RIKEN NiSHiNA CENTER

In-Beam γ-Ray Spectroscopy at the RIBF

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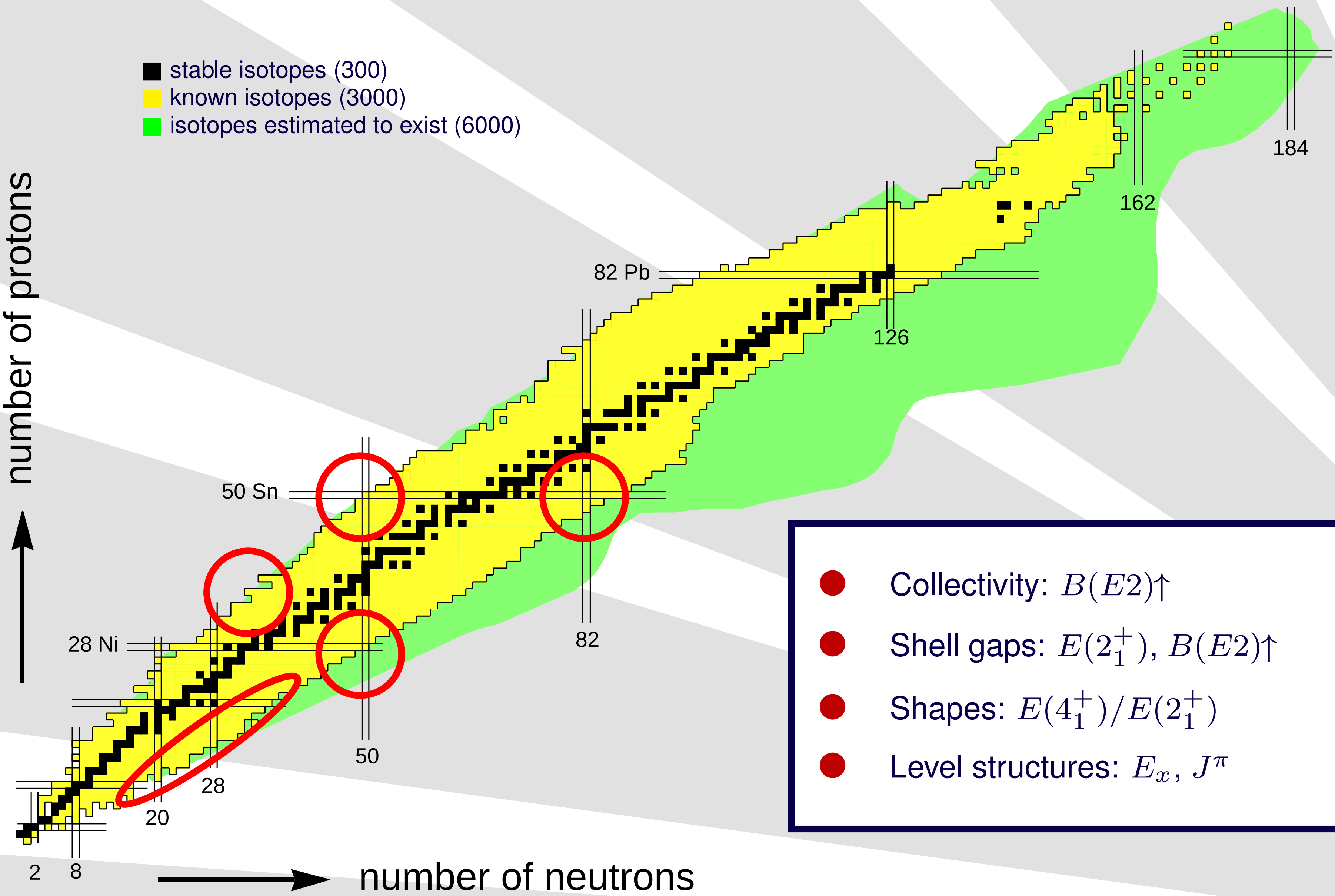
ピーター　ドルネンバル

Outline

- Physics Case
- Experimental Setup
  - BigRIPS/ZeroDegree
  - DALI2
- Results
  - Neutron-rich Si isotopes
  - ^{54}Ca
  - Coulomb excitation of ^{104}Sn
- Future Projects
  - MINOS

Physics Case

Regions of Interest



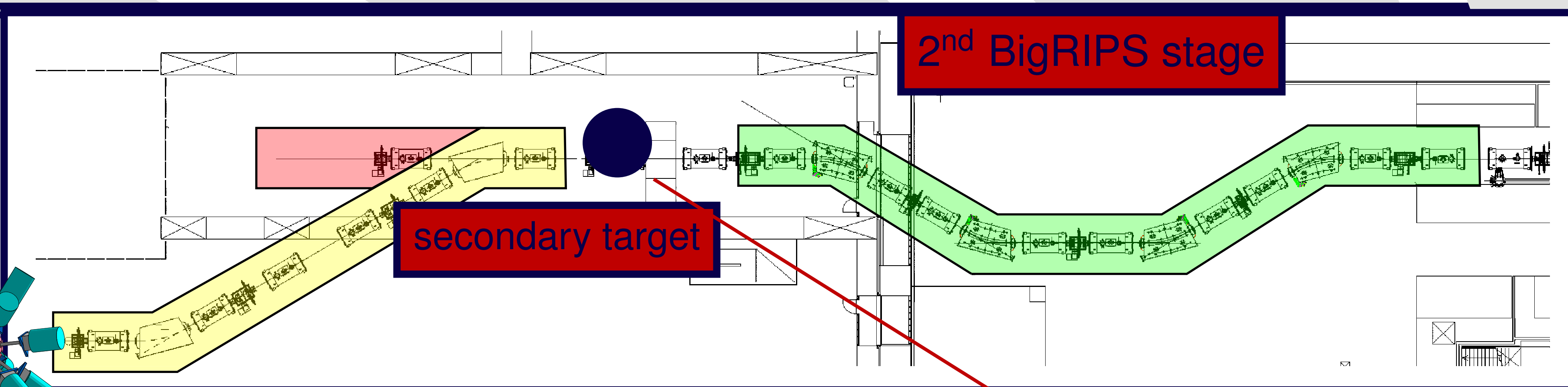
- Collectivity: $B(E2)\uparrow$
- Shell gaps: $E(2_1^+)$, $B(E2)\uparrow$
- Shapes: $E(4_1^+)/E(2_1^+)$
- Level structures: E_x, J^π

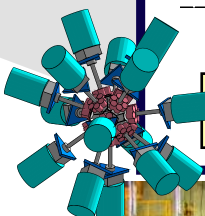
Performed Experiments

- December 2008, Dayone, ^{32}Ne
- December 2009, Test with ^{238}U
- December 2010 ^{48}Ca
  - S. Takeuchi *et al.*, ^{38,40,42}Si
  - H. Scheit *et al.*, ^{36,38}Mg
  - D. Bazin *et al.*, ^{33}Mg
  - P. Fallon *et al.*, ^{40}Mg test
- November/December 2011, ^{238}U
  - K. Yoneda *et al.*, ^{78}Ni
  - N. Aoi *et al.*, Around ^{132}Sn
- July 2012, ^{124}Xe and ^{70}Zn
  - A. Obertelli, P. Doornenbal *et al.*, ^{10x}Sn
  - D. Steppenbeck *et al.*, ^{54}Ca
- May 2013, ^{238}U
  - G. de Angelis *et al.*, $^{73–75}$Ni

Experimental Setup

ZeroDegree Spectrometer





~ 3 m between Q-poles

- DALI2 array, 186 NaI(Tl)
- GRAPE HPGe array
- $E_{\rm beam} \sim 100 - 250$ MeV/u

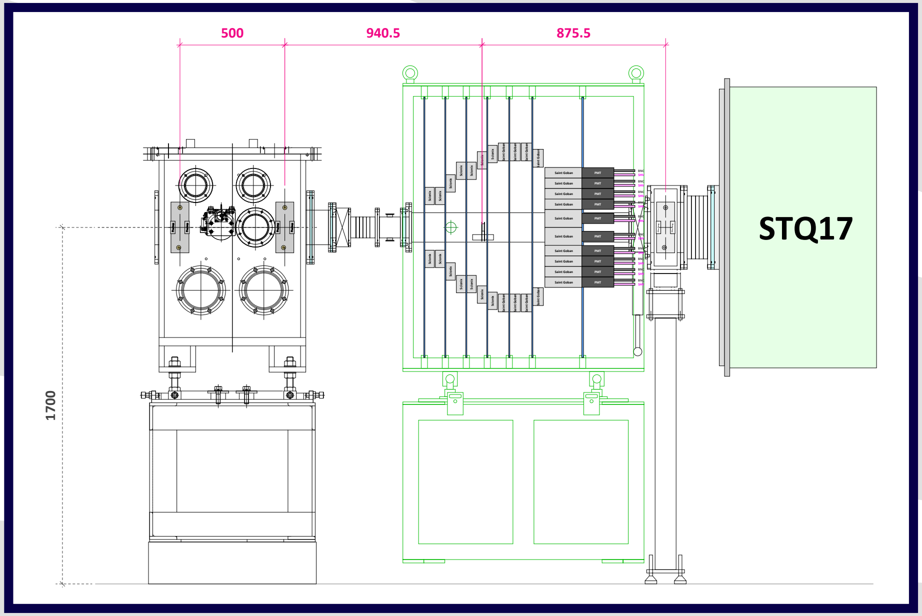
0° Spectrometer ZeroDegree

- **Particle ID** after secondary target
- Fragment momentum distribution
- Various modes of operation

mode	$p/\Delta p$	Δp	Ang. Accep.
Large Accep.	**1240**	± 3**%**	± 45 **mrad(H)** ± 30 **mrad(V)**
High res.(achrom)	2120	± 3%	± 20 mrad(H) ± 30 mrad(V)
Dispersive	4130	± 2%	± 20 mrad(H) ± 30 mrad(V)

F8 Area

- 2 double PPACs in front of reaction target
- 1 double PPAC behind reaction target
- Secondary beam spot size $\approx$ 5 mm (σ)
- Scattering angle reconstruction $\approx$ 5 mrad (σ)
- Open Beam pipe to change reaction target
- Target diameters 30–40 mm
- Target thicknesses of several g/cm^2



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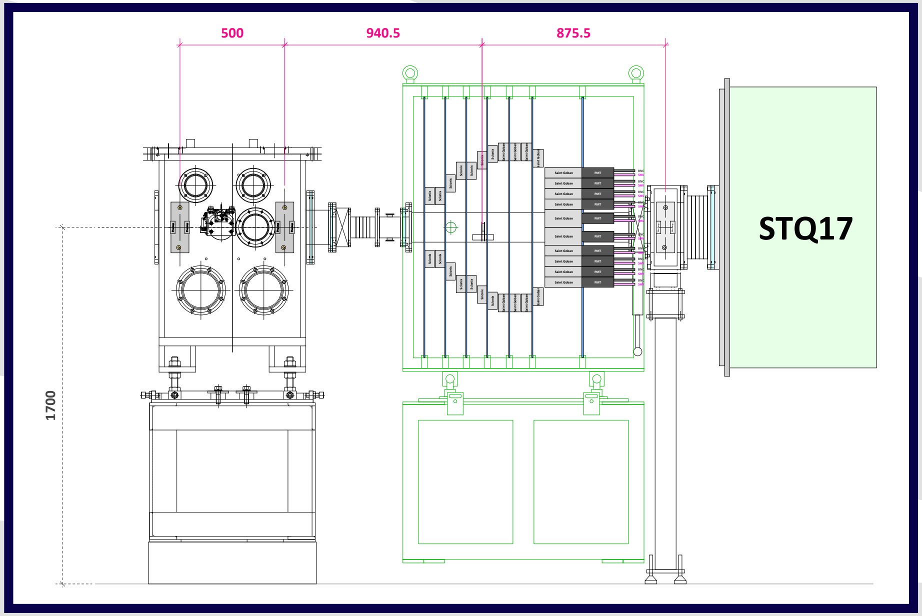
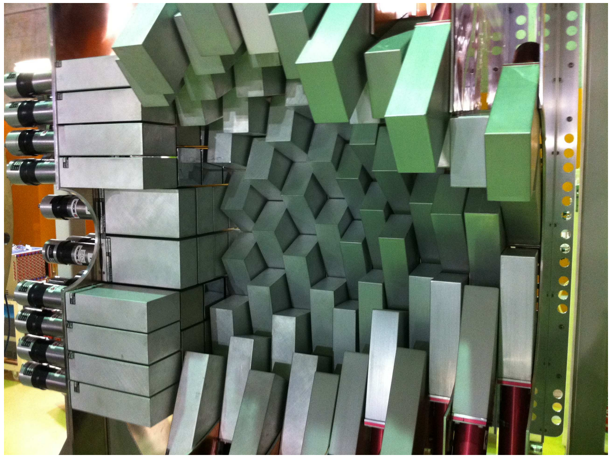
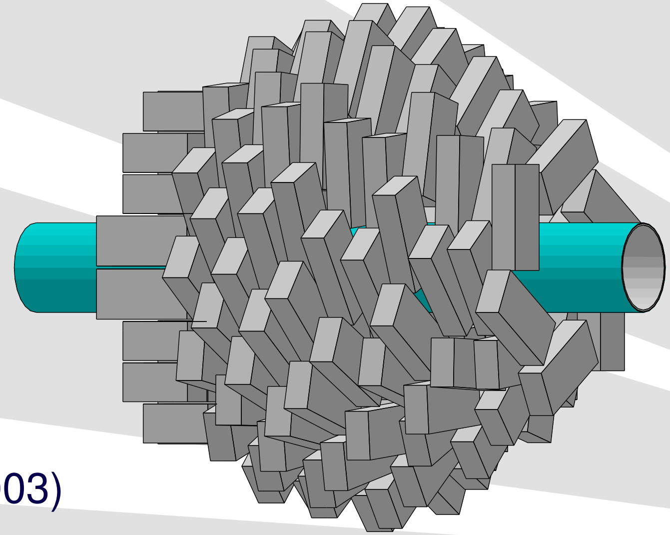


DALI2 (2010–to Present)

