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

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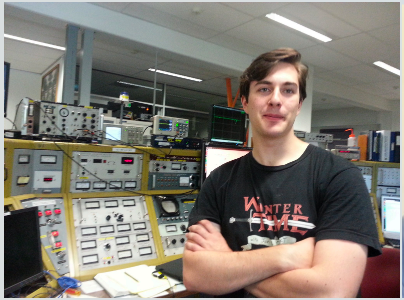
Heavy Ion Accelerators

NCRIS
National Research Infrastructure for Australia
An Australian Government Initiative

Australian Government
Australian Research Council

Australian National University

Collaboration

Thomas Palazzo
ANU MPhil student

Greg Lane
ANU

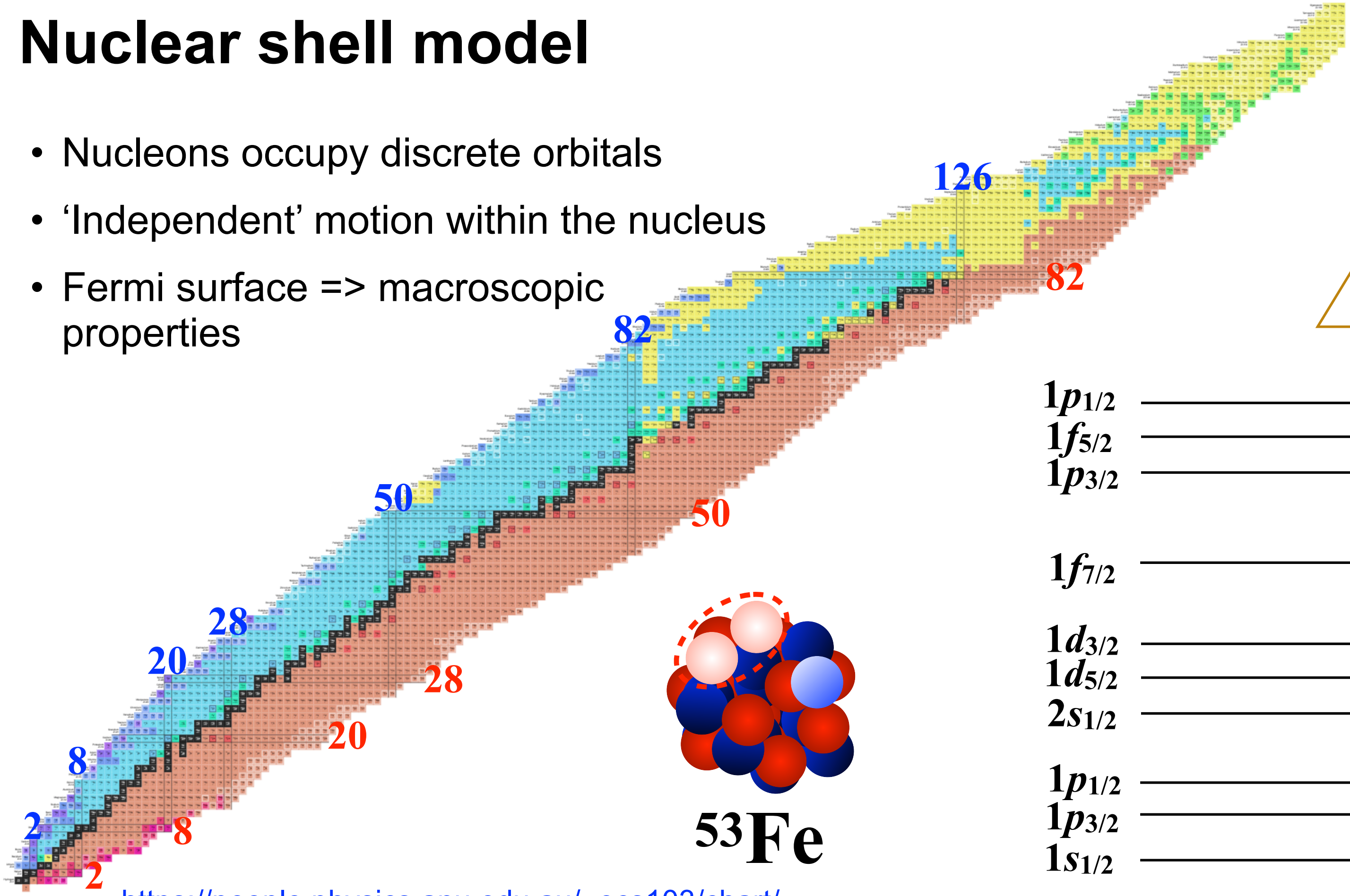
Andrew Stuchbery
ANU

Alex Brown
MSU/FRIB
(Theory)

