Spectroscopy of unstable nuclei using proton inelastic scattering with in-beam γ-ray spectroscopy technique

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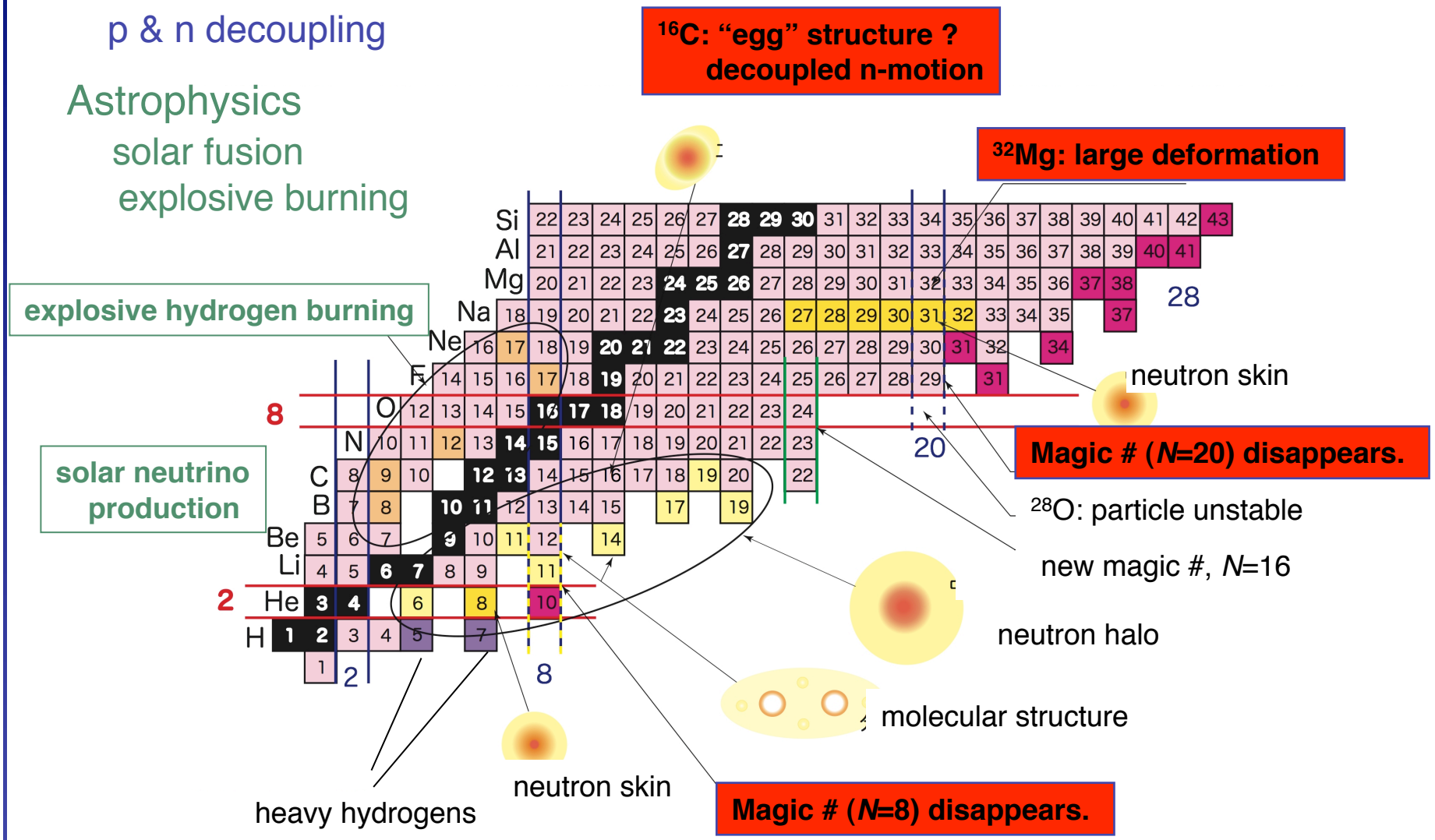
at intermediate energies (v/c ~ 0.3)
RIPS (+ BigRIPS at RIBF new facility) at RIKEN

Exotic nuclear structure

Nuclear Strucuter
- shell closure
- p & n decoupling

Astrophysics
- solar fusion
- explosive burning



- β-decay experiments
- Total reaction cross section
- Secondary Reaction
  - Coulomb Excitation
  - (p,p')
  - Nucleon transfer reaction
  - Fragmentation / knockout
  - …
  - γ-spectroscopy
  - Missing mass
  - Invariant mass

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- β-decay experiments
- Total reaction cross section
- Secondary Reaction
  - Coulomb Excitation
  - (p,p') ←
  - Nucleon transfer reactio
  - Fragmentation / knockou
  - …
  - γ-spectroscopy ←
  - Missing mass
  - Invariant mass

intermediate-energy (p,p')

^{32}Mg(p,p')
4^+, level scheme

^{58}Ti, ^{60}Cr, ^{62}Cr(p,p')
new 2^+, 4^+, deformation

(p,p') as a probe for structure of unstable nuclei

inelastic scattering to 2^+ state

$E_x(2^+)$	Collectivity
$E_x(4^+) / E_x(2^+)$	Type of collectivity
$\delta_{p,p'}(=\beta R)$	Collectivity (proton+neutron)

c.f. Coulomb excitation: collectivity (proton)

(p,p') vs. Coulomb excitation (Coulex) at intermediate *E*

- High sensitivity

$$Y_{2+} \propto \frac{d}{A} \cdot \sigma$$

d: areal density of the target
A: target mass number

Coulex $\sigma(2^+)$: huge

(p,p') $\sigma(2^+)$: large

d/A : large

$Y_{2+}(p,p') > Y_{2+}(Coulex)$

- (p,p'): less selective than Coulex
  excitation to higher excited states
  → Variety of states (4^+, 2_2^+, 3^-, ...) to be investigated

- Proton collectivity (Coulex) ←→ Neutron collectivity (p,p')

- Angular distribution (scattering angle)
  (p,p')→ *l* - angular momentum transfer Coulex → multipolarity

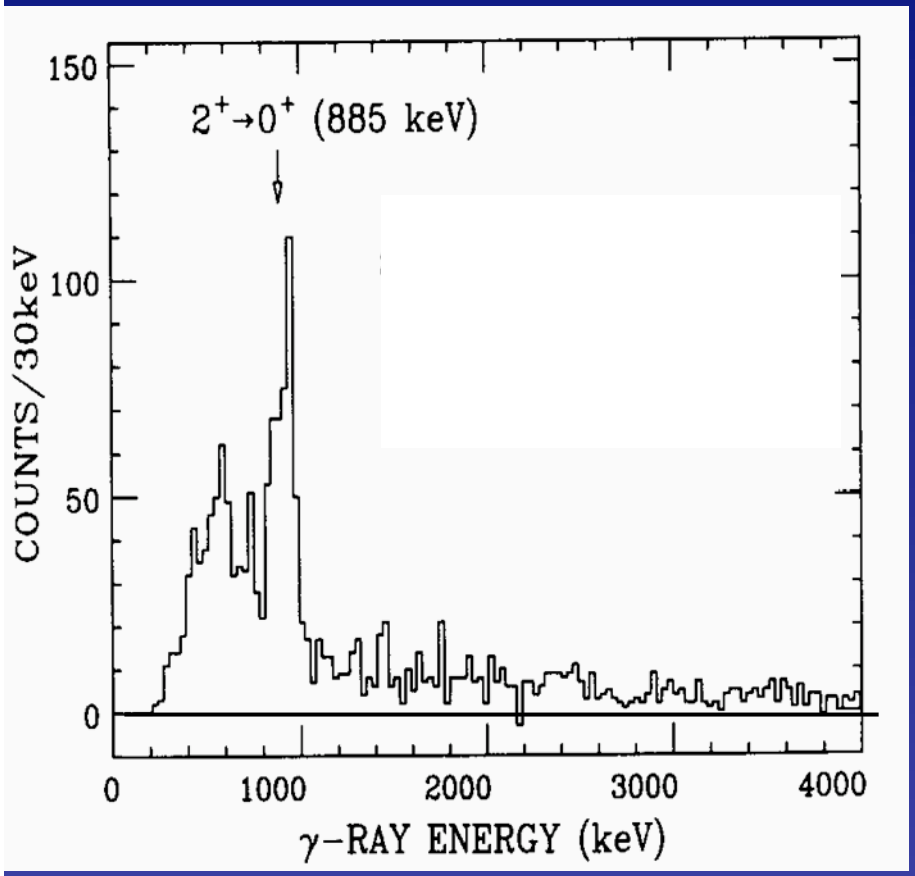
^{32}Mg(p,p') at 46.5 MeV/nucleon

4^+ state

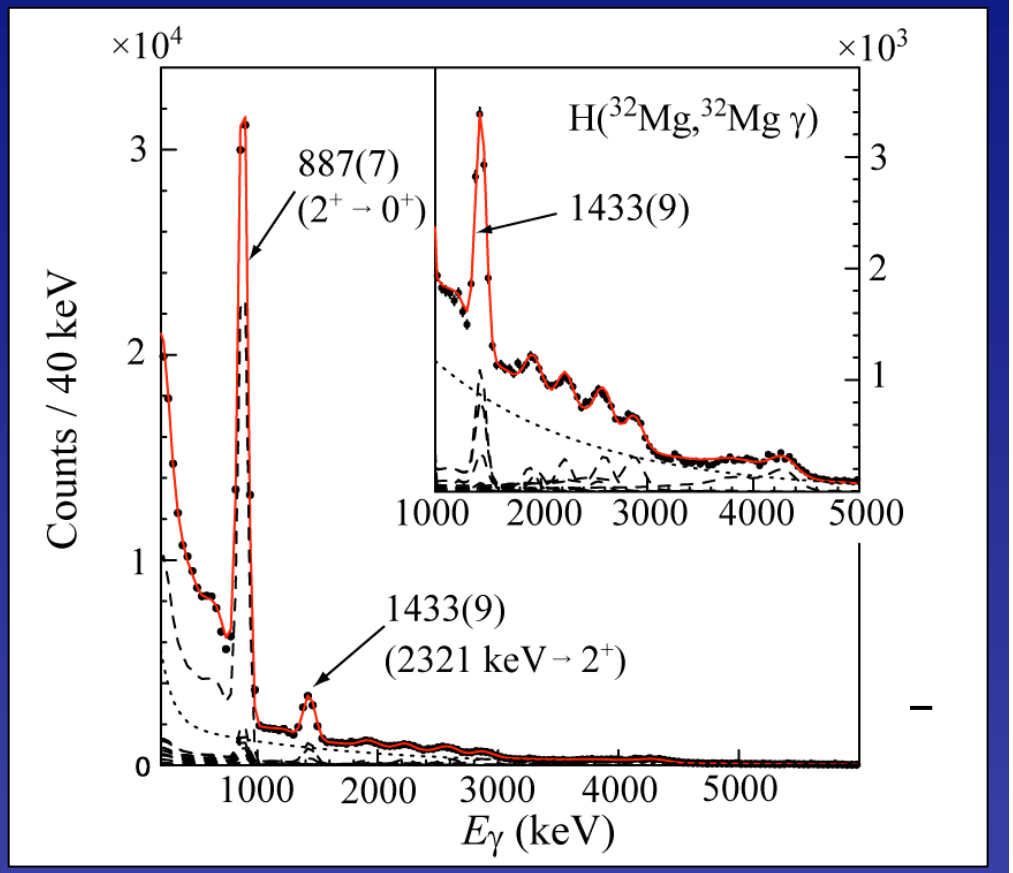
level scheme

^{32}Mg *inelastic scattering*

Coulex



(p,p')

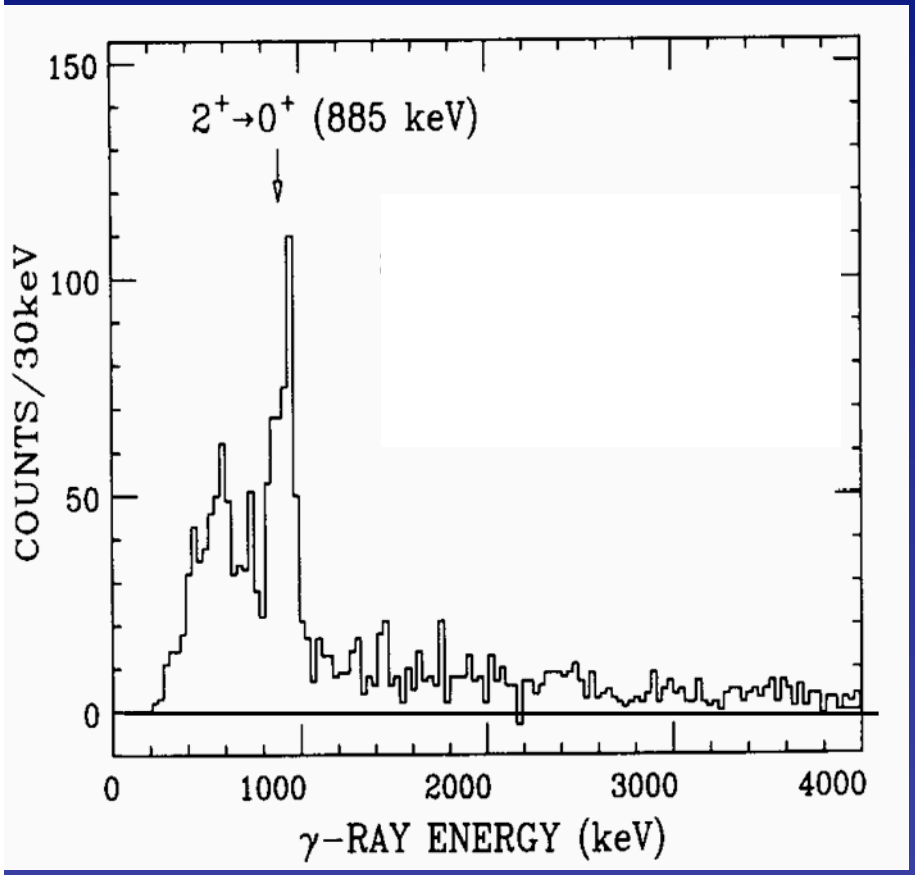


T. Motobayashi et al., PLB346, 9(95)

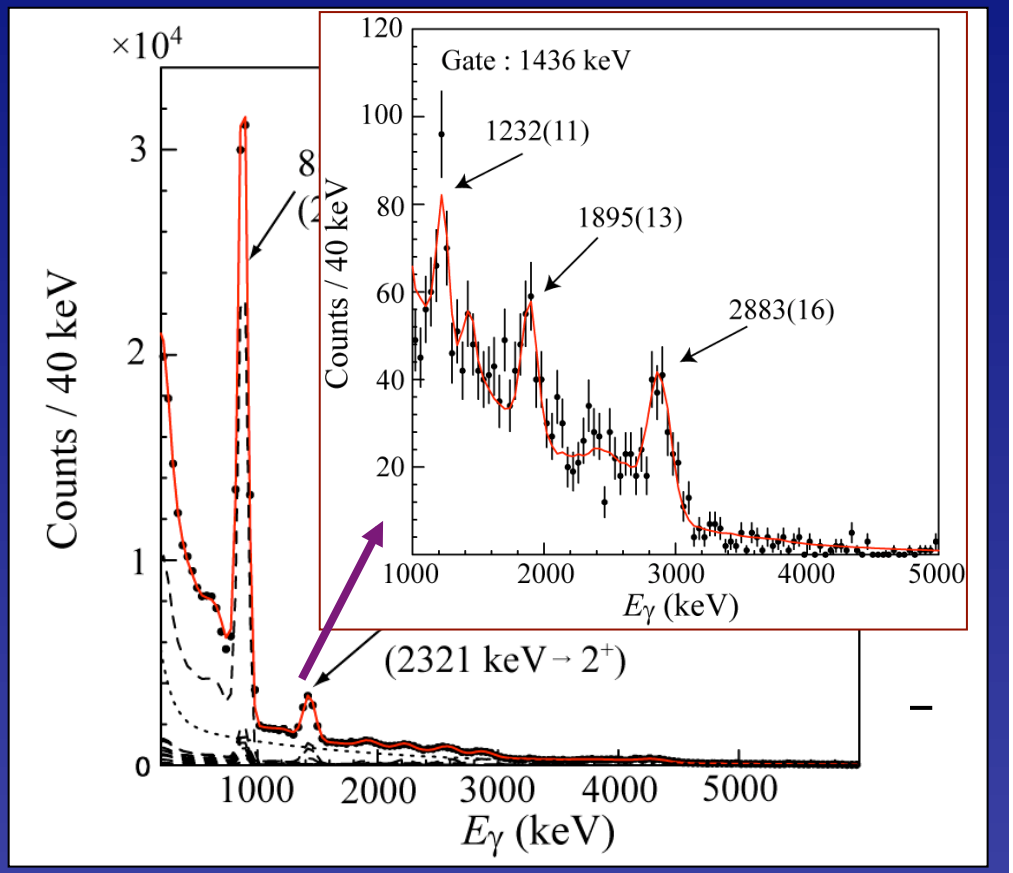
S. Takeuchi et al.

