Characterizing Deformation in the Neutron-Rich Mg Isotopes: *N*=20 to *N*=28

Heather L. Crawford

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Outline

- Structure in neutron-rich Mg
  - Shells and shapes…
  - What do we know (or think we know?)
- ‘High-spin’ nuclear physics in ^{32,33}Mg
  - Reaching to 6^+
  - Pairing in light systems
- The outer limits -- ^{40}Mg
  - Making the most neutron-rich nuclei
  - Physics with 5 events
- Summary

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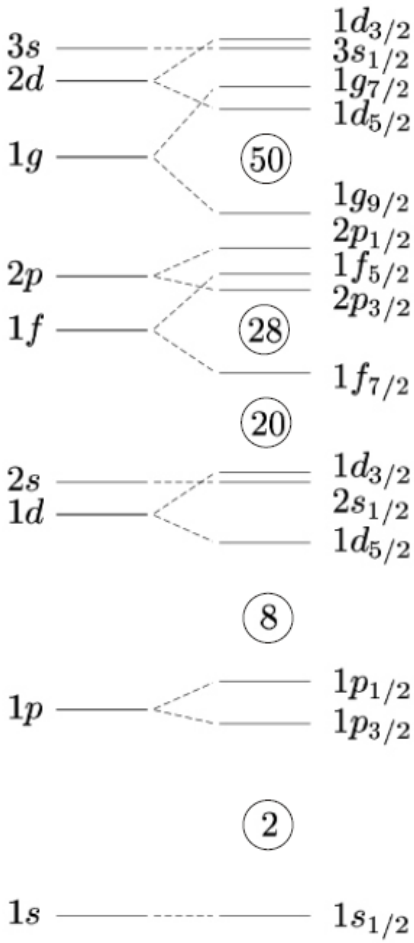
“Exotic” shell structure



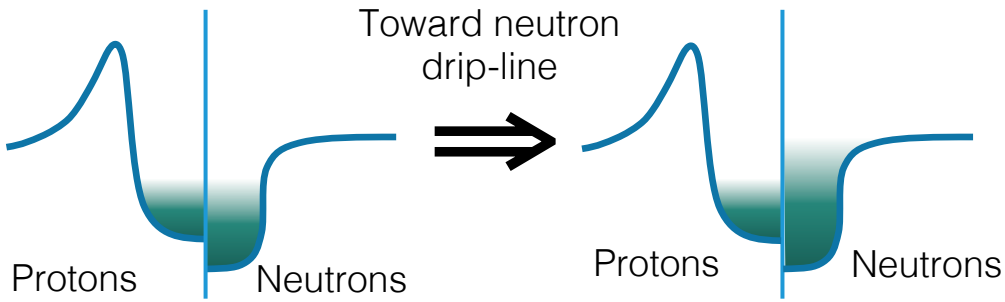
Near the valley of β stability

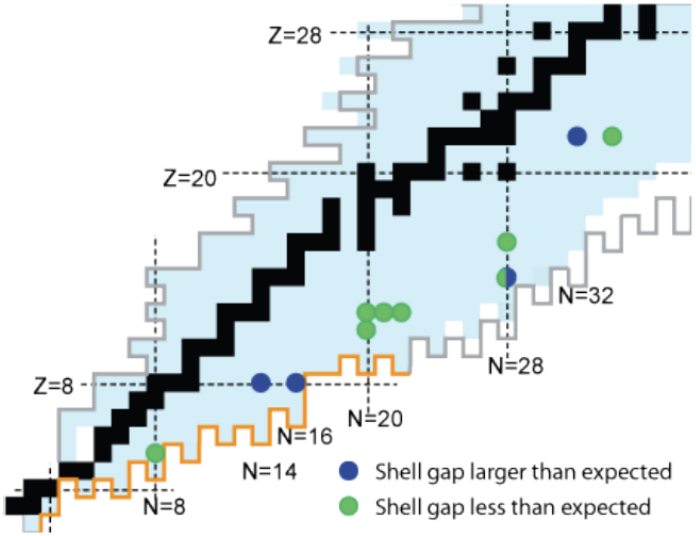
⇒ ?

Approaching the drip-lines

A driving question in nuclear science:

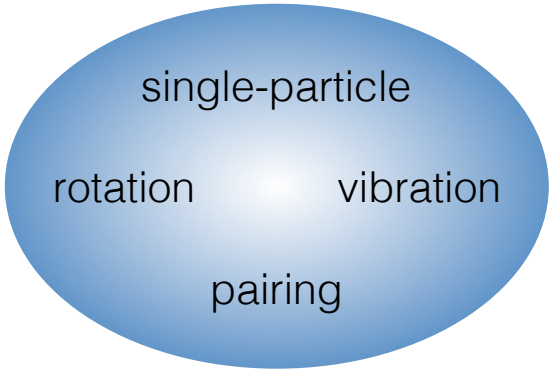
Is the shell-model description static across the entire chart of nuclides?





Elementary Modes of Excitation

Elementary modes of excitation are a central theme in nuclear structure physics

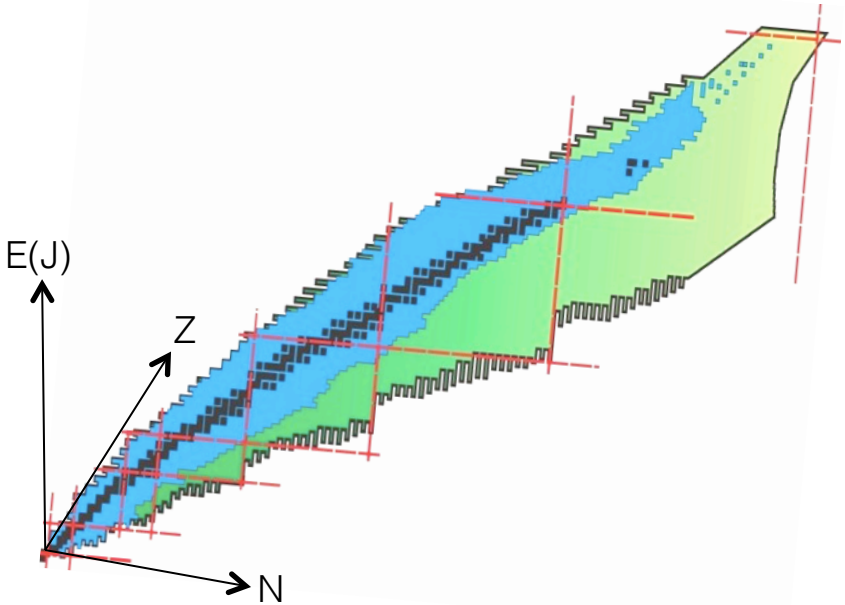


Exist on similar energy scales

A. Bohr and B.R. Mottelson

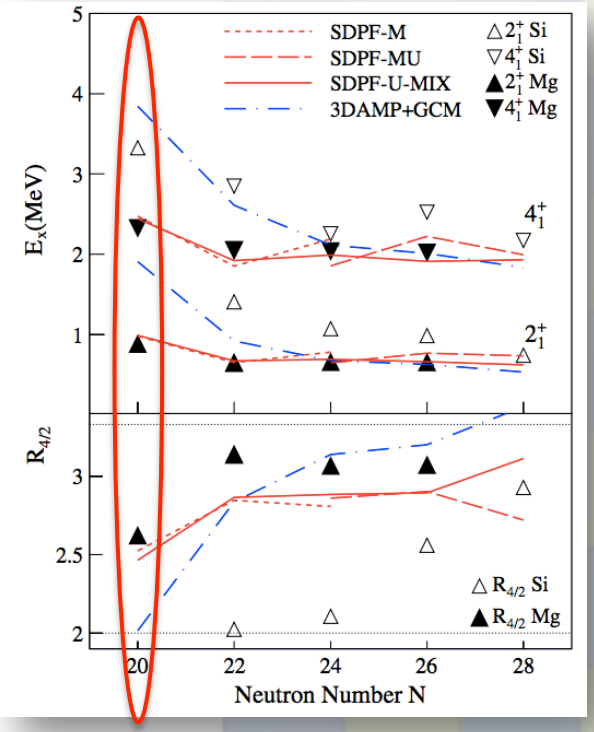
Competition - single-particle, collective

With the development of exotic beams, we have started to chart the evolution of these excitation mechanisms with isospin towards to neutron drip-line

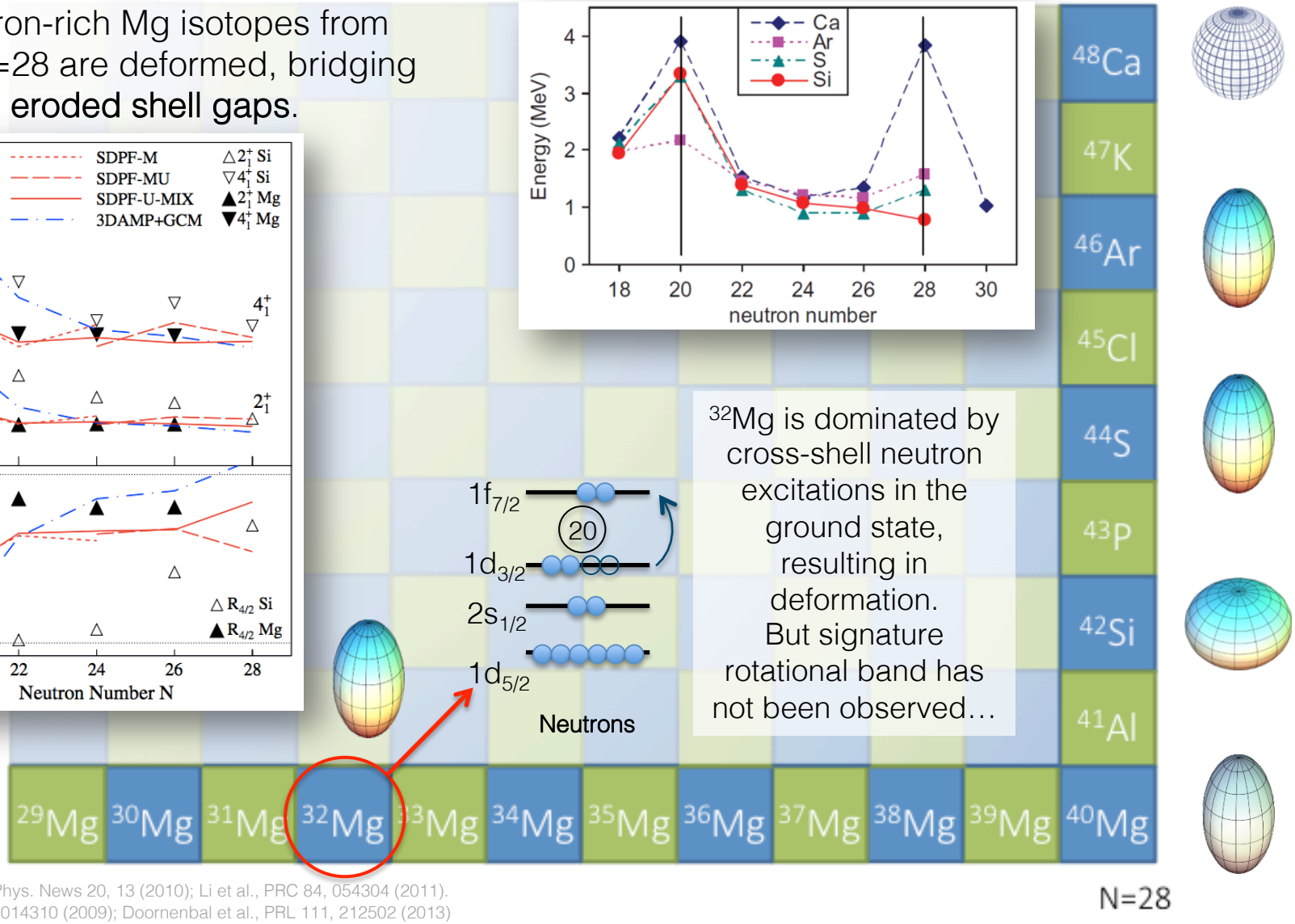


Structure in Neutron-Rich Mg

The neutron-rich Mg isotopes from N=20 to N=28 are deformed, bridging two **eroded shell gaps**.



^{32}Mg is dominated by cross-shell neutron excitations in the ground state, resulting in deformation. But signature rotational band has not been observed…



Gaudefroy and Grevy, Nucl. Phys. News 20, 13 (2010); Li et al., PRC 84, 054304 (2011).
Nowacki and Poves, PRC 79, 014310 (2009); Doornenbal et al., PRL 111, 212502 (2013)

^{32}Mg (Shells and Correlations)

The region near ^{32}Mg (island of inversion) has been a subject of intense work for many years, both experimental and theoretical.

Main Ingredients in the Physics

Interplay between

- Monopole field (spherical mean field)
- Multiple correlations (pairing, Q-Q ..)

Collectivity can arise from both deformation/quadrupole and pairing

- Much evidence for the existence of deformed/collective ground states
- However band structures, the fingerprints of rotational motion and deformation, have not yet been observed and a basic question on what exactly are the excitation spectra and collective modes remains unanswered

Moments of inertia provide basic data on the stability of the deformation, the nucleon-core coupling, and pairing

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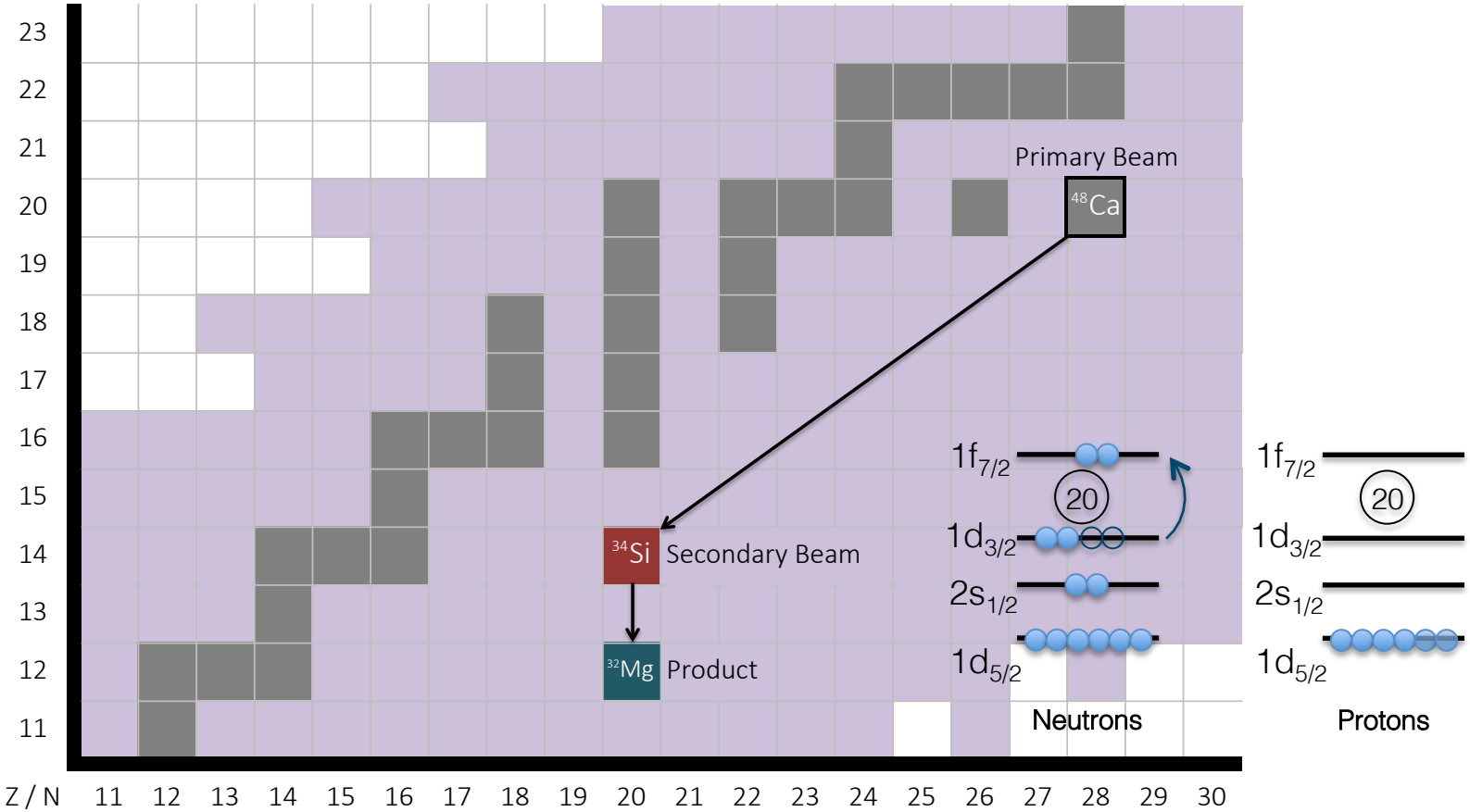
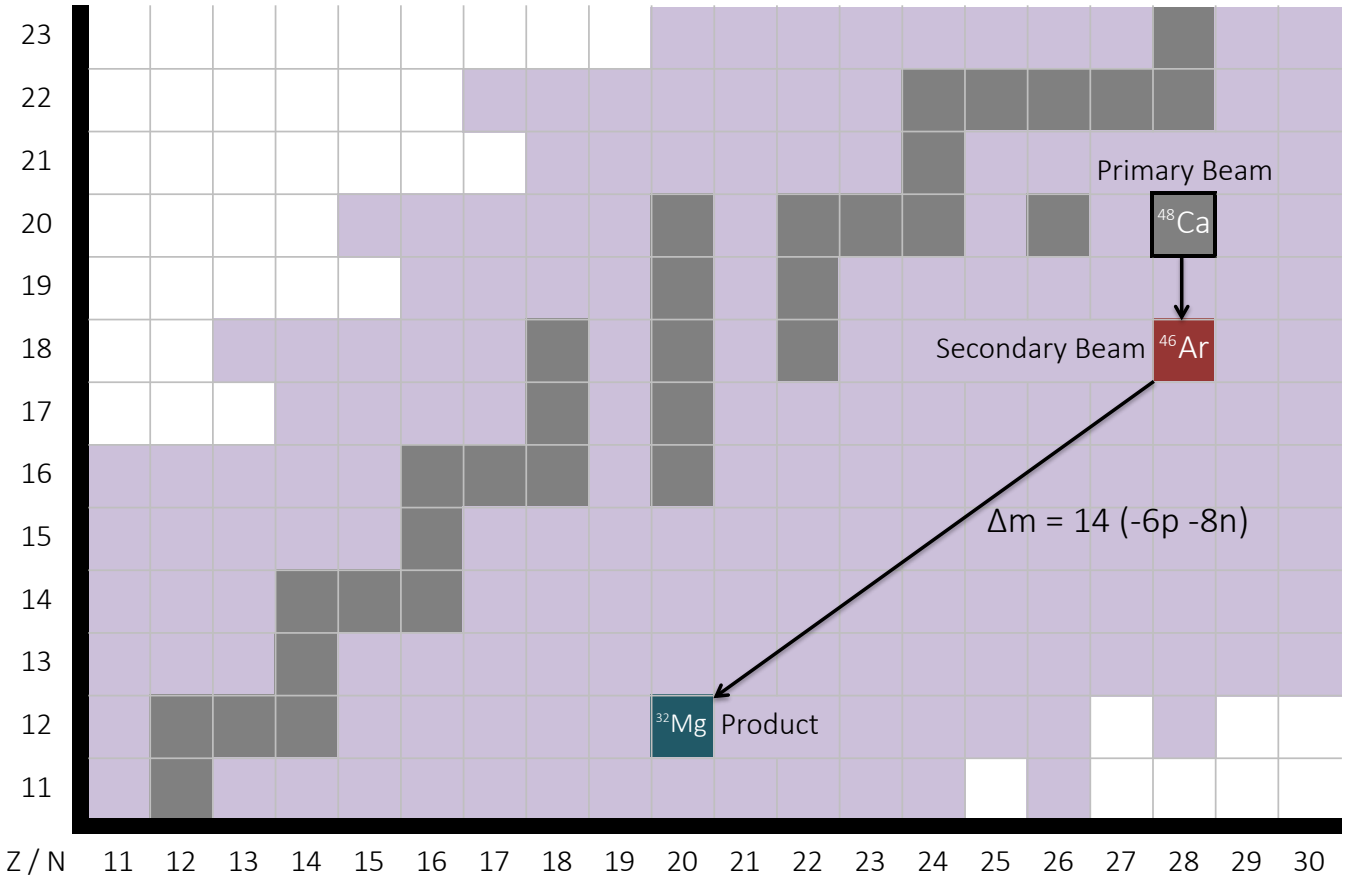
Fast beams - fragmentation



