First Spectroscopy of ^{40}Mg

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Overview

- Neutron-rich Mg Isotopes
  - The “Peninsula” of deformation along Z=12
  - Evolution of shape along the N=28 isotones
- Toward the dripline: ^{40}Mg
  - Current status
- Spectroscopy in ^{40}Mg at RIBF
  - Results
  - Comparison to theory

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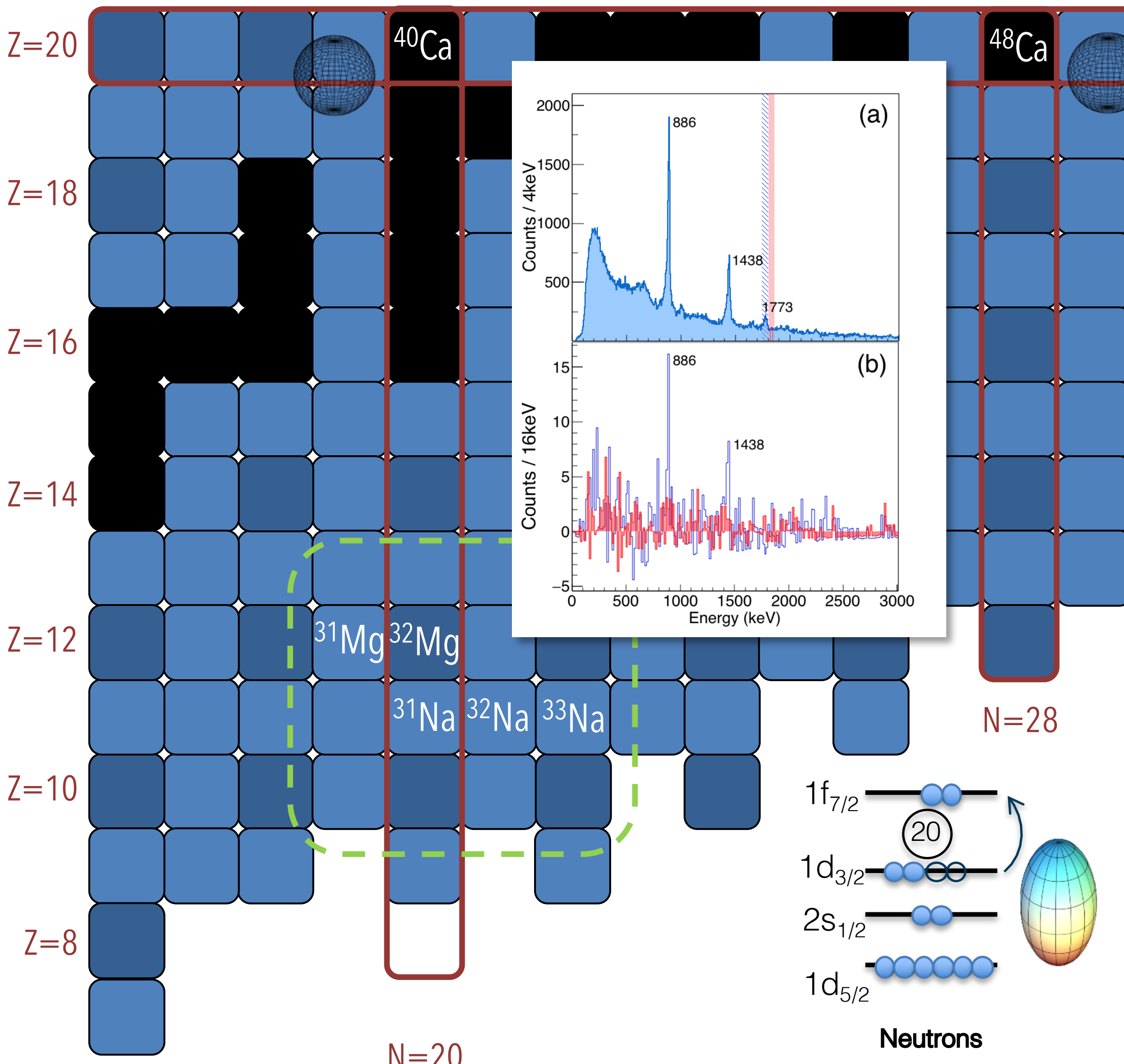
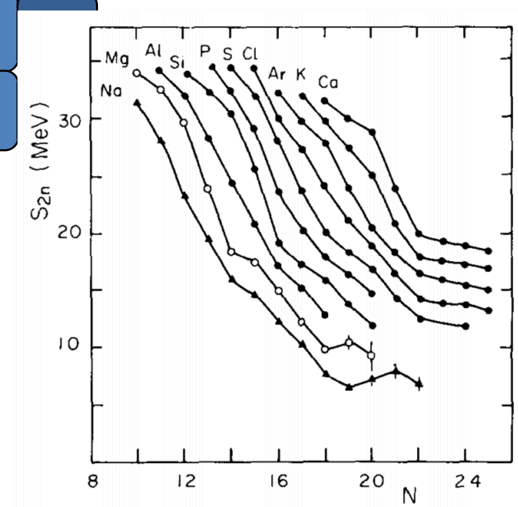
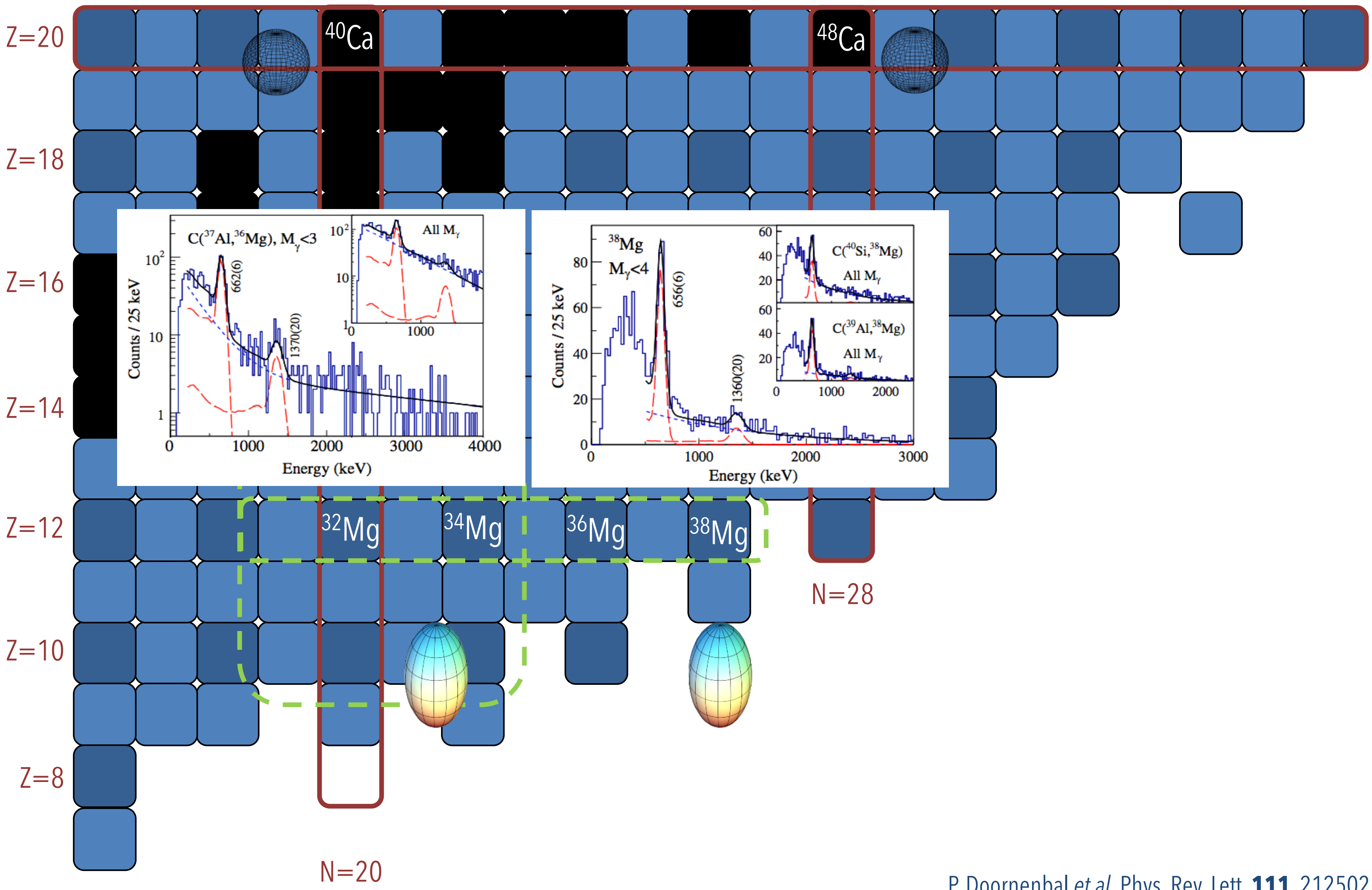
N=20 Island of Inversion





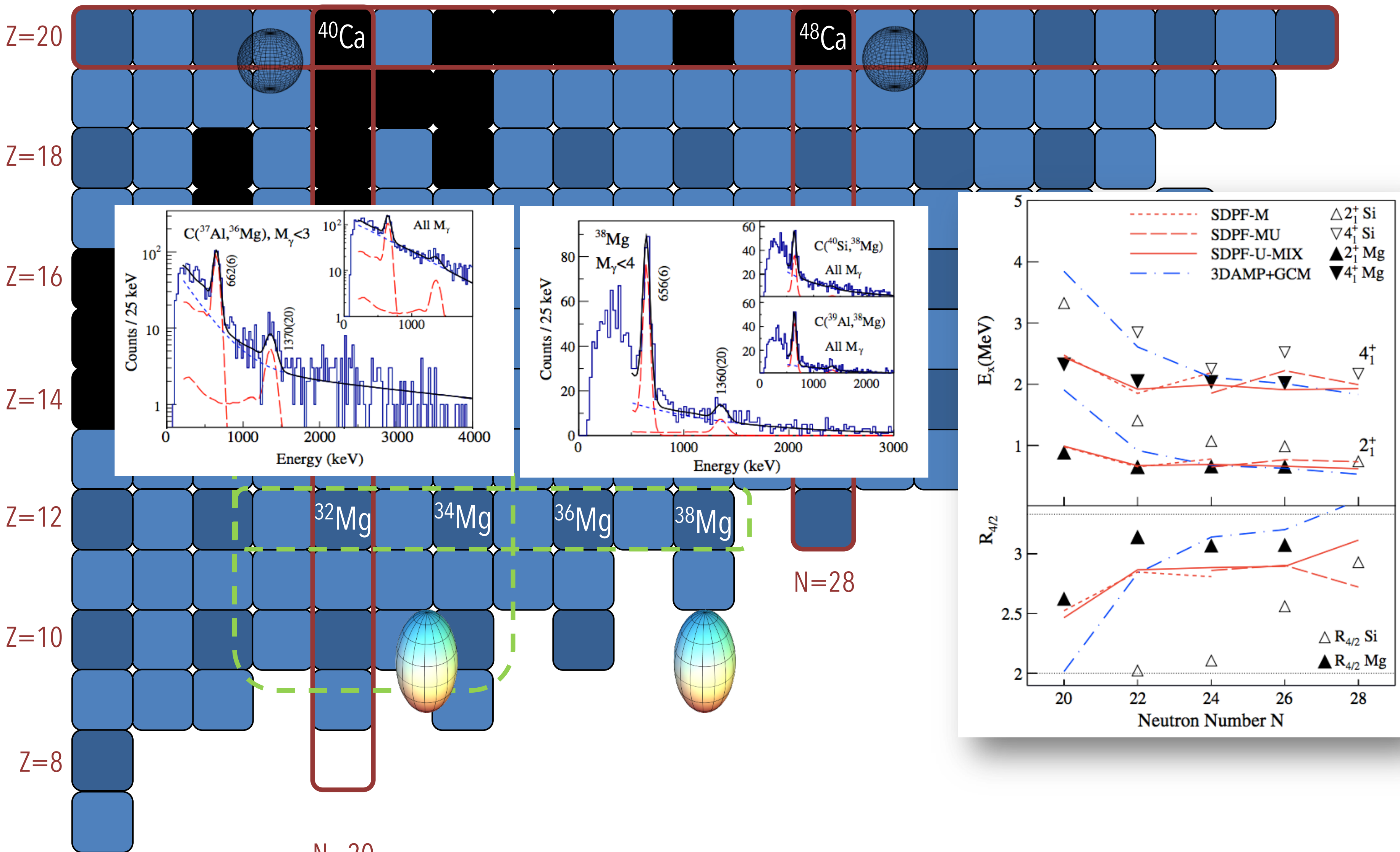
A. Poves and J. Retamosa, Phys. Lett. B **184**, 311 (1987).
E.K. Warburton, J.A. Becker and B.A.Brown, Phys. Rev. C **41**, 1147 (1990).

