MICHIGAN STATE UNIVERSITY

^{25}Si β-decay spectroscopy using the Gaseous Detector with Germanium Tagging (GADGET) system

Lijie Sun

Previews of the Future in Low-Energy Experimental Nuclear Physics

National Postdoctoral Seminar Series

U.S. DEPARTMENT OF ENERGY | Office of Science

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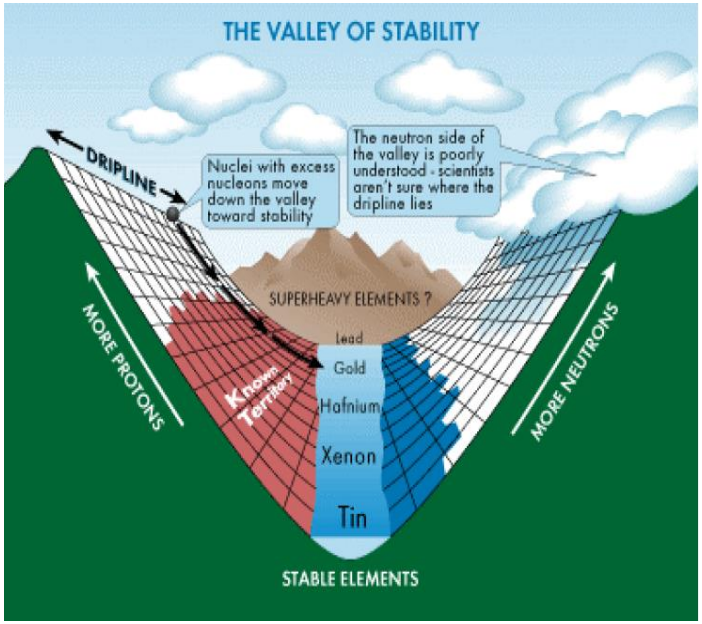
Outline

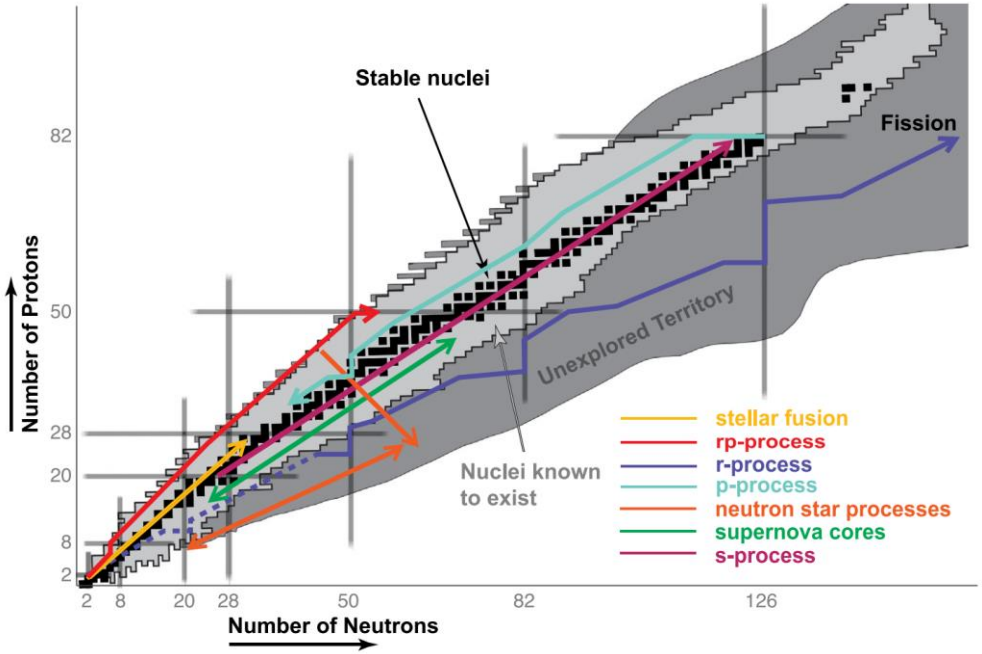
- Introduction
- Experimental techniques
- Results
  - Half-life of ^{25}Si
  - ^{25}Si($\beta\gamma$)^{25}Al
  - ^{25}Si($\beta p\gamma$)^{24}Mg
  - ^{25}Si(βp)^{24}Mg
  - $p\gamma$ coincidence
  - Decay scheme
- Discussion
  - Mirror symmetry
  - Isospin mixing
  - Shell model calculations

Why?

- Fundamental Symmetries and Interactions
- Origin of the Elements in the Universe

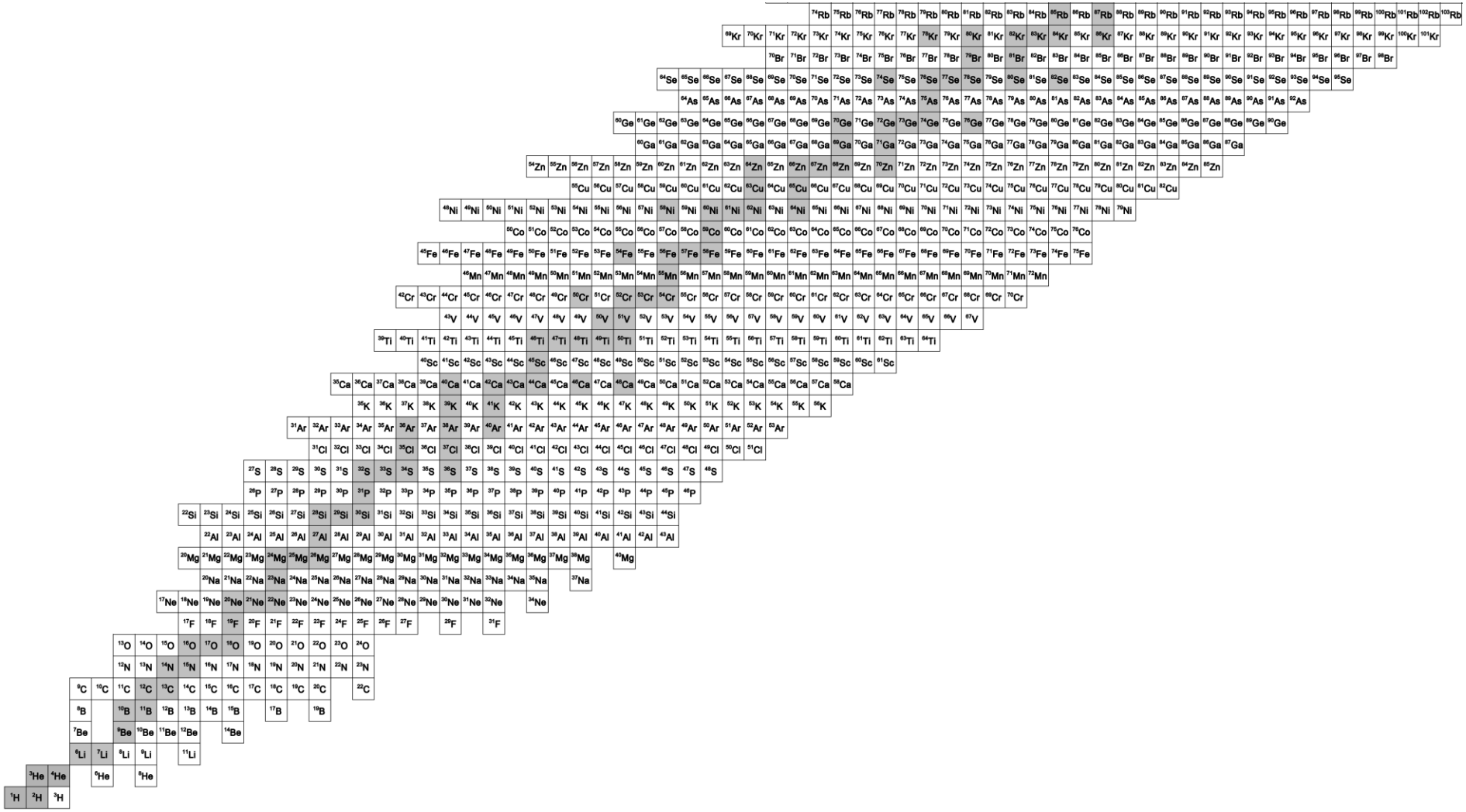


C. Boutin, CERN Courier Feb 2002.



A. Arcones *et al*., Prog. Part. Nucl. Phys. 94, 1 (2017).

Chart of Nuclides



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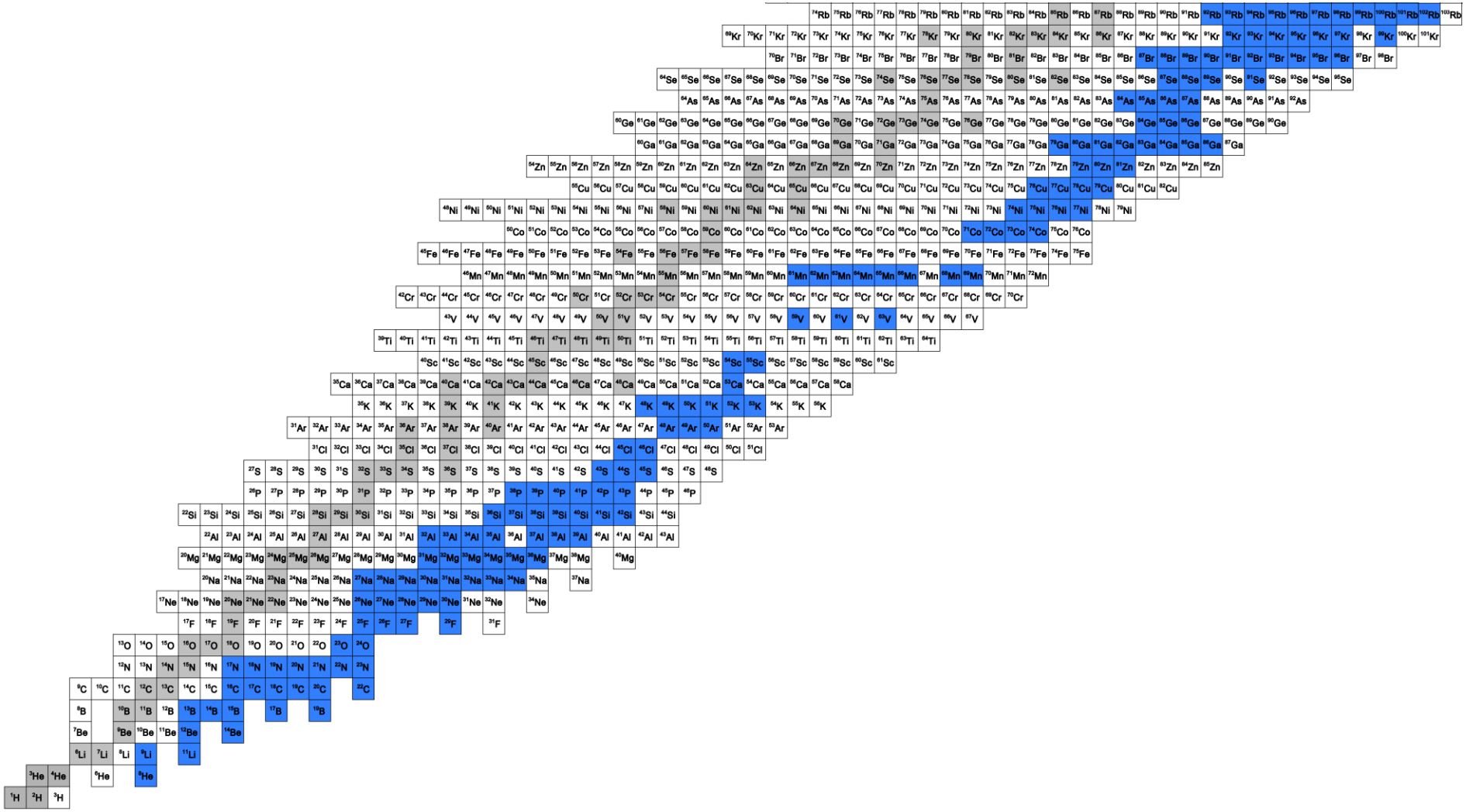

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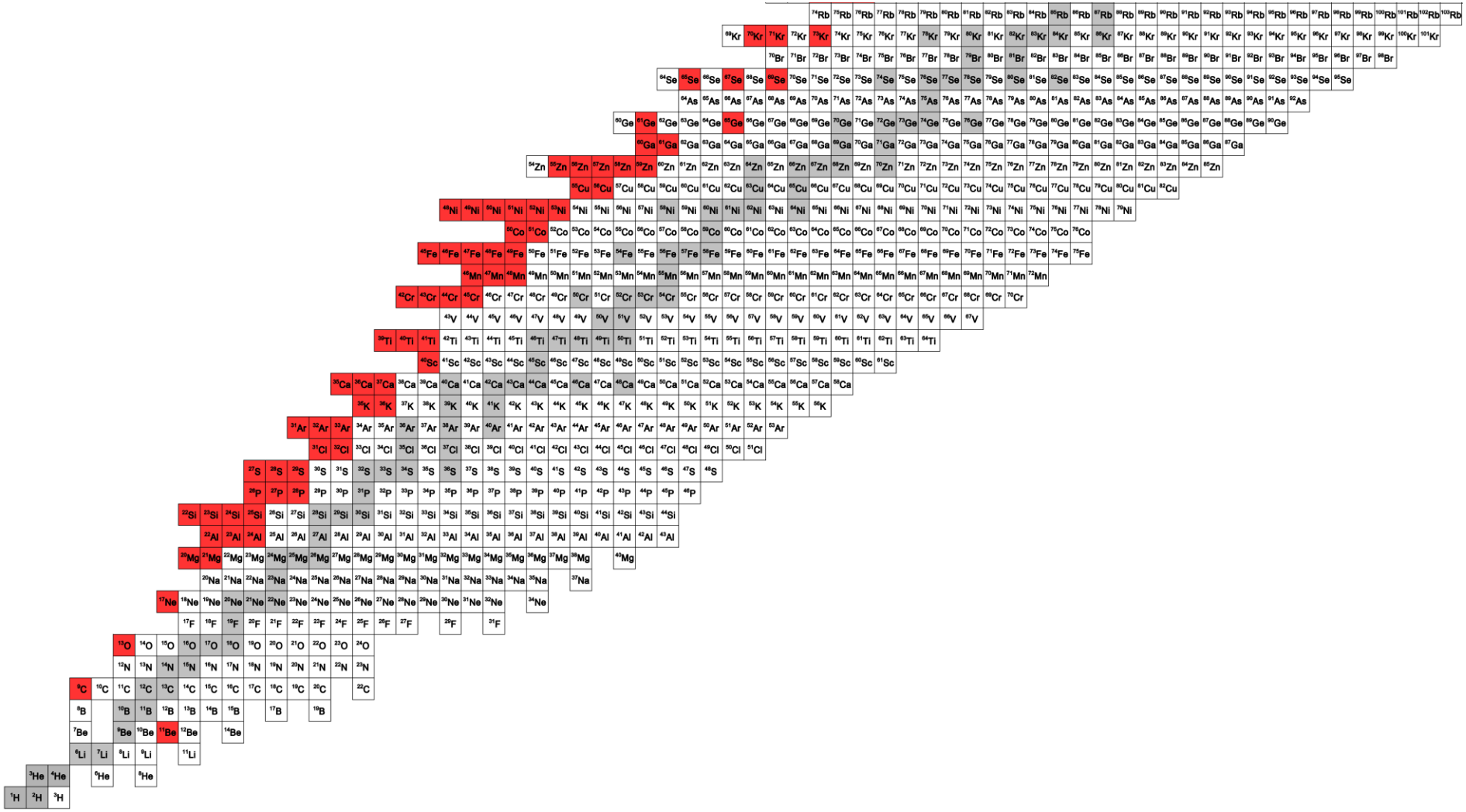


β decay

L. J. Sun *et al.*, Chin. Phys. Lett. 32, 012301 (2015). ^{36,37}Ca

L. J. Sun *et al.*, Nucl. Instrum. Methods Phys. Res. A 804, 1 (2015). ^{23}Al, ^{24}Si

L. J. Sun *et al.*, Phys. Rev. C 95, 014314 (2017). ^{20}Mg

X. X. Xu *et al.*, Phys. Lett. B 766, 321 (2017). ^{22}Si

K. Wang *et al.*, Int. J. Mod. Phys. E 27, 1850014 (2018). ^{23}Si

Y. T. Wang *et al.*, Eur. Phys. J. A 54, 107 (2018). ^{21}Mg

Y. T. Wang *et al.*, Nucl. Sci. Tech. 29, 98 (2018). ^{22}Al

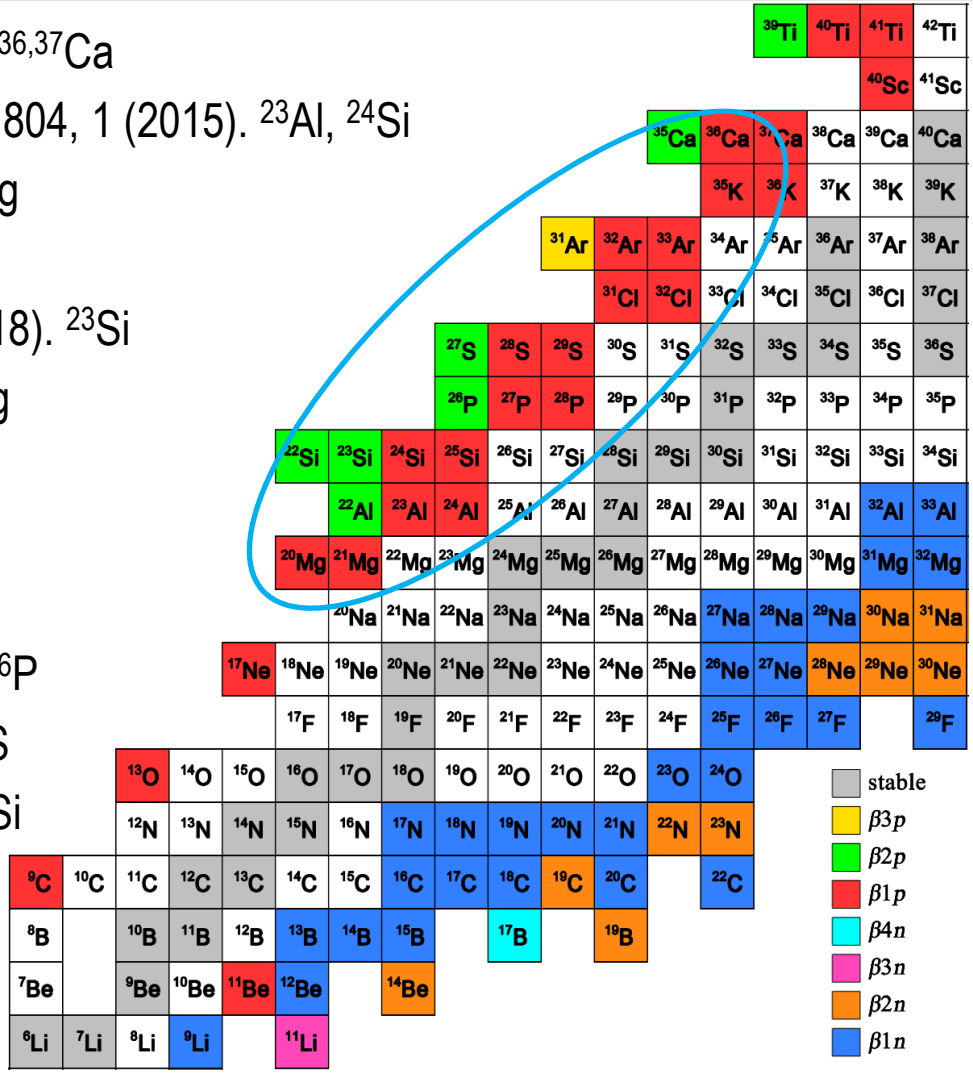
Y. T. Wang *et al.*, Phys. Lett. B 784, 12 (2018). ^{22}Al

L. J. Sun *et al.*, Phys. Rev. C 99, 064312 (2019). ^{27}S

P. F. Liang *et al.*, Phys. Rev. C 101, 015812 (2020). ^{26}P

L. J. Sun *et al.*, Phys. Lett. B 802, 135213 (2020). ^{27}S

J. Lee *et al.*, Phys. Rev. Lett. 125, 192503 (2020). ^{22}Si



β decay

M. B. Bennett *et al.*, Phys. Rev. Lett. 111, 232503 (2013). ^{26}P

B. E. Glassman *et al.*, Phys. Rev. C 92, 042501(R) (2015). ^{20}Mg

S. B. Schwartz *et al.*, Phys. Rev. C 92, 031302(R) (2015). ^{26}P

M. B. Bennett *et al.*, Phys. Rev. Lett. 116, 102502 (2016). ^{31}Cl

D. Pérez-Loureiro *et al.*, Phys. Rev. C 93, 064320 (2016). ^{26}P

M. B. Bennett *et al.*, Phys. Rev. C 93, 064310 (2016). ^{31}Cl

C. Wrede *et al.*, Phys. Rev. C 96, 032801(R) (2017). ^{20}Mg

M. B. Bennett *et al.*, Phys. Rev. C 97, 065803 (2018). ^{31}Cl

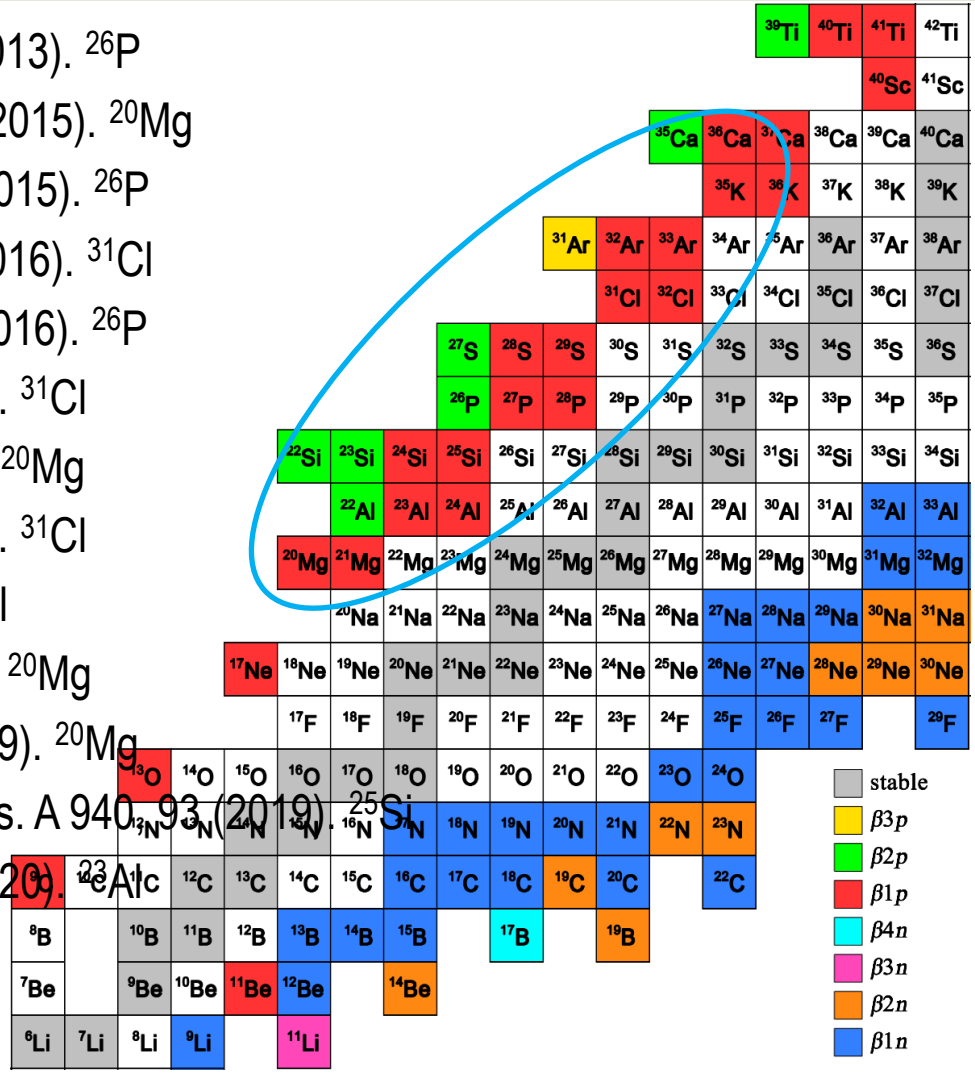
E. Aboud *et al.*, Phys. Rev. C 98, 024309 (2018). ^{32}Cl

B. E. Glassman *et al.*, Phys. Lett. B 778, 397 (2018). ^{20}Mg

B. E. Glassman *et al.*, Phys. Rev. C 99, 065801 (2019). ^{20}Mg

M. Friedman *et al.*, Nucl. Instrum. Methods Phys. Res. A 940, 93 (2019). ^{25}Si

M. Friedman *et al.*, Phys. Rev. C 101, 052802(R) (2020). ^{23}Al



β decay

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C. Wrede *et al.*, Phys. Rev. C 96, 032801(R) (2017). ^{20}Mg

M. B. Bennett *et al.*, Phys. Rev. C 97, 065803 (2018). ^{31}Cl

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B. E. Glassman *et al.*, Phys. Lett. B 778, 397 (2018). ^{20}Mg

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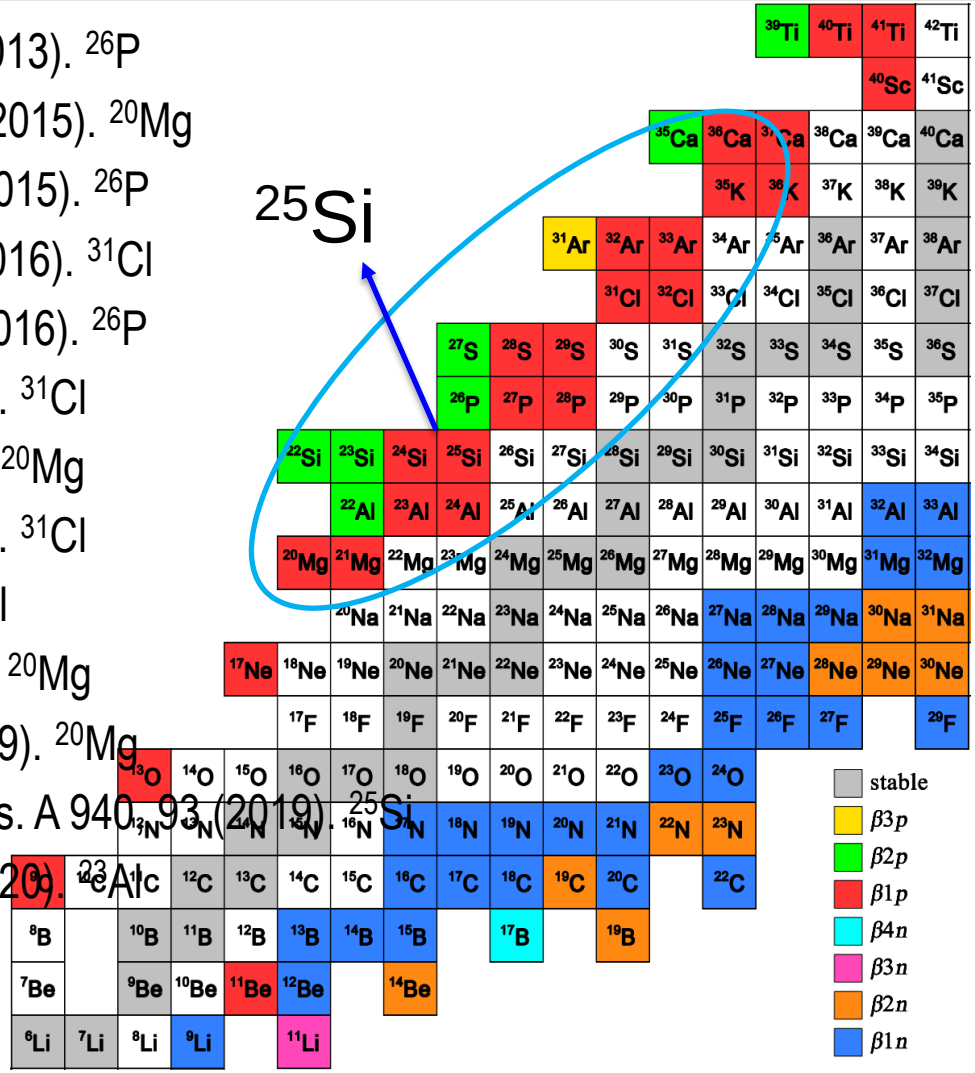

β decay of ^{25}Si

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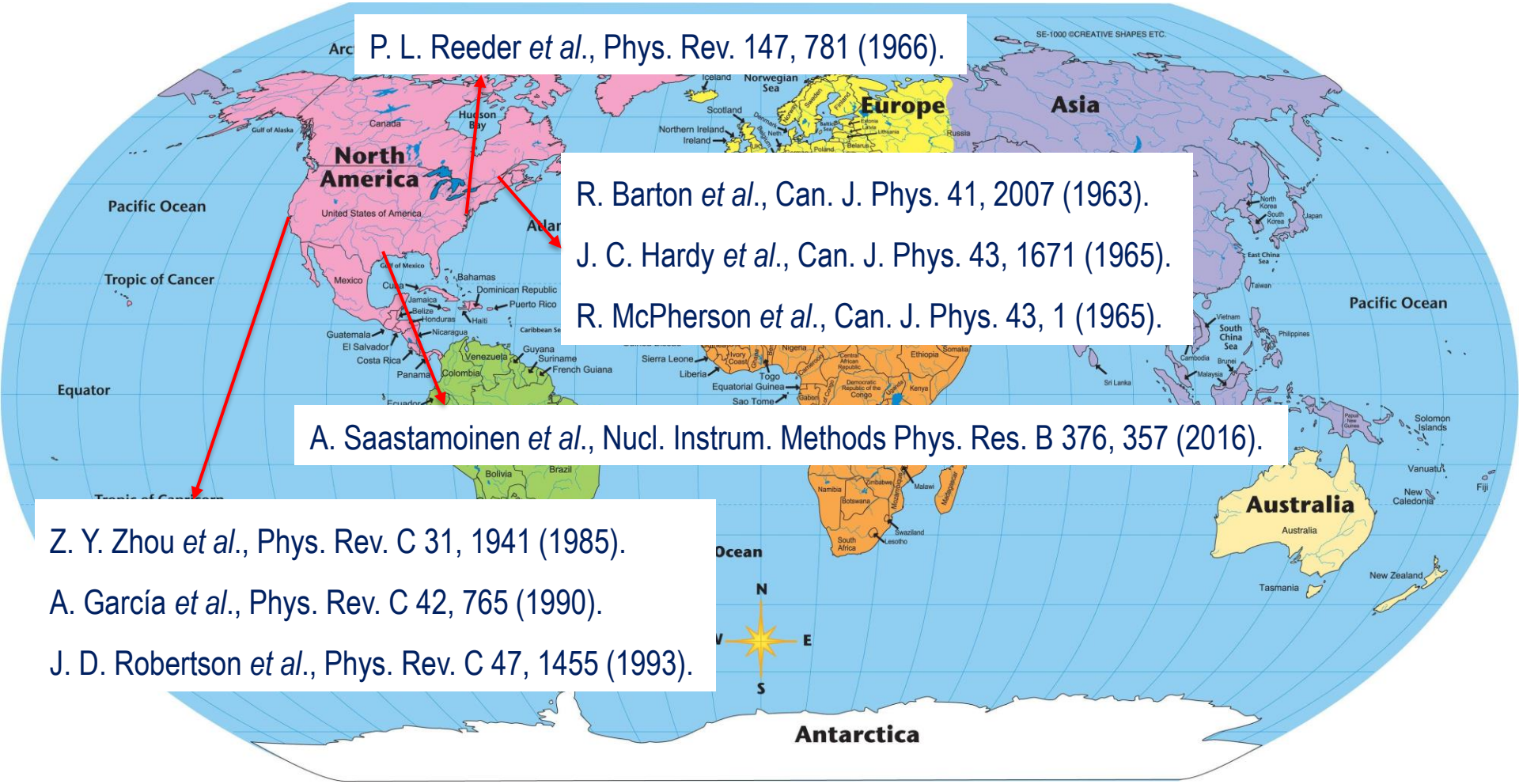
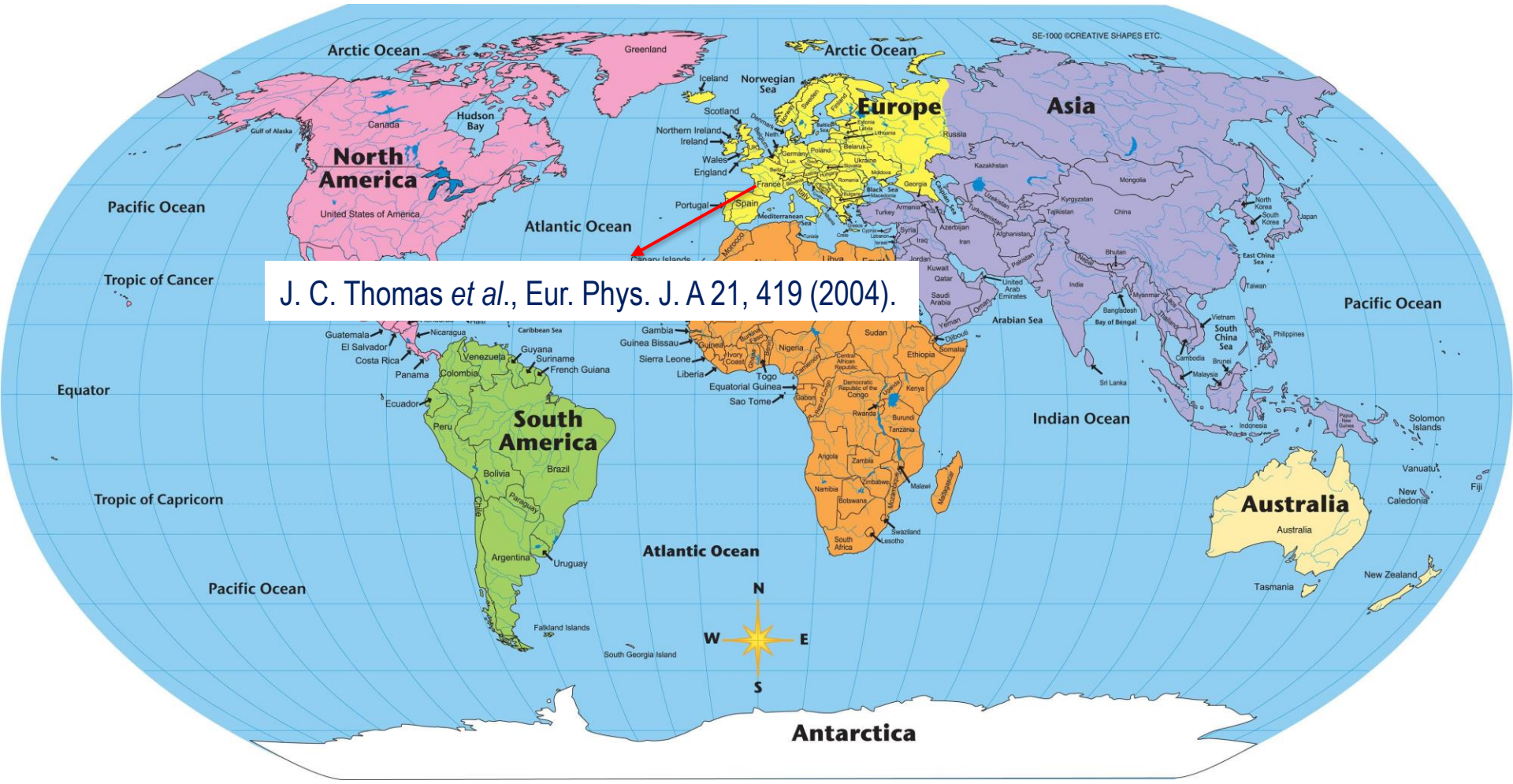
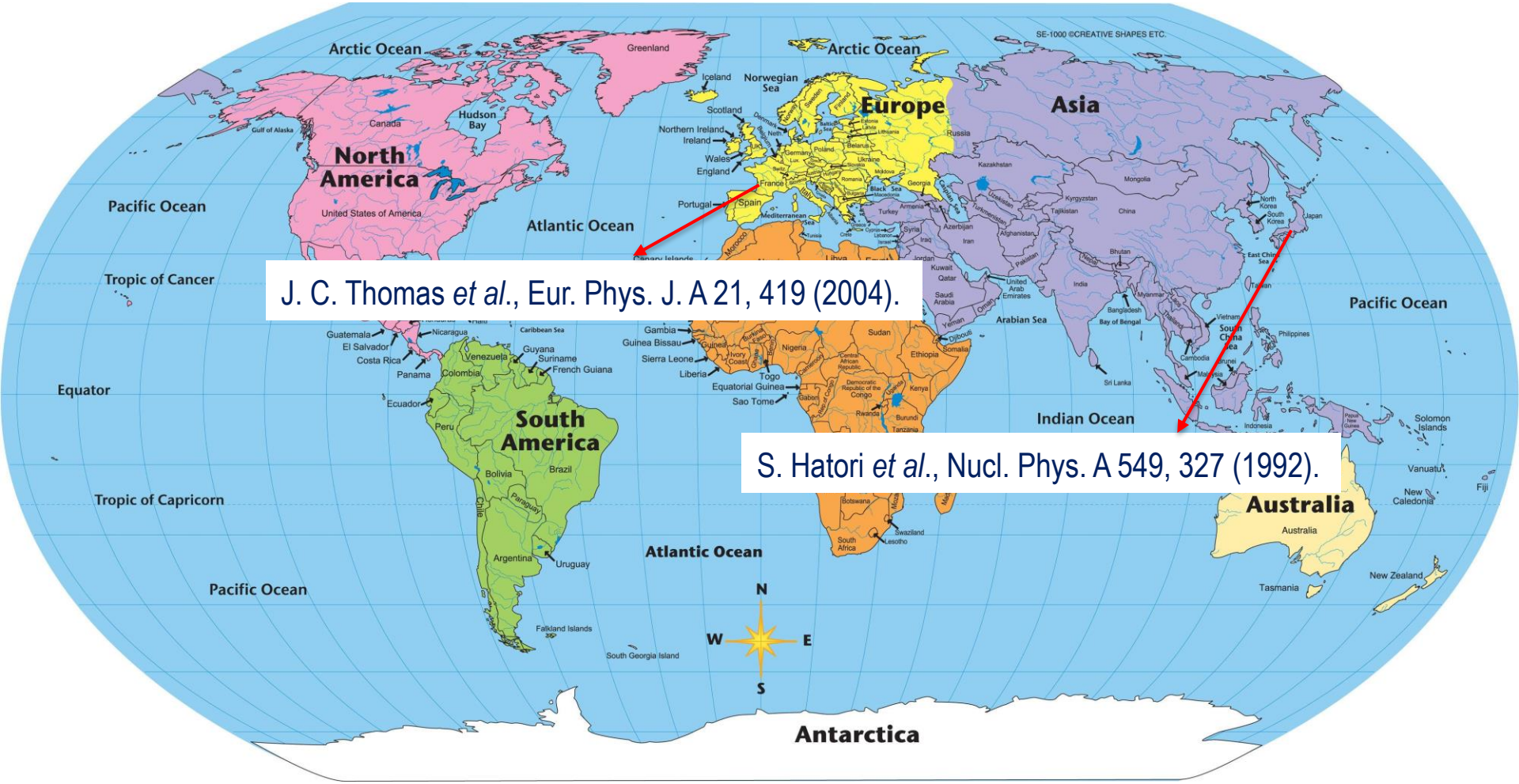


