Shell-model description for beta decays of pfg-shell nuclei

Workshop on
New Era of Nuclear Physics in the Cosmos
– the r-process nucleosynthesis
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Introduction

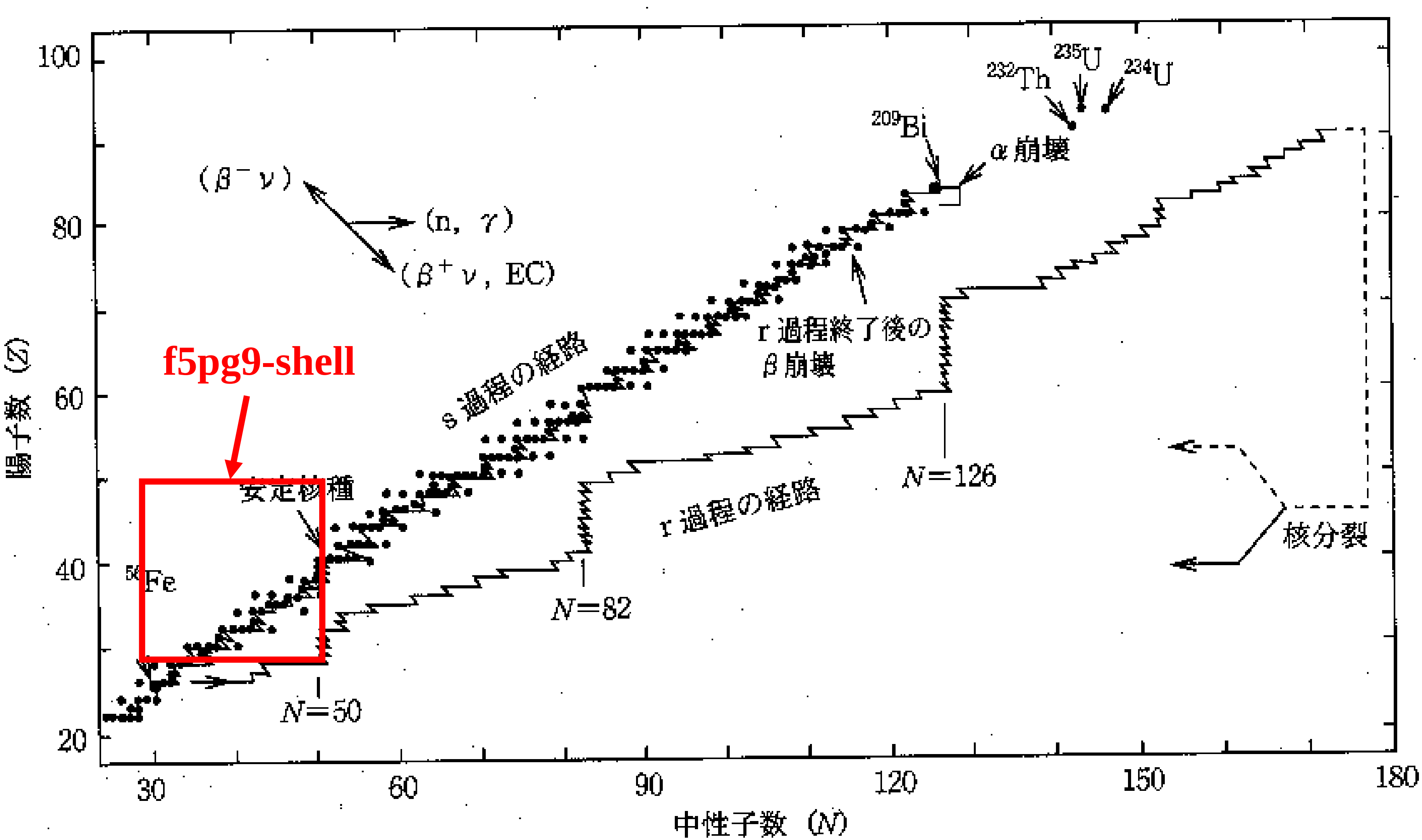
- Precise information of nuclear properties is needed for the analysis of the r-process nucleosynthesis which occur under extreme conditions which are not accessible by current experiments. Therefore, theoretical estimations are useful, and predictions with high accuracy are desired.

- Nuclear structure models based on the mean-field approximation such as RPA are widely used, which are applicable to any nuclei in the nuclear chart by taking sufficiently large model space and provide us reasonable description of gross properties. However, the results are not necessarily accurate because only limited correlations can be treated.

- The shell model can treat any two-body correlations and give accurate descriptions of nuclear structure, but its applicability is limited to relatively light nuclei or semi-magic nuclei because of too heavy numerical tasks. We have to take a small model space and introduce an effective interaction.

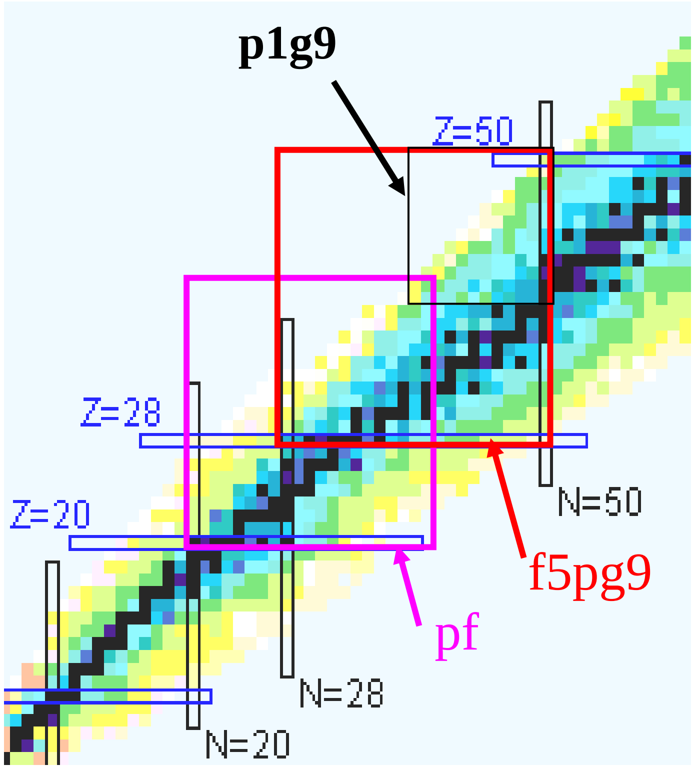
- To what extent can shell model predict nuclear properties which are important for the study of the r-process?

shell model for r-processes



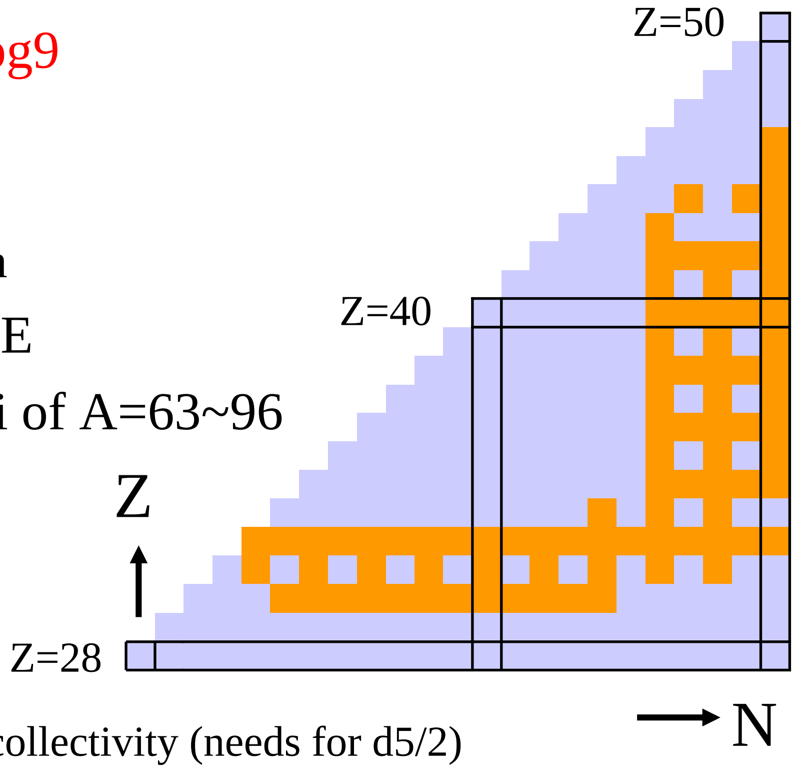
f5pg9-shell

- f5pg9-shell
  - ^{56}Ni inert core
  - Valence orbits : $p_{3/2}$, $f_{5/2}$, $p_{1/2}$, $g_{9/2}$
  - No spurious center-of-mass motion
- Interests
  - Neutron-rich
  - Isomer
  - Shape-coexistence
  - Astorophysics
- Recent shell-model studies
  - S3V… J.Sinatkas, et al., J. Phys. G18, 1377; 1401 (1992)
    - Second order correction to the Sussex matrix elements
    - N=50,49,48 with severe truncation (weak coupling assumption)
  - Lisetskiy… A.F.Lisetskiy et al., PRC70, 044314 (2004)
    - Modify G-matrix interaction by least squares fit
    - T=1 part for proton and neutron (Ni isotopes and N=50 isotones)



Effective interaction

- JUN45 interaction
  - Keep isospin symmetry
  - Modify microscopic interaction G-f5pg9
    M. Hjorth-Jensen, unpublished
    Bonn-C potential
    3rd order Q-box and folded diagram
  - Vary 45 LC's of 133 TBME and 4 SPE
  - Fit to 400 energy data out of 87 nuclei of A=63~96
    - Include low-lying states of
      - even-Z nuclei
      - odd-A nuclei
    - Exclude
      - N<46 for Z>33… large quadrupole collectivity (needs for d5/2)
      - Ni, Cu isotopes … large effects of f7/2 core-excitations
  - Assume $A^{-0.3}$ mass dependence
  - Rms error of 185 keV

