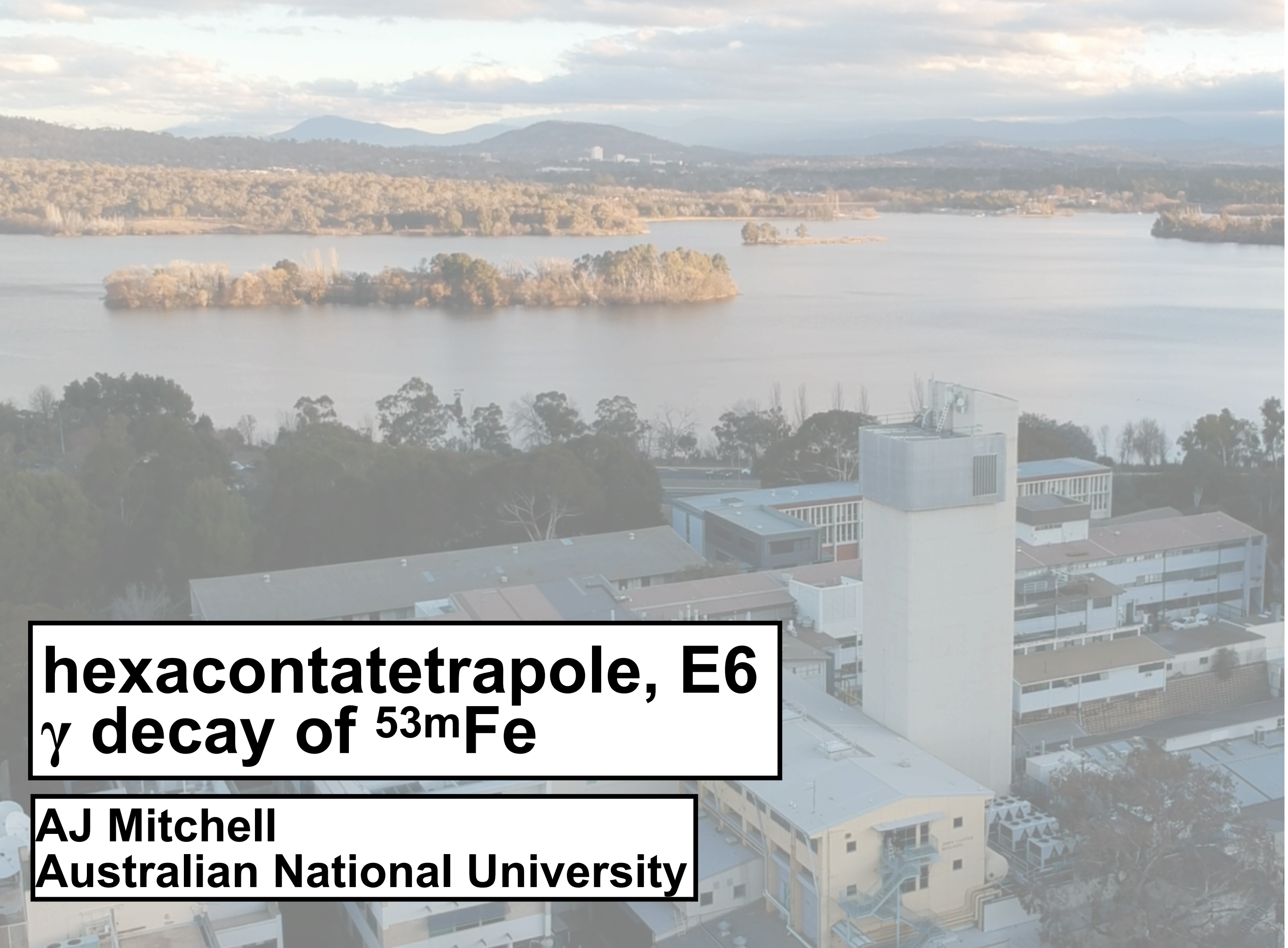


hexacontatetrapole, E6 γ decay of ^{53m}Fe

AJ Mitchell
Australian National University

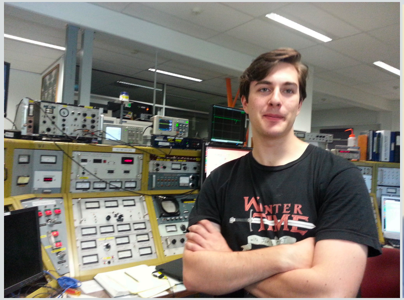
Heavy Ion Accelerators

NCRIS
National Research Infrastructure for Australia
An Australian Government Initiative

Australian Government
Australian Research Council

Australian National University

Collaborators



Thomas Palazzo
ANU MPhil student

Greg Lane
Supervisor

AJM

Andrew Stuchbery

Alex Brown
MSU/FRIB (Theory)

… as well as:
A. Akber, B. J. Coombes,
J. T. H. Dowie, M. S. M. Gerathy,
M. W. Reed, T. Kibedi,
and M. O. de Vries.

Spectroscopy and characterisation of high multipolarity transitions depopulating the metastable state in ^{53}Fe

Thomas Palazzo

A thesis submitted for the degree of
Master of Philosophy
The Australian National University

December, 2017

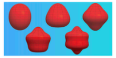
Featured in Physics | Editors' Suggestion | PDF | HTML

Direct Measurement of Hexacontatetrapole, E6 γ Decay from ^{53m}Fe

T. Palazzo, A. J. Mitchell, G. J. Lane, A. E. Stuchbery, B. A. Brown, M. W. Reed, A. Akber, B. J. Coombes, J. T. H. Dowie, T. K. Eriksen, M. S. M. Gerathy, T. Kibédi, T. Tornyi, and M. O. de Vries

Phys. Rev. Lett. **130**, 122503 (2023) – Published 24 March 2023

Physics Synopsis: Highest-Order Electromagnetic Transition Observed



Observations deliver evidence of an exotic "sixth-order" electromagnetic transition in the gamma-ray emission of an iron isotope, a finding that could provide new ways to test nuclear models.

Show Abstract +

Genesis of the project

BA Brown: Several conference presentations drawing attention to *E*6 gamma decay, including Nuclear Data 2013.