Z=12 'Peninsula' of Inversion



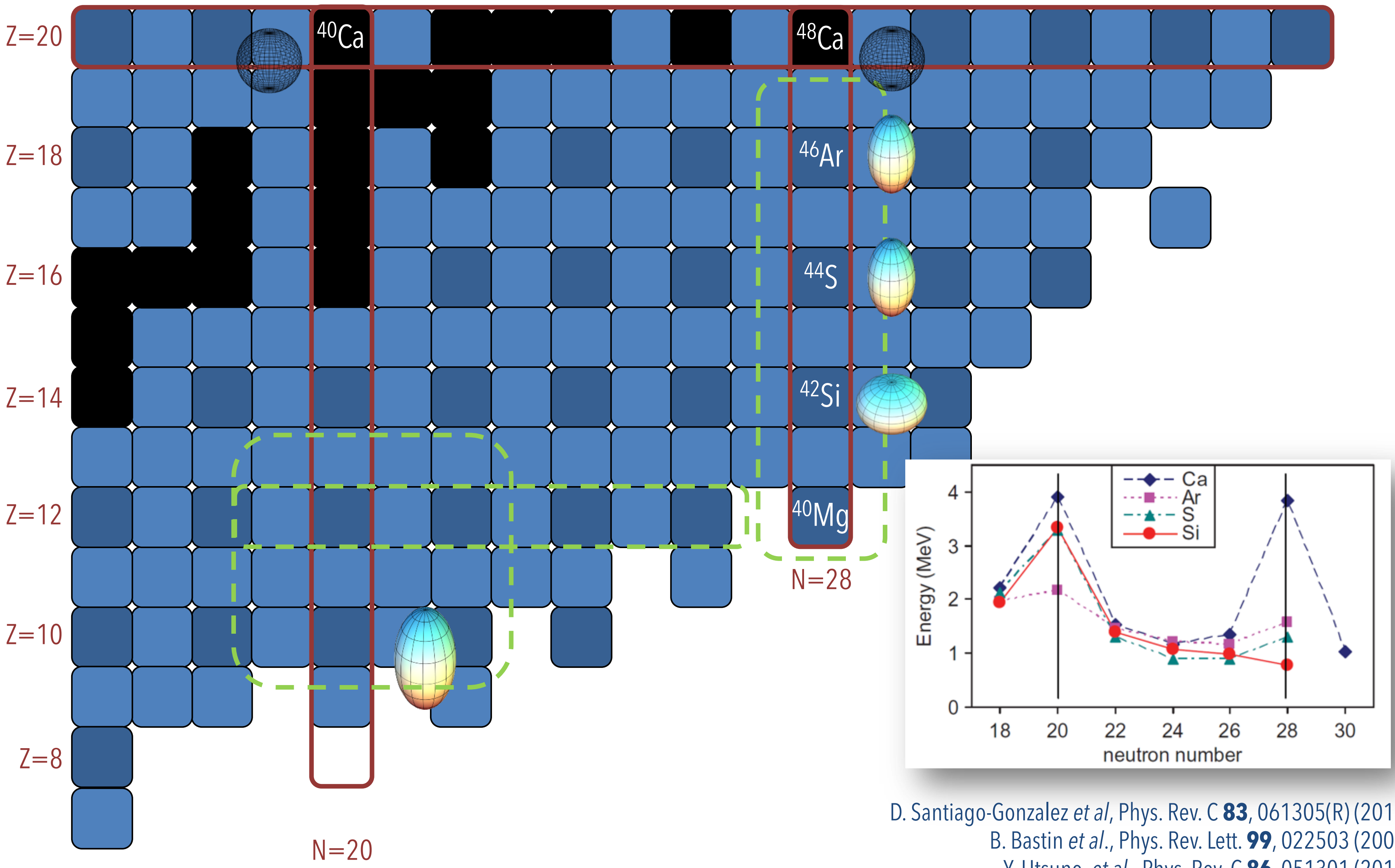
P. Doornenbal *et al*, Phys. Rev. Lett. **111**, 212502 (2013).

Z=12 'Peninsula' of Inversion



P. Doornenbal *et al*, Phys. Rev. Lett. **111**, 212502 (2013).

N=28: Evolution of Nuclear Shapes



D. Santiago-Gonzalez *et al*, Phys. Rev. C **83**, 061305(R) (2011).
B. Bastin *et al*., Phys. Rev. Lett. **99**, 022503 (2007).
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Energy Levels in a Woods Saxon Potential

⇒ In a well bound nucleus

- steady evolution of energy levels in a 1 body potential
- modified by 2-body NN interaction ($\sigma . \tau$, Tensor)

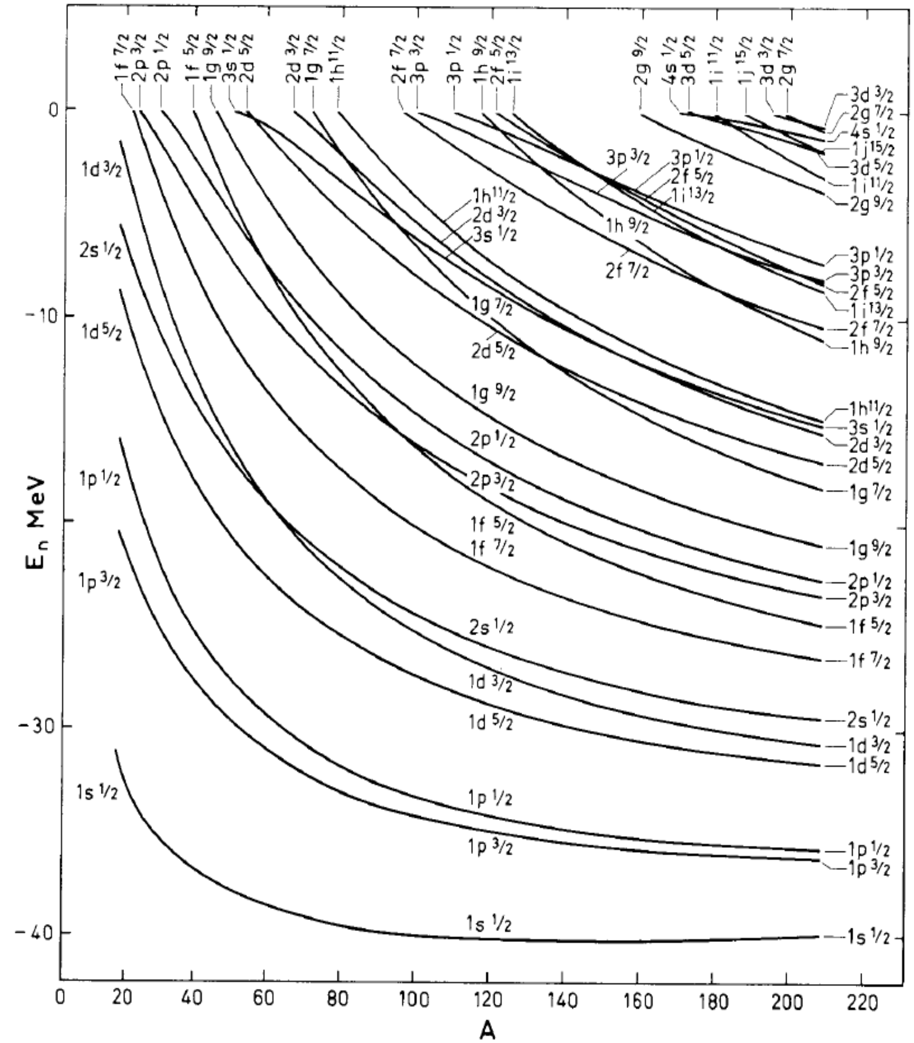


Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).

A.Bohr and B.R. Mottelson, vol. 1

Energy Levels in a Woods Saxon Potential

⇒ In a well bound nucleus
- steady evolution of energy levels in a 1 body potential
- modified by 2-body NN interaction ($\sigma.\tau$, Tensor)

⇒ A second distinct effect is due to weakly bound levels
- low l levels (s, p) ⟶ extended wavefunctions ("halos")
- valence nucleons can become decoupled from the core
- coupling to continuum states

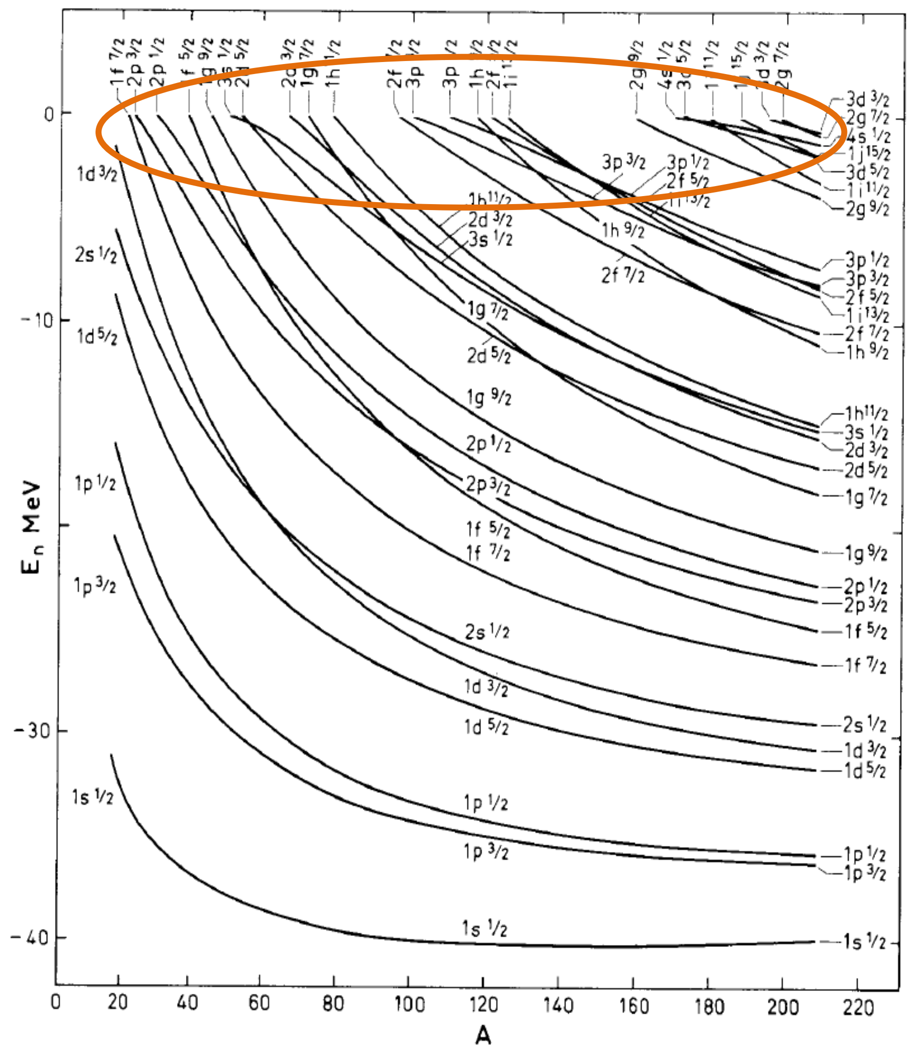
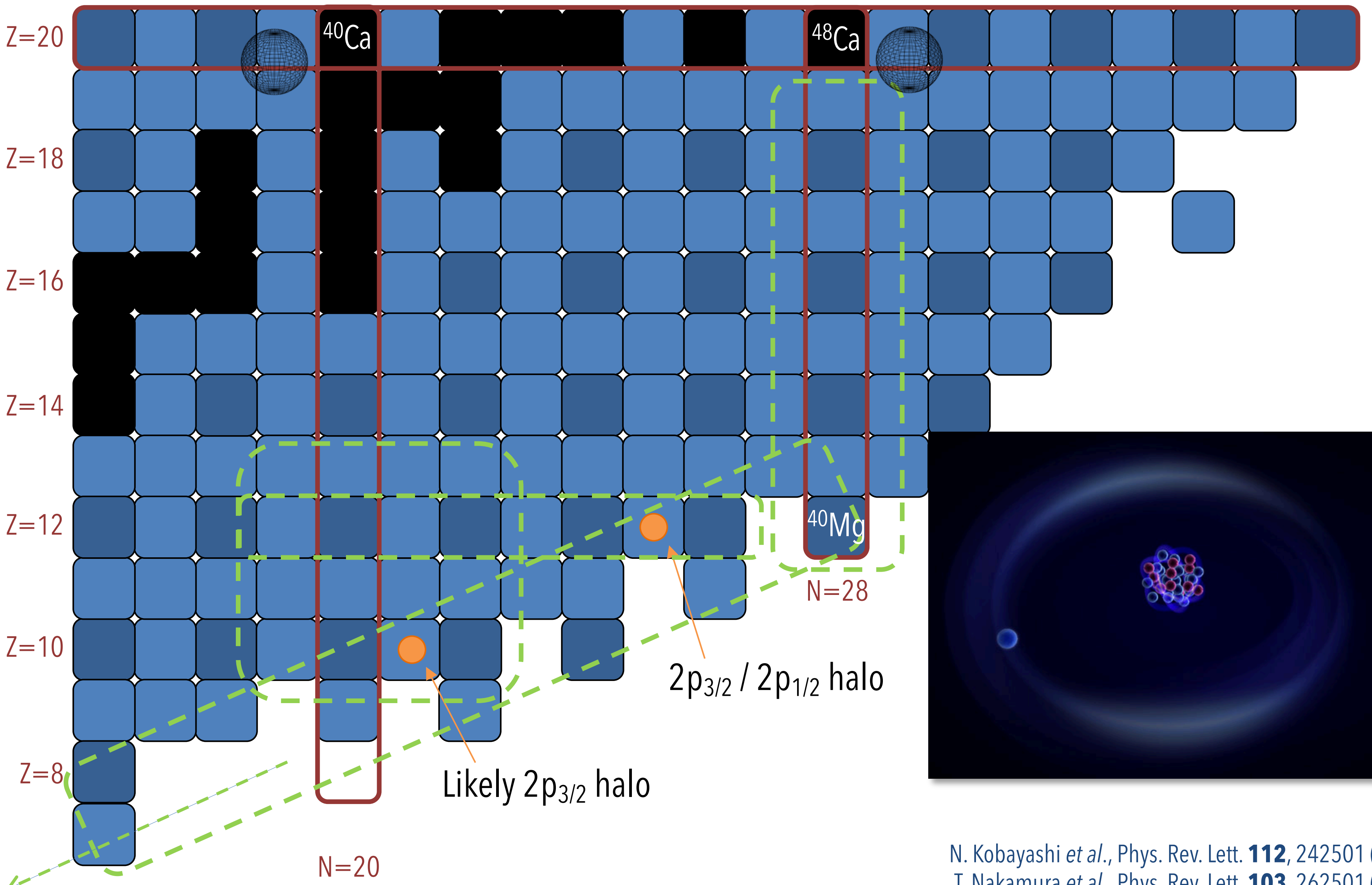


Figure 2-30 Energies of neutron orbits calculated by C. J. Veje (private communication).

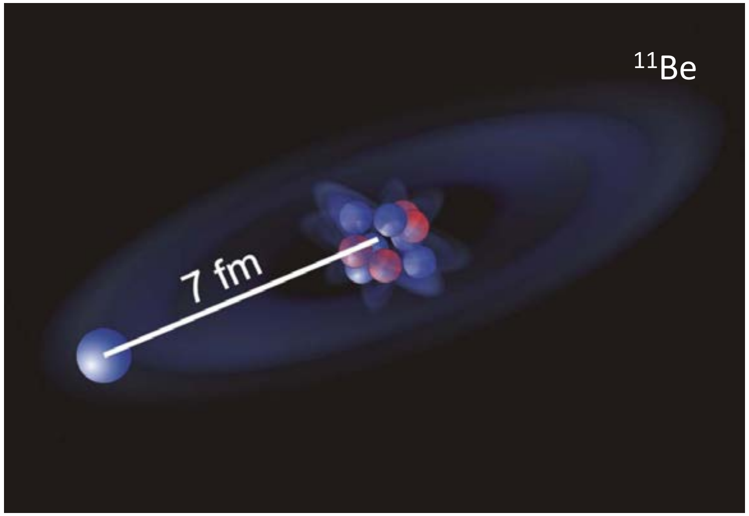
A.Bohr and B.R. Mottelson, vol. 1

Limits of Stability: Halo Nuclei



N. Kobayashi *et al.*, Phys. Rev. Lett. **112**, 242501 (2014).
T. Nakamura *et al.*, Phys. Rev. Lett. **103**, 262501 (2009).

