Structure of neutron-rich Ge and Se isotopes

Dr. Anne Marie Forney

University of Maryland

Department of Chemistry and Biochemistry

Motivation

- Neutrinoless double β decay candidates: ^{76}Ge and ^{82}Se
- Fidelity of the N=50 and Z=32 shell and subshell closures
- Shaped debated in ^{78}Ge
- Shape deformation, shape coexistence and triaxiality reported in ^{72,74,76}Ge
- Triaxiality predicted in Ge nuclei
- Is there deformation in Se isotones?

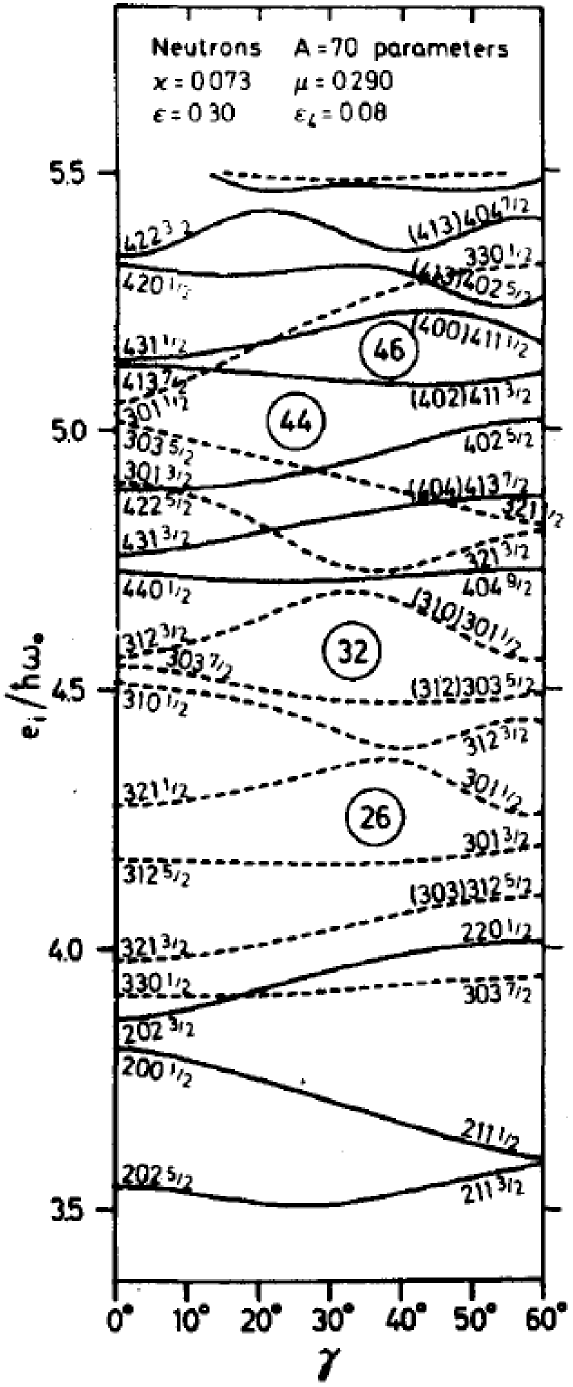
Triaxiality in Ge nuclei

- Deformed structure and departure from an axial symmetry
- Triaxial? Closeness of 3^+ to 2^+ levels.
- Larsson, Leander, Ragnarsson, Alenius

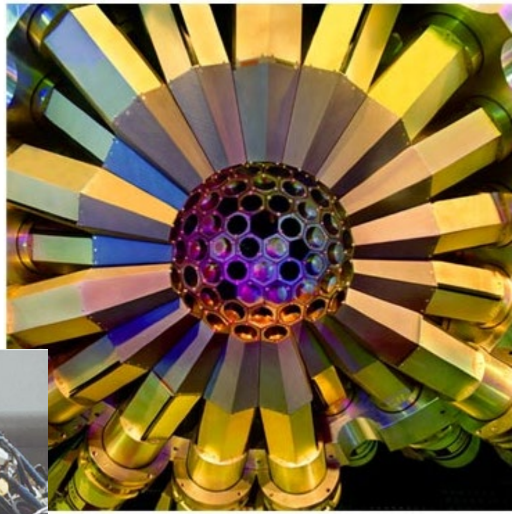
strong shell structure around $\gamma = 30°$ for particle numbers 26, 32 and 44 (46).

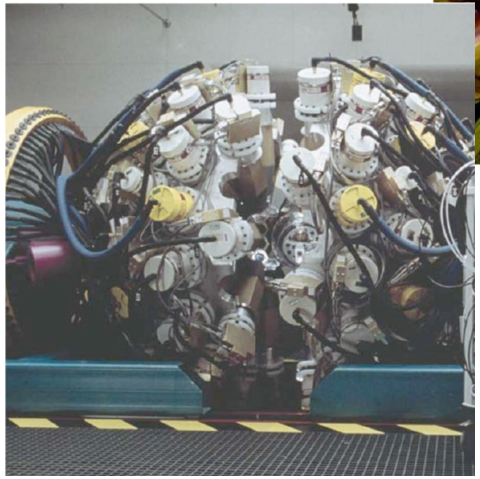
  - Used ^{72,76}Ge as examples

- Ragnarsson, Nilsson and Sheline (Physics Reports 45 (1) 1978) identified certain nuclei as attractive for the presence of a stable triaxial minimum
  - Neutron or Proton numbers: **26, 32, 44, or 46**
  - Predicted ^{76}Ge would be an ideal candidate as a "triaxial double-magic nucleus"
  - Note: ^{78}Ge is also a candidate for triaxial double-magicity.



Gammasphere array (4π detector)

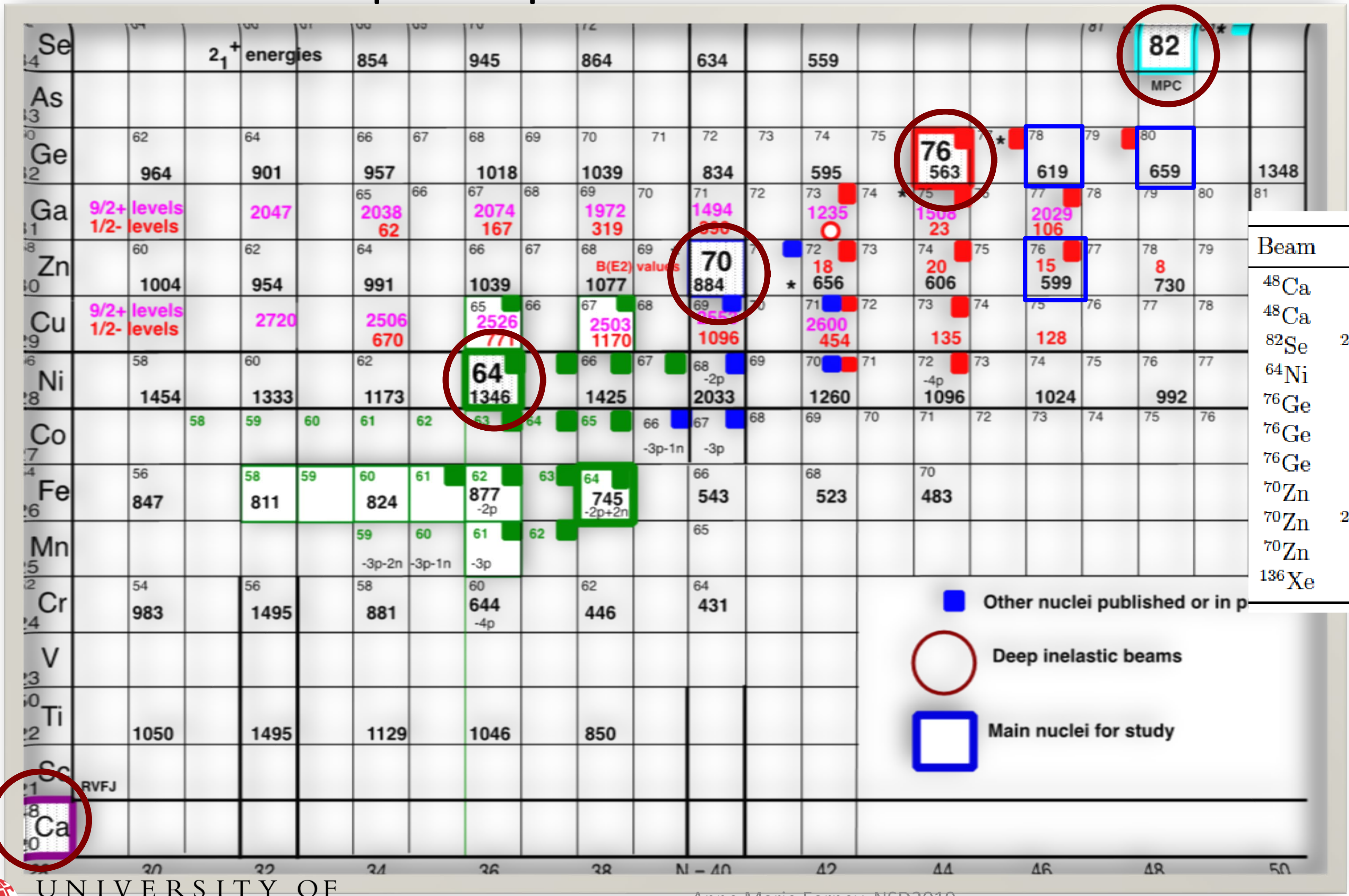




- Argonne National Laboratory ATLAS facility
  - 4π detector array
  - Can hold up to 110 Ge/BGO detectors
  - Argonne Tandem Linear Accelerator System (ATLAS)
- Multi-nucleon transfer reactions
- Detecting de-excitation of γ rays
  - Triple Coincidences

The ANL-Gammasphere deep inelastic reaction data sets

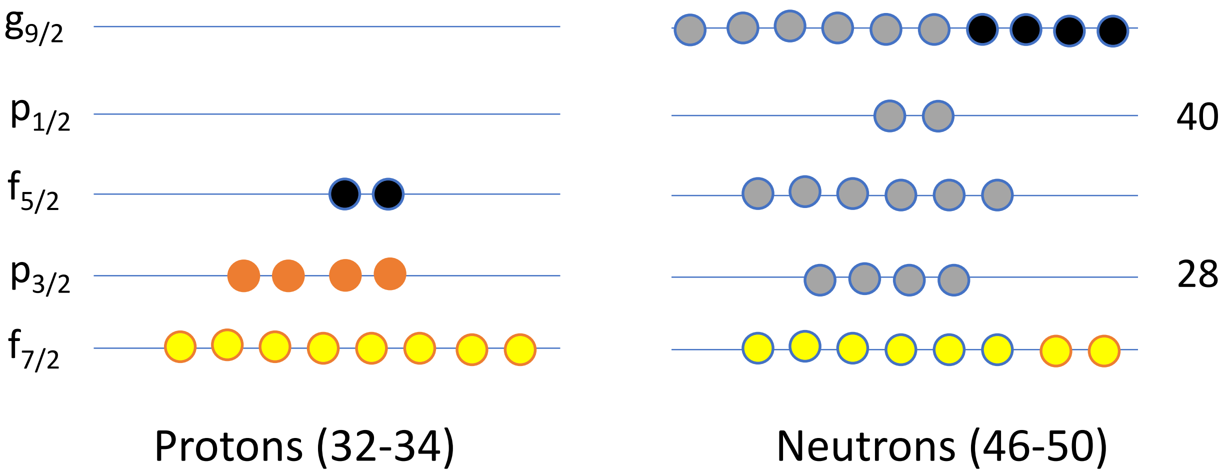
^{198}Pt, ^{197}Au, ^{208}Pb, ^{238}U targets

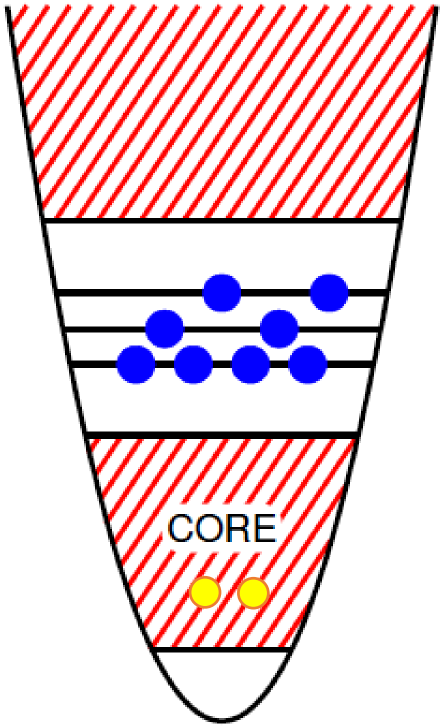


Beam	Target	Beam Energy (MeV)
^{48}Ca	^{208}Pb	305
^{48}Ca	^{238}U	330
^{82}Se	^{208}Pb,^{238}U	525 + 630
^{64}Ni	^{238}U	430
^{76}Ge	^{238}U	425 + 530
^{76}Ge	^{208}Pb	450
^{76}Ge	^{198}Pt	450
^{70}Zn	^{197}Au	430
^{70}Zn	^{208}Pb,^{238}U	440
^{70}Zn	^{208}Pb	440
^{136}Xe	^{208}Pb	450

Applying the shell model

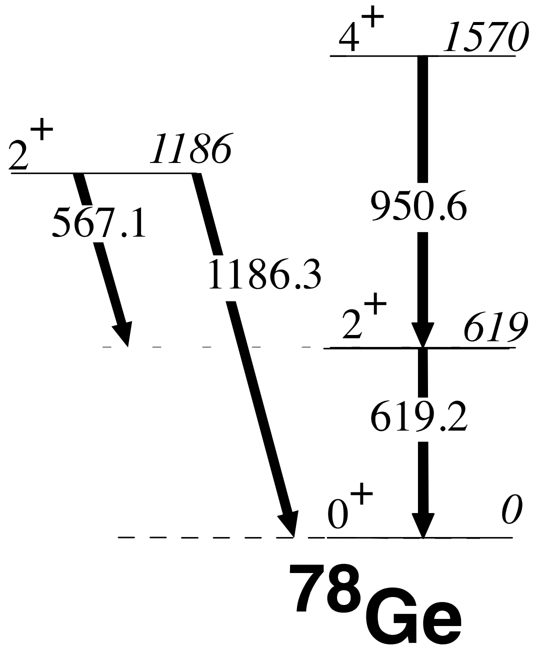
- NuShellX
  - Alex Brown (MSU)
- jj44 model space
- Two Hamiltonians
  - jj44b
  - Jun45
- Level energies
- B(E2) values
- Occupation Numbers

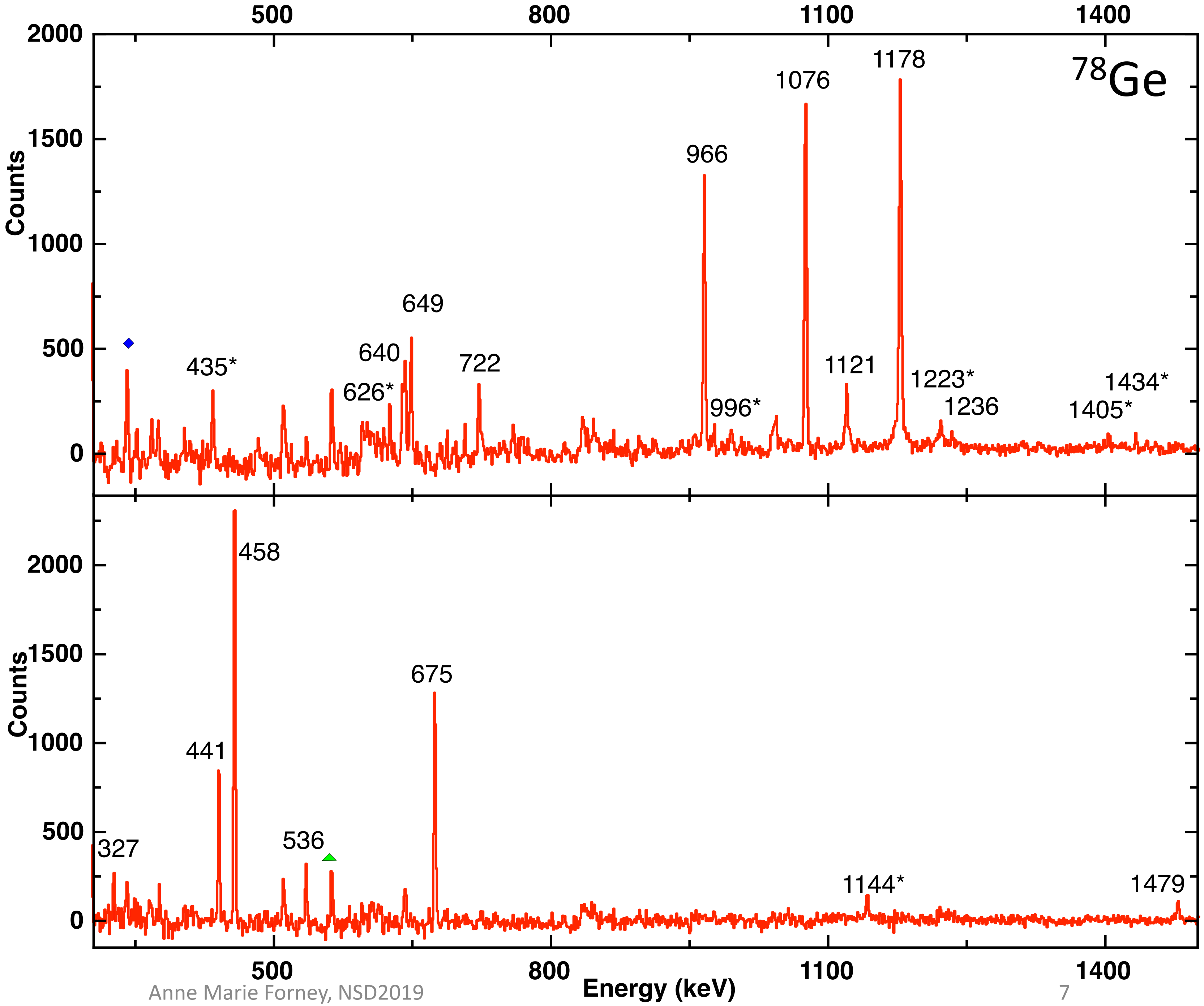




G. M. Pinedo
Shell Model Applications in Nuclear Physics and Astrophysics
10th Euro Summer School on Exotic Beams

- (a) 619-keV $2_1^+ \rightarrow 0_1^+$ in a 950-keV $4_1^+ \rightarrow 2_1^+$ gate
- (b) 619-keV $2_1^+ \rightarrow 0_1^+$ in a 567-keV $2_2^+ \rightarrow 2_1^+$ gate.