β decay of ^{25}Si

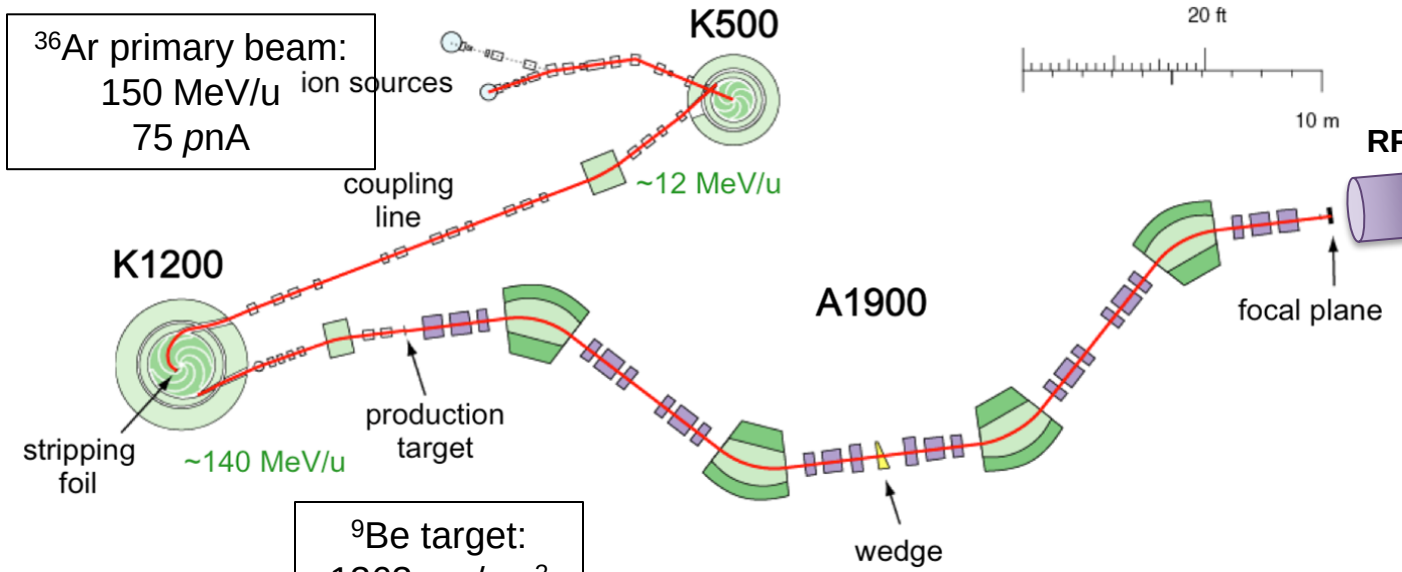


β decay of ^{25}Si

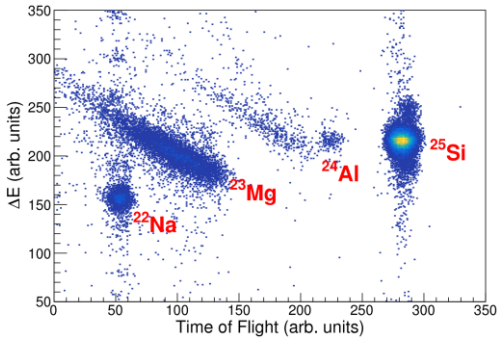


Beam at NSCL

^{36}Ar primary beam:
150 MeV/u
75 *p*nA



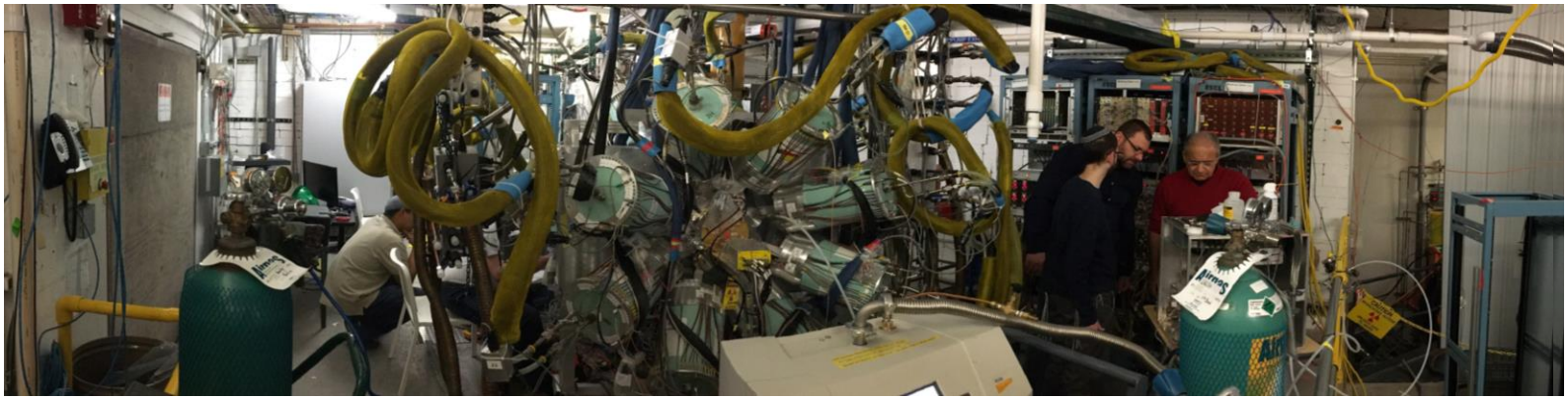
^{25}Si secondary beam:
67% pure
4000 pps



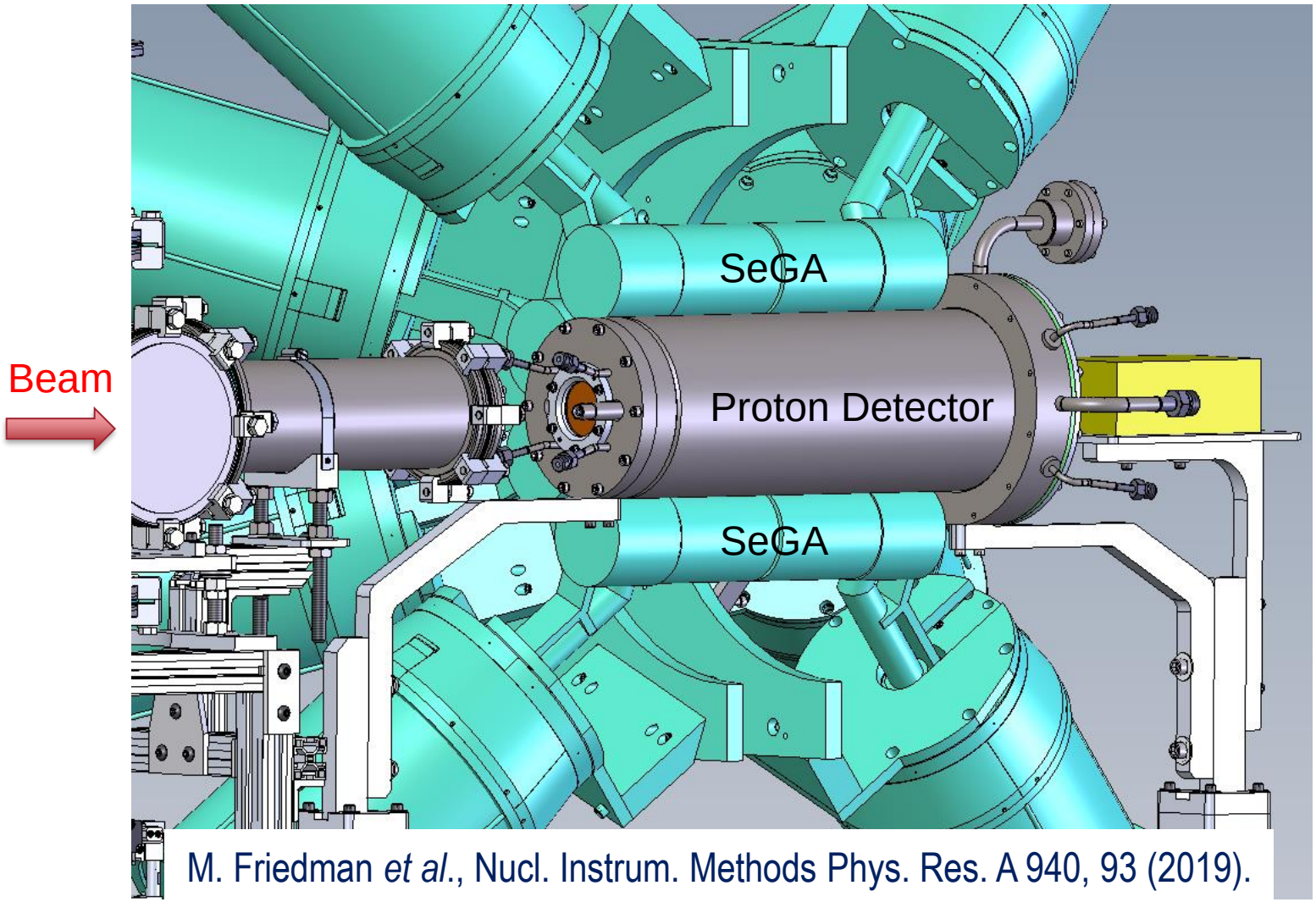
PID at the exit of RFFS

^{9}Be target:
1363 mg/cm^2

Al wedge: 300 mg/cm^2

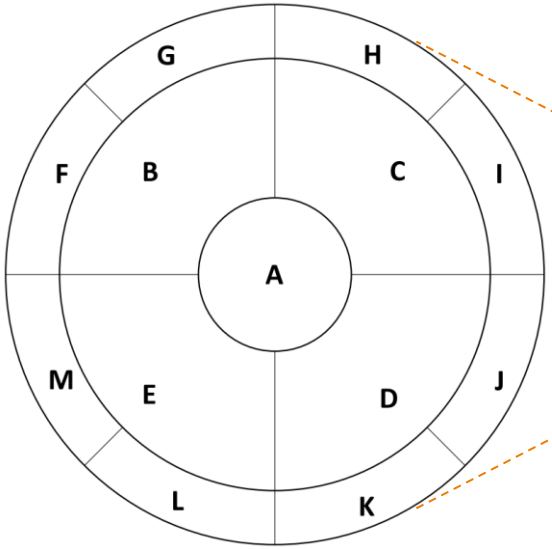


GADGET

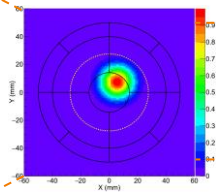


M. Friedman *et al.*, Nucl. Instrum. Methods Phys. Res. A 940, 93 (2019).

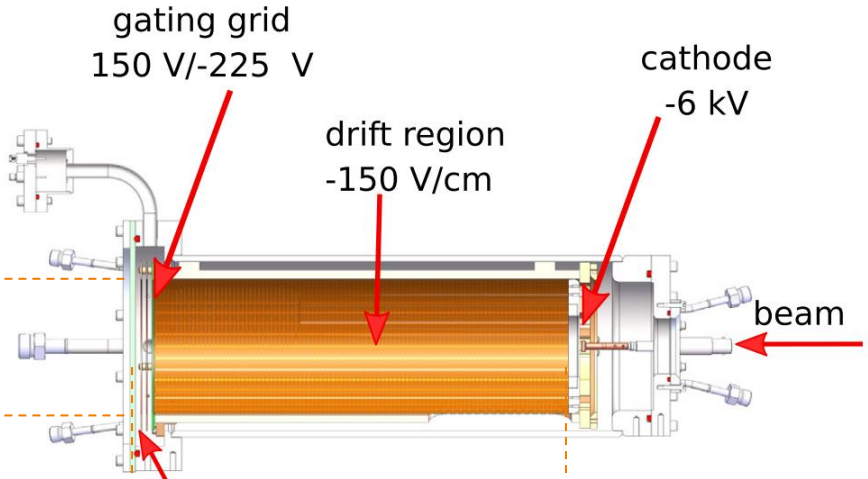
Beam Distribution

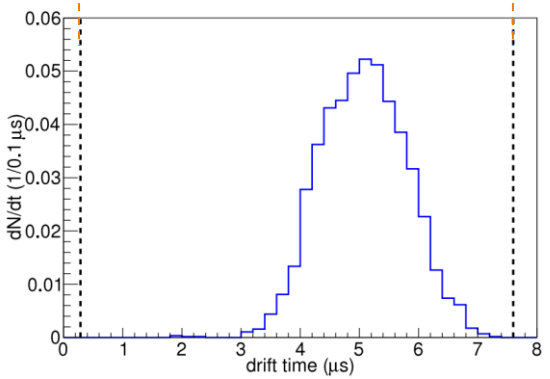


Pad Geometry of the Anode Plane



Beam transverse distribution





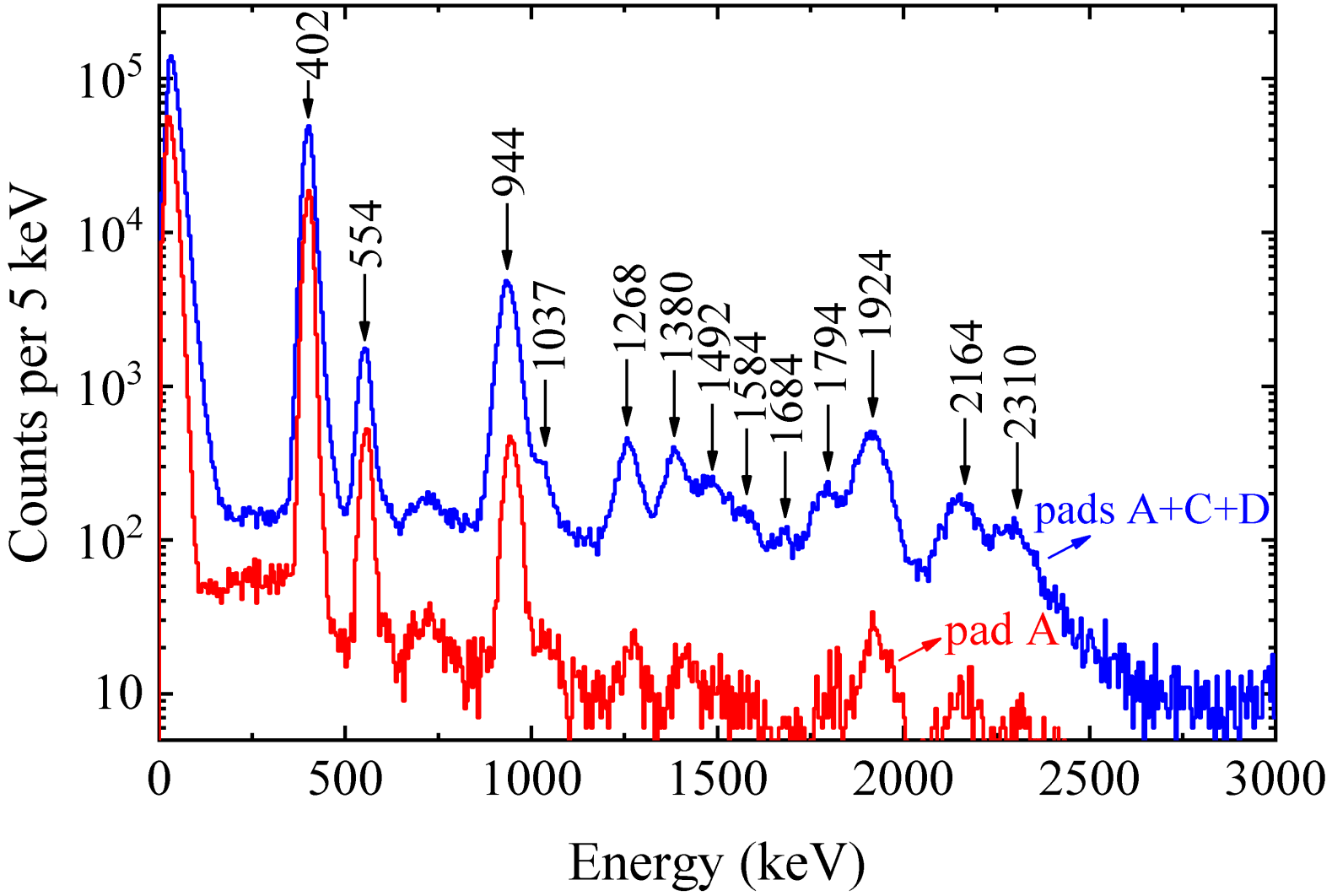
Beam longitudinal distribution

GADGET applications

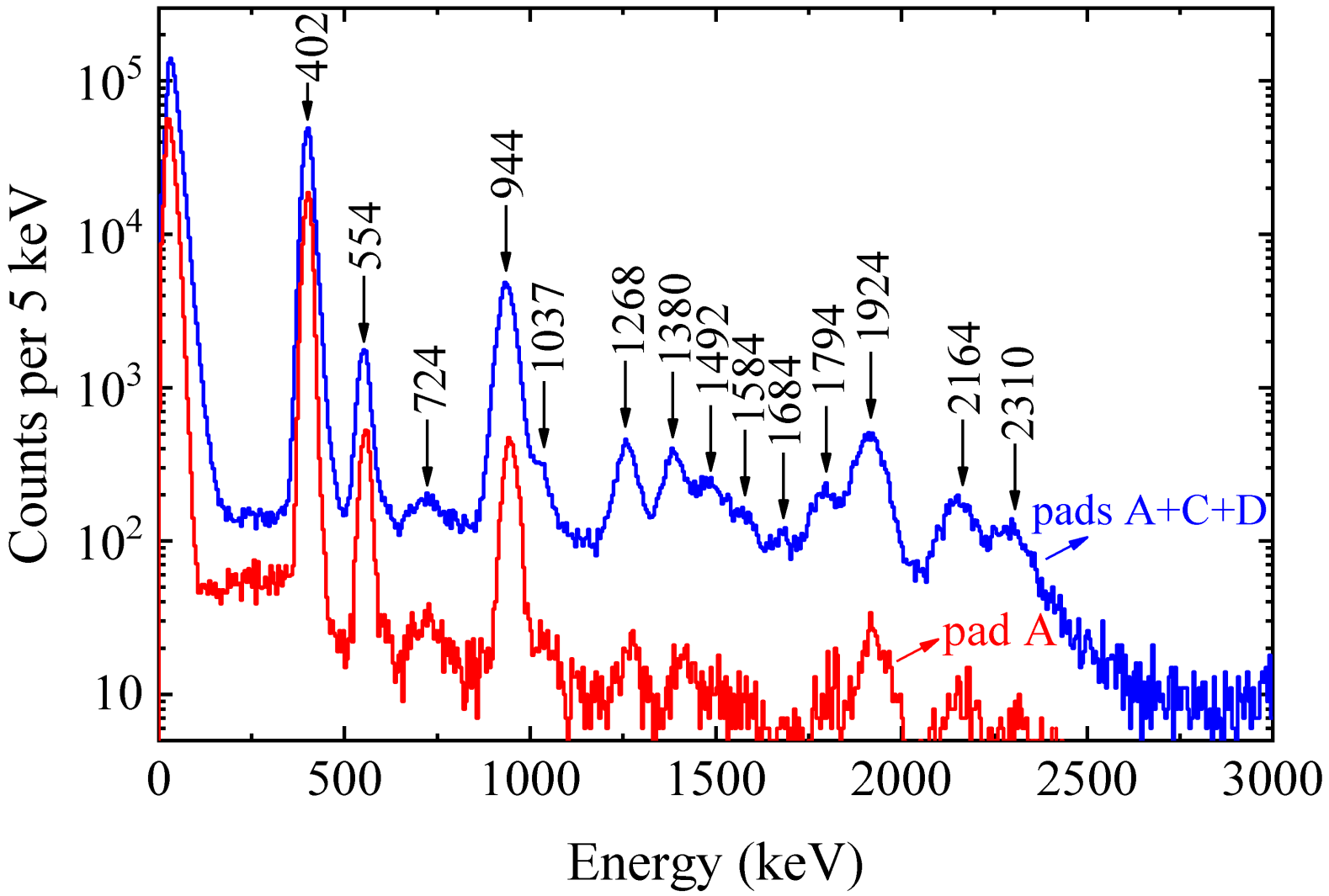
Motivation	Precursor	Particle	E_p (keV)	$I_{\beta p}$
Commissioning setup	^{25}Si	βp	402	6.1×10^{-2}
Nova nucleosynthesis	^{23}Al	βp	204	2.6×10^{-4}
Nova nucleosynthesis	^{31}Cl	βp	259	9.8×10^{-6}
Novel decay	^{11}Be	βp*	196	$0 \sim 1.3 \times 10^{-5*}$
XRB light curve	^{20}Mg	$\beta p \alpha$	503	4.7×10^{-8}

^{25}Si This presentation.
^{23}Al M. Friedman *et al*., Phys. Rev. C 101, 052802(R) (2020).
^{31}Cl T. Budner *et al*., In preparation.
^{11}Be J. Surbrook *et al*., MSU PhD thesis, in progress.
^{20}Mg T. Wheeler *et al*., MSU PhD thesis, in progress.

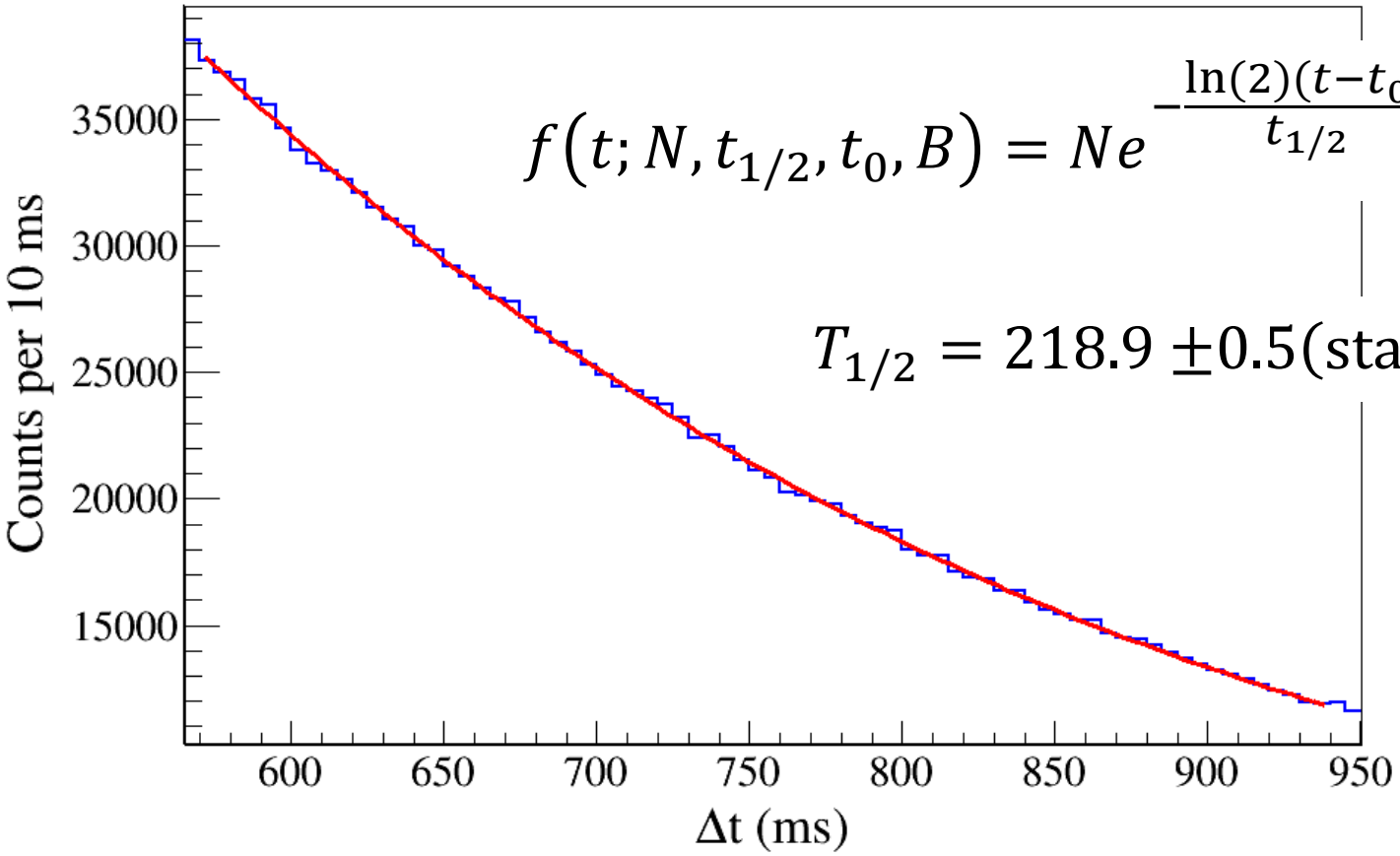
Proton Spectrum



Proton Spectrum



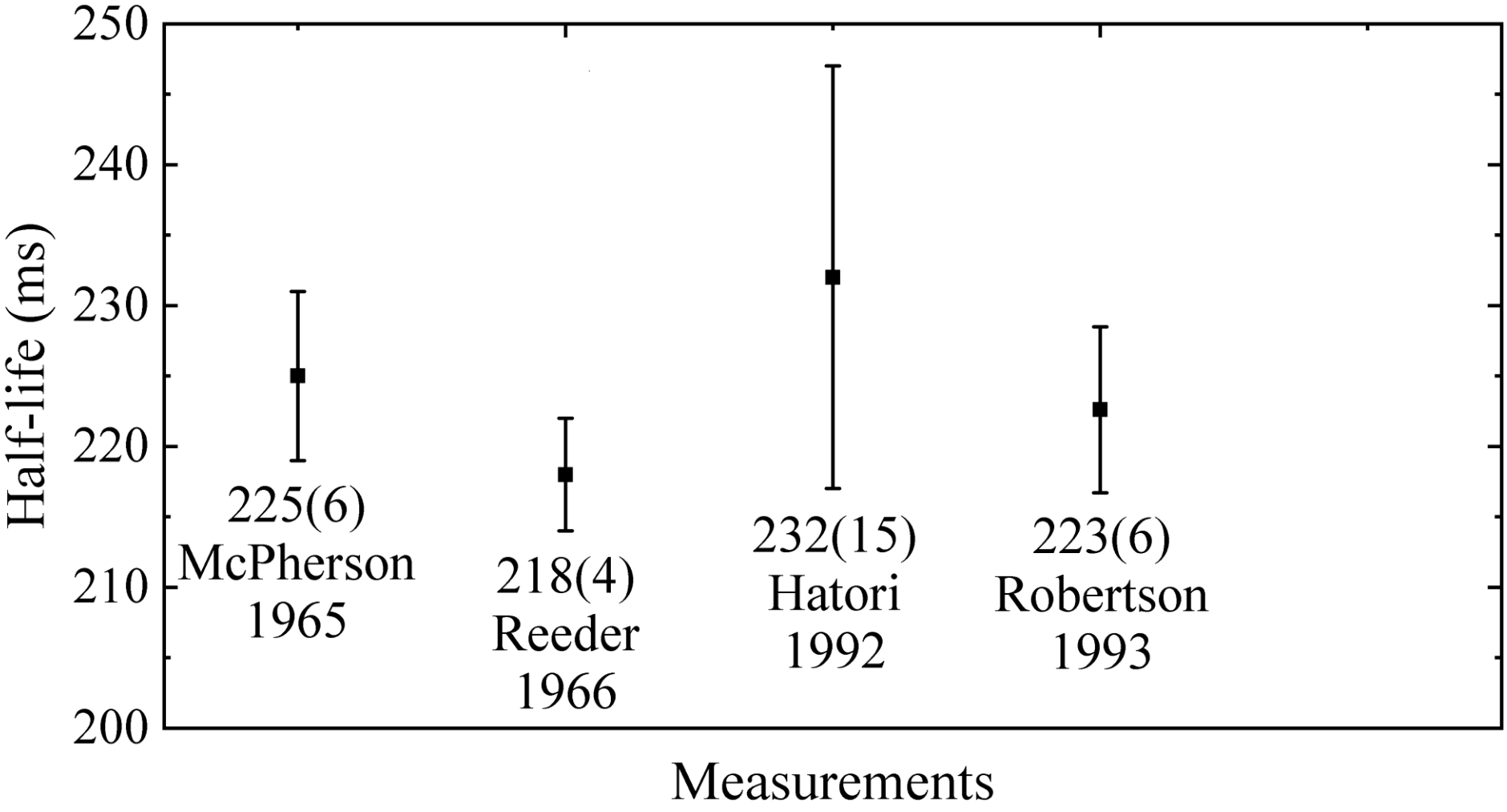
Half-life



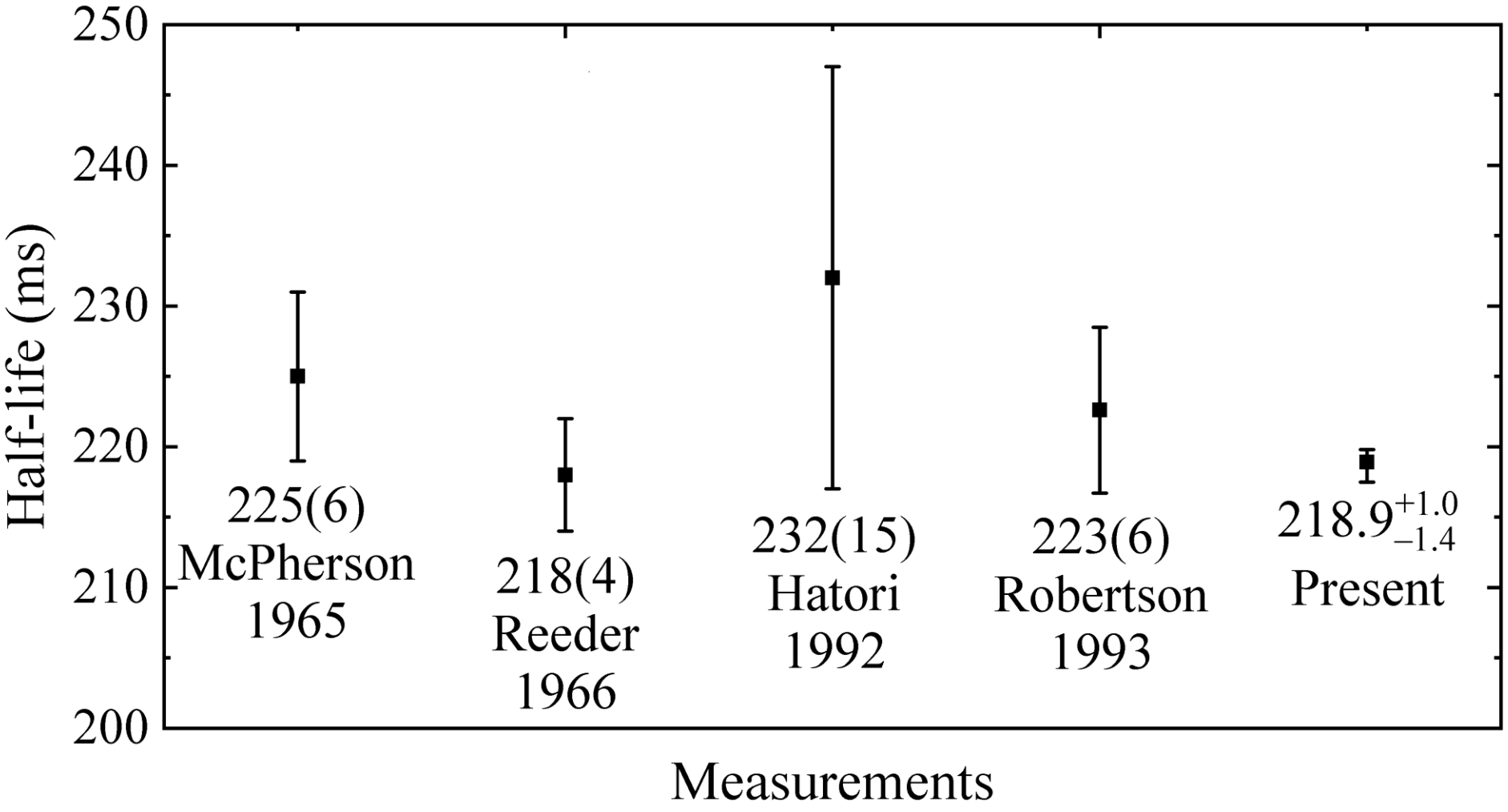
$$f\left(t; N, t_{1/2}, t_0, B\right) = Ne^{-\frac{\ln(2)(t-t_0)}{t_{1/2}}} P_4(t-t_0) + B$$

$$T_{1/2} = 218.9 \pm 0.5(\text{stat})^{+0.9}_{-1.3}\ (\text{syst})\ \text{ms}$$

Half-life


250
240
230
220
210
200
Half-life (ms)
225(6)
McPherson
1965
218(4)
Reeder
1966
232(15)
Hatori
1992
223(6)
Robertson
1993
Measurements