"2-Step Reaction"

- Powerful, Selective: enables "direct reactions" (nucleon removal/pickup)
- Main approach today

Fast beams - fragmentation

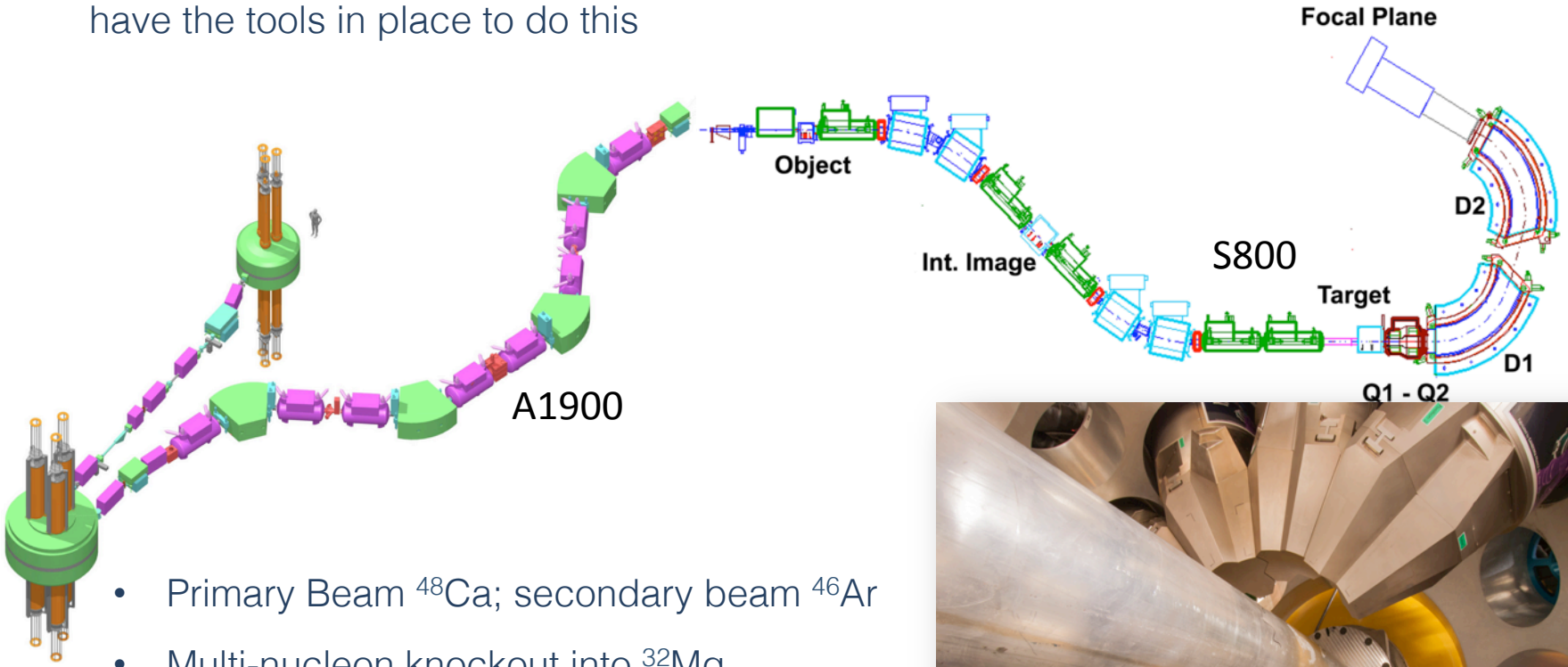


"1-Step Reaction"

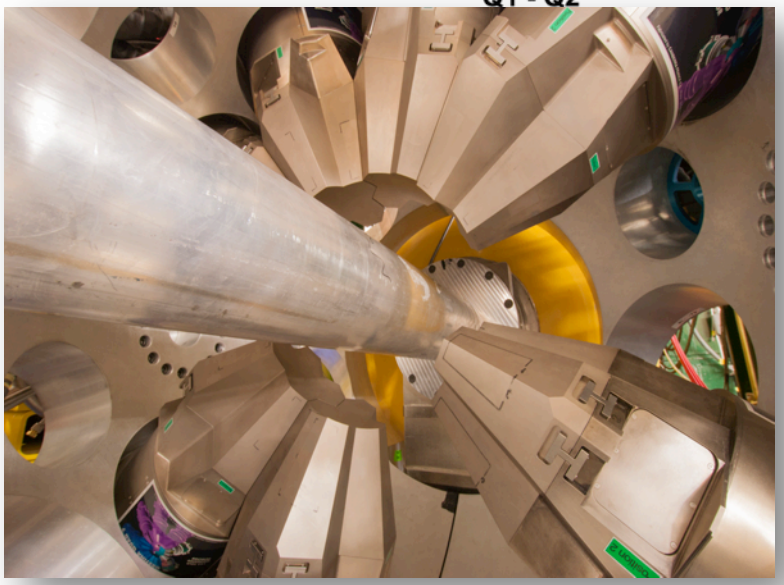
- Less selective – enables "more statistical" population.
- Angular momentum imparted to a nucleus produced in a projectile fragmentation reaction is related to the mass difference (Δm) between the projectile and the final fragment nucleus

Experiment E11029: GRETINA@S800

- GOAL: To see and to study the yrast rotational states (band)
- With the intense beams available at NSCL and the availability of GRETINA, we have have the tools in place to do this



- Primary Beam ^{48}Ca; secondary beam ^{46}Ar
- Multi-nucleon knockout into ^{32}Mg
- GRETINA: All 7 modules at 90 degrees
  - Minimize light particle induced background



GRETINA

Gamma-Ray Energy Tracking In-beam Nuclear Array

$20M funded by US DOE-Nuclear Physics Office

Nuclear Instruments and Methods in Physics Research A 709 (2013) 44–55

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The performance of the Gamma-Ray Energy Tracking In-beam Nuclear Array GRETINA

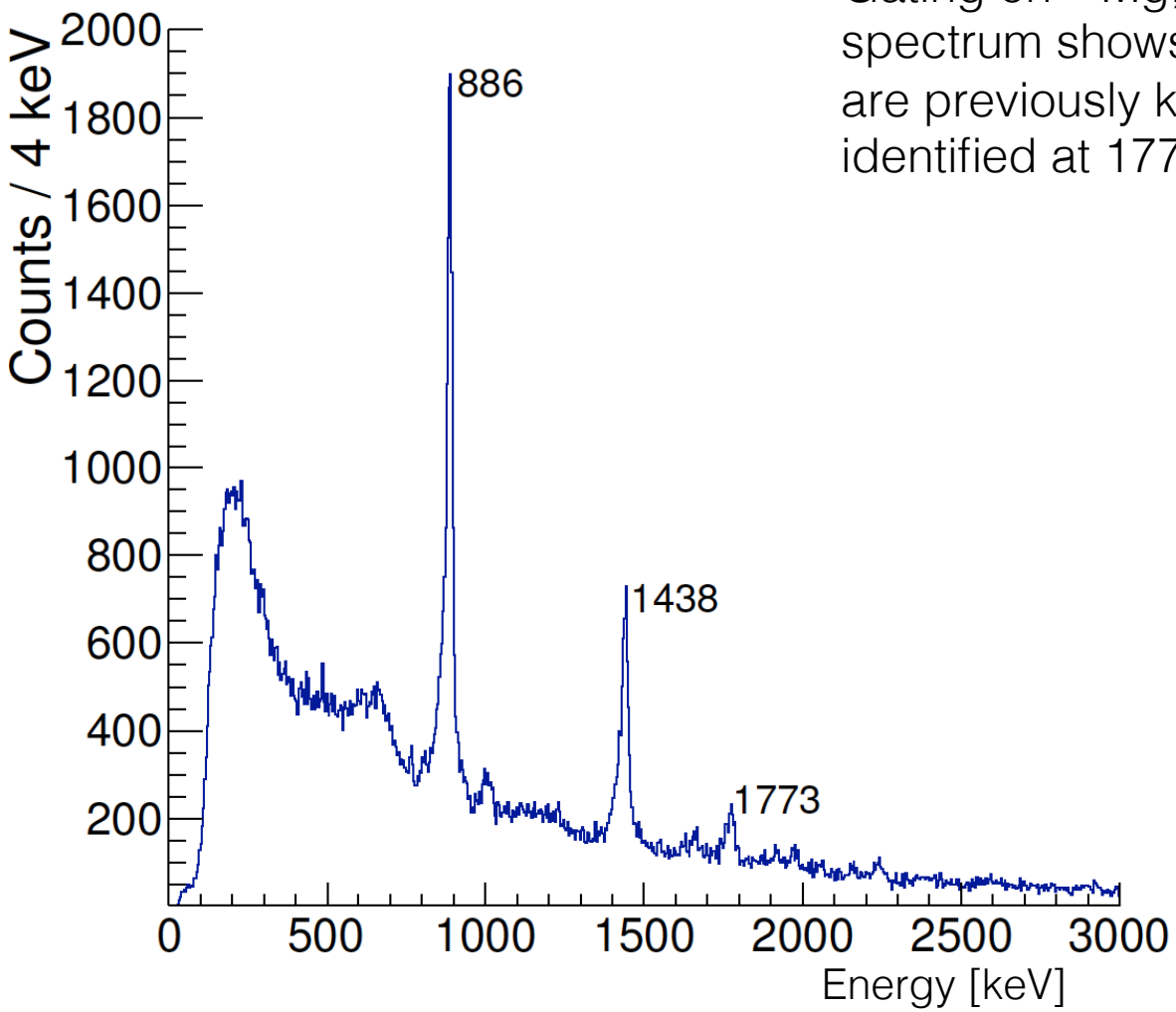
S. Paschalis [a,*], I.Y. Lee [a,**], A.O. Macchiavelli [a], C.M. Campbell [a], M. Cromaz [a], S. Gros [a], J. Pavan [a], J. Qian [a], R.M. Clark [a], H.L. Crawford [a], D. Doering [a], P. Fallon [a], C. Lionberger [a], T. Loew [a], M. Petri [a], T. Stezelberger [a], S. Zimmermann [a], D.C. Radford [b], K. Lagergren [b], D. Weisshaar [c], R. Winkler [c], T. Glasmacher [c], J.T. Anderson [d], C.W. Beausang [e]

[a] Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[b] Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[c] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA
[d] Argonne National Laboratory, Argonne, IL 60439, USA
[e] Department of Physics, University of Richmond, 28 Westhampton Way, Richmond, VA 23173, USA

- Covers approx. ¼ of 4π solid angle
- 28 x 36 fold segmented crystals housed in 7 (quad) modules
- Mechanical support structure, digital data acquisition and data processing software were all developed within the project
- Array represents significant advancements in **all** areas: detector technology, electronics and data processing

I-Yang Lee, Amel Korichi -- *Wednesday*

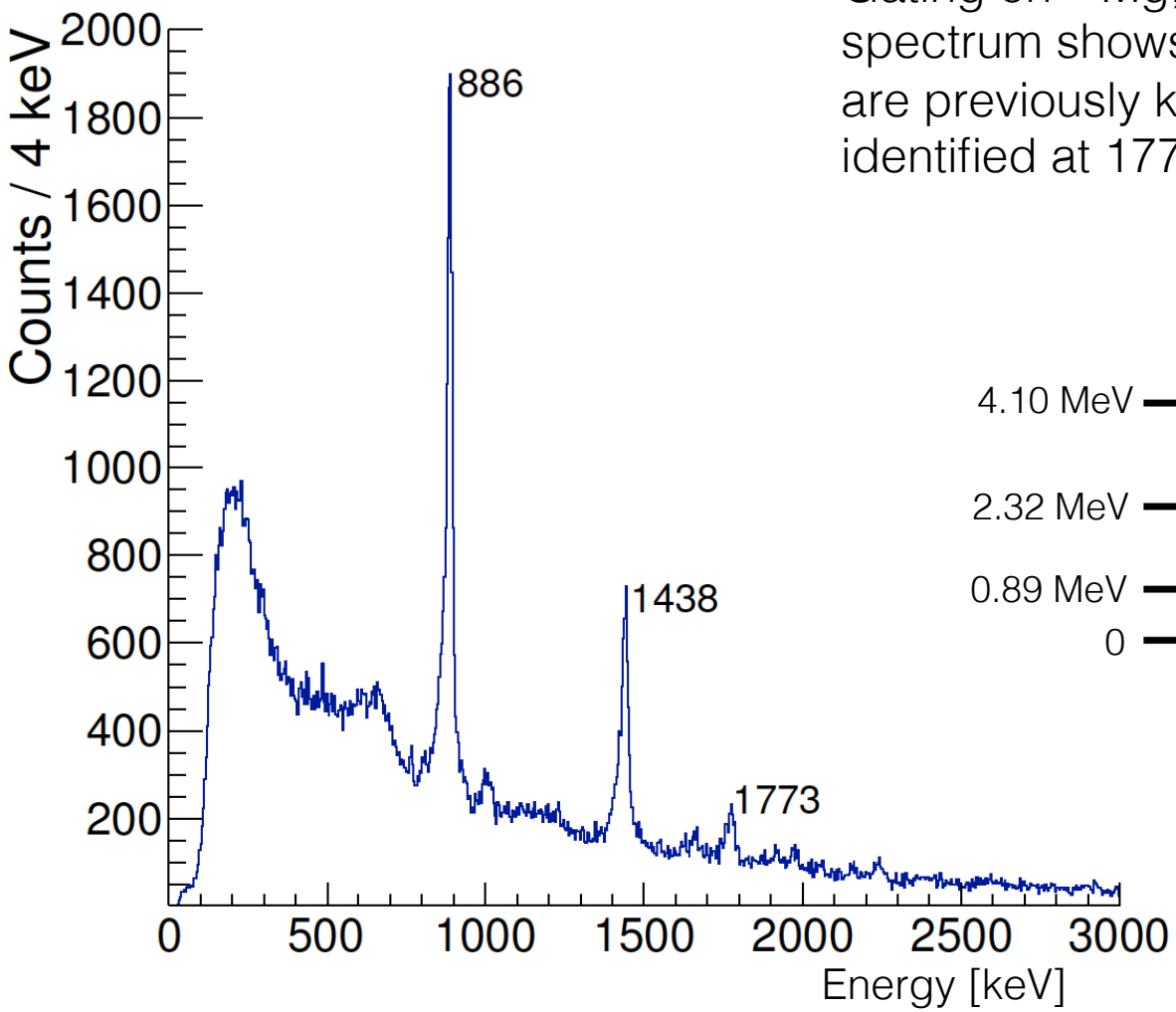
Gamma-Ray Singles



- Gating on ^{32}Mg, gamma-ray singles spectrum shows 3 strong peaks; 2^+ and 4^+ are previously known; candidate 6^+ identified at 1773 keV

C. Detraz *et al.*, PRC **19**, 164 (1979); S. Takeuchi *et al.*, PRC **79**, 054319 (2009); E. Caurier *et al.*, PRC **90**, 014302 (2014).