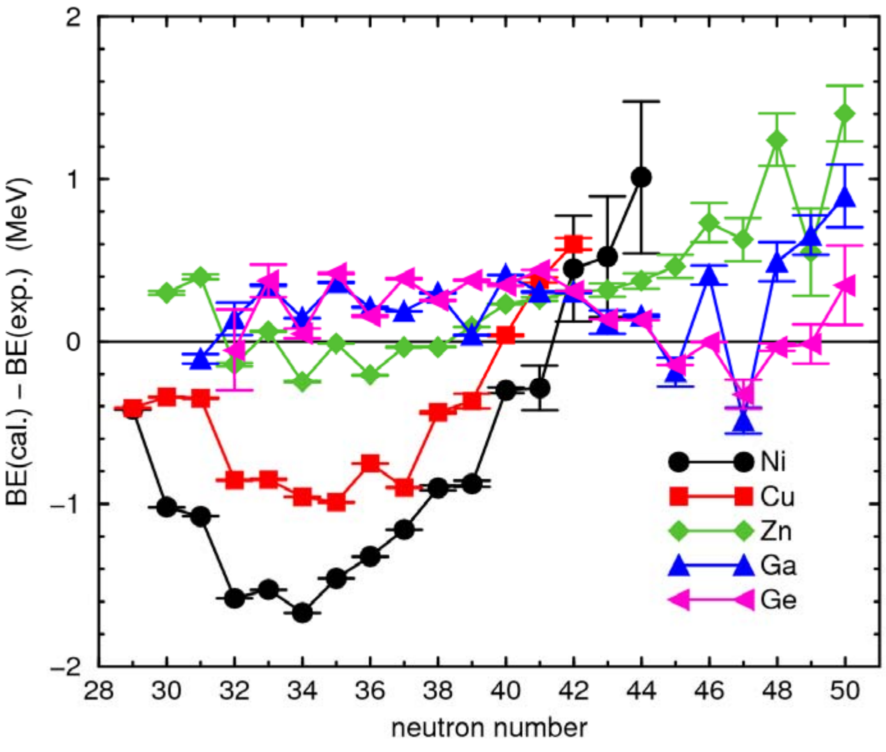


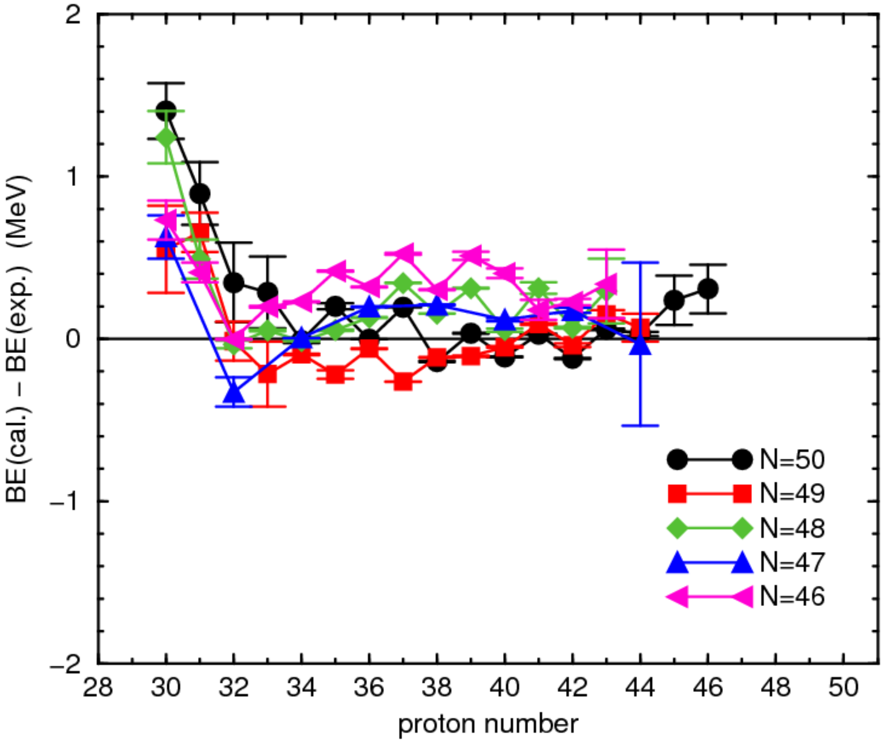
Binding energy

- Empirical Coulomb energy   B.J.Cole, PRC59(1999)726

$$E_C(\pi,\nu) = \varepsilon_C \pi + V_C \frac{\pi(\pi-1)}{2} + b_C[\frac{1}{2}\pi] - \Delta_{\pi\nu}\pi\nu \qquad \pi,\nu \cdots \text{valence nucleon \#}$$

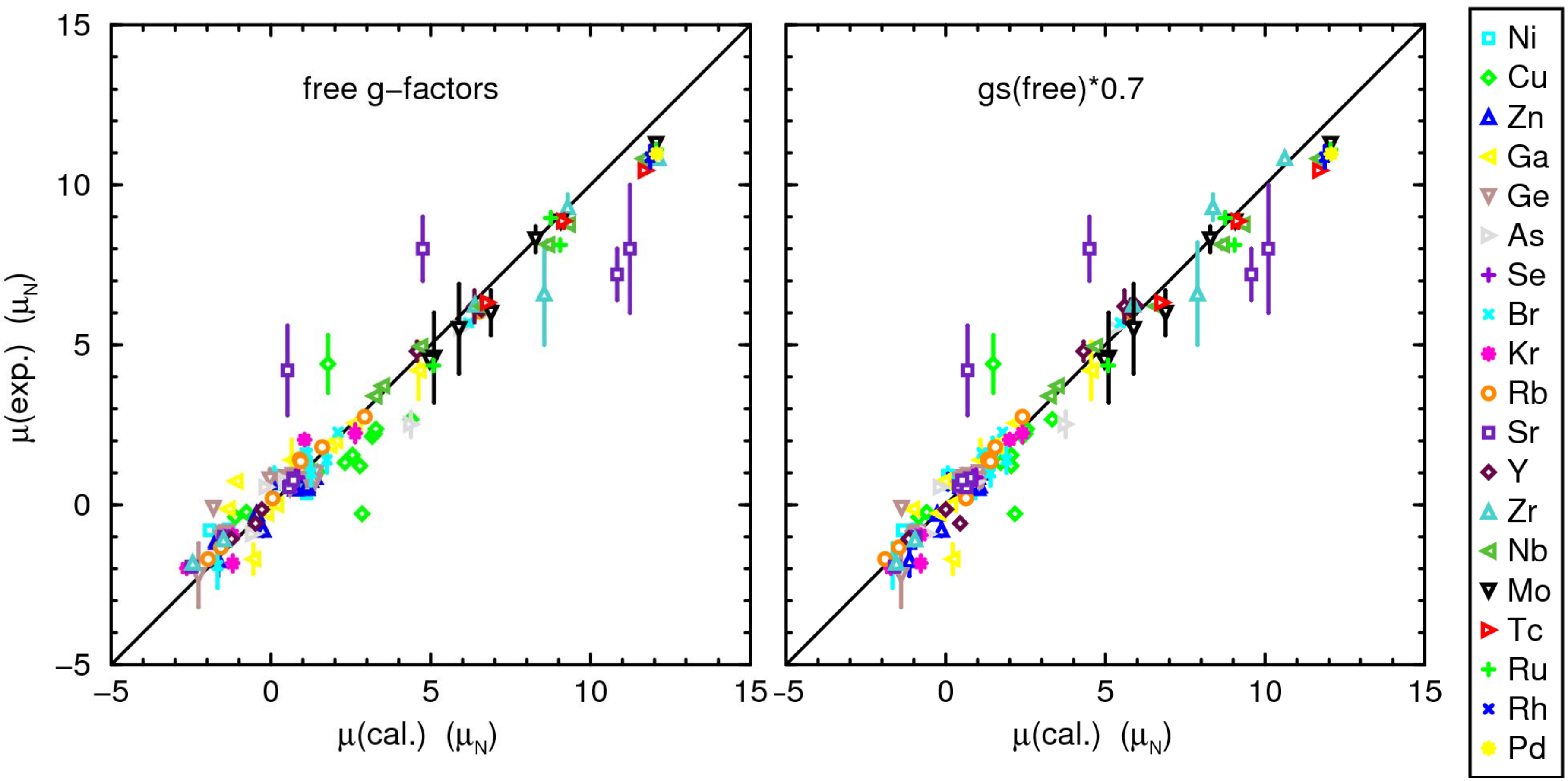
- f7/2 effects ?
  - Underbinding in Ni, Cu with N<40
  - Overbinding in neutron-rich Ni, Cu, Zn, Ga





Magnetic moments

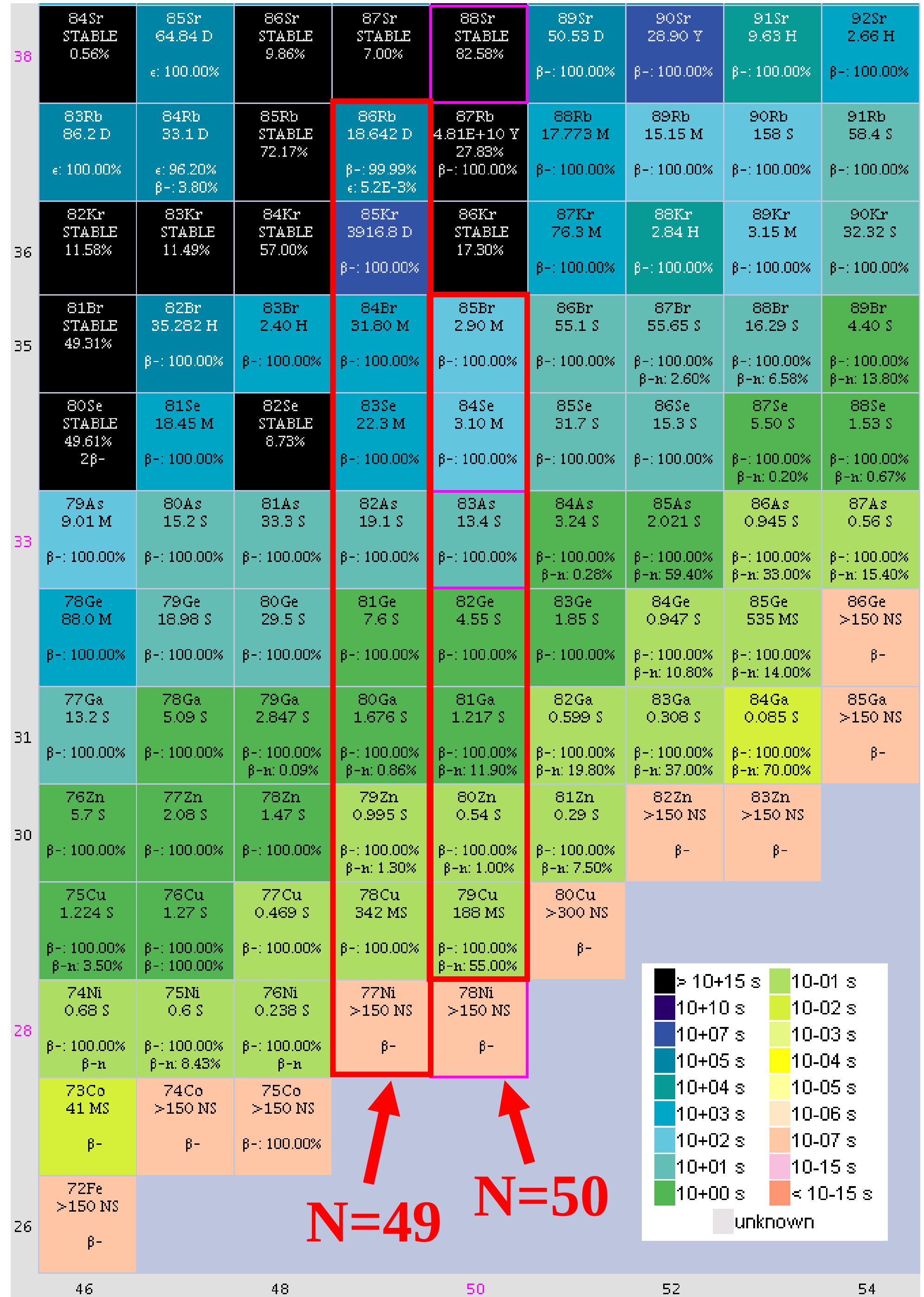
- Effective spin g-factors
  - Free-nucleon values are already good (also for sd- and pf-shell)
  - Slight improvement by effective $g_s(\text{eff})/g_s(\text{free}) \sim 0.7$
  - Note: ~0.85 … GXPF1 for pf-shell



β^- decay

- $Q_{\beta-}$ and $T_{1/2}$
- N=50
  - Waiting point
  - T=1 TBME contributes
  - ^{78}Ni … No valence particles/holes
- N=49
  - Low-lying isomer

