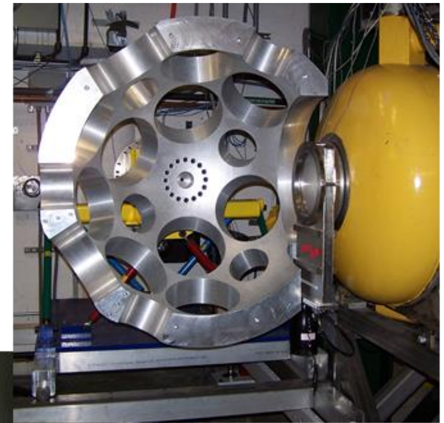
The GRETINA science campaign at NSCL

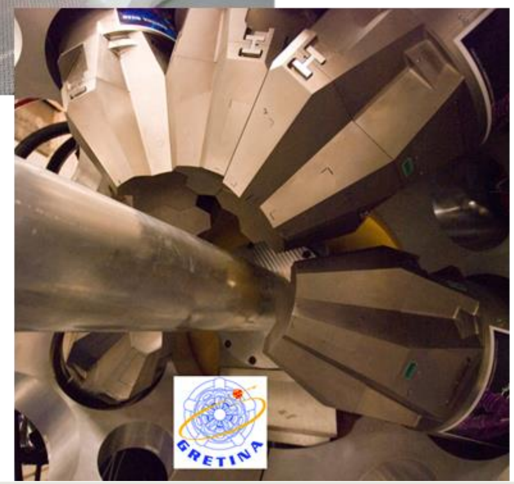
Alexandra Gade
NSCL and Michigan State University

Outline

April 23, 2012 – truck from LBNL at NSCL loading dock



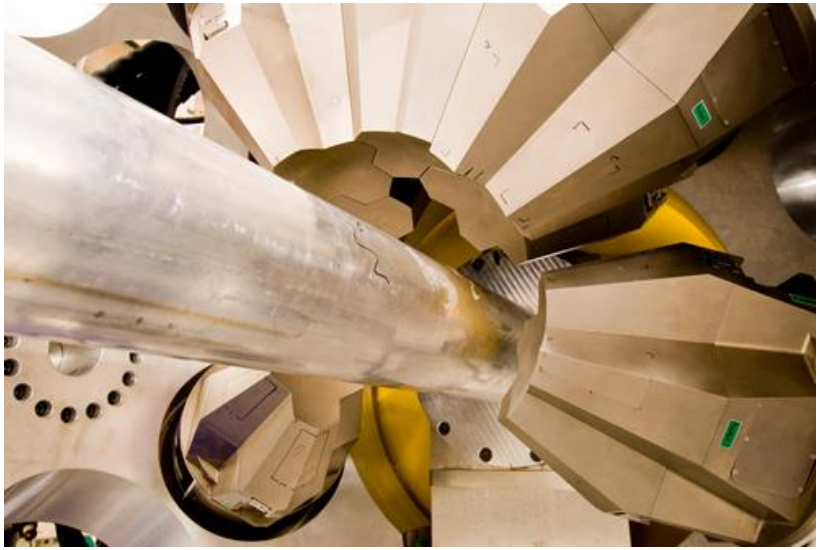
- GRETINA at NSCL
- Selected science examples
  - –Nuclear structure physics (*N=40*)
  - –Collectivity at *N=Z* (^{72}Kr)
  - –Nuclear astrophysics (proton-rich)
  - –Weak interactions and EC rates
  - –Effective charges in n-rich Ca
- Summary and outlook



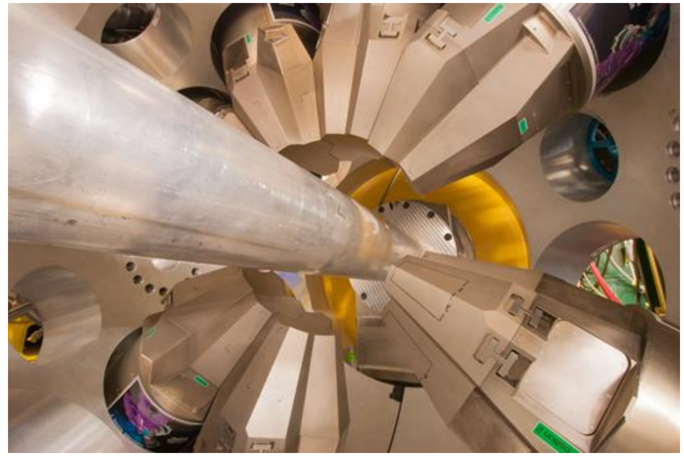
June 2013 – last science run (the 24th experiment)

The different configurations of the GRETINA campaign

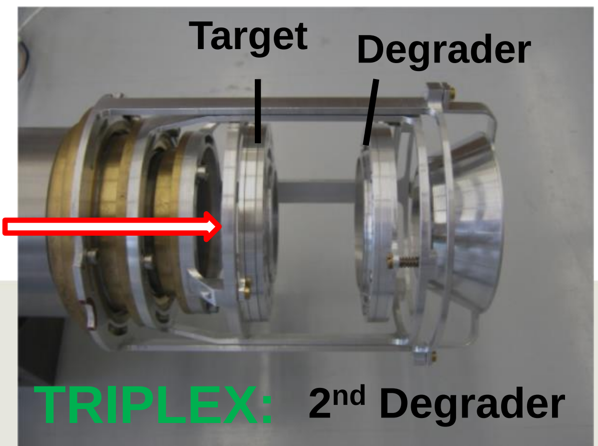
“Standard configuration”:
4 detectors under forward angles and 3 at 90 degree

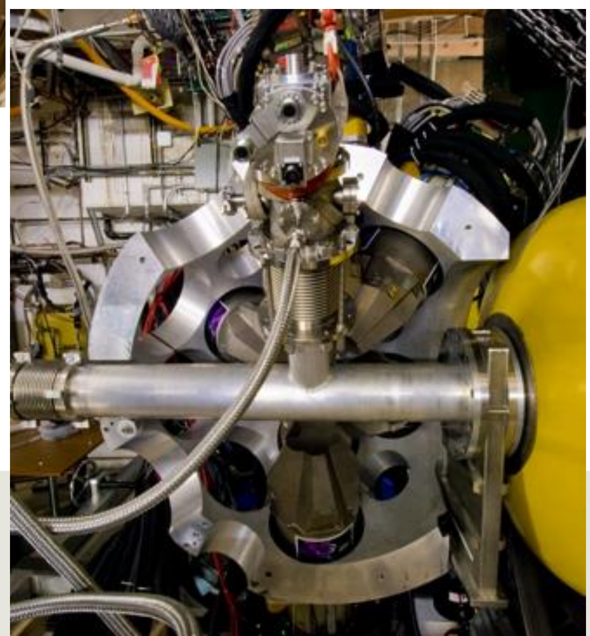


All detectors under 90 degree



Plunger lifetime measurements





All detectors in one hemisphere and LH_2 target in

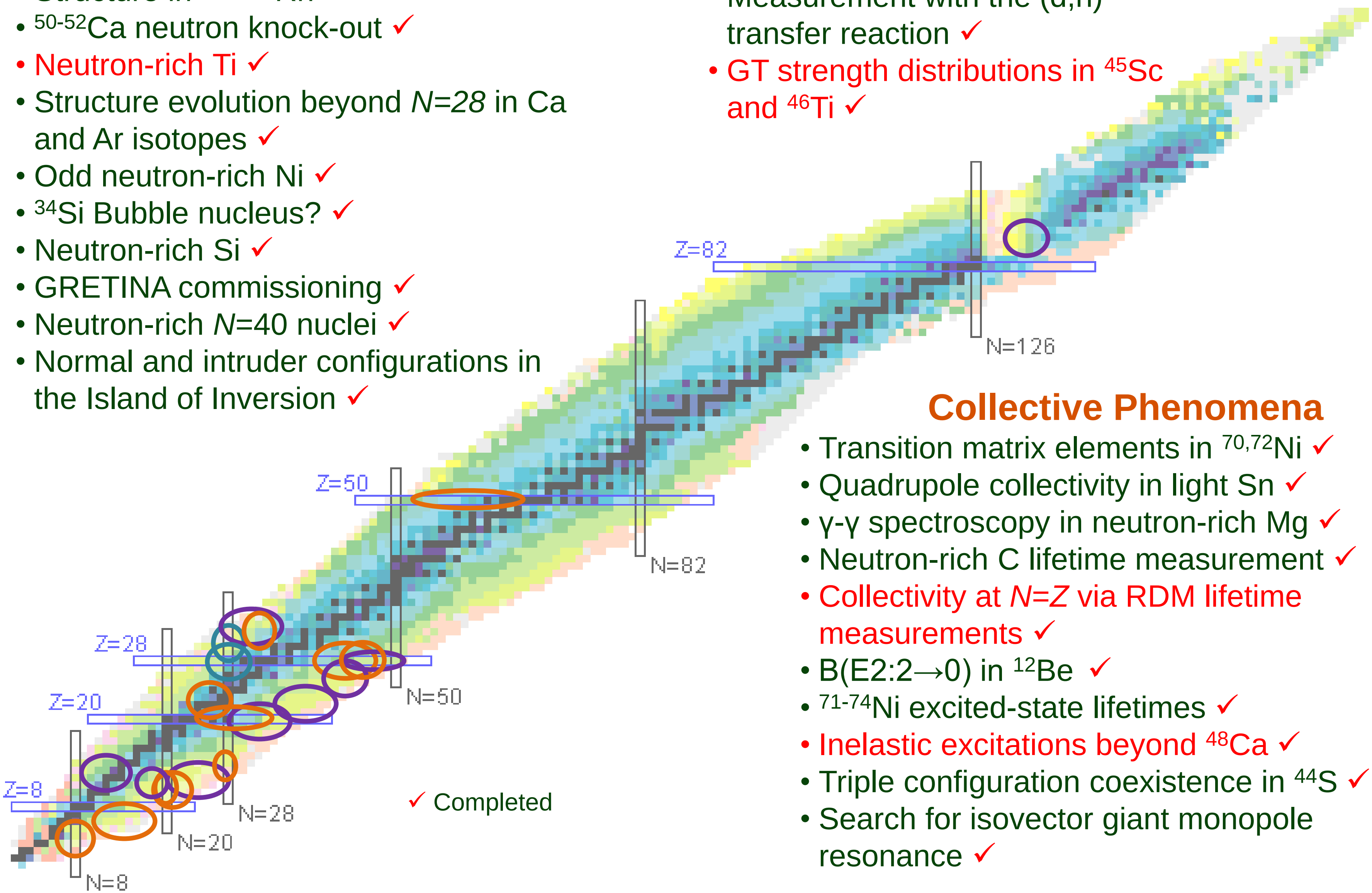
GRETINA at NSCL: beams from *Z=4* to *Z=92* – A campaign of 24 experiments