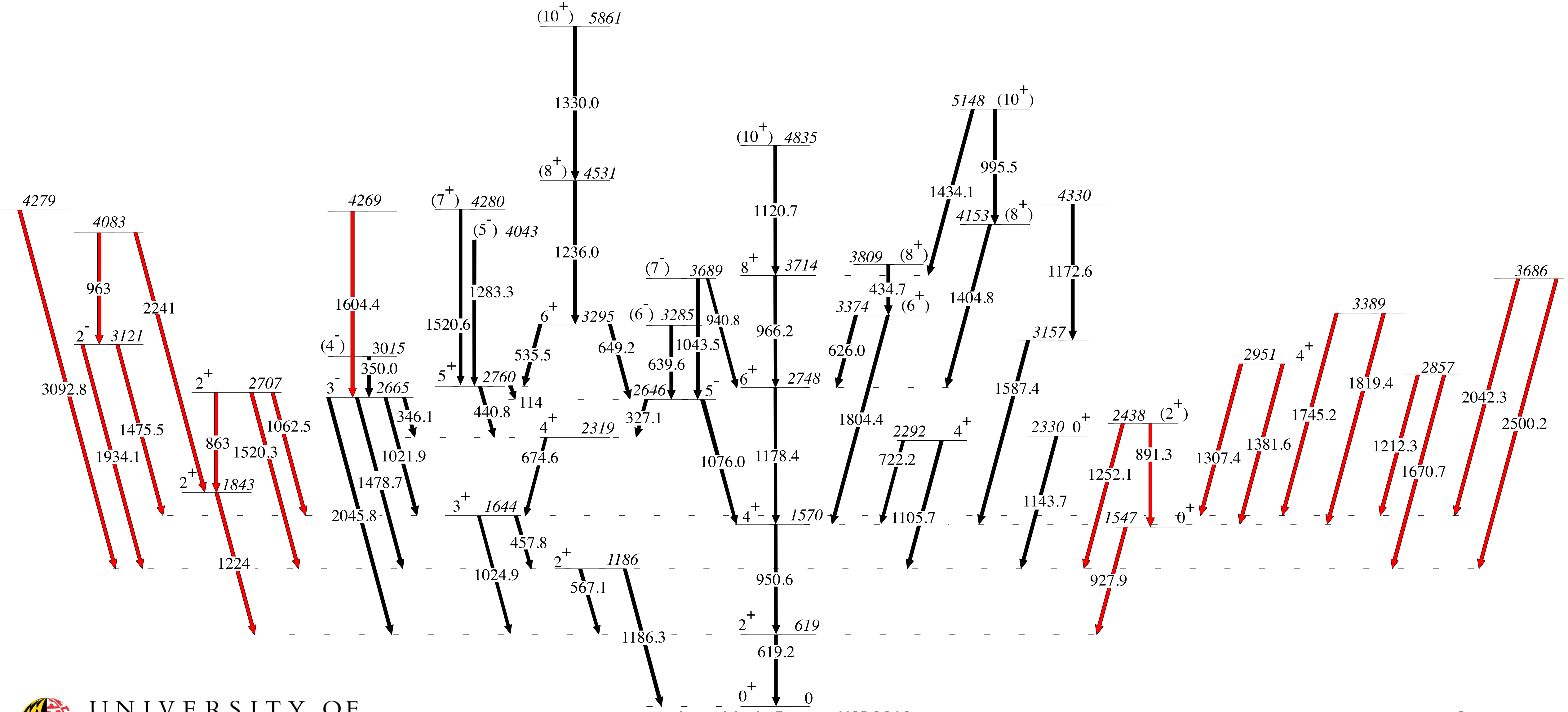




A.M. Forney *et al.*, Phys. Rev. Lett. **120** (2018).

^{78}Ge

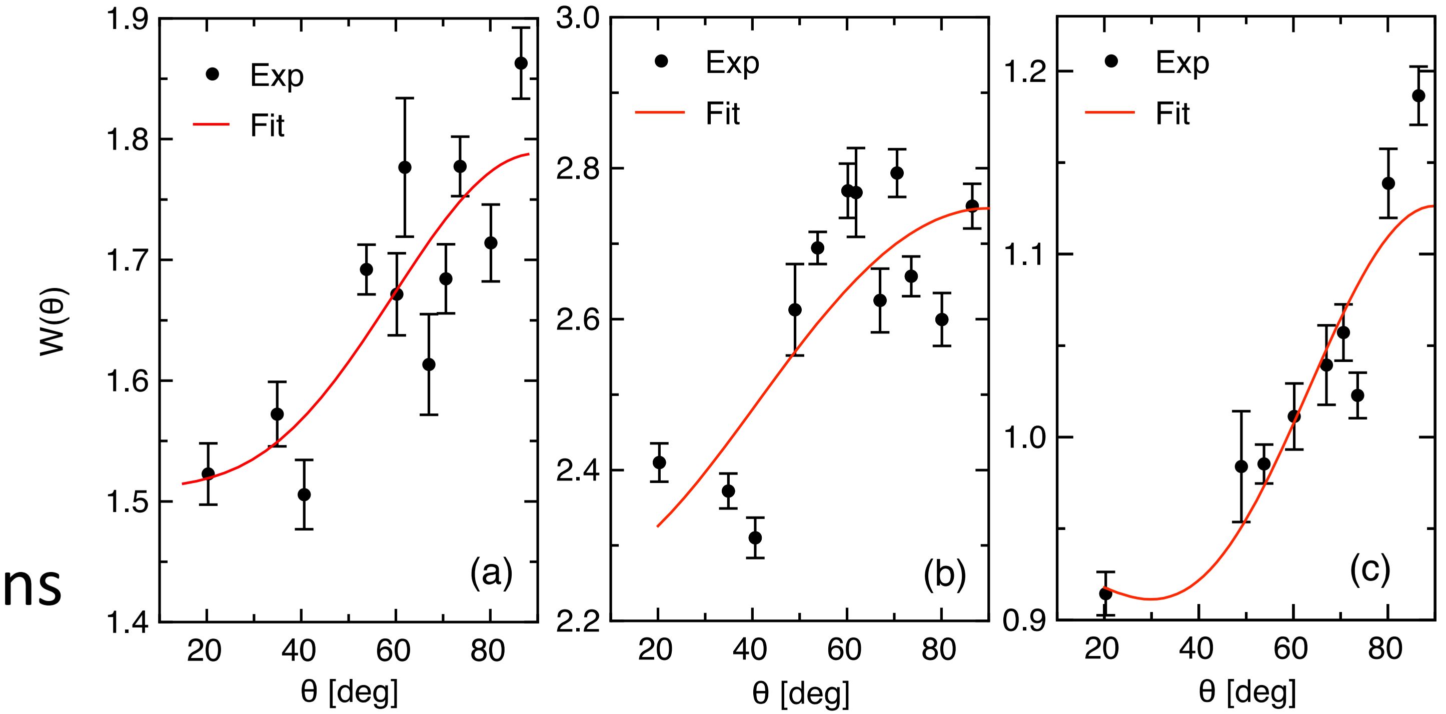
- Confirmed transitions seen in β-decay (using delayed coincidences)
- β-decay parent is confirmed to be a 2^-, not 3^+



Spin and Parity assignments from Angular Correlations

a)950x1076
b)1025x675
c)619x458

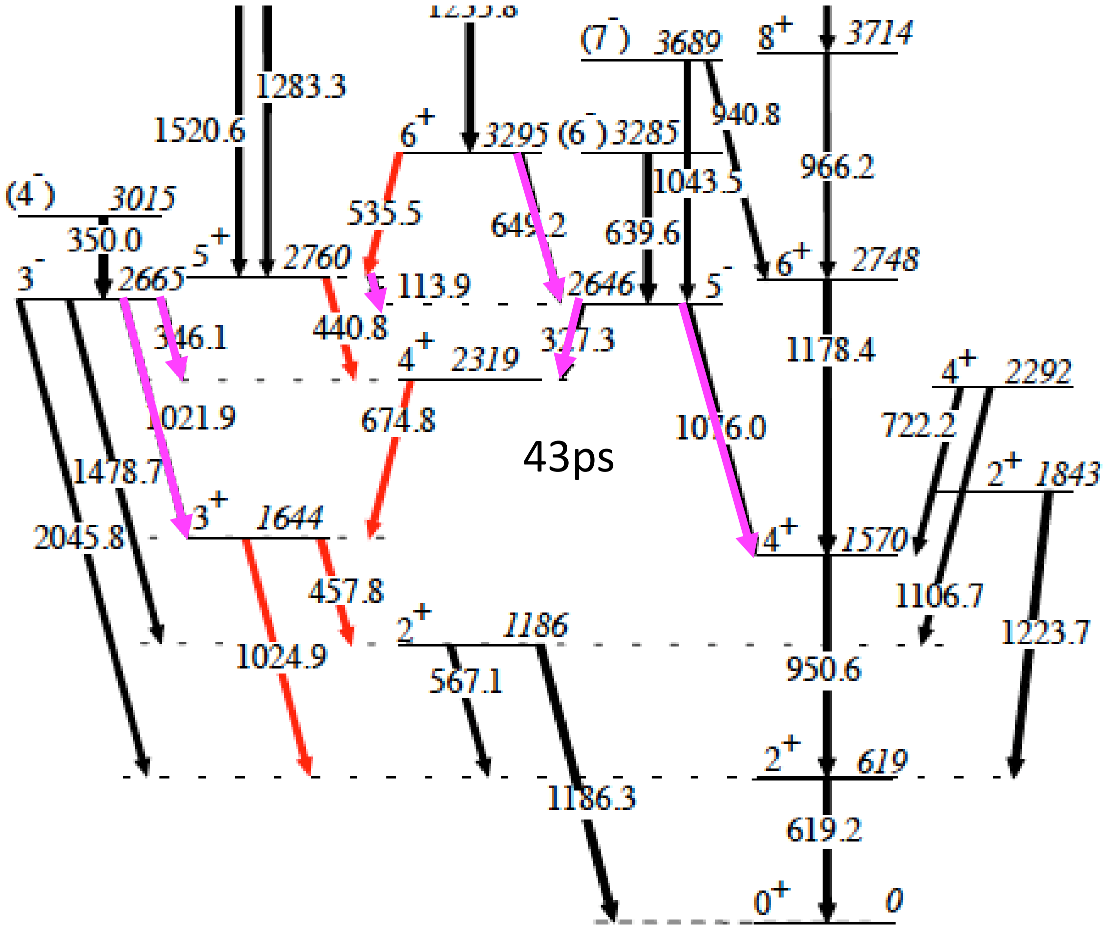
ΔJ=1 transitions



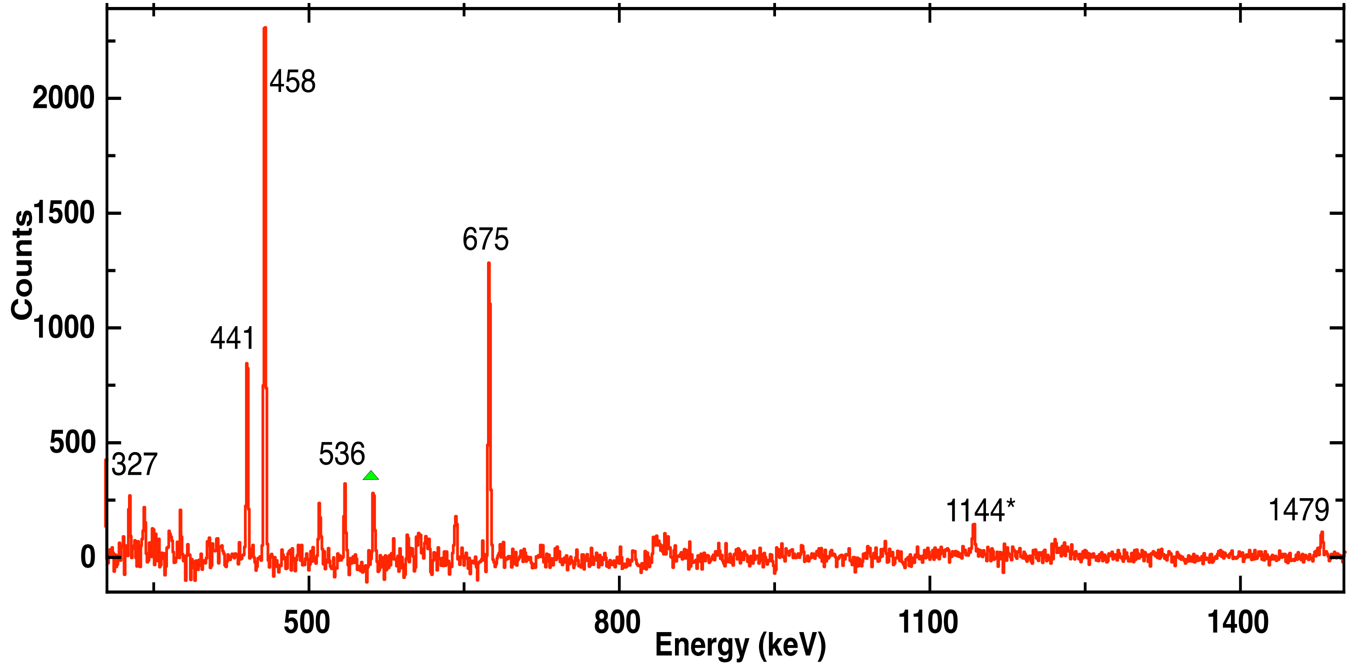
A novel $\Delta J = 1$ sequence in ^{78}Ge: possible evidence for triaxiality

A. M. Forney,[1,*] W. B. Walters,[1,†] C. J. Chiara,[1,2,‡] R. V. F. Janssens,[2,3] A. D. Ayangeakaa,[2,4] J. Sethi,[1] J. Harker,[1,2] M. Alcorta,[2,5] M. P. Carpenter,[2] G. Gürdal,[6,7] C. R. Hoffman,[2] B. P. Kay,[2] F. G. Kondev,[6,§] T. Lauritsen,[2] C. J. Lister,[2,8] E. A. McCutchan,[2,9] A. M. Rogers,[2,8] D. Seweryniak,[2] I. Stefanescu,[1,2] and S. Zhu[2]

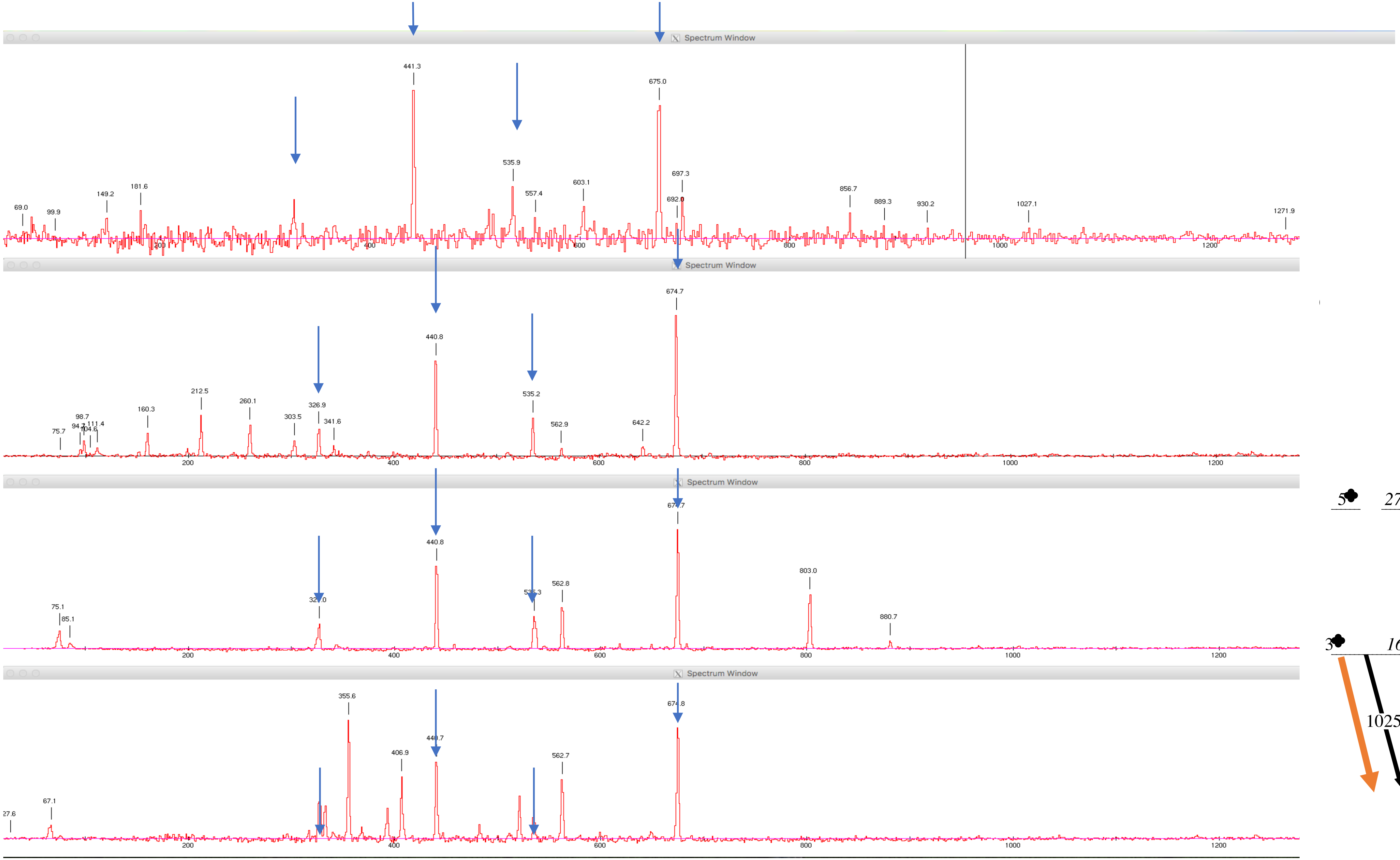
^{78}Ge missing E2 cross-over transitions