NNDC Chart of Nucleids
http://www.nndc.bnl.gov/chart/

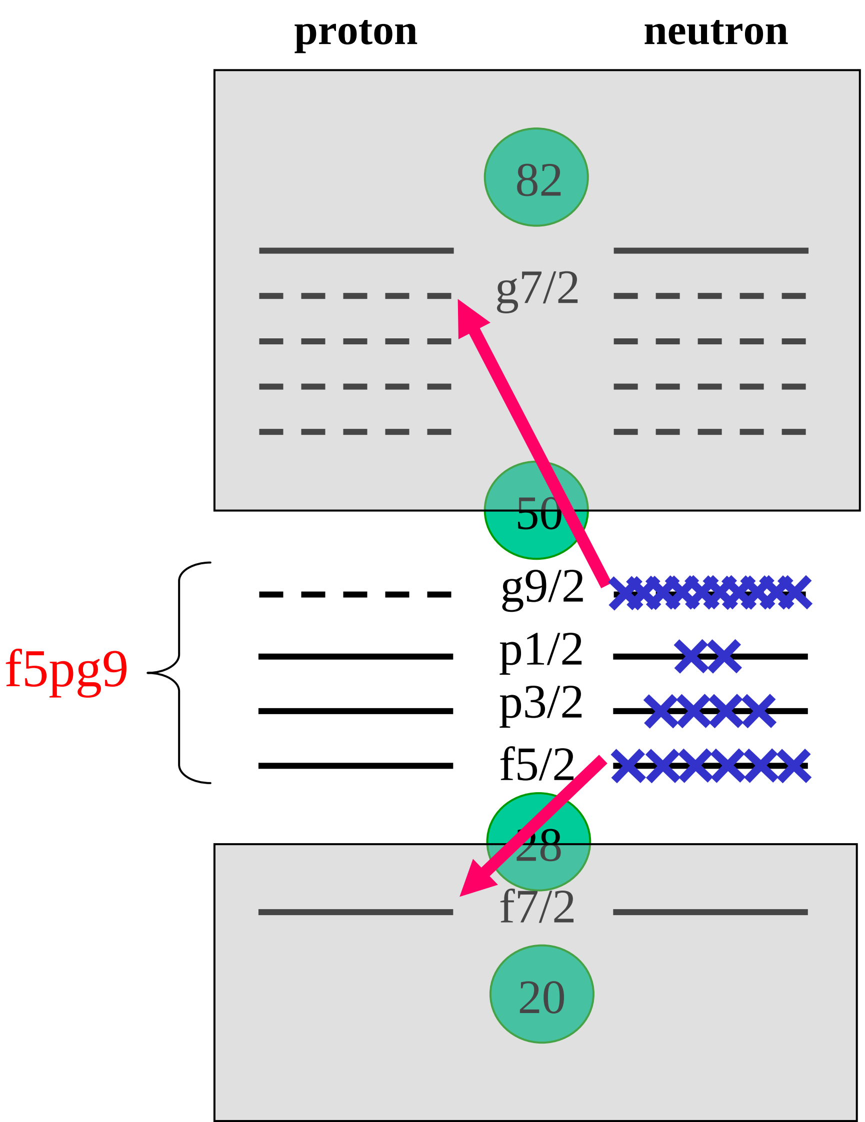


Neutron-rich nuclei

- f5pg9-shell
  Spin-flip decay
  $\nu g9/2 \rightarrow \pi g7/2$
  $\nu f5/2 \rightarrow \pi f7/2$
  are out of the model space

- Large Q-value
  Higher excited states may be important

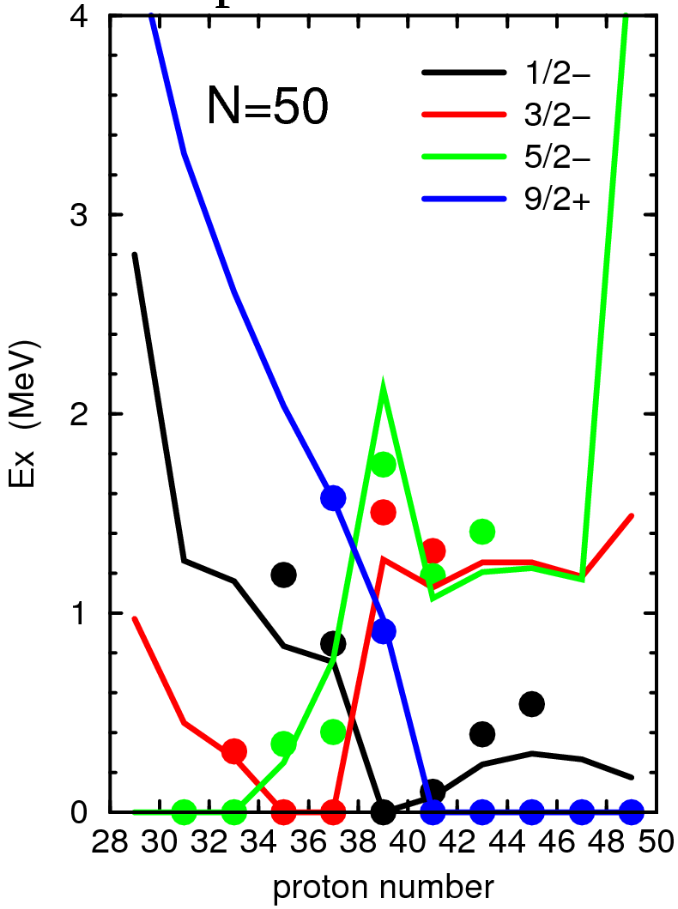
- Phase space factor
  Low-lying states mainly contribute to $T_{1/2}$



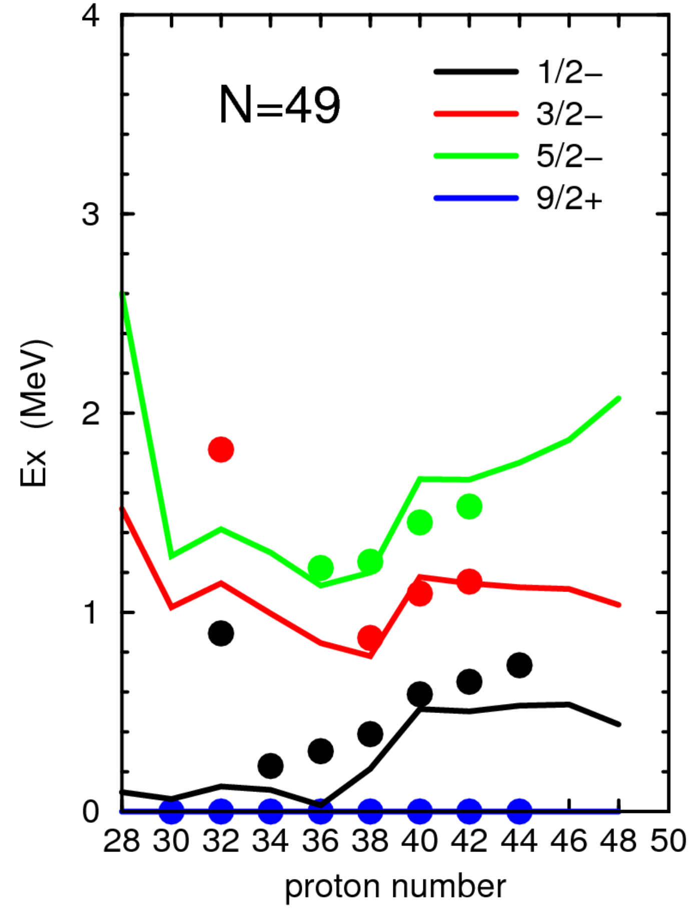
Single-particle levels around N=50

- Low-lying states in odd-A nuclei

proton orbits



neutron orbits



β-decay

- Q-value
  - β– (A, Z)→(A, Z+1) + e⁻ + $\bar{\nu}_e$ $Q = ({}^{A}_{Z}M - {}^{A}_{Z+1}M)c^2$
  - β+ (A, Z) →(A, Z–1) + e⁺ + νe $Q = ({}^{A}_{Z}M - {}^{A}_{Z-1}M)c^2 - 2mc^2$
  - EC (A, Z) + e⁻ → (A, Z–1) + νe $Q = ({}^{A}_{Z}M - {}^{A}_{Z-1}M)c^2 - E_K$
- Allowed transition matrix elements
  - Fermi

$$B(F) = \frac{\left|\left\langle f \left\| \Sigma_k t^k_\pm \right\| i \right\rangle\right|^2}{2J_i+1}$$

$\Delta J=0$, $\Delta\pi=$No

  - Gamow-Teller

$$B(GT) = \frac{\left|\left\langle f \left\| \Sigma_k \sigma^k t^k_\pm \right\| i \right\rangle\right|^2}{2J_i+1}$$

$\Delta J=0, \pm 1$, $\Delta\pi=$No

- Lifetime

$$ft = \frac{6144.4 \pm 1.6 \text{ sec}}{B(F) + (g_A/g_V)^2 B(GT)}$$

  - $g_A/g_V = -1.2720(18)$ … ratio of axial-vector and vector c.c.
  - f … phase space factor

GT quenching

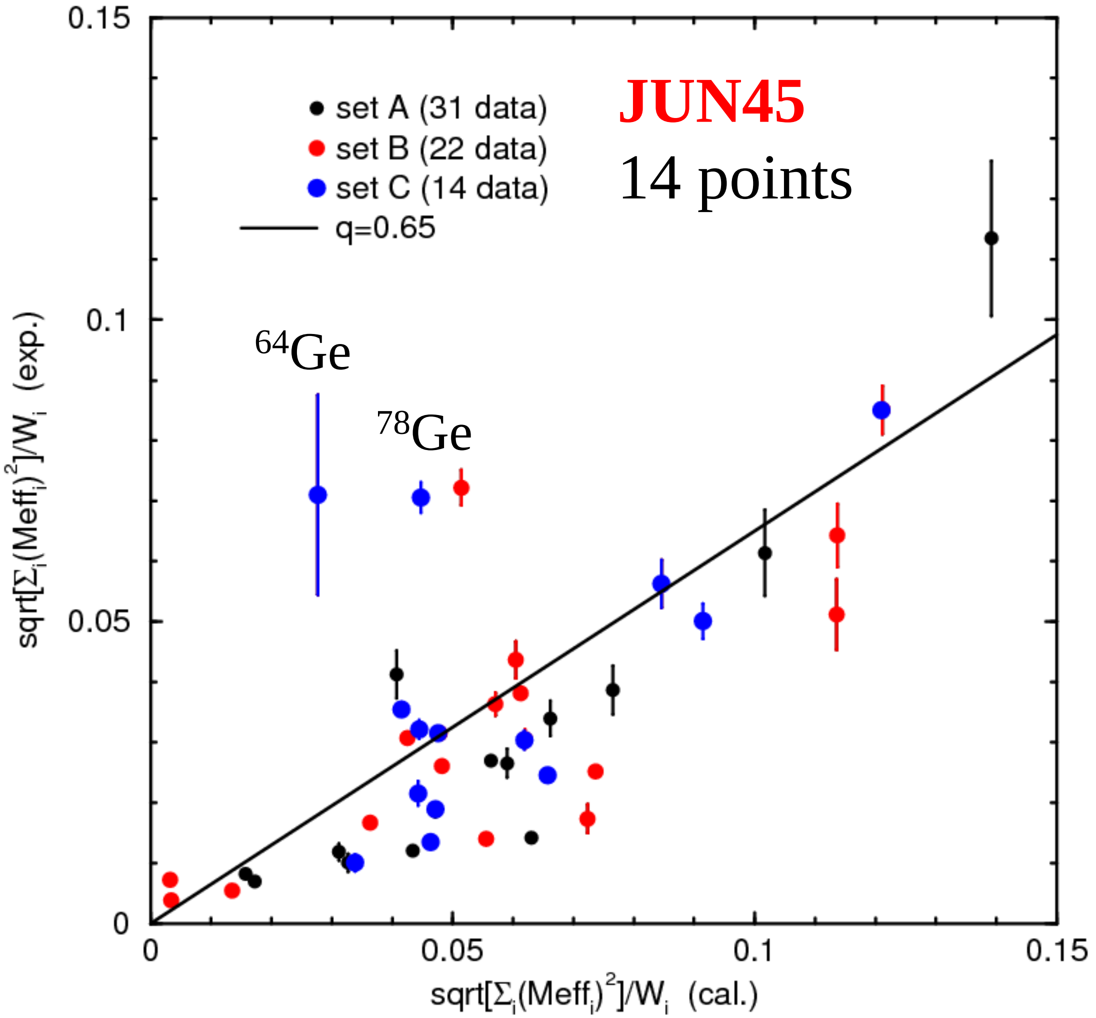
- Quenching of GT operator : $O_{\mathrm{GT}} \rightarrow qO_{\mathrm{GT}}$
  - Take into account the configurations outside the model space
  - p-shell … q = 0.82 W.T.Chou et al, PRC47 (1993) 163
  - sd-shell … q = 0.77 B.H.Wildenthal et al., PRC28 (1983) 1343
  - pf-shell … q = 0.74 G.Martinez-Pinedo et al., PRC53 (1996) R2602
- f5pg9-shell
  - Violate Ikeda sum-rule : $S_- - S_+ = 3(N-Z)$
  - Low-lying transitions … spin-flip contribution may be minor
- Fitting to β-decay data
  - Effective GT matrix element $M_{\mathrm{eff}} = \sqrt{(2J_i+1)B(GT)}$
  - Sum over final states relative to the sum-rule

$$T = \sqrt{\Sigma_i \left(M_{\mathrm{eff}\,i}\right)^2} \Big/ W \qquad W = \begin{cases} |g_A/g_V| \sqrt{(2J_i+1)3|N_i - Z_i|} & (\text{if} \quad N_i \neq Z_i) \\ |g_A/g_V| \sqrt{(2J_f+1)3|N_f - Z_f|} & (\text{if} \quad N_i = Z_i) \end{cases}$$

