
Celebrating 75 Years of the Nuclear Shell Model and Maria Goeppert-Mayer

# Shell model meets in-beam $\gamma$-ray spectroscopy on both sides of the nuclear chart

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# Outline

- The experimental scheme of in-beam γ-ray spectroscopy at MSU
- Science cases and confrontation with shell model
  - First high-resolution γ-ray spectroscopy of $^{41}$Si
  - Probing proton cross-shell excitations through the two-neutron removal from $^{38}$Ca
  - A tale of tails … or high-spin states at the proton dripline


First high-resolution γ-ray spectroscopy of $^{41}$Si

A. Gade,[1,2] B. A. Brown,[1,2] J. A. Tostevin,[3] D. Bazin,[1,2] P. C. Bender,[1,*] C. M. Campbell,[4] H. L. Crawford,[4] B. Elman,[1,2] K. W. Kemper,[5] B. Longfellow,[1,2,†] E. Lunderberg,[1,2] D. Rhodes,[1,2,†] S. R. Stroberg,[6] and D. Weisshaar[1]
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(Dated: July 10, 2024)

PHYSICAL REVIEW C **108**, L061301 (2023)

Letter

**Probing proton cross-shell excitations through the two-neutron removal from $^{38}$Ca**

T. Beck,[1,*] A. Gade,[1,2] B. A. Brown,[1,2] J. A. Tostevin,[3] D. Weisshaar,[1] D. Bazin,[1,2] K. W. Brown,[1,4] R. J. Charity,[5] P. J. Farris,[1,2] S. A. Gillespie,[1] A. M. Hill,[1,2] J. Li,[1] B. Longfellow,[1,2,†] W. Reviol,[6] and D. Rhodes[1,2,‡]
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(Received 28 September 2023; accepted 20 November 2023; published 19 December 2023)

PHYSICAL REVIEW LETTERS **129**, 242501 (2022)

**Dissipative Reactions with Intermediate-Energy Beams: A Novel Approach to Populate Complex-Structure States in Rare Isotopes**

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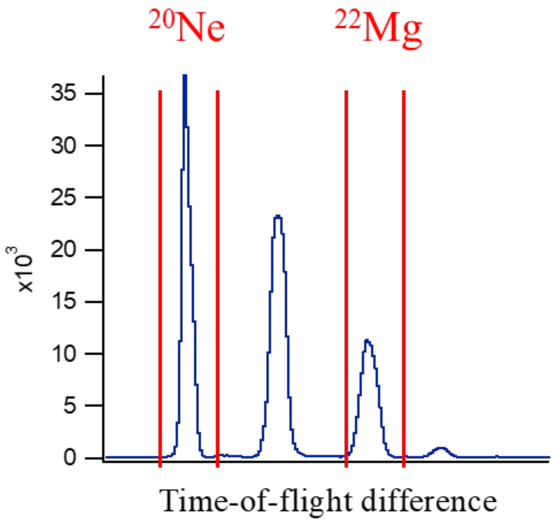
(Received 27 August 2022; revised 11 October 2022; accepted 18 November 2022; published 7 December 2022)

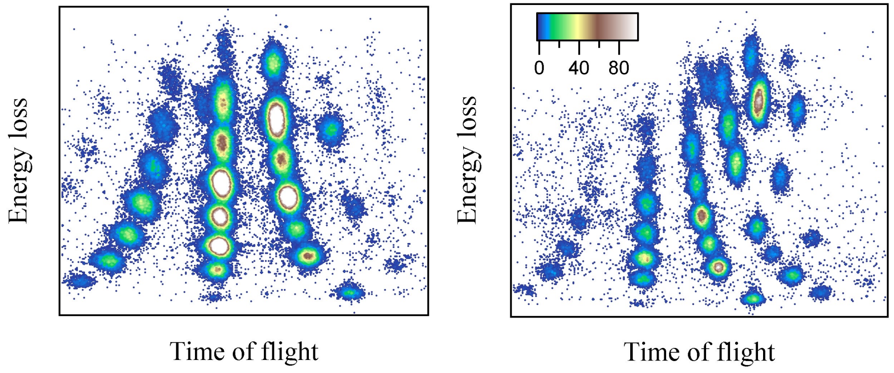
# The experimental scheme at MSU

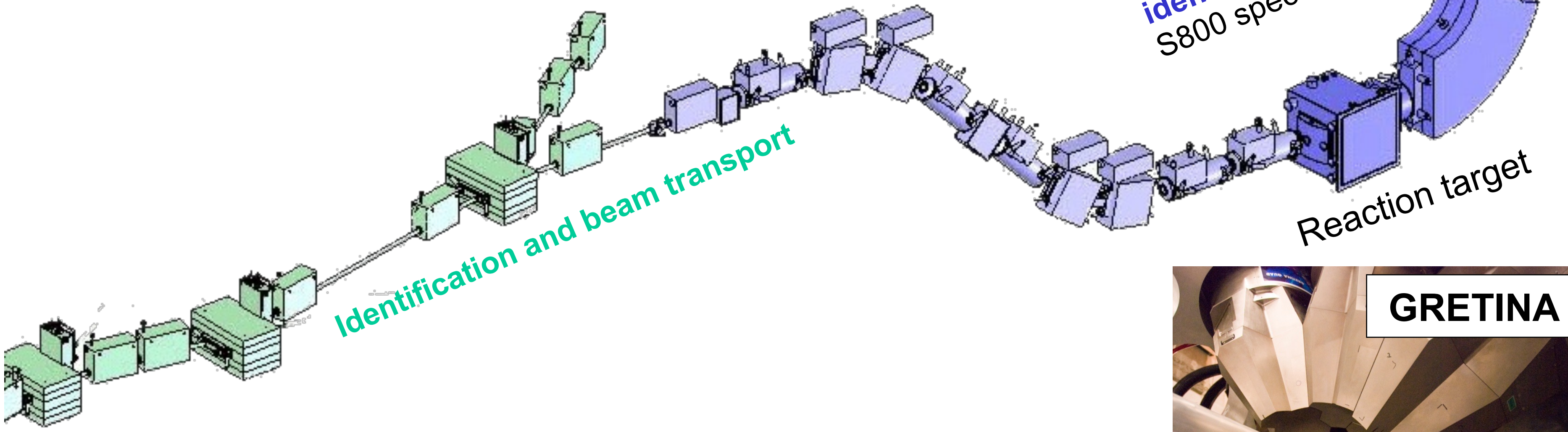
PID of the incoming beam via velocity difference




Reactions induced by $^{20}$Ne

induced by $^{22}$Mg





Driver accelerator

- Fragment separator
- Identification and beam transport
  - Stopped beam experiments
  - Fast beam experiments
    - Secondary reaction
    - Reaction product identification

# First high-resolution γ-ray spectroscopy of $^{41}$Si

## First high-resolution γ-ray spectroscopy of $^{41}$Si

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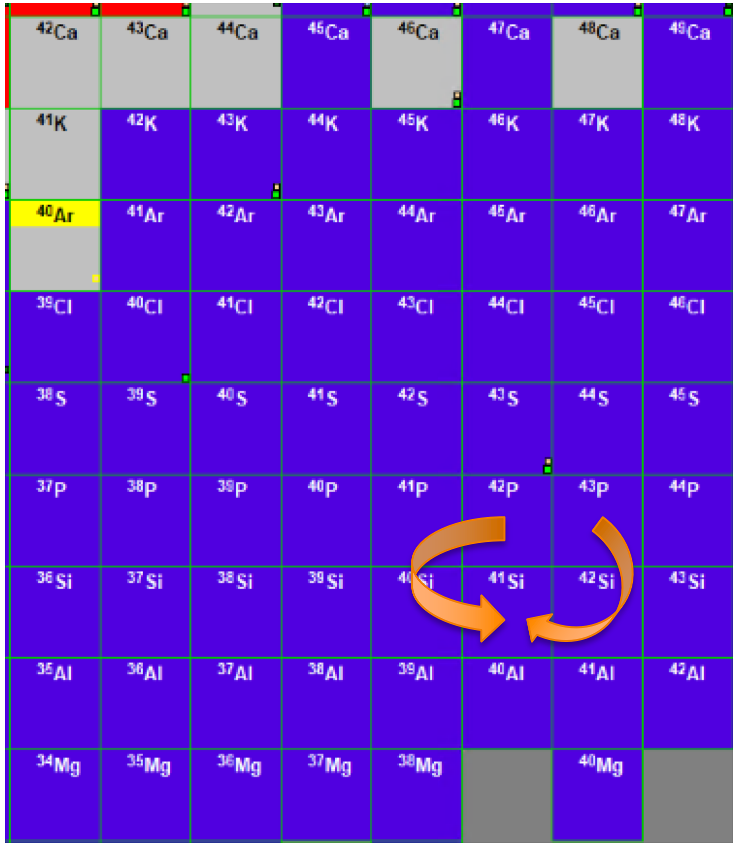
(Dated: July 10, 2024)

Phys Rev. C (in press)