Half-life


250
240
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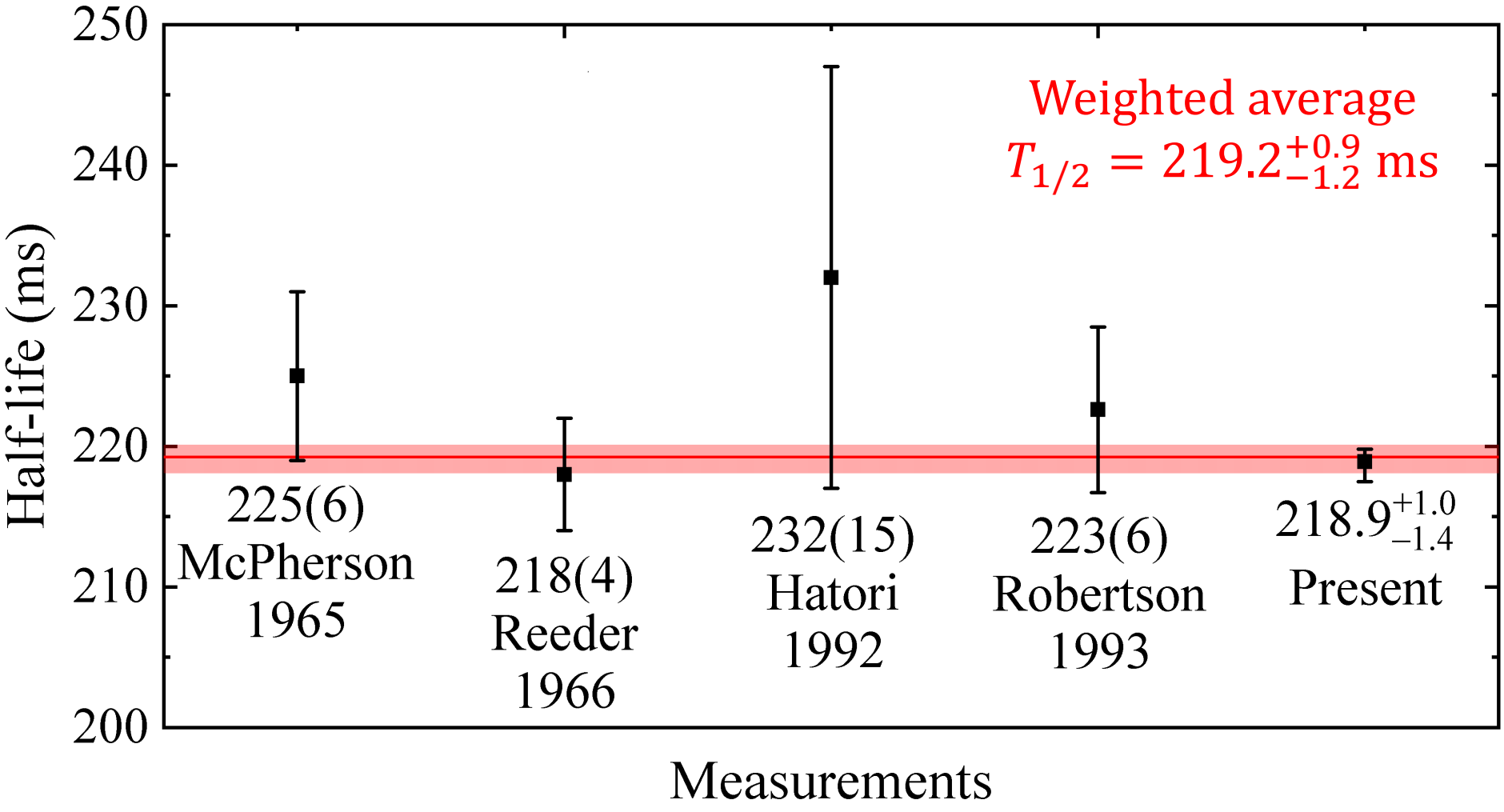
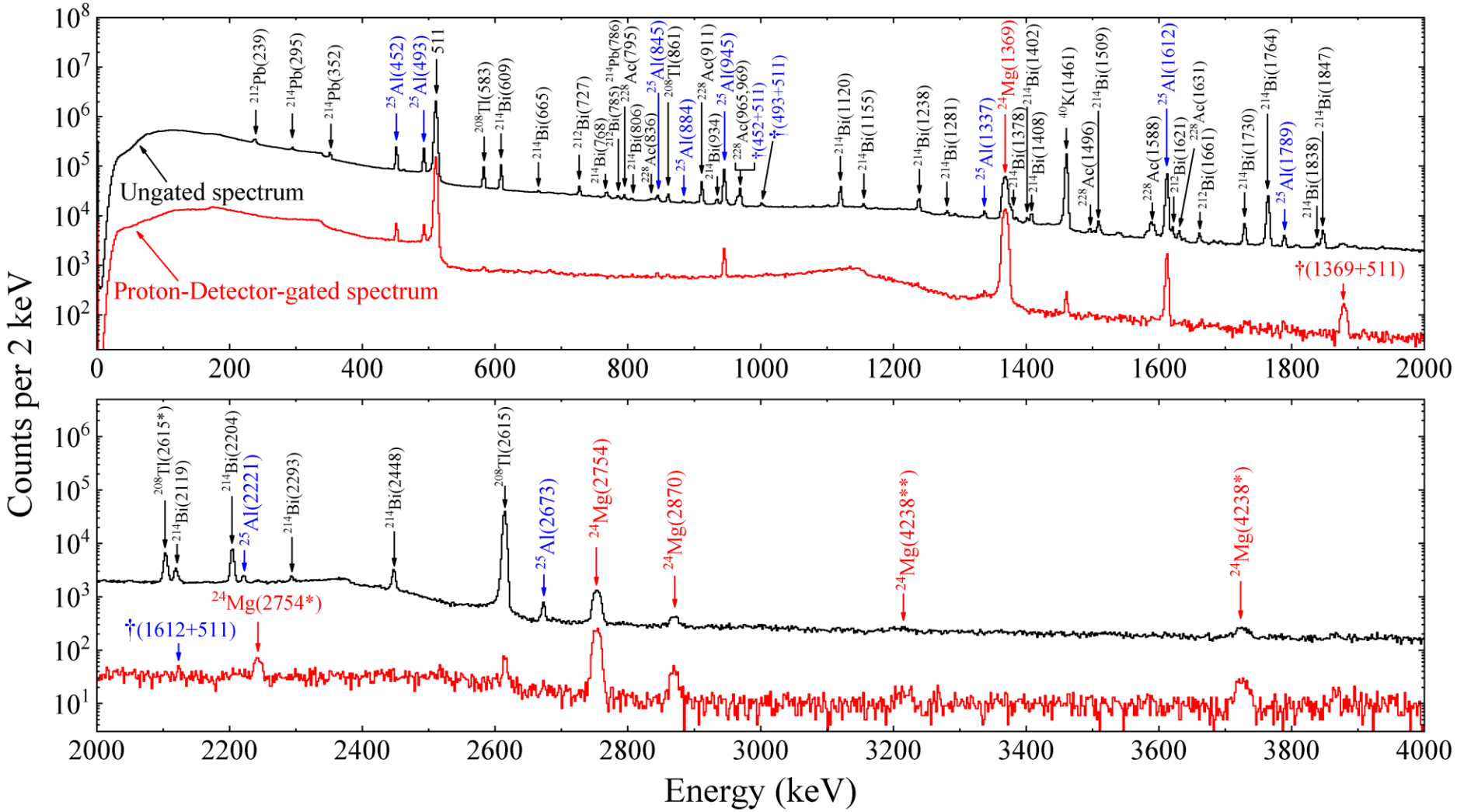
Half-life (ms)
225(6)
McPherson
1965
218(4)
Reeder
1966
232(15)
Hatori
1992
223(6)
Robertson
1993
$218.9^{+1.0}_{-1.4}$
Present
Measurements

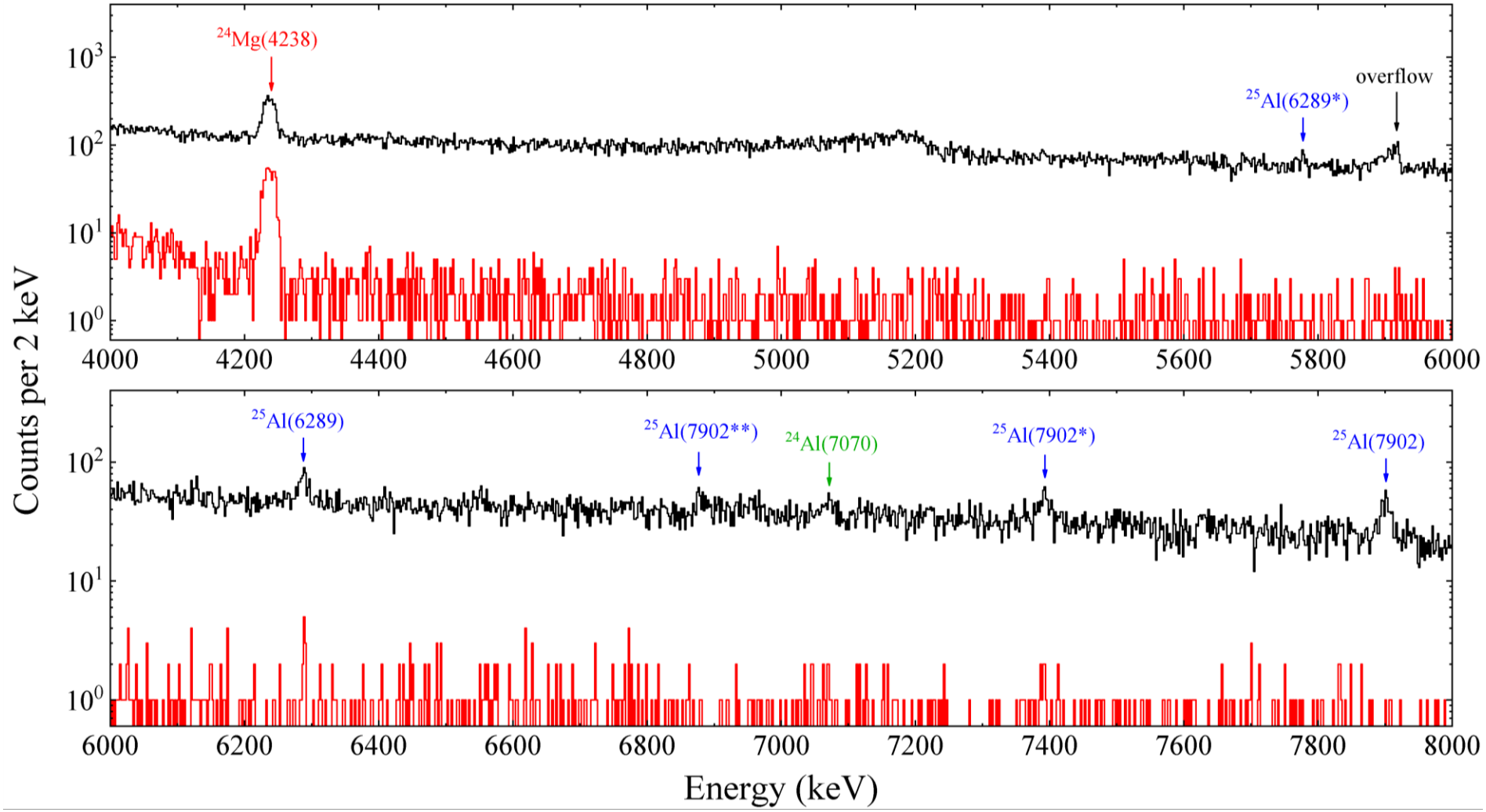
Half-life


Weighted average
$T_{1/2} = 219.2^{+0.9}_{-1.2}$ ms
Half-life (ms)
250
240
230
220
210
200
225(6)
McPherson
1965
218(4)
Reeder
1966
232(15)
Hatori
1992
223(6)
Robertson
1993
$218.9^{+1.0}_{-1.4}$
Present
Measurements

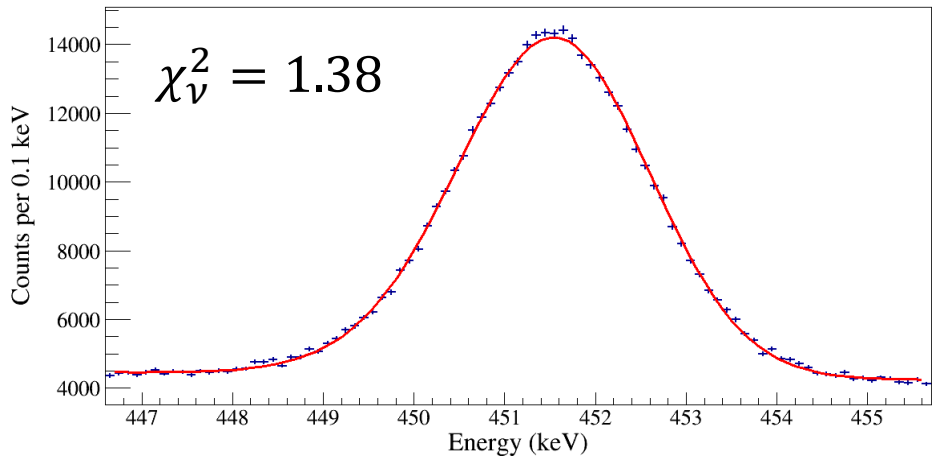
γ-ray Spectrum

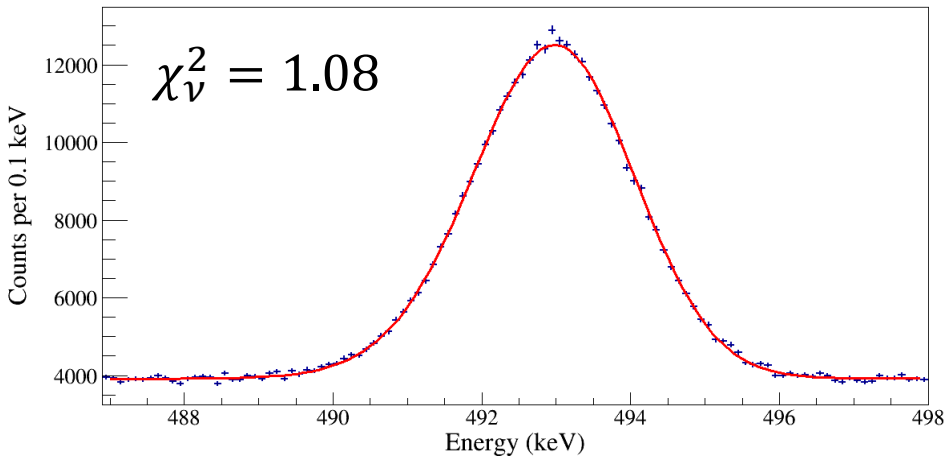


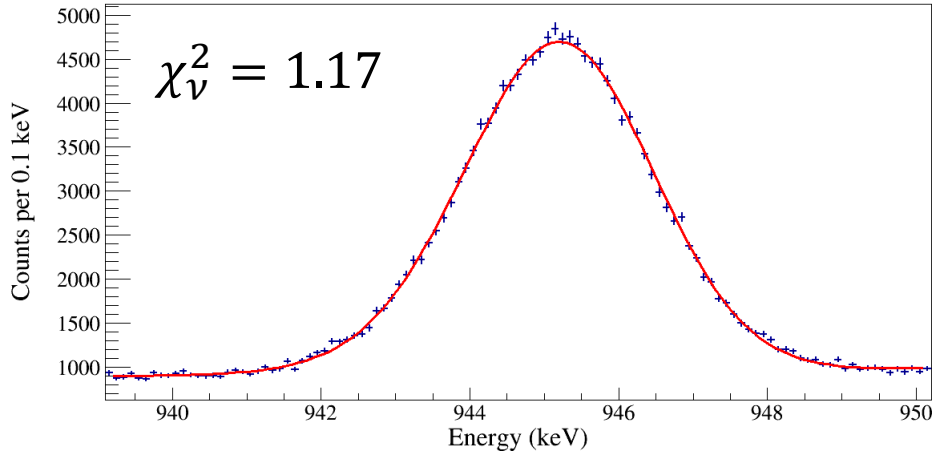
γ-ray Spectrum

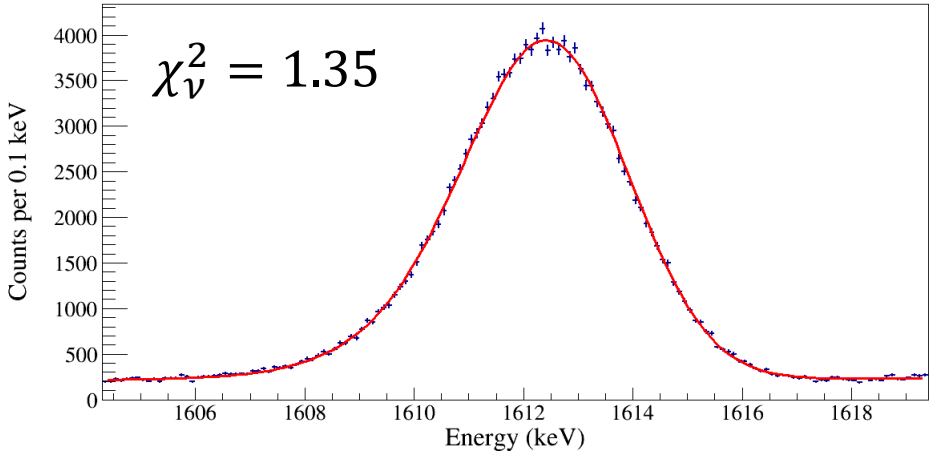


^{25}Si($\beta\gamma$)^{25}Al



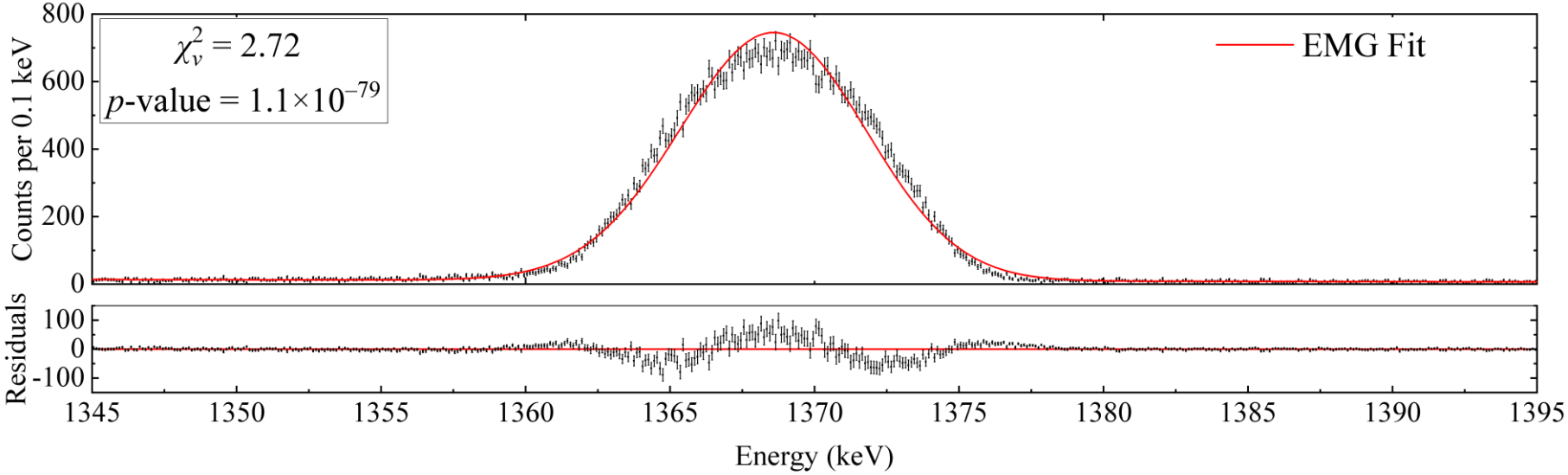




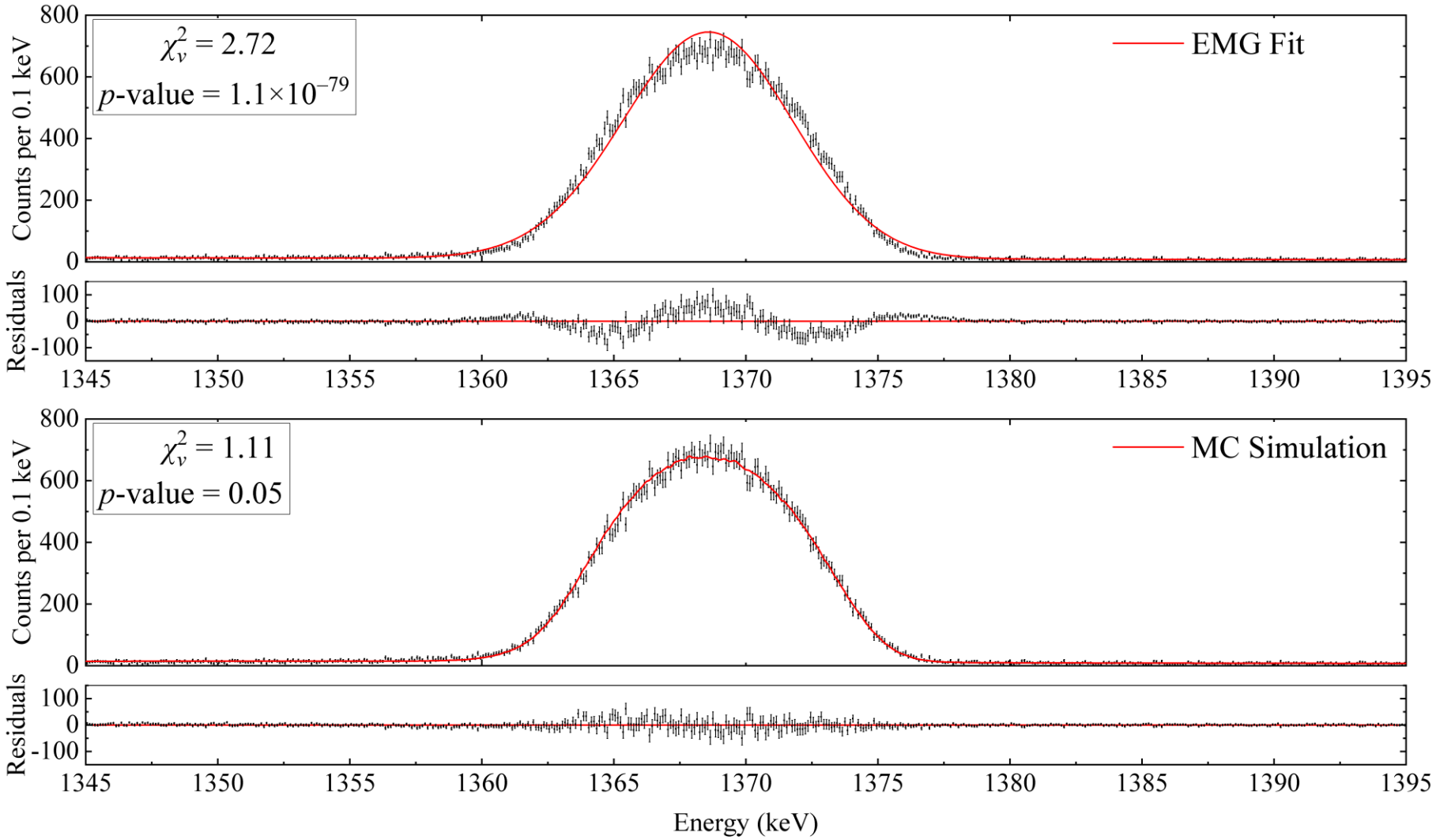


EMG Fit $$f(x;N,\mu,\sigma,\tau,B) = \frac{N}{2\tau}\exp\left[\frac{1}{2}\left(\frac{\sigma}{\tau}\right)^2 + \frac{x-\mu}{\tau}\right] \times \operatorname{erfc}\left[\frac{1}{\sqrt{2}}\left(\frac{\sigma}{\tau} + \frac{x-\mu}{\sigma}\right)\right] + B$$

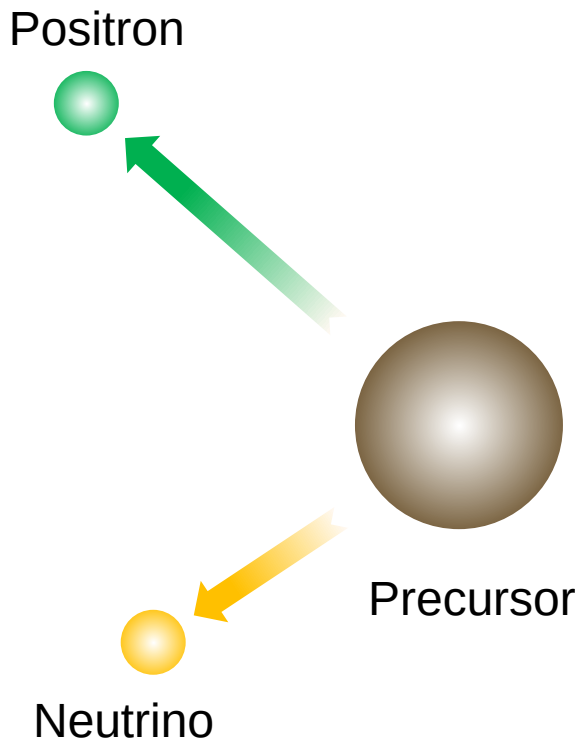
$^{25}Si(\beta p\gamma)^{24}Mg$



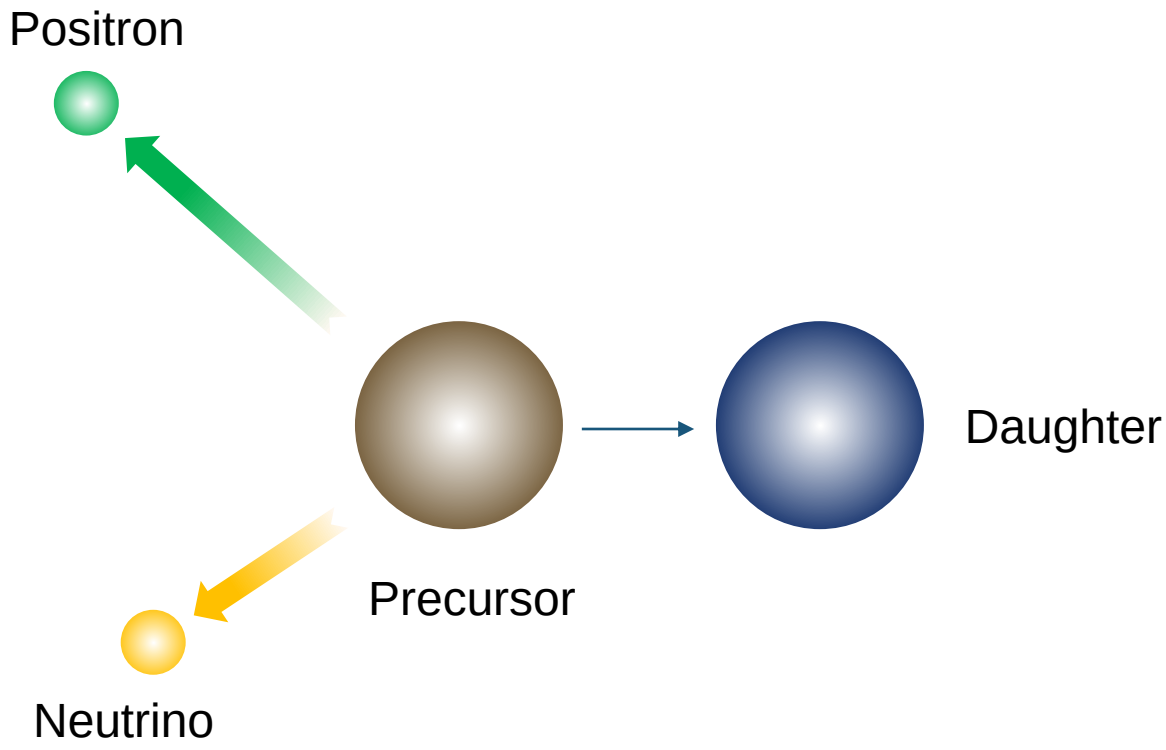
$^{25}Si(\beta p\gamma)^{24}Mg$



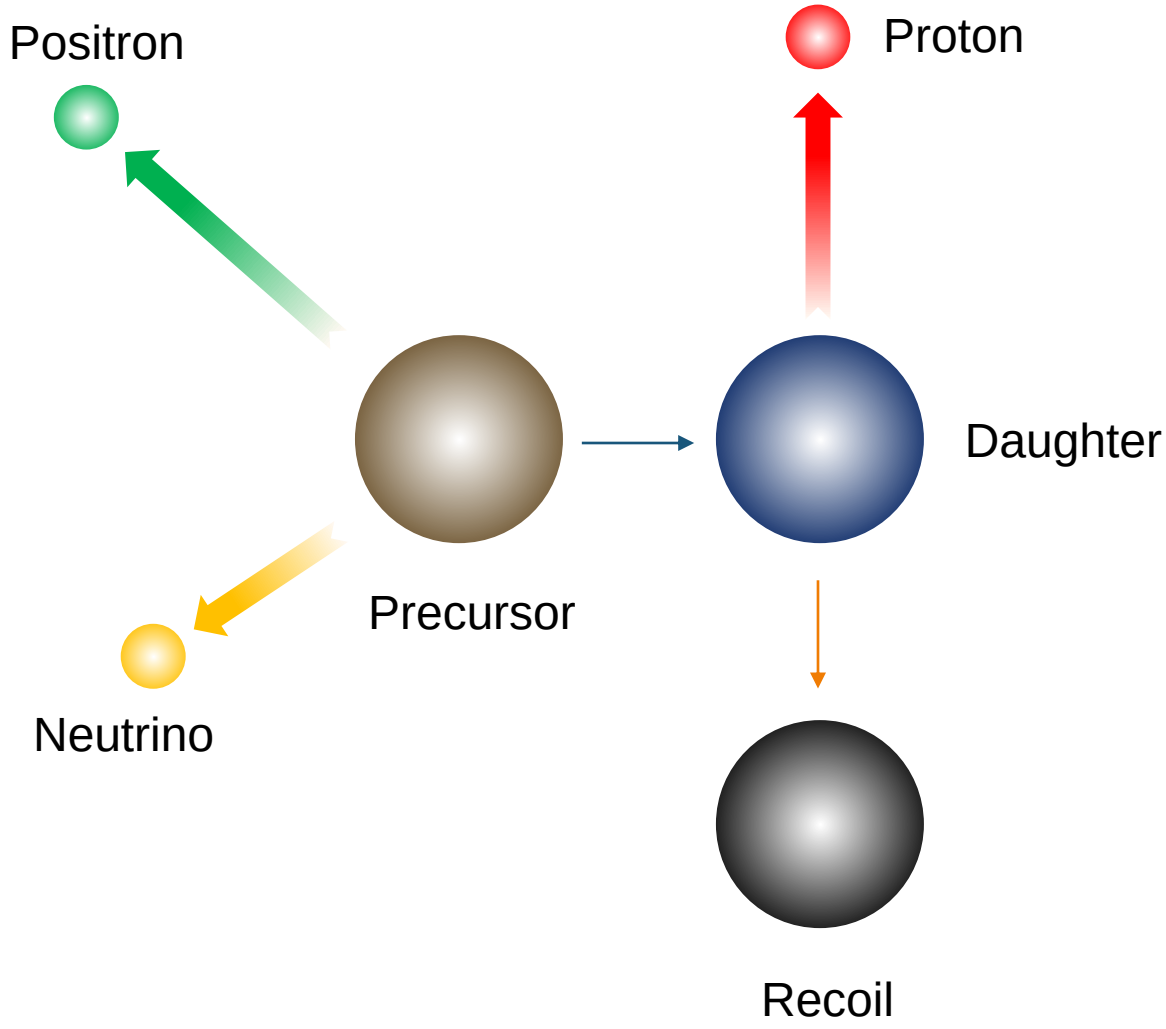
Doppler Broadening of *βpγ*



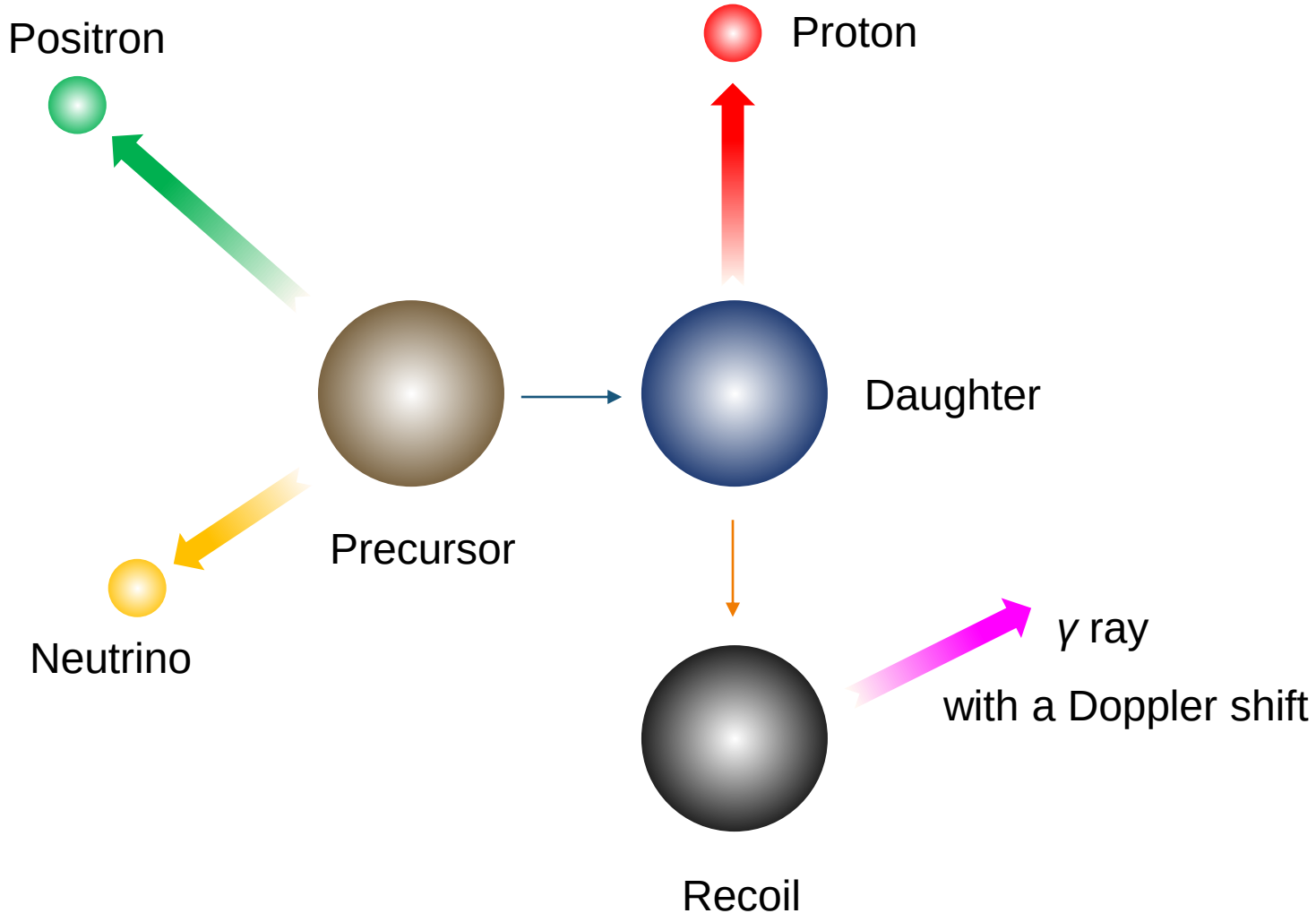
Doppler Broadening of βpγ



Doppler Broadening of βpγ



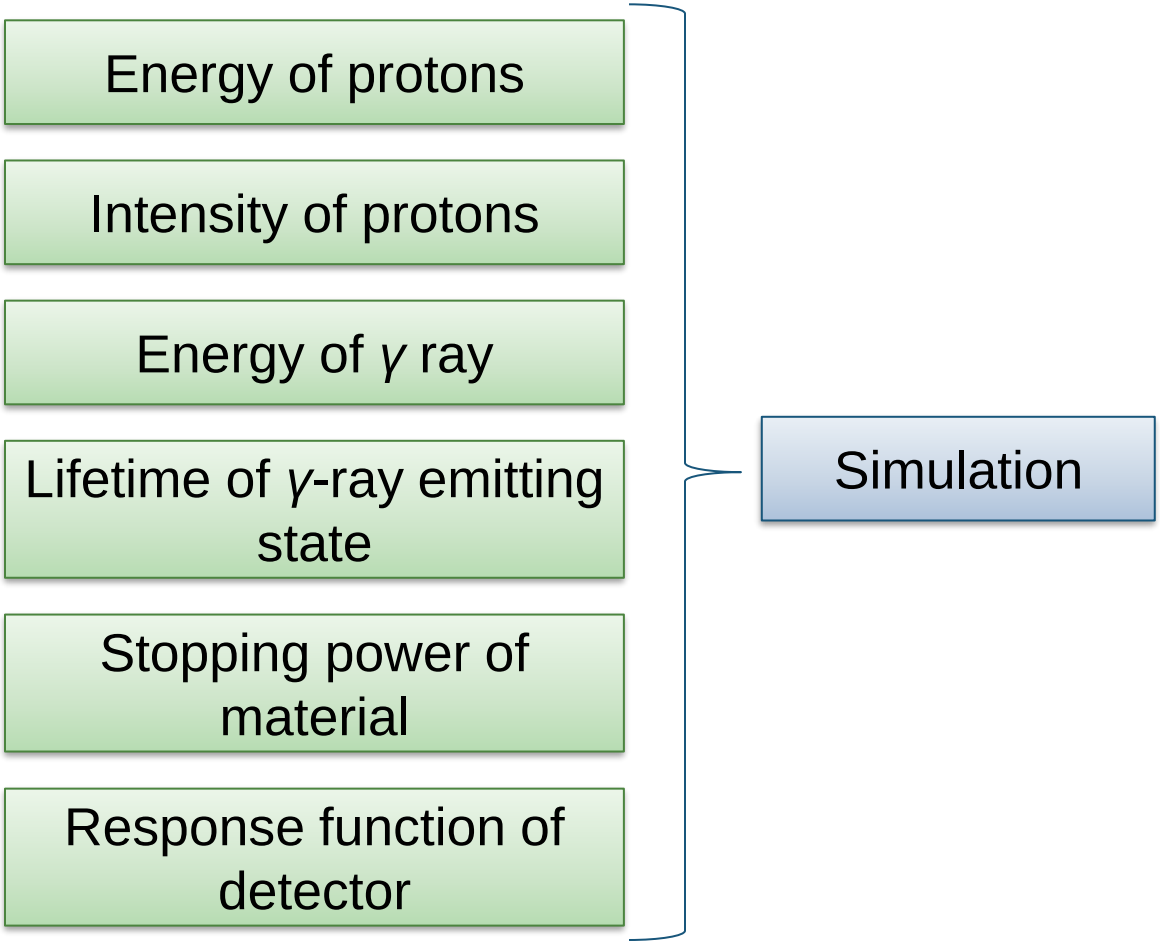
Doppler Broadening of βpγ



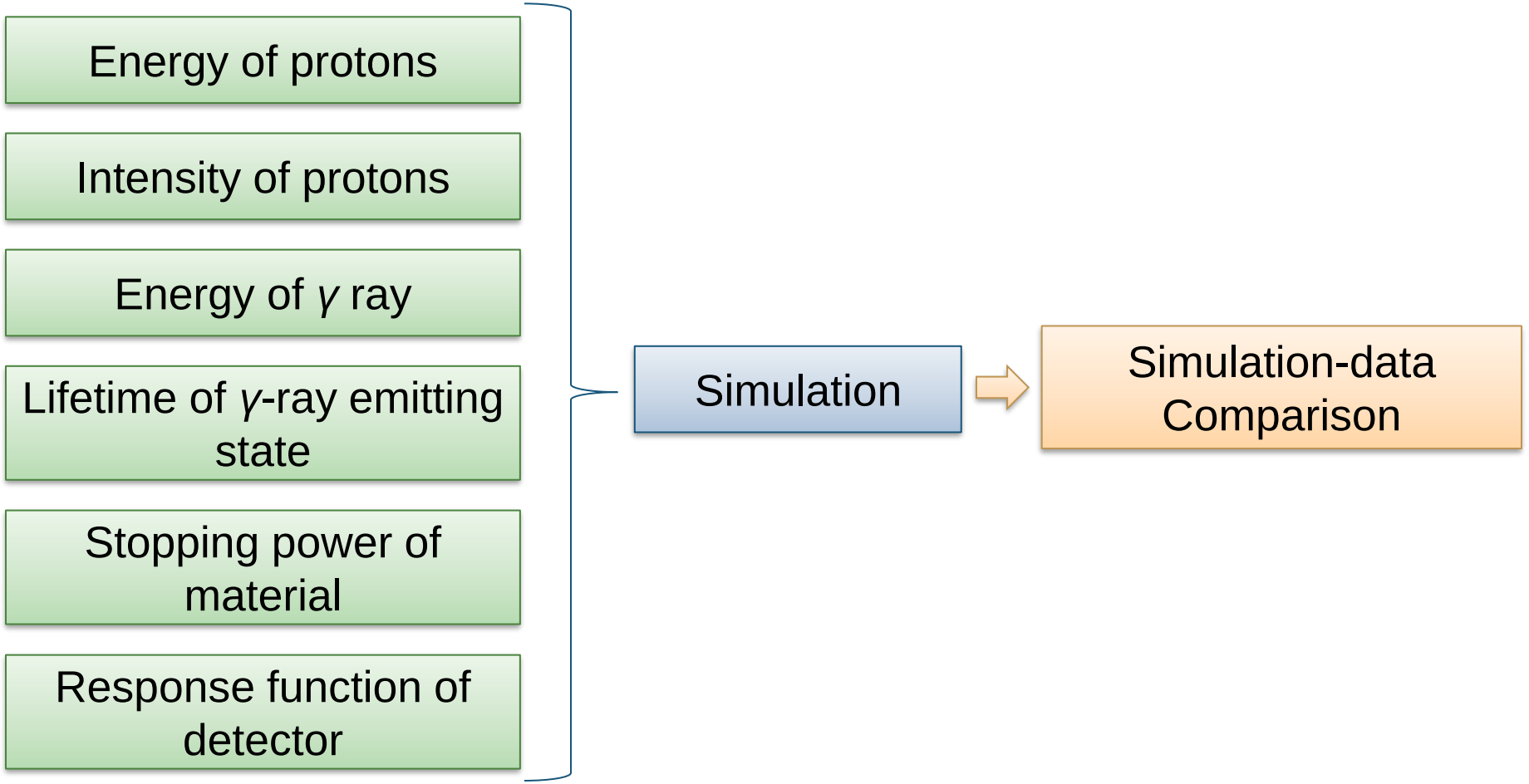
Doppler Broadening Simulation

- Energy of protons
- Intensity of protons
- Energy of γ ray
- Lifetime of γ-ray emitting state
- Stopping power of material
- Response function of detector

