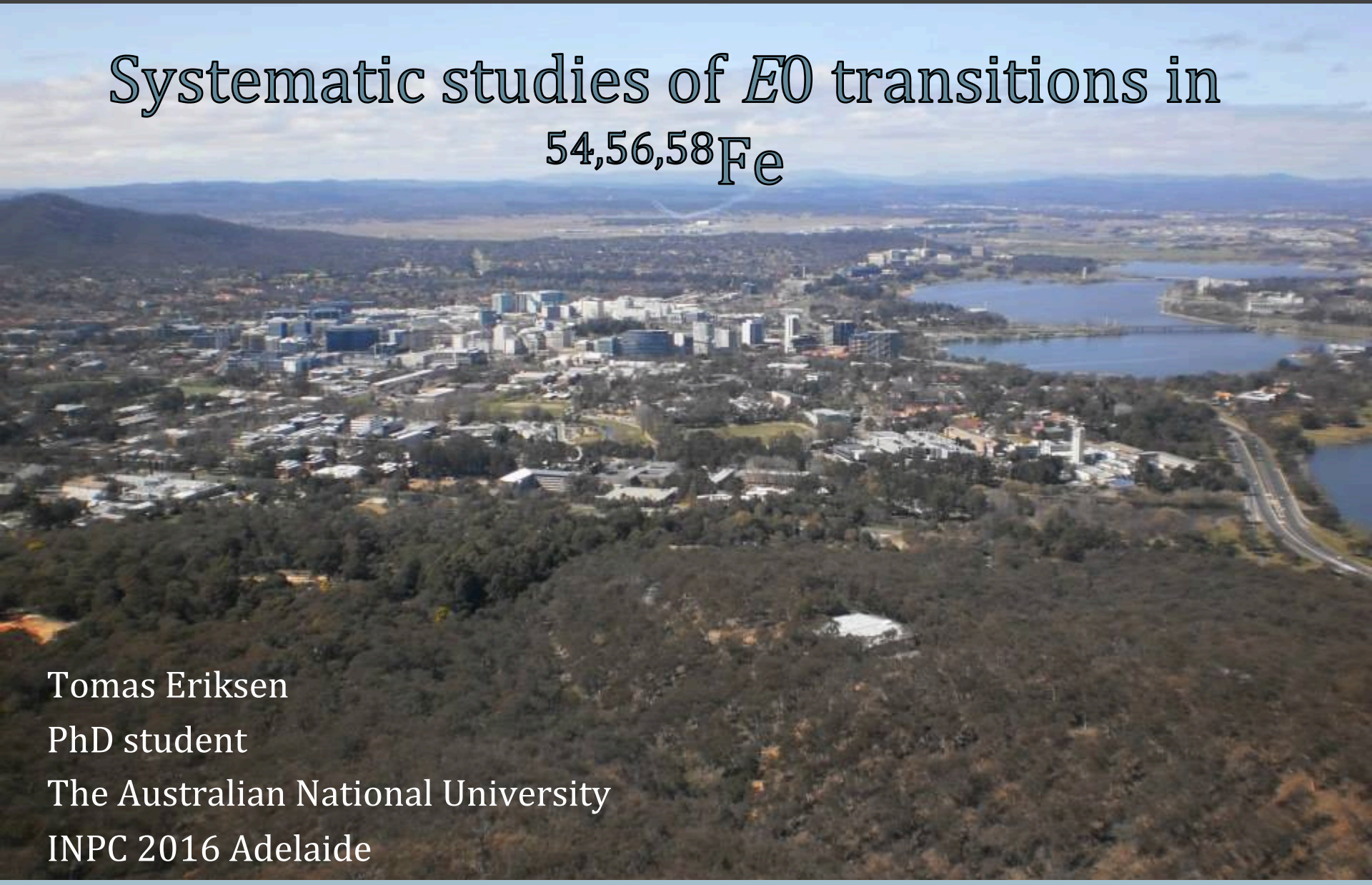
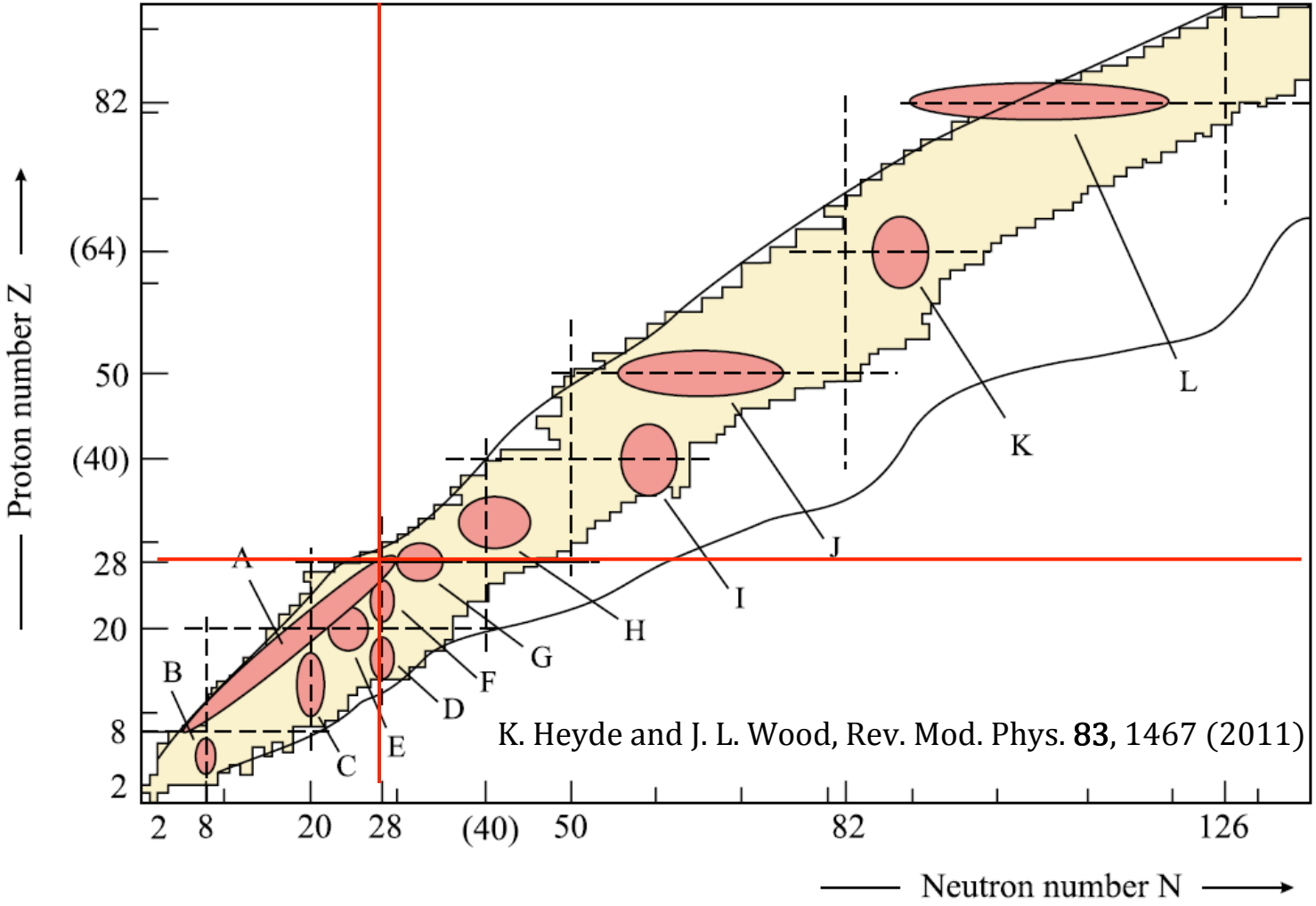
Australian National University

Systematic studies of $E0$ transitions in ^{54,56,58}Fe

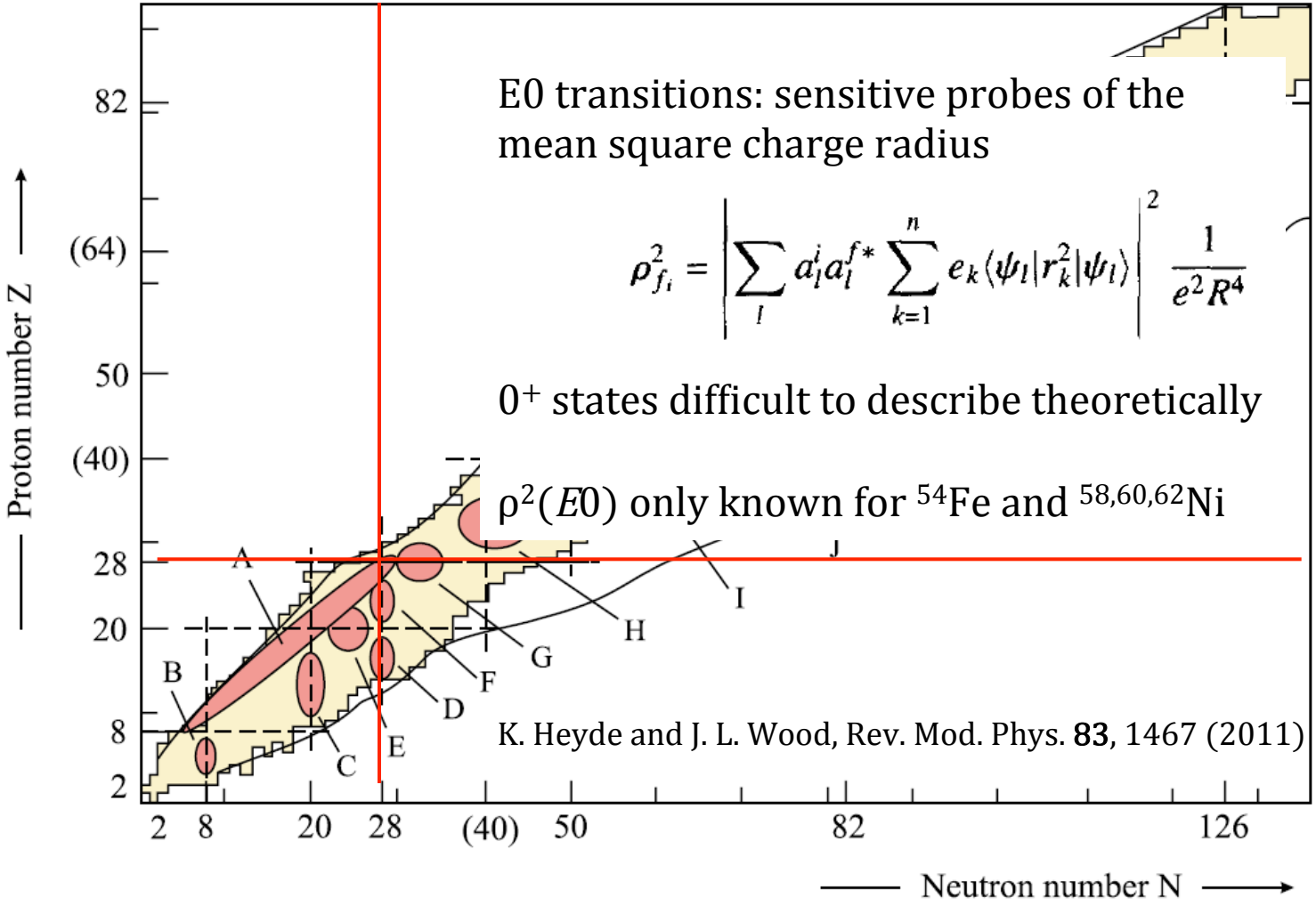


Tomas Eriksen
PhD student
The Australian National University
INPC 2016 Adelaide

Motivation – Shape coexistence



Motivation – Shape coexistence



E0 transitions: sensitive probes of the mean square charge radius

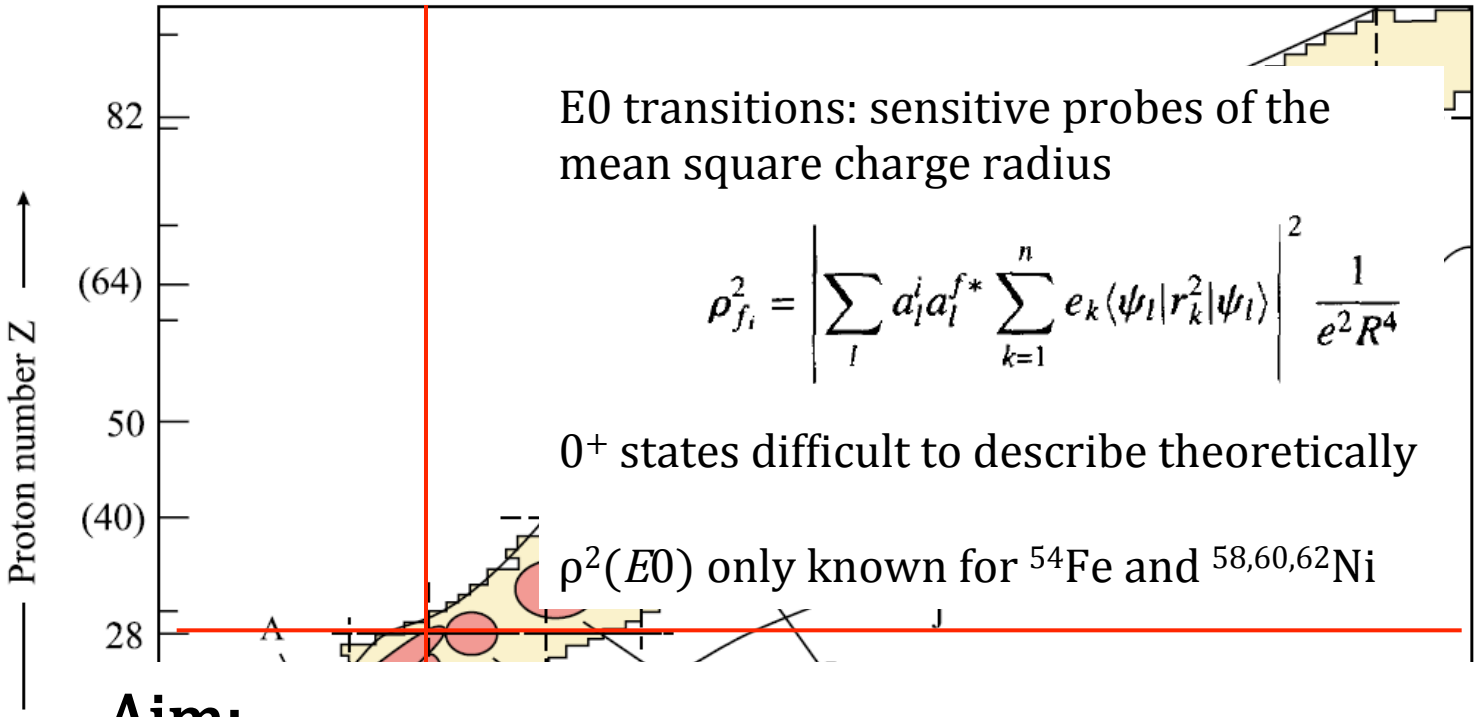
$$\rho^2_{f_i} = \left| \sum_l a^i_l a^{f*}_l \sum_{k=1}^{n} e_k \langle \psi_l | r^2_k | \psi_l \rangle \right|^2 \frac{1}{e^2 R^4}$$

0^+ states difficult to describe theoretically

$\rho^2(E0)$ only known for ^{54}Fe and ^{58,60,62}Ni

K. Heyde and J. L. Wood, Rev. Mod. Phys. **83**, 1467 (2011)

Motivation – Shape coexistence



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$$\rho^2_{f_i} = \left| \sum_l a^i_l a^{f*}_l \sum_{k=1}^{n} e_k \langle \psi_l | r^2_k | \psi_l \rangle \right|^2 \frac{1}{e^2 R^4}$$

0^+ states difficult to describe theoretically

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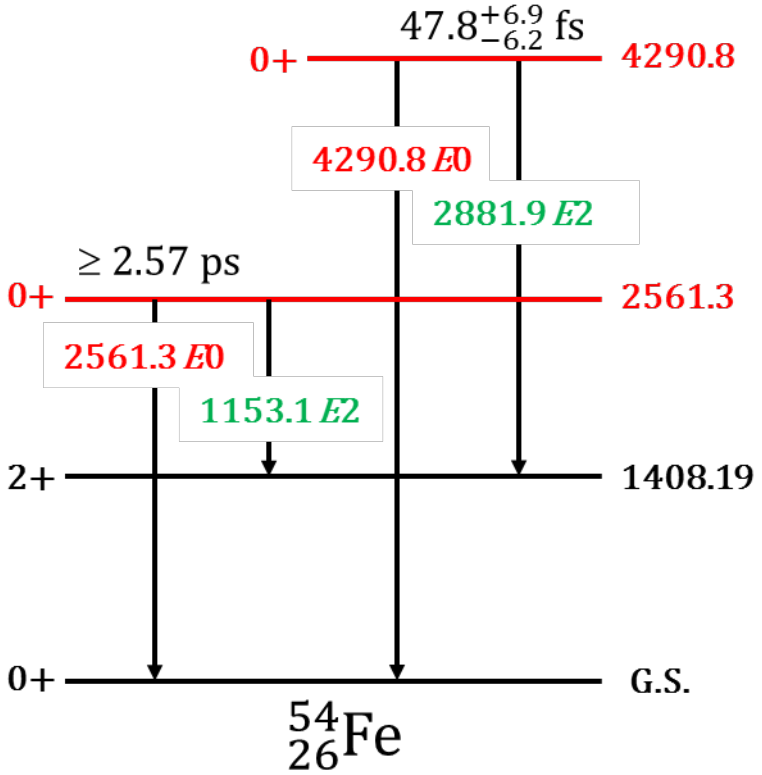
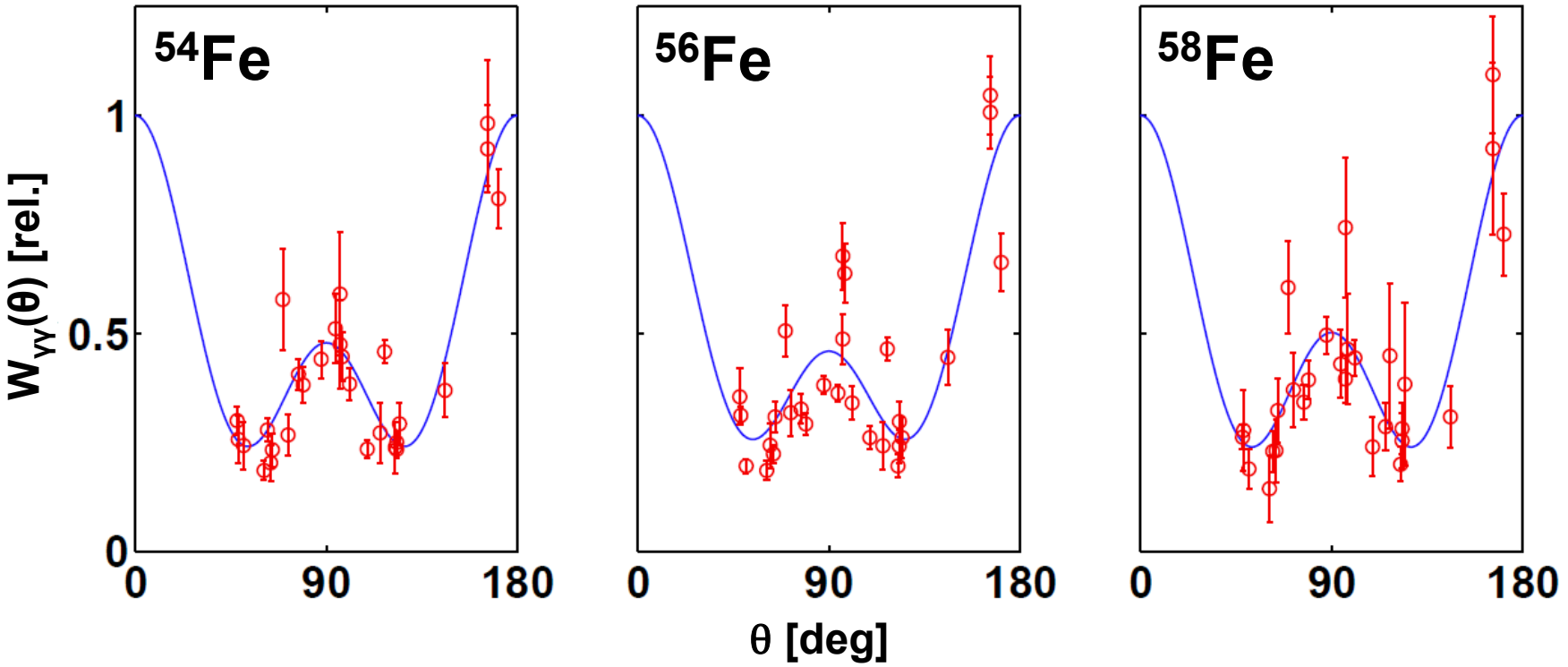
Aim:
identify and characterize 0^+ states and E0 transitions close to Z=N=28

^{54,56,58}Fe experiments

- 14UD Tandem accelerator at ANU
- 6.7 – 7.0 MeV proton beams
- CAESAR: γ and γγ coincidences
- Super-e: conversion e^-, e^-e^+ pairs, γ
- Lifetime information: University of Kentucky