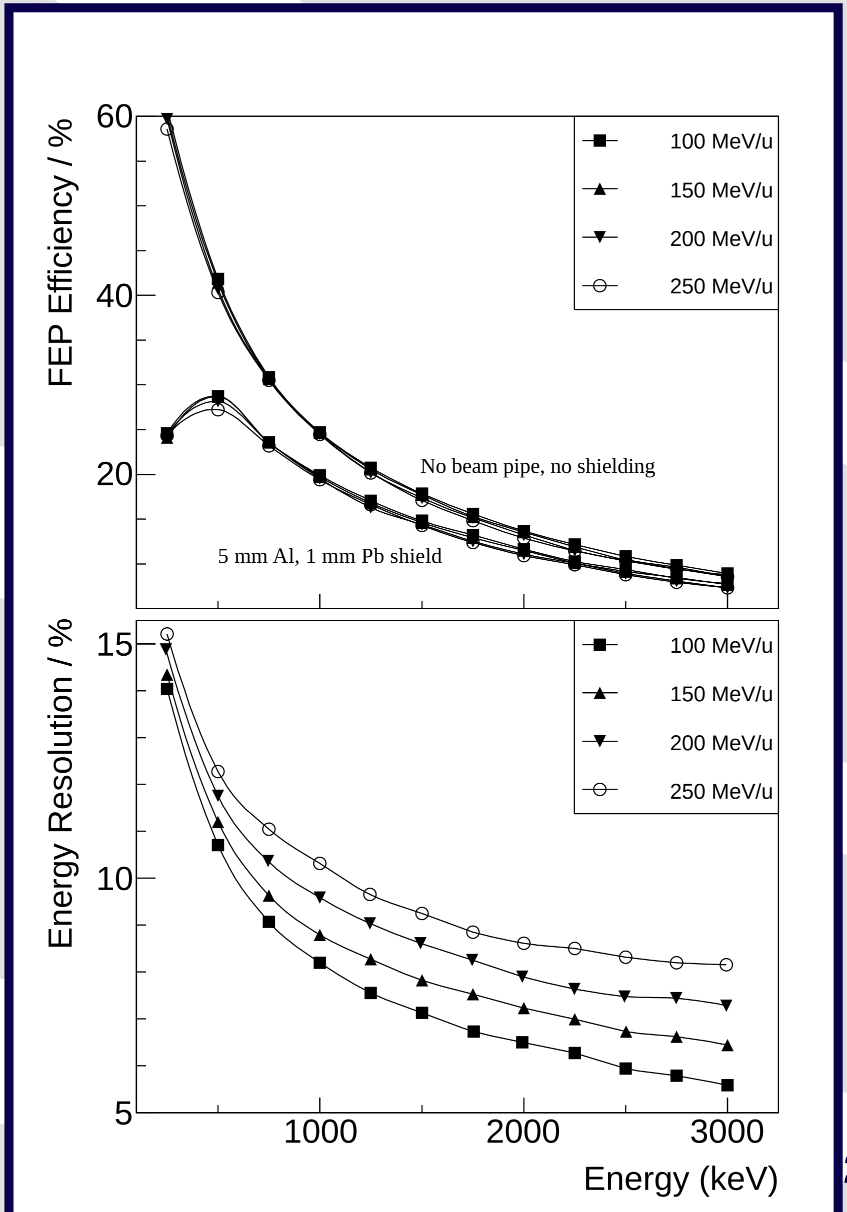
- Forward-wall configuration
- 186 NaI(Tl) detectors
- ϑ coverage 11° to 165°
- 7 % intrinsic resolution at 1 MeV
- $\Delta E/E \approx$**10(11) % at 100(250) MeV/u**
- $\approx$ **20% FEP efficiency at 1 MeV**
- Simplified target holder and beam pipe
- 1mm Pb (+1mm Sn) shielding

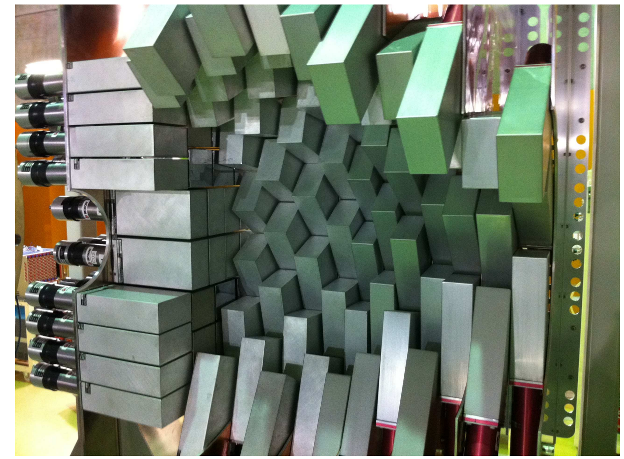




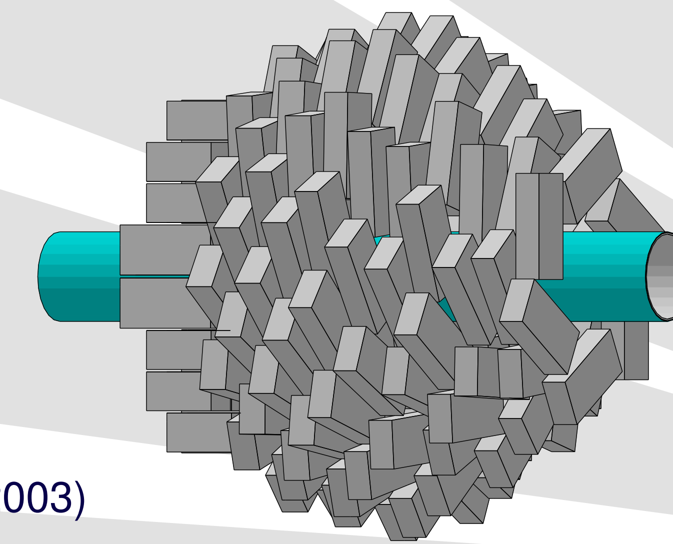
S. Takeuchi *et al.*, RIKEN Pr. Rep. 36, 148 (2003)

DALI2 (2010–to Present)





2003)



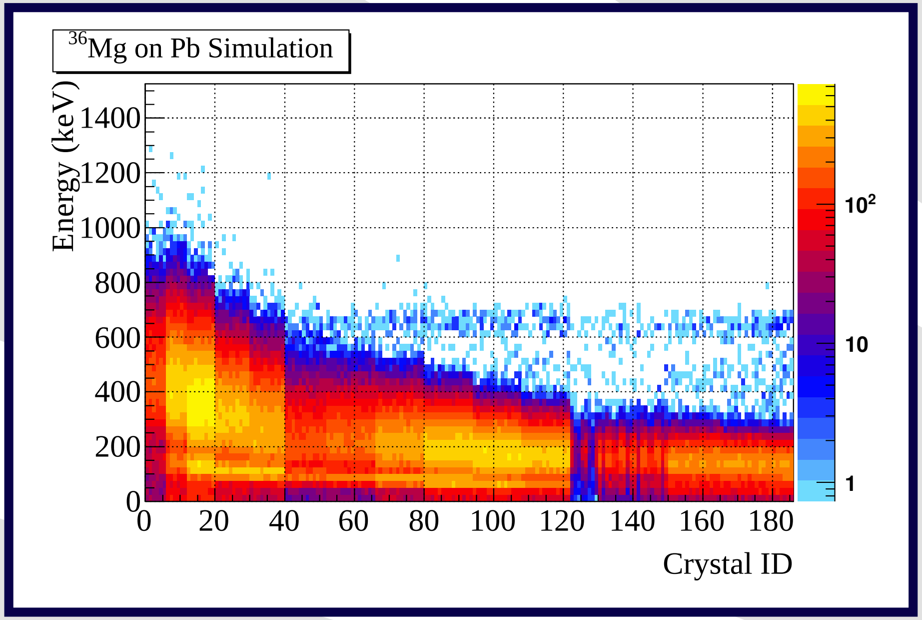
Atomic Background

- target electrons scattering off heavy projectile
- maximum electron energy:

$$E^{e^-}_{\max} = \frac{1}{500} E/A \qquad (\beta \rightarrow 2\beta, \quad m \rightarrow \frac{1}{2000} m)$$

- Components of radiation
  - ✦ Radiative electron capture (Capture of target e^- into bound states of the projectile)
    $\sigma \propto Z_p^2 Z_t$ $W(\theta)$ in proj. frame
  - ✦ Primary bremsstrahlung (Capture of target e^- into continuum states of the projectile)
    $\sigma \propto Z_p^2 Z_t$ $W(\theta)$ in proj. frame
  - ✦ Secondary (electron) bremsstrahlung (**SEB**)
    (Stopping of high energy electrons in the target)
    $\sigma \propto Z_p^2 Z_t^2$ isotropic in lab. frame
- Most important for high-Z targets

Atomic Background Comparison to Experiment – ^{36}Mg on Pb @ 230 MeV/u



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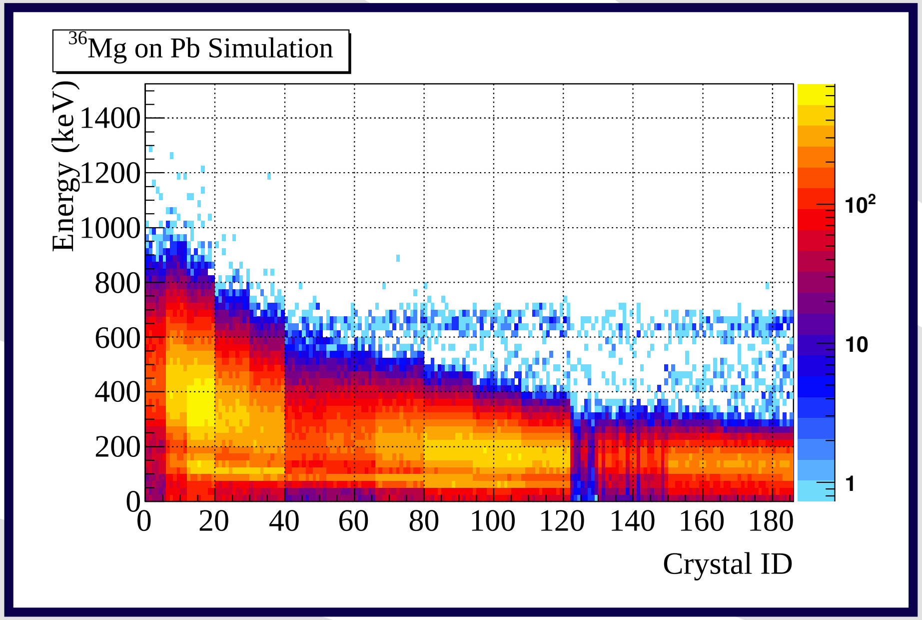

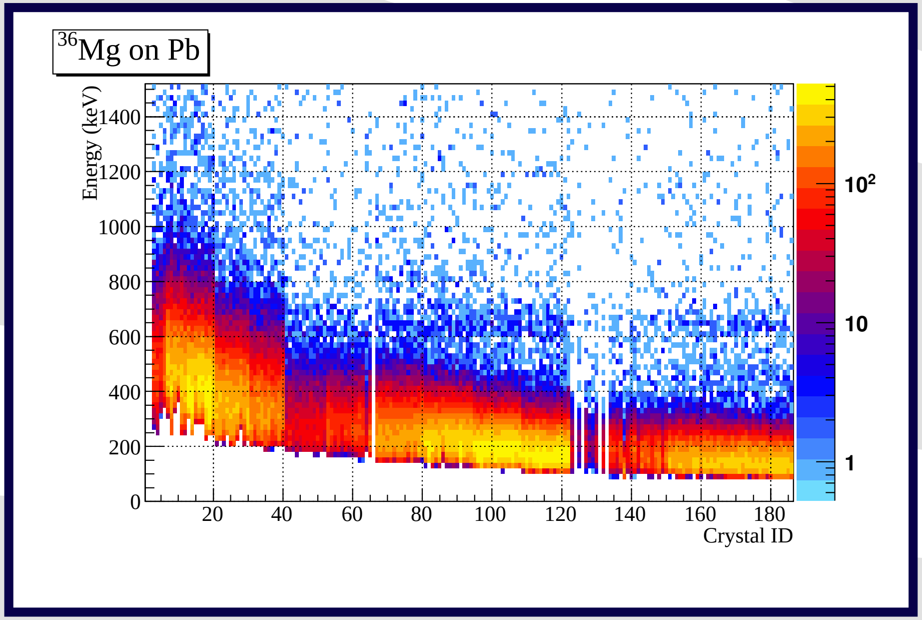

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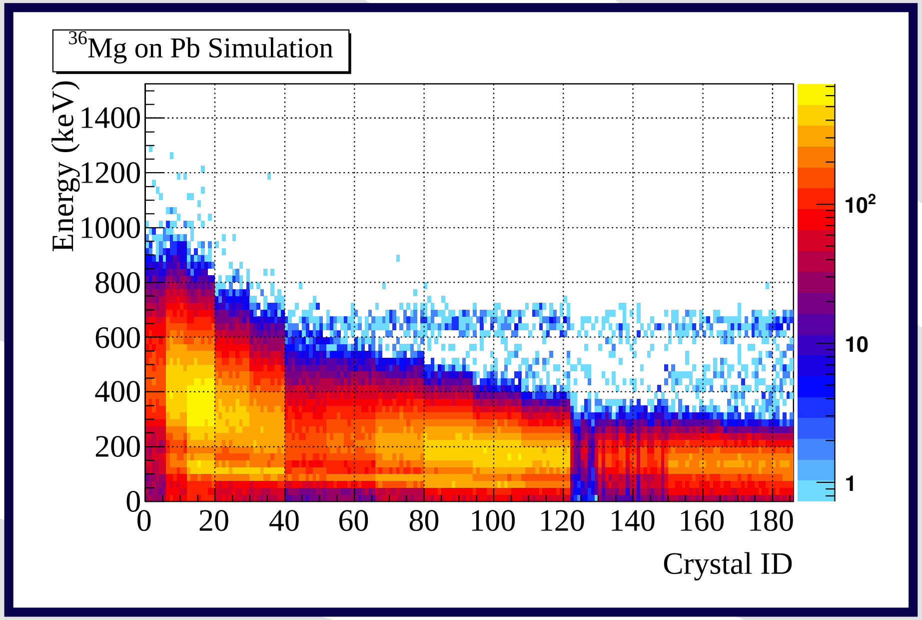
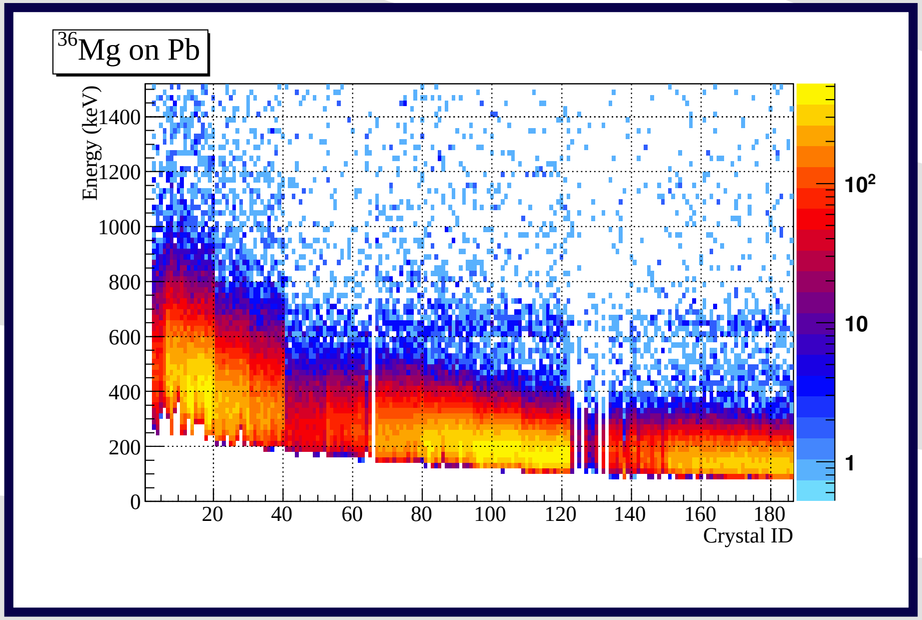
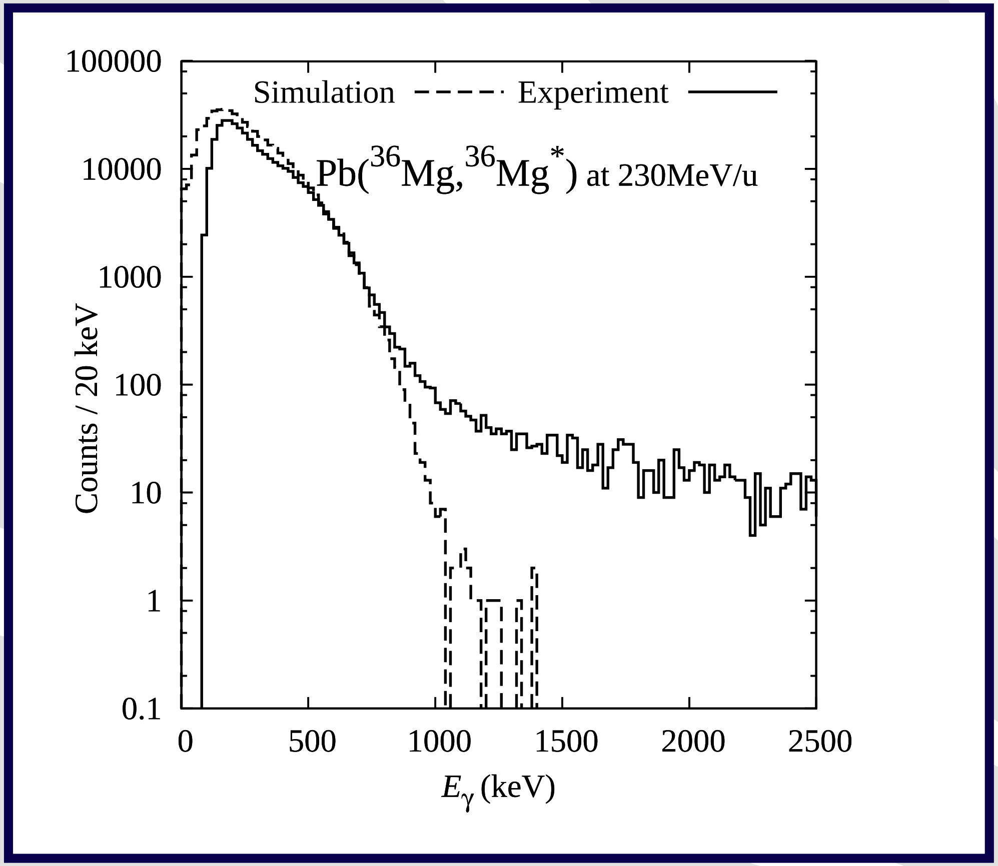