… as well as M. W. Reed, A. Akber, B. J. Coombes, J. T. H. Dowie, M. S. M. Gerathy, T. Kibedi, and M. O. de Vries.
Department of Nuclear Physics and Accelerator Applications, ANU

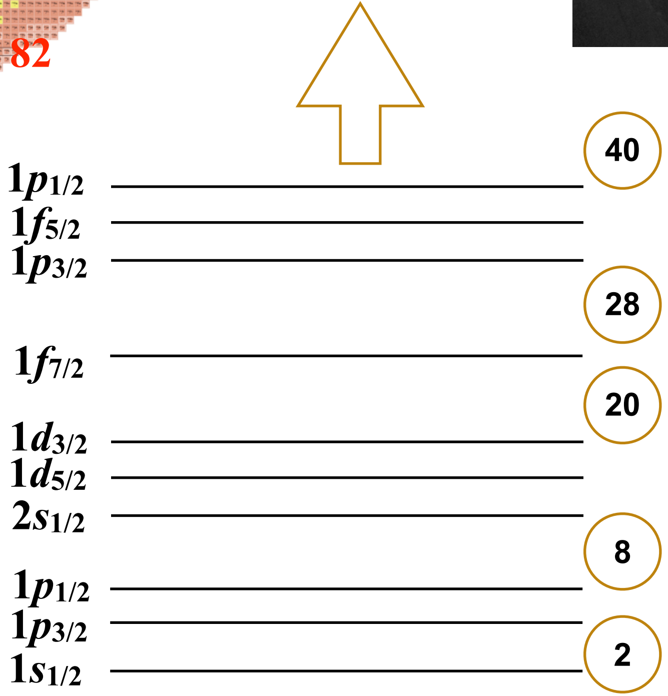
Nuclear shell model

- Nucleons occupy discrete orbitals
- ‘Independent’ motion within the nucleus
- Fermi surface => macroscopic properties

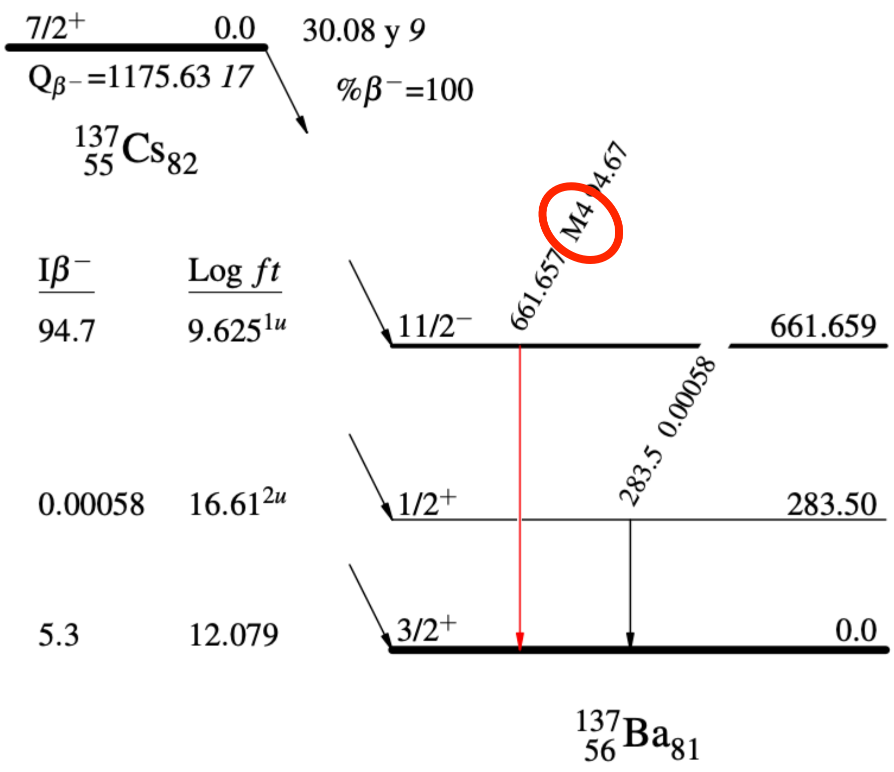


https://people.physics.anu.edu.au/~ecs103/chart/

^{53}Fe



γ decay



E. Browne, J. K. Tuli NDS 108, 2173 (2007)

Rules to obey:

