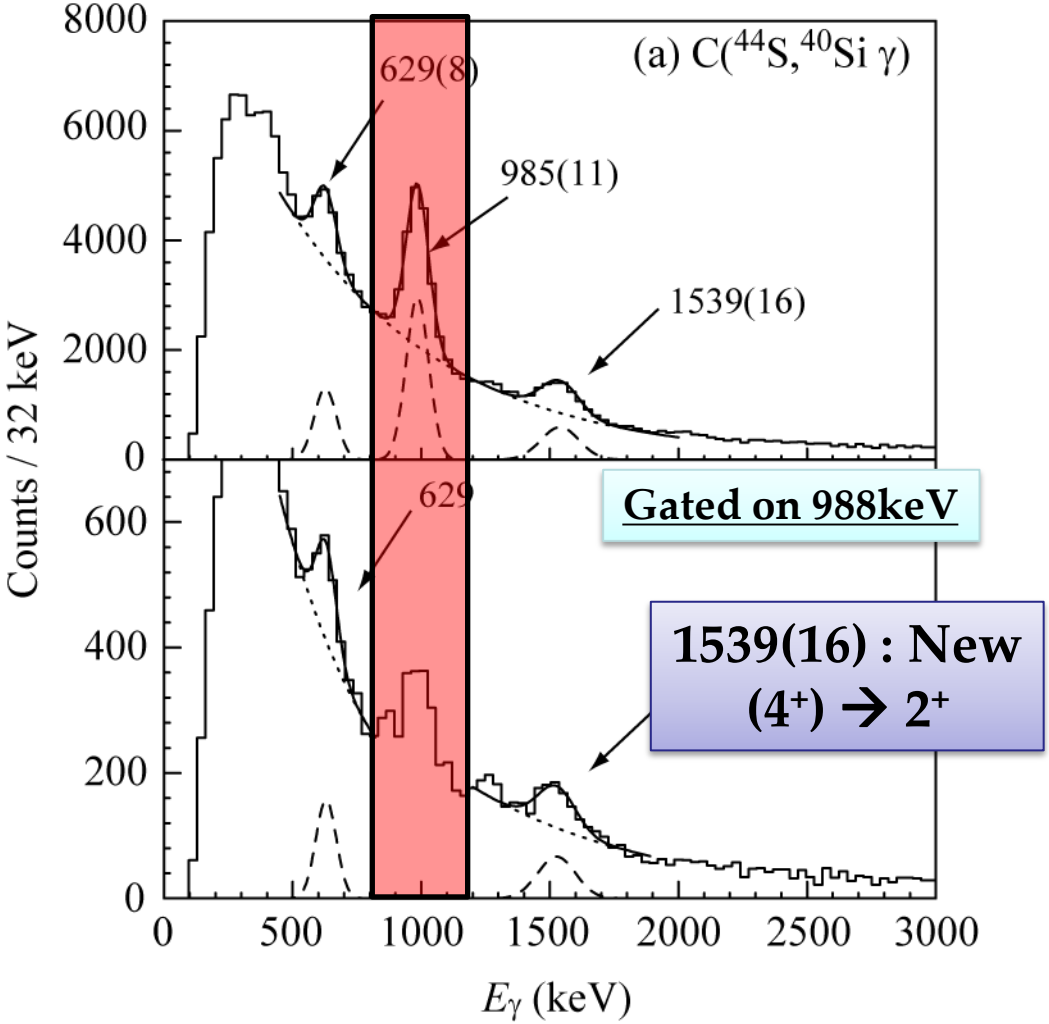
FIG. 1. Doppler-corrected γ-ray spectra observed in coincidence with the reactions $p(^{40}Si, {}^{40}Si + \gamma)p'$ and $p(^{42}P, {}^{40}Si + \gamma)X$.

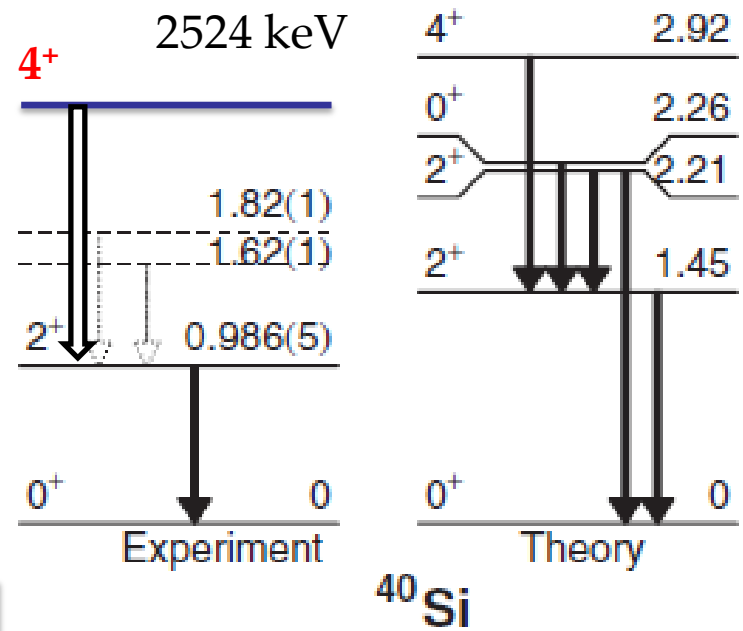
Ref. C.Campbell et al., PRL97(2006)112501

