Shapes and Symmetries in Nuclei Studied with GRETINA

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U.S. DEPARTMENT OF ENERGY | Office of Science

BERKELEY LAB

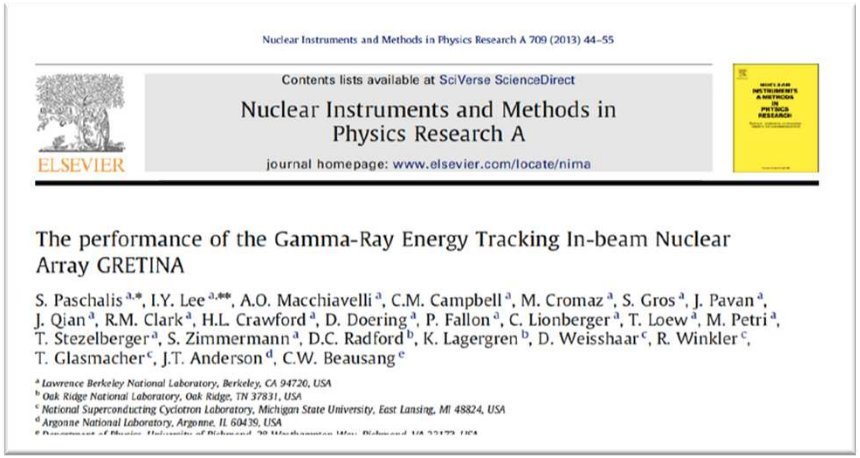
Outline

- GRETINA: A Brief Overview
- GRETINA Physics ⇒ Shapes and Symmetries
  - NSCL Campaign 1.0 – 2012 to 2013
    - "Bubble" Nucleus: ^{34}Si
    - Rotational structure of ^{32}Mg
  - ANL Campaign – 2014 to 2015
    - Octupole deformation in the Ba isotopes
- Summary

GRETINA

GRETINA, covering ¼ of the full solid angle, is the first realization of a γ-ray tracking array, the next generation of spectroscopic tools for the atomic nucleus.

- 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



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Nuclear Instruments and Methods in Physics Research A

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

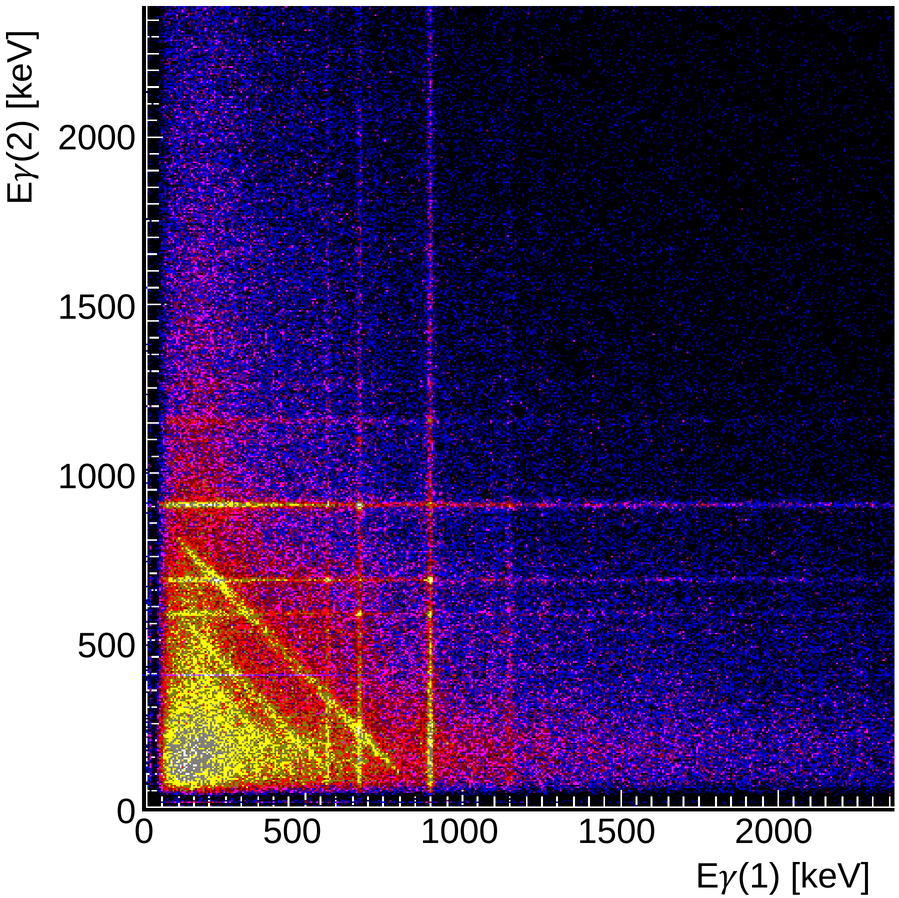
ELSEVIER

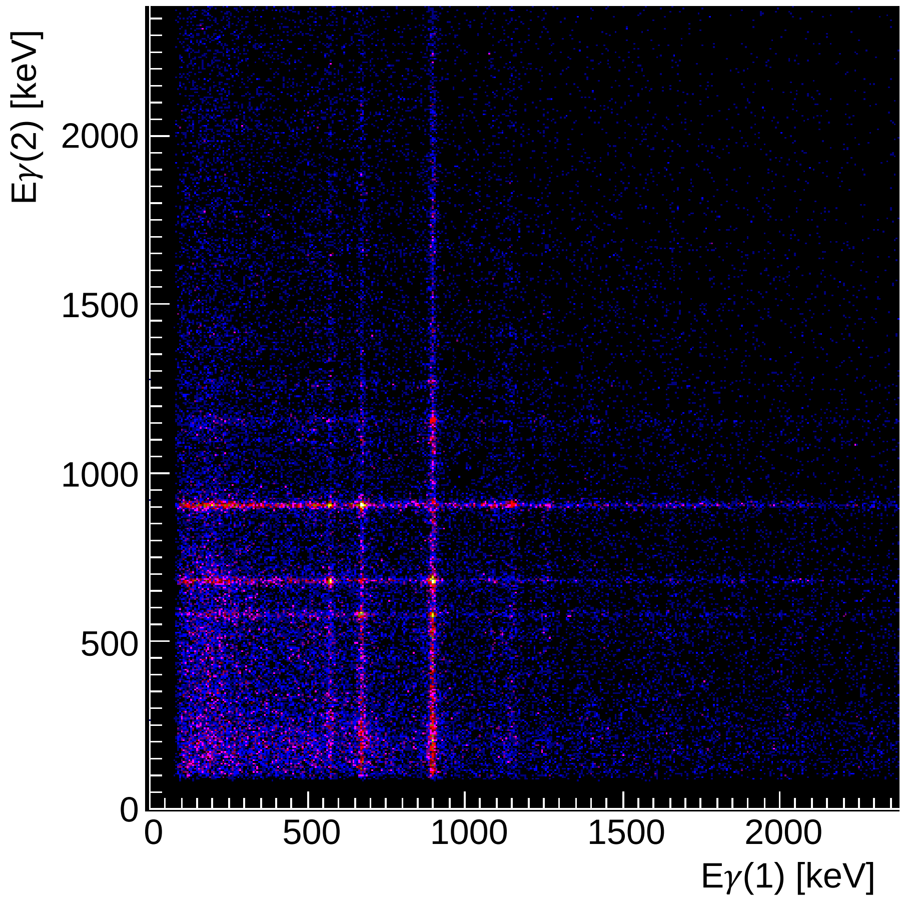
The performance of the Gamma-Ray Energy Tracking In-beam Nuclear Array GRETINA

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

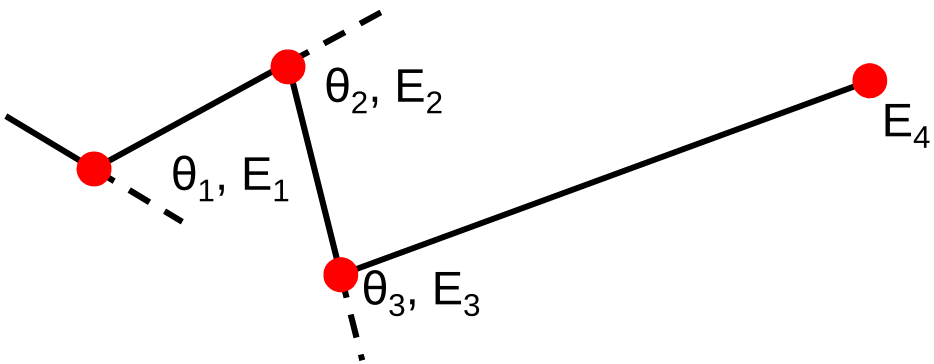
Tracking: Compton Rejection



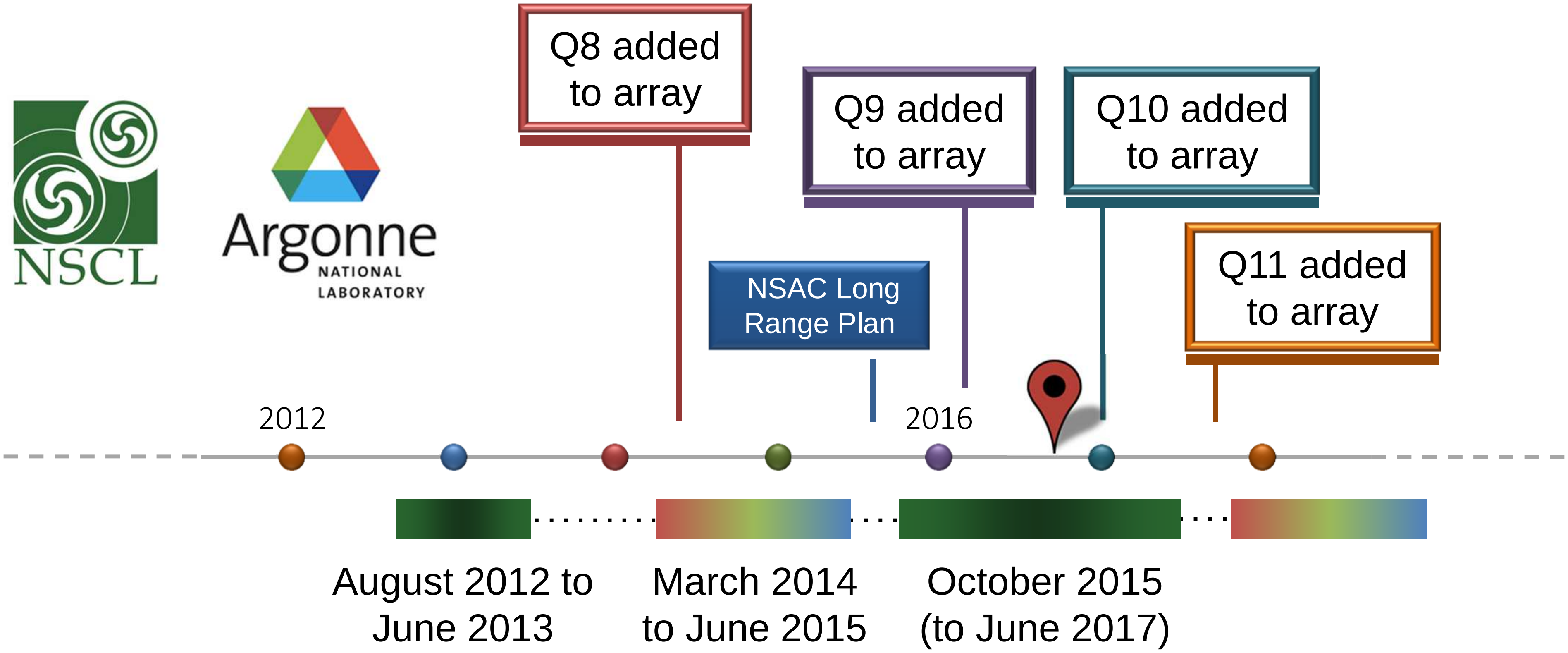


^{64}Ge populated in knockout from ^{65}Ge

Reduction of Compton background by tracking allows spectral quality comparable to arrays with anti-Compton shields.

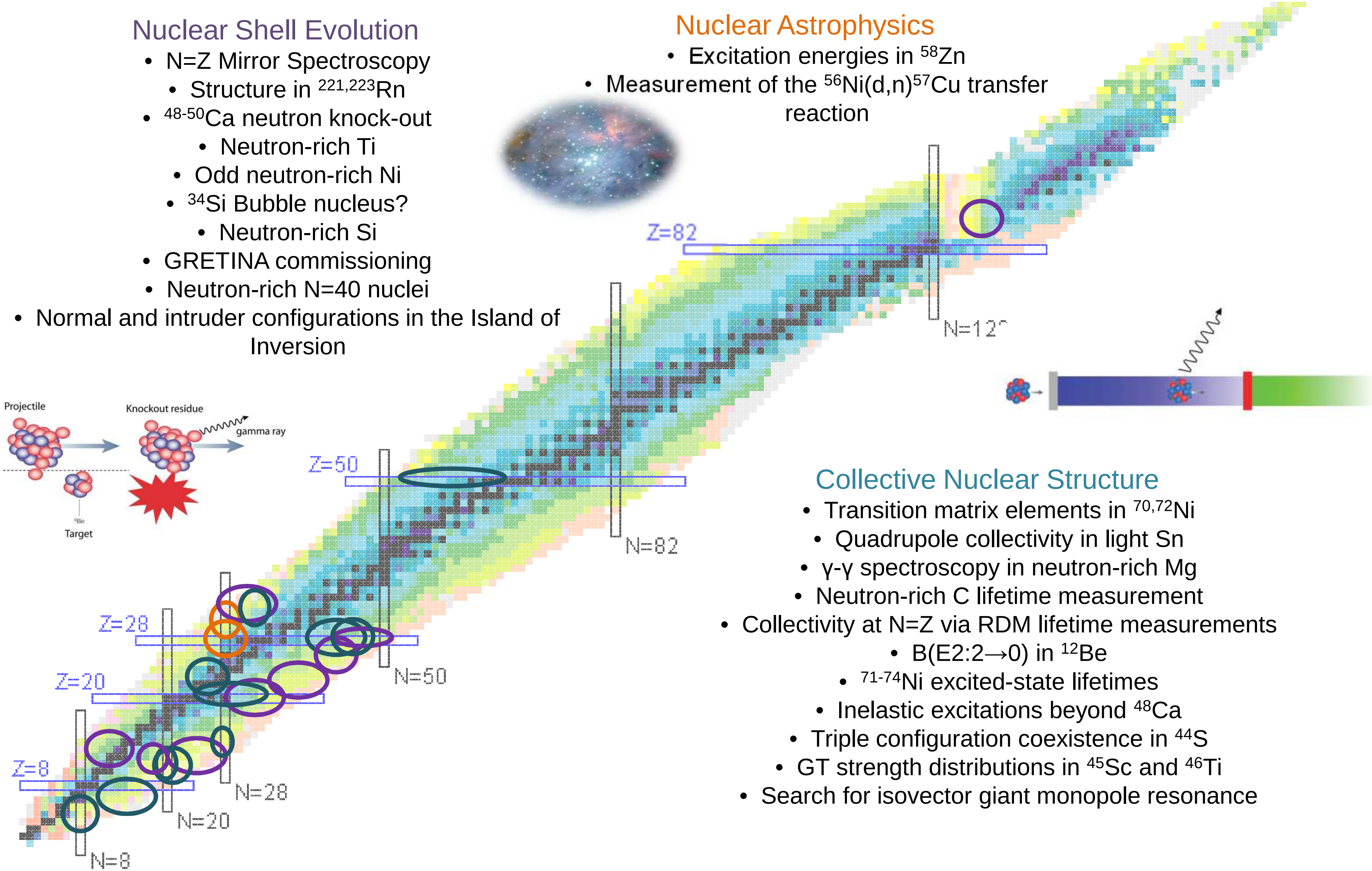


GRETINA Physics Campaigns: Overview



- First physics campaigns at NSCL and ANL (ATLAS/CARIBU) have already produced more than *25* physics papers
- Second NSCL campaign is ongoing, with 24 PAC approved experiments (~3600 hours)

NSCL GRETINA Physics Campaign 1.0



Nuclear Shell Evolution

- N=Z Mirror Spectroscopy
- Structure in $^{221,223}Rn$
- $^{48-50}Ca$ neutron knock-out
- Neutron-rich Ti
- Odd neutron-rich Ni
- ^{34}Si Bubble nucleus?
- Neutron-rich Si
- GRETINA commissioning
- Neutron-rich N=40 nuclei
- Normal and intruder configurations in the Island of Inversion

Nuclear Astrophysics

- Excitation energies in ^{58}Zn
- Measurement of the $^{56}Ni(d,n)^{57}Cu$ transfer reaction