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

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

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

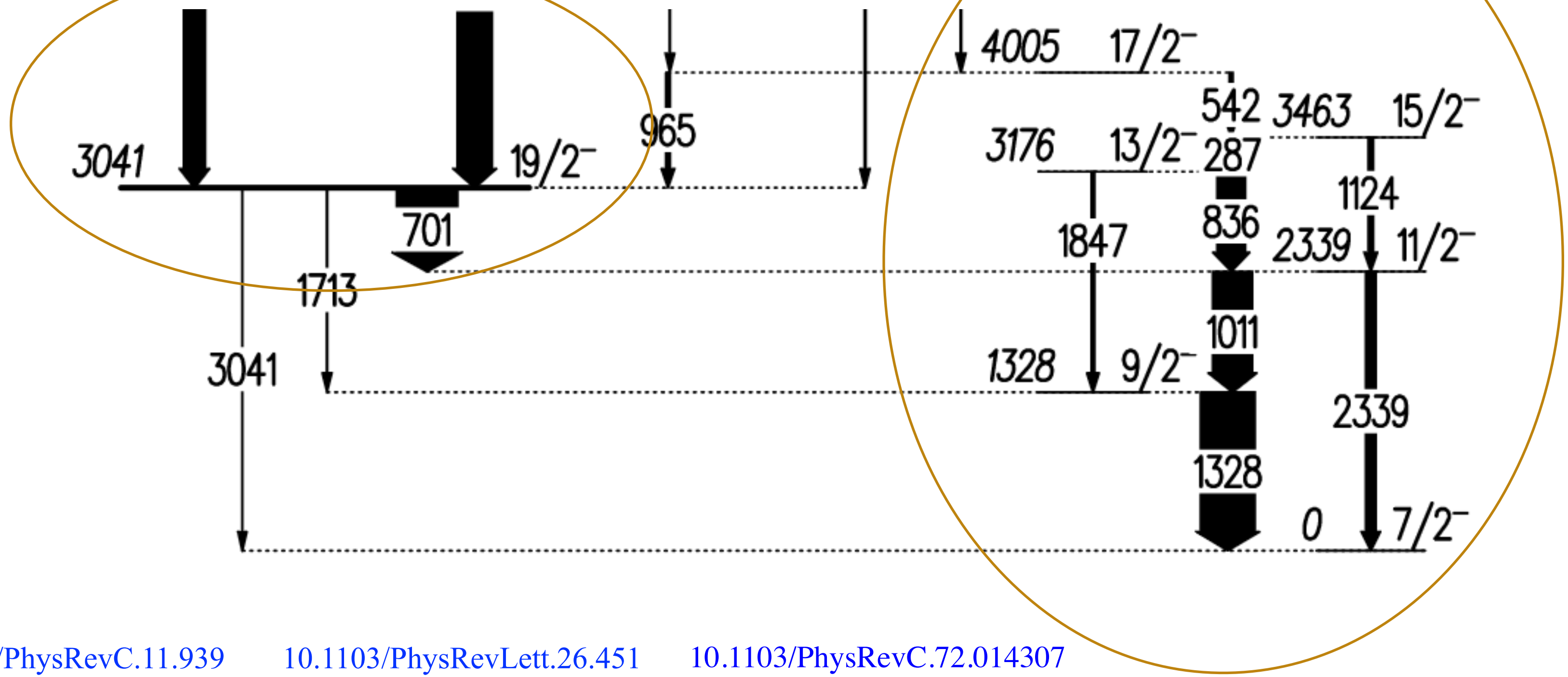
… and $\dfrac{\lambda(EL)}{\lambda(ML)} \approx 10^2$

$L = 1{,}2$ prevalent in atomic and nuclear systems
$L = 3$ rare (around 1100 known)
$L = 4$ very rare (around 170 known)
$L = 5$ very, very rare (around 25 known)
$L = 6$ unique (one claim so far)