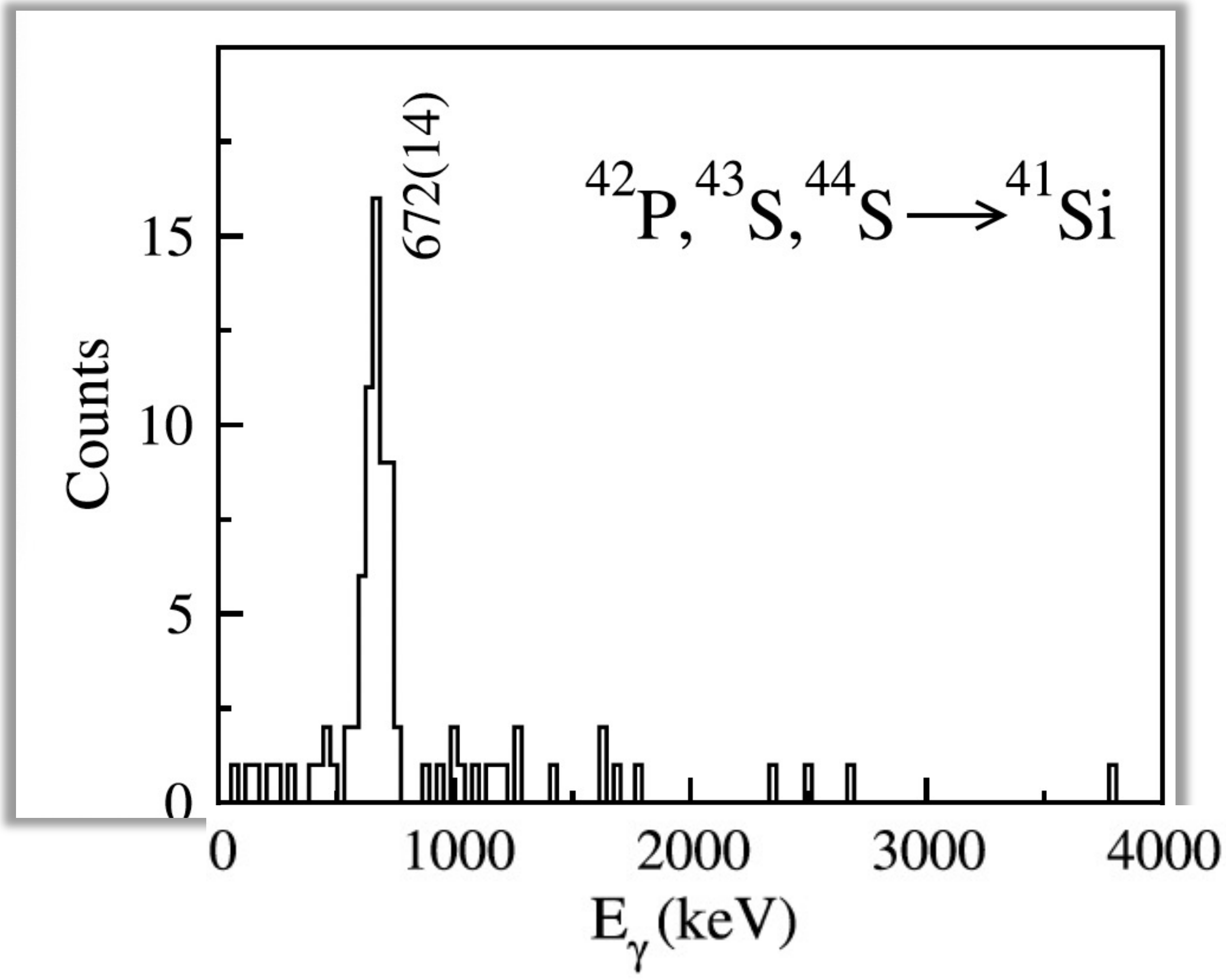
# First high-resolution γ-ray spectroscopy of $^{41}$Si
## Previous knowledge




$$^{9}\mathrm{Be}(^{42,43}\mathrm{P},{}^{41}\mathrm{Si}+\gamma)$$

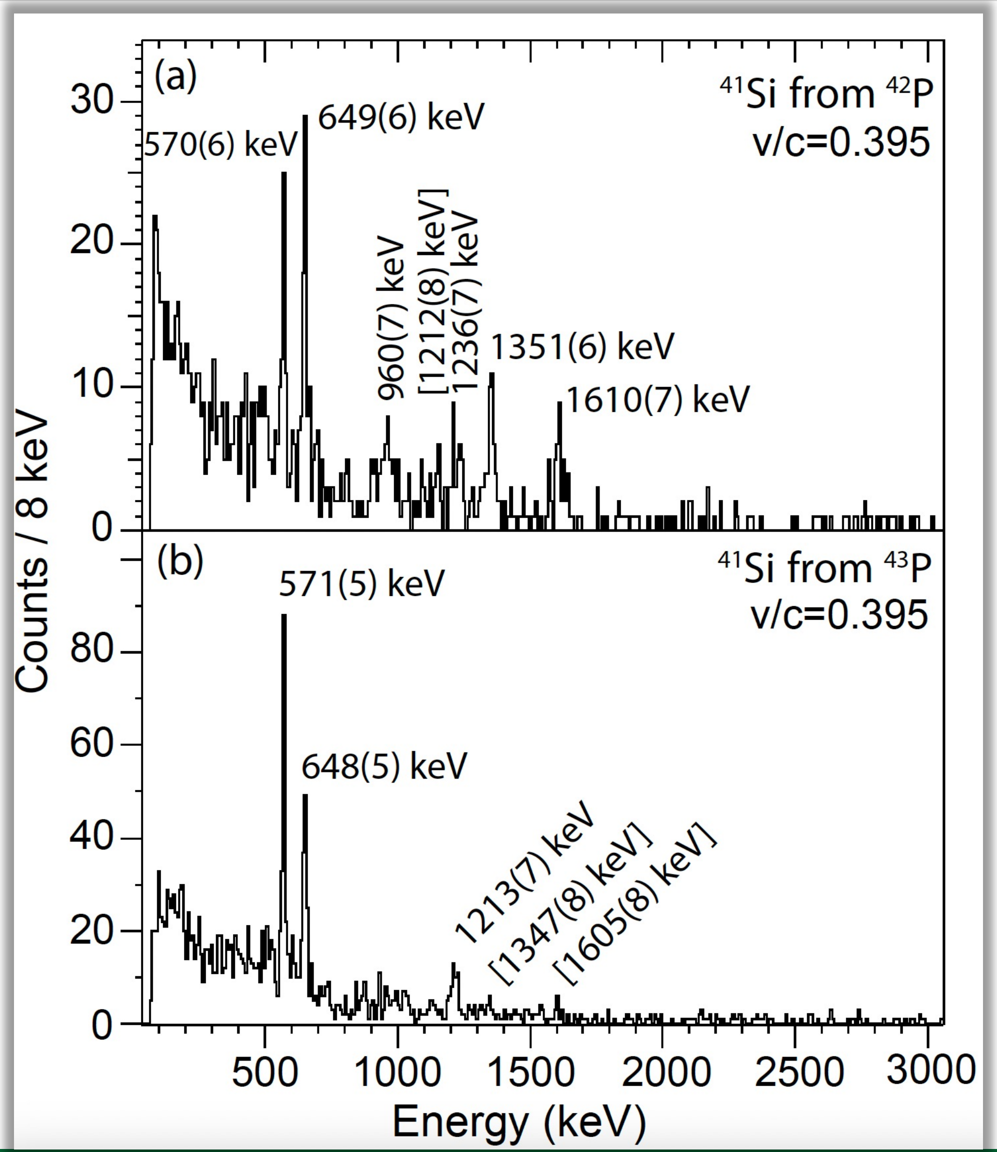
At 86.6 MeV/u

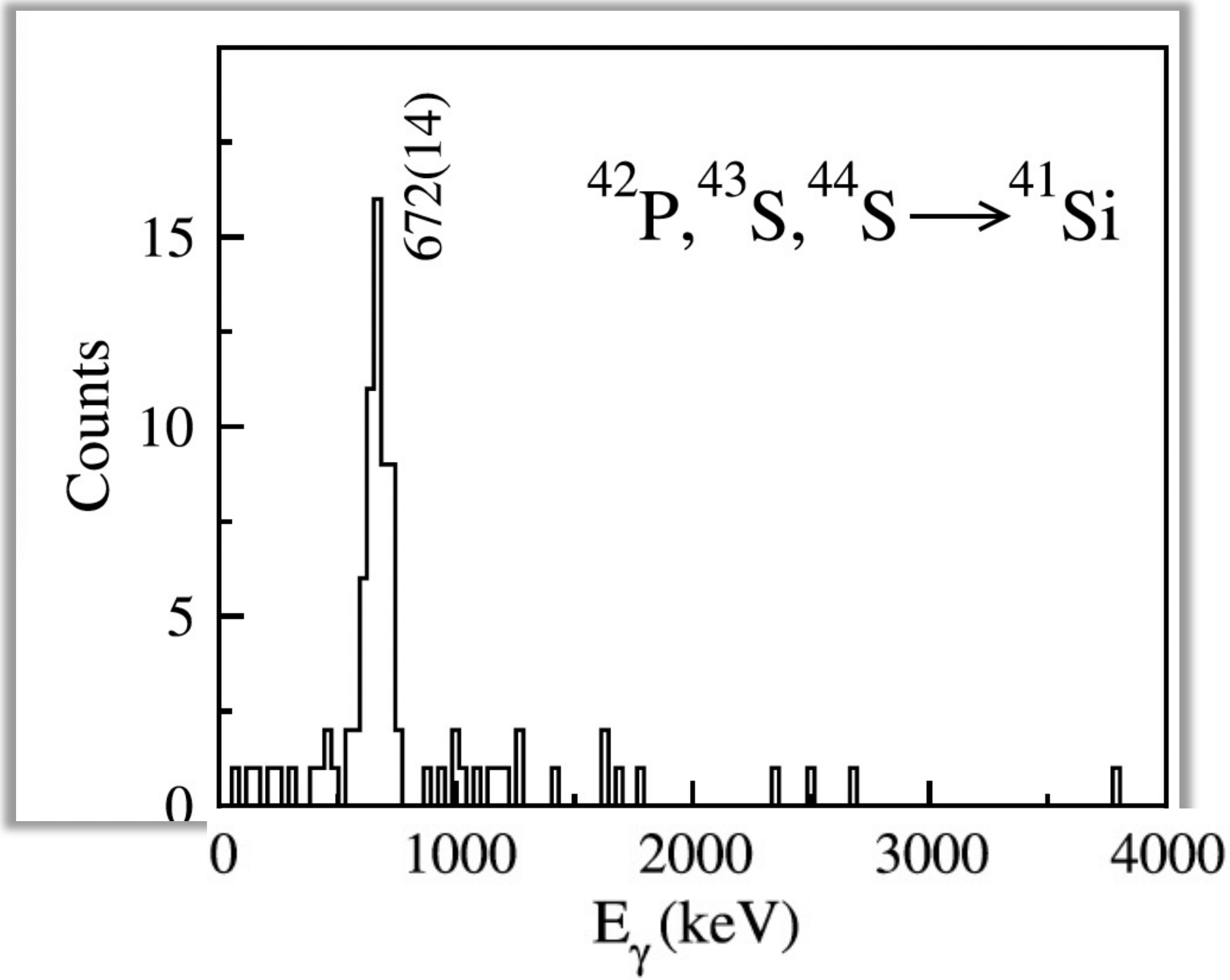
$^{41}$Si is a tenant of the N=28 island of inversion