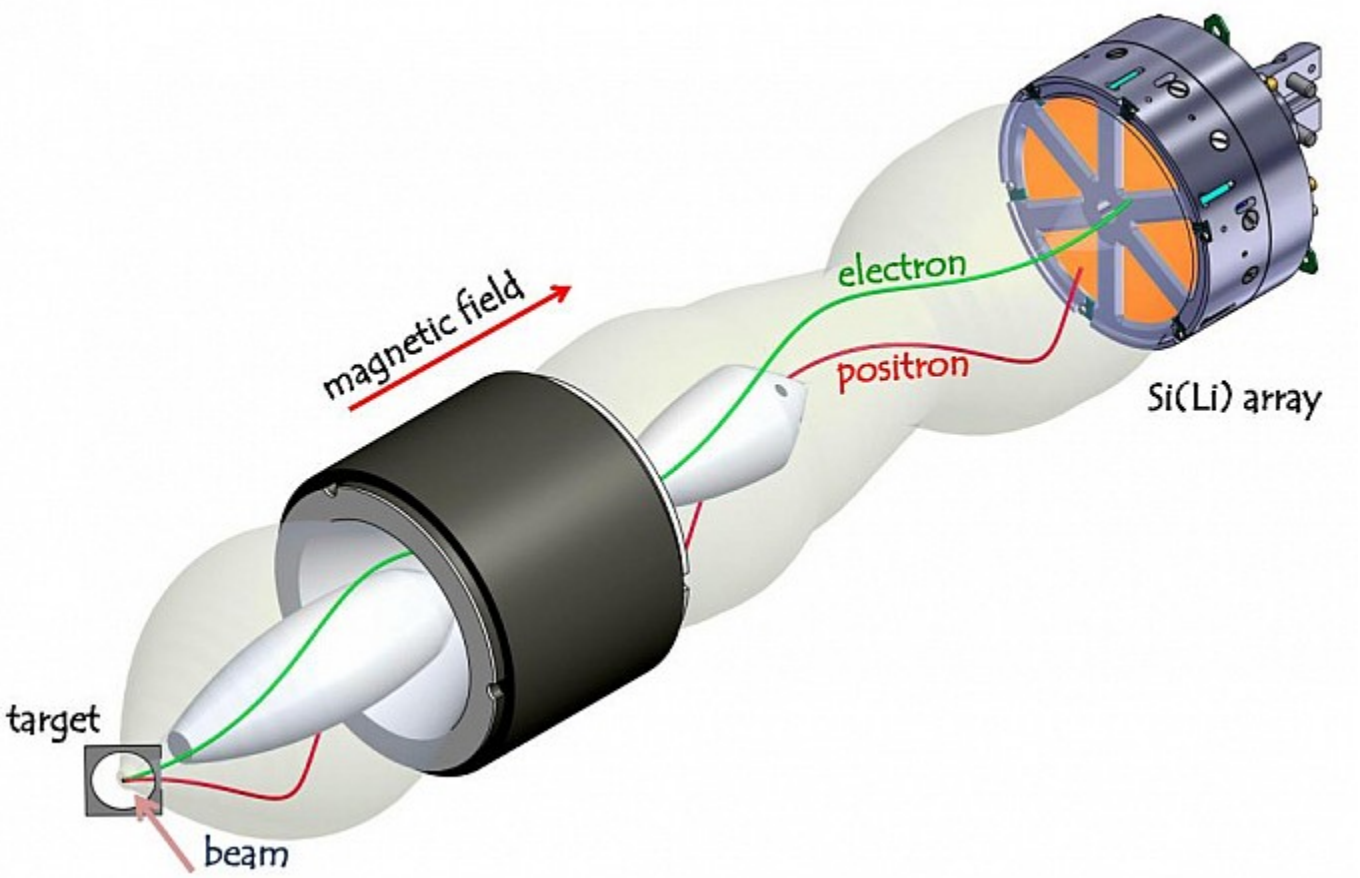
$$W_{\gamma\gamma}(\theta) = N(1 + a_2\cos^2(\theta) + a_4\cos^4(\theta))$$

$$0^+ \rightarrow 2^+ \rightarrow 0^+$$

$$a_2 = -3, a_4 = 4$$

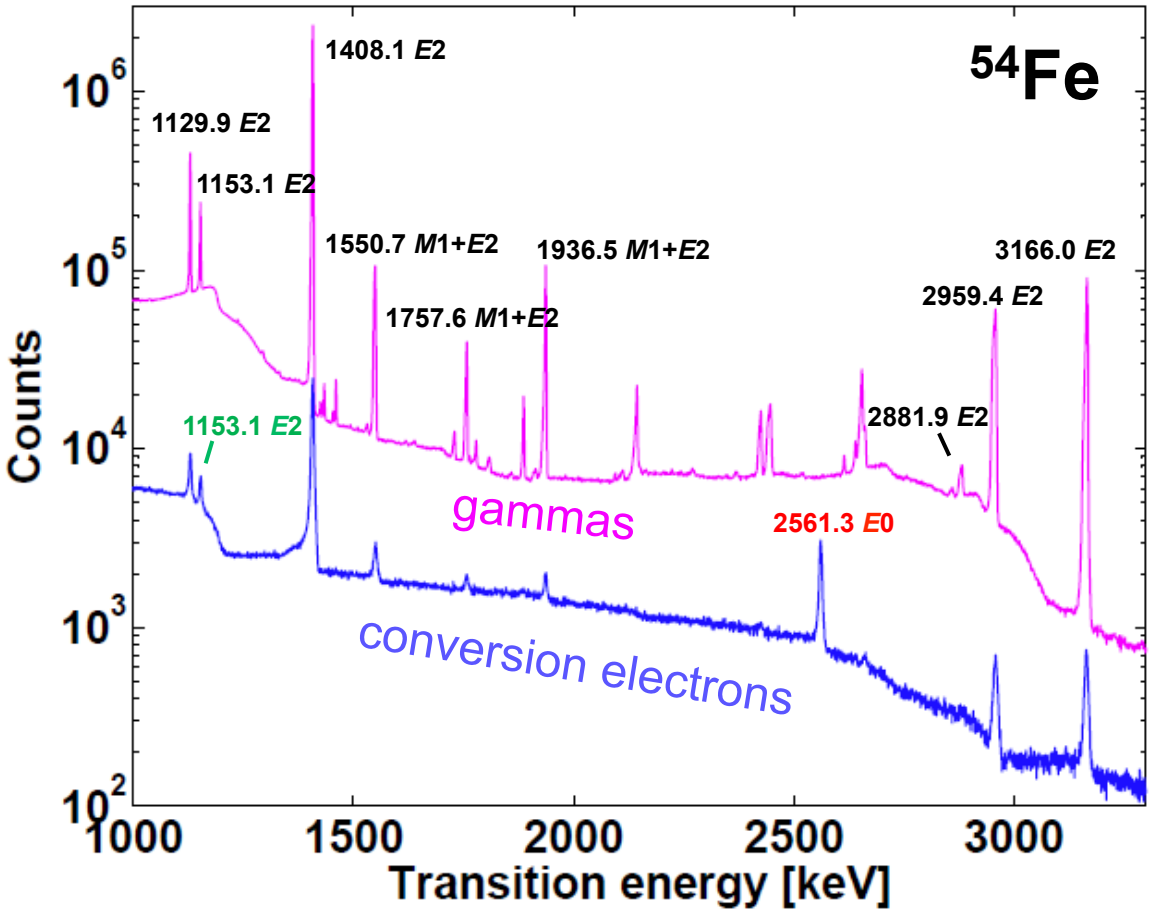
	a_2	a_4
^{54}Fe	−2.8(6)	3.9(7)
^{56}Fe	−2.6(9)	3.7(10)
^{58}Fe	−2.8(8)	3.8(9)

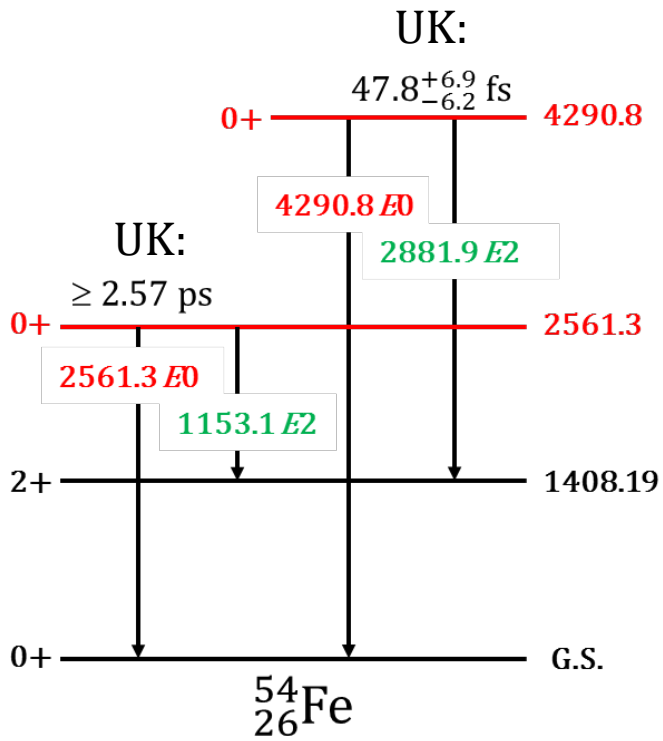
Super-e: conversion e^- and e^-e^+ pairs



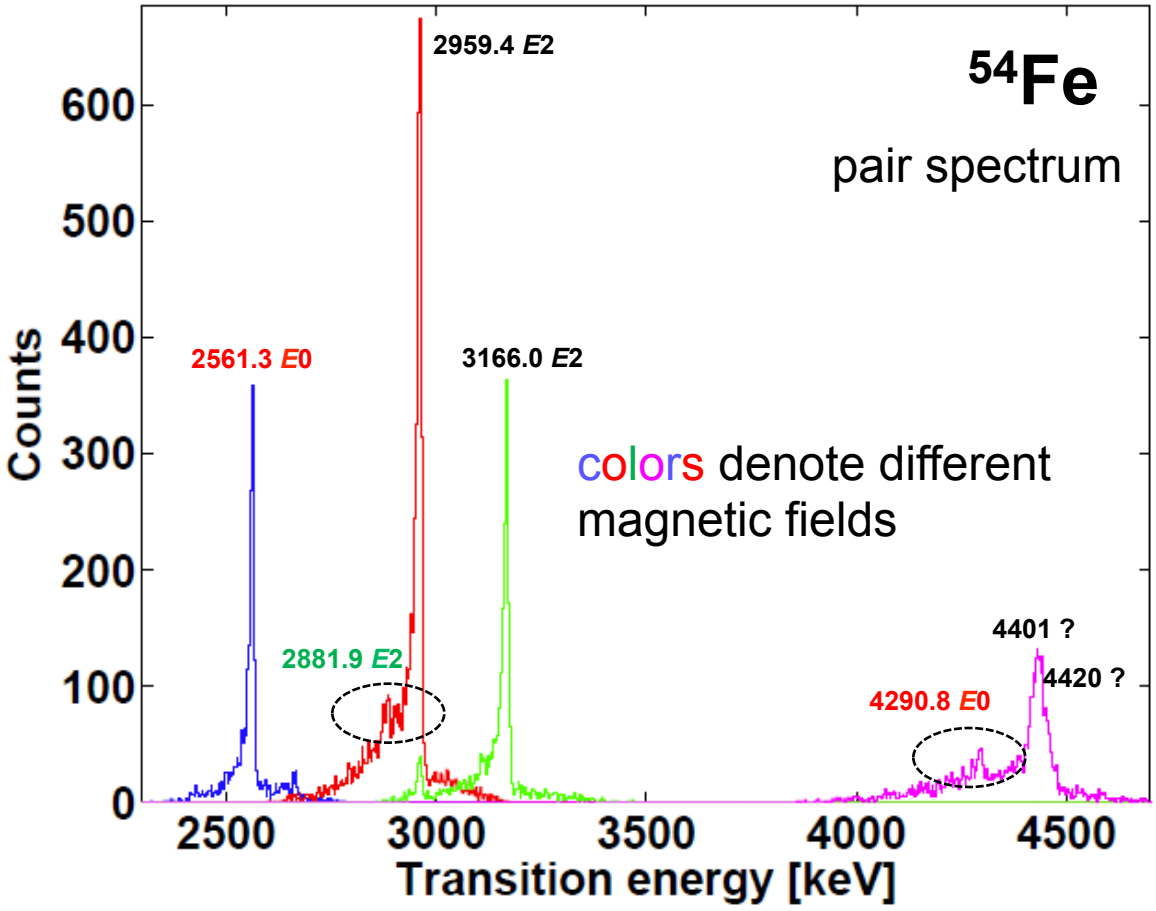
^{54}Fe

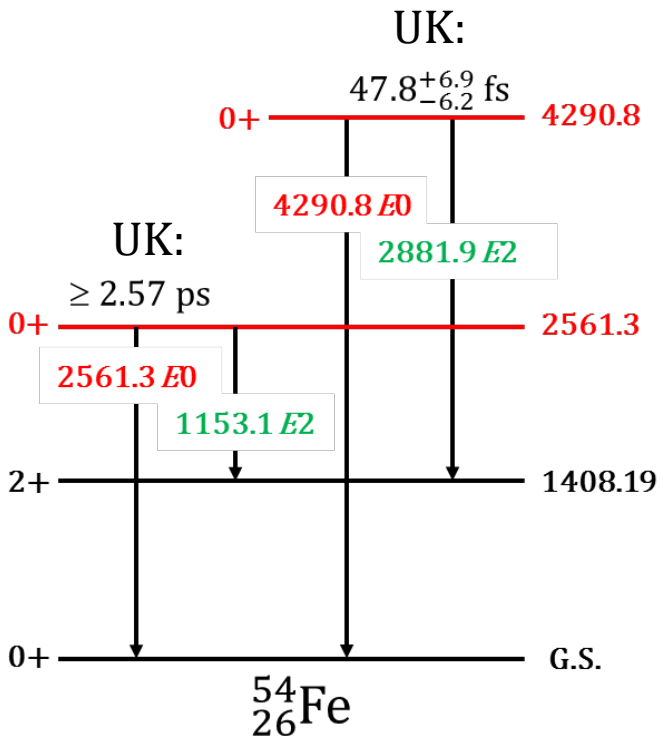
^{54}Fe


54Fe
1408.1 E2
1129.9 E2
1153.1 E2
1550.7 M1+E2
1936.5 M1+E2
3166.0 E2
1757.6 M1+E2
2959.4 E2
1153.1 E2
2881.9 E2
gammas
2561.3 E0
conversion electrons
Counts
Transition energy [keV]


UK:
47.8+6.9−6.2 fs
0+
4290.8
4290.8 E0
2881.9 E2
UK:
≥ 2.57 ps
0+
2561.3
2561.3 E0
1153.1 E2
2+
1408.19
0+
G.S.
54 26Fe

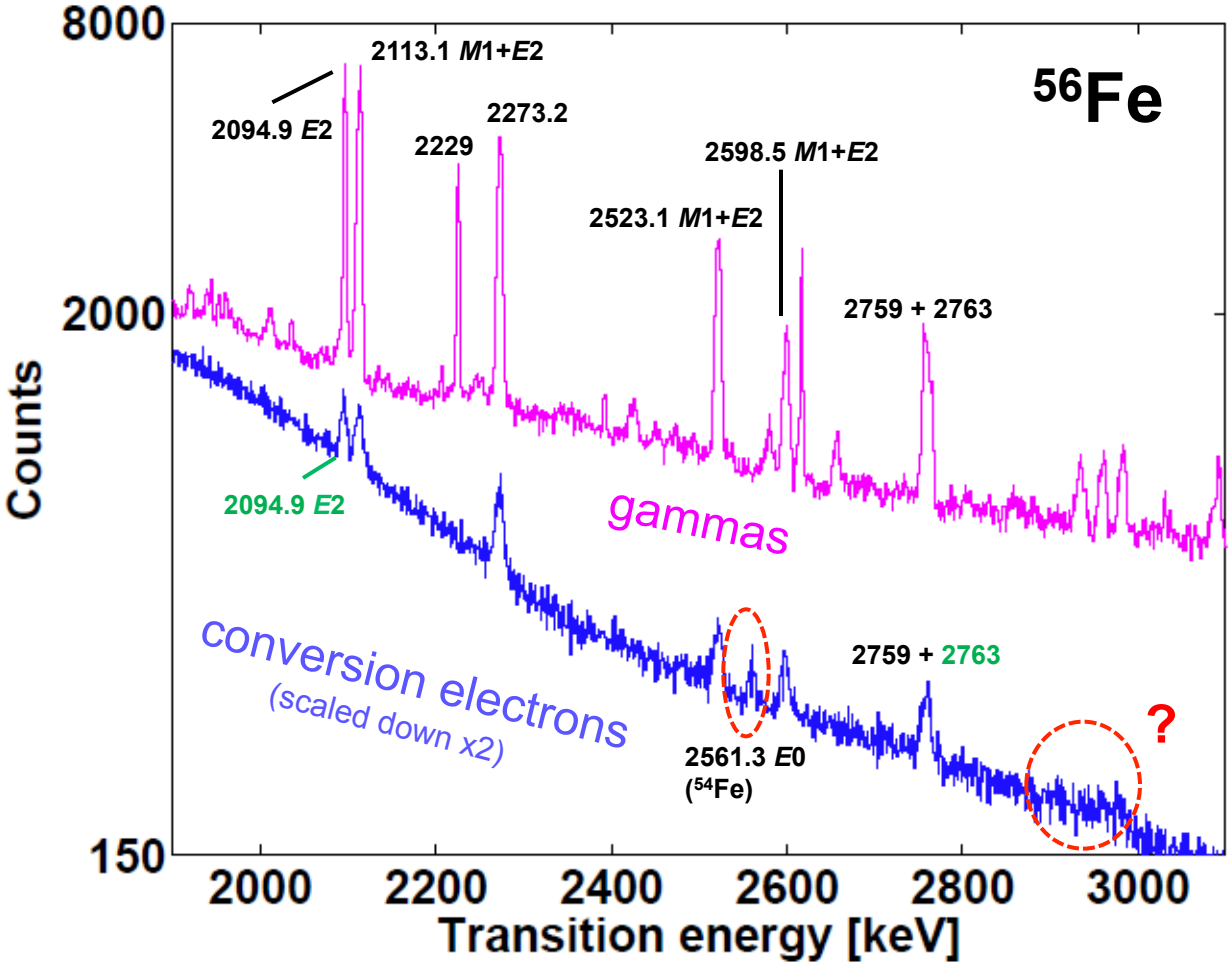
^{54}Fe

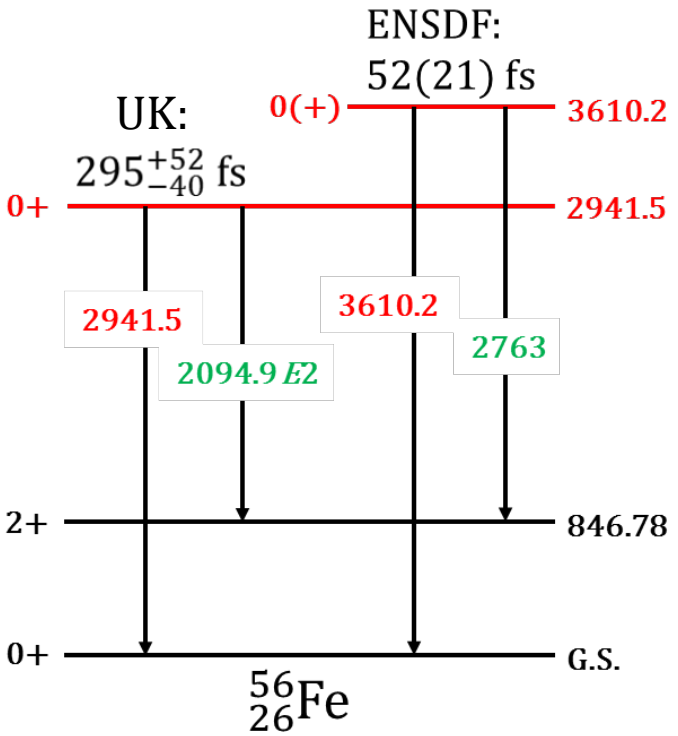

^{54}Fe
pair spectrum
2959.4 E2
2561.3 E0
3166.0 E2
2881.9 E2
4290.8 E0
4401 ?
4420 ?
colors denote different magnetic fields
Counts
Transition energy [keV]
0
100
200
300
400
500
600
2500
3000
3500
4000
4500


UK:
$47.8^{+6.9}_{-6.2}$ fs
0+
4290.8
4290.8 E0
2881.9 E2
UK:
≥ 2.57 ps
0+
2561.3
2561.3 E0
1153.1 E2
2+
1408.19
0+
G.S.
$^{54}_{26}$Fe

