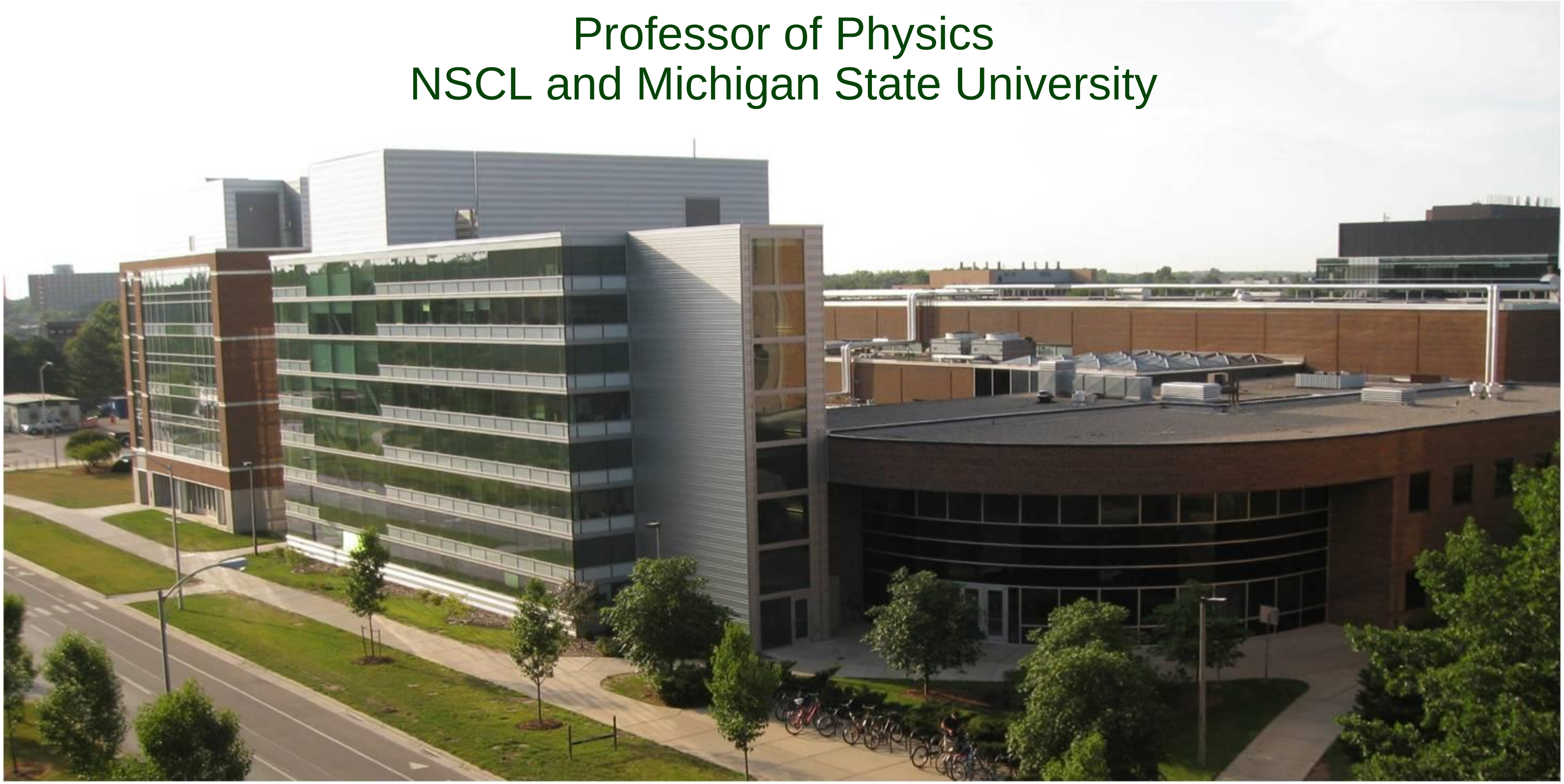
Nuclear spectroscopy with fast exotic beams

Alexandra Gade
Professor of Physics
NSCL and Michigan State University



… or puzzles in the region around *N=28* from ^{48}Ca over ^{46}Ar to ^{42}Si

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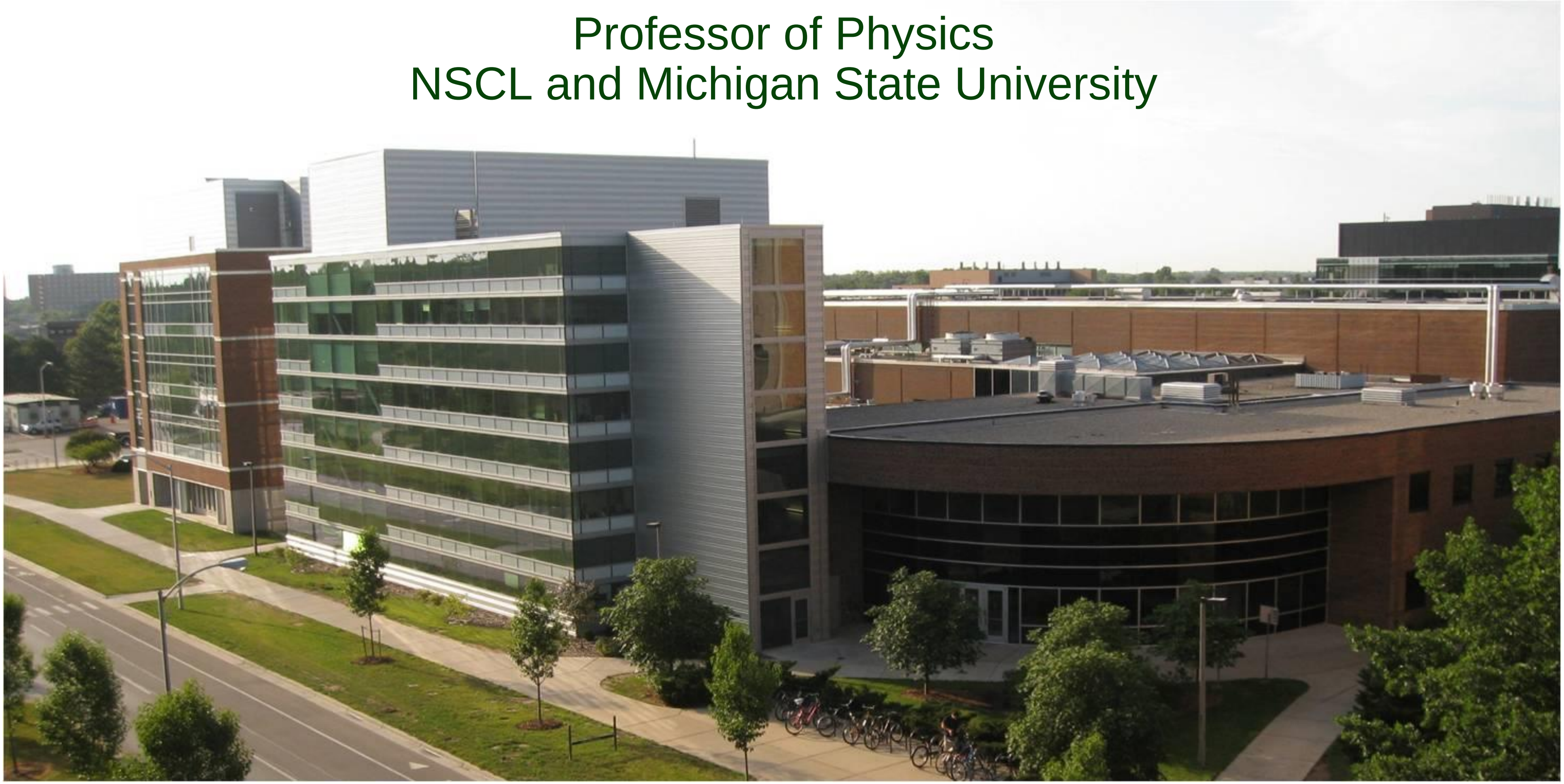
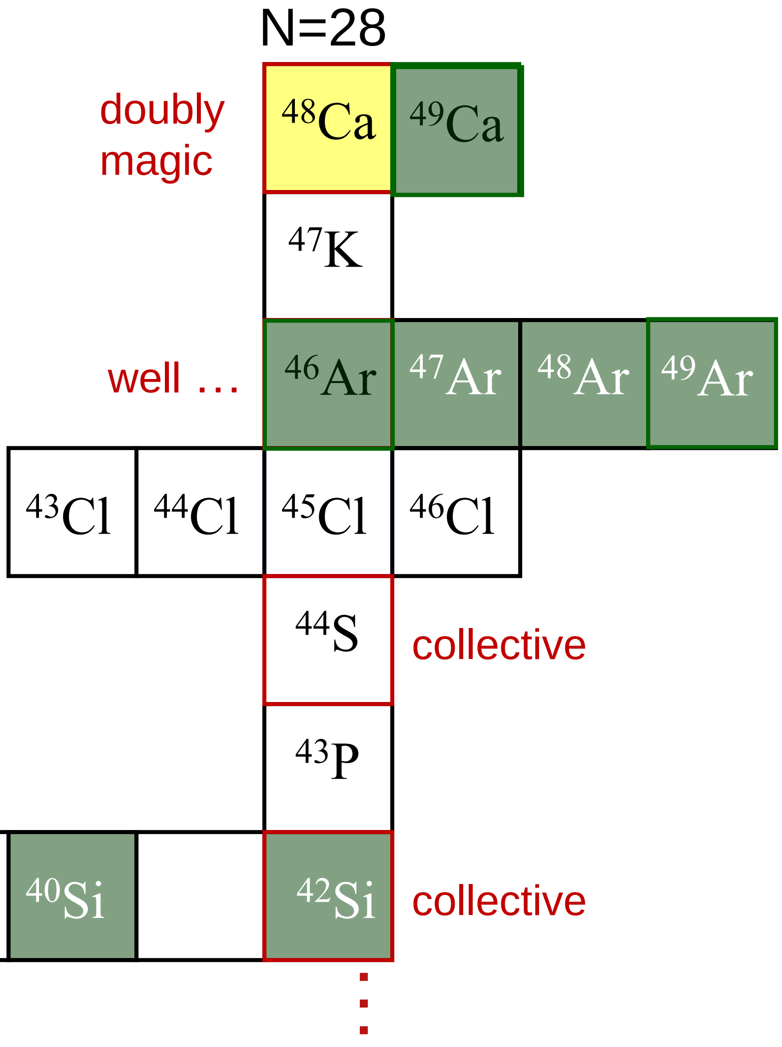


Outline

- A brief history and motivation
- What is wrong with ^{46}Ar?
- Direct neighborhood of ^{46}Ar
- Other chains – Ca isotopes
- Other chains – Si isotopes
- Open questions and outlook

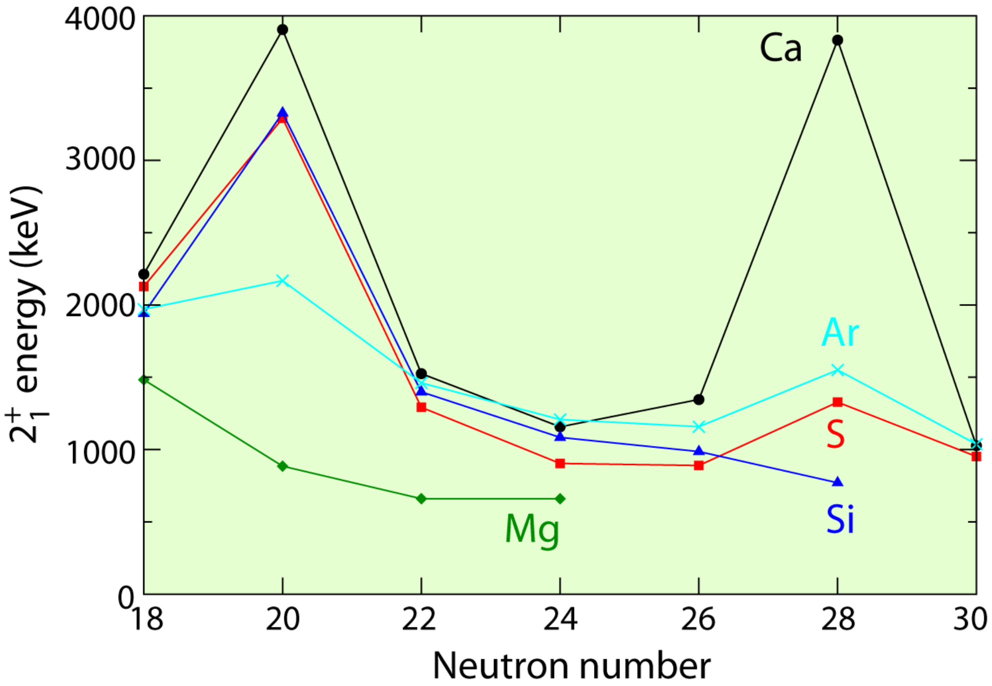


Why is *N*=28 still interesting in neutron-rich nuclei

^{48}Ca	Doubly-magic
^{47}K	
^{46}Ar	Huh?
^{45}Cl	
^{44}S	Collective, shape coexistence proven
^{43}P	
^{42}Si	Collective
^{40}Mg	Anybody?

- Region of rapid shell evolution
- First shell closure due to the spin-orbit force
- Collectivity of ^{46}Ar is not described by shell model – puzzling deviation
- For me personally – ^{46}Ar is a key nucleus on the path from doubly-magic ^{48}Ca to deformed ^{42}Si that theory has to get right if the details of shell evolution are claimed to be understood and implemented in shell model

The breakdown of *N*=28 from ^{48}Ca to ^{42}Si



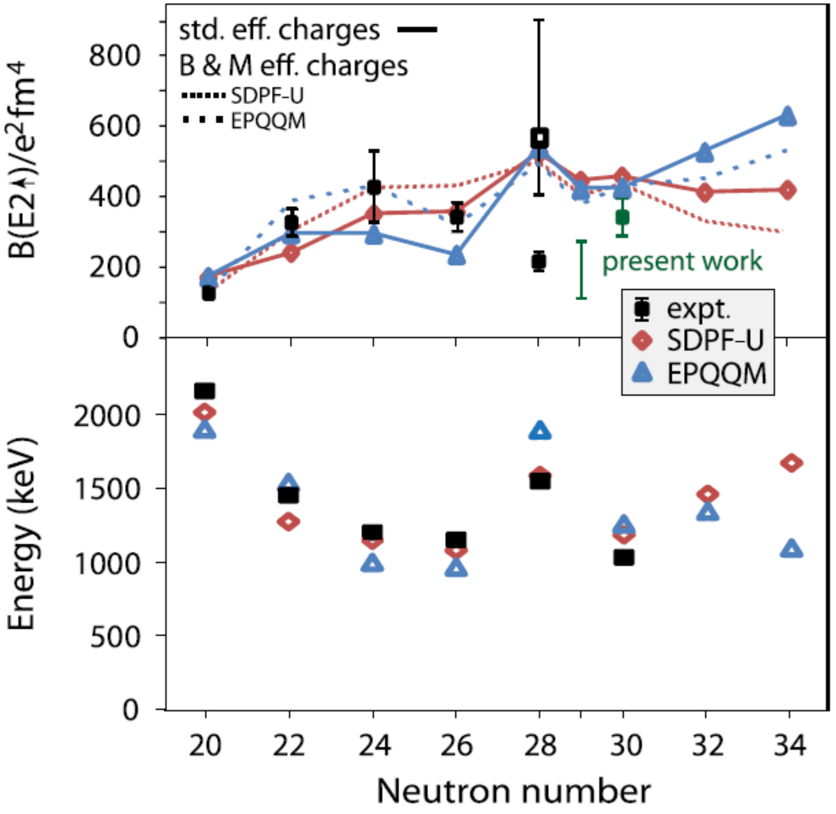
- Neutron $f_{7/2}$ fully filled (as compared to ^{34}Si) and that reduces the $d_{3/2}$-$d_{5/2}$ SO splitting by almost 2 MeV (consistent with tensor force: $d_{3/2}$-$f_{7/2}$ attractive and $d_{5/2}$-$f_{7/2}$ repulsive)
- *N=28* shell gap is reduced by 1 MeV as protons are removed from ^{48}Ca → ^{42}Si
- Particle-hole excitation of sd shell protons and fp shell neutrons to unfilled orbitals with $\Delta\ell=2$ favor quadrupole collectivity

National Science Foundation
Michigan State University

B. Bastin et al., PRL 99, 022503 (2007)

A brief history –Collectivity of ^{46}Ar

- Reported for the first time in 1974 from an ^{48}Ca(^{6}Li,^{8}B) experiment
- 1996: $B(E2)_{up}$=196(39) e^2fm^4 (NSCL Coulex)
- 2003: $B(E2)_{up}$=218(31) e^2fm^4 (NSCL Coulex)
- Unpublished: Lineshape lifetime measurement (Stuchbery) – agrees with Coulex B(E2)
- Shell model: factor of 2.5 higher than the above
- DFT (DD-PCI): $B(E2)_{up}$= 200 e^2fm^4
- 2010: $B(E2)_{up}$=570^{+335}_{-160} e^2fm^4 (INFN lifetime)
- Shell model claims victory … or agreement
- 2012: ^{47}Ar (2^+ x $p_{3/2}$) multiplet B(E2) consistent with low B(E2): $\Sigma_J B(E2; 3/2^- \rightarrow J) = B(E2\uparrow)_{^{46}\mathrm{Ar}}$
- 2014: $B(E2)_{up}$=271^{+22}_{-26} e^2fm^4 (GANIL Coulex)