^{32}Mg *inelastic scattering*

Coulex



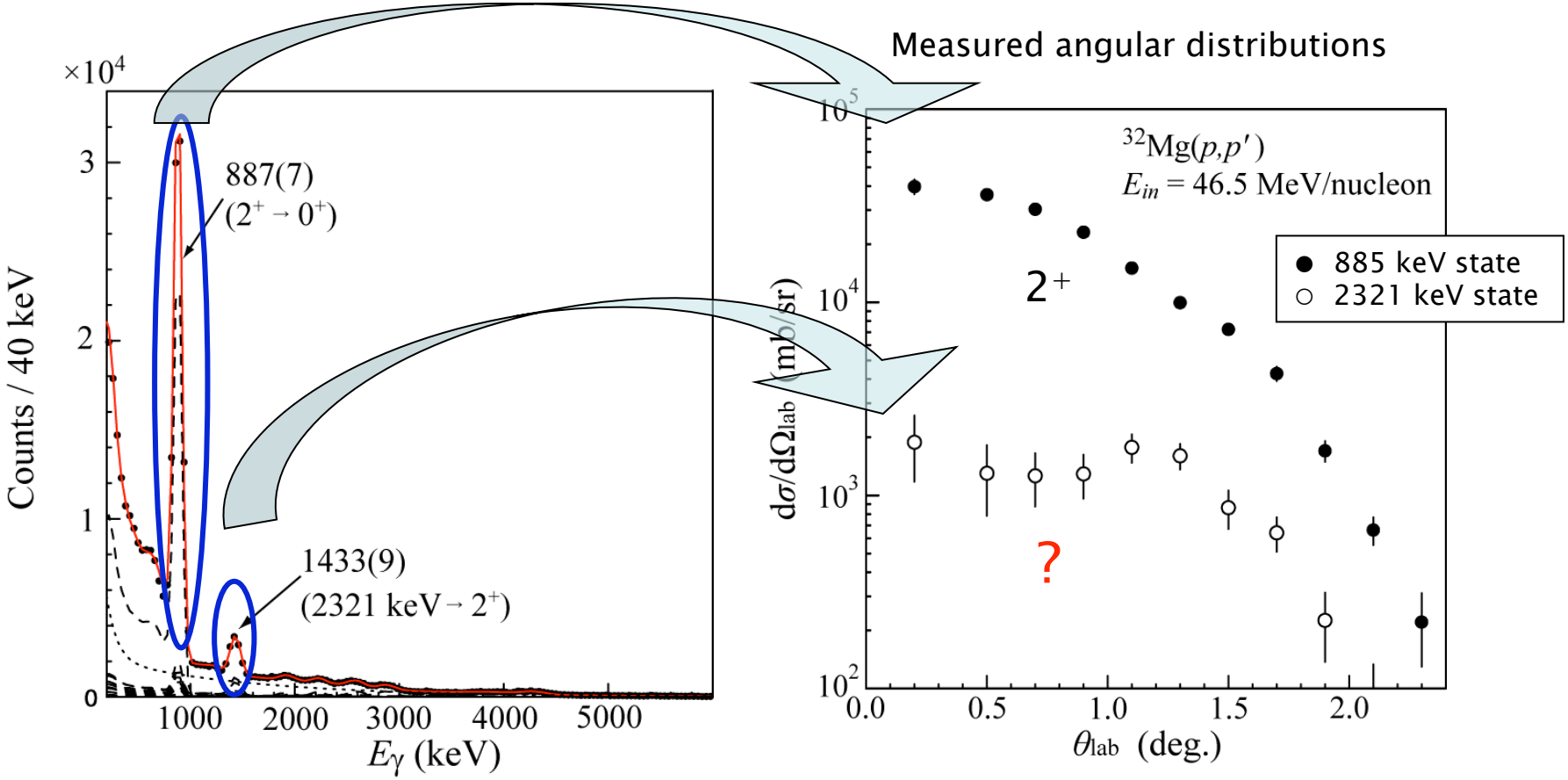
(p,p')



T. Motobayashi et al., PLB346, 9(95)

S. Takeuchi et al.

Angular distributions of scattered ^{32}Mg

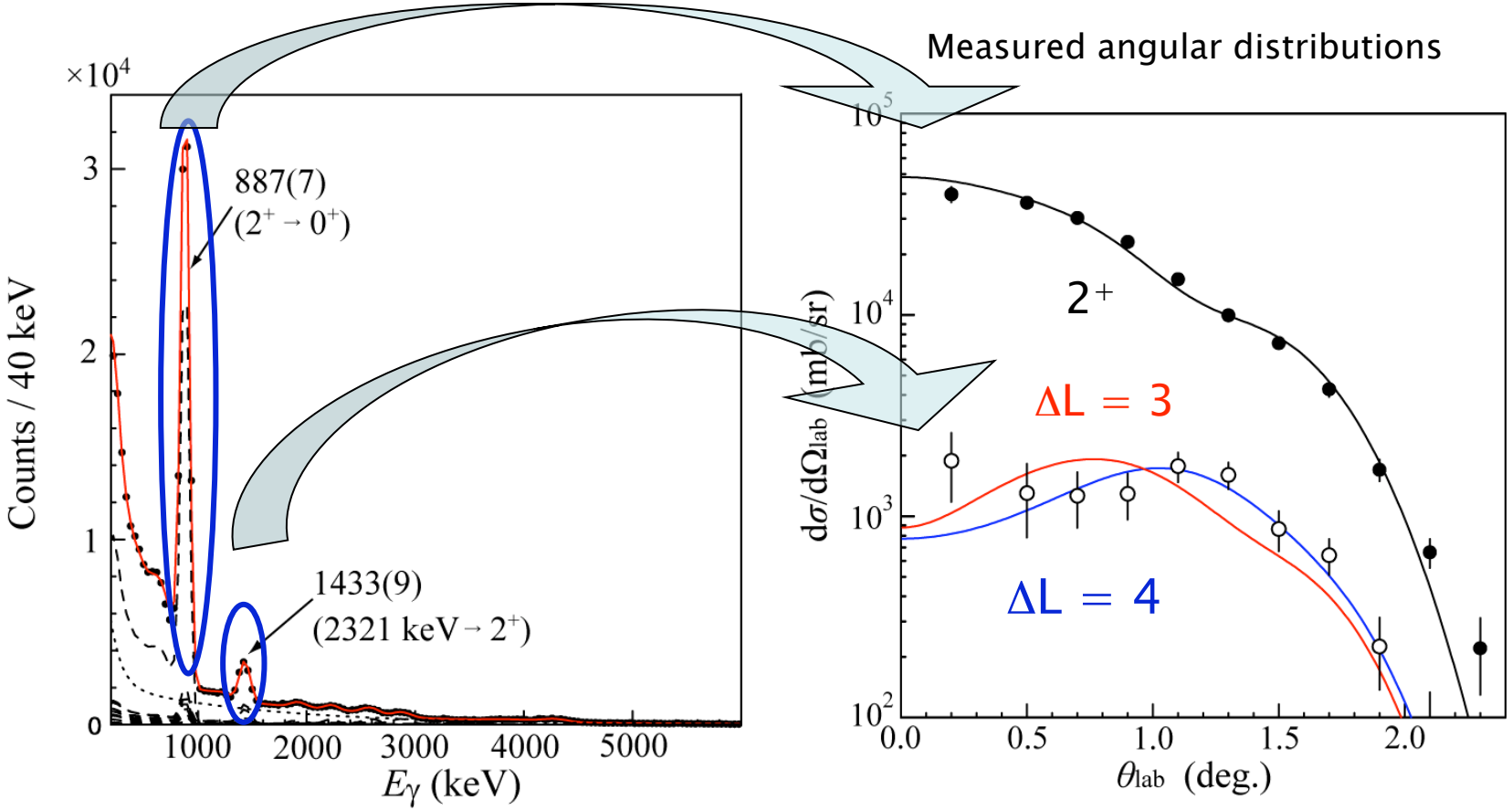


Corrected for feedings from the higher states.

→ Coupled channel calculations

S. Takeuchi et al.

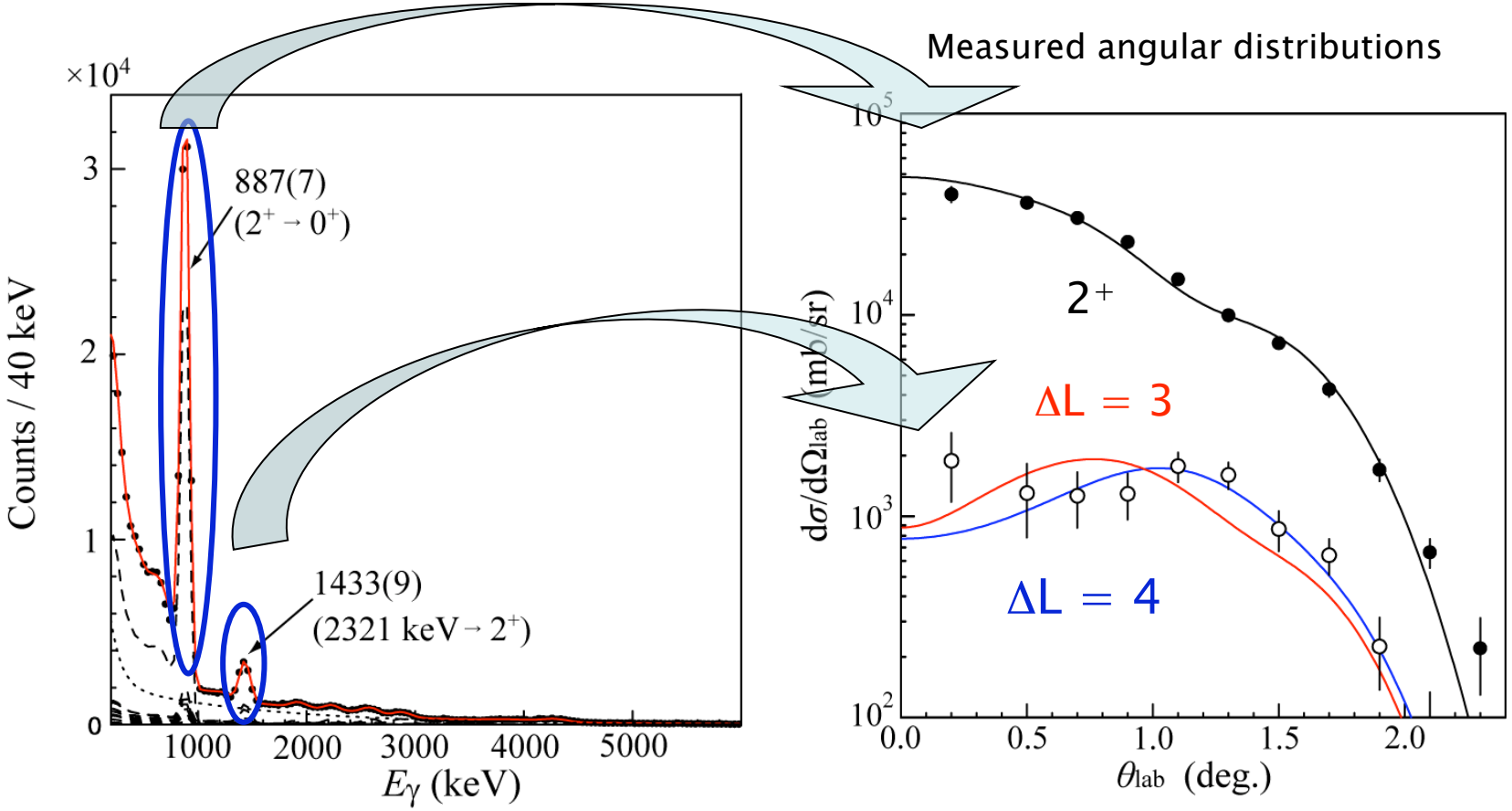
Coupled channel calculations



Reduced χ^2 $\Delta L = 3 : 2.1$, $\Delta L = 4 : 0.6$

Calculation CODE :
ECIS97 (J.Raynal, unpublished. e.g. NOTES ON ECIS94)
Optical potential parameters :
KD02 : A.J.Koning, J.P.Delaroche, Nucl. Phys. A713(2003)231