Nuclear Shell Evolution

- *N=Z* Mirror Spectroscopy ✓
- Structure in ^{221,223}Rn ✓
- $^{50\text{-}52}$Ca neutron knock-out ✓
- Neutron-rich Ti ✓
- Structure evolution beyond *N=28* in Ca and Ar isotopes ✓
- 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 with the (d,n) transfer reaction ✓
- GT strength distributions in ^{45}Sc and ^{46}Ti ✓



Collective Phenomena

- 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 ✓
- $^{71\text{-}74}$Ni excited-state lifetimes ✓
- Inelastic excitations beyond ^{48}Ca ✓
- Triple configuration coexistence in ^{44}S ✓
- Search for isovector giant monopole resonance ✓

GRETINA at NSCL: beams from *Z=4* to *Z=92* – A campaign of 24 experiments

Nuclear Shell Evolution

- *N=Z* Mirror Spectroscopy ✓ ARIS 2014
- Structure in ^{221,223}Rn ✓
- $^{50\text{-}52}$Ca neutron knock-out ✓ NS 2014
- Neutron-rich Ti ✓
- Structure evolution beyond *N=28* in Ca and Ar isotopes ✓
- Odd neutron-rich Ni ✓ Bormio 2014
- ^{34}Si Bubble nucleus? ✓ DREB 2014
- Neutron-rich Si ✓
- GRETINA commissioning ✓
- Neutron-rich *N*=40 nuclei ✓ DREB 2014
- Normal and intruder configurations in the Island of Inversion ✓

Nuclear Astrophysics

- Excitation energies in ^{58}Zn ✓
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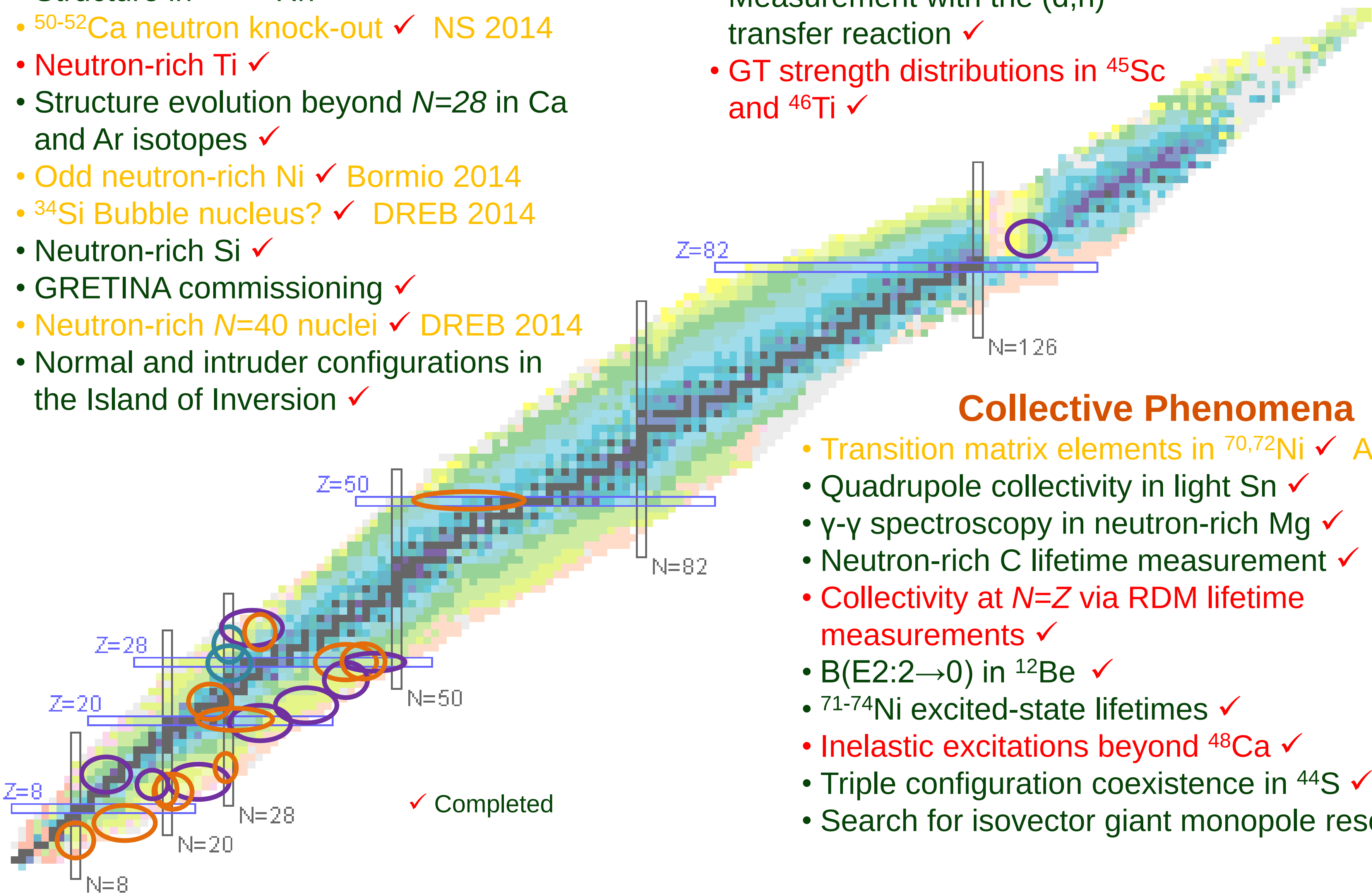

✓ Completed

Collective Phenomena

- Transition matrix elements in ^{70,72}Ni ✓ ARIS 2014
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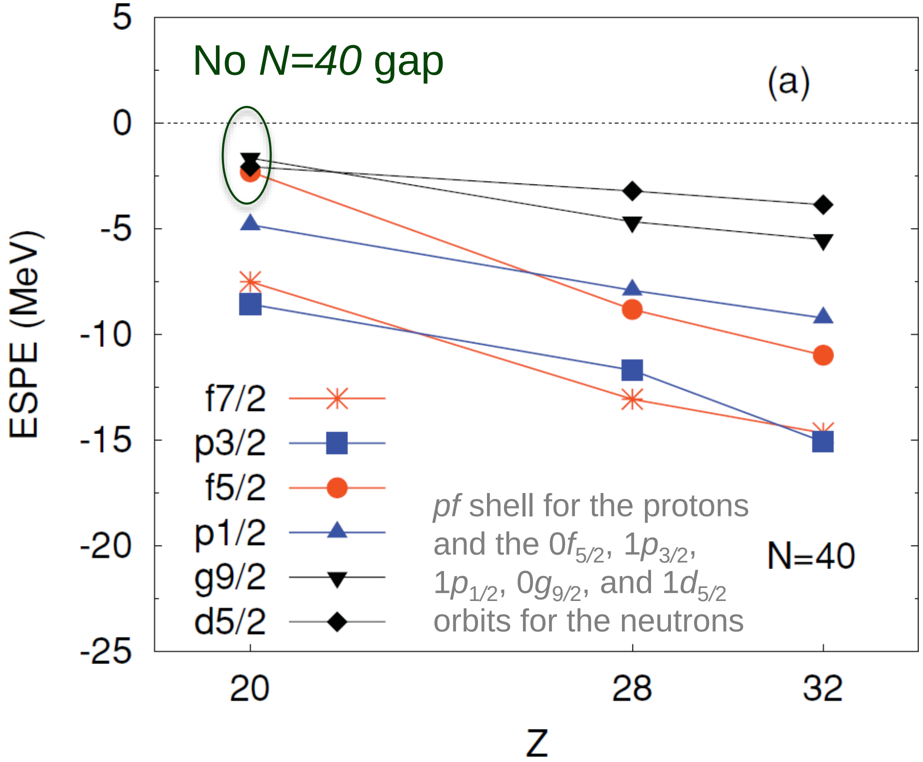
GRETINA surrounding the target position of the S800 spectrograph

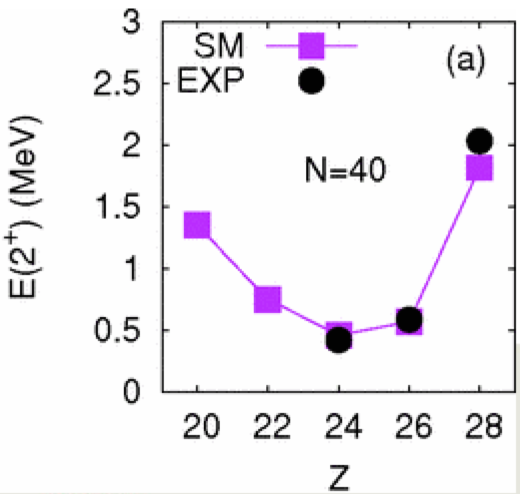
Shell evolution around *N=40* – nuclear structure towards ^{60}Ca