Other isotopes 2: ^{40}Si

By M.Matsushita

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

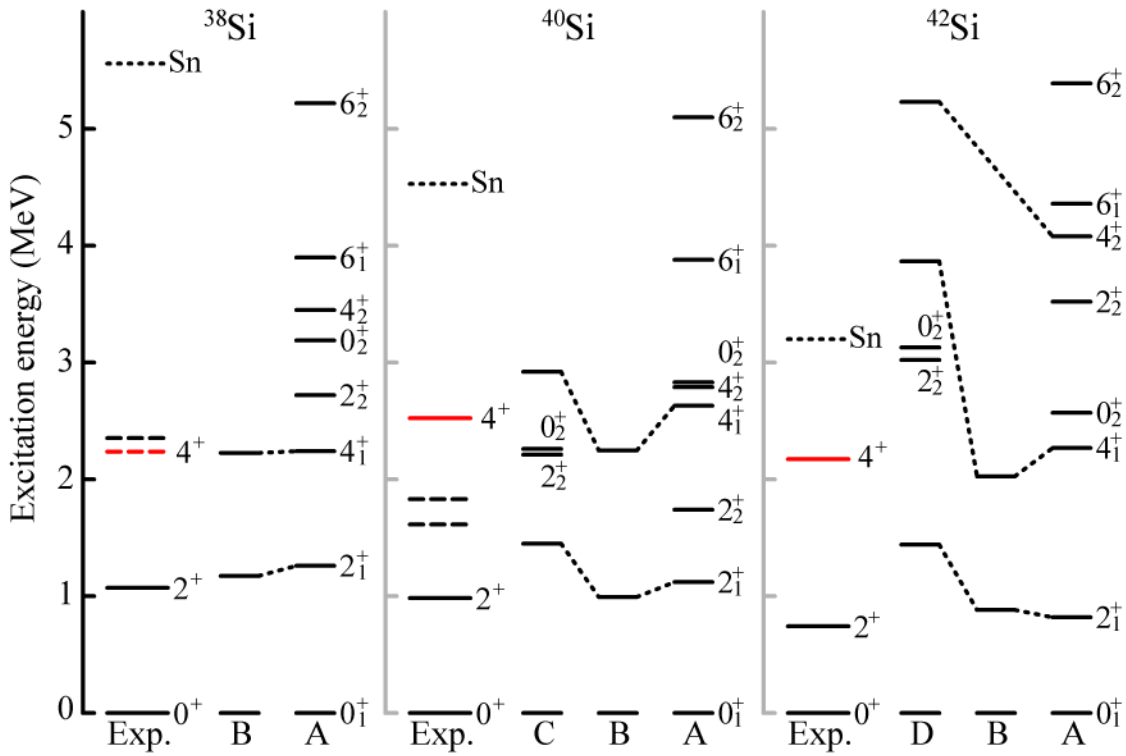




Ref. C.M.Campbell et al., PRL97(2006)112501

R(4/2) = 2.56

Level scheme with theories

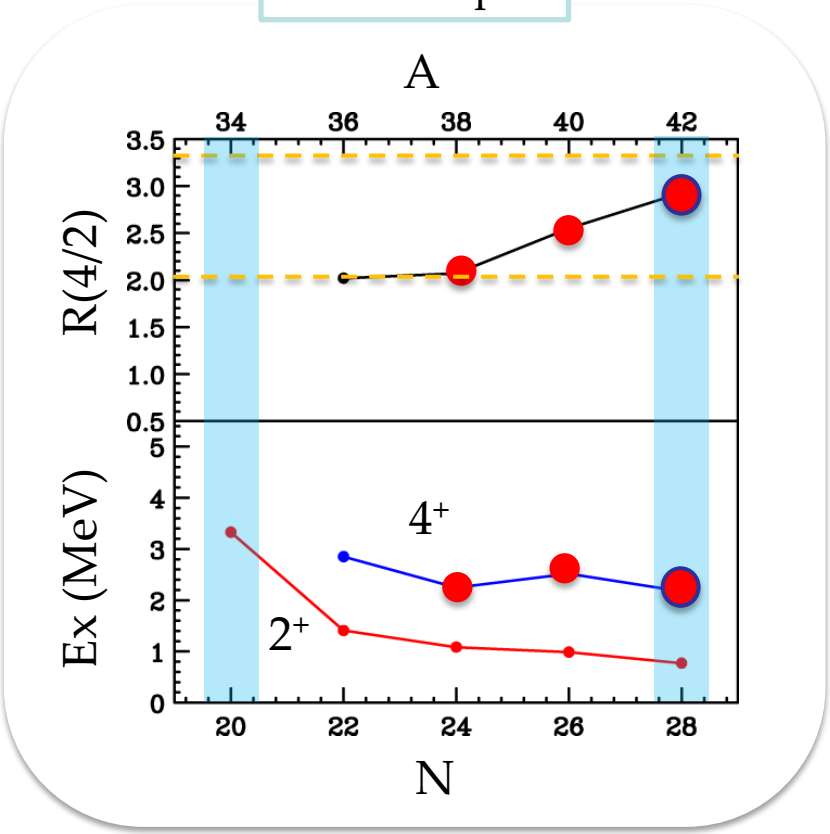


R(4/2)	2.09(5)	2.56(5)	2.93(5)