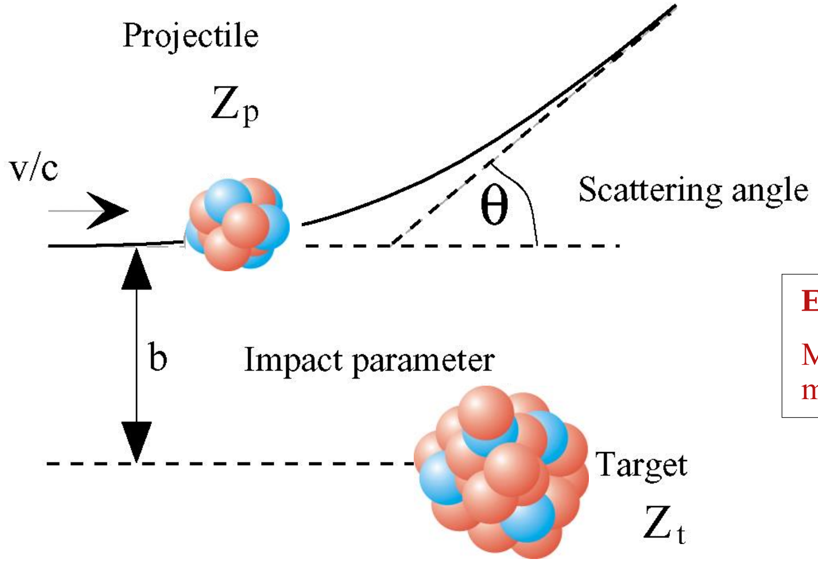


H. Scheit et al., PRL 77, 3967 (1996)
A. Gade *et al.*, PRC 68, 014302 (2003)
Z. P. Li et al., PRC 84, 054304 (2011)
D. Mengoni et al., PRC 82, 024308 (2010)
R. Winkler et al., PRL 108, 182501 (2012)
S. Calinescu et al., Acta Phys. Pol. B 454, 199 (2014)

Intermediate-energy Coulomb excitation

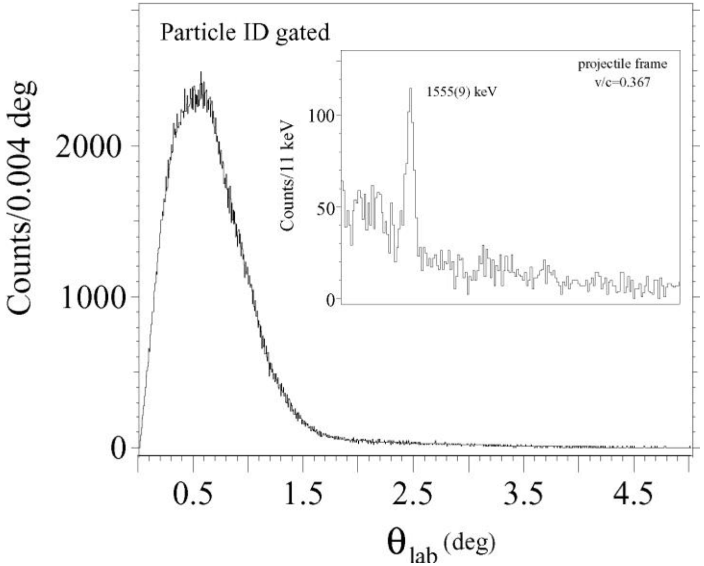
Example: ^{46}Ar + ^{197}Au

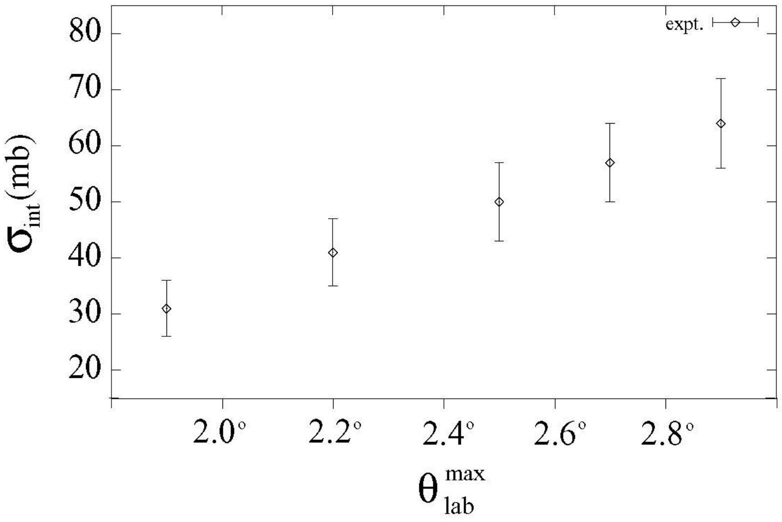
A. Gade *et al.*, Phys. Rev. C 68, 014302 (2003)

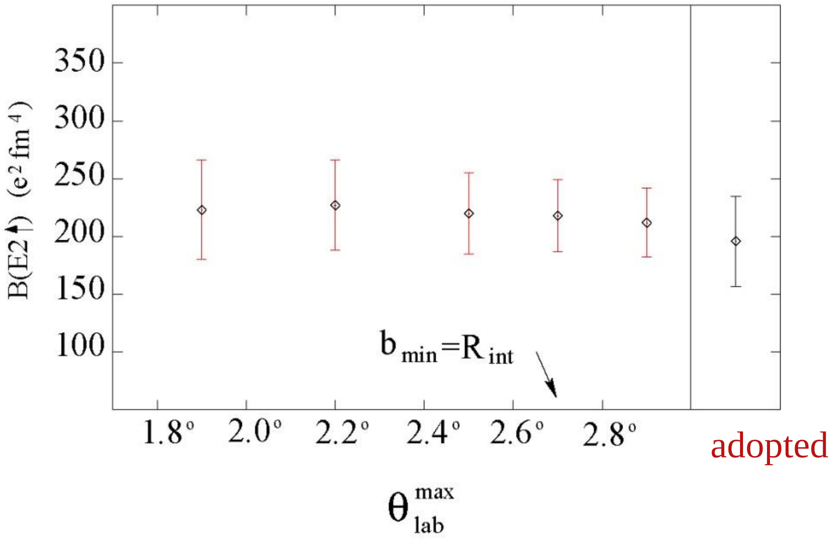


Experiment:

Max. θ determines min. b

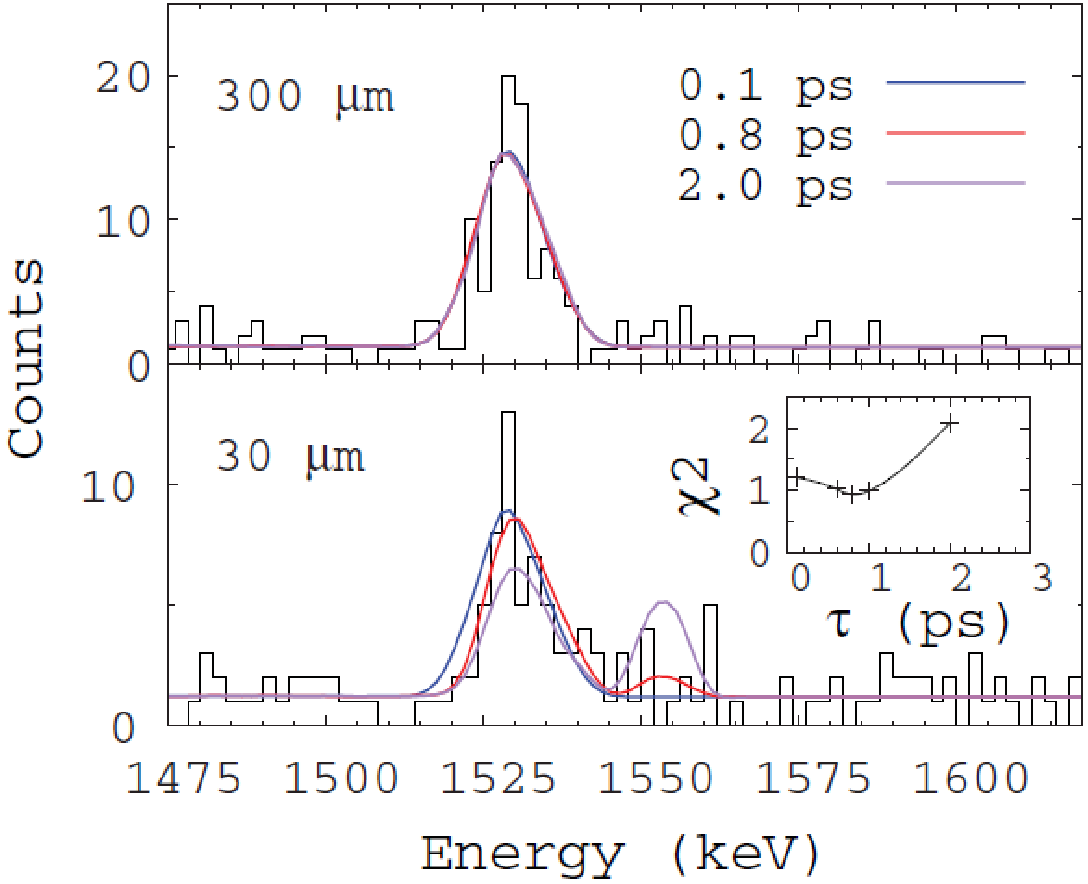






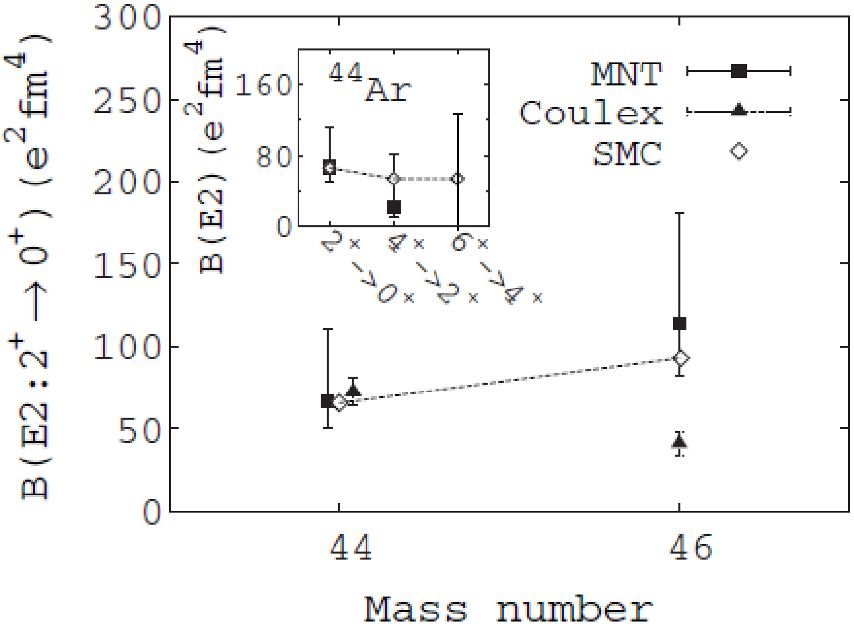
The ^{46}Ar lifetime measurement

D. Mengoni et al., PRC 82, 024308 (2010)



- Plunger measurement, uses intensity ratios of peaks stemming from emission before or after a degrader

- Marginal statistics
- Shell model (SDPF-U with e_p/e_n=1.5/0.5) agrees

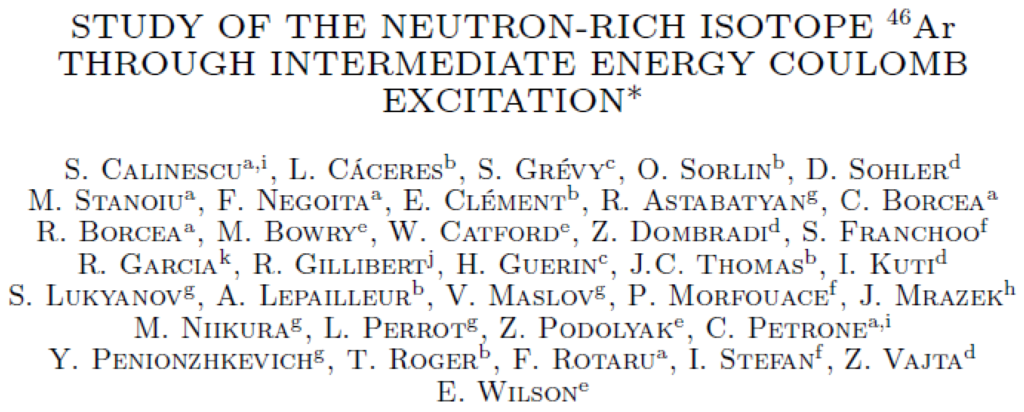


Life is good?

Not so fast … Coulomb excitation at GANIL

S. Calinescu et al., Acta Phys. Pol B45, 199 (2014)

- Intermediate-energy Coulomb excitation of ^{46}Ar measured relative to ^{44}Ca
- And again consistent with a lower $B(E2)_{up}=271^{+22}_{-26}$ e^2fm^4
- Three (3) Coulomb excitation measurements are consistent with each other and lower than the lifetime measurement



STUDY OF THE NEUTRON-RICH ISOTOPE ^{46}Ar THROUGH INTERMEDIATE ENERGY COULOMB EXCITATION*

S. Calinescu[a,i], L. Cáceres[b], S. Grévy[c], O. Sorlin[b], D. Sohler[d]
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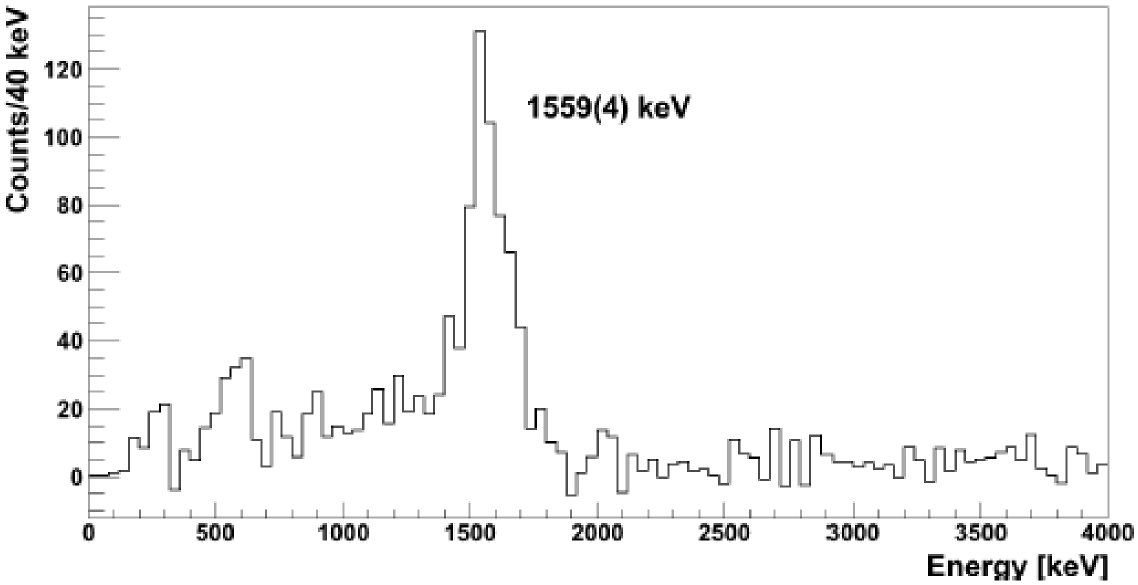
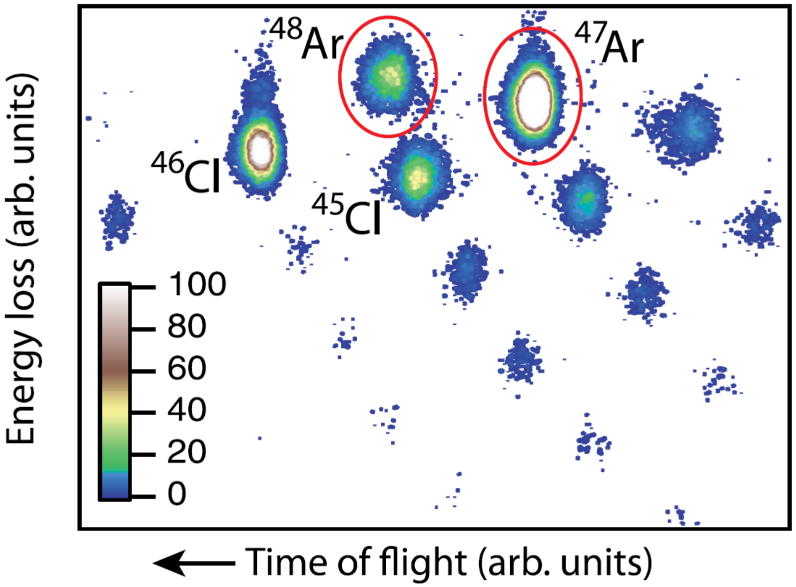
R. Borcea[a], M. Bowry[e], W. Catford[e], Z. Dombradi[d], S. Franchoo[f]
R. Garcia[k], R. Gillibert[j], H. Guerin[c], J.C. Thomas[b], I. Kuti[d]
S. Lukyanov[g], A. Lepailleur[b], V. Maslov[g], P. Morfouace[f], J. Mrazek[h]
M. Niikura[g], L. Perrot[g], Z. Podolyak[e], C. Petrone[a,i]
Y. Penionzhkevich[g], T. Roger[b], F. Rotaru[a], I. Stefan[f], Z. Vajta[d]
E. Wilson[e]

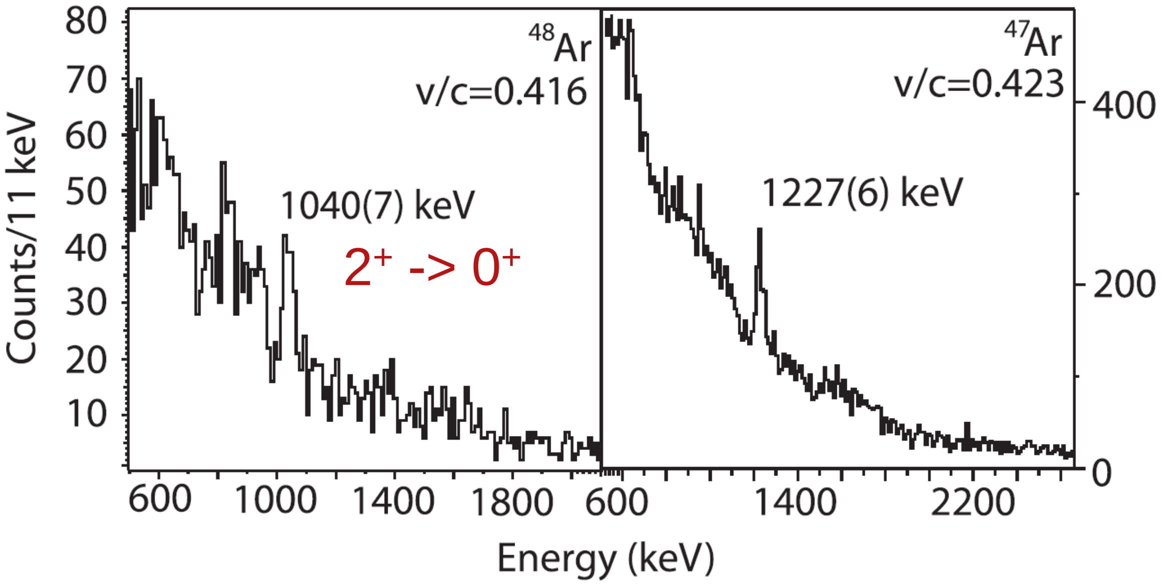


Coulomb excitation of neutron-rich ^{47,48}Ar

R. Winkler *et al.*, PRL 108, 182501 (2012)

- B(E2) values at ^{46}Ar are controversial
- SM does not reproduce the lower of the two values
- Beyond *N=28*, only excitation energies are known
- Goal: Assess collectivity in ^{47,48}Ar