Known before our work: D. Sohler et al., PLB 703, 417 (2011)

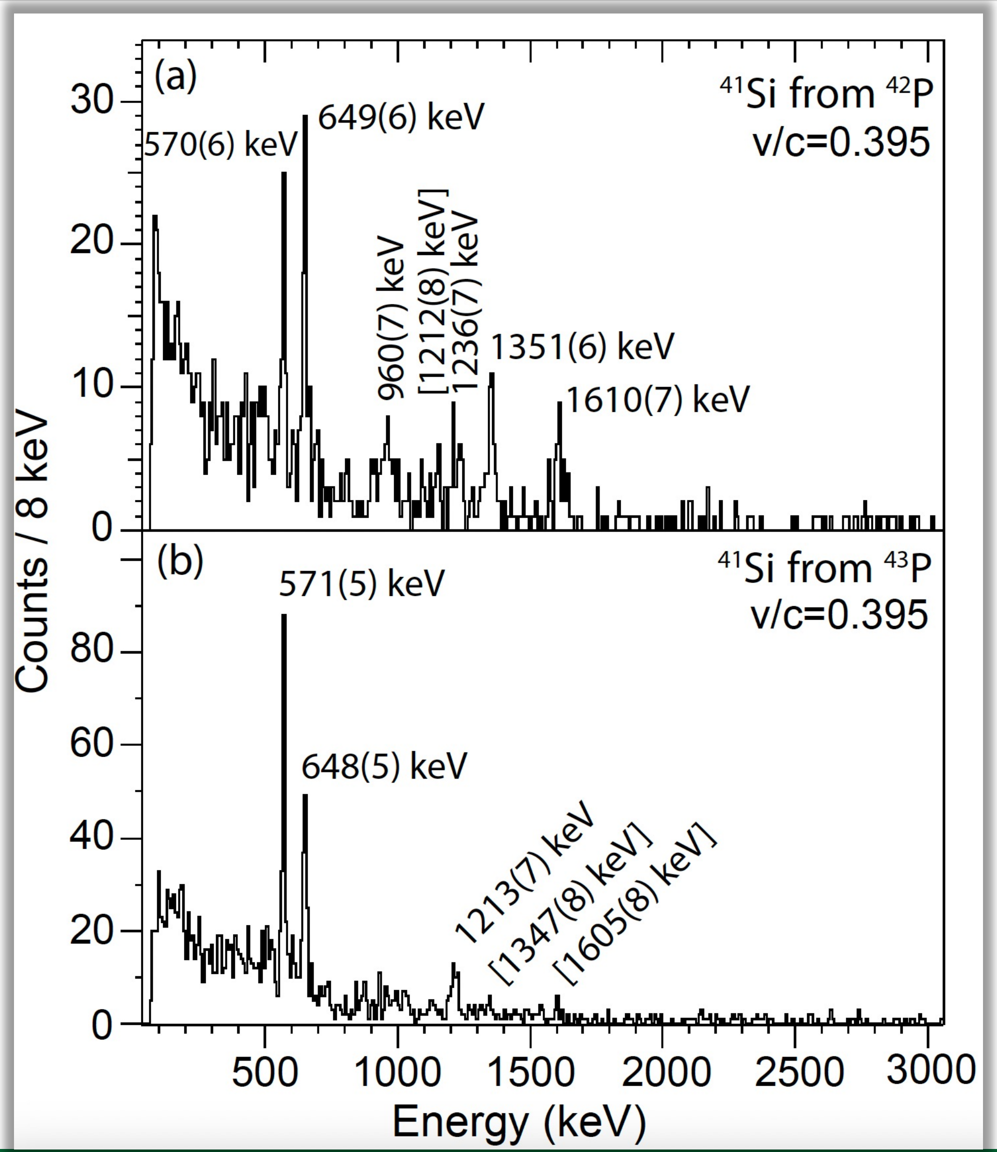
# First high-resolution γ-ray spectroscopy of $^{41}$Si
## **Resolution helps!**

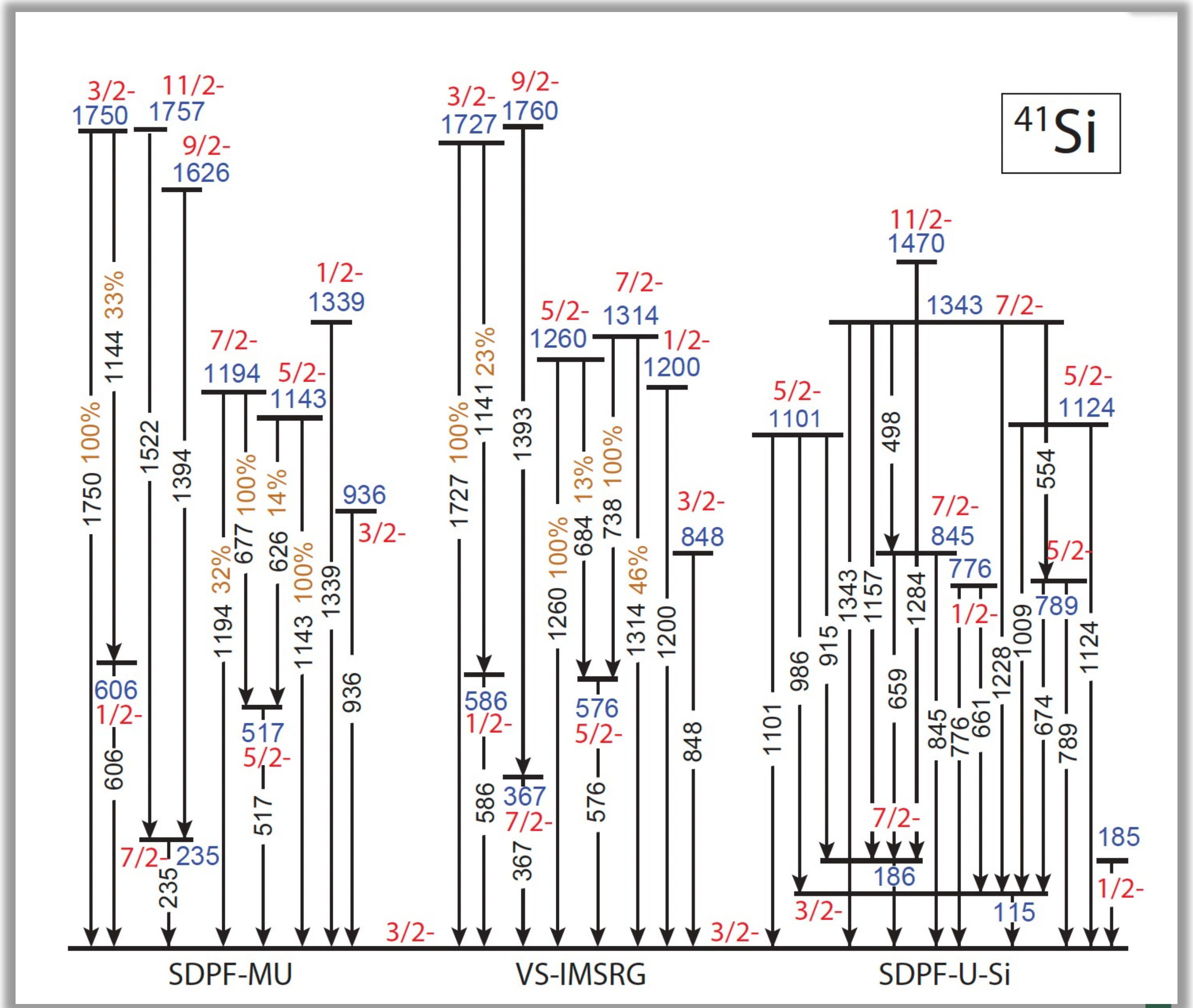


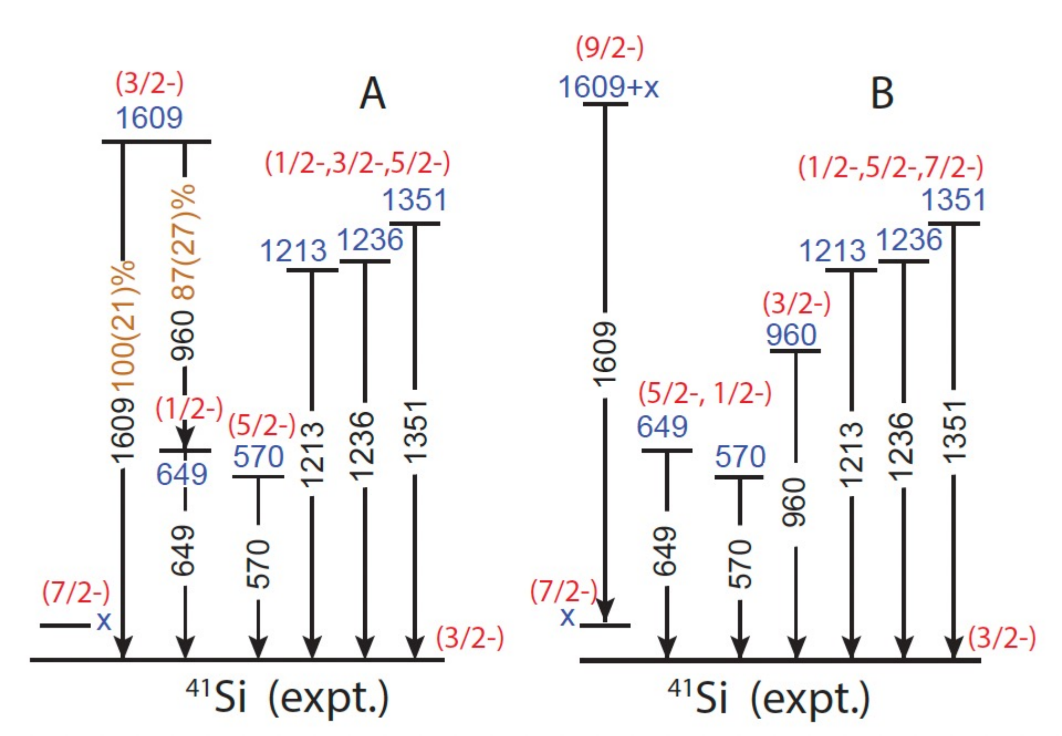

Known before our work: D. Sohler et al., PLB 703, 417 (2011)