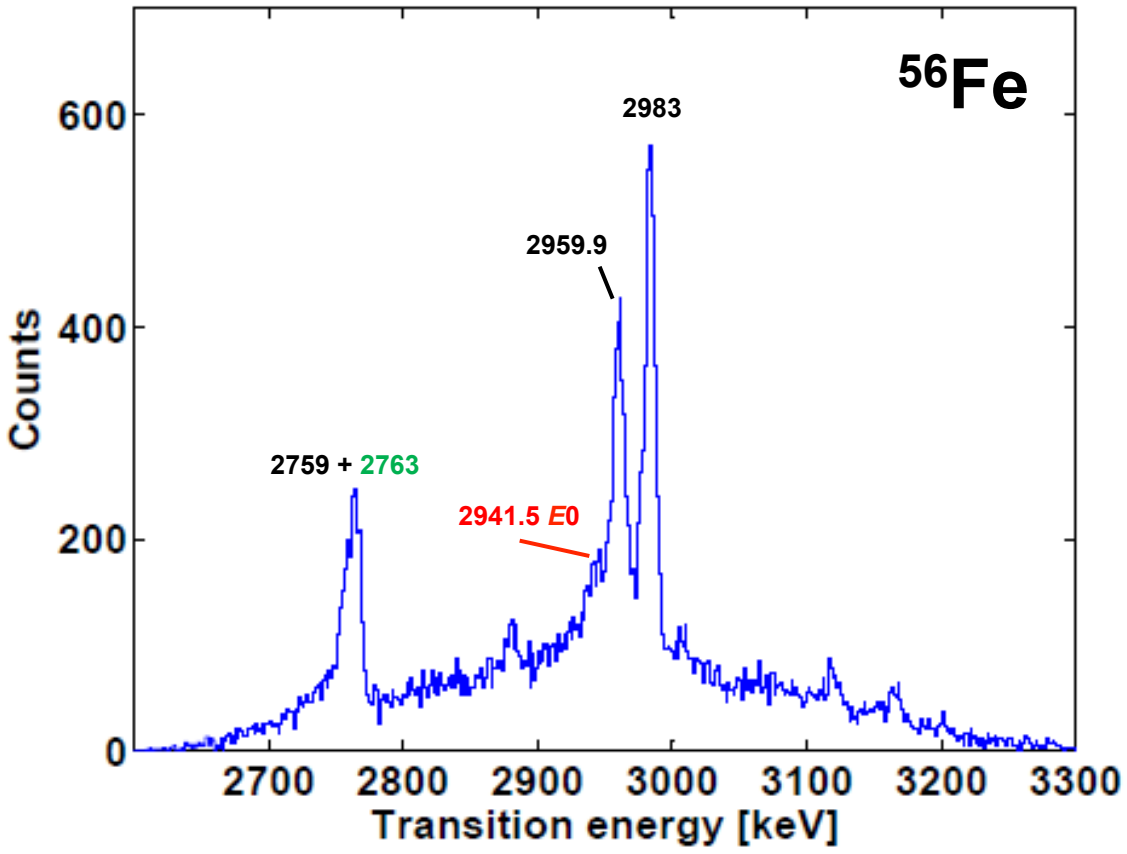
^{56}Fe

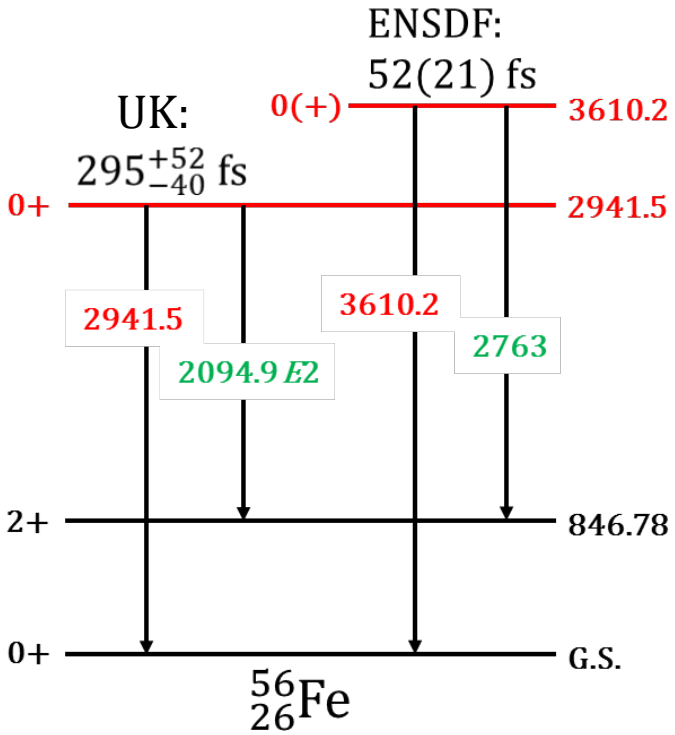
^{56}Fe


8000
2000
150
Counts
2000
2200
2400
2600
2800
3000
Transition energy [keV]
56Fe
2113.1 M1+E2
2094.9 E2
2273.2
2229
2598.5 M1+E2
2523.1 M1+E2
2759 + 2763
gammas
2094.9 E2
conversion electrons
(scaled down x2)
2759 + 2763
2561.3 E0
(54Fe)
?

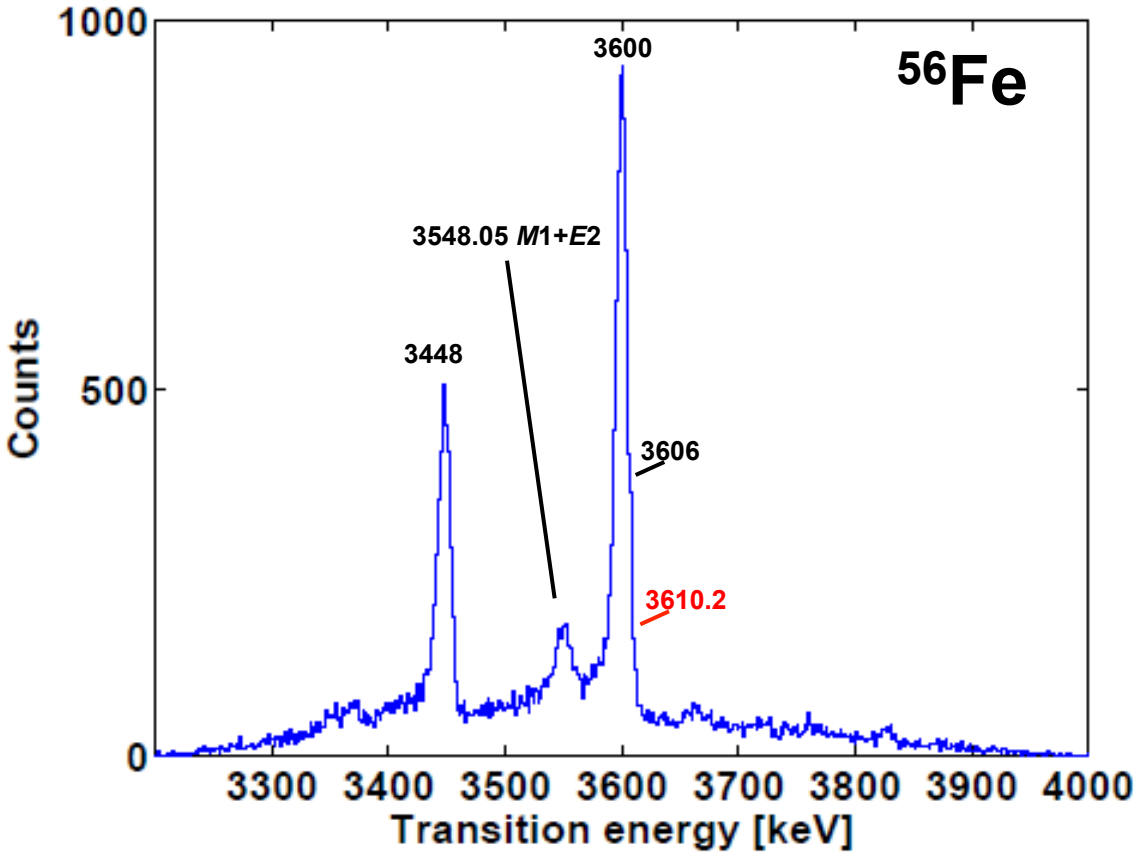

ENSDF:
52(21) fs
UK:
295+52−40 fs
0(+)
3610.2
0+
2941.5
2941.5
2094.9 E2
3610.2
2763
2+
846.78
0+
G.S.
56
26Fe

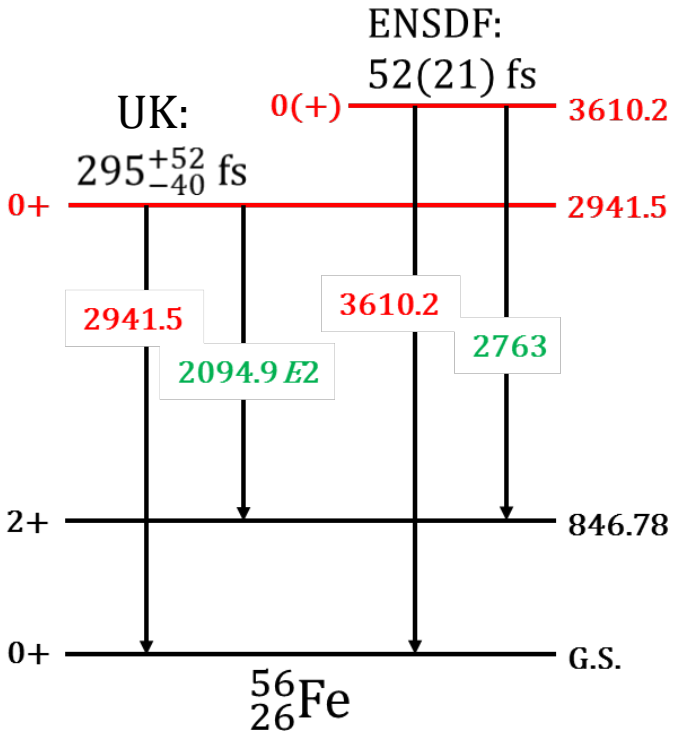
^{56}Fe


56Fe
2983
2959.9
2759 + 2763
2941.5 E0
Counts
600
400
200
0
2700
2800
2900
3000
3100
3200
3300
Transition energy [keV]


ENSDF:
52(21) fs
UK:
295^{+52}_{-40} fs
0(+)
3610.2
0+
2941.5
2941.5
2094.9 E2
3610.2
2763
2+
846.78
0+
G.S.
$^{56}_{26}$Fe

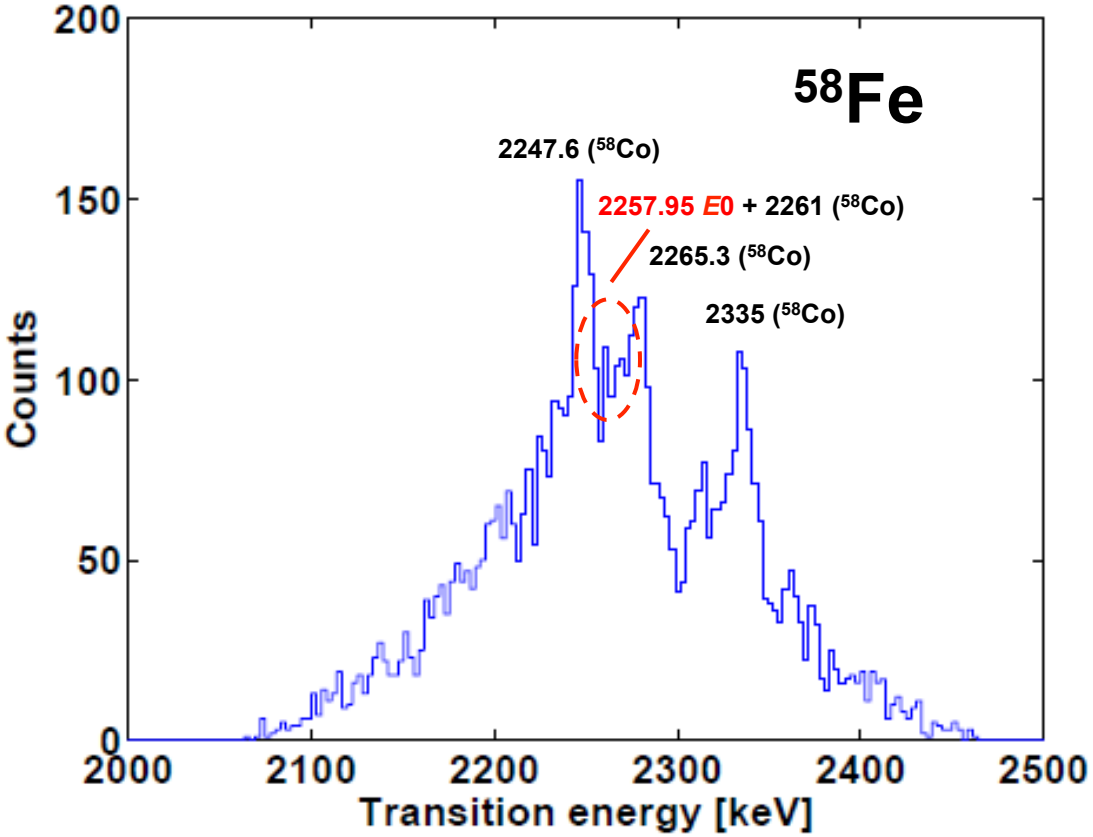
^{56}Fe – second excited 0^+ state

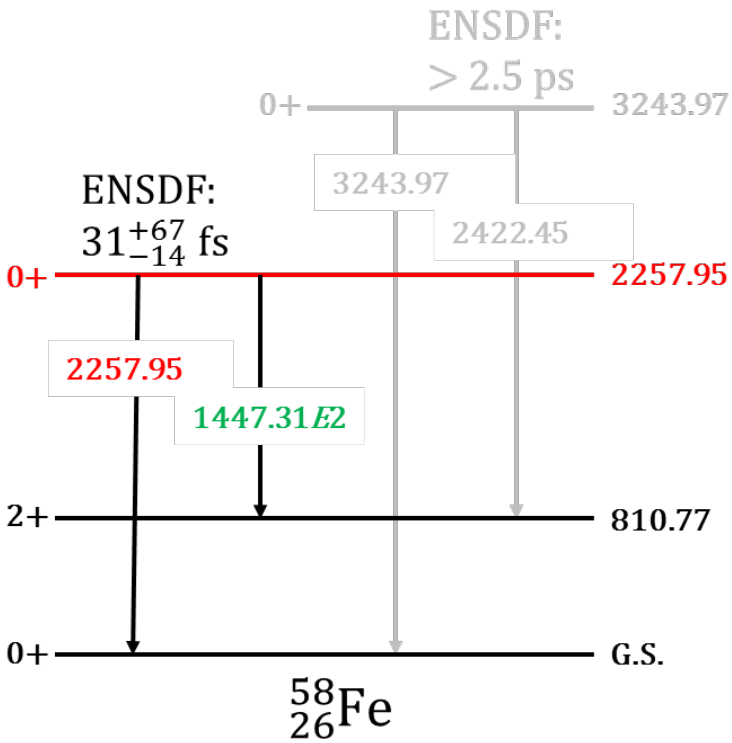




^{58}Fe

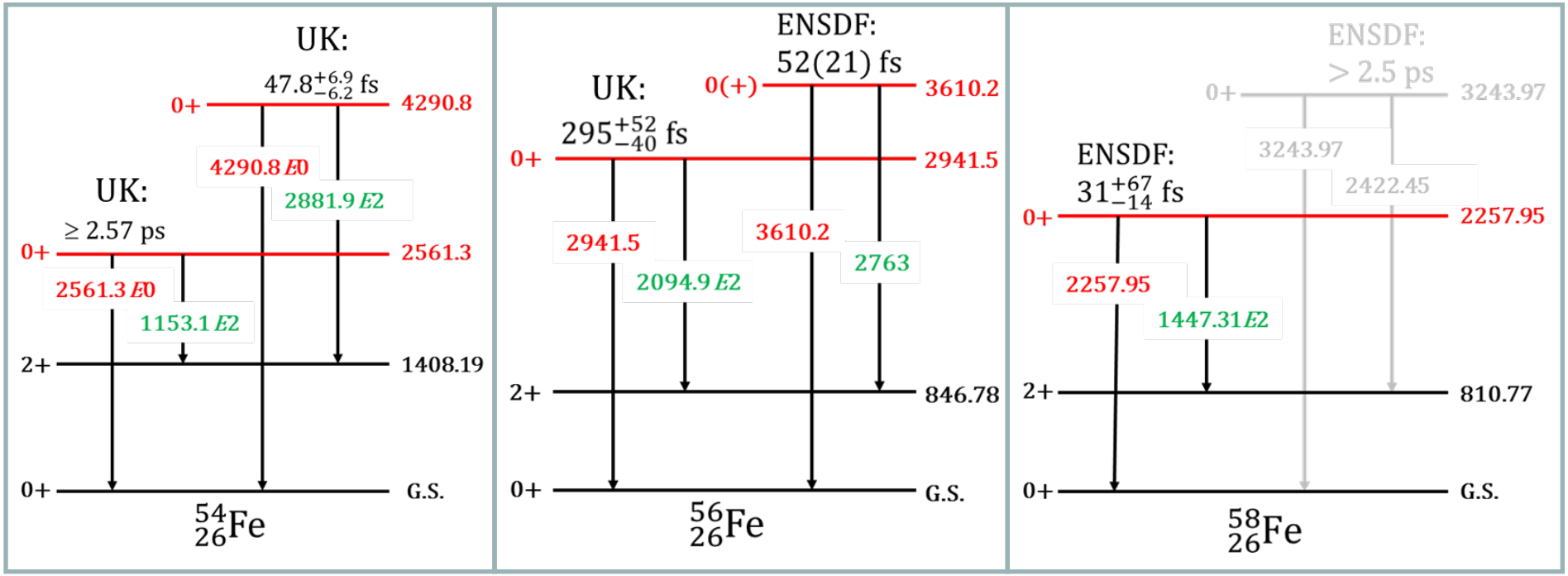
^{58}Fe


58Fe
2247.6 (58Co)
2257.95 E0 + 2261 (58Co)
2265.3 (58Co)
2335 (58Co)
Counts
Transition energy [keV]
0
50
100
150
200
2000
2100
2200
2300
2400
2500


ENSDF:
> 2.5 ps
ENSDF:
31+67−14 fs
0+
3243.97
3243.97
2422.45
0+
2257.95
2257.95
1447.31E2
2+
810.77
0+
G.S.
58
26Fe

Results

Results


UK:
$47.8^{+6.9}_{-6.2}$ fs
0+
4290.8
4290.8 E0
2881.9 E2
UK:
≥ 2.57 ps
0+
2561.3
2561.3 E0
1153.1 E2
2+
1408.19
0+
G.S.
$^{54}_{26}$Fe
ENSDF:
52(21) fs
UK:
295^{+52}_{-40} fs
0(+)
3610.2
0+
2941.5
2941.5
2094.9 E2
3610.2
2763
2+
846.78
0+
G.S.
$^{56}_{26}$Fe
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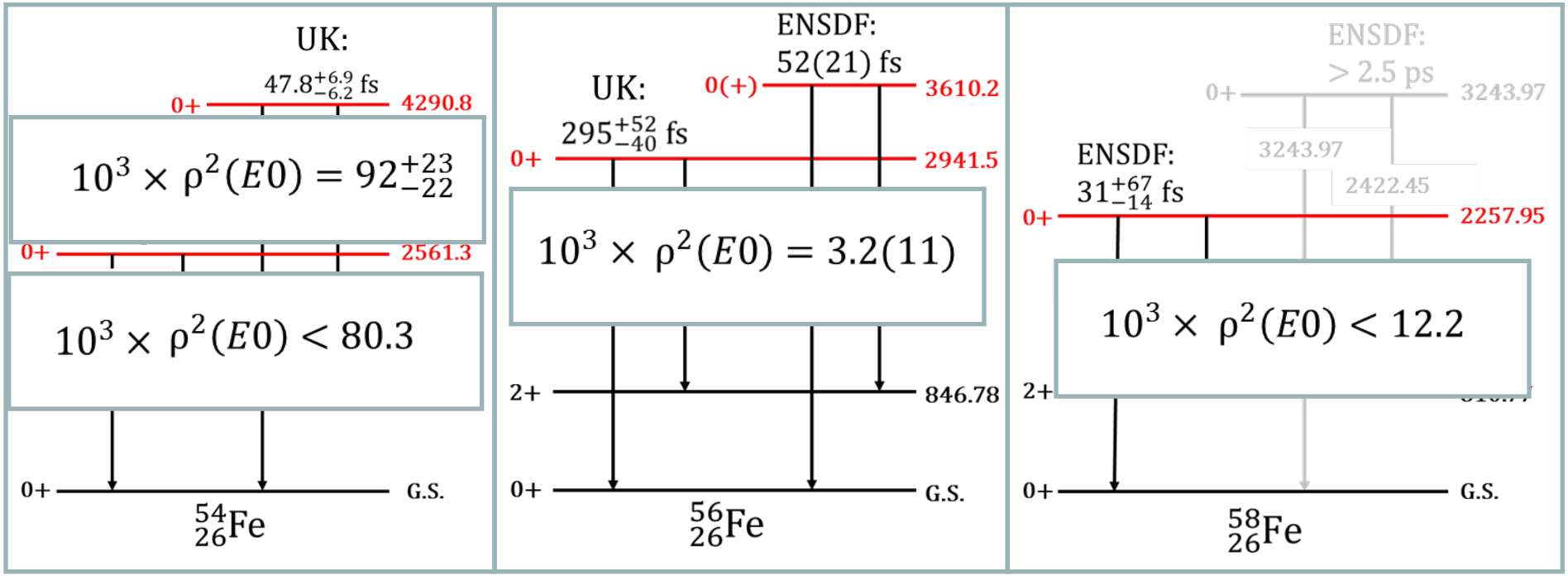
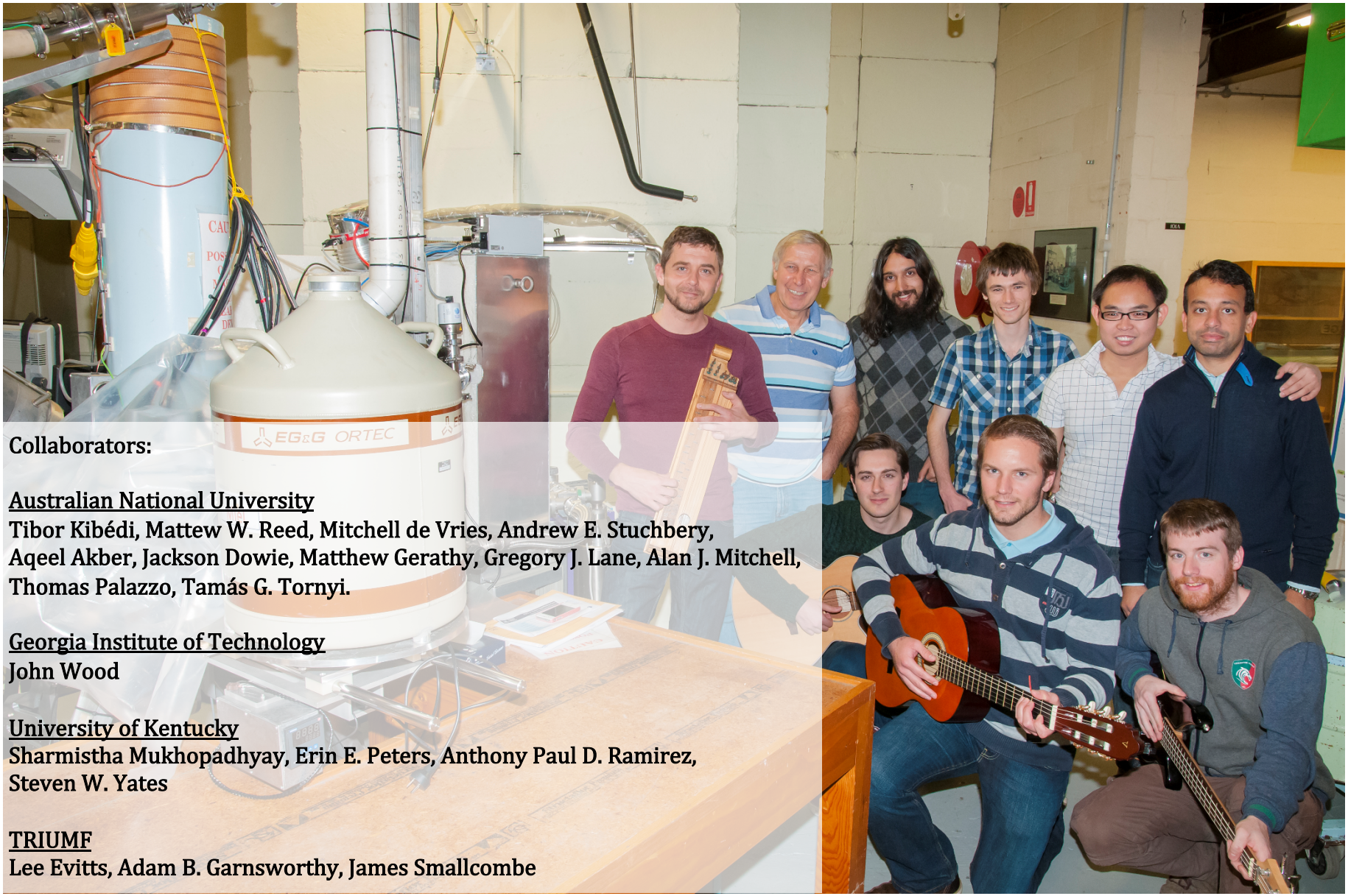
> 2.5 ps
0+
3243.97
3243.97
2422.45
ENSDF:
31^{+67}_{-14} fs
0+
2257.95
2257.95
1447.31 E2
2+
810.77
0+
G.S.
$^{58}_{26}$Fe