Coupled channel calculations

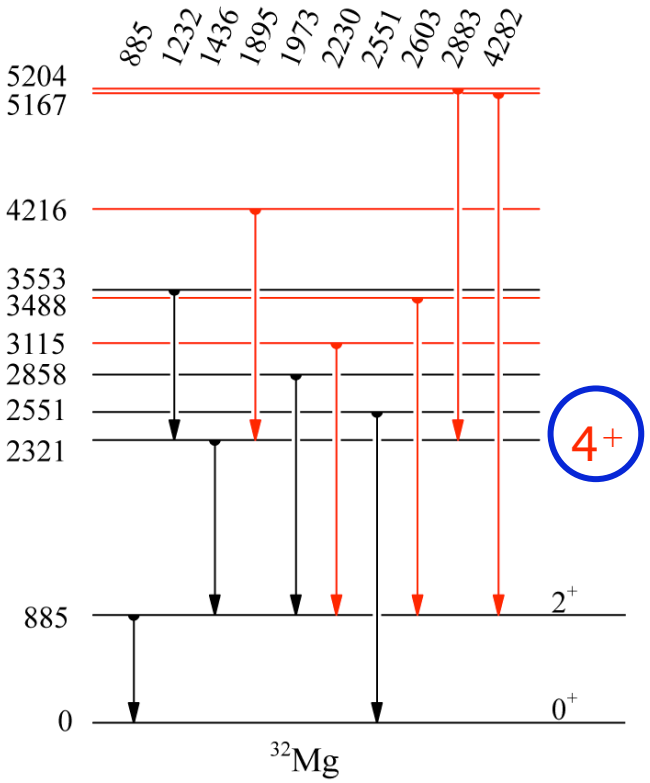


Reduced χ^2 $\Delta L = 3 : 2.1$, $\Delta L = 4 : 0.6$

➔ $J^{\pi}(2321\text{keV}) = 4^+$

Calculation CODE :
ECIS97 (J.Raynal, unpublished. e.g. NOTES ON ECIS94)
Optical potential parameters :
KD02 : A.J.Koning, J.P.Delaroche, Nucl. Phys. A713(2003)231

the 2321-keV state: $J^{\pi} = 4^{+}$



$E(4^{+})/E(2^{+})$ or $R_{4/2}$

vibrator rigid rotor

$2.0 < R_{4/2} = 2.6 < 3.3$

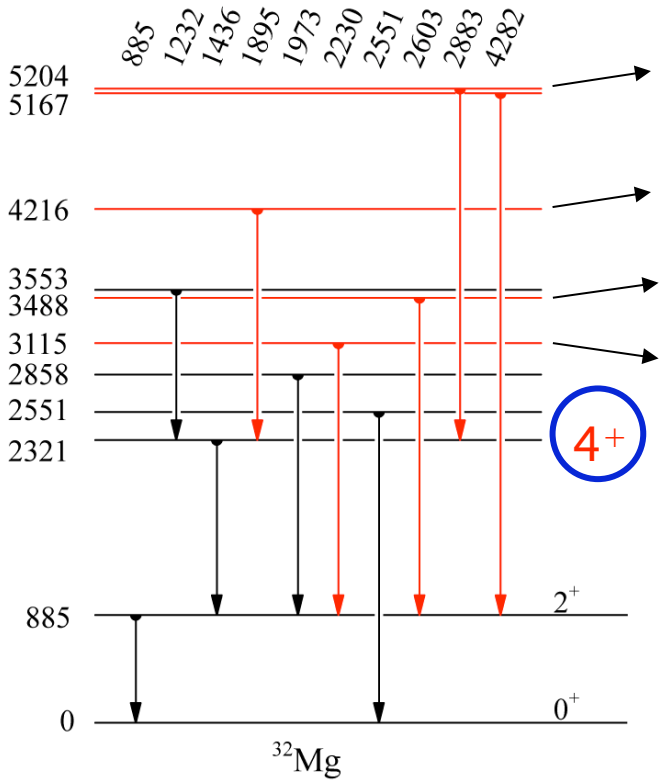
transitional ?
γ-soft ?

→ Theoretical study

→ 2nd 2^{+} search?

S. Takeuchi et al.

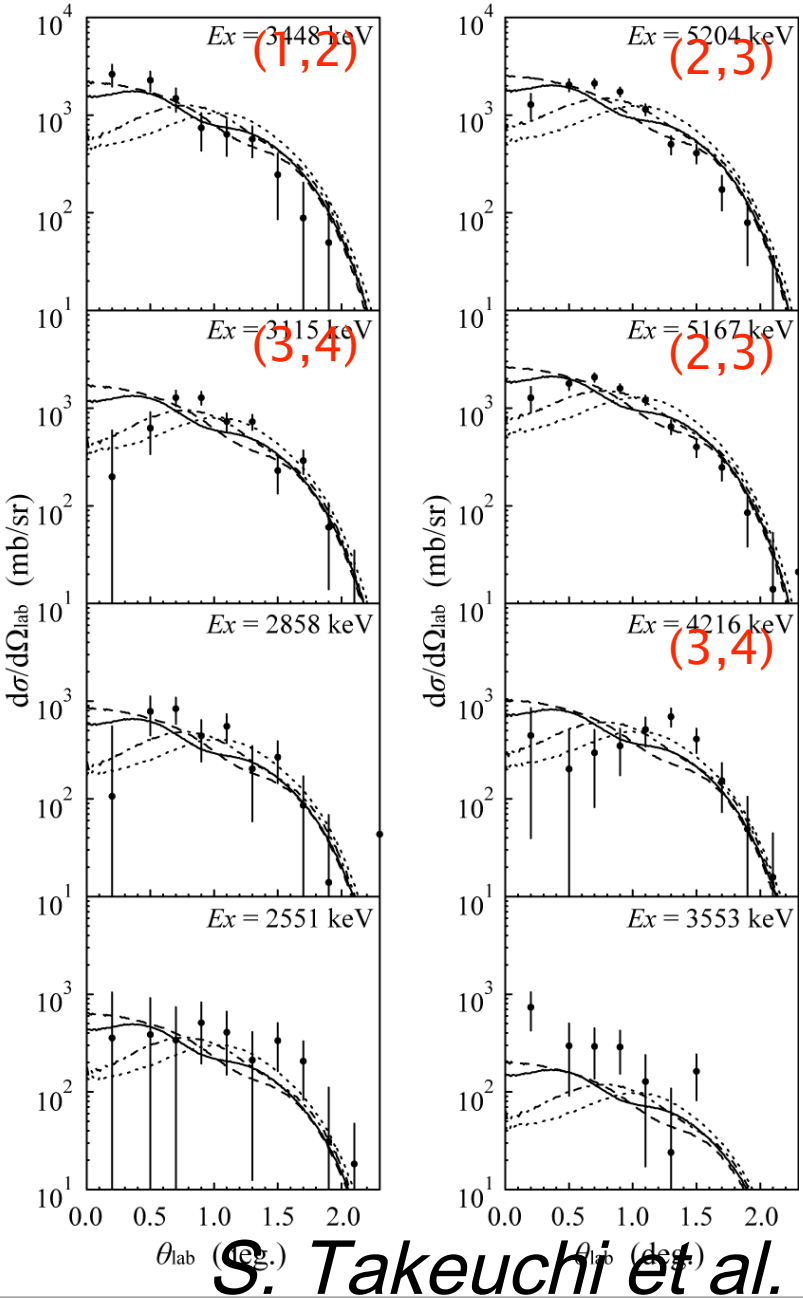
J^{π} of higher states ← new constraints



C.S. (mb)

(2,3)	2.7
	2.9
(3,4)	1.1
(1,2)	2.3
(3,4)	1.7
	3.7
	47.6

DWBA calculations
ΔL = 1 : solid
ΔL = 2 : dash
ΔL = 3 : dotdash
ΔL = 4 : dot



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Structure of neutron-rich Ti and Cr* isotopes

studied by (p,p') scattering

populating their 2^+ and 4^+ states

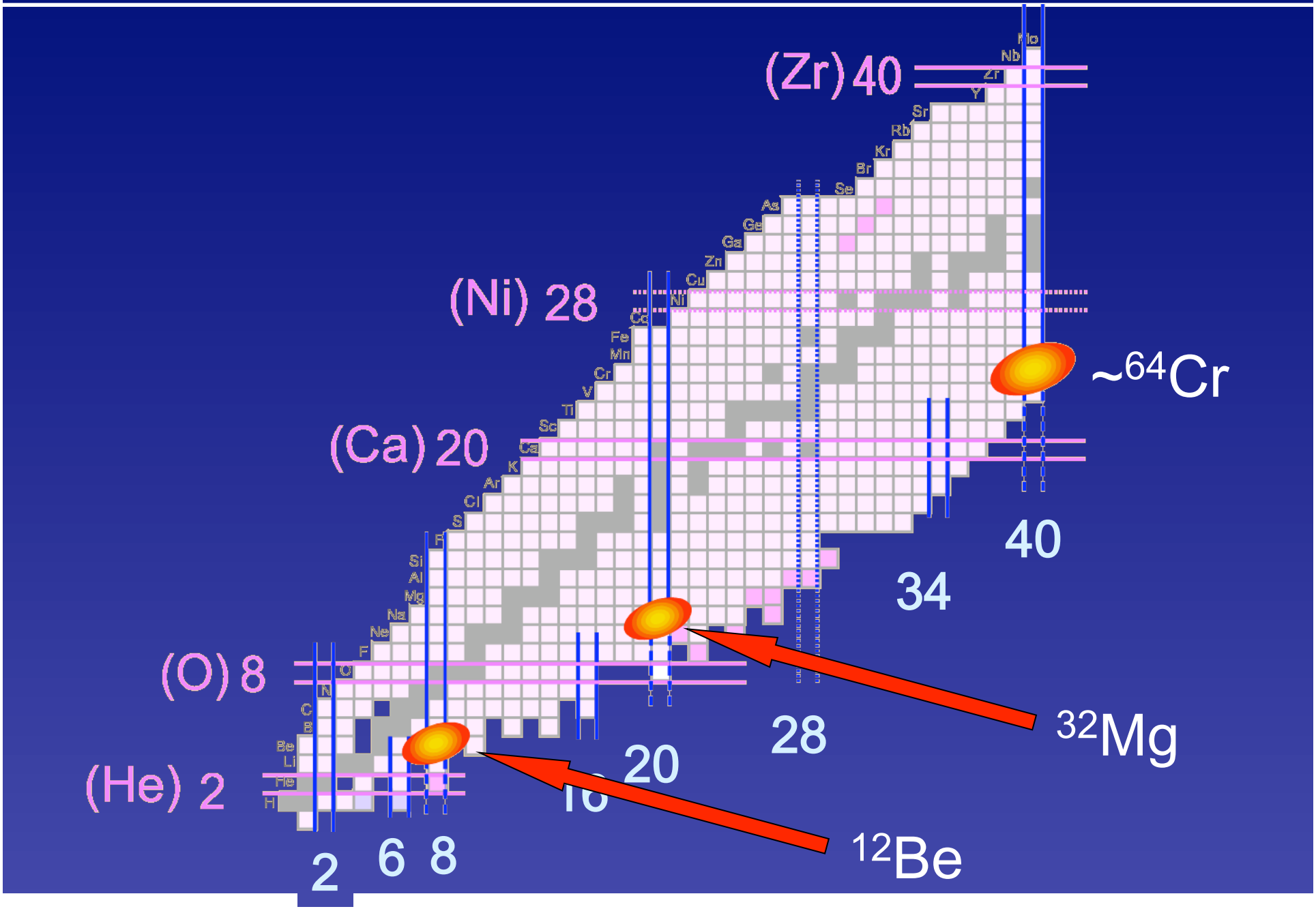
$E_x(2^+)$

$E_x(4^+)$

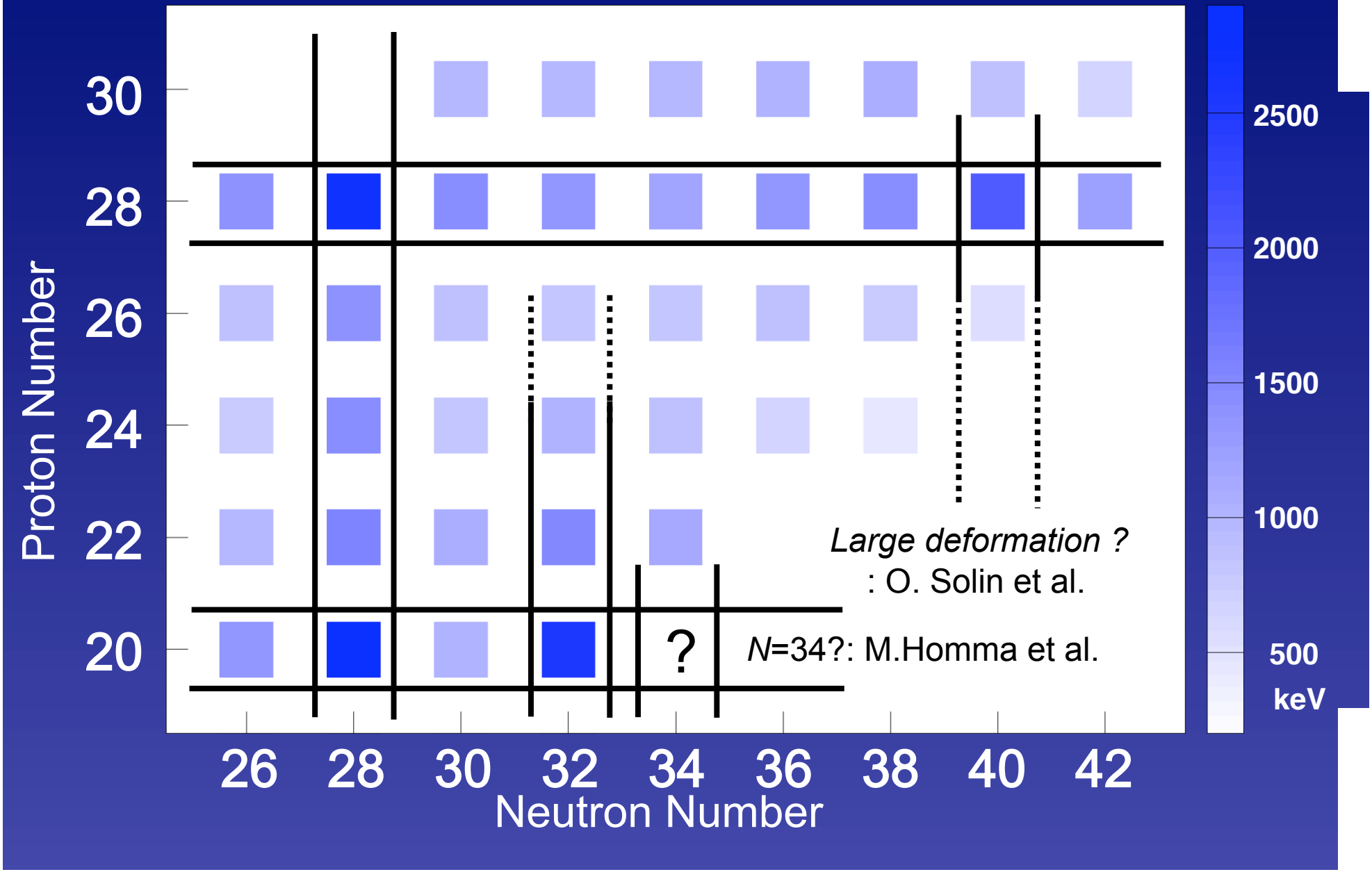
$\sigma(0^+ \rightarrow 2^+) \rightarrow \delta\ (=\beta_2 R)$