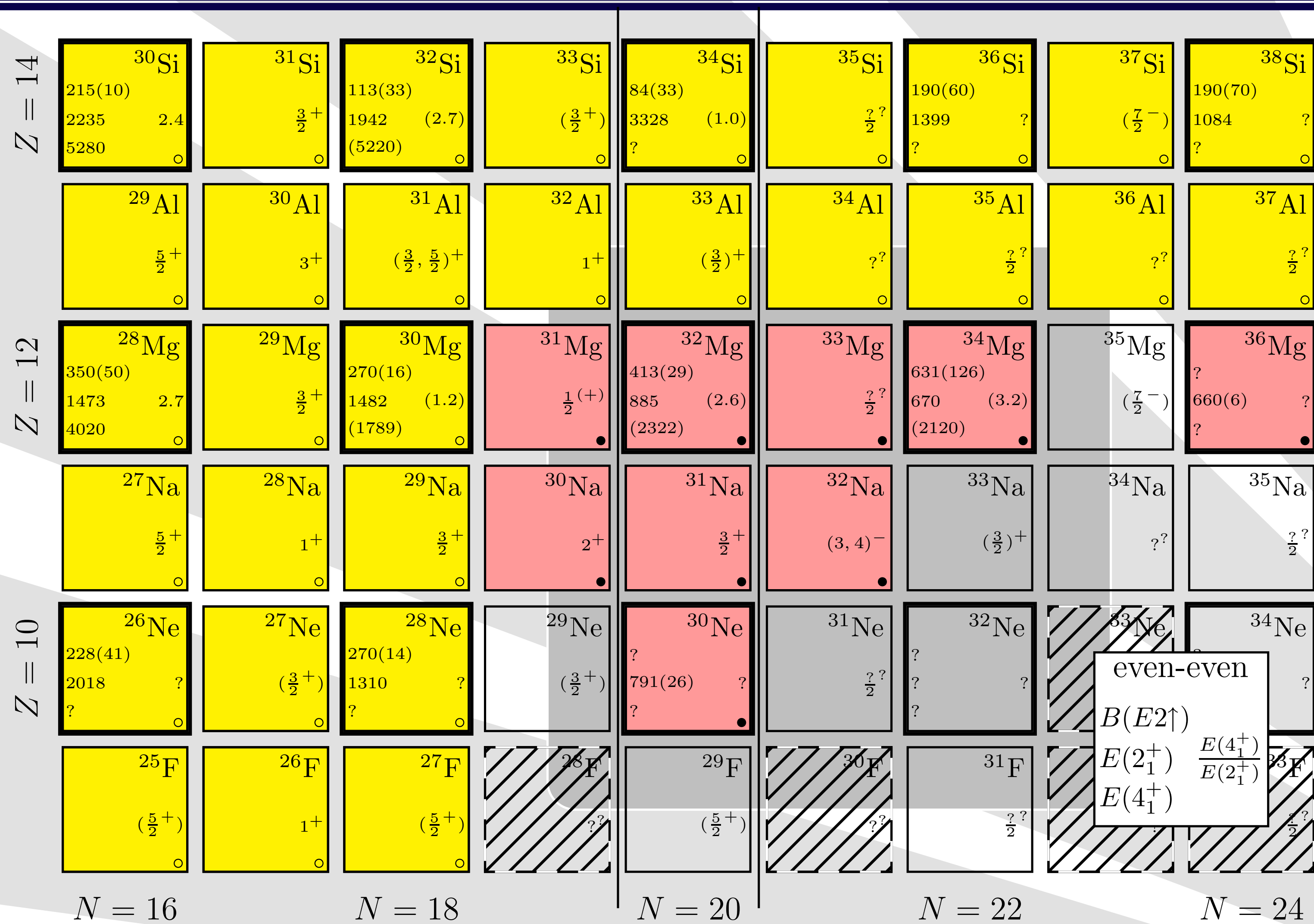




The "Island of Inversion"

A Closer Look at the “Island of Inversion”

- Physics Case
- Setup
- The “Island of Inversion”
  - ❖ Closeup View
  - ❖ ^{36,38}Mg
  - ❖ Systematics
  - ❖ ^{27,29}F
- Neutron-Rich Si
- ^{54}Ca
- Proton-rich Sn nuclei
- MINOS
- Summary and Outlook



Prediction by E. K. Warburton *et al.*, Phys. Rev. C **41**, 1147 (1990)

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Physics Case

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❖ ^{36,38}Mg

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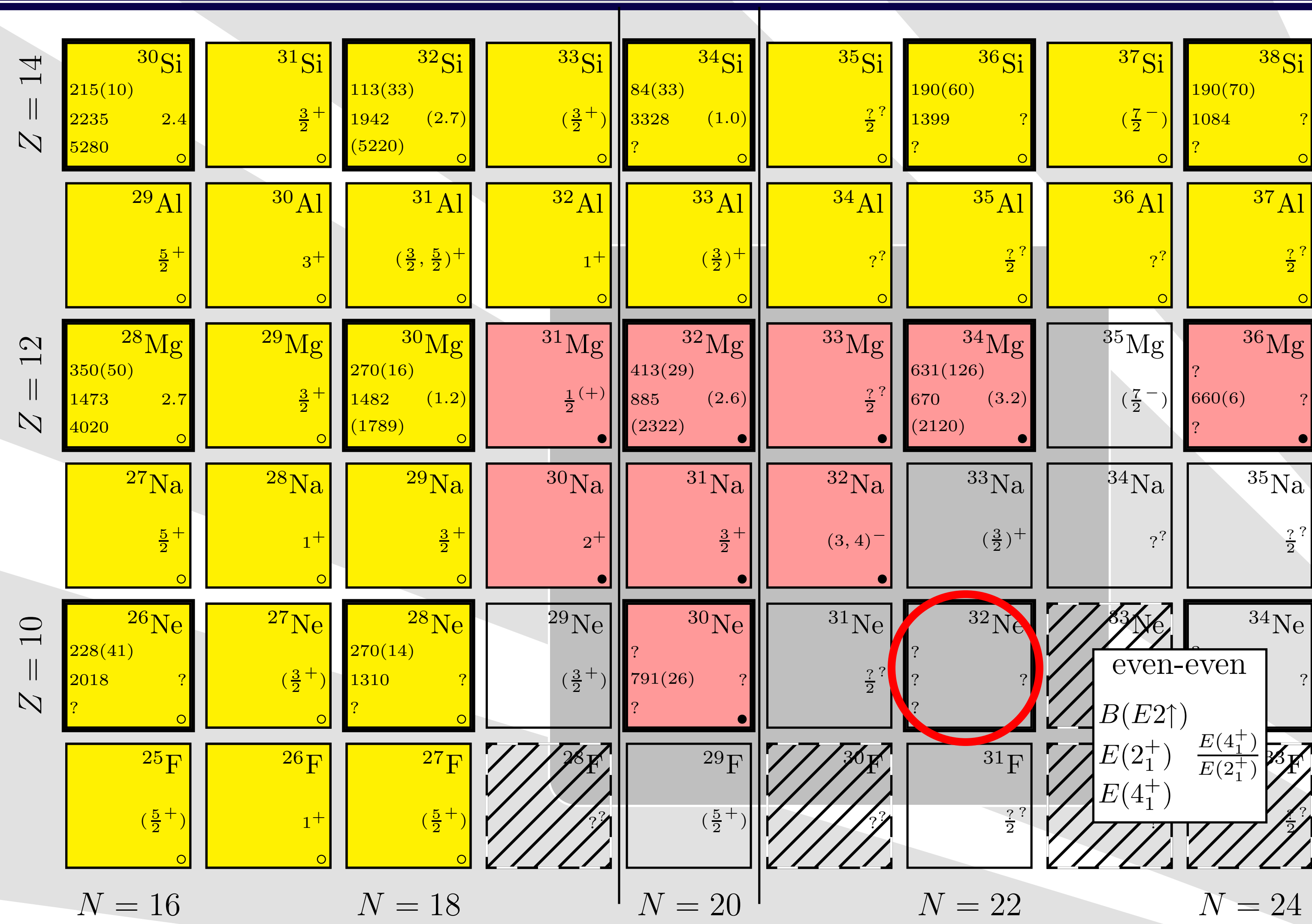

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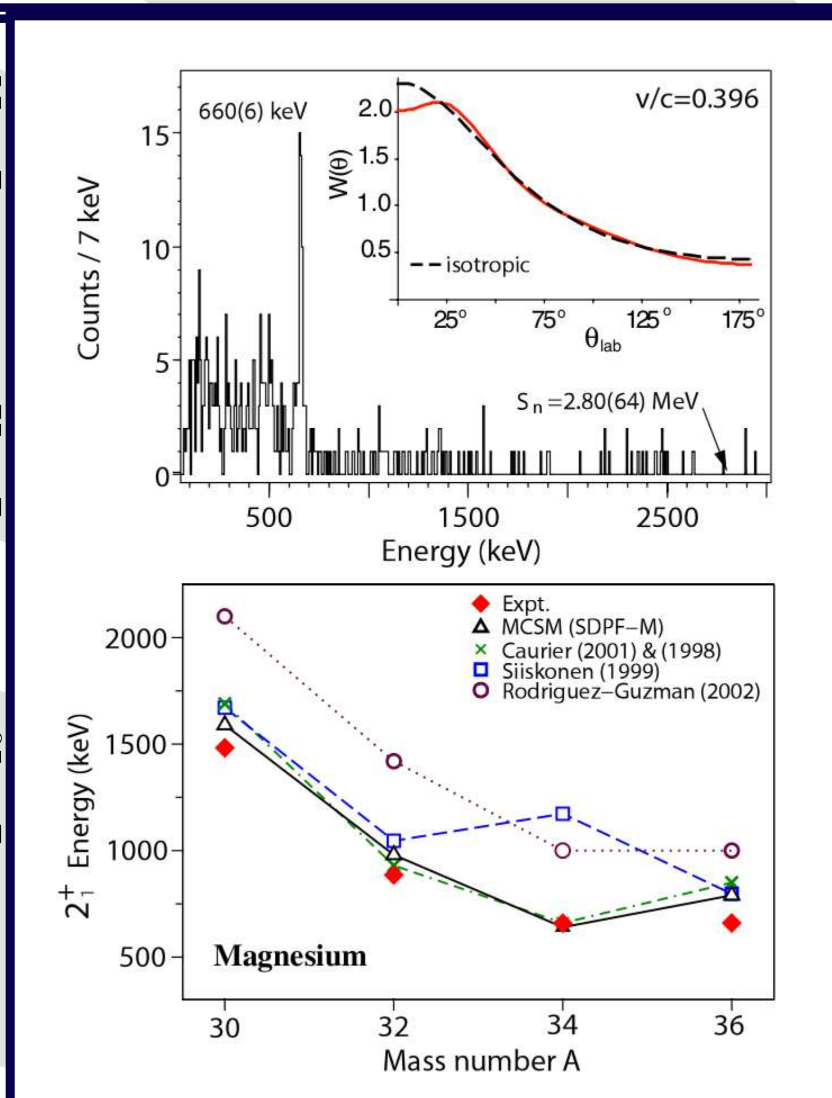