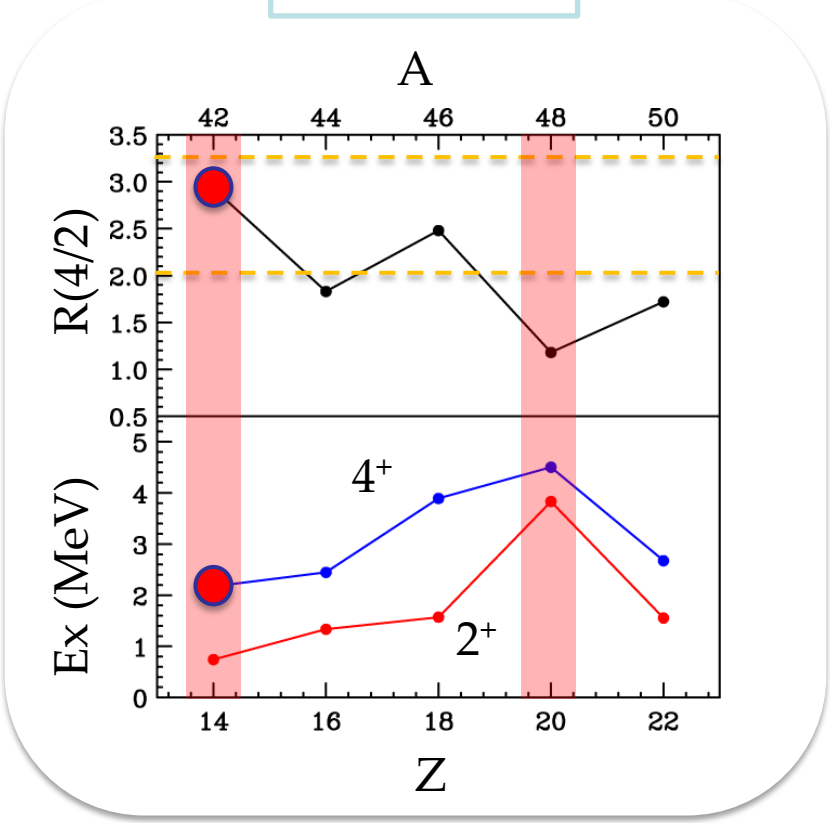
A:	SM with SDPF-MU	T. Otsuka *et al.*, NPA805,127c (2008); Y. Utsuno *et al.*, to be published in PRC
B:	SM with SDPF-U-MIX	F. Rotaru *et al*, PRL109, 092503 (2012).
C:	SM	C. M. Campbell *et al.*, PRL97, 112501 (2006).
D:	mean field calc. with DD-PC1	Z. P. Li *et al.*, PRC84, 054304 (2011).