* PRL accepted

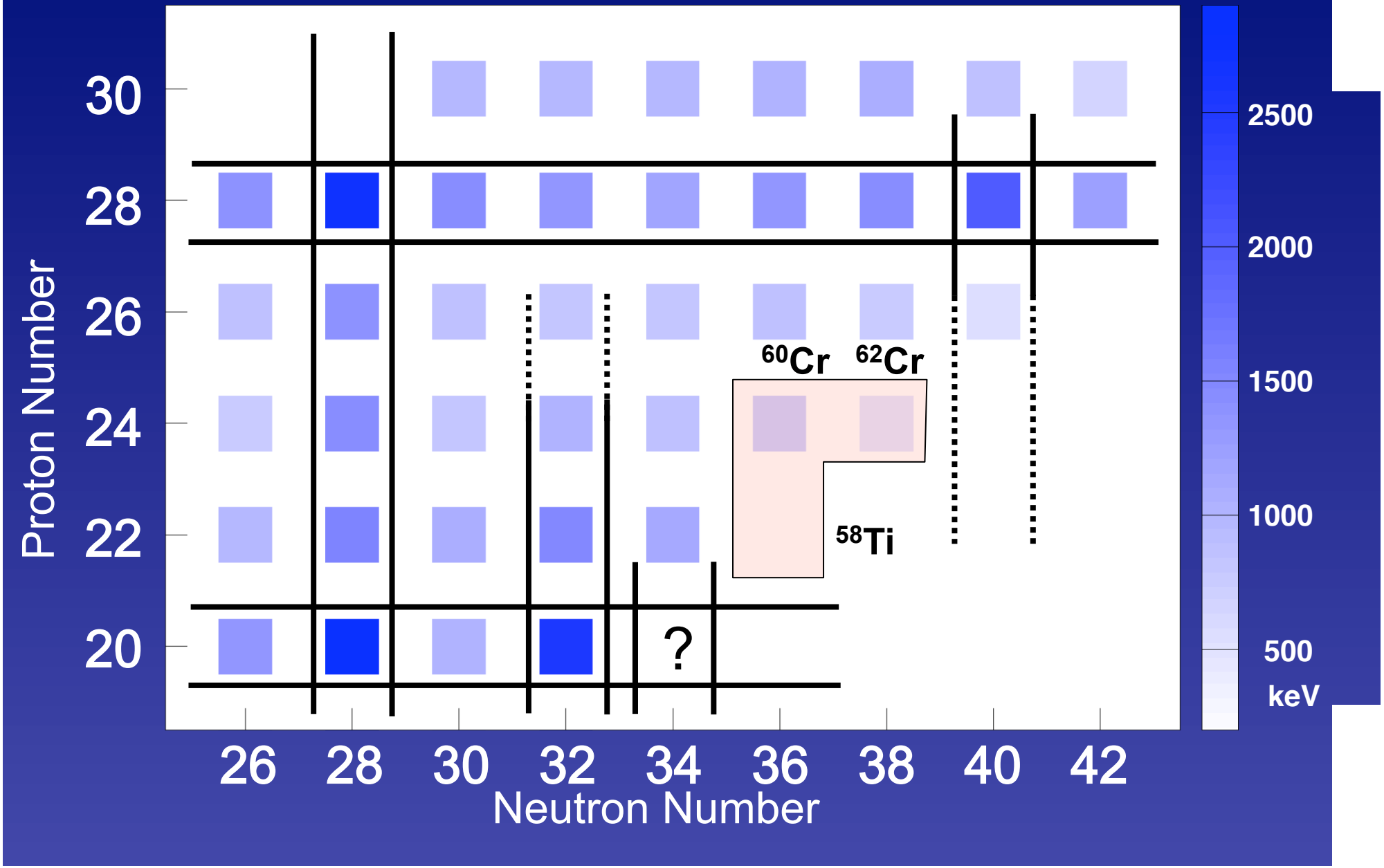
Anomalous deformation in neutron-rich nuclei



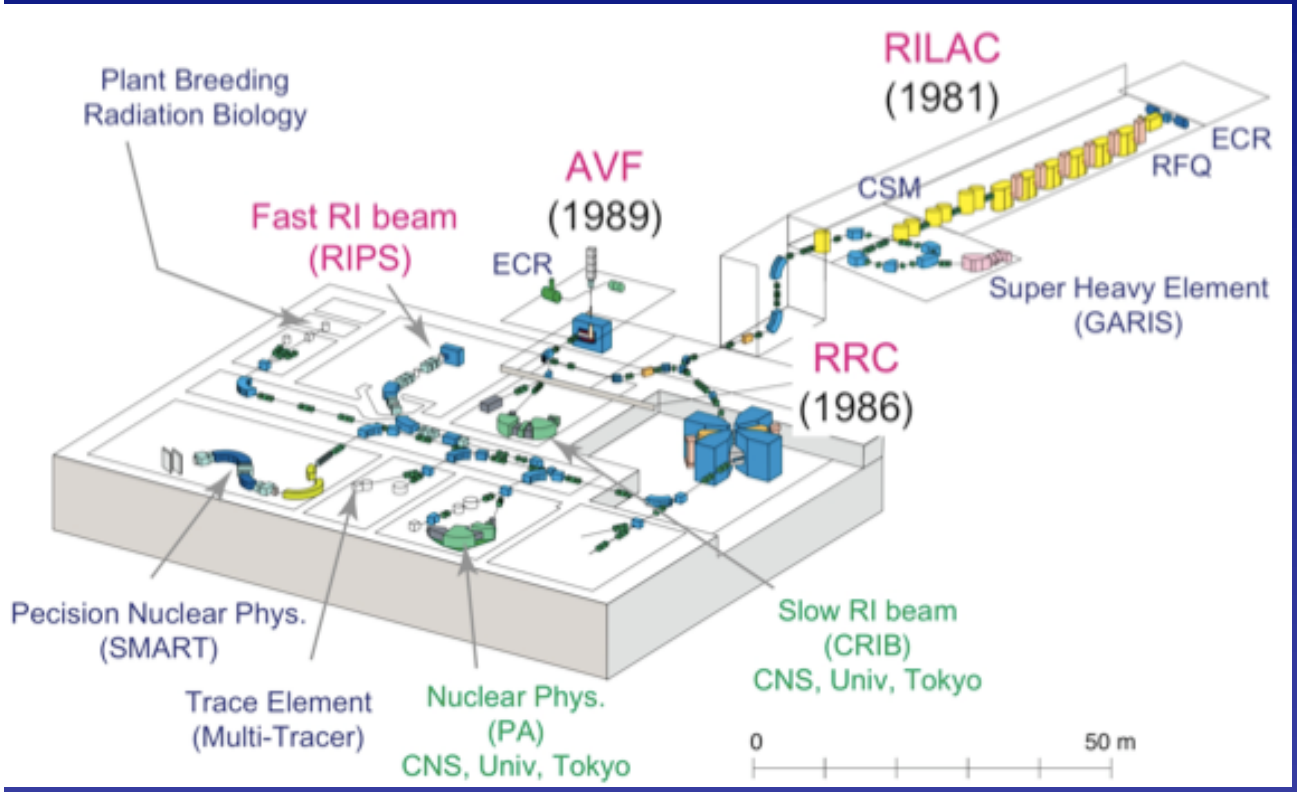
$E_x(2^+)$ in *pf*-shell nuclei



$E_x(2^+)$ in *pf*-shell nuclei



RIKEN Nishina Center --- K540 Ring Cyclotron



Heavy ion Accelerator
(Ring Cyclotron,
K=540 RRC)
Since 1986

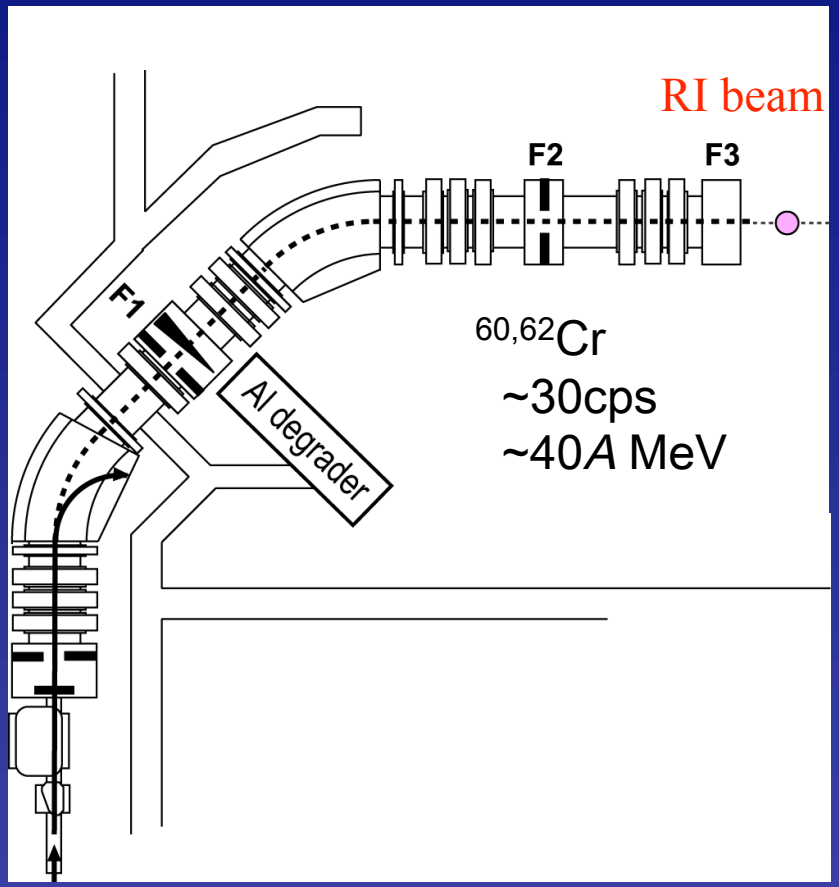
E = 63~135 AMeV

RIKEN Projectile-fragment
Separator (RIPS)
Since 1990

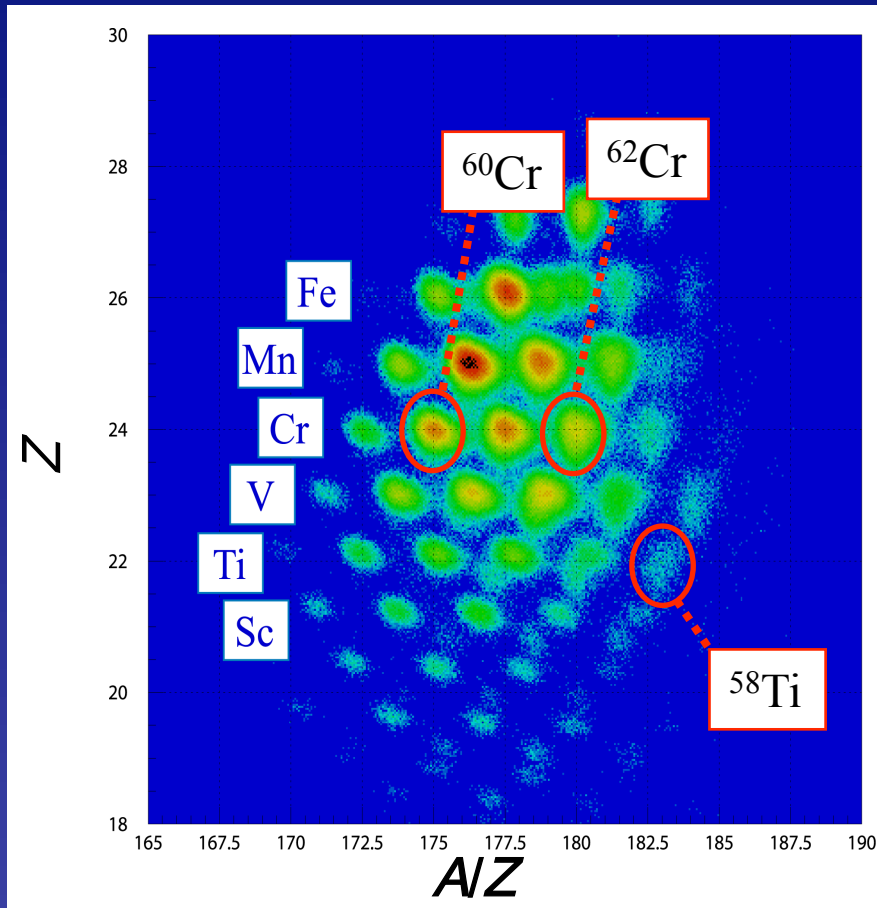
Experimental Setup

RIPS(RIKEN projectile-fragment separator)

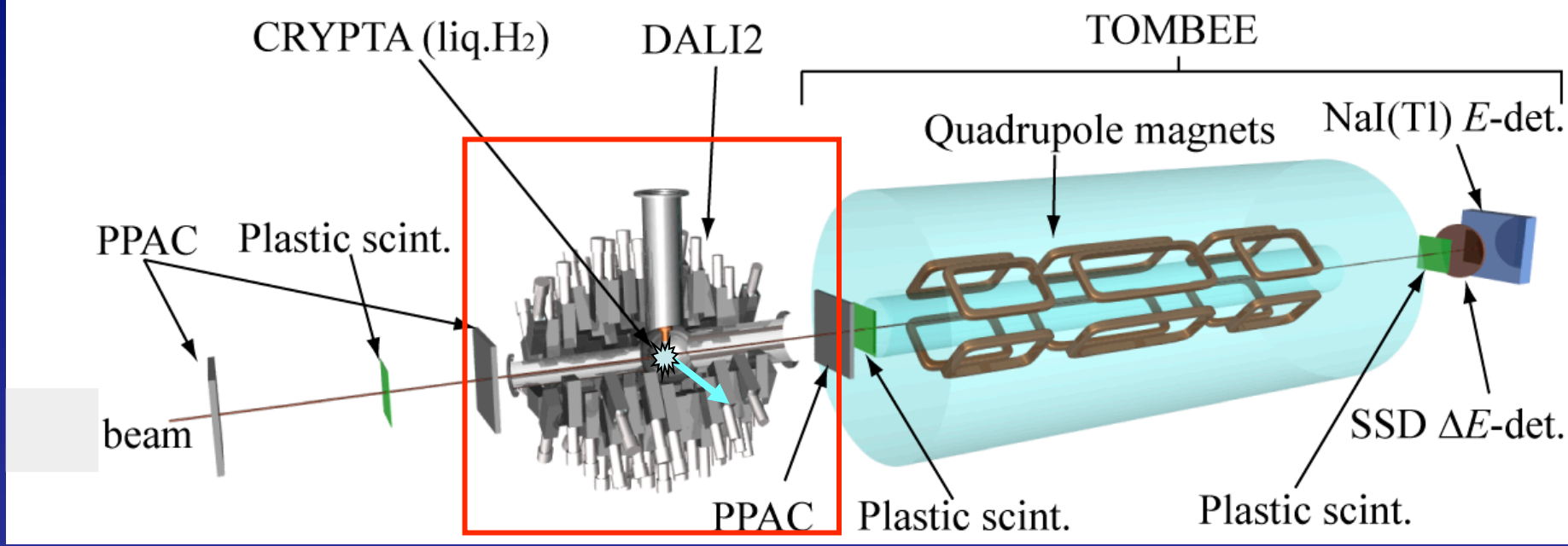
T.Kubo *et al.*, NIMB **70** (1992) 309.