Weak binding phenomena



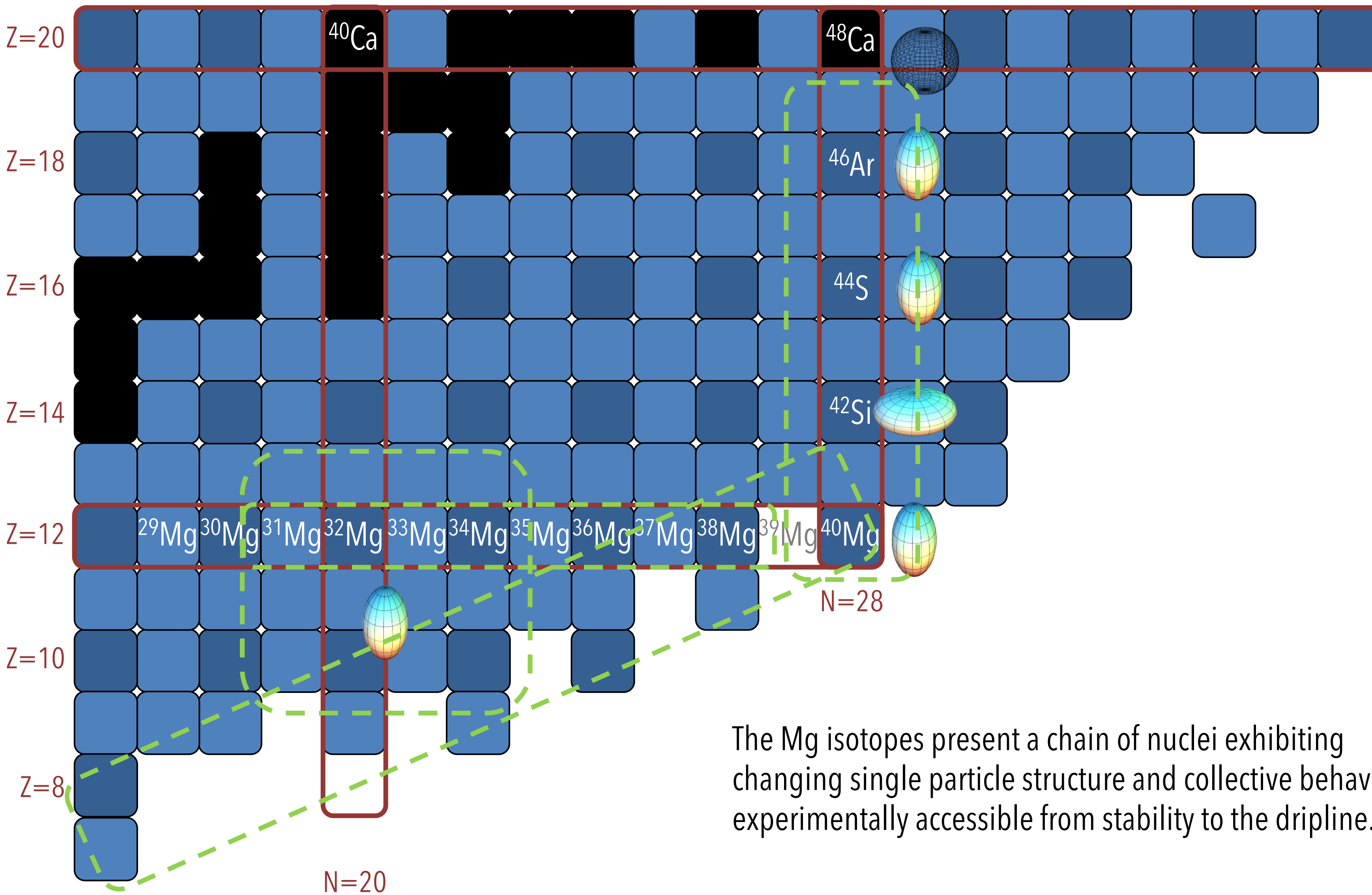
- Currently we know of examples of weak binding and delocalized wavefunctions giving rise to nuclear halos

- What about spectroscopic observables ?
  - transition energies, rates …

- When we do have halo structures then what is the nature of the valance-core interaction?
  - Do the delocalized, weakly bound nucleons
    - decouple from the core and/or
    - couple to the continuum ?

Data on excited states (γ decay) can help answer these questions…

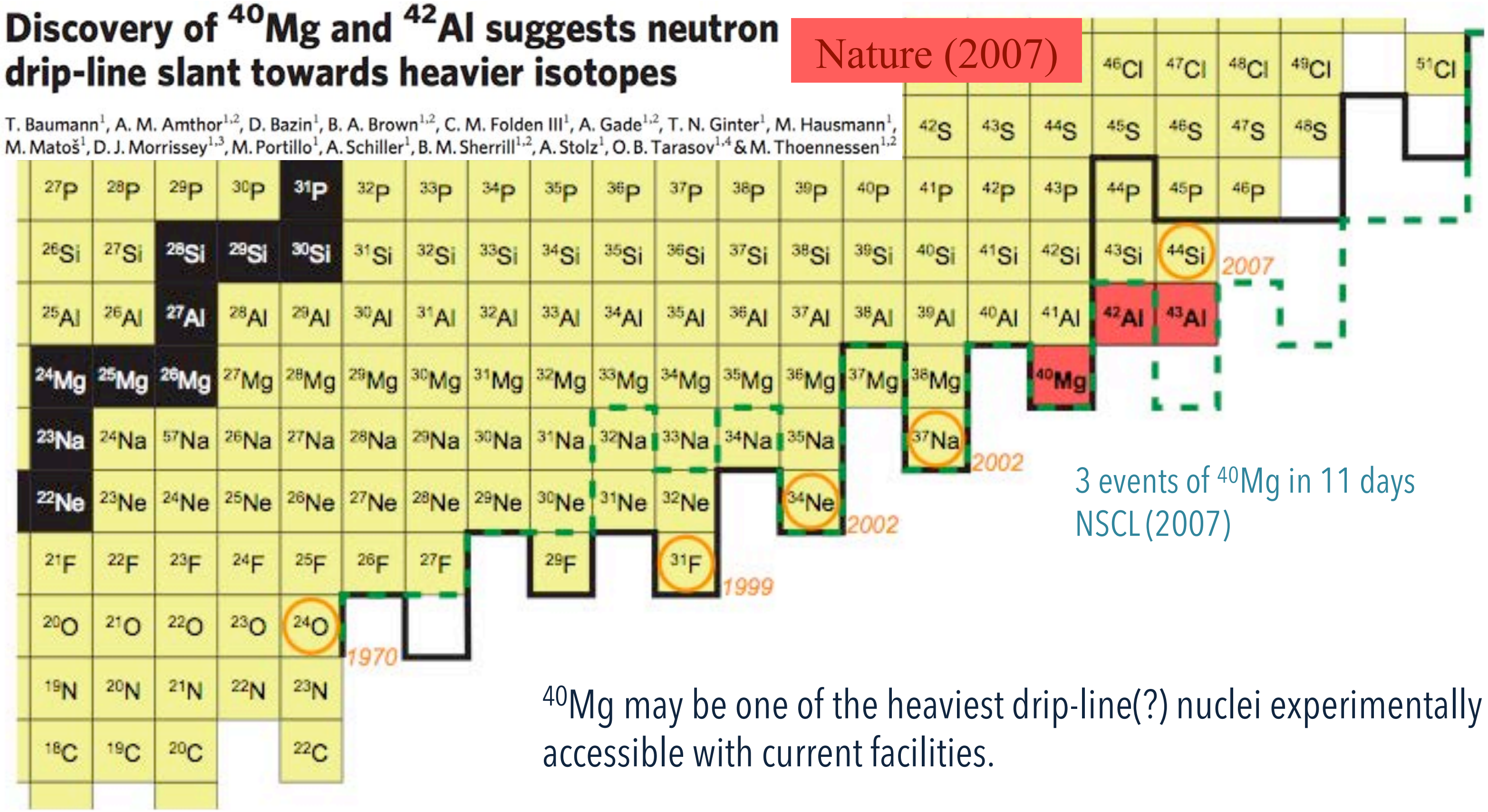
^{40}Mg: The Intersection Point



The Mg isotopes present a chain of nuclei exhibiting changing single particle structure and collective behavior, experimentally accessible from stability to the dripline.

Mapping the Dripline in the sd Shell

Previously ..



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

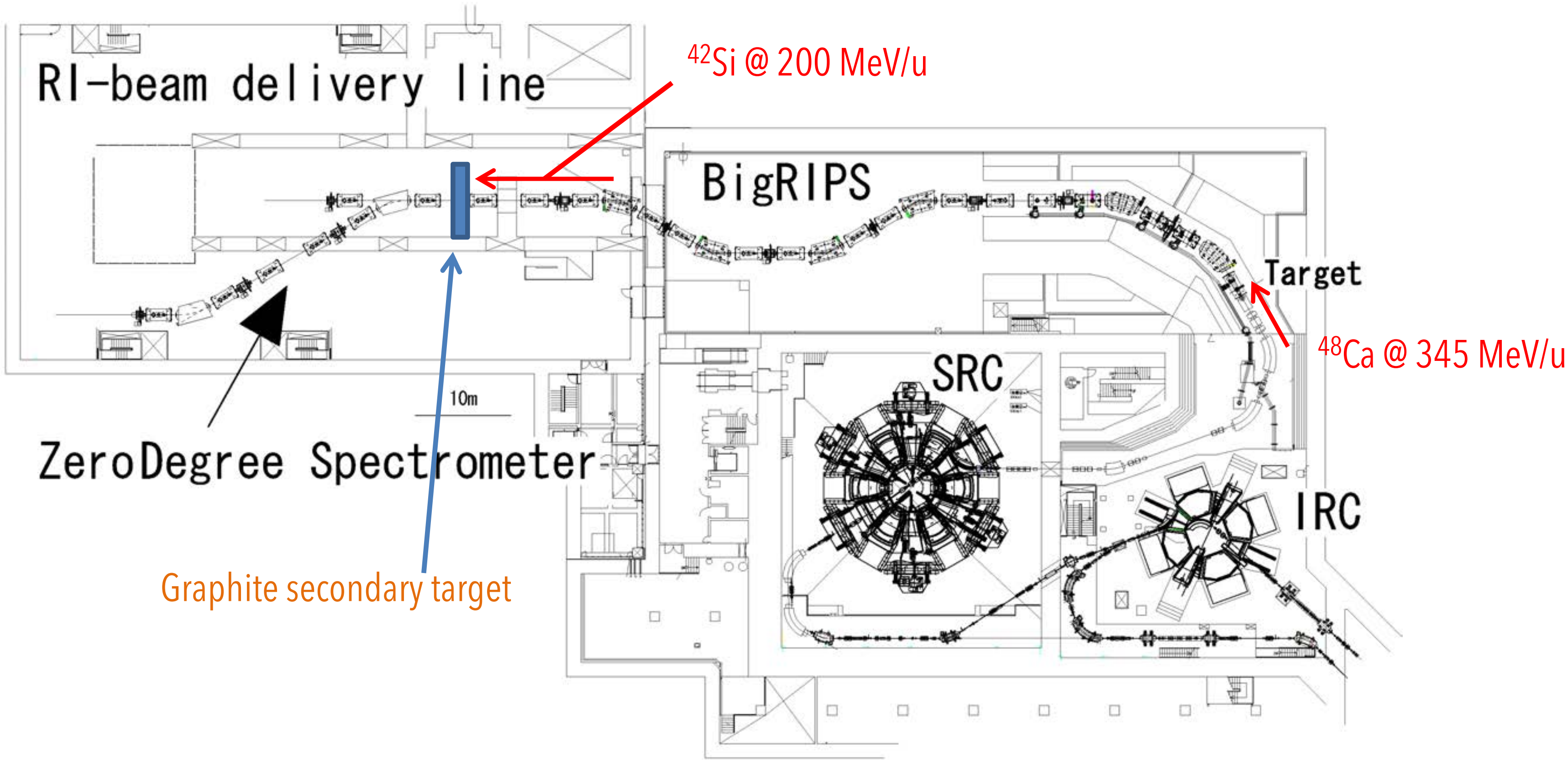
^{40}Mg may be one of the heaviest drip-line(?) nuclei experimentally accessible with current facilities.

Beam intensities at RIBF today allow spectroscopy in ^{40}Mg.