Collective Nuclear Structure

- Transition matrix elements in $^{70,72}Ni$
- Quadrupole collectivity in light Sn
- γ-γ spectroscopy in neutron-rich Mg
- Neutron-rich C lifetime measurement
- Collectivity at N=Z via RDM lifetime measurements
- B(E2:2→0) in ^{12}Be
- $^{71-74}Ni$ excited-state lifetimes
- Inelastic excitations beyond ^{48}Ca
- Triple configuration coexistence in ^{44}S
- GT strength distributions in ^{45}Sc and ^{46}Ti
- Search for isovector giant monopole resonance

NSCL GRETINA Physics Campaign 1.0

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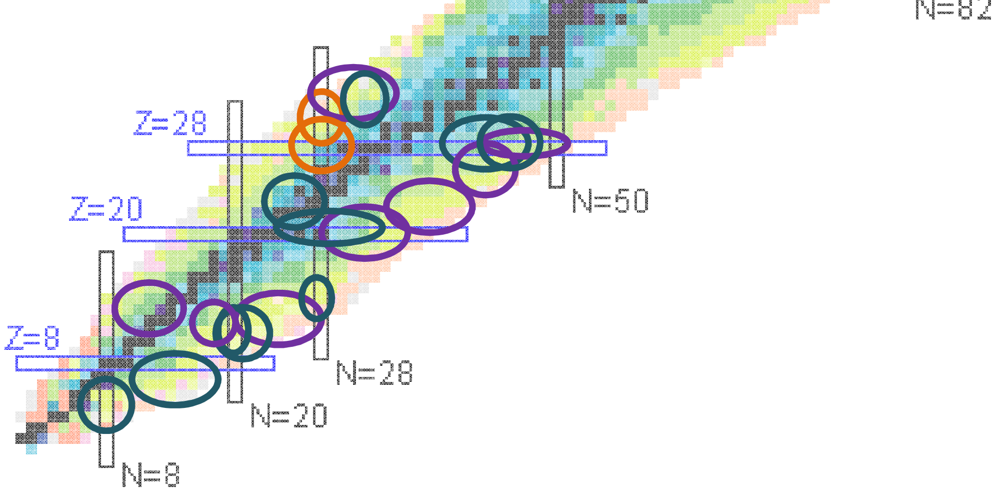

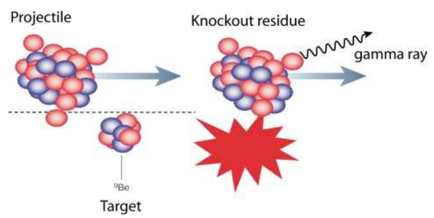

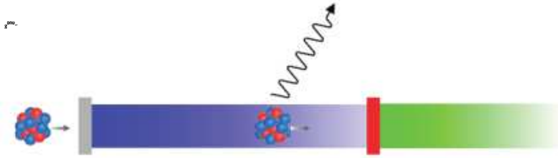

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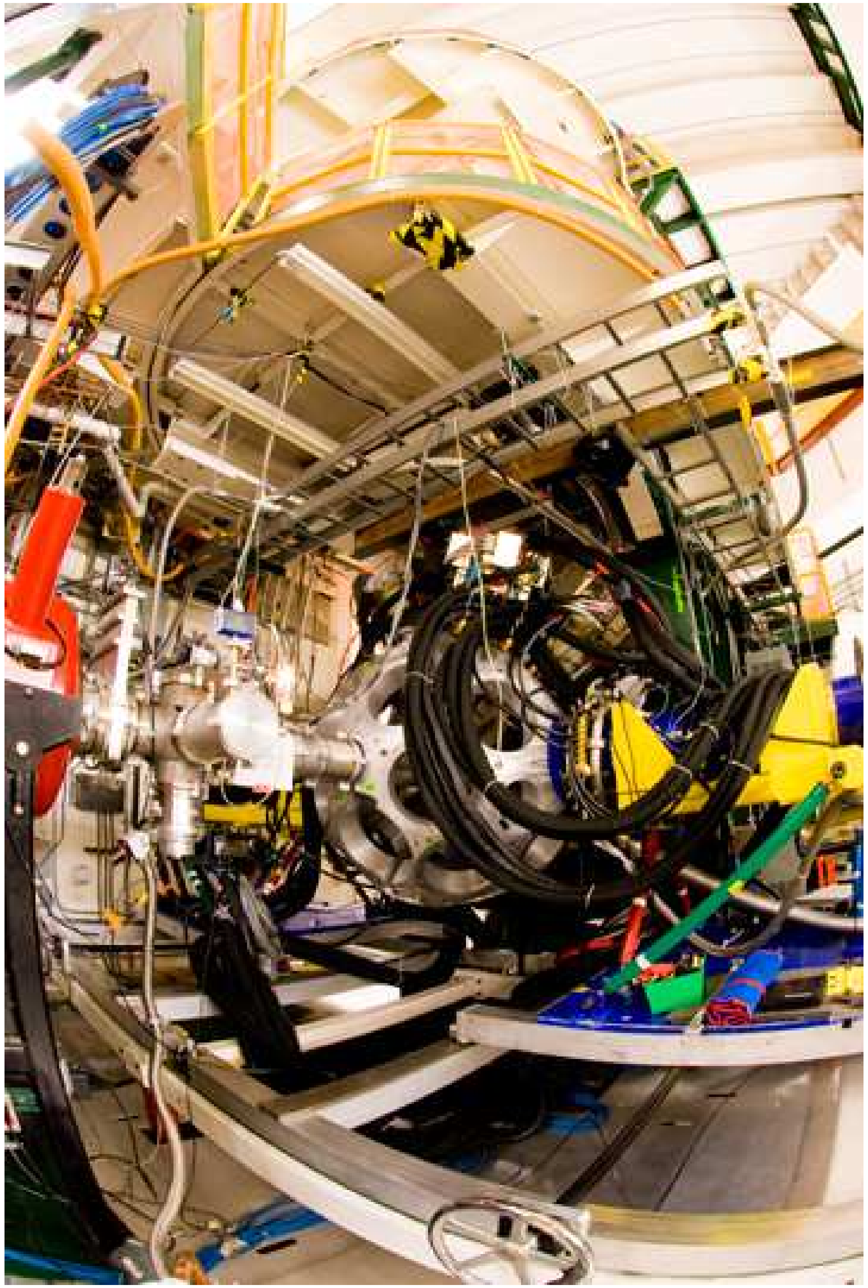
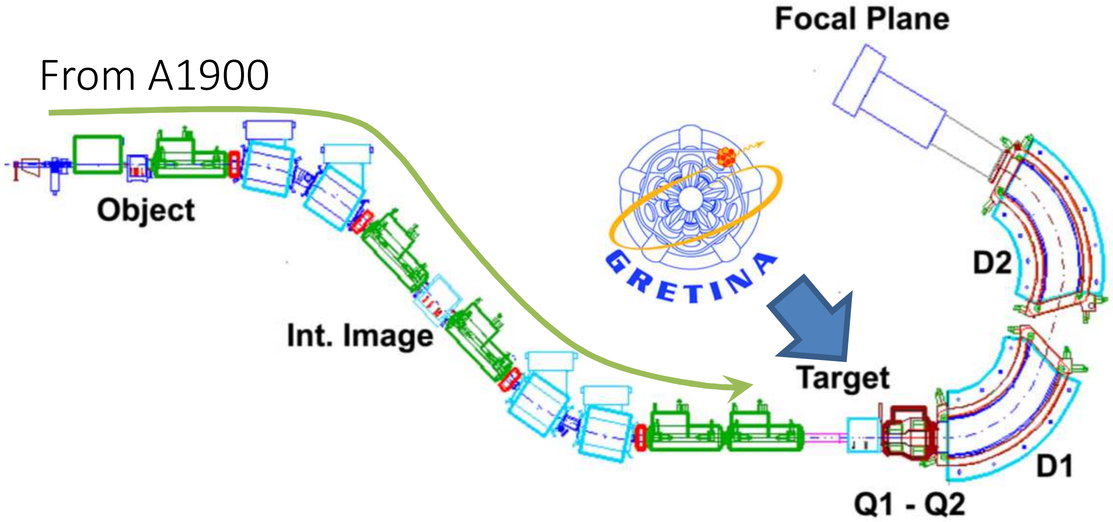
First NSCL Physics Campaign (2012-2013)





- First physics campaign coupled GRETINA with the S800 spectrograph for fast fragmentation beam (in-beam) spectroscopy
- Reaction channel selection is possible event-by-event in the S800

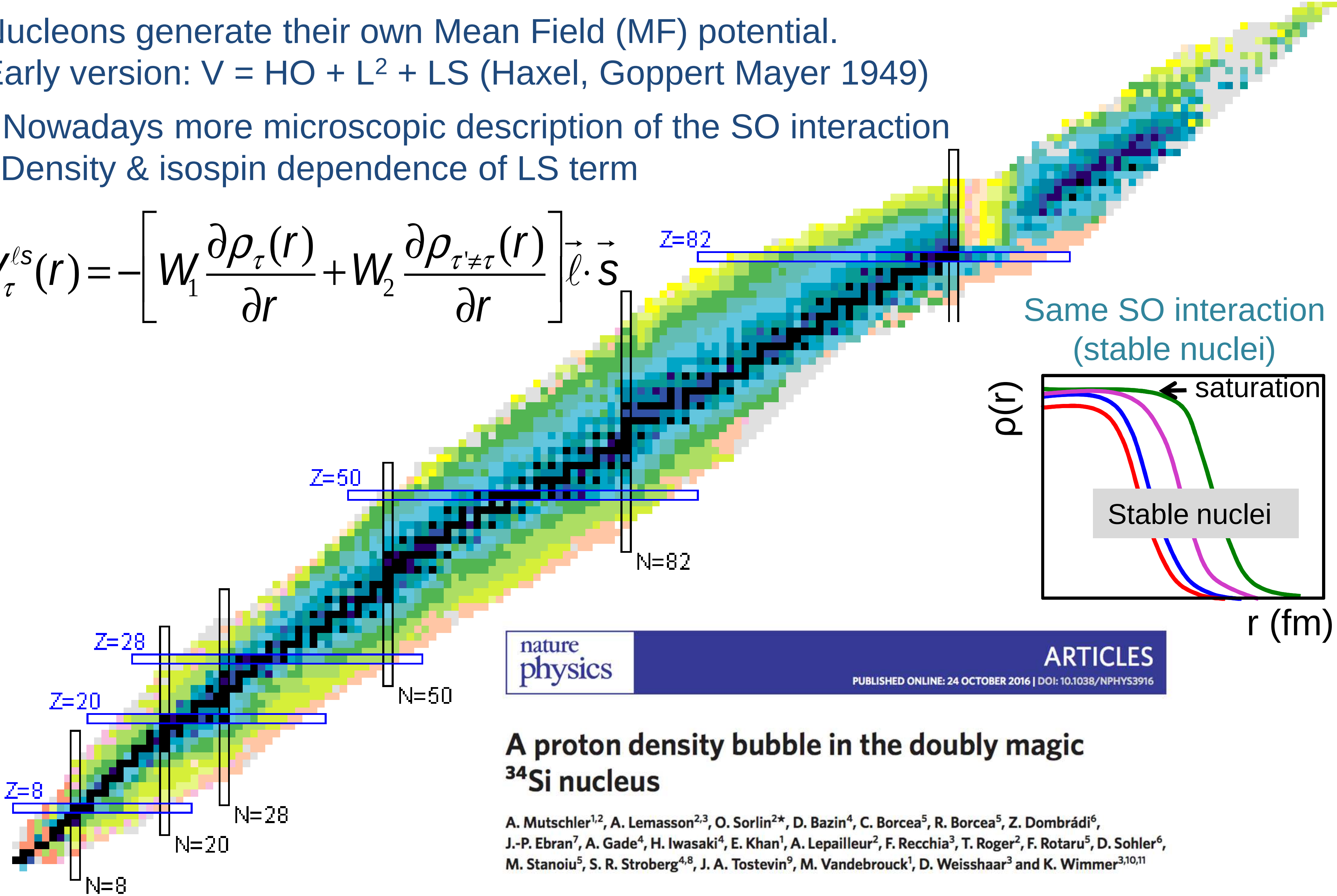
Challenges:
- High beam velocities (β ≈ 0.35) – 2mm spatial resolution of GRETINA optimizes Doppler correction
- Low beam rates (as low as a few pps) – efficiency of GRETINA, in singles and γγ is critical

A "Bubble" Nucleus to Study the SO Interactions

Nucleons generate their own Mean Field (MF) potential.
Early version: V = HO + L^2 + LS (Haxel, Goppert Mayer 1949)

- Nowadays more microscopic description of the SO interaction
  Density & isospin dependence of LS term

$$V_\tau^{\ell s}(r) = -\left[W_1 \frac{\partial \rho_\tau(r)}{\partial r} + W_2 \frac{\partial \rho_{\tau' \neq \tau}(r)}{\partial r} \right] \vec{\ell} \cdot \vec{s}$$



Same SO interaction
(stable nuclei)

ρ(r)
saturation
Stable nuclei
r (fm)

nature physics

ARTICLES

PUBLISHED ONLINE: 24 OCTOBER 2016 | DOI: 10.1038/NPHYS3916

A proton density bubble in the doubly magic ^{34}Si nucleus

A. Mutschler[1,2], A. Lemasson[2,3], O. Sorlin[2*], D. Bazin[4], C. Borcea[5], R. Borcea[5], Z. Dombrádi[6], J.-P. Ebran[7], A. Gade[4], H. Iwasaki[4], E. Khan[1], A. Lepailleur[2], F. Recchia[3], T. Roger[2], F. Rotaru[5], D. Sohler[6], M. Stanoiu[5], S. R. Stroberg[4,8], J. A. Tostevin[9], M. Vandebrouck[1], D. Weisshaar[3] and K. Wimmer[3,10,11]

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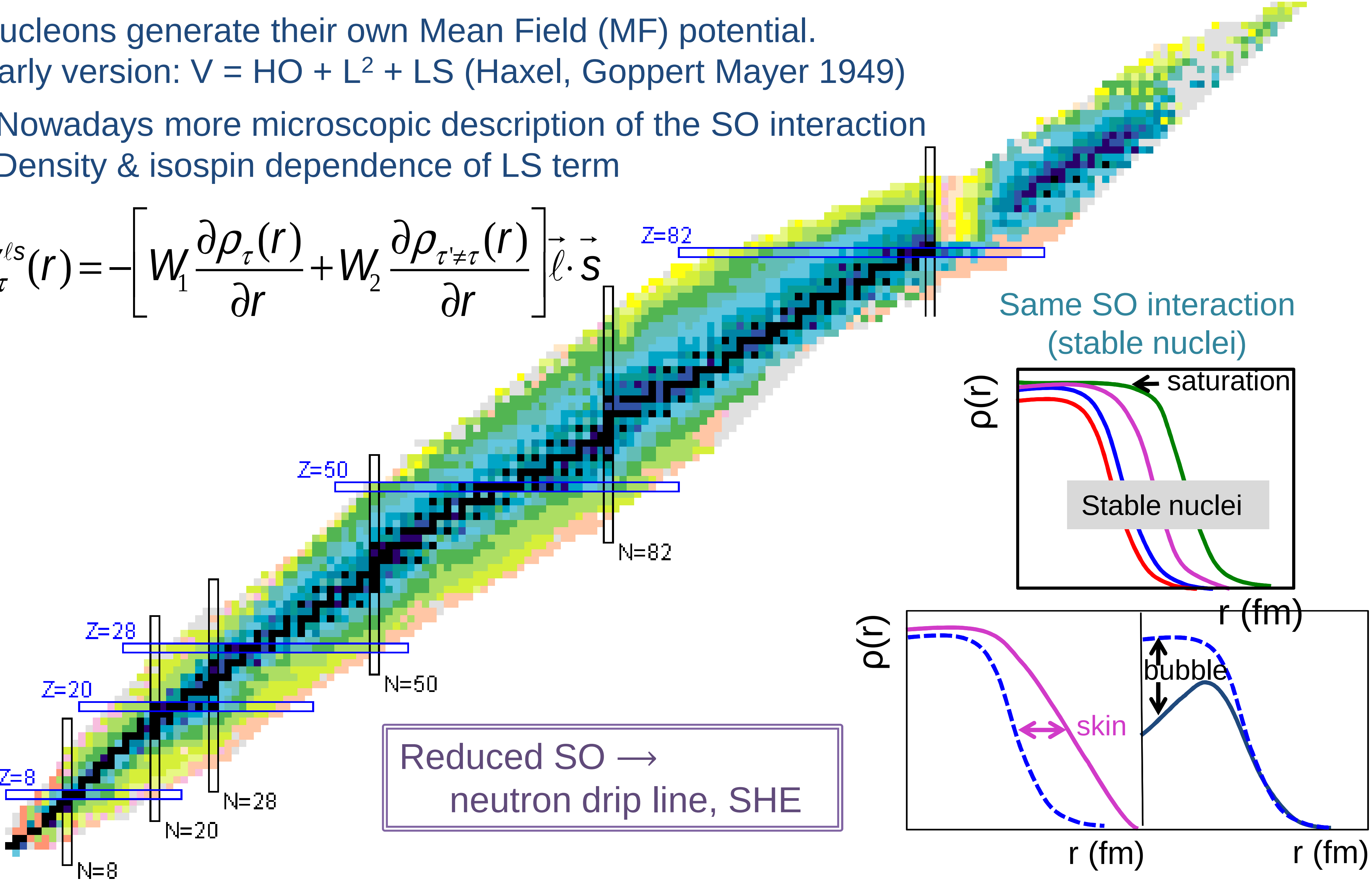