A. Gade *et al.*, PRL 112, 112503 (2014)

LNPS effective interaction



- Effective shell model interaction with the largest model space available predict $f_{5/2}$, $d_{5/2}$, $g_{9/2}$ degenerate – essentially no *N=40* gap at all
- The 12 CSkP Skyrme functionals by B. A. Brown [PRL 111, 232502 (2013)] give an *N=40* shell gap between 3-4 MeV and this would change the particle-hole content of the wave functions in this region
- Experimental information is needed



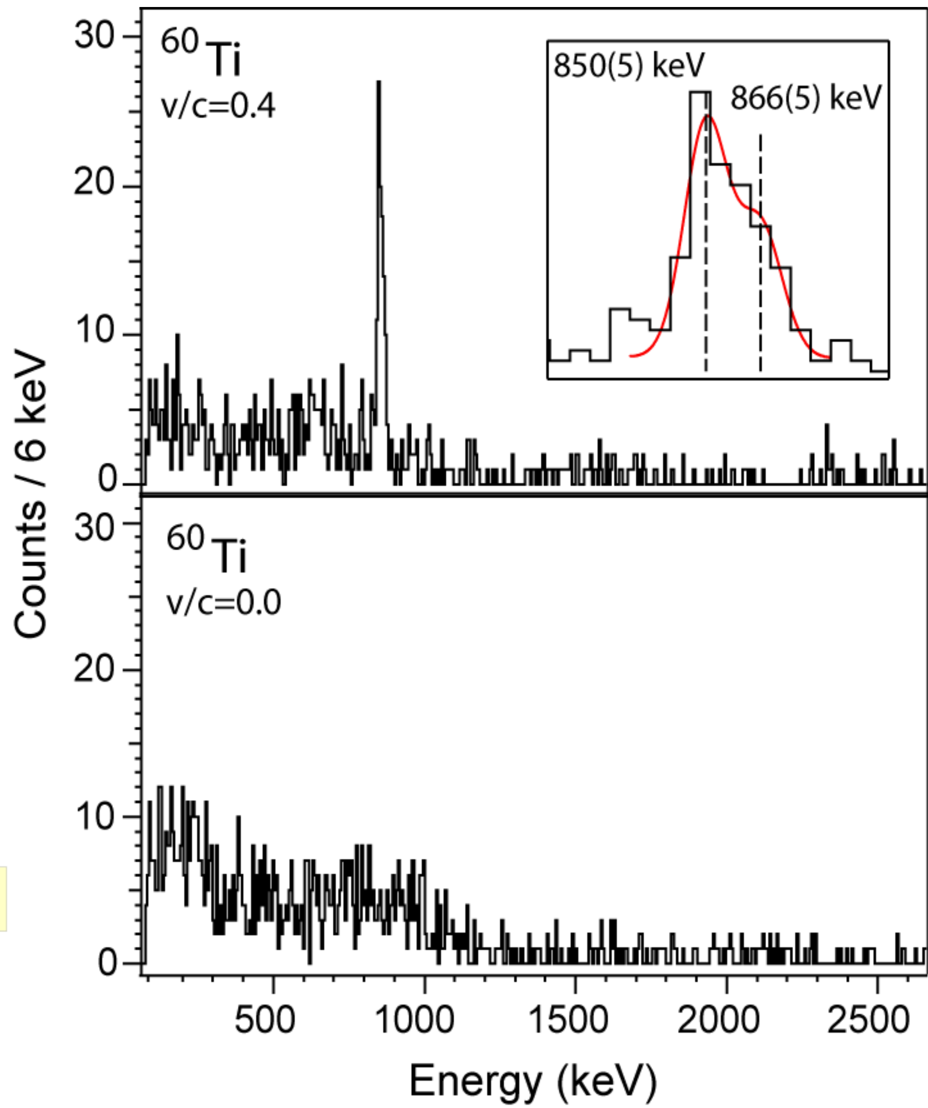
Nucleus	$\nu g_{9/2}$	$\nu d_{5/2}$	0p0h	2p2h	4p4h	6p6h	E_{corr}
^{68}Ni	0.98	0.10	55.5	35.5	8.5	0.5	−9.03
^{66}Fe	3.17	0.46	1	19	72	8	−23.96
^{64}Cr	3.41	0.76	0	9	73	18	−24.83
^{62}Ti	3.17	1.09	1	14	63	22	−19.62
^{60}Ca	2.55	1.52	1	18	59	22	−12.09

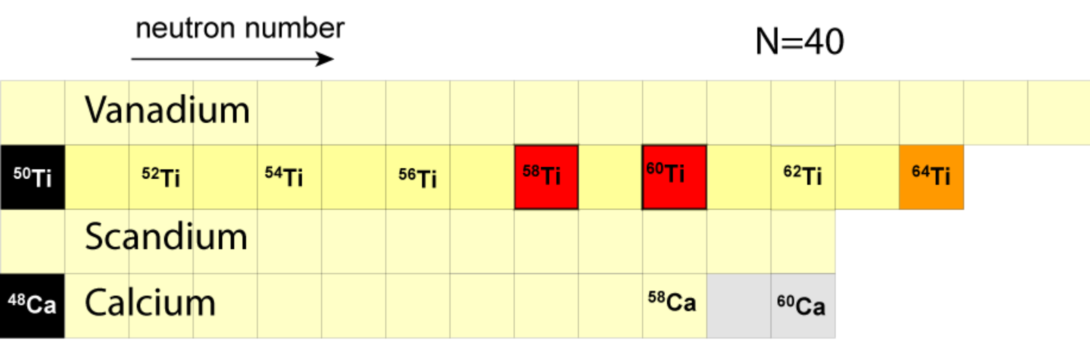
S. Lenzi et al., PRC 82, 054301 (2010)

Shell evolution toward ^{60}Ca: First spectroscopy of ^{60}Ti with ^{9}Be(^{61}V,^{60}Ti+γ)X

A. Gade *et al.*, PRL 112, 112503 (2014)

- The structure of neutron-rich Ti-Ni isotopes is subject to shell evolution largely driven by the monopole parts of the *pn* tensor force
- Excited states are often one of the first benchmarks. Only one excited state was known in ^{58}Ti, nothing in ^{60}Ti.
- Excited states in ^{58,60}Ti were populated in nucleon removal reactions and will provide first benchmarks towards *N=40* in the Ti isotopes