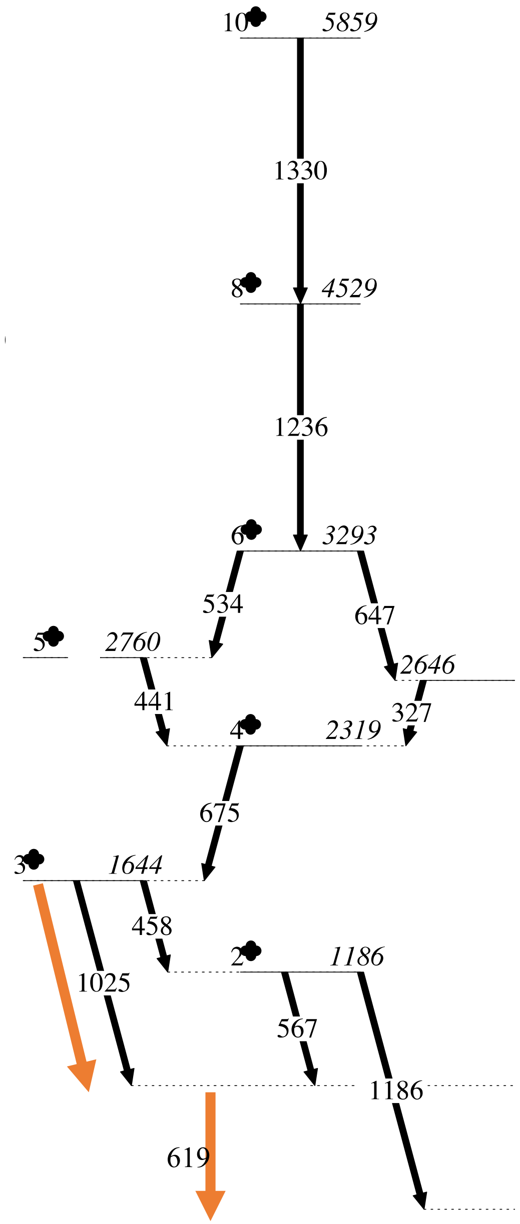


Relative intensities normalized to the 951 keV transition,
Members of the κ-band
and E1 transitions

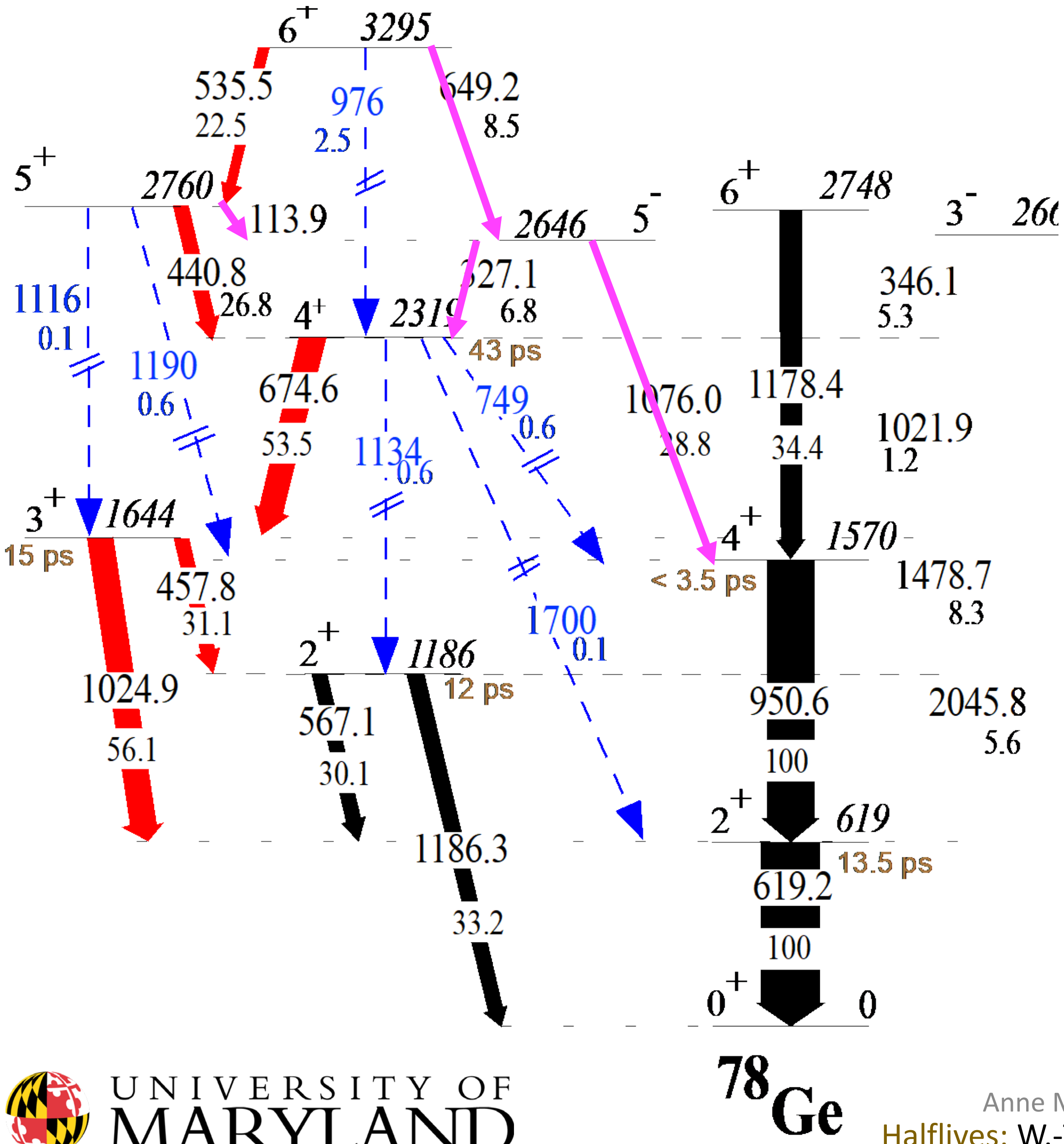


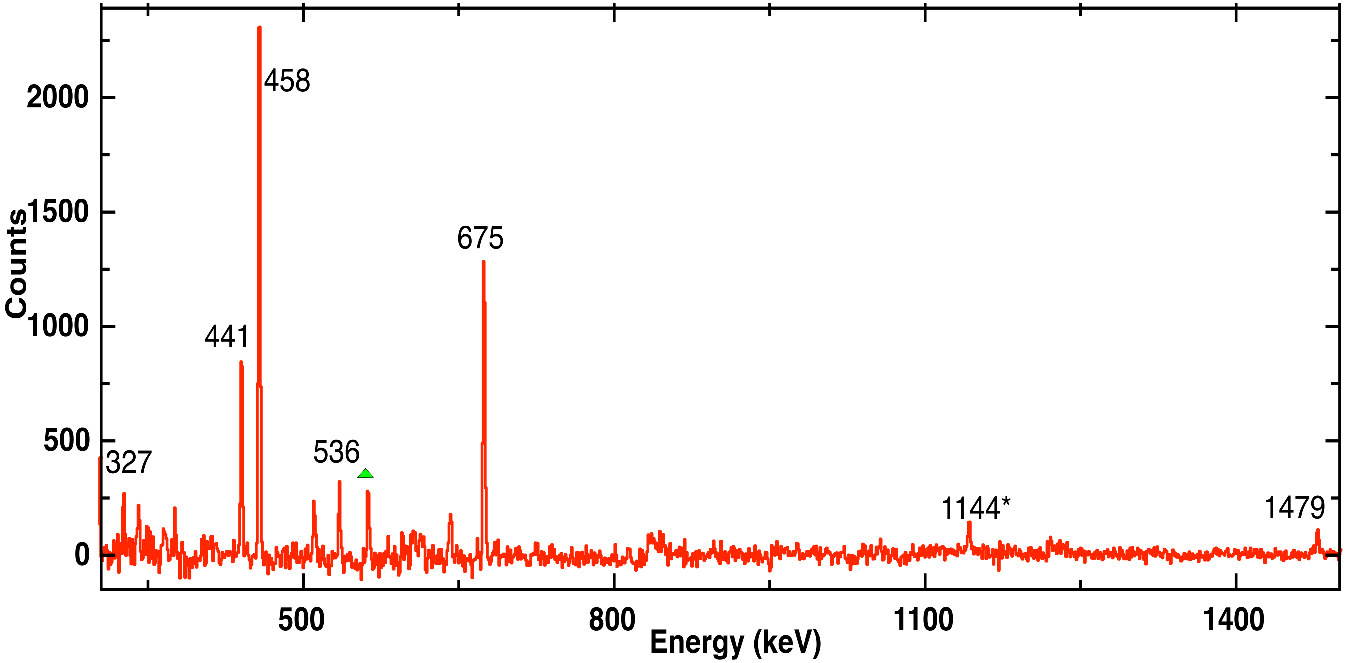
Halflives: W.-T. Chou *et al.*, Phys. Rev. C **47** (1993).


Spectrum Window
441.3
675.0
535.9
697.3
603.1
557.4
692.0
856.7
889.3
930.2
1027.1
1271.9
181.6
149.2
69.0
99.9
Spectrum Window
674.7
440.8
535.2
326.9
212.5
260.1
160.3
303.5
341.6
562.9
642.2
98.7
75.7
111.4
104.6
Spectrum Window
440.8
803.0
562.8
880.7
75.1
85.1
Spectrum Window
355.6
406.9
562.7
67.1
27.6
200
400
600
800
1000
1200


10
5859
1330
8
4529
1236
6
3293
534
647
5
2760
2646
441
327
4
2319
675
3
1644
458
1025
2
1186
567
1186
619

^{78}Ge missing E2 cross-over transitions





Relative intensities normalized to the 951 keV transition,
Members of the κ-band,
E1 transitions, and
missing transitions

E_{lev} (KeV)	E_{γ} (KeV)	E_f (KeV)	Upper limit Intensity
3295	976	2319	2.5
2319	1700	619	0.1
	1134	1186	0.6
	749	1570	0.6
2760	1114	1644	0.6
	1190	1570	0.1

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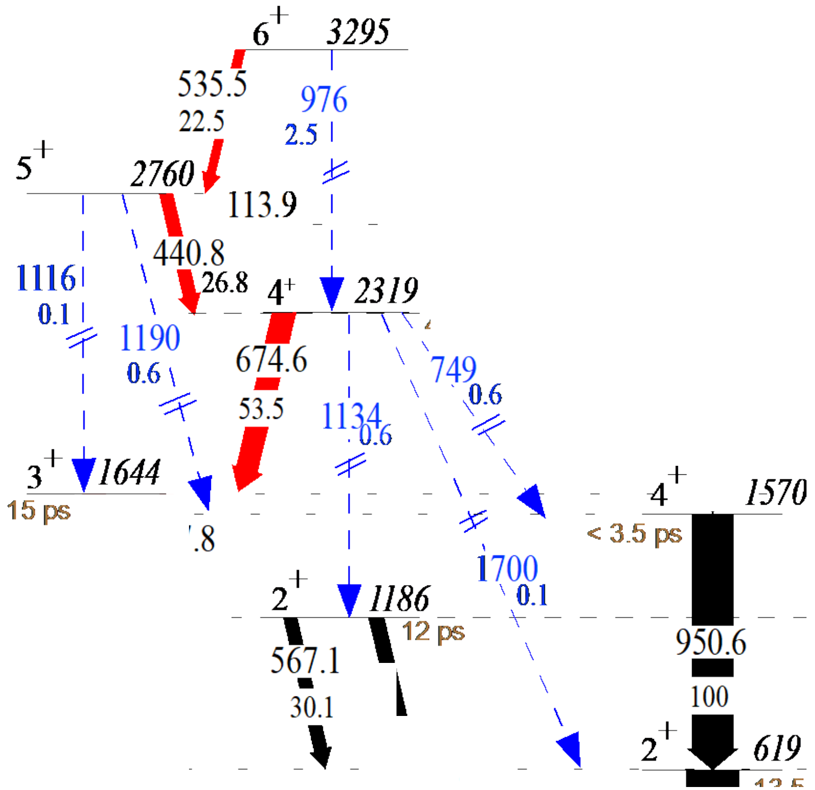
Halflives: W.-T. Chou *et al.*, Phys. Rev. C **47** (1993).

Do results line up with theory?

- What do current theoretical transitions predict in ^{78}Ge
  - Do they suppress the E2 transition rates (blue transitions)?



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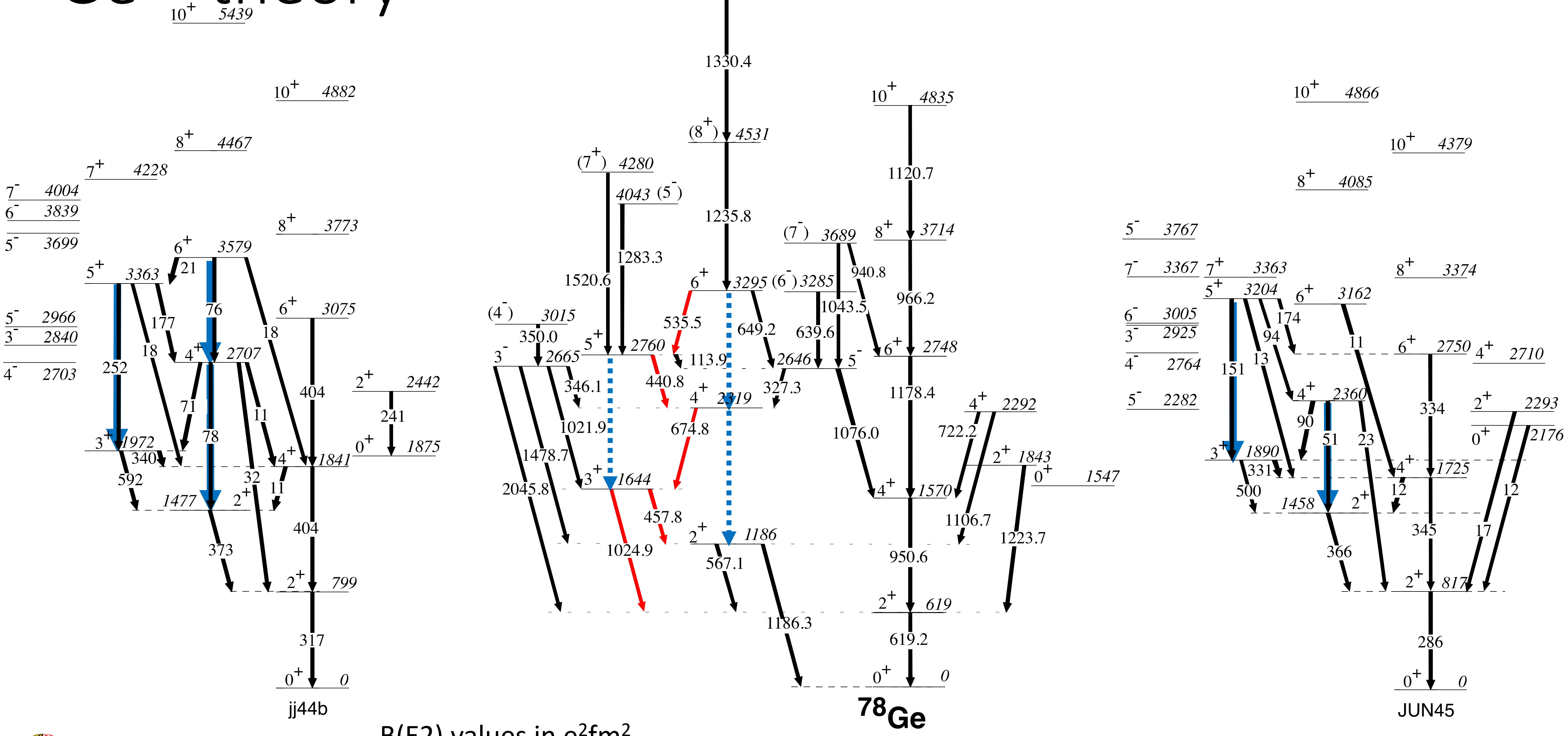
^{78}Ge – theory



B(E2) values in e^{2}fm^2

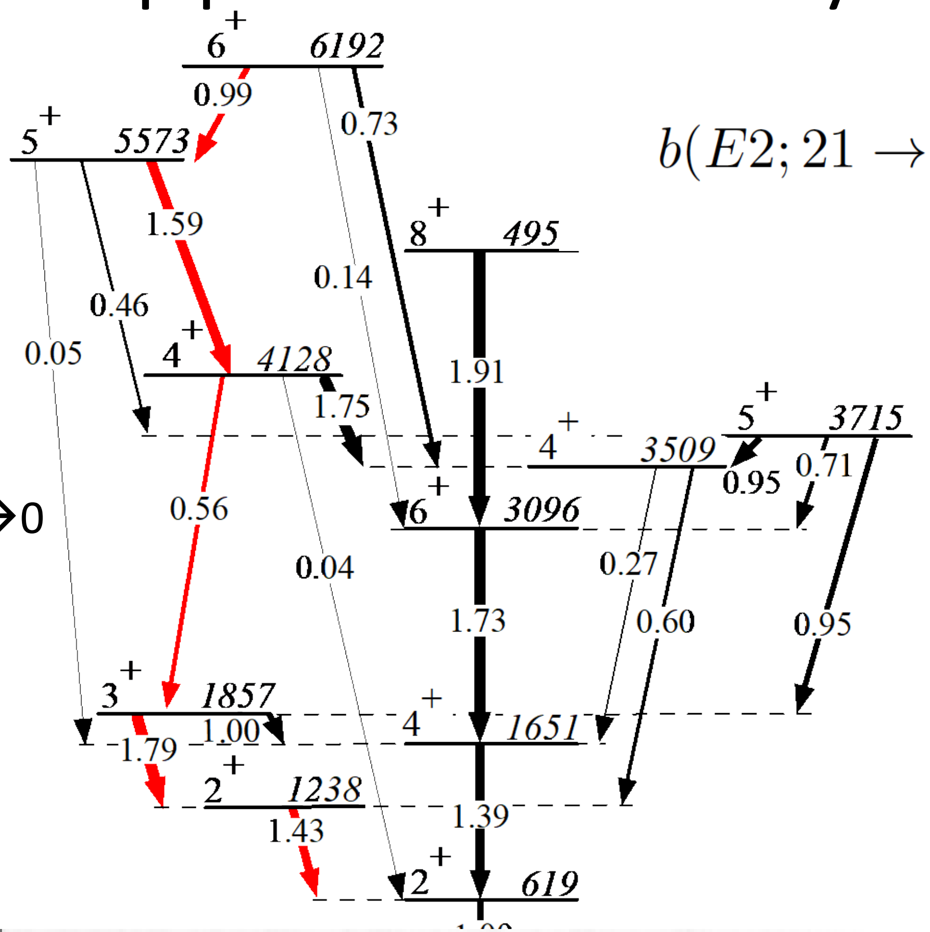
Davydov-Filippov-Rostovsky with γ=30° for ^{78}Ge

Occurs when these states have lost all symmetry.