Reduced SO ⟶
neutron drip line, SHE

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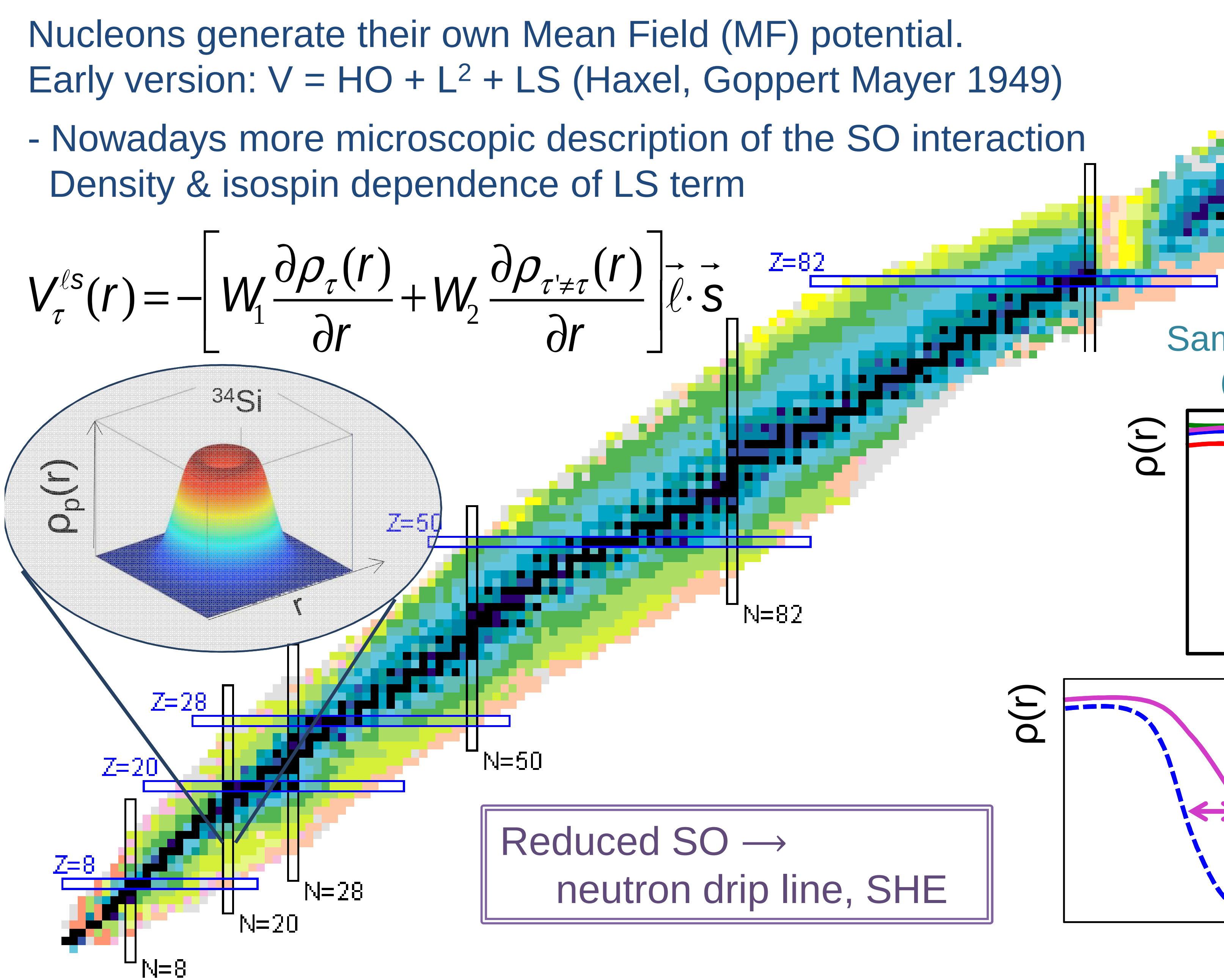
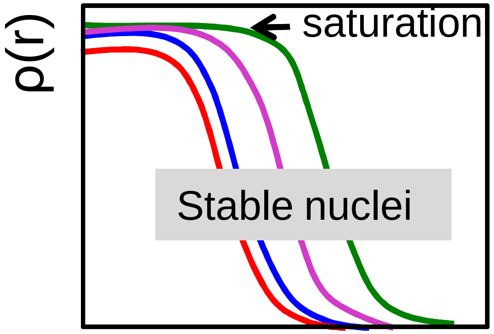
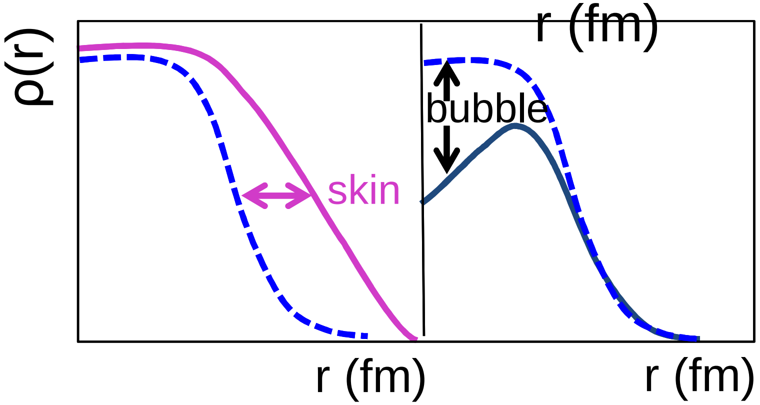


Same SO interaction
(stable nuclei)





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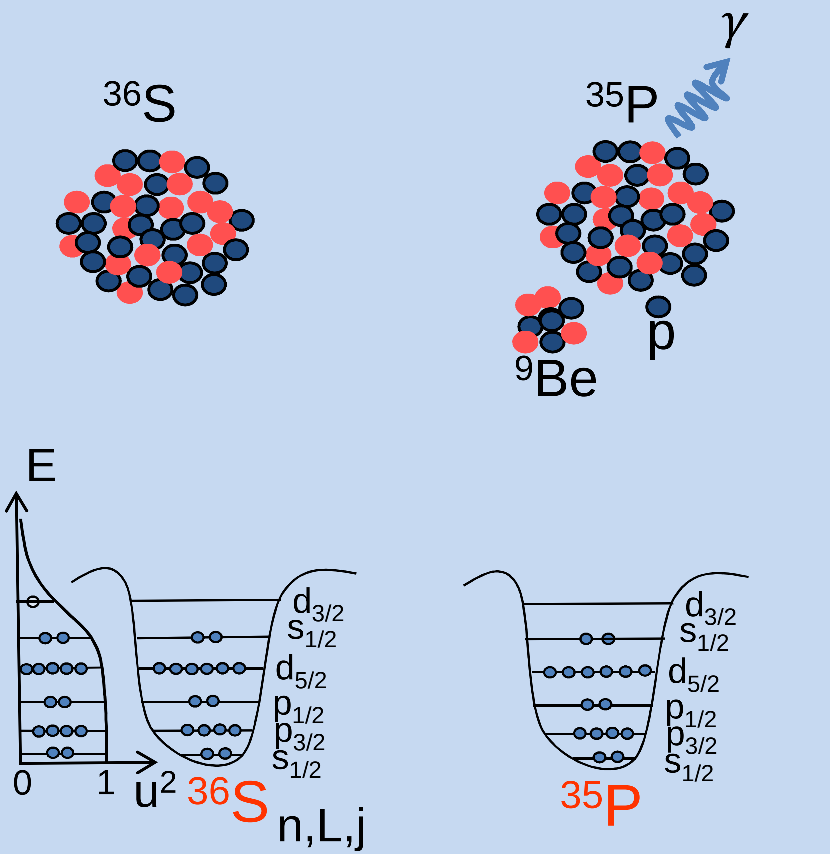
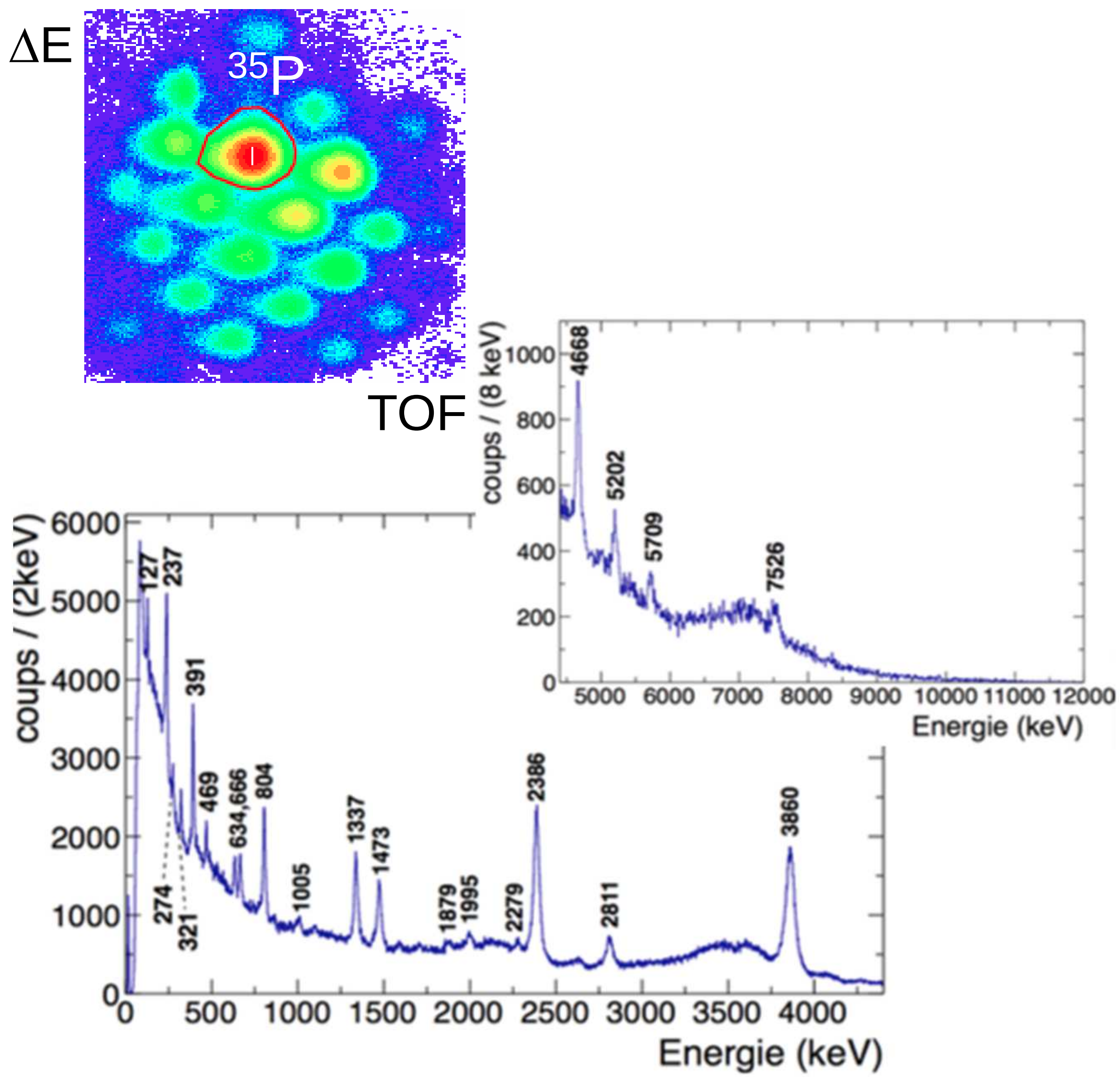
Proton Densities in ^{36}S and ^{34}Si

Knock-out reactions at β≈0.4

$$\sigma_{-1p}(n,L) = C^2S\,(j,n,L)\quad \sigma_{sp}(j,S_p)\,R_S$$

occupancy — reaction theory





Protons knockout reaction gives composition of orbital occupancies.

Large $^{36}S(-1p)$ cross section for L=0 knock out ⇒ $s_{1/2}$ orbit is almost fully occupied in ^{36}S

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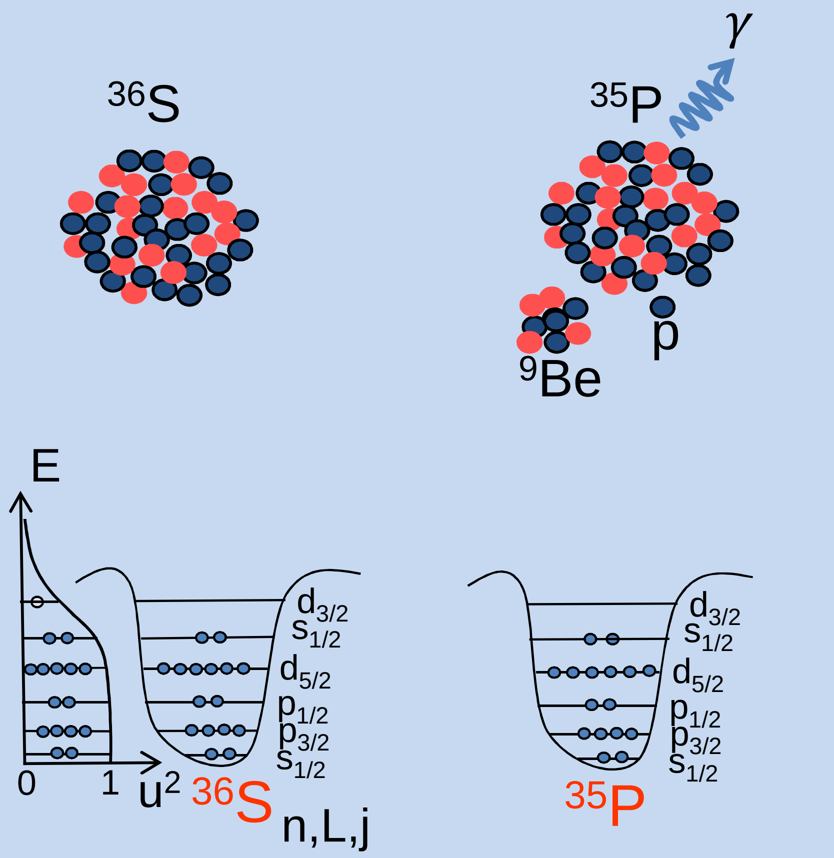

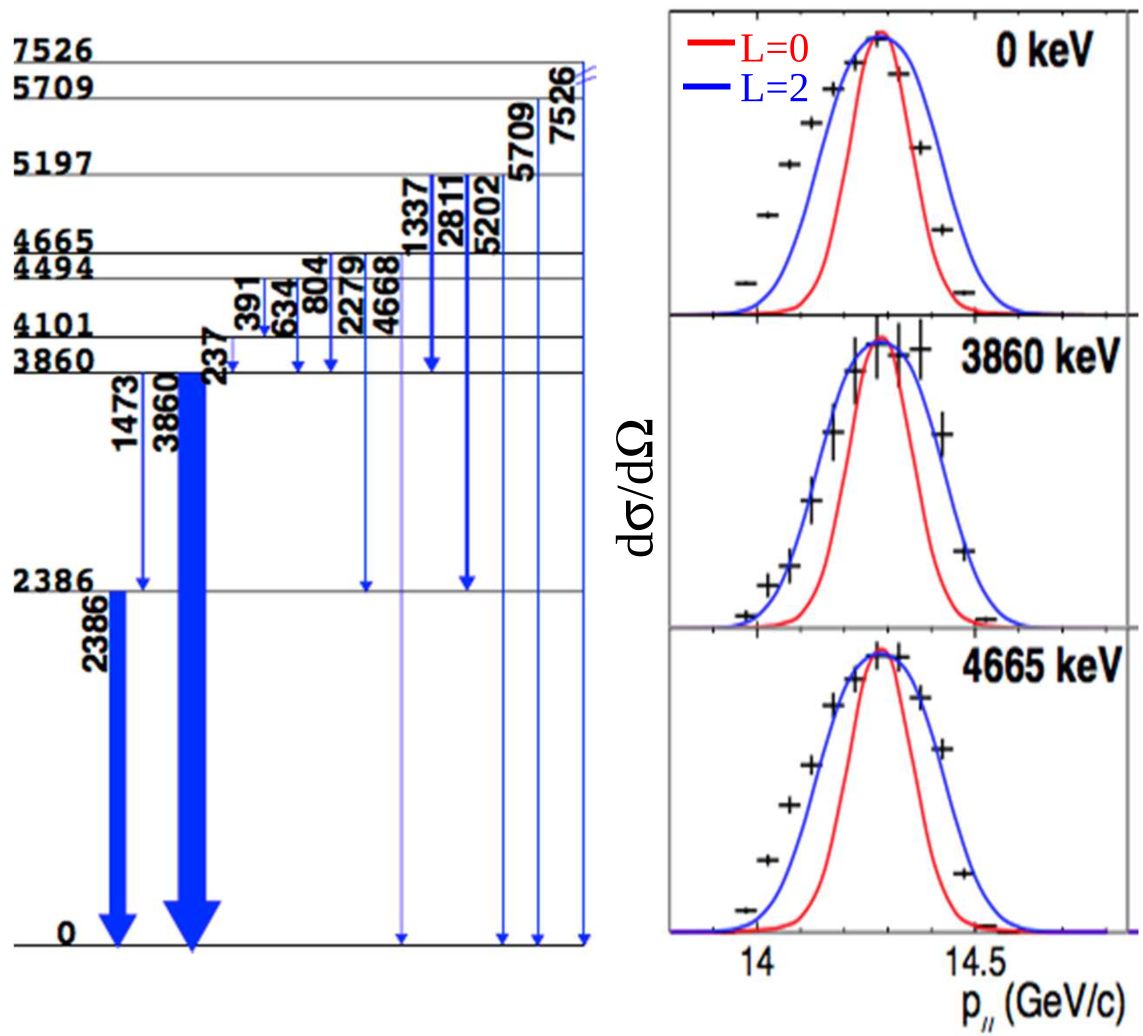

➡ ^{36}S – full $d_{5/2}$ and $s_{1/2}$ orbitals, minimum scattering to upper $d_{3/2}$ orbital