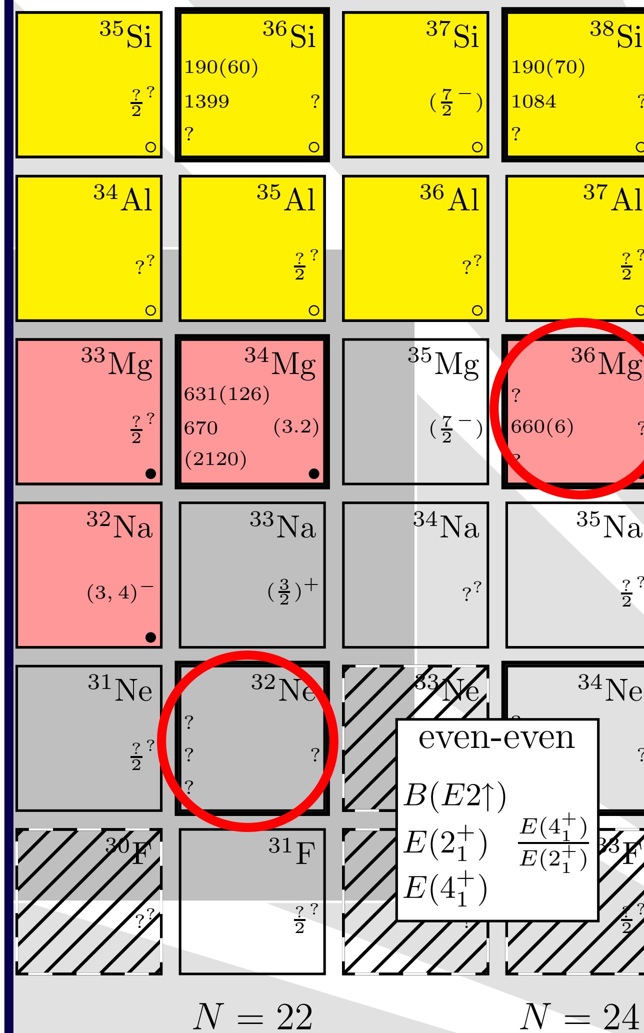

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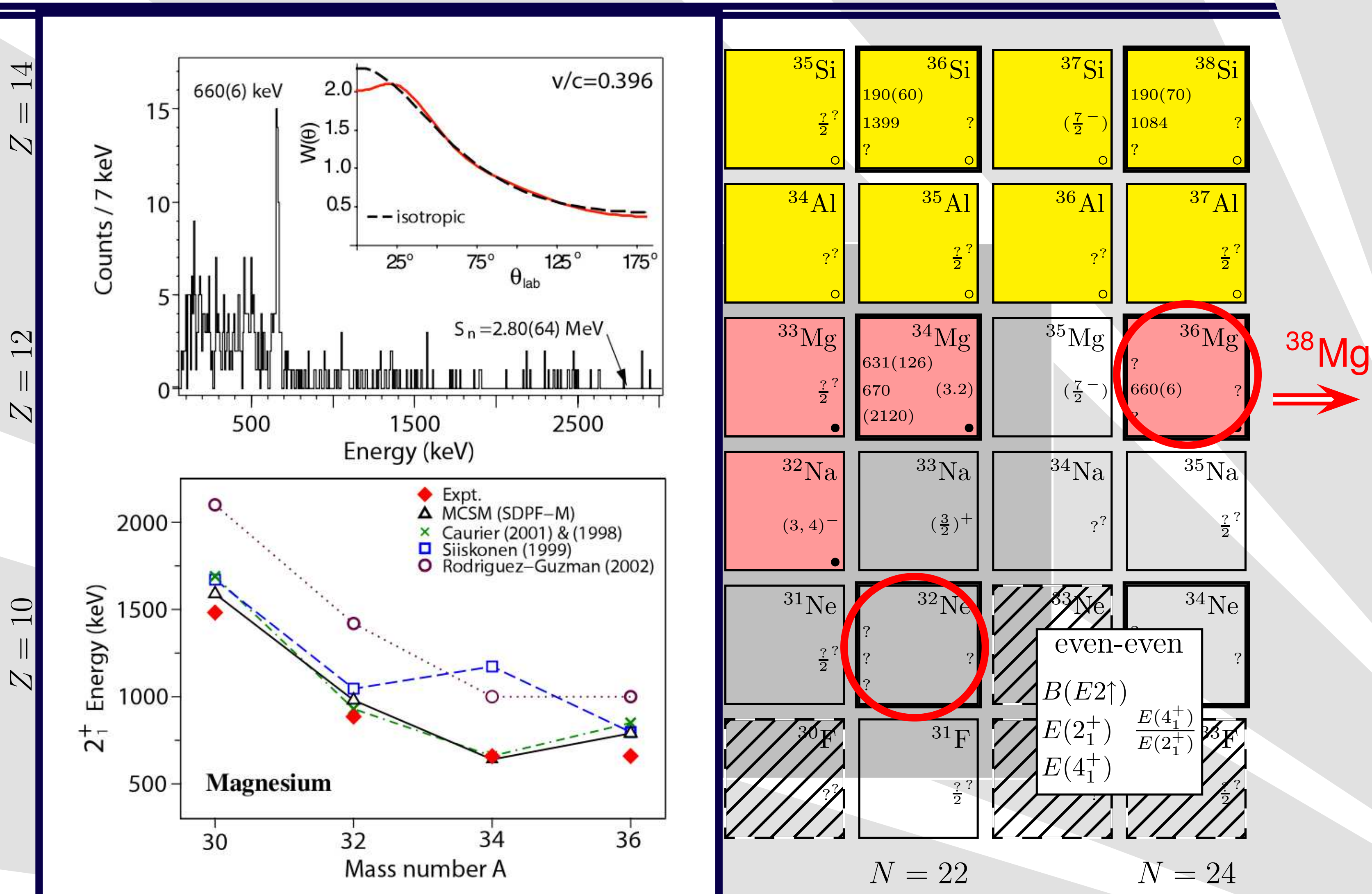

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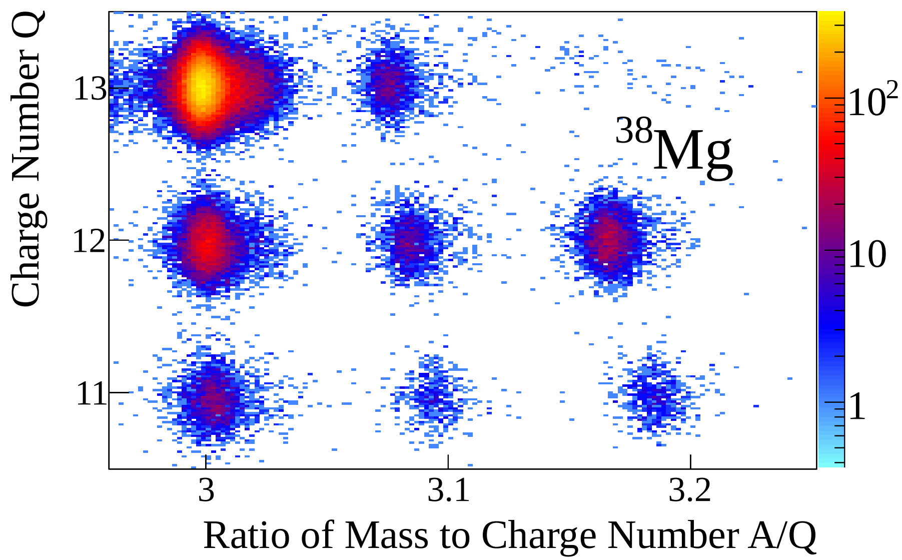
In-Beam γ-Ray Spectroscopy of ^{36,38}Mg

Particle identification behind target



- ^{48}Ca, 70 pnA primary beam
- C(^{40}Si,^{38}Mg*), C(^{39}Al,^{38}Mg*)
- F8 target: $^{nat.}$C, 2.54 g/cm^2
- ^{40}Si: 3000 pps, 230 MeV/u
- ^{39}Al: 110 pps, 220 MeV/u
- **15 hours data taking**
- ^{38}Mg $E(2_1^+)$ 655(6) keV
- $E(4_1^+)/E(2_1^+) \approx 3$

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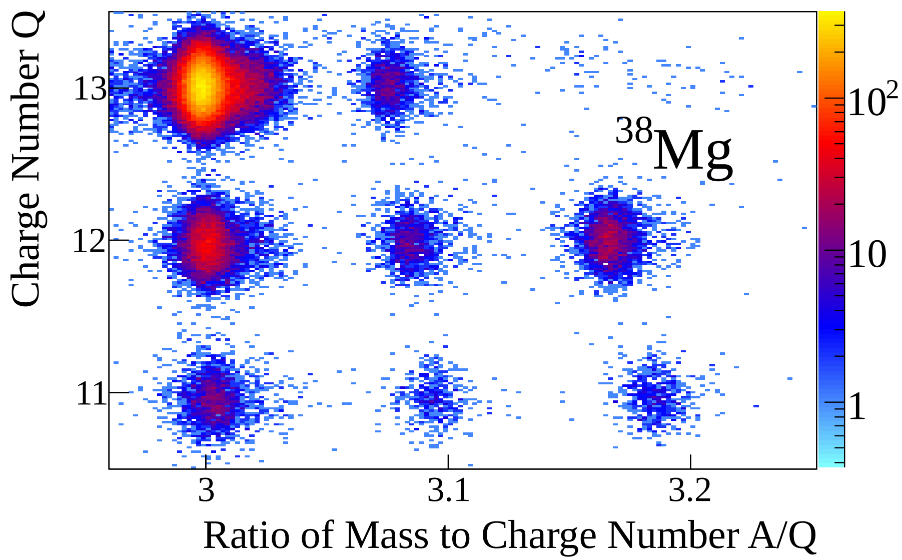

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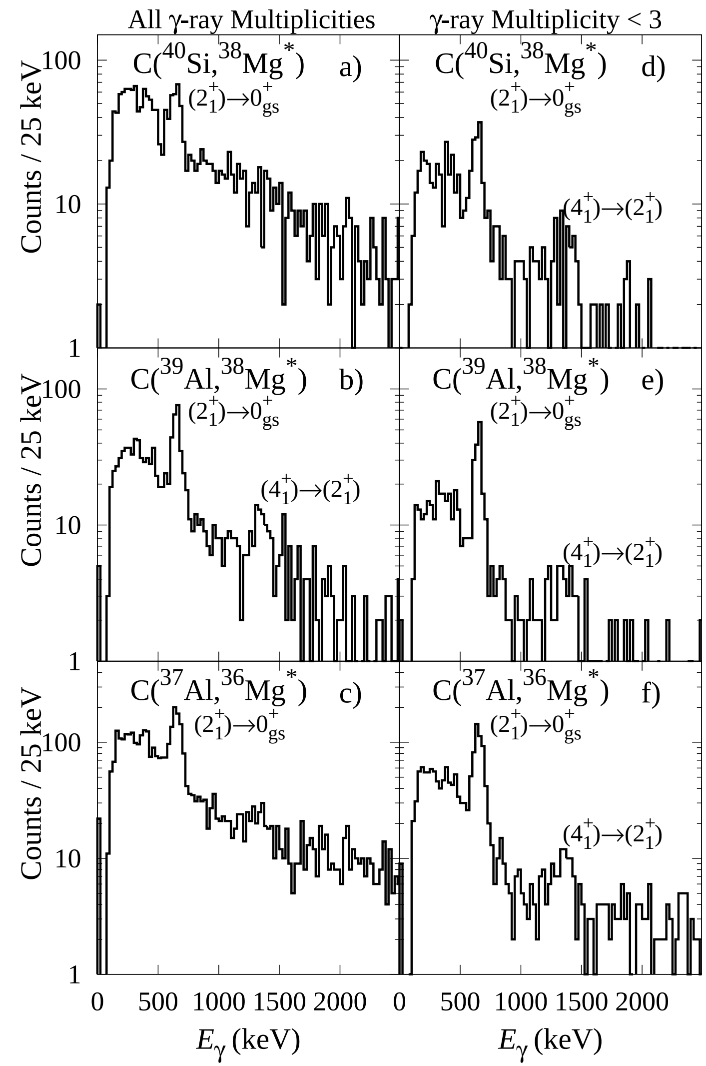
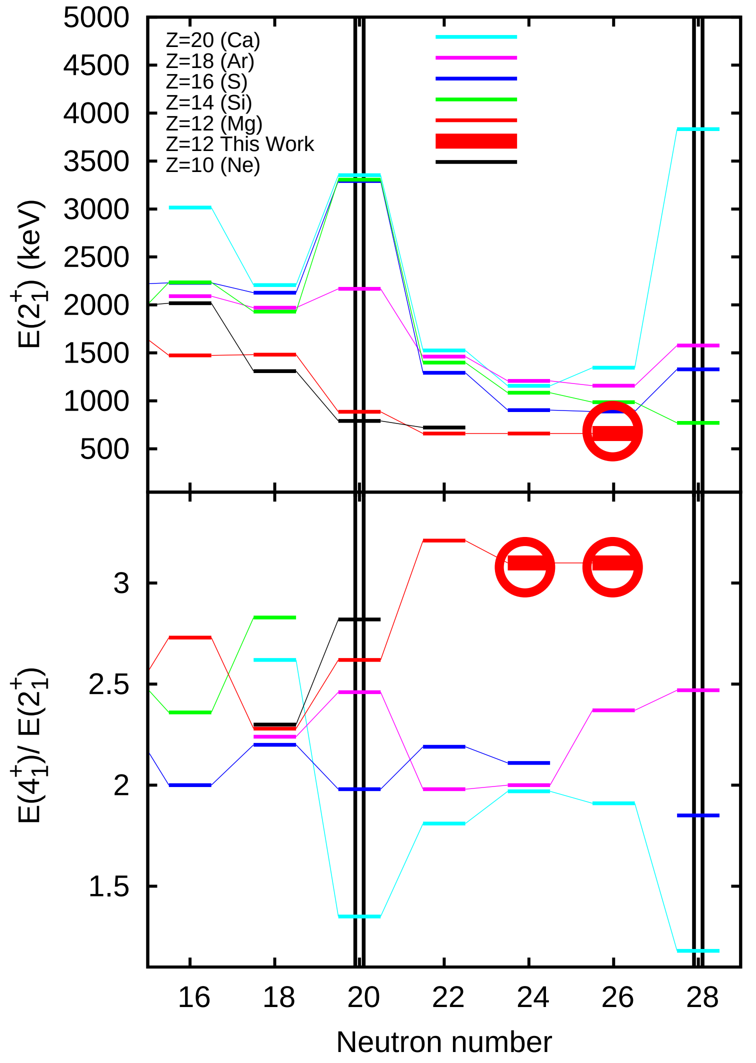
Doppler corrected γ-ray energy



2_1^+ Level and $E(4_1^+)/E(2_1^+)$ ratio Systematics in $sd-pf$ shell



[32]Mg 4$^+$: S. Takeuchi *et al.*, Phys. Rev. C 79, 054319 (2009)
[34]Mg: K. Yoneda *et al.*, Phys. Lett. B 499, 233 (2001)