Gamma-Ray Singles



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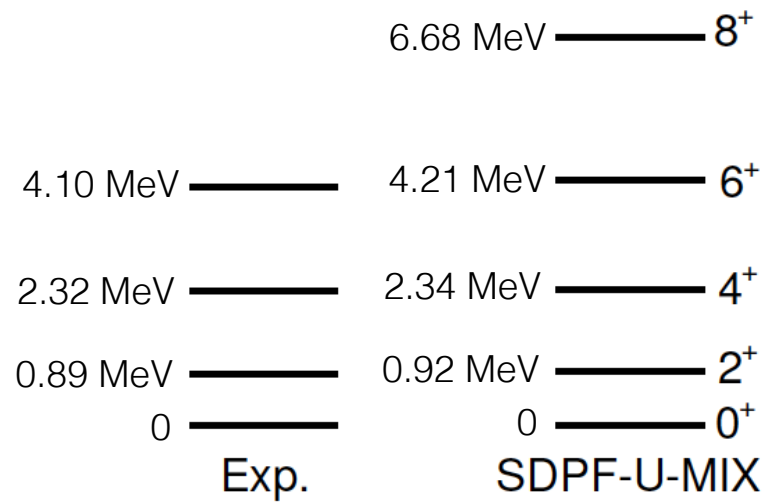

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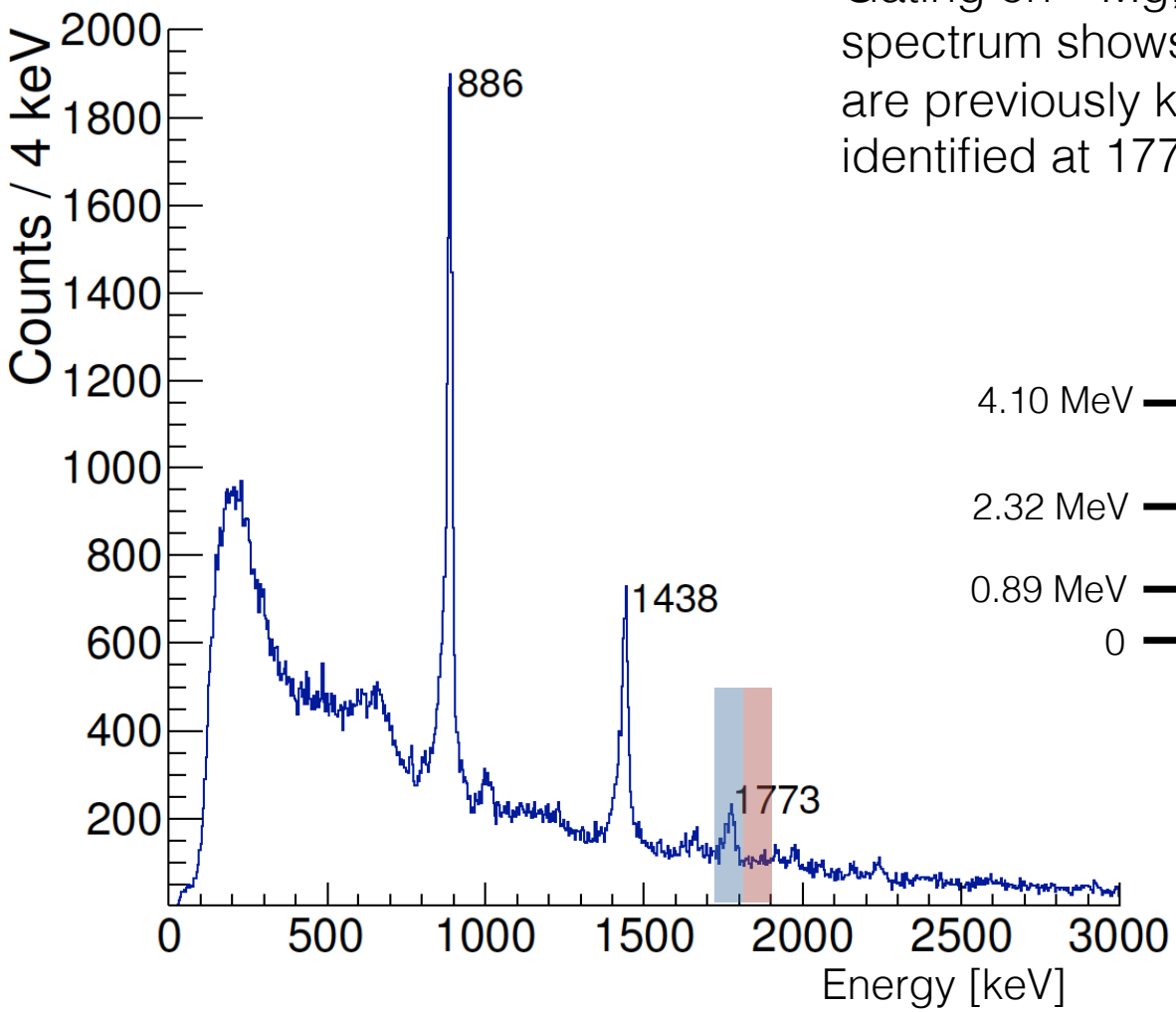

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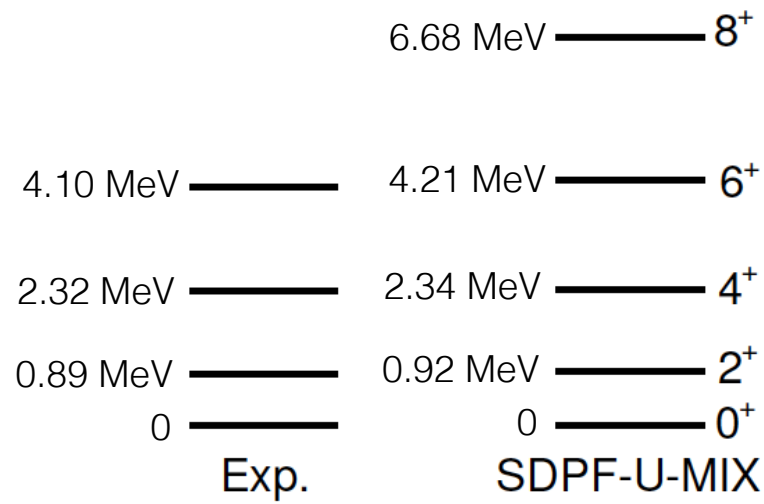

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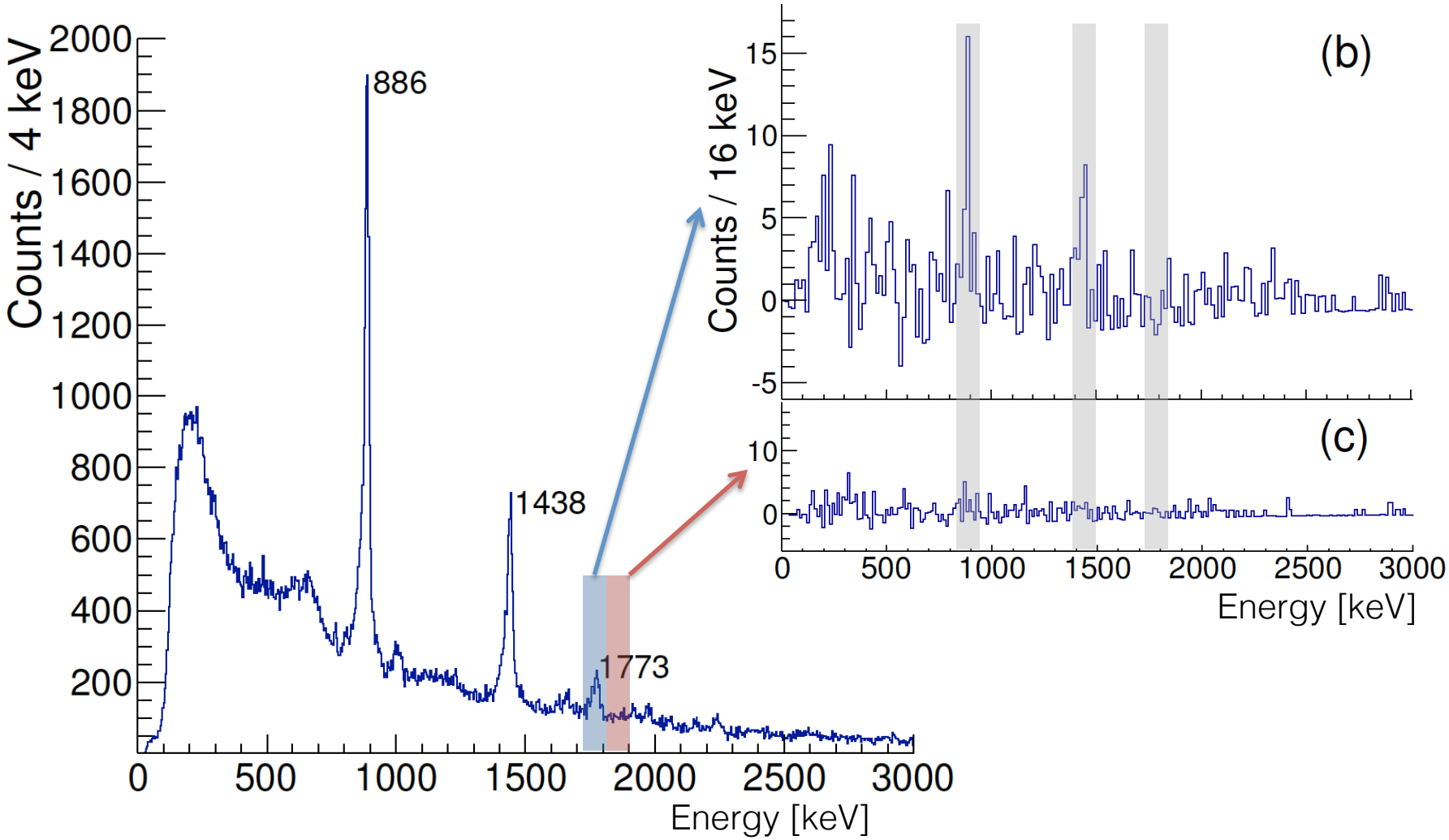
Gamma-Ray Singles



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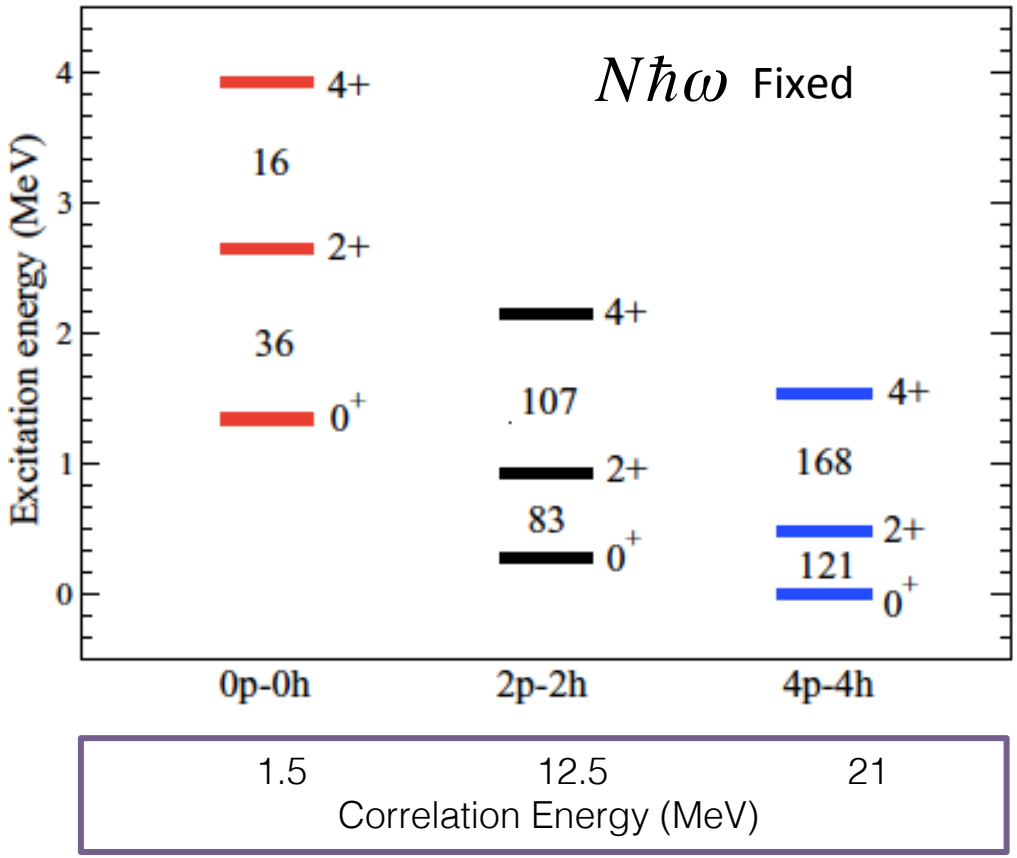
^{32}Mg Shell Model

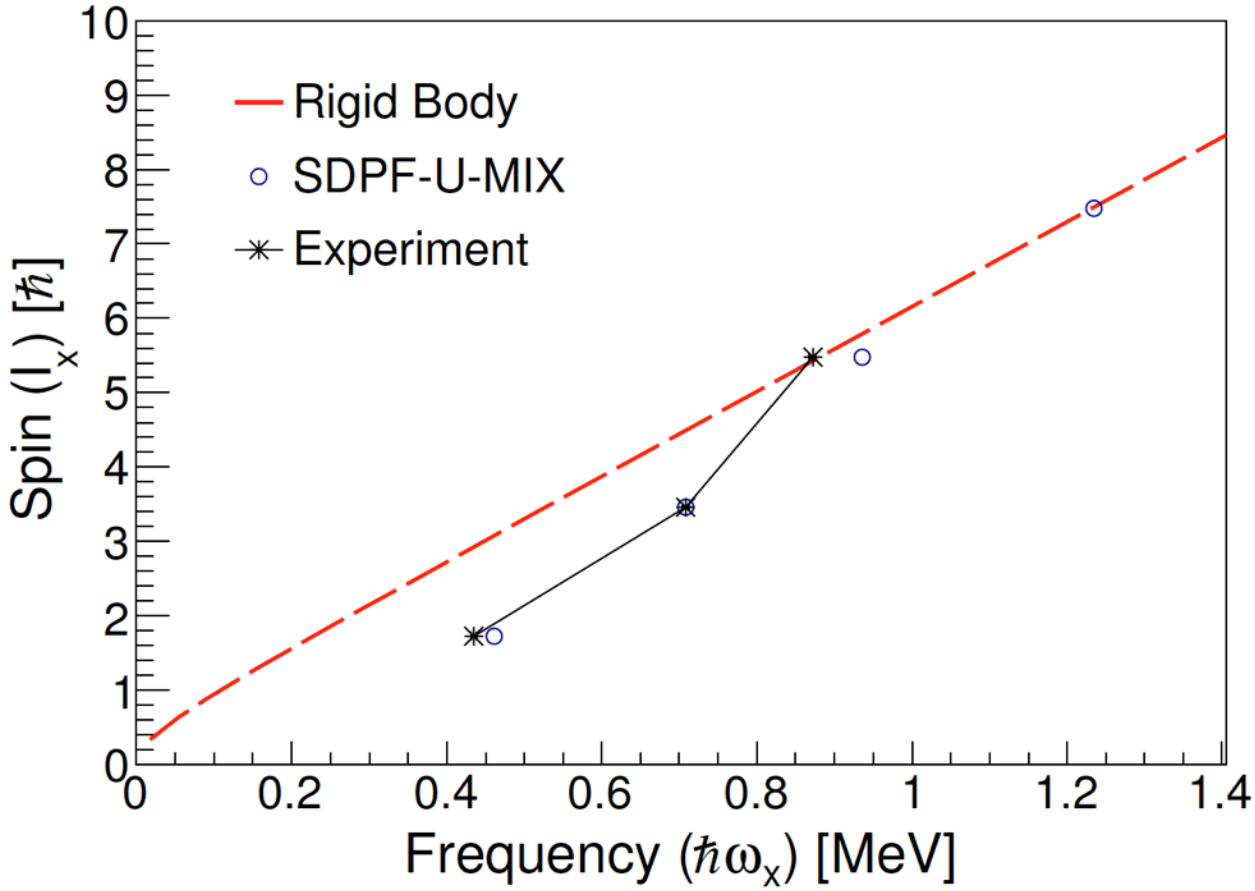
Spin	2p-2h (%)	4p-4h (%)	Q_0
0	53	37	--
2	43	54	56.2
4	31	68	67.8
6	31	68	65.4
8	10	90	59.5

- ^{32}Mg mixed 2p-2h and 4p-4h
- "constant deformation"
- 4p-4h fixed configuration is an "ideal rotor" (superdeformed bands in ^{36}Ar and ^{40}Ca)

Caurier, Nowacki, Poves PRC 90, 0914302 (2014)
SDPF-U-MIX interaction



Spin vs. Rotational Frequency



$J^{(1)} = I/\omega$

$\omega = E_\gamma/2$

I/ω plot shows:

$2^+ - 0^+$ $J^{(1)} \sim 0.5 * J_{rigid}$

$6^+ - 4^+$ $J^{(1)} \sim J_{rigid}$

$J^{(1)} < J_{rigid}$ reflects the presence of correlations (pairing)

Origin of a changing moment of inertia

- Changing moment of inertia
  - Change in deformation with increasing angular momentum
  - Quasiparticle alignment (a "CSM picture")
  - Change in pairing with angular momentum (decrease)