-B(E2) arbitrary scale

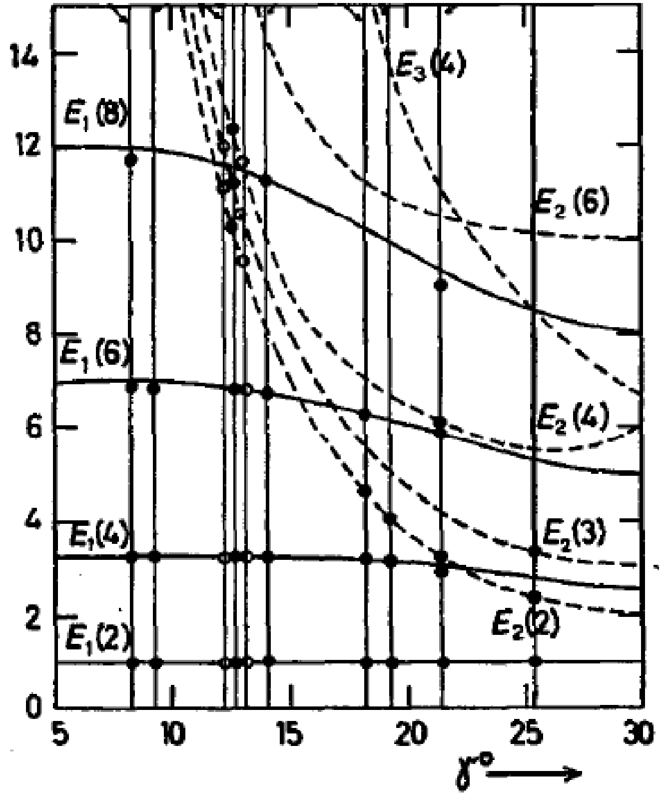
-Energies scaled to yrast 2→0

-Produces THREE 4+ levels



$$b(E2;21\to 0) = \frac{B(E2;21\to 0)}{\left(\frac{e^2 Q_0^2}{16\pi}\right)} = \frac{1}{2}\left[1-\frac{3-2\sin^2(3\gamma)}{\sqrt{9-8\sin^2(3\gamma)}}\right]$$

$$b(E2;22\to 21) = \frac{10}{7}\left[\frac{\sin^2(3\gamma)}{\sqrt{9-8\sin^2(3\gamma)}}\right]$$



Despite years of popularity of the Davydov model because of its simplicity and analytic formulas, there is virtually no evidence for rigid triaxial behavior. Axial asymmetry in nuclei seems associated with γ softness instead.

Casten 1990

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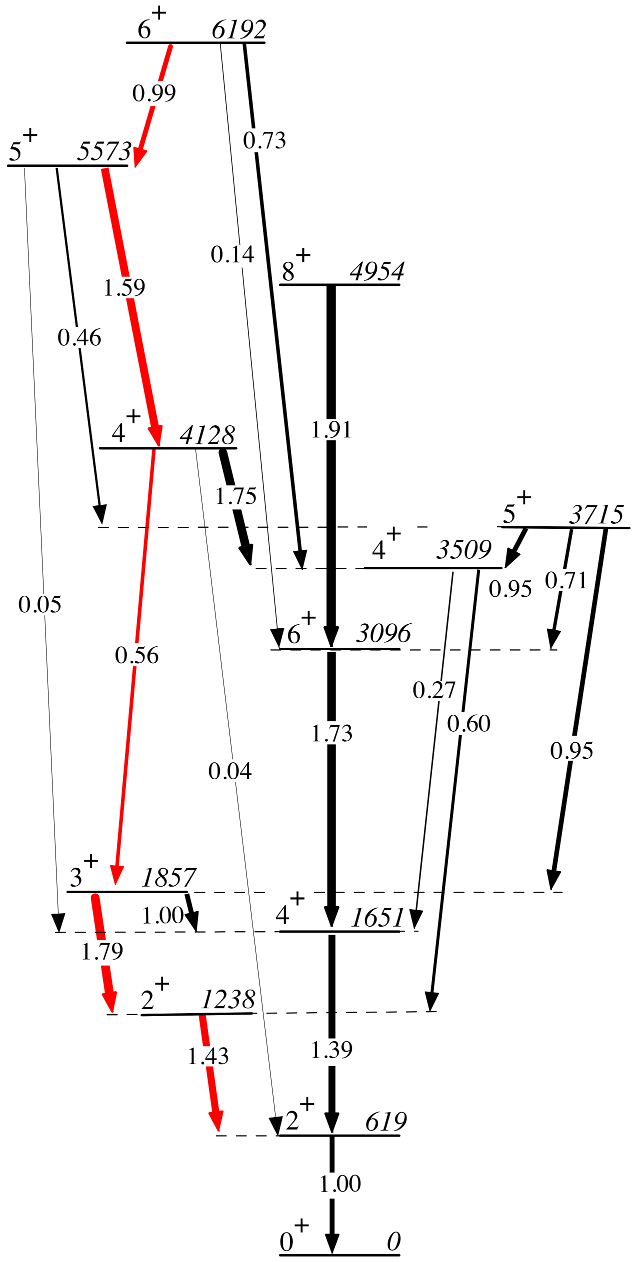
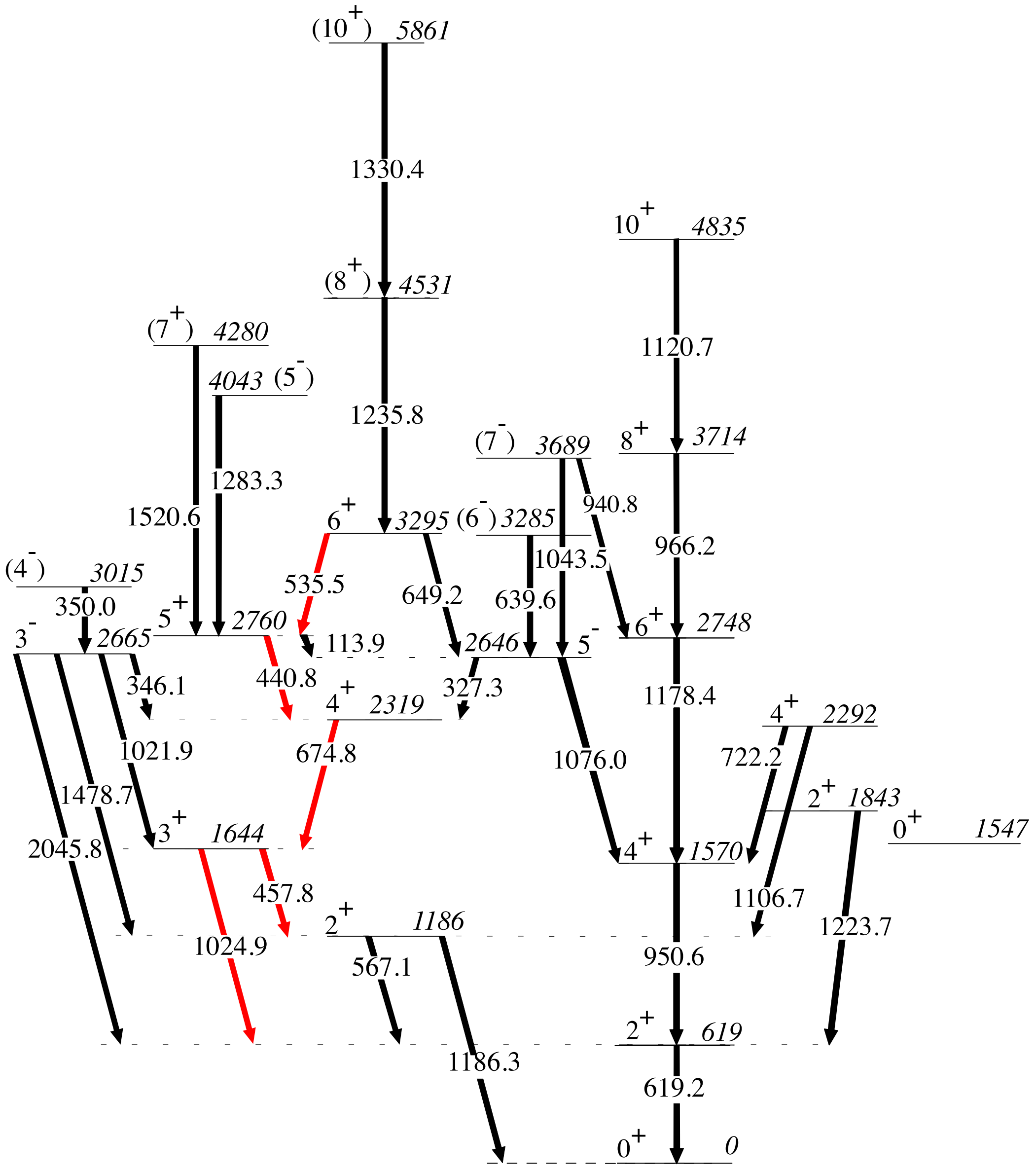


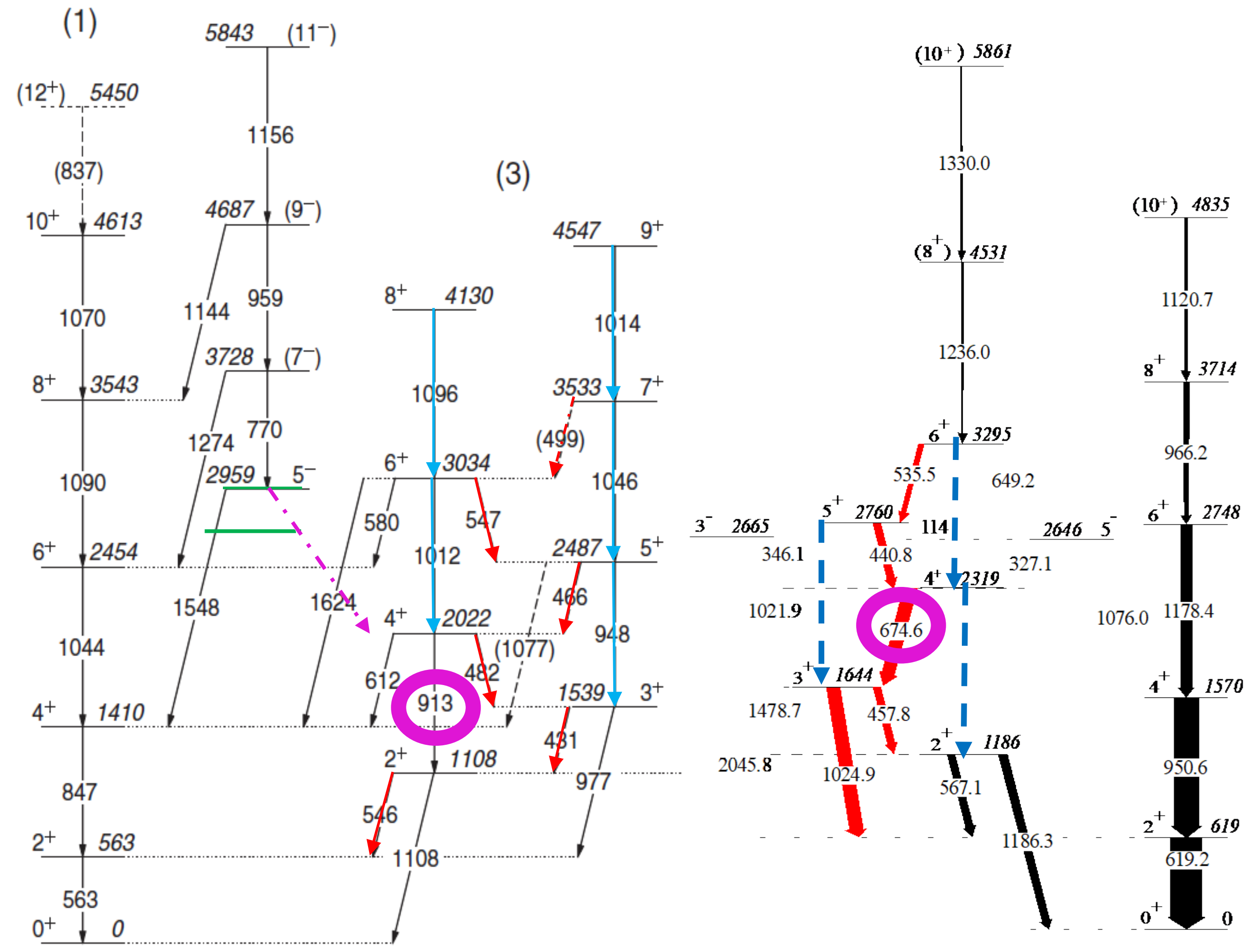
Davydov-Filippov-Rostovsky



^{78}Ge

Sequence unlike neighbors

	^{76}Ge	^{78}Ge
4^+ decay	ΔJ= 0, 1, 2	ΔJ=1
$4^+ \rightarrow 2^+$ branching	50 %	2 % (upper limit)
B(E2) $4^+ \rightarrow 2^+$ (W.u.)	18 (8)	0.007 (calculated upper limit)
δ (mixing ratio)	A2=+0.0167 , A4 =+0.049. $4_2^+ \rightarrow 4_1^+$	A2=+0.0157 (0.016), A4 =+0.074 (0.023). $4^+ \rightarrow 3^+$, $3^+ \rightarrow 2^+_2$



Y. Toh *et al*,. Phys Rev C **87**, (2013) 041304 (R).

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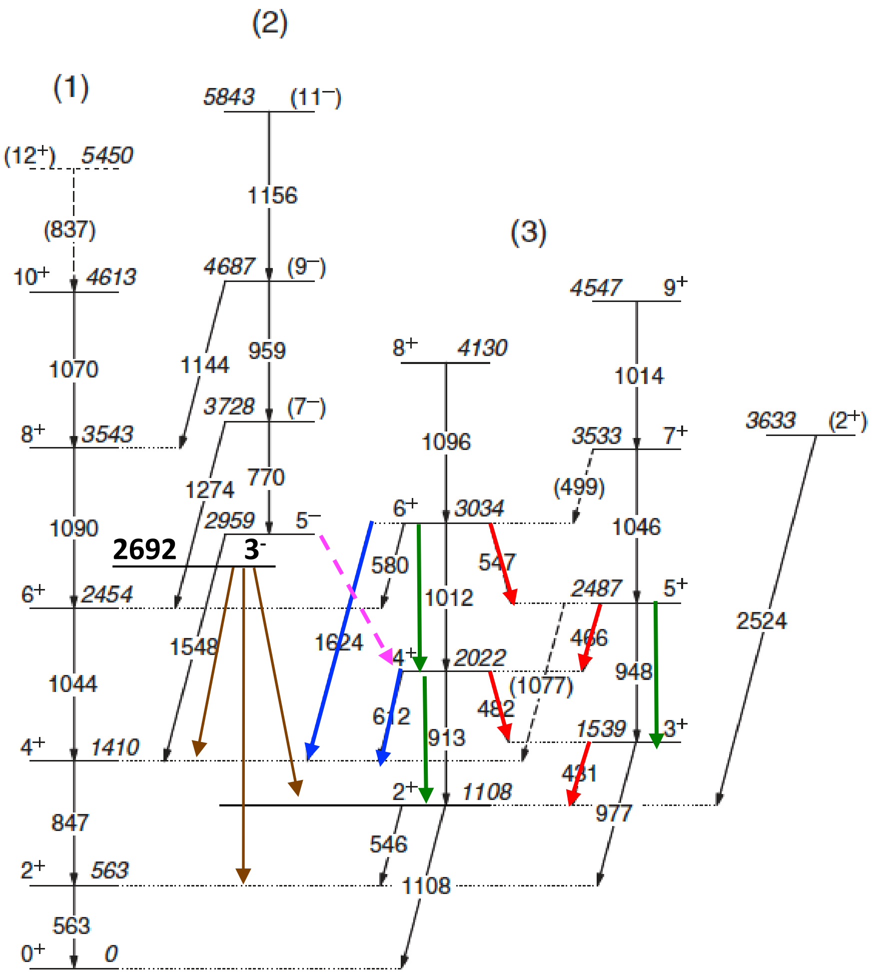


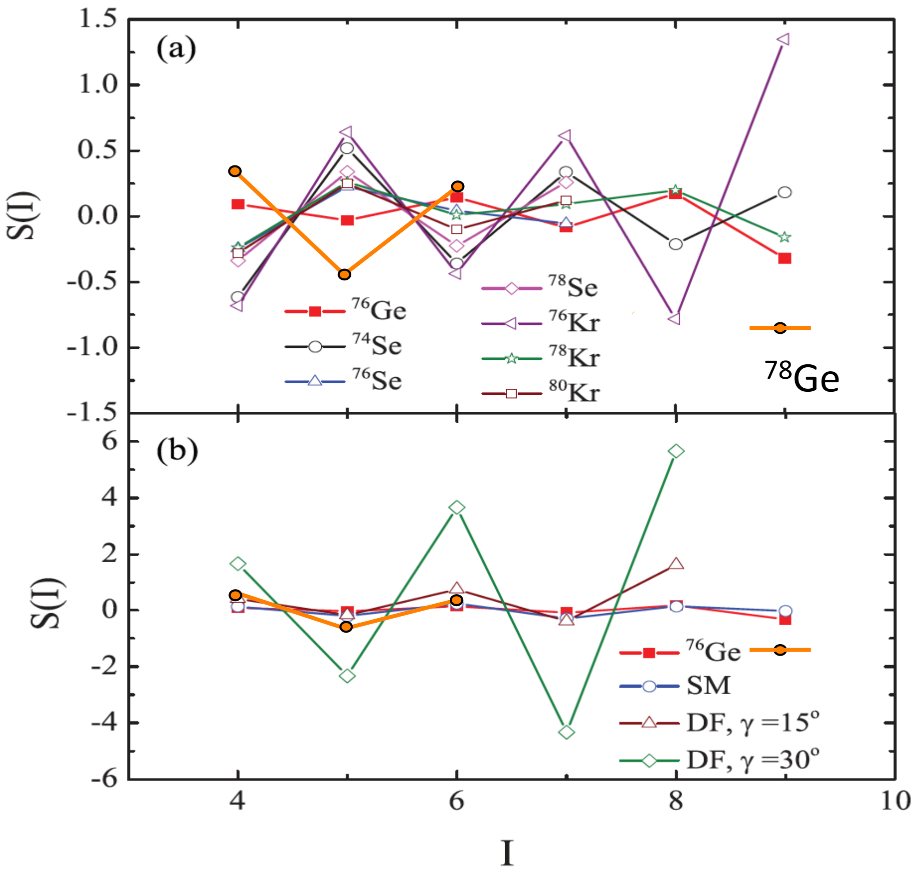
FIG. 1. Partial level scheme of ^{76}Ge deduced from the prompt data in this work. Level and transition energies are given in keV. Only those states relevant to the discussion are shown; all are given in Table I.