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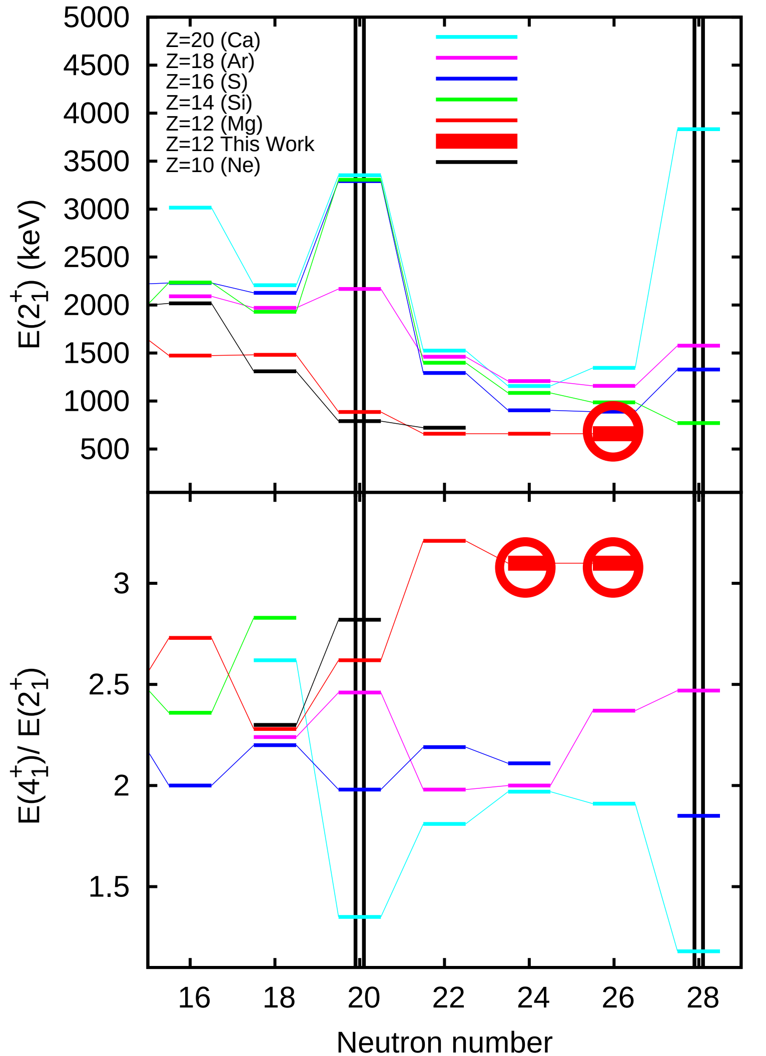
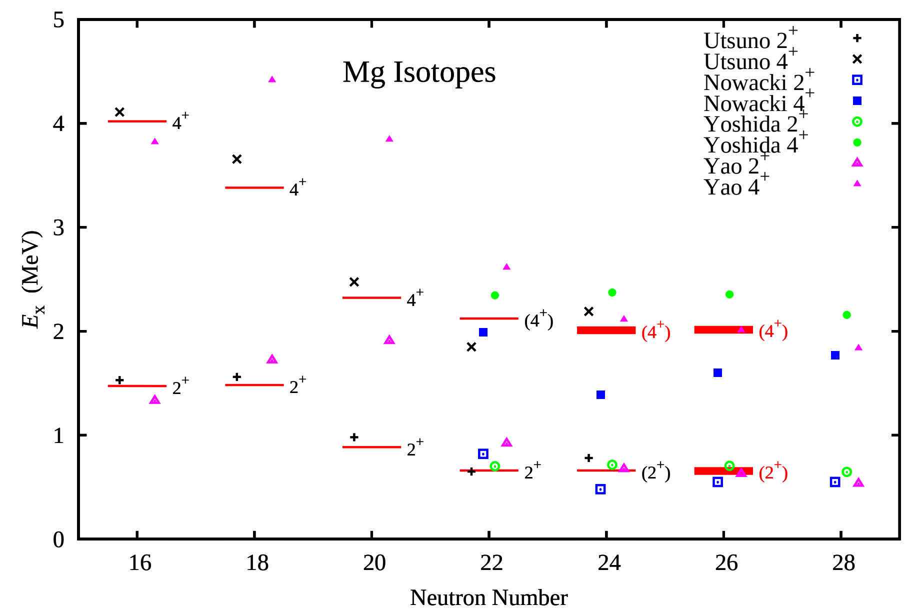
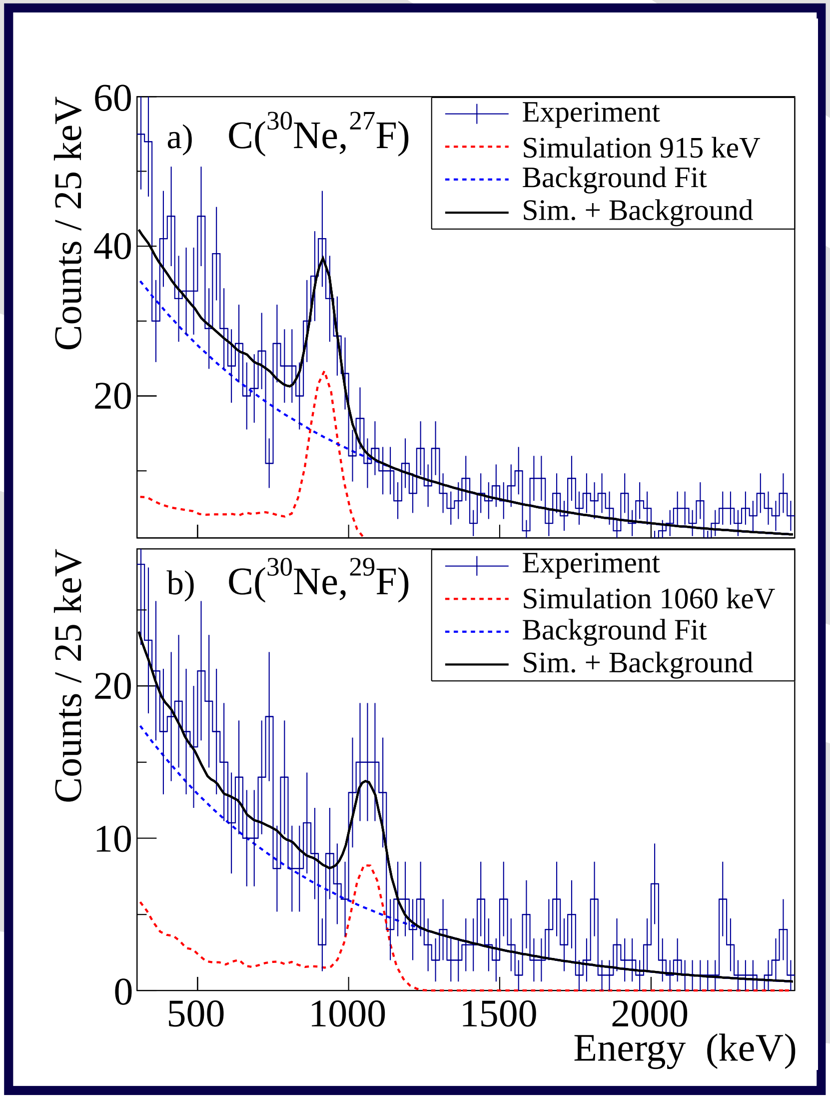




^{32}Mg 4^+: S. Takeuchi *et al.*, Phys. Rev. C 79, 054319 (2009)
^{34}Mg: K. Yoneda *et al.*, Phys. Lett. B 499, 233 (2001)

SDPF-M: Y. Utsuno *et al.*, Phys. Rev. C 60, 054315 (1999)
SDPF-NR $(0\hbar\omega)$: F. Nowacki and A. Poves, Phys. Rev. C 79, 014310 (2009)
Skyrme-QRPA: K. Yoshida, Eur. Phys. J. 42, 583 (2009)
3DAMP+GCM: J. M. Yao *et al.*, Phys. Rev. C 83, 014308 (2011)

In-Beam γ-Ray Spectroscopy of $^{27,29}F$



USDA/B: B. Alex Brown and W. A. Richter, Phys. Rev. C 74, 034315 (2006)
SDPF-M: Y. Utsuno *et al.*, Phys. Rev. C 60, 054315 (1999)

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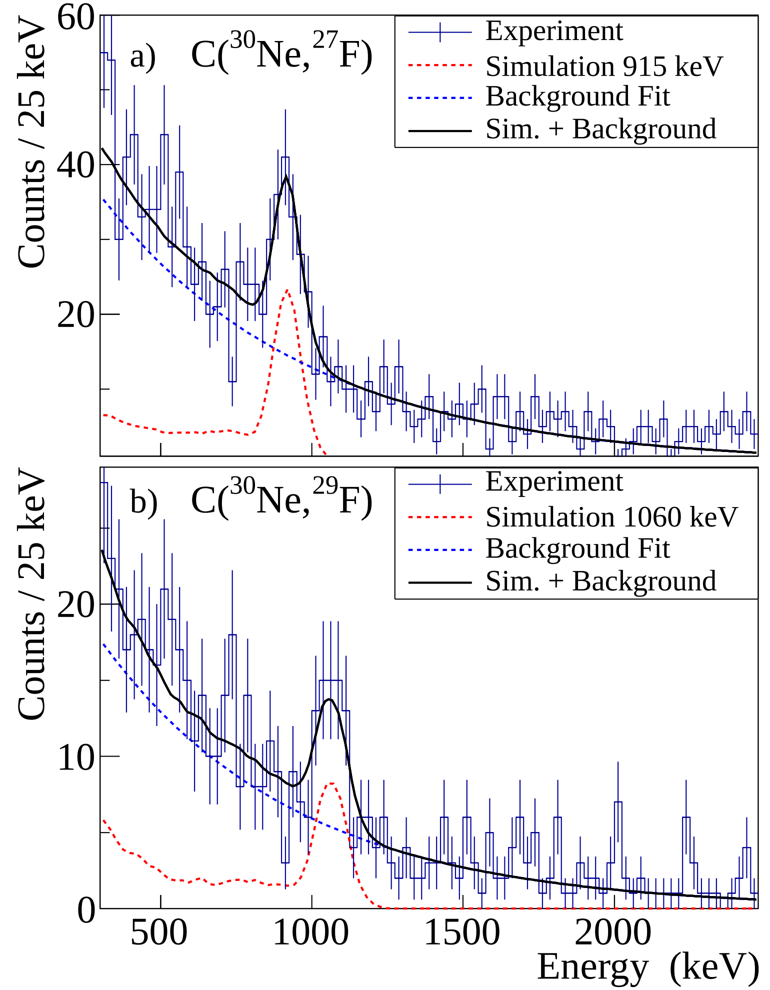
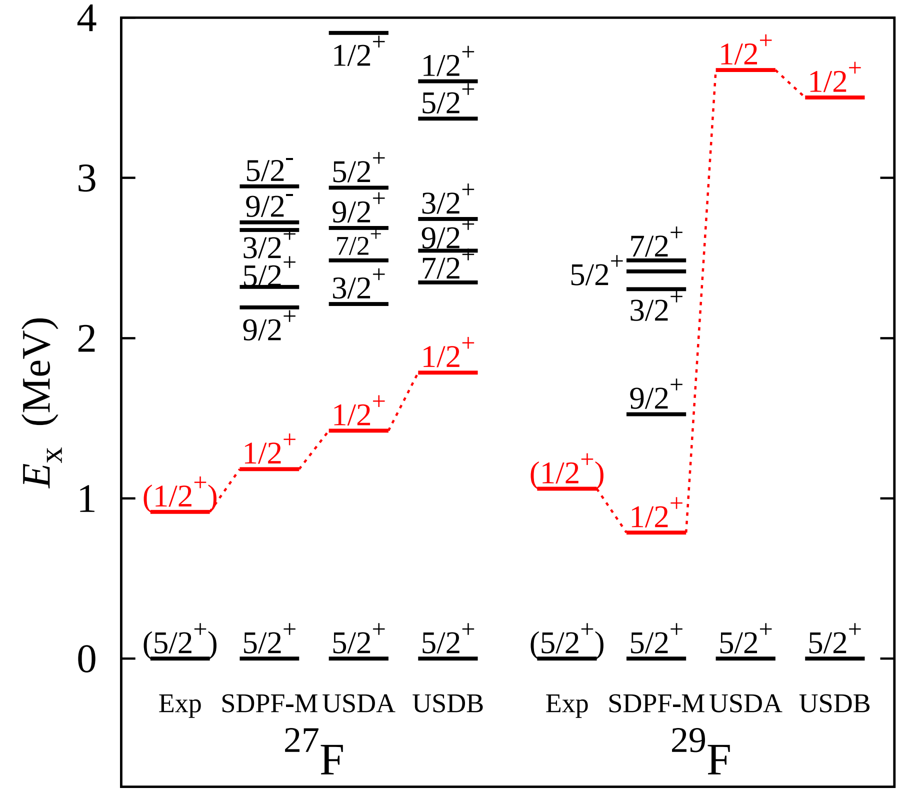




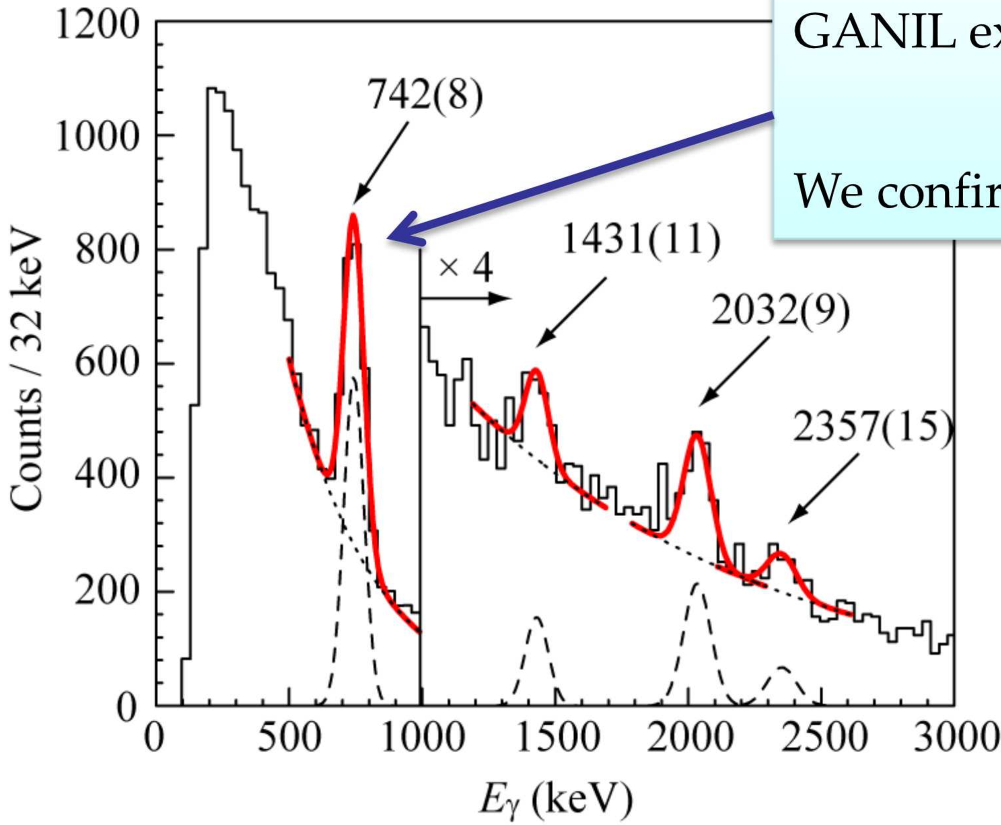
USDA/B: B. Alex Brown and W. A. Richter, Phys. Rev. C 74, 034315 (2006)
SDPF-M: Y. Utsuno *et al.*, Phys. Rev. C 60, 054315 (1999)