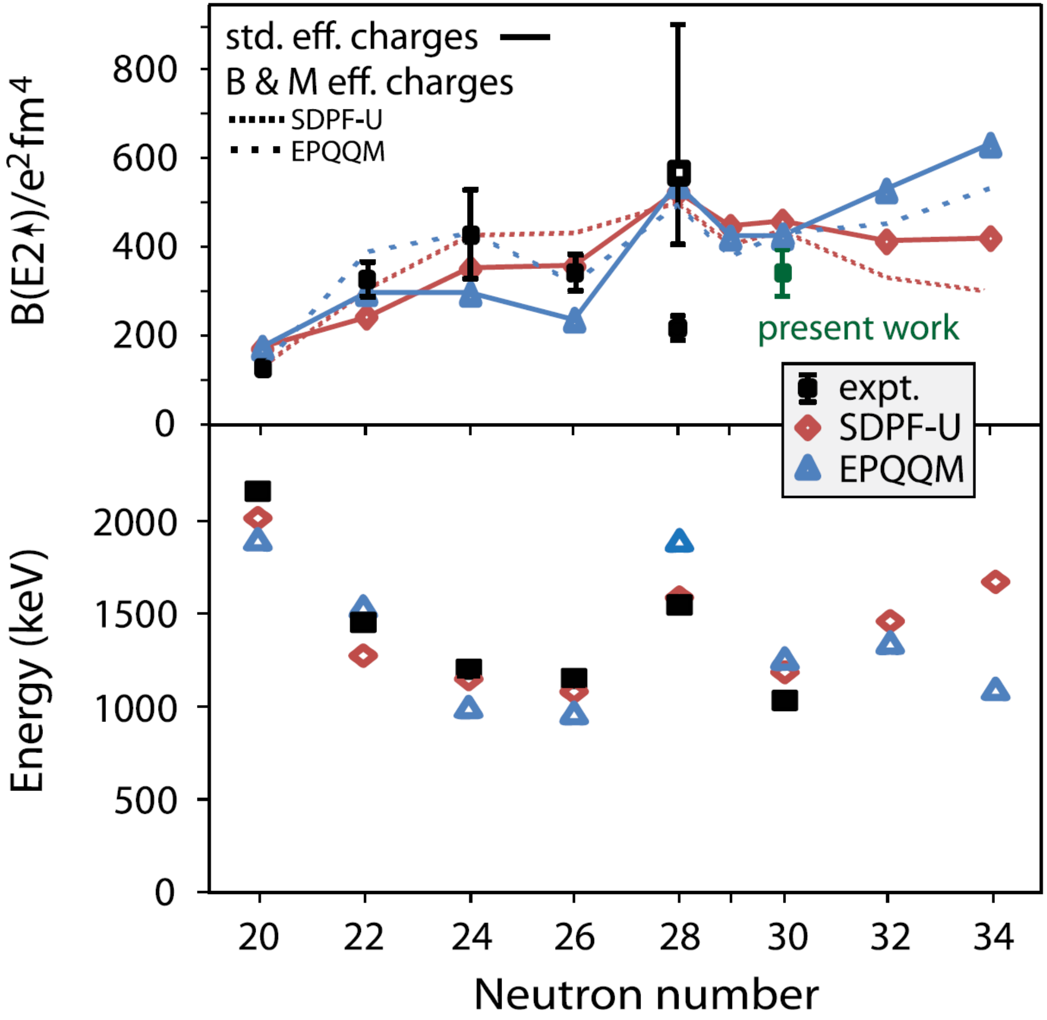


- Intermediate-energy Coulex
- PID with the S800 spectrograph
- Gamma-ray spectroscopy with SeGA
- Collectivity in Ar isotopes beyond *N=28*

Quadrupole collectivity in Ar isotopes

R. Winkler *et al.*, PRL 108, 182501 (2012)

- B(E2) value for ^{48}Ar determined for the first time from Coulex
- Agrees with SM within 2σ
- Both effective interactions fail to describe the low B(E2) at ^{46}Ar (if it turns out to be correct)
- N/Z-dependent effective charges are not a venue to lower the SM B(E2) at *N=28*
- ^{47}Ar ΣB(E2;3/2$^-$ -> J) is low, as one may expect if ^{46}Ar has little collectivity

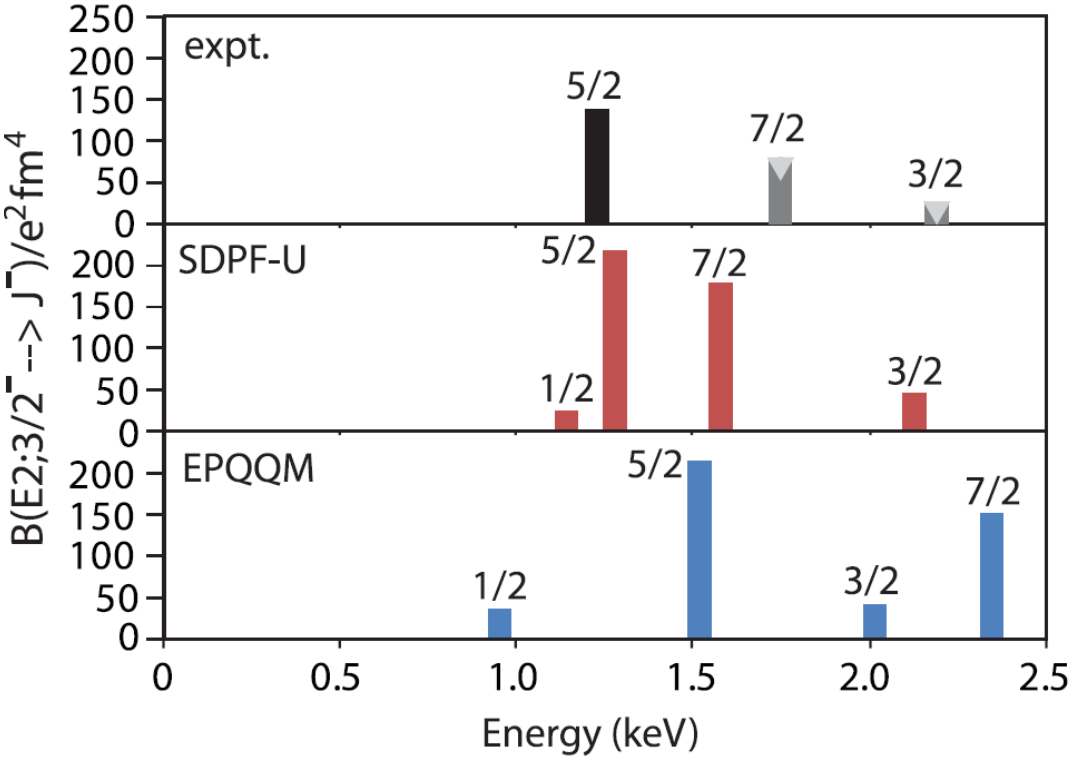


SDPF-U: Nowacki and Poves, PRC 79, 014310 (2009)
EPQQM: K. Kaneko et al., PRC 83, 014320 (2011)

Spectroscopy of neutron-rich Ar nuclei

R. Winkler *et al.*, PRL 108, 182501 (2012)

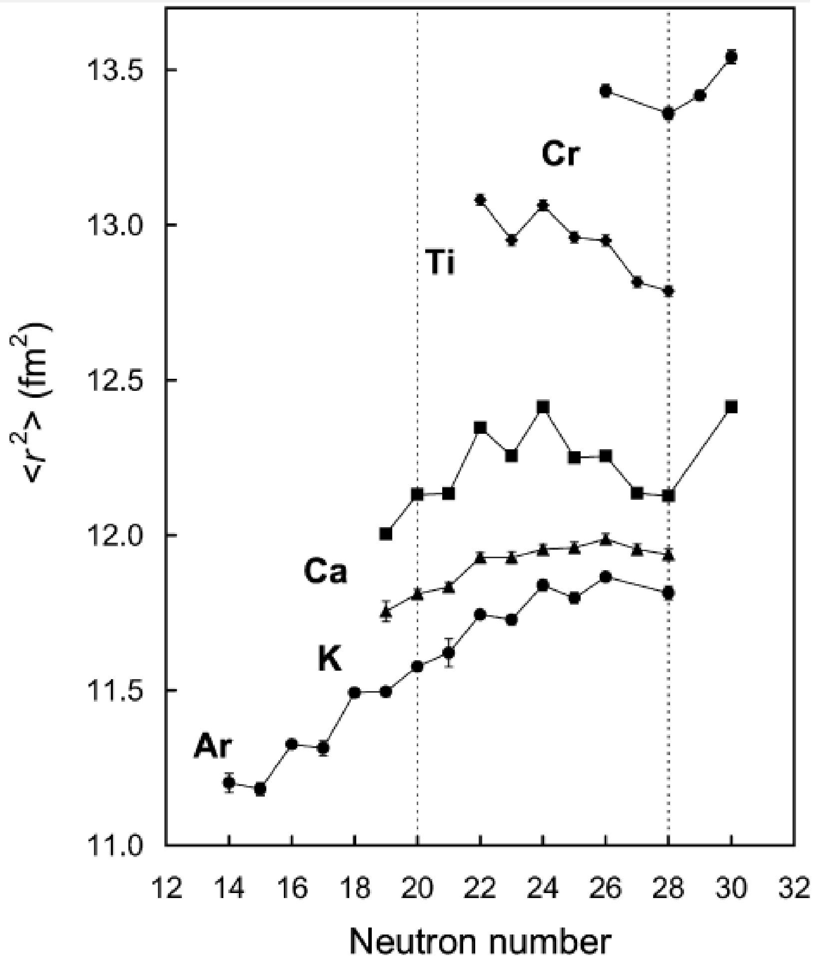
- In the experiment, only the $5/2^-$ -> $3/2^-$ decay is observed
- The B(E2) values for the $7/2^-$ and $3/2^-$ states are generous upper limits
- Both shell model effective interactions massively overpredict the low-lying quadrupole collectivity of ^{47}Ar
- While the two effective interactions give a similar description of the even-even nuclei, the odd-*A* nucleus ^{47}Ar emerges as a discriminator

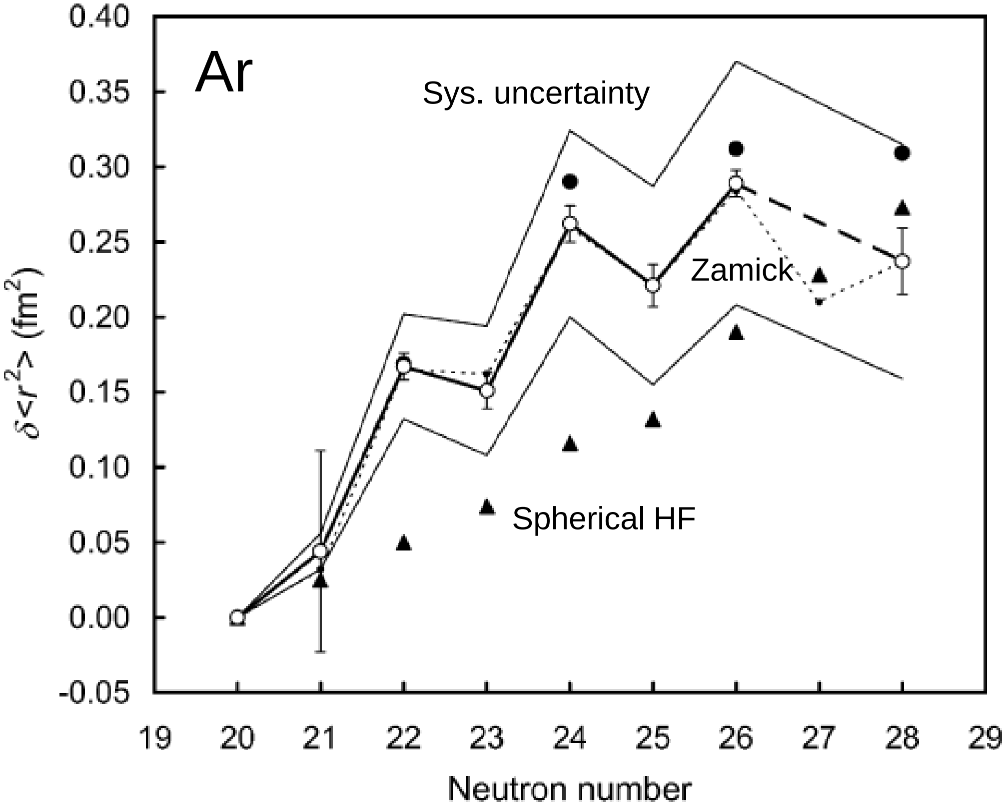


- Shell structure at *N=28,29* may not be understood in Ar

SDPF-U: Nowacki and Poves, PRC 79, 014310 (2009)
EPQQM: K. Kaneko et al., PRC 83, 014320 (2011)

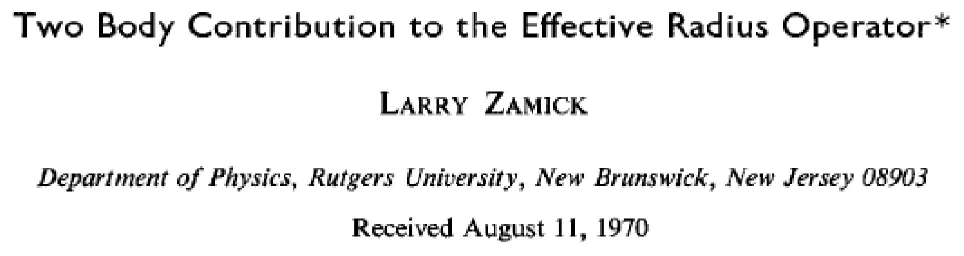
Other observables – charge radii





$$\delta\langle r^2\rangle^{20,20+n} = \langle r^2\rangle^{20+n} - \langle r^2\rangle^{20} = nC + \frac{n(n-1)}{2}\alpha + \left[\frac{n}{2}\right]\beta.$$

A. Klein et al., NPA 607, 1 (1996)
K. Blaum et al., NPA 799, 30 (2008)
L. Zamick, Ann. Phys. 66, 784 (1971)



Two Body Contribution to the Effective Radius Operator*

LARRY ZAMICK

Department of Physics, Rutgers University, New Brunswick, New Jersey 08903

Received August 11, 1970

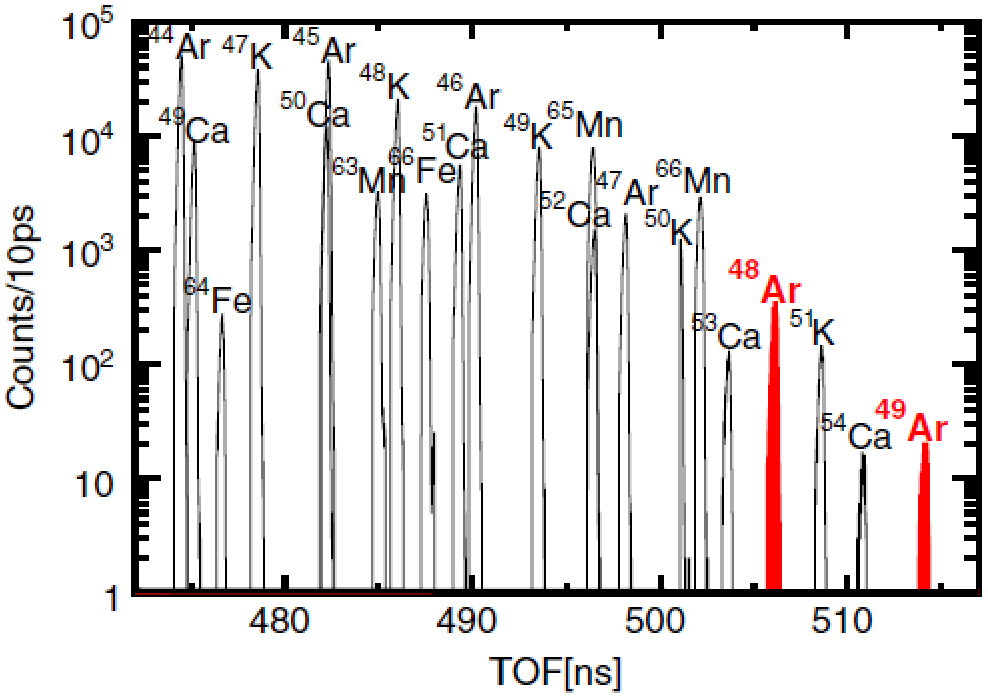
Other observables – mass

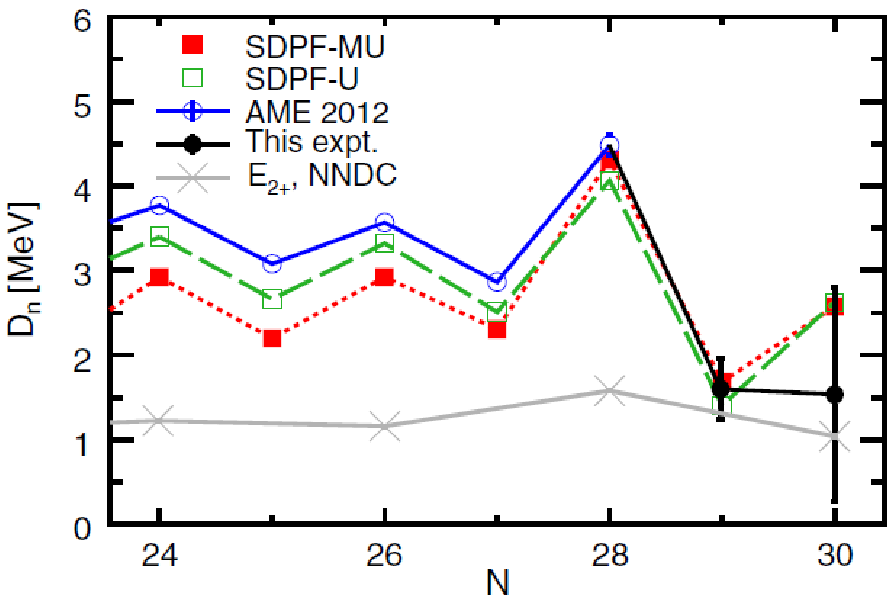
Z. Meisel et al., PRL 114, 022501 (2015)