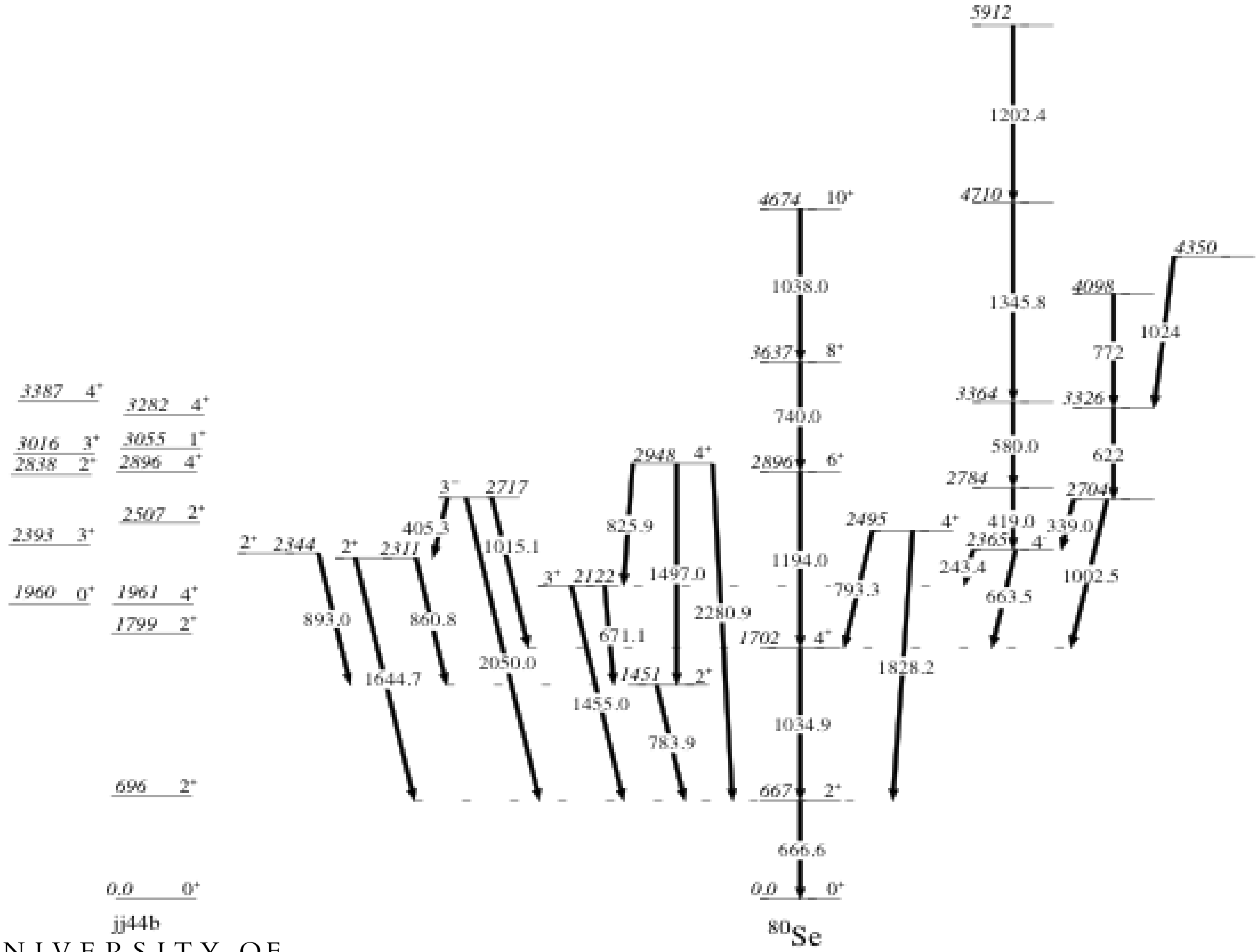
Evidence for rigid triaxial deformation at low energy in ^{76}Ge

Y. Toh,[1,2] C. J. Chiara,[2,3] E. A. McCutchan,[2,4] W. B. Walters,[3] R. V. F. Janssens,[2] M. P. Carpenter,[2] S. Zhu,[2] R. Broda,[5] B. Fornal,[5] B. P. Kay,[2] F. G. Kondev,[6] W. Królas,[5] T. Lauritsen,[2] C. J. Lister,[2,*] T. Pawłat,[5] D. Seweryniak,[2] I. Stefanescu,[2,3] N. J. Stone,[7,8] J. Wrzesiński,[5] K. Higashiyama,[9] and N. Yoshinaga[10]

TABLE I. Staggering values $S(J)$ observed in the even $_{32}$Ge and $_{34}$Se isotopes for $J = 4, 5, 6$.

	^{78}Ge$_{46}$	^{76}Ge$_{44}$	^{74}Ge$_{42}$	^{72}Ge$_{40}$
$S(4)$	0.35	0.09	-0.04	-0.24
$S(5)$	-0.38	-0.03	0.11	0.26
$S(6)$	0.15	0.15	0.14	-0.35
	^{80}Se$_{46}$	^{78}Se$_{44}$	^{76}Se$_{42}$	^{74}Se$_{40}$
$S(4)$	-0.36	-0.25	-0.16	-0.53
$S(5)$		0.25	0.15	0.4
$S(6)$		-0.17	0.03	-0.28





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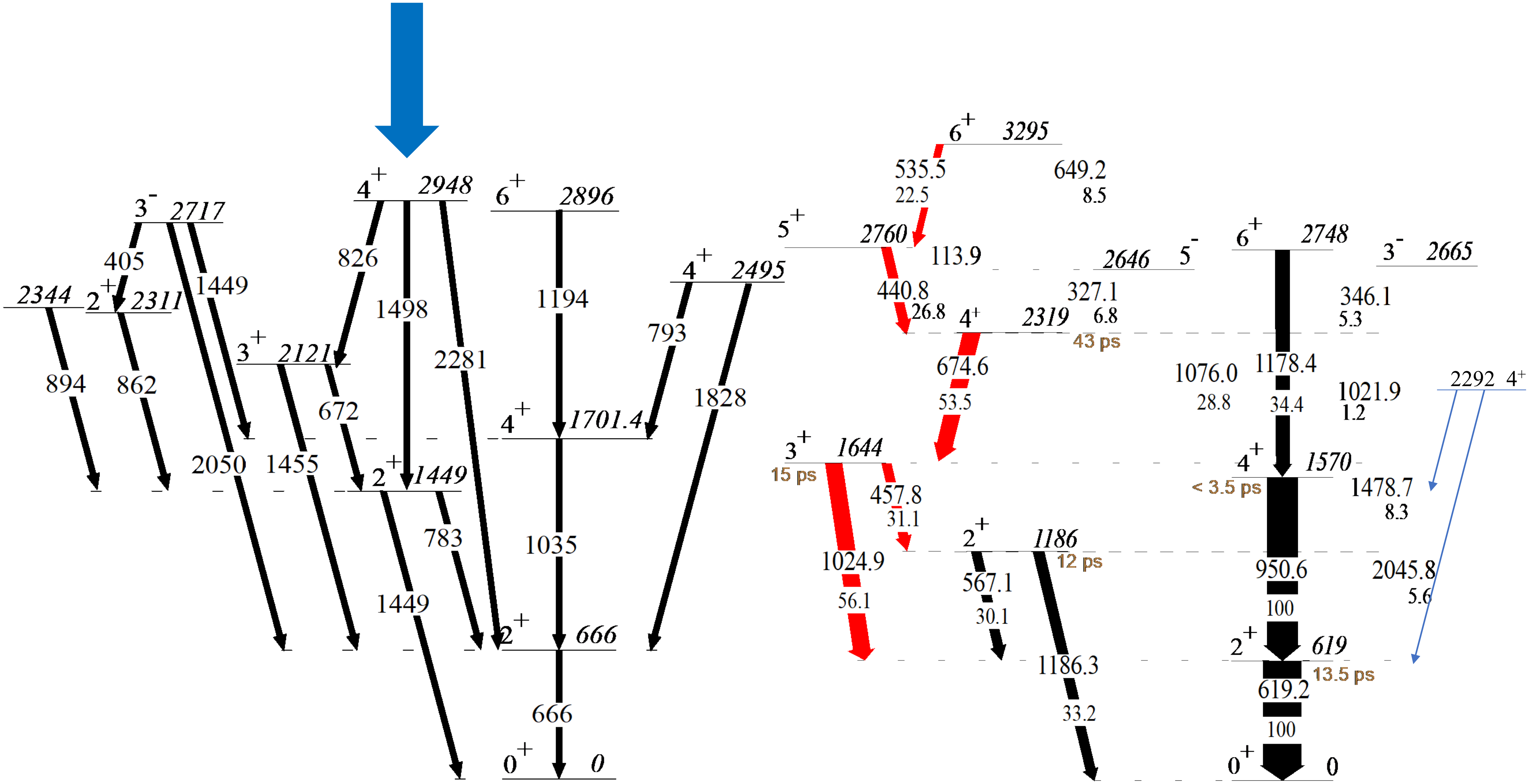
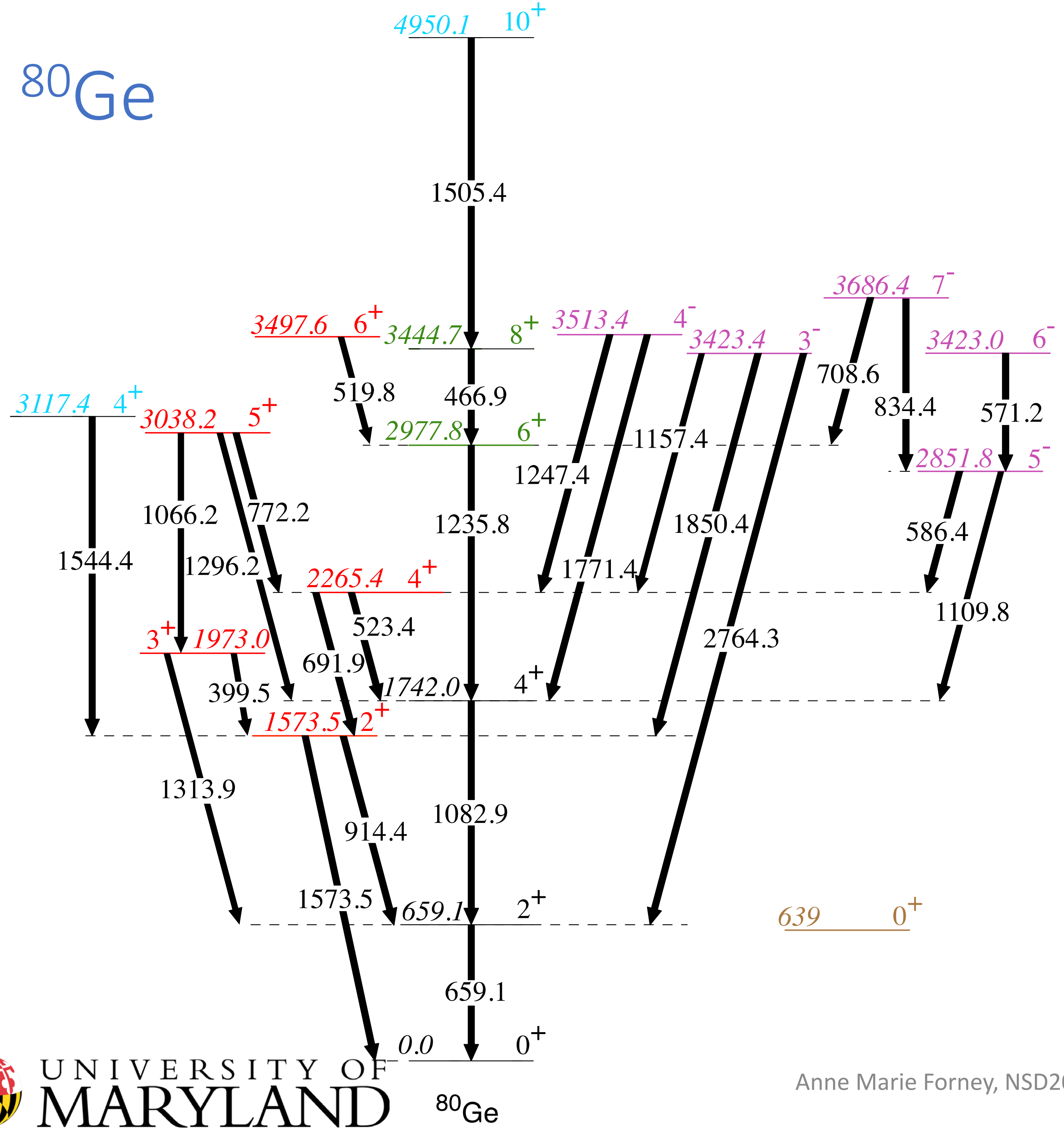