- ^{32}Mg: shell model suggests constant deformation

Spin	2p-2h (%)	4p-4h (%)	Q_0
0	53	37	--
2	43	54	56.2
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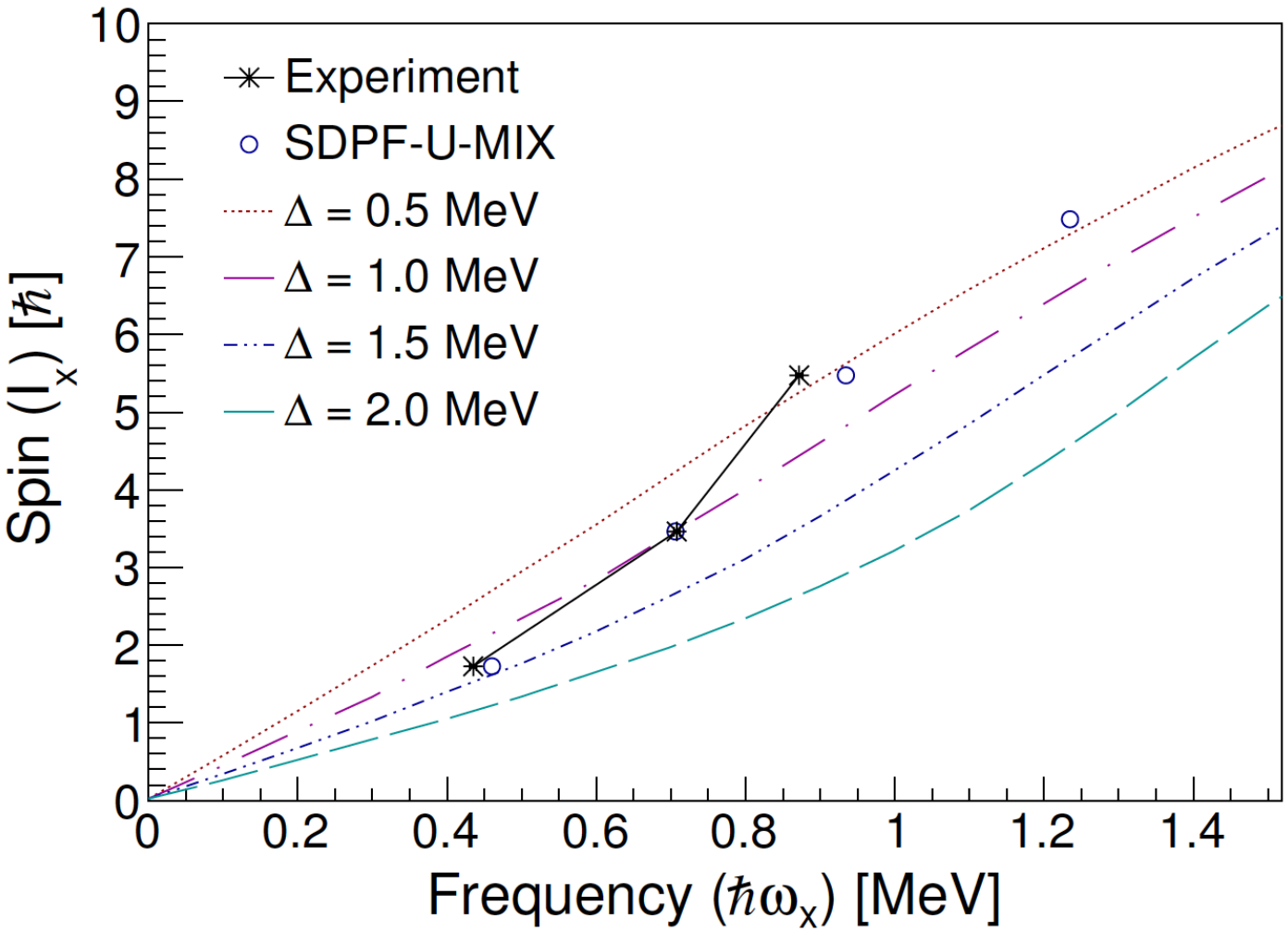
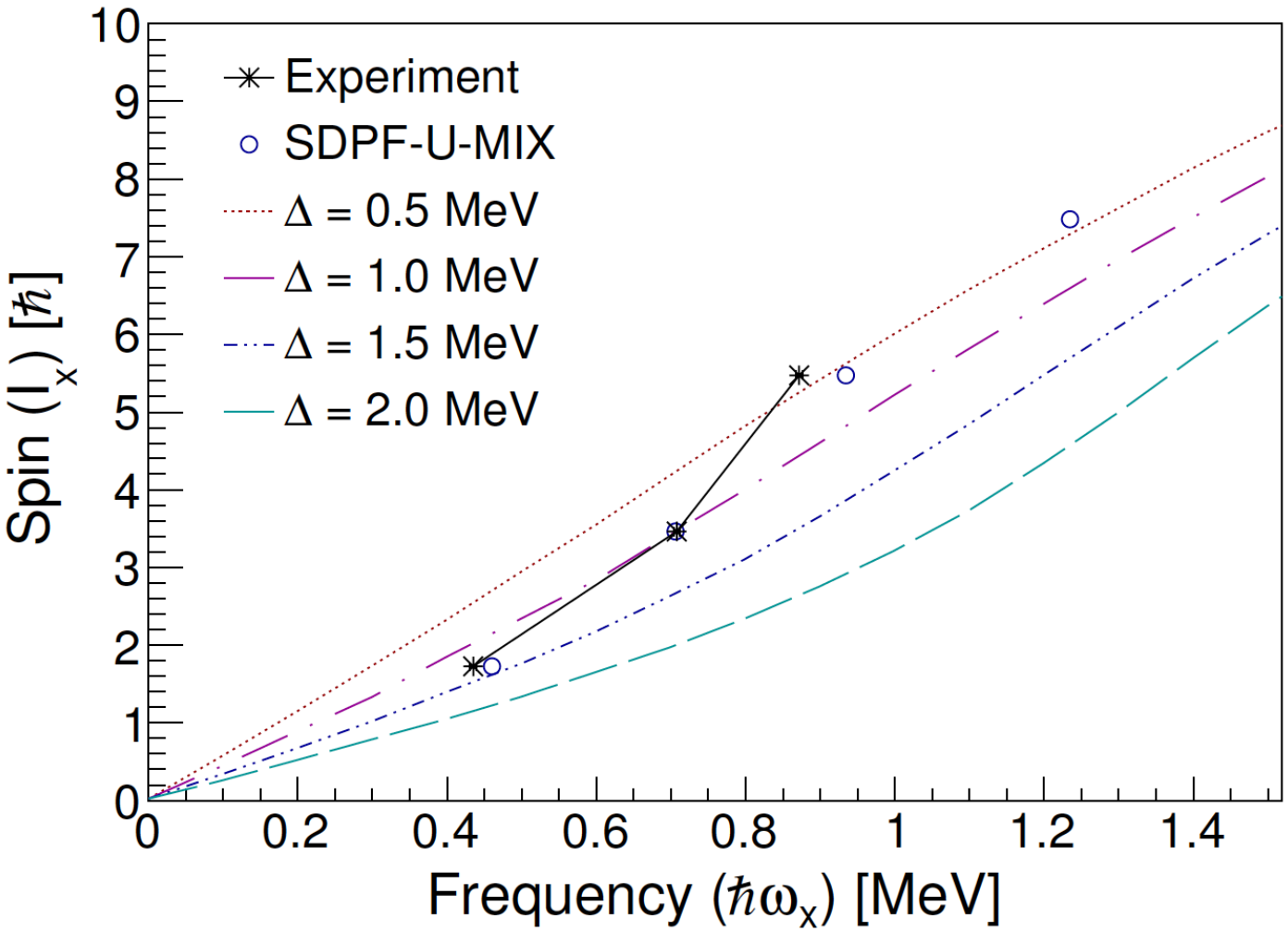
6	31	68	65.4

- There is a change in nucleon configuration however – investigate alignment effects within more traditional rotational cranked-shell model

Cranked Shell Model



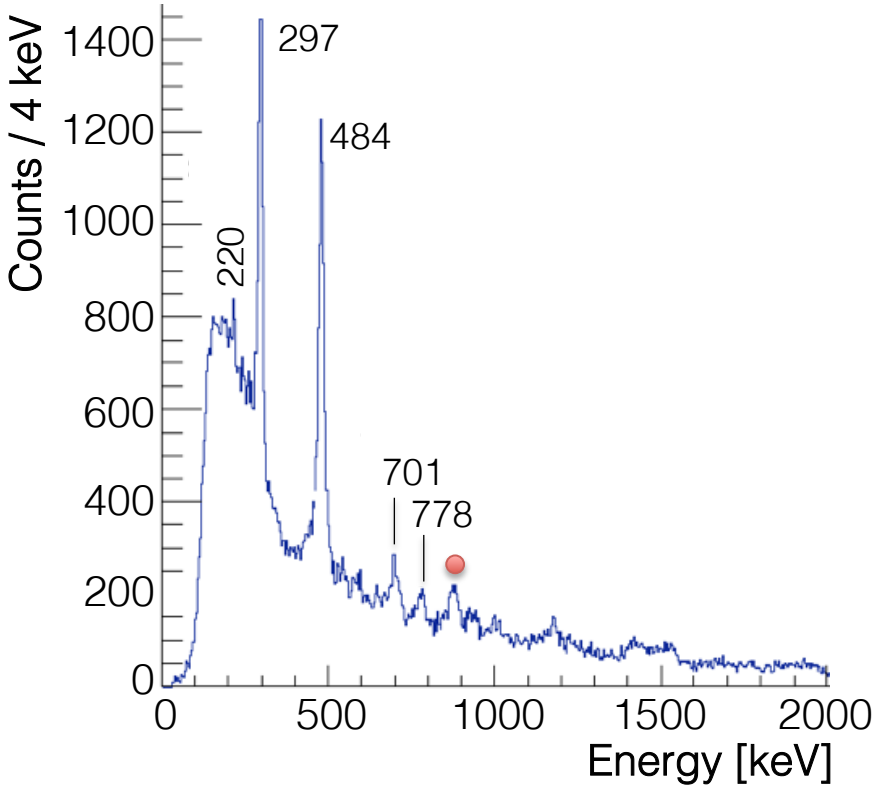
Cranked Shell Model



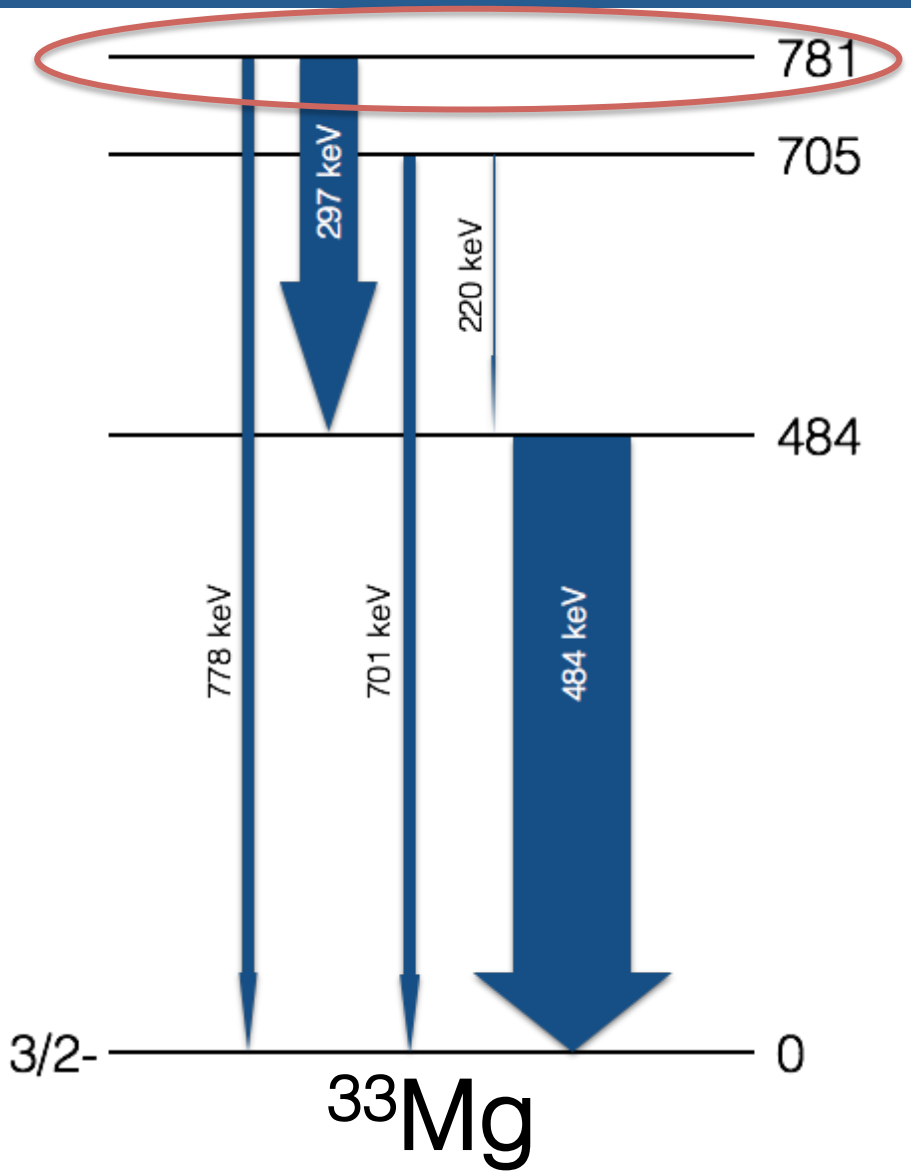
--> Alignment alone (with constant pair gap) does not reproduce upwards bend in the I-ω plot

--> To reproduce data, require change in pair gap by > 50%

Next-door Neighbour: ^{33}Mg



Thesis work of A. Richard
(Ohio University)

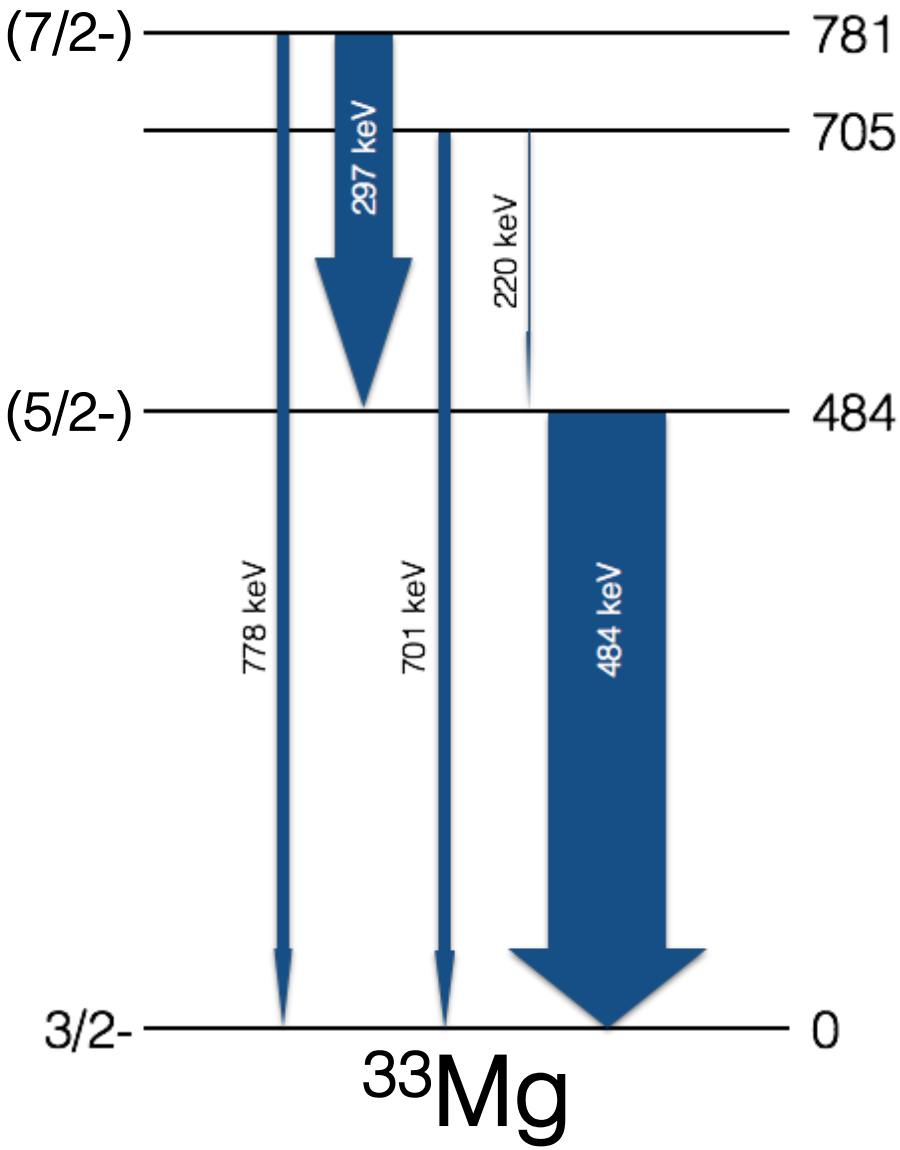


Next-door Neighbour: ^{33}Mg

Treatment as $^{33}Mg = (^{32}Mg + vp_{3/2})$ in the strong-coupling limit provides very good agreement…

g_k and g_R fit to reproduce ground-state g-factor = -0.50 ---> I(E2) / I(M1) from $7/2^-$ state = 0.16

Experimental ratio = 0.15(4)



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Structure in Neutron-Rich Mg

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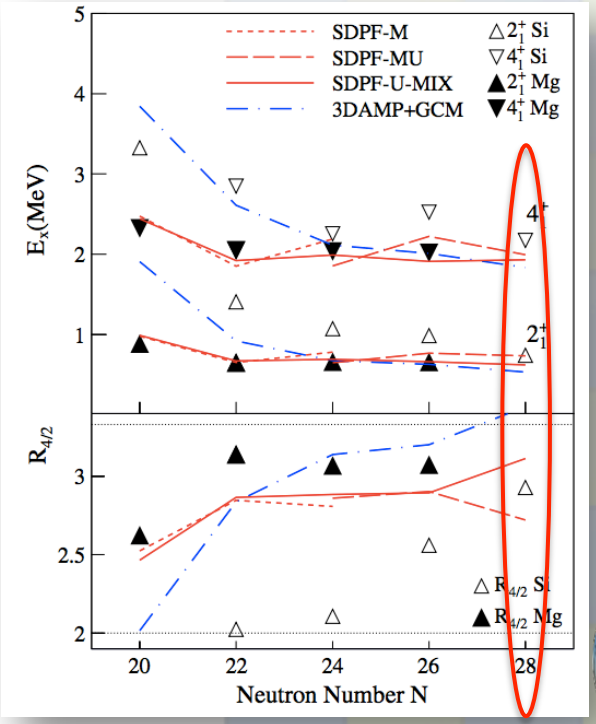
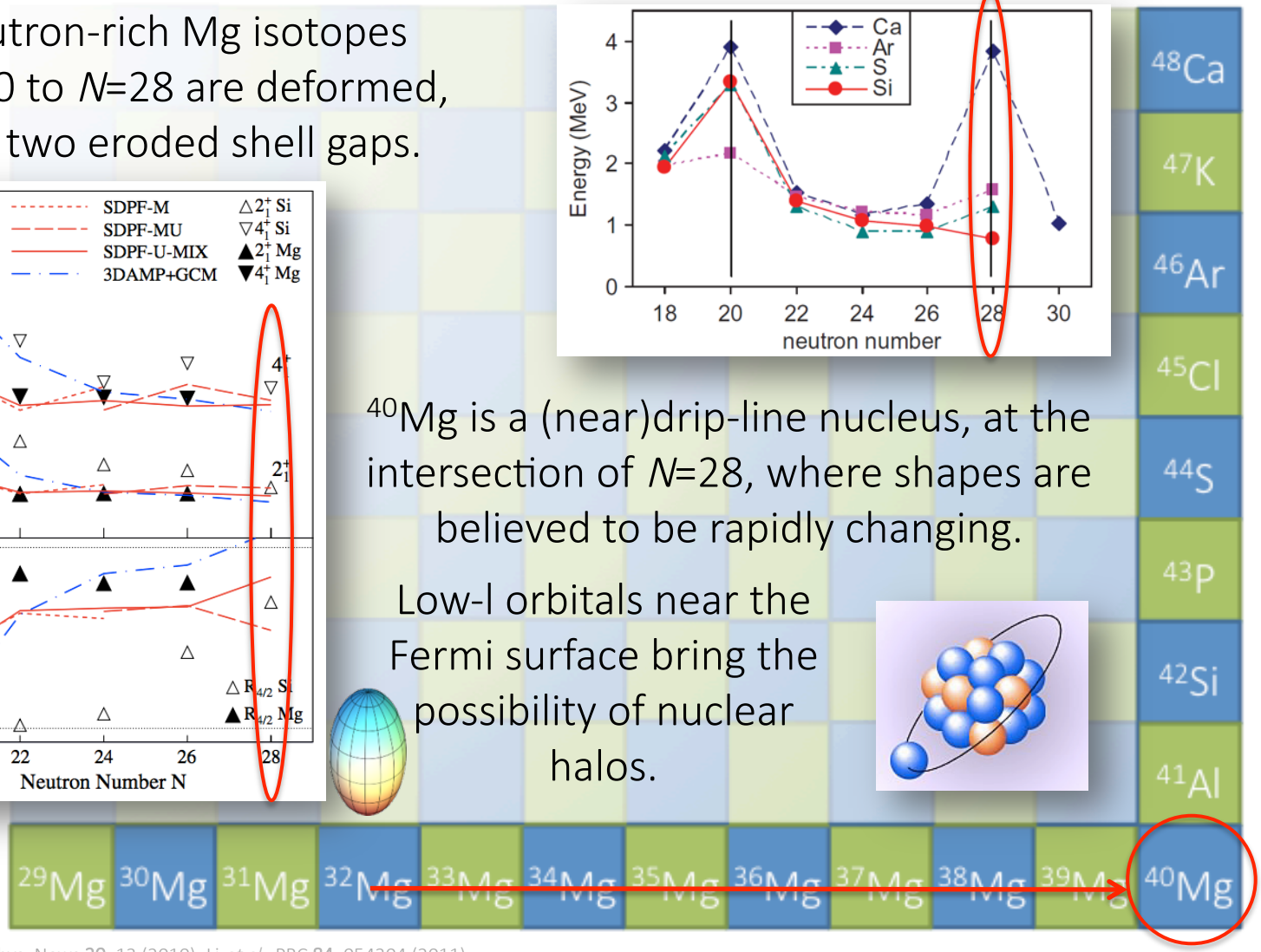


^{40}Mg is a (near)drip-line nucleus, at the intersection of *N*=28, where shapes are believed to be rapidly changing.