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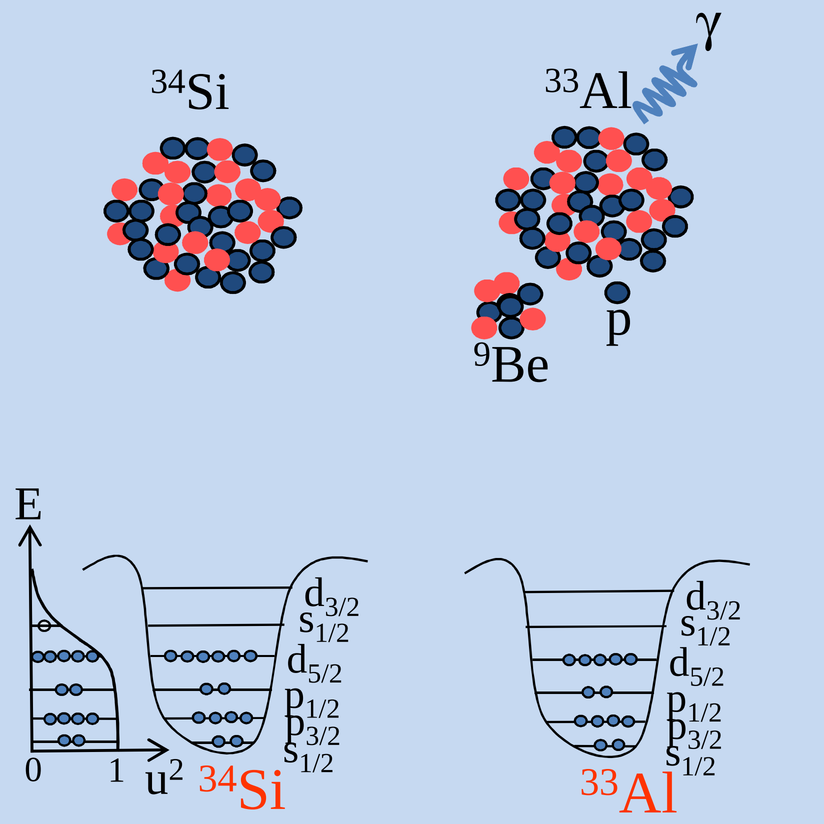

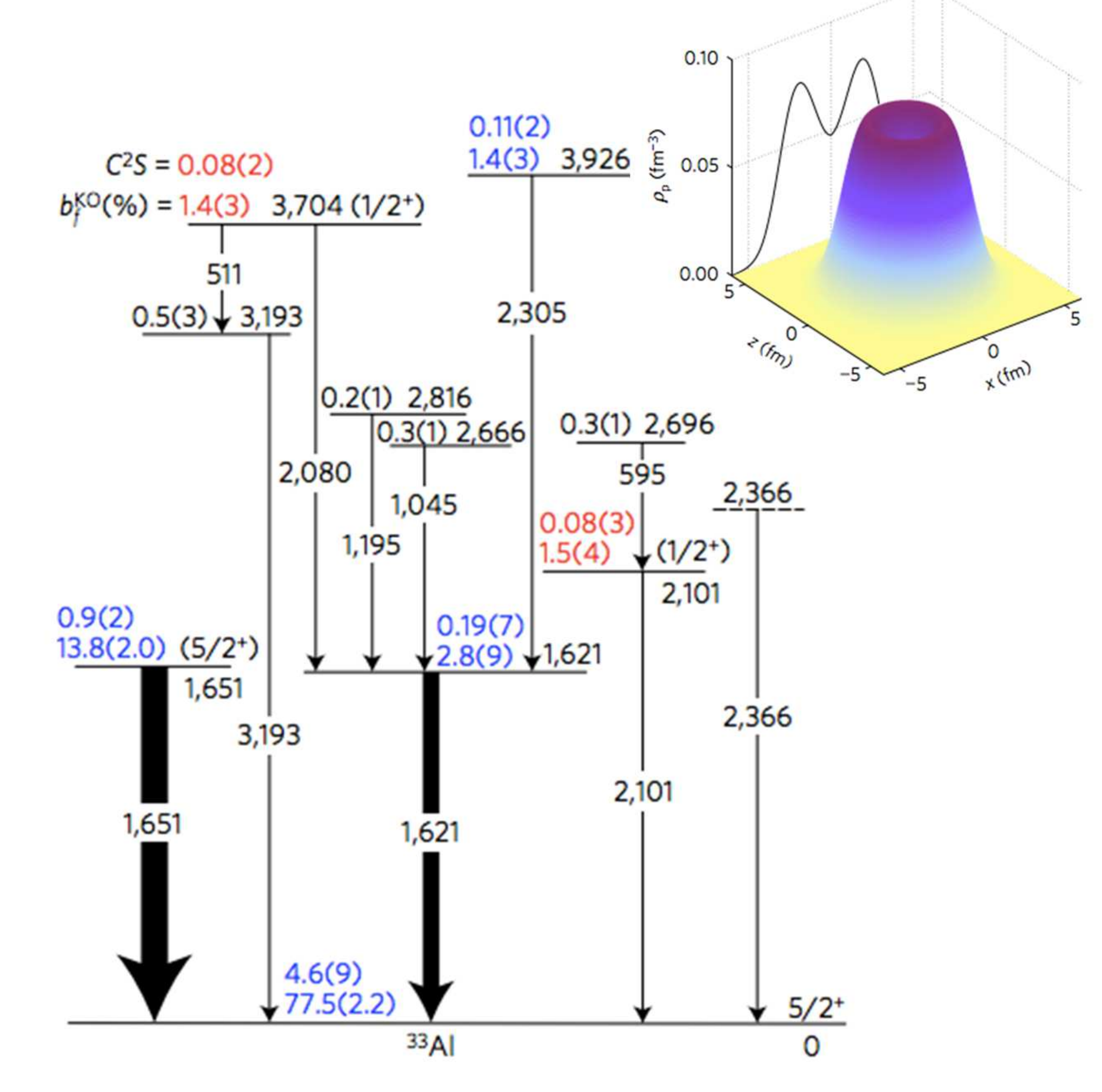

^{34}Si – ~ empty proton $s_{1/2}$ orbitals, neutron $s_{1/2}$ is full ⇒ proton bubble

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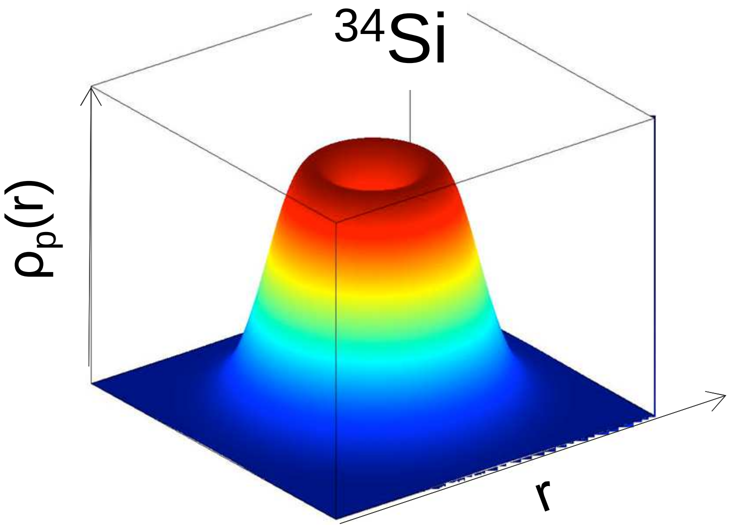
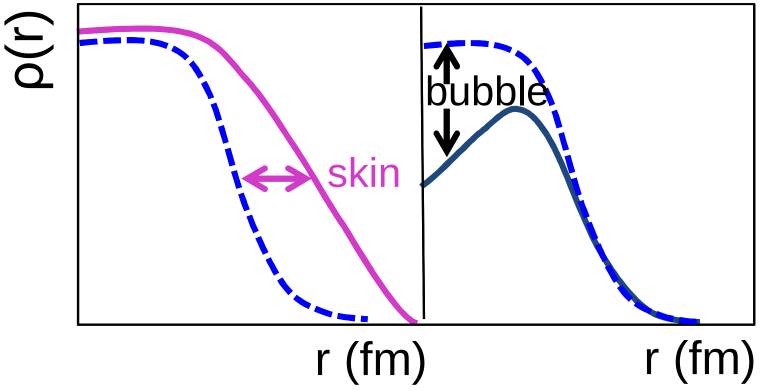


Isospin dependence
$W_1 \approx W_2$ in RMF (no isospin dependence)

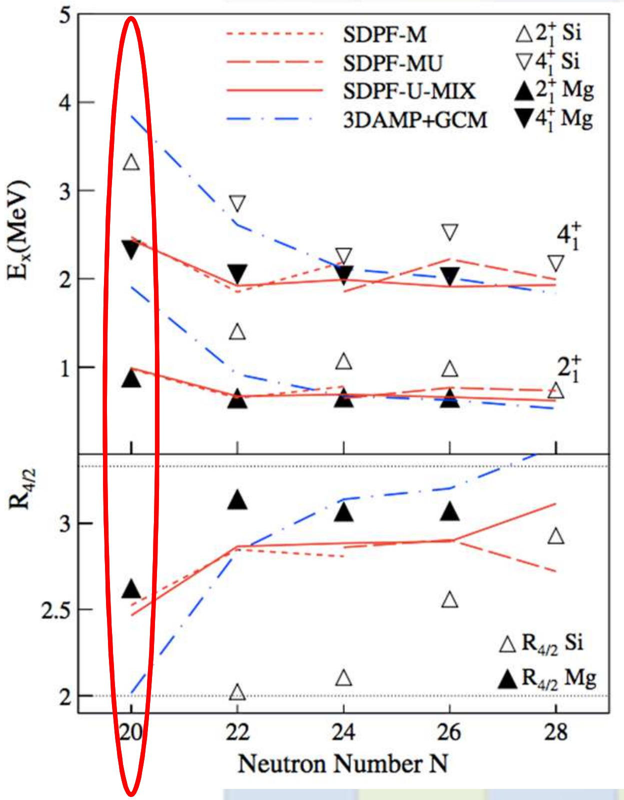
Density dependence

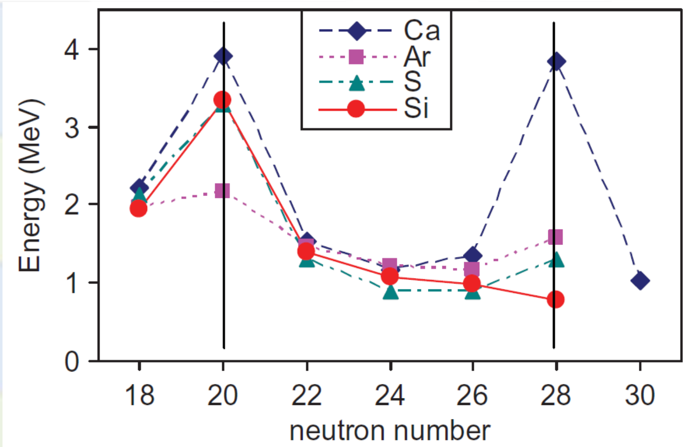
$$V_\tau^{\ell s}(r) = -\left[W_1 \frac{\partial \rho_\tau(r)}{\partial r} + W_2 \frac{\partial \rho_{\tau' \neq \tau}(r)}{\partial r} \right] \vec{\ell} \cdot \vec{s}$$

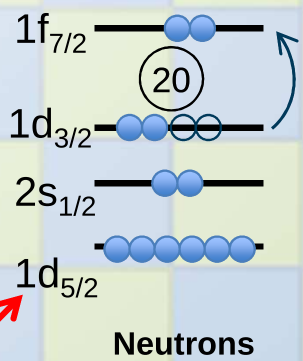


Structure in Neutron-Rich Mg

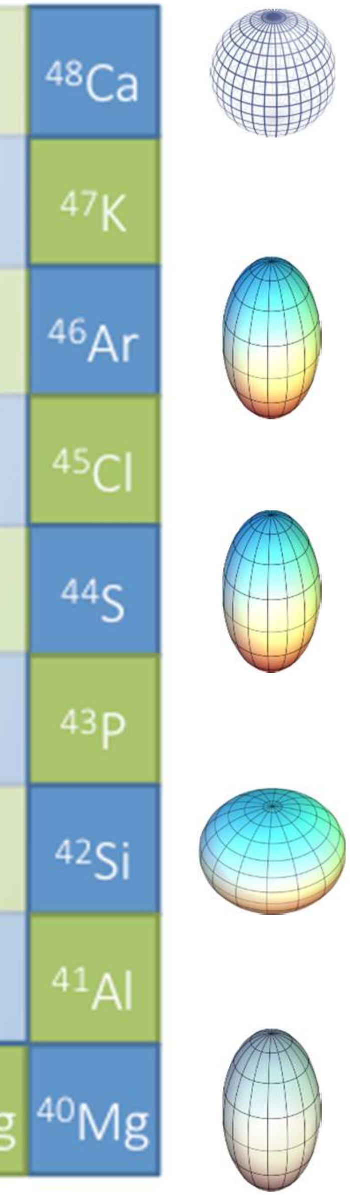
The neutron-rich Mg isotopes from N=20 to N=28 are deformed, bridging two **eroded shell gaps**.