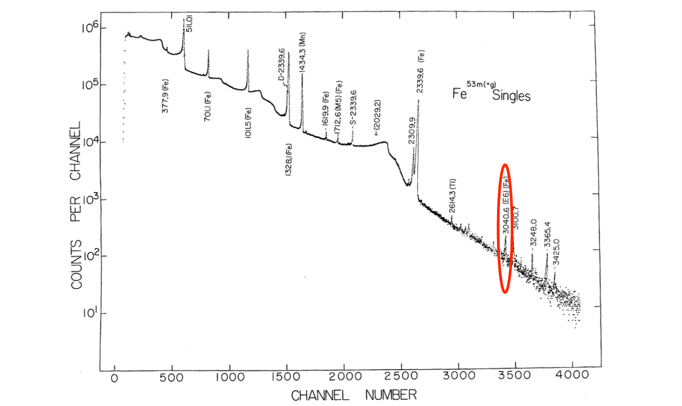


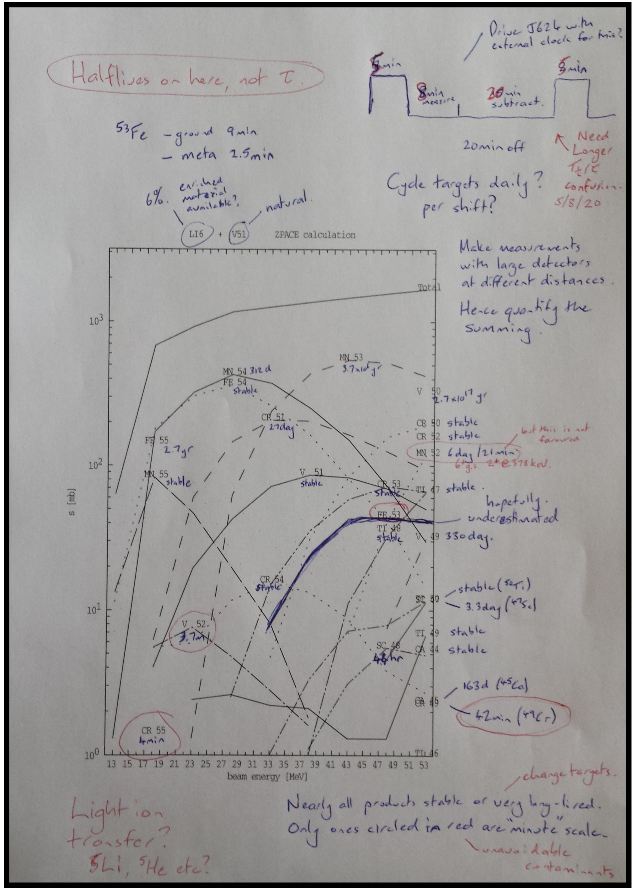
FIG. 2. γ-ray spectrum of $Fe^{53m(+g)}$ taken with a 3.6% Ge(Li) detector. This spectrum represents a 24-h accumulation of data. The *E*6 and *M*5 peaks are so labeled, and the arrow (at 2029.2 keV) shows where a sum peak between the 701.1- and 1328.1-keV transitions would appear.

J.N. Black *et al.*, Phys. Rev. Lett **26**, 451 (1971).

ND2013 audience: "*I bet that's a sum-peak*".

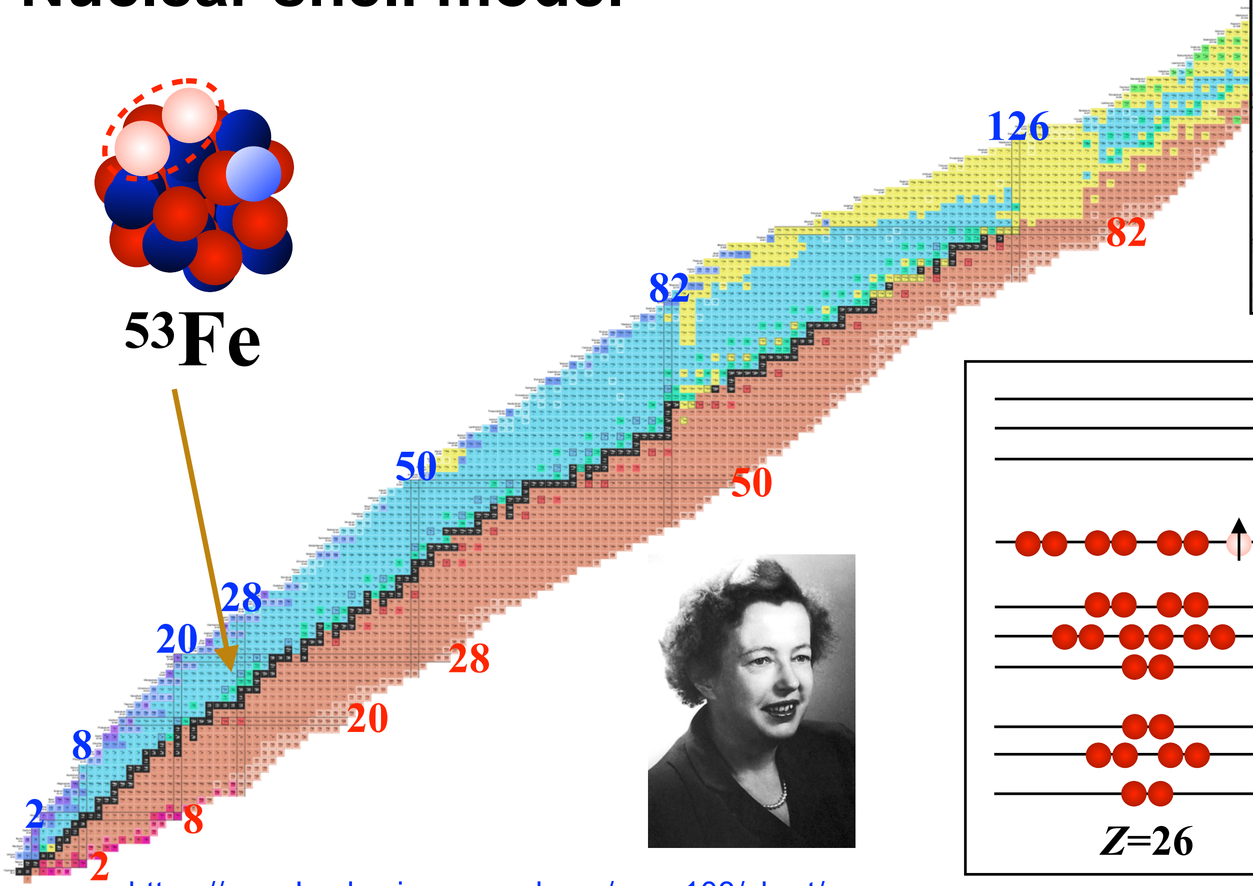
AE Stuchbery to T Kibedi: "*I bet we could measure that*".

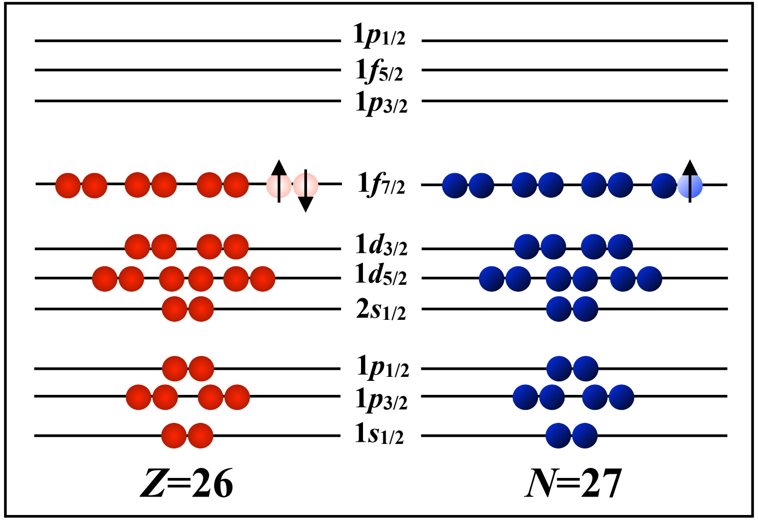
GJ Lane (2015): "*This might work*".