^{53}Fe: High-spin states

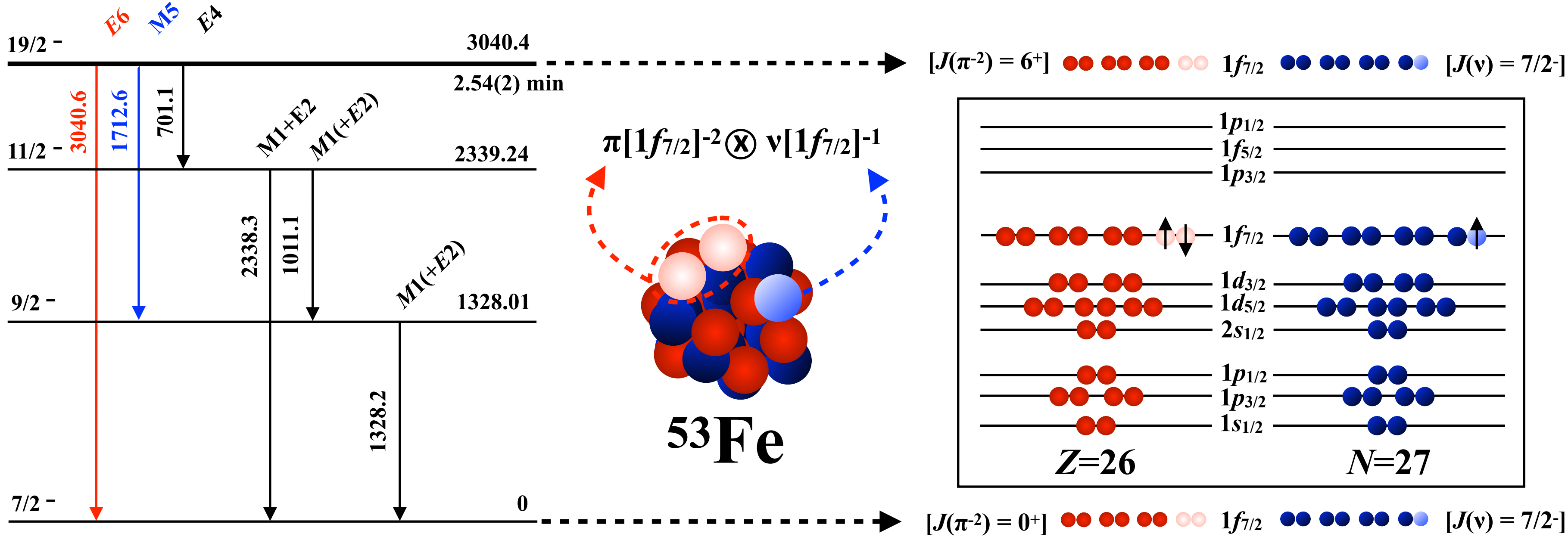
Something out of place

Yrast cascade based on g.s.



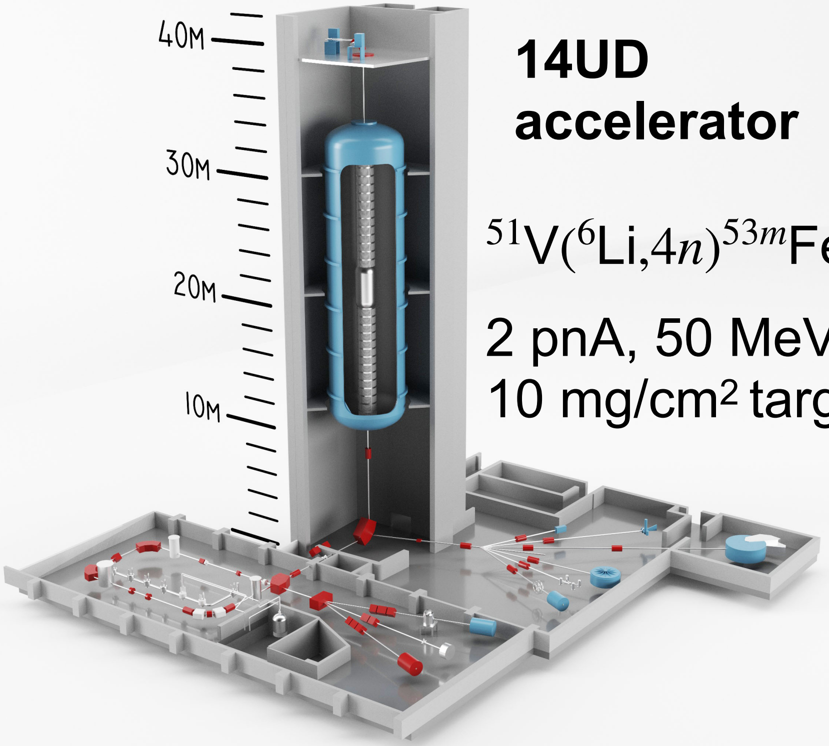
10.1103/PhysRevC.11.939 10.1103/PhysRevLett.26.451 10.1103/PhysRevC.72.014307