Masses can be deduced from the simultaneous measurement of an **ion's time-of-flight**, **charge**, and **magnetic rigidity** thorough a **magnetic system of a known flight path**

B. A. Brown, PRL 111, 162502 (2013)

$$
\begin{aligned}
D_n(N) &= (-1)^{N+1}[S_n(Z,N+1) - S_n(Z,N)] \\
&= (-1)^N[2\mathrm{BE}(Z,N) - \mathrm{BE}(Z,N-1) - \mathrm{BE}(Z,N+1)]
\end{aligned}
$$

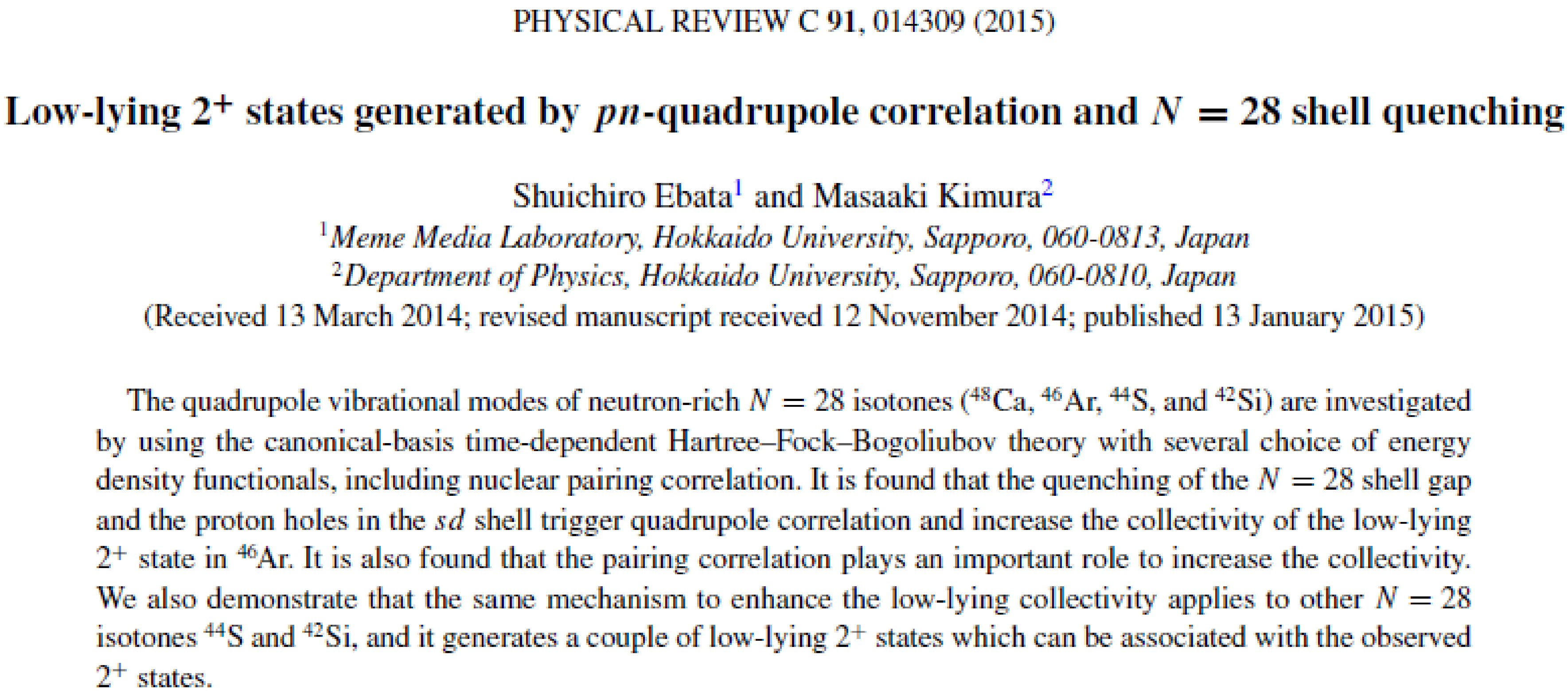




D_n shows a clear signature of a shell closure, in agreement with shell model → *N=28* gap well described by theory

How does ^{46}Ar get collective?

… at least one view of it



PHYSICAL REVIEW C 91, 014309 (2015)

Low-lying 2^+ states generated by pn-quadrupole correlation and $N = 28$ shell quenching

Shuichiro Ebata[1] and Masaaki Kimura[2]
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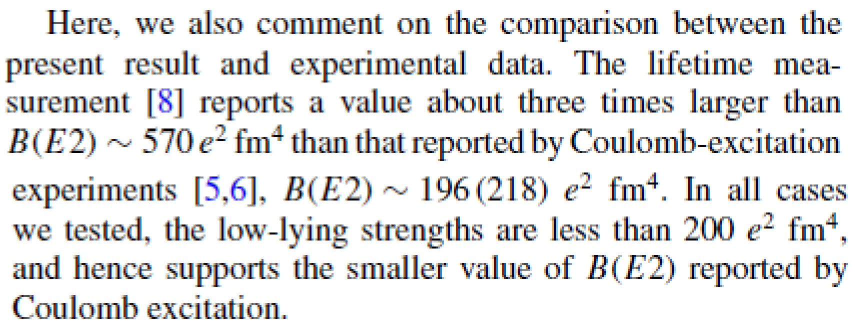
(Received 13 March 2014; revised manuscript received 12 November 2014; published 13 January 2015)

The quadrupole vibrational modes of neutron-rich $N = 28$ isotones (^{48}Ca, ^{46}Ar, ^{44}S, and ^{42}Si) are investigated by using the canonical-basis time-dependent Hartree–Fock–Bogoliubov theory with several choice of energy density functionals, including nuclear pairing correlation. It is found that the quenching of the $N = 28$ shell gap and the proton holes in the *sd* shell trigger quadrupole correlation and increase the collectivity of the low-lying 2^+ state in ^{46}Ar. It is also found that the pairing correlation plays an important role to increase the collectivity. We also demonstrate that the same mechanism to enhance the low-lying collectivity applies to other $N = 28$ isotones ^{44}S and ^{42}Si, and it generates a couple of low-lying 2^+ states which can be associated with the observed 2^+ states.

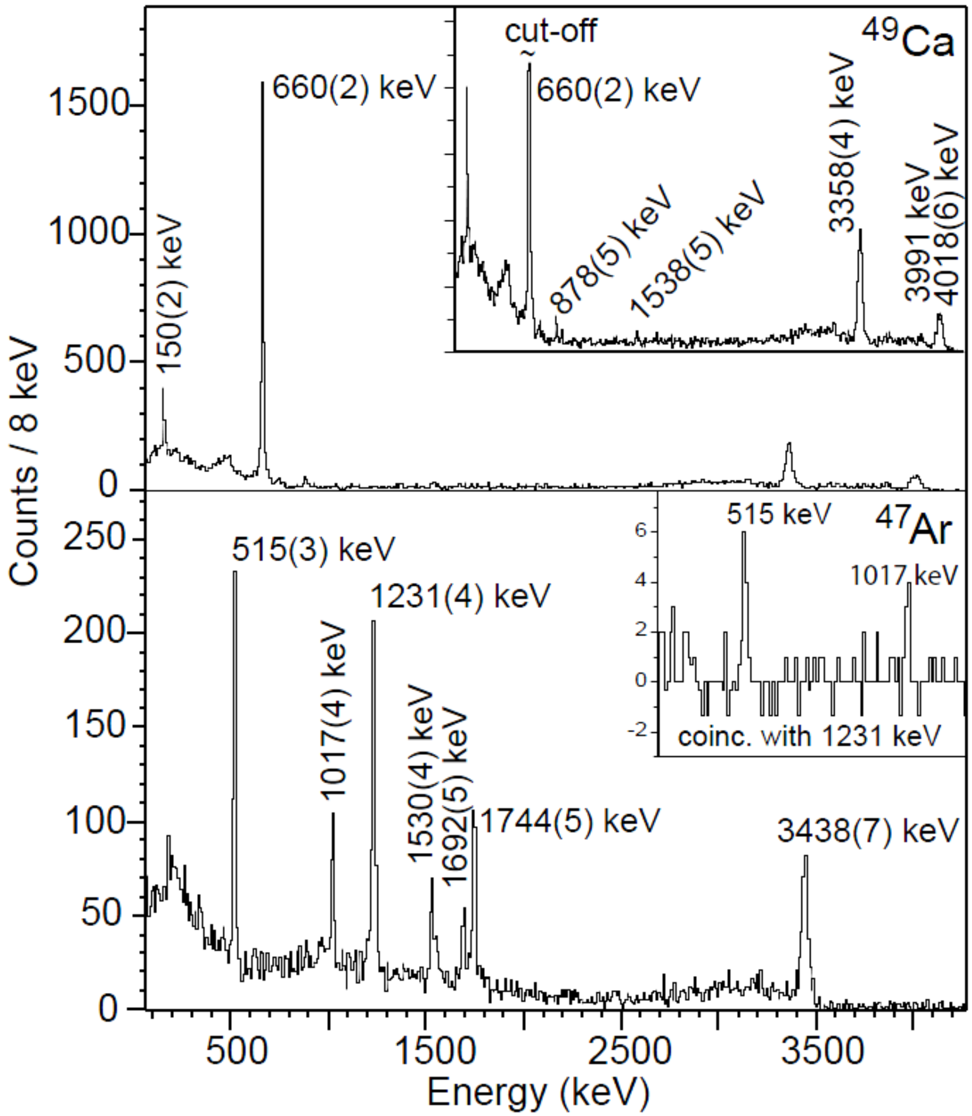
Part of their conclusion:



Here, we also comment on the comparison between the present result and experimental data. The lifetime measurement [8] reports a value about three times larger than $B(E2) \sim 570\, e^2$ fm^4 than that reported by Coulomb-excitation experiments [5,6], $B(E2) \sim 196\,(218)\ e^2$ fm^4. In all cases we tested, the low-lying strengths are less than 200 e^2 fm^4, and hence supports the smaller value of $B(E2)$ reported by Coulomb excitation.

ℓ=3 and ℓ=4 in ^{49}Ca and ^{47}Ar from neutron-adding transfer

- ^{12}C(^{48}Ca,^{49}Ca+γ) and ^{12}C(^{46}Ar,^{47}Ar+γ) at ~60 MeV/u to populate high orbital-angular-momentum neutron single-particle states (momentum matching at high beam energies and picking up a deeply bound neutron!)
- Two-body reaction, finite-range DWBA, distorting interactions for ^{12}C+projectile (entrance) and ^{11}C+pickup residue (exit) channels via double-folding with an effective NN interaction, Gaussian density (r=2.32fm) for C and SkX densities for the projectile-like systems

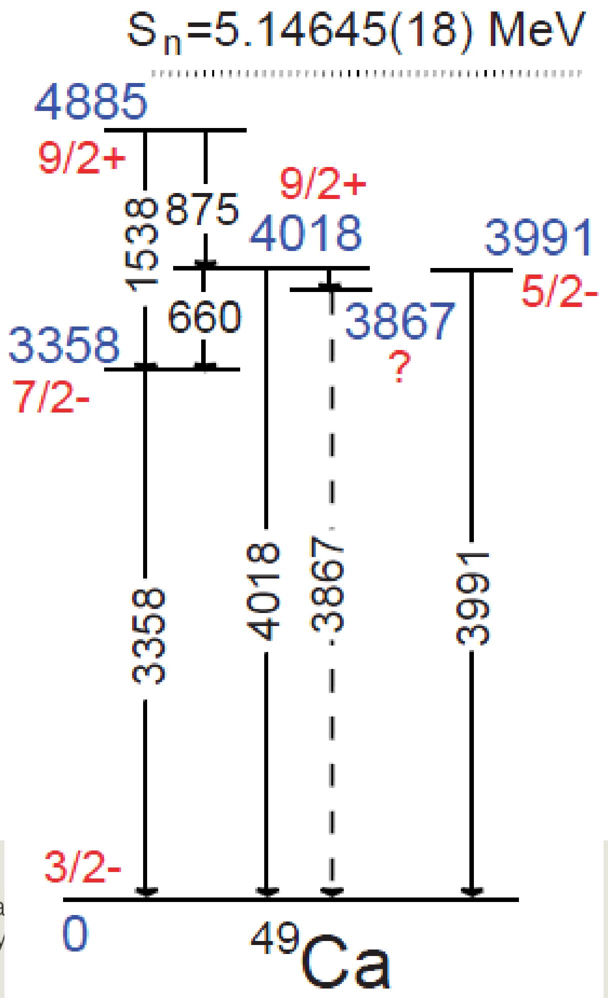


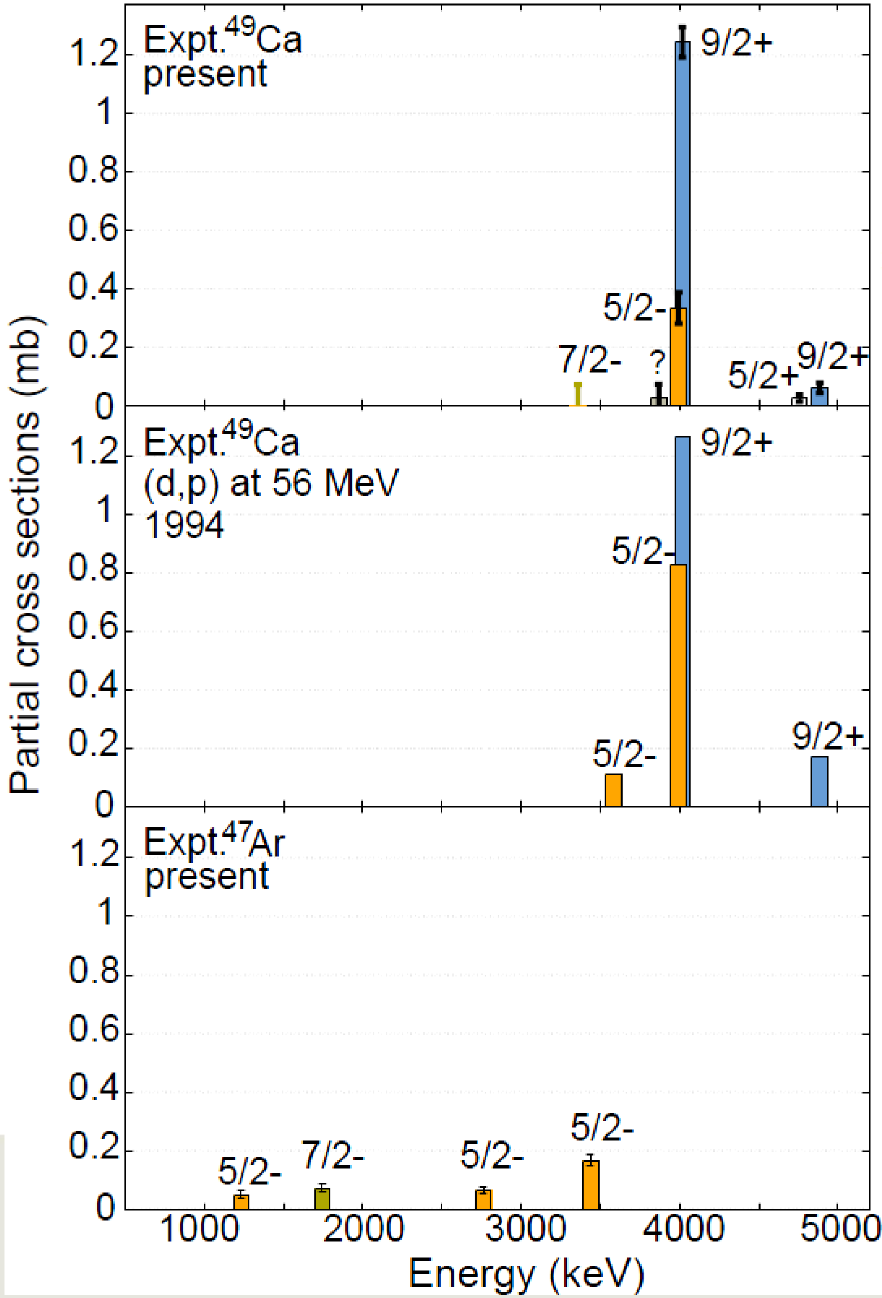
S. McDaniel et al., Phys. Rev. C 85, 014610 (2012)
A. Gade et al., Phys. Rev. C 83, 054324 (2011)
A. Gade et al., Phys. Rev. C 76 , 061302(R) (2007)

ℓ=3 and ℓ=4 in ^{49}Ca

A. Gade, J. A. Tostevin et al., to be published

- Comparison of present measurement (cross sections) with
  theory = single-particle xsec · spec. factor





^{49}Ca from *(d,p)* transfer (1994)

- 3.99 and 4.02 MeV states cannot be resolved
- Normalization of DWBA?