Low-l orbitals near the Fermi surface bring the possibility of nuclear halos.



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Nowacki and Poves, PRC **79**, 014310 (2009); Doornenbal *et al.*, PRL 111, **212502 (2013)**

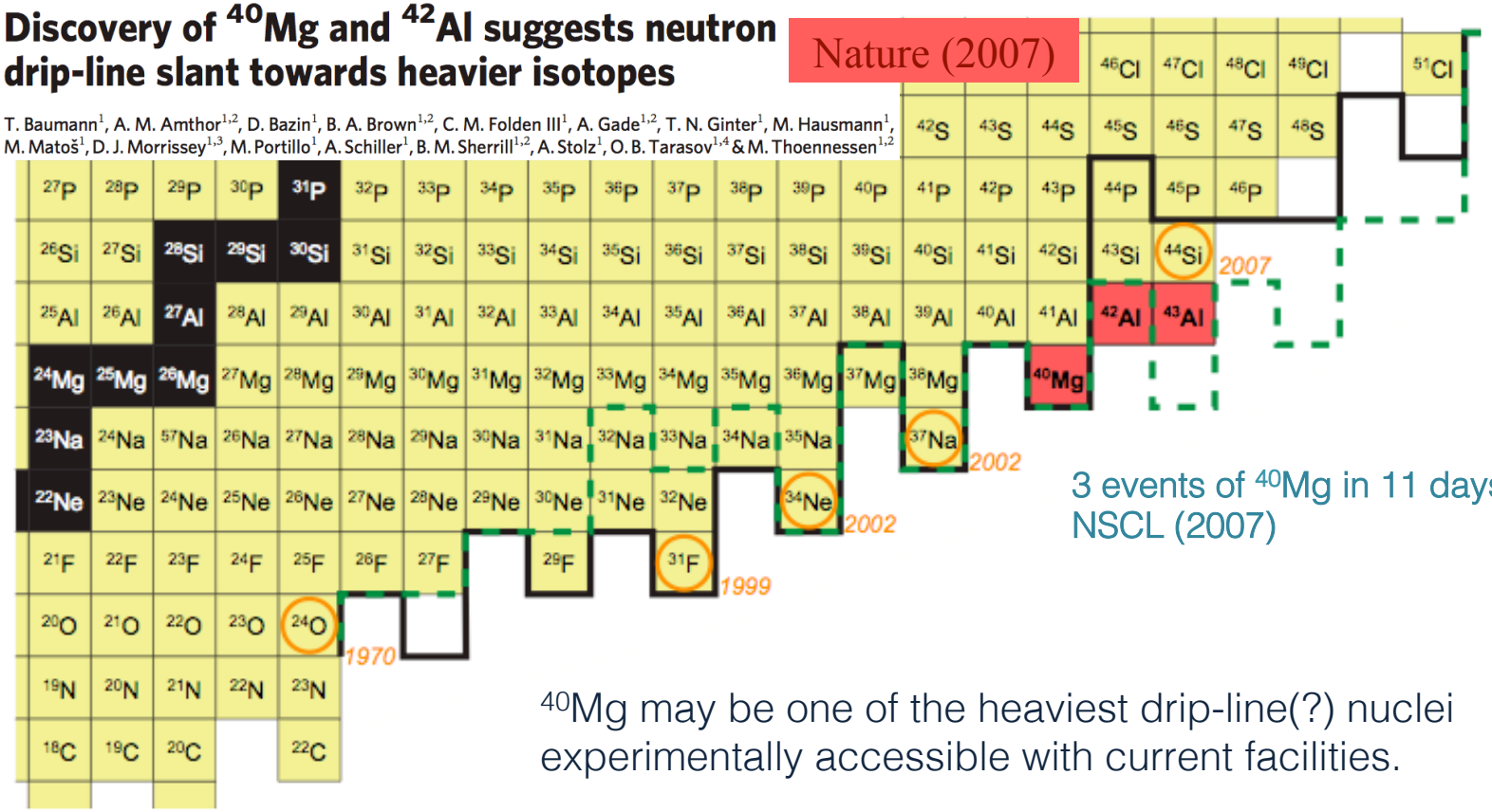
Mapping the Dripline in the sd Shell

Previously ..

Discovery of ^{40}Mg and ^{42}Al suggests neutron drip-line slant towards heavier isotopes

Nature (2007)

T. Baumann[1], A. M. Amthor[1,2], D. Bazin[1], B. A. Brown[1,2], C. M. Folden III[1], A. Gade[1,2], T. N. Ginter[1], M. Hausmann[1], M. Matoš[1], D. J. Morrissey[1,3], M. Portillo[1], A. Schiller[1], B. M. Sherrill[1,2], A. Stolz[1], O. B. Tarasov[1,4] & M. Thoennessen[1,2]

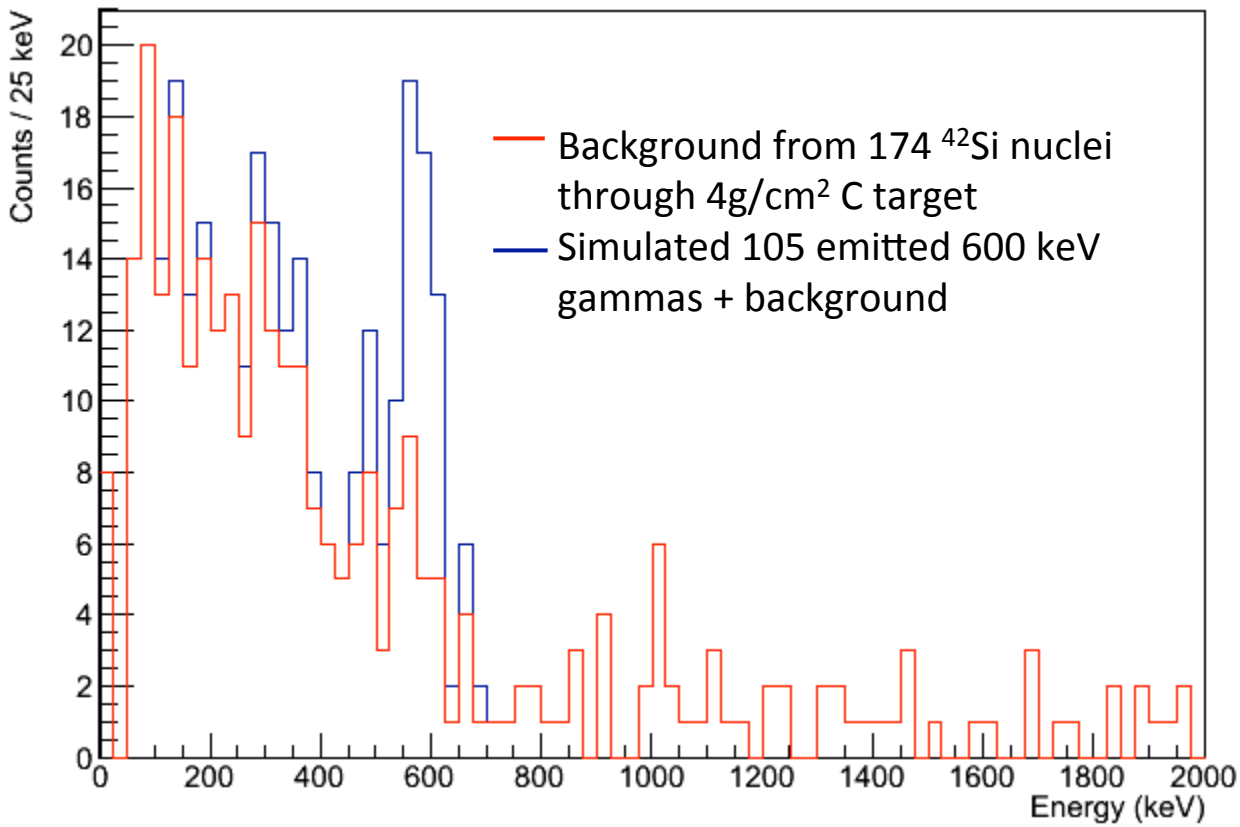


3 events of ^{40}Mg in 11 days
NSCL (2007)

^{40}Mg may be one of the heaviest drip-line(?) nuclei experimentally accessible with current facilities.

Today … beam intensities are available to perform spectroscopy in ^{40}Mg.

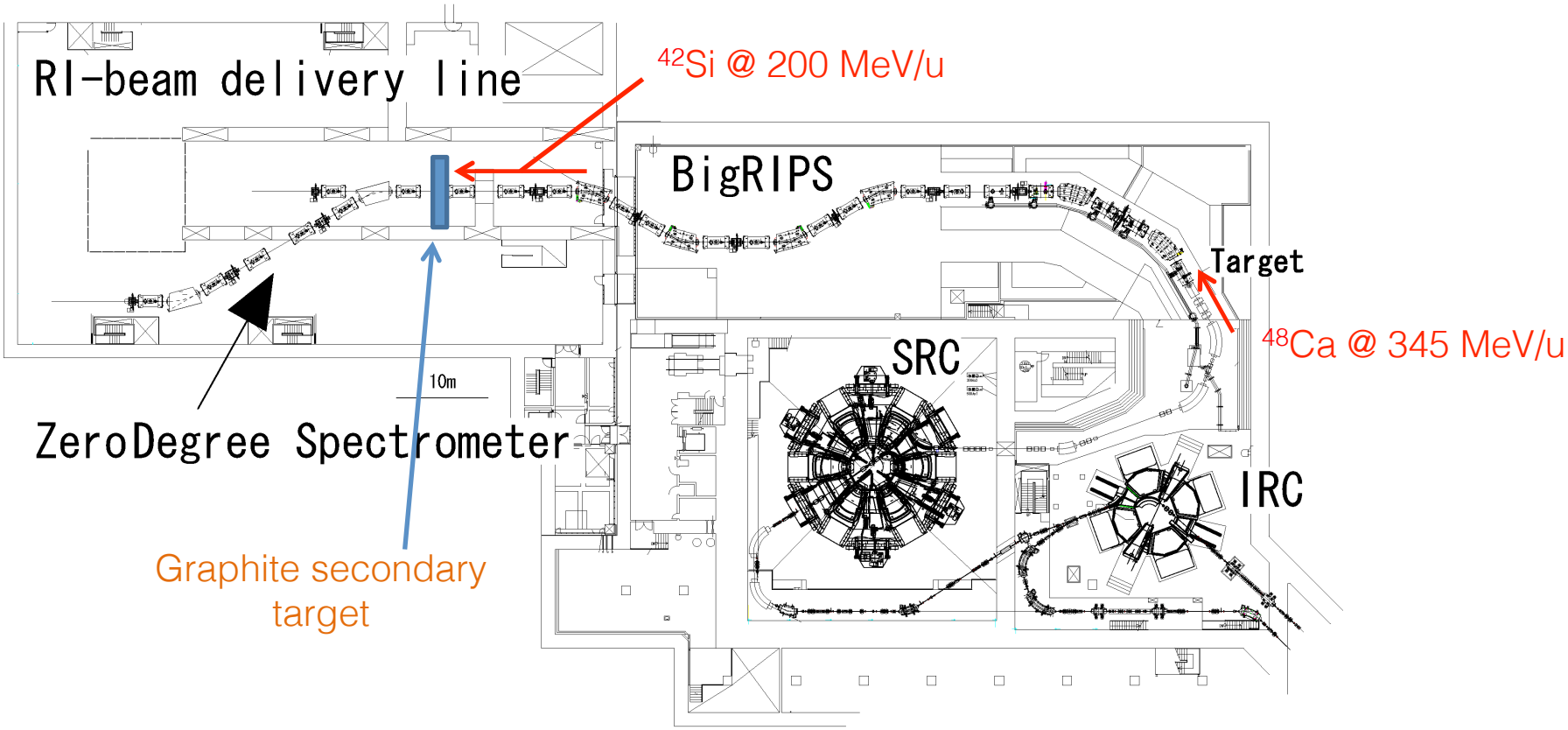
The Goal (to be continued…this Fall?)



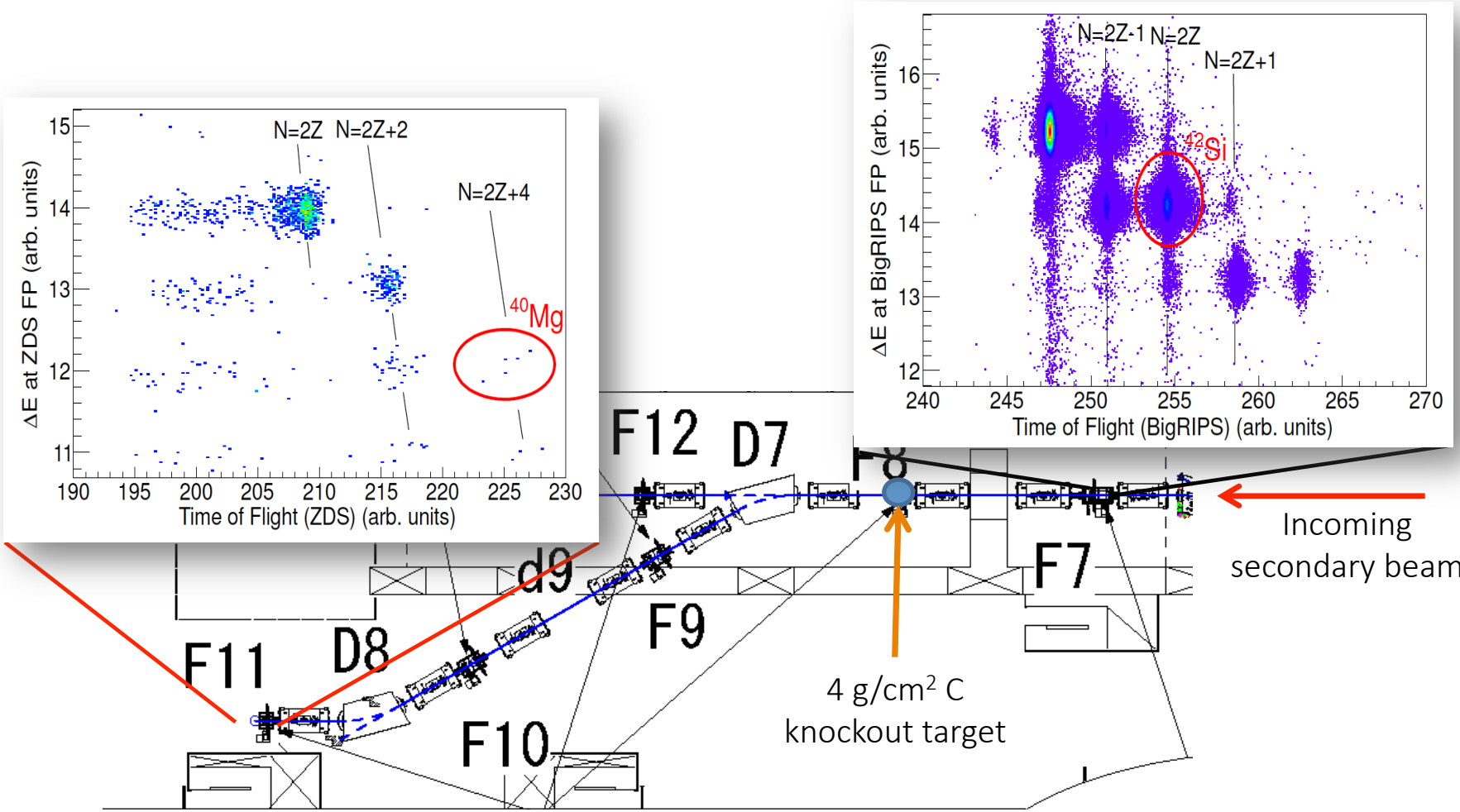
Nucleon Knockout at RIBF

December 2010 – Sunday Campaign (NP1312-RIBF03)

^{42}Si produced at a rate of 25 pps/100 pnA following fragmentation of a high-intensity ^{48}Ca primary beam at RIBF in RIKEN