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

Z=14 isotopes



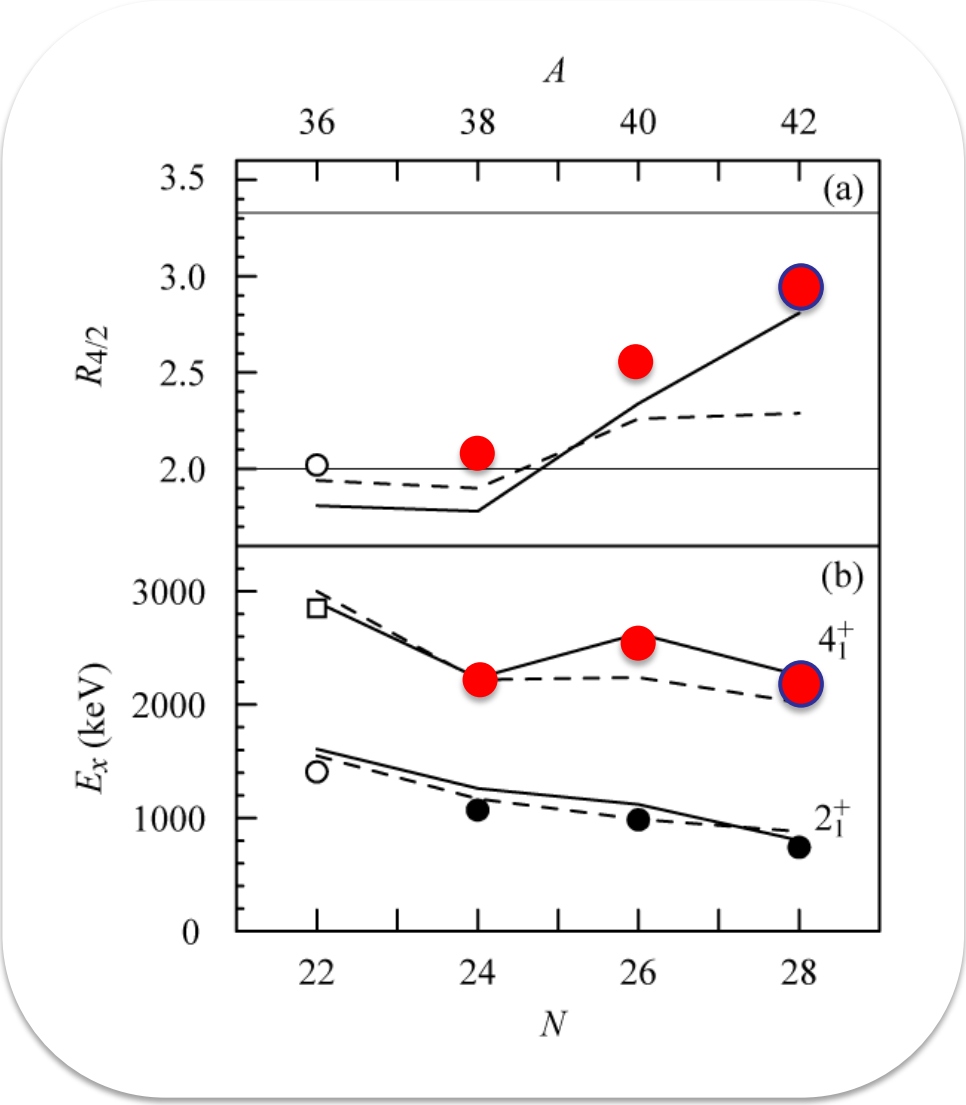
N=28 isotones



R(4/2) shows a rapid development of deformation in Si isotopes.
R(4/2) of ^{42}Si is the largest also among N=28 isotones.

^{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



Energy ratio between 2^+ and 4^+ states
R(4/2) = 2.93

^{42}Si is characteristic of a well-deformed rotor despite the magic numbers N=28 and Z=14.

Summary

- Two-proton removal reaction has been measured in coincidence with de-excitation γ rays with high intense ^{44}S beam and high efficiency detector array DALI2 at RIKEN RIBF.
- The excitation energy of the 2^+ state was obtained to be **742(8) keV**, which is consistent with the result obtained in the GANIL experiment.
- The candidate of the 4^+ state was found at **2173(19) keV** in ^{42}Si from γ-γ coincidence anaysis.
- Shell model calculations by Utsuno-san and Otsuka-san (→ oblate deformation) are in good agreement with experimental data.
- The energy ratio between the 2^+ and 4^+ states is obtained to be **R(4/2) = 2.93**, which indicates ^{42}Si is well deformed like rigid rotor.

Collaborators

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ANL:	C.HOFFMAN
GANIL:	L.CACERES
Frankfurt/GSI:	T.L.BLEIS
IN2P3:	S.GREVY, A.MATTA
LBNL:	H.CRAWFORD, P.FALLON, M.PETRI,
LPC CAEN:	J.GIBELIN
NSCL:	D.BAZIN, R.WINKLER
RICHMOND:	R.HUGHES
YORK:	D.JENKINS

THANK YOU FOR YOUR ATTENTION ☺