Results


UK:
$47.8^{+6.9}_{-6.2}$ fs
0+
4290.8
$10^3 \times \rho^2(E0) = 92^{+23}_{-22}$
0+
2561.3
$10^3 \times \rho^2(E0) < 80.3$
0+
G.S.
$^{54}_{26}$Fe
ENSDF:
52(21) fs
UK:
0(+)
3610.2
295^{+52}_{-40} fs
0+
2941.5
$10^3 \times \rho^2(E0) = 3.2(11)$
2+
846.78
0+
G.S.
$^{56}_{26}$Fe
ENSDF:
> 2.5 ps
0+
3243.97
ENSDF:
3243.97
31^{+67}_{-14} fs
2422.45
0+
2257.95
$10^3 \times \rho^2(E0) < 12.2$
2+
0+
G.S.
$^{58}_{26}$Fe



Collaborators:

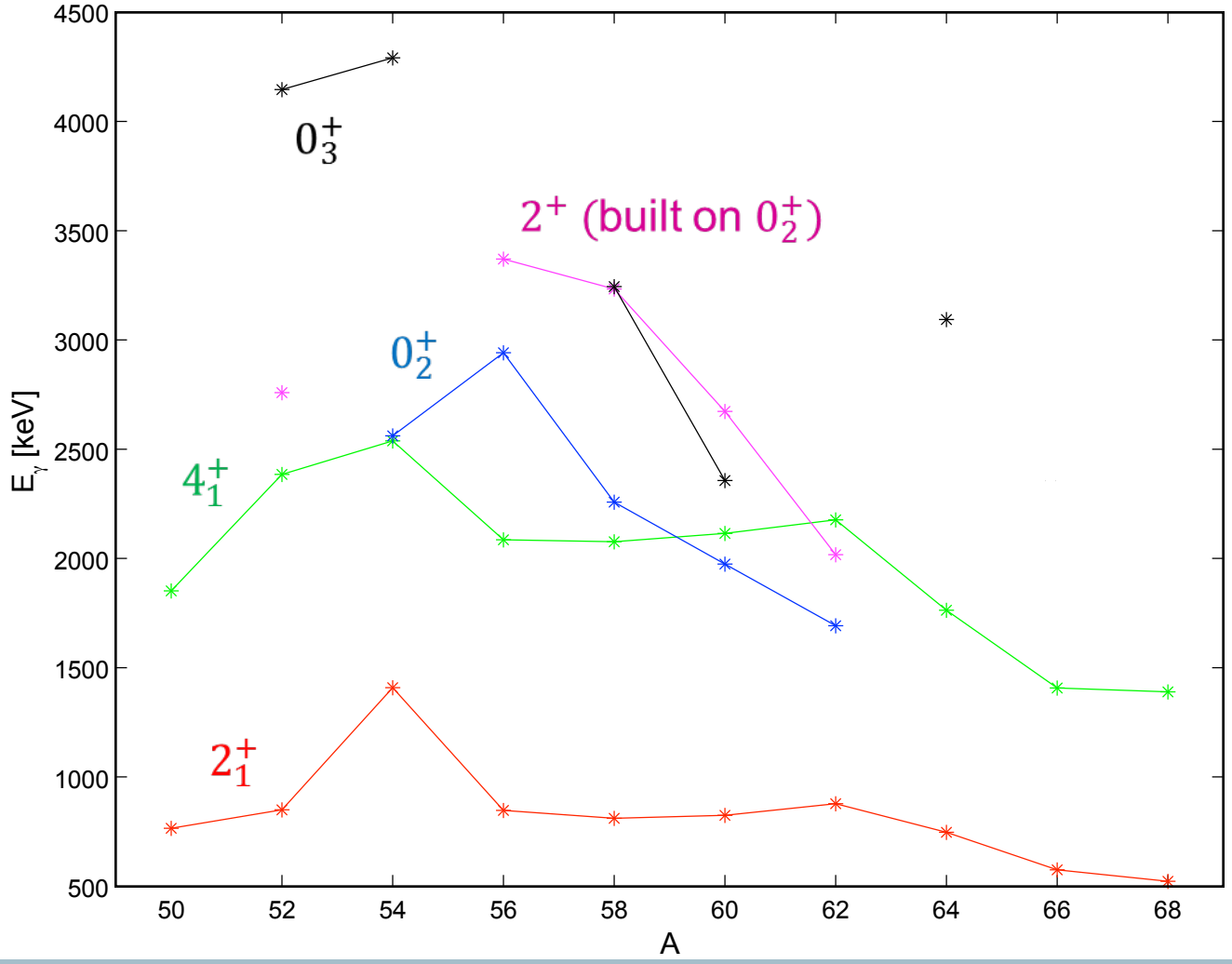
Australian National University
Tibor Kibédi, Mattew W. Reed, Mitchell de Vries, Andrew E. Stuchbery, Aqeel Akber, Jackson Dowie, Matthew Gerathy, Gregory J. Lane, Alan J. Mitchell, Thomas Palazzo, Tamás G. Tornyi.

Georgia Institute of Technology
John Wood

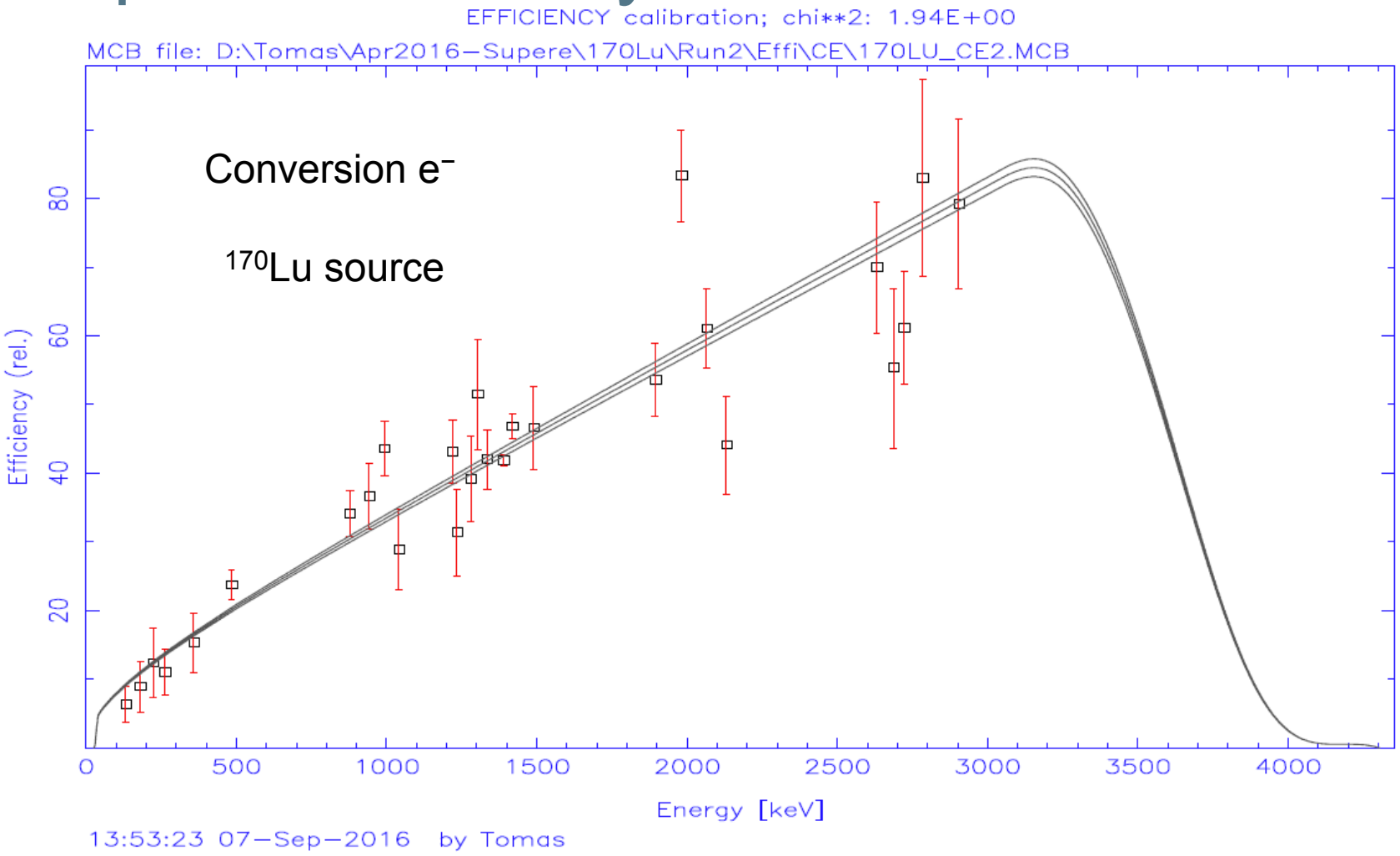
University of Kentucky
Sharmistha Mukhopadhyay, Erin E. Peters, Anthony Paul D. Ramirez, Steven W. Yates

TRIUMF
Lee Evitts, Adam B. Garnsworthy, James Smallcombe

Level systematics for Z = 26

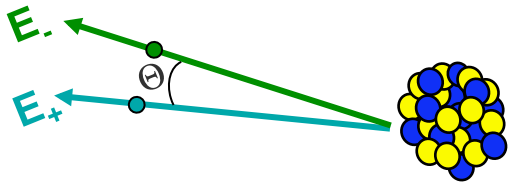


Super-e efficiency

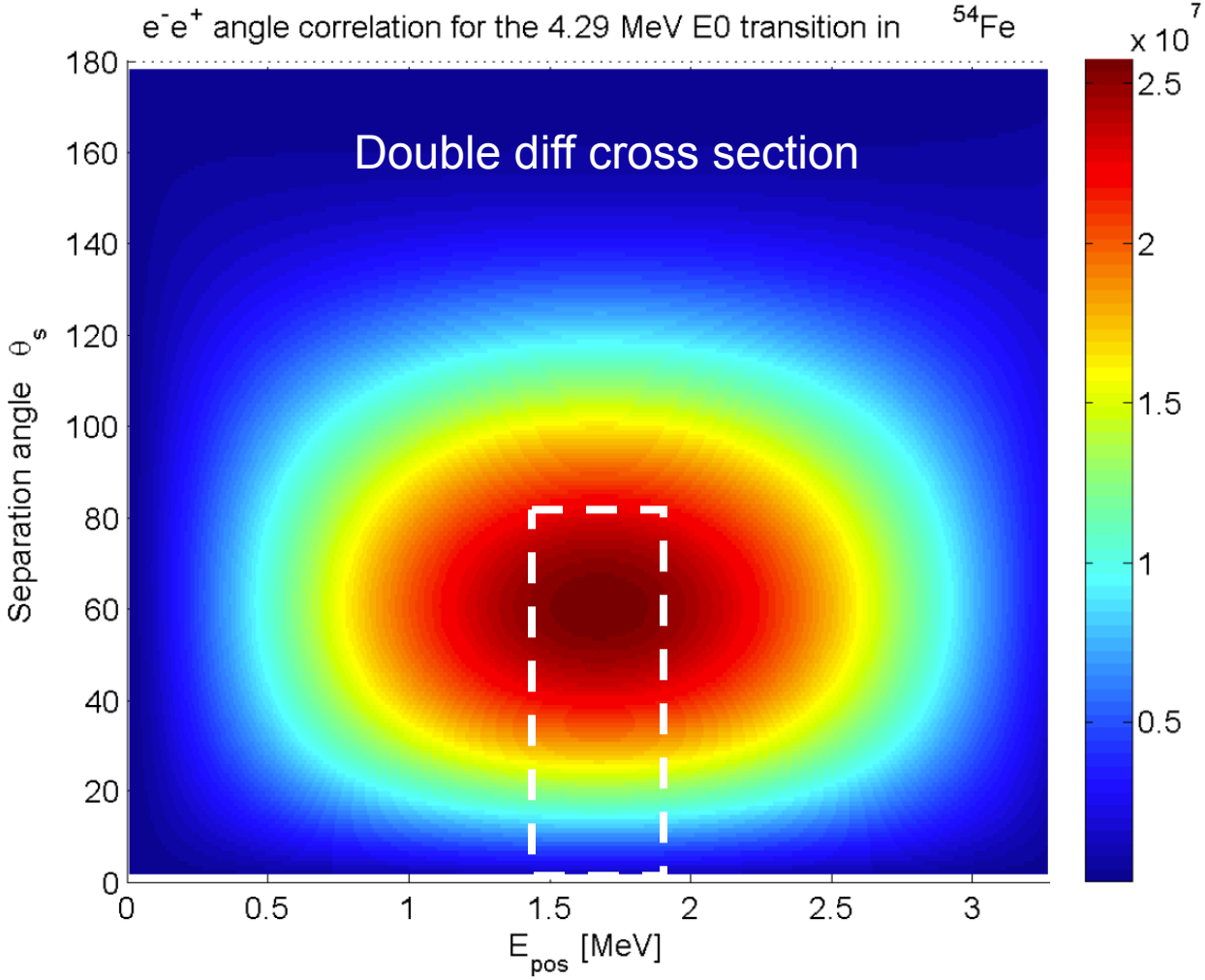


Super-e efficiency

- Have to consider angular correlations between the e^-e^+

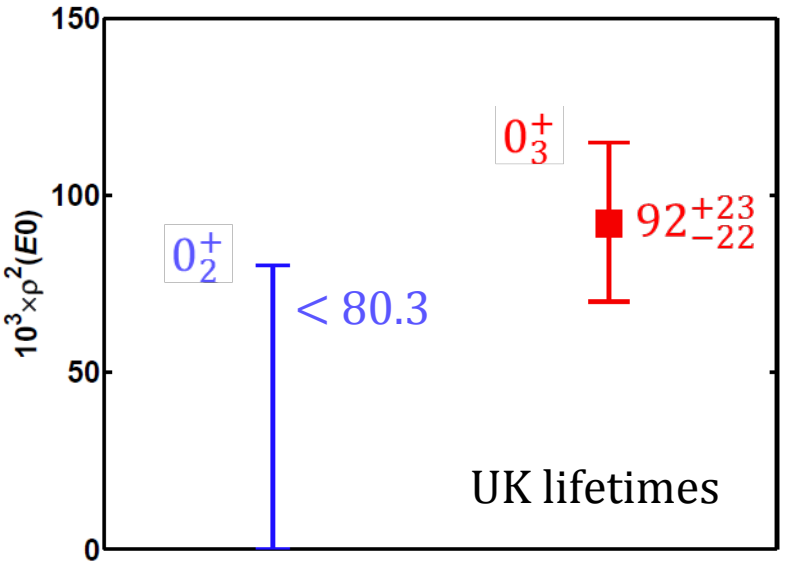


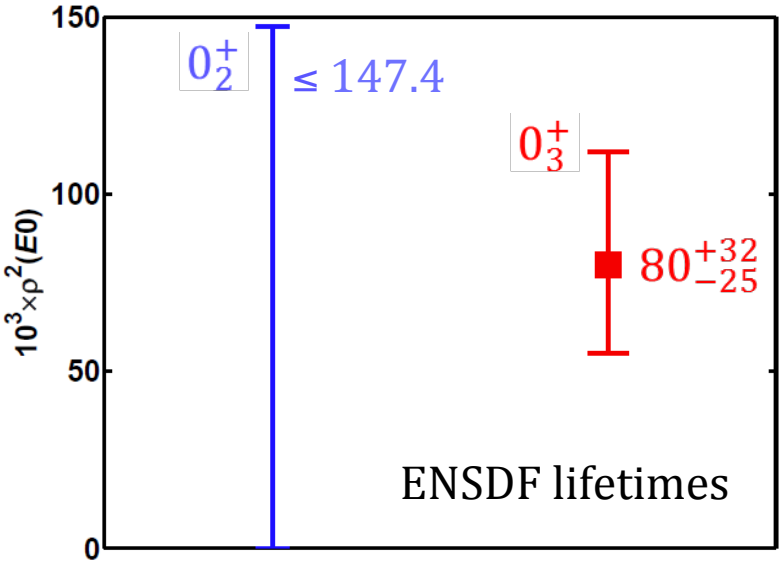
- MC simulation of the pair emission in 4π



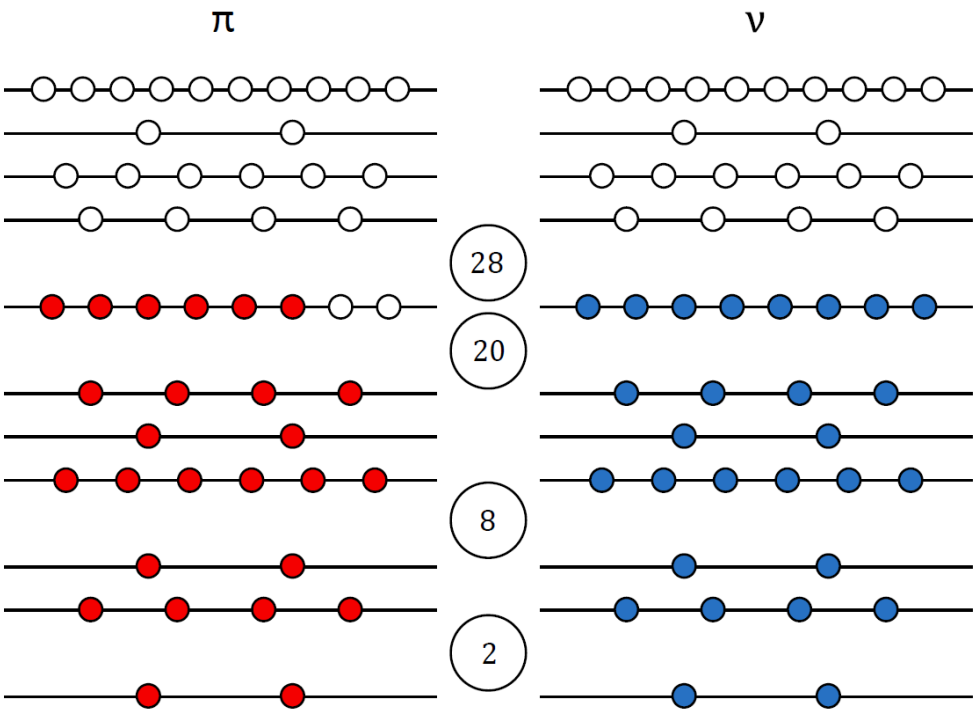
Results ^{54}Fe

$$\rho(E0) = \frac{|M(E0)|}{eR^2} \quad \text{or} \quad \rho^2(E0) = \frac{B(E0)}{e^2R^4}$$