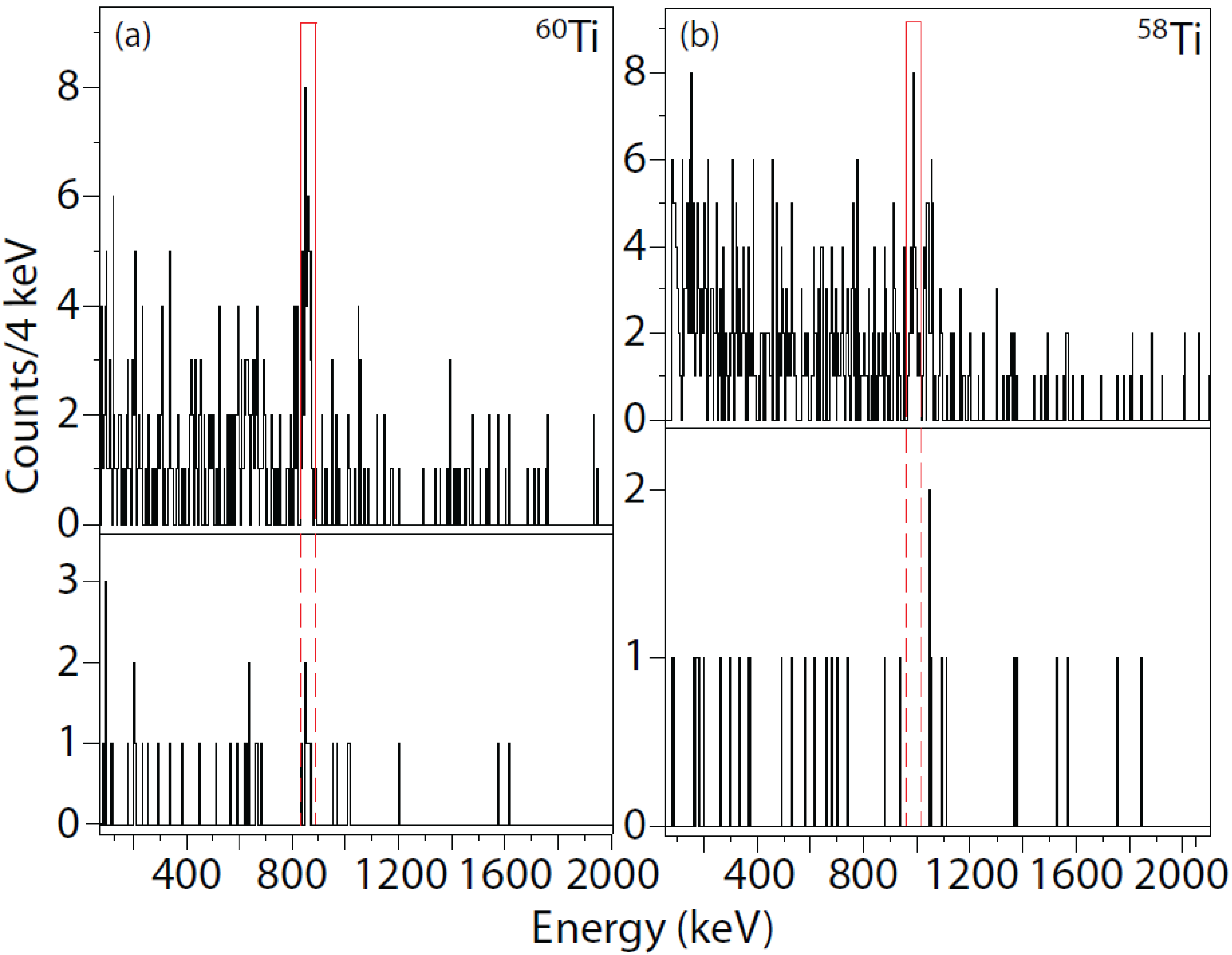


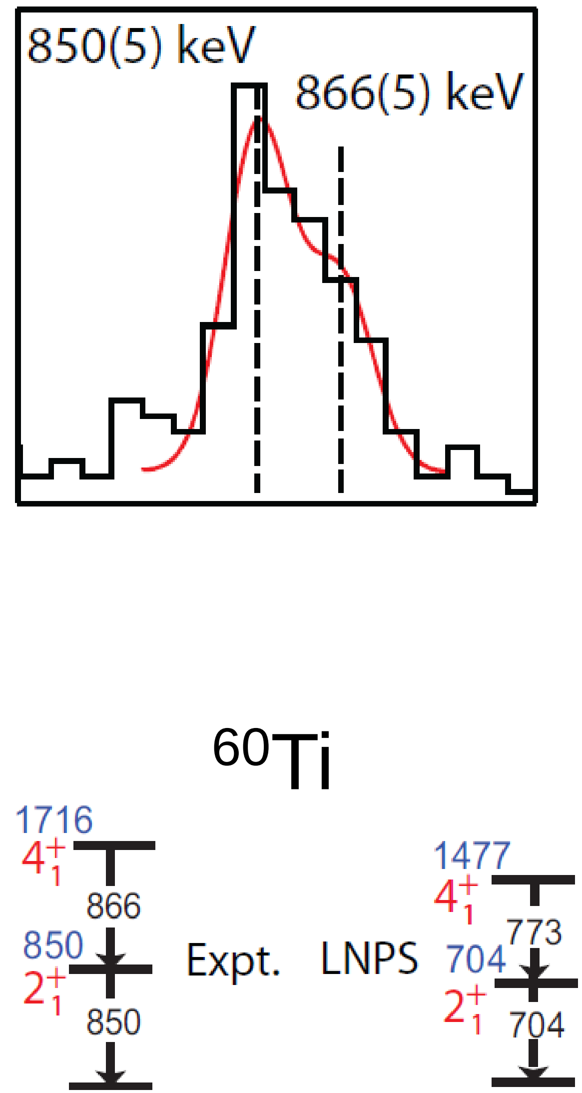
^{50}Ti and ^{48}Ca are the last stable titanium and calcium isotope

^{64}Ti and ^{58}Ca are the last titanium and calcium isotopes known to exist

Looks like a doublet, smells like a doublet …

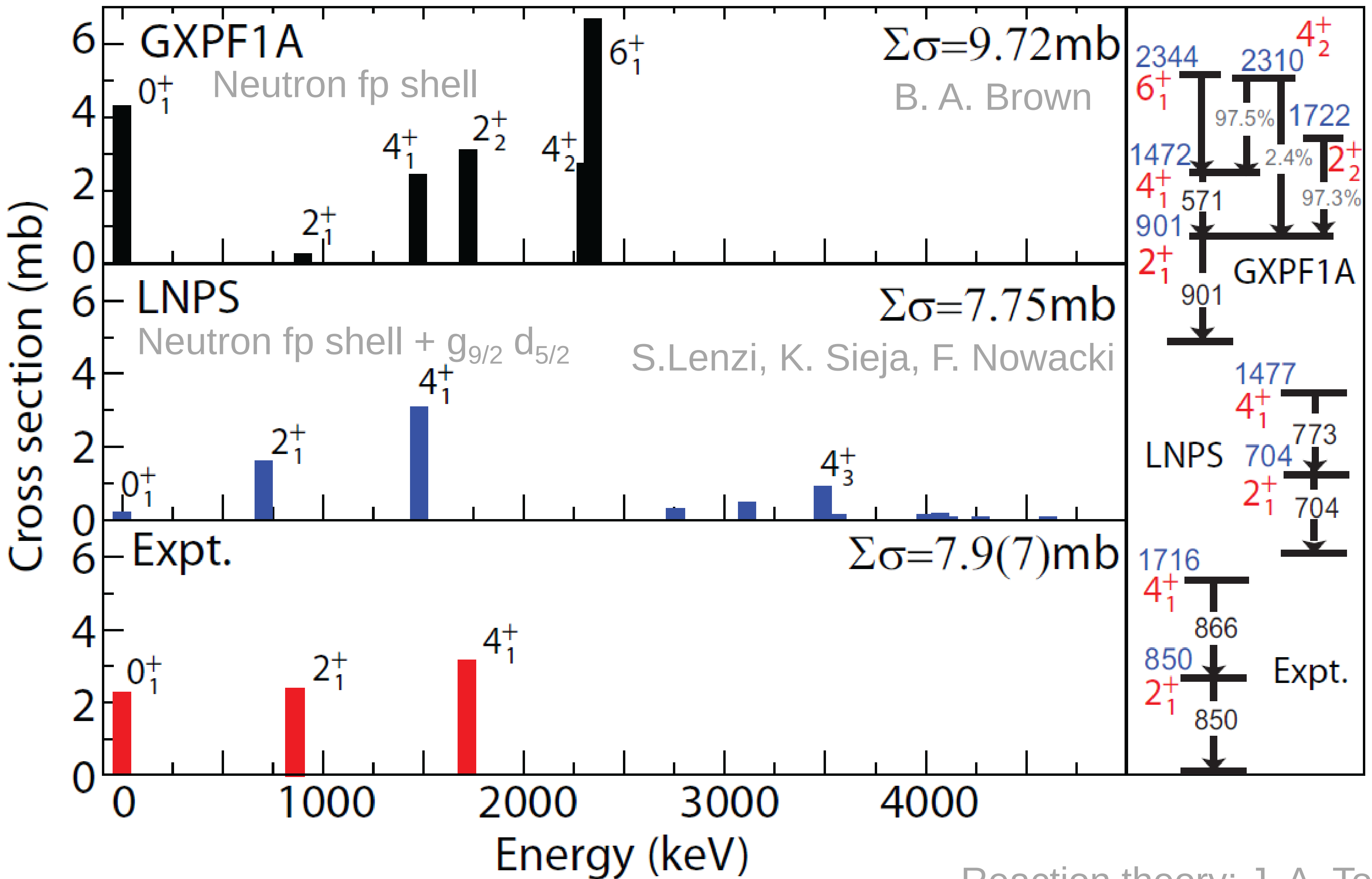
A. Gade *et al.*, PRL 112, 112503 (2014)





The power of direct reactions

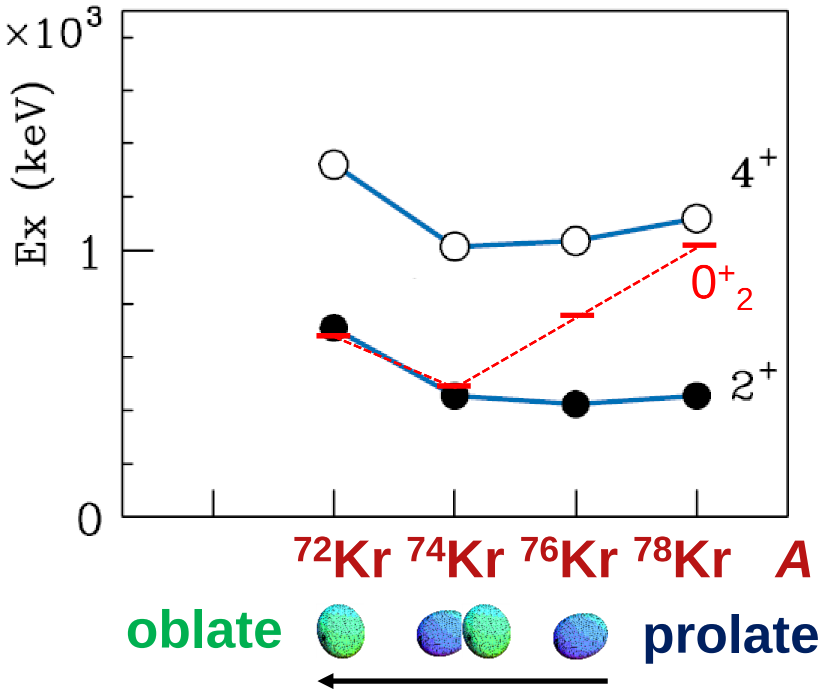
A. Gade *et al.*, PRL 112, 112503 (2014)