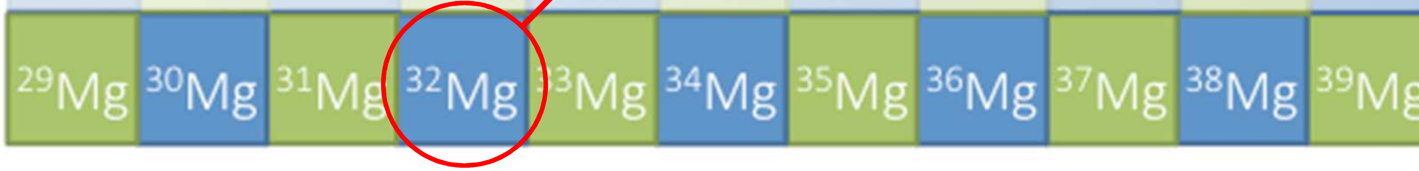






^{32}Mg is dominated by cross-shell neutron excitations in the ground state, resulting in deformation. But signature rotational band has not been observed…

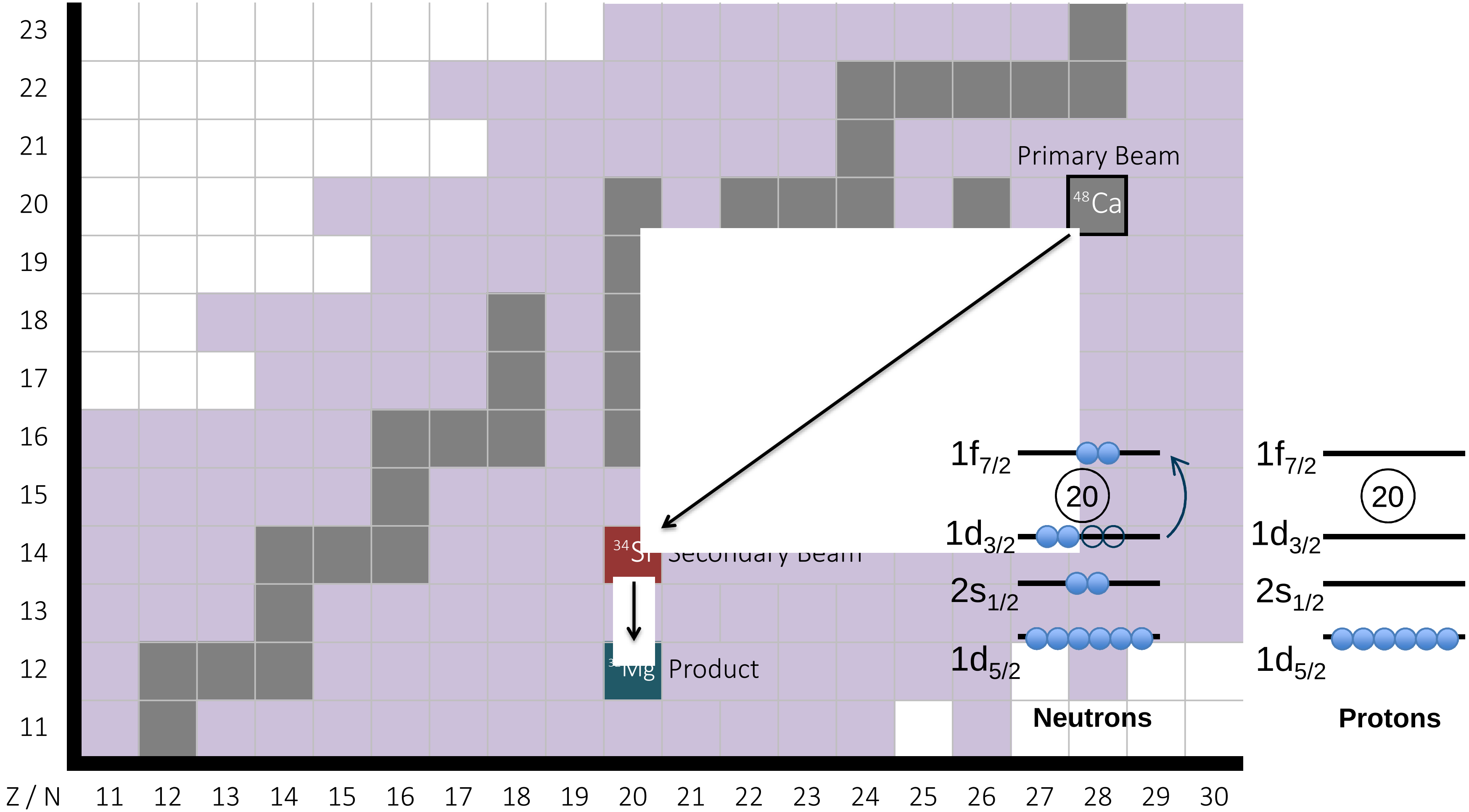




N=28

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)

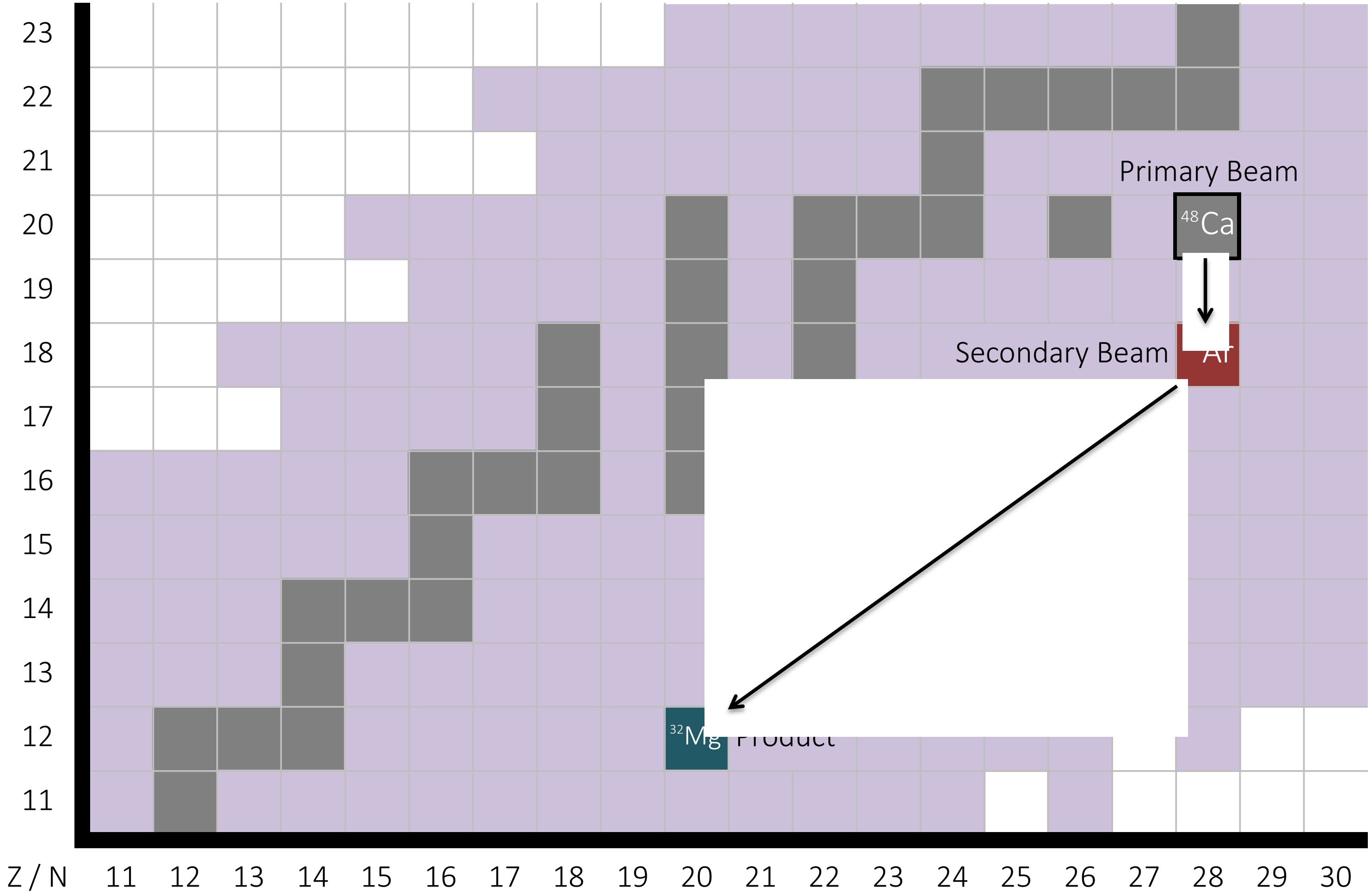
Fast beams - fragmentation



"2-Step Reaction"

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

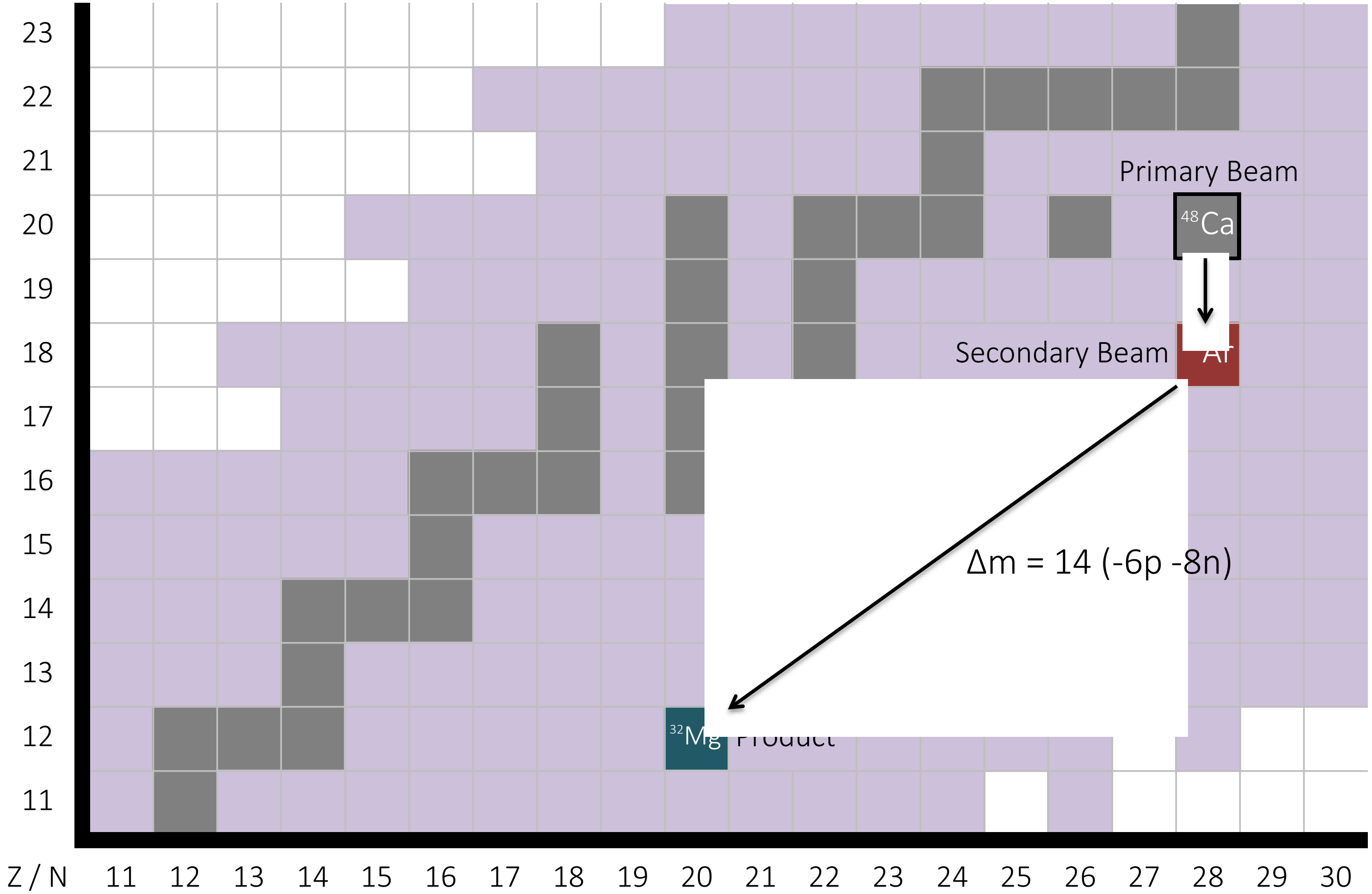
Fast beams - fragmentation



"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

Fast beams - fragmentation



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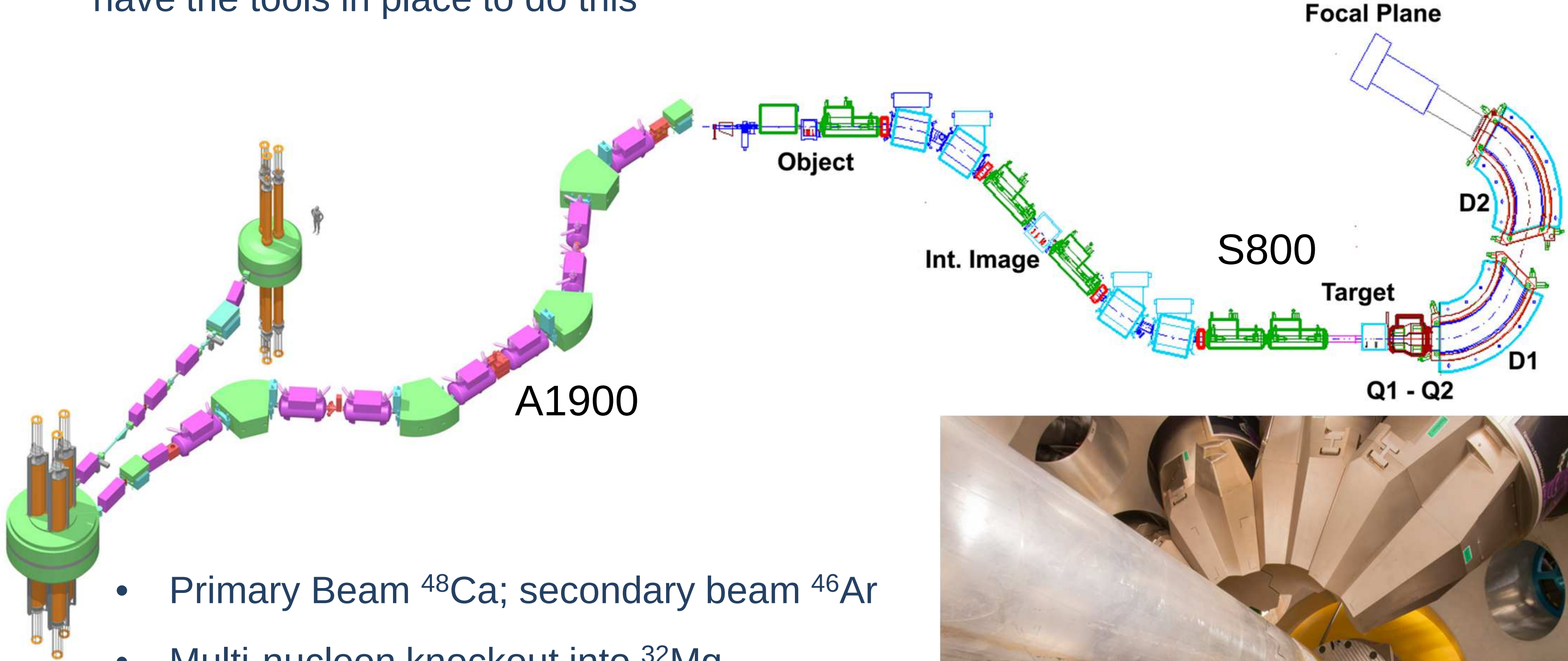
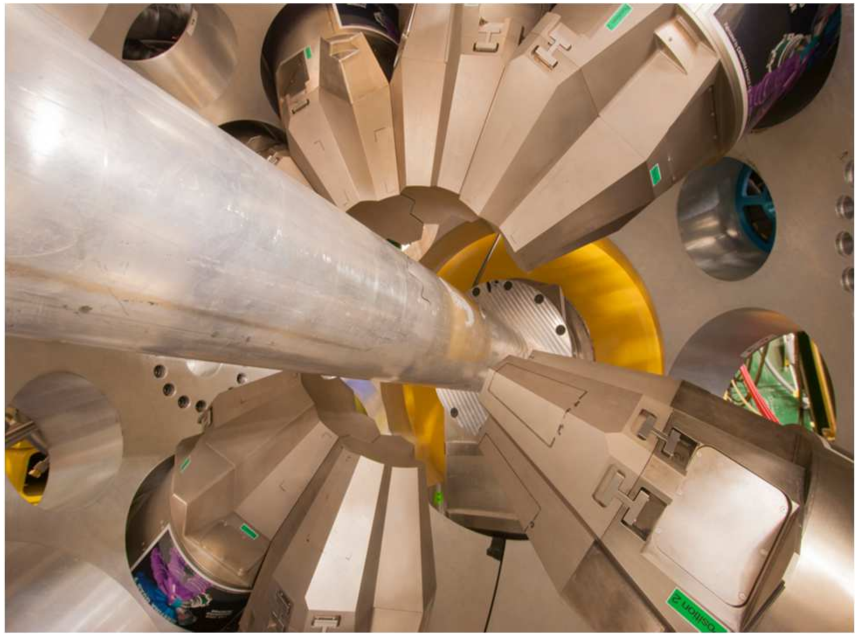
Experiment E11029: GRETINA@S800