Doppler Broadening Simulation



Doppler Broadening Simulation



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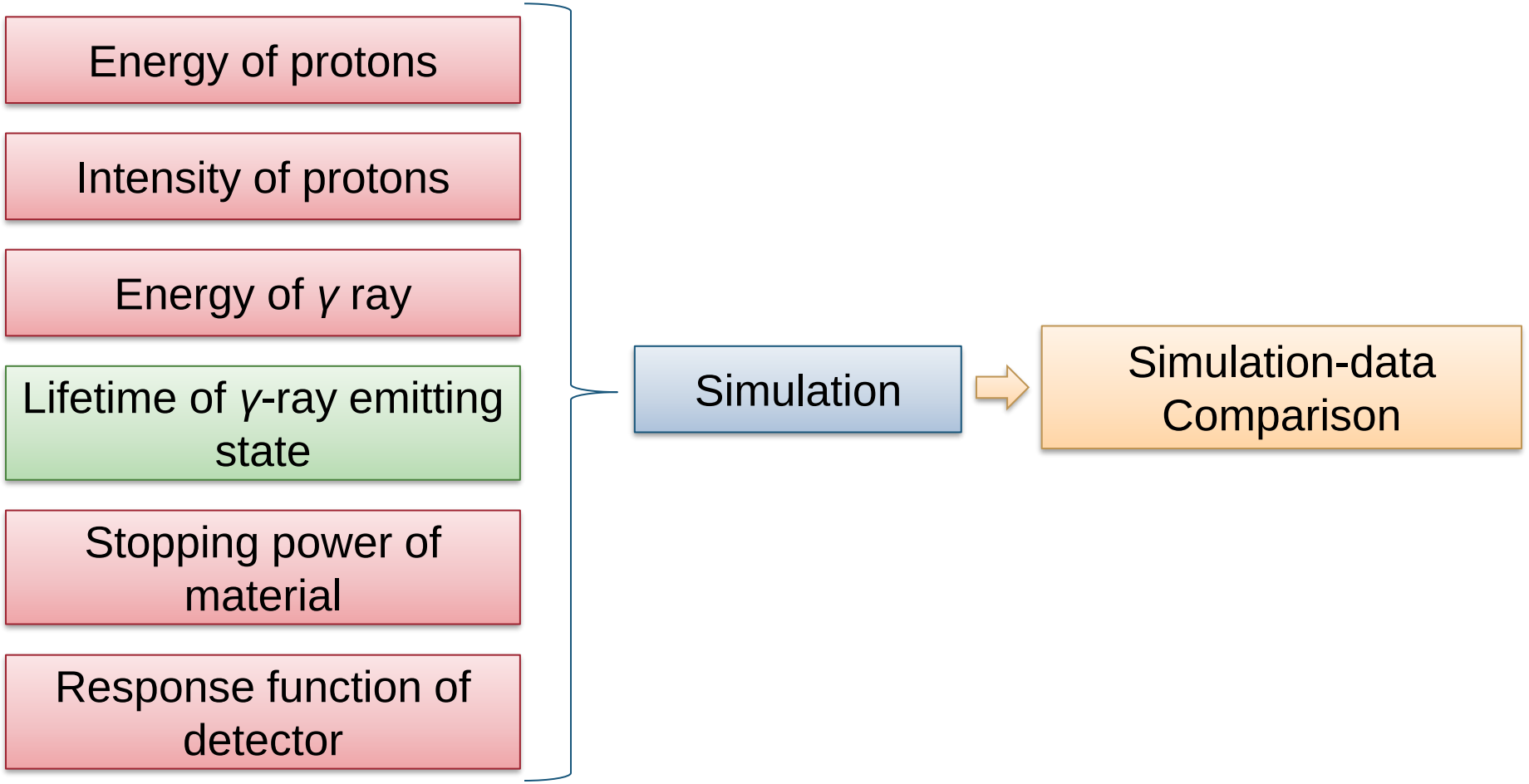

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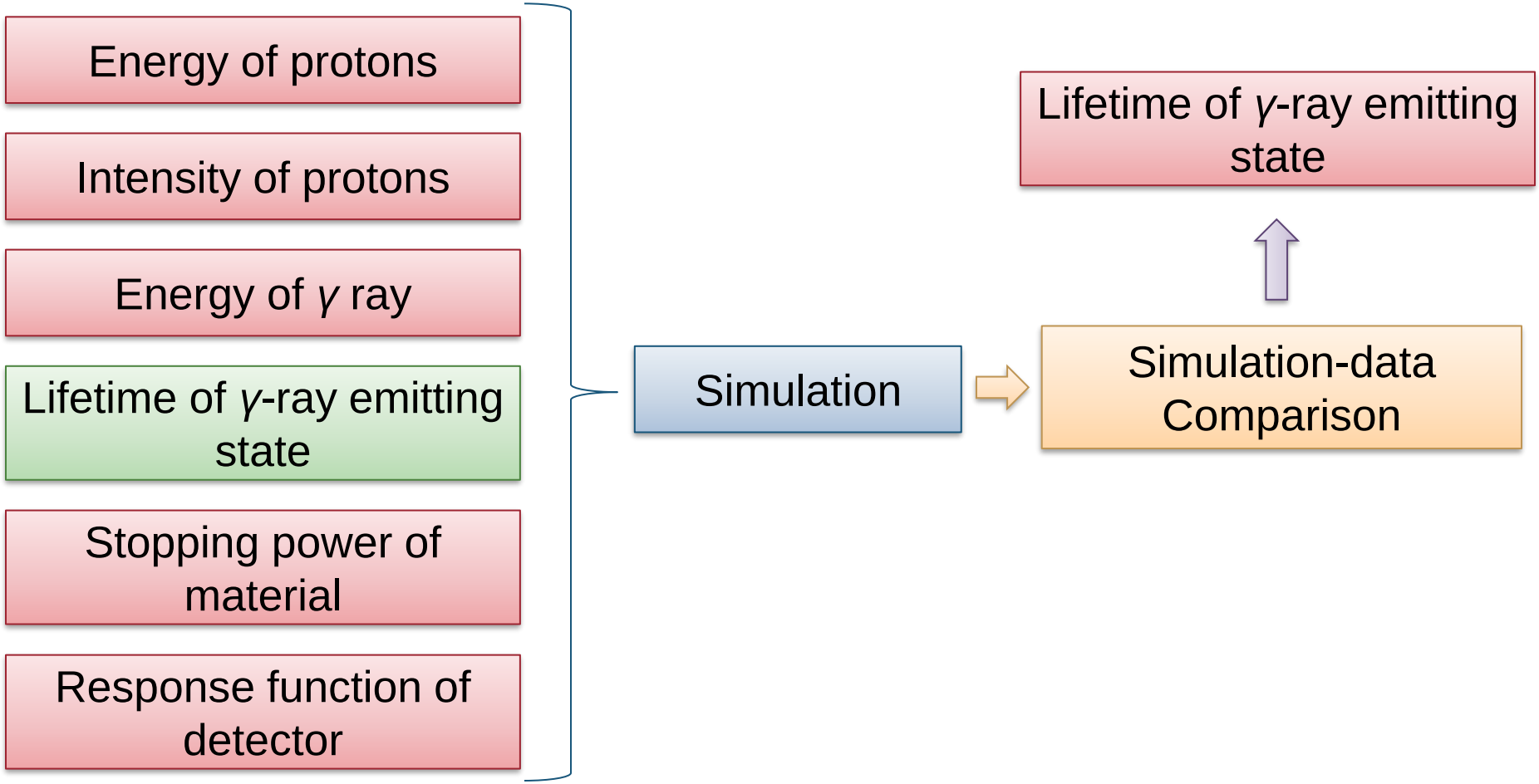

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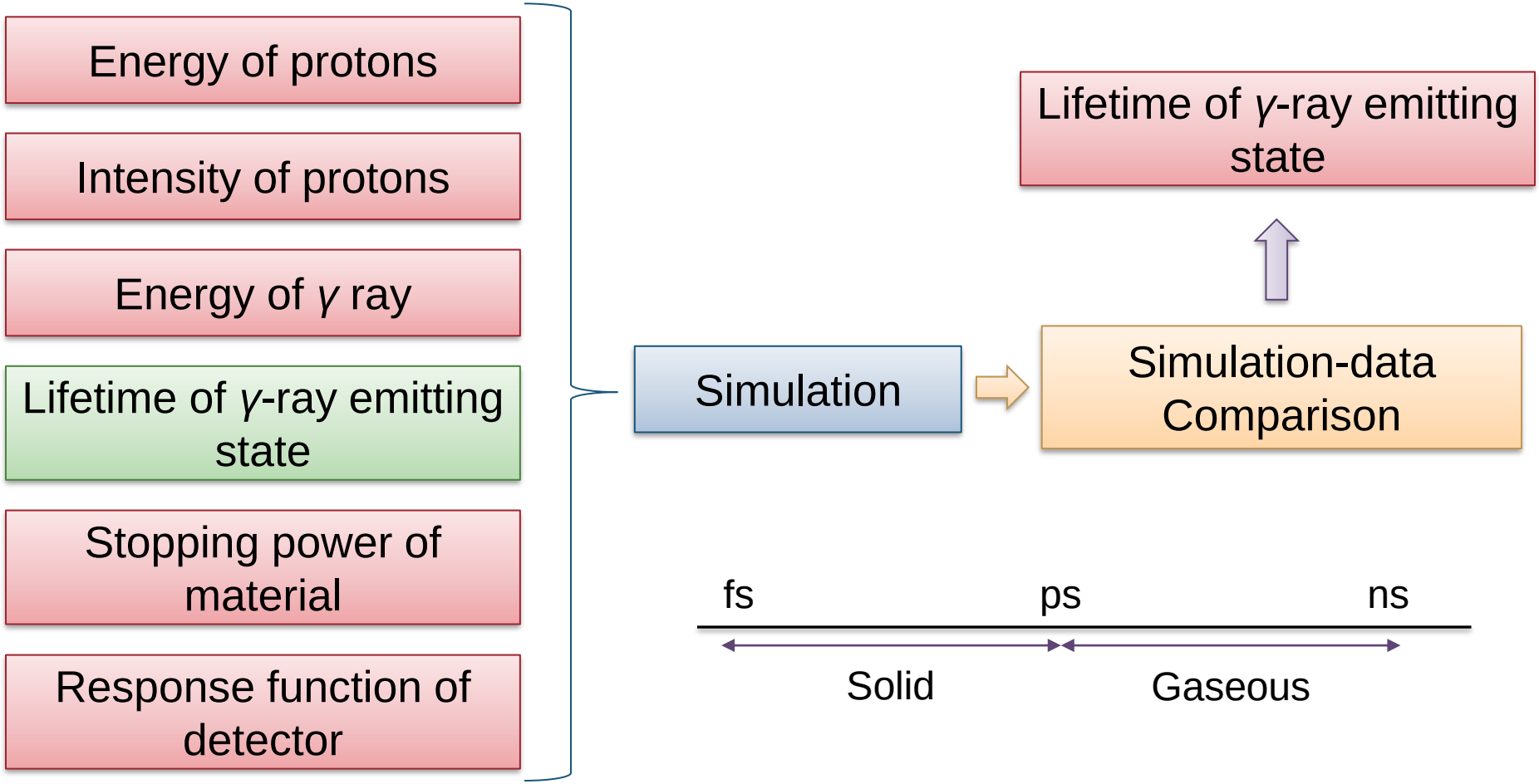
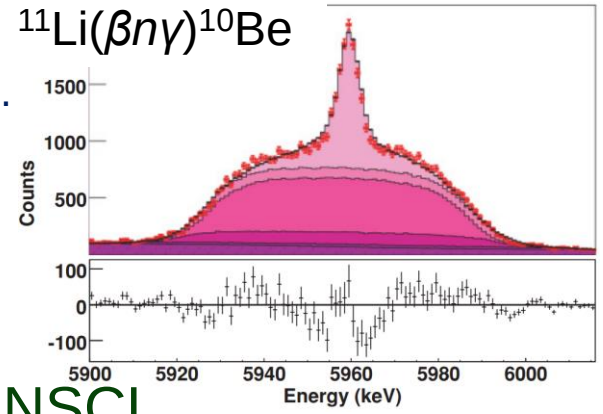
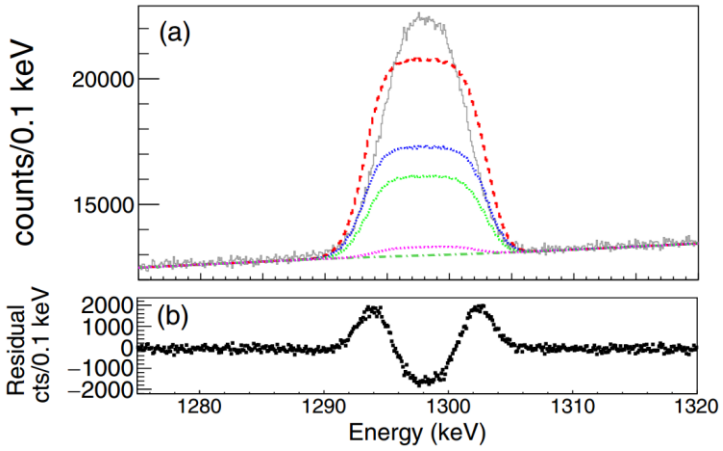


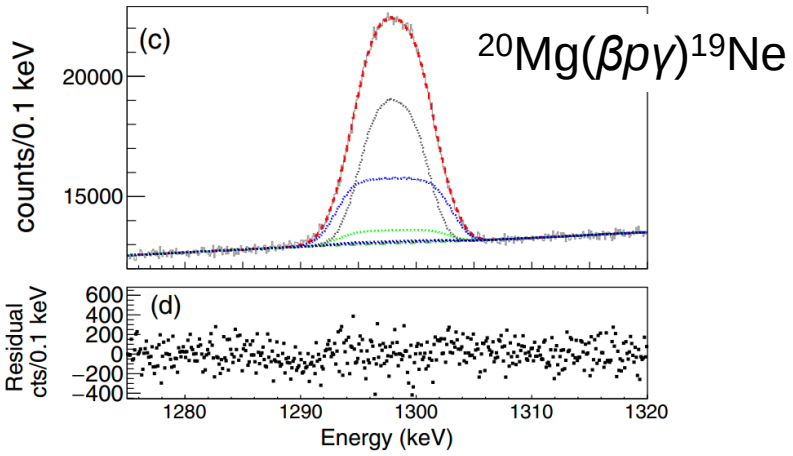
Doppler Broadening Technique

- ^{11}Li($\beta n\gamma$)^{10}Be by ISOLDE and TRIUMF.
  - H. Fynbo *et al*., Nucl. Instrum. Methods Phys. Res. B 207, 275 (2003).
  - H. Fynbo *et al*., Nucl. Phys. A 736, 39 (2004).
  - F. Sarazin *et al*., Phys. Rev. C 70, 031302(R) (2004).
  - C. M. Mattoon *et al*., Phys. Rev. C 80, 034318 (2009).

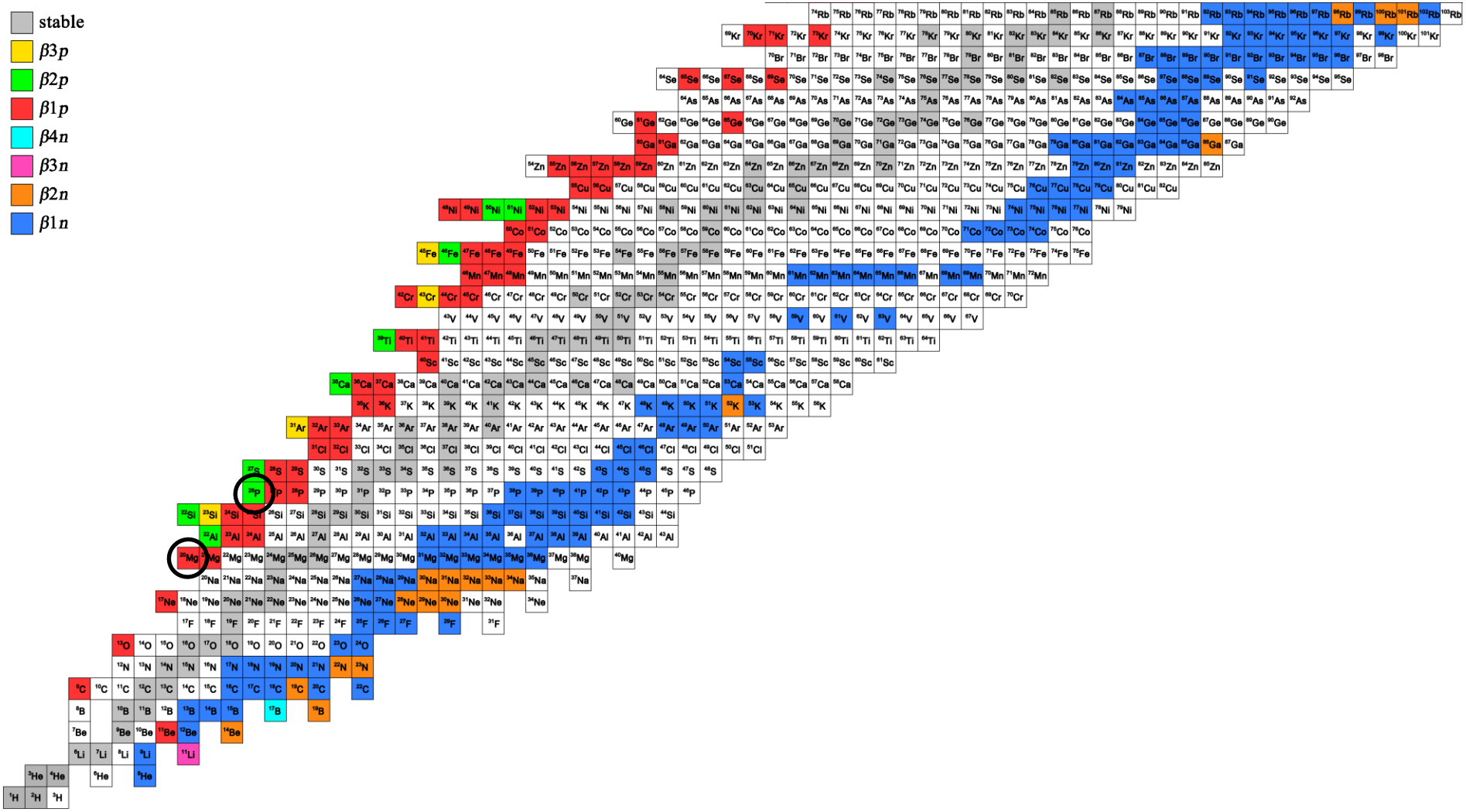


- ^{26}P($\beta p\gamma$)^{25}Al, ^{20}Mg($\beta p\gamma$)^{19}Ne by Wrede Group at NSCL.
  - S. B. Schwartz *et al*., Phys. Rev. C 92, 031302(R) (2015).
  - B. E. Glassman *et al*., Phys. Rev. C 99, 065801 (2019).





Scientific Value



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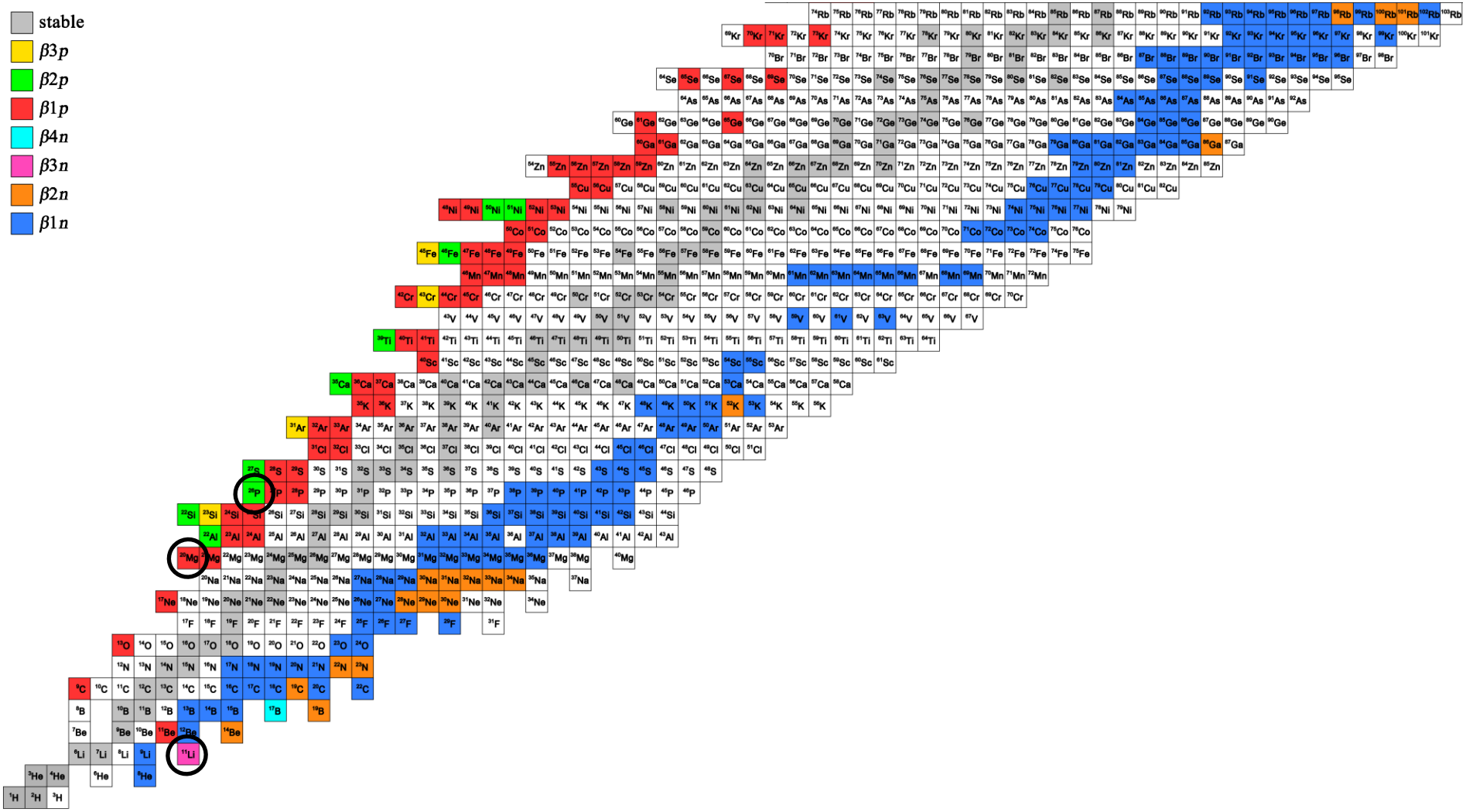

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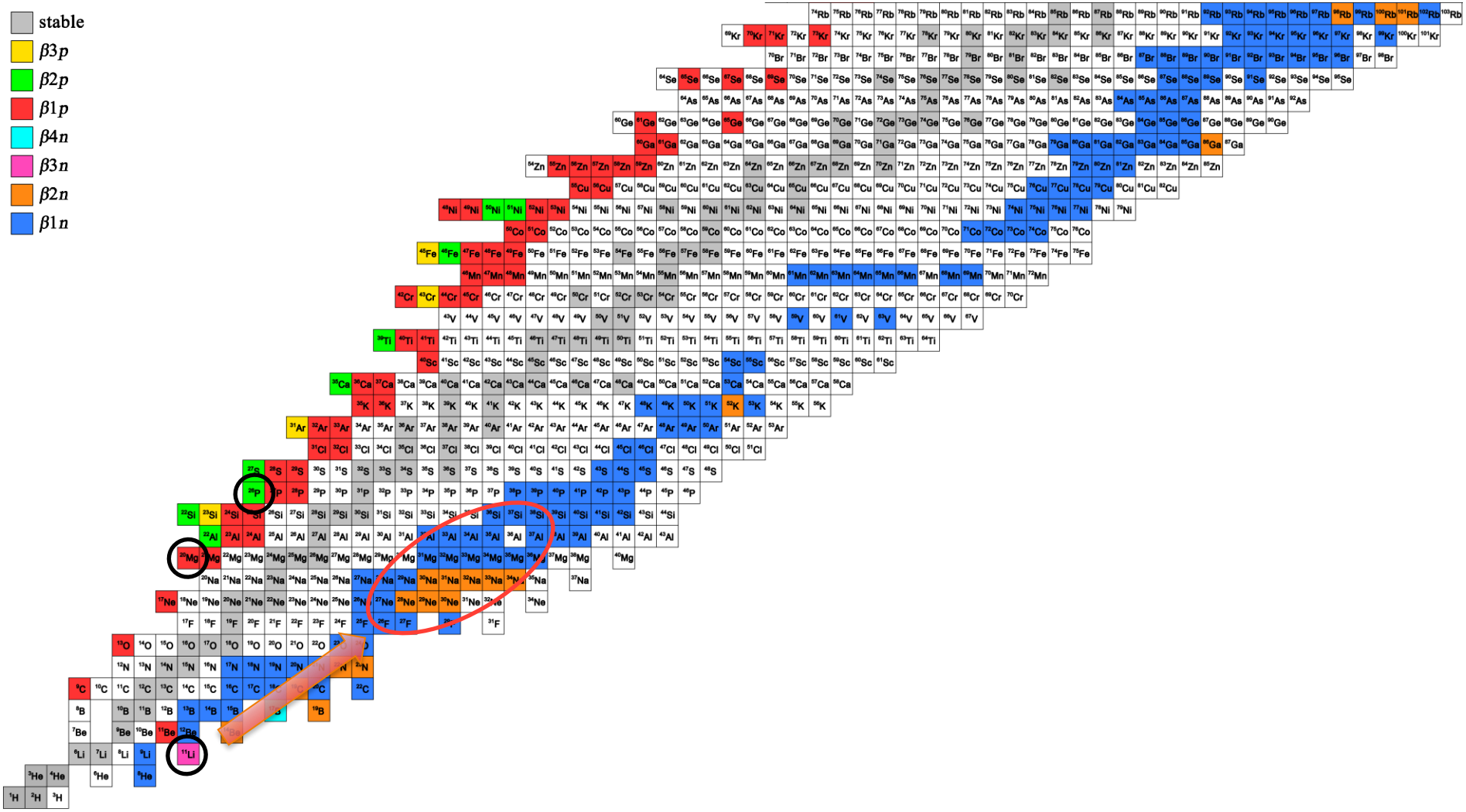
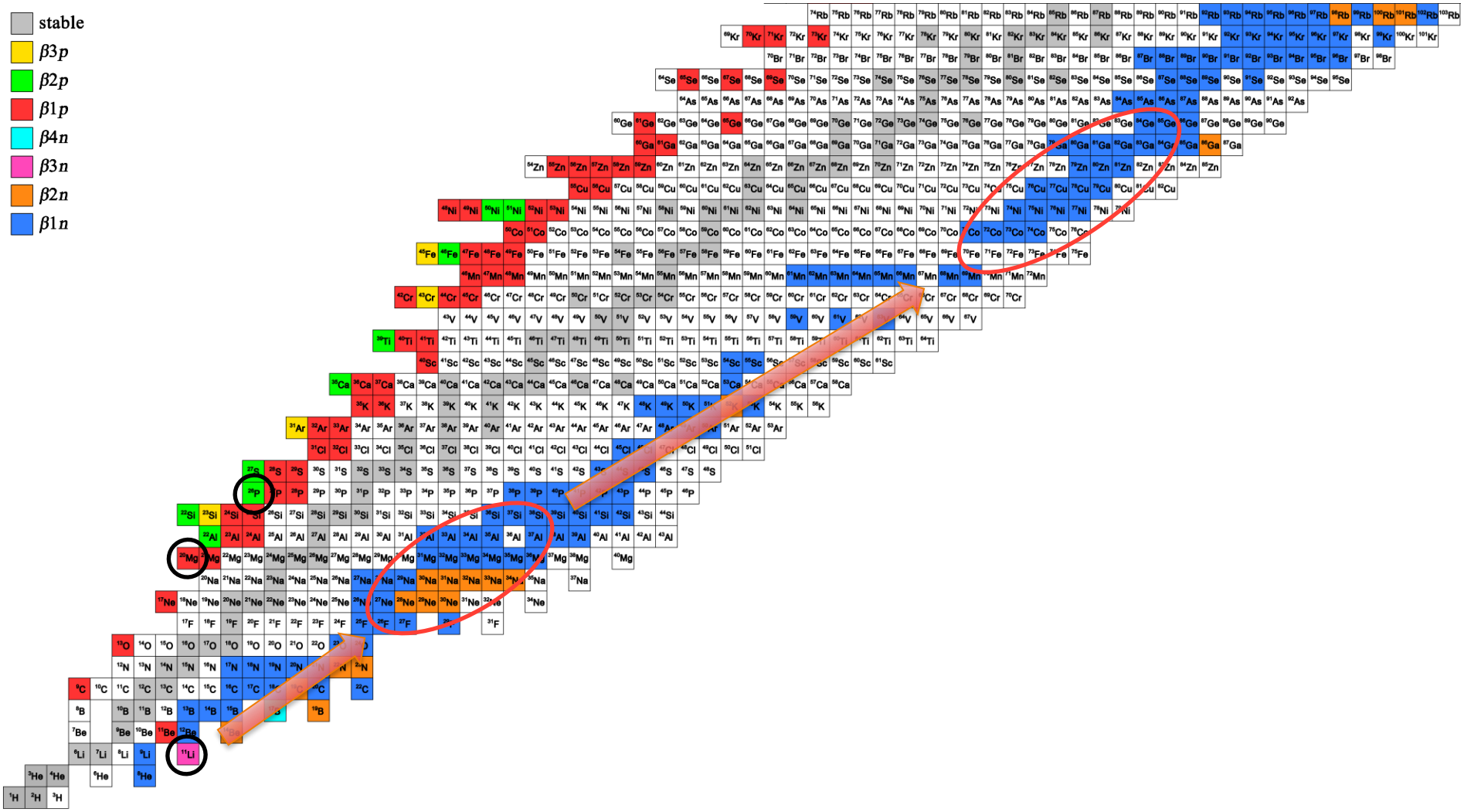
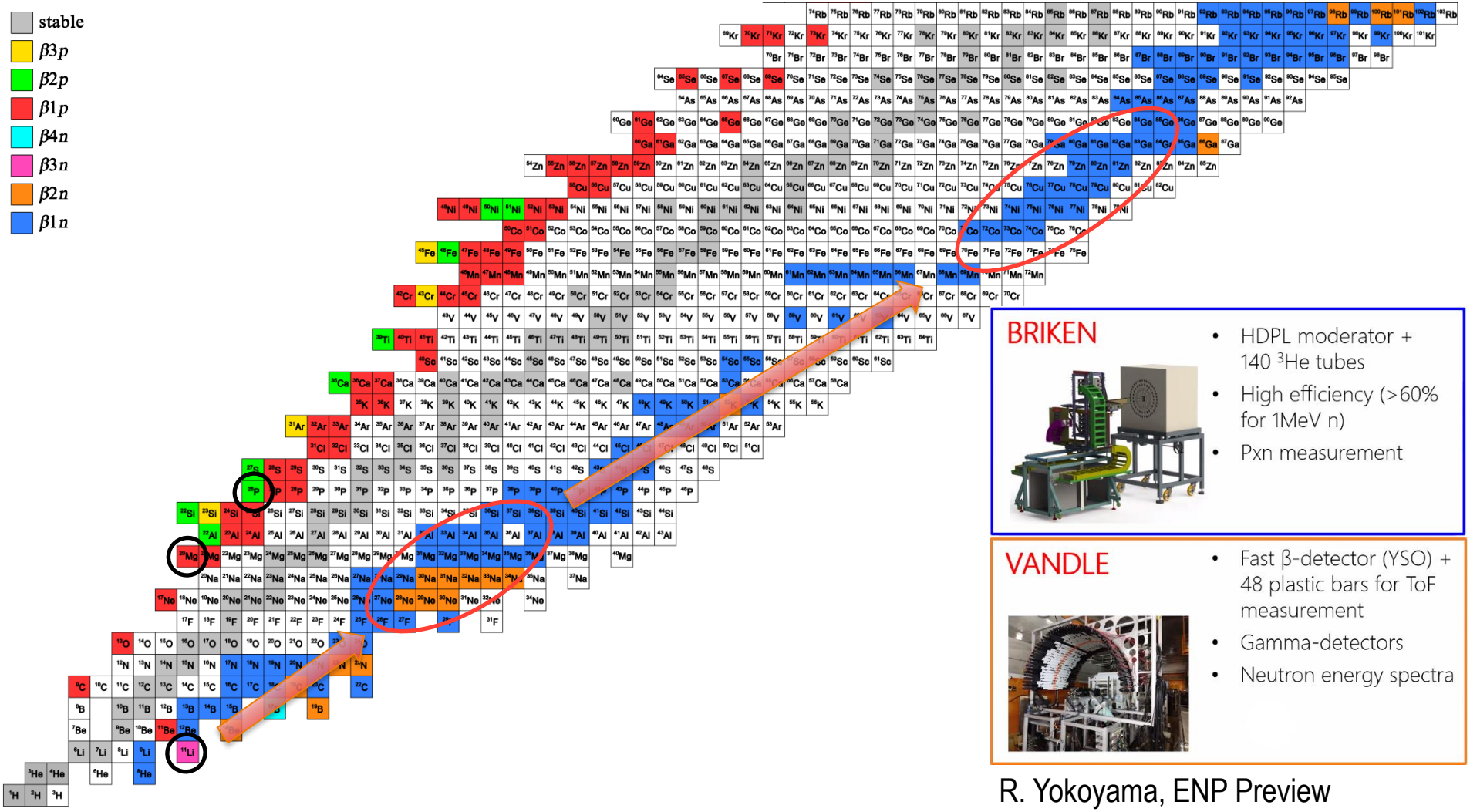