Y. Uozumi *et al.*, NPA 576, 123 (1994)

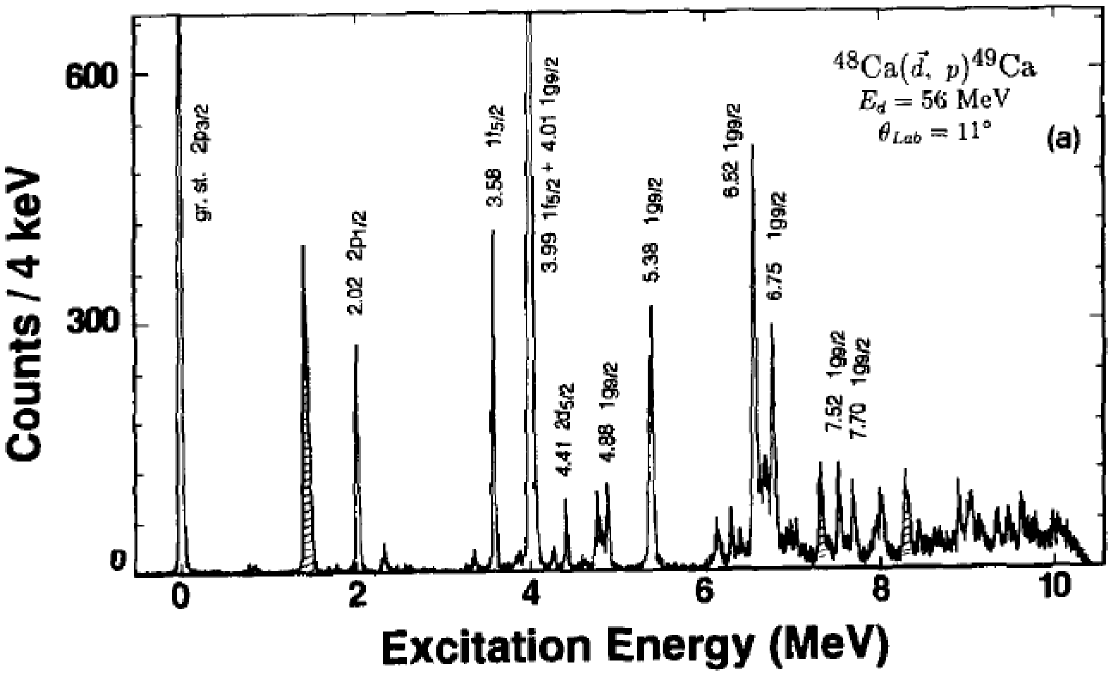


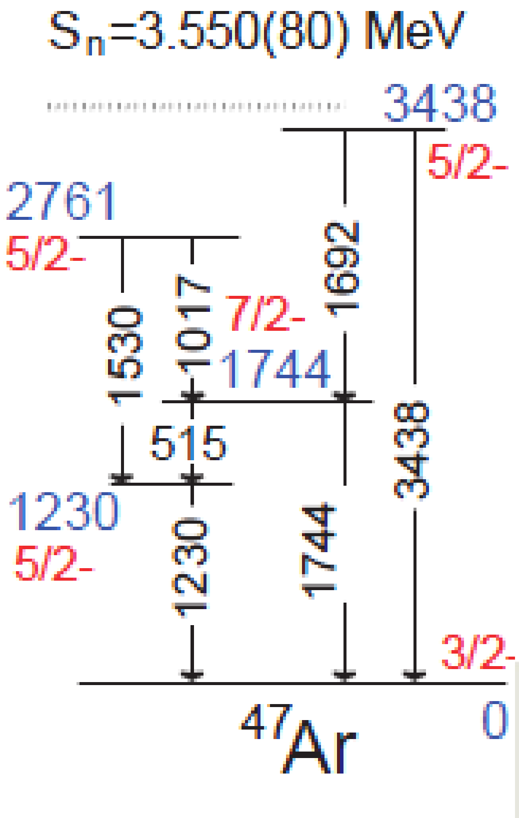
Fig. 1a. Proton spectrum for the ^{48}Ca($\vec{d}$, p)^{49}Ca reaction by using 56 MeV deuterons with spin-up orientation taken at θ_{Lab} = 11°. The number of protons in every 4 keV energy bin is plotted versus the excitation energy of ^{49}Ca. Typical single-particle states are labeled with the excitation energies and the spin–parities. Impurity peaks are identified by shading.

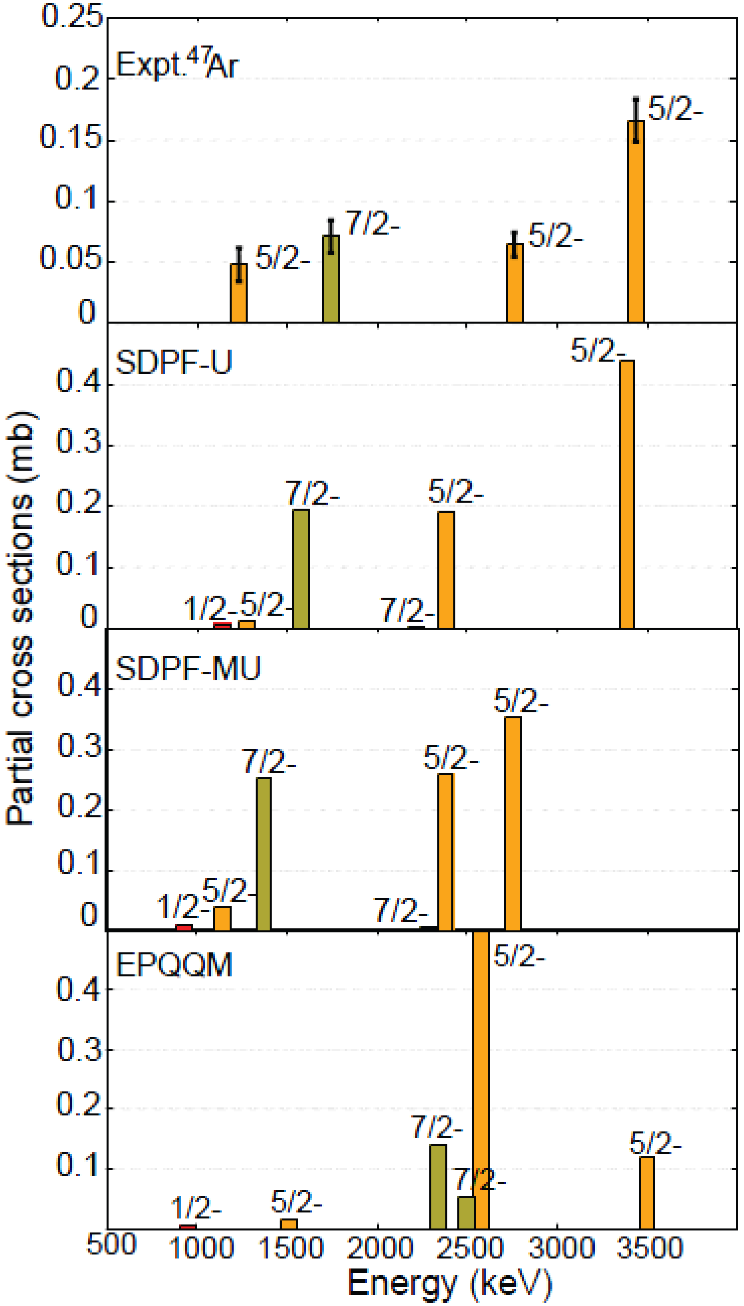
ℓ=3 neutron-rich ^{47}Ar nuclei

A. Gade, J. A. Tostevin et al., to be published

- Measured cross sections compared to calculated cross sections wit shell-model spectroscopic factors

Y. Utsuno et al., PRC 86, 051301(R)
F. Nowacki et al., PRC 79, 014310 (2009)
K. Kaneko et al., PRC 83, 014320 (2011)

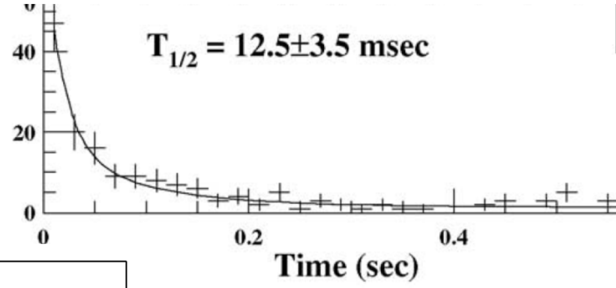


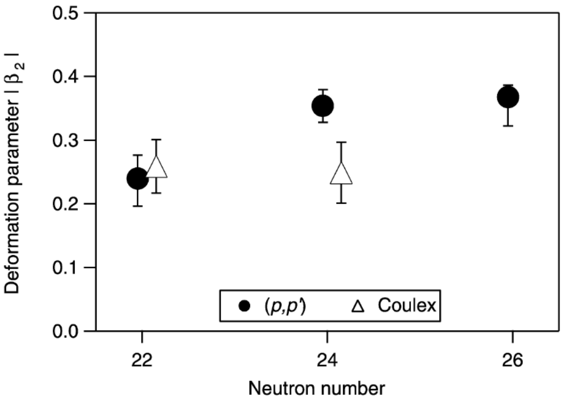


Si history
… sorry, experiment only

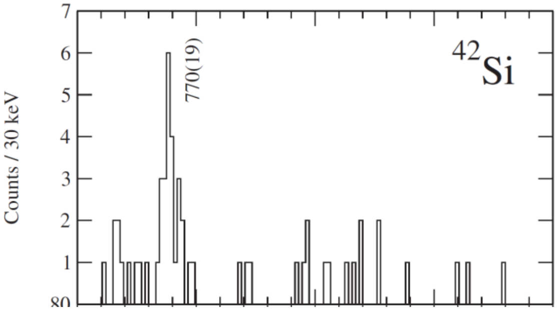
- M. Lewitowicz et al., Z.Phys. A335, 117 (1990) – Discovery of ^{42}Si
- R.W. Ibbotson et al., Phys. Rev. Lett. 80, 2081 (1998) – B(E2) values in $^{32-38}$Si
- S. Grevy et al., Phys.Lett. B 594, 252 (2004) – Beta-decay half-life
- J. Fridmann et al., Nature 435, 922 (2005) and Phys. Rev. C 74, 034313 (2006) – Small ^{44}S-2p knockout cross section
- C.M. Campbell et al., Phys. Rev. Lett. 97, 112501 (2006) – Excited states in ^{40}Si
- B. Jurado et al,. Phys. Lett. B 649, 43 (2007) – TOF mass measurement
- C.M. Campbell et al., Phys. Lett. B 652, 169 (2007) – deformation parameters for $^{36-40}$Si
- B. Bastin et al., Phys. Rev. Lett. 99, 022503 (2007) – First observation of the 2^+_1 in ^{42}Si
- S. Takeuchi et al., arXiv:1207.6191 (2012) – Level scheme of ^{42}Si

2004

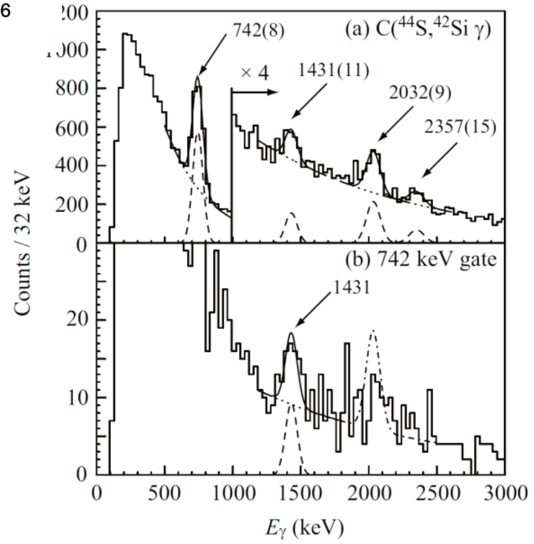




2007

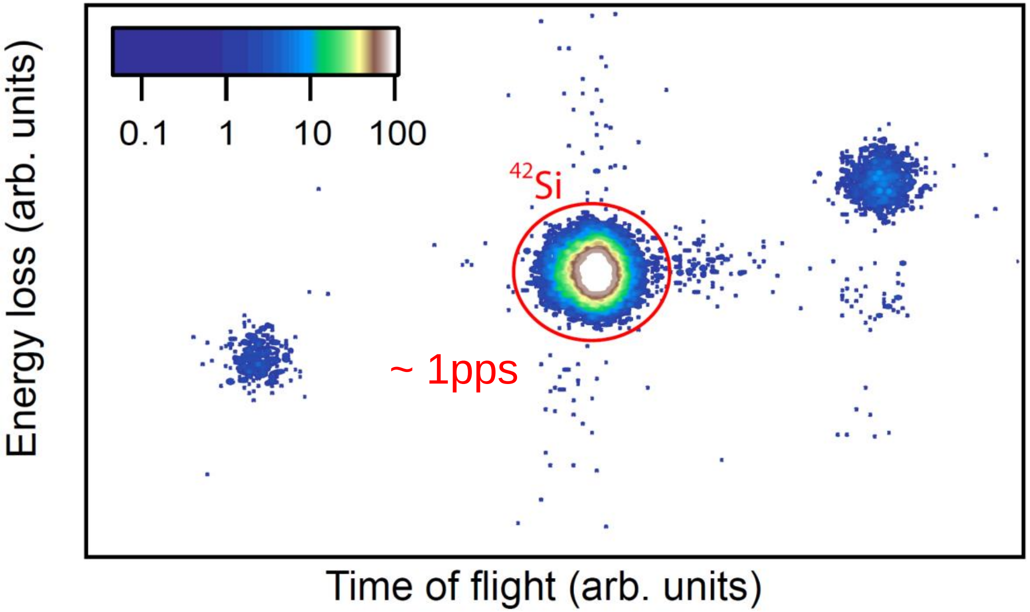


2012

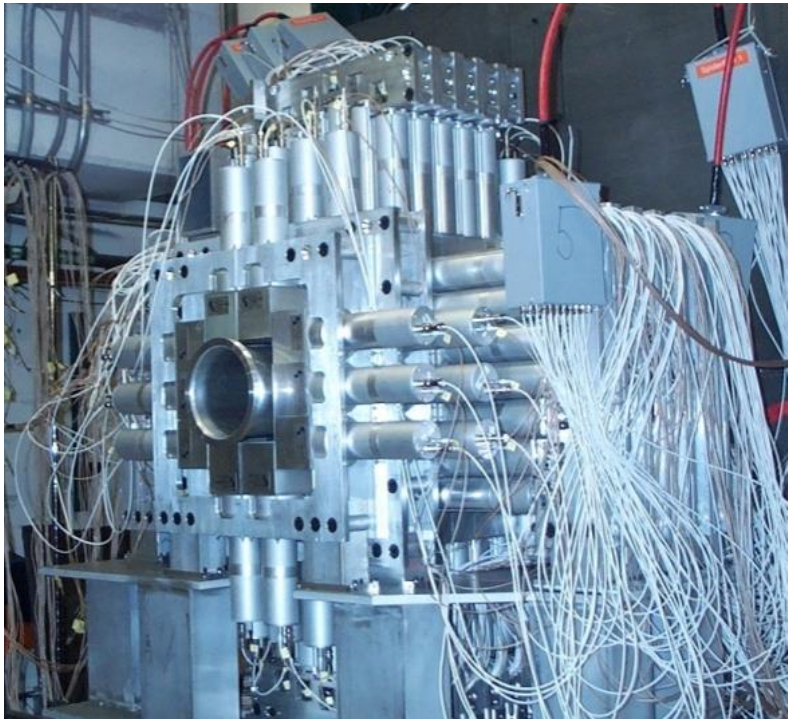


Coulomb excitation of $^{34\text{-}42}$Si

A. Ratkiewicz *et al.*, to be published



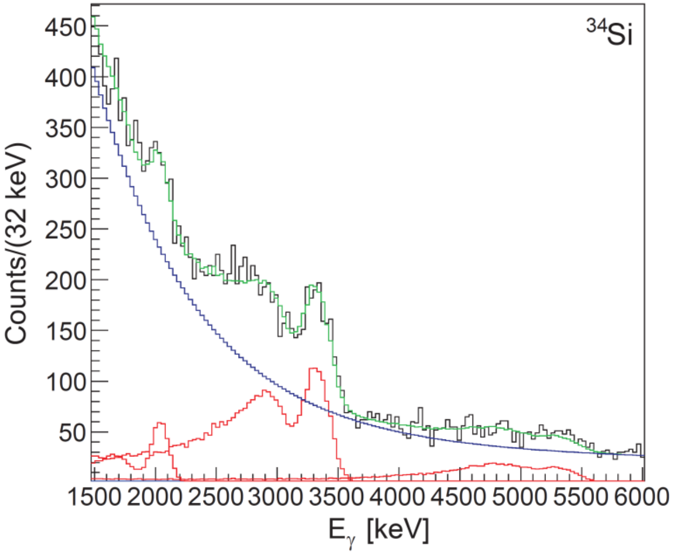
- Intermediate-energy Coulomb excitation of $^{34\text{-}42}$Si on Au and Bi targets (^{42}Si)
- Particle rates between several thousand pps and 1pps in the S800 focal plane
- CAESAR used for in-beam γ-ray spectroscopy in coincidence with particle ID in the S800 spectrograph

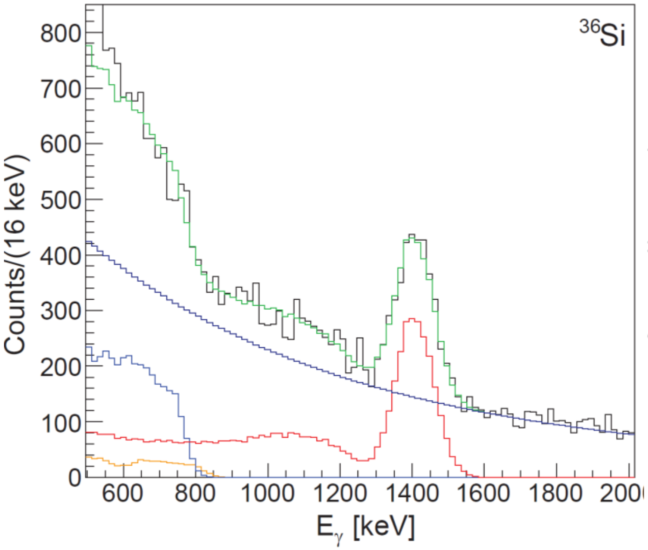


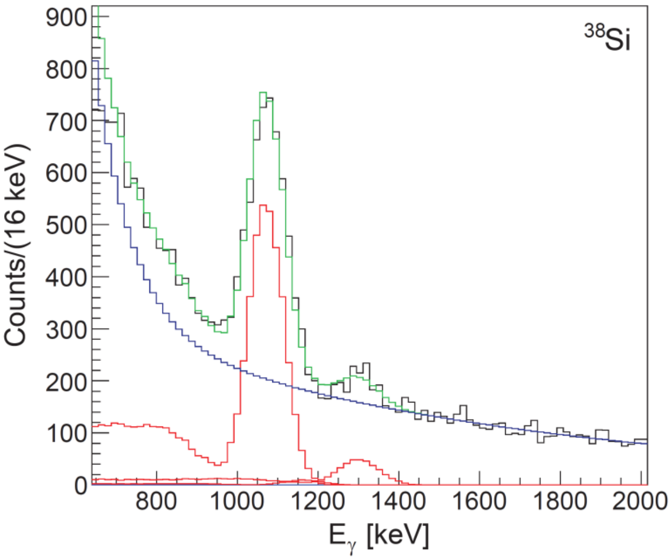
- Use CAESAR instead of SeGA and trade efficiency for resolution