G.J. Lane, private communication (2015)

Nuclear shell model

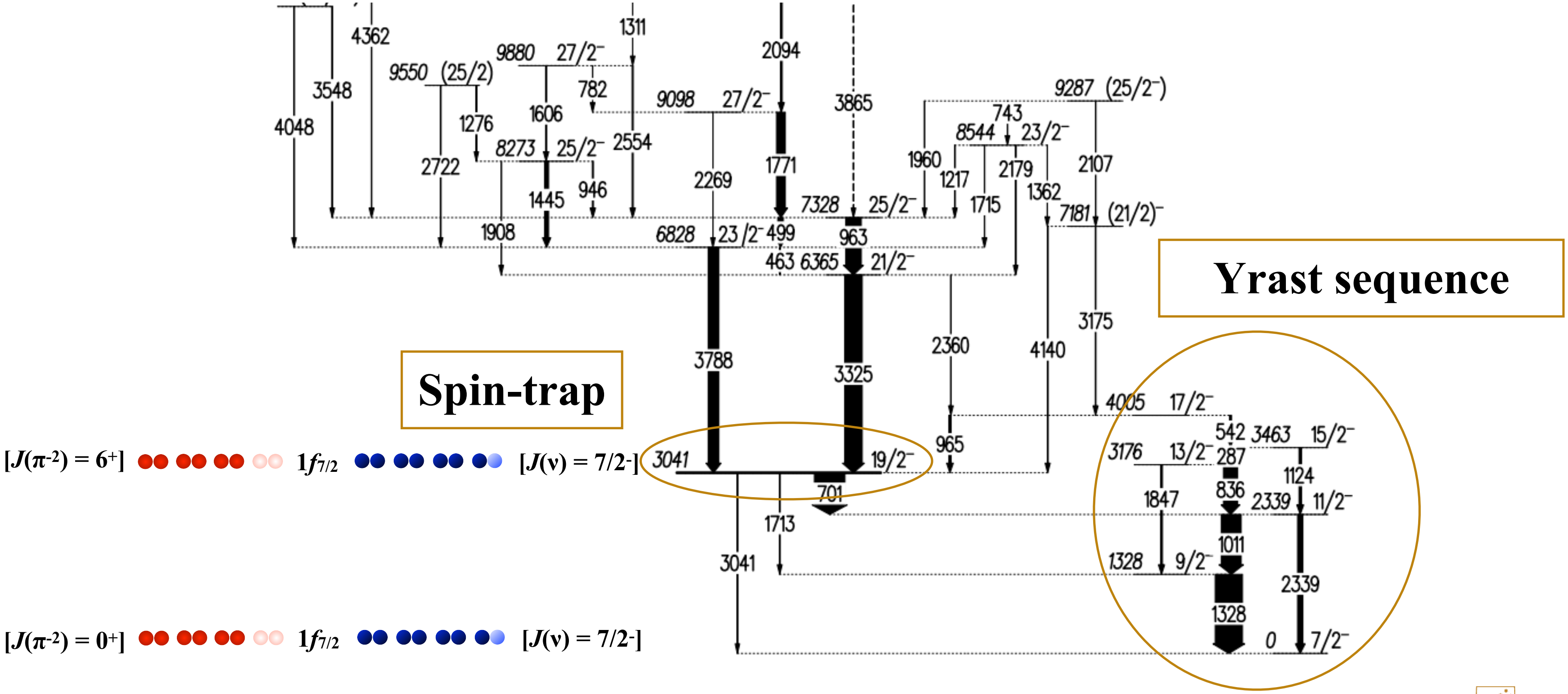




https://people.physics.anu.edu.au/~ecs103/chart/

High-spin states in ^{53}Fe

R. Du Rietz *et al.*, Phys. Rev. C **72**, 014307 (2005).



^{53m}Fe decay

Selection rules:

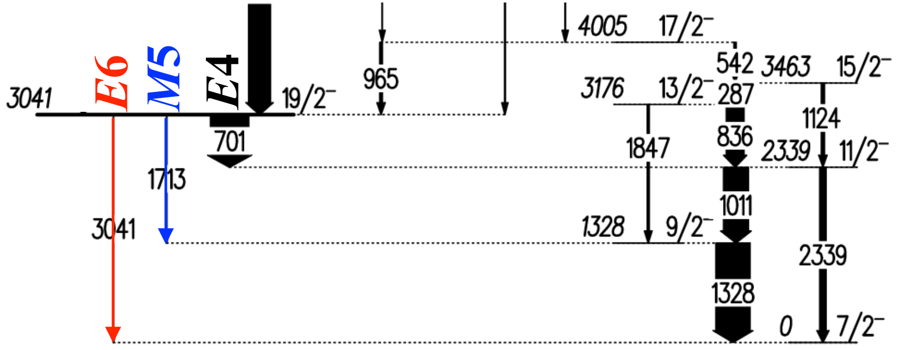
- $|I_i - I_f| \leq L \leq |I_i + I_f|$
- $\Delta P = (-1)^L$ or $(-1)^{L-1}$

In general, gamma decay is dominated by the lowest multipole order permitted:

$$\frac{\lambda(E(L+1))}{\lambda(EL)} \approx 10^{-5}$$

$$\frac{\lambda(M(L+1))}{\lambda(ML)} \approx 10^{-5}$$

$$\frac{\lambda(EL)}{\lambda(ML)} \approx 10^{2}$$



$L = 1, 2$ are prevalent in atomic and nuclear systems
$L = 3$ is rare (around 1100 known)
$L = 4$ is very rare (around 170 known)
$L = 5$ is very, very rare (around 25 known)
$L = 6$ is <u>unique</u> (one claim so far)

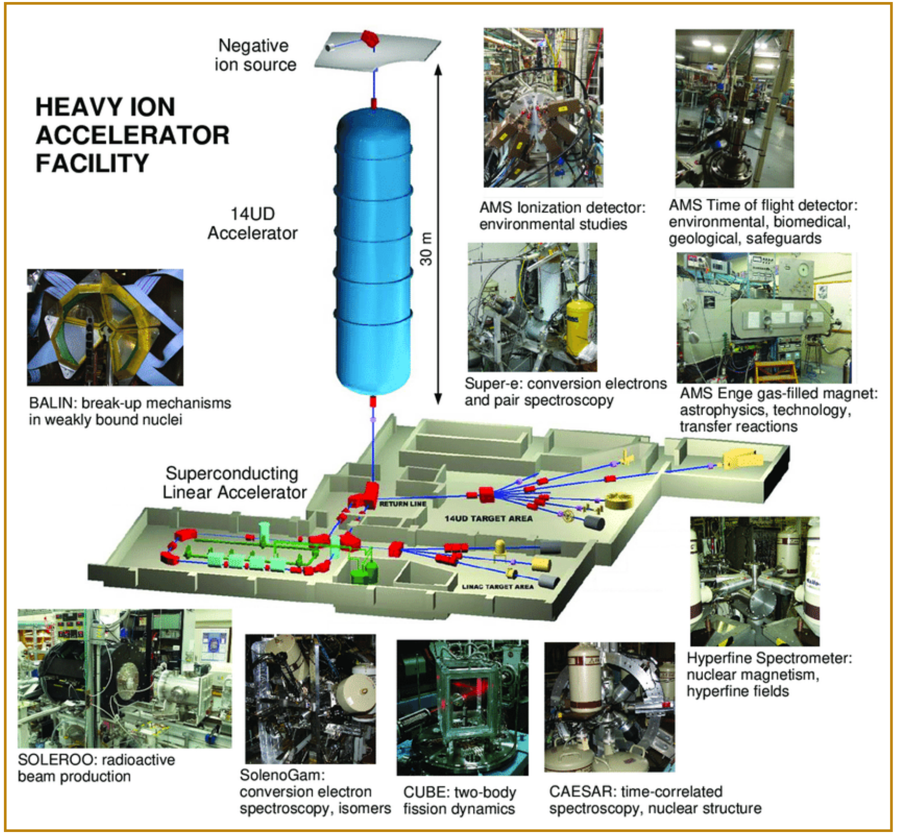
Australian Heavy Ion Accelerator Facility (HIAF)

Accelerators:
- 14UD tandem accelerator (~ 14 MV)
- LINAC (6 MV)