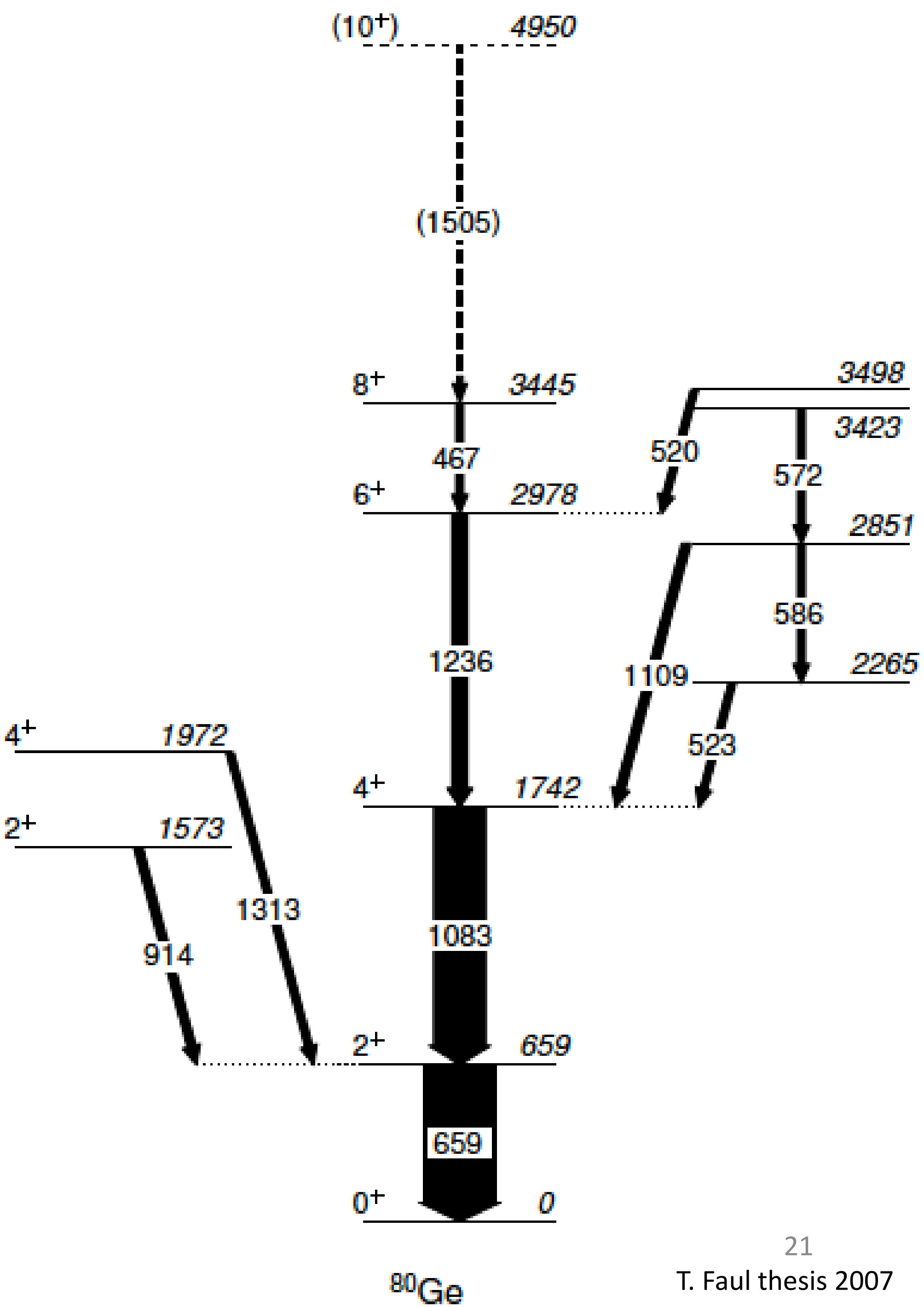
^{80}Se

^{78}Ge

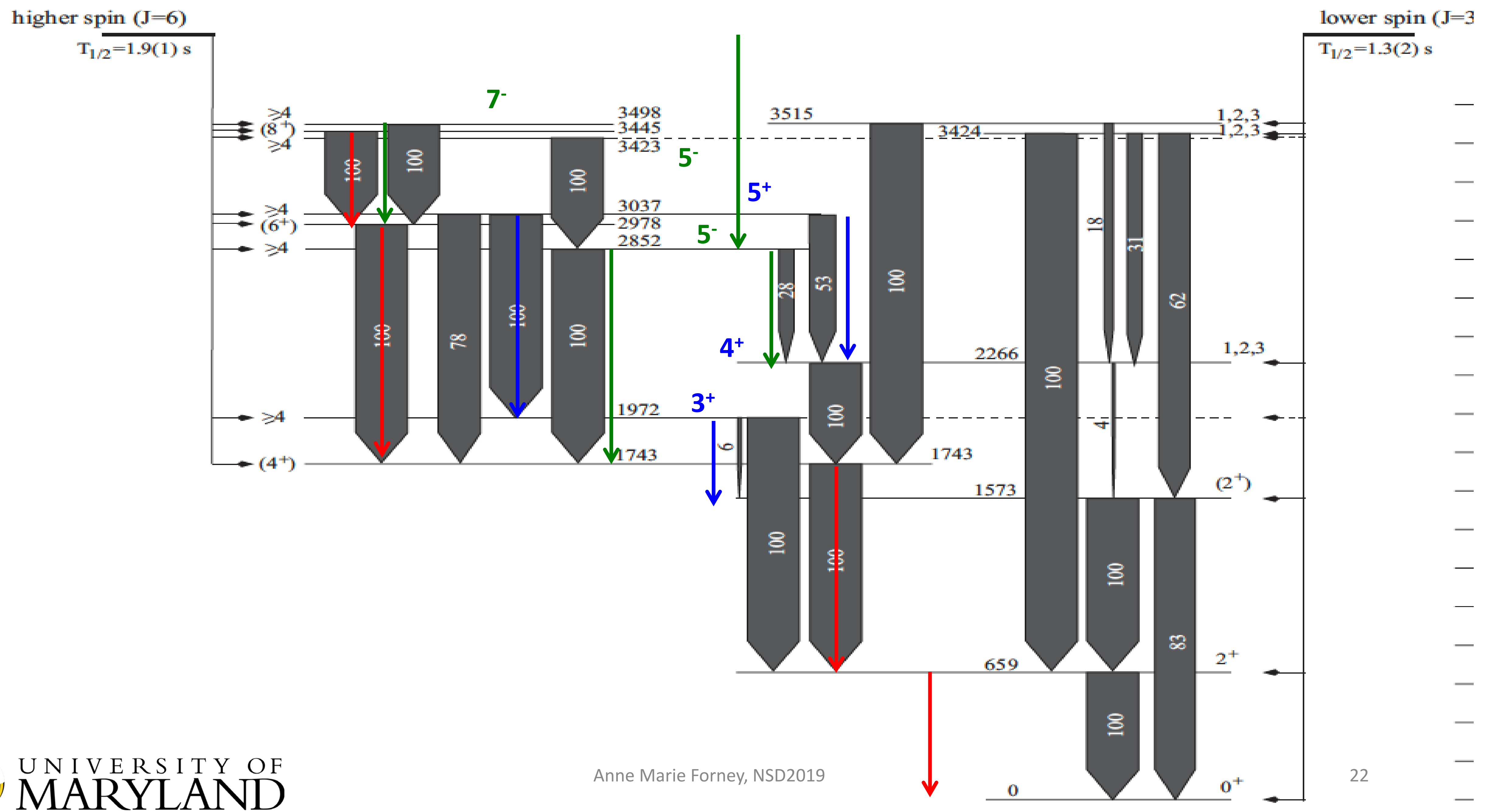
Halflives: W.-T. Chou *et al.*, Phys. Rev. C **47** (1993).

^{80}Ge





T. Faul thesis 2007


higher spin (J=6)
$T_{1/2}$=1.9(1) s
lower spin (J=3
$T_{1/2}$=1.3(2) s
7-
5-
5+
5-
4+
3+
3498
3445
3423
3037
2978
2852
1972
1743
3515
3424
2266
1743
1573
659
0
≥4
(8+)
≥4
≥4
(6+)
≥4
≥4
(4+)
1,2,3
1,2,3
1,2,3
(2+)
2+
0+
100
100
100
100
78
100
100
28
53
100
100
18
31
62
100
4
6
100
100
100
83
100

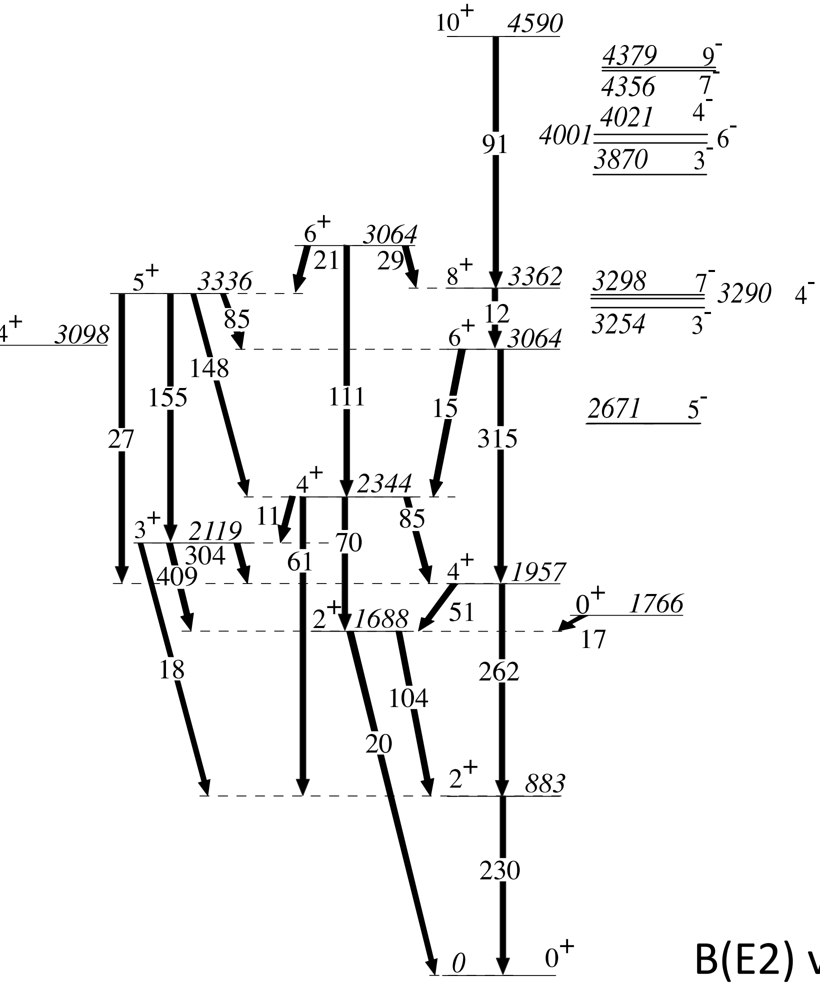
^{80}Ge

PHYSICAL REVIEW C **78**, 021304(R) (2008)

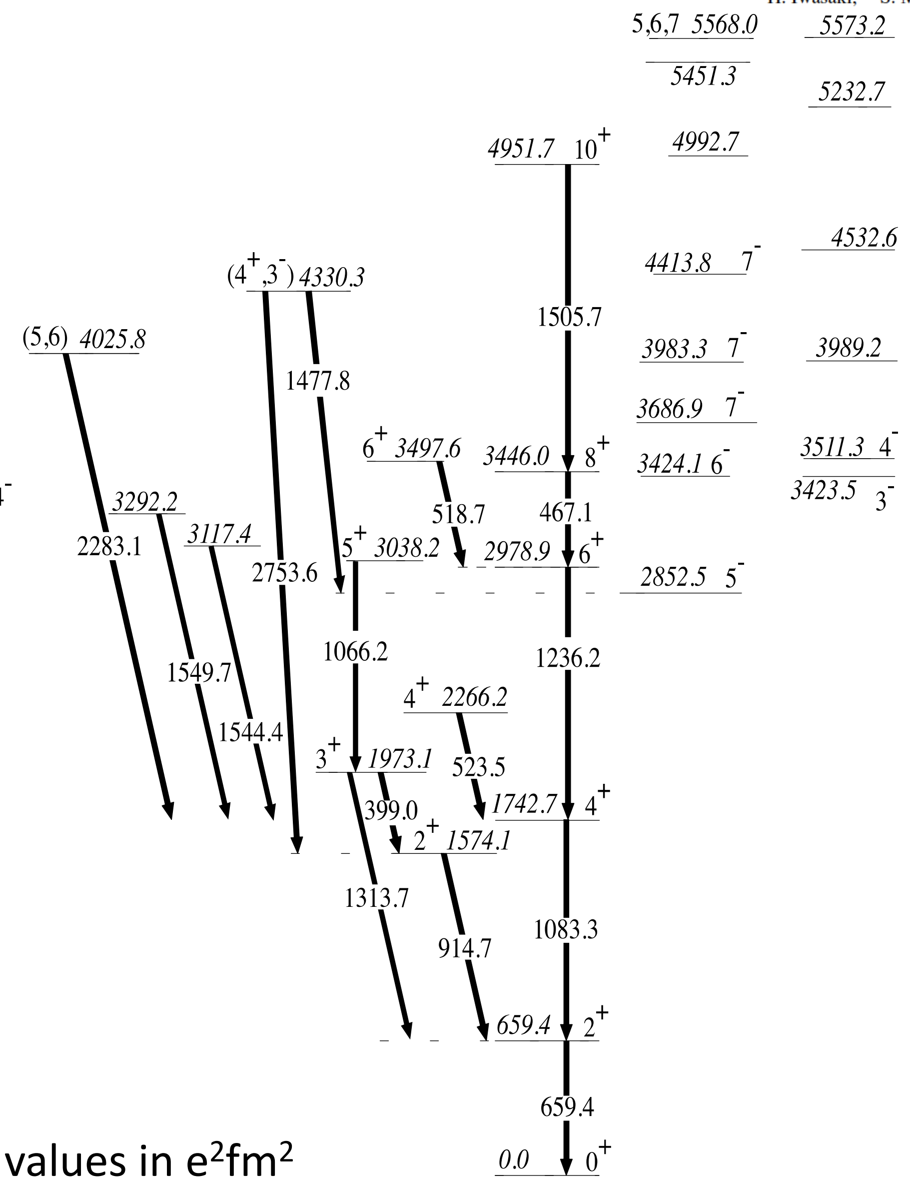
Persistence of the $N = 50$ shell closure in the neutron-rich isotope ^{80}Ge

H. Iwasaki,[1,*] S. Michimasa,[2] M. Niikura,[2] M. Tamaki,[2] N. Aoi,[3] H. Sakurai,[3] S. Shimoura,[2] S. Takeuchi,[3] S. Ota,[4]

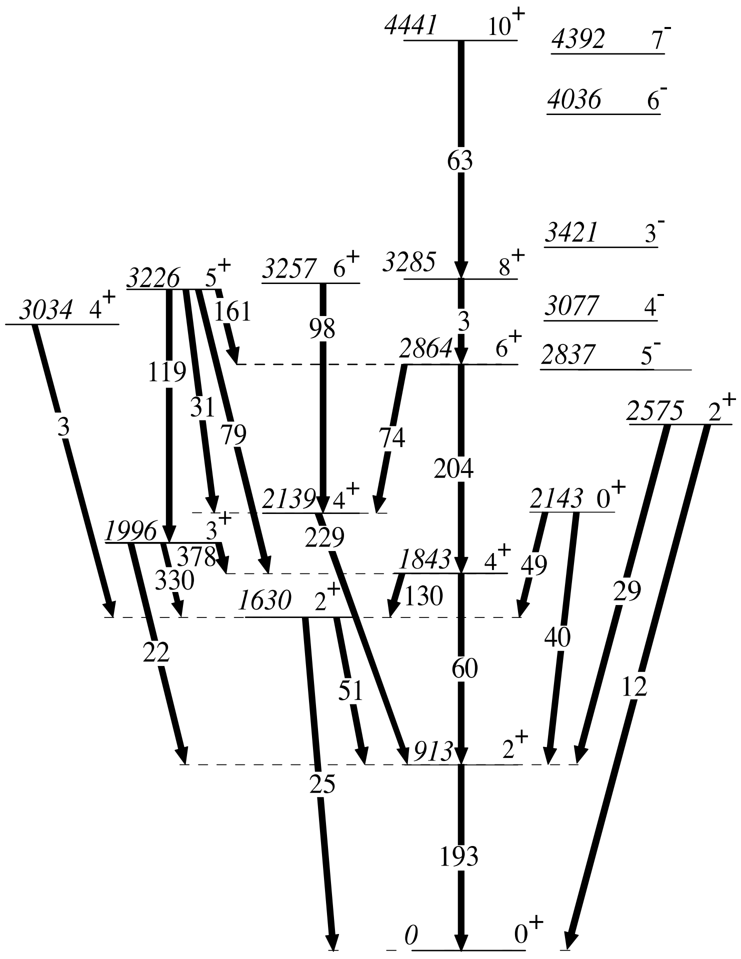
^{A}Z	J^{π}	E_x (keV)	σ_{exp} (mb)	$B(E2)_{\text{exp}}$	$B(E2)_{\text{ref}}$	$B(E2)_{\text{thr}}$
^{80}Ge	2_1^+	662(7)	469(52)	200(26)	278(54)	256
	2_2^+	1579(15)	59(19)	23(7)	–	20