# First high-resolution γ-ray spectroscopy of $^{41}Si$
## Who ordered this mess of a level scheme?

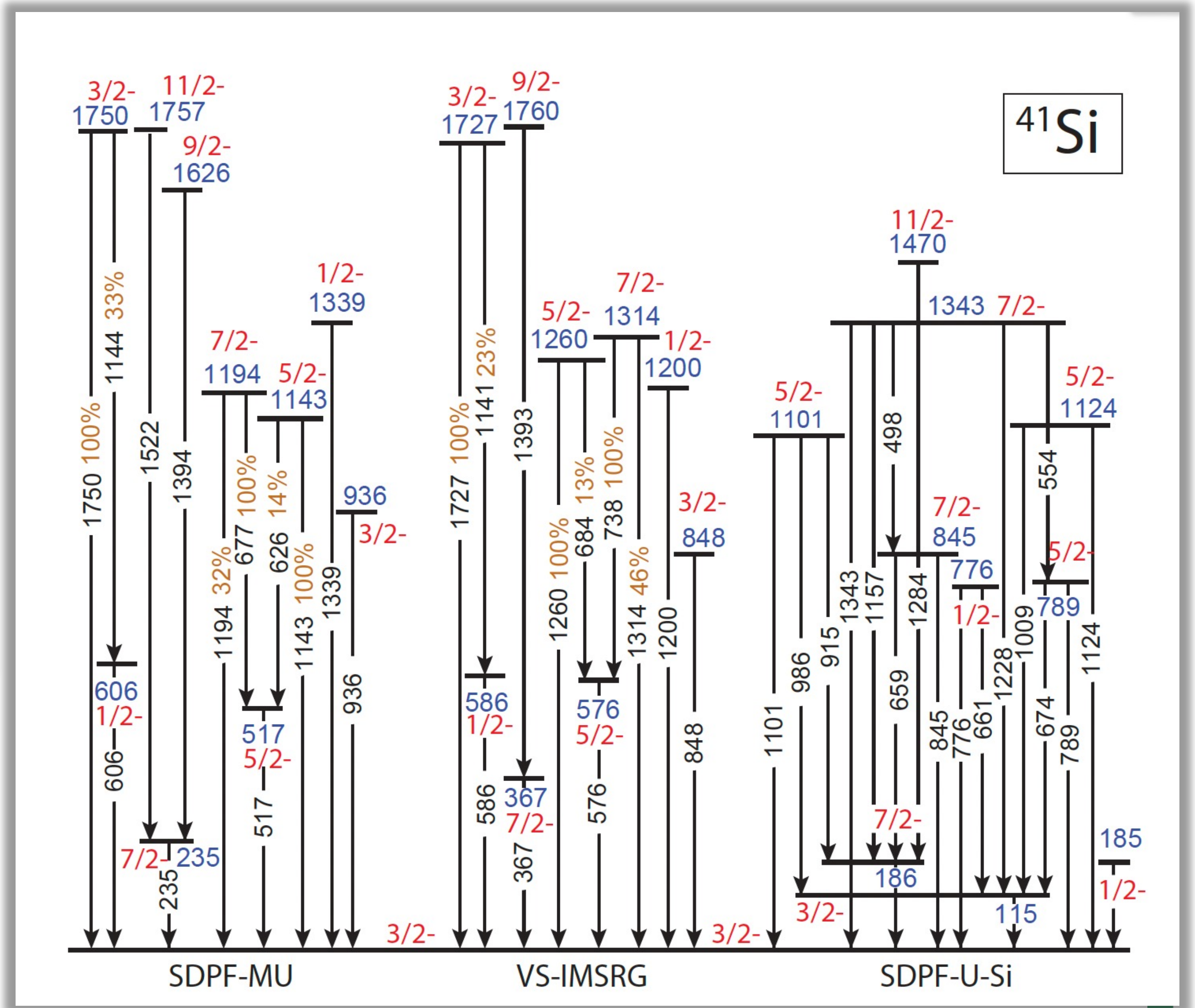


# First high-resolution γ-ray spectroscopy of $^{41}$Si
## Putting the puzzle together

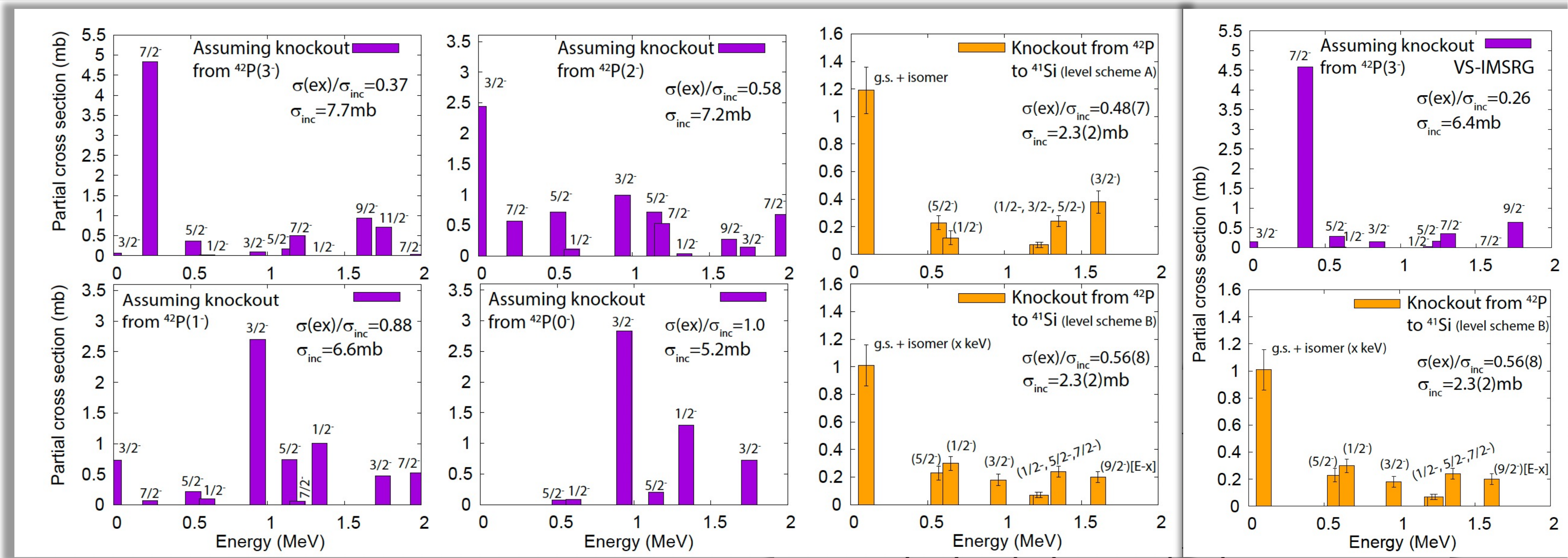



Possible level schemes from experiment

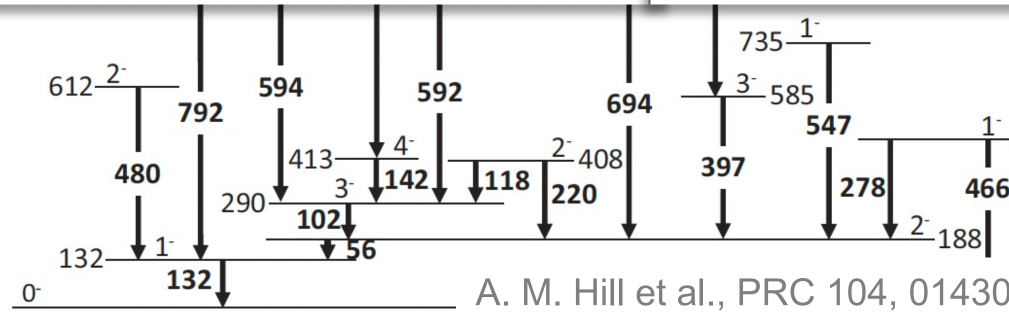



Challenge to Augusto and Heather: How about that mess in Nilsson?

# First high-resolution $\gamma$-ray spectroscopy of $^{41}$Si
## Cross sections teach us about $^{41}$Si and $^{42}$P!




1⁻ and 0⁻ parent spin of $^{42}$P are excluded, seems most likely that knockout occurs from the first 3⁻ or 2⁻ state of $^{42}$P - isomer and g.s. population can distinguish 3⁻ and 2⁻



# Probing proton cross-shell excitations through the two-neutron removal from $^{38}$Ca

PHYSICAL REVIEW C **108**, L061301 (2023)