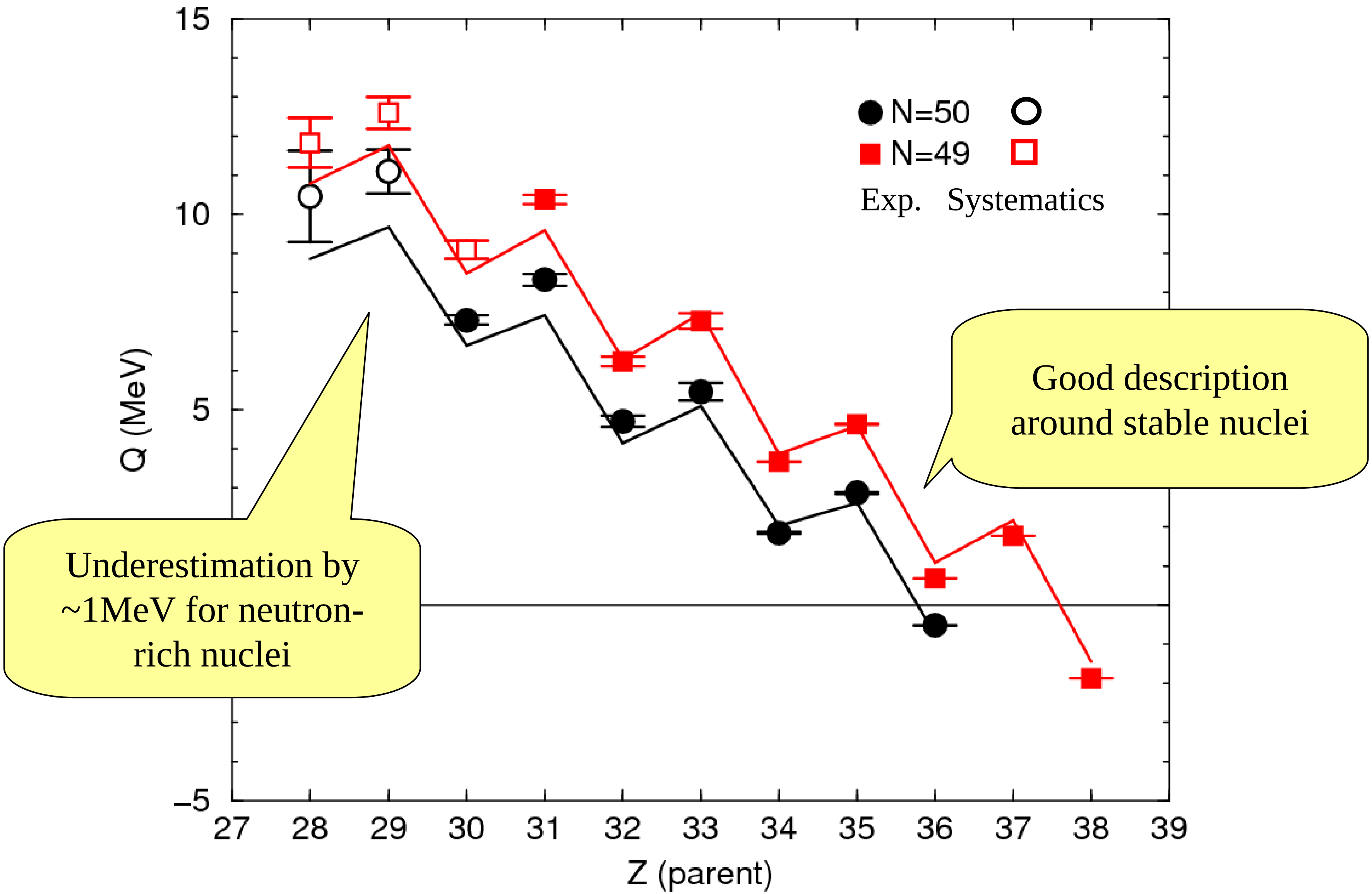
Summed strength (f5pg9-shell)

- Exp. Data
  - setA … all data
  - setB … spin assigned
  - setC … error in Ex < 0.1MeV
- Fit to setC
  - $\Rightarrow q \sim 0.65$
  - (with ^{64}Ge, ^{78}Ge)
  - $\Rightarrow q \sim 0.59$
  - (without ^{64}Ge, ^{78}Ge)

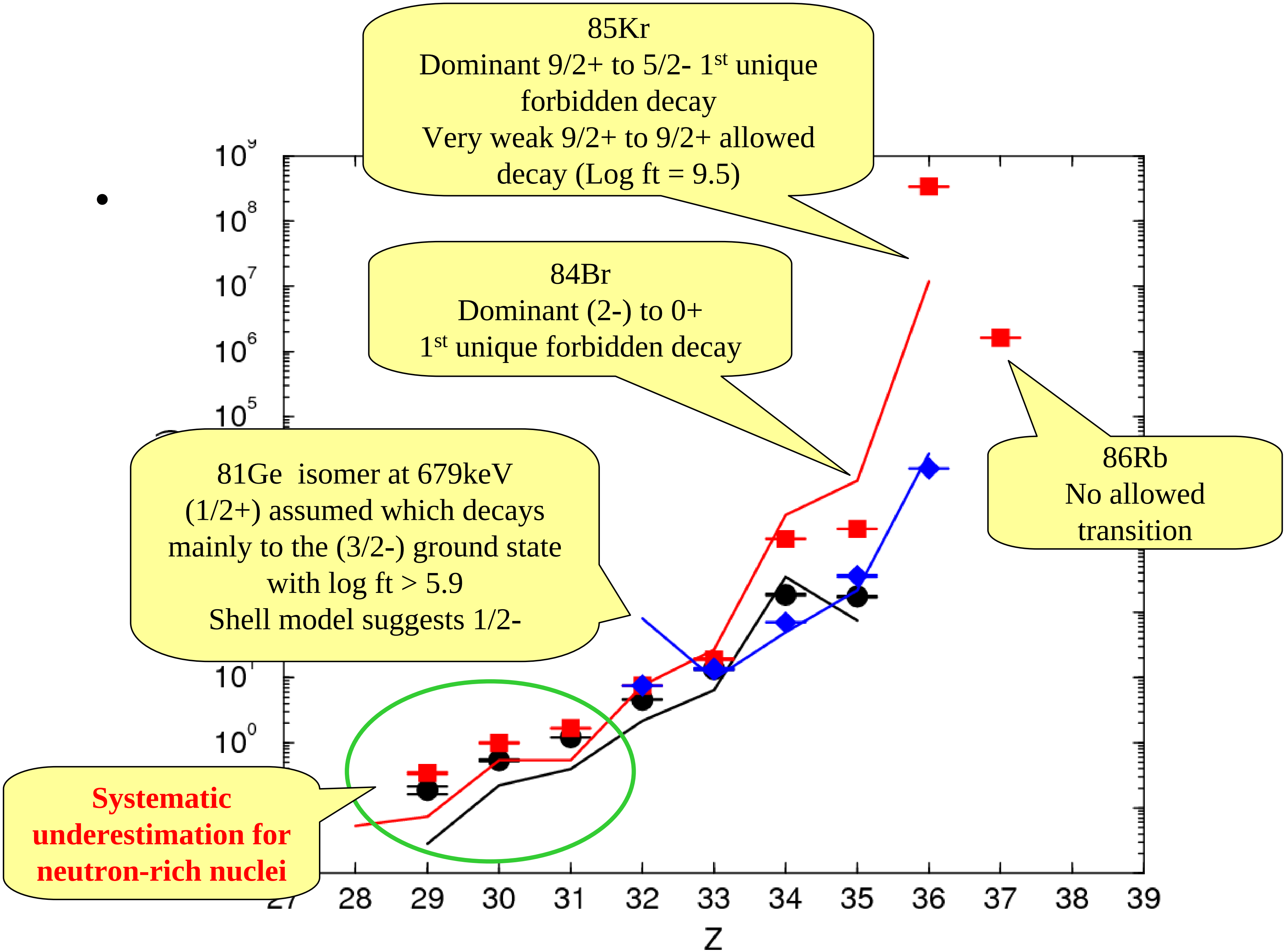
Adopt
$q = 0.6$
(large uncertainty)



Q-value



15
10
5
−5
Q (MeV)
27
28
29
30
31
32
33
34
35
36
37
38
39
Z (parent)
N=50
N=49
Exp.
Systematics
Good description around stable nuclei
Underestimation by ~1MeV for neutron-rich nuclei


85Kr
Dominant 9/2+ to 5/2- 1st unique forbidden decay
Very weak 9/2+ to 9/2+ allowed decay (Log ft = 9.5)
84Br
Dominant (2-) to 0+
1st unique forbidden decay
81Ge isomer at 679keV
(1/2+) assumed which decays mainly to the (3/2-) ground state with log ft > 5.9
Shell model suggests 1/2-
86Rb
No allowed transition
Systematic underestimation for neutron-rich nuclei
Z
27
28
29
30
31
32
33
34
35
36
37
38
39
10^9
10^8
10^7
10^6
10^5
10^1
10^0

^{79}Cu

- No experimental level scheme

Shell model
5/2- ground state
Q(cal) = 9.67MeV
$T_{1/2}$(cal.) = 0.028 s

^{79}Cu β$^-$ Decay (188 ms) 1991Kr15 **200206**

Published: 2002 Nuclear Data Sheets.

^{79}Cu Parent: E_x=0.0; $T_{1/2}$=188 ms *25*; $Q_{g.s.\text{->}g.s.}$=11742 *SY*

History

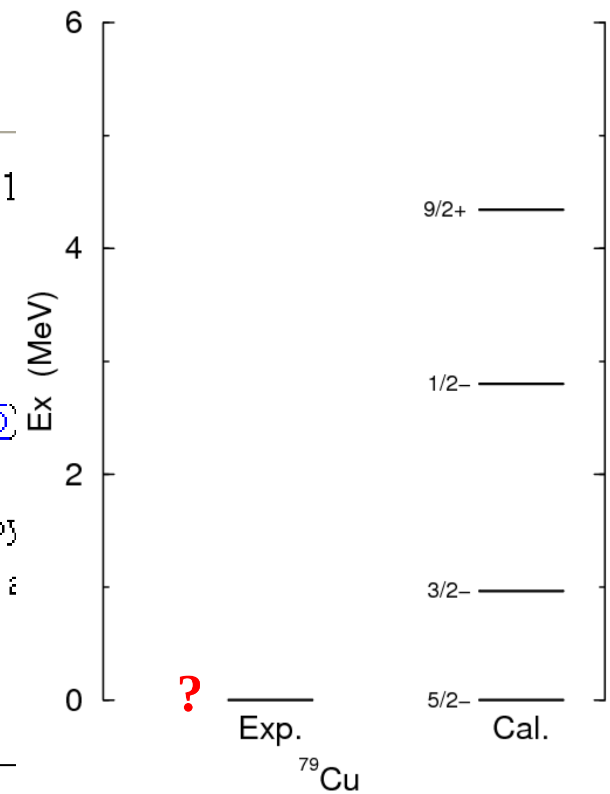
Type	Author	Citation
Full evaluation	Balraj Singh	Nuclear Data Sheets 96, 1

Measured $T_{1/2}$, %β$^-$n.