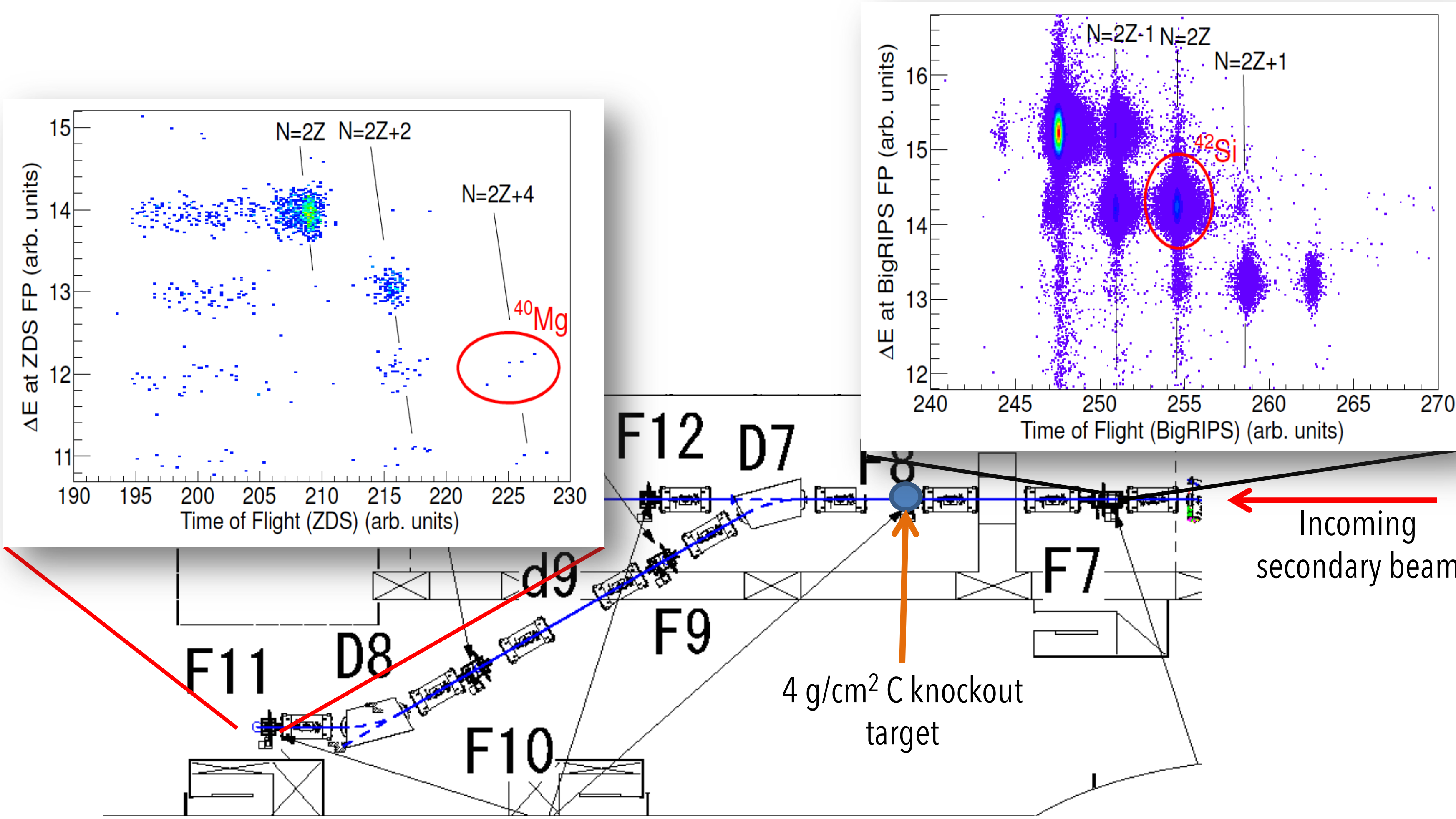
2010: Nucleon Knockout at RIBF

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: $^{42}Si \Rightarrow {}^{40}Mg$



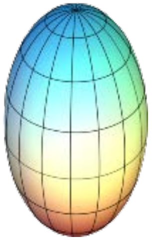
- Approximately 10 hours of beam-on-target
- 5 events of ^{40}Mg observed -- measured inclusive $\sigma_{(-2p)}$ of 40(18) μb

^{40}Mg: Where we left it in 2014

Based on the inclusive cross-section from ^{42}Si(-2p):

- ^{40}Mg likely only has one bound 0^+ state (the ground state)
- The ground state deformation is likely opposite in sign to that of ^{42}Si

^{40}Mg



Open questions:

- Are there any bound excited states? (S_n = 1.997(716) MeV)
- Is $E(2^+)$ in line with expectations from shell-model?
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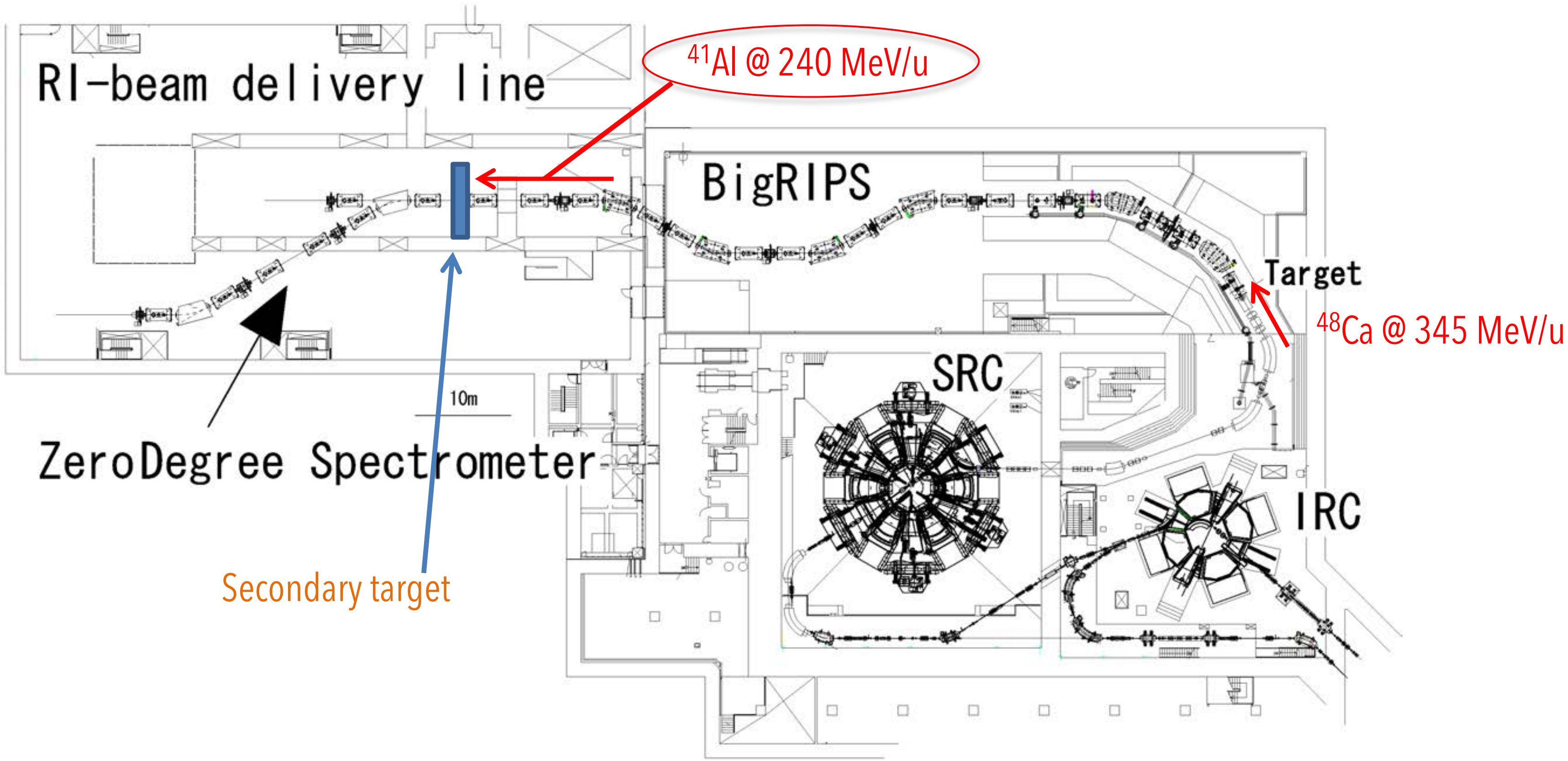
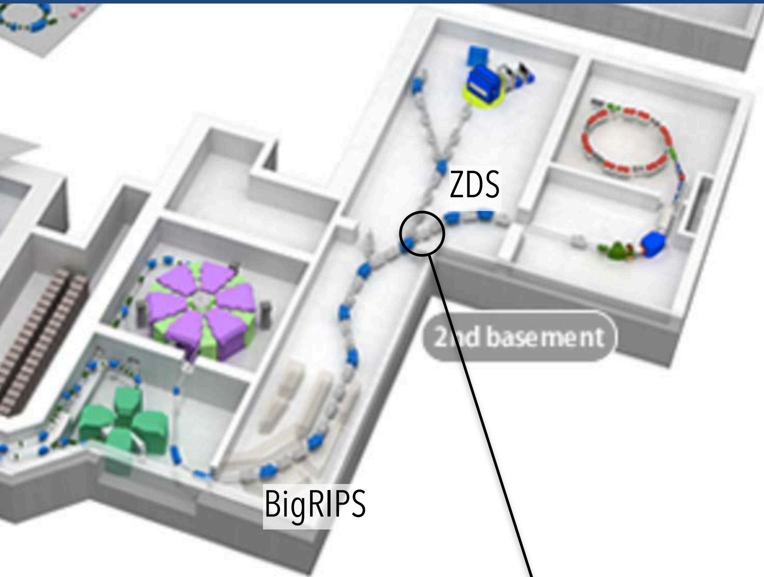
December 2016 at RIBF – NP1312-RIBF03R2

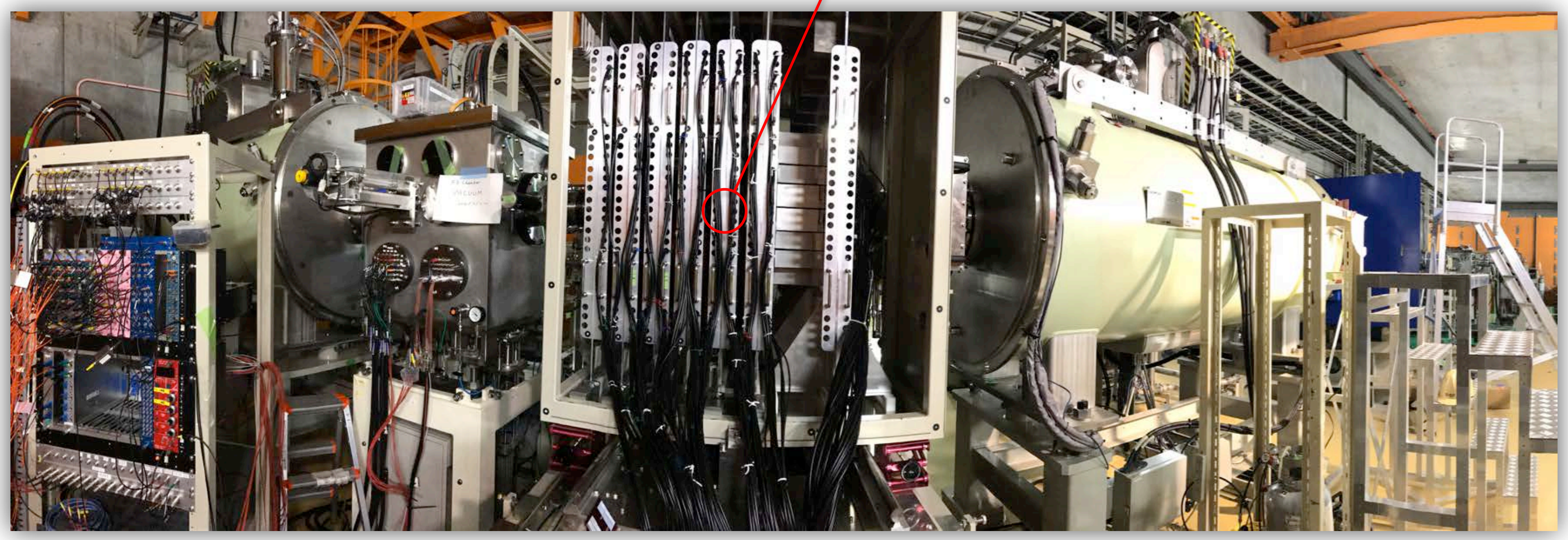
^{41}Al produced following fragmentation of a high-intensity ^{48}Ca primary beam at RIBF in RIKEN



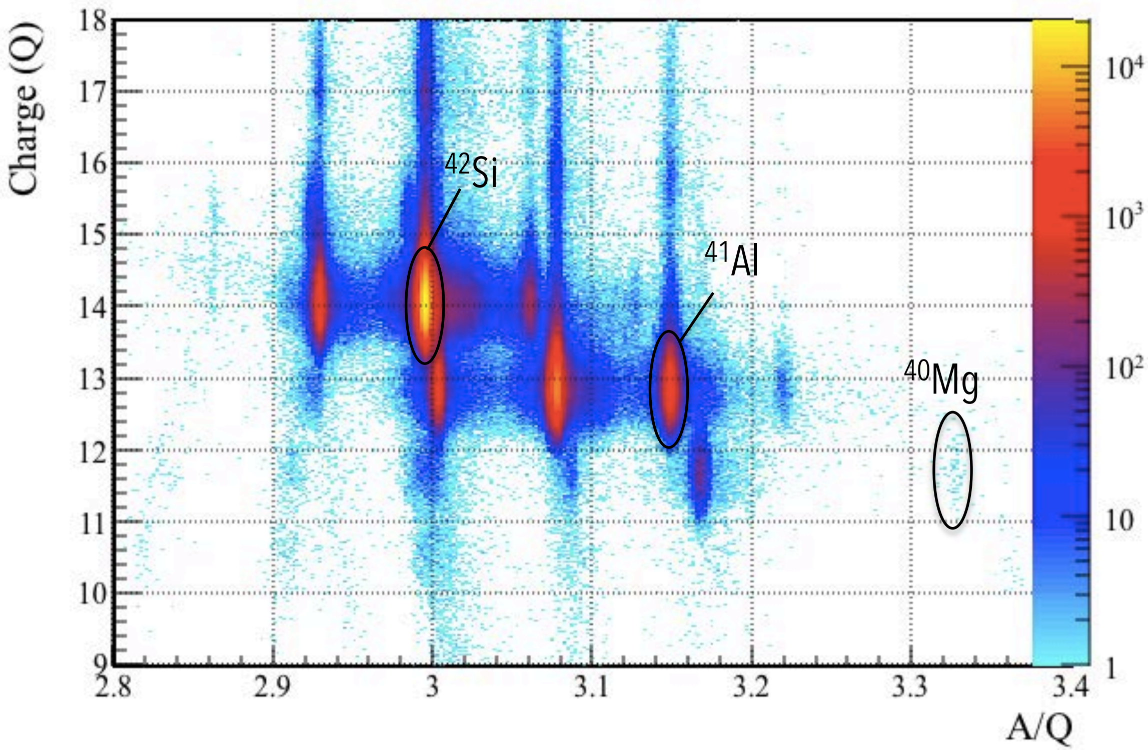
December 2016 at RIBF – NP1312-RIBF03R2



Self-supporting Carbon (graphite) and CH_2 targets
$CH_2 \Rightarrow 3.82$ g/cm^2; Carbon $\Rightarrow 3.80$ g/cm^2