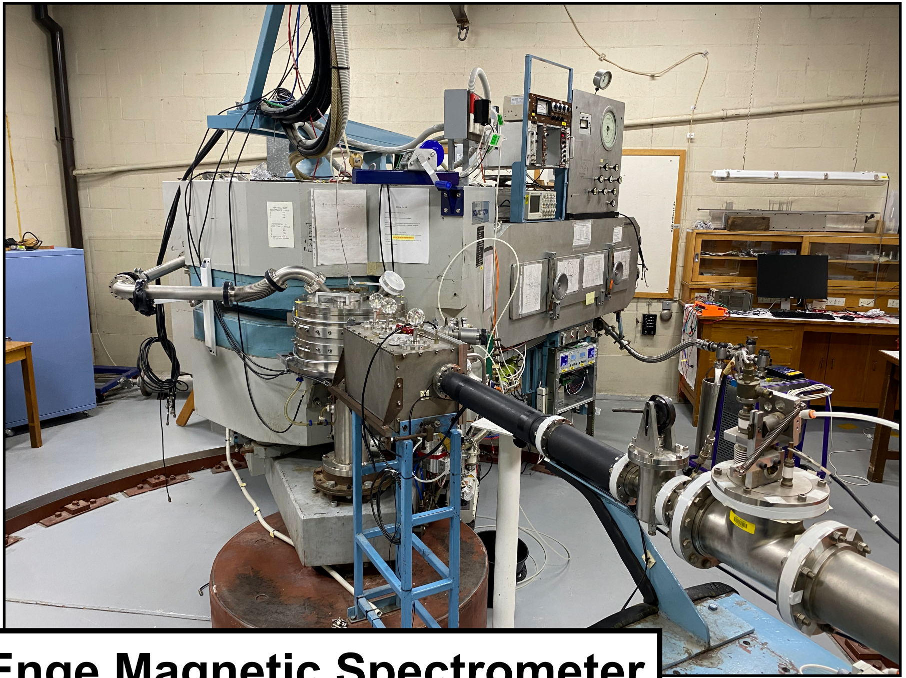
10 beam lines:
- Fundamental research
- Space Irradiation Beam Line

Research:
- Nuclear structure
- Nuclear reaction dynamics
- AMS
- Dark Matter / Astroparticle physics

https://physics.anu.edu.au/tour/nuclear/

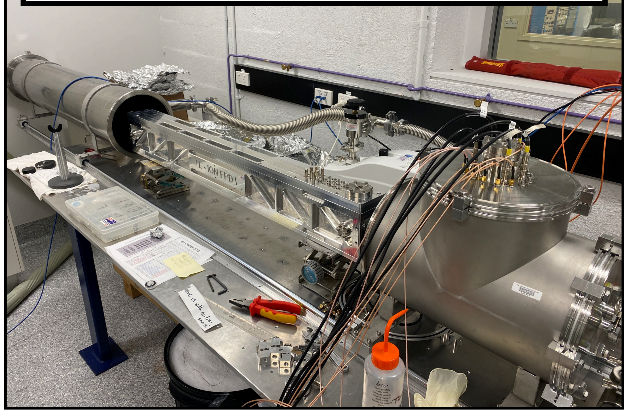


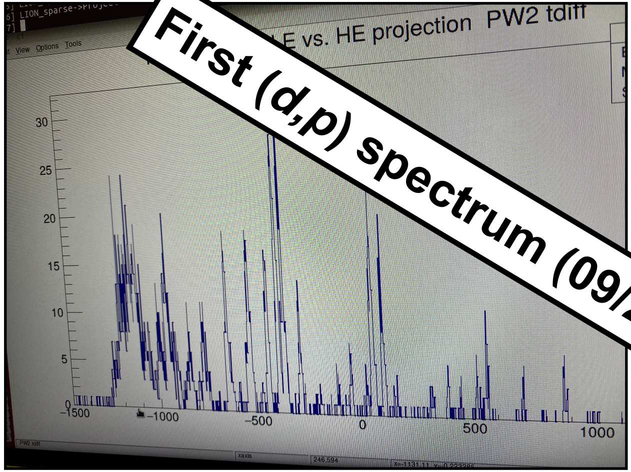
Side-step



Enge Magnetic Spectrometer

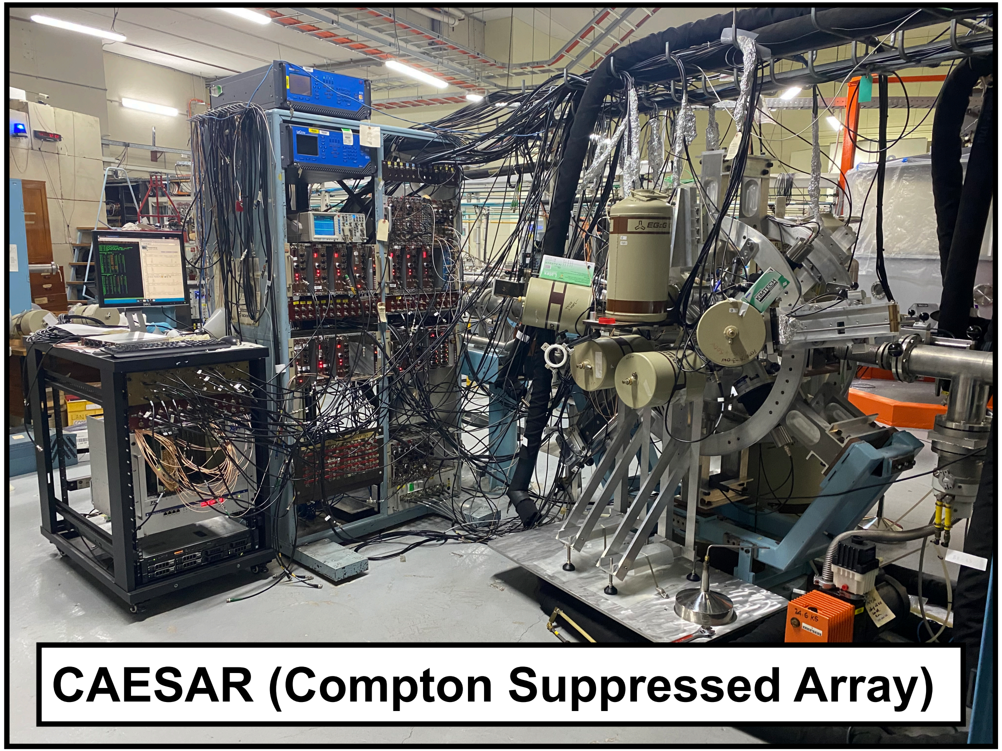
Light-Ion (Lion) detector



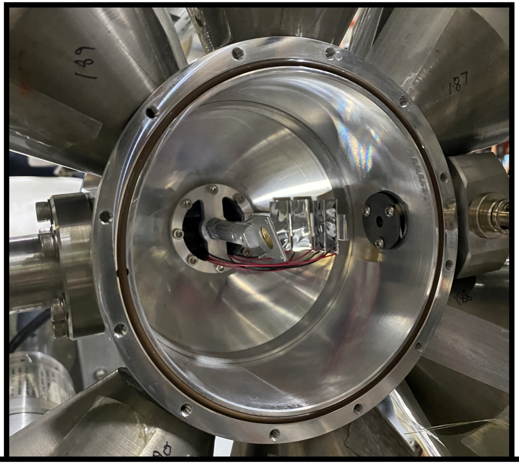


First (d,p) spectrum (09/24)

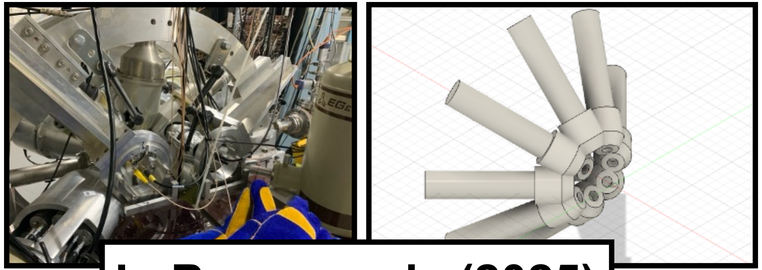
γ-ray spectroscopy



CAESAR (Compton Suppressed Array)