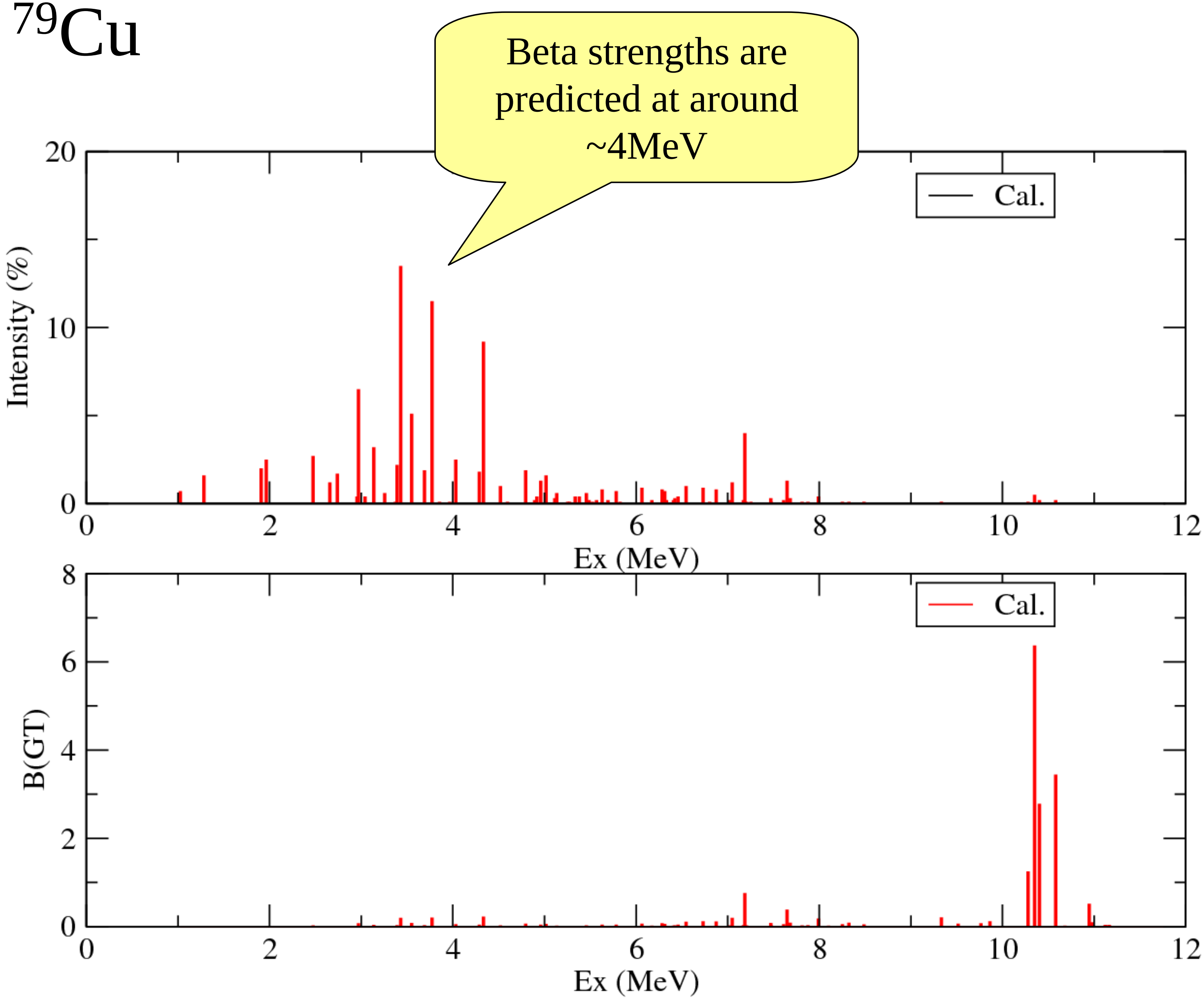
Q(β$^-$)(^{79}Cu)=11742 943 (syst,1995Au04); %β$^-$n=55 17 (1991Kr15)

The isotope produced by ^{238}U(p,X) E=600 MeV reaction followed by and mass separation techniques. 1995En07 use ^{9}Be(^{238}U,F) reaction a and magnetic methods to identify ^{79}Cu.

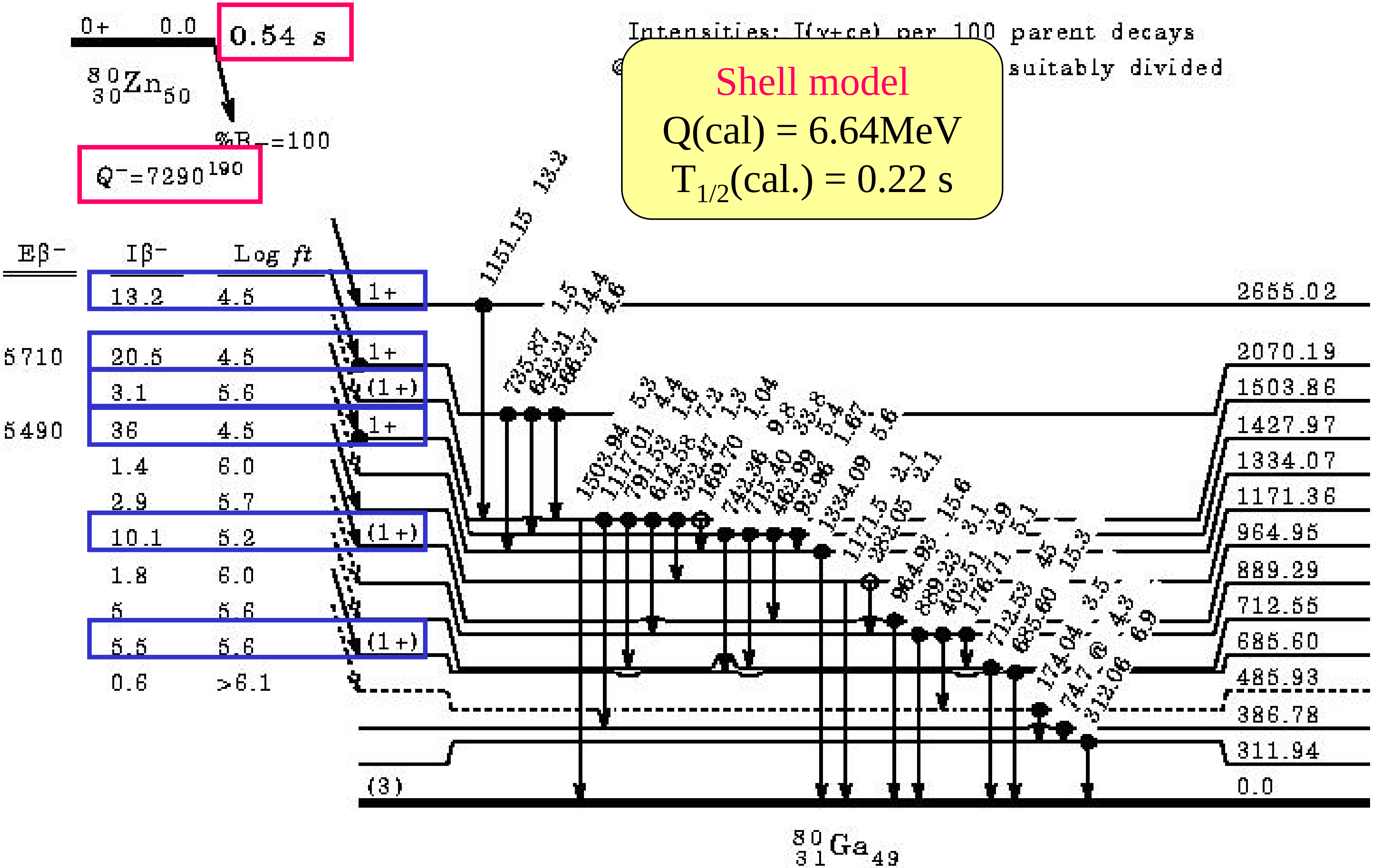
The details of this decay mode are not known.



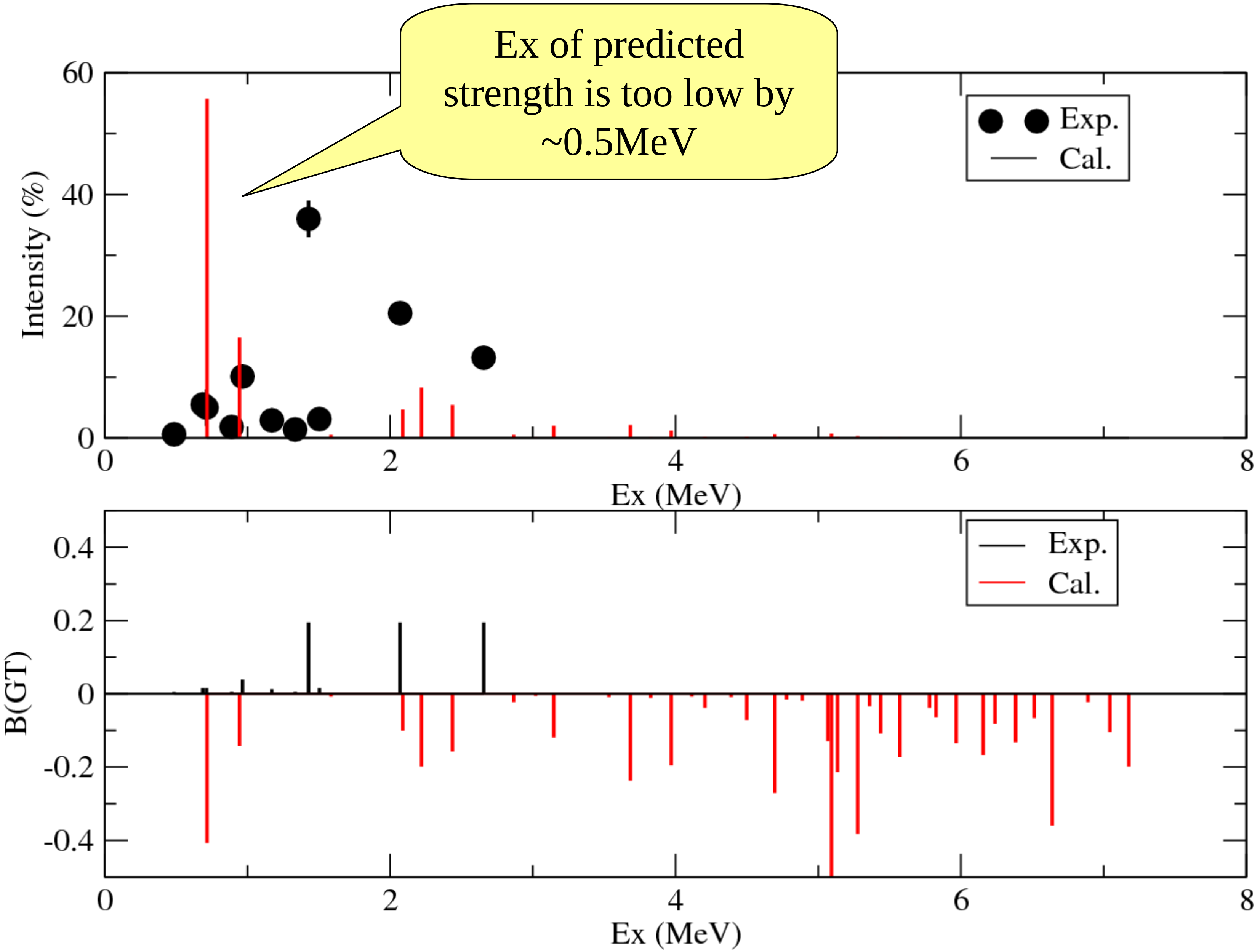
^{79}Cu


Beta strengths are predicted at around ~4MeV
Intensity (%)
Cal.
Ex (MeV)
B(GT)
Cal.
Ex (MeV)

^{80}Zn


0+ 0.0
0.54 s
80 30 Zn 50
%B−=100
Q−=7290 190
Intensities: I(γ+ce) per 100 parent decays
suitably divided
Shell model
Q(cal) = 6.64MeV
T1/2(cal.) = 0.22 s
Eβ− Iβ− Log ft
13.2 4.5 1+ 2655.02
5710 20.5 4.5 1+ 2070.19
3.1 5.6 (1+) 1503.86
5490 36 4.5 1+ 1427.97
1.4 6.0 1334.07
2.9 5.7 1171.36
10.1 5.2 (1+) 964.95
1.8 6.0 889.29
5 5.6 712.55
5.5 5.6 (1+) 685.60
0.6 >6.1 485.93
386.78
311.94
(3) 0.0
80 31 Ga 49