^{53m}Fe decay



Unique testing ground for nuclear structure.
Requires very careful experiments…

Experiments: Heavy Ion Accelerator Facility

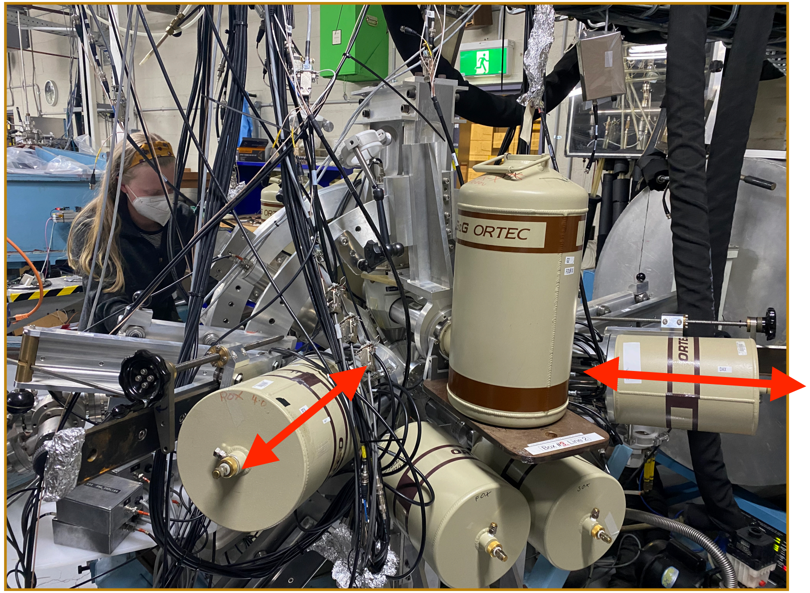


14UD accelerator

^{51}V(^{6}Li,4n)^{53m}Fe

2 pnA, 50 MeV
10 mg/cm^2 targets

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



CAESAR array ⟷

Moved from ≈ 8.5 cm to ≈ 12 cm

Martha Reece, Tuesday 3 pm

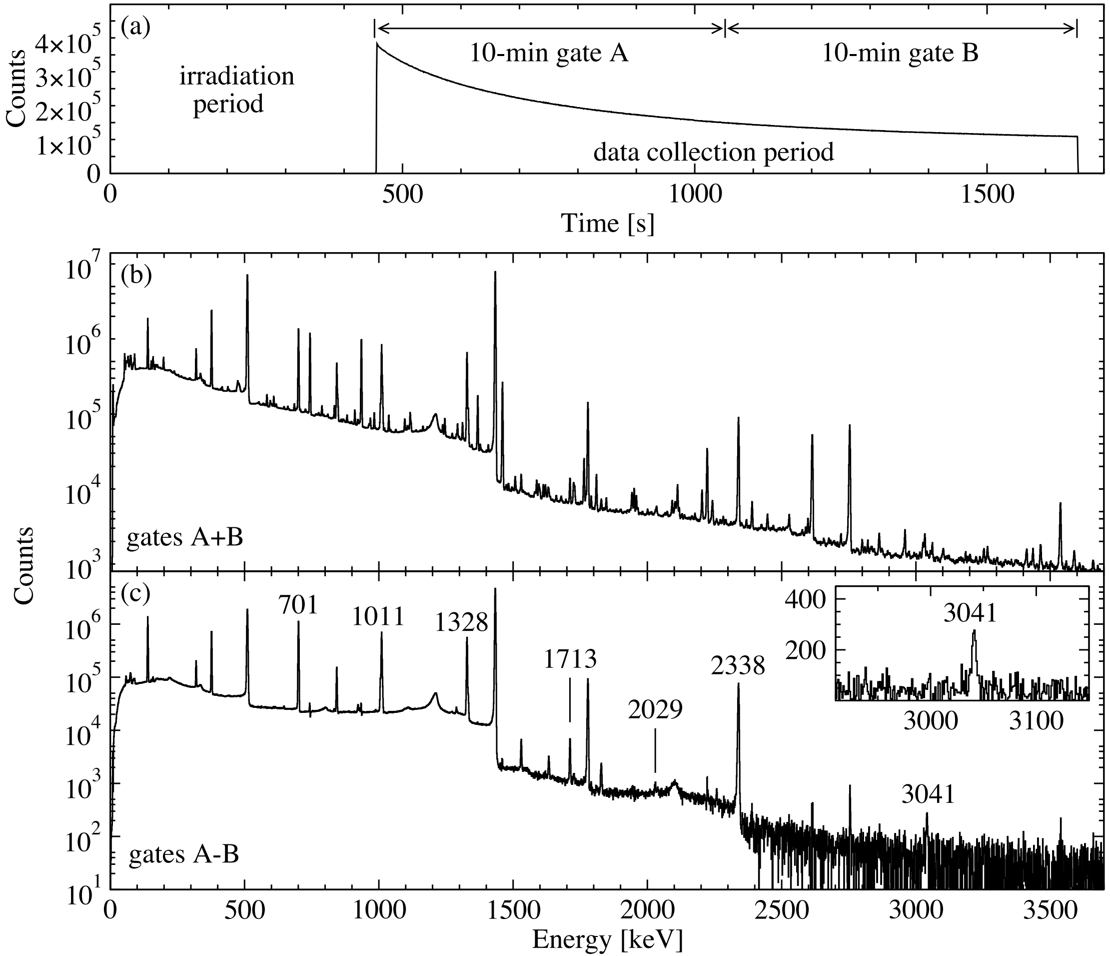
γ-ray data

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

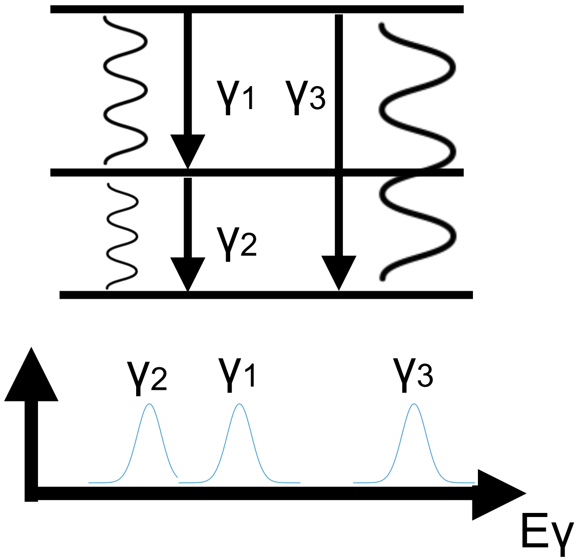
Gates A + B:
~ 10 different nuclides.