Letter

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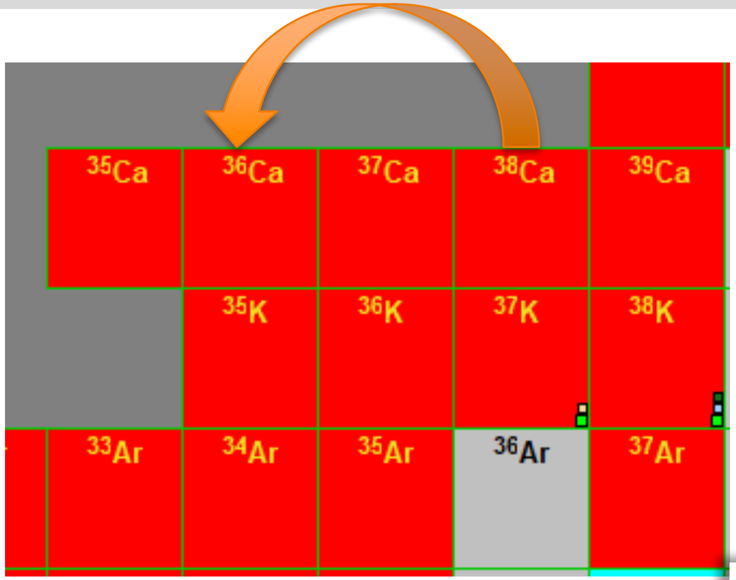
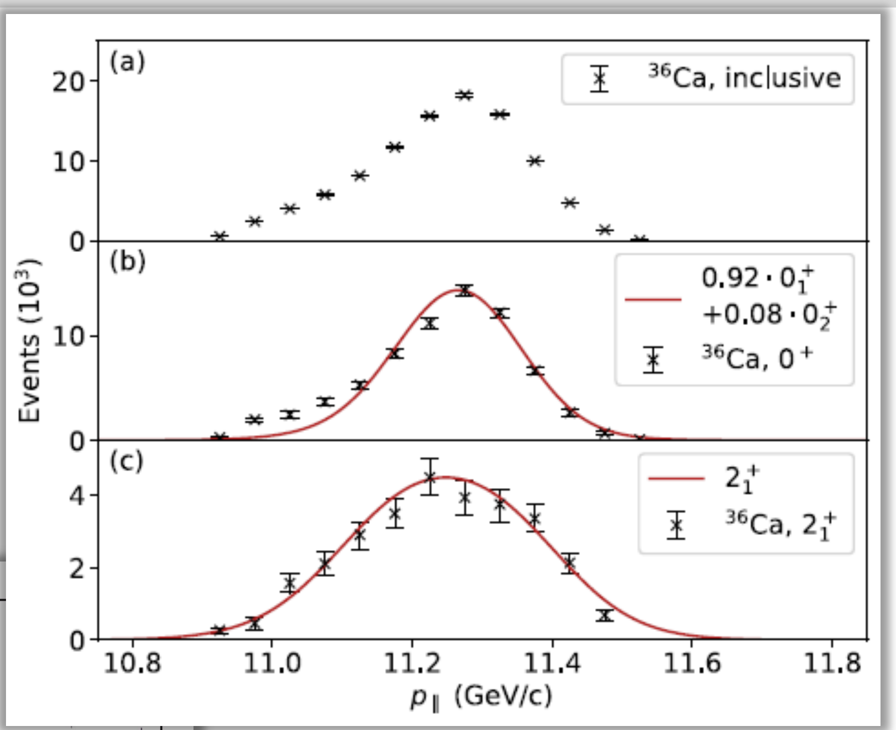
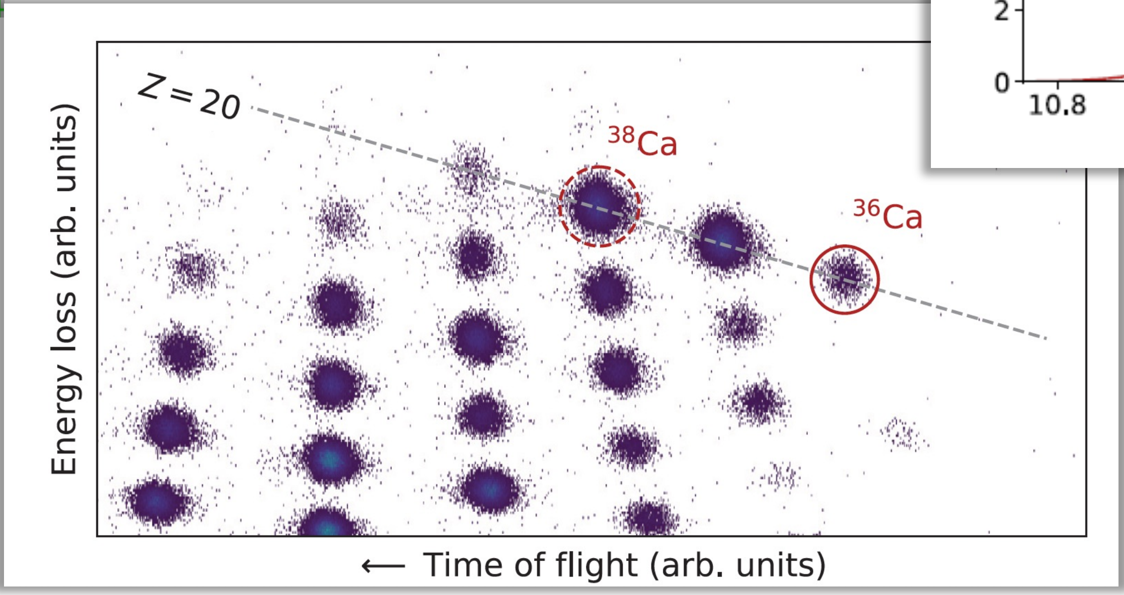
Work by Tobias Beck, FRIB Gamma Group postdoc

# Two-neutron knockout from proton-rich nuclei is a direct reaction




Two-neutron removal from proton-rich nuclei is a direct reaction, probing the wavefunction overlaps of the projectile and projectile-like residue.
Width of $p_{||}$ is sensitive to *J*.

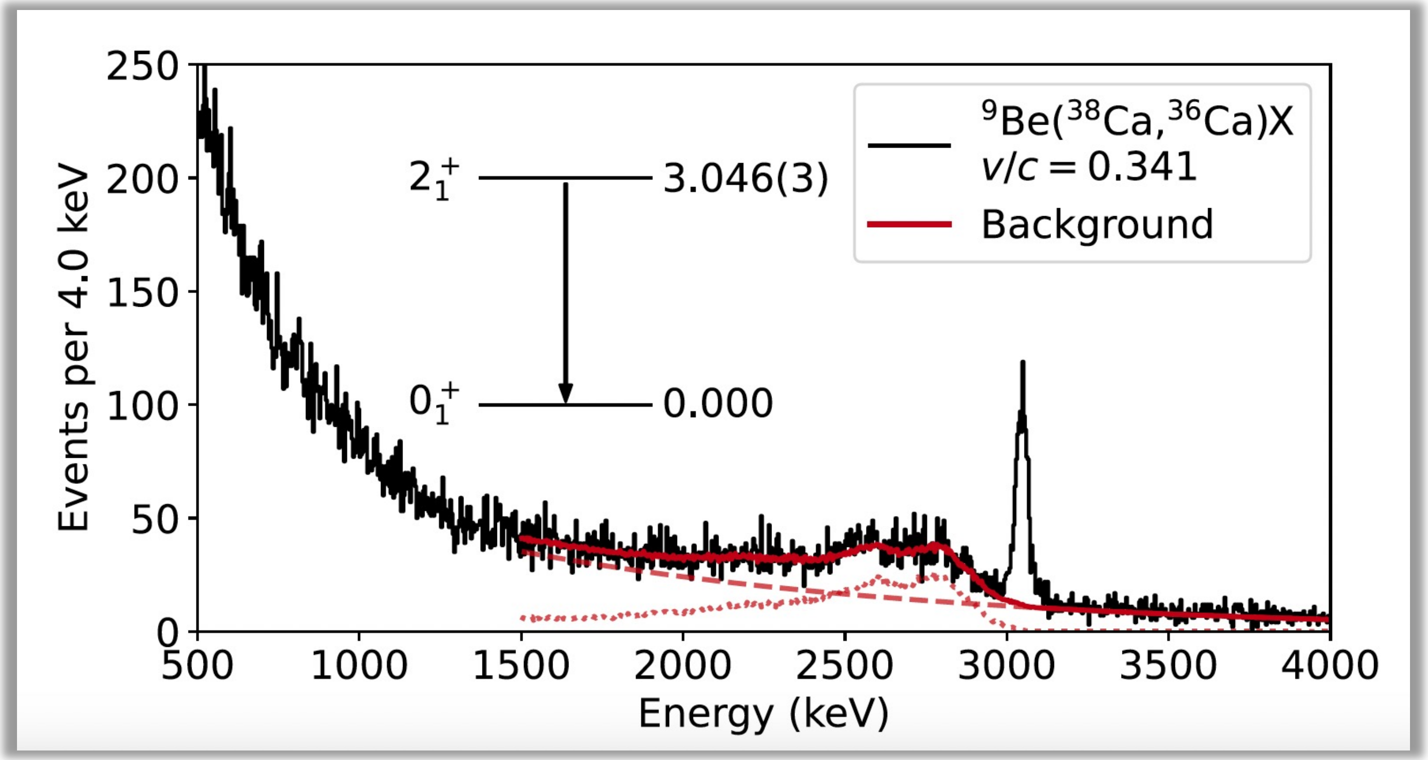



**Experiment:** $^{38}$Ca beam at 61 MeV/u from NSCL's A1900 fragment separator guided to a 188 mg/cm$^2$ $^9$Be target at the target position of the S800 spectrograph with the magnetic field set to center $^{36}$Ca

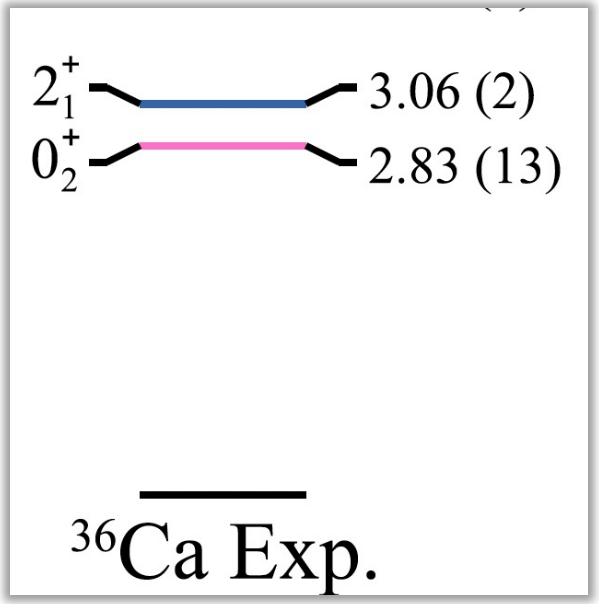
# A simple level scheme … or not?

GRETINA detects prompt $^{36}$Ca $\gamma$ rays emitted in flight. Only the $2^+_1$ to $0^+_1$ transition is observed.