Scientific Value

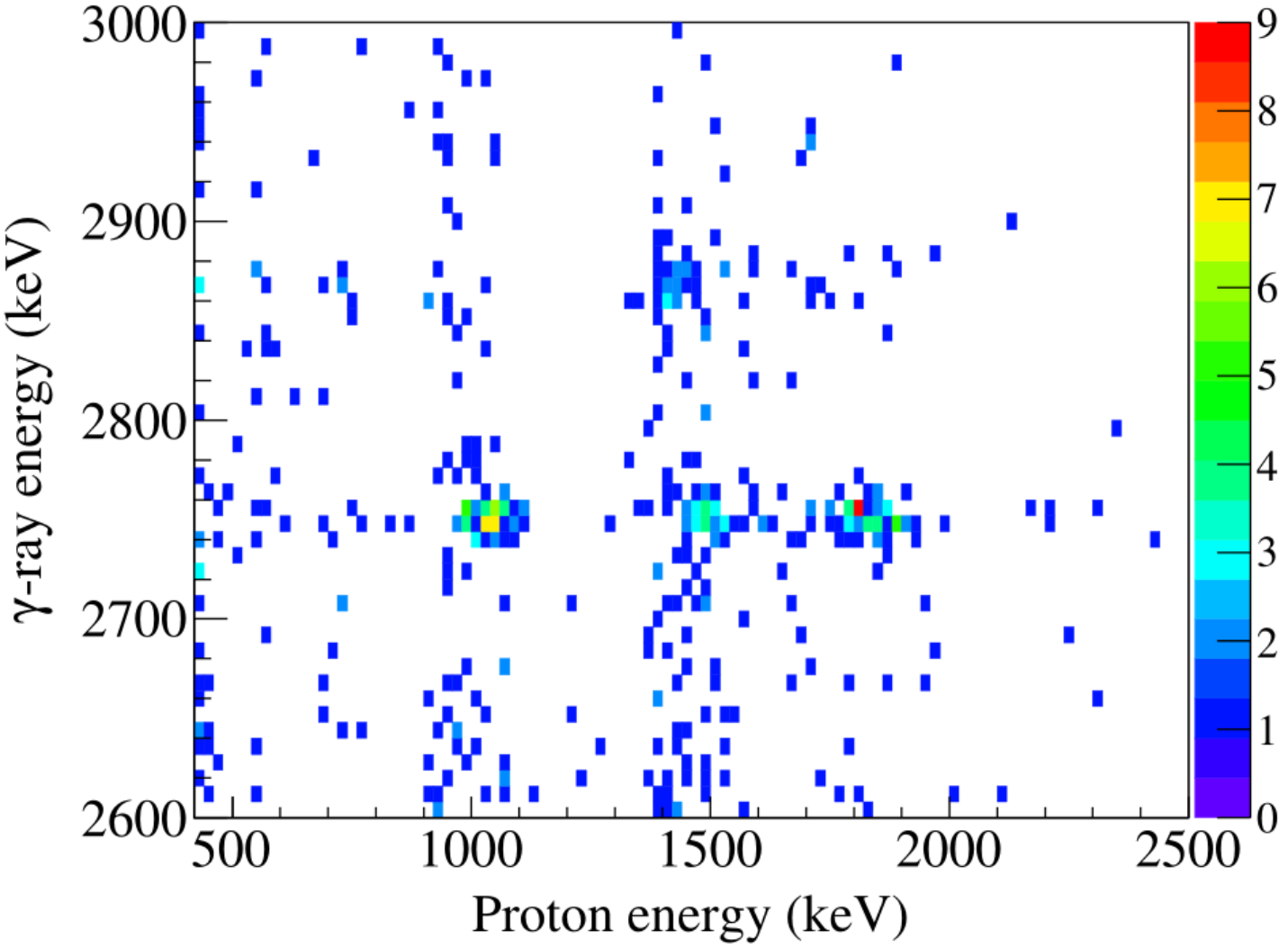


Scientific Value

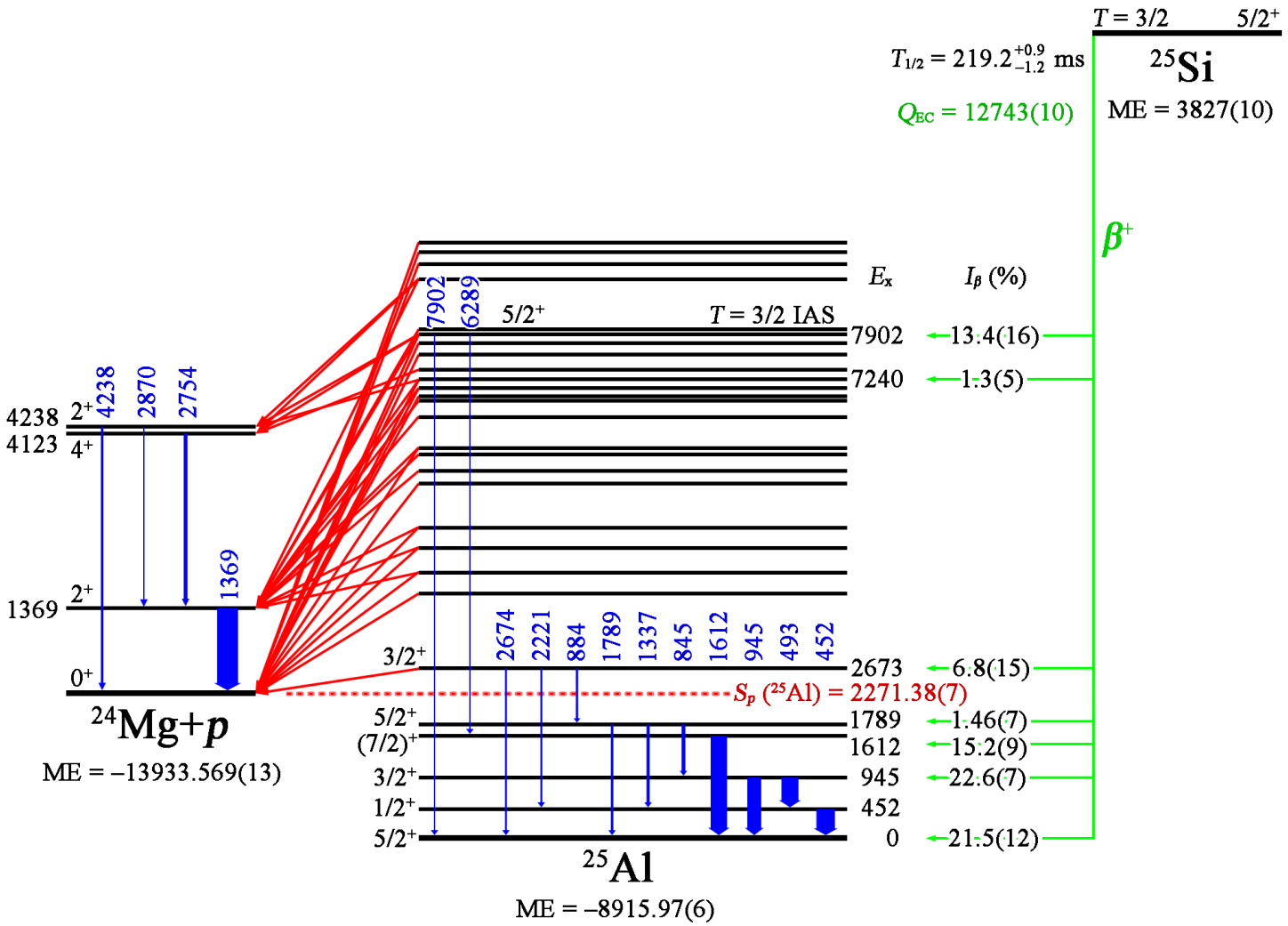


R. Yokoyama, ENP Preview

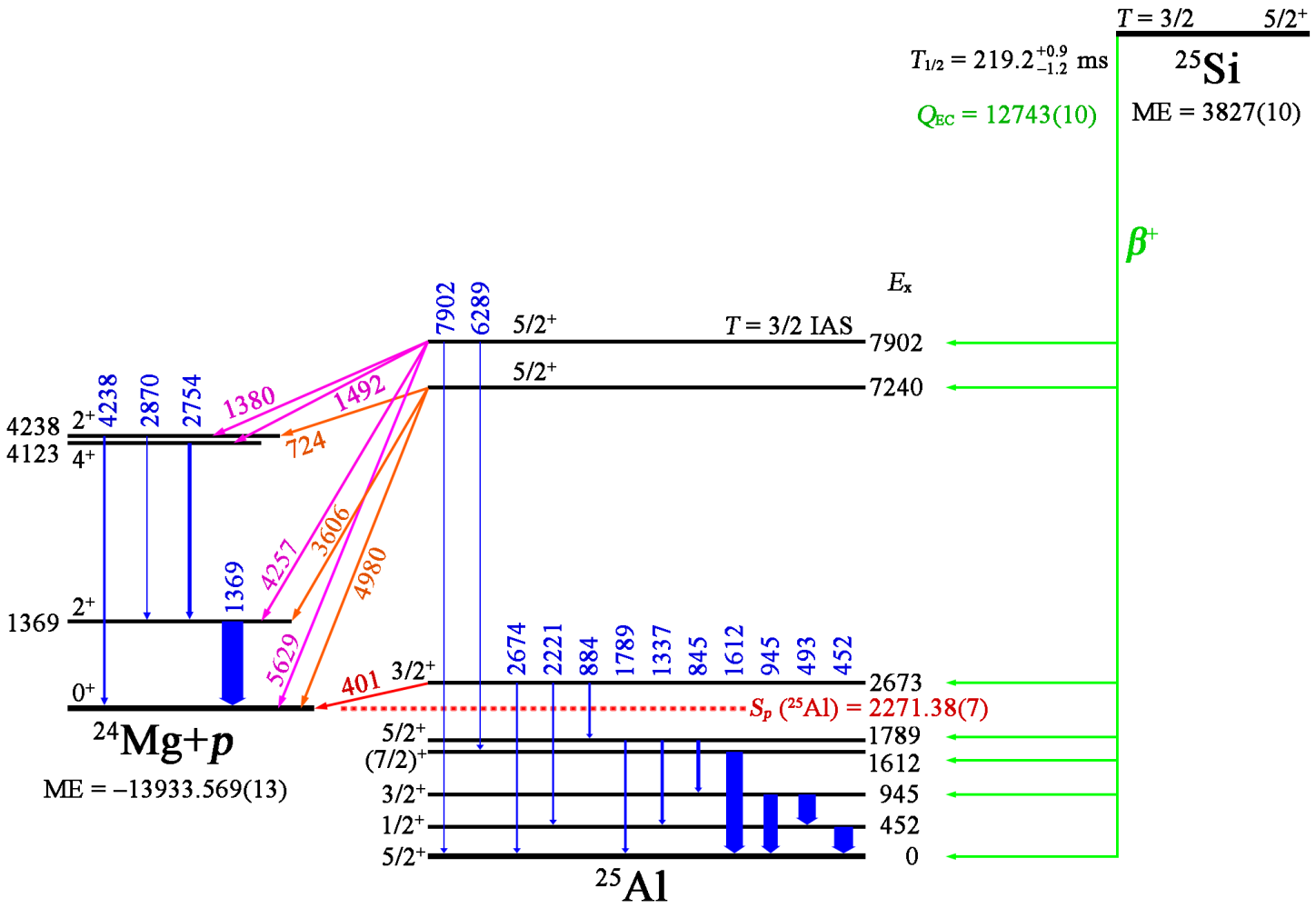
pγ Coincidence



^{25}Si Decay Scheme

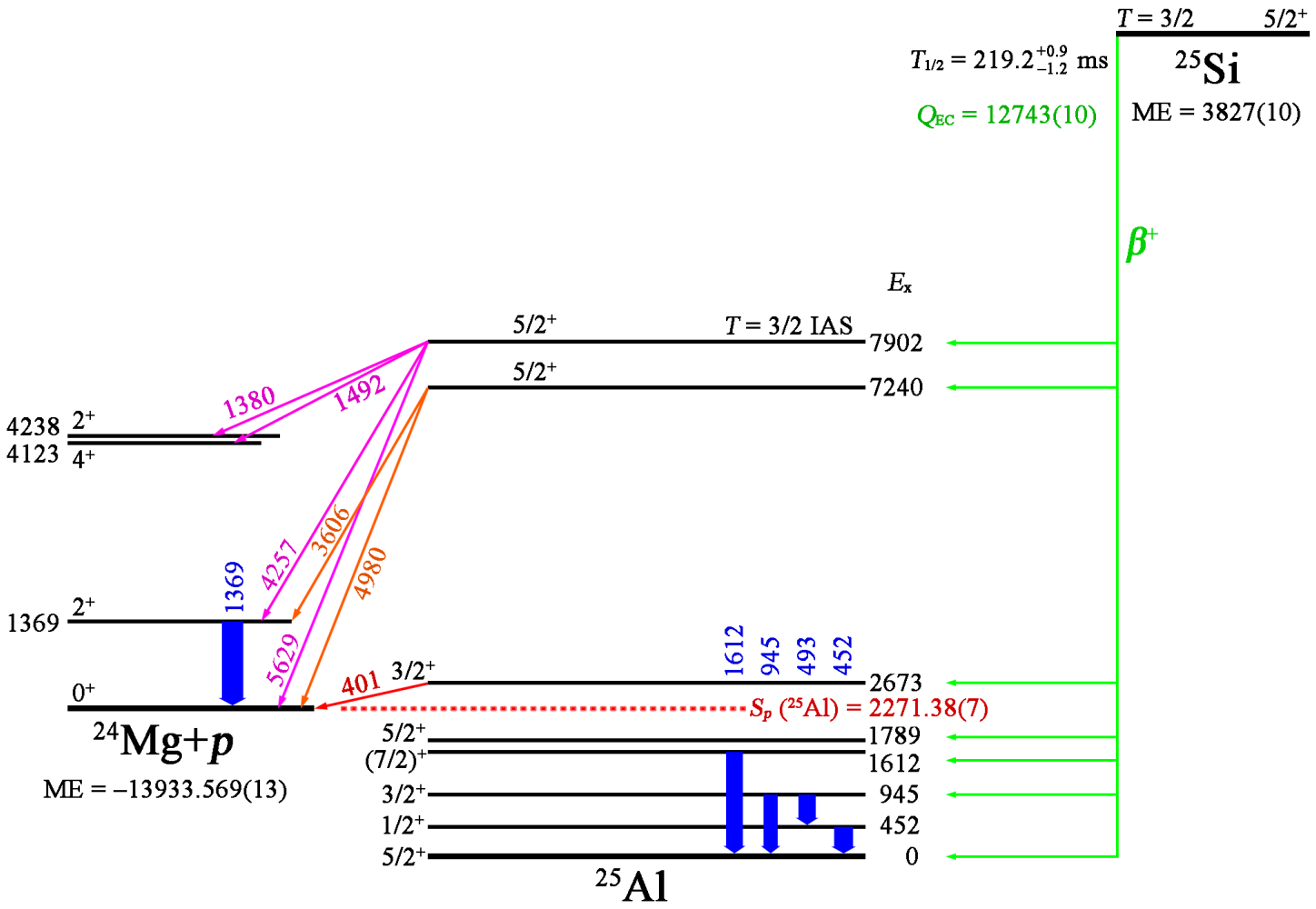


^{25}Si Decay Scheme



*For the sake of brevity, some proton branches are omitted.

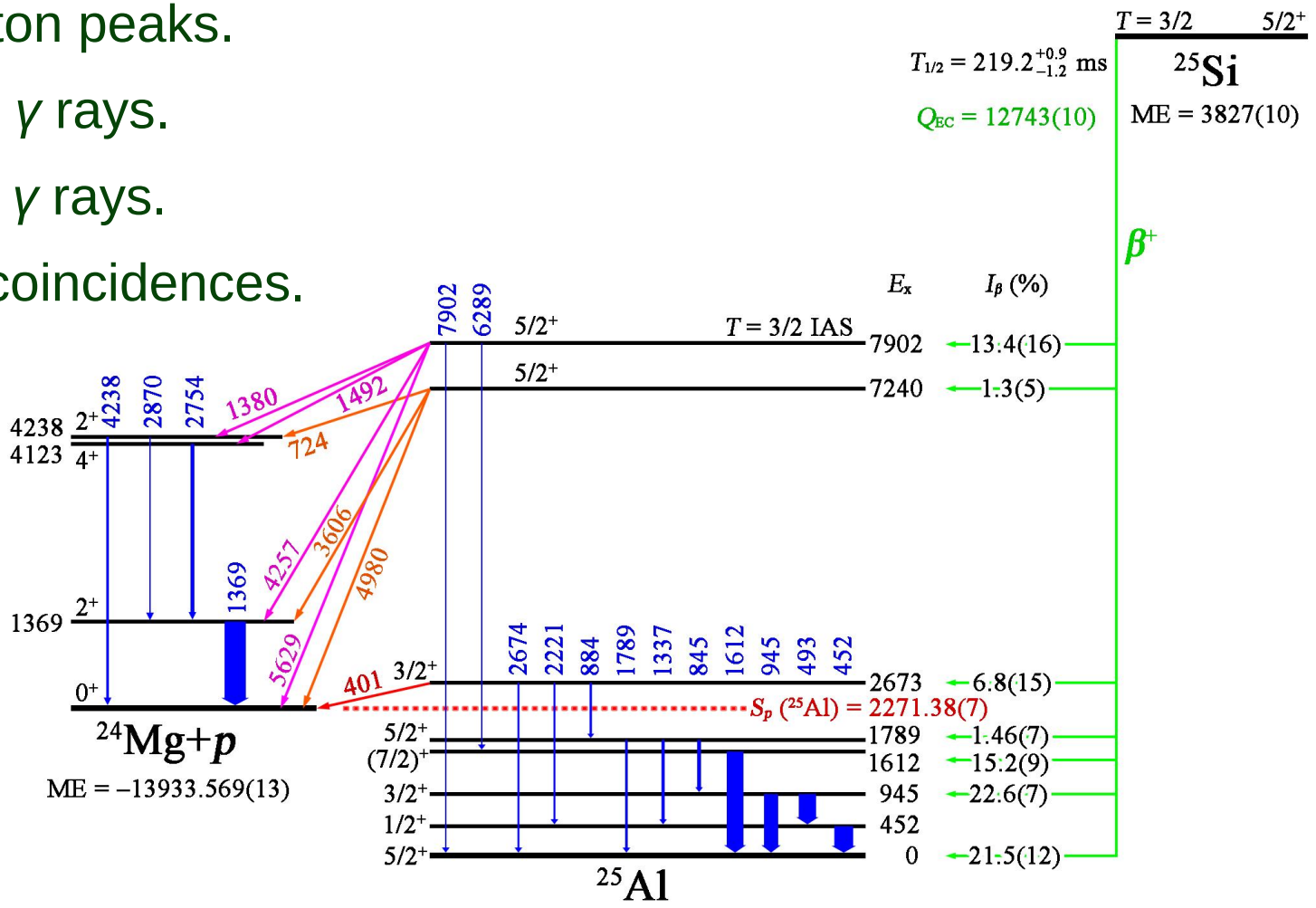
^{25}Si Decay Scheme



*For the sake of brevity, some proton branches are omitted.

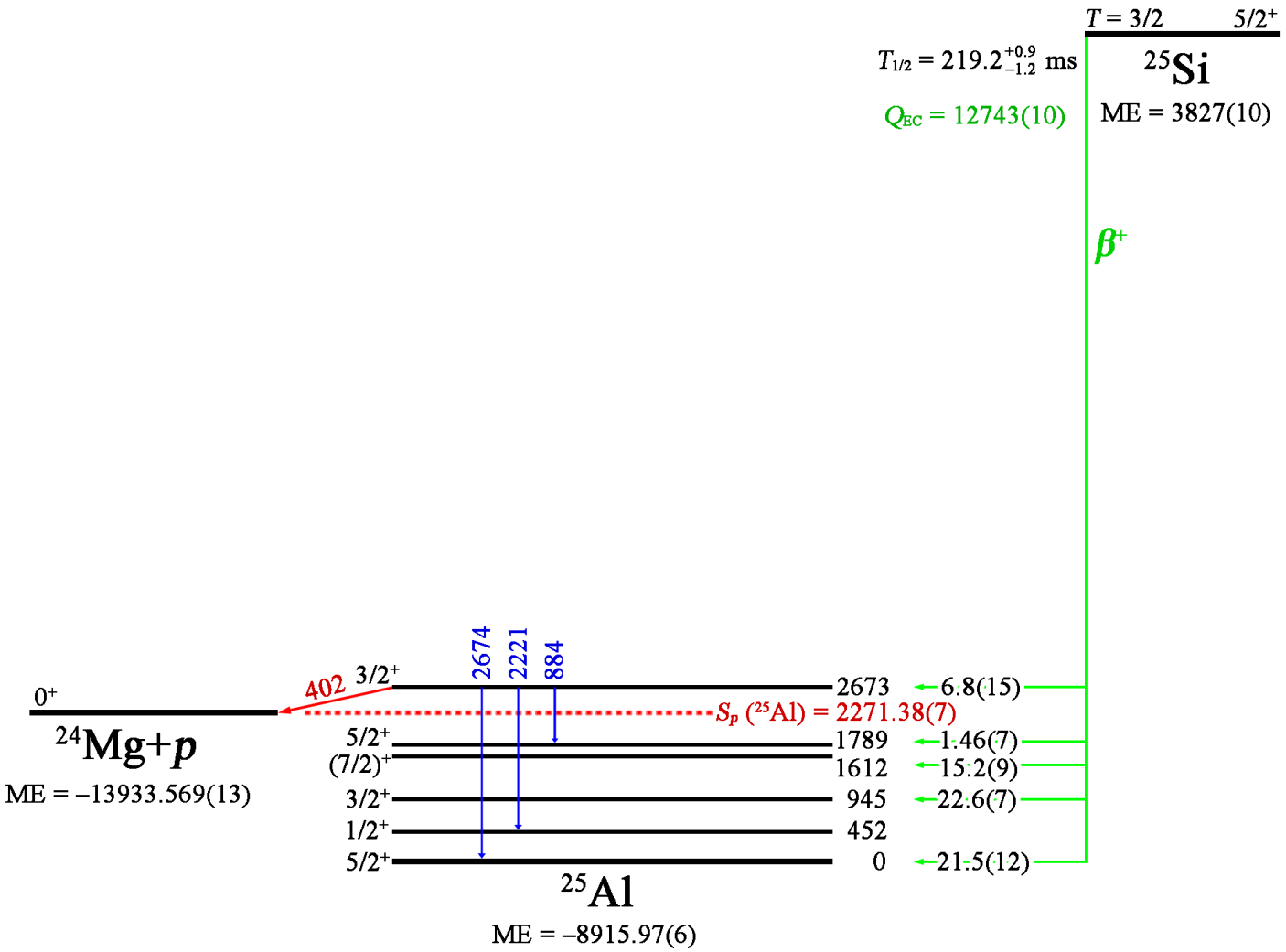
^{25}Si Decay Scheme

- 14 proton peaks.
- 12 ^{25}Al γ rays.
- 4 ^{24}Mg γ rays.
- 17 $p\gamma$ coincidences.



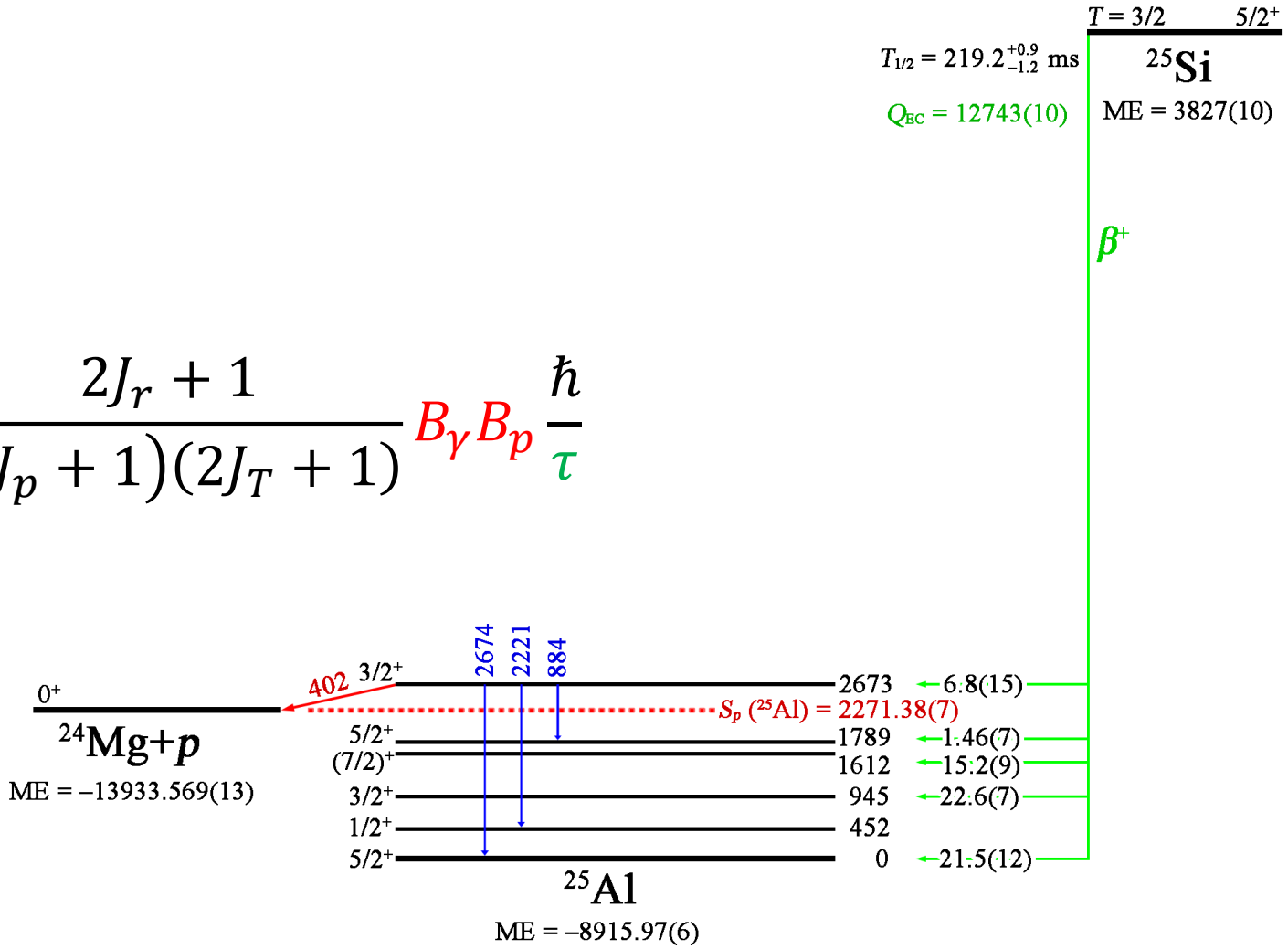
*For the sake of brevity, some proton branches are omitted.

^{25}Al 2673-keV state



^{25}Al 2673-keV state

$$\omega\gamma = \frac{2J_r + 1}{(2J_p + 1)(2J_T + 1)} B_\gamma B_p \frac{\hbar}{\tau}$$

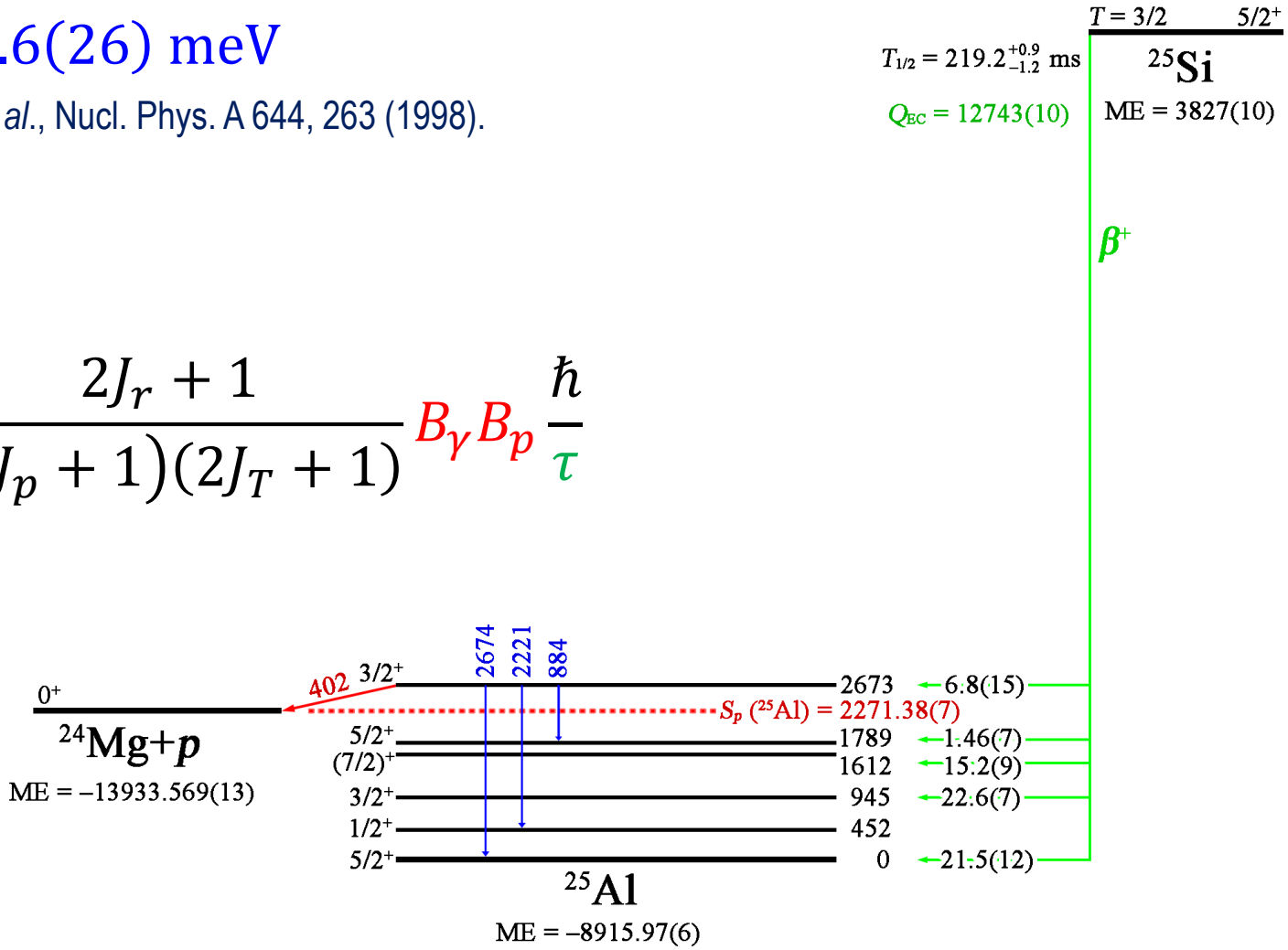


^{25}Al 2673-keV state

$\omega\gamma = 41.6(26)$ meV

D. C. Powell *et al.*, Nucl. Phys. A 644, 263 (1998).

$$\omega\gamma = \frac{2J_r + 1}{(2J_p + 1)(2J_T + 1)} B_\gamma B_p \frac{\hbar}{\tau}$$

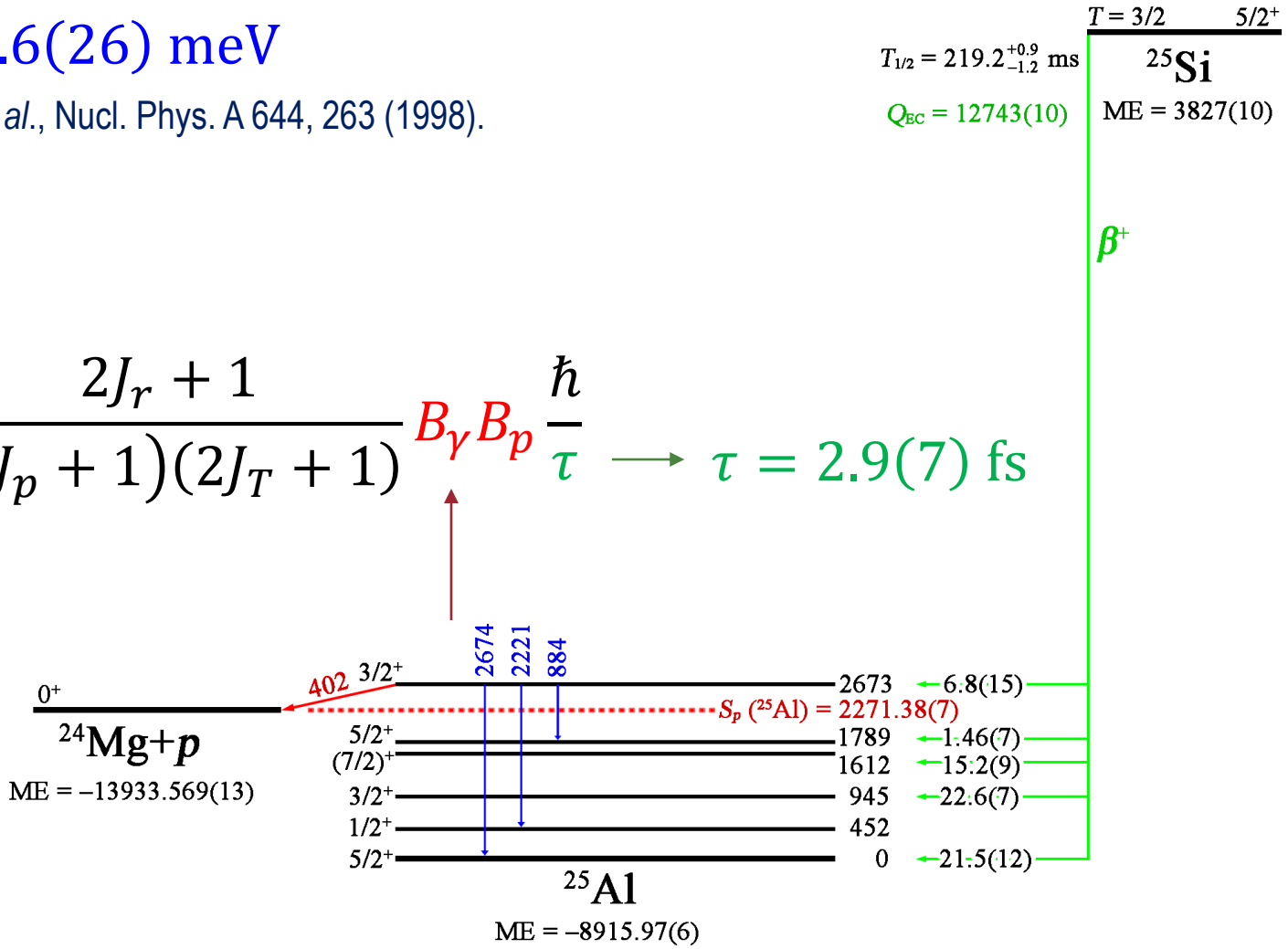


^{25}Al 2673-keV state

$\omega\gamma = 41.6(26)$ meV

D. C. Powell *et al.*, Nucl. Phys. A 644, 263 (1998).

$$\omega\gamma = \frac{2J_r + 1}{(2J_p + 1)(2J_T + 1)} B_\gamma B_p \frac{\hbar}{\tau} \longrightarrow \tau = 2.9(7)\ \text{fs}$$



^{25}Al 2673-keV state

$\omega\gamma = 41.6(26)$ meV

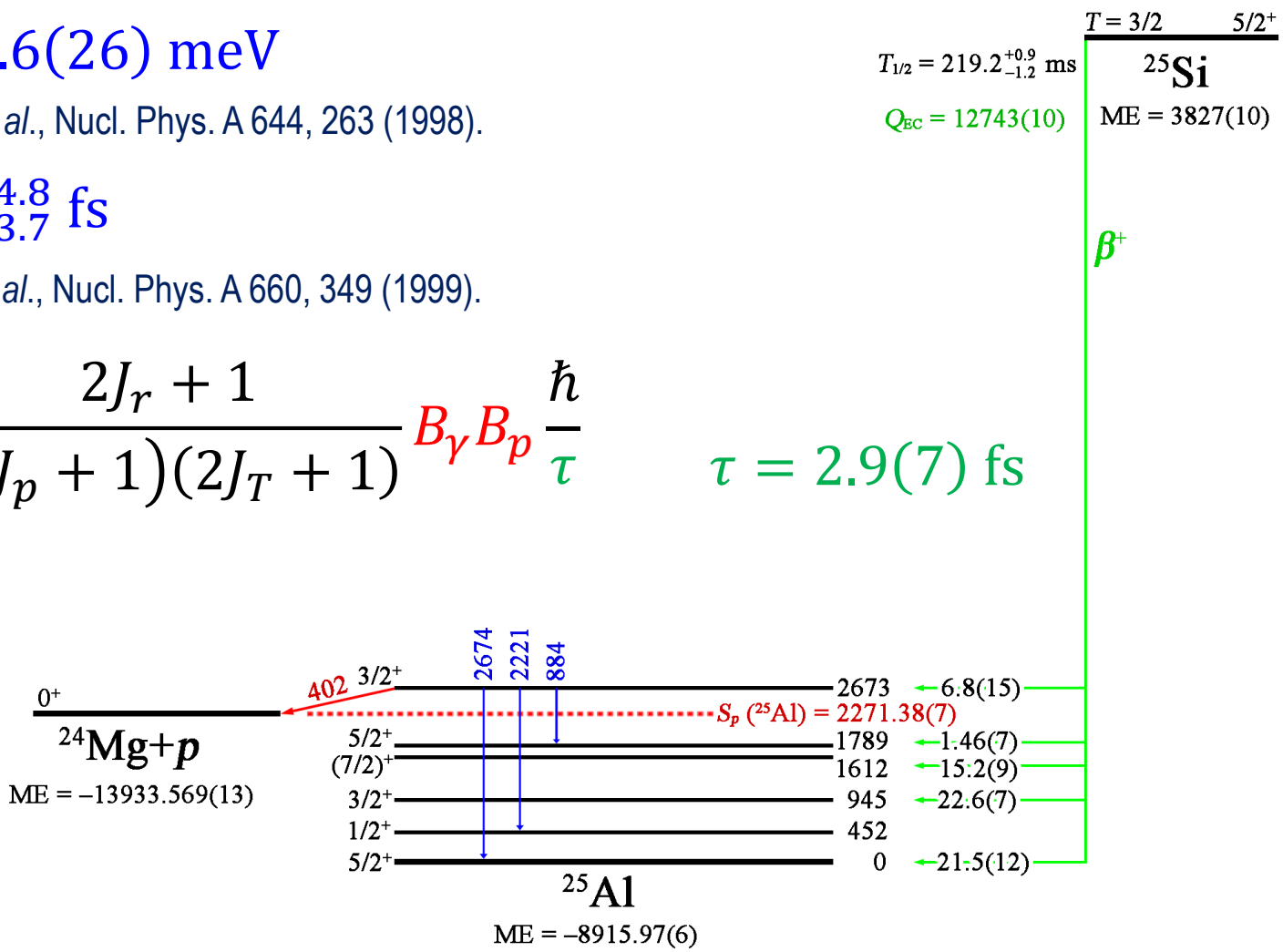
D. C. Powell *et al.*, Nucl. Phys. A 644, 263 (1998).