^{42}Si

Neutron-rich Si Isotopes

^{42}Si With High Statistics

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



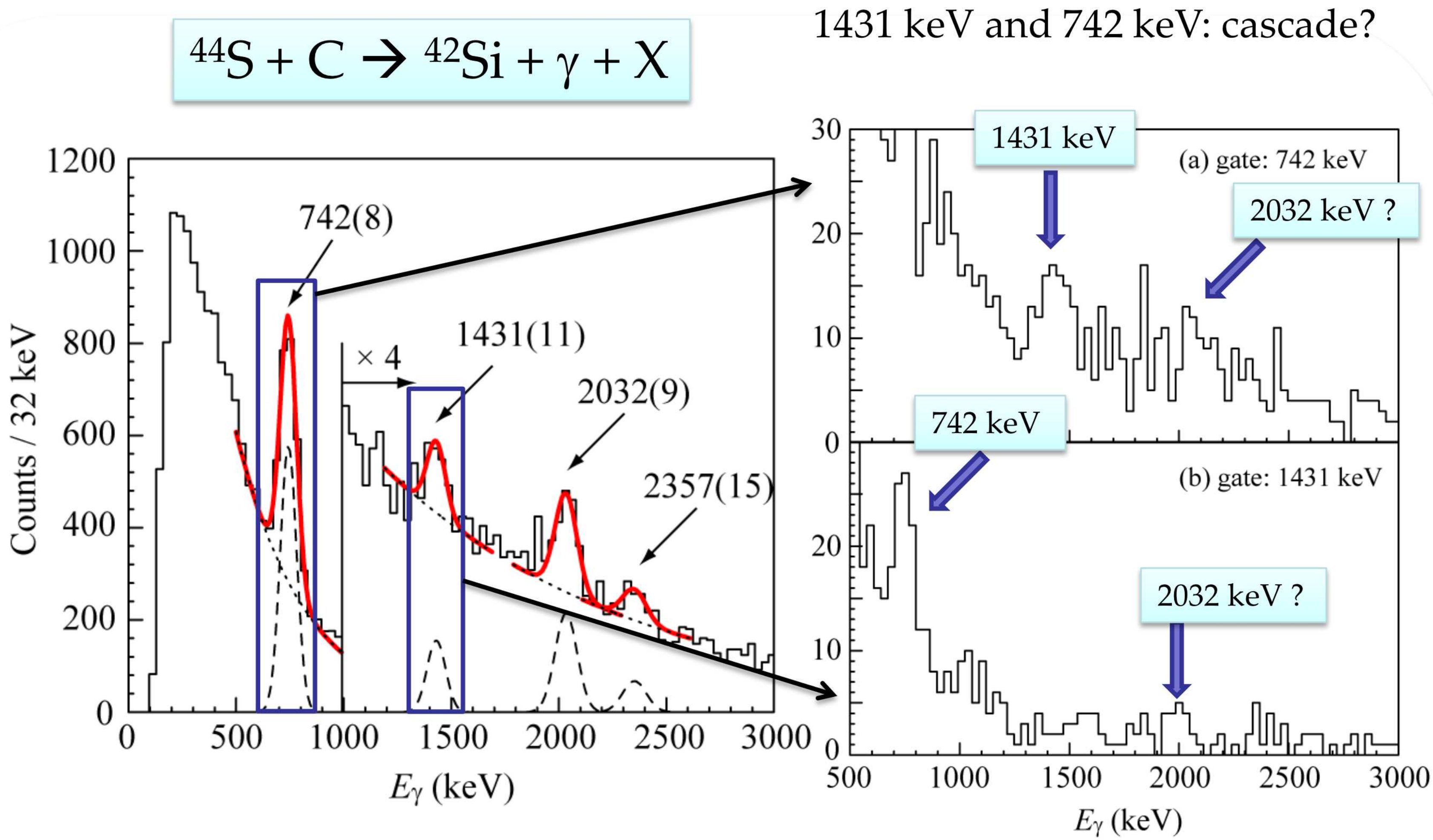
GANIL exp. : 770(19) keV
B.Bastin *et al.*, Phys. Rev. Lett. 99, 022503 (2007).

We confirmed γ line observed at GANIL.

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.

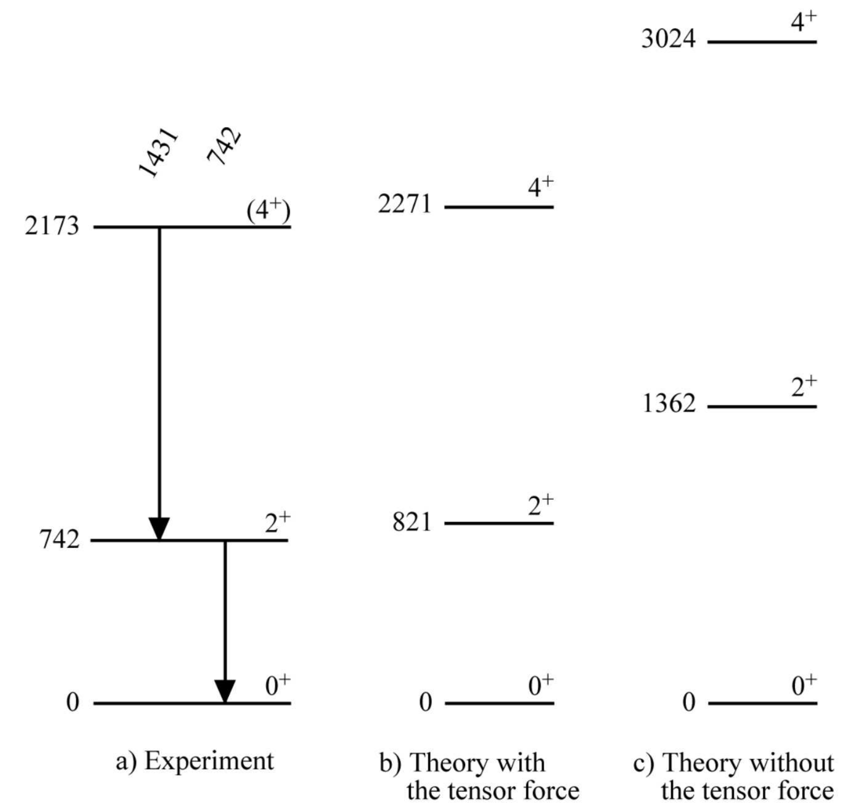
$\gamma - \gamma$ *Coincidences*



*Widths are fixed to simulated values.

The 4^+ State of ^{42}Si

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



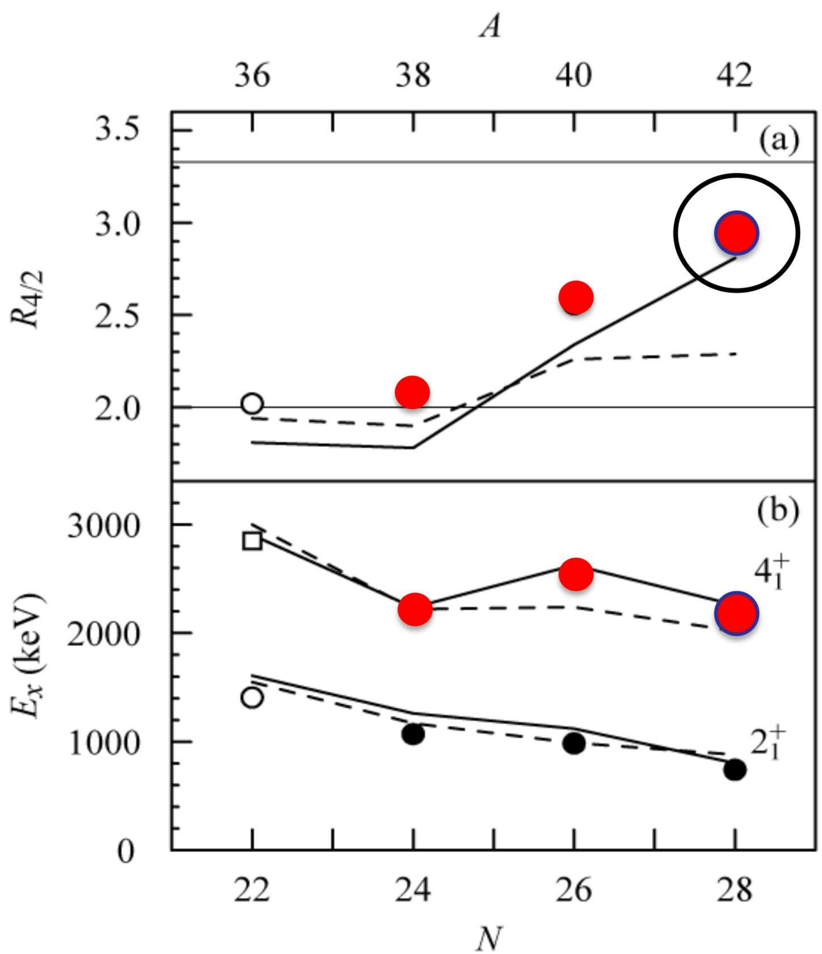
$E_x(4^+)/E_x(2^+) = 2.93$
→ well-deformed shape

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.

Well Deformed ^{42}Si



Low 2^+ excitation energy

R(4/2) = 2.93: well deformed

Development of deformation toward N=28

→ indicate disappearance of N=28

Solid: MCSM with tensor force by Utsuno, Otsuka
Dash: np-nh configuration using the SDPF-U-MIX interatcion by Poves et al.

S. Takeuchi *et al.*, Phys. Rev. Lett. **109**, 182501 (2012)

^{54}Ca

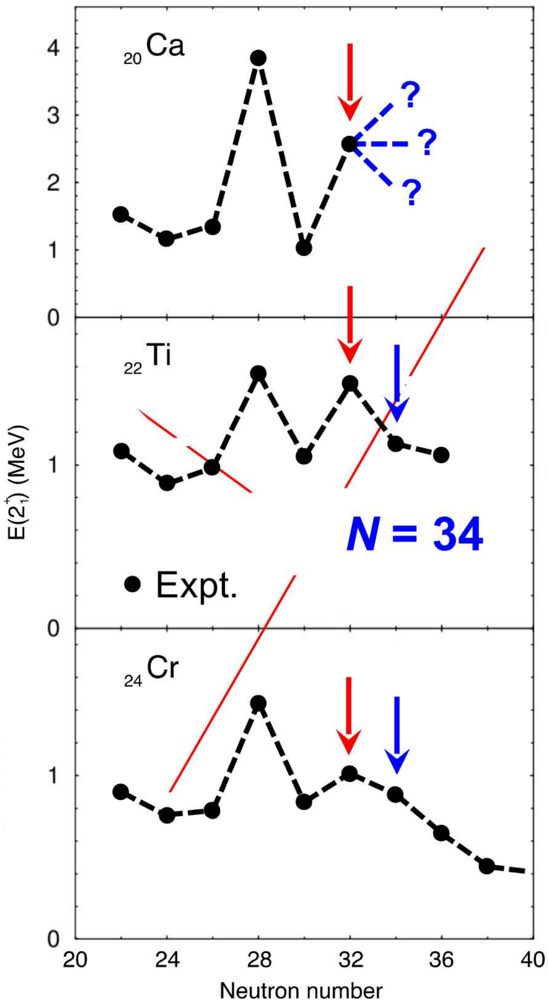
$E(2_1^+)$ and $B(E2)\uparrow$ Values of Cr, Ti, and Ca Isotopes

Significant *N* = 32 subshell gaps observed in 52Ca [2,3], 54Ti [4,5] and 56Cr [6,7] from *E*(2+) and *B*(*E*2) transition rates

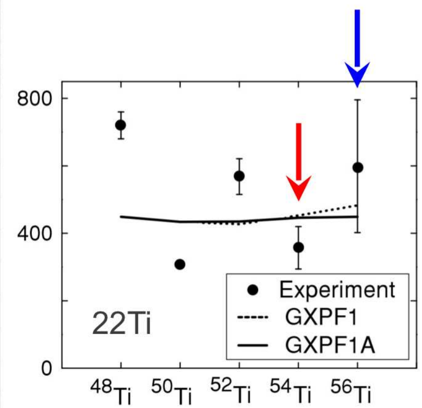
[2] A. Huck *et al.*, PRC **31** (1985) 2226
[3] A. Gade *et al.*, PRC **74** (2006) 021302(R)
[4] R.V.F. Janssens *et al.*, PLB **546** (2002) 55
[5] D.-C. Dinca *et al.*, PRC **71** (2005) 041302(R)
[6] J.I. Prisciandaro et al., PLB **510** (2001) 17
[7] A. Bürger *et al.*, PLB **622** (2005) 29

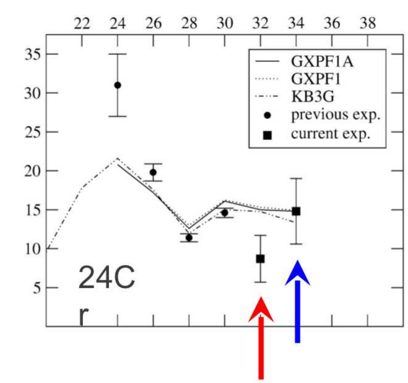
- However, no *N* = 34 subshell gap in 56Ti [5,8] or 58Cr [7,9], which is predicted by some shell models

[8] S.N. Liddick *et al.*, PRL **92** (2004) 072502
[9] S. Zhu *et al.*, PRC **74** (2006) 064315