Gamma-ray spectra of $^{34-42}$Si

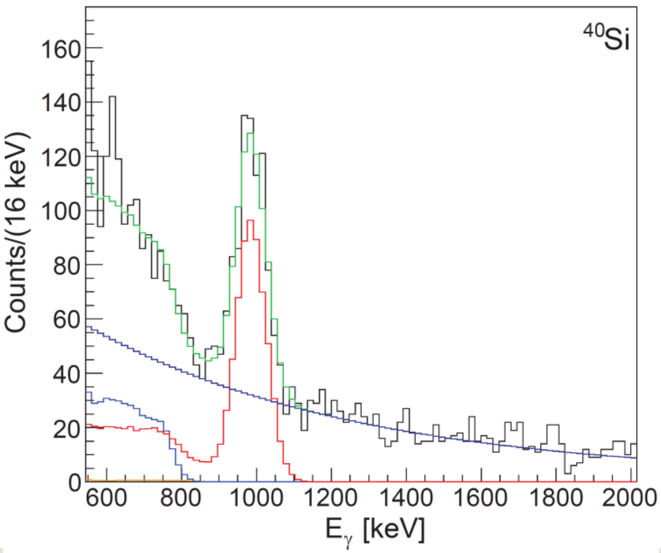
A. Ratkiewicz *et al.*, to be published

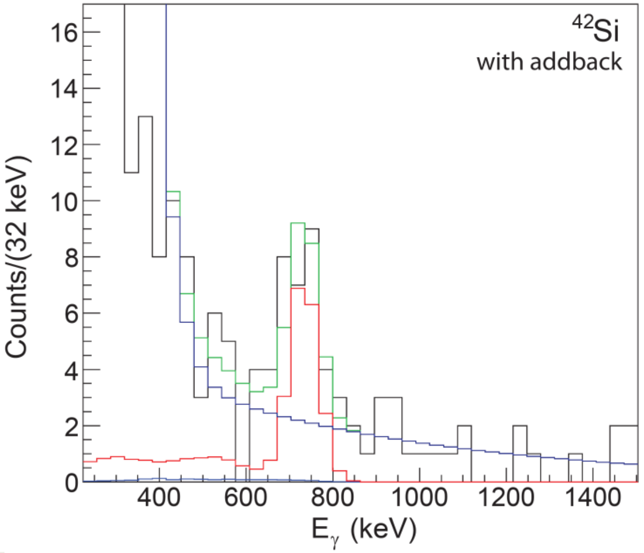






- Number of γ-rays is determined from a fit of GEANT simulations to data
- The 2^+_2 states are observed in ^{34,38}Si

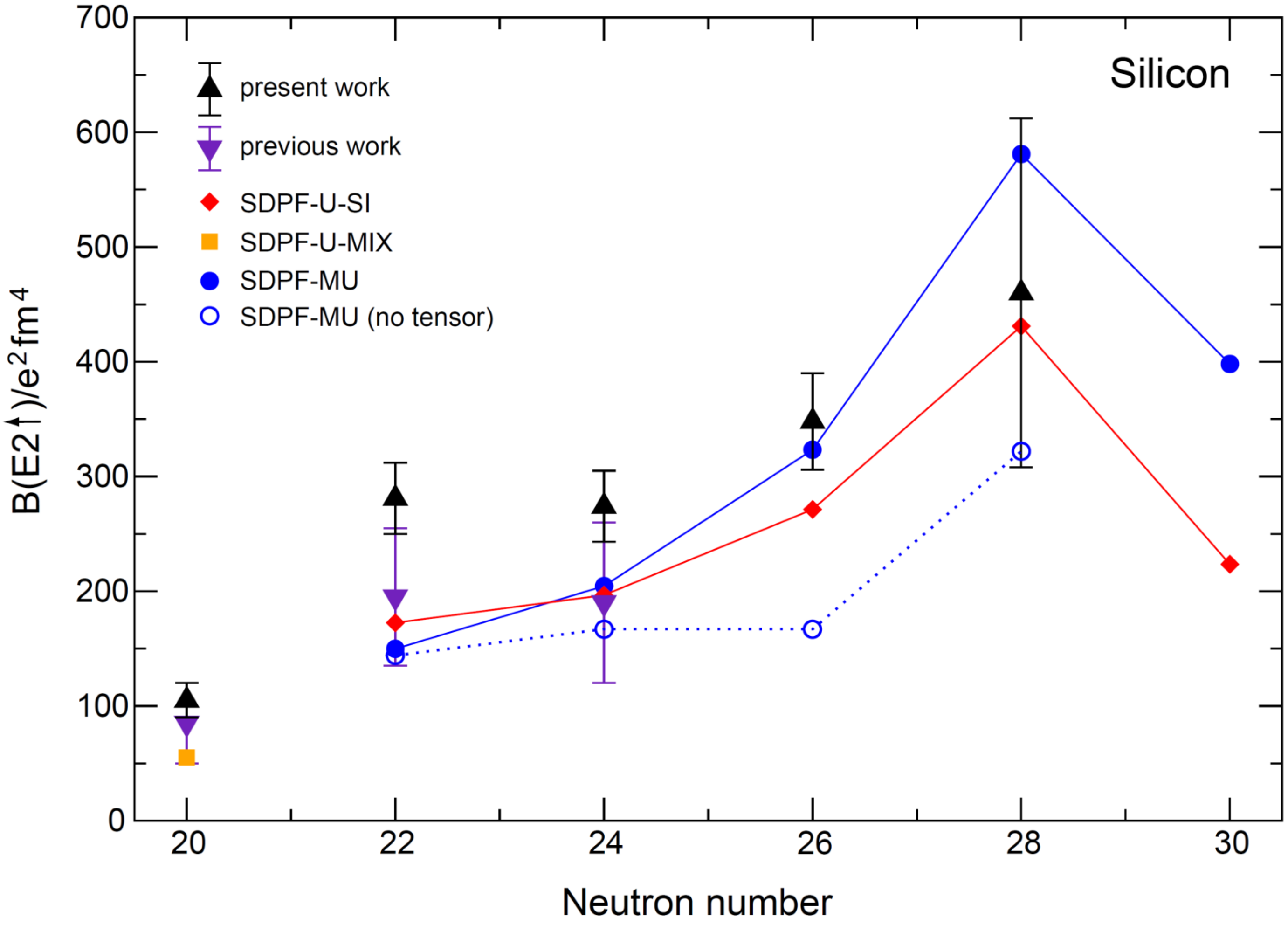




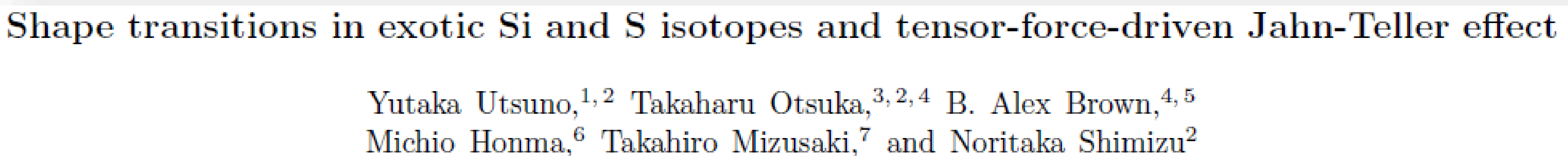
Preliminary B(E2) values for $^{34-42}$Si

A. Ratkiewicz *et al.*, to be published

- The new SDPF-MU effective interaction describes the trend well if the tensor contributions are included
- ^{40}Si is a key discriminator
- Underestimated B(E2) values at *N=22* and 24 is attributed to the absence of *sd* shell proton intruders in the model spaces



SDPF-MU from:

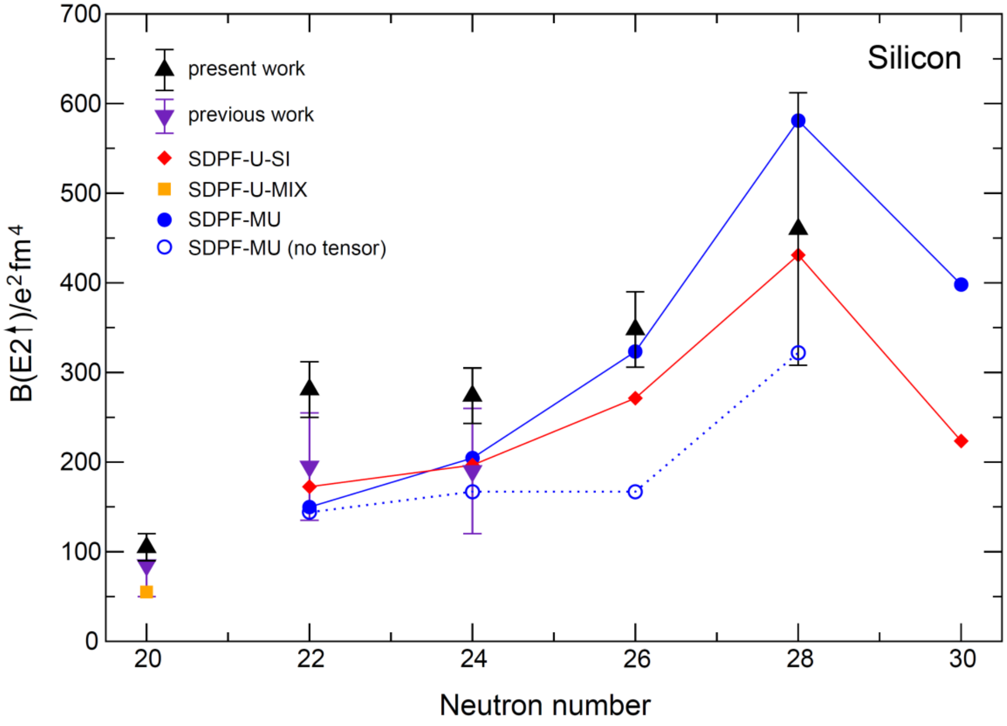


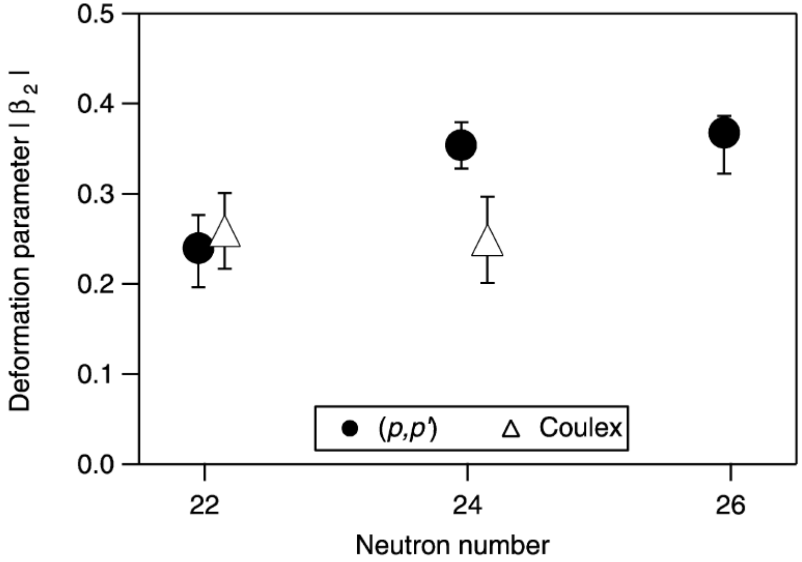
Shape transitions in exotic Si and S isotopes and tensor-force-driven Jahn-Teller effect

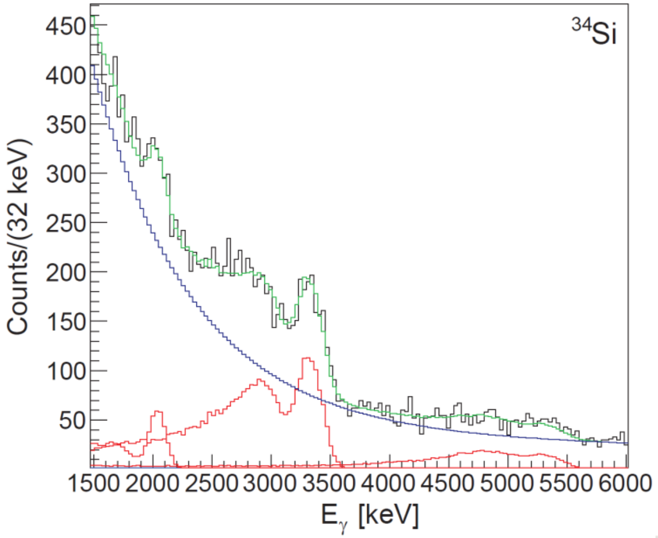
Yutaka Utsuno,[1,2] Takaharu Otsuka,[3,2,4] B. Alex Brown,[4,5]
Michio Honma,[6] Takahiro Mizusaki,[7] and Noritaka Shimizu[2]

Still to come …

A. Ratkiewicz *et al.*, to be published

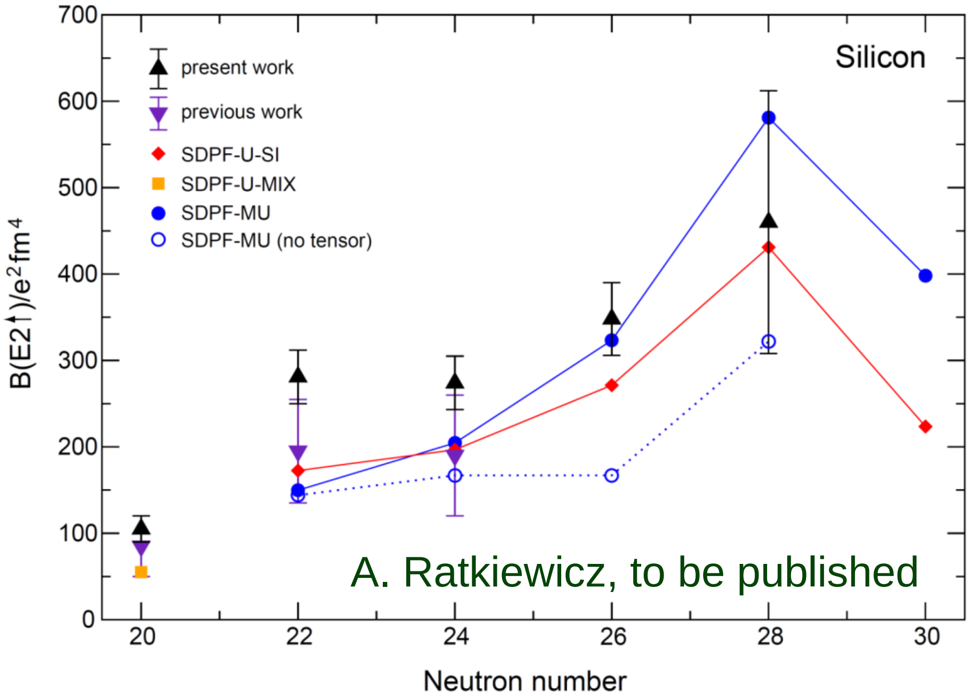




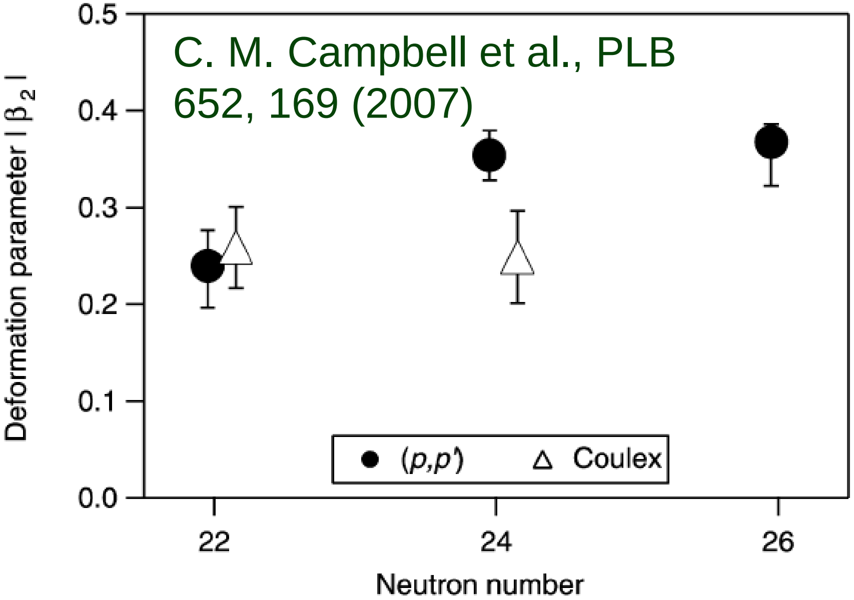


- Evaluate the proton and neutron contributions to collectivity from proton scattering data (out to ^{40}Si)
- Extract and analyze the B(E2) values for the second 2$^+$ states in ^{34}Si and ^{38}Si