2p Knockout: $^{42}Si \Rightarrow {}^{40}Mg$



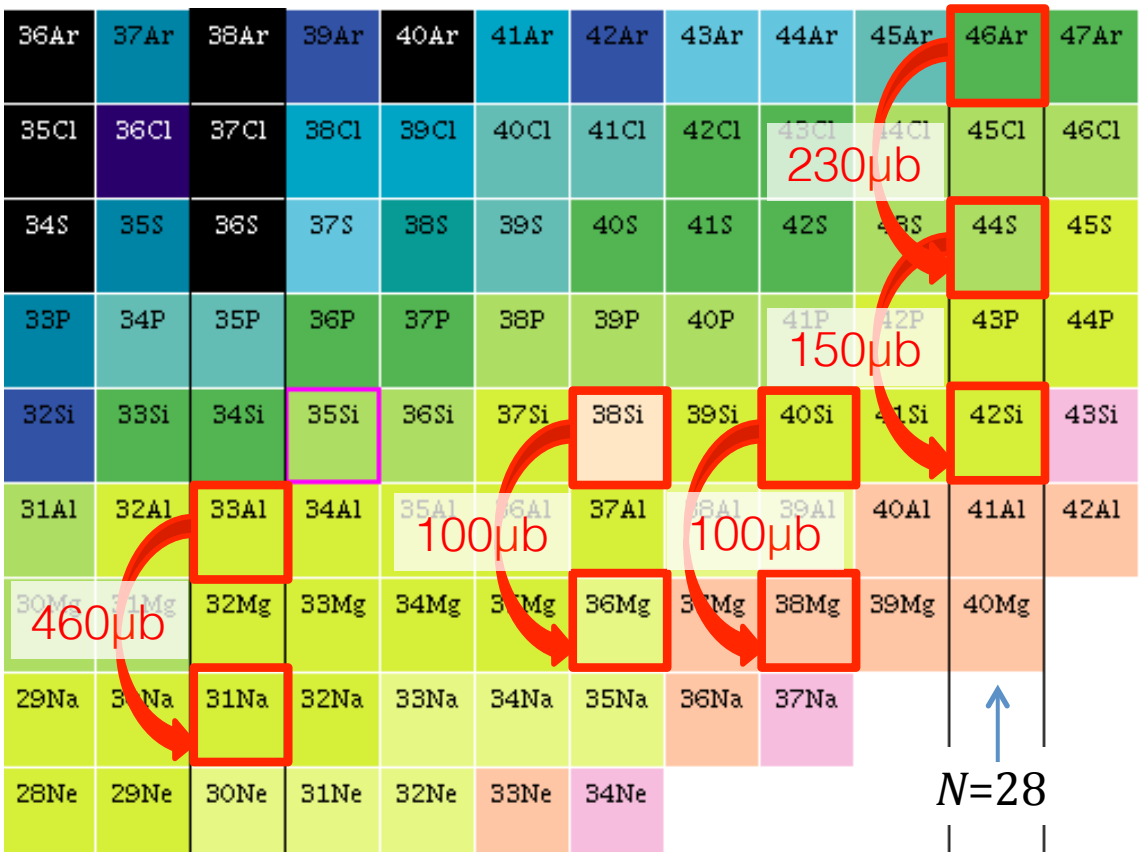
- Approximately 10 hours of beam-on-target
- 5 events of ^{40}Mg observed -- inclusive 2p knockout cross-section of 40(18) μb

Expected Cross-Section: The Lay of the Land

$\sigma_{-2p\ (inclusive)}(^{42}Si \rightarrow {}^{40}Mg) = 40(18)\ \mu b$

In this region, 2p inclusive removal cross-sections are nominally on order of a few hundred μb

⇒ cross-section into ^{40}Mg appears to be low



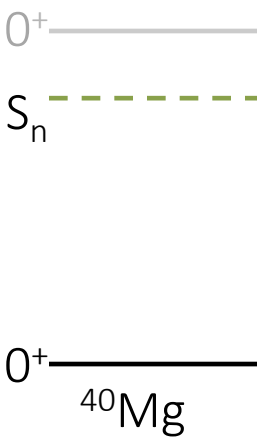
This is a direct reaction:

cross-section depends on initial and final state overlap (structure)

Shell Model + Eikonal Reaction: ^{42}Si -2p

Brown and Tostevin

State	Energy (MeV)	σ_{theor} (μb)	$R_s(2N)\times\sigma_{theor}$ (μb)	σ_{exp} (μb)
0^+	0	102	51	–
2_1^+	0.732	31	16	–
0_2^+	1.683	156	78	–
4_1^+	1.995 (unbound)	3	2	–
Inclusive	–	289	145	40(18)



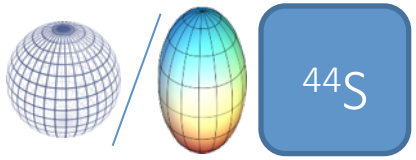
- Experimental cross-section is suppressed compared to predictions using the SDPF-MU shell-model effective interaction and eikonal reaction theory.
- Cross-section is consistent with ONLY ONE bound 0^+ state (calculated s = 67μb) (2012 Atomic Mass Evaluation Sn = 1.74(79))
- Magnitude of the experimental ^{42}Si-2p knockout cross-section provides information regarding the **number of bound states** in ^{40}Mg. It is not possible to use the magnitude alone to discriminate between possible configurations for the ^{40}Mg(0^+) ground state

N = 28 Coexisting Shapes

Calculations and data indicate that the low-energy structure in ^{44}S, ^{42}Si, and ^{40}Mg is dominated by two major, co-existing configurations:

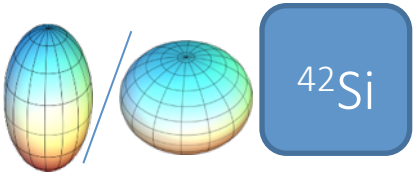
Spherical and Prolate in ^{44}S, Oblate and Prolate in ^{42}Si and ^{40}Mg.

This suggests that a two-state(shape) mixing model can provide a description of their structure.



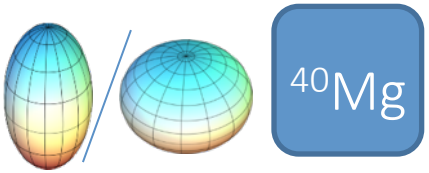
$$|^{44}\mathrm{S}, 0_1^+\rangle = 0.35\,|0^+;\mathrm{S}\rangle + 0.94\,|0^+;\mathrm{P}\rangle$$

Force et al., Phys. Rev. Lett. 105, 102501 (2010).



$$|^{42}\mathrm{Si}, 0_1^+\rangle = +\alpha\,|0^+;\mathrm{O}\rangle + \beta\,|0^+;\mathrm{P}\rangle$$

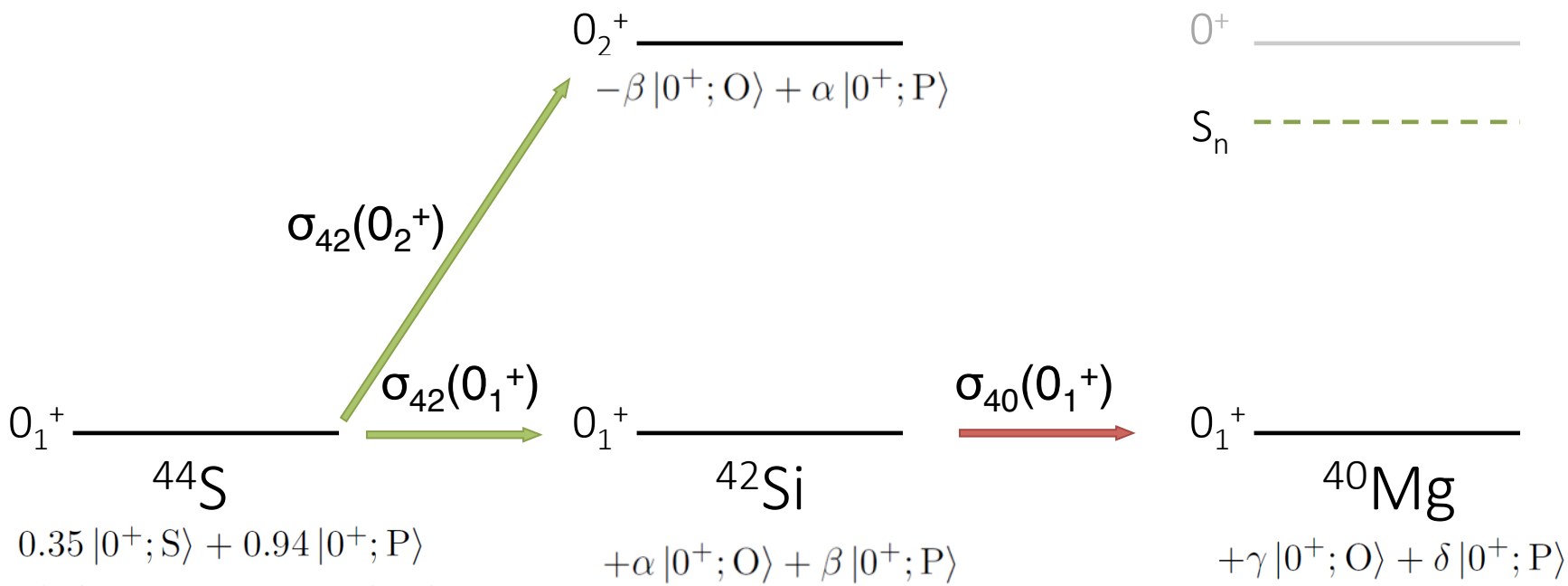
$$|^{42}\mathrm{Si}, 0_2^+\rangle = -\beta\,|0^+;\mathrm{O}\rangle + \alpha\,|0^+;\mathrm{P}\rangle$$



$$|^{40}\mathrm{Mg}, 0_1^+\rangle = +\gamma\,|0^+;\mathrm{O}\rangle + \delta\,|0^+;\mathrm{P}\rangle$$

σ Ratios to Constrain "Shape" Amplitudes

$$\mathcal{R} = \overbrace{[\sigma_{42}(0_1^+) + \sigma_{42}(0_2^+)]}^{^{44}\text{S-2p}} / \overbrace{\sigma_{40}(0_1^+)}^{^{42}\text{Si-2p}}$$



Force et al., Phys. Rev. Lett. 105, 102501 (2010).

σ Ratios to Constrain "Shape" Amplitudes

Cross-section ration R plotted as a function of the prolate component (probability) in the ^{42}Si (α^2) and ^{40}Mg (β^2) ground-state wave functions.

$$\mathcal{R} = [\sigma_{44\to42}(0_1^+) + \sigma_{44\to42}(0_2^+)]/\sigma_{42\to40}(0_1^+)$$

$$|^{42}\mathrm{Si}, 0_1^+\rangle = +\alpha\,|0^+;\mathrm{O}\rangle + \beta\,|0^+;\mathrm{P}\rangle$$

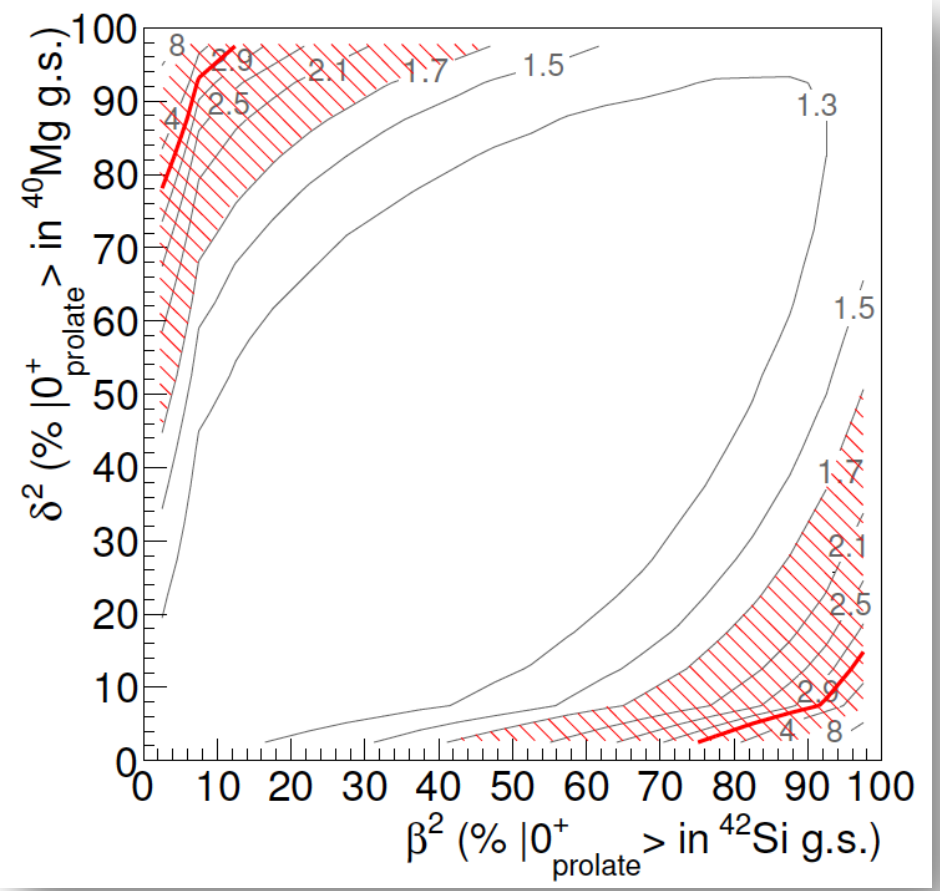
$$|^{42}\mathrm{Si}, 0_2^+\rangle = -\beta\,|0^+;\mathrm{O}\rangle + \alpha\,|0^+;\mathrm{P}\rangle$$

$$|^{40}\mathrm{Mg}, 0_1^+\rangle = +\gamma\,|0^+;\mathrm{O}\rangle + \delta\,|0^+;\mathrm{P}\rangle$$

Experimental value

$$\mathcal{R} = 3.3^{+2.4}_{-1.6}$$

Dominant deformations in the ^{42}Si and ^{40}Mg ground states are consistently opposite.



Shape Evolution Along *N*=28

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **89**, 041303(R) (2014)

Shell and shape evolution at $N = 28$: The ^{40}Mg ground state

H. L. Crawford,[1,*] P. Fallon,[1] A. O. Macchiavelli,[1] R. M. Clark,[1] B. A. Brown,[2] J. A. Tostevin,[2,3] D. Bazin,[2] N. Aoi,[4] P. Doornenbal,[4] M. Matsushita,[4] H. Scheit,[4] D. Steppenbeck,[4] S. Takeuchi,[4] H. Baba,[4] C. M. Campbell,[1] M. Cromaz,[1] E. Ideguchi,[5] N. Kobayashi,[6] Y. Kondo,[6] G. Lee,[6] I. Y. Lee,[1] J. Lee,[4] K. Li,[4] S. Michimasa,[5] T. Motobayashi,[4] T. Nakamura,[6] S. Ota,[5] S. Paschalis,[1] M. Petri,[1,†] T. Sako,[5] H. Sakurai,[4] S. Shimoura,[5] M. Takechi,[4] Y. Togano,[4] H. Wang,[4] and K. Yoneda[4]

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Summary

- The most intense radioactive beam facilities are allowing spectroscopy at the driplines up to Z=12, and in the future beyond
- Closer to stability, there is still much to be learned, exploring other dimensions of structure

- ^{32}Mg ground-state rotational band provides first information on dynamics of pairing etc.
- Requirement for low-lying 0p0h, 2p2h and 4p4h excitations near *N*=20 is clear
- Even without spectral information, cross-sections for direct reactions probe structure
  - ^{40}Mg has a limited number of bound states, with a second 0^+ likely unbound
  - The ground state in ^{40}Mg is a different dominant configuration (shape) than ^{42}Si

Acknowledgements – ^{32,33}Mg

H. L. Crawford[1,2], P. Fallon[1], A. O. Macchiavelli[1], A. Poves[3], V. Bader[4,5], D. Bazin[4], M. Bowry[4], C. M. Campbell[1], M. Carpenter[6], R. M. Clark[1], M. Cromaz[1], A. Gade[4,5], E. Ideguchi[7], H. Iwasaki[4,5], C. Langer[4], C.R. Loelius[4,5], E. Lunderberg[4,5], C. Morse[4,5], A. L. Richard[2], J. Rissanen[1], D. D. Smalley[4], R. Stroberg[4,5], D. Weisshaar[4], K. A. Whitmore[4,5], A. Wiens[1], S. J. Williams[4], K. Wimmer[8], and T. Yamamato[7]

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Acknowledgements – ^{40}Mg

H. L. Crawford,[1,*] P. Fallon,[1] A. O. Macchiavelli,[1] R. M. Clark,[1] B. A. Brown,[2] J. A. Tostevin,[2,3] D. Bazin,[2] N. Aoi,[4] P. Doornenbal,[4] M. Matsushita,[4] H. Scheit,[4] D. Steppenbeck,[4] S. Takeuchi,[4] H. Baba,[4] C. M. Campbell,[1] M. Cromaz,[1] E. Ideguchi,[5] N. Kobayashi,[6] Y. Kondo,[6] G. Lee,[6] I. Y. Lee,[1] J. Lee,[4] K. Li,[4] S. Michimasa,[5] T. Motobayashi,[4] T. Nakamura,[6] S. Ota,[5] S. Paschalis,[1] M. Petri,[1,†] T. Sako,[5] H. Sakurai,[4] S. Shimoura,[5] M. Takechi,[4] Y. Togano,[4] H. Wang,[4] and K. Yoneda[4]

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[6]*Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan*

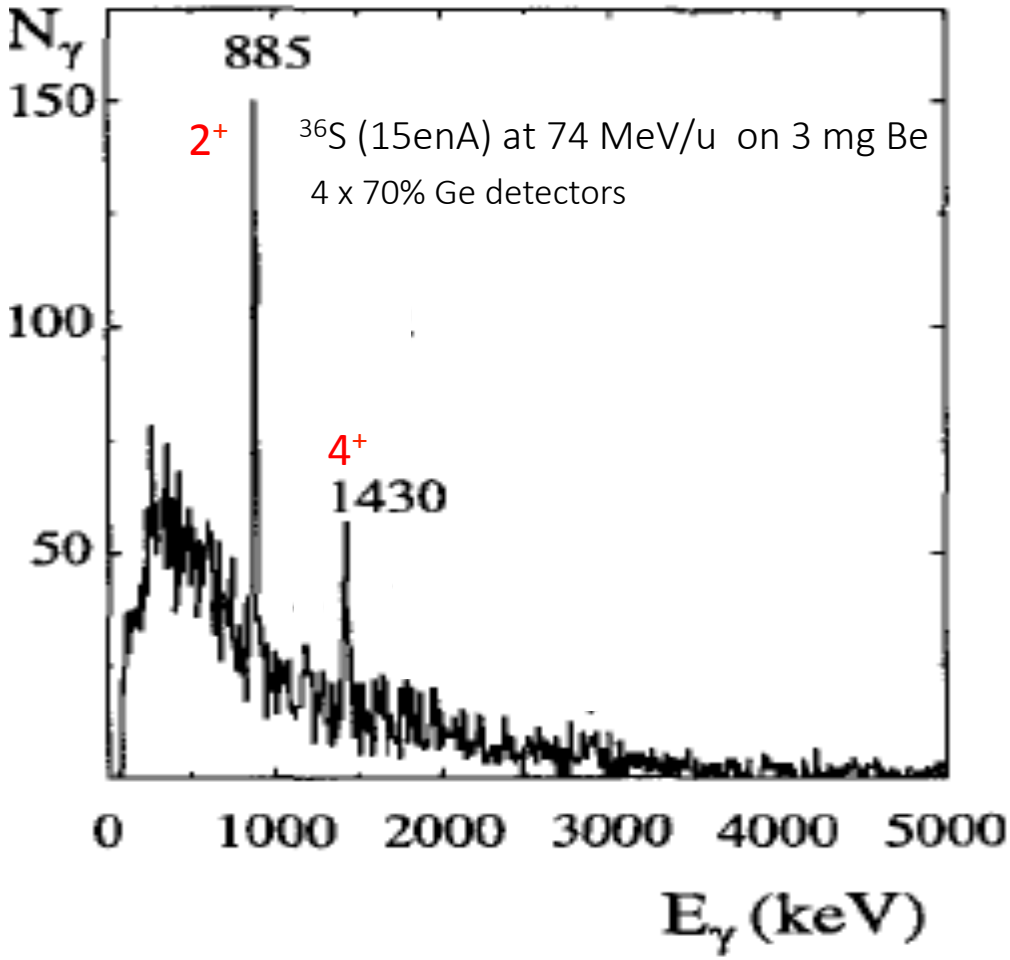
Thank you!