^{70}Zn, 63 *A*MeV
150 pnA



Experiment – γ-ray detection array –

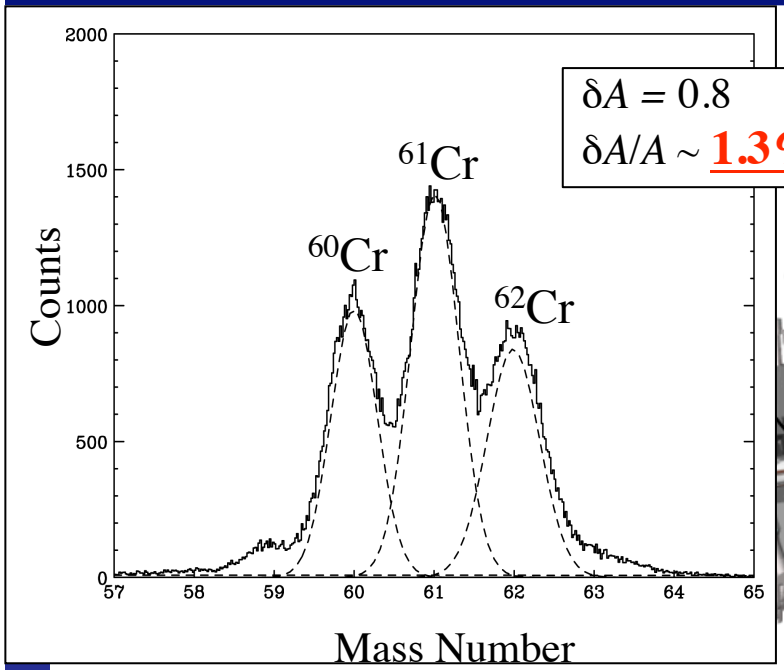


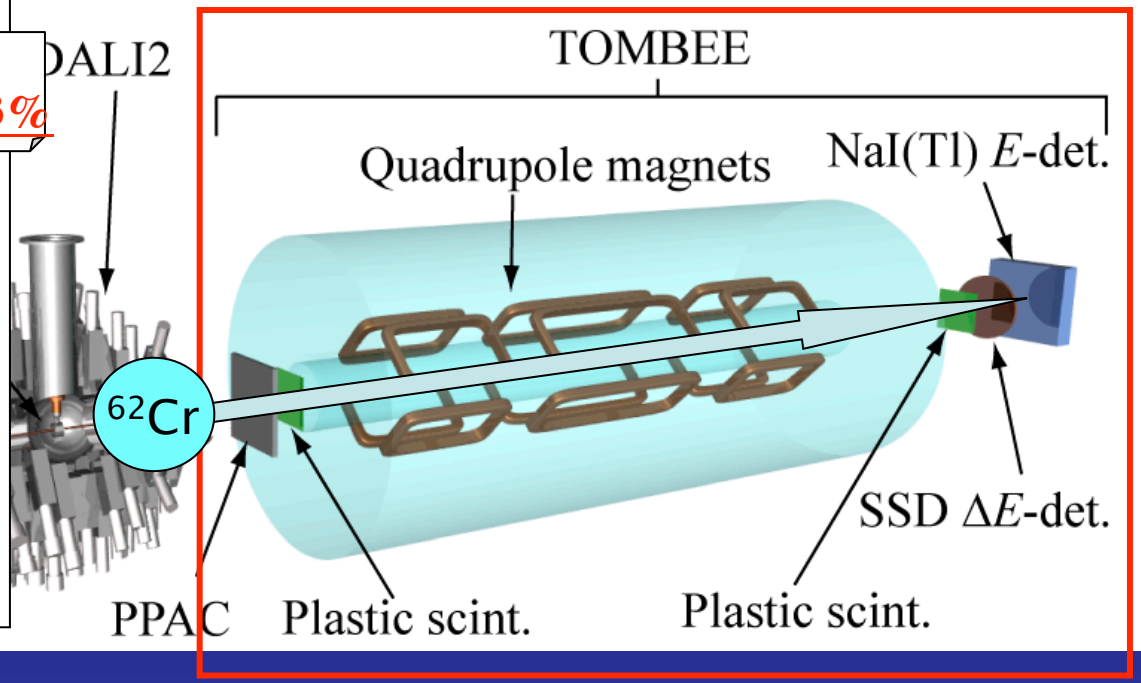
DALI2 (Detector Array for Low Intensity radiation)

Detector size	: 4 x 8 x 16 cm^3
Number of Det.	: 160
Angular resolution	: ~ 8 degrees (ave.)
Energy resolution	: 10% @ 1MeV (v/c = 0.3)
Efficiency	: 24% @ 1MeV (v/c = 0.3)

Ref. S.Takeuchi et al., RIKEN Accel. Prog. Rep. **36**(2003)148

Experiment – Particle identification device –





TOMBEE (TOf Mass analyzer for exotic Beam Experiment)

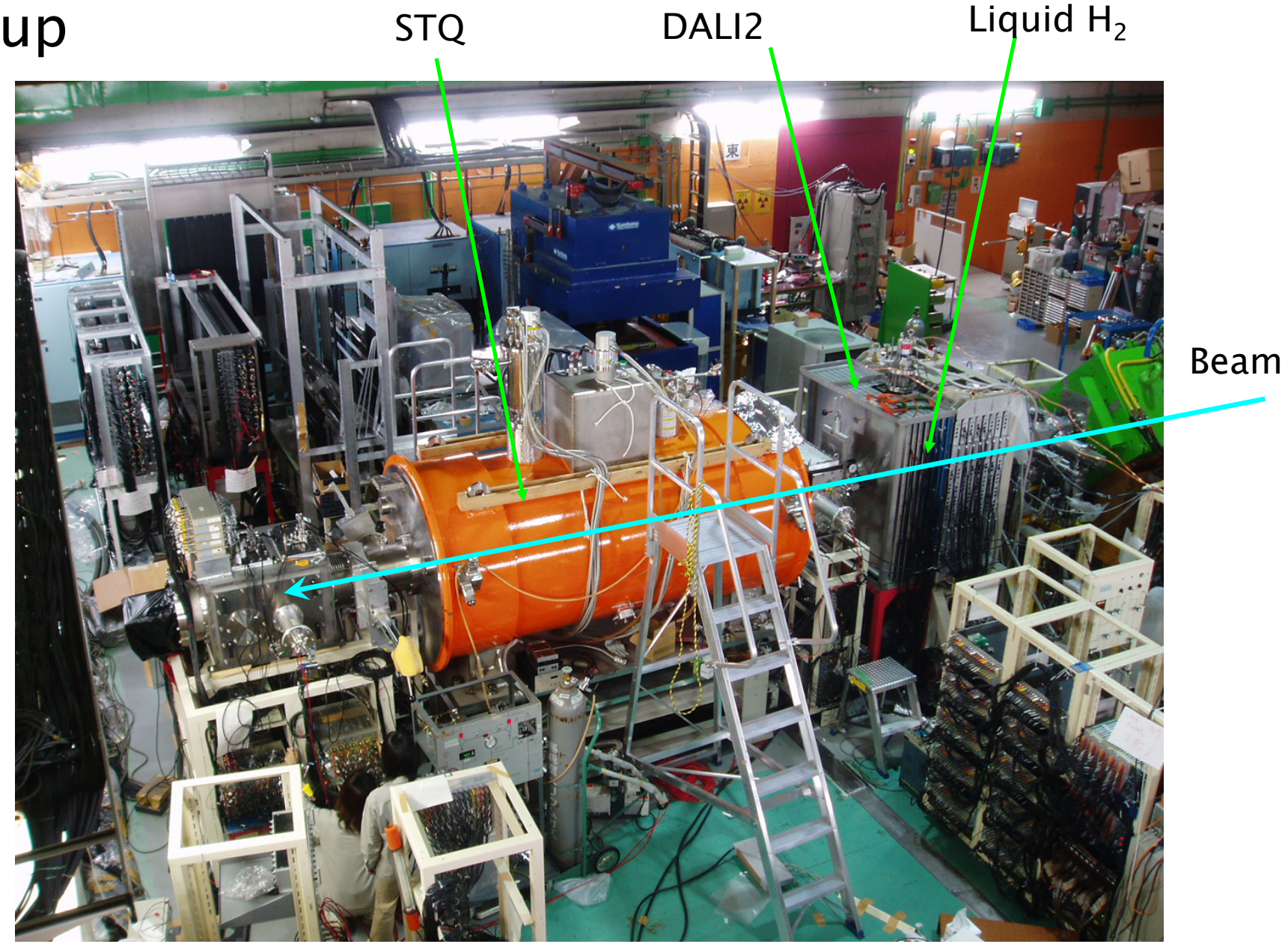
TOF : Plastic scintillators (0.3, 0.5mm)
δTOF/TOF ~ 140ps/40ns = 0.4%

ΔE : Si detectors (320mm)
$\delta\Delta E/\Delta E$ ~ 1.6%

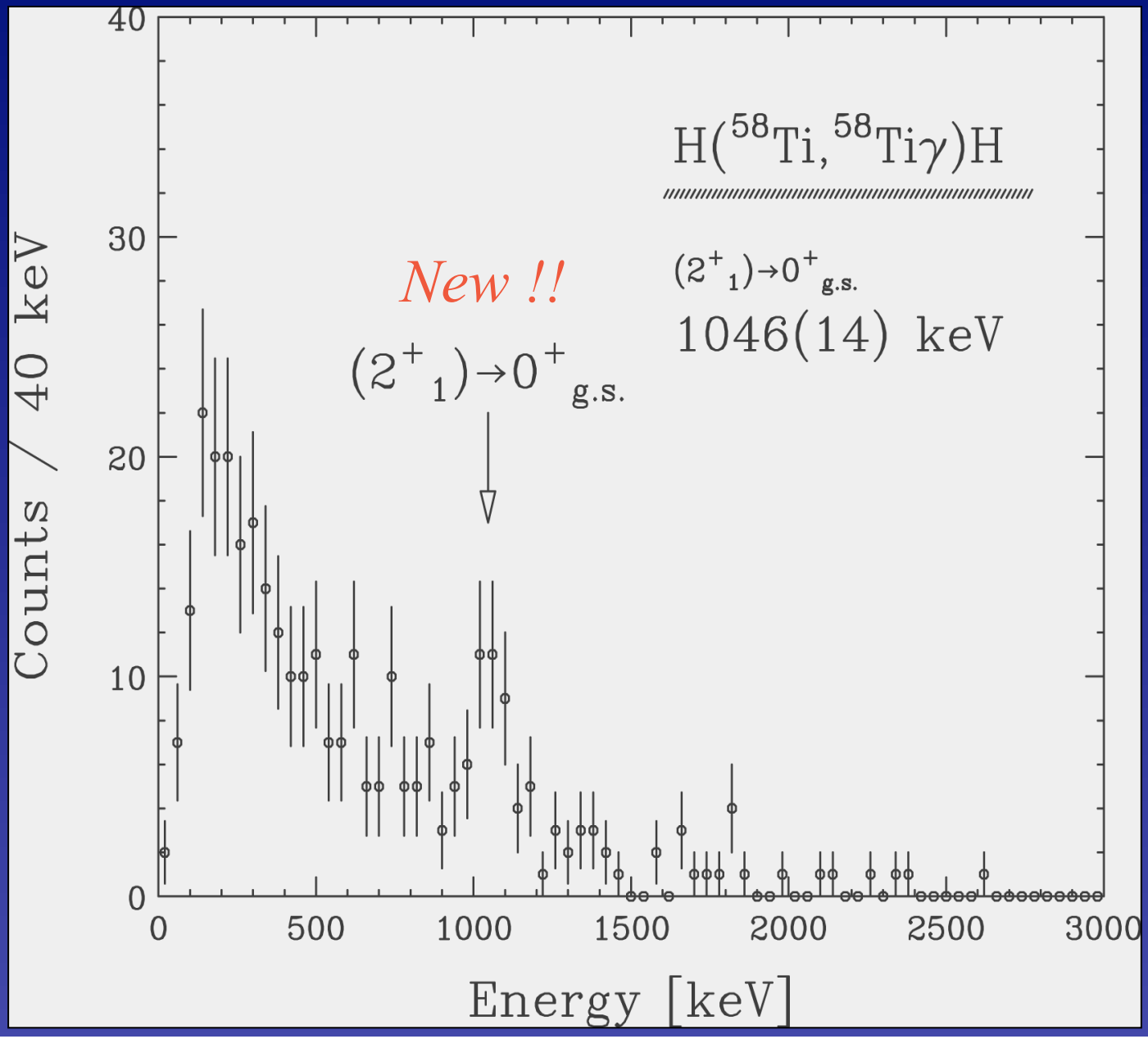
E : NaI(Tl) detectors (6x6)
$\delta E/E$ ~ 1.3%