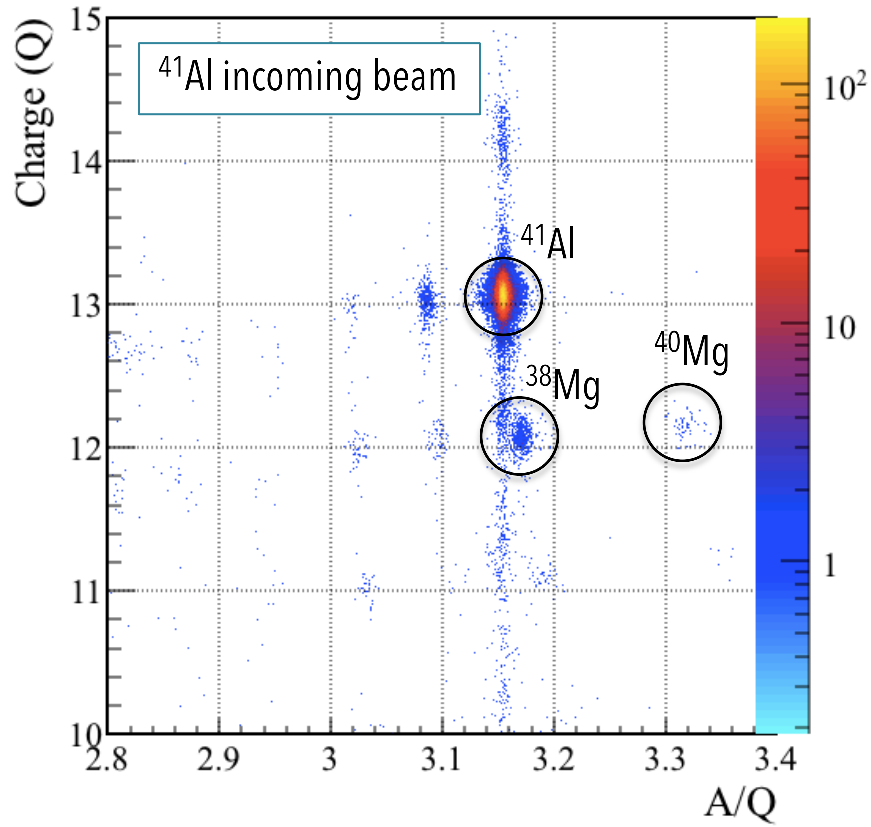


Incoming Beam in BigRIPS



- BigRIPS fragment separator was centered on ^{41}Al
- ~3% of incoming beam was ^{41}Al; ^{42}Si and ^{40}Mg were both in acceptance of BigRIPS
- Average ^{48}Ca primary beam intensity of order 400 pnA

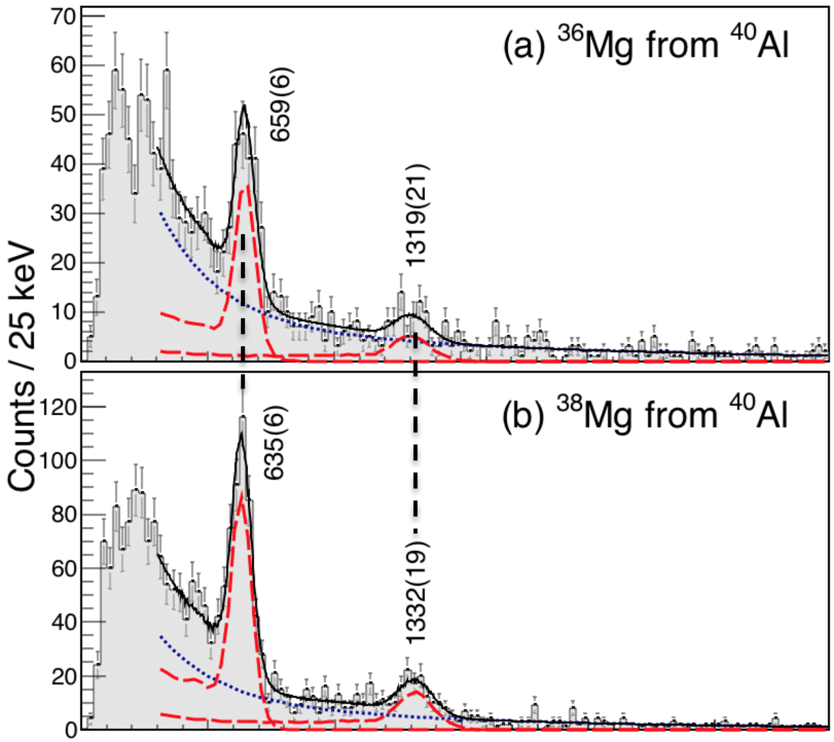
ZeroDegree PID and Cross-Sections

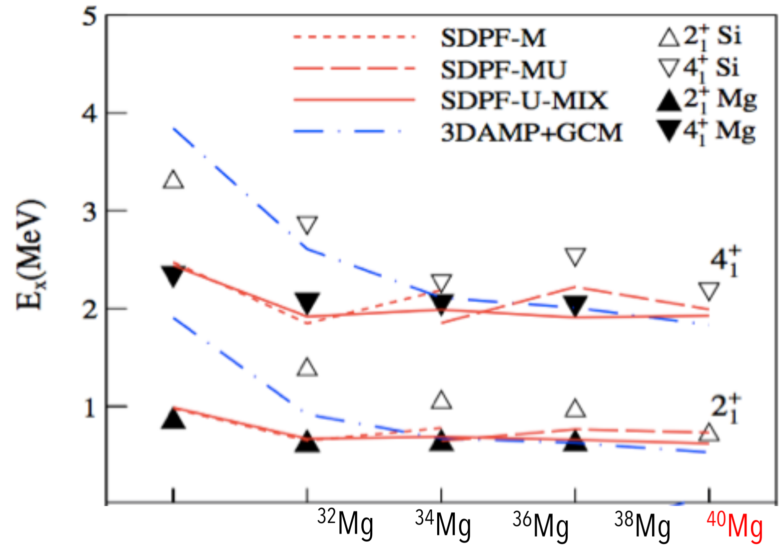


Cross-section analysis – relative to ^{42}Si(-2p)

- Inclusive cross-section for ^{41}Al(-1p) is ~ 30 × $\boldsymbol{\sigma}_{42Si\text{-}2p}$ ⇒ ~1.2 mb
- Cross-section from SDPF-MU for states below 0_2^+ for ^{41}Al(-1p) = 2.45 mb (without suppression factor); 0.74 mb with suppression

Results: ^{36,38}Mg and ^{40}Mg Spectra





P. Doornenbal et al., PRL **111**, 212502 (2013).

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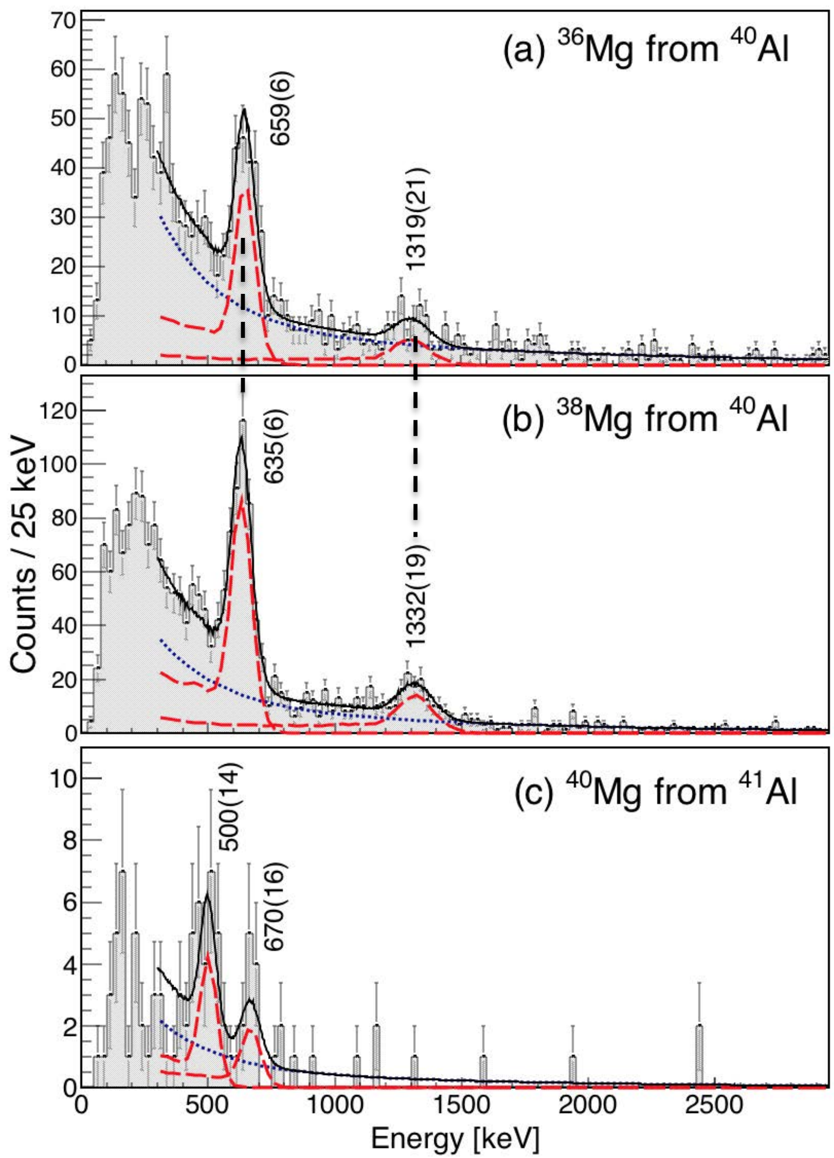