$\tau = 6.1^{+4.8}_{-3.7}$ fs

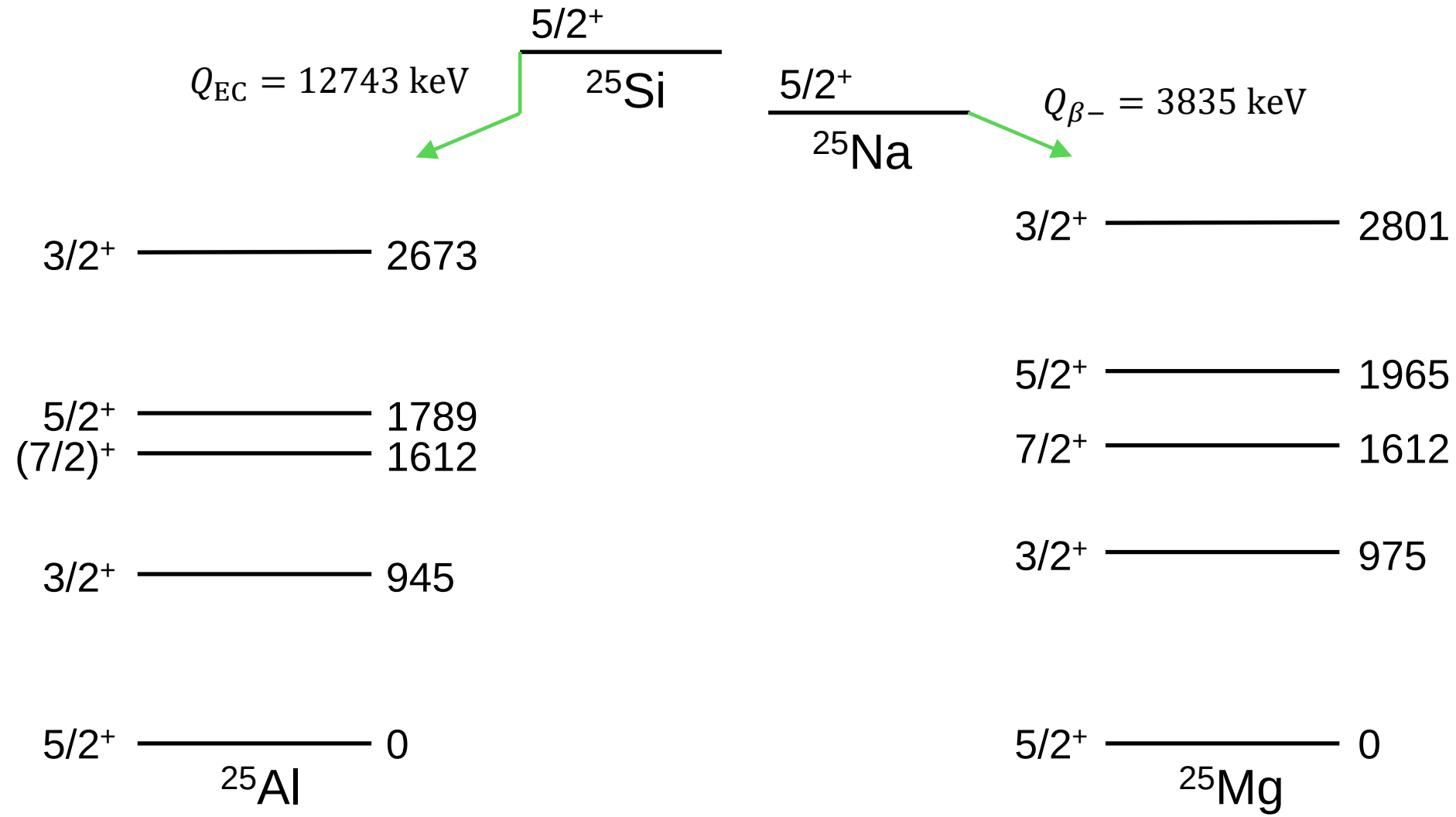
D. C. Powell *et al.*, Nucl. Phys. A 660, 349 (1999).

$$\omega\gamma = \frac{2J_r + 1}{(2J_p + 1)(2J_T + 1)} B_\gamma B_p \frac{\hbar}{\tau}$$

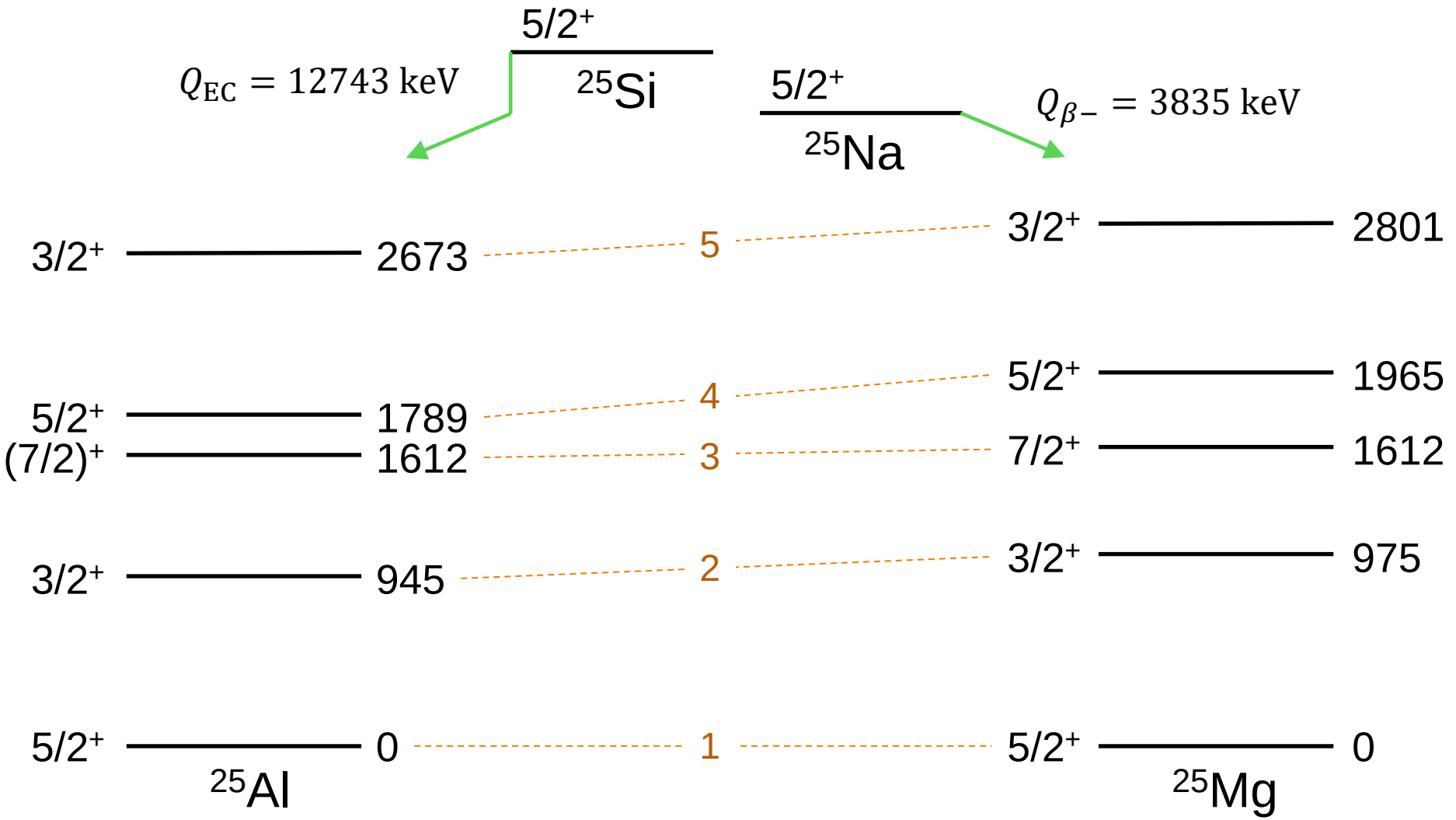
$\tau = 2.9(7)$ fs



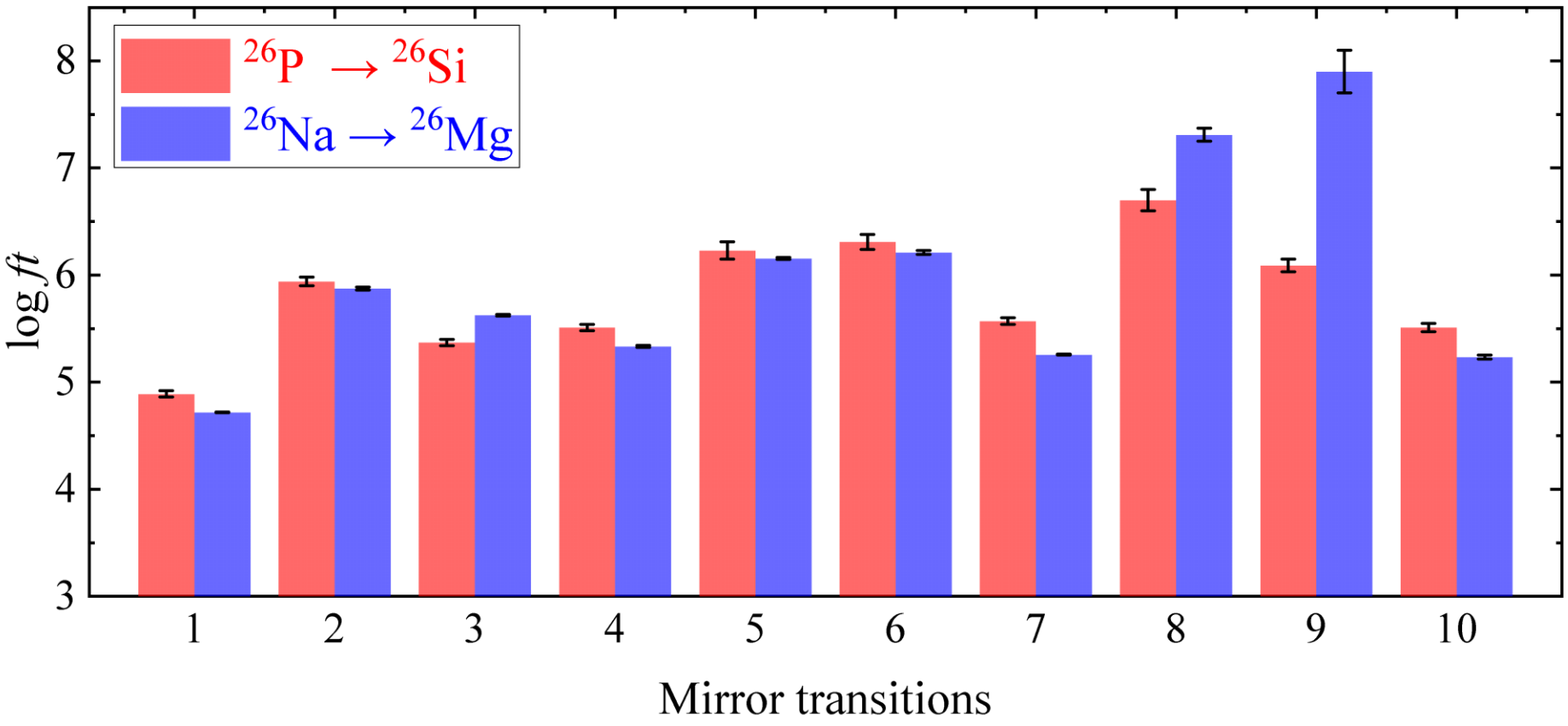
Mirror Symmetry



Mirror Symmetry

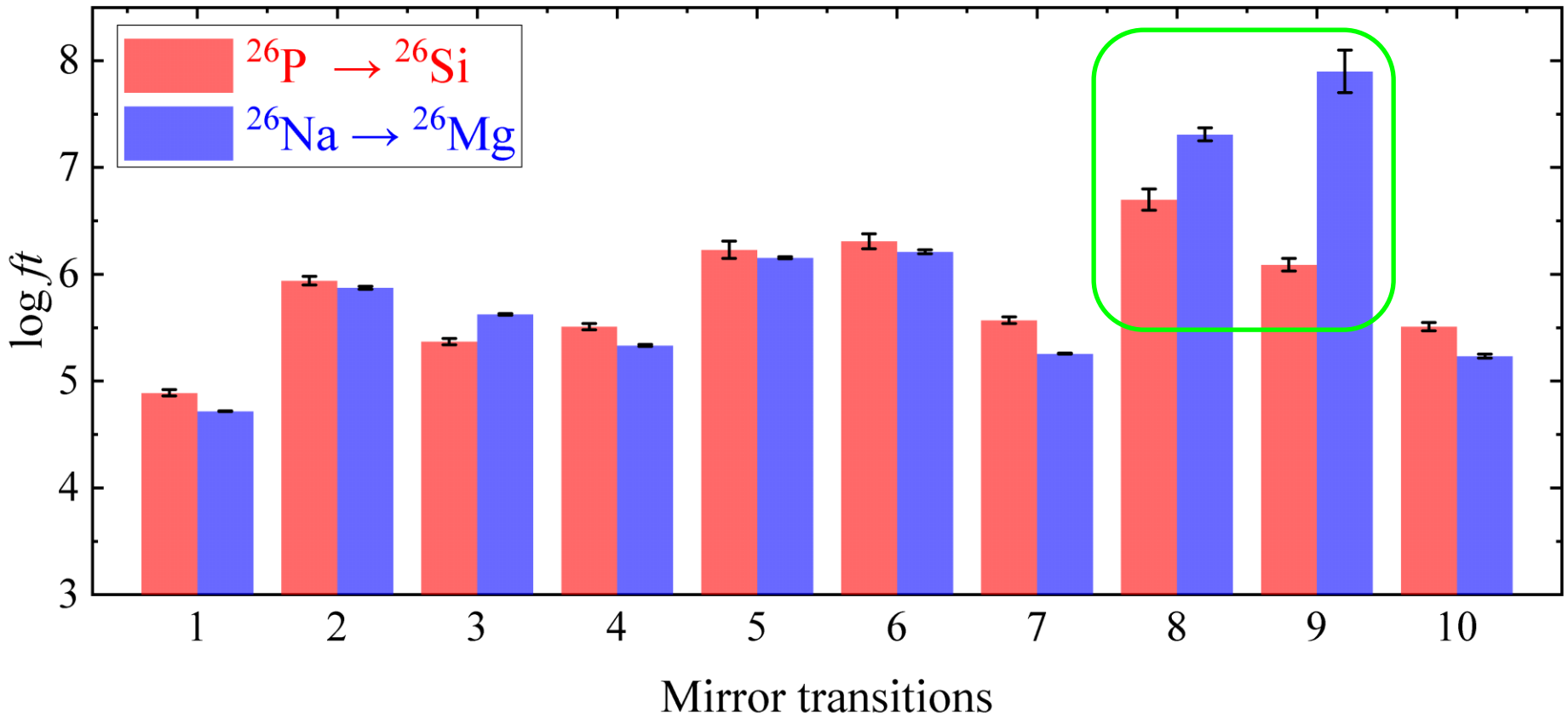


Mirror Symmetry



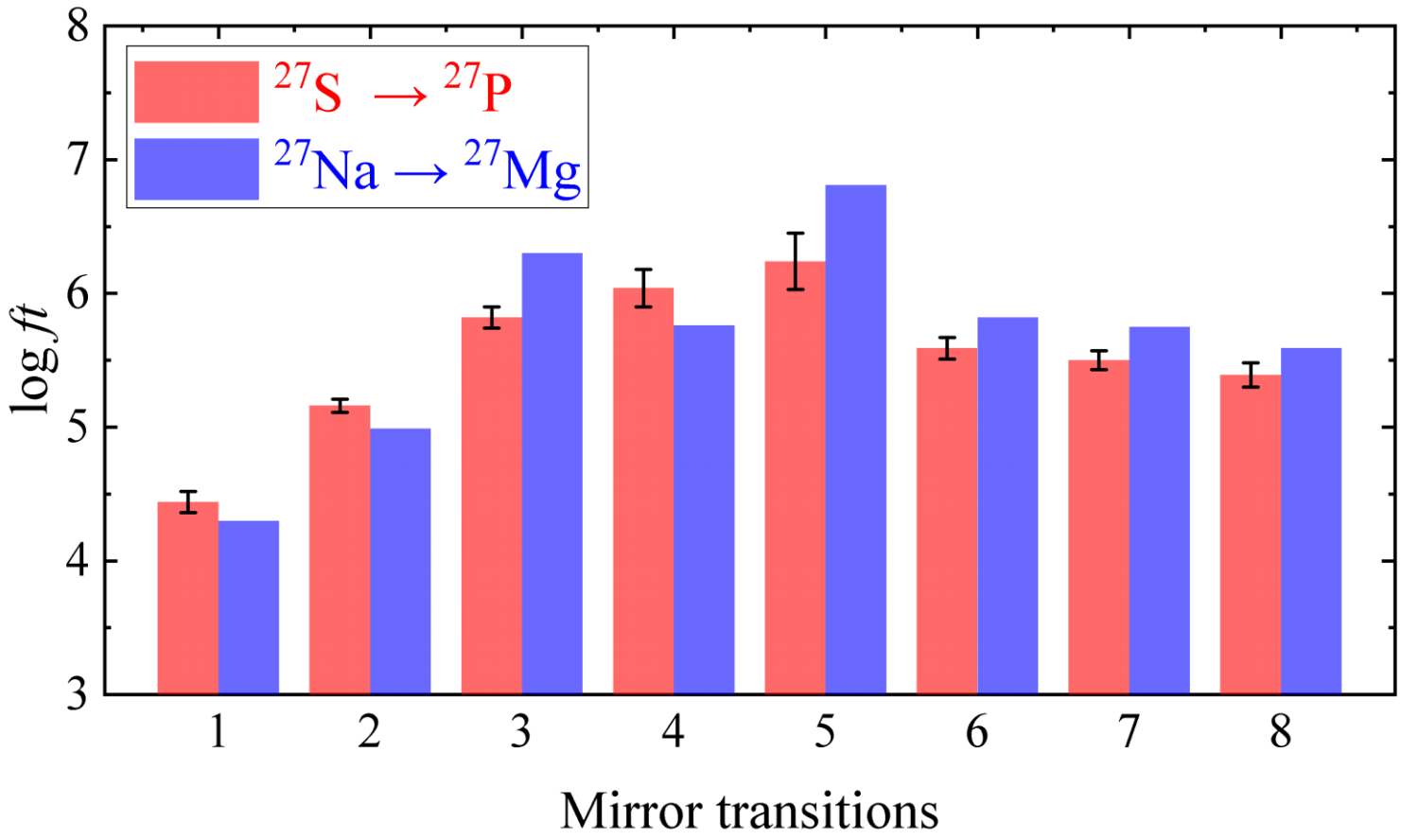
D. Pérez-Loureiro *et al.*, Phys. Rev. C 93, 064320 (2016).
G. F. Grinyer *et al.*, Phys. Rev. C 71, 044309 (2005).

Mirror Symmetry



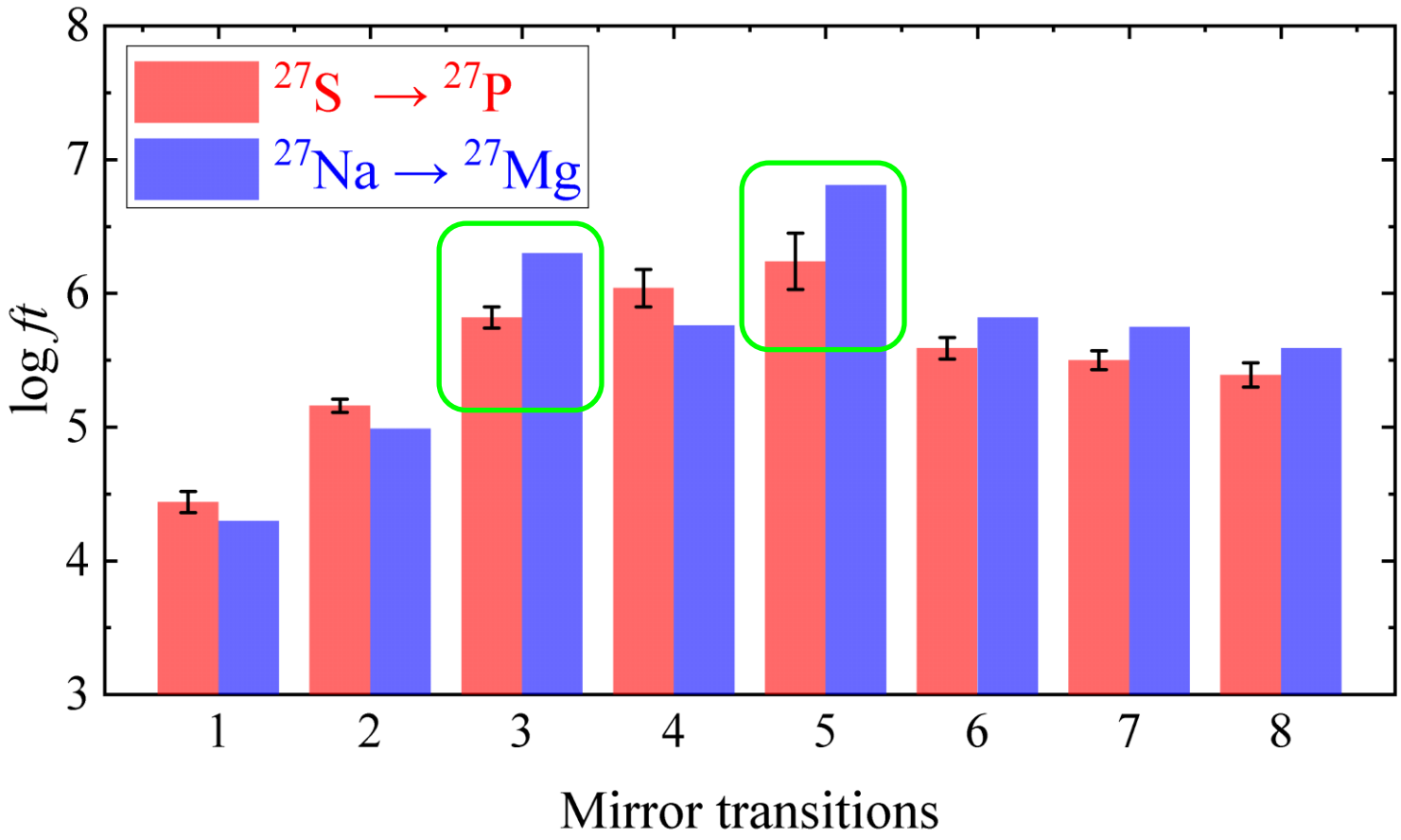
D. Pérez-Loureiro *et al.*, Phys. Rev. C 93, 064320 (2016).
G. F. Grinyer *et al.*, Phys. Rev. C 71, 044309 (2005).

Mirror Symmetry



L. J. Sun *et al.*, Phys. Rev. C 99, 064312 (2019).
D. Guillemaud-Mueller *et al.*, Nucl. Phys. A 426, 37 (1984).

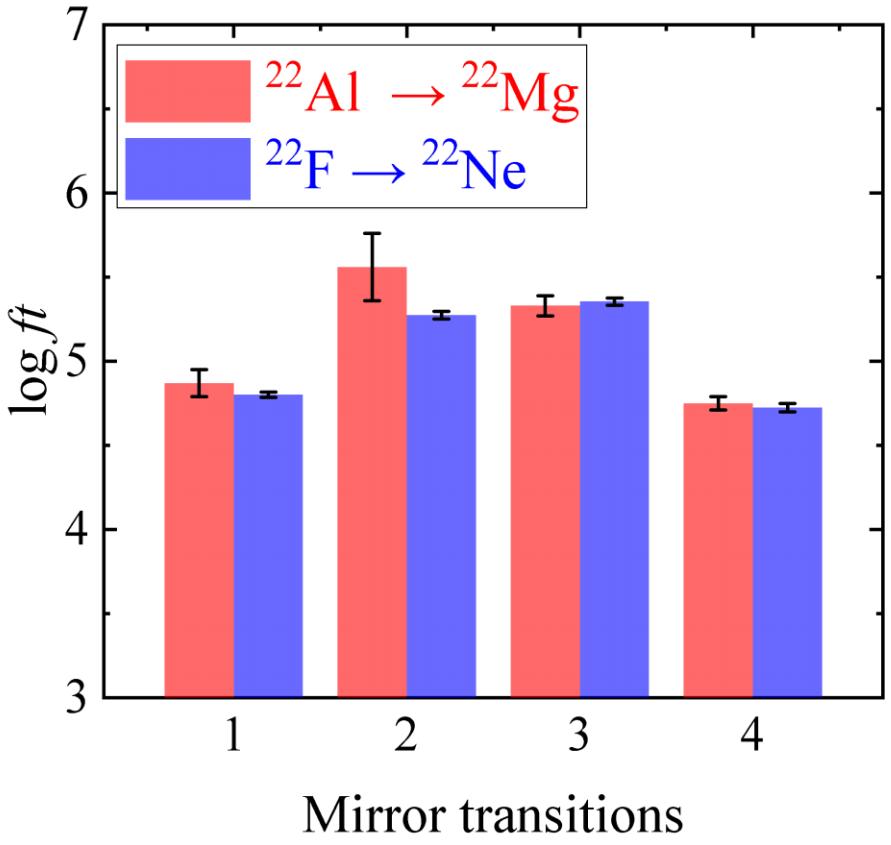
Mirror Symmetry



L. J. Sun *et al.*, Phys. Rev. C 99, 064312 (2019).

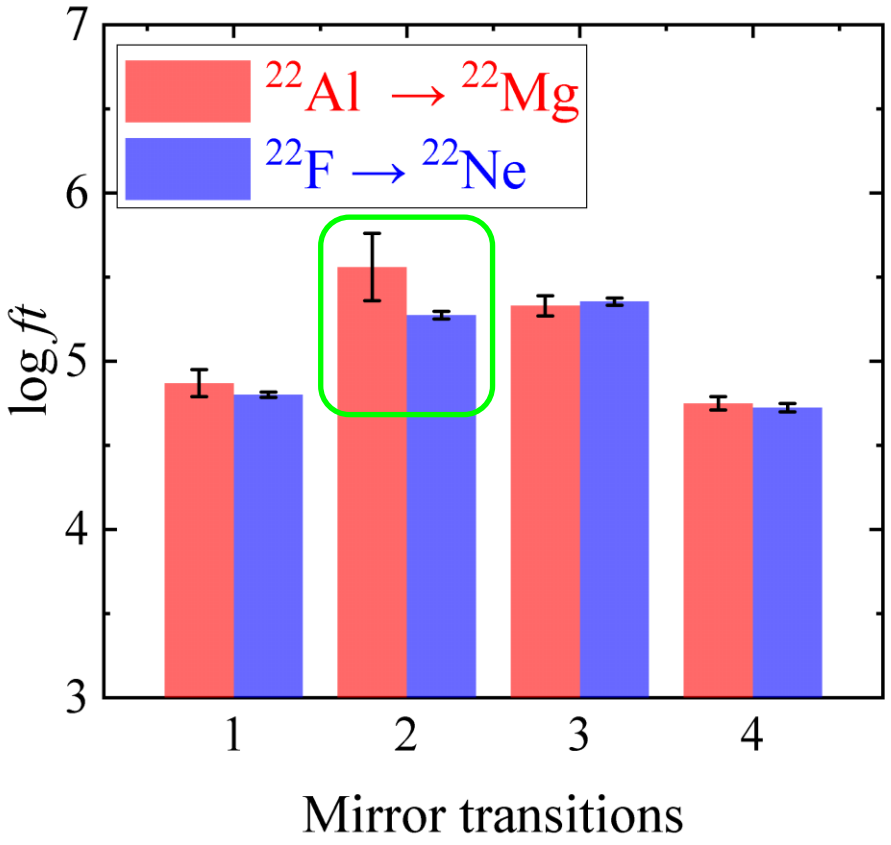
D. Guillemaud-Mueller *et al.*, Nucl. Phys. A 426, 37 (1984).

Mirror Symmetry



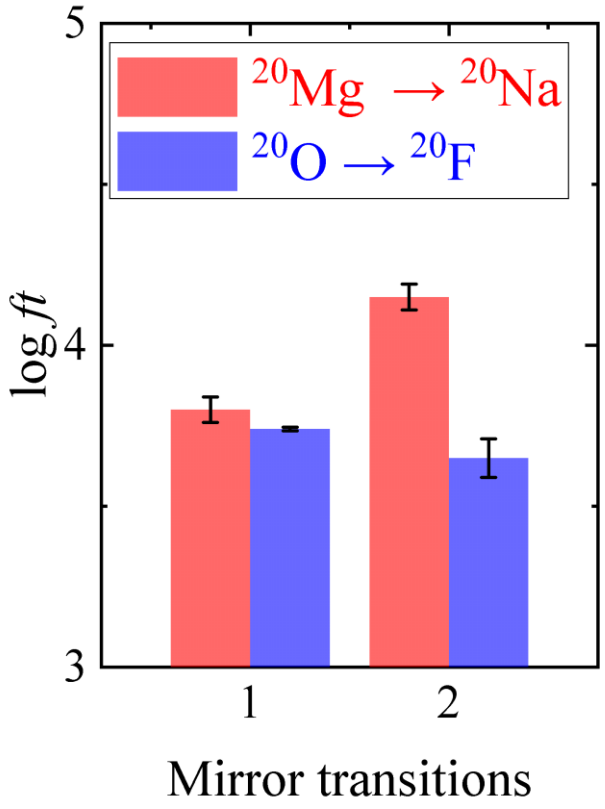
N. L. Achouri *et al.*, Eur. Phys. J. A 27, 287 (2006).
C. N. Davids *et al.*, Phys. Rev. C 9, 216 (1974).

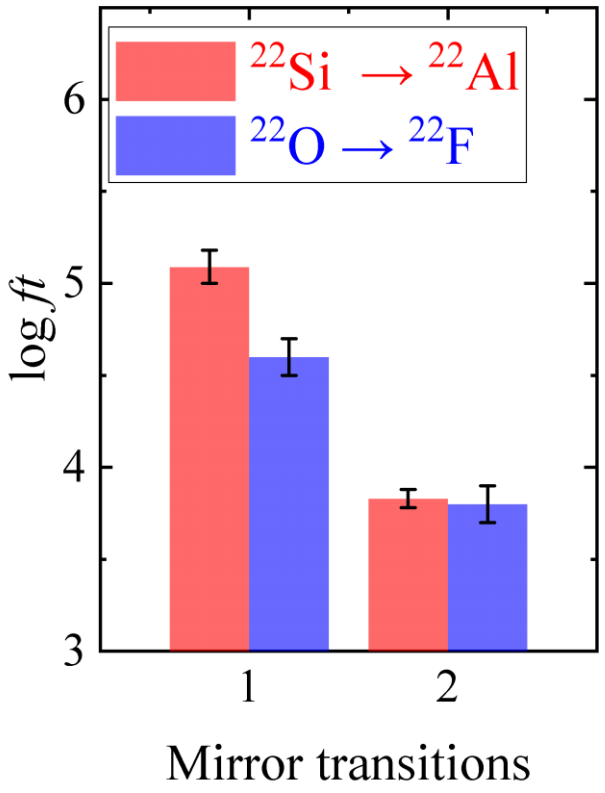
Mirror Symmetry



N. L. Achouri *et al.*, Eur. Phys. J. A 27, 287 (2006).
C. N. Davids *et al.*, Phys. Rev. C 9, 216 (1974).

Mirror Symmetry

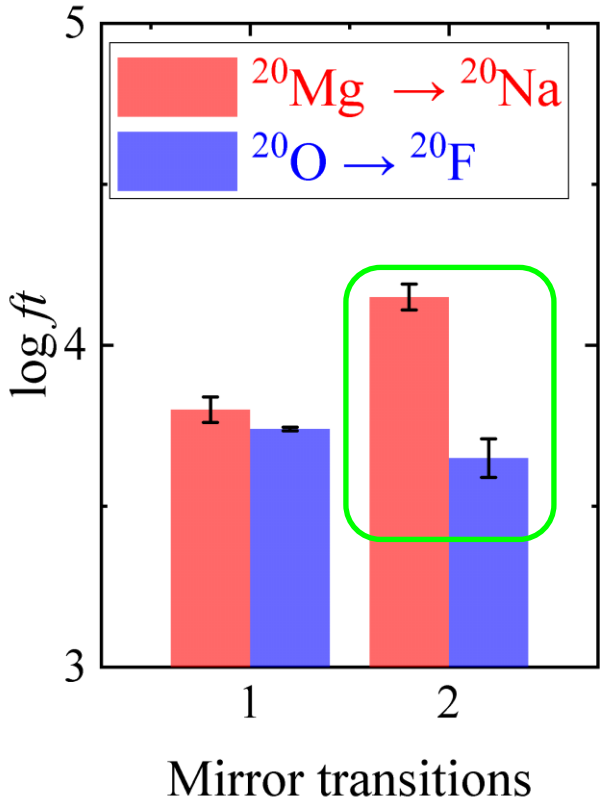


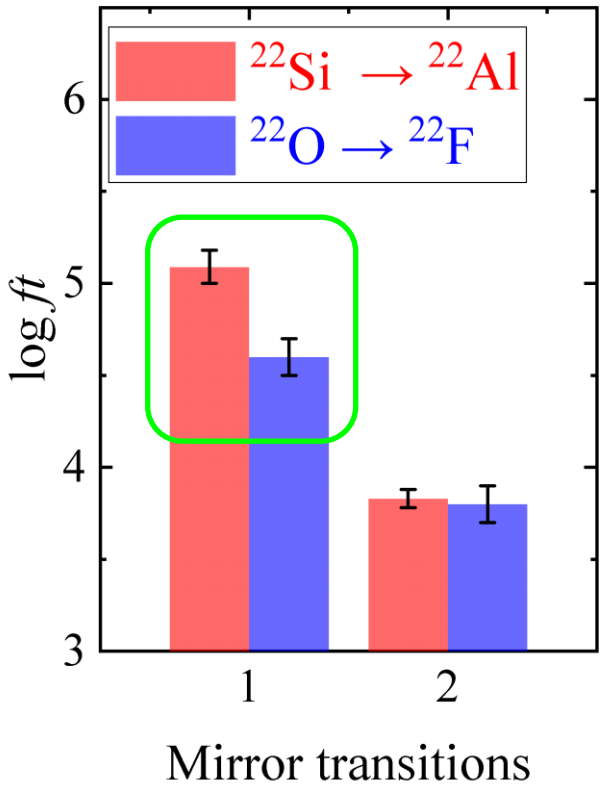


L. J. Sun *et al.*, Phys. Rev. C 95, 014314 (2017).
D. E. Alburger *et al.*, Phys. Rev. C 35, 1479 (1987).

J. Lee *et al.*, Phys. Rev. Lett. 125, 192503 (2020).
L. Weissman *et al.*, J. Phys. G: Nucl. Part. Phys. 31, 553 (2005).