New target chamber (2022)



$LaBr_3$ upgrade (2025)

^{53m}Fe γ-ray data

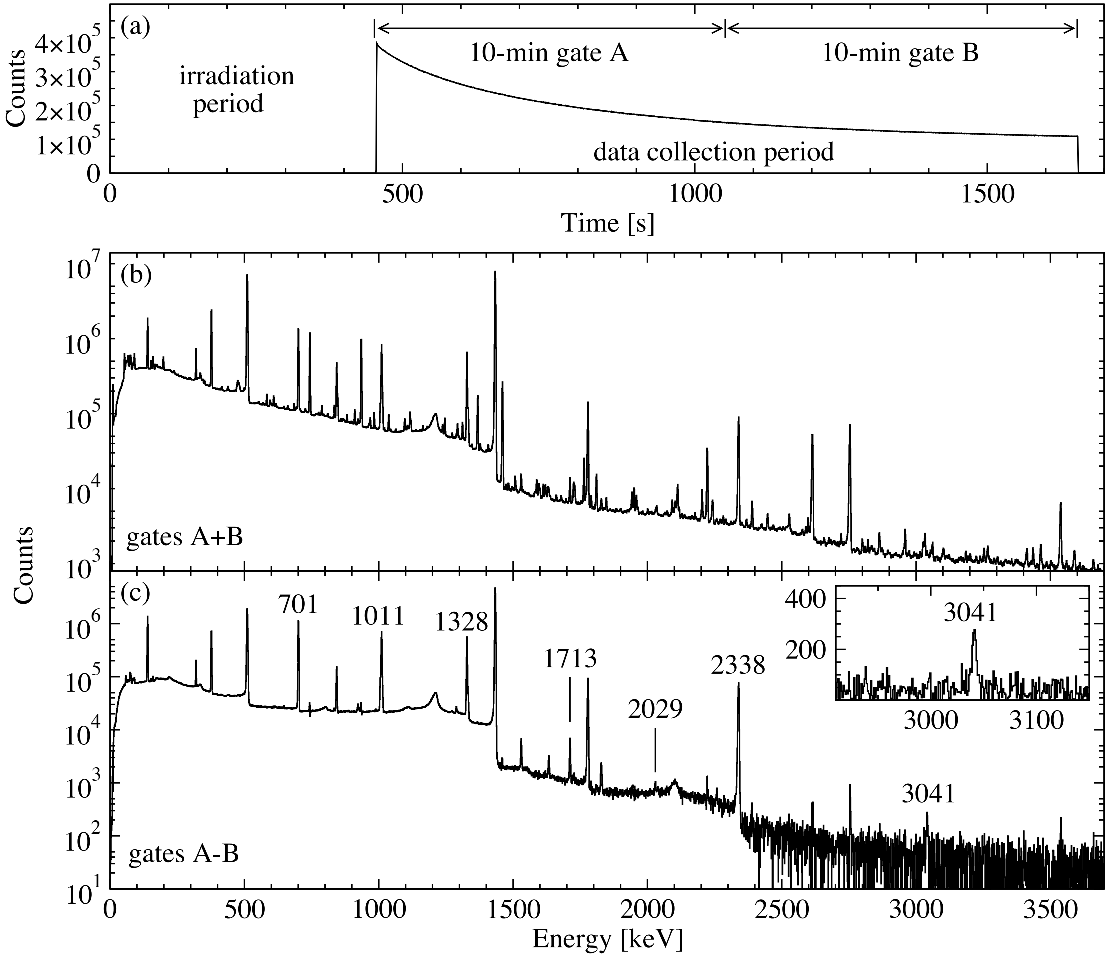
^{51}V(^{6}Li,4n)^{53m}Fe, 2 pnA, 50 MeV
10 mg/cm^2 targets

Repeating irradiation cycle:
7.5 minutes beam on (production)
20 minutes beam off (isomer decay)

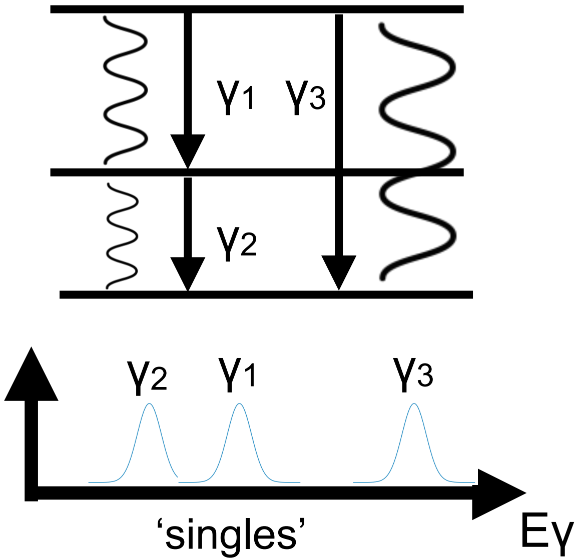
Gates A + B:
~ 10 different nuclides.

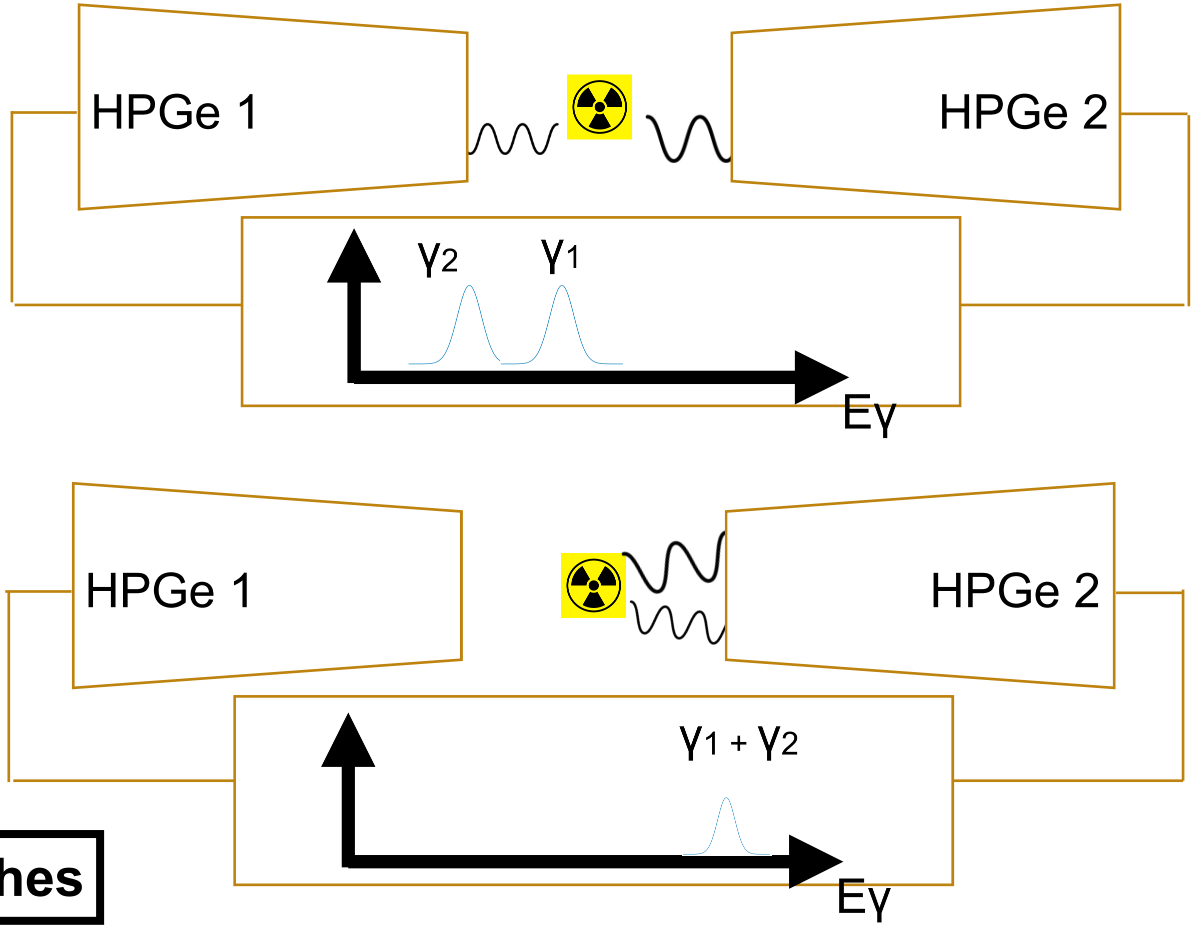
Gates A - B:
Isolate ^{53m}Fe decay.