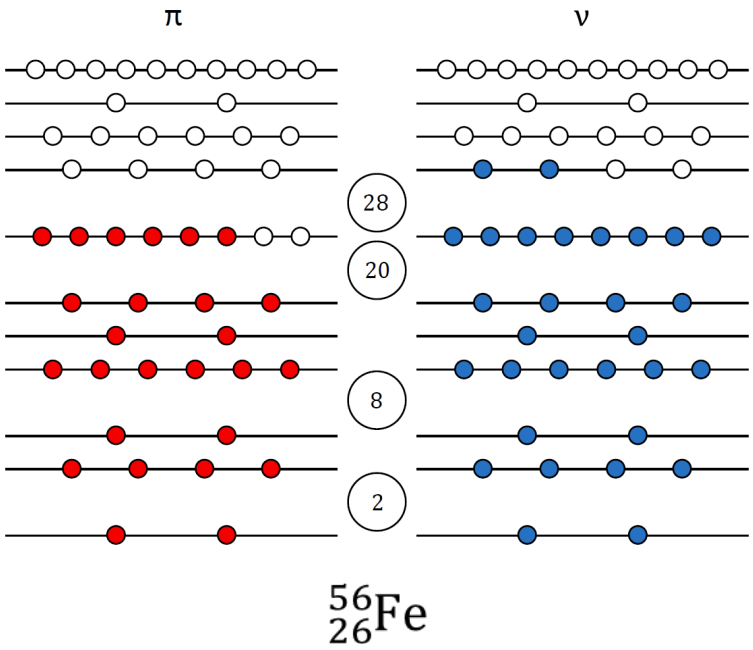


Interpretation $E0$ strengths

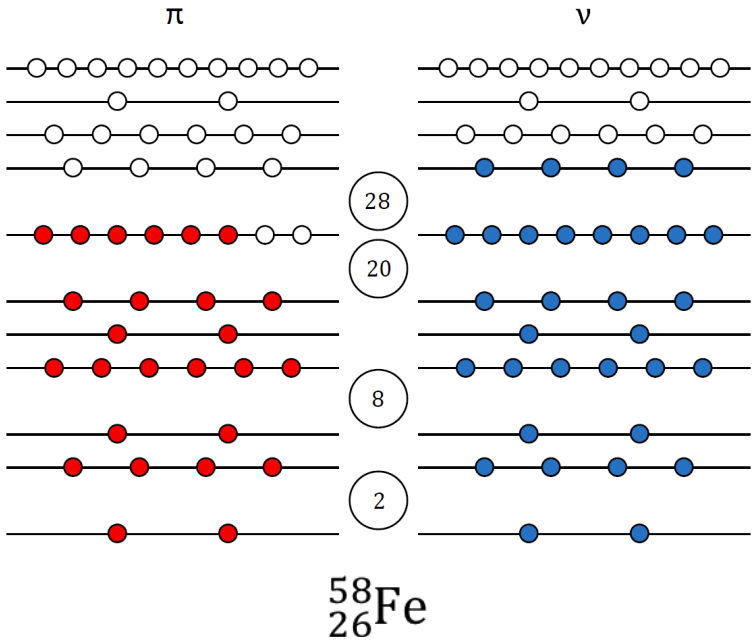


$^{54}_{26}\mathrm{Fe}$

Interpretation $E0$ strengths

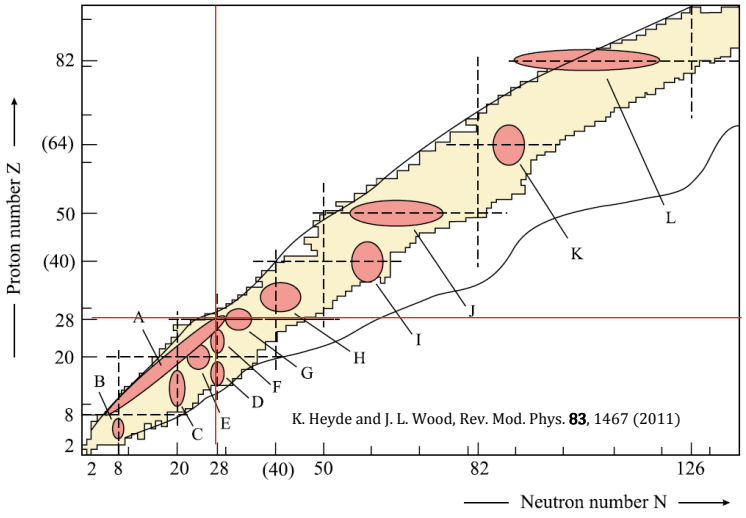


$^{56}_{26}\mathrm{Fe}$



$^{58}_{26}\mathrm{Fe}$

Motivation – Shape coexistence



E0 transitions: sensitive probes of the mean charge radius

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0^+ states difficult to describe theoretically

$\rho^2(E0)$ only known for ^{54}Fe and ^{58,60,62}Ni

Aim:
identify and characterize 0^+ states and E0 transitions close to Z=N=28

Additional lifetime info, thanks to

- Departments of Chemistry, and Physics & Astronomy, University of Kentucky
- Doppler shift attenuation following inelastic neutron scattering

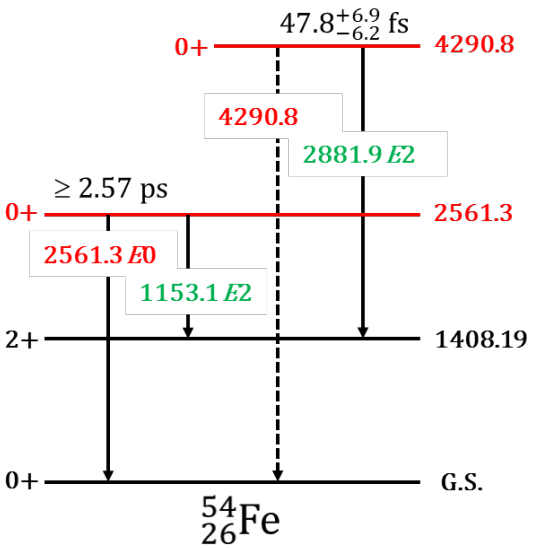
Background

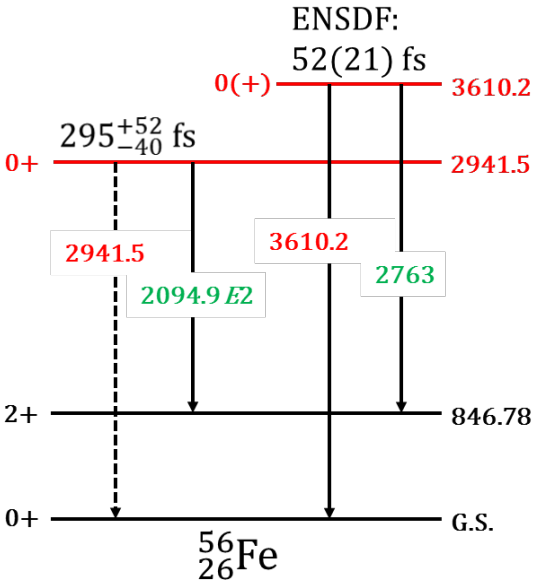
- N-rich Ni-isotopes (Z=28) and isotones (N=28) exhibit spherical shape coexistence

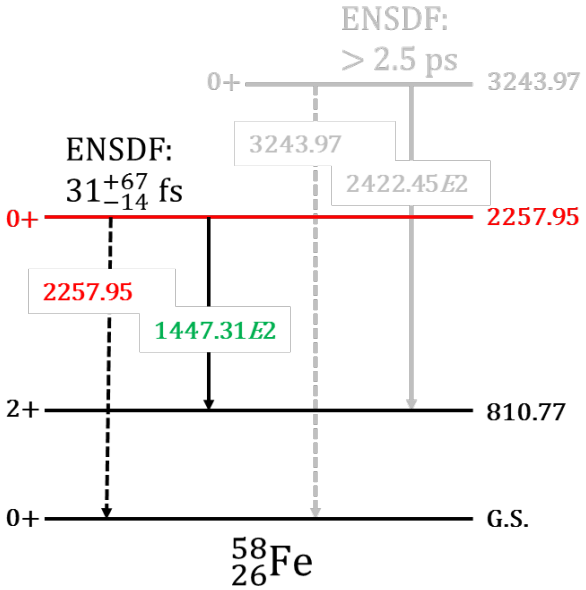
- The stable even-even iron isotopes suitable for investigating behavior close to Z=N=28 shell gaps

0^+ states and $E0$ transitions

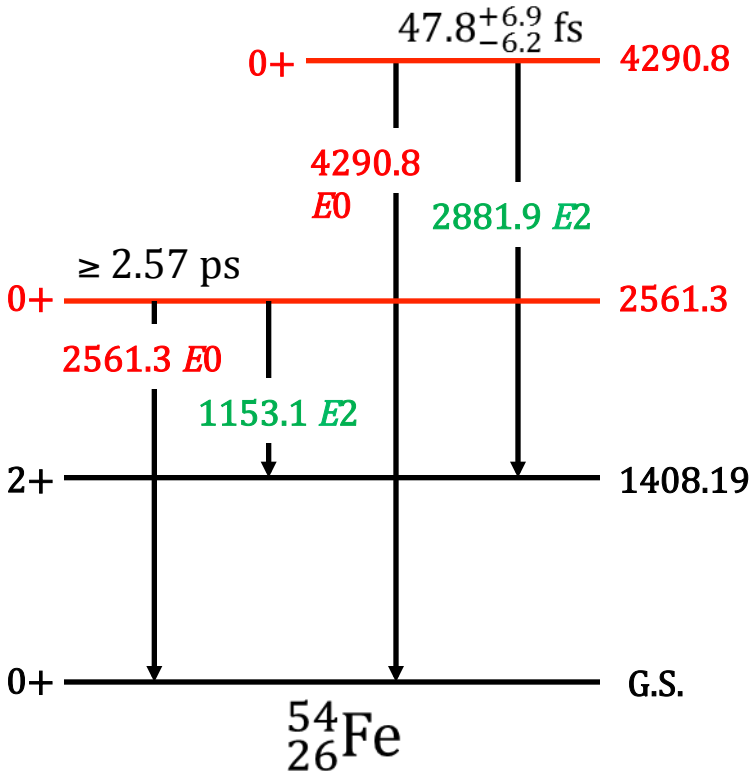
0^+ states and $E0$ transitions



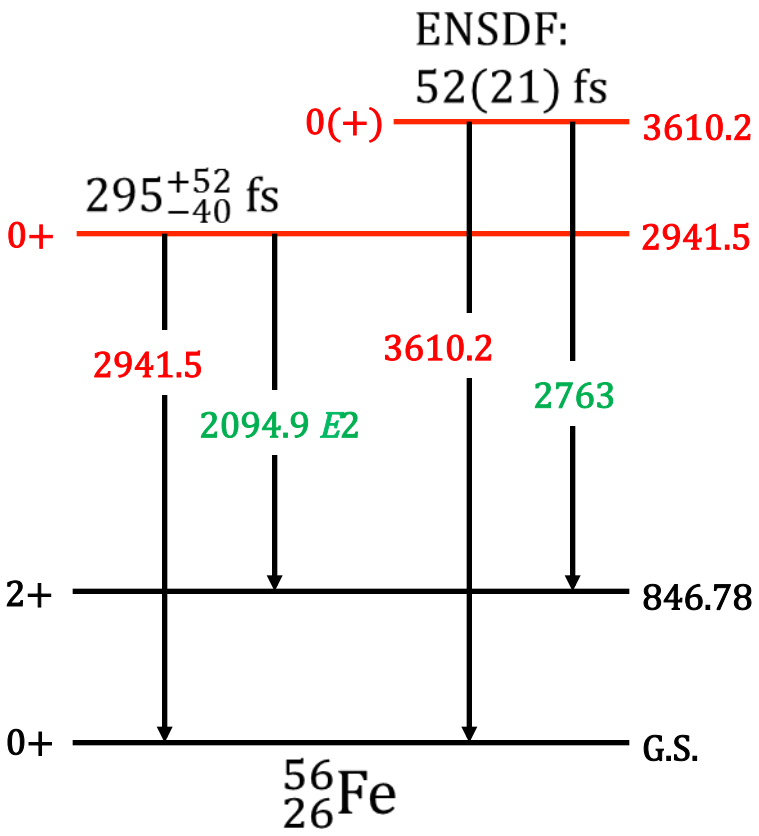




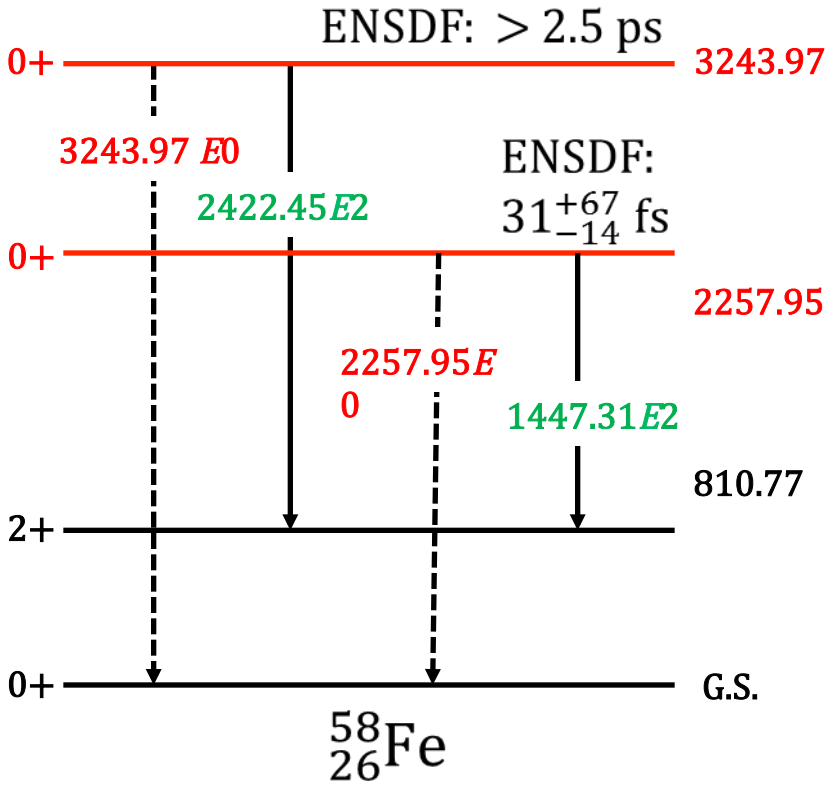
^{54}Fe


$47.8^{+6.9}_{-6.2}$ fs
0+
4290.8
4290.8
E0
2881.9 E2
≥ 2.57 ps
0+
2561.3
2561.3 E0
1153.1 E2
2+
1408.19
0+
G.S.
$^{54}_{26}$Fe

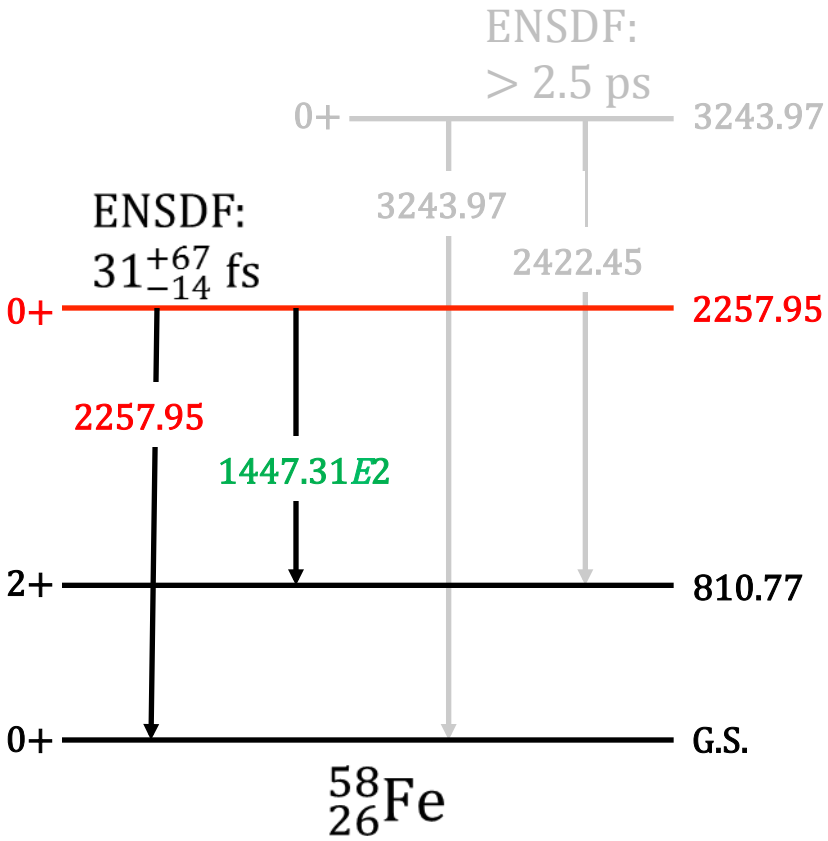
^{56}Fe


ENSDF:
52(21) fs
0(+)
3610.2
295^{+52}_{-40} fs
0+
2941.5
2941.5
2094.9 E2
3610.2
2763
2+
846.78
0+
G.S.
$^{56}_{26}$Fe

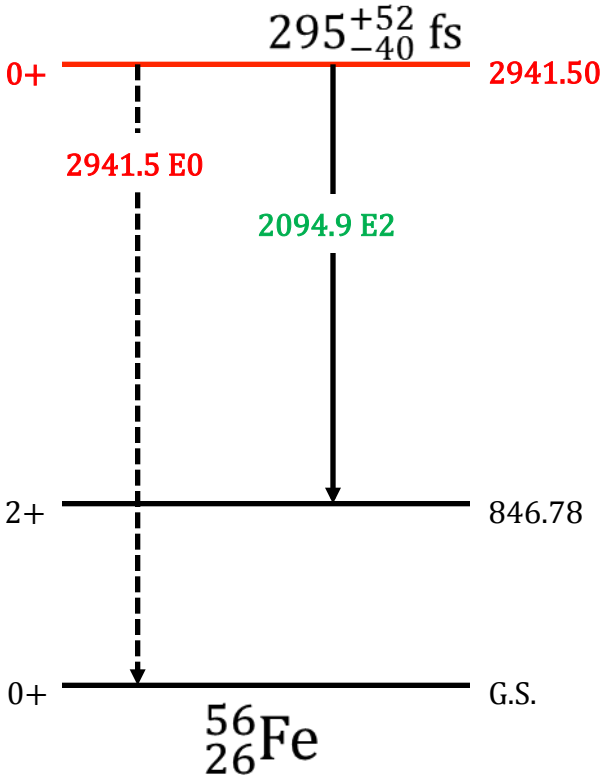
^{58}Fe

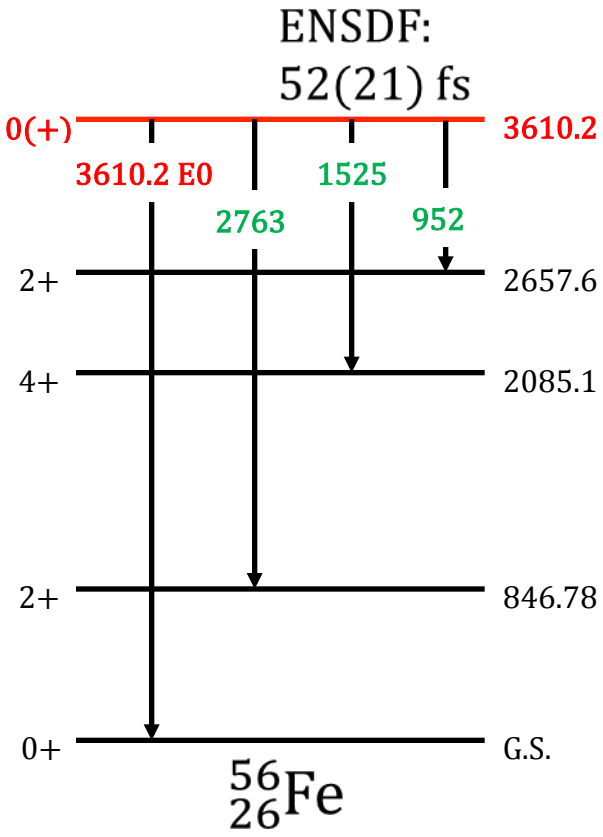

ENSDF: > 2.5 ps
0+
3243.97
3243.97 E0
2422.45E2
ENSDF:
31 +67 −14 fs
0+
2257.95
2257.95E
0
1447.31E2
810.77
2+
0+
G.S.
58 26Fe

^{58}Fe


ENSDF:
> 2.5 ps
0+
3243.97
3243.97
2422.45
ENSDF:
31^{+67}_{-14} fs
0+
2257.95
2257.95
1447.31E2
2+
810.77
0+
G.S.
$^{58}_{26}$Fe

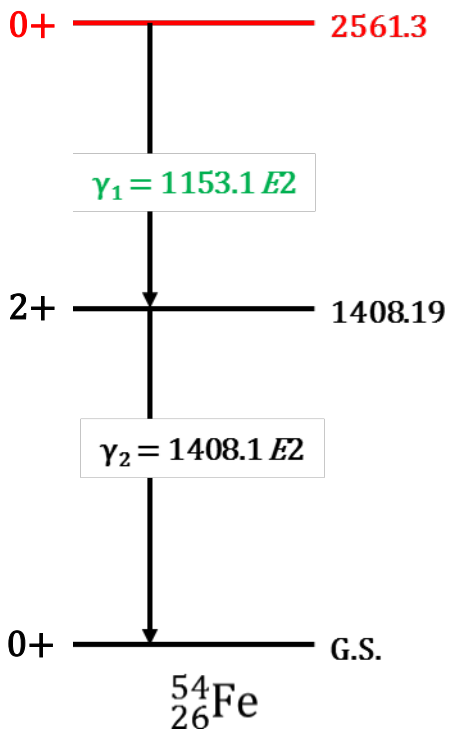
^{56}Fe

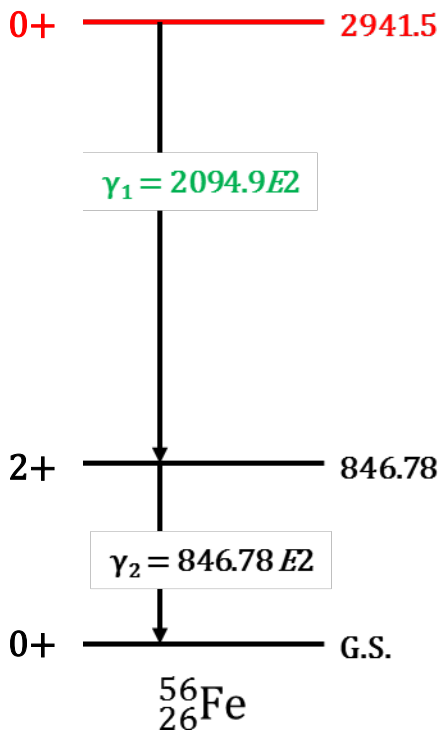

295^{+52}_{-40} fs
0+
2941.50
2941.5 E0
2094.9 E2
2+
846.78
0+
G.S.
$^{56}_{26}$Fe