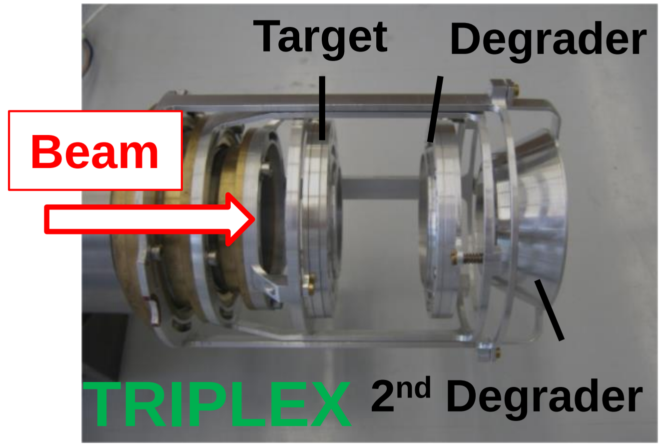


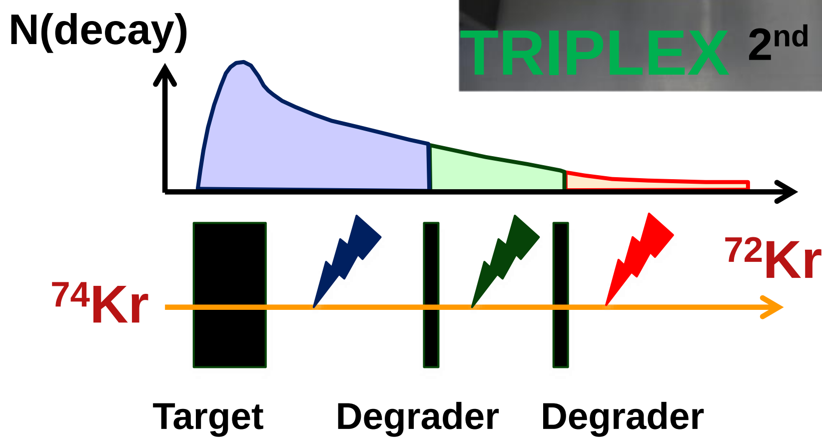
Reaction theory: J. A. Tostevin

Shape coexistence in ^{72}Kr and lifetime measurements

H. Iwasaki *et al.*

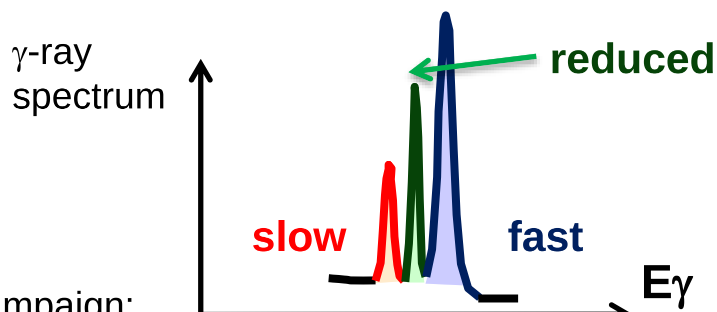






- Shape transition in the Kr ground states (lowering of the 0^+_2 across the chain)
- How about excited states (2^+ and 4^+) in ^{72}Kr ? *)
  *) e.g. H. Dejbakhsh et al., PLB 249, 195 (1990)

→ B(E2) measurement with GRETINA

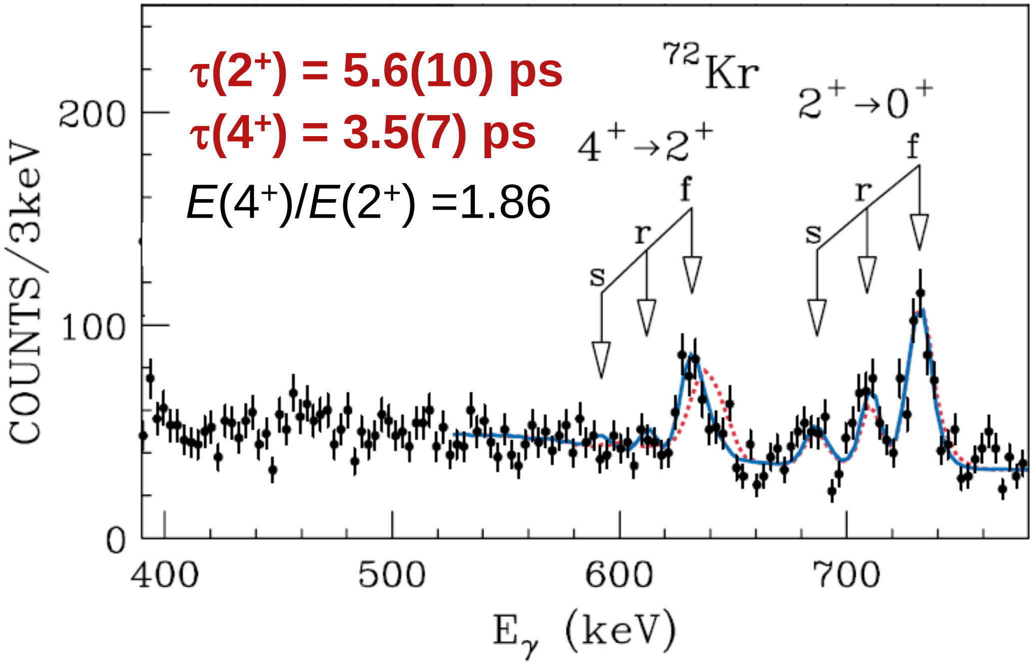


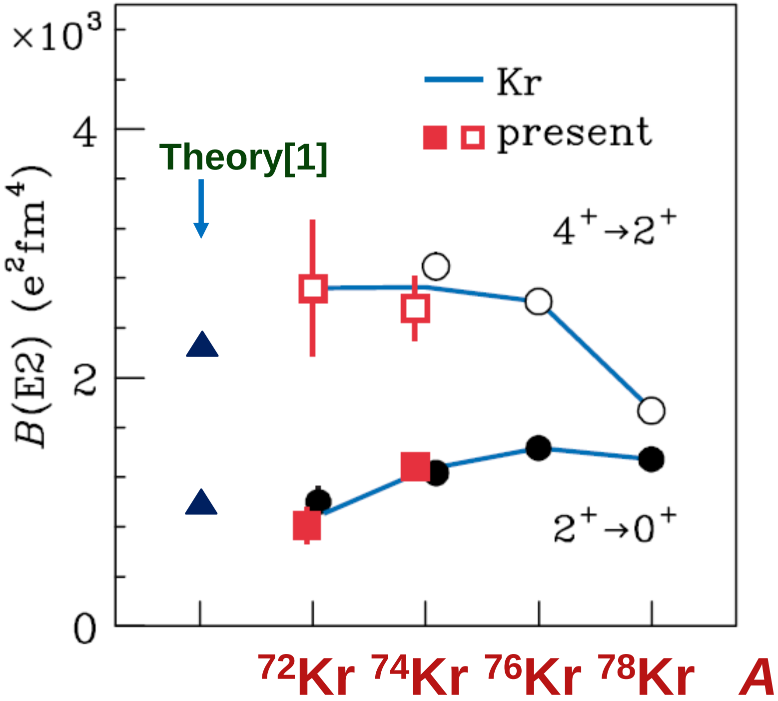
First TRIPLEX campaign:
A. Nichols, R. Wadsworth, H. Iwasaki *et al.*, PLB 733, 52 (2014)

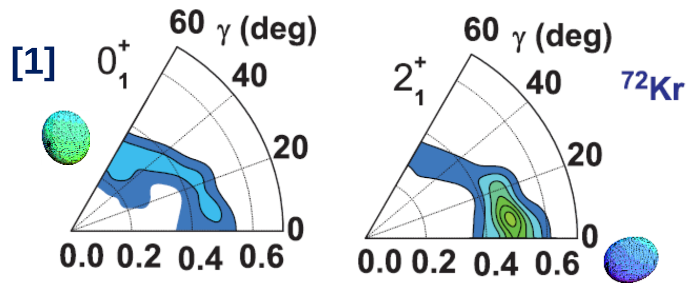
Rapid shape transition in ^{72}Kr

H. Iwasaki *et al.*, PRL 112, 142502 (2014)

Model independent B(E2) values







Rapid evolution of collectivity in yrast states with $B(\mathrm{E2};4^+\rightarrow2^+)/B(\mathrm{E2};2^+\rightarrow0^+) = 3.4$ confirmed

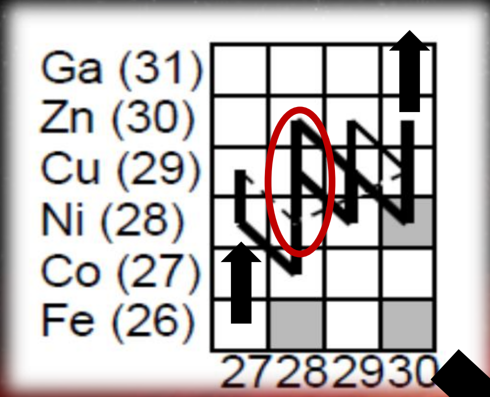
→ possible oblate-prolate transition between the yrast 0^+ and 2^+ states in ^{72}Kr

[1] Beyond relativistic mean-field studies with PC-PK1 Force, Y.Fu et al., PRC 87, 054305 (2013)

See Zuker, Poves, Nowacki, Lenzi, arXiv:1404.0224 for recent SM work

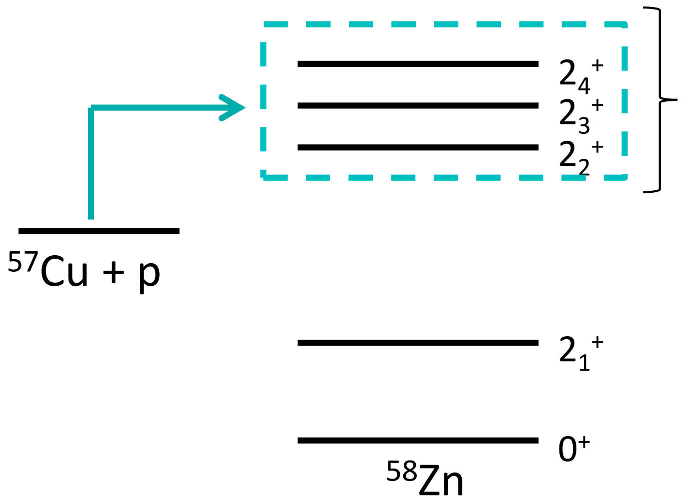
Nuclear Astrophysics - Spectroscopy of proton-rich ^{58}Zn

Nuclear reaction flow powers X-ray bursts through important waiting point ^{56}Ni