Excited $0^+$ state, if populated, will not have a $\gamma$-ray transition and so will look like knockout to the ground state

However, the lowest-lying excited state is a $0^+$

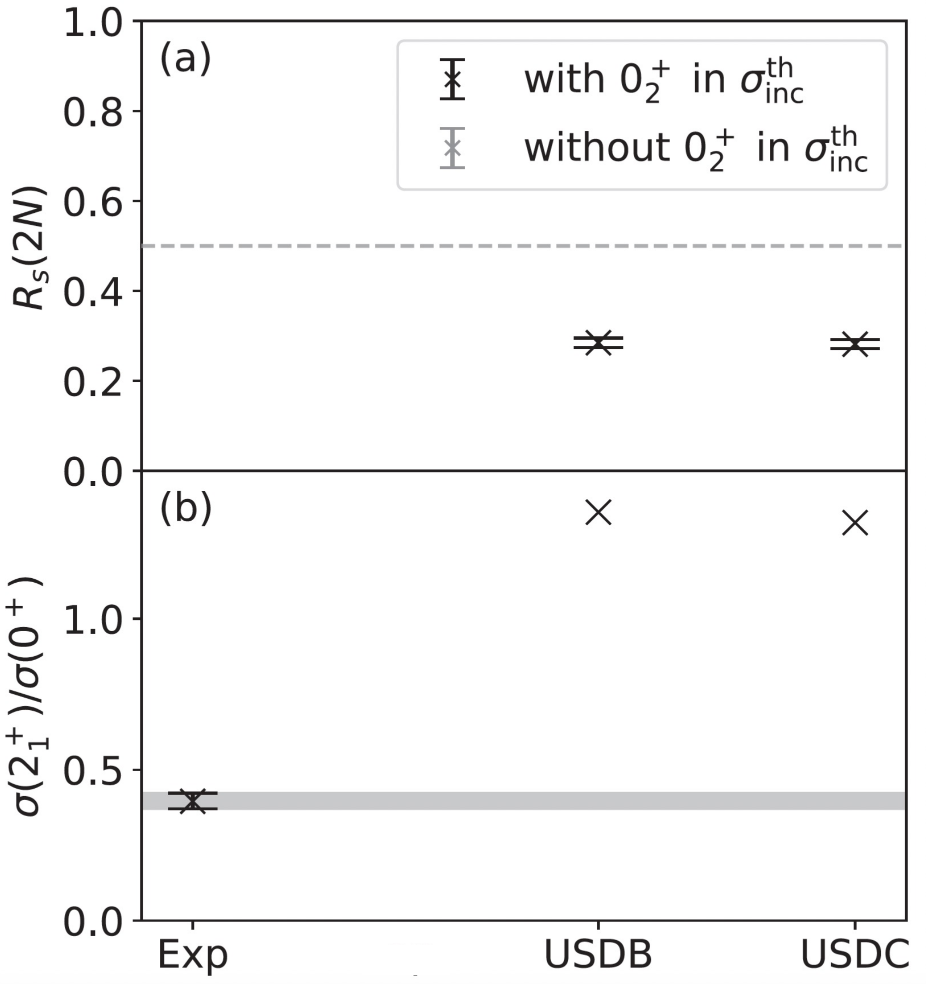


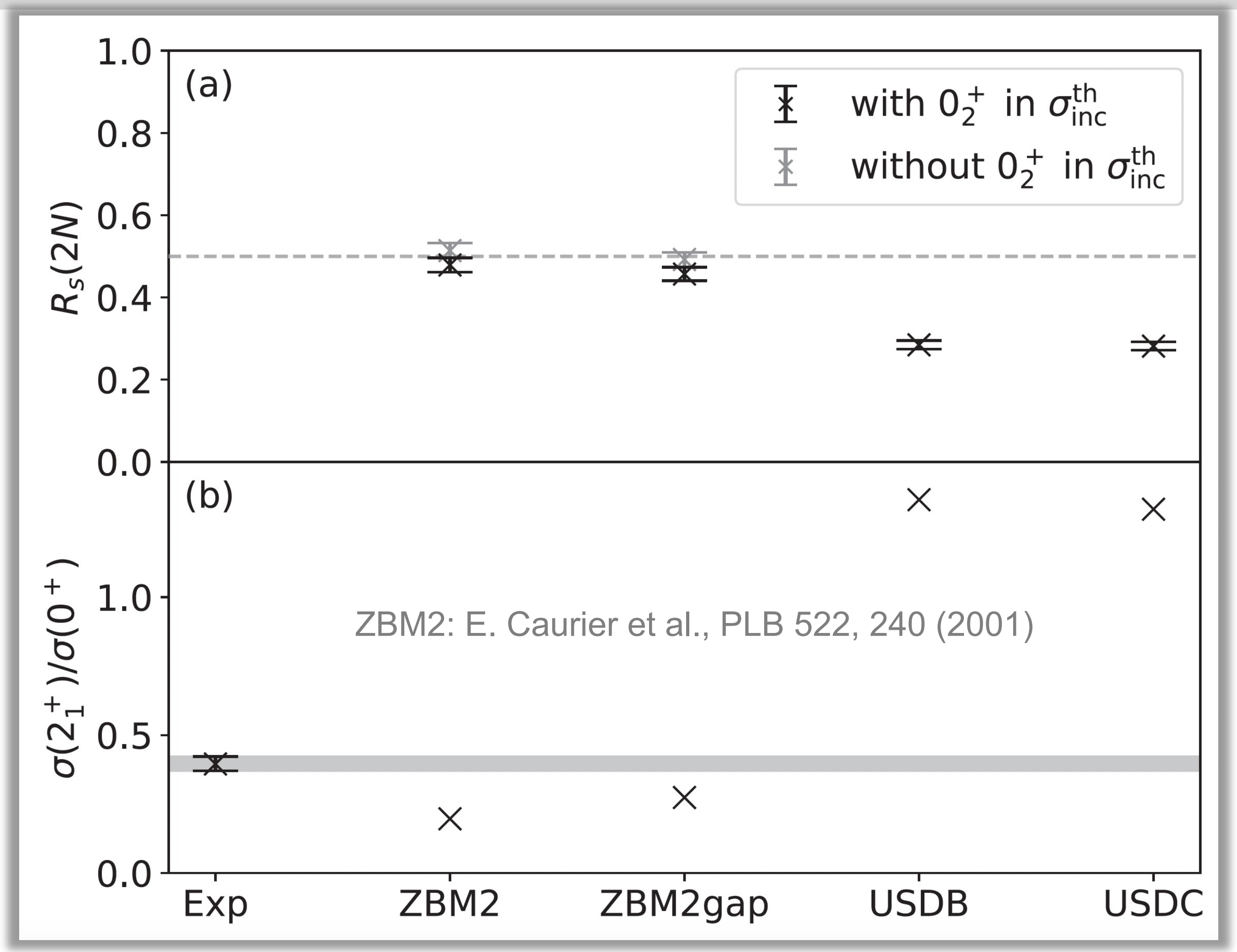

L. Lalanne et al., PRL 129, 122501 (2022)

$\sigma_{inc} - \sigma(2^+_1) = \sigma(0^+)$ measured

$\sigma(0^+) = \sigma(0^+_1) + \sigma(0^+_2)$

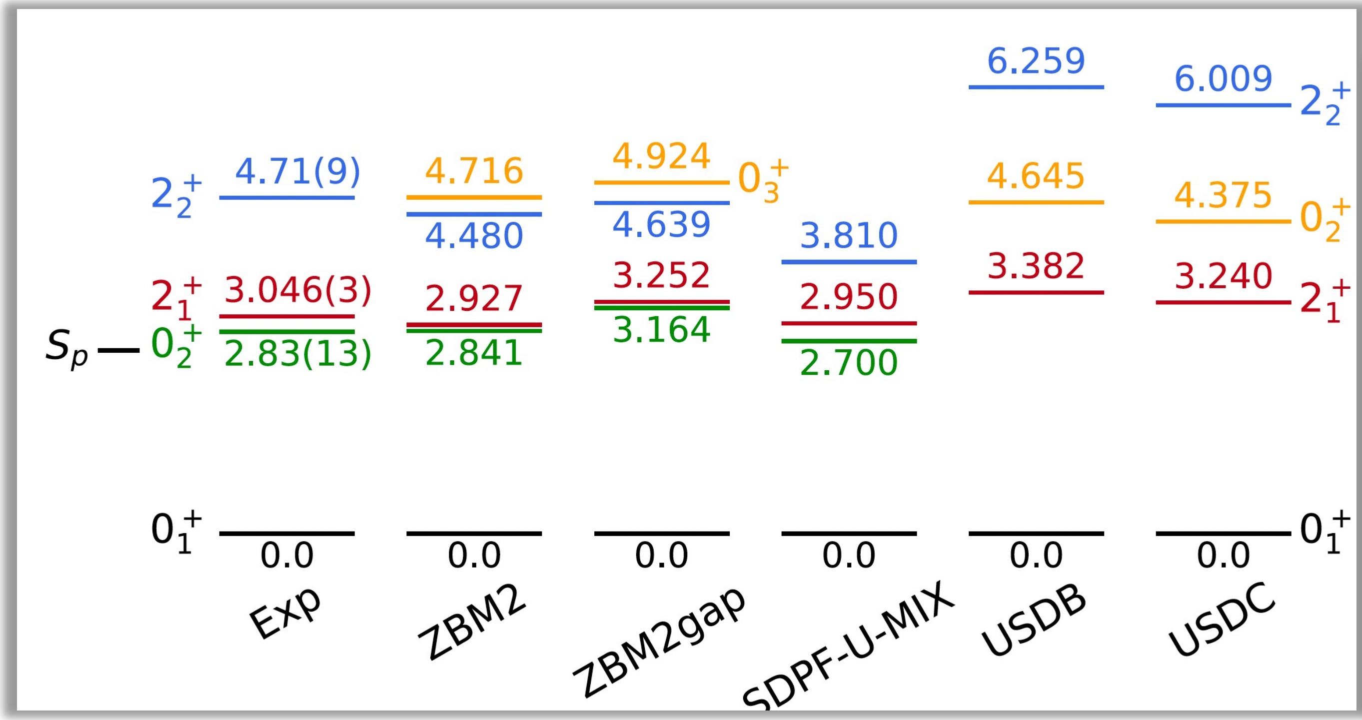
# Cross section ratios tell a story




Only a shell-model effective interaction that allows for proton cross-shell excitations across Z=20 reproduces the data: ZBM2 and ZBM2gap (gap between *sd* and *pf* shell increased by 250 keV)