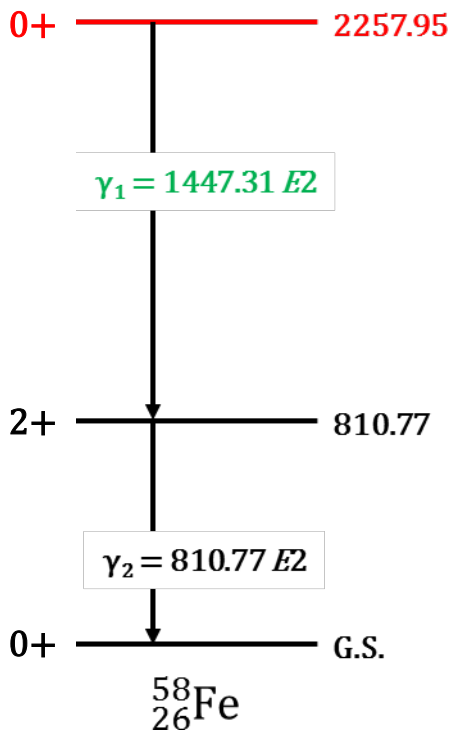

ENSDF:
52(21) fs
0(+)
3610.2
3610.2 E0
2763
1525
952
2+
2657.6
4+
2085.1
2+
846.78
0+
G.S.
$^{56}_{26}$Fe

Angular correlations CAESAR

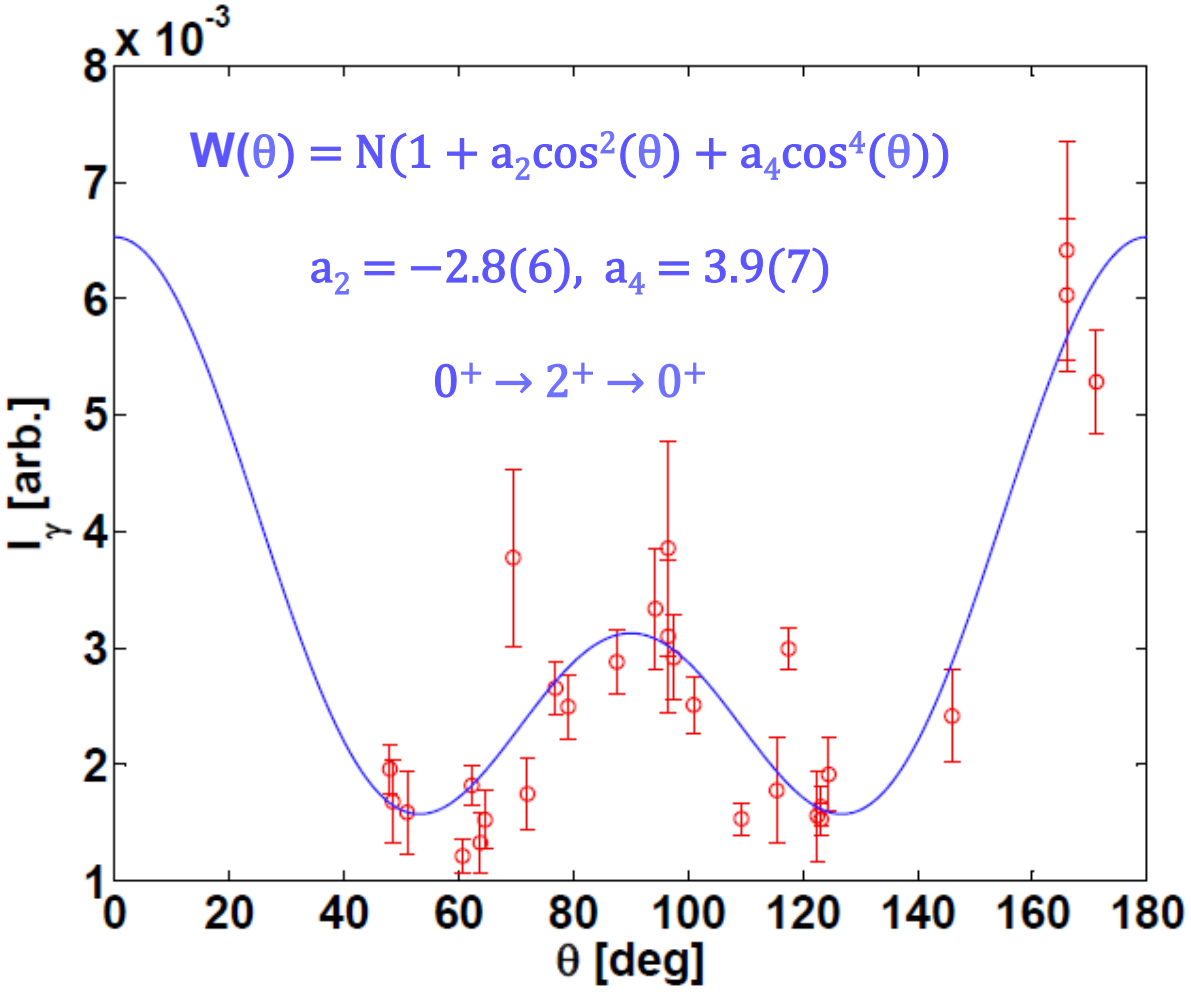
Angular correlations CAESAR



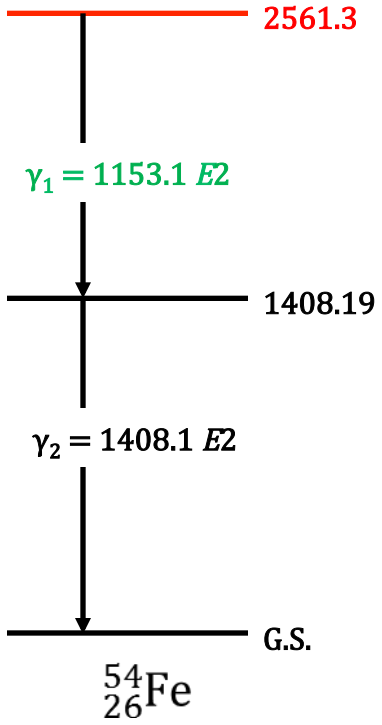




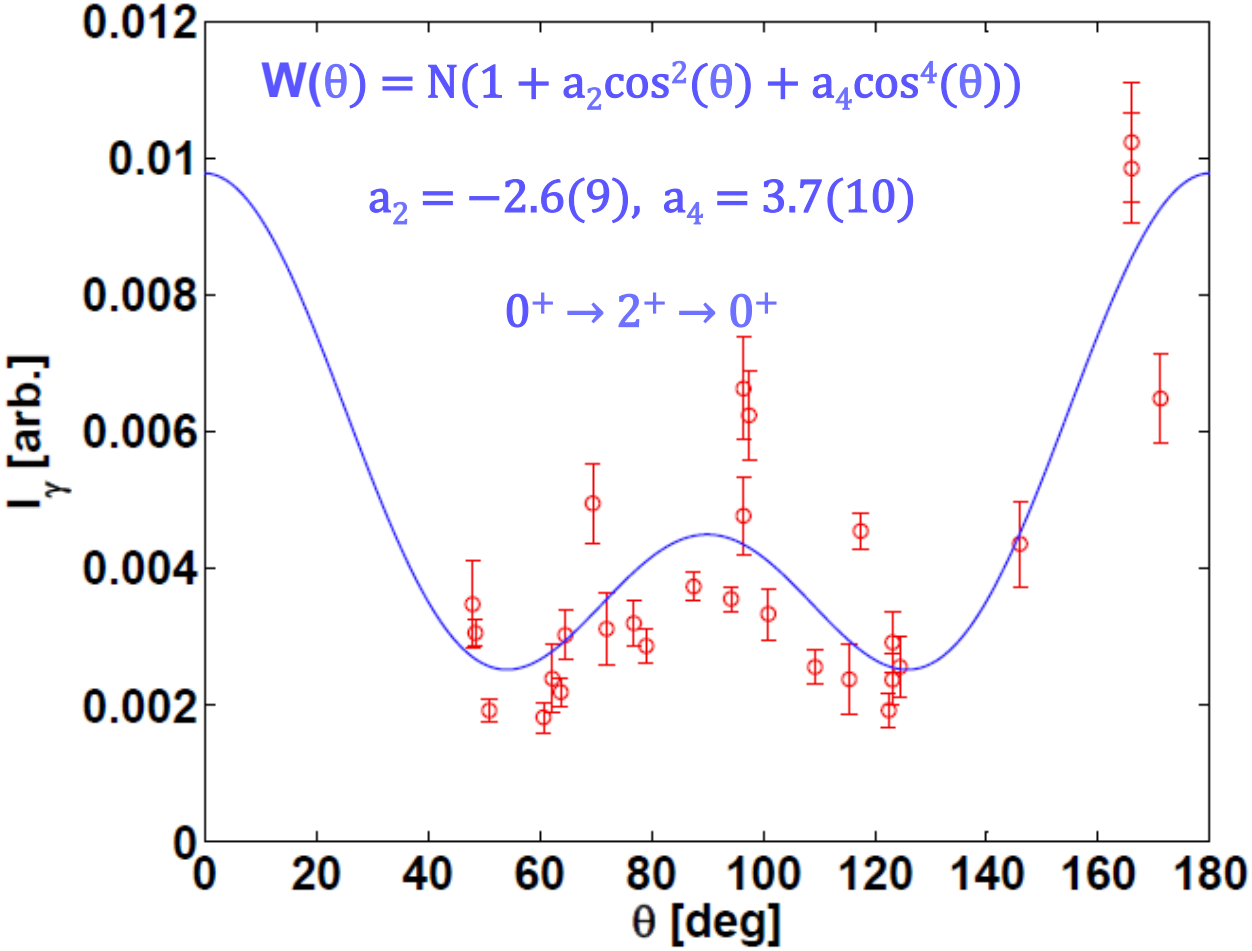
^{54}Fe



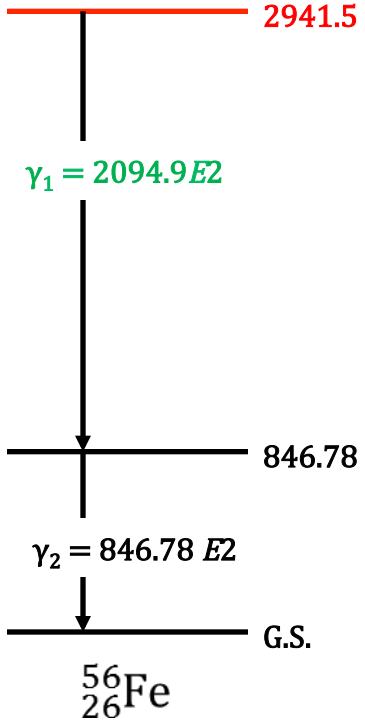
Angular correlation



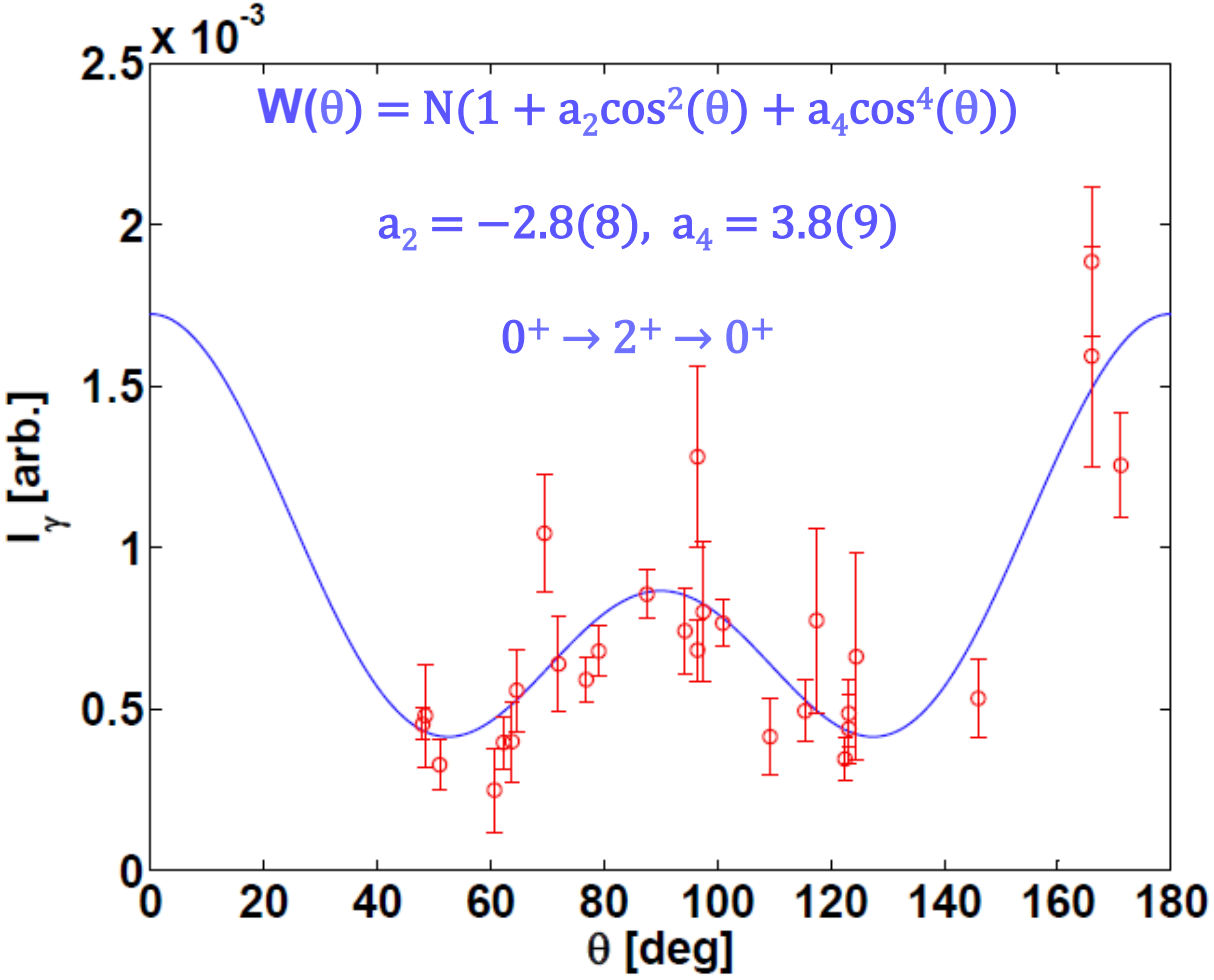
^{56}Fe



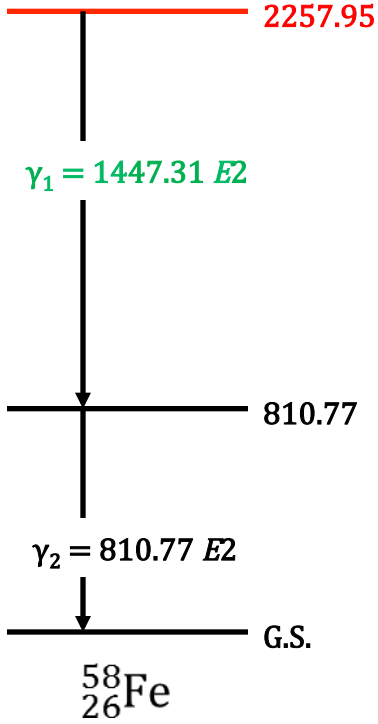
Angular correlation



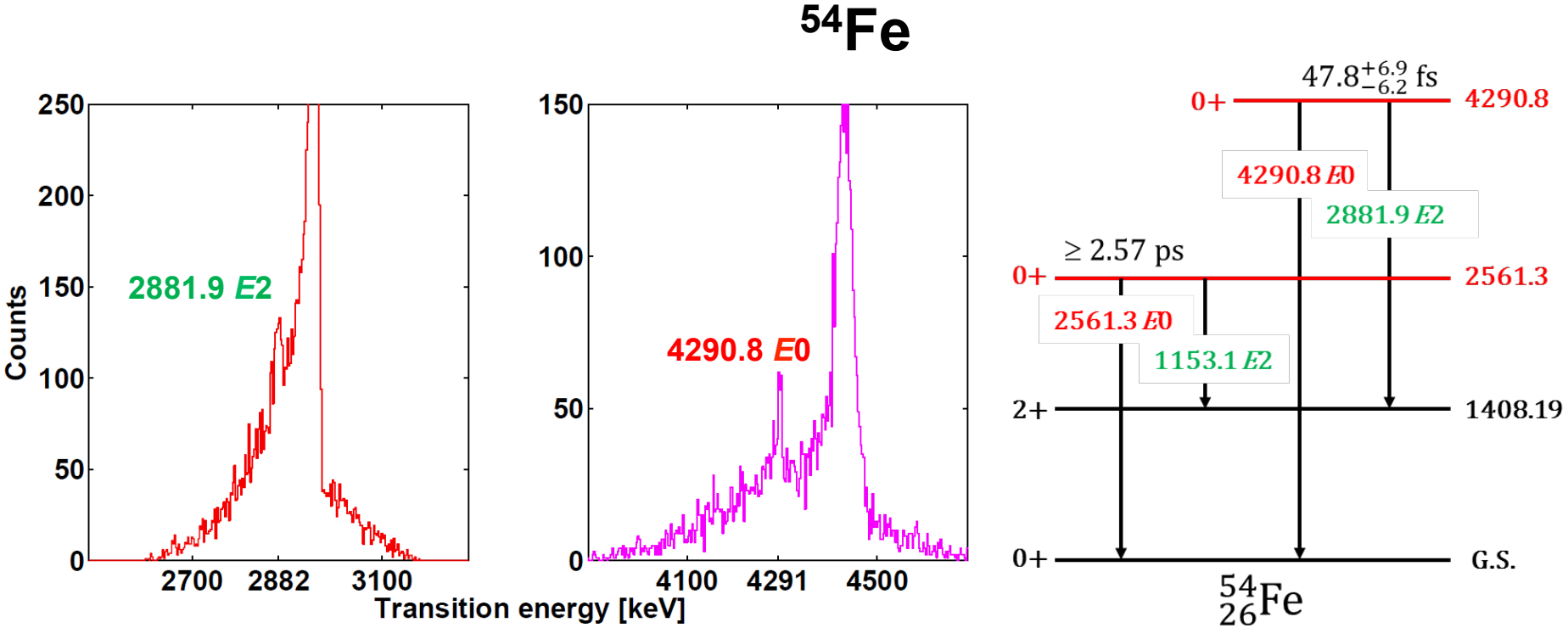
^{58}Fe



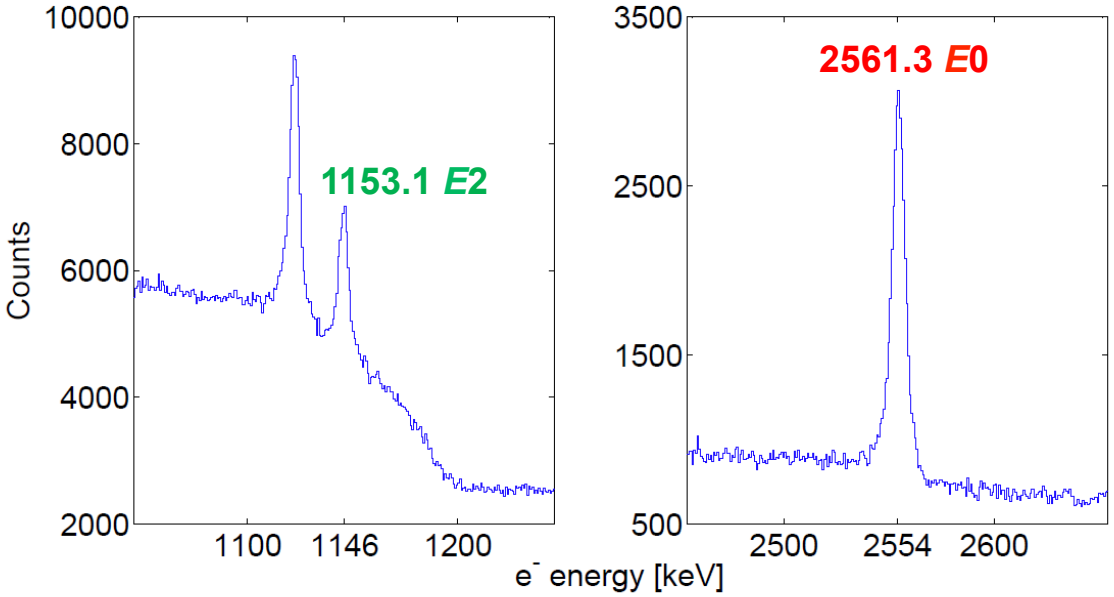
Angular correlation



^{54}Fe – second excited 0^+ state



^{54}Fe – first excited 0^+ state

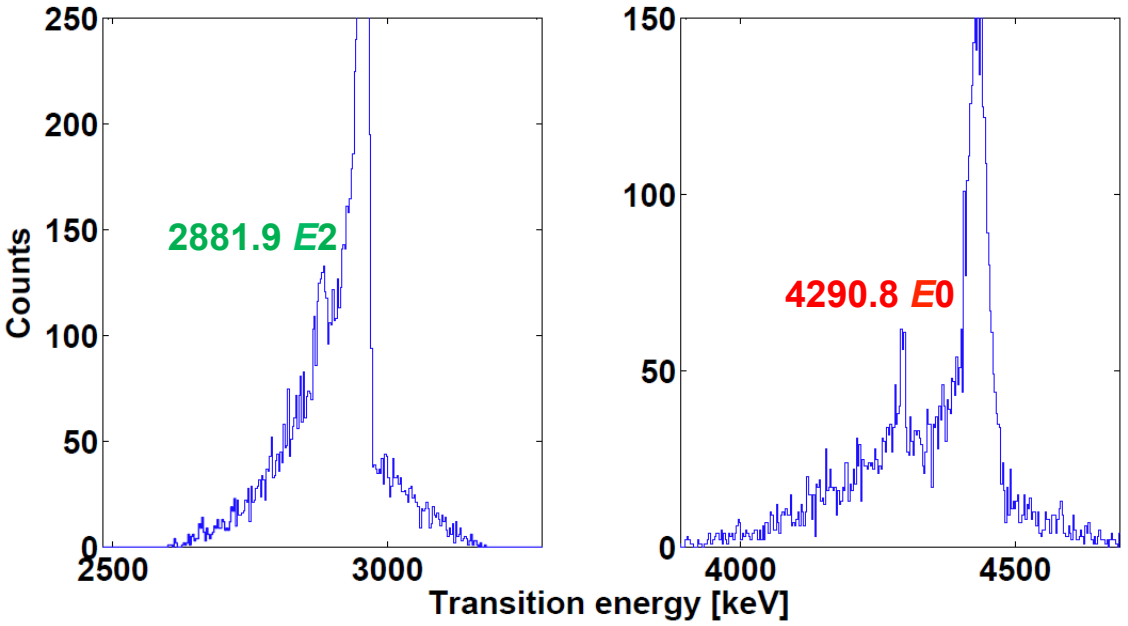


$$q_K^2(E0/E2) = \frac{I_K(E0)}{I_K(E2)} = 0.55(2)$$

$$X(E0/E2) \equiv \frac{B(E0)}{B(E2)} = 0.30(1)$$

Transition [keV]	Peak area	Relative efficiency	Relative intensity
1153.1	20724(506)	41.5(8)	499(16)
2561.3	21882(260)	79.6(15)	275(6)