- Known γ rays from ^{53m}Fe
- Including (weak) peak at 3041 keV
- And a feature at 2029 keV



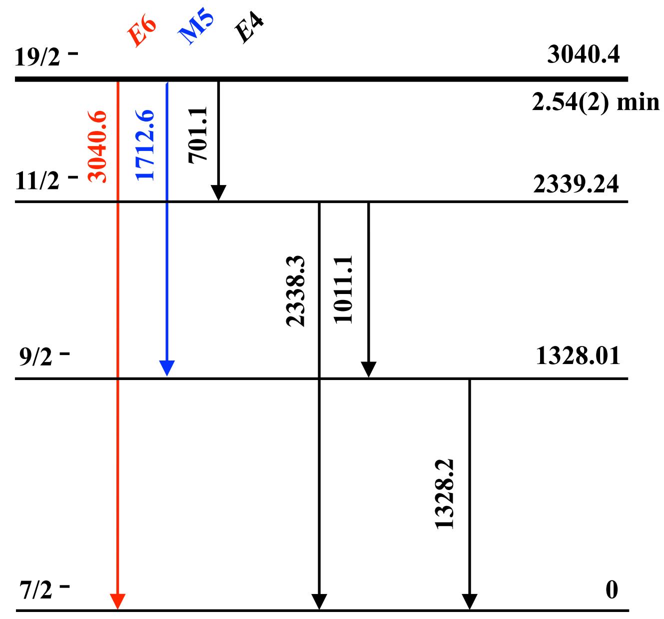
γ-ray summing





Problem for weak branches

γ-ray summing



$$Y_\gamma = I_\gamma + \Sigma S_i,$$

Method 1: 'Experimental'

$$Y_{2029} = S_{2029} = I_{701} \cdot \varepsilon_{701} \cdot b_{1011} \cdot b_{1328} \cdot \varepsilon_{1328} \times \overline{W}_{701,1328}(0).$$

Expressions that connect sum components to S_{2029}, I_i, b_i, ε_i, $\overline{W}_{i,j}(0)$.

Method 2: 'Geometric'

Considering the change in counting efficiency with moving the radial detectors.

Method 3: 'Computational'

Single expression that combines quantities that were measured in the experiment.

$$\begin{aligned} Y_{3041} = {} & I_{3041} \cdot \varepsilon_{3041} \\ & + I_{701} \cdot b_{2338} \cdot \varepsilon_{701} \cdot \varepsilon_{2338} \cdot \overline{W}_{701,2338}(\theta) \\ & + I_{1713} \cdot b_{1328} \cdot \varepsilon_{1713} \cdot \varepsilon_{1328} \cdot \overline{W}_{1713,1328}(\theta) \\ & + I_{701} \cdot b_{1011} \cdot b_{1328} \cdot \varepsilon_{701} \cdot \varepsilon_{1011} \cdot \varepsilon_{1328} \\ & \times \overline{W}_{701,1011,1328}(\theta). \end{aligned}$$

Method 4: 'Monte Carlo'

Decay of ^{53m}Fe proceeds via randomised pathways that are weighted by the measured transition branching ratios.

Sum-component is ≈ 50% of the total yield of the 3041-keV γ ray

Results

E_{Level}	E_γ	σL	I_γ			$B(\sigma\lambda)$ (W.u)		$B(\sigma\lambda)$ ($e^2fm^{2\lambda}$, μ_N^2 $fm^{2\lambda-2}$)	
			This work	Ref. [1]	Ref. [2]	This work	I_γ [2]	This work	I_γ [2]
3040.4	701.1(1)	$E4$	≡100	≡100	≡100	0.2593(21)	0.2587(21)	$6.46(5)\times10^2$	$6.44(6)\times10^2$
	1712.6(3)	$M5$	1.05(5)	0.7(1)	1.3(1)	4.34(21)	5.4(4)	$3.31(16)\times10^5$	$4.1(3)\times10^5$
	3040.6(5)	$E6$	0.056(17)	0.020(5)	0.06(1)	0.42(12)	0.45(8)	$2.61(81)\times10^5$	$2.8(5)\times10^5$

[1] 10.1103/PhysRevLett.26.451

[2] 10.1103/PhysRevC.11.939

- Sum contributions to *E4*, *M5*, *E6* accounted for.
- Reduced transition strengths deduced.
- Consistent with the 1975 value of Black *et al*, and an unpublished result in D. Geesaman's PhD thesis.

$$B(XL; J_i \to J_f) = \frac{L[(2L+1)!!]^2}{8\pi(L+1)}\left(\frac{\hbar c}{E_\gamma}\right)^{2L+1} P_\gamma(XL; I_i \to I_f)$$

$$B_w(EL; J_i \to J_f) = \frac{1}{4\pi}\left(\frac{3}{L_\gamma+3}\right)^2 r^{2L}\ \{e^2(fm)^{2L}\}$$

$$B_w(ML; J_i \to J_f) = \frac{10}{\pi}\left(\frac{3}{L_\gamma+3}\right)^2 r^{2L-2}\ \{\mu_n^2(fm)^{2L-2}\}$$

Interpretation

Reduced transition strength → $$B(XL; J_i \rightarrow J_f) = \frac{\mathscr{M}^2}{2J_i + 1}$$ ← Reduced matrix element

$\mathscr{A}_{p,n}$ calculated

$$\mathscr{M} = \mathscr{A}_p \cdot \epsilon_p + \mathscr{A}_n \cdot \epsilon_n$$

Effective nucleon charge

Proton

Neutron

$$\epsilon_{p,n} = e_{p,n} + \delta_{p,n}$$

Bare nucleon charge

Core-polarisation charge

SM theory

Nuclear Data Sheets
Volume 120, June 2014, Pages 115-118

The Shell-Model Code NuShellX@MSU

B.A. Brown[a], W.D.M. Rae[b]

- Shell-model calculations: **restricted ($f_{7/2}$)^{13}** and **full *fp* shell**
- GFPX1A and KB3G Hamiltonians used
  - Restricted model space similar to historical work.
  - Full model space reduced by roughly half.

σL	$\mathcal{A}_p \times 10^3$	$\mathcal{A}_n \times 10^3$	$\mathcal{M} \times 10^3$	$\mathcal{M}_p^{\text{expt.}} \times 10^3$
$E4$	0.142(17)	0.045(7)	-	0.1137(5)
$M5$	5.09(76)	-0.11(2)	4.98(76)	2.57(6)
$E6$	3.52(63)	0.22(4)	-	2.29(35)

Two 'observations':
- *E*2 transitions are generally enhanced in the full *fp*-shell model space.
- Dominated by the proton component (A_p and A_n similar in strong *B*(*E*2)s in the region).