Mirror Symmetry

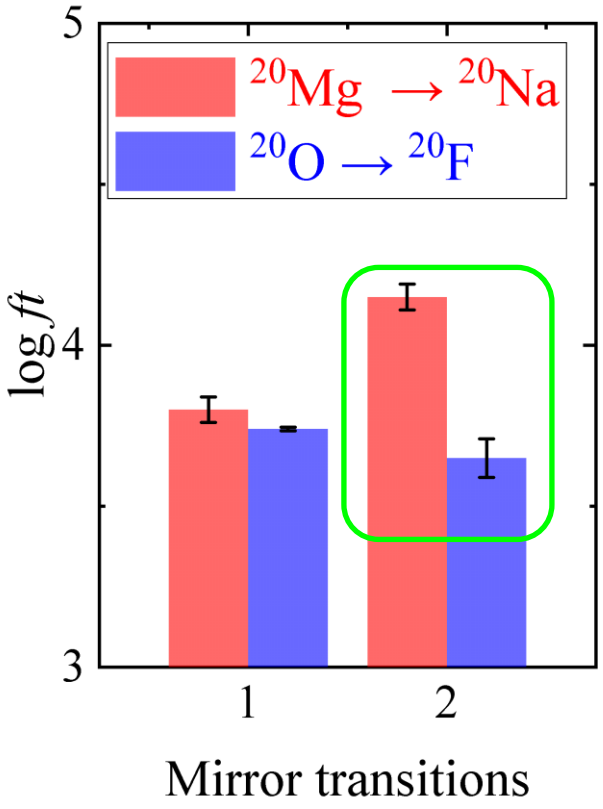




L. J. Sun *et al.*, Phys. Rev. C 95, 014314 (2017).
D. E. Alburger *et al.*, Phys. Rev. C 35, 1479 (1987).

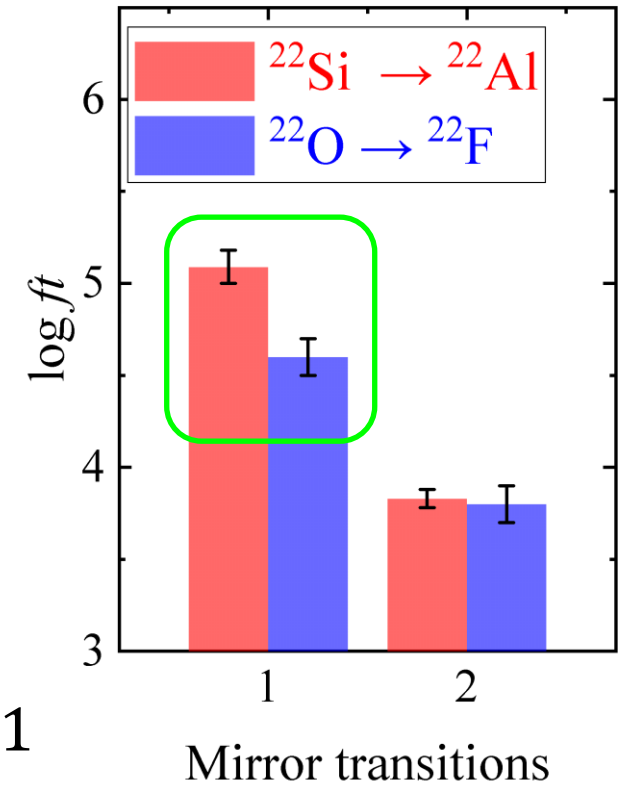
J. Lee *et al.*, Phys. Rev. Lett. 125, 192503 (2020).
L. Weissman *et al.*, J. Phys. G: Nucl. Part. Phys. 31, 553 (2005).

Mirror Symmetry



$$\delta = \frac{ft^+}{ft^-} - 1$$

Mirror-asymmetry parameter



L. J. Sun *et al.*, Phys. Rev. C 95, 014314 (2017).
D. E. Alburger *et al.*, Phys. Rev. C 35, 1479 (1987).

J. Lee *et al.*, Phys. Rev. Lett. 125, 192503 (2020).
L. Weissman *et al.*, J. Phys. G: Nucl. Part. Phys. 31, 553 (2005).

Isospin-Symmetry Breaking

$$H = H_0 + H_{\mathrm{INC}}$$

H_0: Isospin-conserving interaction

H_{INC}: Isospin-nonconserving interactions

Coulomb interaction

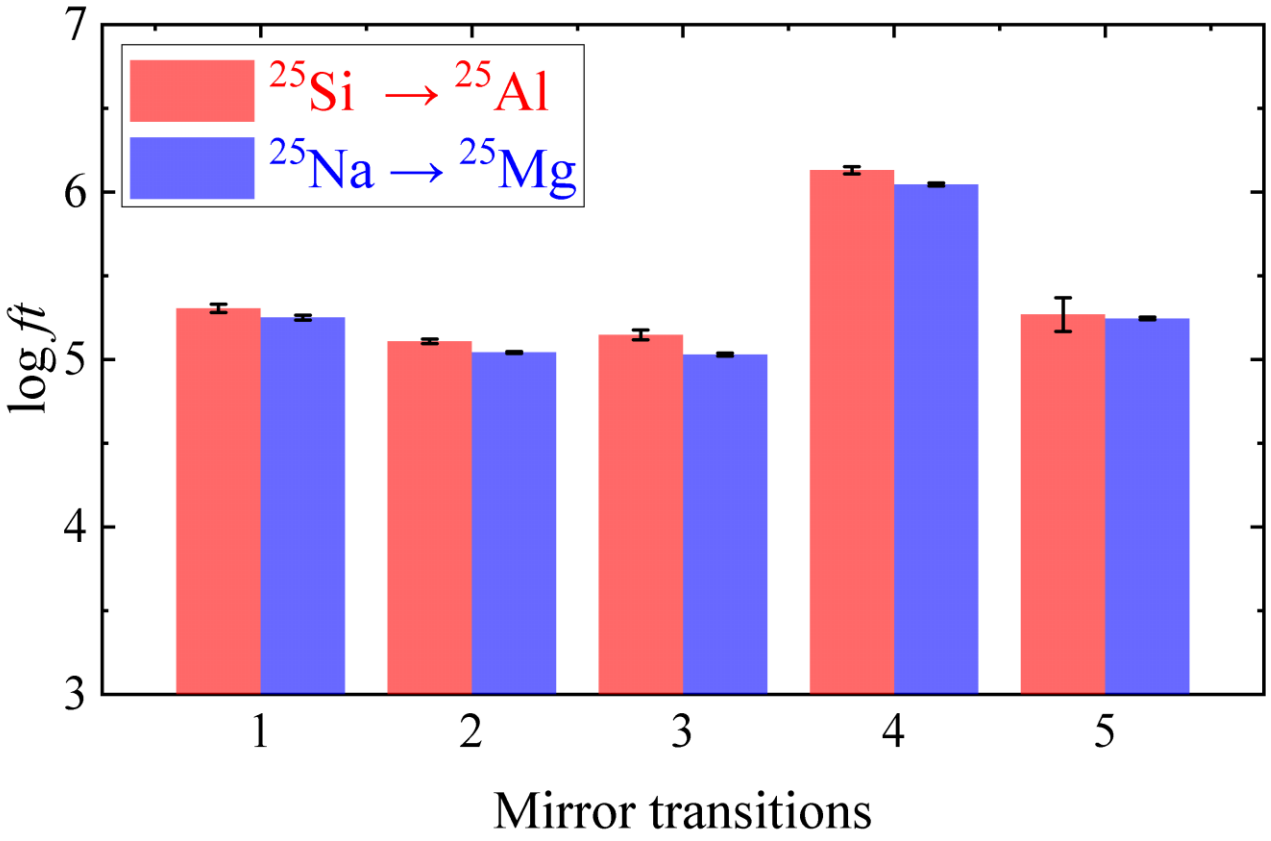
Charge-dependent parts of nuclear force

Mirror asymmetry

Proton halo structure

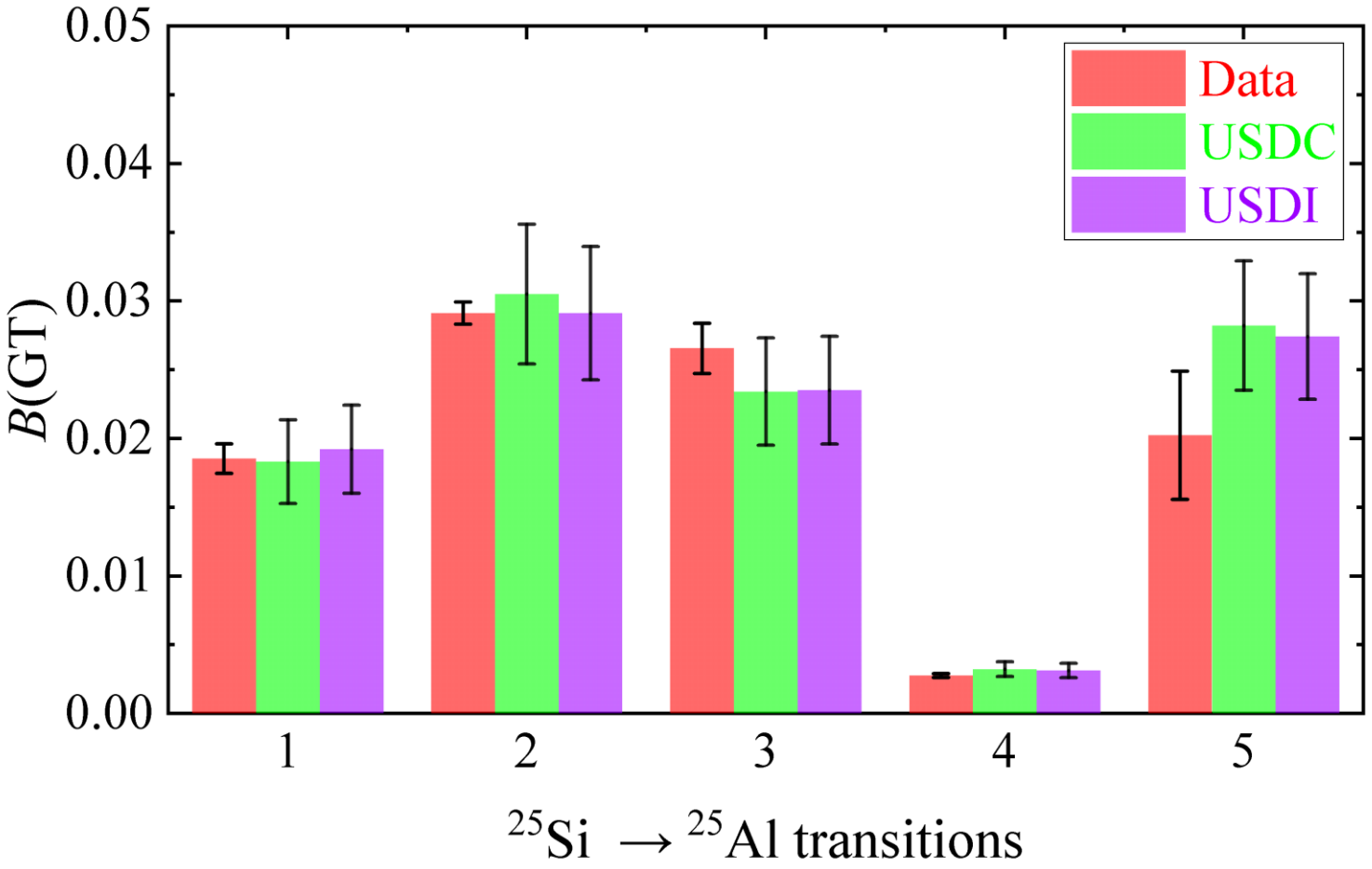
Loosely bound $s_{1/2}$ orbit

Mirror Symmetry



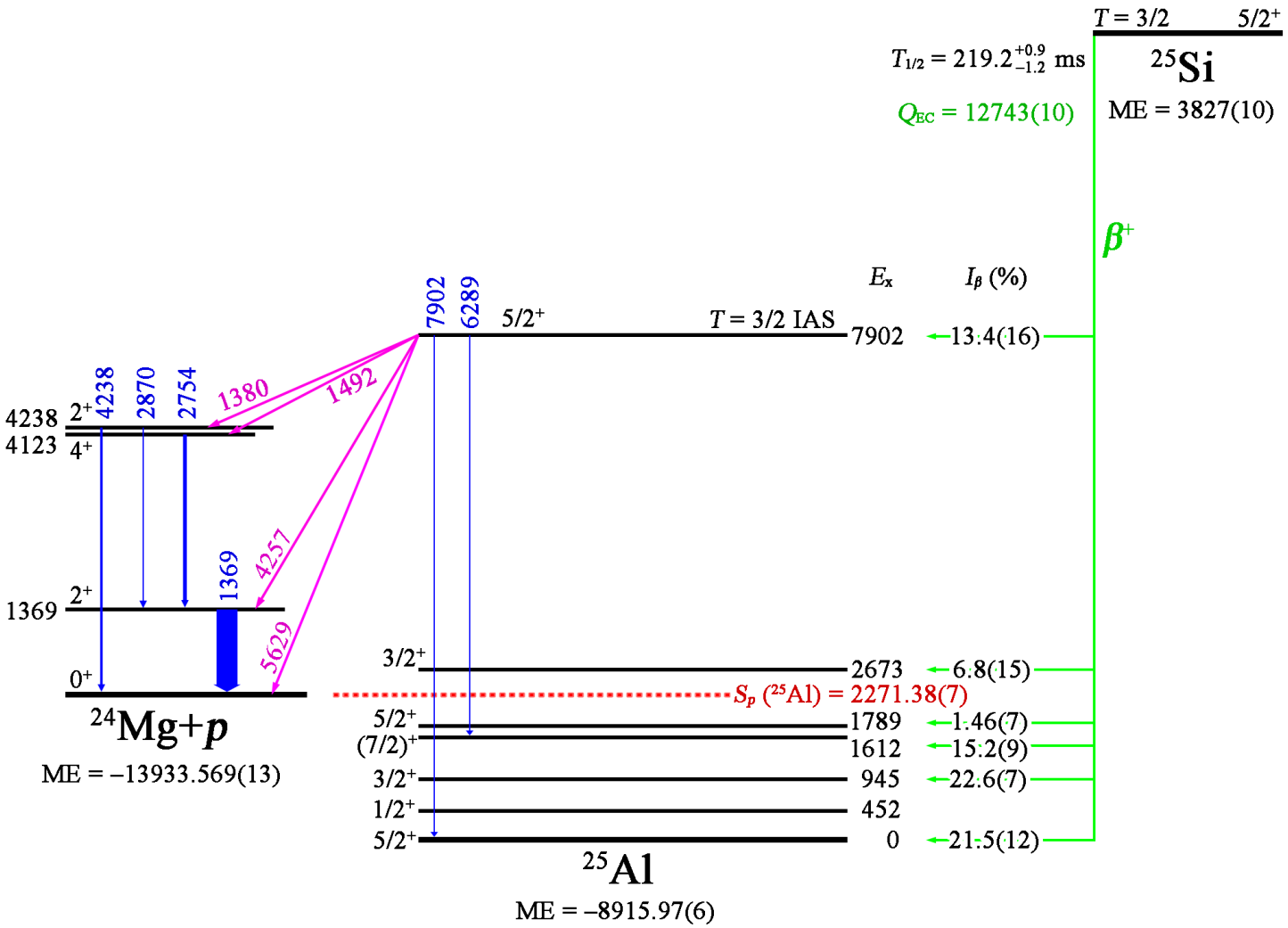
D. E. Alburger *et al.*, Phys. Rev. C 3, 1957 (1971).
D. E. Alburger *et al.*, Nucl. Phys. A 385, 474 (1982).

Shell-model Calculations and Mirror Symmetry



A. Magilligan *et al.*, Phys. Rev. C 101, 064312 (2020).

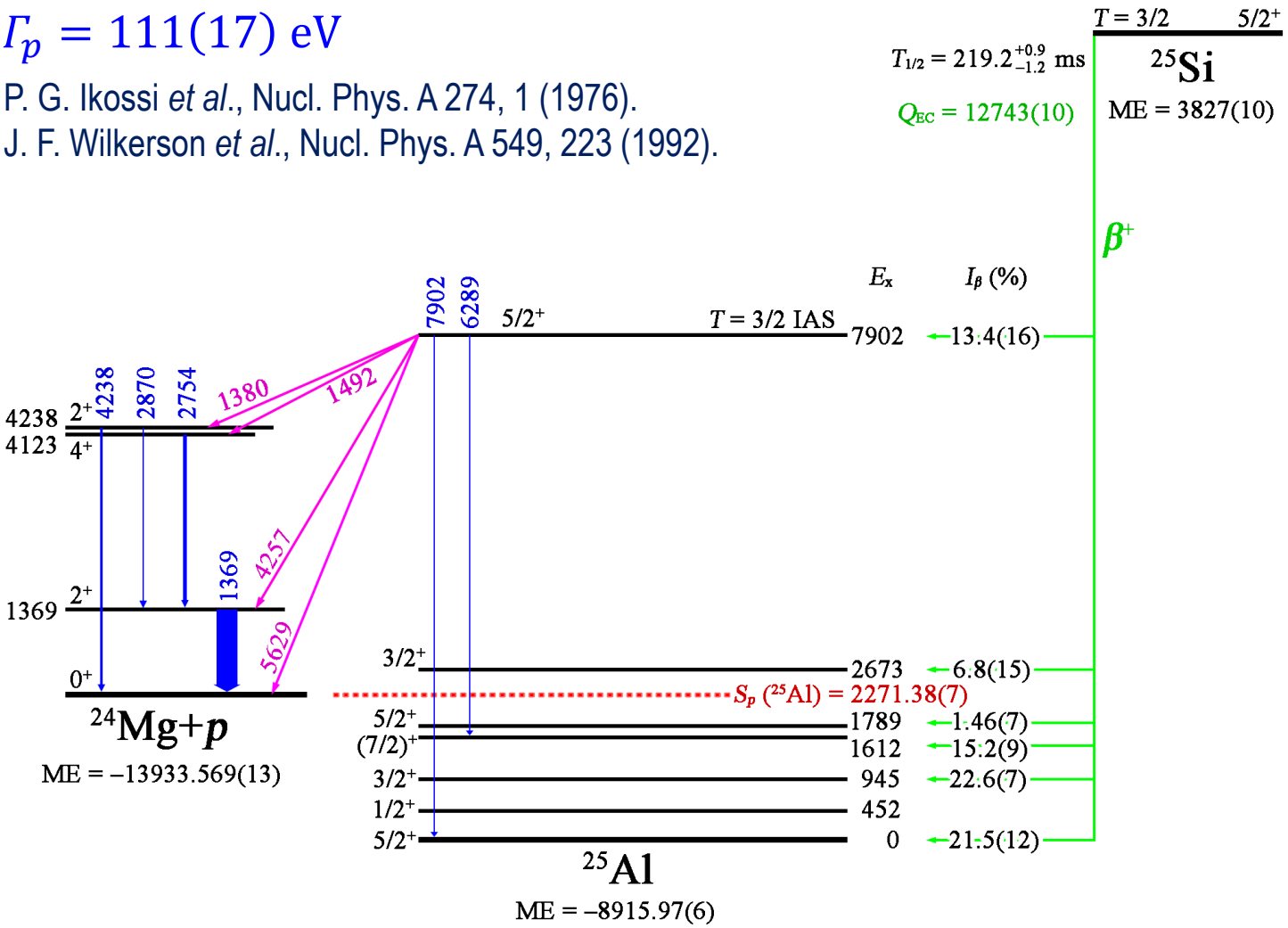
7902-keV $5/2^+$ $T = 3/2$ IAS in ^{25}Al



7902-keV $5/2^+$ $T = 3/2$ IAS in ^{25}Al

$\Gamma_p = 111(17)$ eV

P. G. Ikossi *et al.*, Nucl. Phys. A 274, 1 (1976).
J. F. Wilkerson *et al.*, Nucl. Phys. A 549, 223 (1992).



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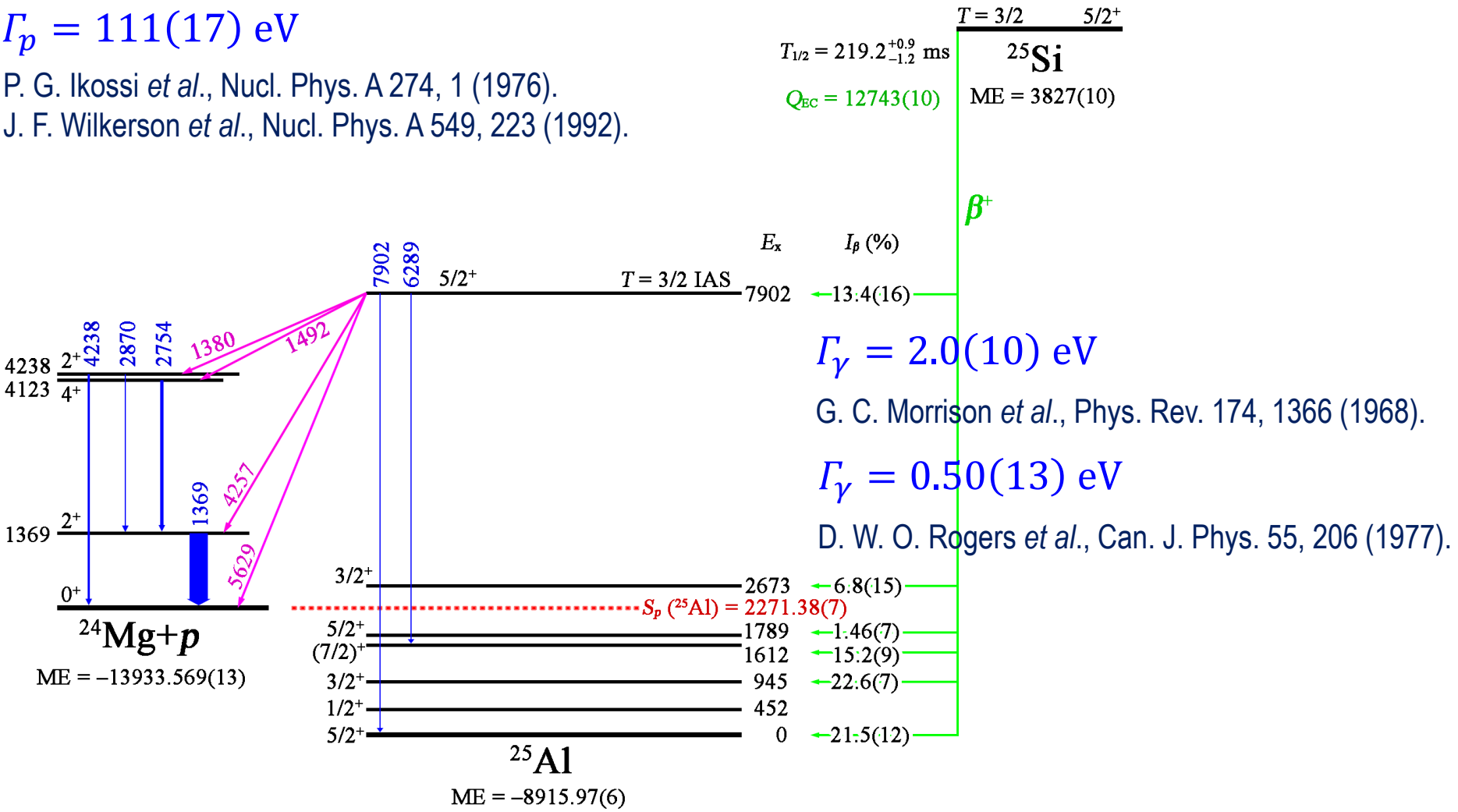


$\Gamma_\gamma = 2.0(10)$ eV

G. C. Morrison *et al.*, Phys. Rev. 174, 1366 (1968).

$\Gamma_\gamma = 0.50(13)$ eV

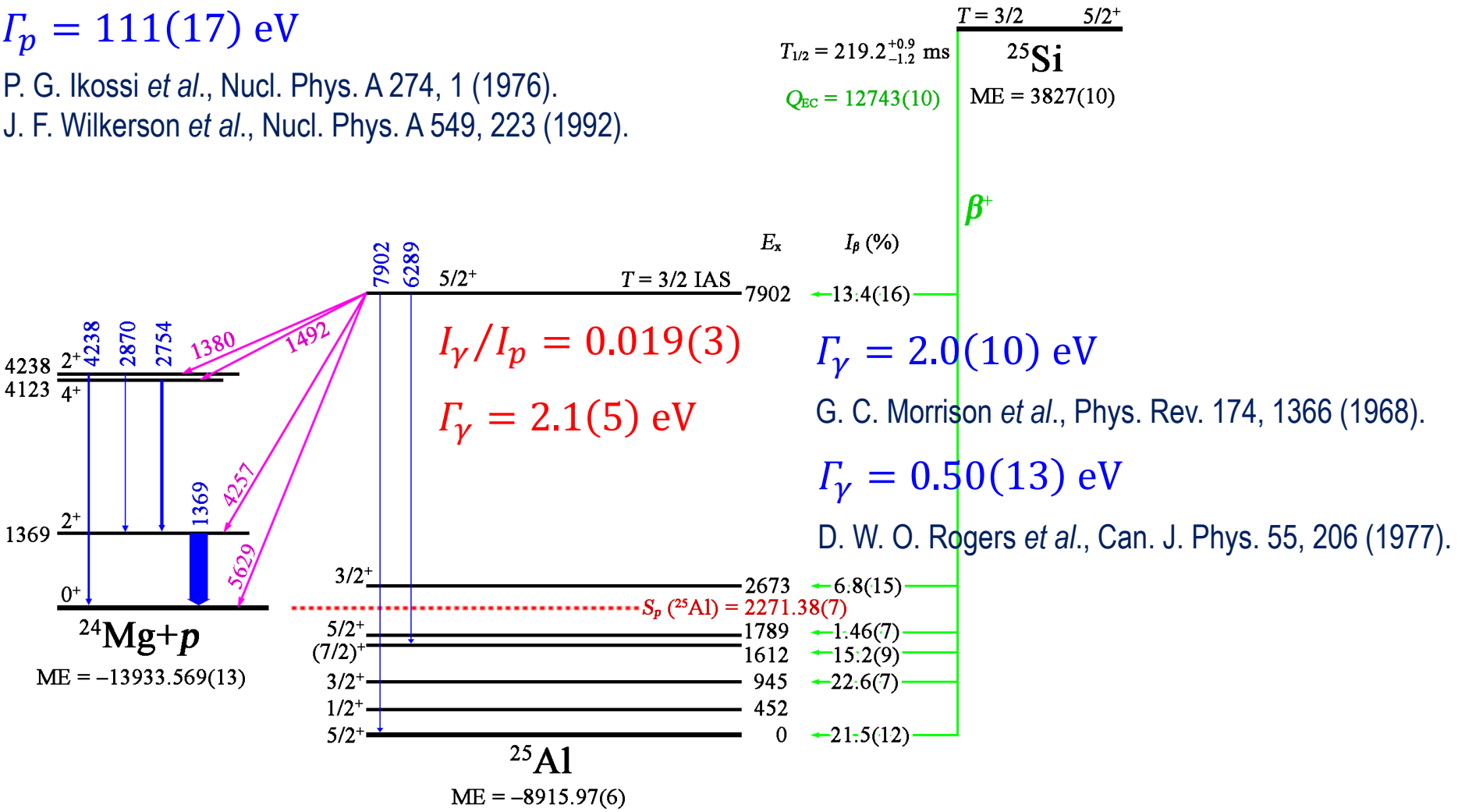
D. W. O. Rogers *et al.*, Can. J. Phys. 55, 206 (1977).

7902-keV $5/2^+$ $T = 3/2$ IAS in ^{25}Al

$\Gamma_p = 111(17)$ eV

P. G. Ikossi *et al.*, Nucl. Phys. A 274, 1 (1976).

J. F. Wilkerson *et al.*, Nucl. Phys. A 549, 223 (1992).



$I_\gamma / I_p = 0.019(3)$

$\Gamma_\gamma = 2.1(5)$ eV

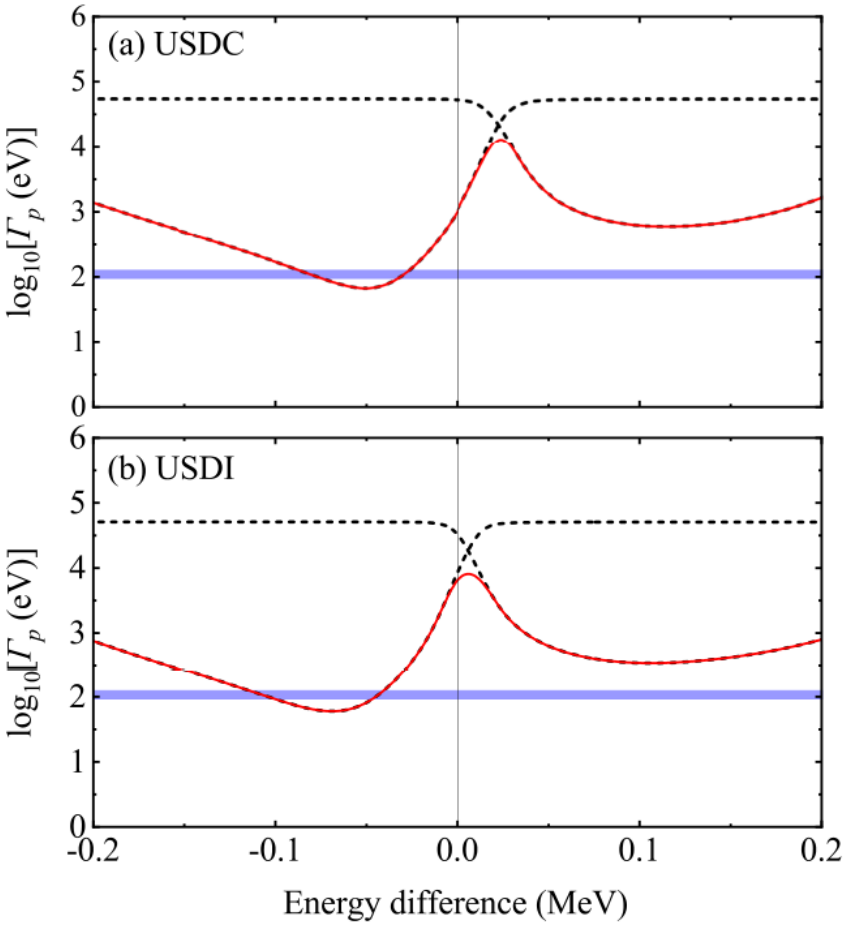
$\Gamma_\gamma = 2.0(10)$ eV

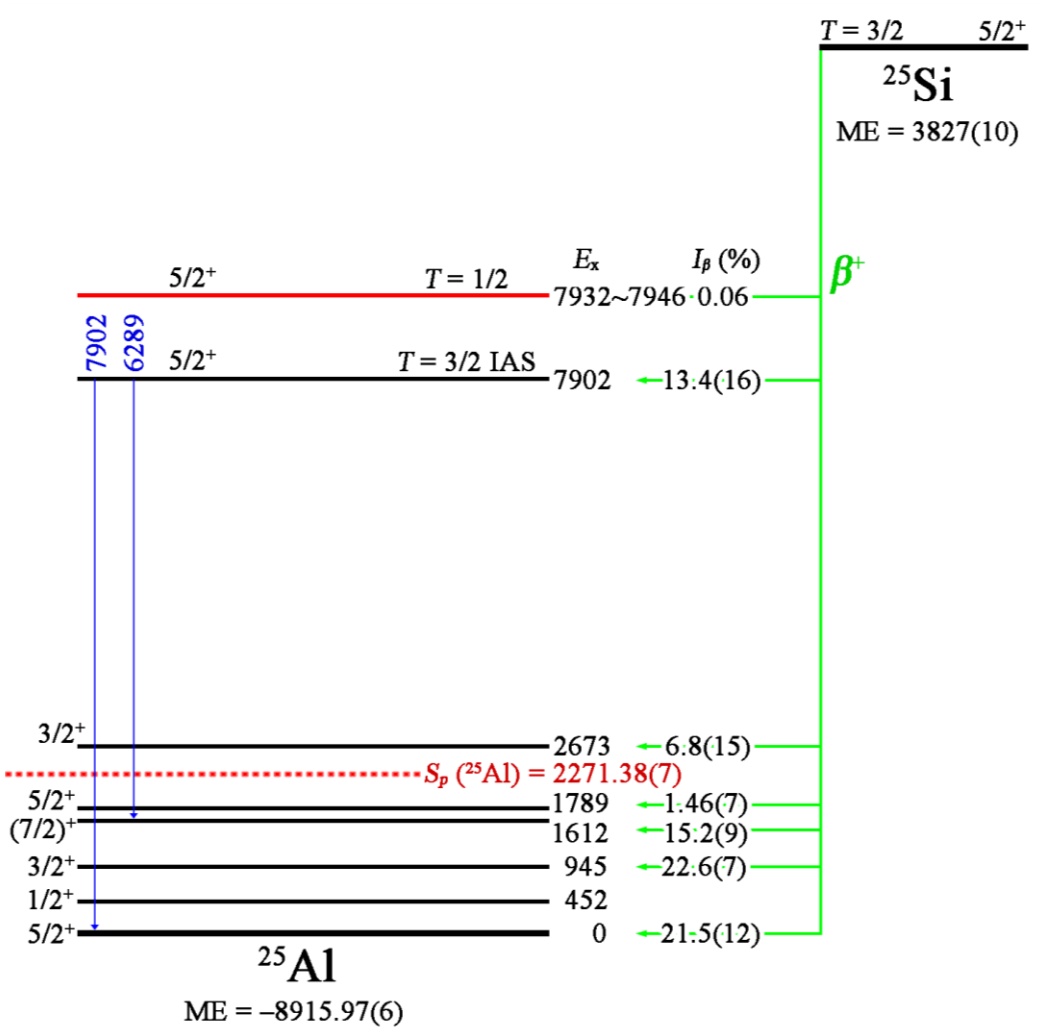
G. C. Morrison *et al.*, Phys. Rev. 174, 1366 (1968).

$\Gamma_\gamma = 0.50(13)$ eV

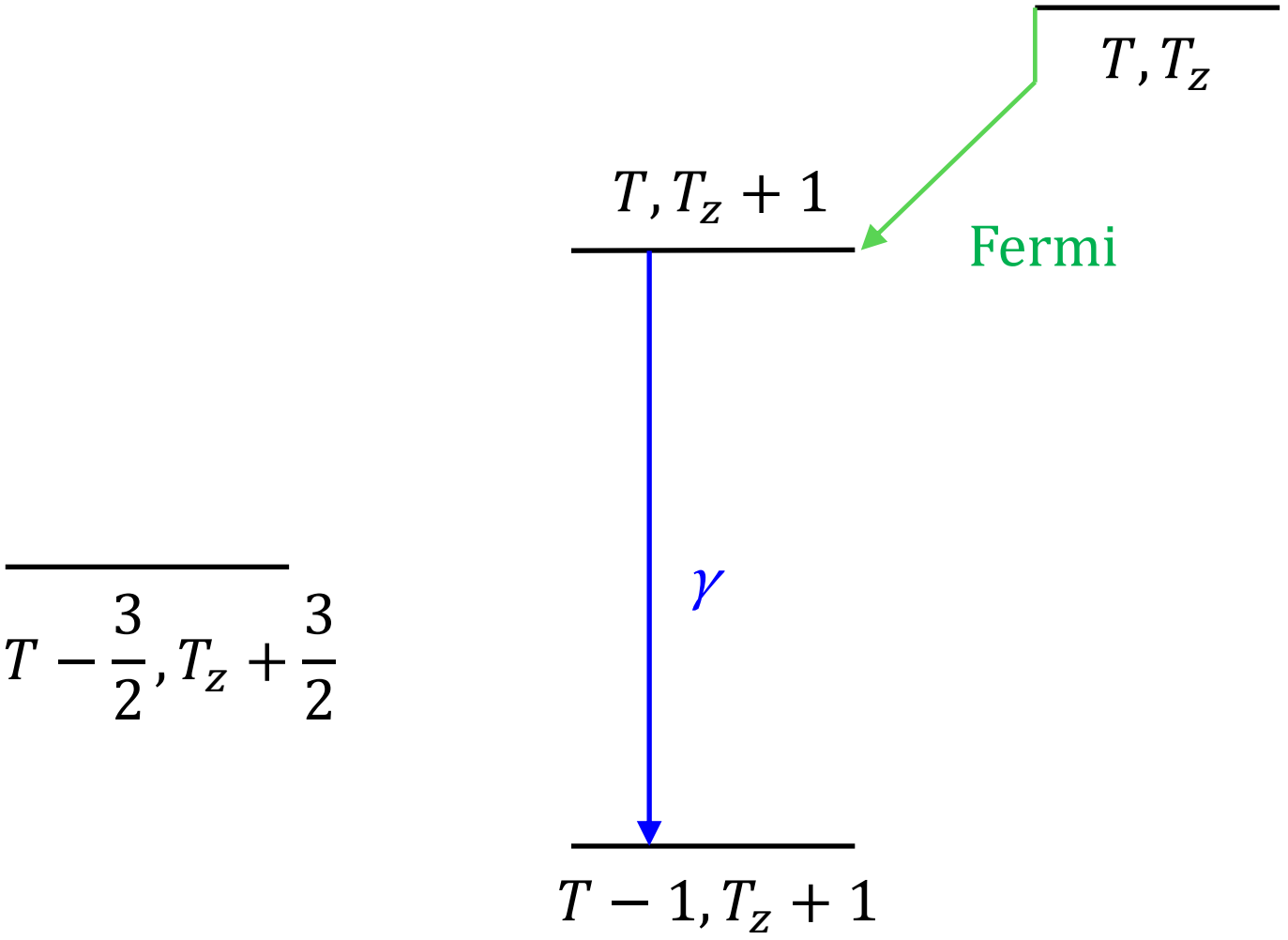
D. W. O. Rogers *et al.*, Can. J. Phys. 55, 206 (1977).