^{54}Fe – second excited 0^+ state



$$q_\pi^2(E0/E2) = \frac{I_\pi(E0)}{I_\pi(E2)} = 0.69(14)$$

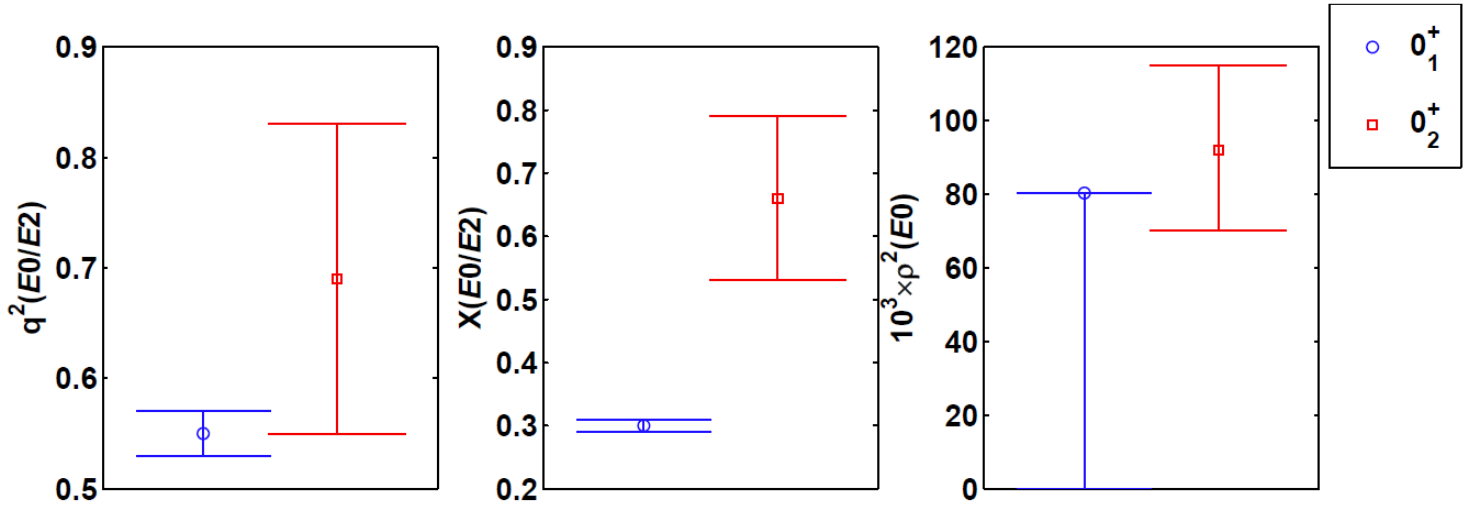
$$X(E0/E2) \equiv \frac{B(E0)}{B(E2)} = 0.66(13)$$

Transition [keV]	Peak area	Efficiency (rel.)	Intensity (rel.)
2881.9	278(39)	9.1	30.6(43)
4290.8	122(18)	5.8	21.0(31)

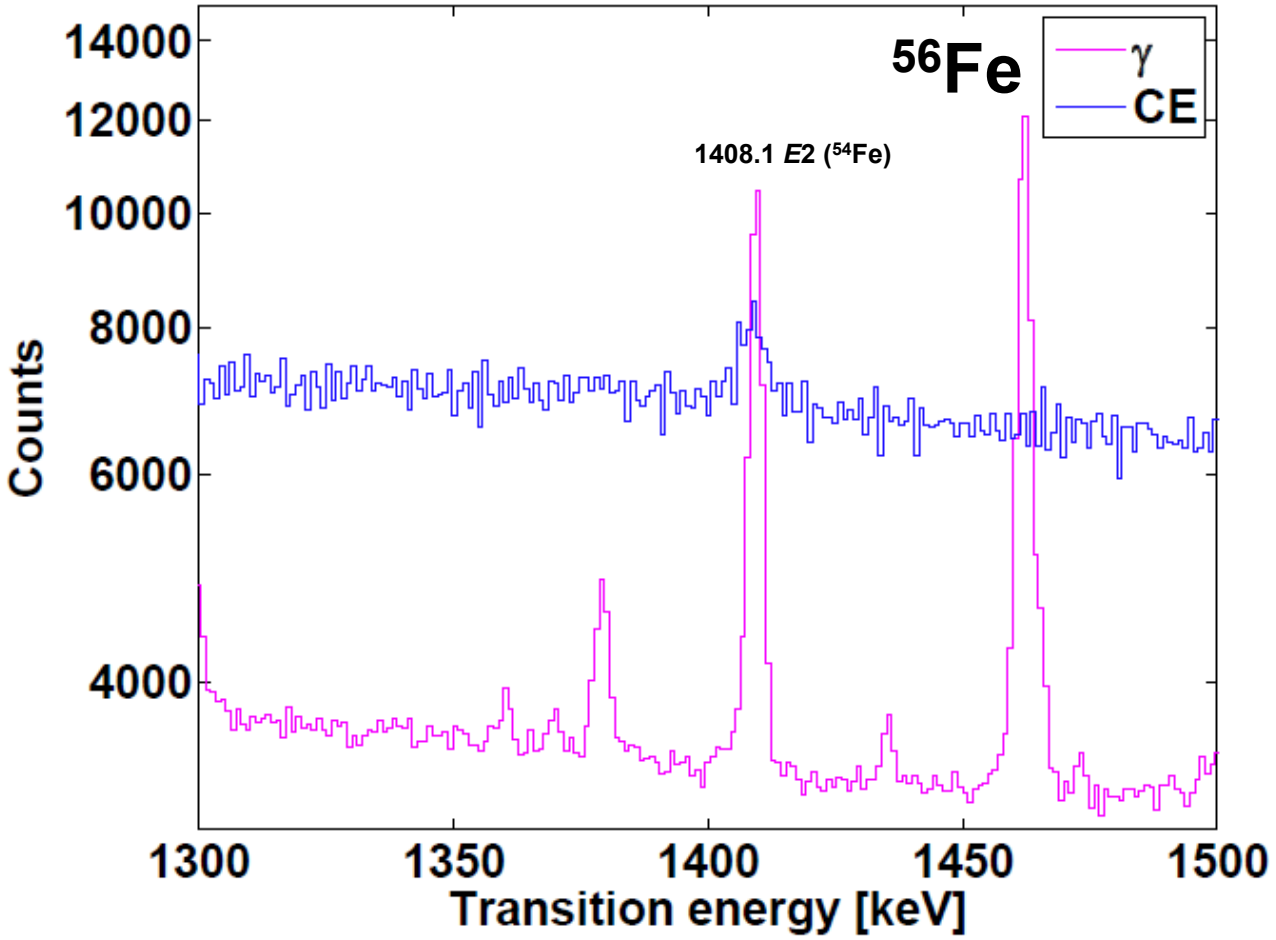
^{54}Fe summary

$$\rho(E0) = \frac{|\mathrm{M}(E0)|}{eR^2}$$

	Kentucky		ENSDF	
	τ(E2)	$10^3 \times \rho^2(E0)$	τ(E2)	$10^3 \times \rho^2(E0)$
0_1^+	> 3706.2 fs	< 80.3	≥ 2020 fs	≤ 147.4
0_2^+	69^{+10}_{-9} fs	92^{+23}_{-22}	79^{+25}_{-20} fs	80^{+32}_{-25}



^{56}Fe – first excited 0^+ state

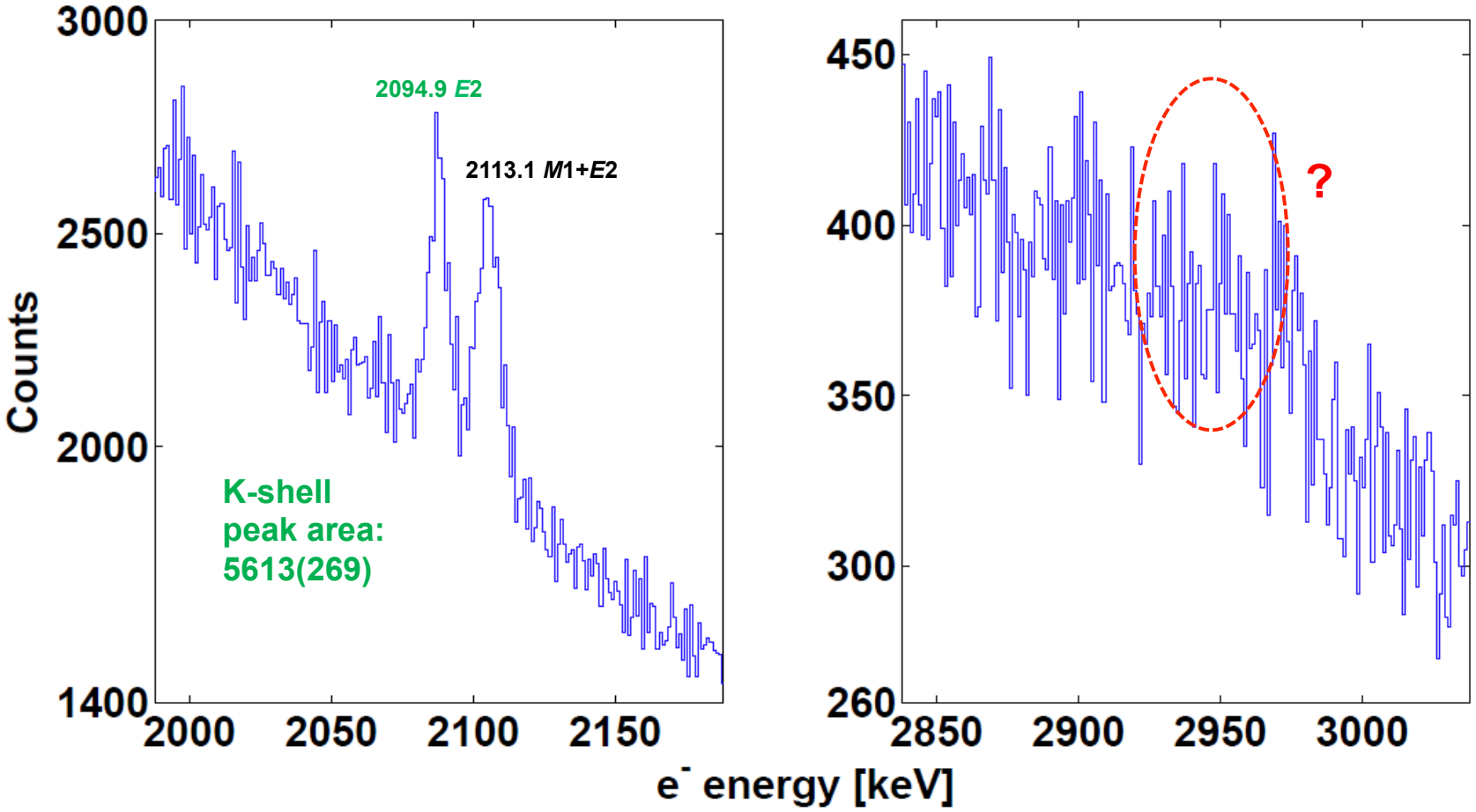


Ratio of the 1408 and 2561 keV transitions:

^{54}Fe dataset:
$R = 199524/22600 \approx 9$

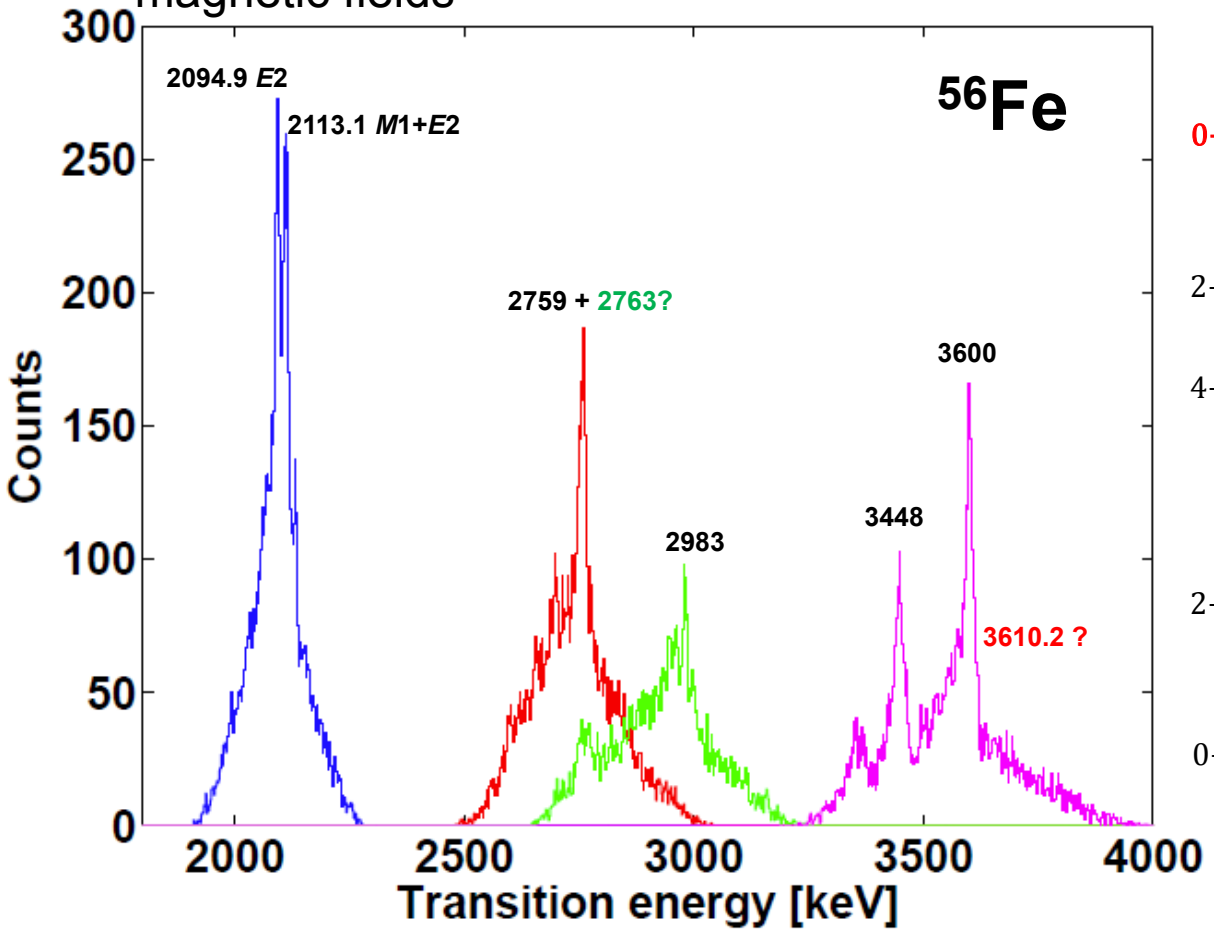
^{56}Fe dataset:
$R = 8671/977 \approx 9$