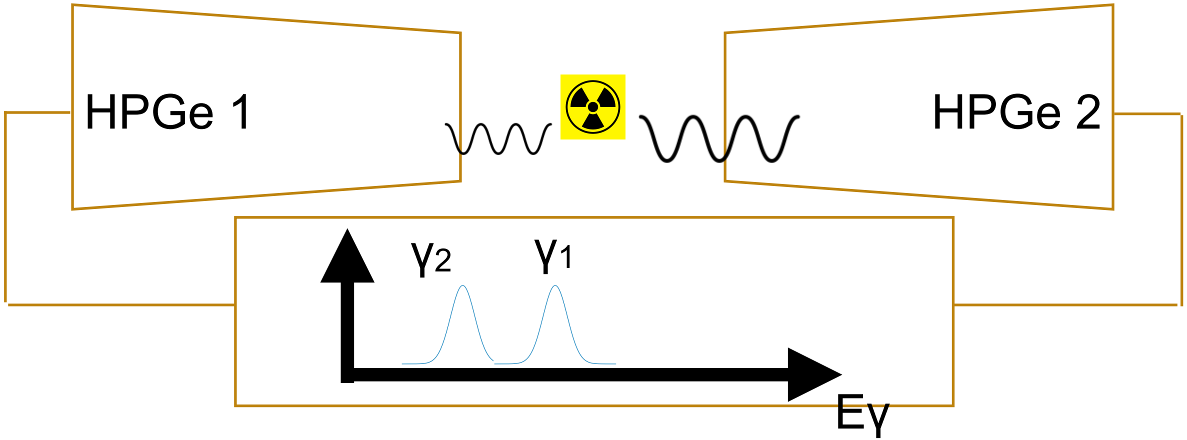
Gates A - B:
Isolate ^{53m}Fe decay.

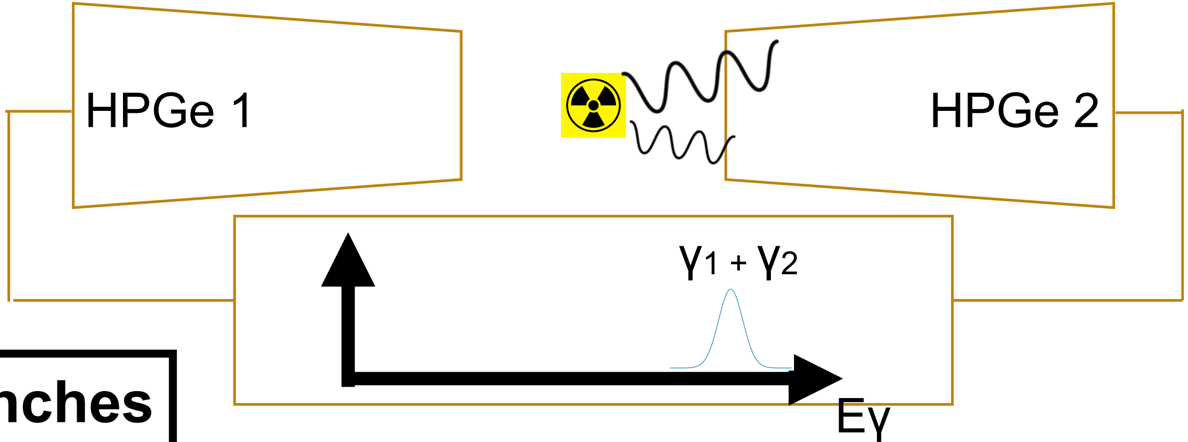
- Known γ rays from ^{53m}Fe
- Including (weak) peak at 3041 keV
- And a feature at 2029 keV