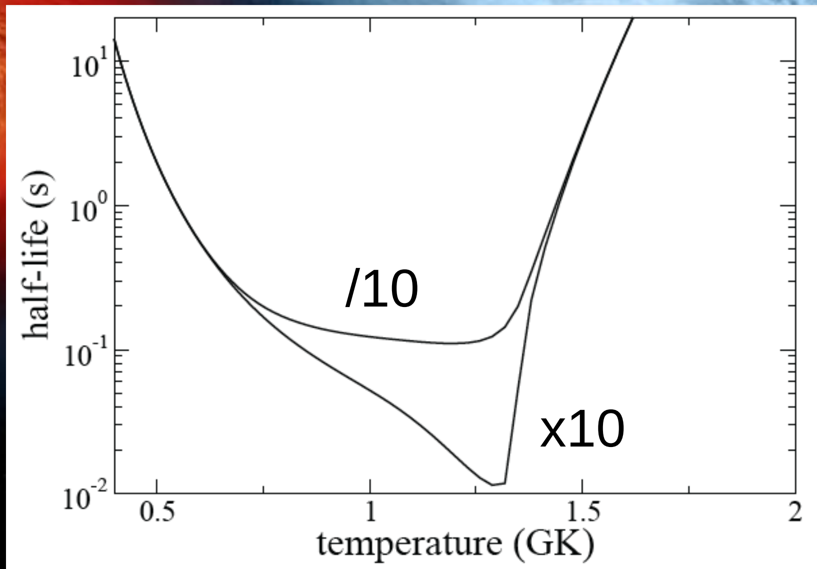


Explore structure with GRETINA

Variations of $^{57}Cu(p,\gamma)^{58}Zn$ affect the eff. lifetime of ^{56}Ni



Reaction rate dominated by 2^+ resonances

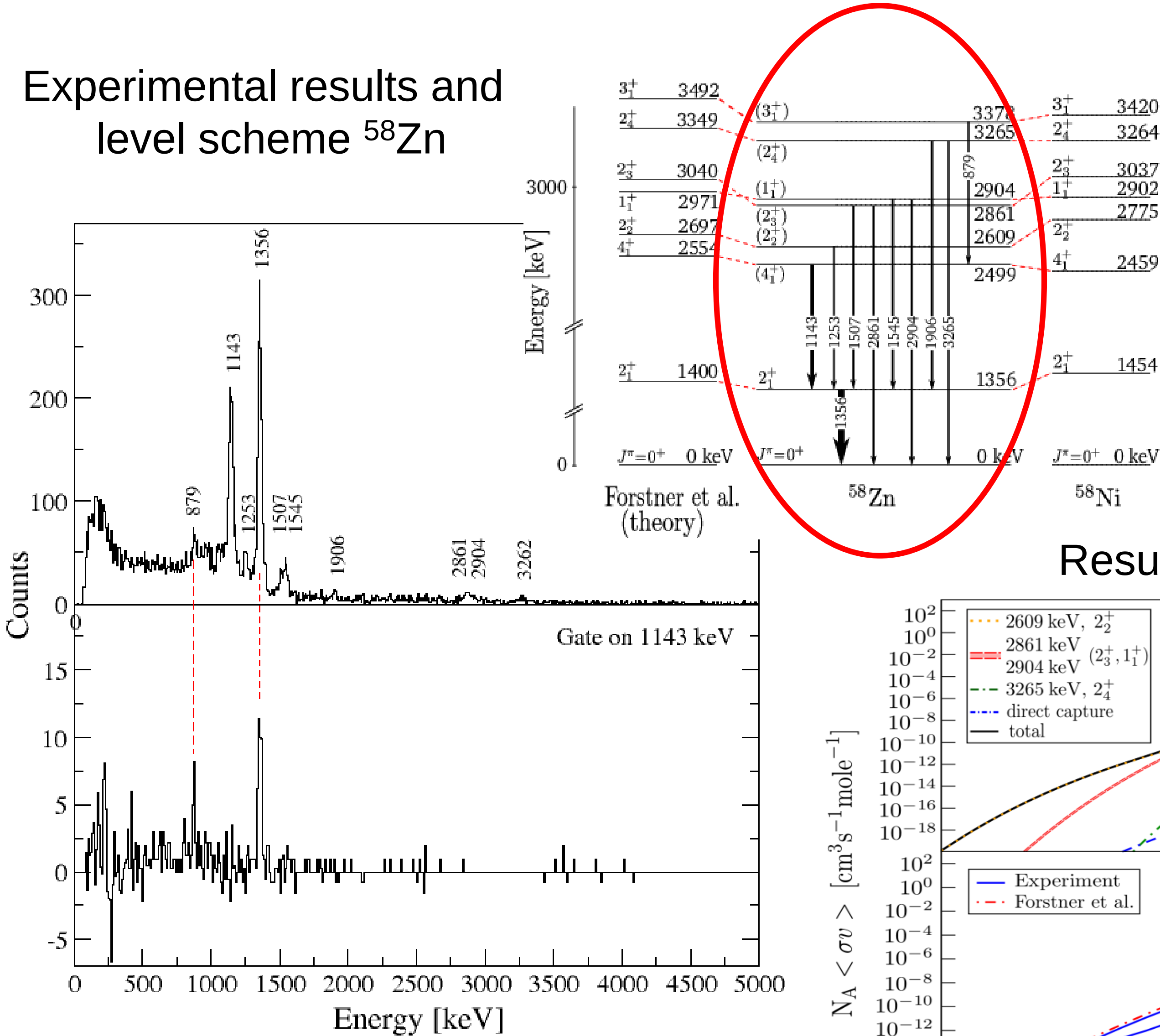


C. Langer, F. Montes *et al.*, PRL, in press

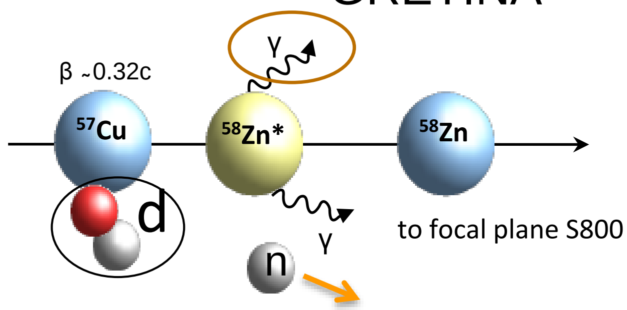
Spectroscopy of ^{58}Zn and reduced uncertainty in important reaction rate