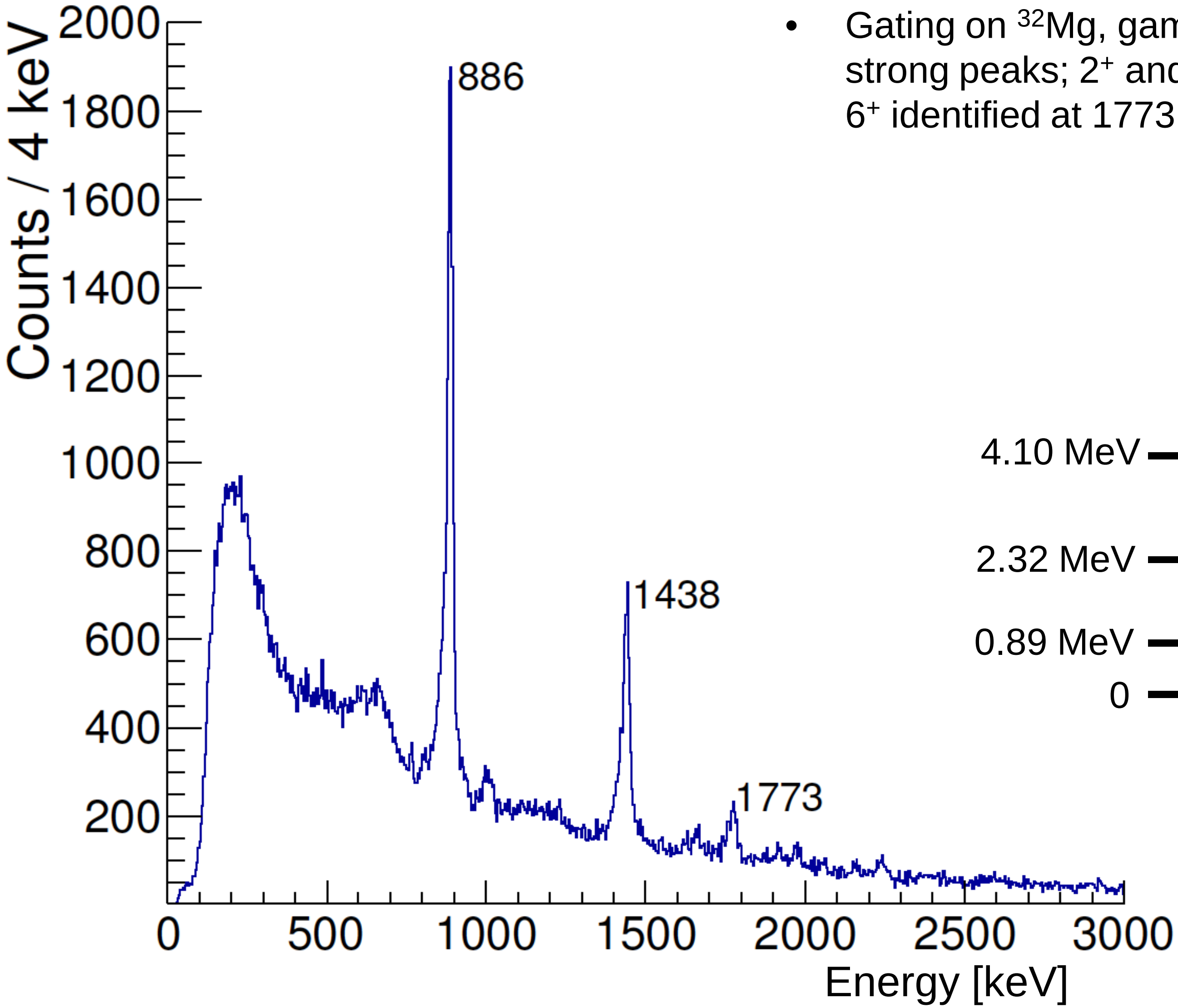
- GOAL: To see and to study the yrast rotational states (band)
- With the intense beams available at NSCL and the availability of GRETINA, we have have the tools in place to do this



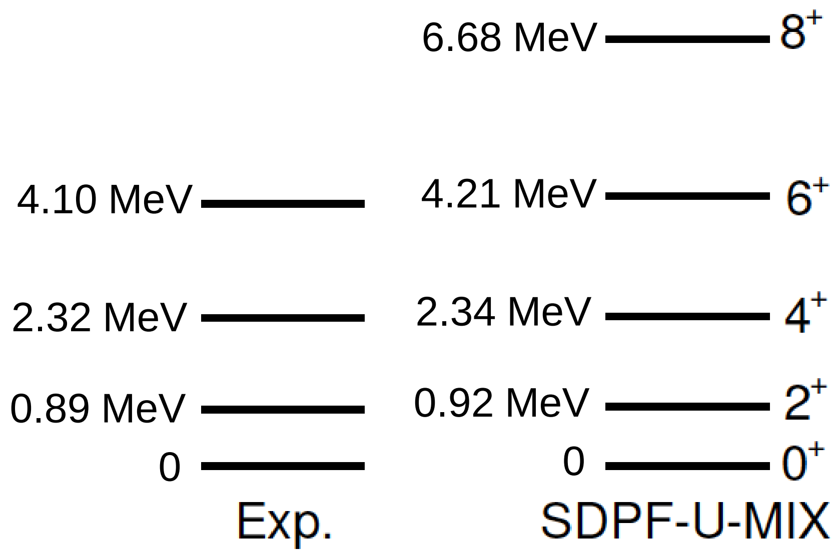
- Primary Beam ^{48}Ca; secondary beam ^{46}Ar
- Multi-nucleon knockout into ^{32}Mg
- GRETINA: All 7 modules at 90 degrees
  - Minimize light particle induced background



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).

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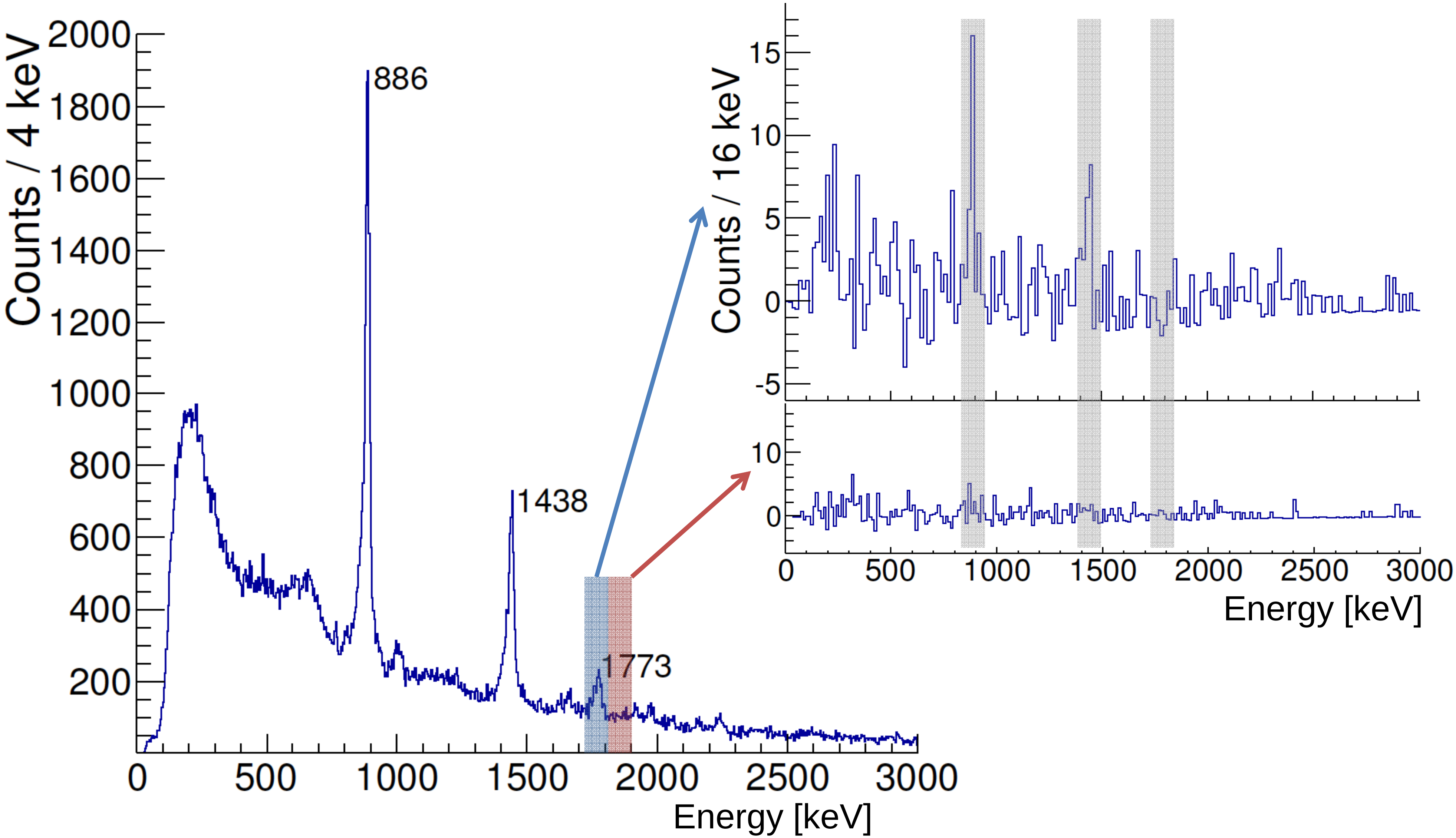

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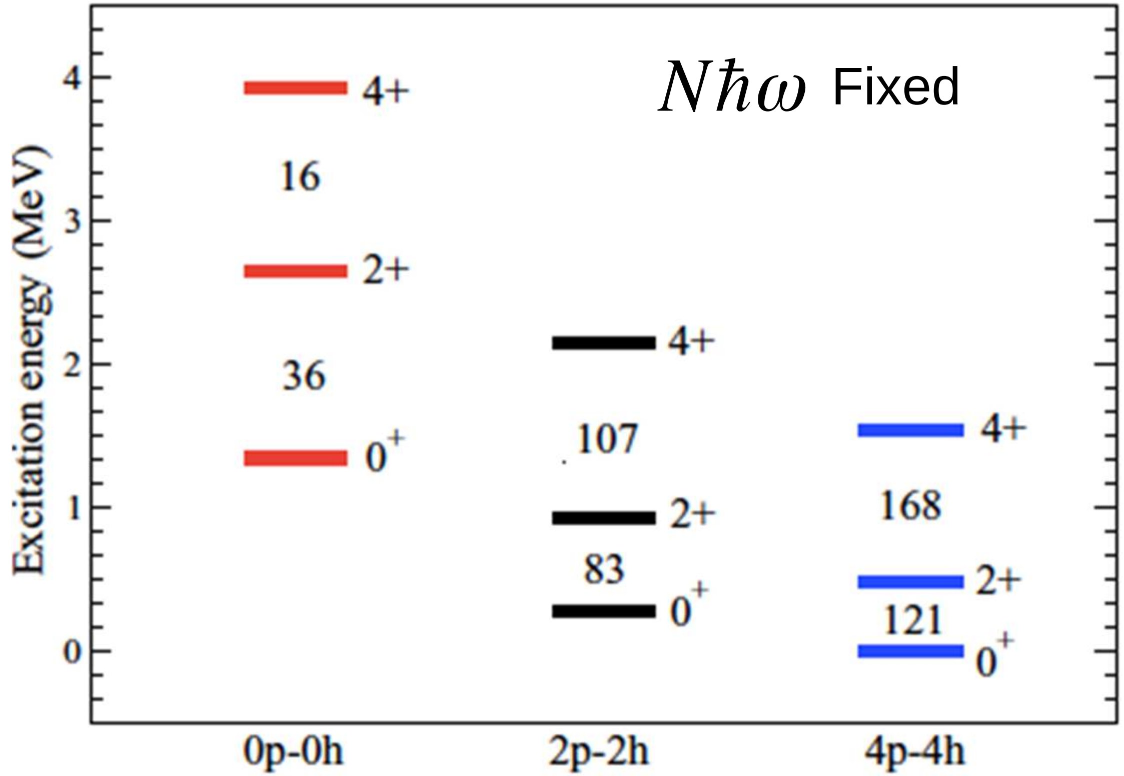
^{32}Mg Shell Model

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

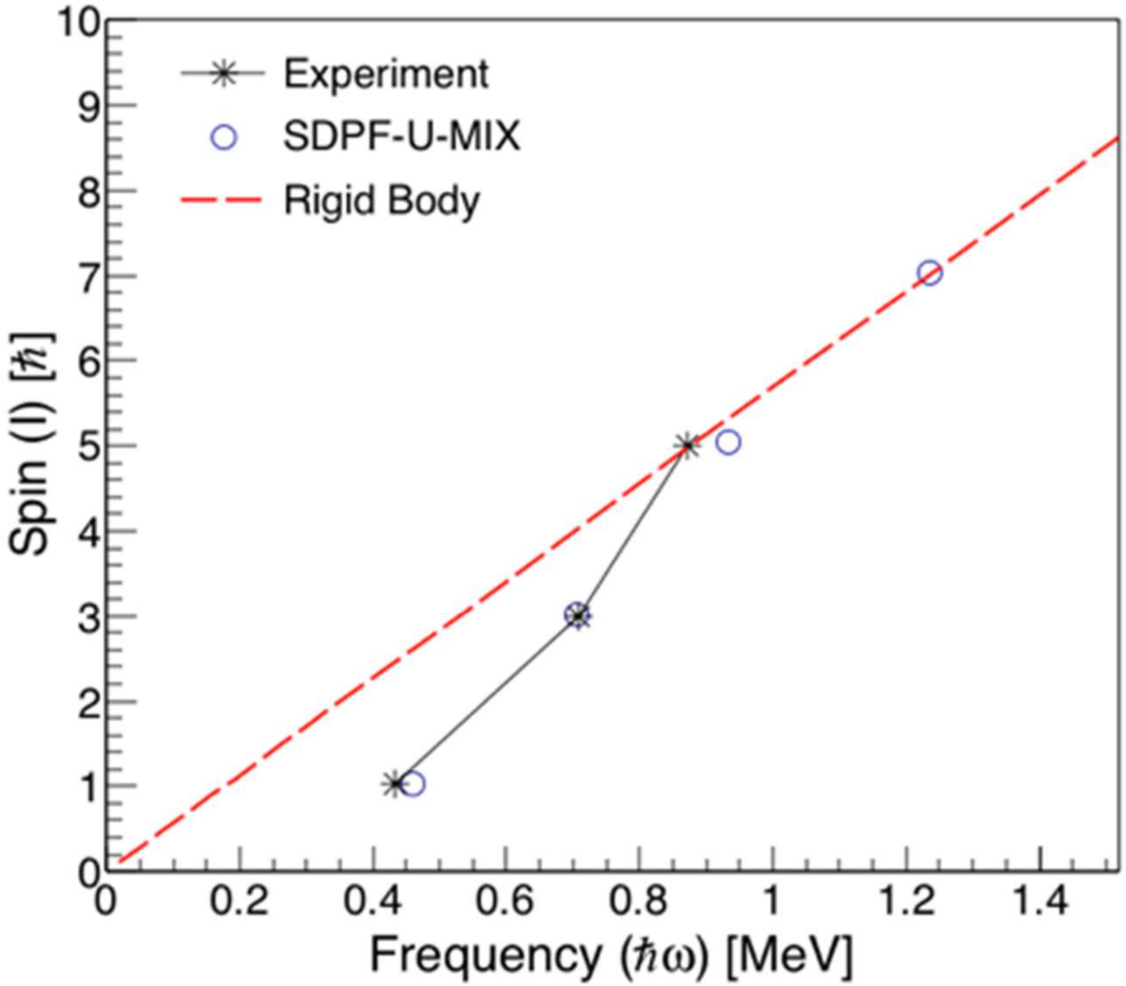
- ^{32}Mg mixed 2p-2h and 4p-4h
- "constant deformation"
- 4p-4h fixed configuration is an "ideal rotor" (superdeformed bands in ^{36}Ar and ^{40}Ca)

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



1.5	12.5	21
Correlation Energy (MeV)		