Proton effective charges

$\epsilon_p + \epsilon_n \approx 2.0$

***E*2 effective charge:** $\epsilon_p \approx 1.12$

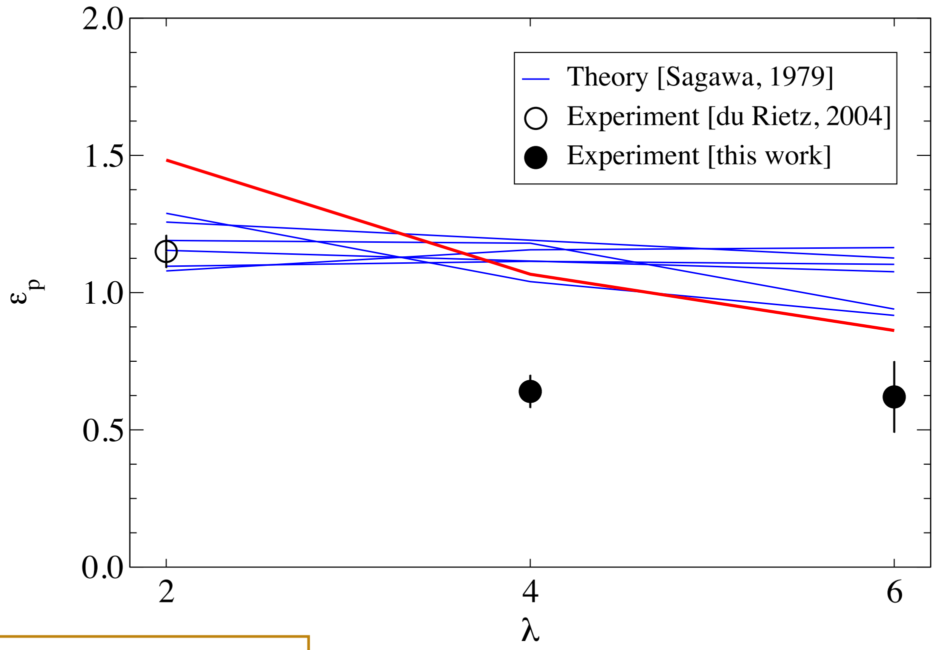
***E*4 effective charge:** $\epsilon_p = 0.64(6)$

***E*6 effective charge:** $\epsilon_p = 0.62(13)$

These can be evaluated by considering coupling of valence nucleons to (core) particle-hole excitations.

Choice of—**and sensitivity to**—the residual particle-hole interaction adopted in the calculation.

Considered for seven interactions by Sagawa.
- Wigner-type (red) interaction closest match.



Excellent agreement for λ = 2

All of the theoretical results are too large for λ=4 and λ=6.

10.1103/PhysRevC.19.506

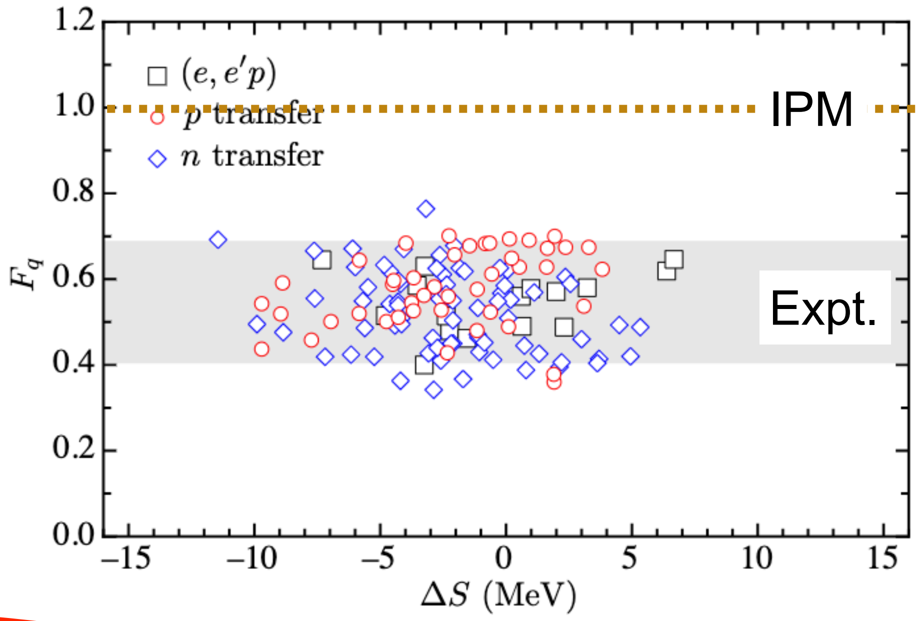
Connection to single-particle behaviour?

***E*6 matrix element and (*e,e’p*) cross sections:**

- both expressed in spectroscopic amplitudes.
- both ‘quenched’ by a similar magnitude.

Attributed to short- and long-range correlations.

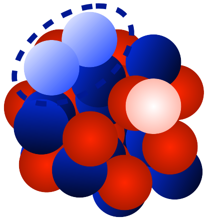
Similarities suggest these are connected.



Any model developed to understand quenching of reaction cross sections should be extended to calculations of electromagnetic matrix elements.

10.1103/PhysRevLett.111.042502

Where to from here?



^{53}Co

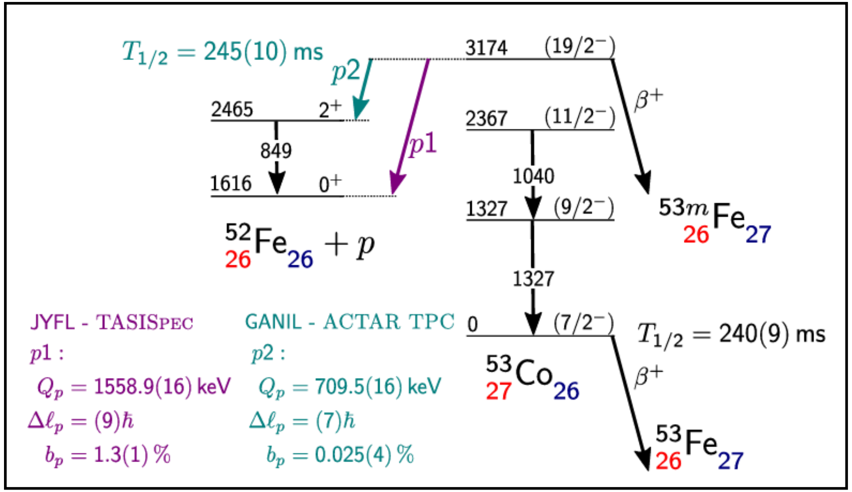
L. G. Sarmiento, *et al.* Nat. Commun. **14**, 5961 (2023).