γ-ray summing

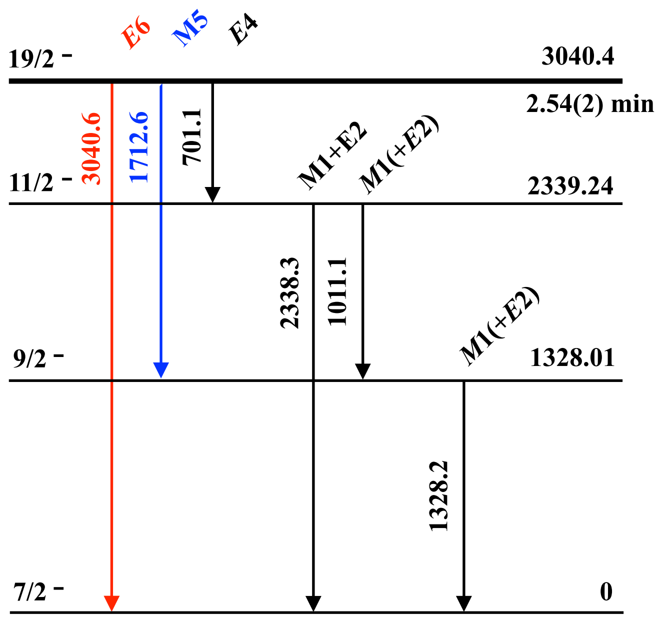






Problem for weak branches

γ-ray summing



$$Y_3 = I_3 \cdot \varepsilon_3 + S_{2,1},$$

$$S_{2,1} = I_2 \cdot \varepsilon_2 \cdot b_1 \cdot \varepsilon_1 \cdot \overline{W}_{2,1}(0),$$

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.

Method 3: 'Computational'

Single expression that only includes quantities that were measured directly 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 of this work.

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)		$B(\sigma\lambda)$ ($e^2\text{fm}^{2\lambda}$, μ_N^2 $\text{fm}^{2\lambda-2}$)	
			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)	$2.61(81)\times10^5$	$2.8(5)\times10^5$
2339.24	1011.2(2)	$M1(+E2)$	79.4(3)	86(9)	86(9)				
	2338.3(5)	$M1+E2$	22.3(2)	13(2)	13(2)				

- Sum contributions to *E4*, *M5*, *E6* accounted for
- **Confirmation that the *E6* is real**
- Confident measurement of the branching ratios
- Reduced transition strengths deduced for the isomer

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

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

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

[1] 10.1103/PhysRevLett.26.451 [2] 10.1103/PhysRevC.11.939

Terminology

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

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

Effective nucleon charge

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

Proton

Neutron

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

Bare nucleon charge

Core-polarisation charge

Theory

ELSEVIER

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 in restricted $(f_{7/2})^{13}$ and full *fp* shell
- GFPX1A and KB3G Hamiltonians used
- Restricted model space similar to historical work
- Full model space x2 smaller than restricted model space

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 surprises:

- **E2 transitions generally enhanced in the full *fp*-shell model space**
- **Dominated by the proton component (A_p and A_n similar in strong B(E2)s in the region)**

Proton effective charges

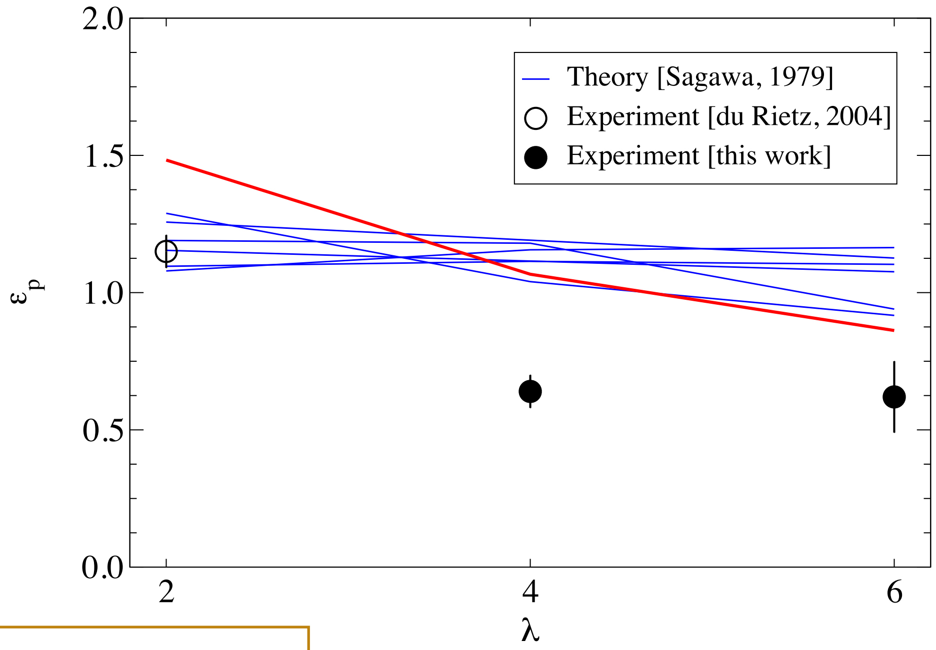
$$\epsilon_p + \epsilon_n \approx 2.0$$

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.