C. Langer, F. Montes *et al.*, PRL, in press

Experimental results and level scheme ^{58}Zn

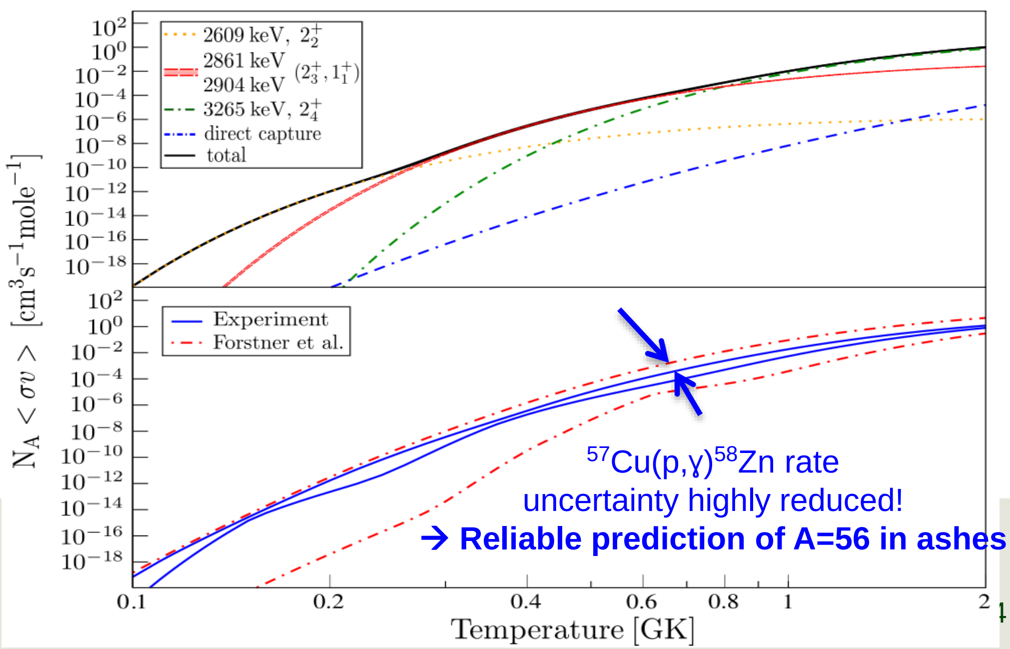


GRETINA



^{57}Cu(d,n)^{58}Zn @ 75 MeV/u

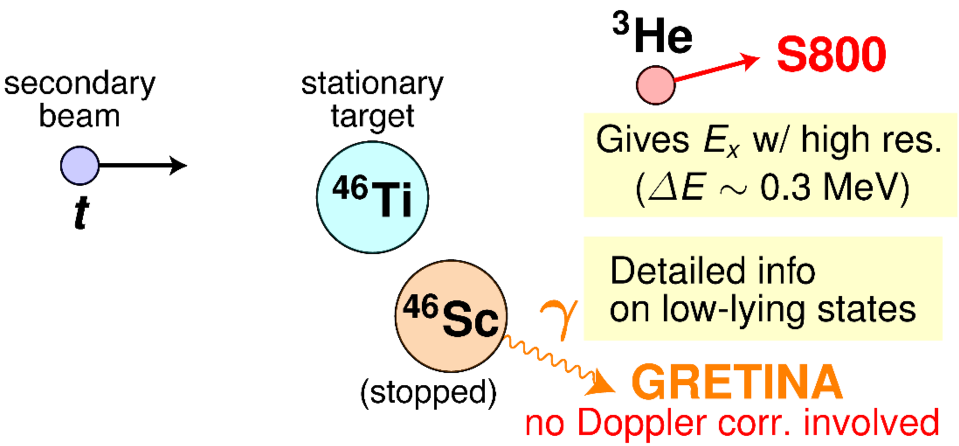
Resulting astrophysical rate

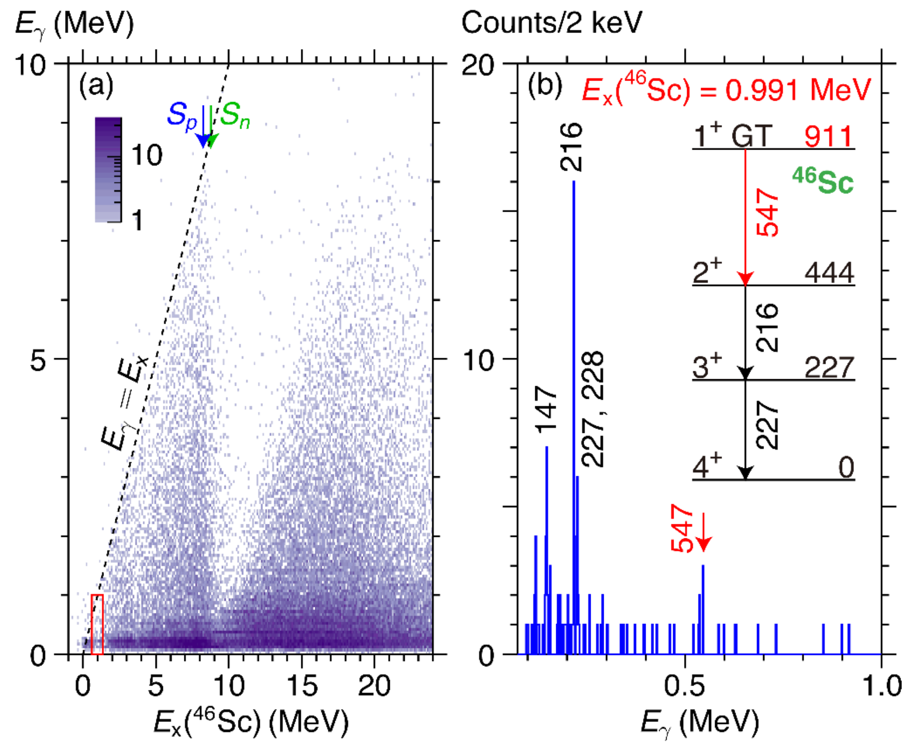


β^+ Gamow-Teller Transition Strengths from ^{46}Ti and Stellar Electron-Capture Rates

S. Noji, R. Zegers *et al.*, PRL, in press

- *B*(GT) in lower *fp*-shell
  - Electron capture rates of astrophysical importance: Type Ia, II supernova, neutron star
  - EC rates from charge-exchange data for *fp*-shell nuclei: Cole, *et al.*, PRC **86** 015809 (2012)
    - Shell model does well overall; but deficiencies possible for the lightest ones (e.g. ^{46}Ti)
  - Detailed knowledge of the lowest-lying GT transition is critical for estimating EC rates
- Charge-Exchange reaction + γ-ray coincidence
  - ^{46}Ti(t,^{3}He)^{46}Sc measurement at S800
    - High resolution & wide E_x range
    - Multipole decomposition analysis
  - GRETINA: γ-rays from stopped ^{46}Sc residue





β^+ Gamow-Teller Transition Strengths from ^{46}Ti and Stellar Electron-Capture Rates

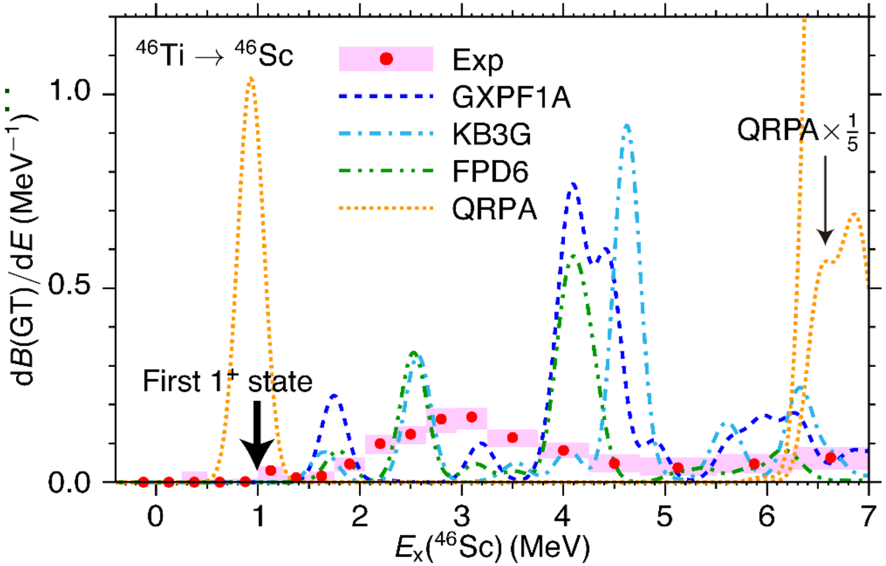
S. Noji, R. Zegers *et al.*, PRL, in press

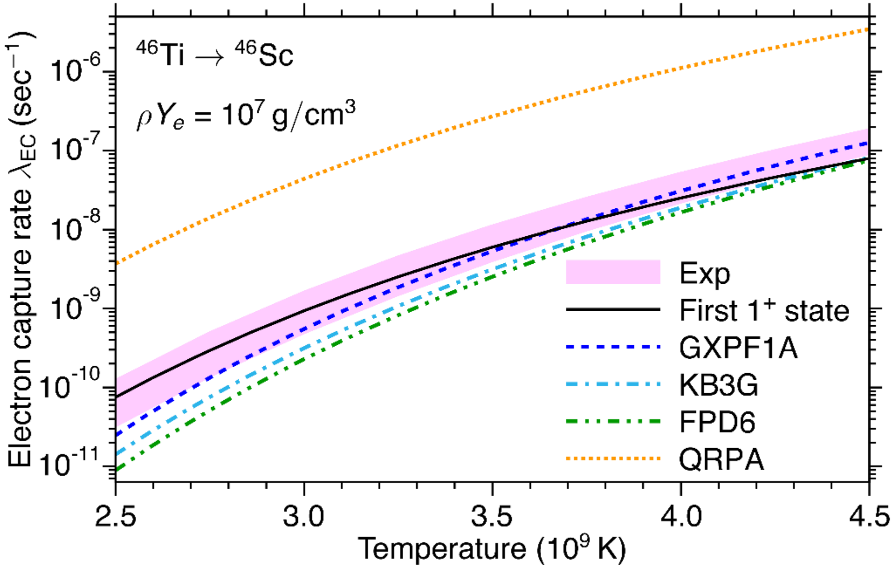
- Results: *B*(GT) from ^{46}Ti obtained
  - *B*(GT) for the 1st 1+ state (911 keV) from γ rays: most critical to the EC rates for astrophysics
  - Shell-model calculations in *fp*-shell **do not reproduce** the results:
    - Intruder configurations due to *sd*-shell will need to be included
  - QRPA calculations **fail**:
  - The EC rate significantly overestimated
  - **Further improvements of theory are important for lower *fp*-shell**

High-resolution CE spectroscopy	High-resolution γ-ray spectroscopy
B(GT) distrib. up to up to high-lying states	Detailed knowledge of low-lying states

Accurate EC rates have been made available

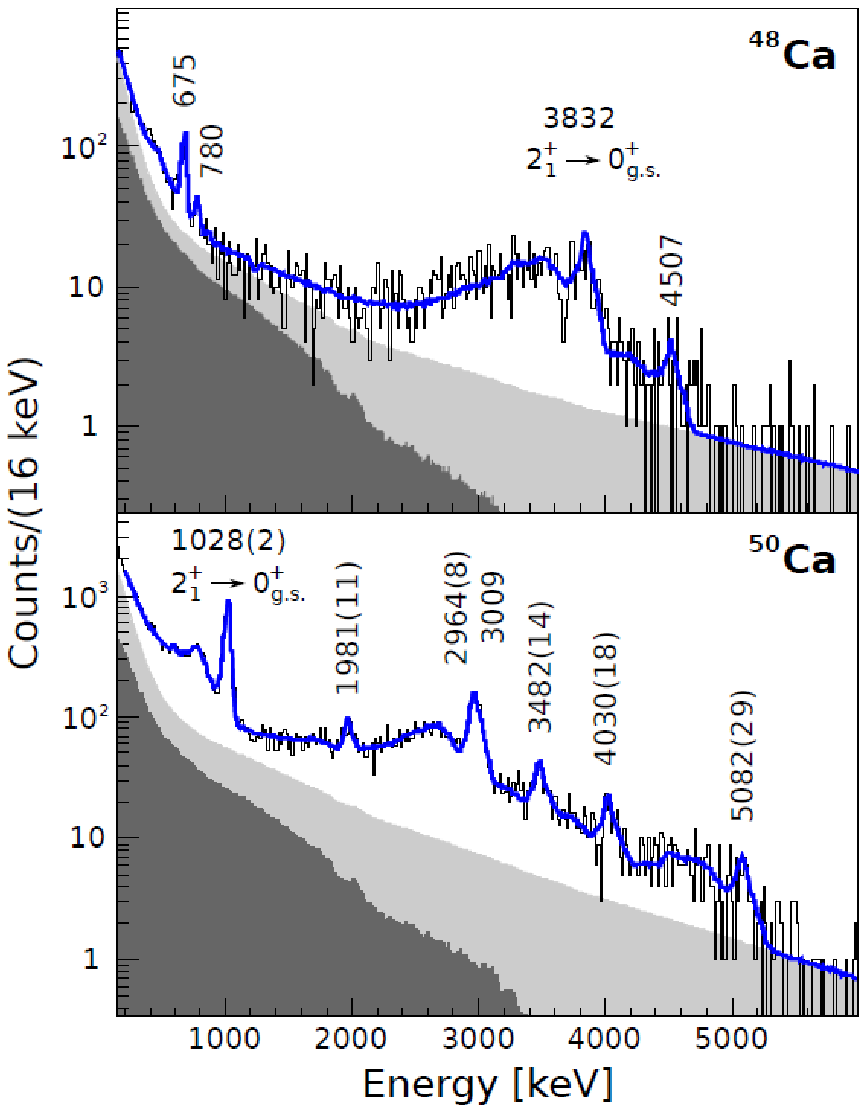
γ rays help CE experiments in inverse kinematics achieve detailed spectroscopic information