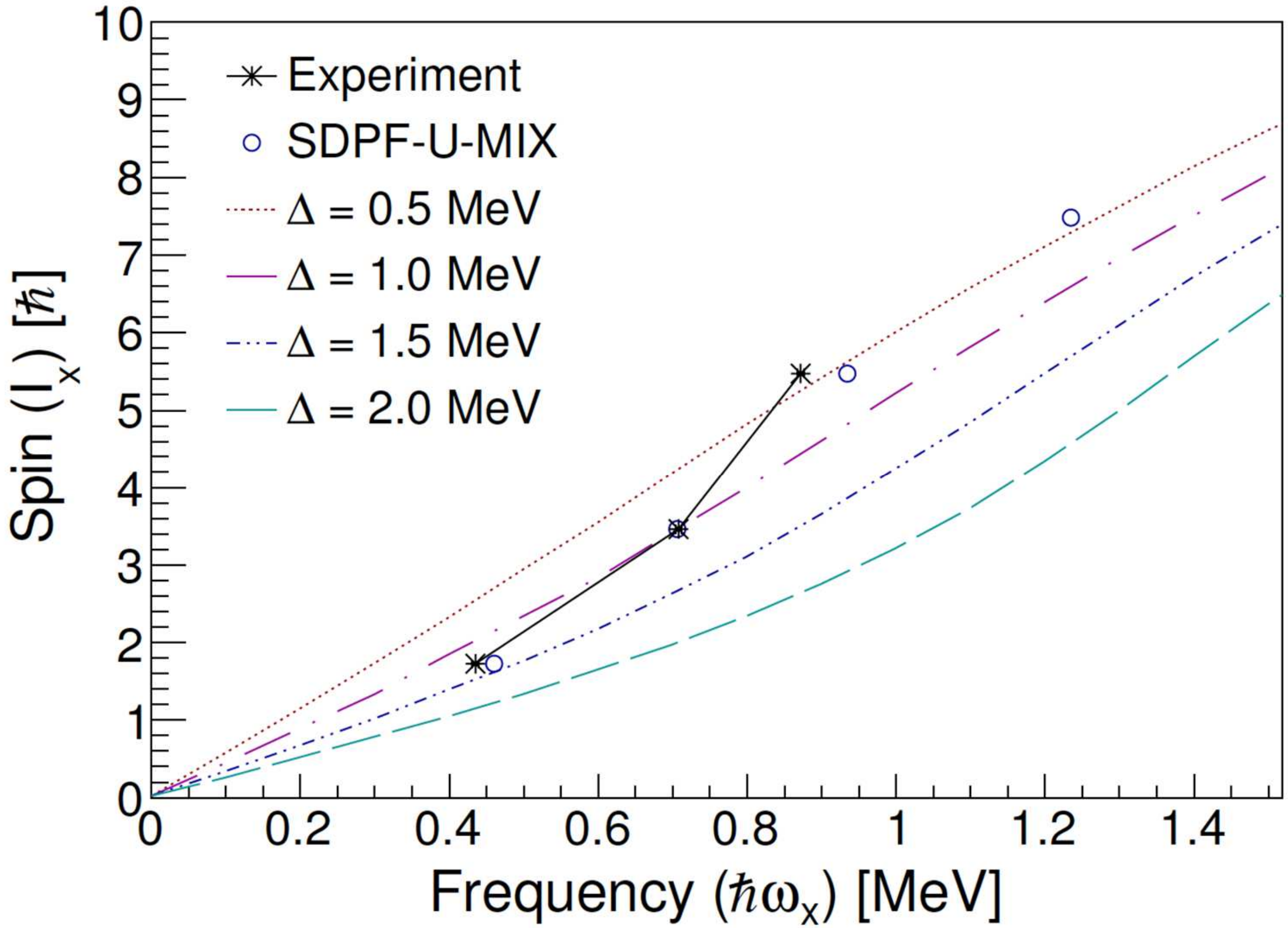
Rotational band structure in ^{32}Mg



$$\frac{\mathcal{J}}{\mathcal{J}_{rig}} \approx \left(\frac{1}{1 + (2\Delta/\epsilon_2 \hbar\omega_0)^2} \right)^{3/2}$$

Cranked Shell Model

Cranked Shell Model calculations: motion of independent-(quasi)particles in a rotating nucleus with a static deformed shape and pair field



$$h'_{q.p.} = h_{s.p.}(\epsilon) - \omega j_x - \Delta(P^+ + P^-) - \lambda\hat{N}.$$

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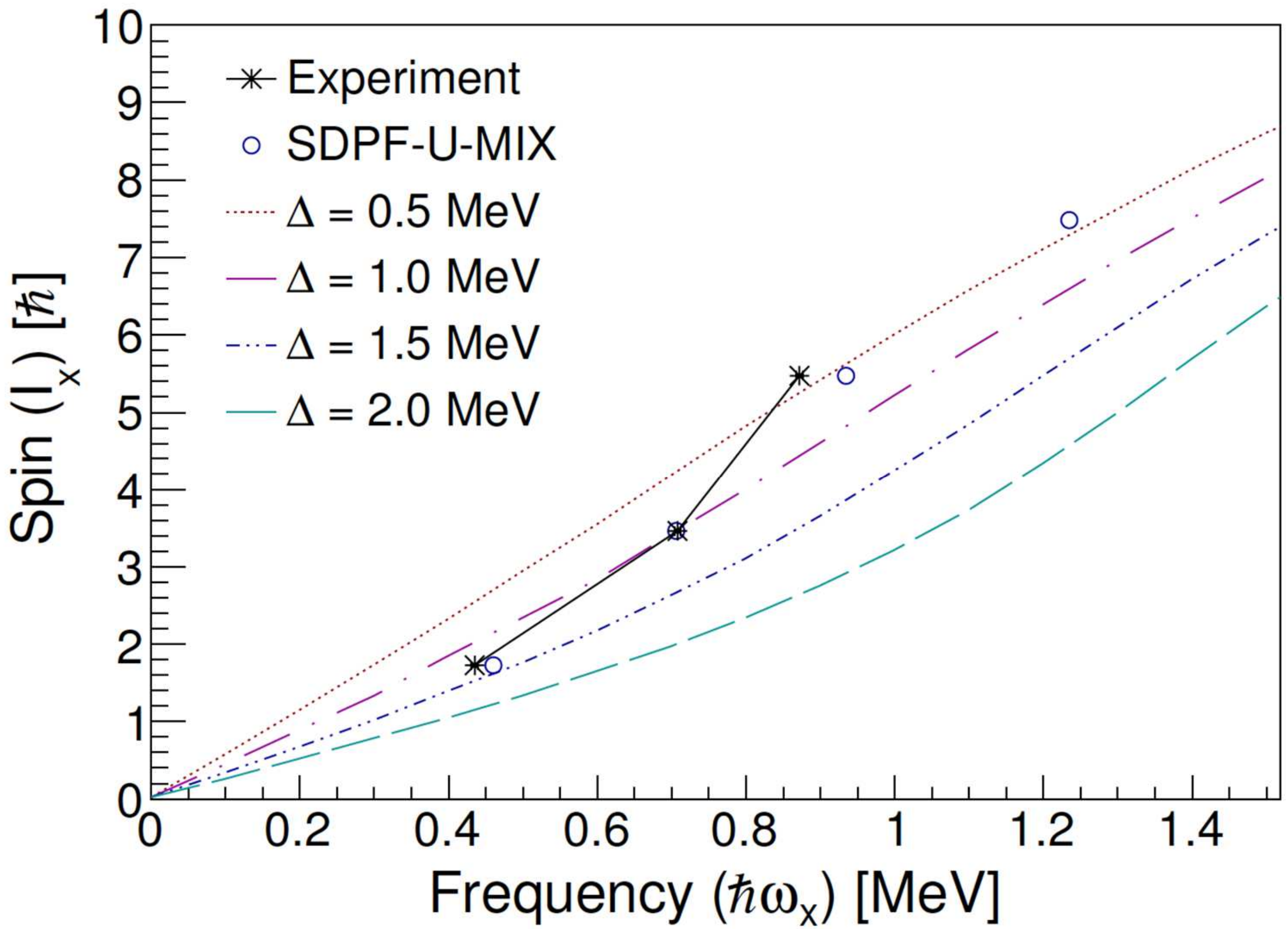
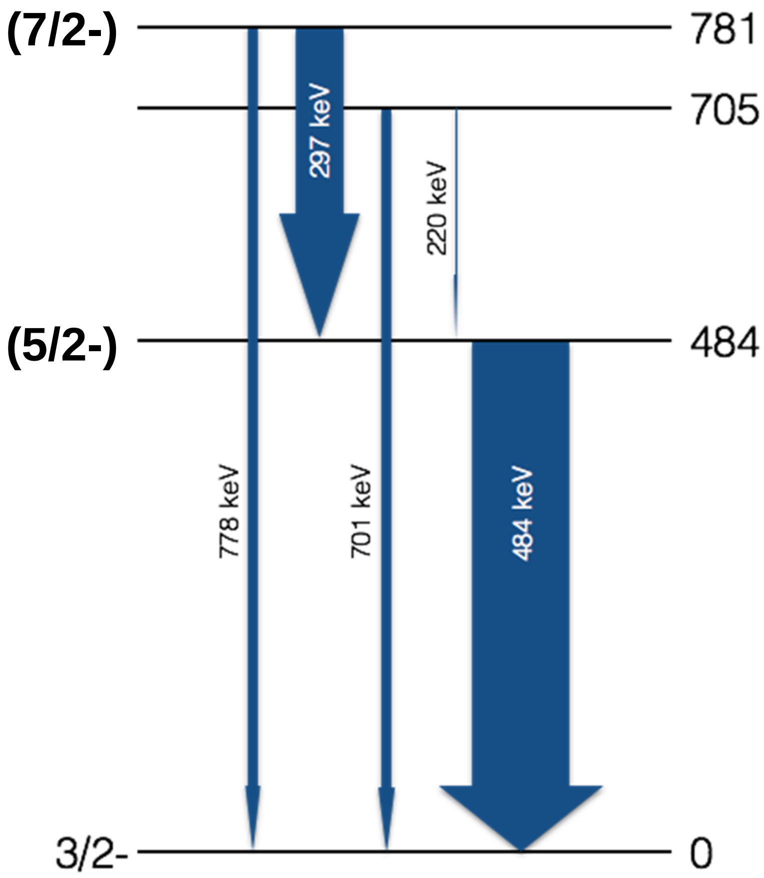
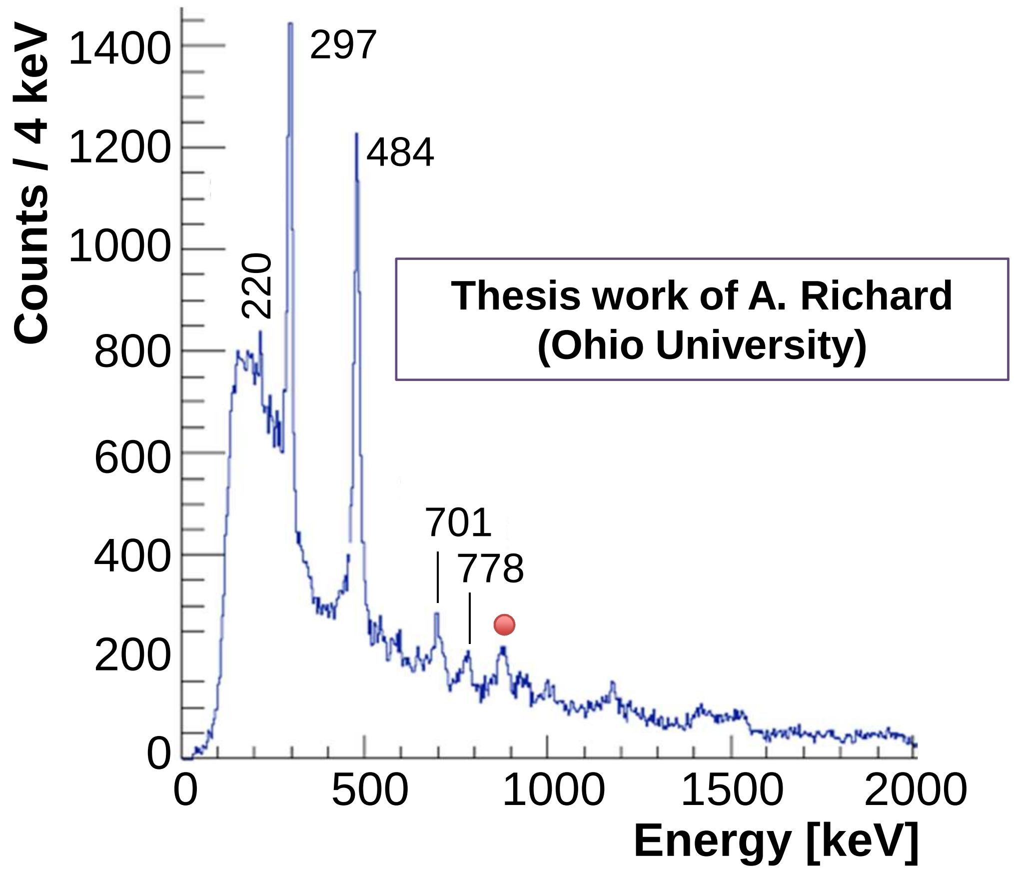


--> Alignment alone (with constant pair gap) does not reproduce upwards bend in the I-ω plot

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

Rotational Band in ^{33}Mg





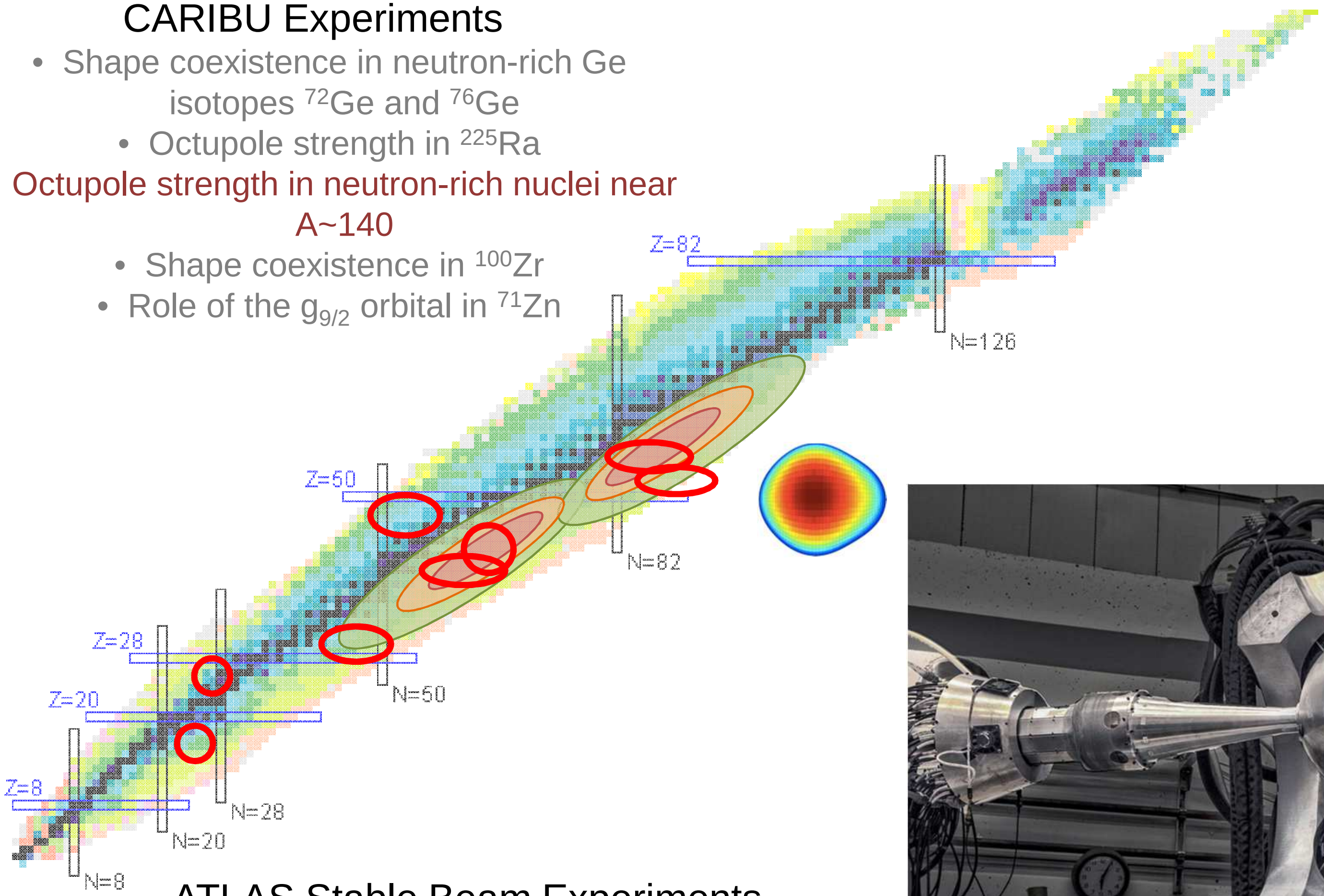
- ^{33}Mg populated in the same secondary fragmentation shows a rotational band well-described as a neutron (Nilsson 3/2[321]) coupled to the ^{32}Mg core
- Leading order estimates for E2/M1 intensities show remarkable agreement with experiment

$$\lambda = \left[\frac{E_\gamma}{E_{\gamma'}}\right]^5 \frac{(I+1)(I-1+K)(I-1-K)/2K^2(2I+1)}{1+1.148[(g_K-g_R)/Q_0]^2(I+1)(I-1)E_{\gamma'}{}^{-2}}$$

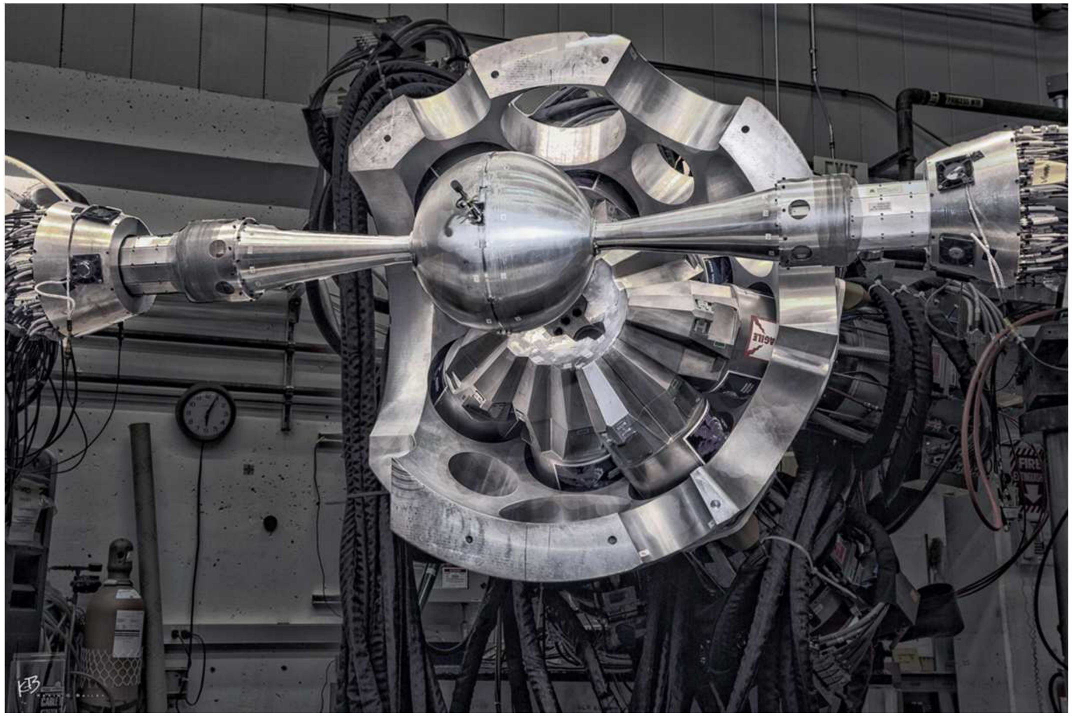
First ANL Physics Campaign (2014-2015)

CARIBU Experiments

- Shape coexistence in neutron-rich Ge isotopes ^{72}Ge and ^{76}Ge
- Octupole strength in ^{225}Ra
- Octupole strength in neutron-rich nuclei near A~140
- Shape coexistence in ^{100}Zr
- Role of the $g_{9/2}$ orbital in ^{71}Zn



First physics campaign at ANL made use of the unique opportunities with CARIBU beams, and the combination of GRETINA with particle detectors such as CHICO-2 and the WashU Phoswich Wall.