^{80}Zn



Ex of predicted strength is too low by ~0.5MeV
Exp.
Cal.
Intensity (%)
60
40
20
0
0
2
4
6
8
Ex (MeV)
Exp.
Cal.
B(GT)
0.4
0.2
0
-0.2
-0.4
0
2
4
6
8
Ex (MeV)

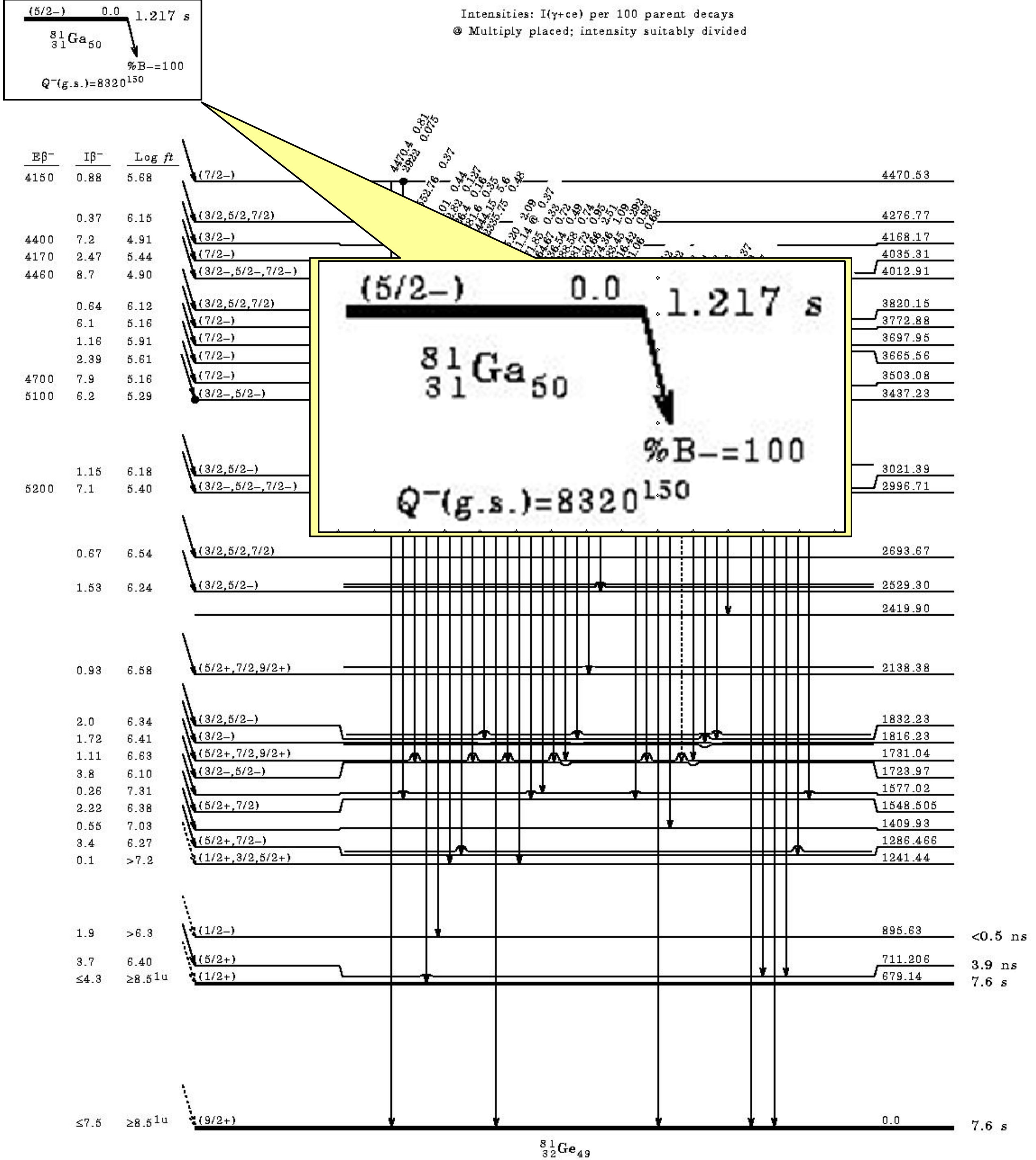
^{81}Ga

Shell model

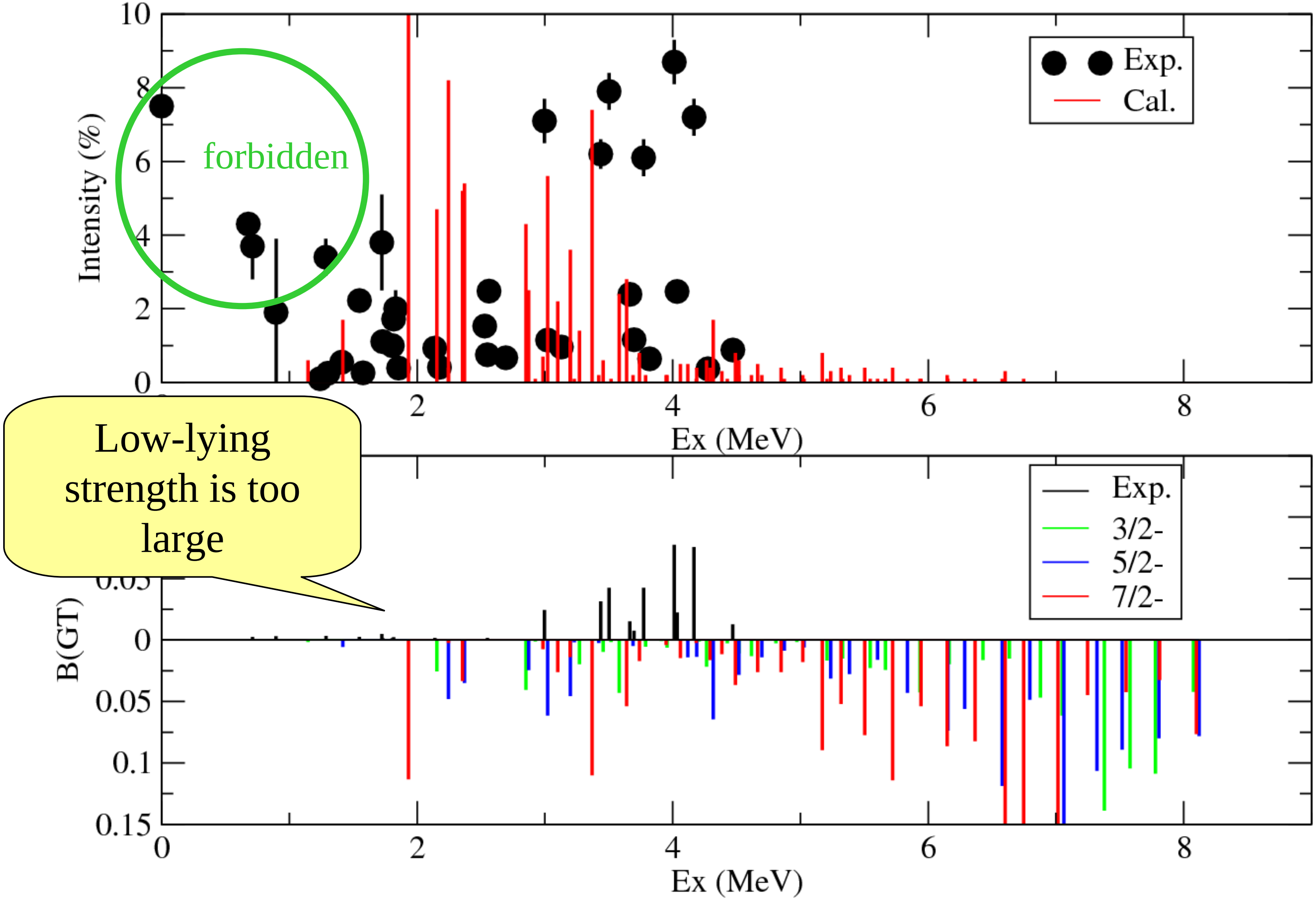
5/2- ground state

Q(cal) = 7.41MeV

$T_{1/2}$(cal.) = 0.39 s

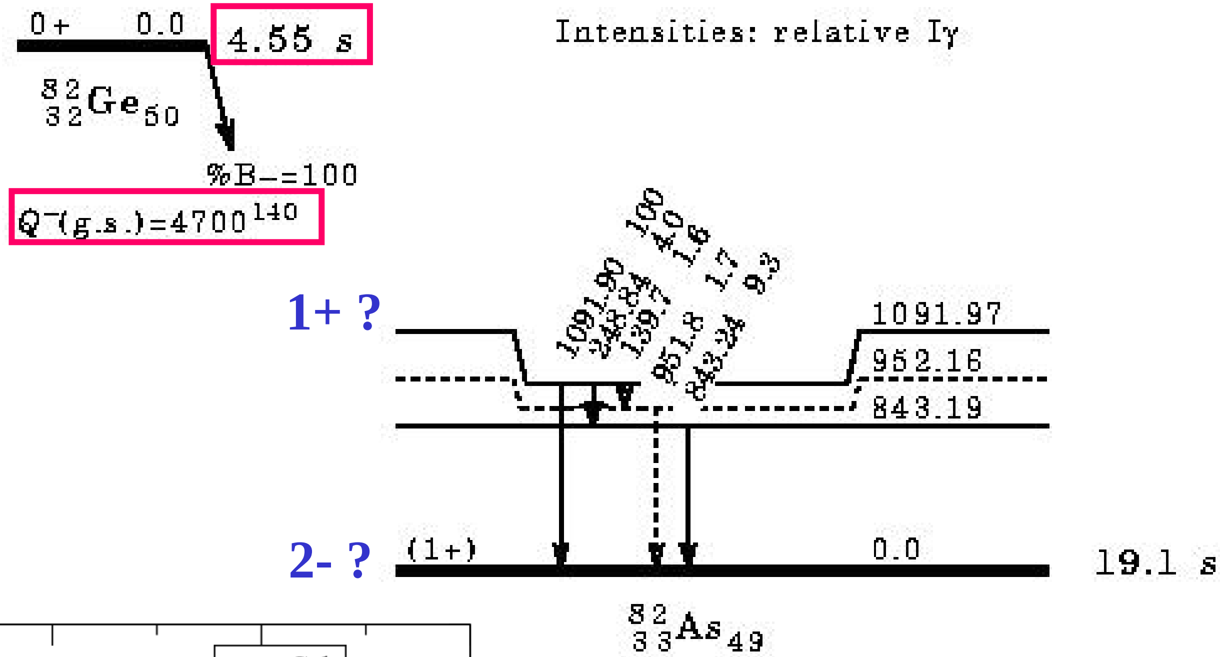


^{81}Ga

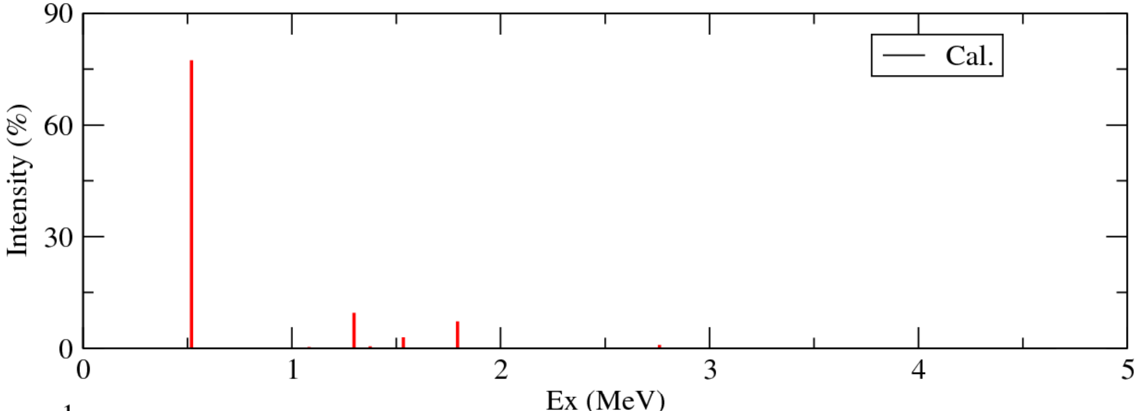


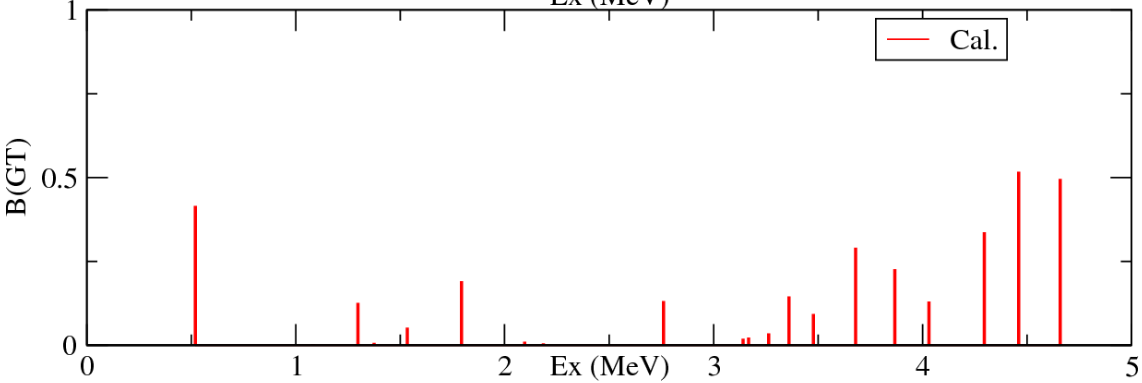
forbidden
Exp.
Cal.
Intensity (%)
Ex (MeV)
Low-lying strength is too large
B(GT)
Exp.
3/2-
5/2-
7/2-
Ex (MeV)

^{82}Ge



Shell model
Q(cal) = 4.14MeV