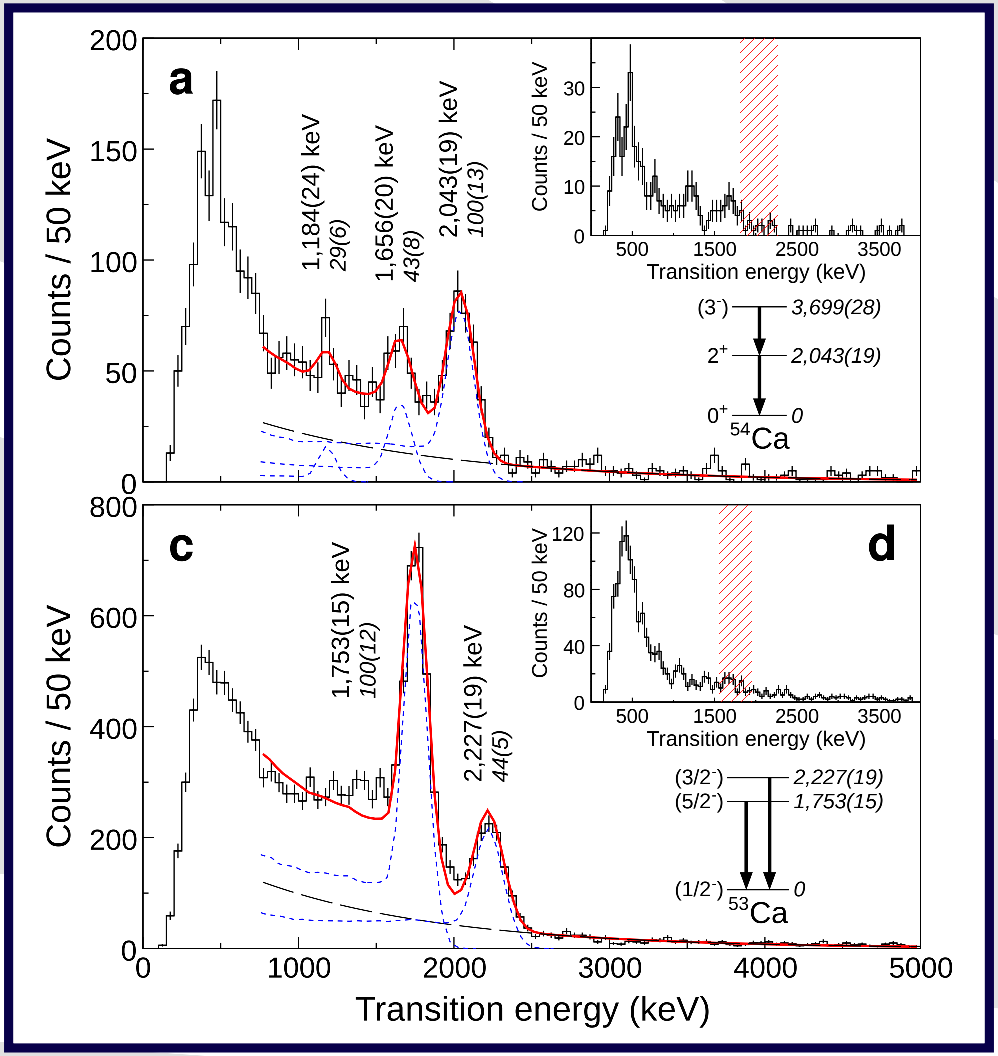


Left: First 2+ energies
Below: *B*(*E*2) rates





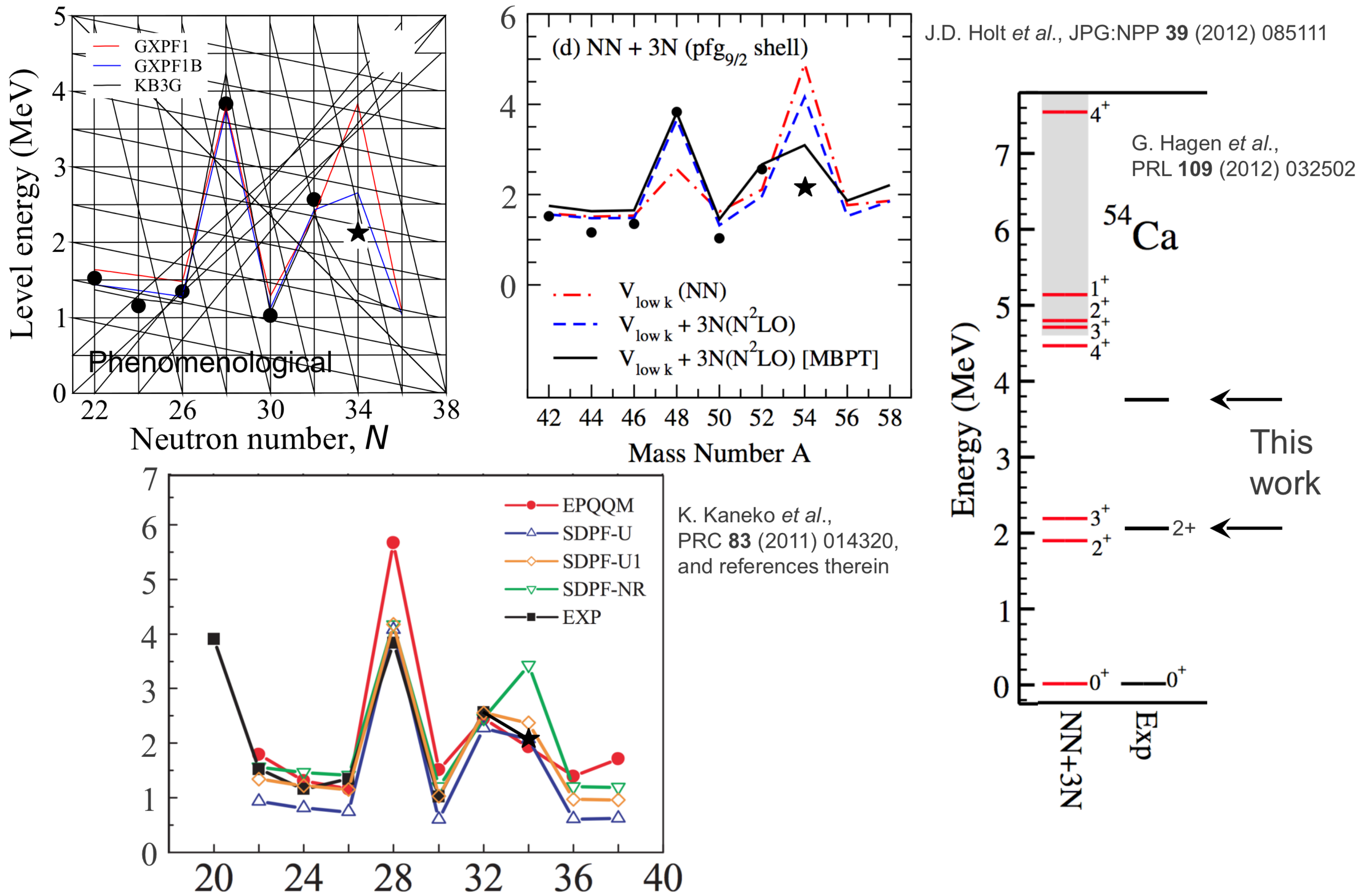
In-Beam γ-Ray Spectra of ^{53,54}Ca



- ^{70}Zn, 60 pnA primary beam
- Be(^{55}Sc,^{54}Ca*), Be(^{56}Ti,^{54}Ca*)
- F8 target: ^{9}Be, 1.85 g/cm^2
- 124 pps/pnA ^{56}Ti
- 12 pps/pnA ^{55}Sc
- **40 hours data taking**
- $E(2_1^+)$ at 2043(19) keV in ^{54}Ca
- Additional new γ-rays

^{53}Ca: 2200(1) keV level observed, F. Perrot *et al.*, PRC **74**, 014313 (2006)

Comparison to Shell-Model Calculations



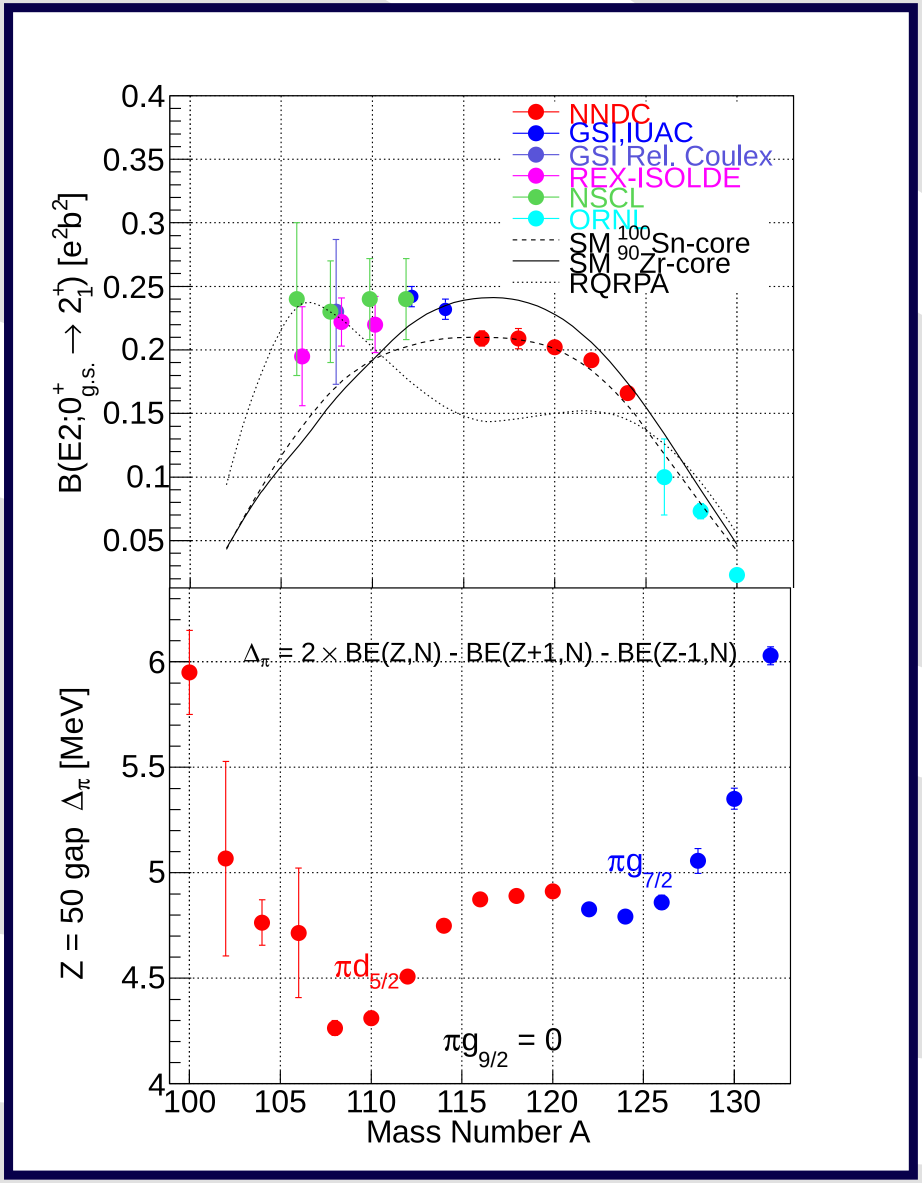
J.D. Holt *et al.*, JPG:NPP **39** (2012) 085111

K. Kaneko *et al.*, PRC **83** (2011) 014320, and references therein

G. Hagen *et al.*, PRL **109** (2012) 032502

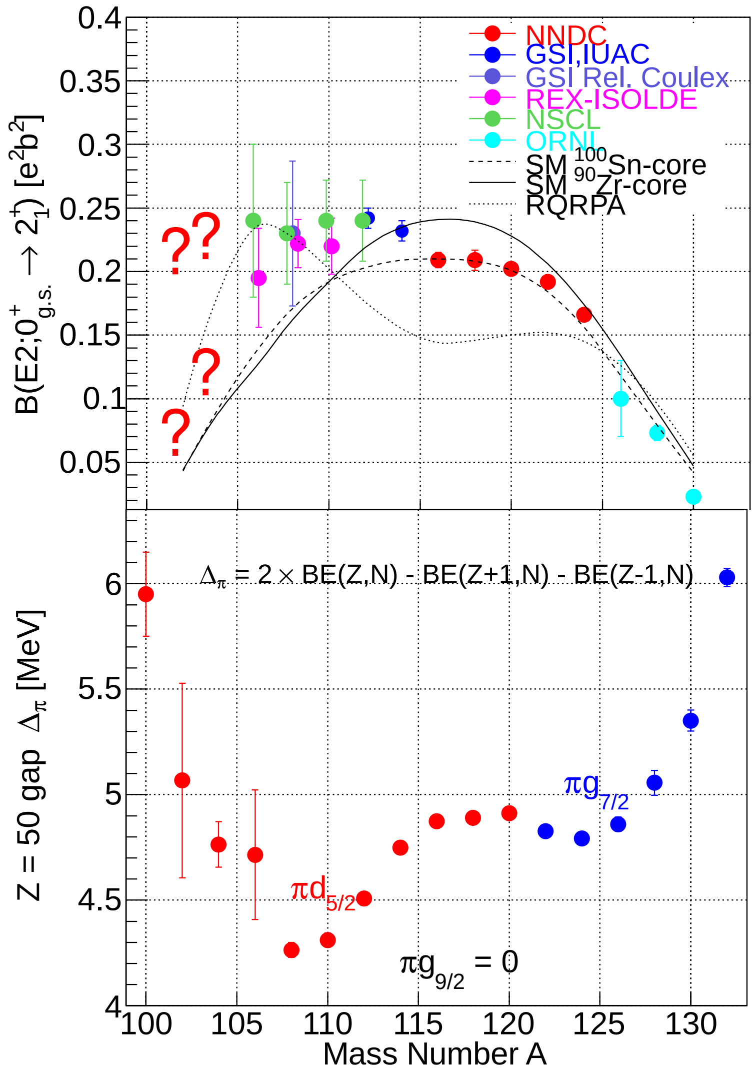
Proton-rich Sn nuclei

$B(E2)\uparrow$ *Systematics in the Tin Isotopes*



- Shell model calculations:
  - SM ^{100}Sn-core (M. Hjorth-Jensen *et al.*): $\nu(d_{5/2}g_{7/2}d_{3/2}s_{1/2}h_{11/2})$; $e_\nu = 1.0e$
  - SM ^{90}Zr-core (F. Nowacki *et al.*): $\nu(d_{5/2}g_{7/2}d_{3/2}s_{1/2}h_{11/2})$; $e_\nu = 0.5e$ $\pi(g_{9/2}g_{7/2}d_{5/2}d_{3/2}s_{1/2})$; $e_\pi = 1.5e$ up to $4p4h$-excitations across the $Z = 50$ shell
- Observations:
  - gap stays constant between $A = 126$ and 116
  - Below $A = 116$ gap reduces by 600 keV before increasing toward the double shell closure at $N = 50$

$B(E2)\uparrow$ Systematics in the Tin Isotopes

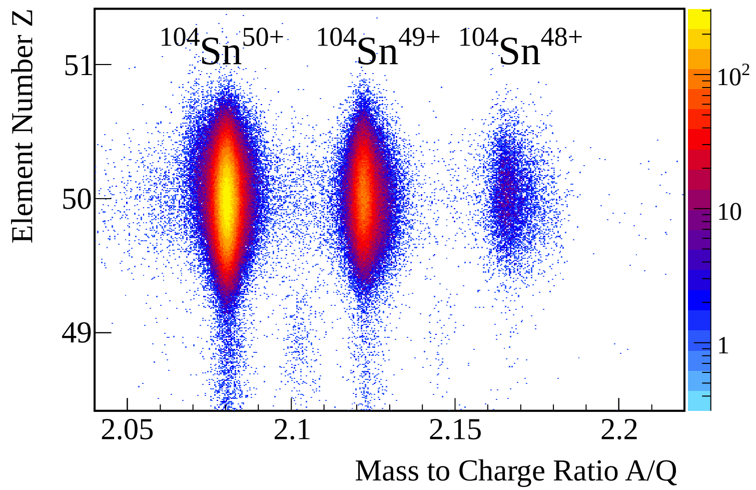


- Shell model calculations:
  - SM ^{100}Sn-core (M. Hjorth-Jensen *et al.*): $\nu(d_{5/2}g_{7/2}d_{3/2}s_{1/2}h_{11/2})$; $e_\nu = 1.0e$
  - SM ^{90}Zr-core (F. Nowacki *et al.*): $\nu(d_{5/2}g_{7/2}d_{3/2}s_{1/2}h_{11/2})$; $e_\nu = 0.5e$ $\pi(g_{9/2}g_{7/2}d_{5/2}d_{3/2}s_{1/2})$; $e_\pi = 1.5e$ up to $4p4h$-excitations across the $Z = 50$ shell
- Observations:
  - gap stays constant between $A = 126$ and 116
  - Below $A = 116$ gap reduces by 600 keV before increasing toward the double shell closure at $N = 50$