$$Z \propto \sqrt{\Delta E} \;/\; TOF$$
$$A \propto E \times (TOF)^2$$

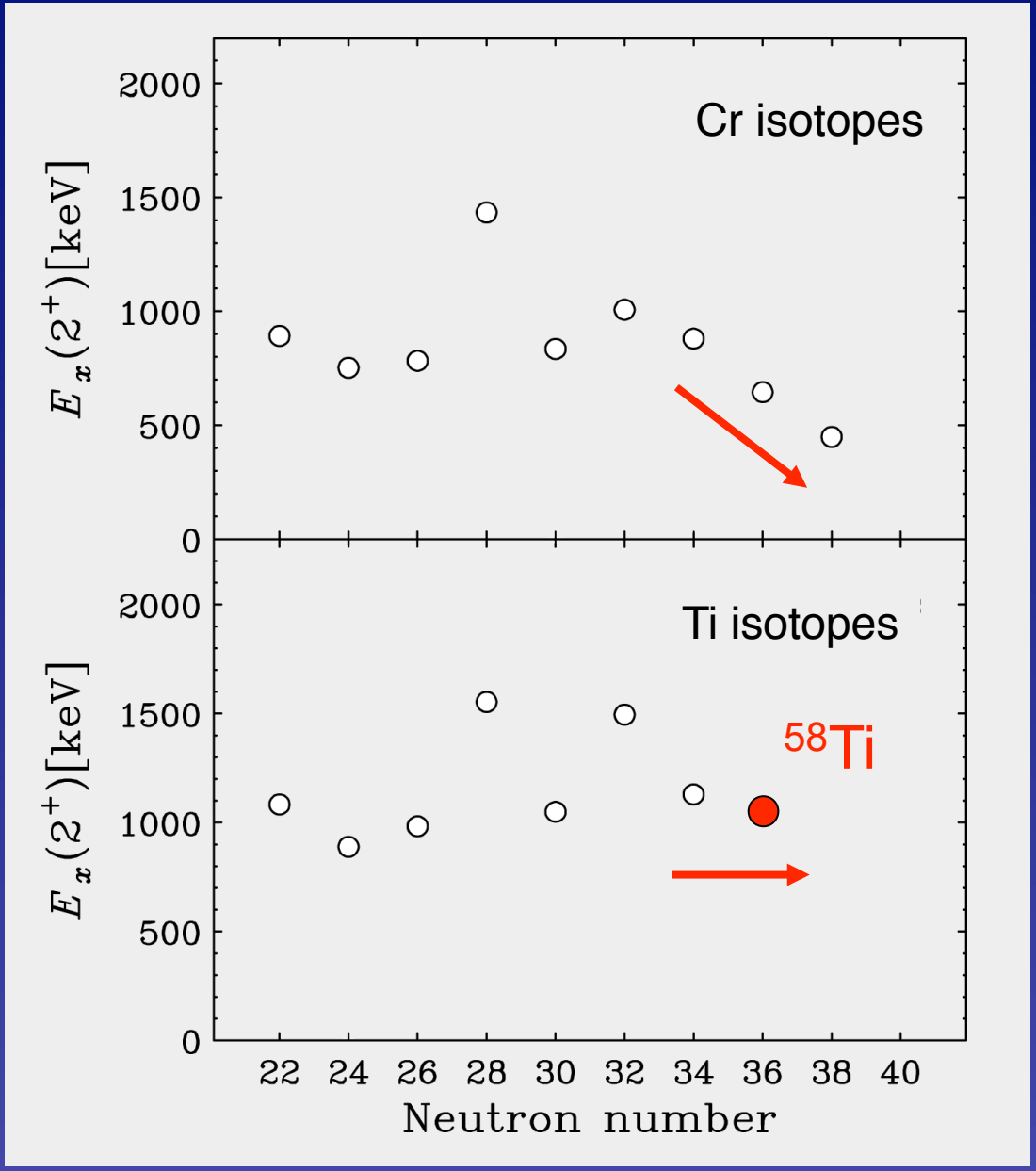
Setup



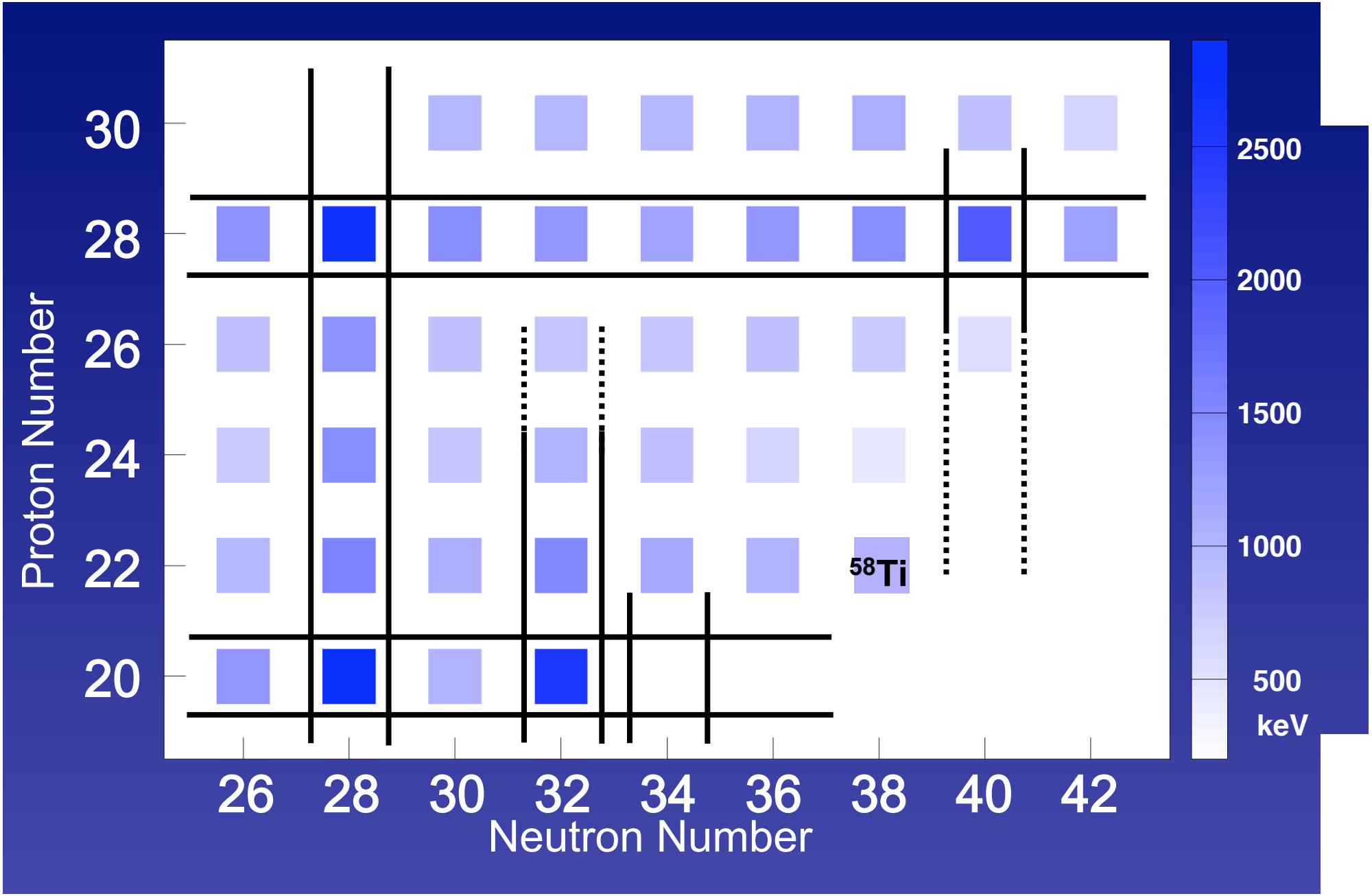
γ-ray spectrum for ^{58}Ti(p,p')



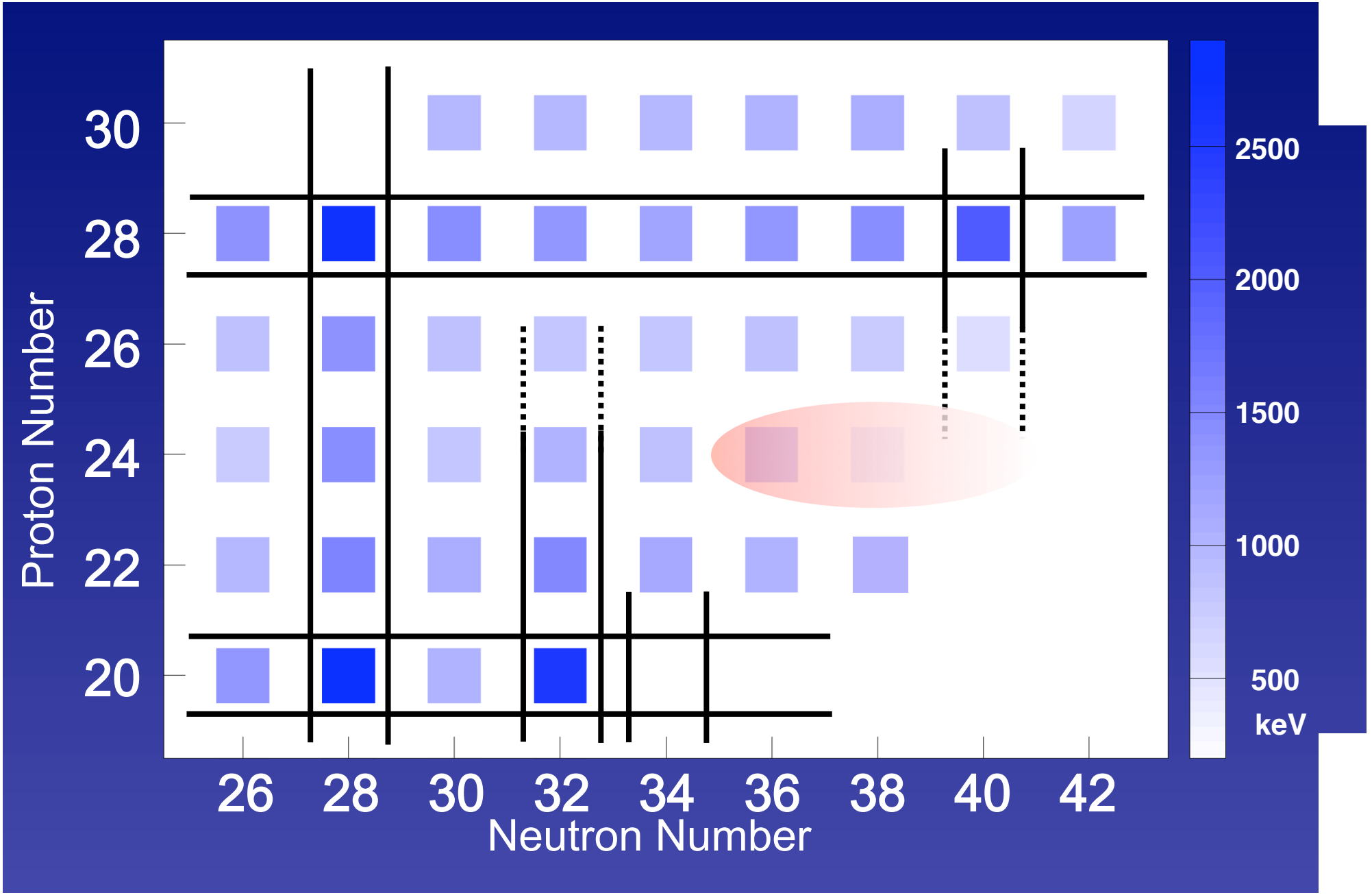
Systematics of $E_x(2^+)$ in Ti



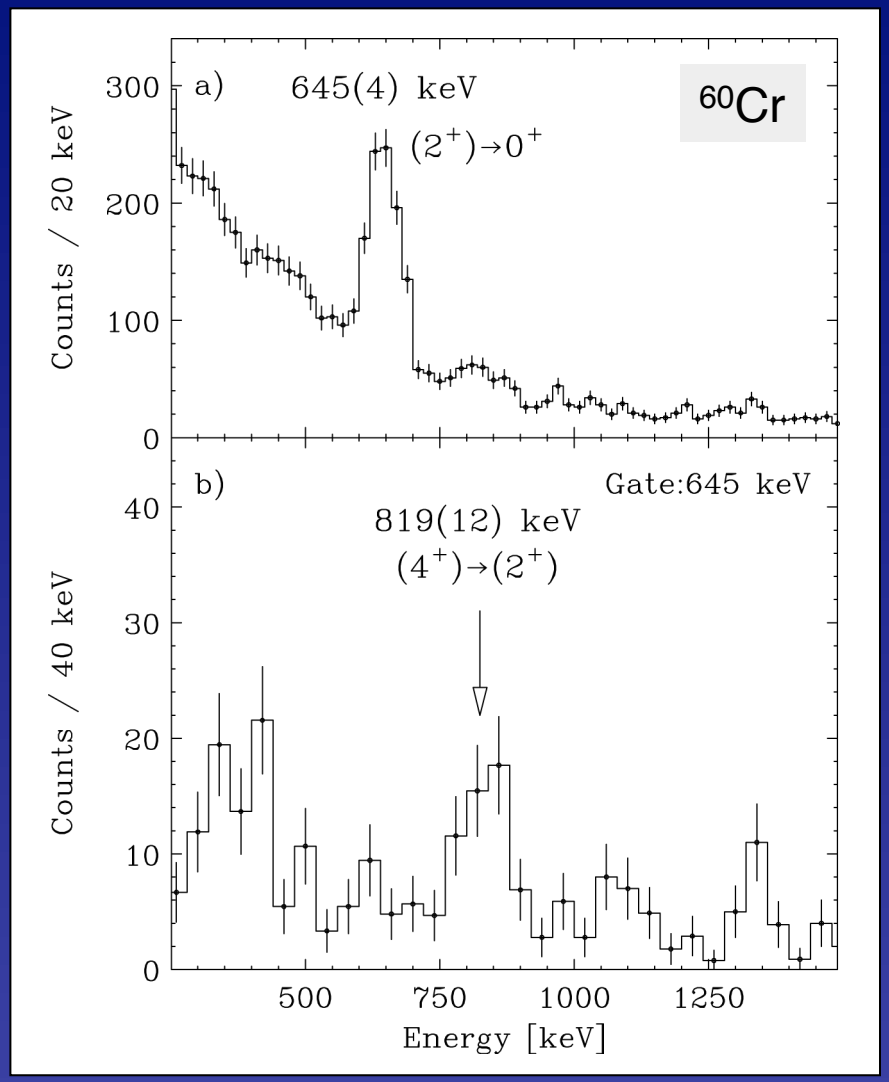
$E_x(2^+)$ in *pf*-shell nuclei

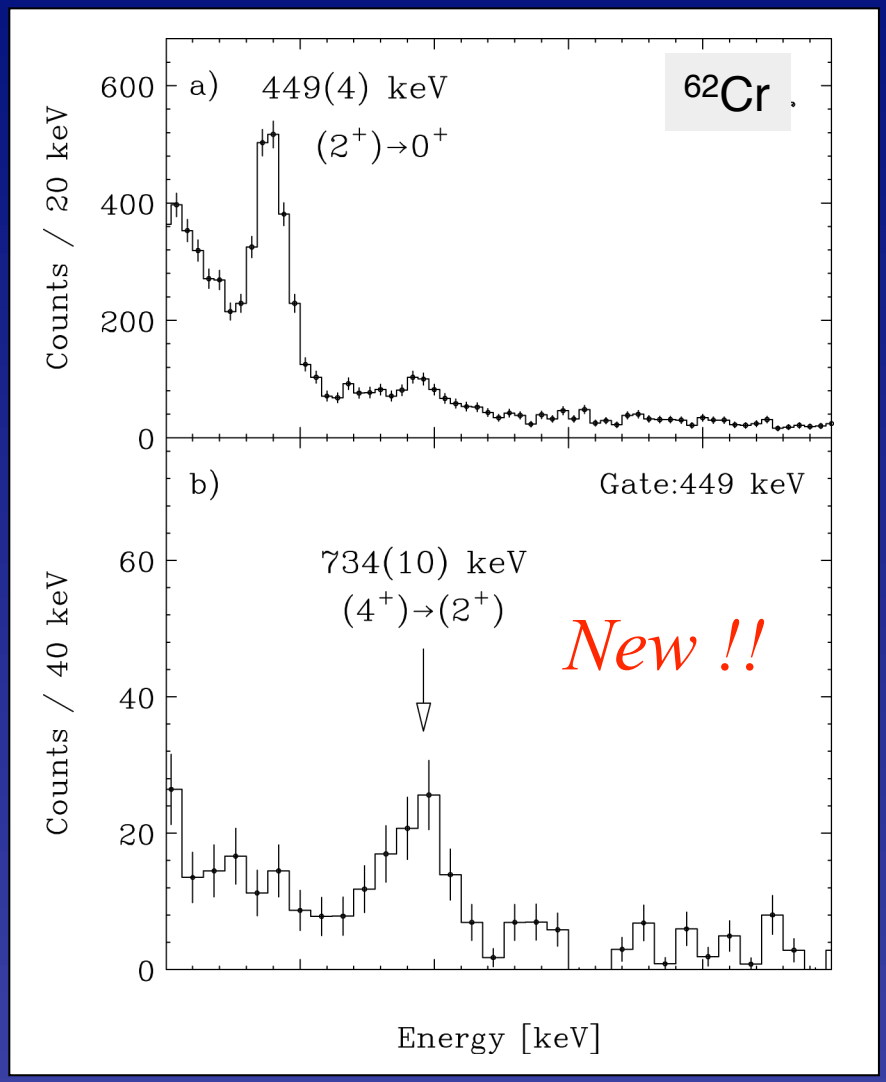


Ridge of large collectivity --- deformation ?