$T_{1/2}$(cal.) = 2.18 s



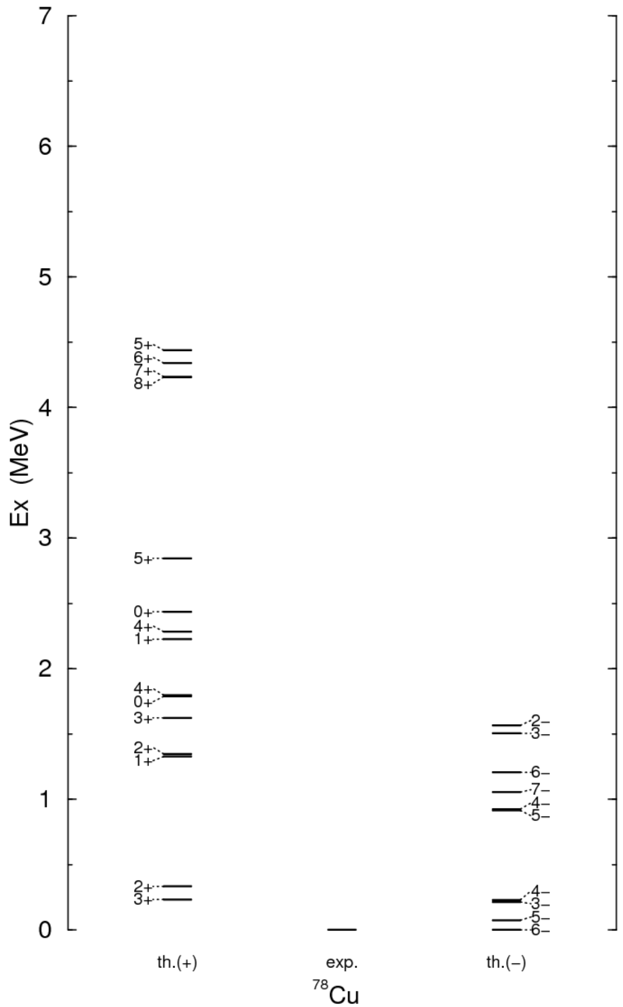


Calculation predicts 2- or 5- ground state for ^{82}As.

Predicted 1+ state at 0.519MeV almost explains the half life.

^{78}Cu

Shell model
6- ground state
Q(cal) = 11.76MeV
$T_{1/2}$(cal.) = 0.074 s



Adopted Levels

Q_{β^-}=13270 *SY* S_n=3540 *SY* S_p=14760 *SY* 1995Au04

History

Type	Author	Cutoff Date	Comments
Update	J. Blachot	1-Jan-1997	CODED FROM NP A424, 1 (1997)

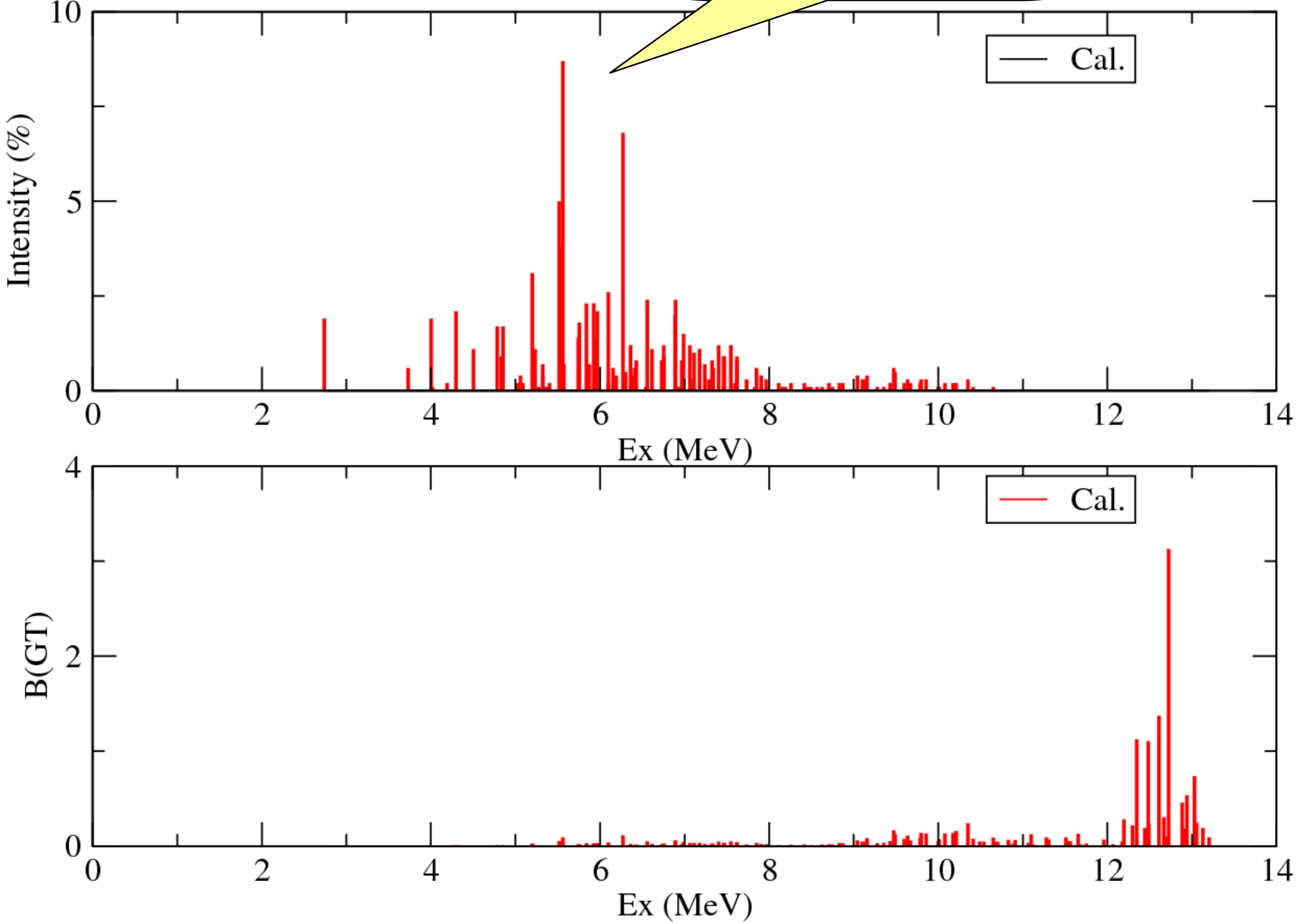
measured $T_{½}$ (1987LuZX,1997Au04).

^{78}Cu levels

E_{level}	$T_{½}$	Comments
0.0	342 ms *11*	%β^-=100 $T_{½}$: from 1987LuZX.