Backup

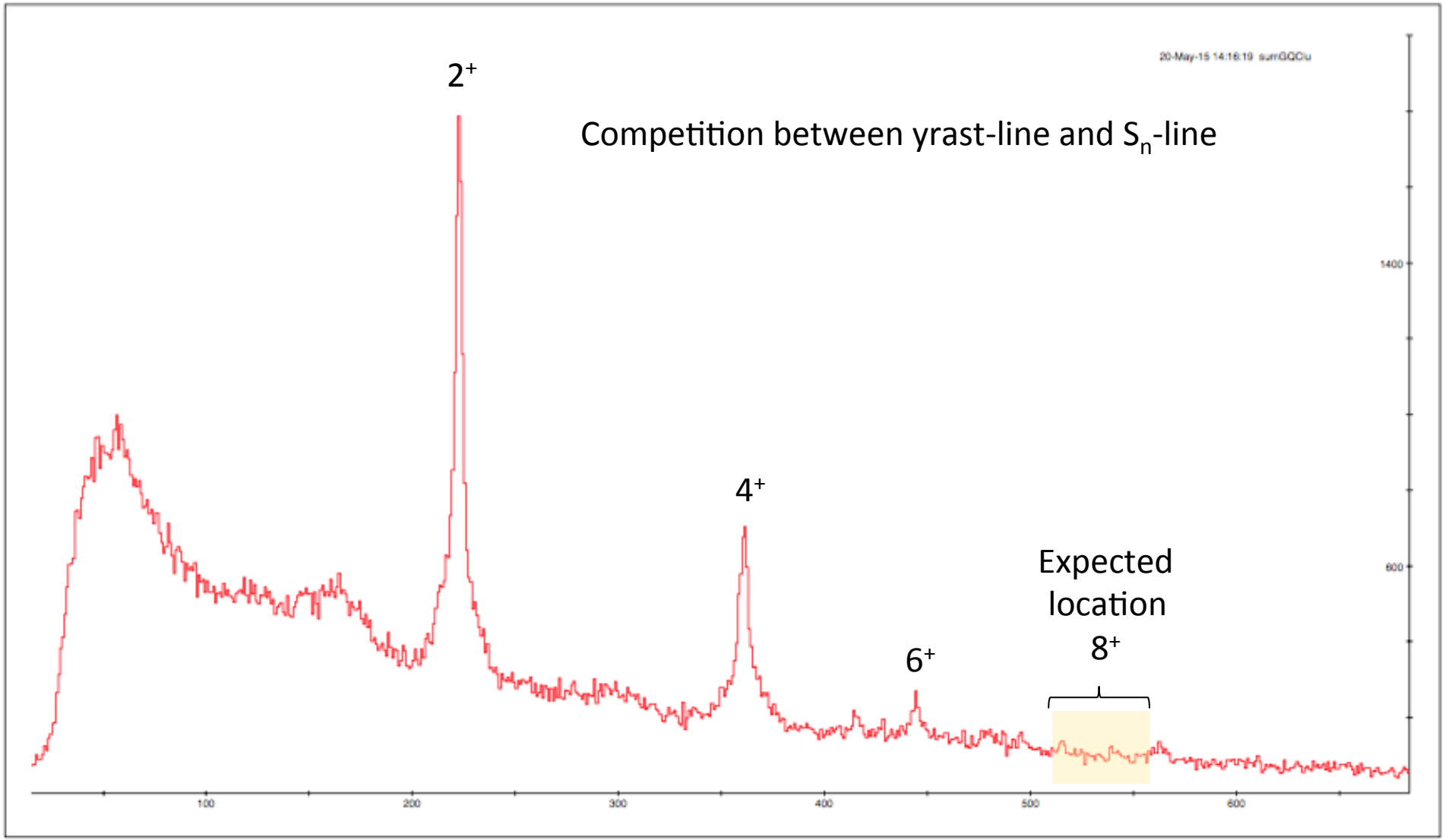
Early inspiration

Direct fragmentation of a ^{36}S primary beam at GANIL

M.Belleguic *et al.*, Nucl. Phys. A**682**, 136c (2001).

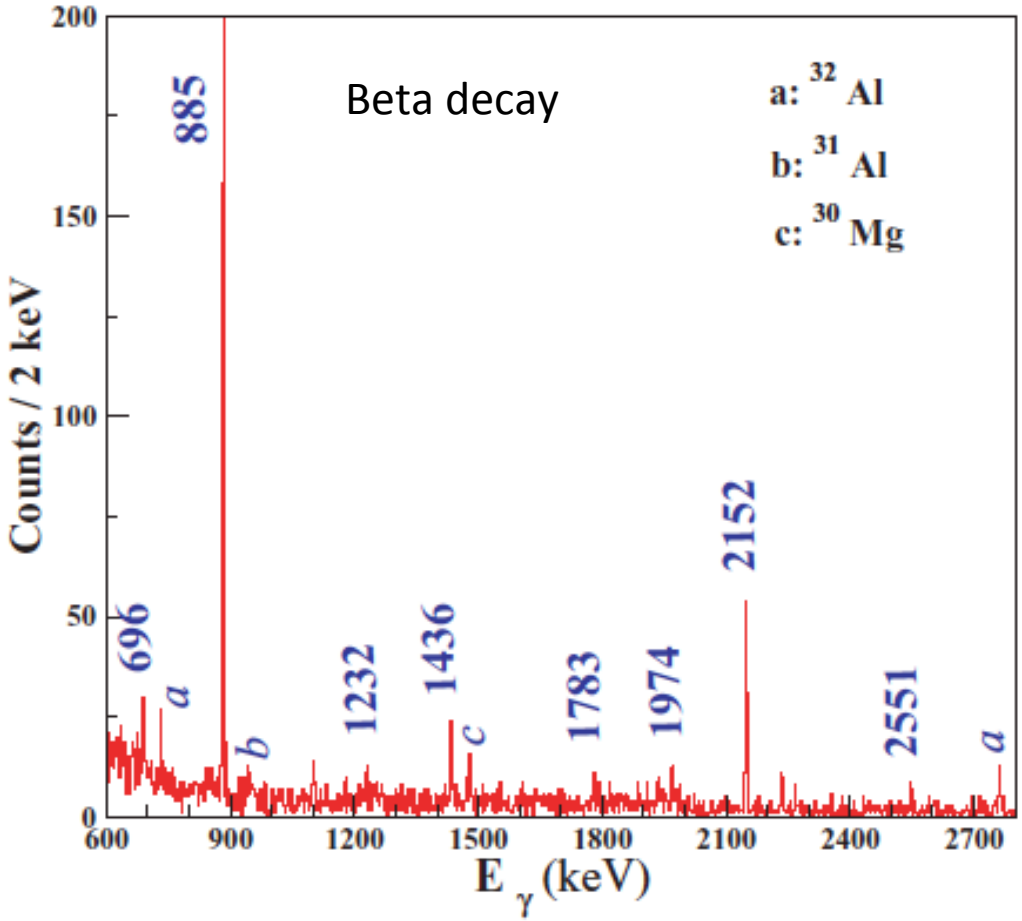


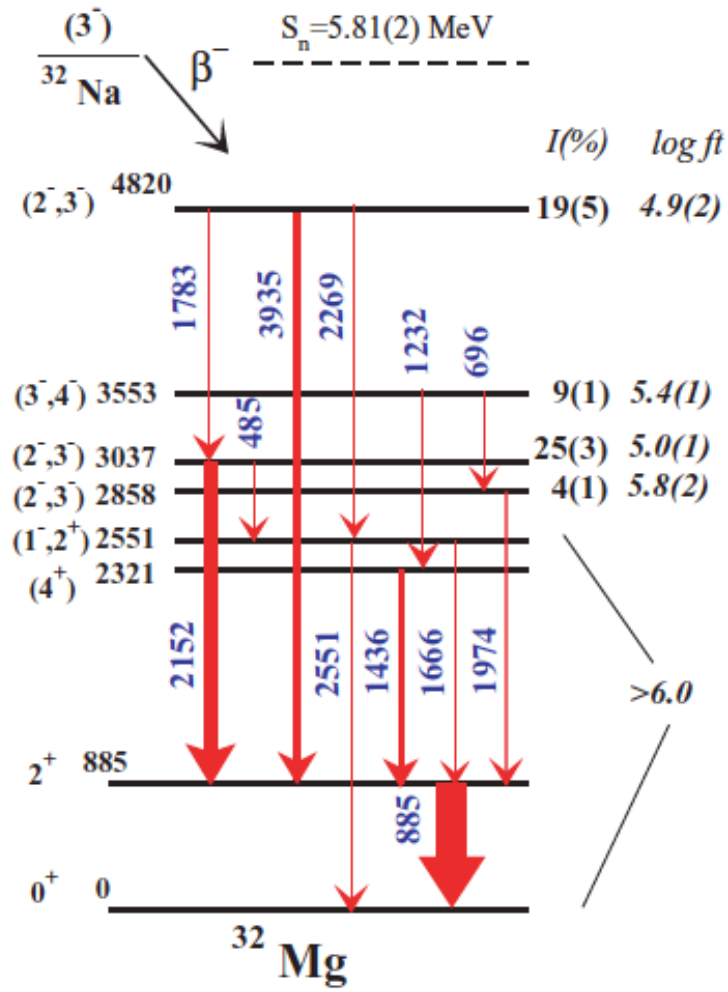
Maximum Spin ?



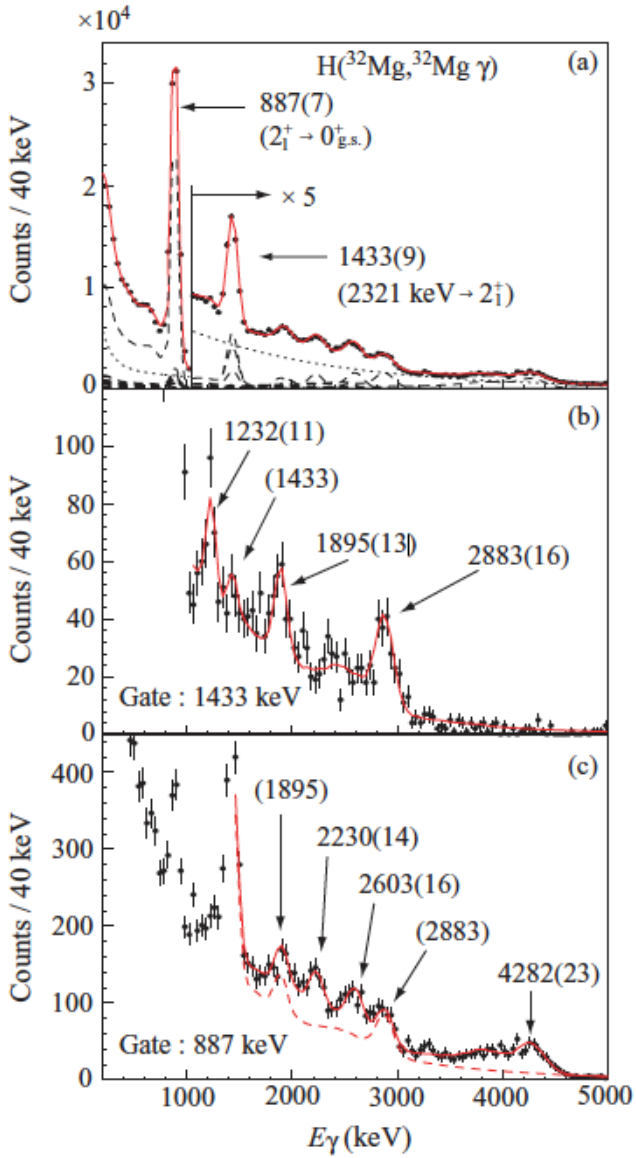
^{32}Mg (comparison to other reactions)

VANDANA TRIPATHI et al. PRC 77, 034310 (2008)

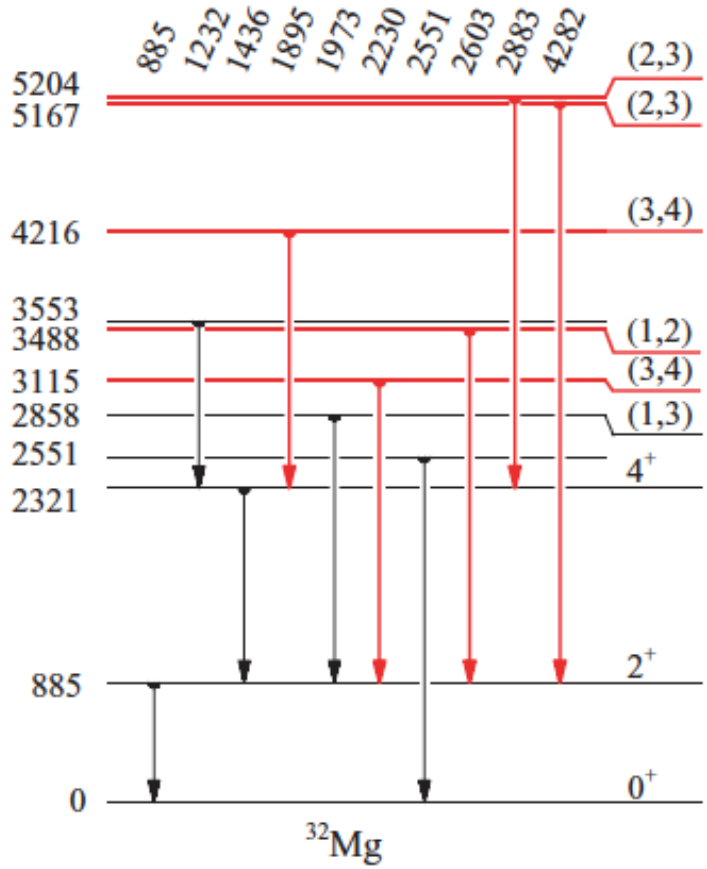




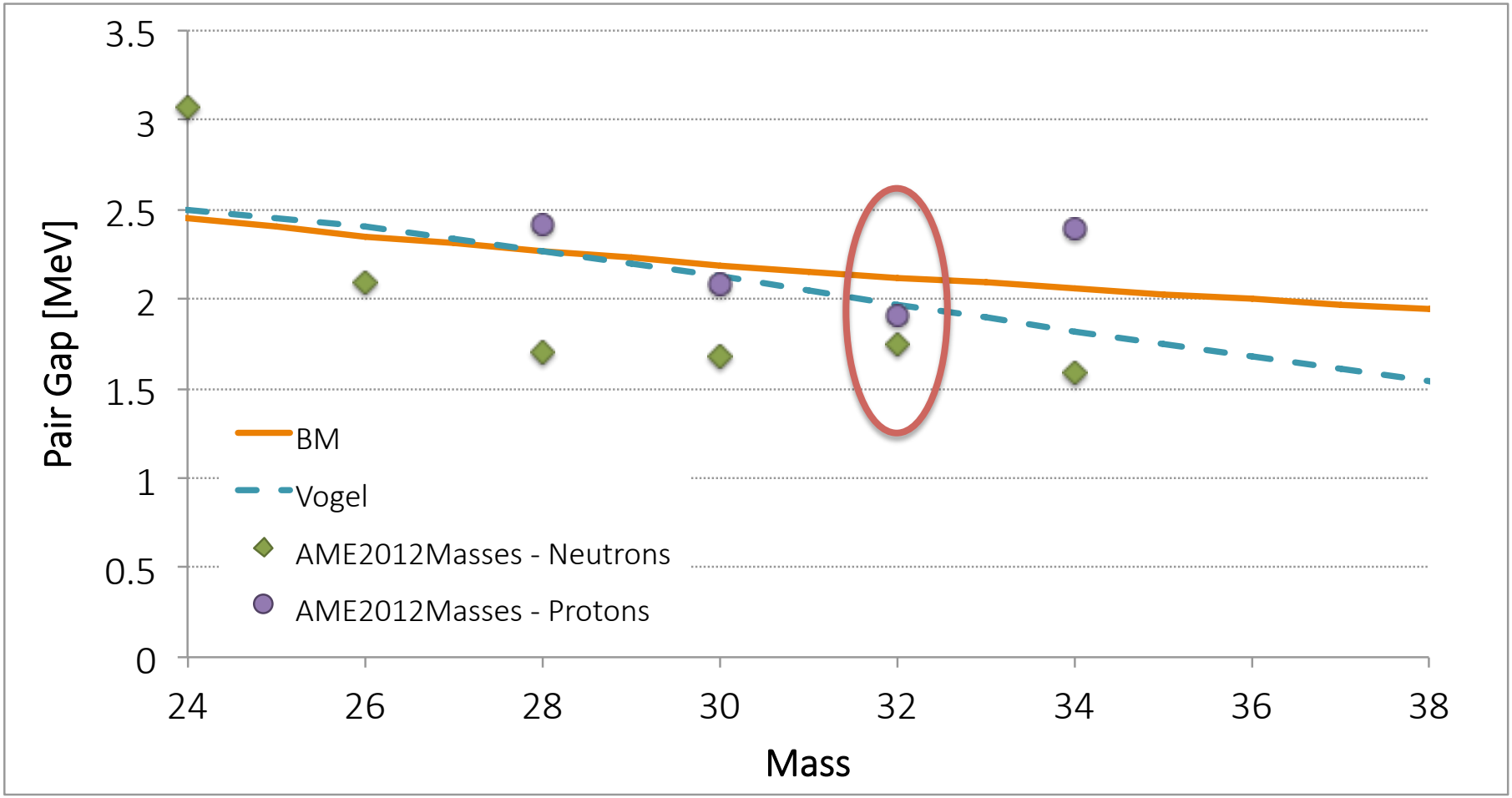
^{32}Mg (comparison to other reactions)