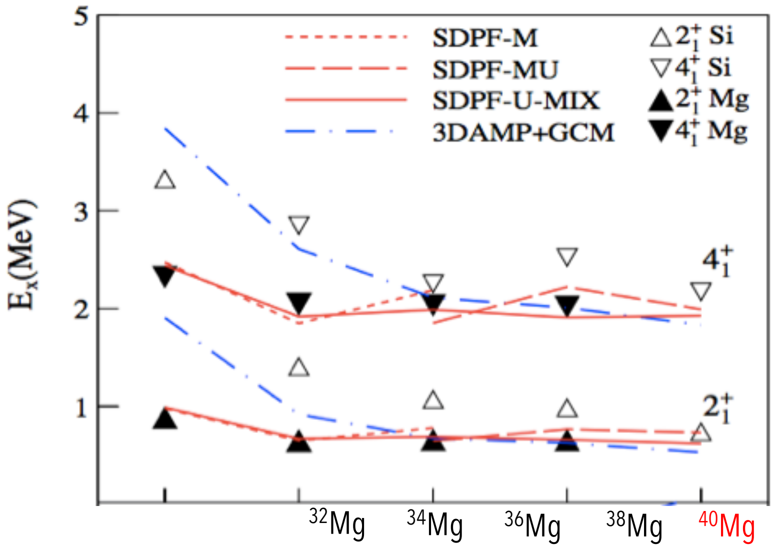

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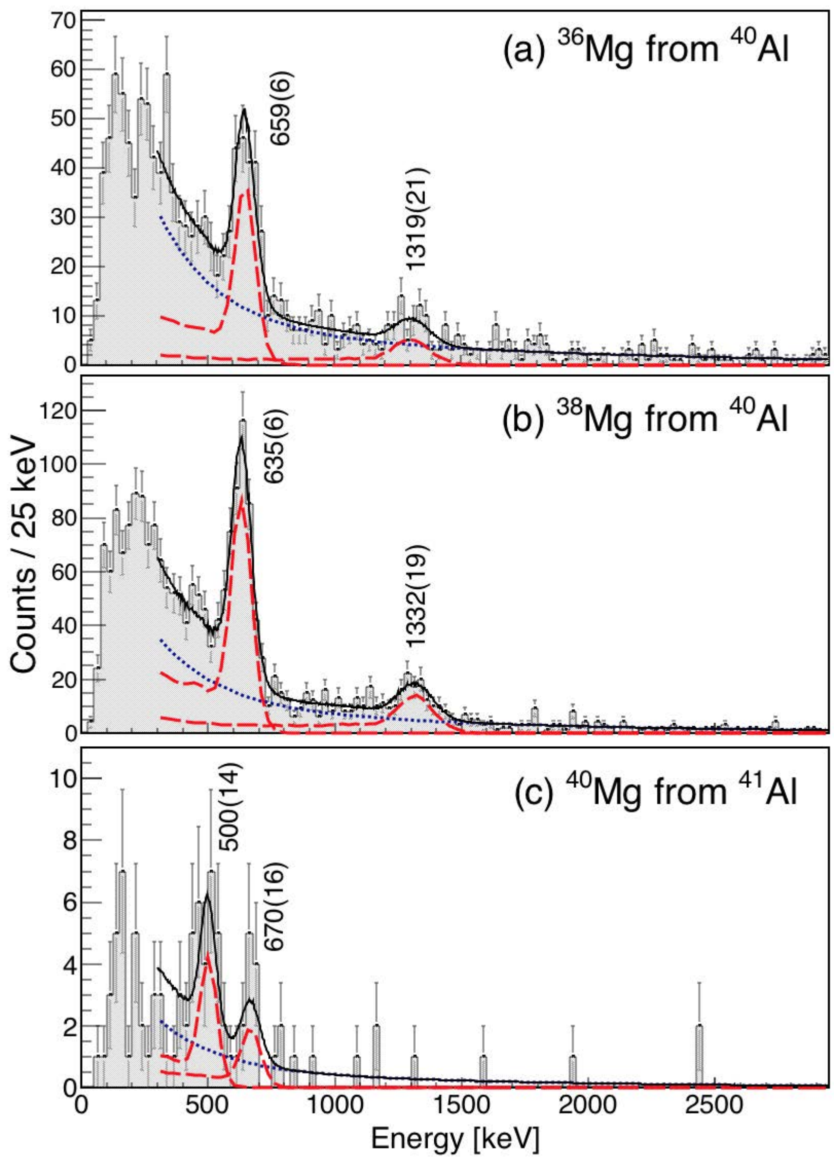
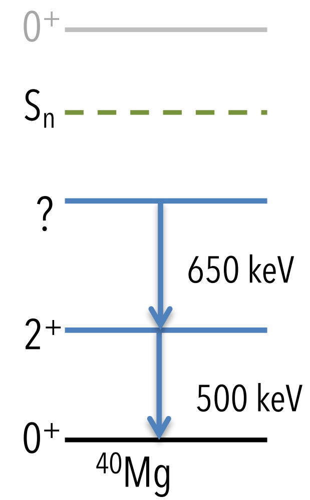
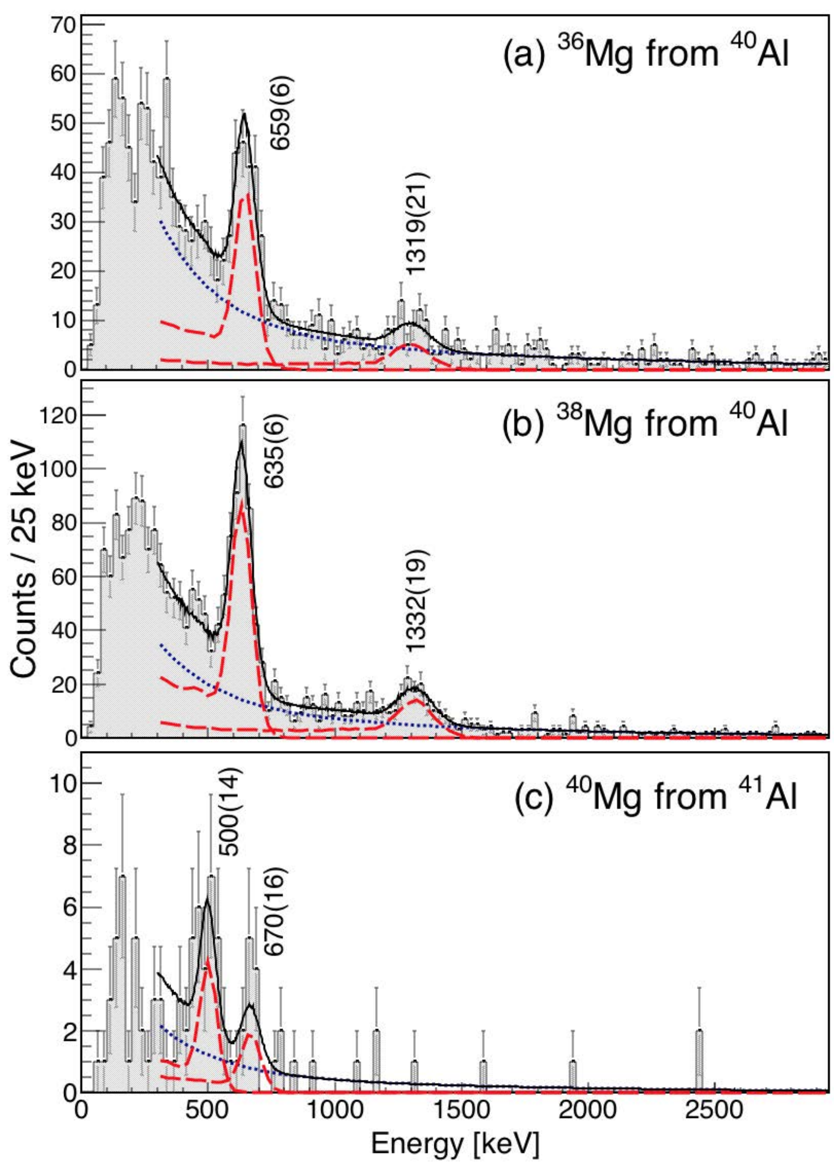
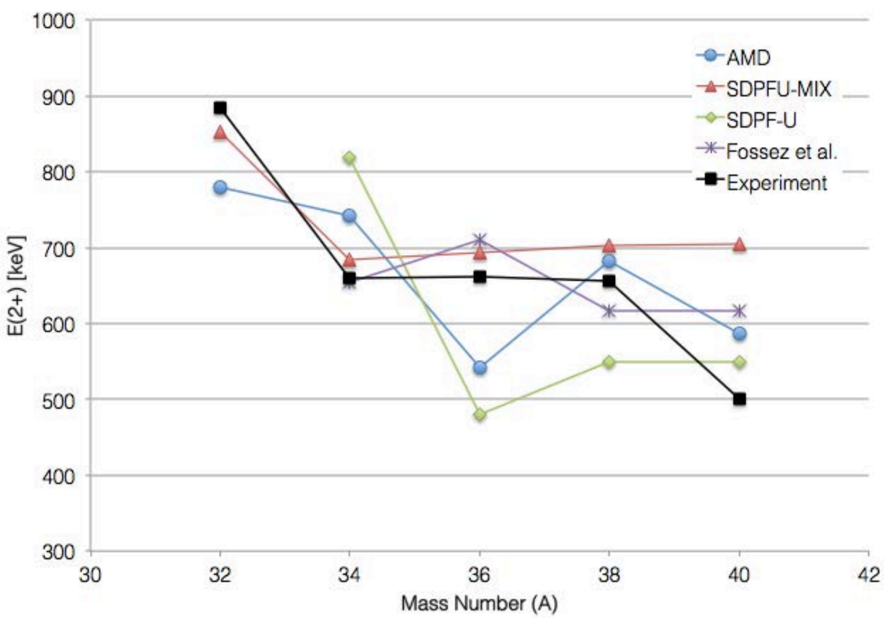




- 500 keV transition assigned to $2_1^+ \rightarrow 0_1^+$
- 650 keV transition ?
  $2_2^+ \rightarrow 2_1^+$ $0_2^+ \rightarrow 2_1^+$ $4_1^+ \rightarrow 2_1^+$ + ...
- No scenario fits with existing expectations (systematics) nor predictions from calculation
- Breakdown of systematics and theory predictions suggests something new is happening at the dripline

Results: ^{36,38}Mg and ^{40}Mg Spectra





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Where are we now?

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- Is $E(2^+)$ in line with expectations from shell-model?
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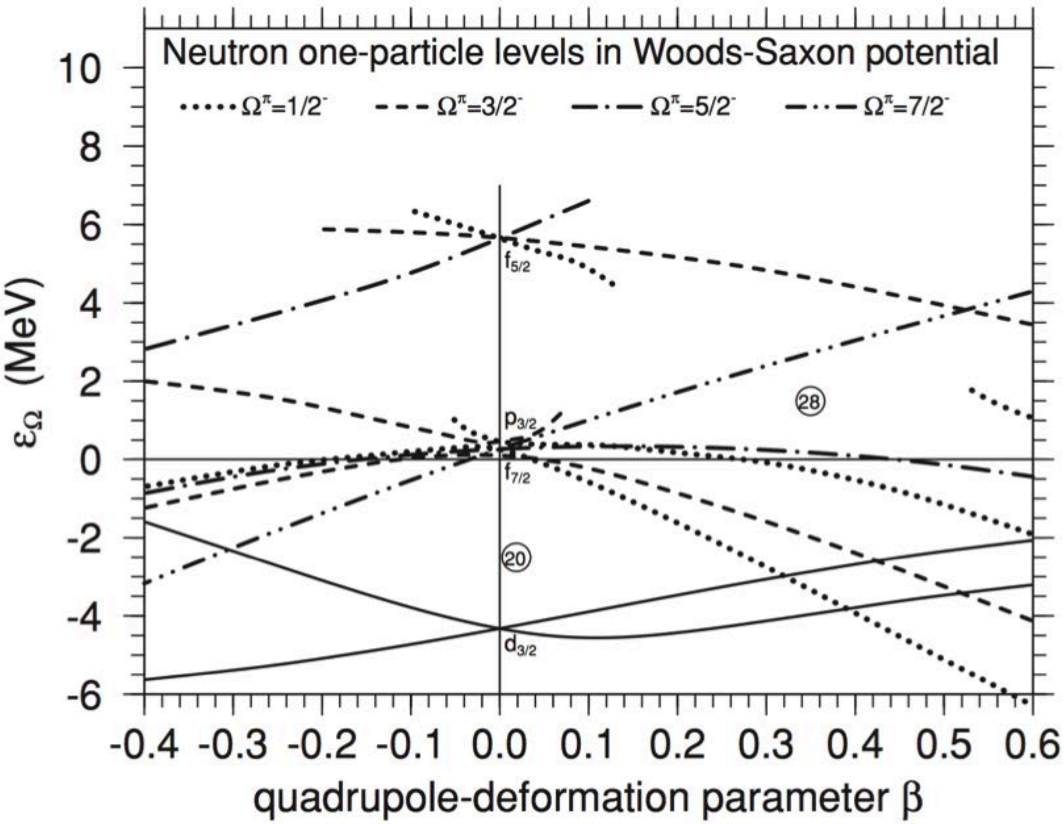
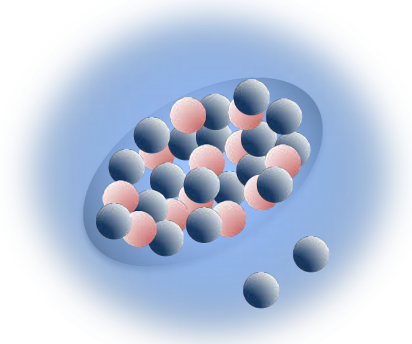
Weakly bound neutrons in ^{40}Mg

- 2-body NN interaction ($\sigma.\tau$, Tensor) works to modify the N=28 shell gap
- Occupation of low l levels ($p_{3/2}$) leads to extended wavefunctions ("halos")



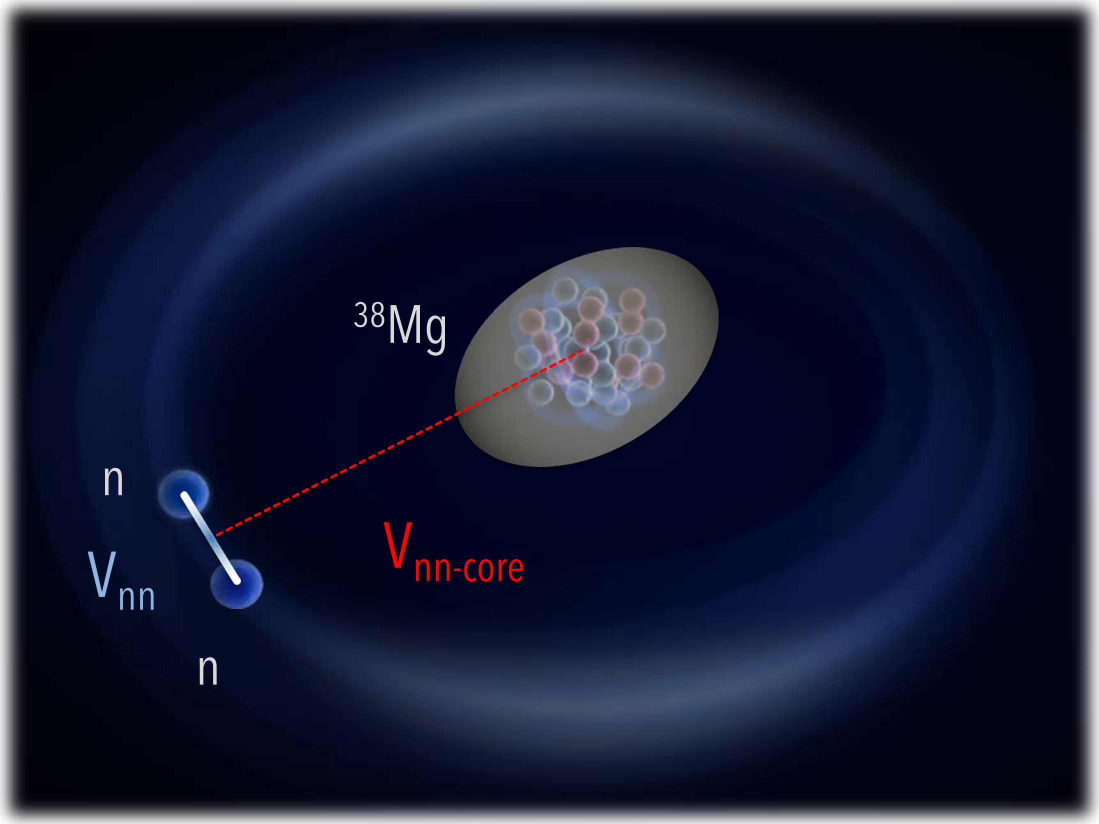
I.Hamamoto



- Consider ^{40}Mg as a deformed ^{38}Mg core and a 2-neutron p-wave halo
- How do the halo neutrons interact with the core in ^{40}Mg ?

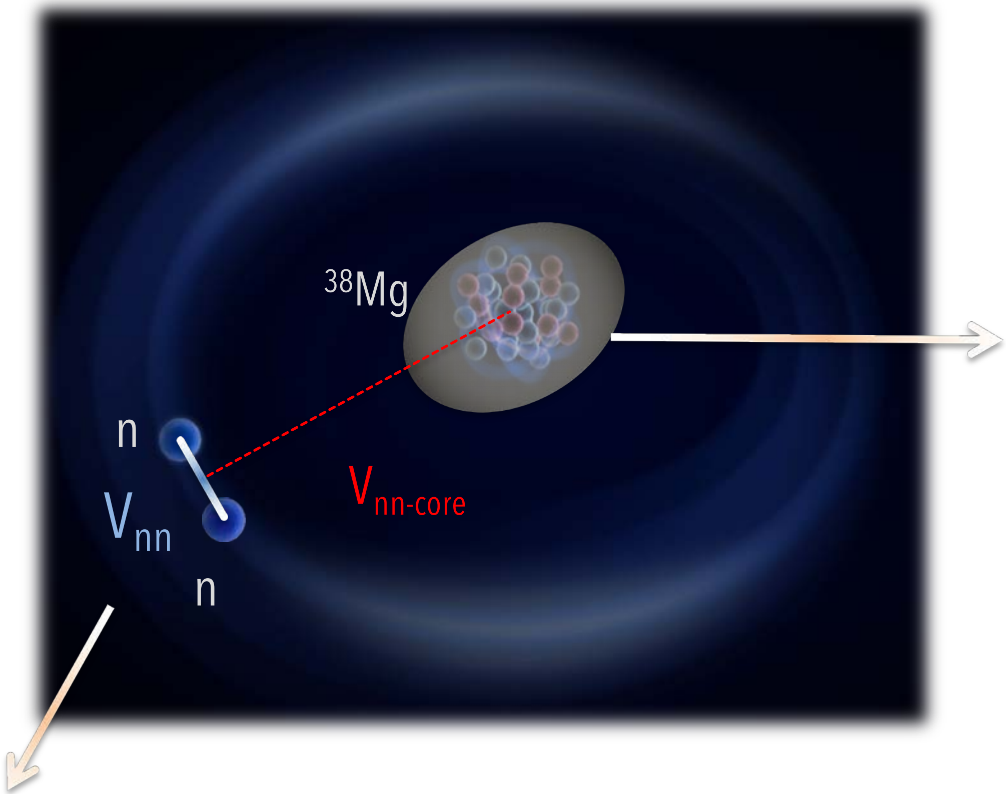
Coupling of valence (halo) neutrons to the core