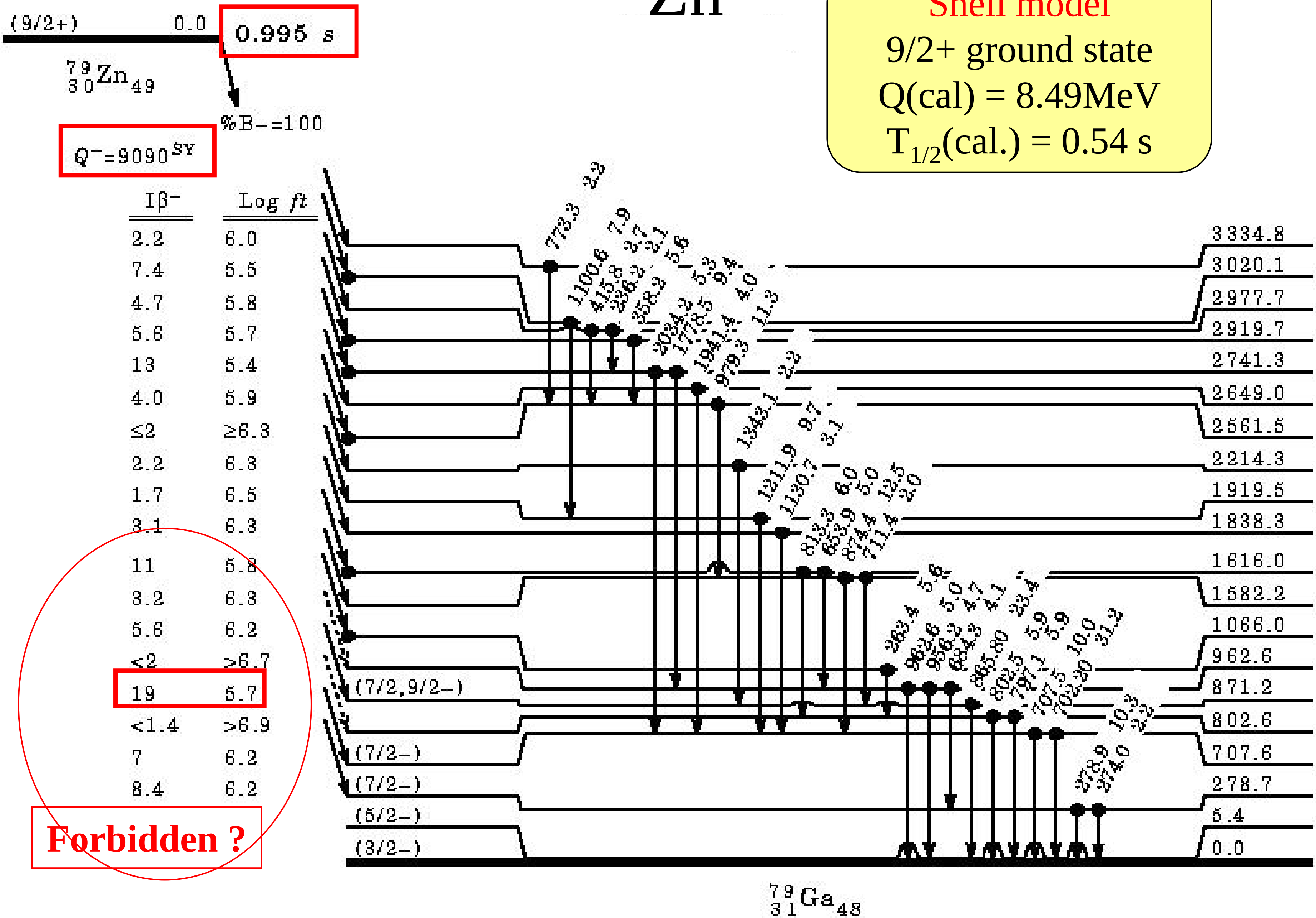
^{78}Cu

Beta strengths are predicted at around ~6MeV



^{79}Zn

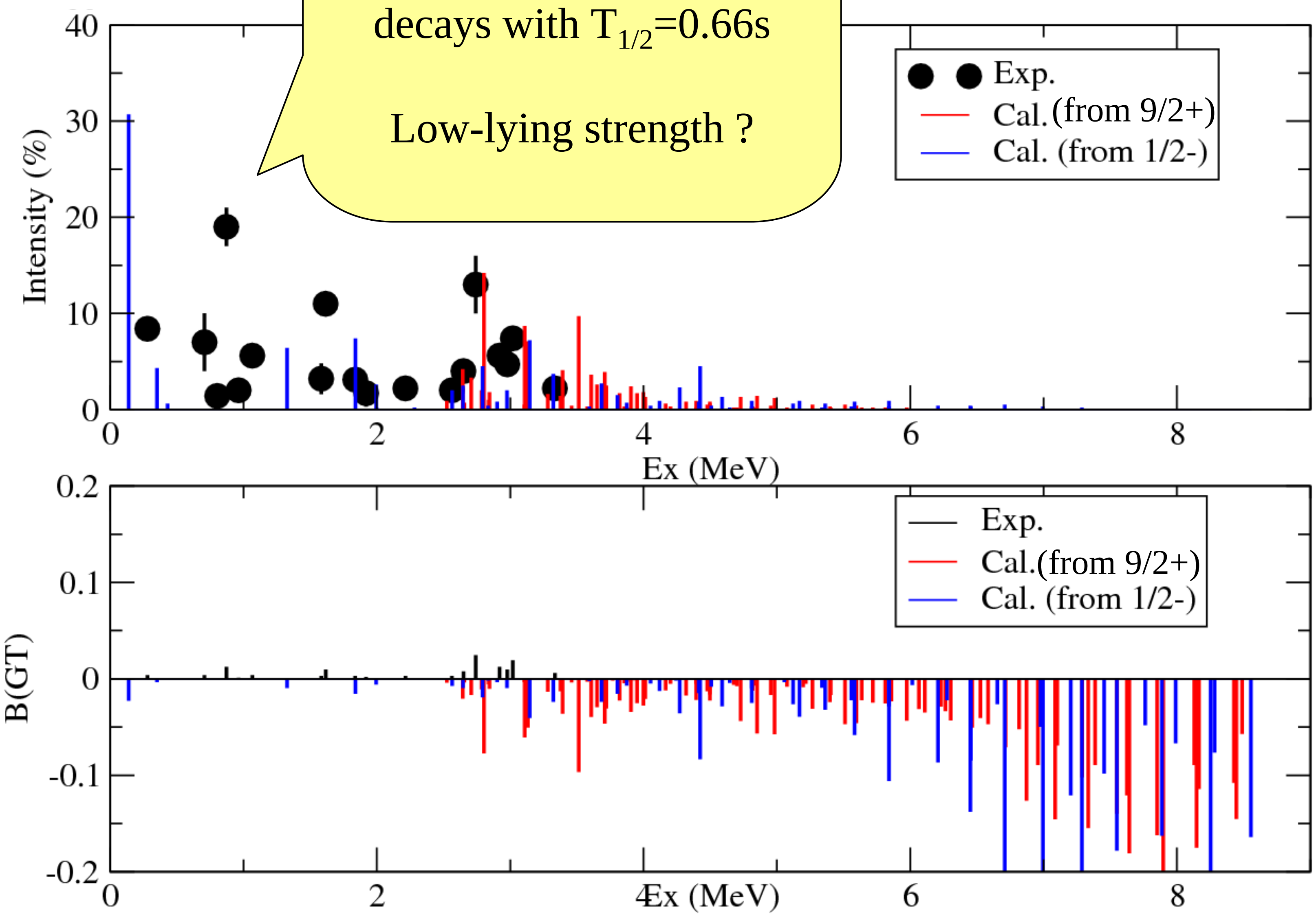
Shell model
9/2+ ground state
Q(cal) = 8.49MeV
$T_{1/2}$(cal.) = 0.54 s



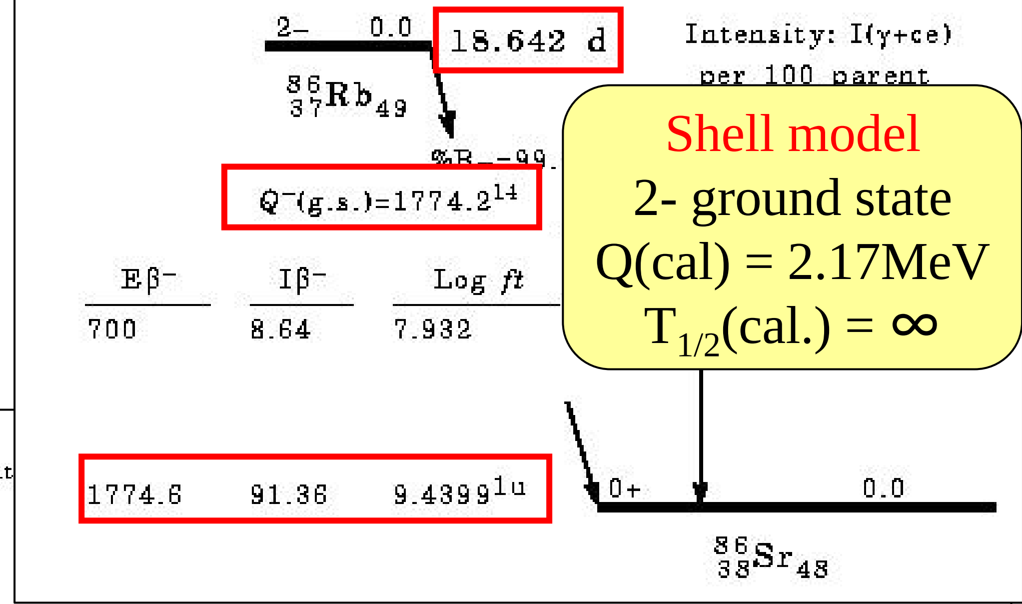
^{79}Zn

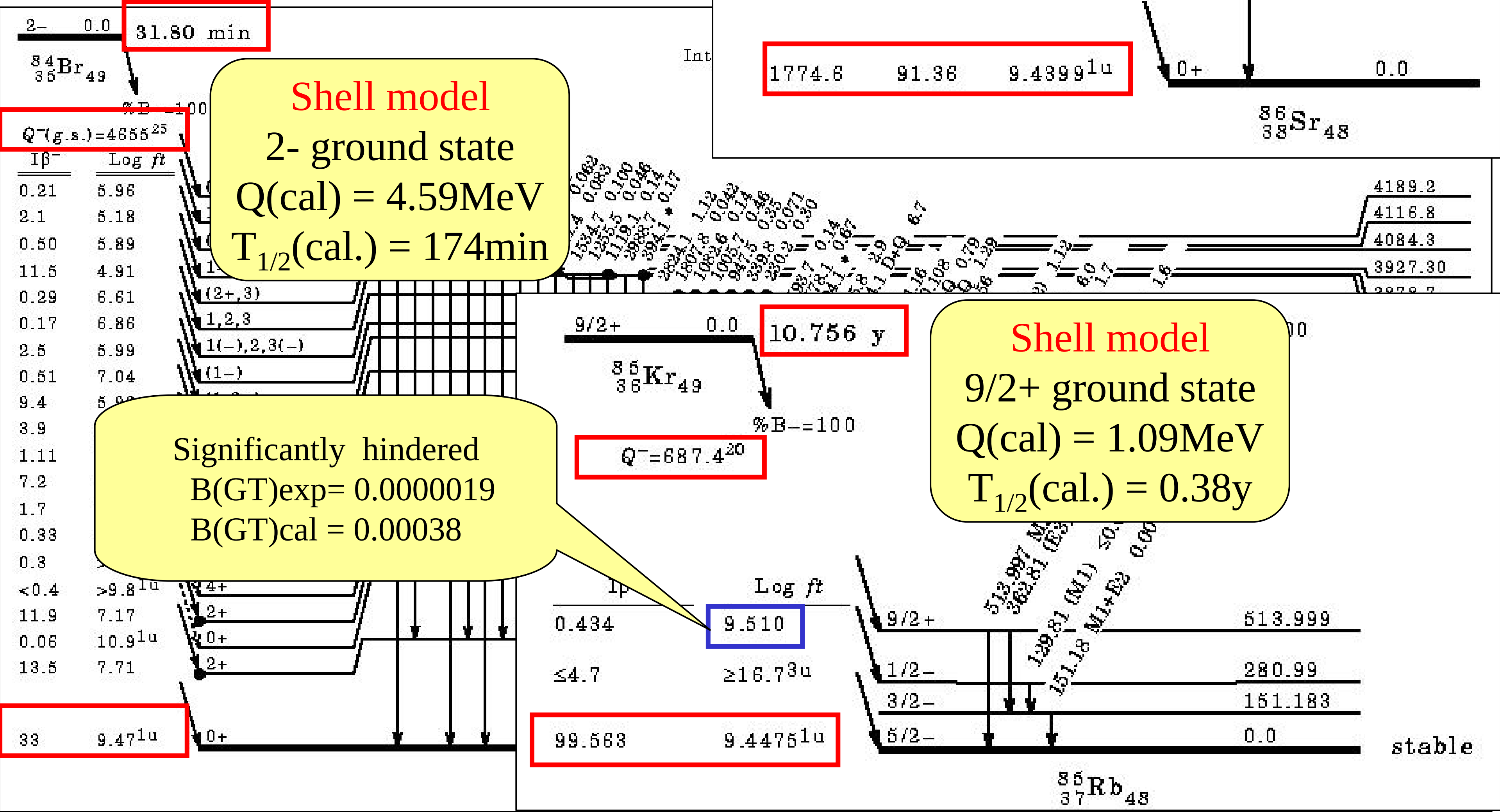
Shell model predicts 1/2- isomer at 65keV which decays with $T_{1/2}$=0.66s

Low-lying strength ?



^{84}Br, ^{85}Kr, ^{86}Rb





Unique forbidden decay

• ^{84}Br		(2-) → 0+ 33%	Q=4655(25)keV
	Exp.	$\log f^{1u}t$ = 9.47	$T_{1/2}$=31.80(8)min
	Cal.	8.7	174min → 14.2min
• ^{85}Kr		9/2+ → 5/2- 99.563%	Q=687.4(20)keV
	Exp.	$\log f^{1u}t$ = 9.4475	$T_{1/2}$=10.756(18)y
	Cal.	8.5	0.38y → 0.28y
• ^{86}Rb		2- → 0+ 91.36%	Q=1774.2(14)keV
	Exp.	$\log f^{1u}t$ = 9.4399	$T_{1/2}$=18.642(18)d
	Cal.	8.5	∞ → 2.0d

Calculation underestimates the half-life

Summary

- Beta-decay properties for N=50 and 49 nuclei can be described reasonably well by the shell model
- f5pg9-shell with JUN45 interaction
- Quenching factor q=0.6 for Gamow-Teller operator
- Underestimate Q-values by ~1 MeV for neutron-rich nuclei
- Predicted half-life agrees with experimental data within a factor of 2 ~ 3 near the stable nuclei, while it systematically underestimates for neutron-rich nuclei probably because of insufficient correlations
- Allowed transitions already give reasonable predictions for N=50 cases, but forbidden decays sometimes play a crucial role for N=49 cases near the stable nuclei.
- Enlarged model space is desired for better description