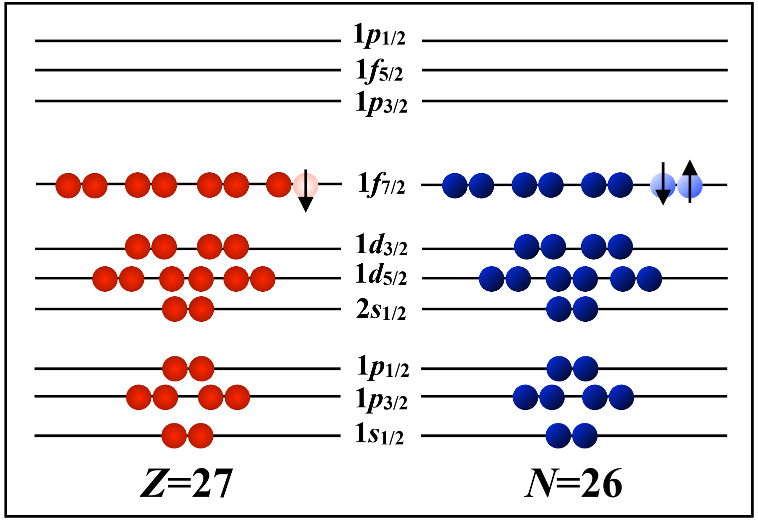
nature communications

Article

https://doi.org/10.1038/s41467-023-39389-2

Elucidating the nature of the proton radioactivity and branching ratio on the first proton emitter discovered ^{53m}Co





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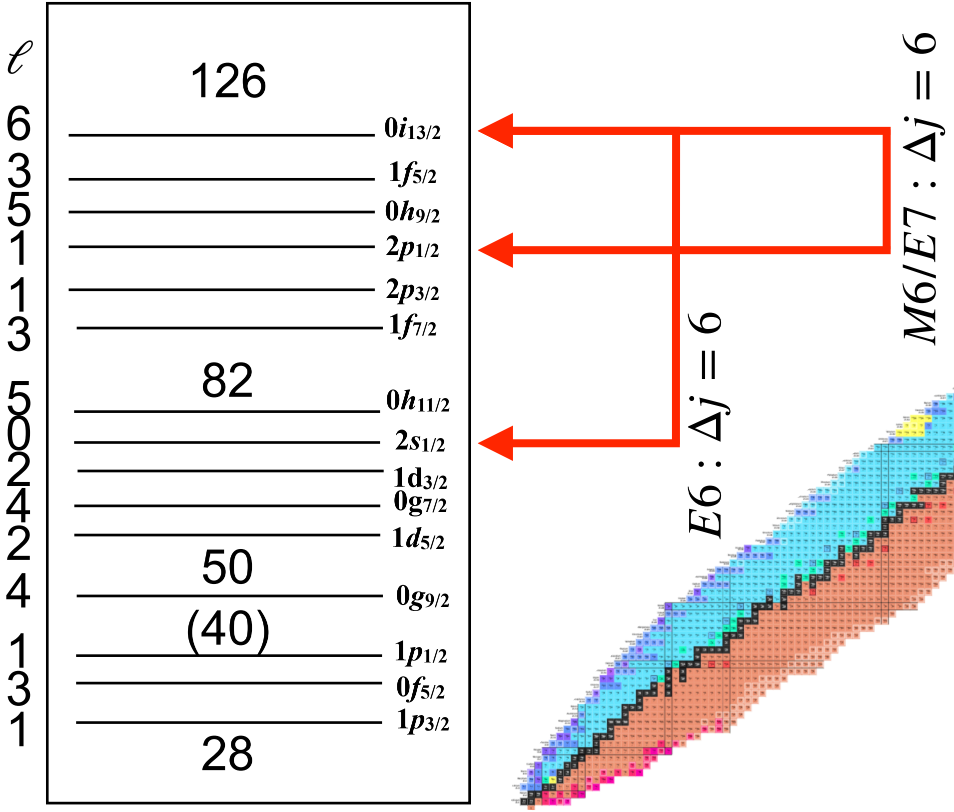
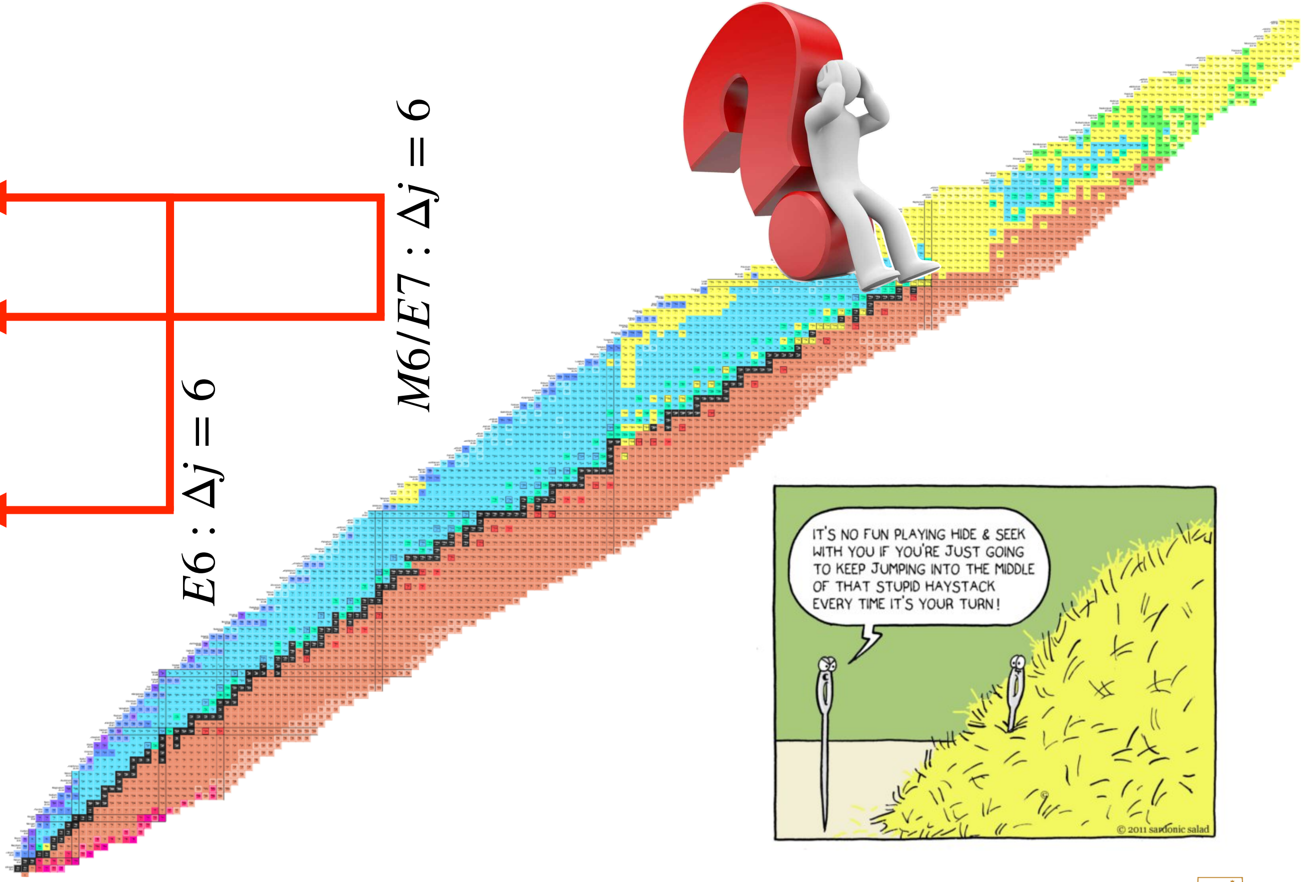
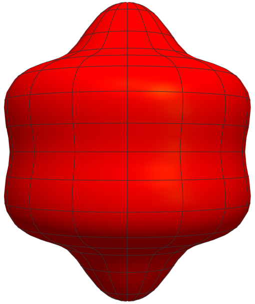




Summary

- **Unambiguous confirmation** of the highest-known transition multipolarity in nature (*E*6).
- **Transition strengths** for the high-multipolarity transitions from the 2.54-minute, J=19^- isomer in ^{53}Fe have been determined.
- **Shell-model calculations** highlight the need for cross-shell mixing to explain the experimentally observed strengths.
- **Proton effective charges** are suppressed in high-multipolarity, electric transitions, which are fundamentally different in nature from collective *E*2 transitions.
- **Deeper theoretical investigation required to fully understand the difference.**



THANK YOU

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National
University