J44b



Experiment



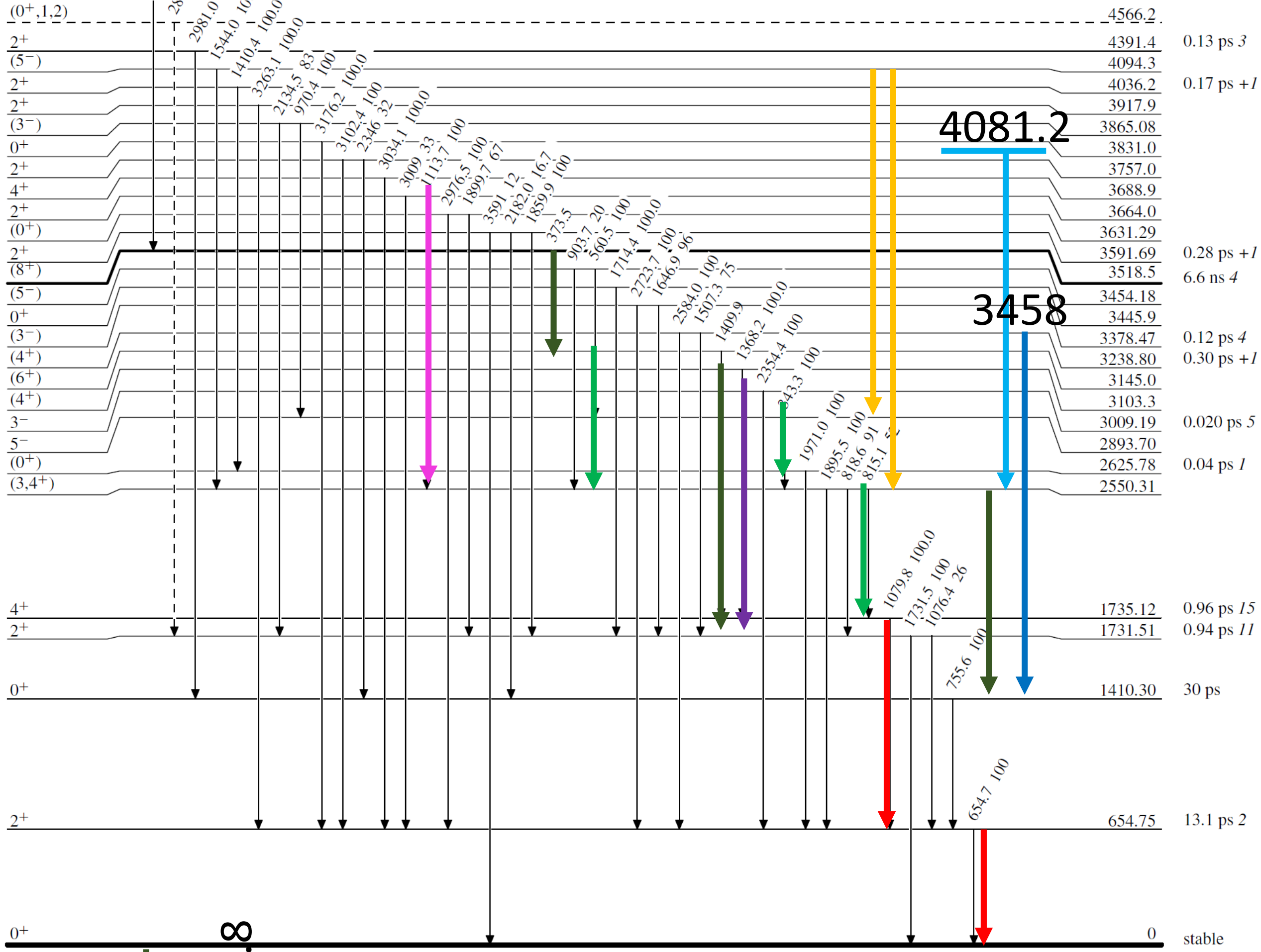
JUN45

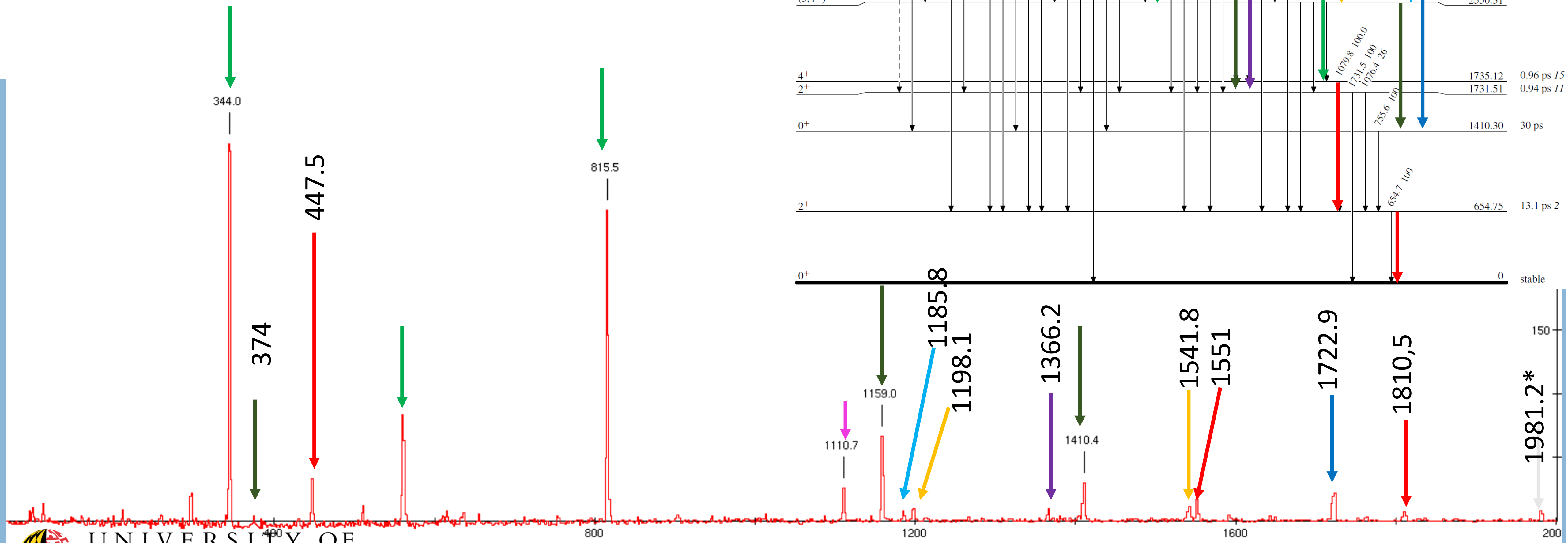
B(E2) values in e^{2}fm^2

^{82}Se

DDD yrast 655/1080.8:

*side of 1896 peak—leak through





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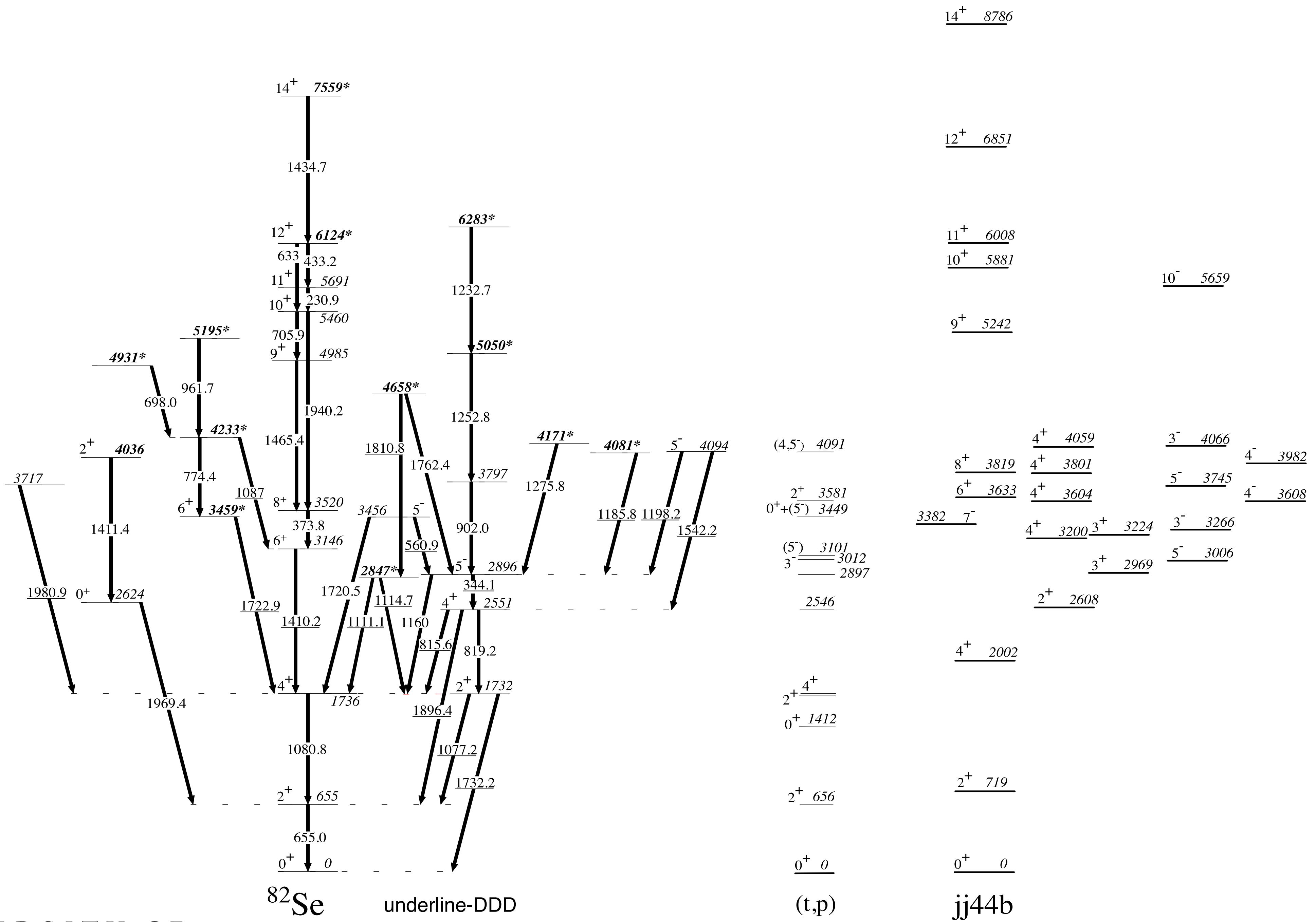
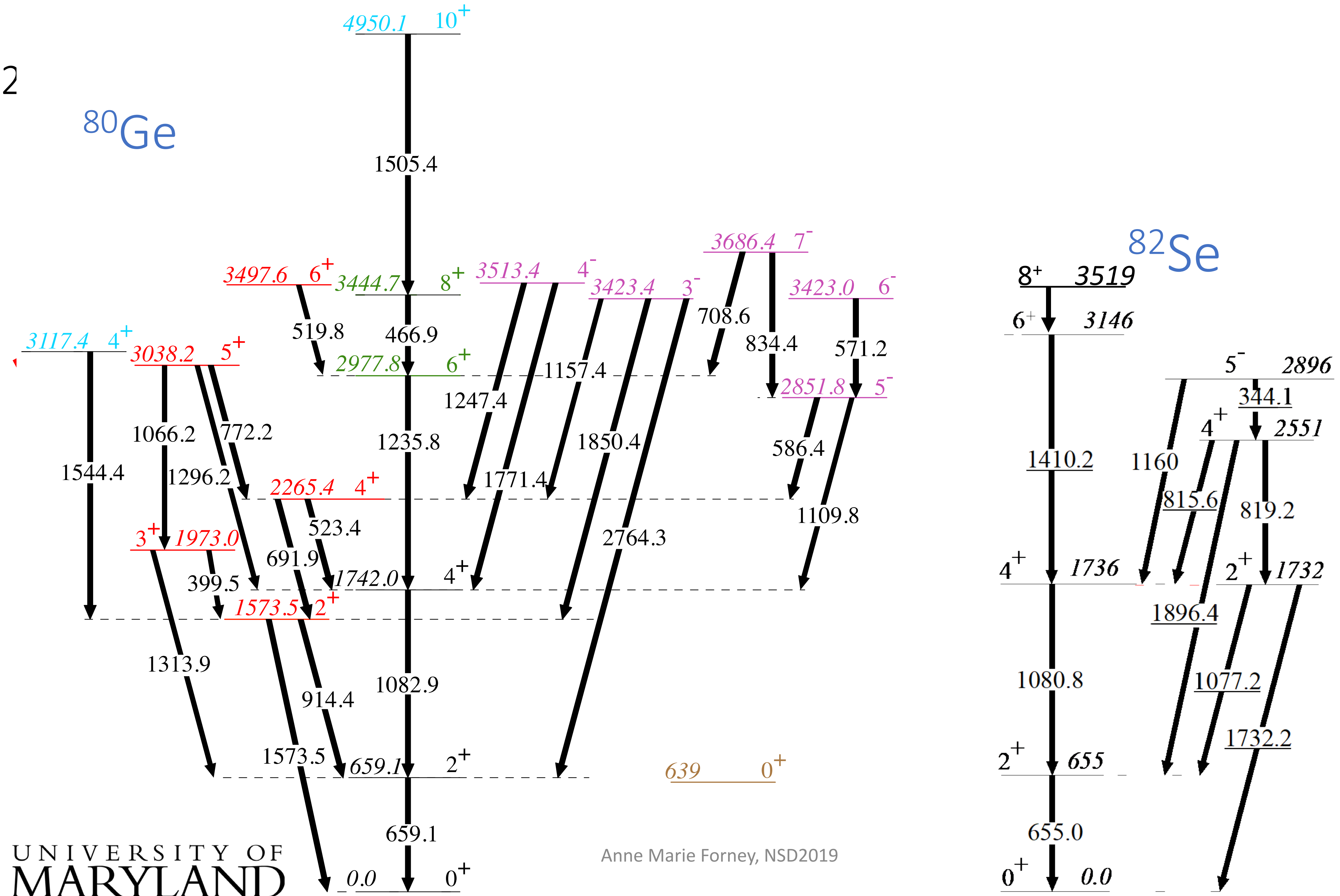

82Se
underline-DDD
(t,p)
jj44b

82



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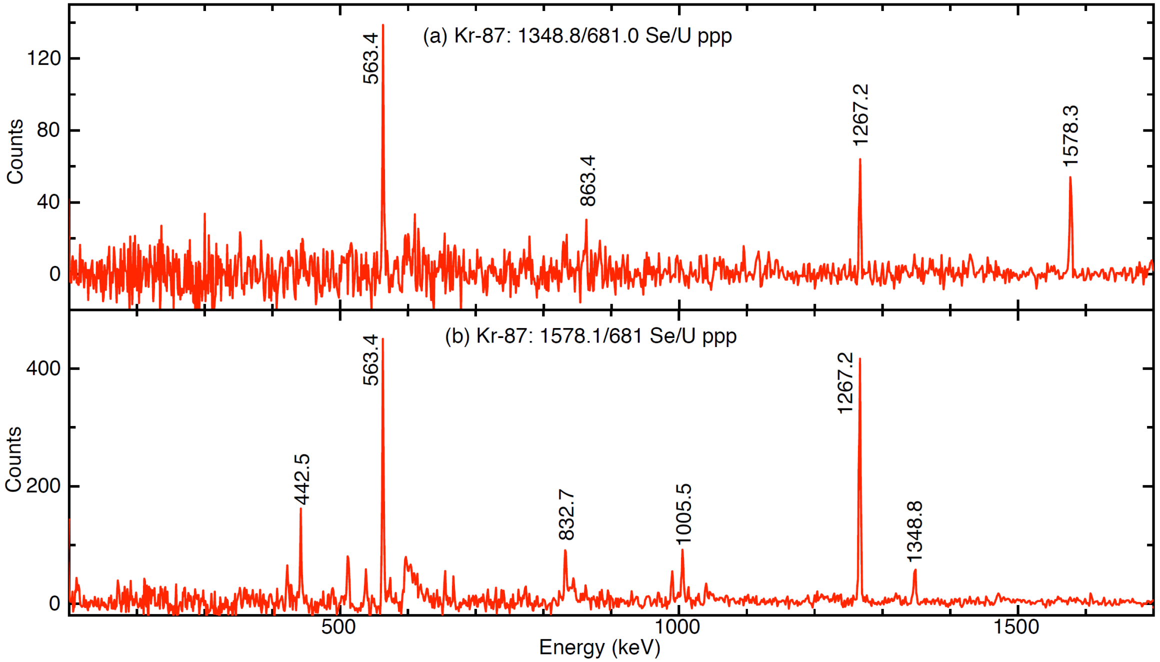