γ-ray spectra for ^{60}Cr(p,p') and ^{62}Cr(p,p')





c.f. $(2^+) \rightarrow 0^+_{g.s.}$: 645 keV
O. Sorlin *et al.*, EPJA **16** (2003) 55

$(4^+) \rightarrow (2^+)$: 817 keV
N. Marginean *et al.*, PLB **633** (06) 696.

c.f. $(2^+) \rightarrow 0^+_{g.s.}$: 446 keV
O. Sorlin *et al.*, EPJA **16** (2003) 55

Cross section $\sigma(2^+)$ → deformation parameter $\beta_{pp'}$

- $\delta_{pp'}$ ($\beta_{pp'}$) ←(DWBA)← $\sigma_{p,p'}(2^+)$

  ^{60}Cr : $\delta_{pp'}$ =1.12(16) ($\beta_{pp'}$ = 0.23 (3))
  ^{62}Cr : $\delta_{pp'}$ =1.36(14) ($\beta_{pp'}$ = 0.27 (3))

- Optical potential

  Global optical potential

  - R.L. Varner *et al.*, Phys. Rep. **201** (1991) 57.
  - A.J. Koning *et al.*, Nucl. Phys. A **713** (2003) 231.
  - F.D. Becchetti *et al.*, Phys. Rev. **182** (1969) 1190.

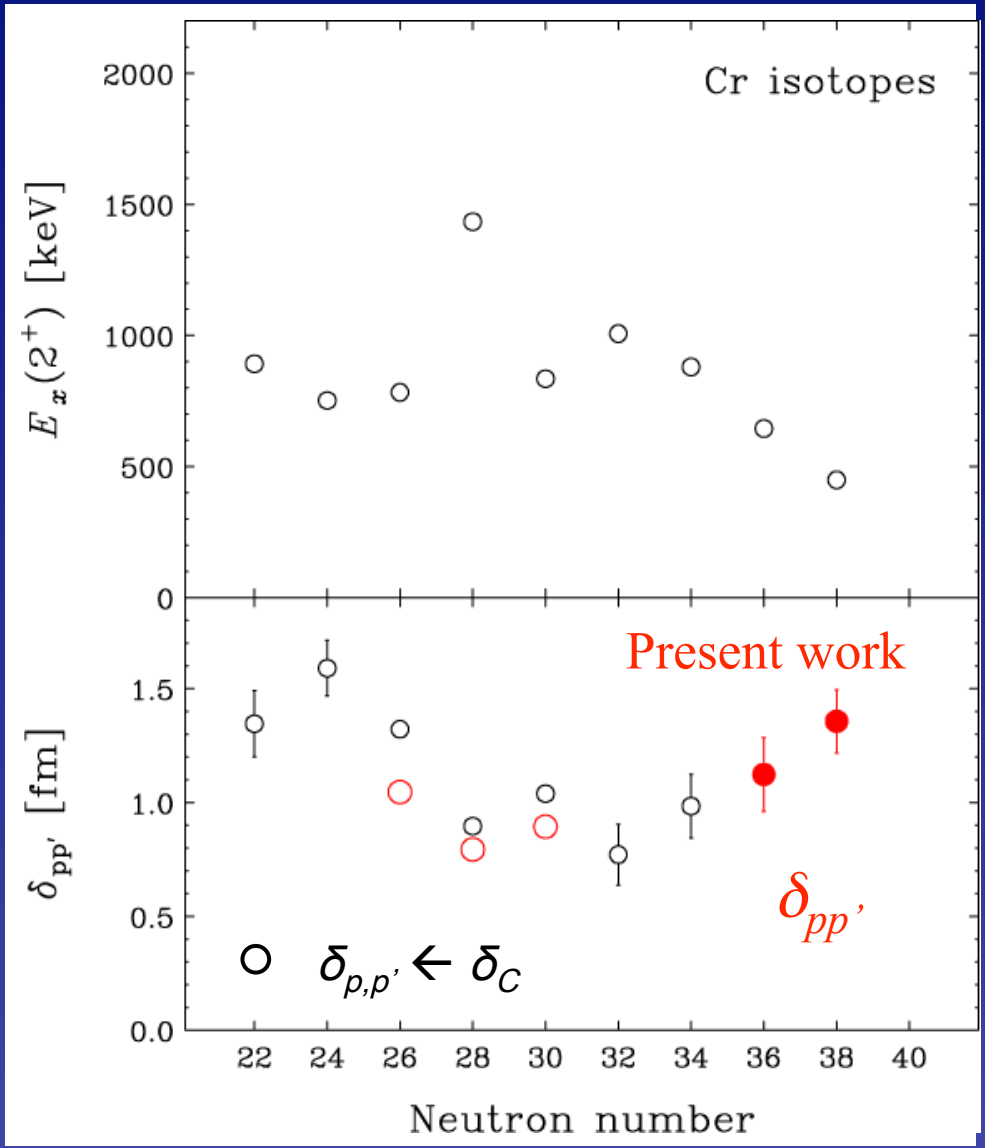
  Elastic proton scattering of ^{50,52,54}Cr

  - E.Fabrici *et al.*, Phys. Rev. C **21** (1980) 844.

  Difference from the optical potential → ~10%

- Vibrational model

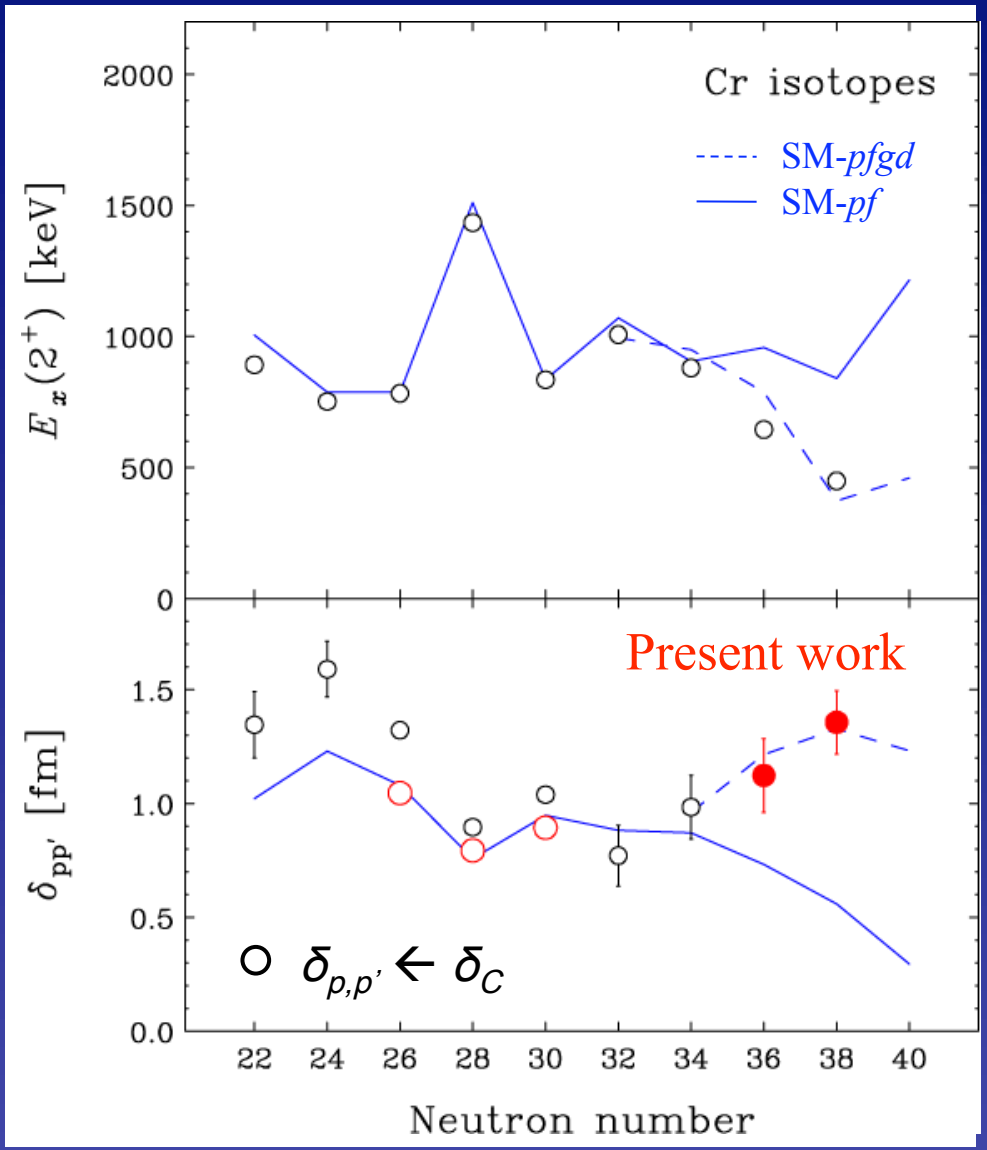
Systematics of $E_x(2^+)$, δ (δ_c, $\delta_{pp'}$)



- $E_x(2^+)$ decreases ~N = 40.
- Large $\delta_{p,p'}$ in ^{60,62}Cr

F.D. Becchetti *et al.*, PLC **21** (80) 844. M. Burger *et al.*, PLB **622** (05) 20.

Systematics of $E_x(2^+)$, δ (δ_c, $\delta_{pp'}$)



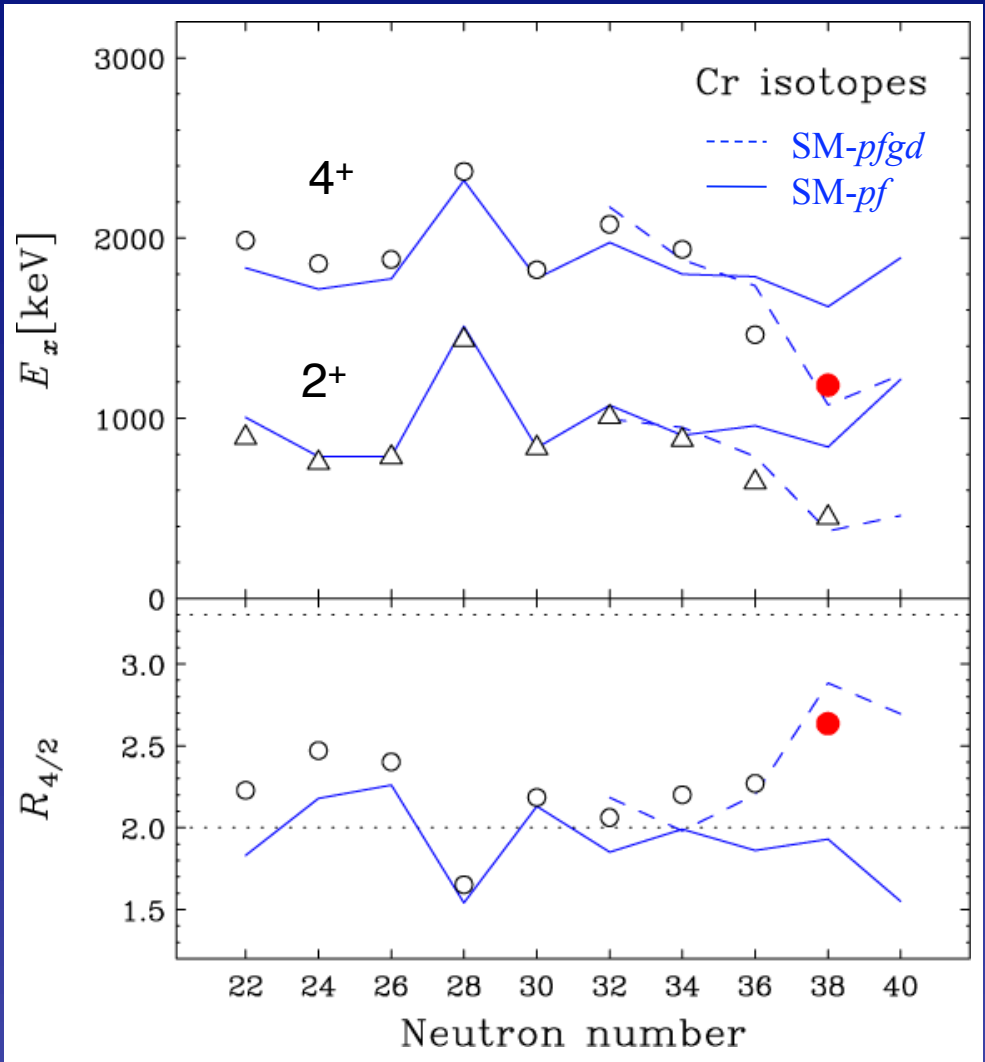
- $E_x(2^+)$ decreases ~N = 40.
- Large $\delta_{p,p'}$ in ^{60,62}Cr
- SM-*pf* ^{60,62}Cr ☹
- SM-*pfgd* ^{60,62}Cr ☺

M. Honma *et al.*, PRC **69** (04) 034335 private comm.

Large collectivity in the Cr isotopes.
$\nu\, g_{9/2}$ & $\nu\, d_{5/2}$ contribution is large.

F.D. Becchetti *et al.*, PLC **21** (80) 844. M. Burger *et al.*, PLB **622** (05) 20.