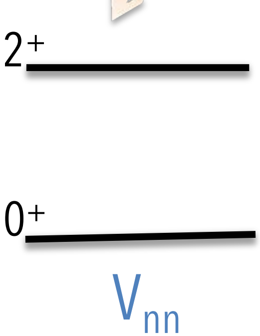
- ^{11}Li – "strong" coupling – ^{9}Li core surface is "soft" towards surface vibrations
- ^{6}He – "weak" coupling – ^{4}He core surface is "hard"



- The way the halo couples to the core will affect the low-lying spectrum
- Propose that observed ^{40}Mg spectrum to arise from weakly coupled "halo"

Weak coupling of two degree of Freedom

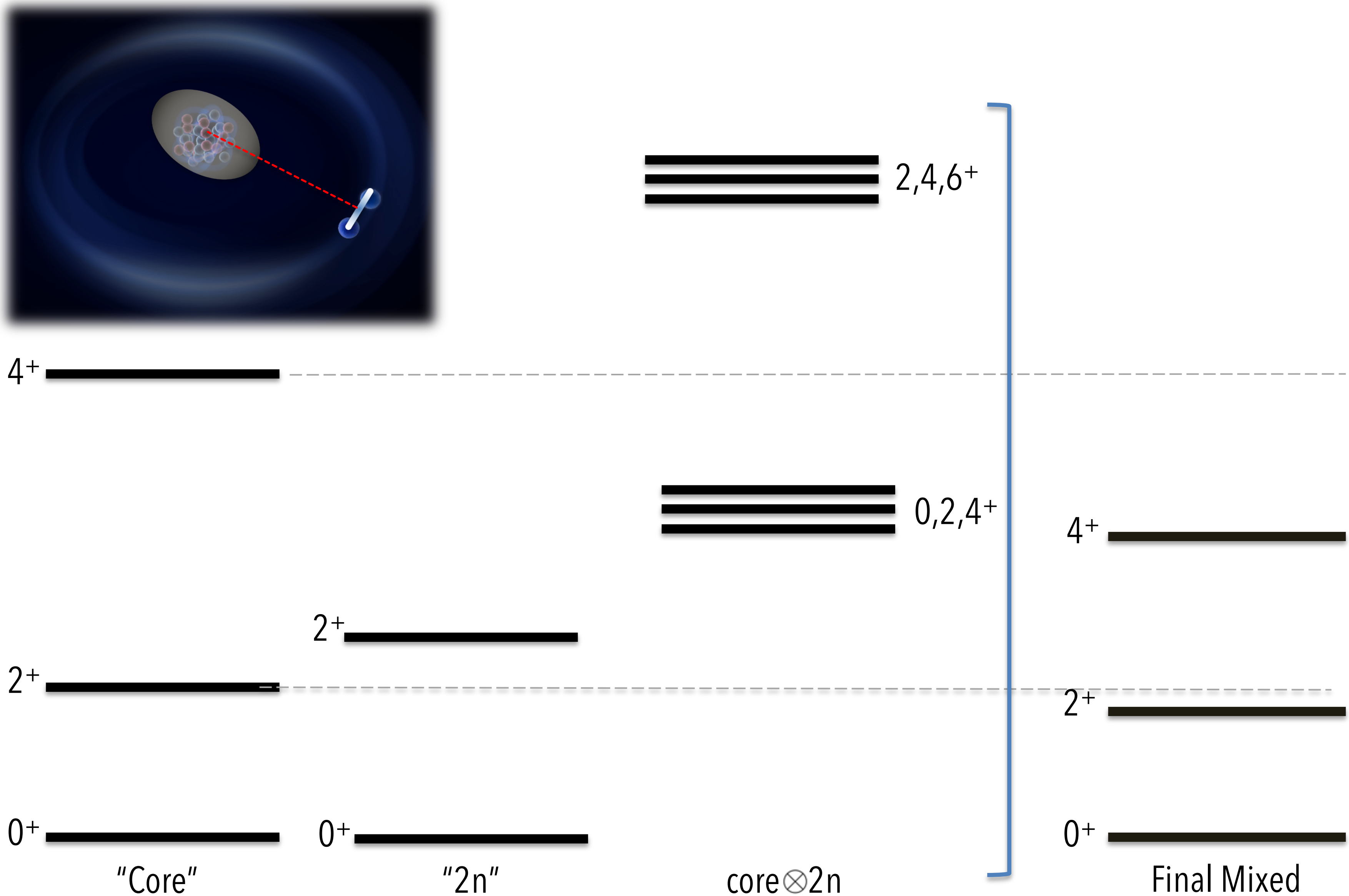




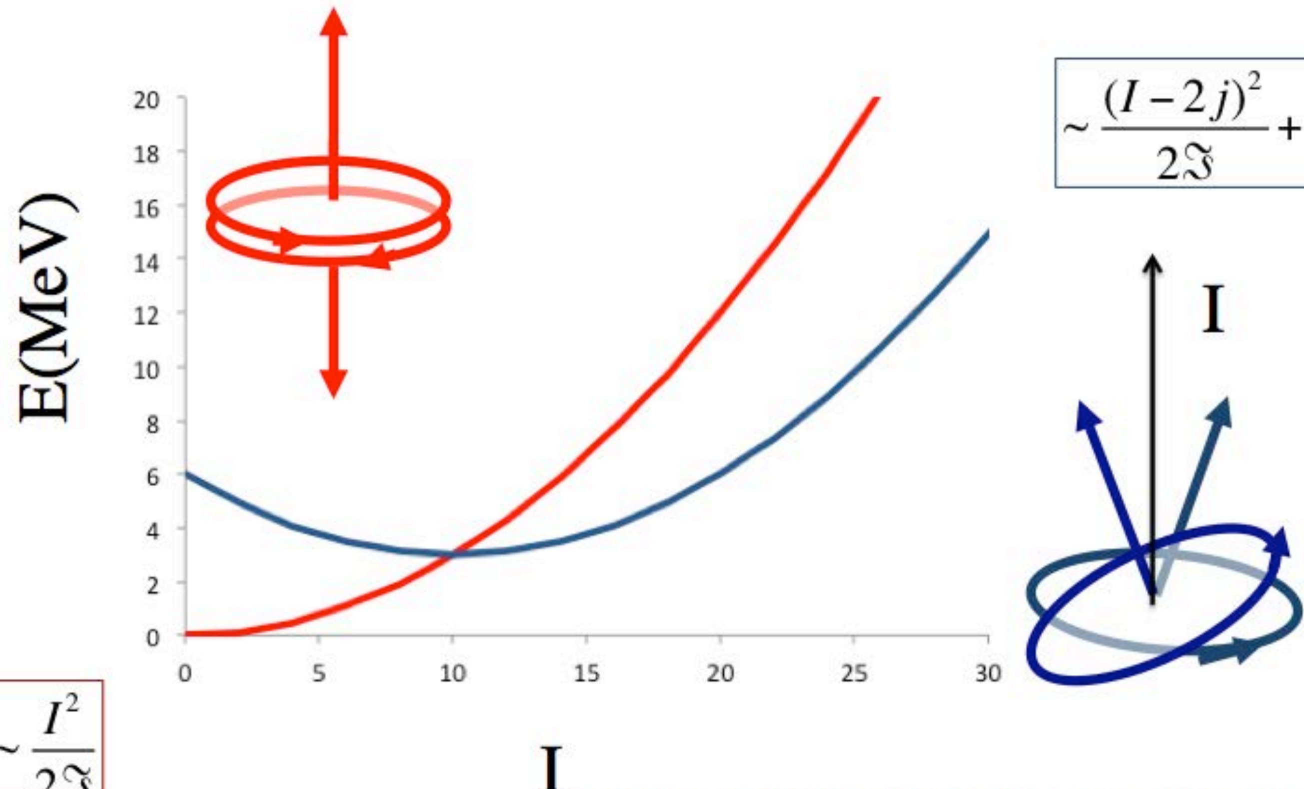
$$H_{40Mg} = \underbrace{H_{38Mg} + V_{nn}}_{\text{Core} \otimes \text{2n basis}} + \underbrace{V_{nn\text{-core}}}_{\text{Mixing}}$$

Weak Coupling of two degrees of freedom

Weak coupling of two degree of Freedom



Rotation and Alignment

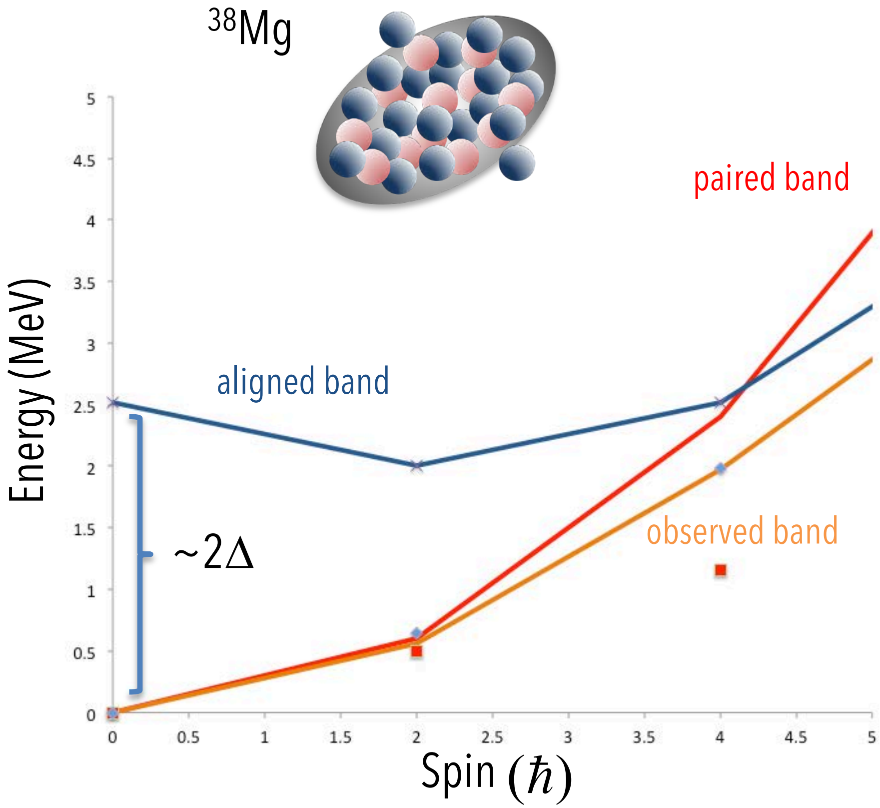


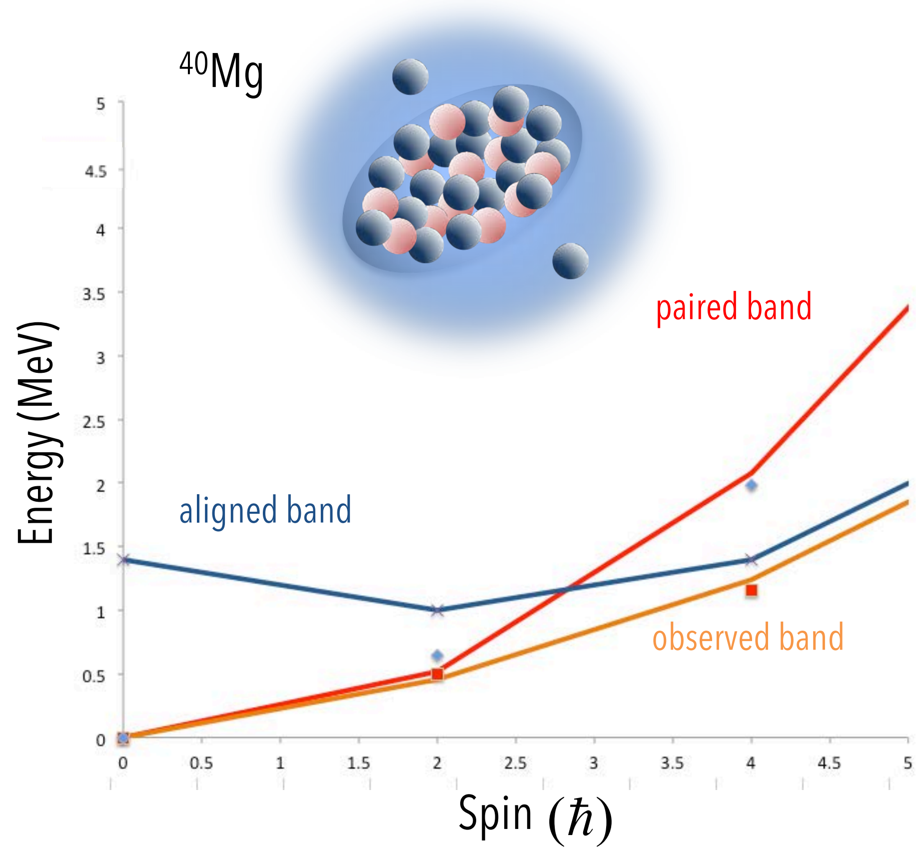
$$\sim \frac{(I-2j)^2}{2\Im} + 2\Delta$$

$$\sim \frac{I^2}{2\Im}$$

F. S. Stephens and R. S. Simon, Nucl. Phys. A183,257 (1972).

Rotation in ^{40}Mg – "decoupled valence pair"





In ^{40}Mg, the energy to break pair is reduced ("diagonal pair" matrix element only)

Summary

- A successful spectroscopic measurement of ^{40}Mg has been made at RIBF using the $^{41}Al(-1p)$ knockout reaction
- At least two excited bound states exists in ^{40}Mg, experimentally confirming a binding energy above ~500 keV
- Observed excitation energy spectrum in ^{40}Mg is outside expectations from systematics and theoretical predictions
- Possible evidence of weak-binding effects?