# Evidence for importance of proton cross-shell excitations from more than one side




N. Dronchi et al., PRC 107, 034306 (2023)

TABLE II. Comparison of $B(E2; 0^+ \rightarrow 2_1^+)$ values between experiment and theory. The ZBM2 and USDB results use effective charges of $e_p = 1.36$ and $e_n = 0.45$. The *sdpfu*-mix result [43] uses $e_p = 1.31$ and $e_n = 0.46$.

| | $B(E2\uparrow)$ ($e^2$fm$^4$) | | | |
|---|---|---|---|---|
| | exp | ZBM2 [2] | USDB [42] | *sdpfu*-mix [43] |
| $^{36}$Ca | 131(20) | 179 | 11.8 | 23.5 |
| $^{36}$S | 89(9) | 116 | 108 | 98 |
| $^{38}$Ca | 101(11) | 110 | 14.0 | - |
| $^{38}$Ar | 125(4) | 179 | 128 | - |

Also, spectroscopic factors from $^{37}$Ca to $^{36}$Ca (Lalanne et al.) are in better agreement with ZBM2

# A tale of tails – What else happens when a fast beam of $^{38}Ca$ meets a $^{9}Be$ target

PHYSICAL REVIEW LETTERS **129,** 242501 (2022)

**Dissipative Reactions with Intermediate-Energy Beams: A Novel Approach to Populate Complex-Structure States in Rare Isotopes**

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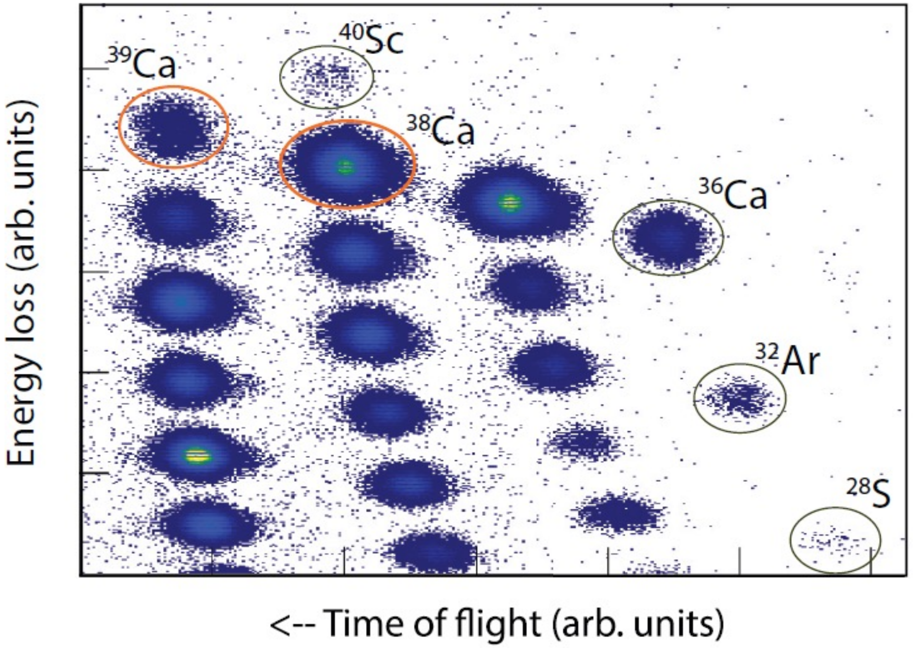
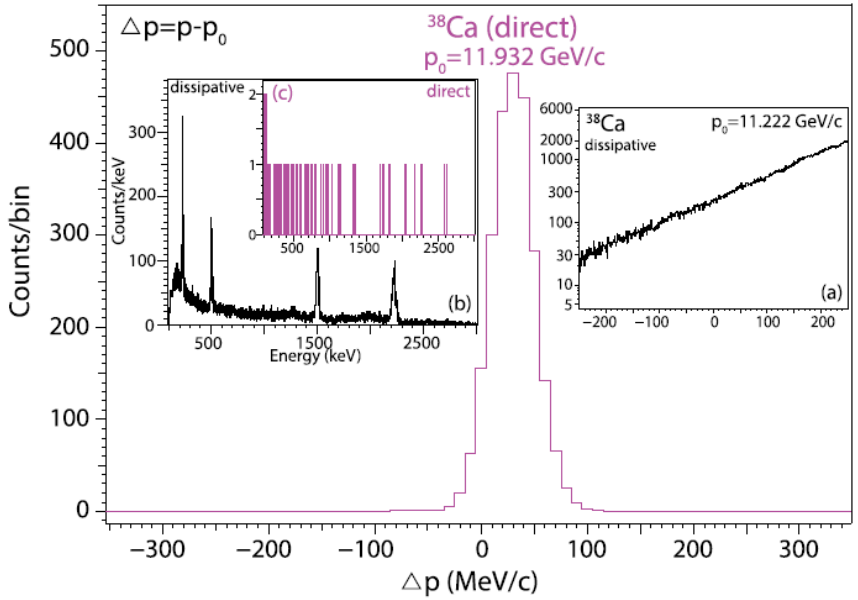
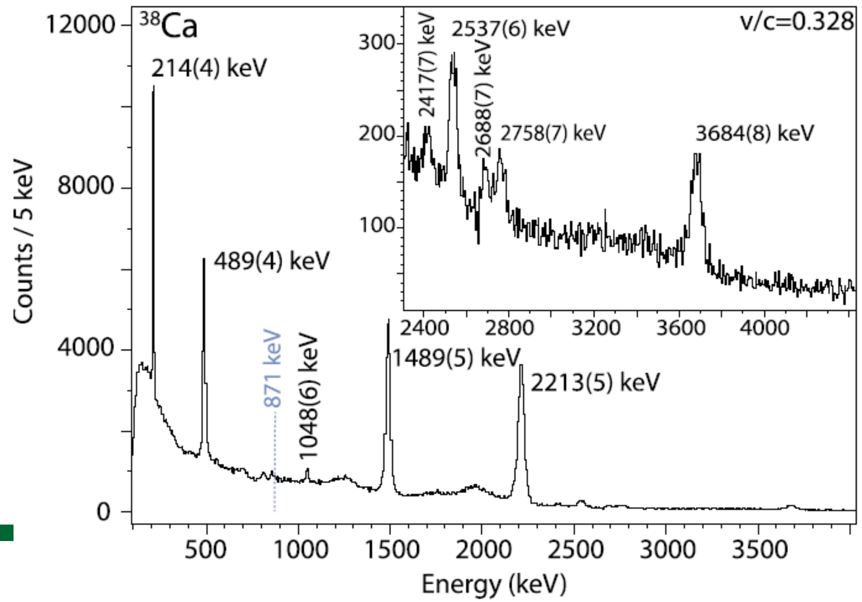
# What else happens when a fast beam of $^{38}$Ca meets a $^{9}$Be target

$^{9}$Be($^{38}$Ca,$^{38,39}$Ca+$\gamma$)X reaction channels explored as by-product in a $^{38}$Ca+$^{9}$Be reaction setting with the S800 magnetic rigidity centered on $^{36}$Ca




$^{38}$Ca at 61MeV/u energy and ~160,000 pps intensity on a 188 mg/cm$^{2}$ $^{9}$Be target



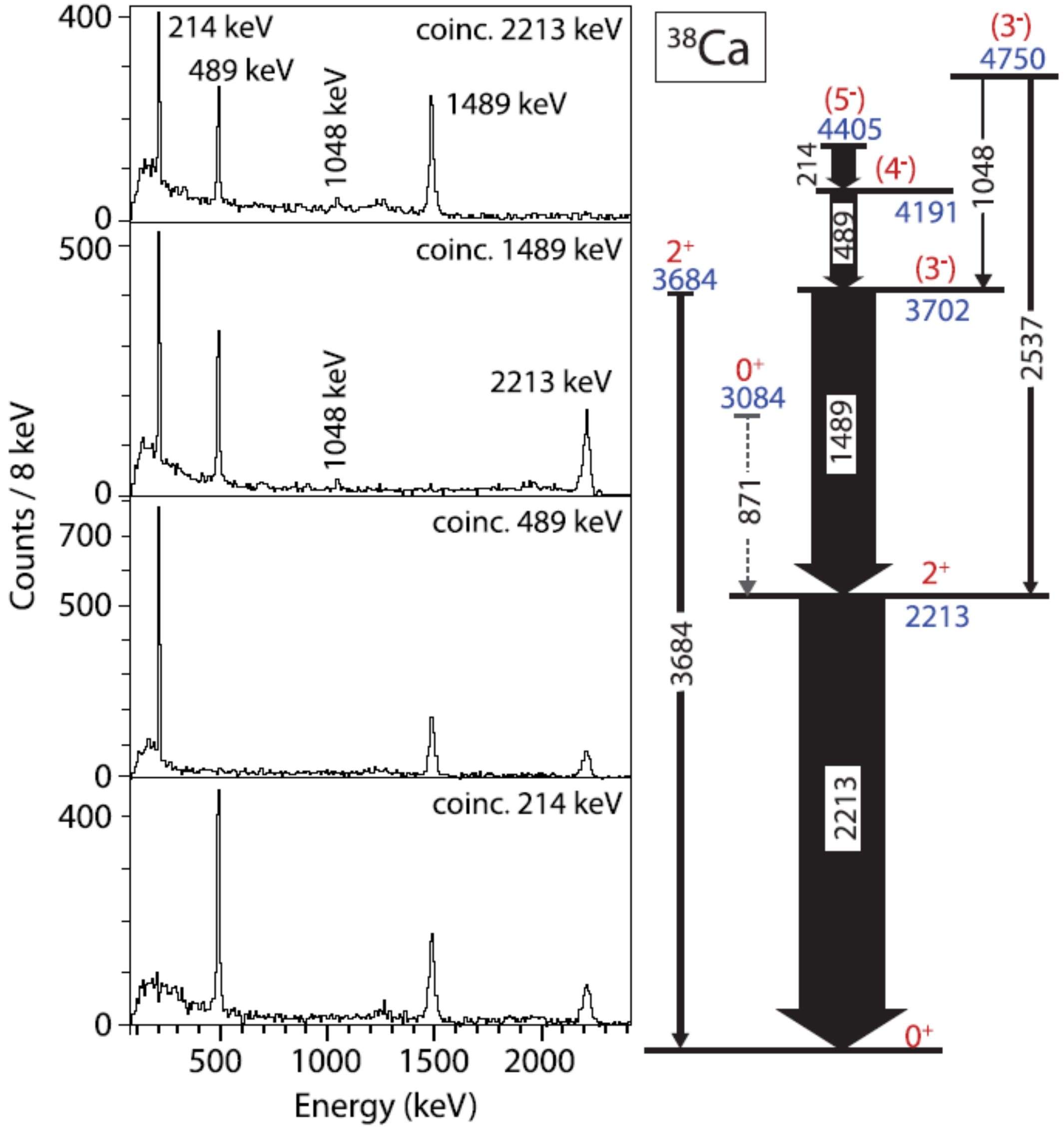

Setting 1 (purple): The spectrograph is set just accounting for the energy loss in the target