Calculated for seven interactions by Sagawa.

- **Wigner-type** interactions is closest matched.



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?

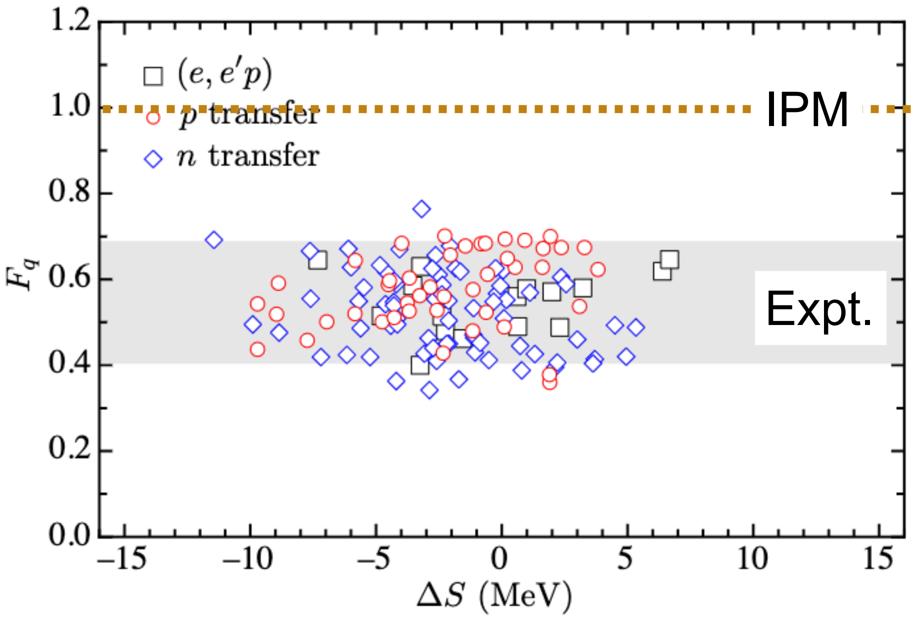
Similar surprises noted in single-particle strength from transfer reactions

=> short- and long-range correlations

=> clues about the nuclear mean field?

Matrix elements of single-particle operators expanded as overlap integrals between eigenstates of *A* and (*A*+1)

=> high-multipolarity transitions appear to be sensitive probes of single-particle features in atomic nuclei.

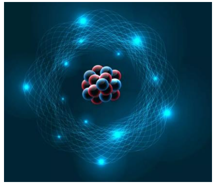


10.1103/PhysRevLett.111.042502

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 from the newly measured branching ratios.
- **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.**

You're all invited!



14 DECEMBER 2022

AUSTRALIAN INSTITUTE OF PHYSICS CONGRESS FOCUSED SESSION: NATIONAL VISION FOR NUCLEAR SCIENCE AND APPLICATIONS

The 2021 AUKUS security agreement brought Australia's sovereign capability in nuclear science sharply into focus. However, **research in nuclear and radiation science and its applications** extends far beyond the realm of nuclear-powered submarines (e.g., targeted radiotherapy and diagnostics, space-related industry, quantum technology, nuclear engineering, environmental monitoring, critical minerals and mining industries to name a few). To facilitate this, **a national and multi-level approach to nuclear education** is urgently required to uplift capacity and train a capable workforce.

This **Focused Session at the Australian Institute of Physics Congress** aims to connect many of the nation's nuclear experts to address this topic through short presentations and discussion. It will enable established and emerging research and education groups to further identify areas of common interest, and develop ideas to achieve a national approach to nuclear science and applications.

Participants from all backgrounds are welcome. For more information, please visit the Congress website or contact the session convenor.

https://aip-congress.org.au/

aip AUSTRALIAN INSTITUTE OF PHYSICS

Confirmed speakers

Prof Eva Bezak,
University of South Australia.

Dr Ceri Brenner,
Australian Nuclear Science and Technology Organisation.

Prof Mahananda Dasgupta,
Australian National University.

Dr Jacinda Ginges,
University of Queensland.

Gary Hale,
Curtin University

Cameron Jeffries,
Australasian Radiation Protection Accreditation Board.

Dr Edward Obbard,
University of New South Wales.

A/Prof Scott Penfold,
Australian Bragg Centre for Proton Therapy and Research, and University of Adelaide.

Prof Nigel Spooner,
University of Adelaide.

Convened by Dr AJ Mitchell,
Australian National University.

EVENT DETAILS

Location: Adelaide Convention Centre

Date: 14 December 2022

Session 1: 11:00 – 12:30
Session 2: 14:00 – 15:30

Contact: aj.mitchell@anu.edu.au

Focused Session

Wednesday

11:00-12:30

14:00-15:50

THANK YOU

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^{53}Fe: High-spin states