Isospin Mixing

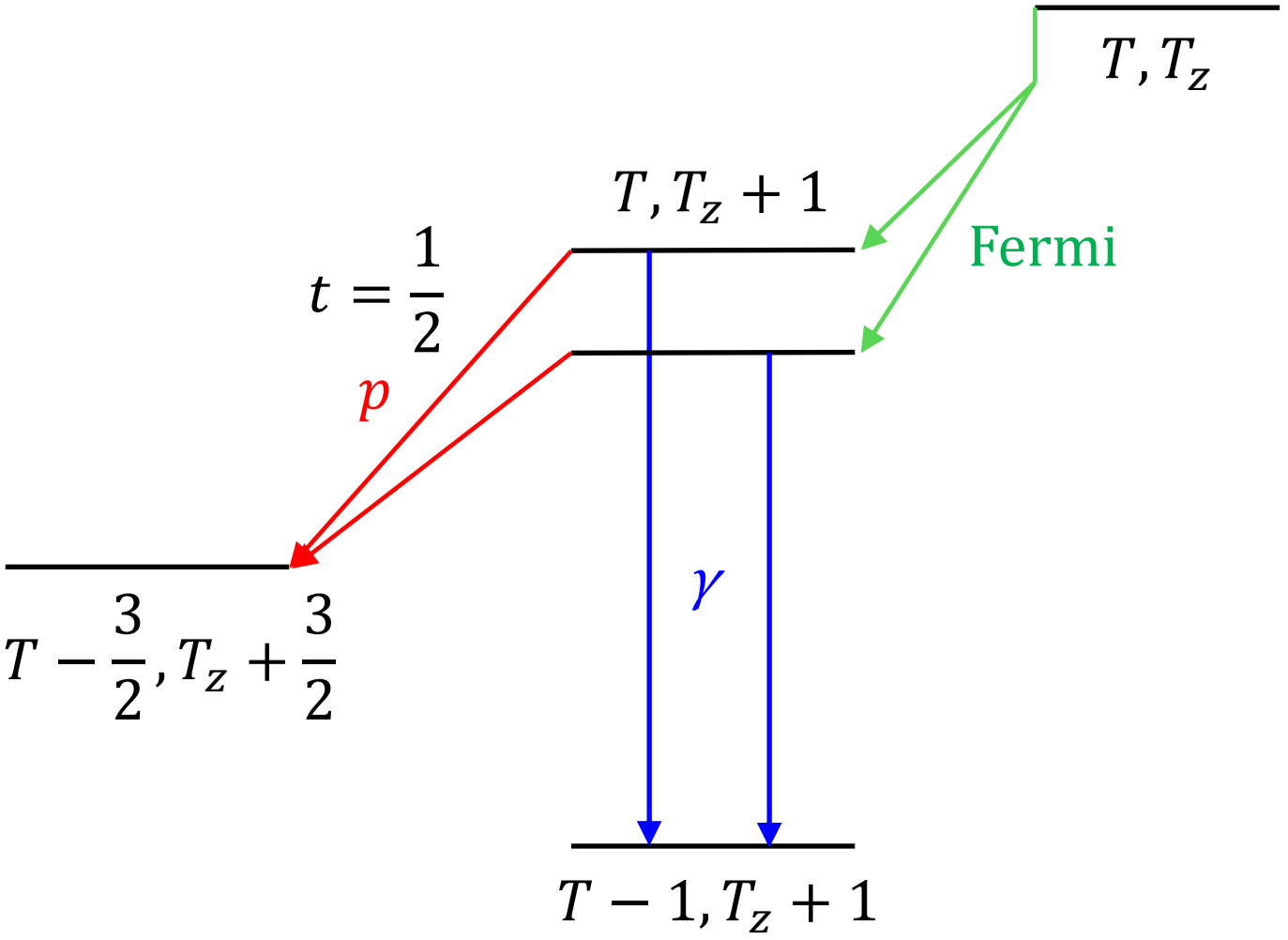




Isospin Conservation

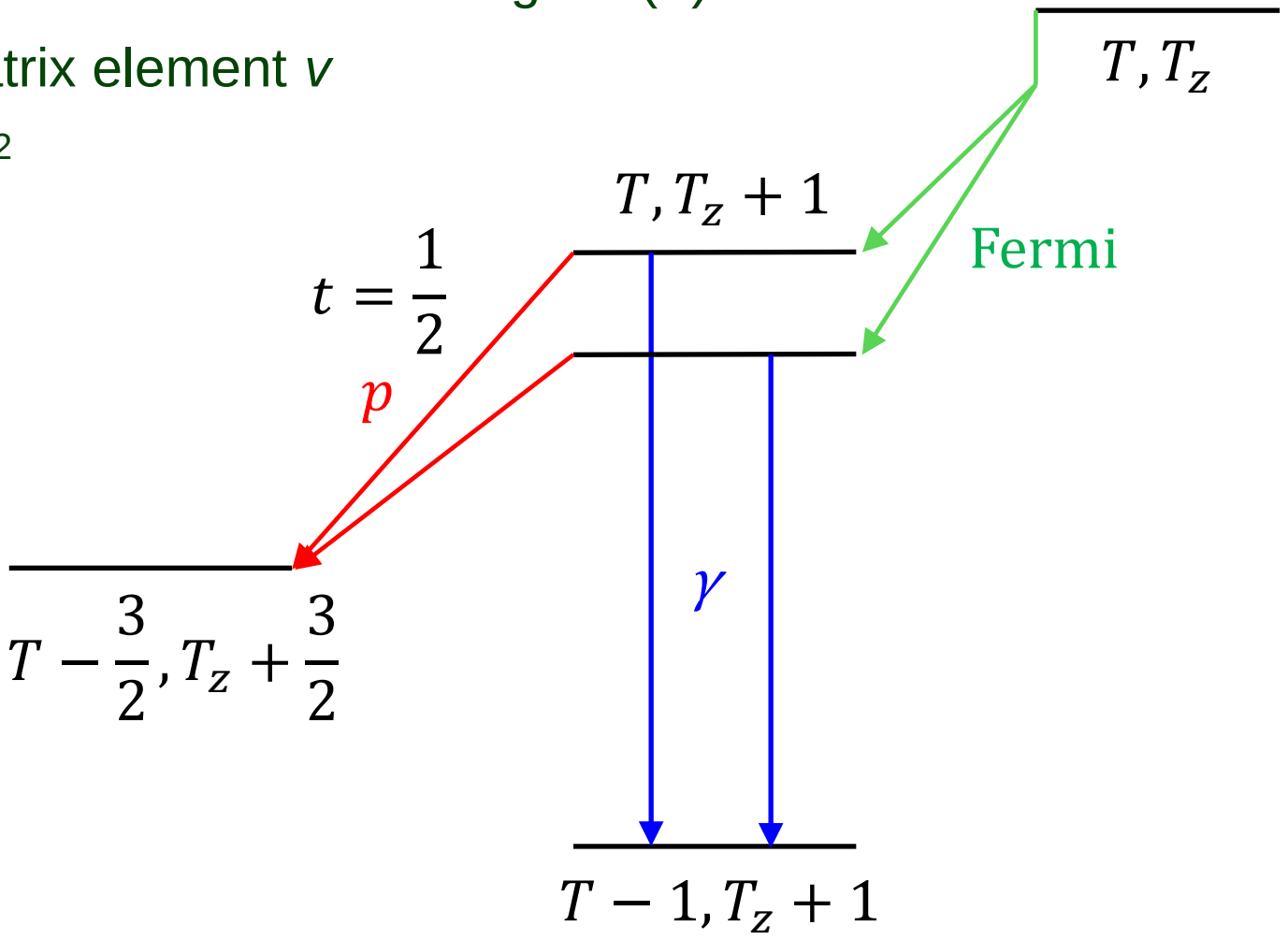


Isospin Mixing



Isospin Mixing

- Fragmentation of Fermi transition strength *B*(F)
- Isospin mixing matrix element *v*
- Isospin impurity α^2

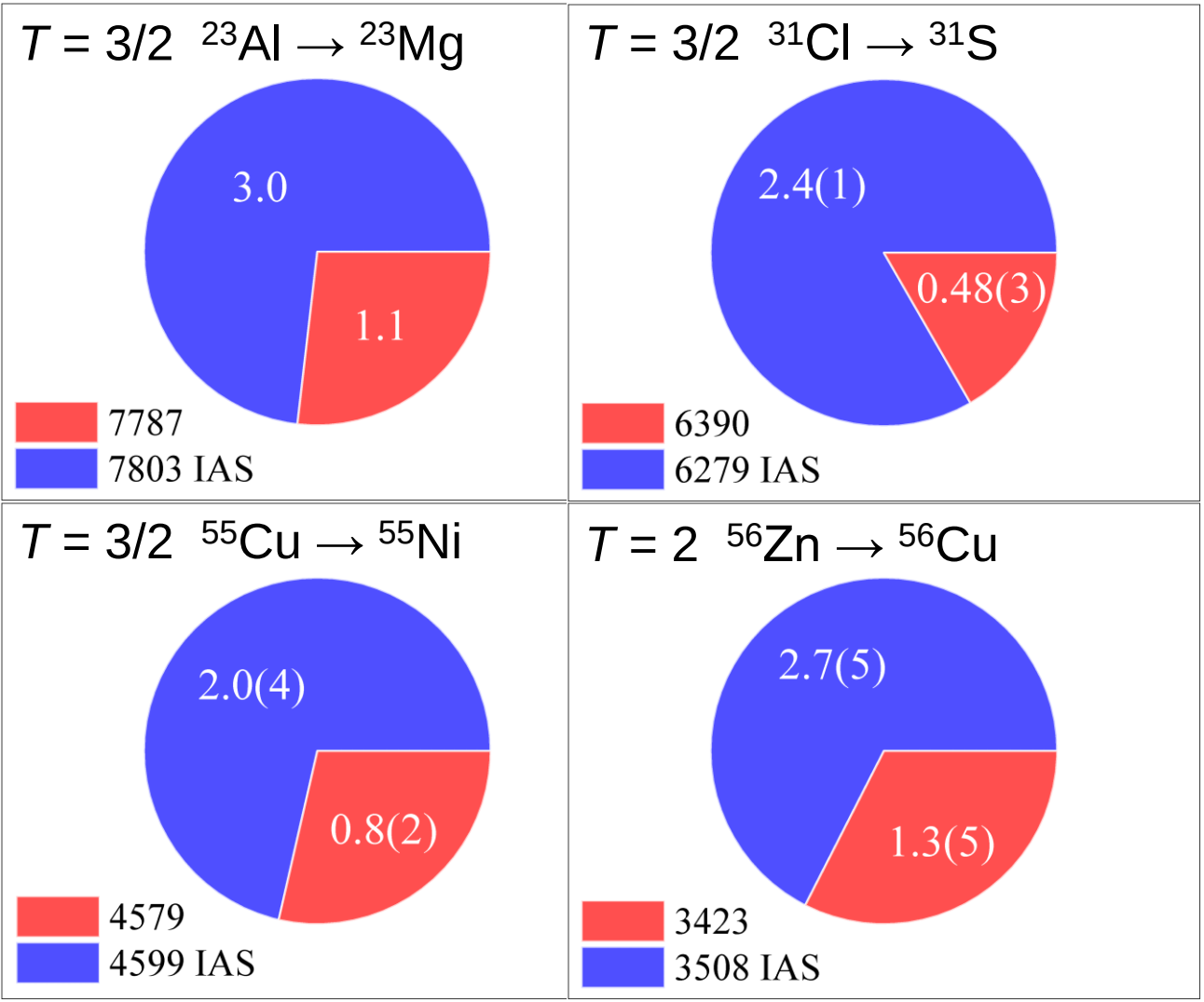


Isospin Mixing

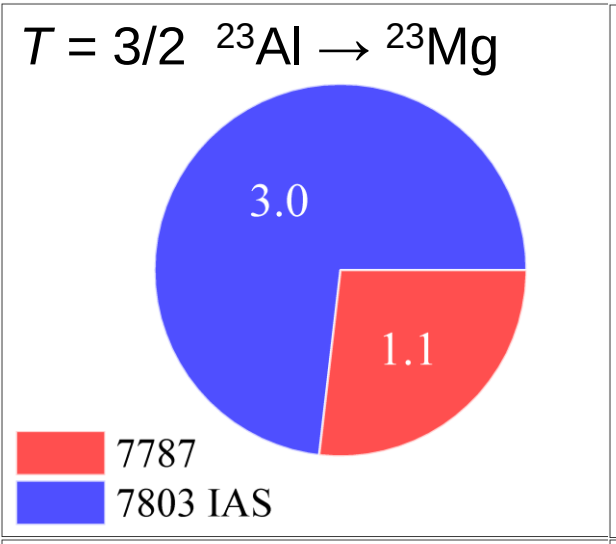
Decay	E_x (keV)	T	J^π	B	B(F)	B(GT)	$I_{\beta\gamma}$ (%)	$I_{\beta p}$ (%)	Γ_γ (eV)	Γ_p (eV)	V (keV)	α^2 (%)
^{23}Al → ^{23}Mg	**7803(2)**	3/2	5/2$^+$	3.0(2)			13.69(72)				7.0	26
S_p = 7580.7(7)	7787(2)	1/2	5/2$^+$			1.1(1)	3.95(37)	0.0257(17)				
^{31}Cl → ^{31}S	6390.2(7)	1/2	3/2$^+$	0.48(3)			3.38(18)				41(1)	17
S_p = 6130.64(24)	**6279.0(6)**	3/2	3/2$^+$	2.4(1)			18.7(11)	-				
^{53}Ni → ^{53}Co	4385(11)	1/2	7/2$^-$		0.00765		-	5.8(7)			3.0	0.26
S_p = 1615(7)	**4325(2)**	3/2	7/2$^-$	2.7(6)	2.98	0.12	50(11)	<0.9	0.36	0.033		
^{55}Cu → ^{55}Ni	**4599**	3/2	3/2$^-$	2.0(4)		0.3(1)	48(8)	-		-	9(1)	29
S_p = 4614.9(7)	4579	1/2	3/2$^-$	0.8(2)		0-0.2	19(4)	-		-		
^{56}Zn → ^{56}Cu	**3508(140)**	2	0$^+$	2.7(5)			19.2(50)	18.8(10)			40(23)	33(10)
S_p = 560(140)	3423(140)	1	0$^+$	1.3(5)		<0.32		21.2(10)				

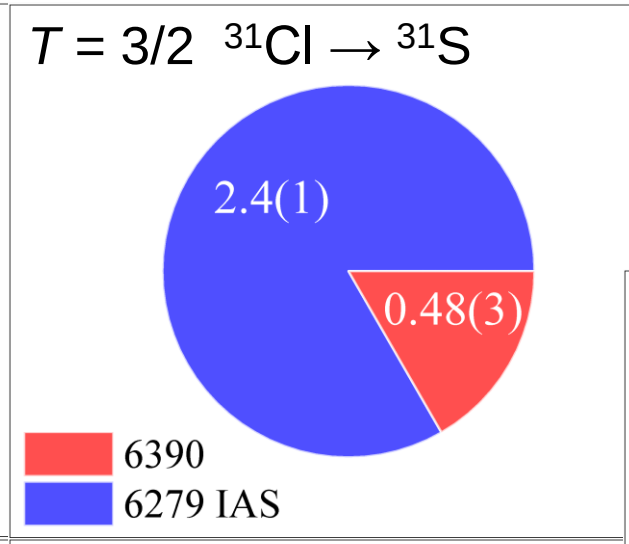
^{23}Al V. E. Iacob *et al*., Phys. Rev. C 74, 045810 (2006).
^{31}Cl M. B. Bennett *et al*., Phys. Rev. Lett. 116, 102502 (2016).
^{53}Ni J. Su *et al*., Phys. Lett. B 756, 323 (2016).
^{55}Cu V. Tripathi *et al*., Phys. Rev. Lett. 111, 262501 (2013).
^{56}Zn S. E. A. Orrigo *et al*., Phys, Rev, Lett. 112, 222501 (2014).

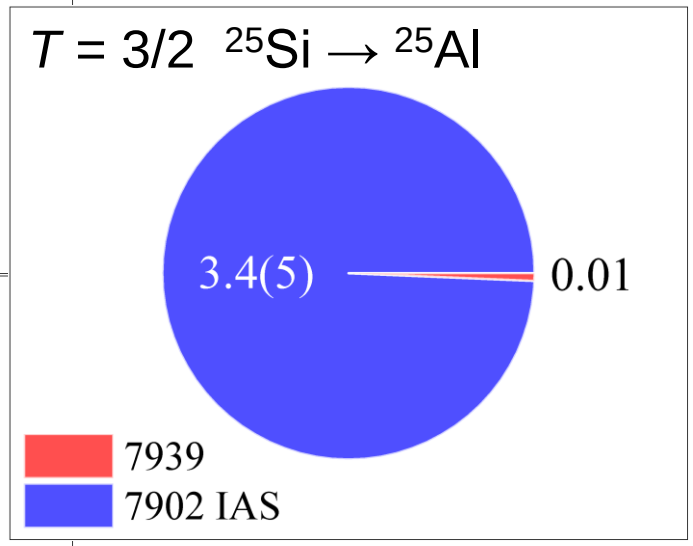
Fragmentation of the *B*(F)

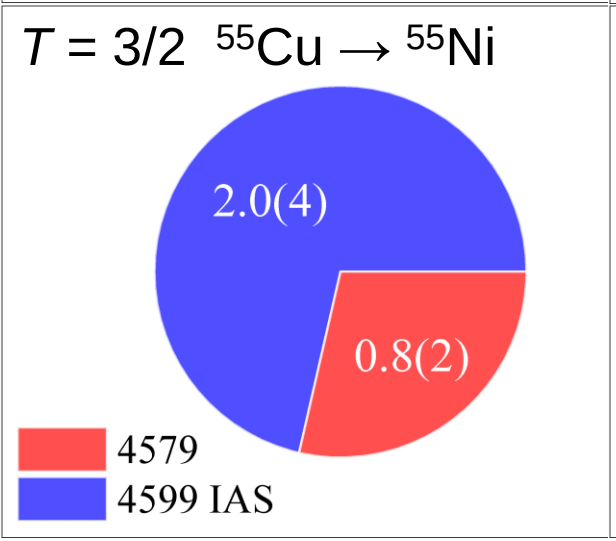


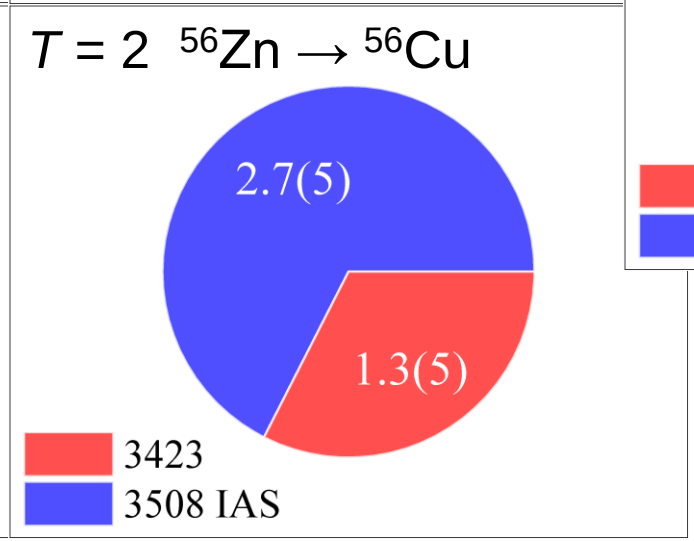
Fragmentation of the *B*(F)



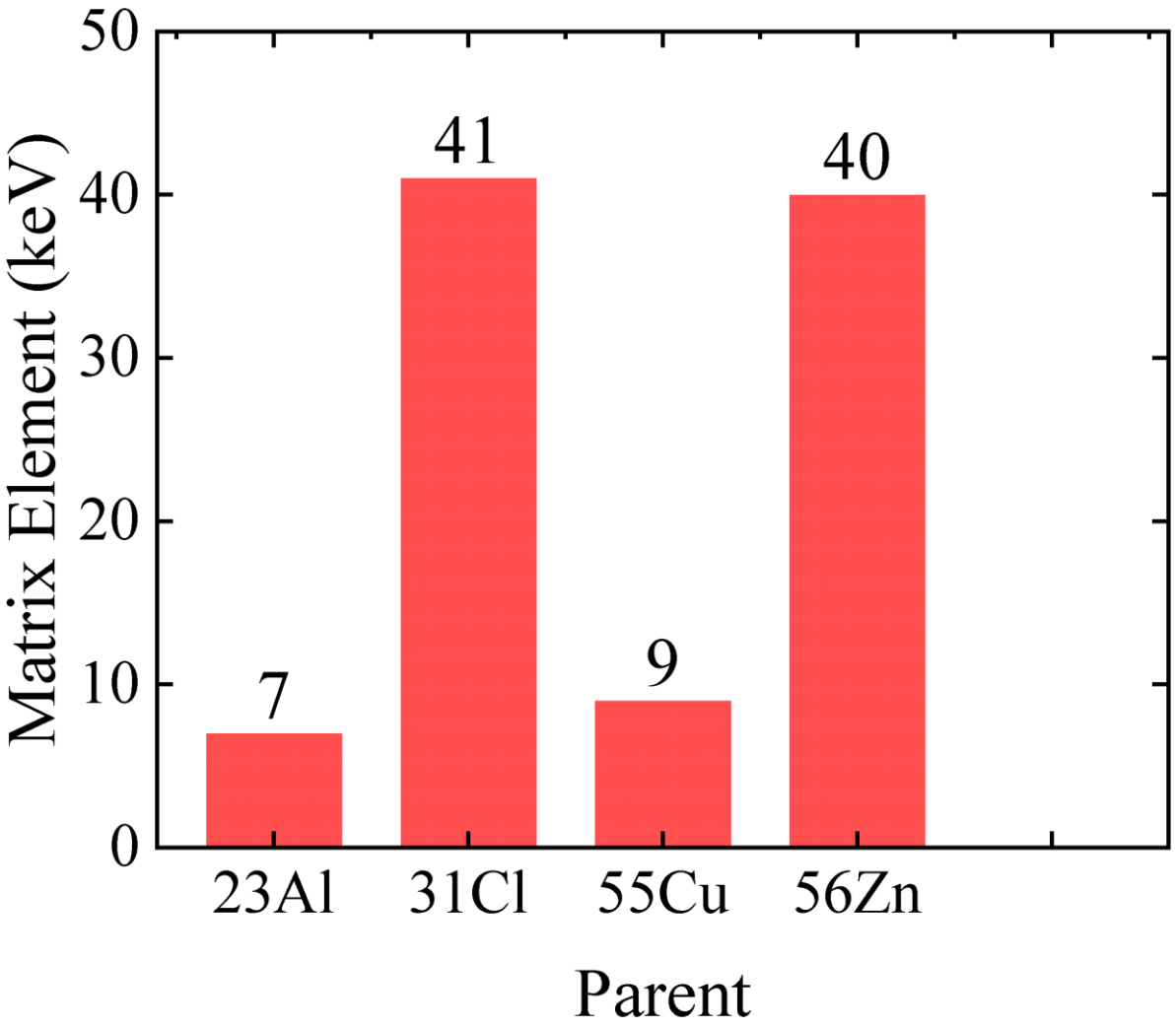




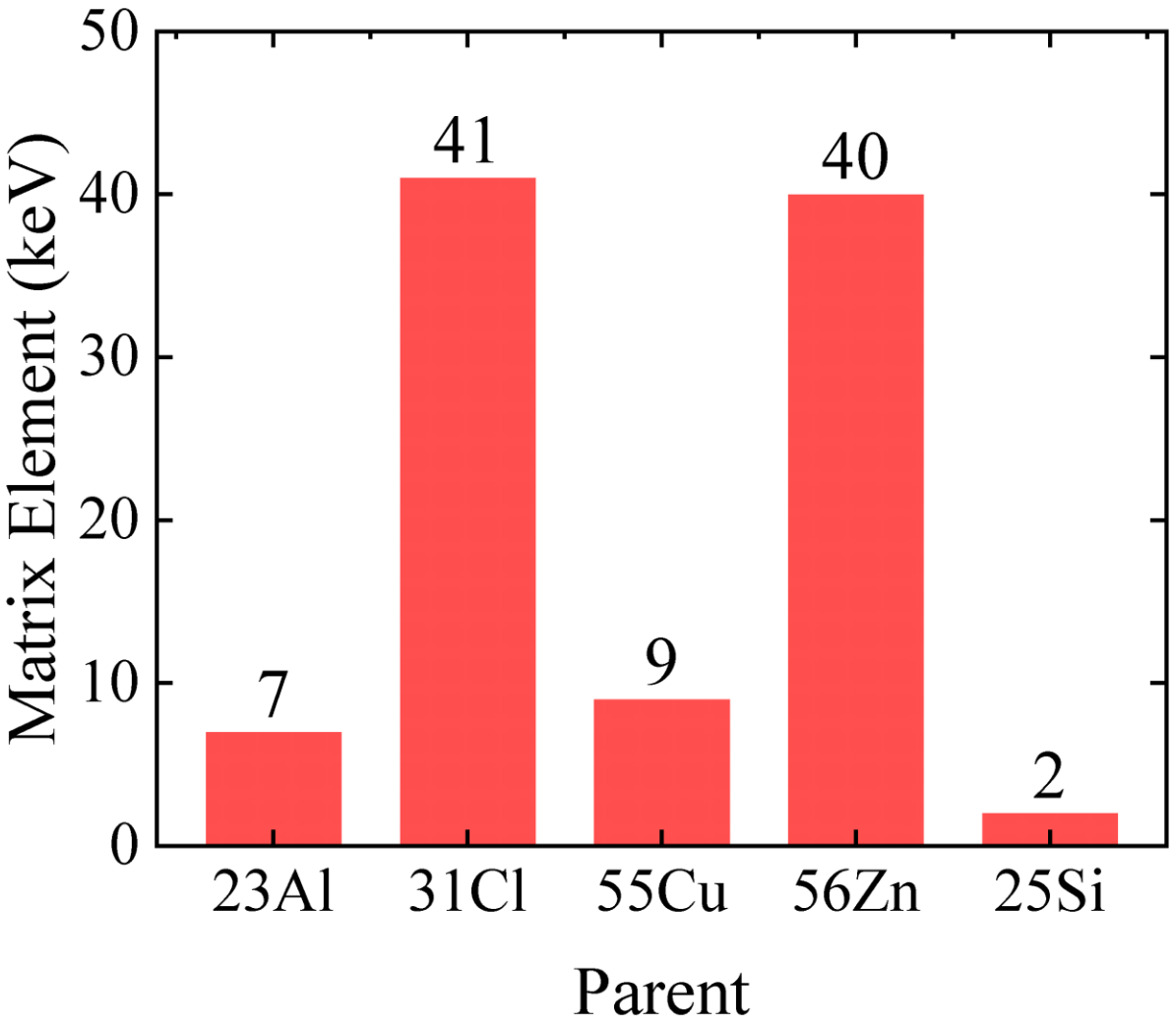




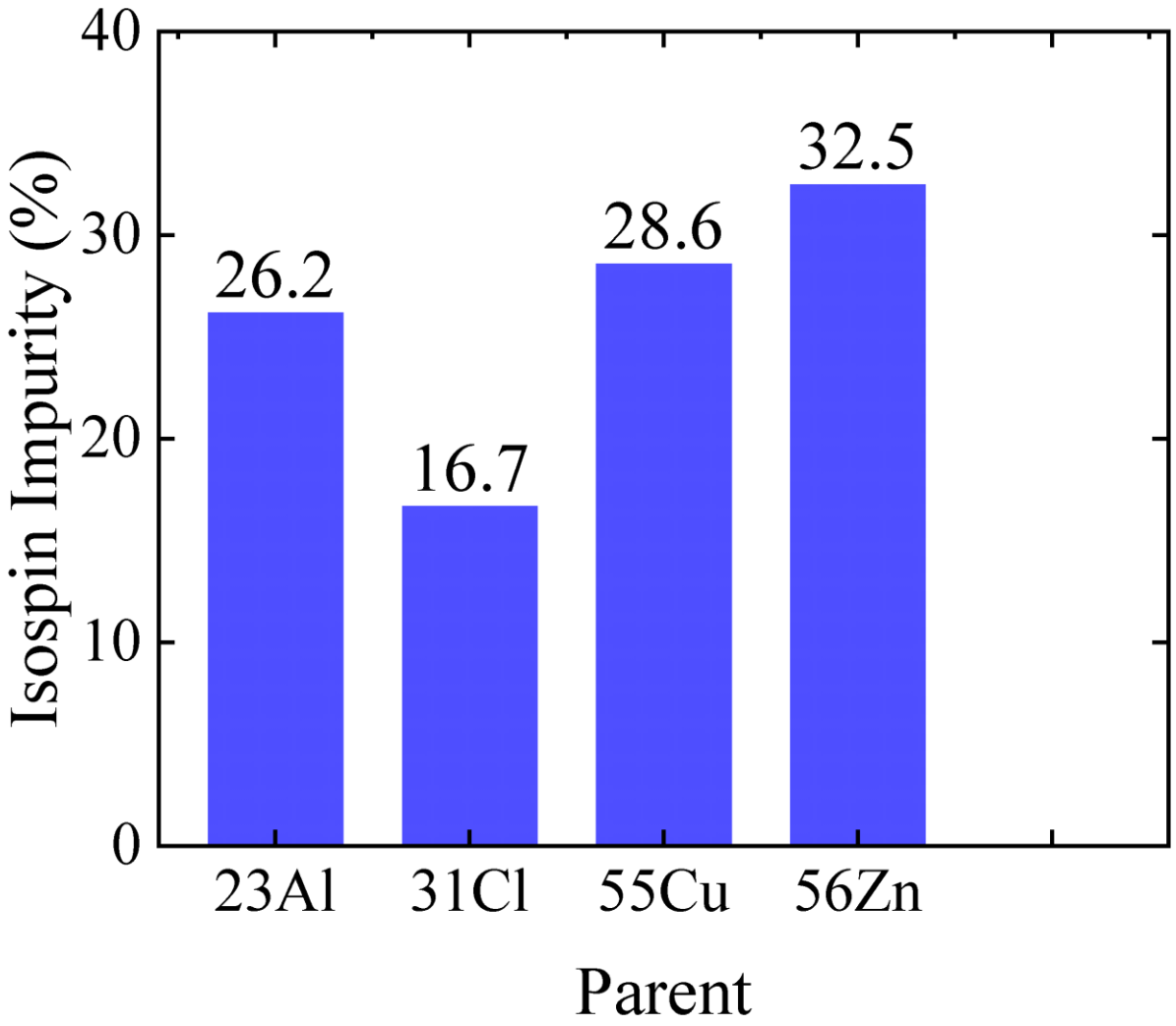
Isospin Mixing Matrix Element



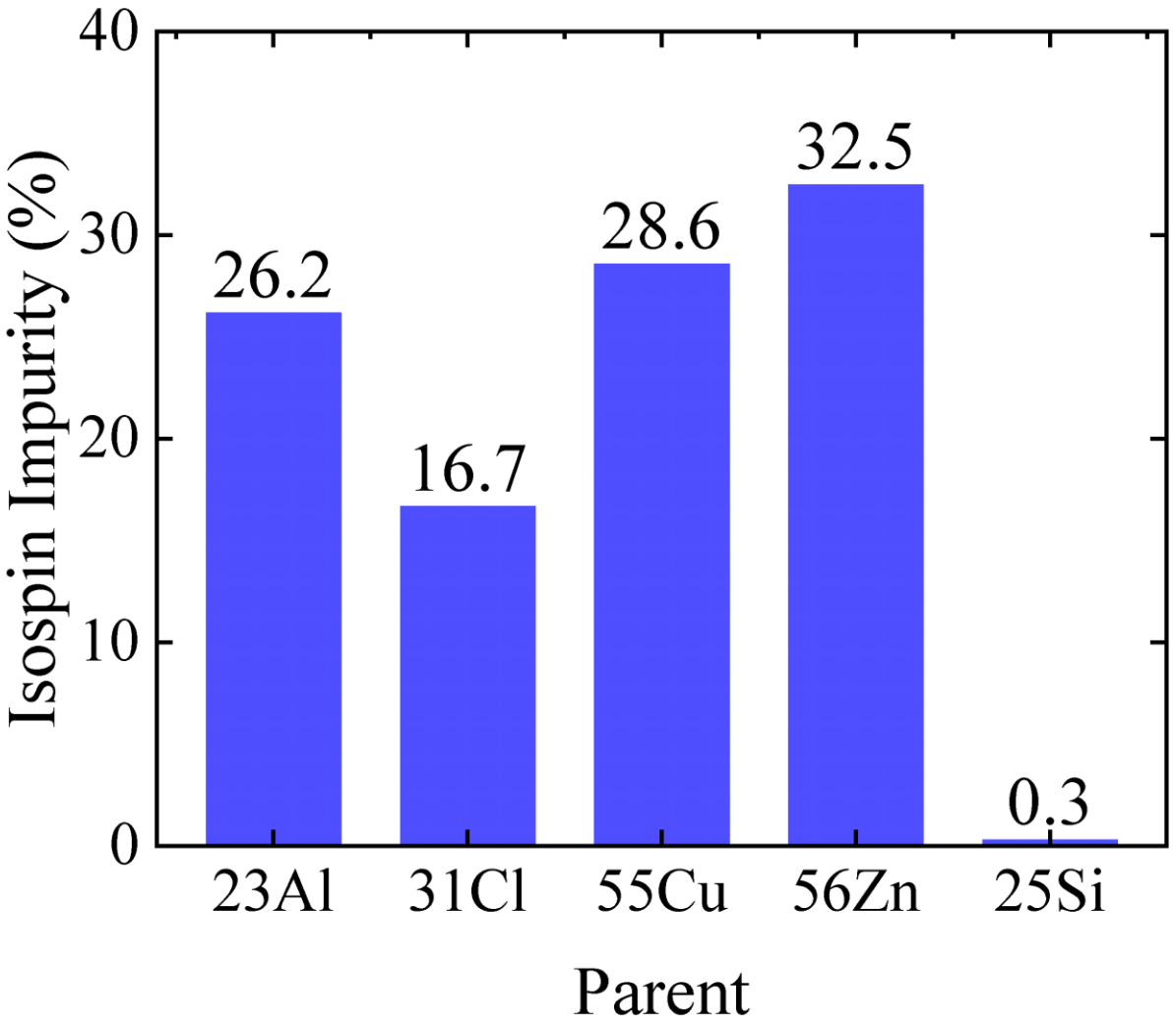
Isospin Mixing Matrix Element



Isospin Impurity



Isospin Impurity



Summary

- A fruitful decay spectroscopy
  - The most precise ^{25}Si half-life to date is obtained.
  - A total of 14 β-delayed proton branches, including a new proton branch at 724(4) keV are identified.
  - Three ^{24}Mg γ-ray lines and eight ^{25}Al γ-ray lines are observed for the first time in ^{25}Si decay.
  - New proton-γ-ray coincidences are observed.
  - Doppler-broadening line shape analysis is conducted.
  - Mirror symmetry is confirmed.
  - Isospin mixing is investigated.

- The results are in excellent agreement with theoretical nuclear structure calculations and enhance the utility of ^{25}Si as a calibration standard for future experiments.

Acknowledgement

^{25}Si β^+-decay spectroscopy

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A. Kruskie[1,4], A. Magilligan[1,4], M. Roosa[1,4], J. Stomps[1,4], J. Surbrook[1,4], and P. Tiwari[1,4]

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Thank you for your attention!