ATLAS Stable Beam Experiments

- Comparison of the performance of GRETINA and Gammasphere
- High-energy gamma-ray performance
- The polarization sensitivity of GRETINA
- Multi-particle-hole states in neutron-rich ^{34}P
- Understanding the low-energy enhancement of the photon-strength function

Octupole Deformation in ^{144}Ba

PRL **116,** 112503 (2016) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2016

Direct Evidence of Octupole Deformation in Neutron-Rich ^{144}Ba

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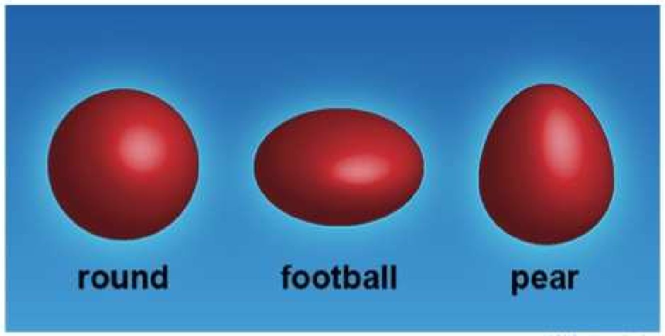
Physics ABOUT BROWSE JOURNALISTS

Synopsis: Nucleus is Surprisingly Pear Shaped

- Understand octupole collectivity and effects on nuclear structure
- Important in the regions with Z,N ~ 34, 56, 88, 134, where ΔJ,Δl =3 orbitals lie near the Fermi surface

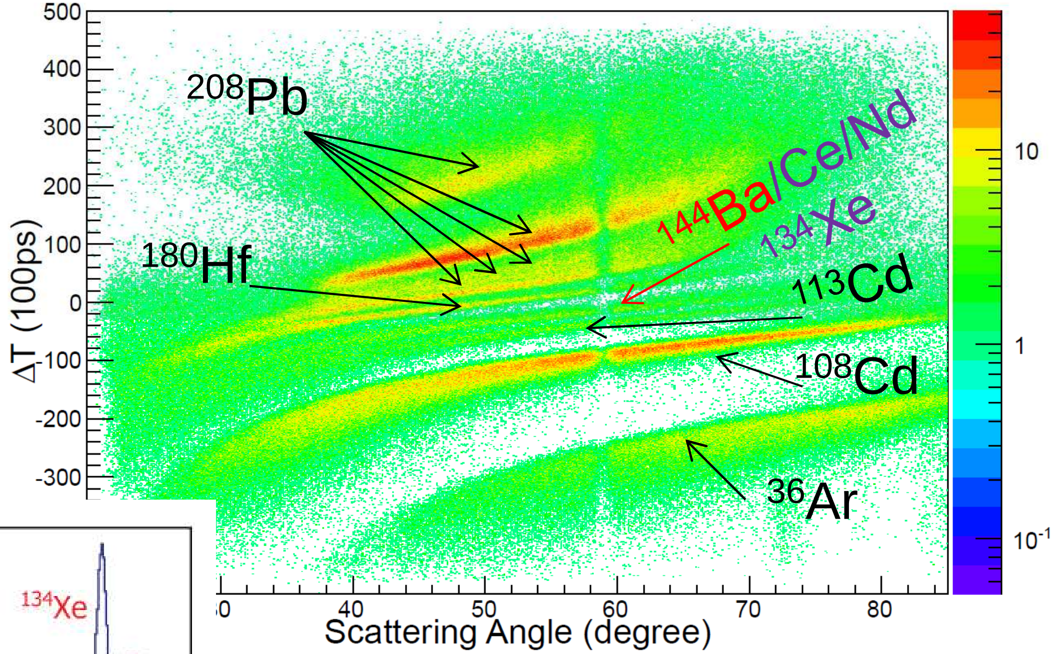


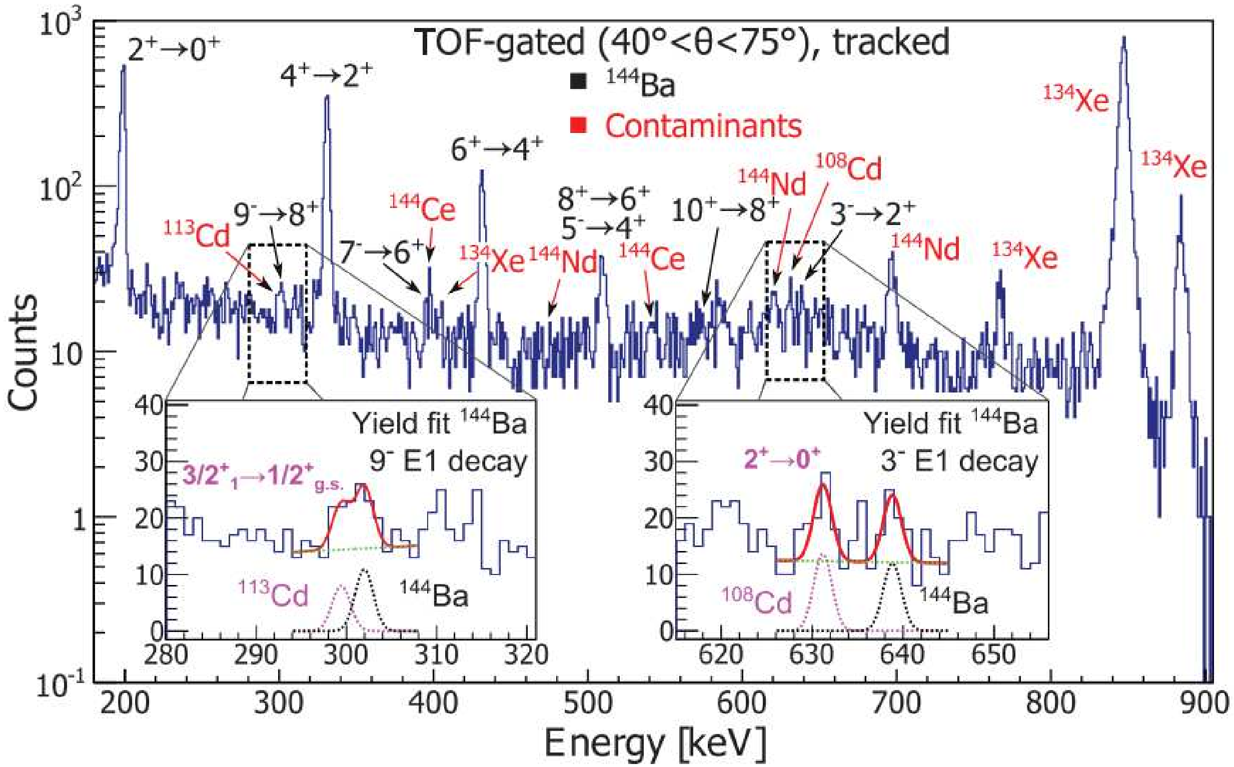
APS/Alan Stonebraker

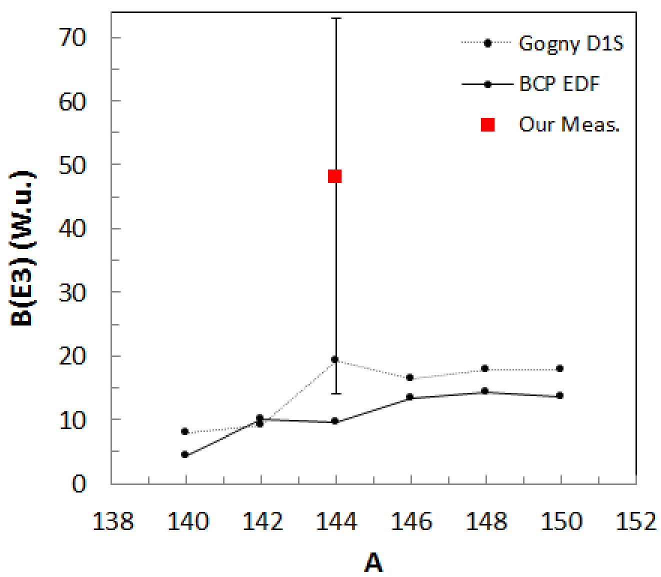
Octupole Collectivity in $^{144,146}Ba$

Octupole deformation predicted with ΔJ,Δl =3 orbitals near the Fermi surface

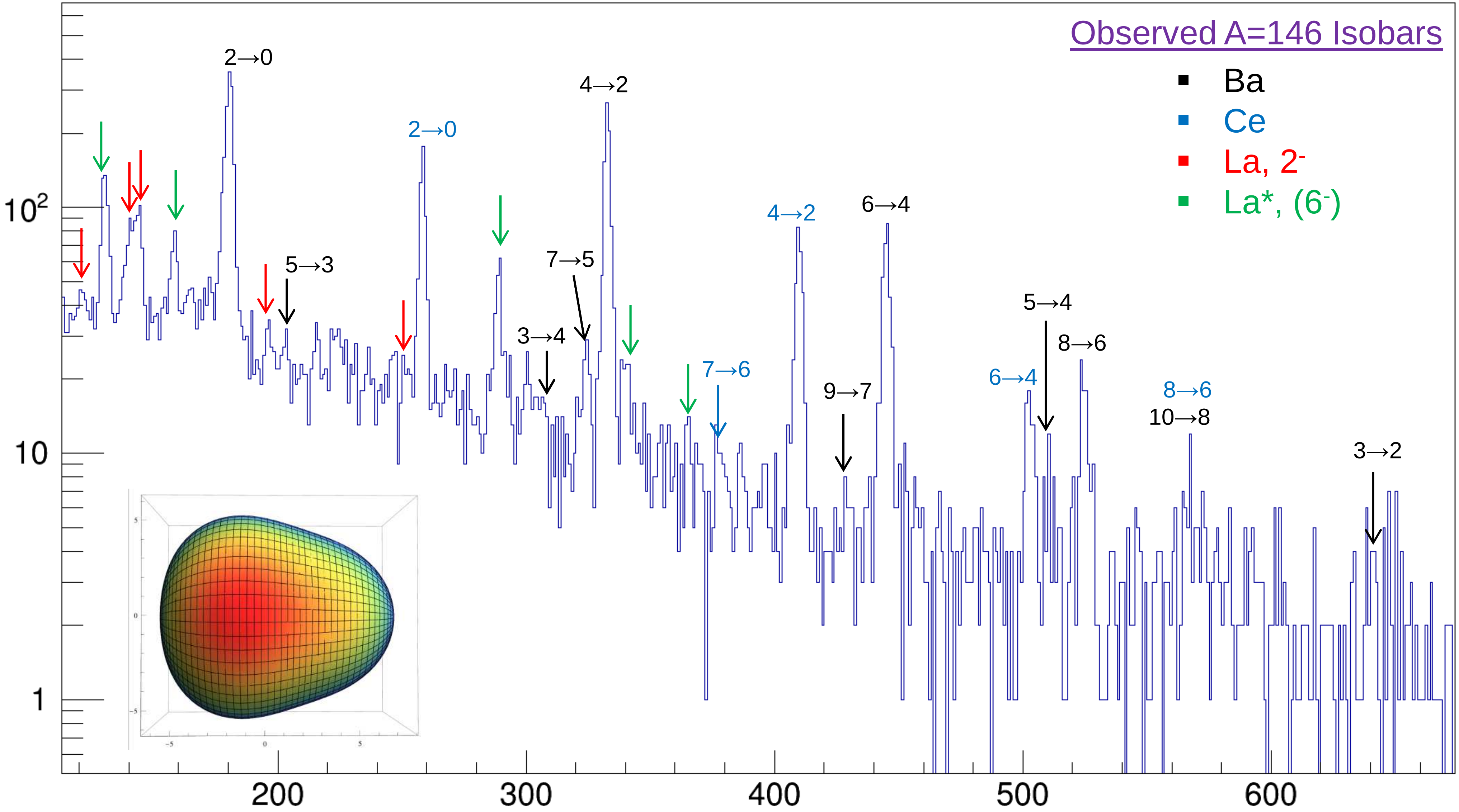
Qualitative agreement with theory (GCM), but quantitatively higher





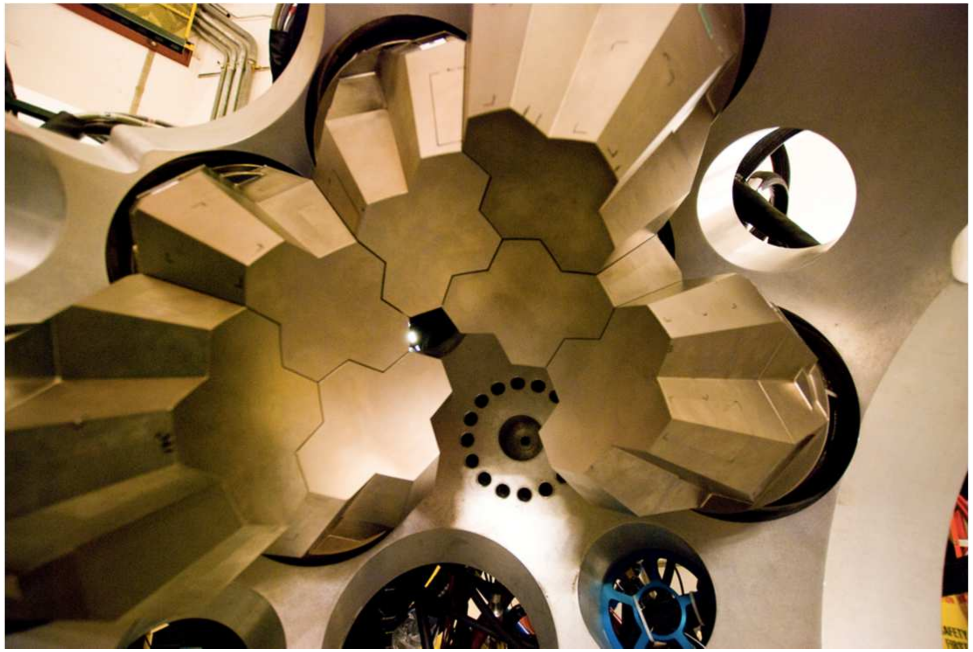


Octupole Collectivity in $^{144,146}Ba$



Summary

- GRETINA has proven an invaluable tool for nuclear structure studies, including sensitive tests for exotic nuclear shapes
- NSCL Physics Campaign 1.0:
  - ^{34}Si: “Bubble” nucleus offers unique laboratory for studying spin-orbit interaction
  - ^{32,33}Mg: Rotational structure identified is in good agreement with rotational models; first suggestion of reduced pairing with increasing angular momentum
- ANL Campaign:
  - ^{144,146}Ba Coulex consistent with octupole deformation



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http://gretina.lbl.gov/
http://greta.lbl.gov/

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Merci!