Coulomb Excitation of $^{104,112}Sn$

- ^{124}Xe, 6 pnA primary beam
- Pb(^{104}Sn,^{104}Sn*), Pb(^{112}Sn,^{112}Sn*)
- F8 target: $^{nat.}$Pb, 0.557 g/cm^2
- 150, 170 MeV/u in front of F8 target
- 600 pps ^{112}Sn @F11
- 168 pps ^{104}Sn @F11
- 5;17 hours data taking
- Rates including F8 PPAC efficiencies and
- Only fully stripped ions

PID in the ZD spectrometer



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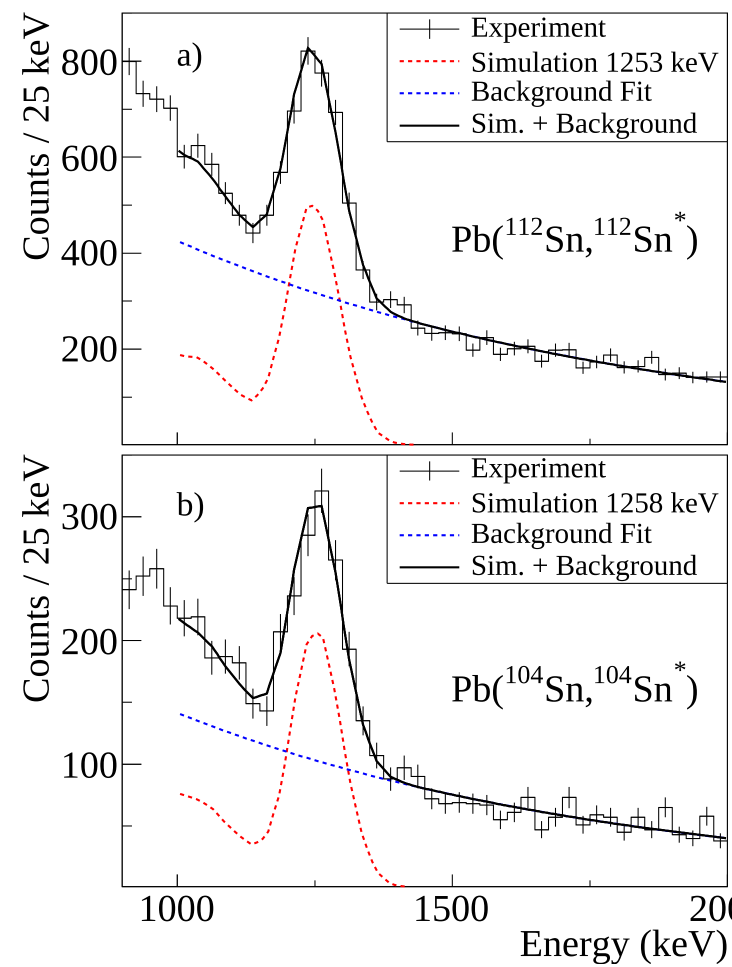
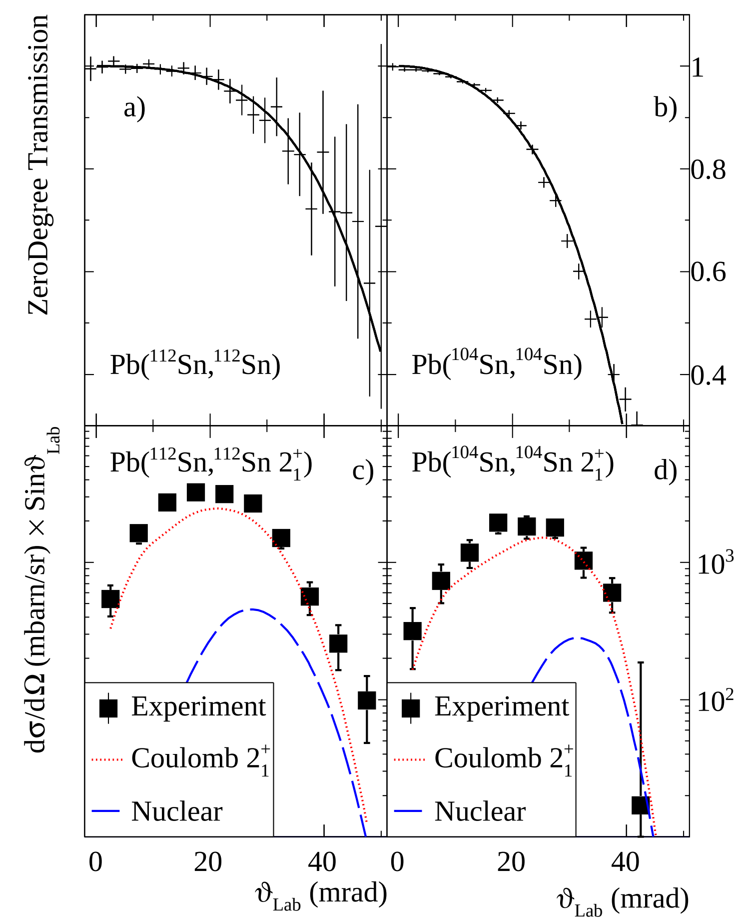
Doppler corrected γ-ray energy



$B(E2)\uparrow$ Values in Sn Isotopes

- Scattering angle reconstruction resolution $\approx$ 5 mrad
- Angular straggling 6–8 mrad
- Grazing angle 25–30 mrad
- Integration over all scattering angles
- Nuclear contributions determined from runs on carbon targets and DWEIKO calculations
- $B(E2)\uparrow$ from absolute cross-sections $\sigma_{2_1^+} = \sigma_n + \sigma_c + \sigma_f$
- Folded with ZeroDegree transmission



$B(E2)\uparrow$ *Values in Sn Isotopes*

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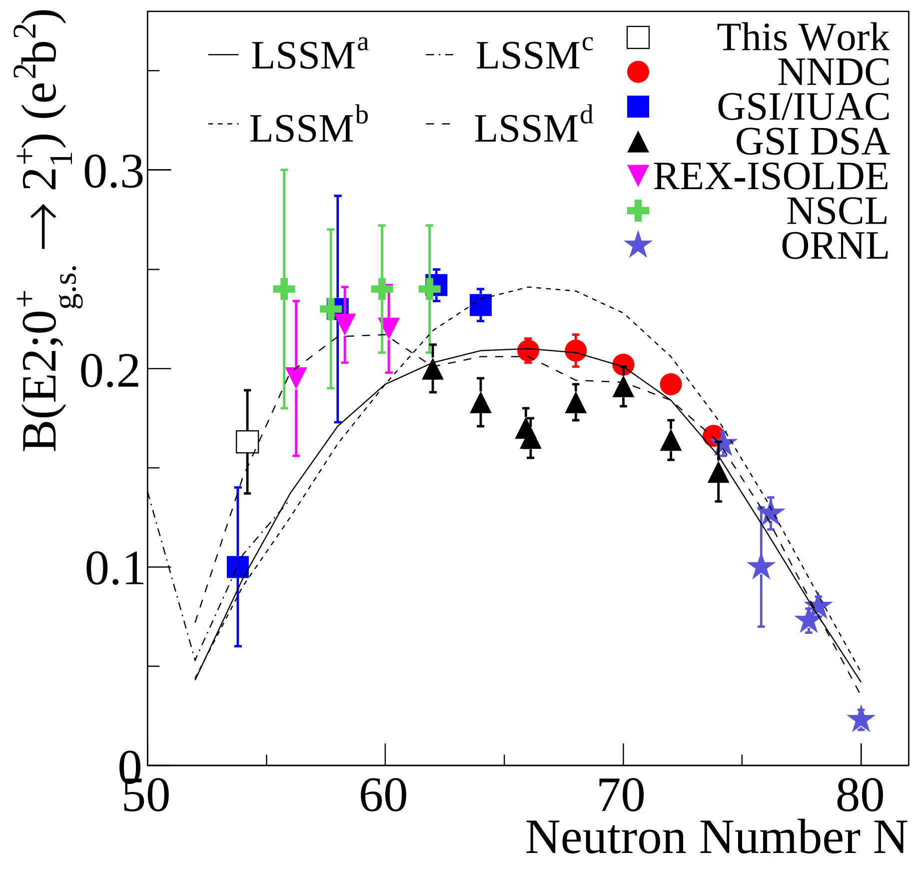
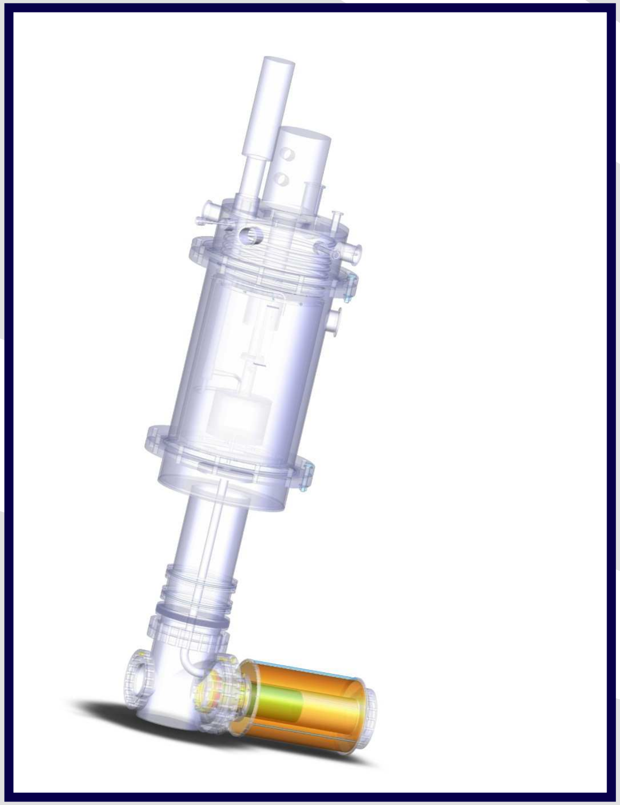
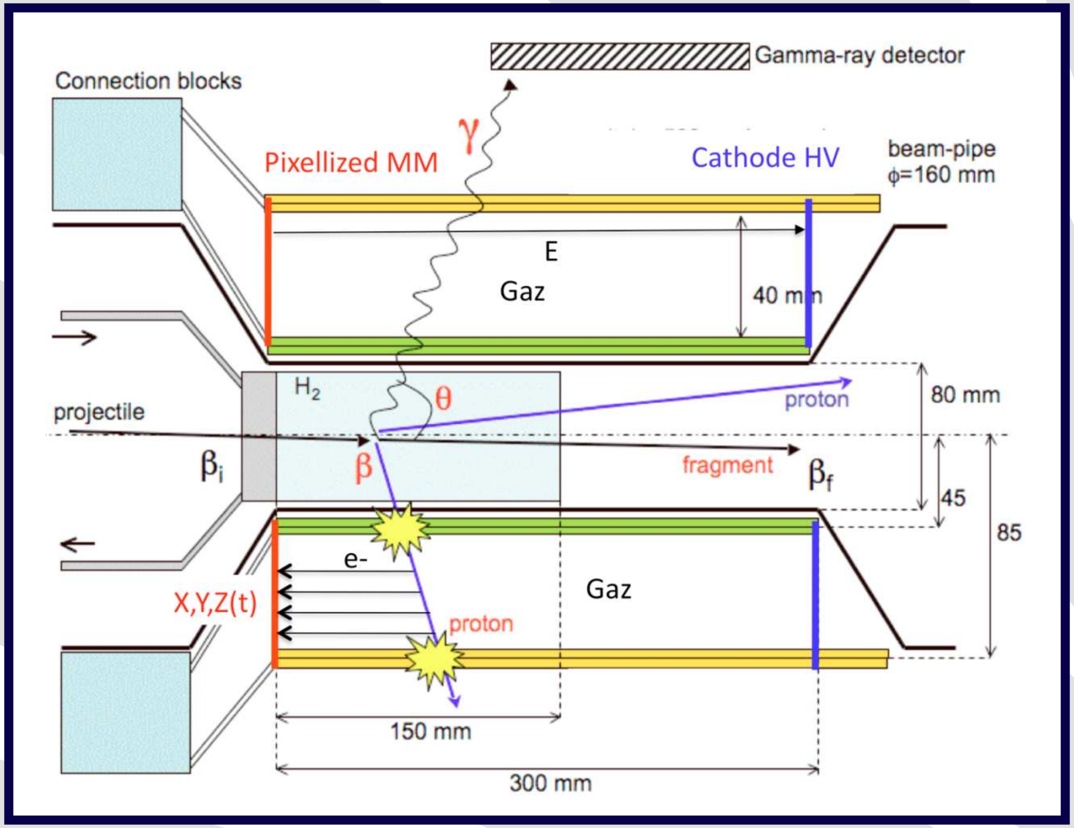


LSSM[a]: ^{100}Sn core, $e_\nu = 1.0e$, A. Banu *et al.*, PRC 72, 061305(R) (2005)
LSSM[b]: ^{90}Zr core, $e_\nu = 0.5e, e_\pi = 1.5e$, A. Banu *et al.*, PRC 72, 061305(R) (2005)
LSSM[c]: ^{80}Zr core, $e_\nu = 0.5e, e_\pi = 1.5e$, G. Guastalla *et al.*, PRL 110, 172501 (2013)
LSSM[d]: ^{90}Sn core, isospin dependent e_ν, T. Bäck *et al.*, PRC 87, 031306(R) (2013)

MINOS: MagIc Numbers Off Stability

MINOS: Coupling of a Liquid Hydrogen Target with a TPC





- Developed at the CEA Saclay (Project Manager: A. Obertelli)
- Up to 1 g/cm^2 liquid hydrogen
- Goal: 3 mm resolution (FWHM), 80 % efficiency
- Experiments from FY 2014
- Surrounded by DALI2

Summary and Outlook

SUNFLOWER: **S***pectroscopy of* **U***nstable* **N***uclei with* **F***ast and s***LOW** *beam* **E***xperiments at the* **R***IBF*

- The SUNFLOWER collaboration was launched in 2012 to enhance activities of the in-beam γ-ray spectroscopy at RI Beam Factory (RIBF)
- SUNFLOWER stands for “Spectroscopy of Unstable Nuclei with Fast and sLOW beam Experiments at the RIBF”
- and is a framework to coordinate researchers in the field of nuclear structure studies of unstable nuclei using fast and decelerated RI beams at RIBF by means of g-ray measurements
- See `http://www.nishina.riken.jp/collaboration/SUNFLOWER` and register

Summary and Outlook

- DALI2 is present workhorse for in-beam γ-ray spectroscopy at the RIBF
- Experimental data obtained so far very promising for all performed experiments
- MINOS was delivered to RIKEN in June 2013
  - Tests at RIKEN (w/o beam) and HIMAC (w/ beam, TPC only) this calendar year
  - Experiments from FY 2014

THE END

Backup slides from now