Systematics of $E_x(2^+)$, $E_x(4^+)$, $R_{4/2}$



- $R_{4/2} = E_x(4^+) / E_x(2^+)$

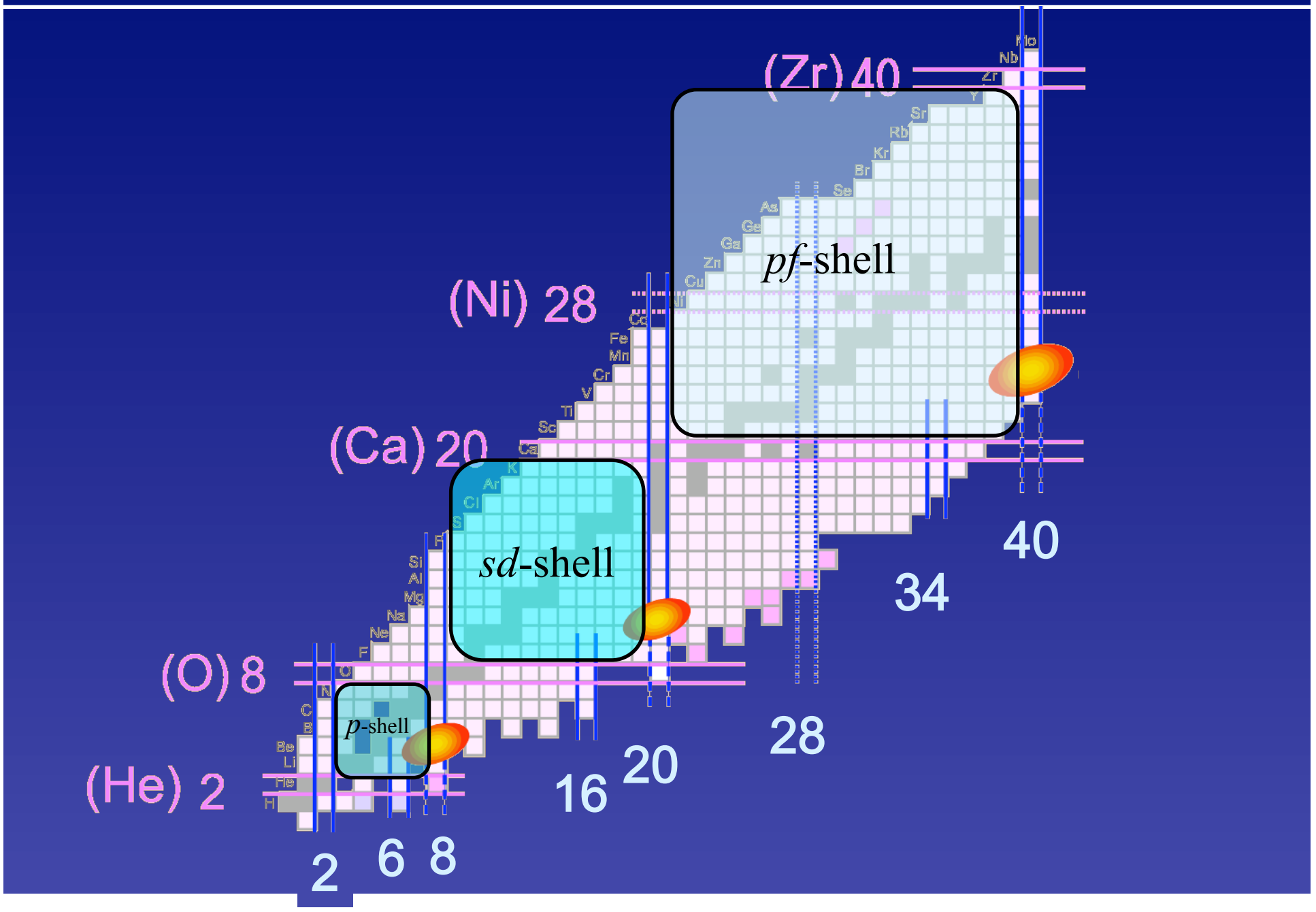
^{60}Cr : 2.3
Vibrational

^{62}Cr : 2.7
Rotational

Large static deformation in ^{62}Cr

[N. Marginean *et al.*, PLB **633** (2006) 696.]
[S. Zhu *et al.*, PRC **74** (2006) 064315.]

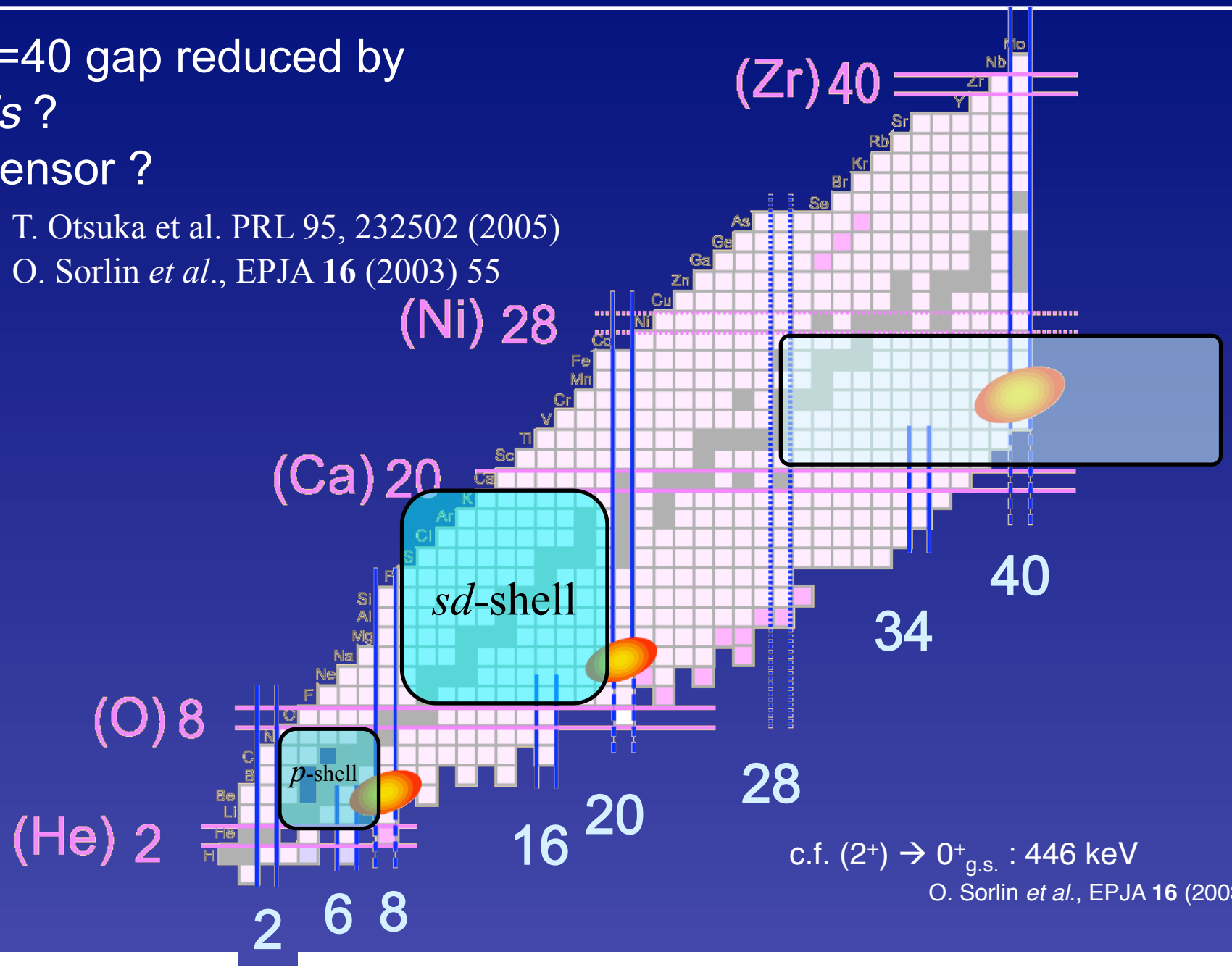
Large deformation at the edge of shell



Large deformation at the edge of shell

N=40 gap reduced by
ls ?
tensor ?

T. Otsuka et al. PRL 95, 232502 (2005)
O. Sorlin *et al.*, EPJA **16** (2003) 55

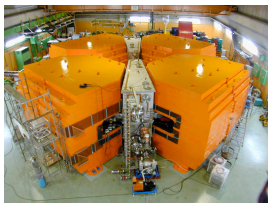


c.f. $(2^+) \rightarrow 0^+_{g.s.}$: 446 keV
O. Sorlin *et al.*, EPJA **16** (2003) 55

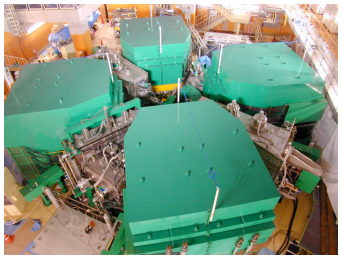
Layout of RIKEN RI beam factory (RIBF)

ZeroDegree

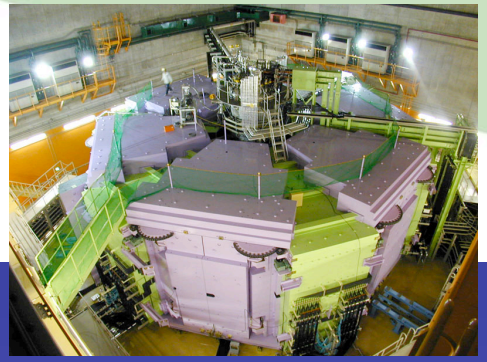
fRC



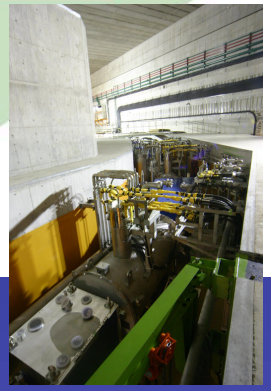
IRC



SRC



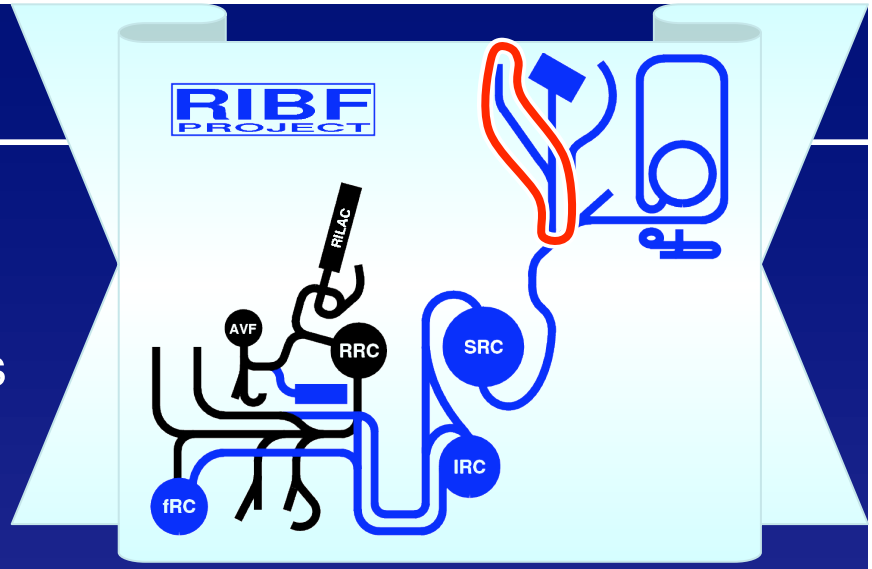
BigRIPS

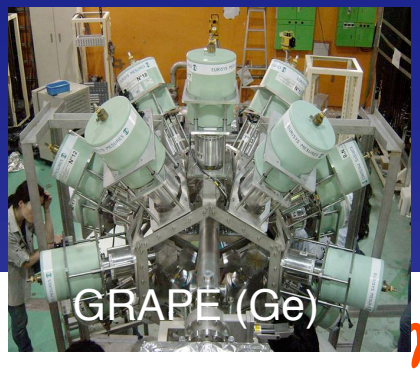


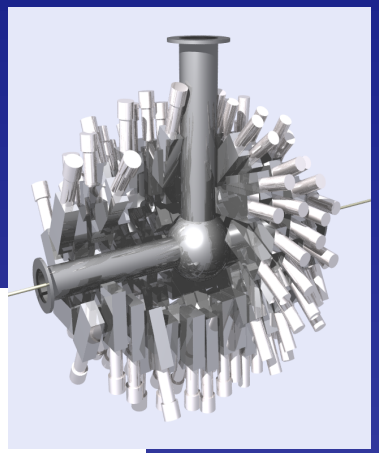
Zero-degree spectrometer

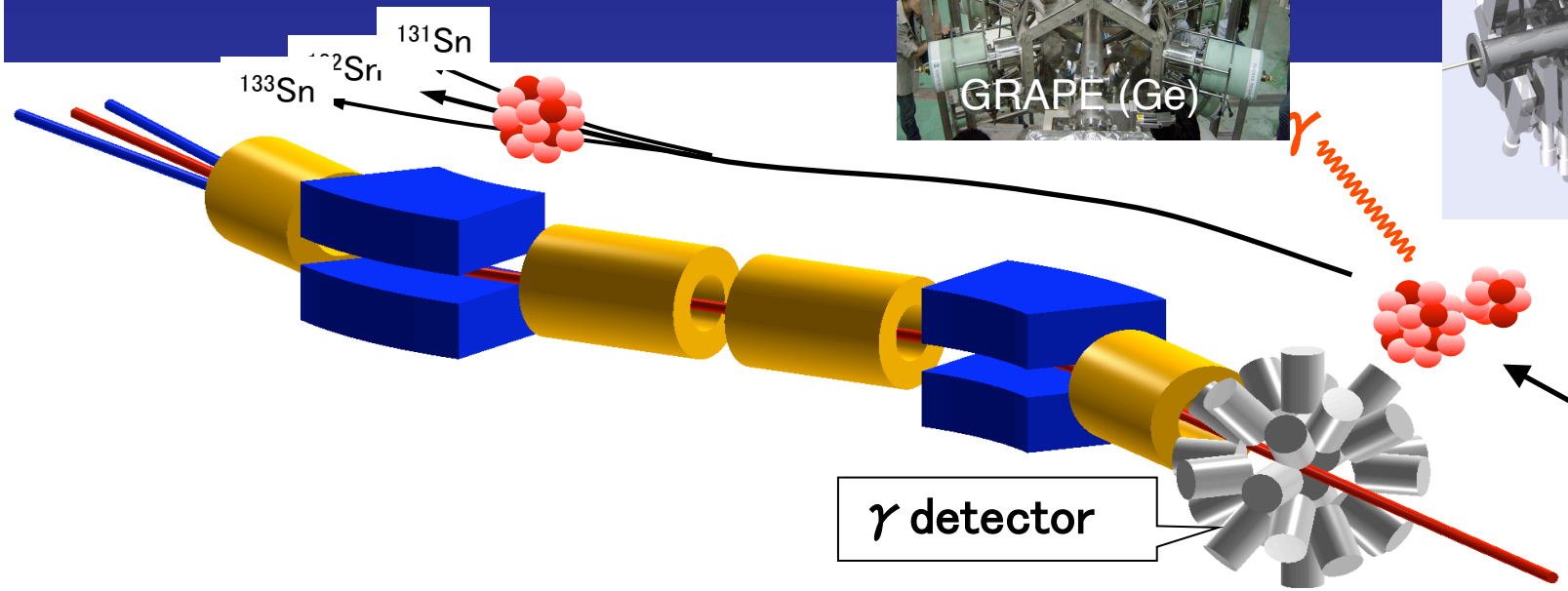
particle ID / momentum analysis

e.g. Doppler shifted γ-ray measurements with identification of products









DALI2 (NaI)

^{132}Sn

From BigRIPS

Day One Experiment

from the next week!!

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