Acknowledgements

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Editors' Suggestion

First Spectroscopy of the Near Drip-line Nucleus ^{40}Mg

H. L. Crawford,[1,*] P. Fallon,[1] A. O. Macchiavelli,[1] P. Doornenbal,[2] N. Aoi,[3] F. Browne,[2] C. M. Campbell,[1] S. Chen,[2] R. M. Clark,[1] M. L. Cortés,[2] M. Cromaz,[1] E. Ideguchi,[3] M. D. Jones,[1,†] R. Kanungo,[4,5] M. MacCormick,[6] S. Momiyama,[7] I. Murray,[6] M. Niikura,[7] S. Paschalis,[8] M. Petri,[8] H. Sakurai,[2,7] M. Salathe,[1] P. Schrock,[9] D. Steppenbeck,[9] S. Takeuchi,[2,10] Y. K. Tanaka,[11] R. Taniuchi,[7] H. Wang,[2] and K. Wimmer[7]

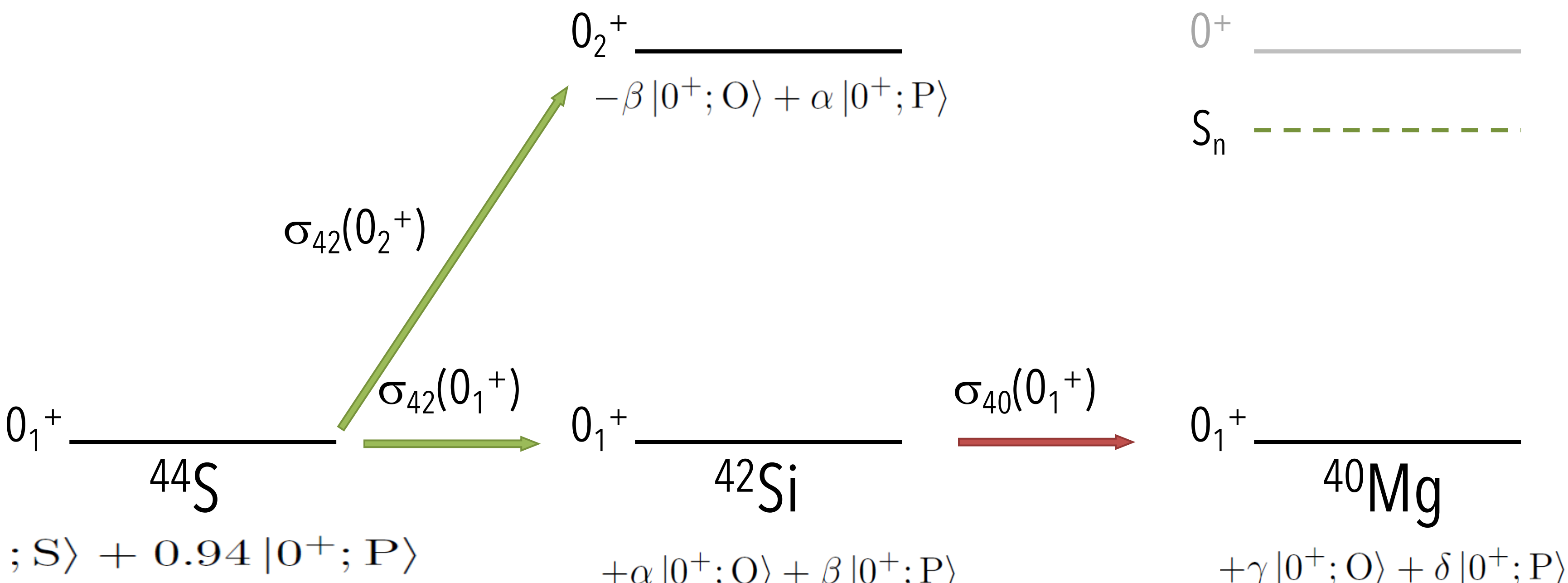
Thank you!

Back up Slides

σ Ratios to Constrain “Shape” Amplitudes

^{44}S-2p ^{42}Si-2p

$$\mathcal{R} = [\sigma_{42}(0_1^+) + \sigma_{42}(0_2^+)]/\sigma_{40}(0_1^+)$$



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

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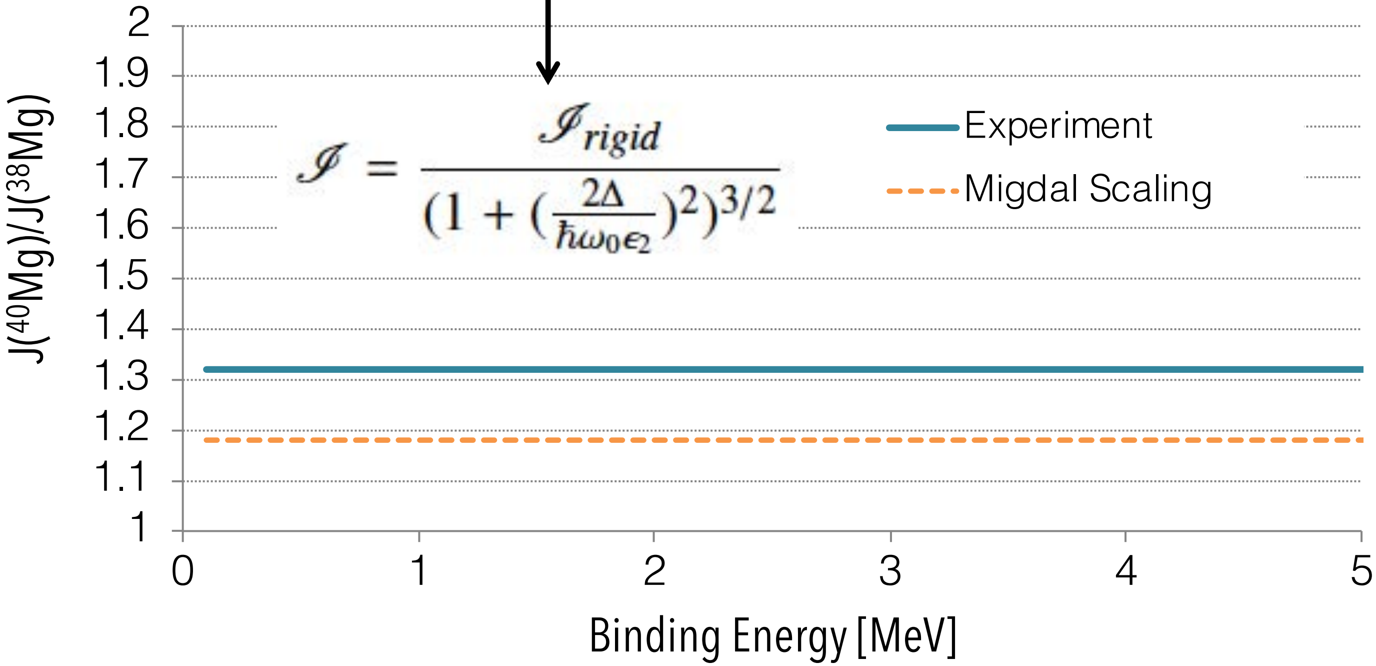
$$\mathscr{I} = \frac{\mathscr{I}_{rigid}}{(1 + (\frac{2\Delta}{\hbar\omega_0\epsilon_2})^2)^{3/2}}$$



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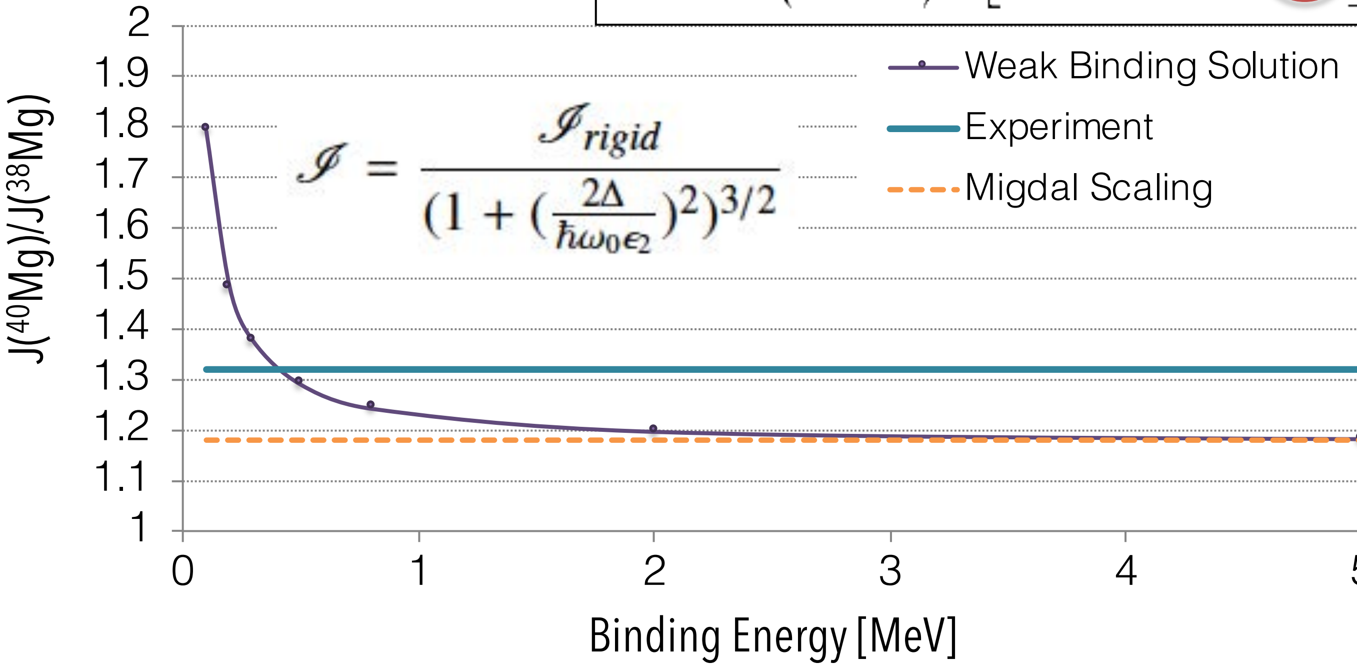
Introduce dependence on BE

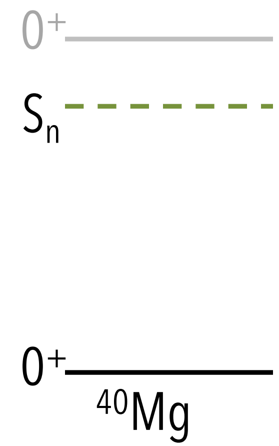
$$\langle r_m^2 \rangle^{1/2} = \left(\frac{M}{M+m}\right)^{1/2} \left[\langle r_c^2 \rangle + \frac{m}{M+m}\langle r^2 \rangle\right]^{1/2}$$



Shell Model + Eikonal Reaction Theory: ^{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)



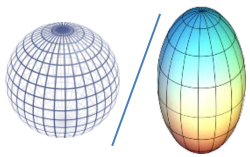
- Experimental cross-section is suppressed compared to predictions using the SDPF-MU shell-model effective interaction and eikonal reaction theory.
- Cross-section is consistent with ONLY ONE bound 0^+ state (calculated s = 67μb) (2012 Atomic Mass Evaluation Sn = 1.74(79))
- Magnitude of the experimental ^{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.

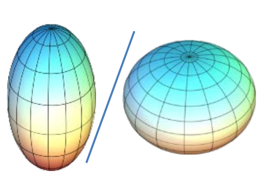
This suggests that a two-state(shape) mixing model can provide a description of their structure.



^{44}S

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

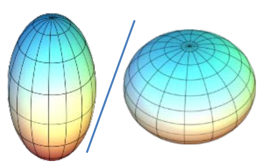
Force et al., Phys. Rev. Lett. 105, 102501 (2010).



^{42}Si

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

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



^{40}Mg

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

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

σ Ratios to Constrain "Shape" Amplitudes

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

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

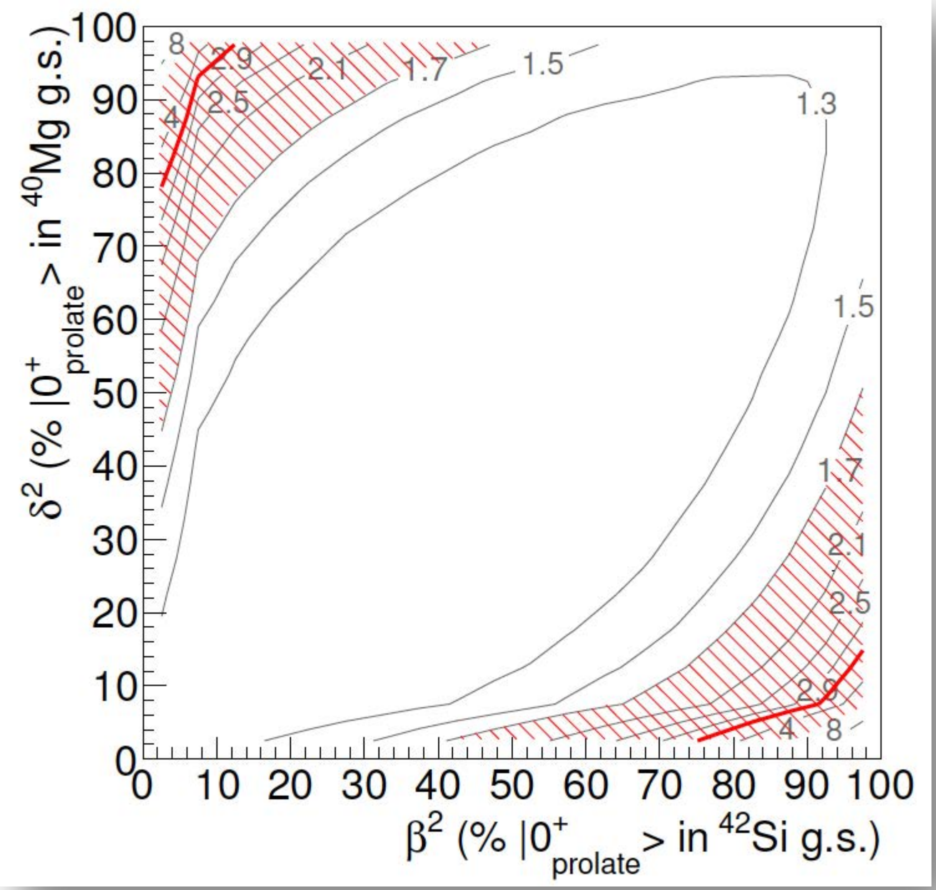
$$|^{42}\mathrm{Si}, 0_2^+\rangle = -\beta\,|0^+;\mathrm{O}\rangle + \alpha\,|0^+;\mathrm{P}\rangle$$

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

Experimental value

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

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



Crawford et al., Phys. Rev. C 89, 041303(R) (2014).