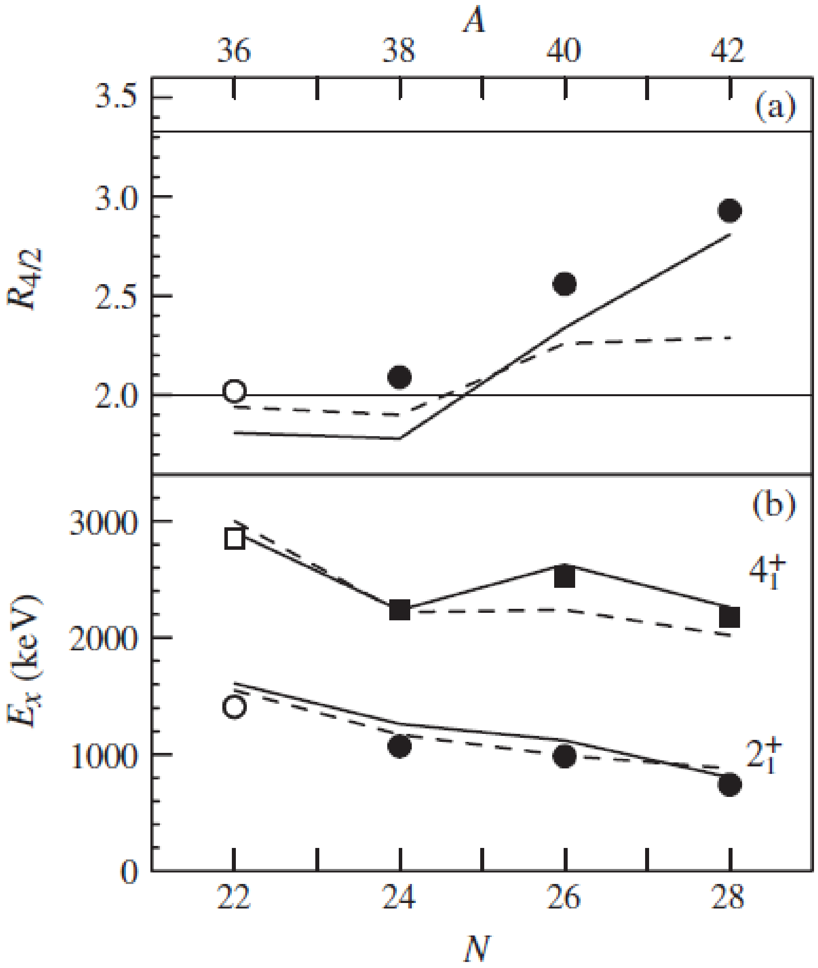
Shell evolution in Si toward *N*=28 largely from collective observables



A. Ratkiewicz, to be published



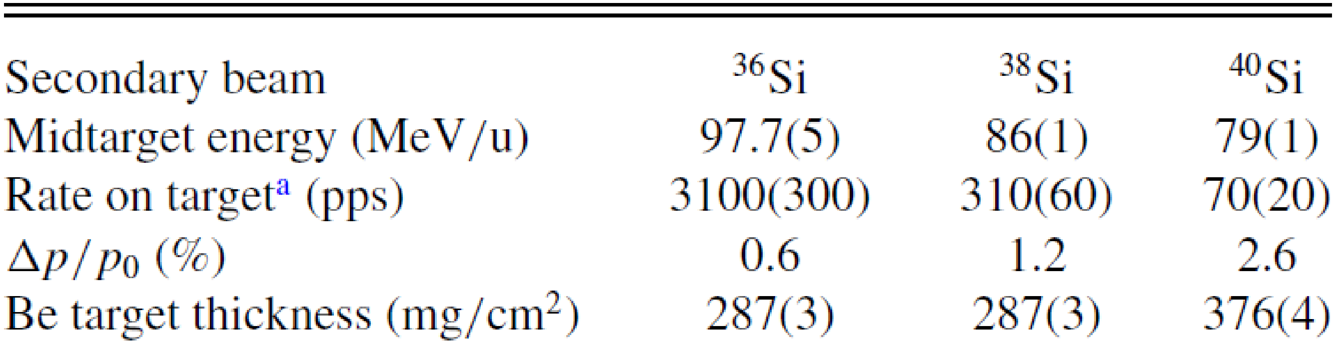
C. M. Campbell et al., PLB 652, 169 (2007)



S. Takeuchi et al.,PRL 109, 182501 (2012)

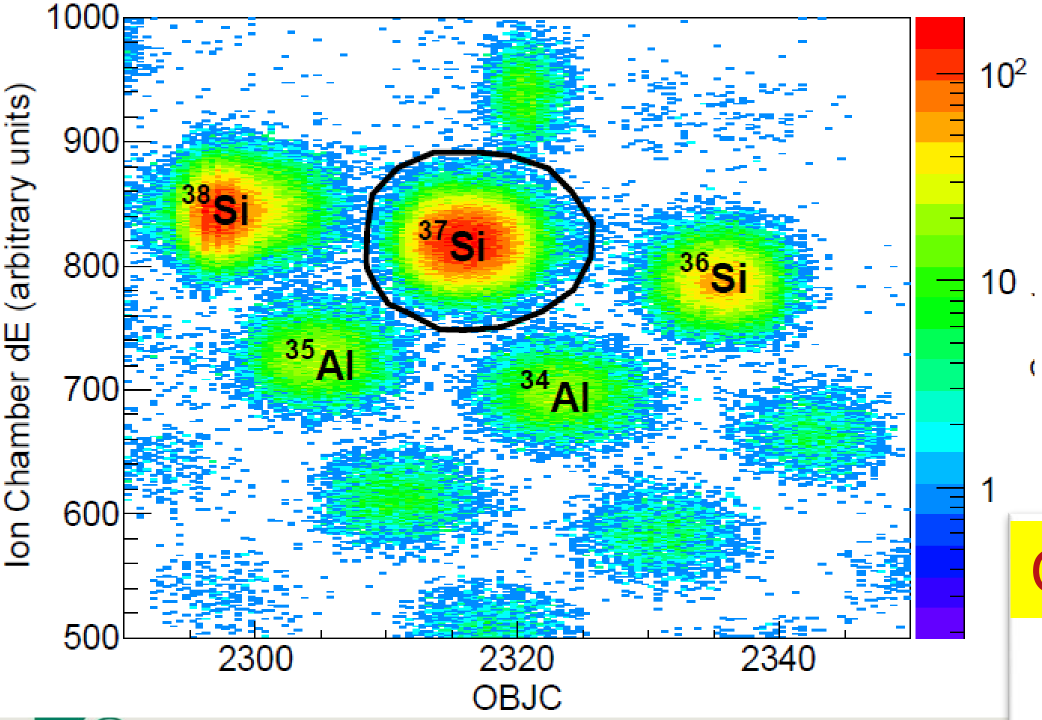
Single-particle degree of freedom: One-nucleon knockout reactions

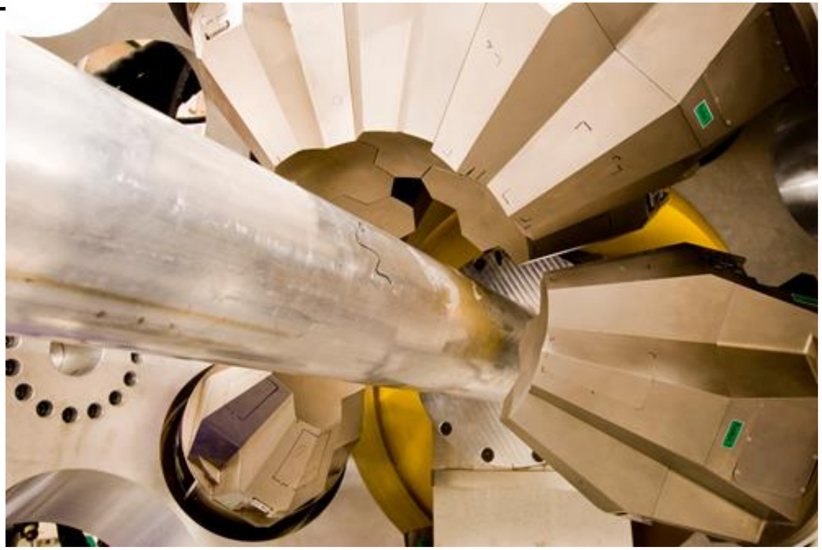
S. R. Stroberg et al., PRC 90, 034301 (2014)

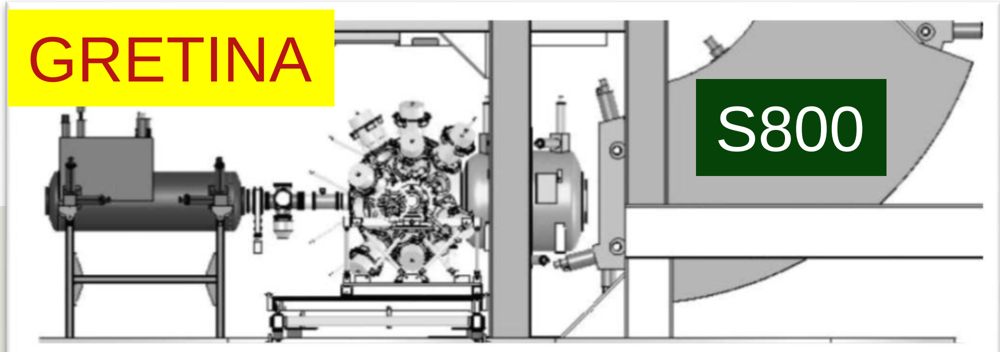


Secondary beam	^{36}Si	^{38}Si	^{40}Si
Midtarget energy (MeV/u)	97.7(5)	86(1)	79(1)
Rate on target[a] (pps)	3100(300)	310(60)	70(20)
$\Delta p/p_0$ (%)	0.6	1.2	2.6
Be target thickness (mg/cm^2)	287(3)	287(3)	376(4)

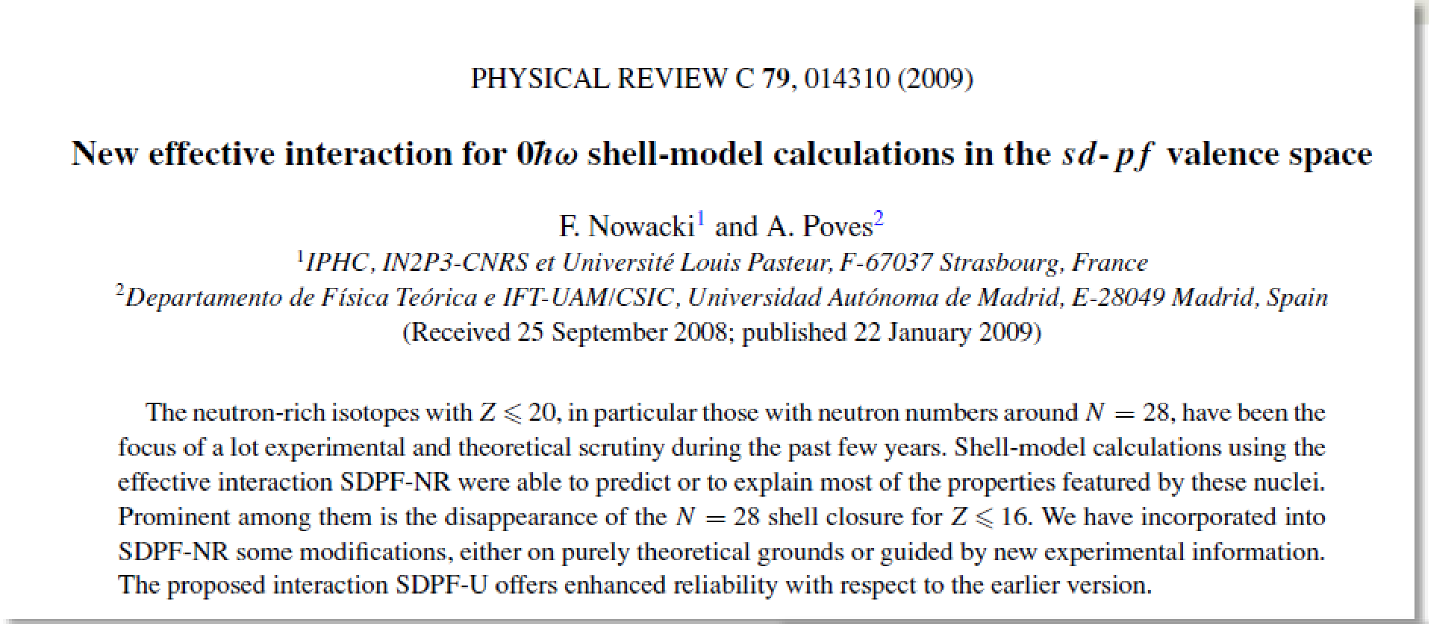
One-neutron and one-proton knockout reactions to ^{35,37,39}Si and ^{35,37,39}Al







Shell-model effective interactions used



PHYSICAL REVIEW C **79**, 014310 (2009)

New effective interaction for $0\hbar\omega$ shell-model calculations in the sd-pf valence space

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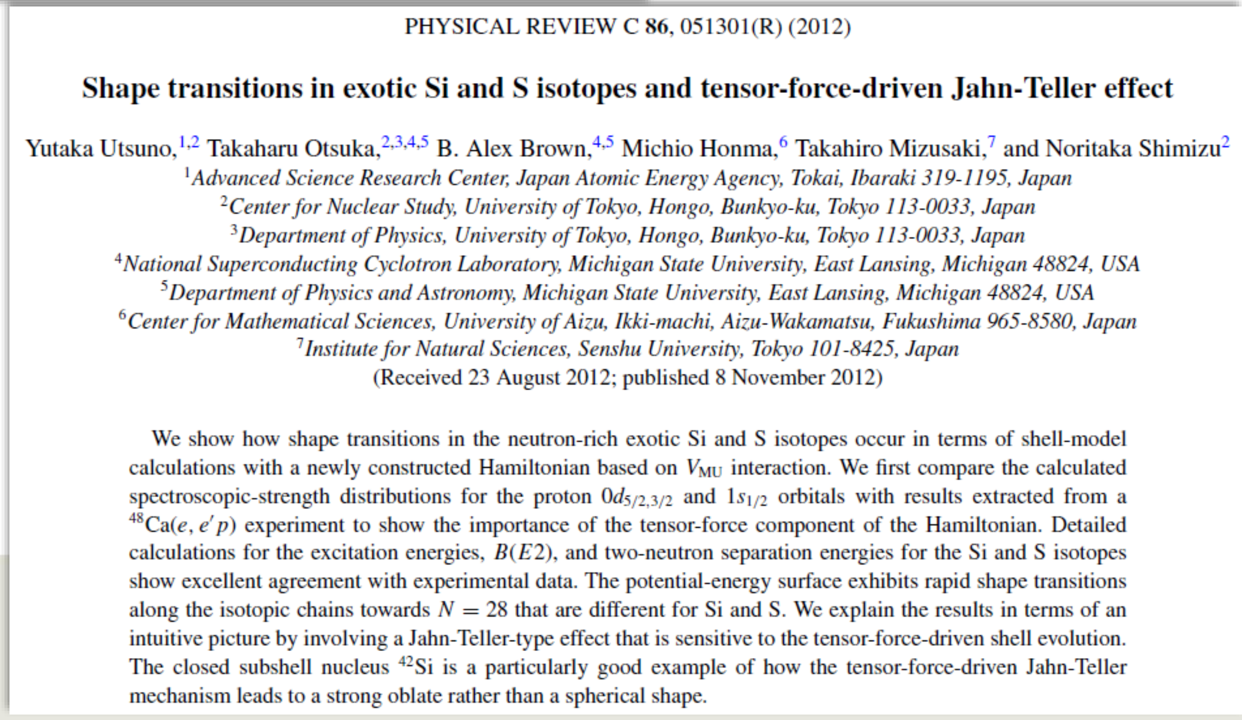
(Received 25 September 2008; published 22 January 2009)

The neutron-rich isotopes with $Z \leqslant 20$, in particular those with neutron numbers around $N = 28$, have been the focus of a lot experimental and theoretical scrutiny during the past few years. Shell-model calculations using the effective interaction SDPF-NR were able to predict or to explain most of the properties featured by these nuclei. Prominent among them is the disappearance of the $N = 28$ shell closure for $Z \leqslant 16$. We have incorporated into SDPF-NR some modifications, either on purely theoretical grounds or guided by new experimental information. The proposed interaction SDPF-U offers enhanced reliability with respect to the earlier version.

SDPF-U

SDPF-MU



PHYSICAL REVIEW C **86**, 051301(R) (2012)

Shape transitions in exotic Si and S isotopes and tensor-force-driven Jahn-Teller effect

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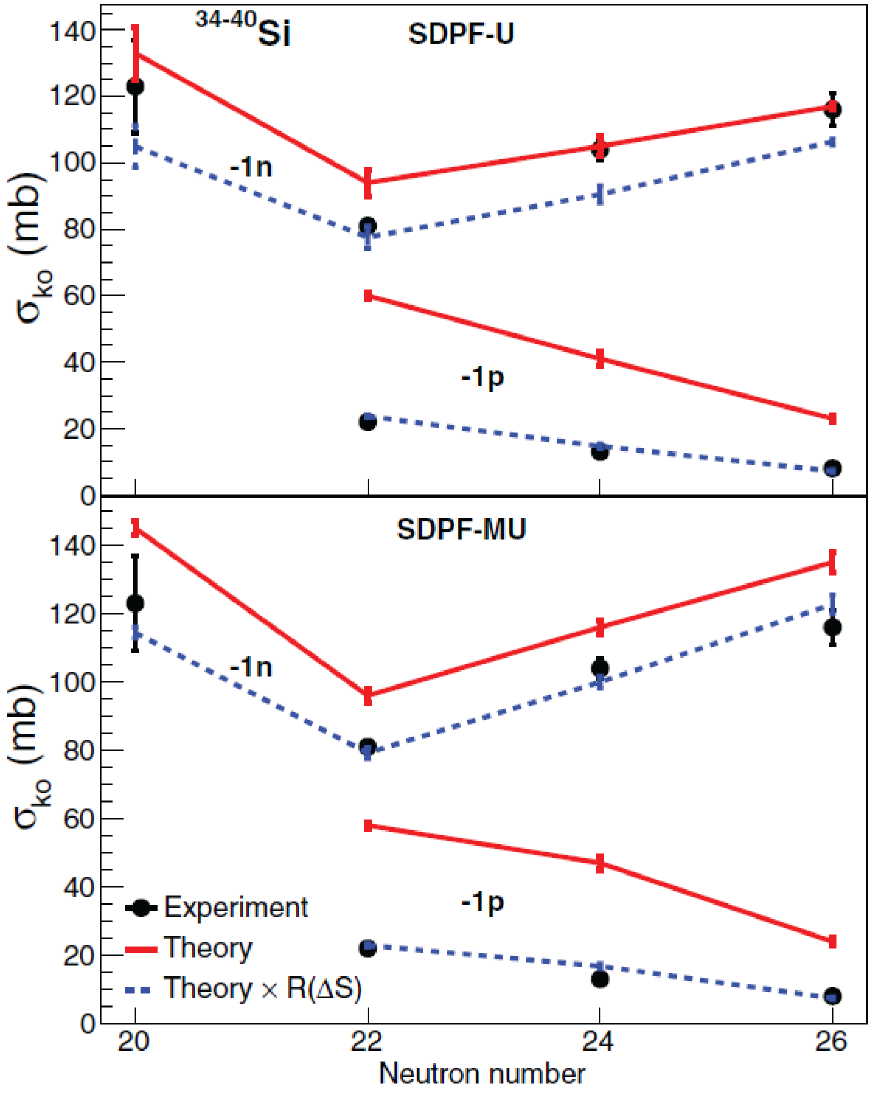
(Received 23 August 2012; published 8 November 2012)

We show how shape transitions in the neutron-rich exotic Si and S isotopes occur in terms of shell-model calculations with a newly constructed Hamiltonian based on V_{MU} interaction. We first compare the calculated spectroscopic-strength distributions for the proton $0d_{5/2,3/2}$ and $1s_{1/2}$ orbitals with results extracted from a ^{48}Ca$(e, e'p)$ experiment to show the importance of the tensor-force component of the Hamiltonian. Detailed calculations for the excitation energies, $B(E2)$, and two-neutron separation energies for the Si and S isotopes show excellent agreement with experimental data. The potential-energy surface exhibits rapid shape transitions along the isotopic chains towards $N = 28$ that are different for Si and S. We explain the results in terms of an intuitive picture by involving a Jahn-Teller-type effect that is sensitive to the tensor-force-driven shell evolution. The closed subshell nucleus ^{42}Si is a particularly good example of how the tensor-force-driven Jahn-Teller mechanism leads to a strong oblate rather than a spherical shape.