Setting 2 (black): The spectrograph is set to accept $^{38}$Ca that has lost 700 MeV/c in momentum

Stunning difference, the $\gamma$-ray spectra on the right are in coincidence with (c) 179,000 $^{38}$Ca and with (b) 100,500 $^{38}$Ca

Very rich spectrum for the highly dissipative setting

# Unexpected spectroscopy of $^{38}$Ca in the tail

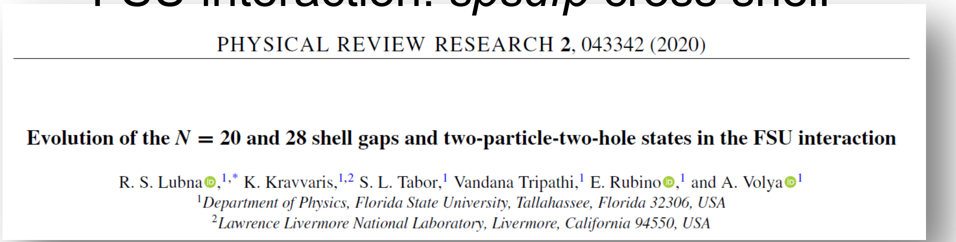



Peculiar level scheme with a zoo of negative-parity states populated

$(5^-) \rightarrow (4^-) \rightarrow (3^-) \rightarrow 2^+$ is the most intense cascade

Note that the first excited $0^+$ state is not observed

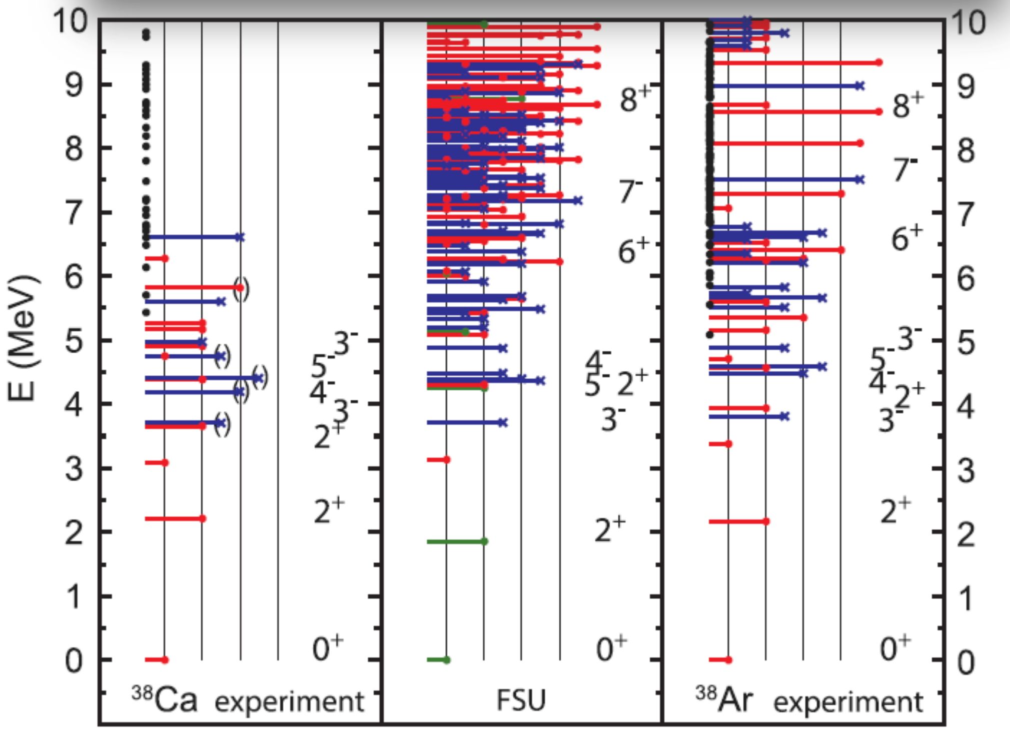
FSU interaction: *spsdfp* cross shell


PHYSICAL REVIEW RESEARCH **2**, 043342 (2020)

**Evolution of the $N = 20$ and 28 shell gaps and two-particle-two-hole states in the FSU interaction**

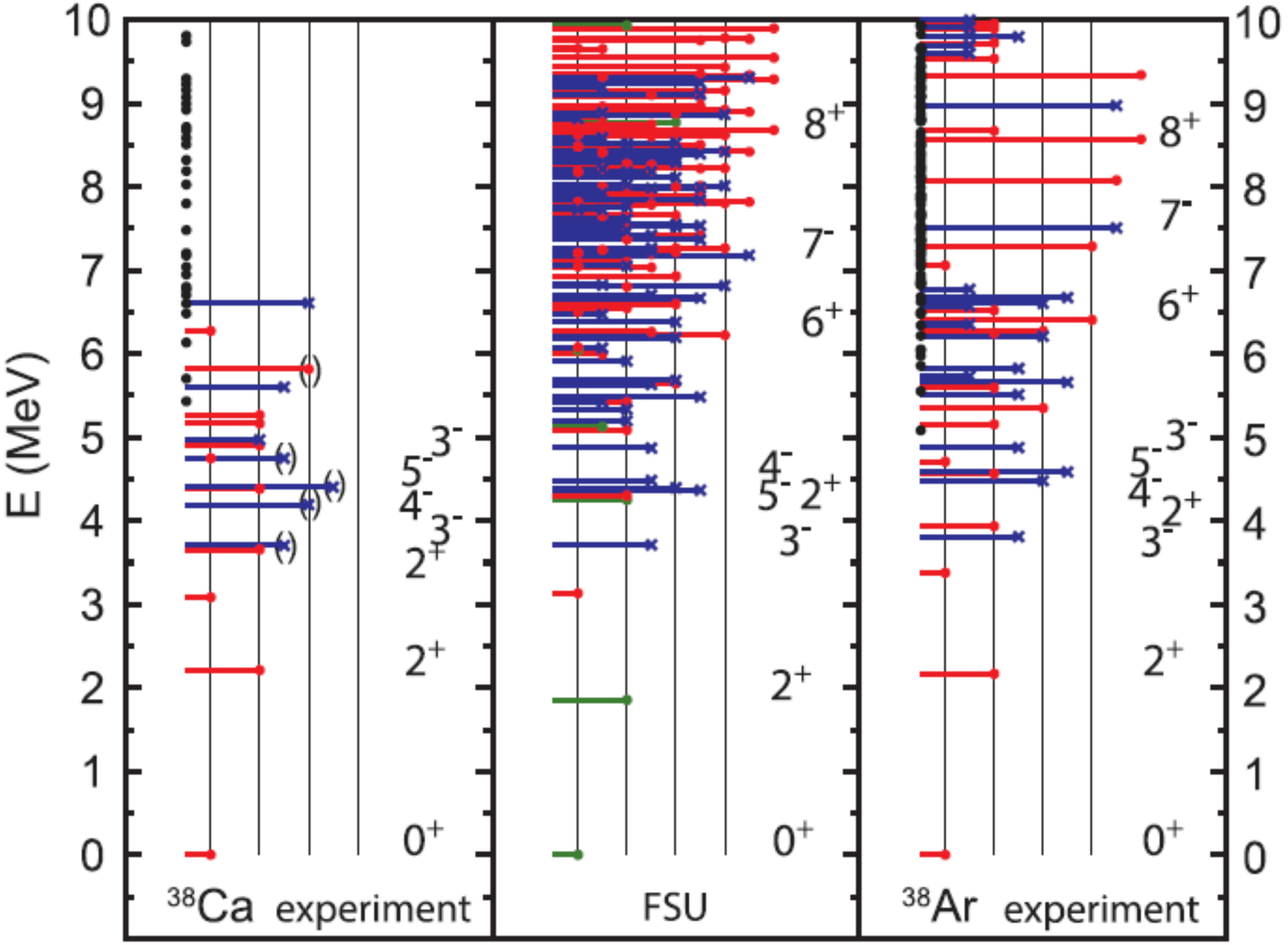
R. S. Lubna,[1,*] K. Kravvaris,[1,2] S. L. Tabor,[1] Vandana Tripathi,[1] E. Rubino,[1] and A. Volya[1]

[1]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[2]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*




In the FSU panel, green: Δ=0 positive parity (*sd* shell), blue: Δ=1 negative parity, and red: Δ=2 positive parity

# Who ordered these complex-structure states?




In the FSU panel, green: Δ=0 positive parity (*sd* shell), blue: Δ=1 negative parity, and red: Δ=2 positive parity

- At 200 MeV of energy lost in the target: $^{9}$Be target nucleus must disintegrate into a number of high-energy fragments
- **The emerging picture is then one of multiple nucleons interacting in a single collision with the formation of complex multiparticle-multihole configurations**, in contrast to the situation in far-less-dissipative, surface-grazing collisions

**Scenarios excluded:** $^{38}$Ca projectile undergoes multiple collisions within the target. Creating mp−nh excitations would require a sequence of knockout and/or pickup processes, and such pickup mechanism cross sections are small - with a typical upper limit of 2 mb at these beam energies

# Summary and Outlook

- There are still new discoveries to be made in the N=28 Island of Inversion (and high-resolution spectroscopy helps!)
- Strong evidence for proton cross-shell excitations across Z=20 around $^{36}$Ca
- Dissipative reactions with fast beams allow for spectroscopy of complex-structure states in rare isotopes

Hoping for many more decades of shell model fun!

*Thank you!*

*A.G. is supported by the U.S. Department of Energy (DOE), Office of Science, Office of Nuclear Physics, under Award No. DESC0023633*