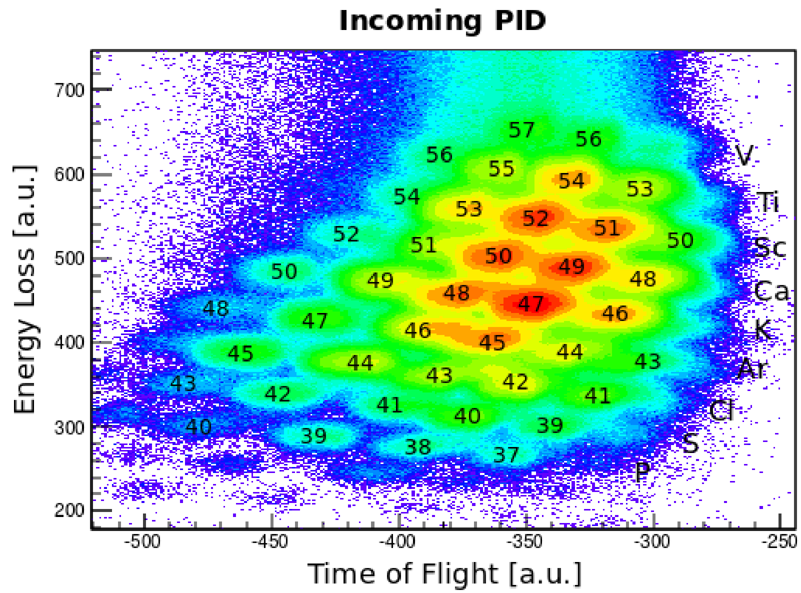


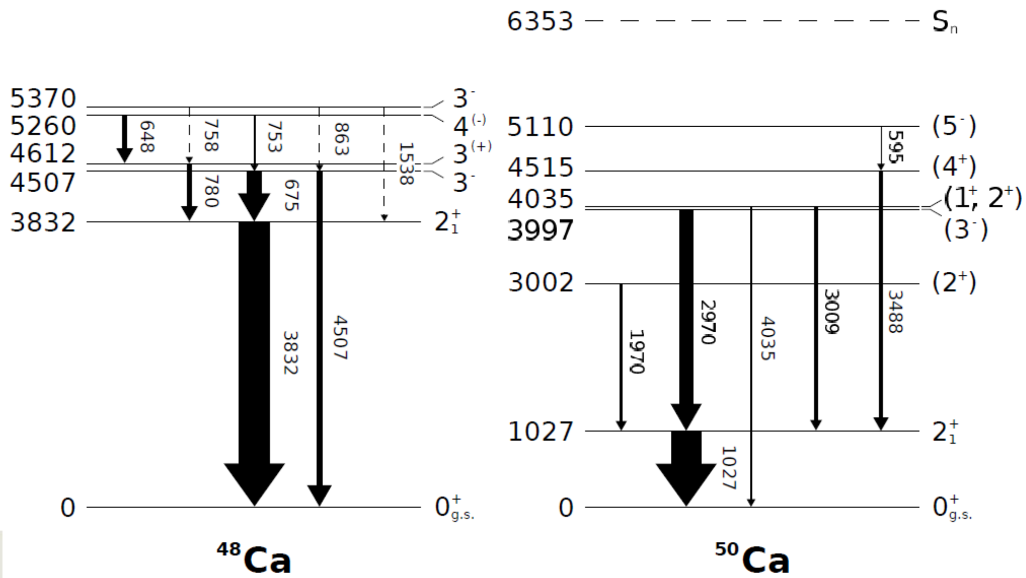


Probing proton and neuron degrees of freedom with (p,p')

L. A. Riley *et al.*, PRC, submitted



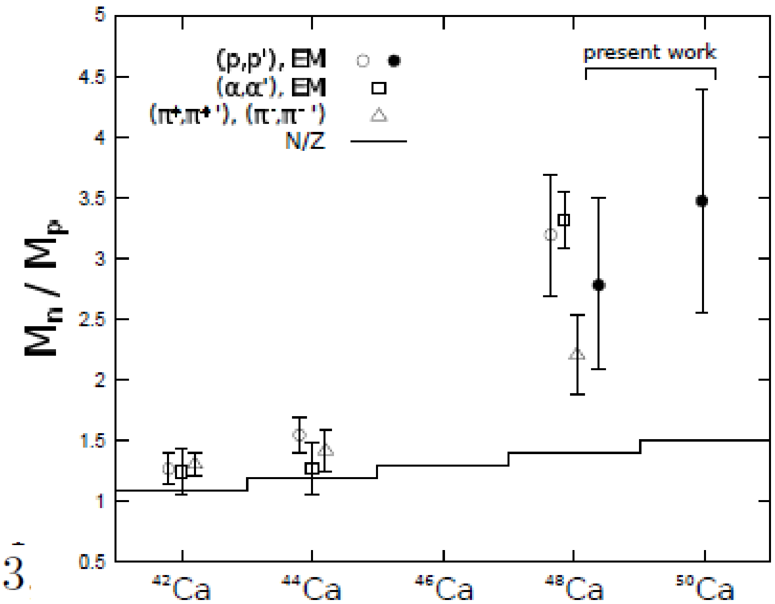




Effective charges in the shell model around ^{50}Ca

L. A. Riley *et al.*, PRC, submitted

- Quadrupole effective charges are needed in shell model descriptions of transition strengths to account for core excitations and related contributions outside of the model space
- Inelastic proton scattering together with independent B(E2) or τ information, allows to determine e_p/e_n following Brown and Wildenthal (1980)



$$\frac{M_n}{M_p} = \frac{b_p}{b_n}\left(\frac{\delta_{(p,p')}}{\delta_p}\left(1+\frac{b_n}{b_p}\frac{N}{Z}\right)-1\right) \quad b_n/b_p = 1 \text{ and } b_n/b_p = 3$$

$$M_n/M_p = 3.5(9)$$

$$M_p = A_p(1+\delta_{pp}) + A_n\delta_{pn},\ A_p = 0$$

$$M_n = A_n(1+\delta_{nn}) + A_p\delta_{np}$$

$$\frac{M_n}{M_p} = \frac{1+\delta_{nn}}{\delta_{pn}} \qquad e_p = 1+\delta_{pp} = 1+\delta_{nn} \qquad e_n = \delta_{pn} \qquad \frac{e_p}{e_n} = \frac{M_n}{M_p}$$

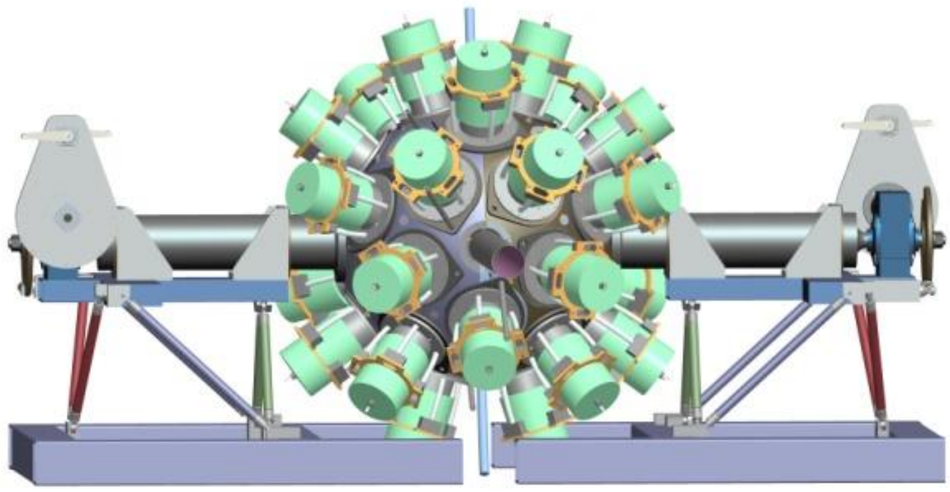
$e_p/e_n=3$ M. Honma, (GXPF1)
$e_p/e_n = 1.4$, R. du Rietz,
$e_p/e_n = 3.5(9)$ Our work

In agreement with conclusions in J. J. Valiente-Dobon et al., PRL 102, 242502 (2009)

Brown, Wildenthal, PRC 21, 2107 (1980)
M. Honma et al., PRC 69, 034335 (2004)
R. du Rietz et al., PRL 93, 222501 (2004)

Outlook – The future is bright

- In-beam γ-ray spectroscopy is prospering around the world with great opportunities afforded by advanced arrays, clever targets and powerful accelerators
- GRETINA at NSCL was a great success and it just started its second science campaign at ATLAS/ANL
  - First NSCL results are out (see also talks at DREB next week)
- GRETINA will return to NSCL for a second fast beam campaign in 2015 after the ANL campaign is completed (likely with more detectors!)



Partners in crime …

- ^{58}Zn science slides contributed by C. Langer and H. Schatz (MSU)
- ^{72}Kr slides provided by H. Iwasaki (MSU)
- ^{50}Ca slides provided by L. A. Riley (Ursinus College)
- (^{46}Ti,^{46}Sc) slides provided by S. Noji and R. Zegers (MSU)

GRETINA @ NSCL

Acknowledgement *(for setting up and keeping GRETINA going at NSCL)* :

LBNL: I.Y. Lee, A.O. Macchiavelli, C.M. Campbell, H. Crawford, M. Cromaz, C. Lionberger, A. Wiens

ORNL: D. Radford, J. M. Allmond

NSCL: **D. Weisshaar**, **F. Recchia**, T. Baugher, C. Langer, E. Lunderberg, A. Lemasson, S. Noji, M. Scott, D. Smalley, K. Wimmer, and R. Fox (NSCL DAQ), and D. Bazin, S. Williams (S800), Hiro Iwasaki (Plunger)

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