First observable: Inclusive cross sections to all bound states



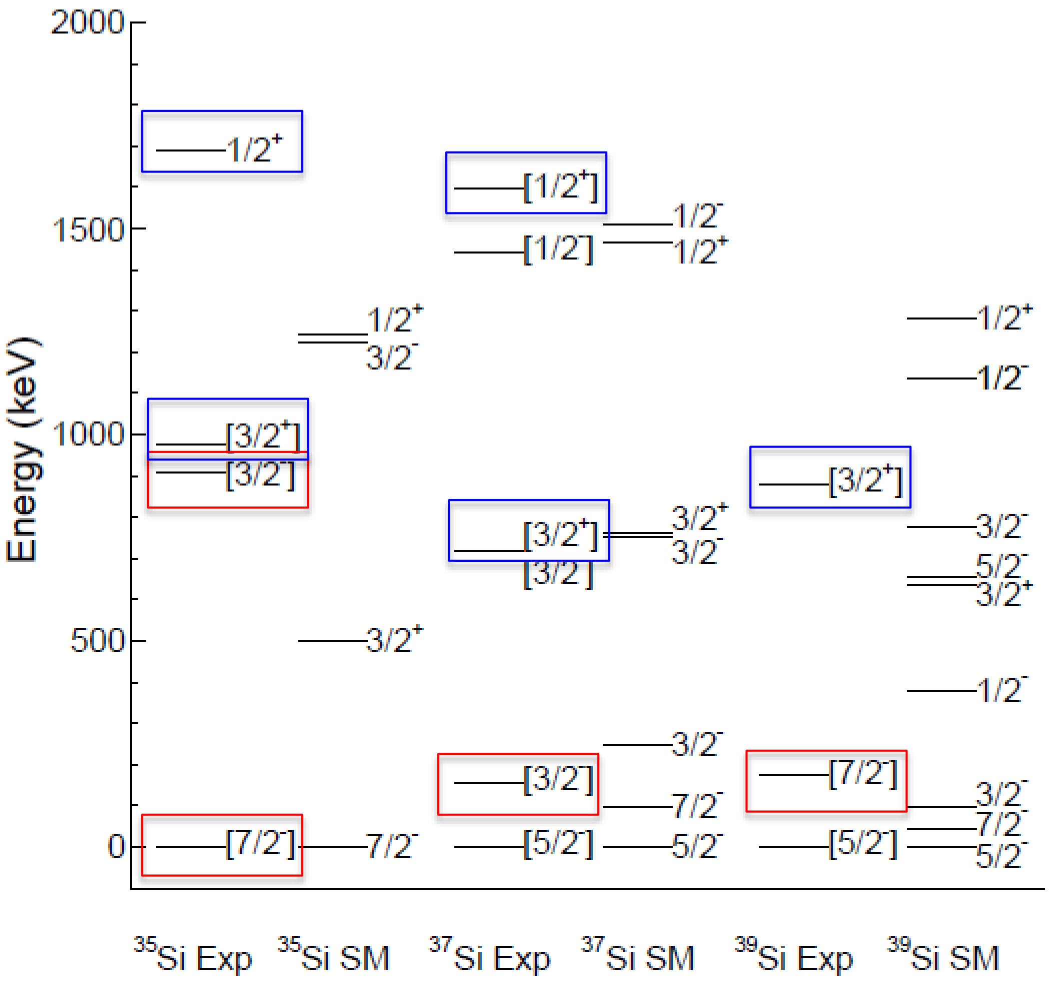
- Measured: Cross section to all bound states
- Calculated: Eikonal reaction theory (J. A. Tostevin) and shell-model spectroscopic factors for the given effective interaction [consistently following the prescription of PRC 77, 044306 (2008)]
- The calculations are scaled by the asymmetry dependent reduction factor from PRC 77, 044306 (2008)
- Total strength to bound states well described by shell model

S. R. Stroberg et al., PRC 90, 034301 (2014)

Shell evolution – the neutron perspective … and the complications

Interesting:

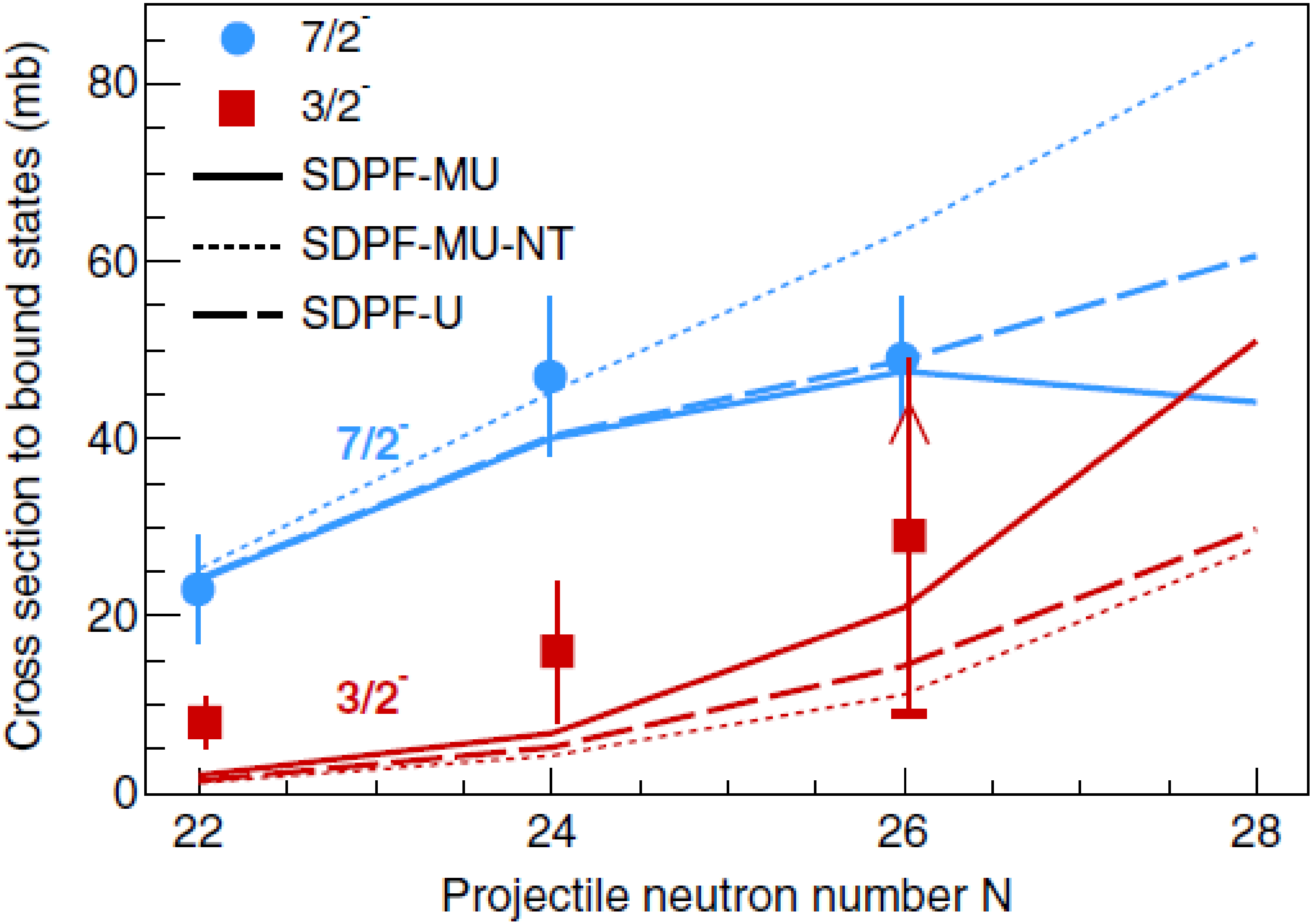
- What is the evolution of the $f_{7/2} – p_{3/2}$ gap
- What do we learn from the cross shell excitations (positive-parity states)



- ^{35}Si – The measured ground state momentum distribution contains a $d_{3/2}$ component due to the $3/2^+$ isomer
- ^{37}Si – The $3/2^-$ state is a ns isomer. The $7/2^-$ state has not been observed yet. It will be an isomer, and so look like the ground state
- ^{39}Si – The $3/2^-$ has not been observed yet (will be near the ground state or maybe is the ground state – large uncertainty), the $7/2^-$ is a ns isomer. No$1/2^+$ state known

S. R. Stroberg et al., PRC 90, 034301 (2014)

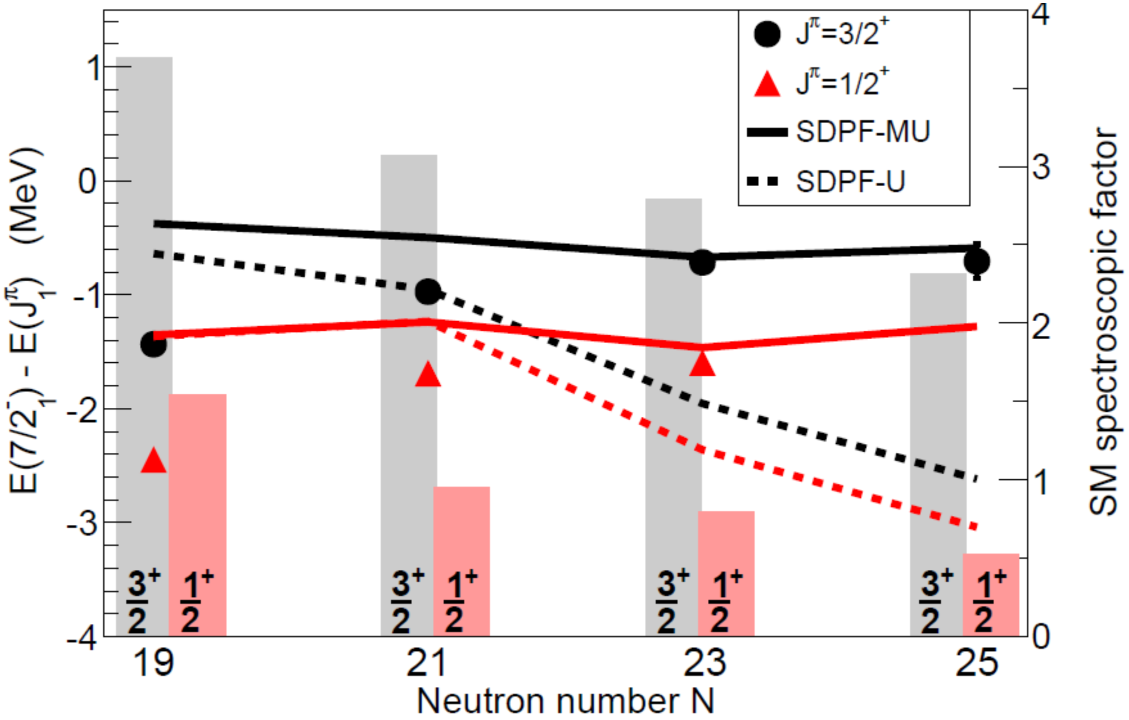
The evolution of the 7/2⁻ - 3/2⁻ gap and the tensor force

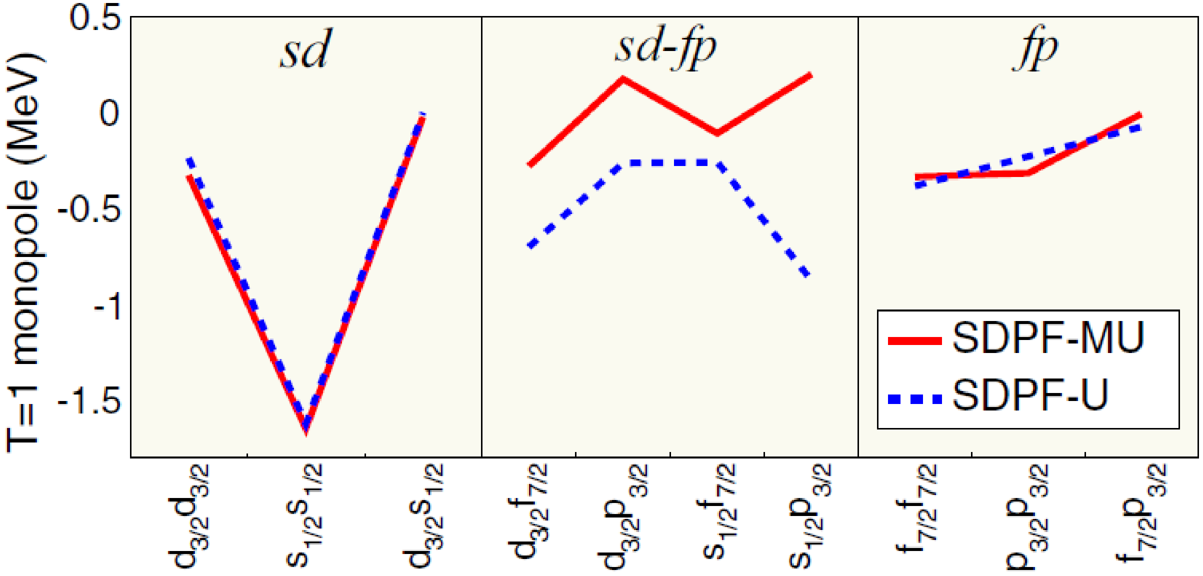


S. R. Stroberg et al., PRC 91, 041302(R) (2015)

Cross shell excitations from positive parity states

S. R. Stroberg et al., PRC 91, 041302(R) (2015)

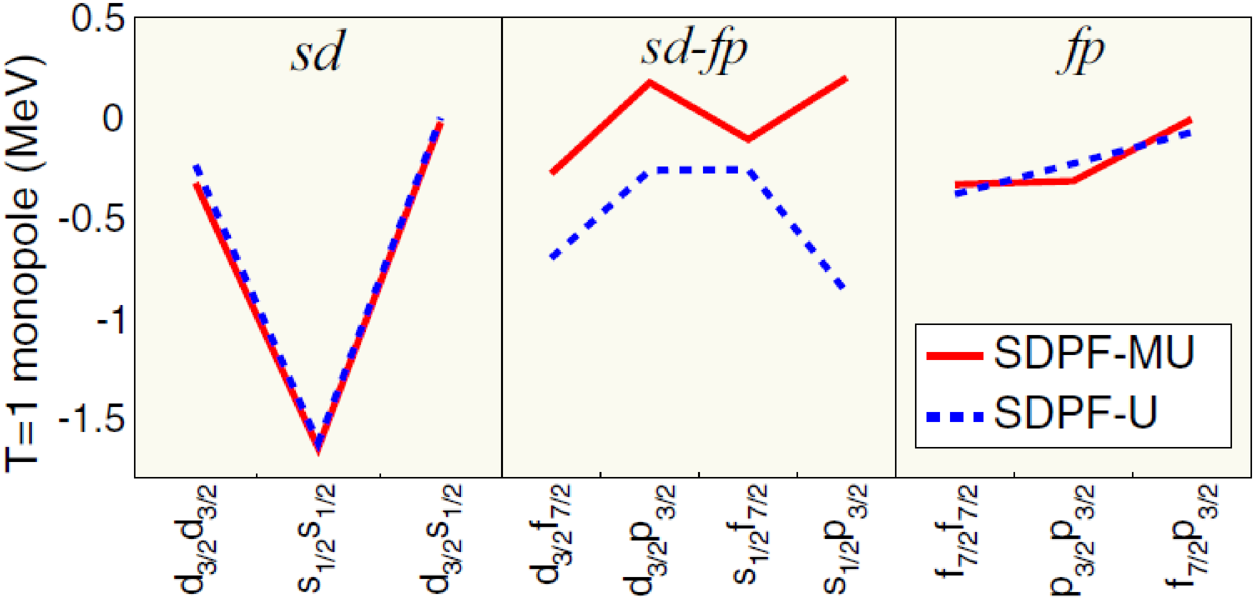




- SDPF-U and SDPF-MU describe the spectroscopy in the region well
- Both have similar *sd* and *fp* monopoles and are successful in reproducing the spectroscopy of the region
- More attractive SDPF-U cross-shell monopoles overbind the neutron *sd* orbits as neutrons are added to the *fp* shell, leading to the observed trend.

3N in cross-shell T=1 channel

S. R. Stroberg et al., PRC 91, 041302(R) (2015)



- **SDPF-U:** due to insufficient experimental data, the cross-shell part of the interaction was left as essentially the two-body *G* matrix.

- **SDPF-MU:** generated from the schematic potential V_{MU} which includes approximately – through fits to data – the repulsive contribution of 3N forces to the effective $T = 1$ two-body interaction
- This same repulsive $T = 1$ effect has been shown to be robust consequence of the Fujita-Miyazawa process which is crucial in reproducing the oxygen dripline

Take away

- All might not be well at N=28 (^{48}Ca -> ^{42}Si) in neutron-rich nuclei, the text book example of shell evolution – maybe some missing piece in the puzzle of shell evolution?
- We experimenters can measure many more things than “just” energies and electromagnetic transition strength – think about the use of cross sections, please!
- That gets me to something important – the interface of nuclear structure and reactions: Huge opportunities to connect to experiment!
- Tell us what quantities would be important to constrain your models, we often can find ways to get there experimentally!

Thank you!