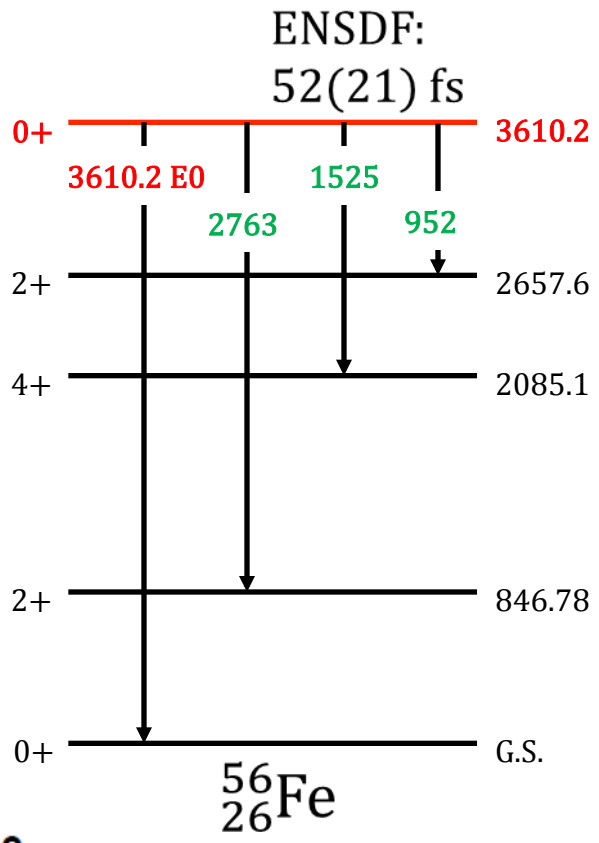
^{56}Fe – first excited 0^+ state



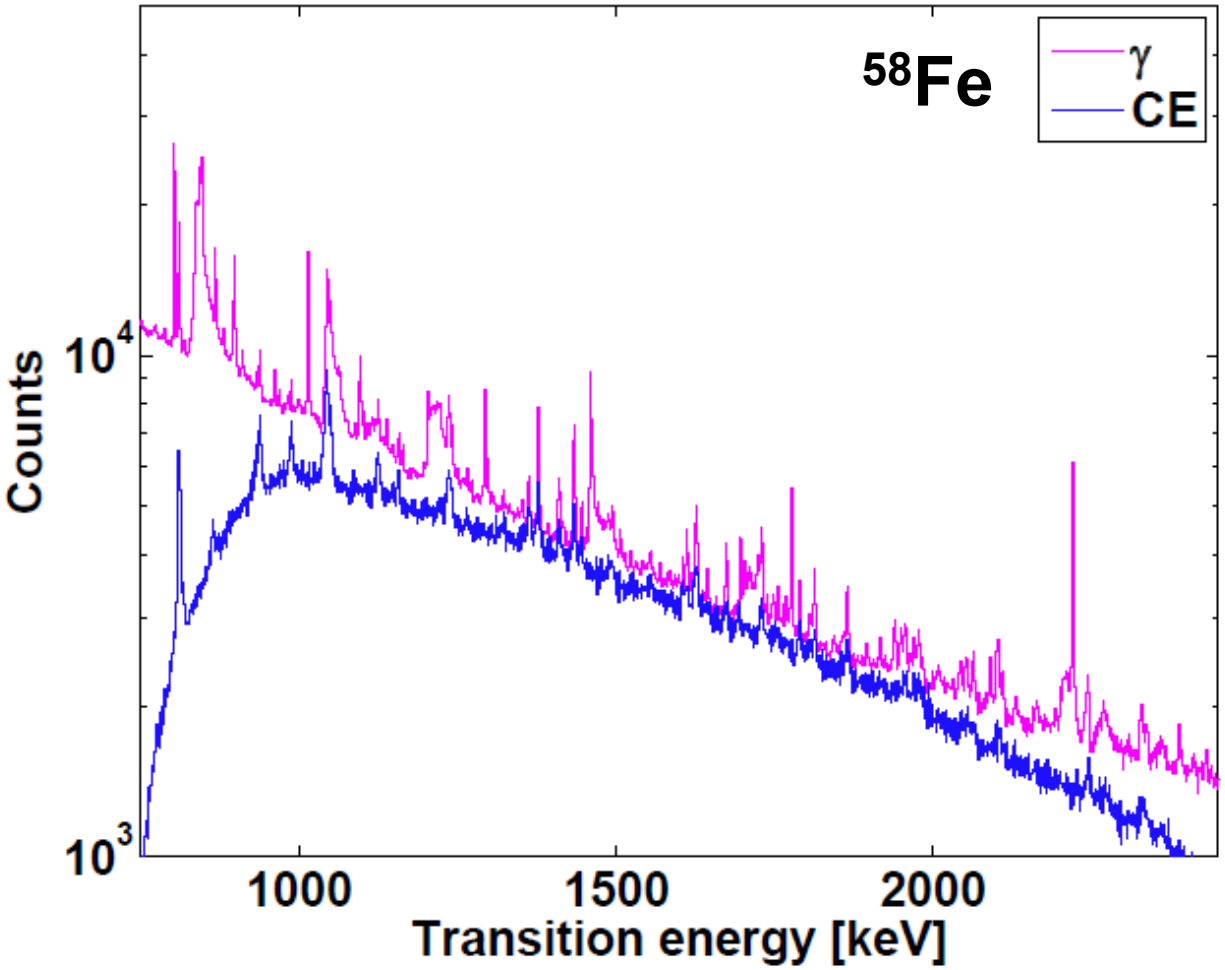
^{56}Fe

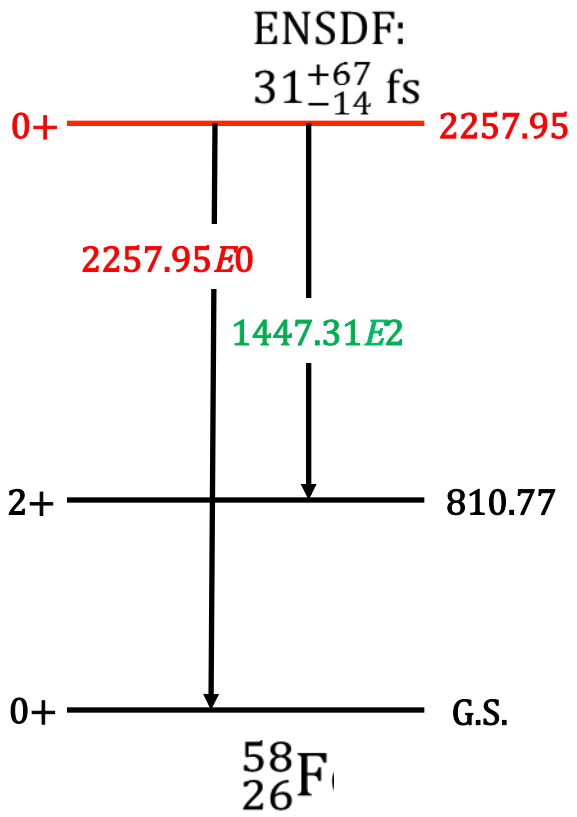
colors denote different magnetic fields



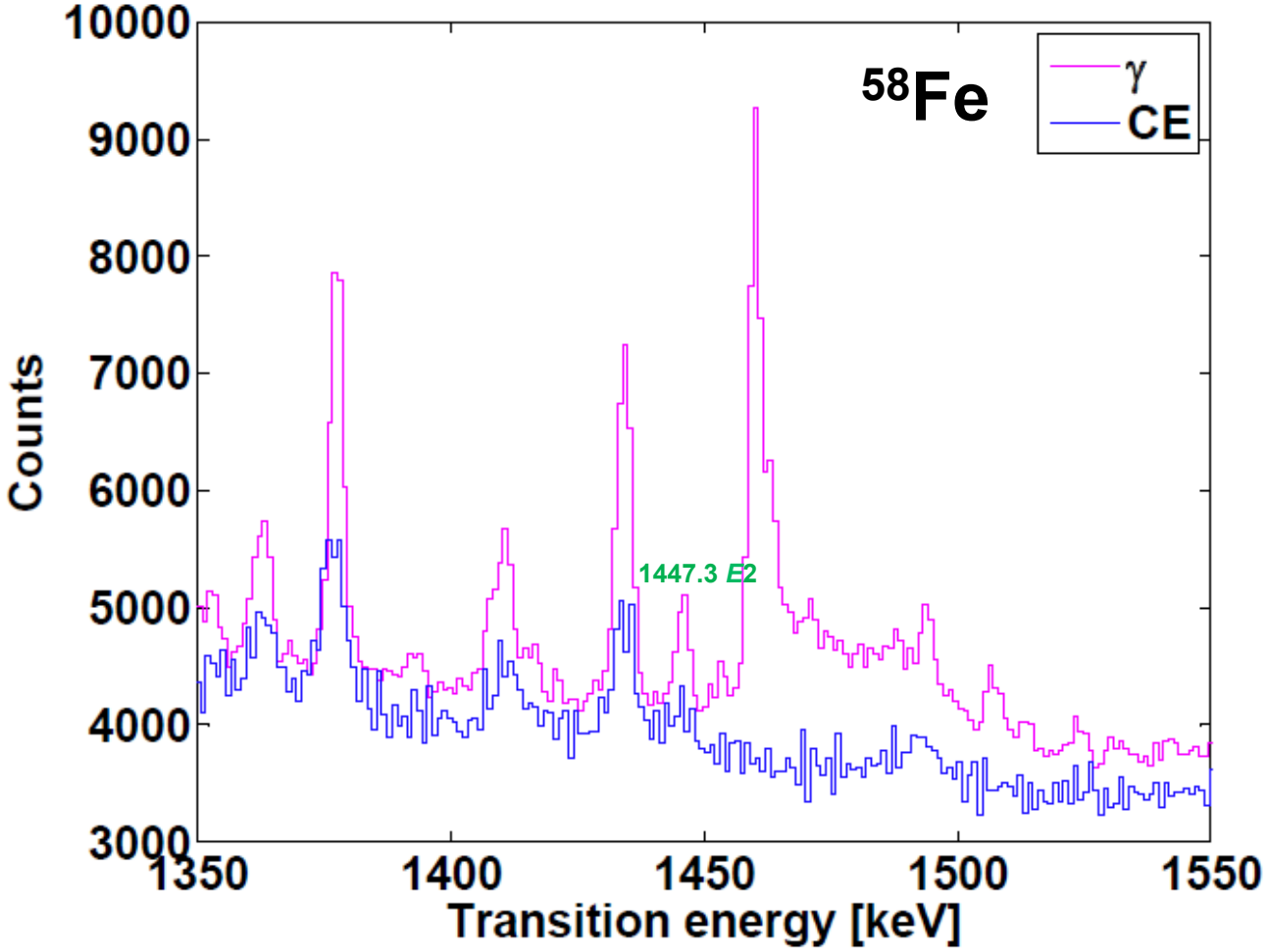


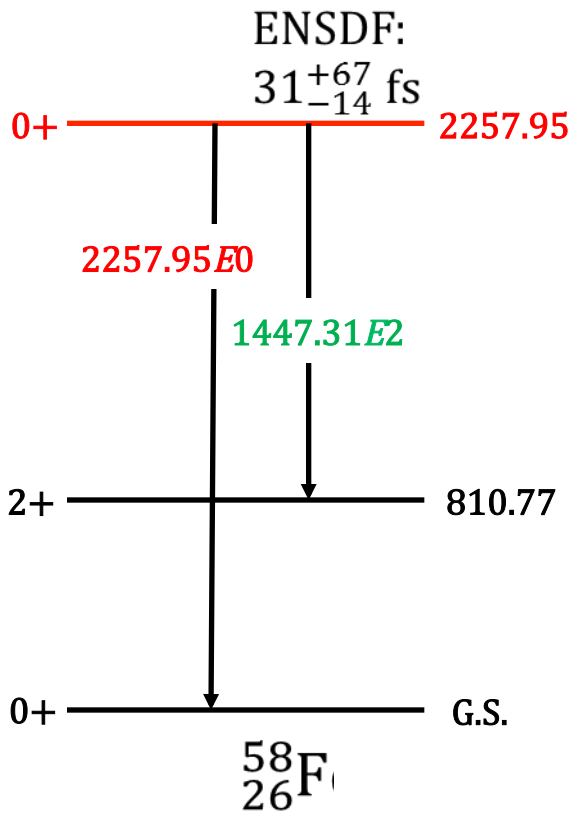
^{58}Fe


58Fe
γ
CE
Counts
10^4
10^3
1000
1500
2000
Transition energy [keV]


ENSDF:
31 +67 −14 fs
0+
2257.95
2257.95E0
1447.31E2
2+
810.77
0+
G.S.
58 26 F

^{58}Fe – first excited 0$^+$ state

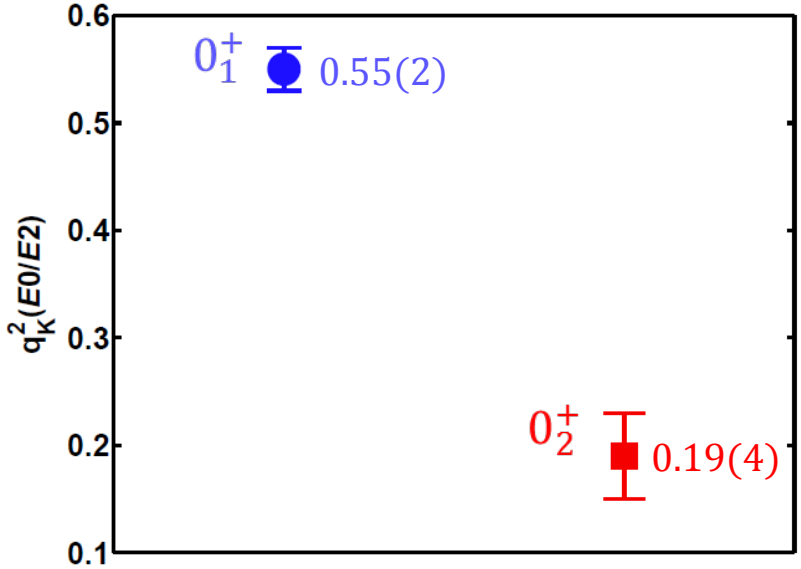


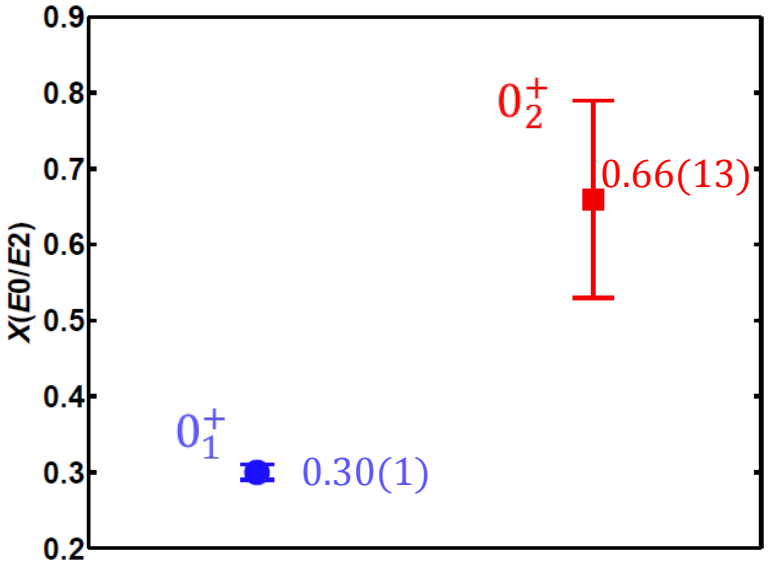


Results ^{54}Fe

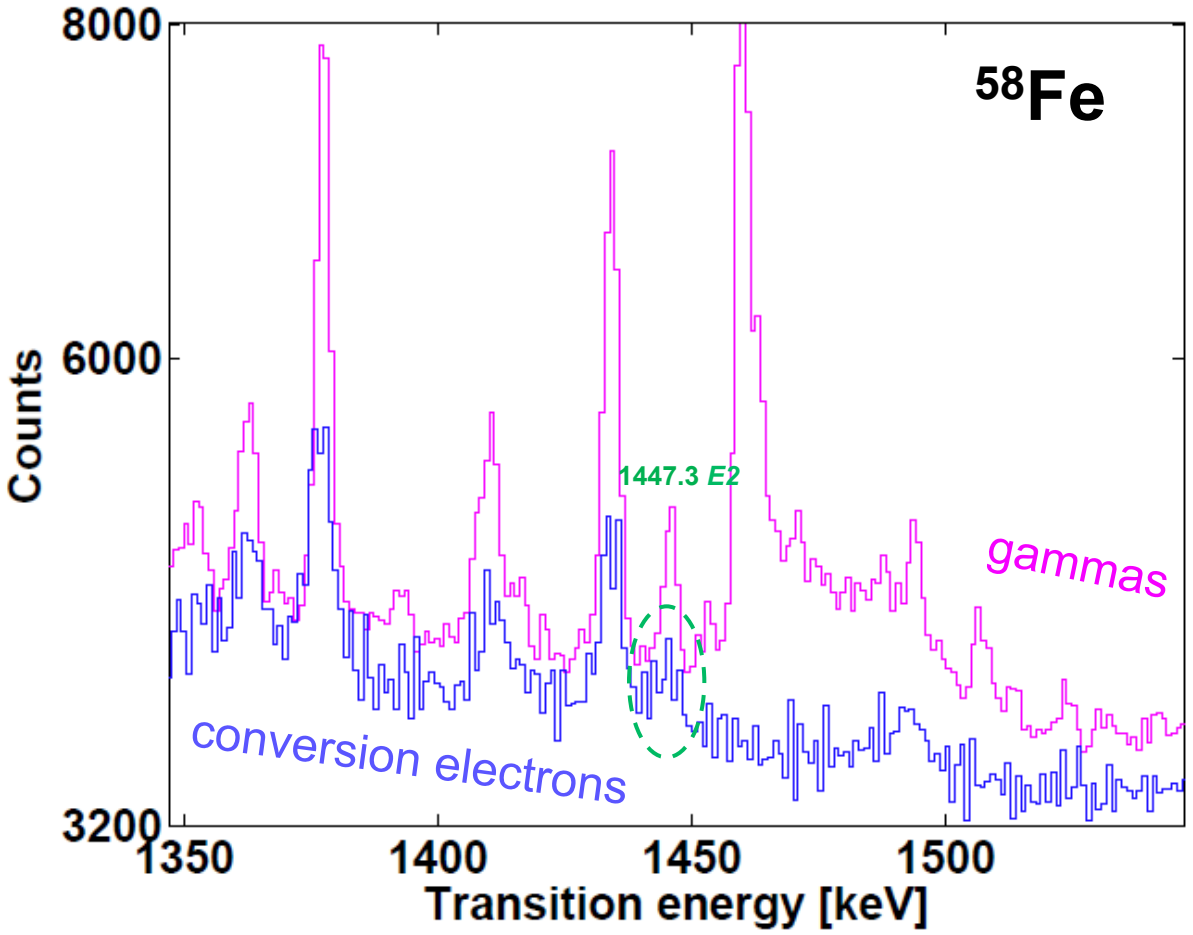
$$q_K^2(E0/E2) = \frac{I_K(E0)}{I_K(E2)}$$

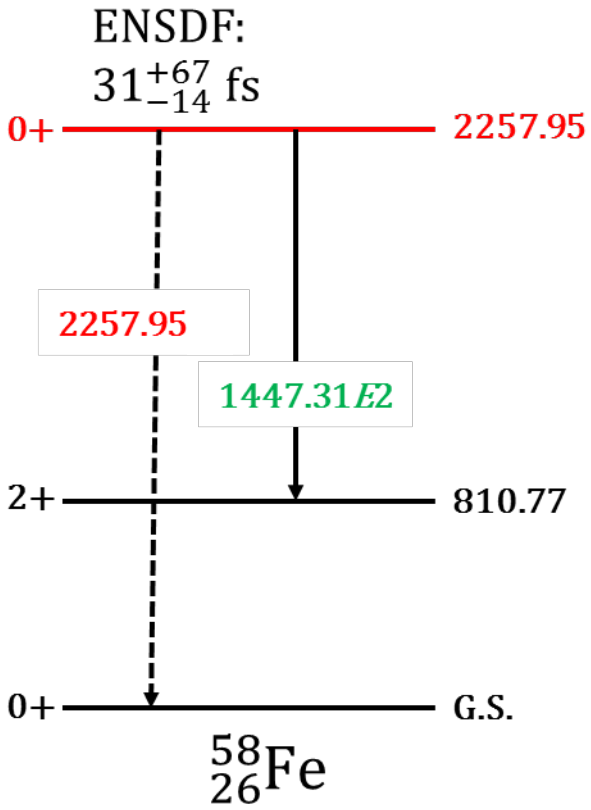
$$X(E0/E2) \equiv \frac{B(E0)}{B(E2)}$$



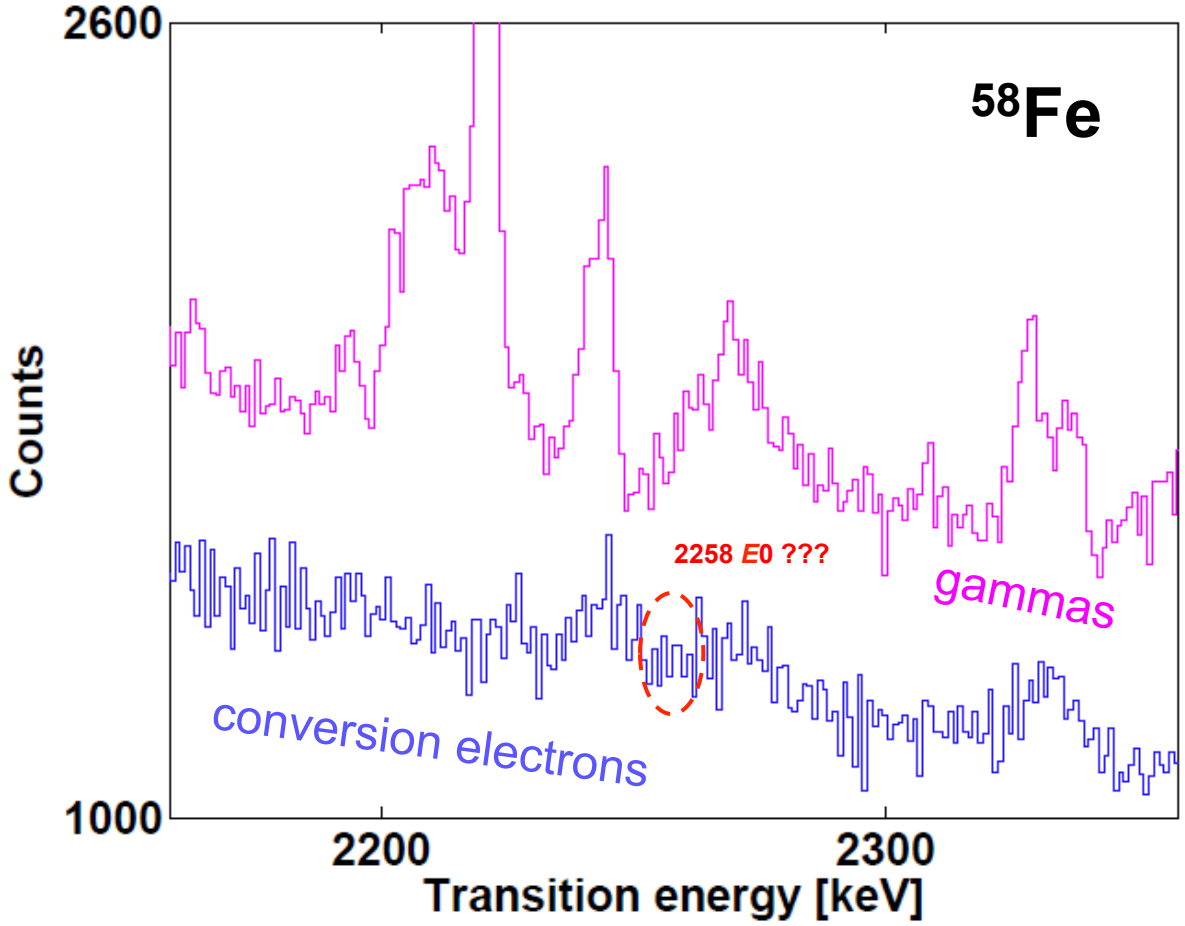


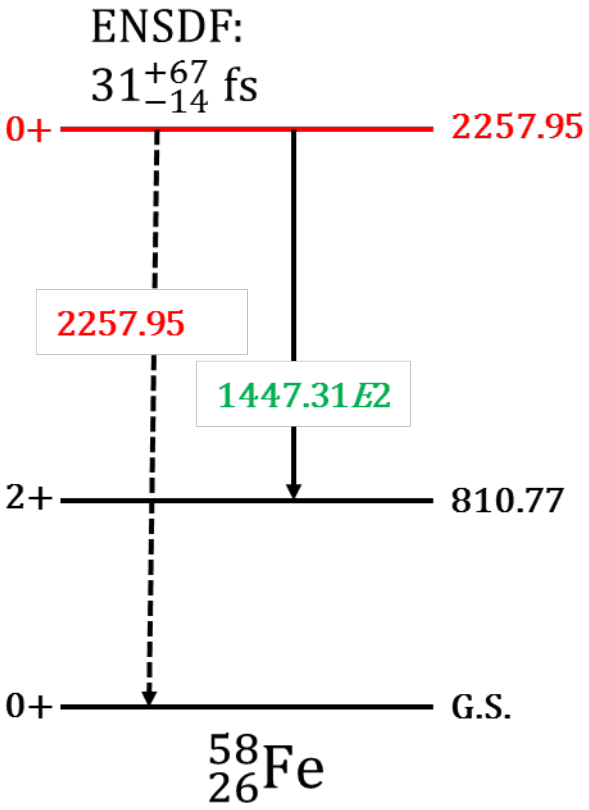
^{58}Fe


8000
6000
3200
Counts
1350
1400
1450
1500
Transition energy [keV]
58Fe
1447.3 E2
gammas
conversion electrons


ENSDF:
31+67−14 fs
0+
2257.95
2257.95
1447.31E2
2+
810.77
0+
G.S.
58
26Fe

^{58}Fe


2600
1000
Counts
2200
2300
Transition energy [keV]
58Fe
2258 E0 ???
gammas
conversion electrons


ENSDF:
31+67−14 fs
0+
2257.95
2257.95
1447.31E2
2+
810.77
0+
G.S.
58 26Fe