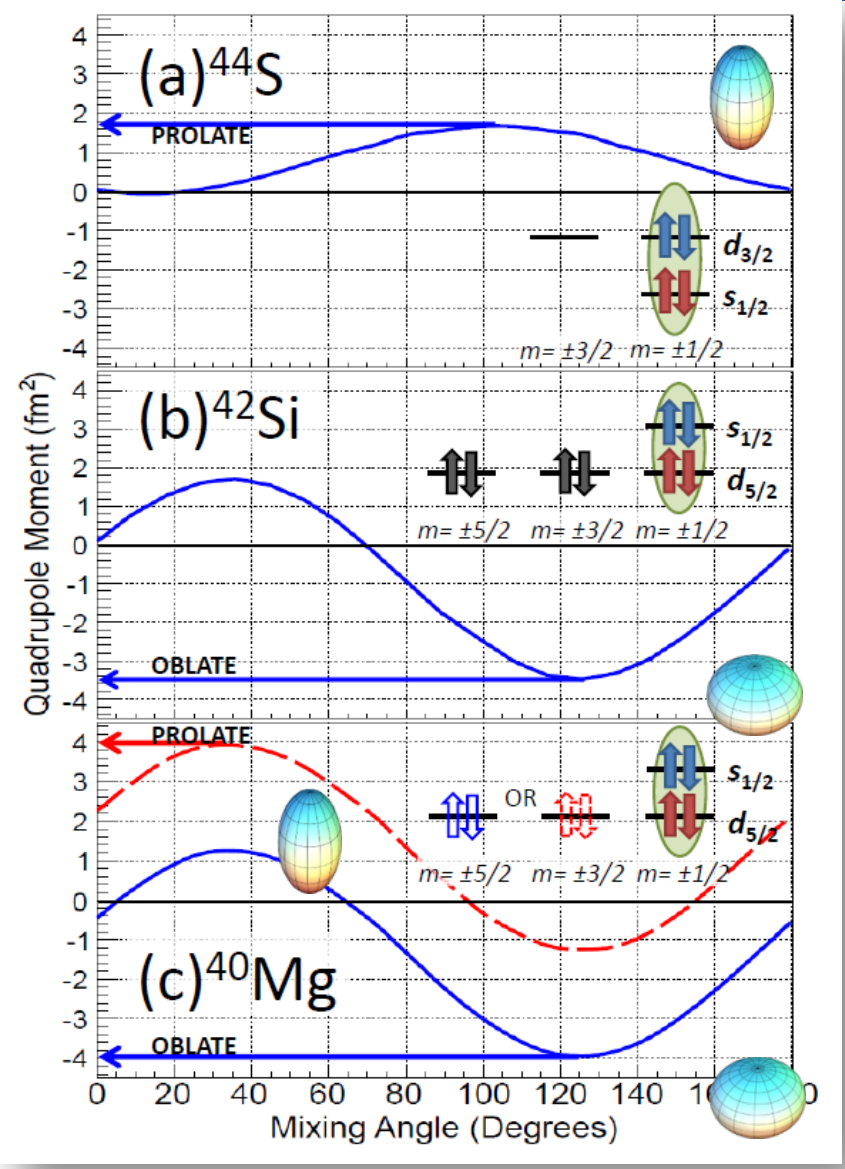
p,p’ Takeuchi et al. PRC 79, 054319 (2009)



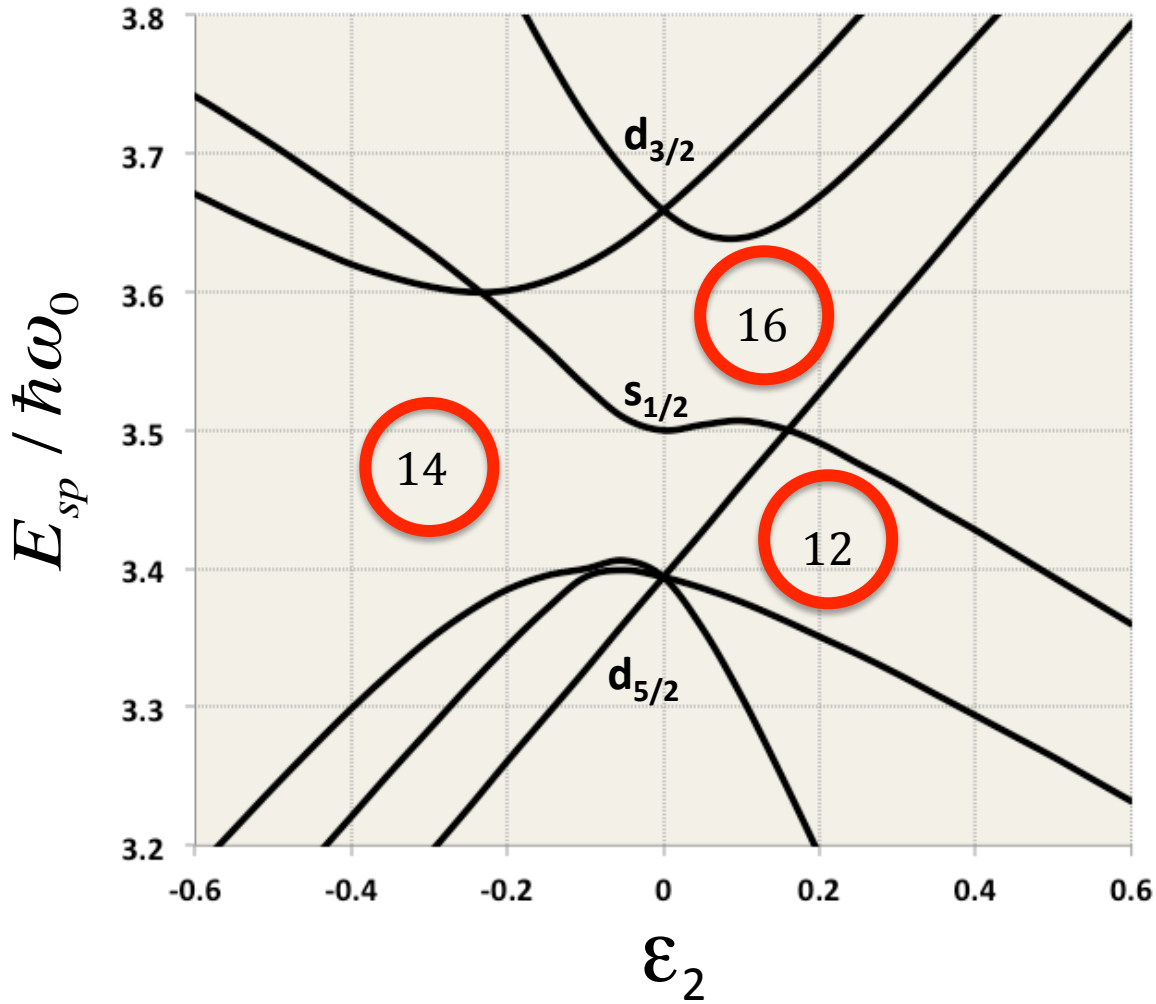
Pair gap in ^{32}Mg



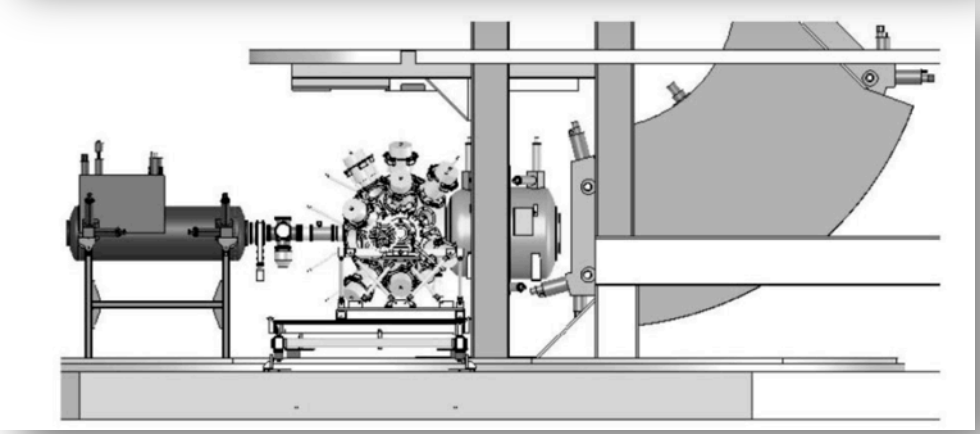
Mixing and Shapes Along *N*=28

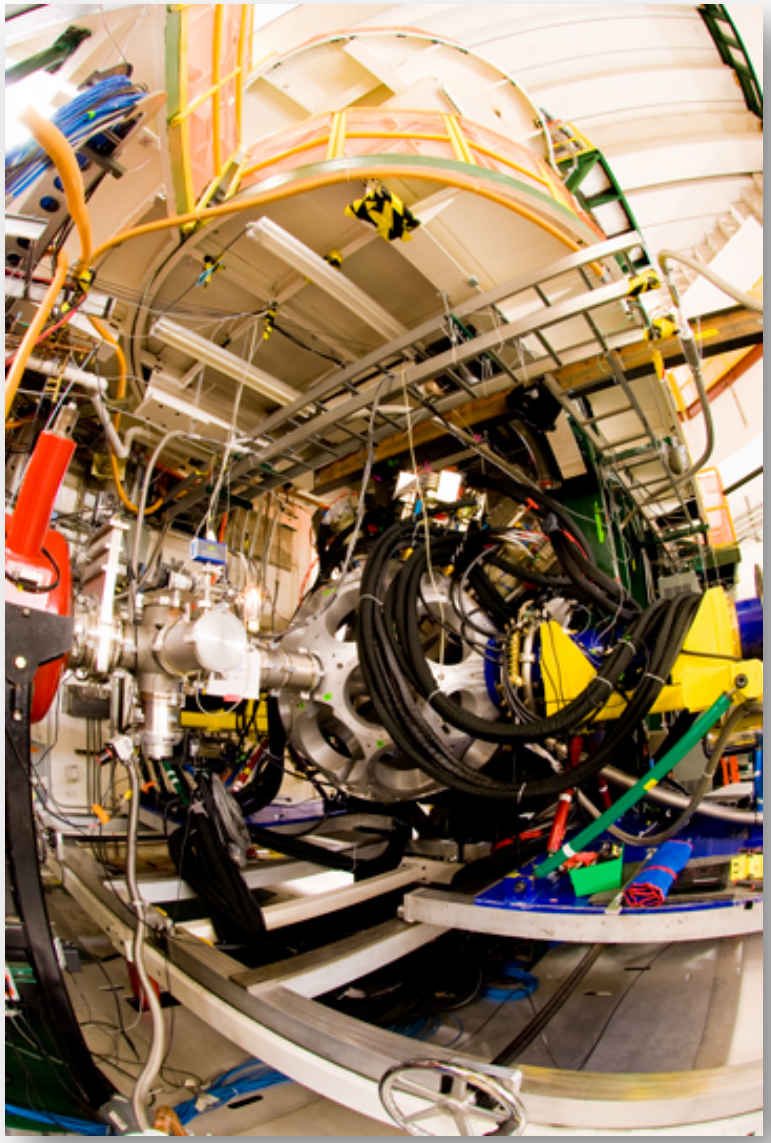


What About a Nilsson Picture?

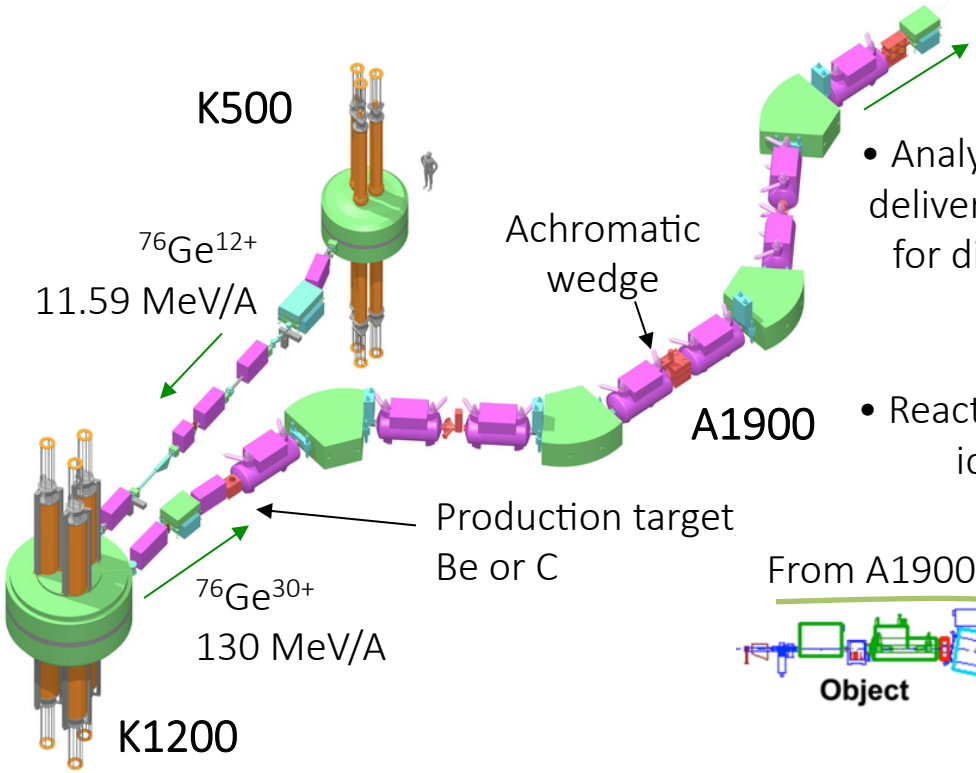


GRETINA + S800

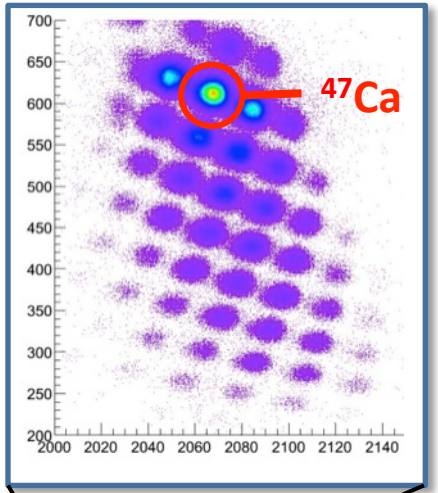


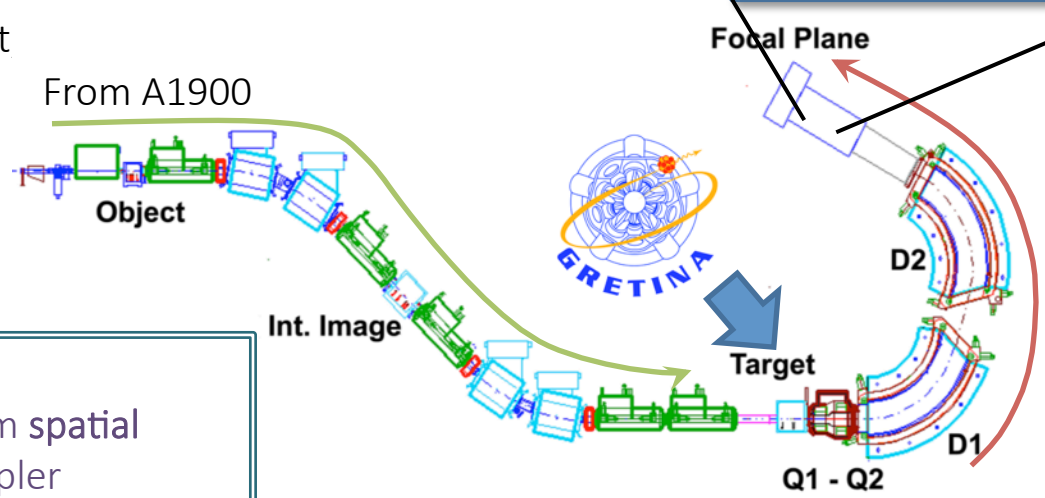


GRETINA with fast beams + S800



- Analyzed secondary beams are delivered to experimental areas for direct study or secondary reactions
- Reaction products are uniquely identified in the S800





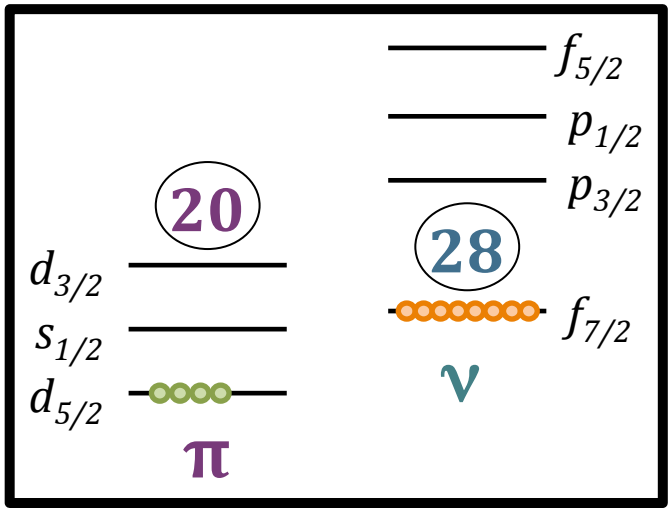
Challenges:

- High beam velocities ($\beta \approx 0.35$) – 2mm spatial resolution of GRETINA optimizes Doppler correction
- Low beam rates (as low as a few pps) – efficiency of GRETINA, in singles and $\gamma\gamma$ is critical

Morrissey, *et al.*, NIM B **204**, 90 (2003).
Bazin, *et al.*, NIM B **204**, 629 (2003).

Toward the Dripline at Z=12

^{40}Mg is at the edge of the experimentally-known neutron dripline, and the last bound neutron orbital is expected to be the $2p_{3/2}$ state.



Neutron configuration with l=1 occupancy can lead to formation of neutron halo.