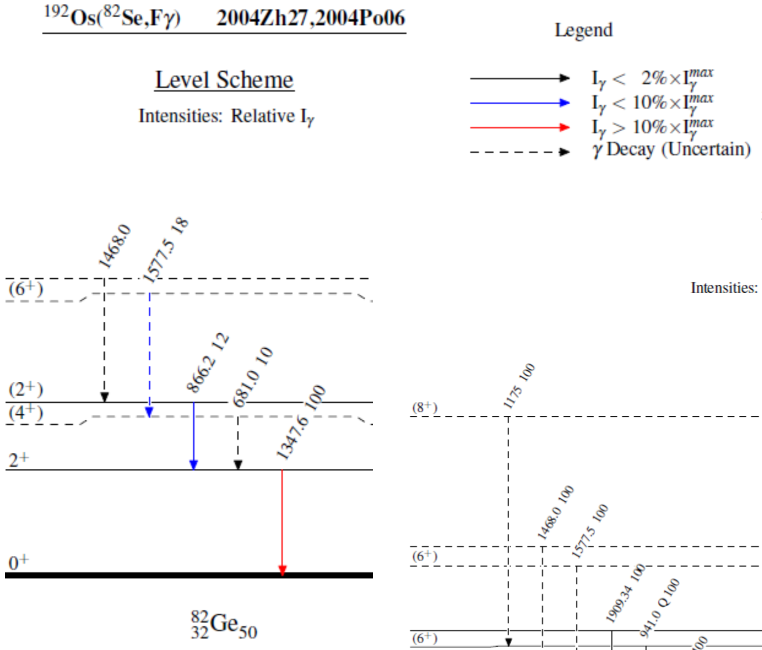

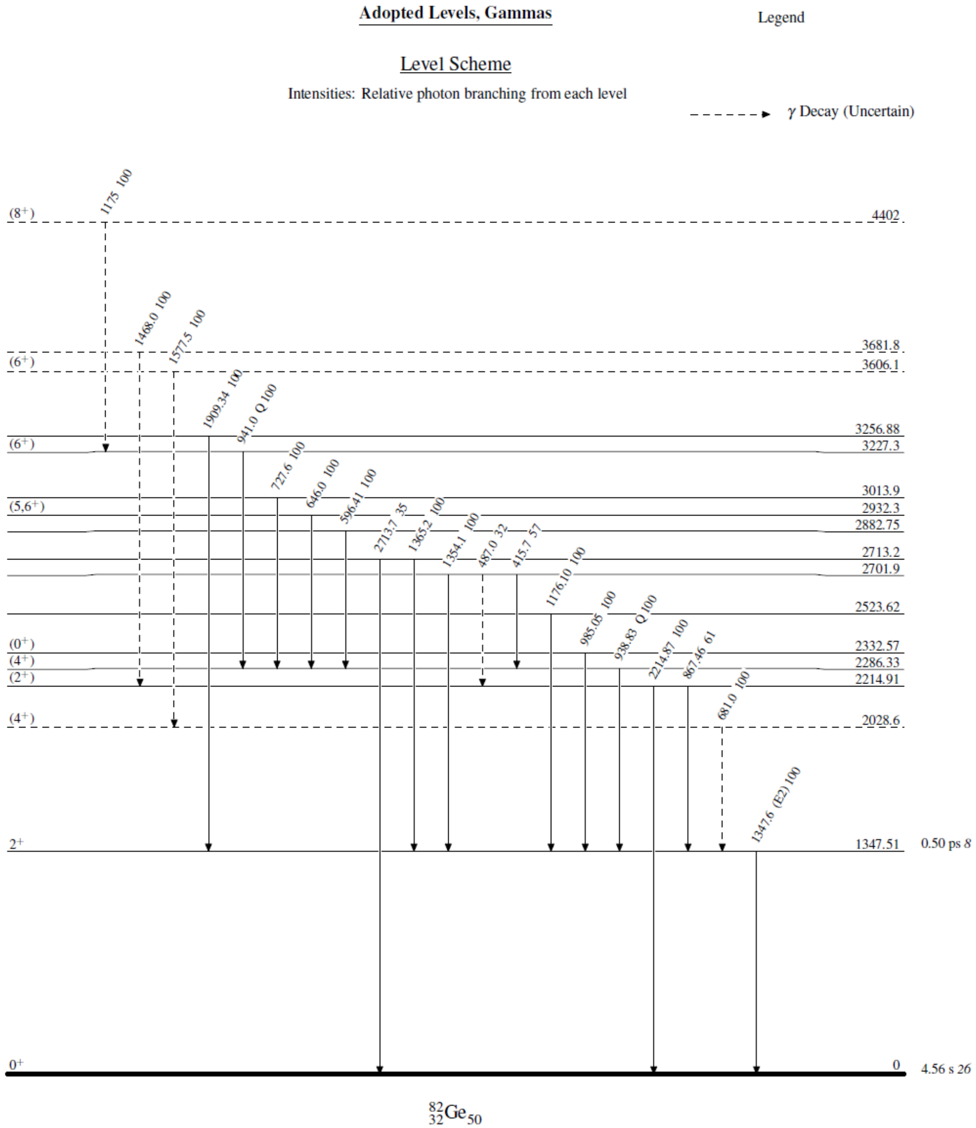

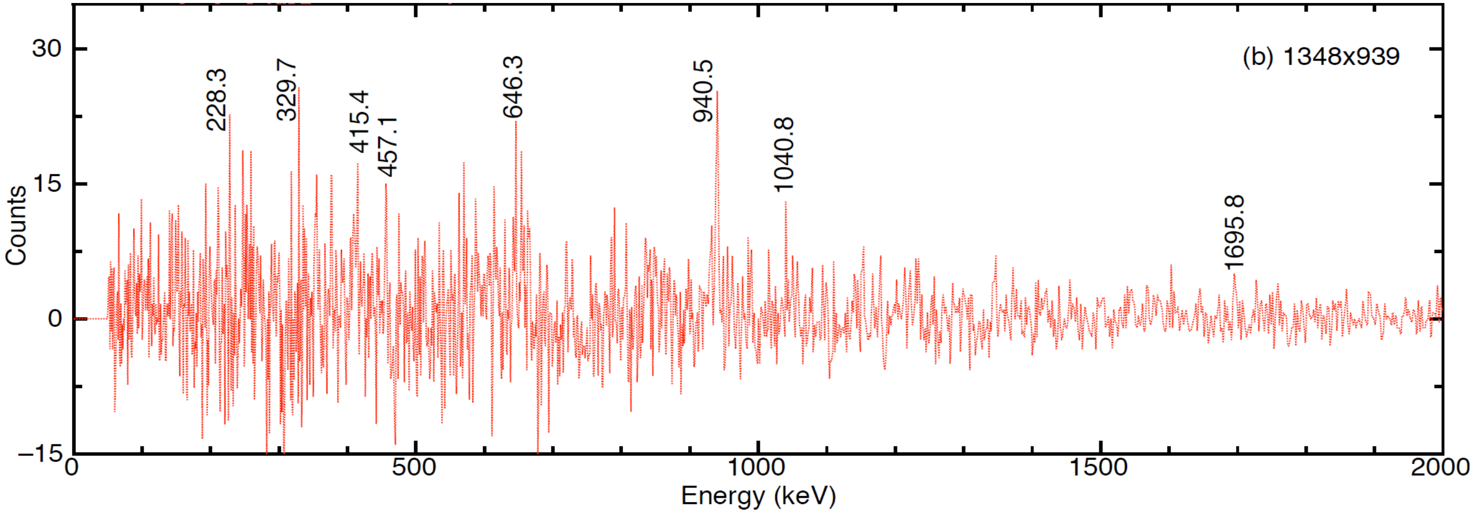

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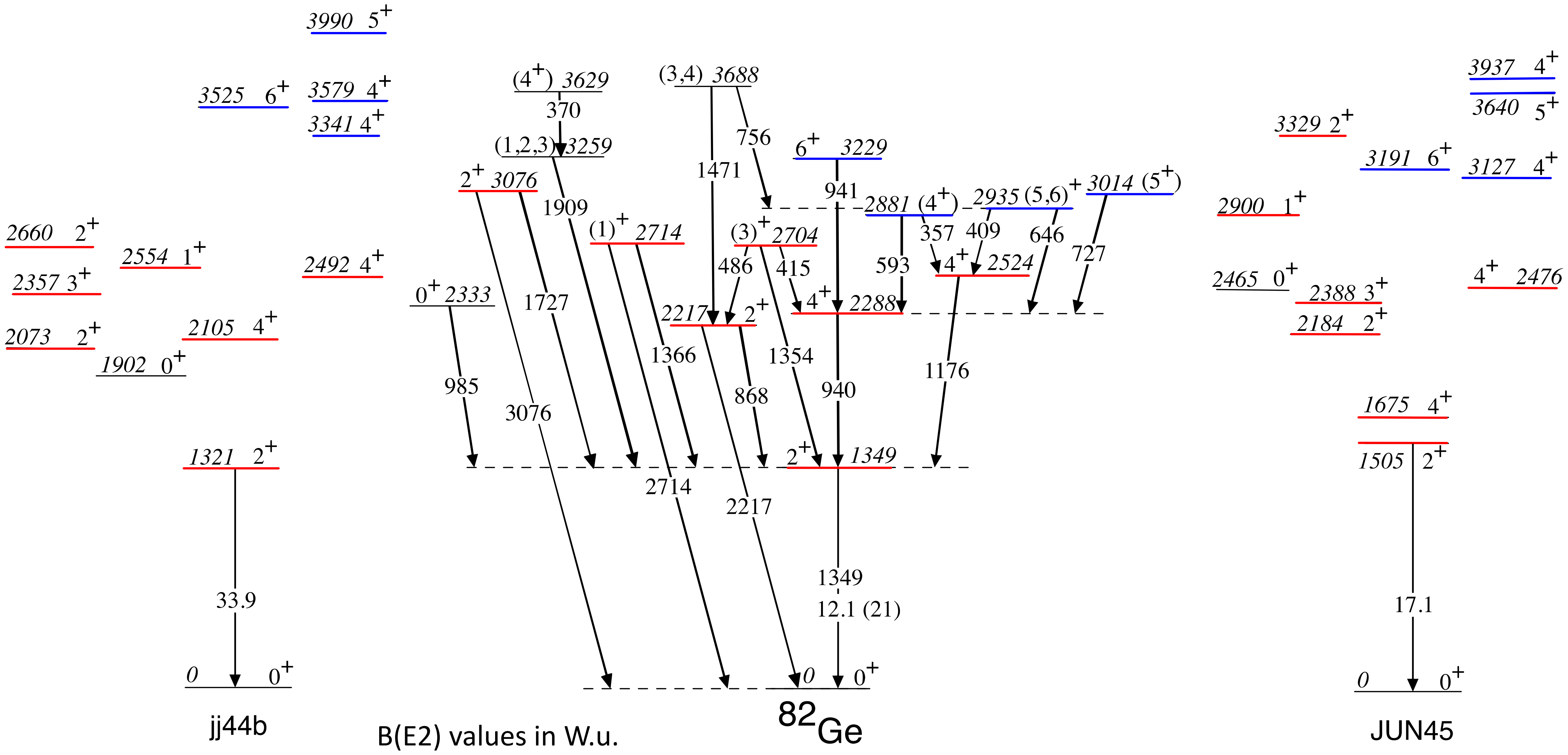
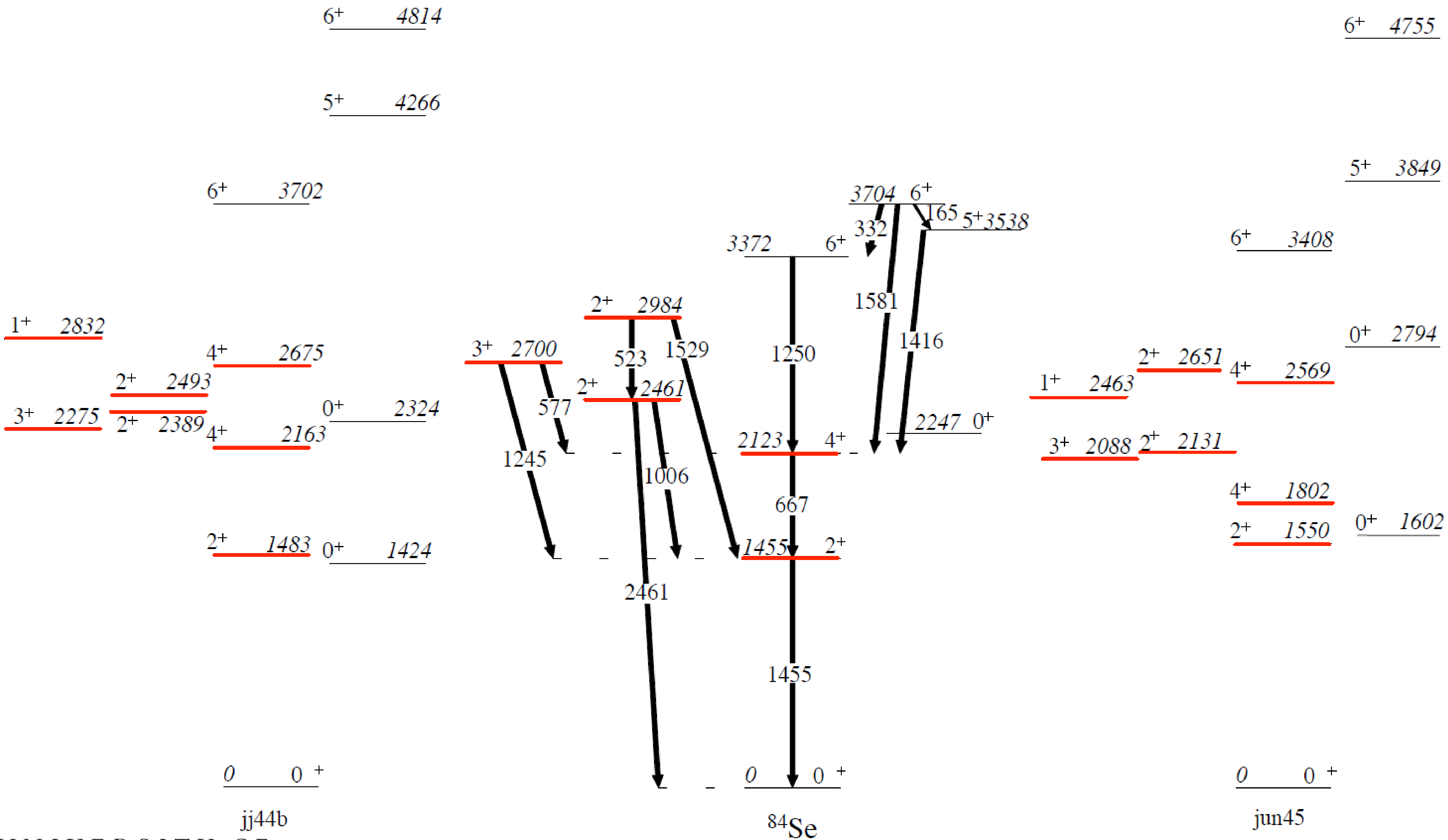


B(E2) values in W.u.

^{82}Ge

Red levels: Two-particle states of $f_{5/2}$ $p_{3/2}$



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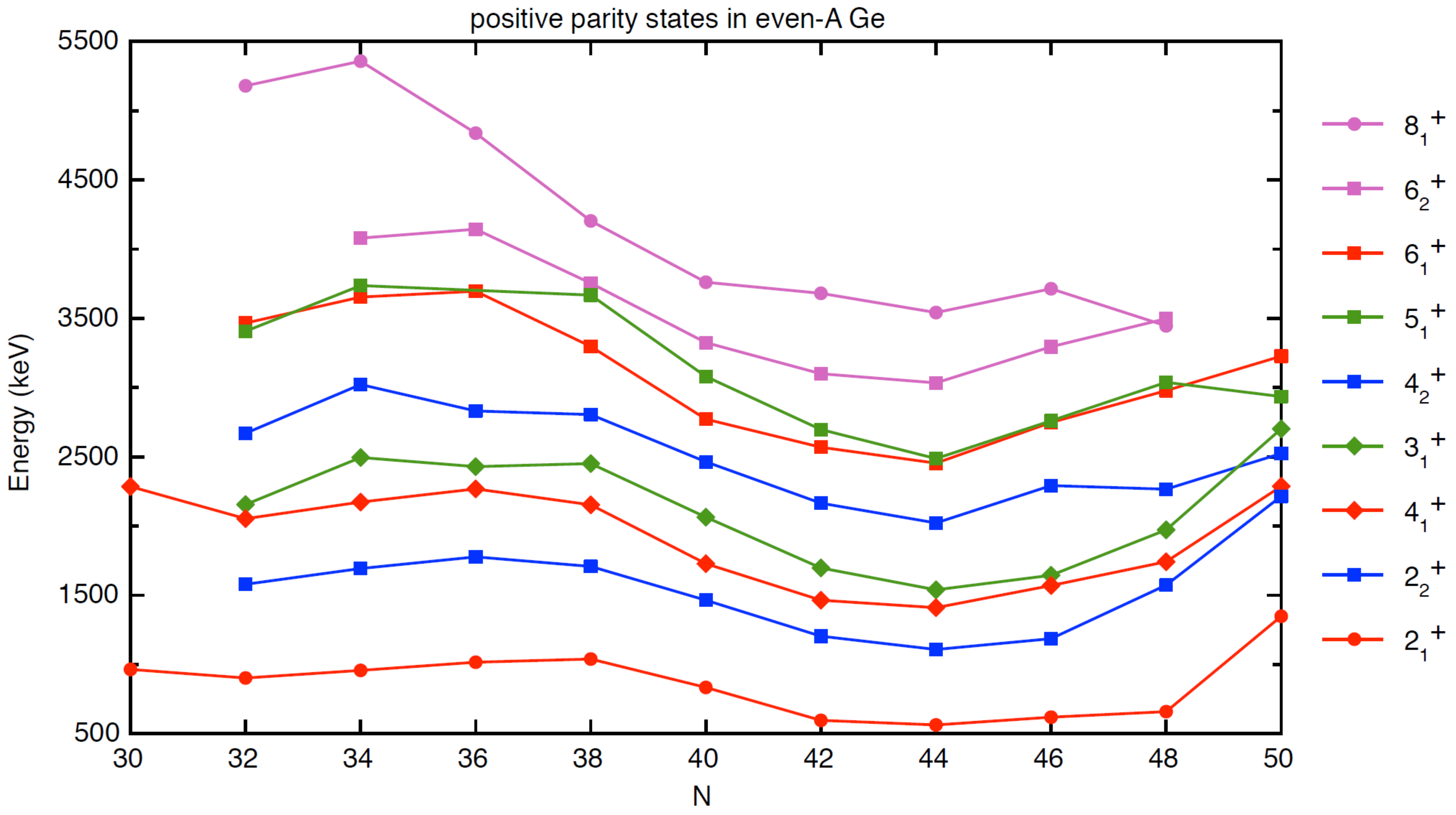
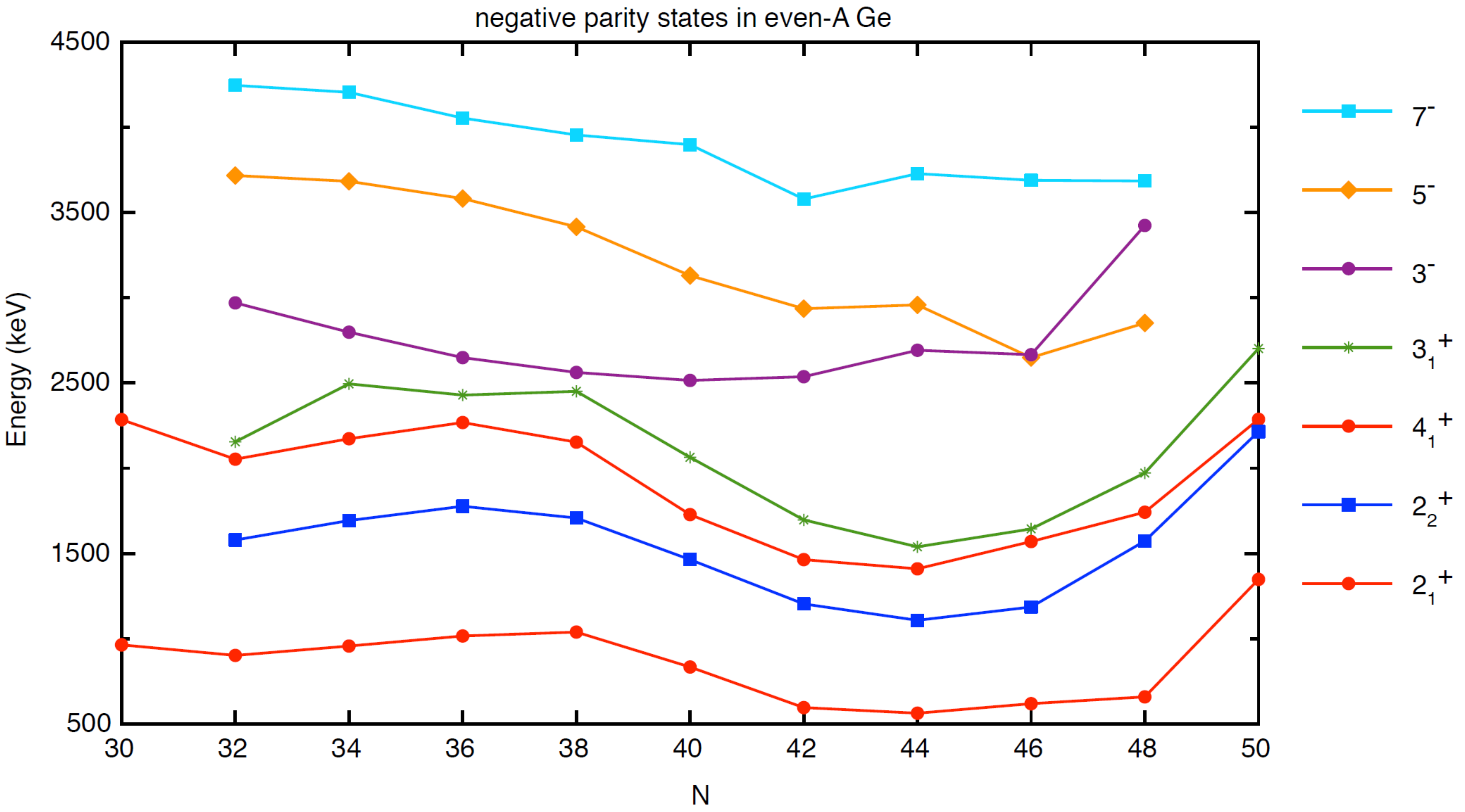

positive parity states in even-A Ge
Energy (keV)
N
5500
4500
3500
2500
1500
500
30
32
34
36
38
40
42
44
46
48
50
8_1^+
6_2^+
6_1^+
5_1^+
4_2^+
3_1^+
4_1^+
2_2^+
2_1^+



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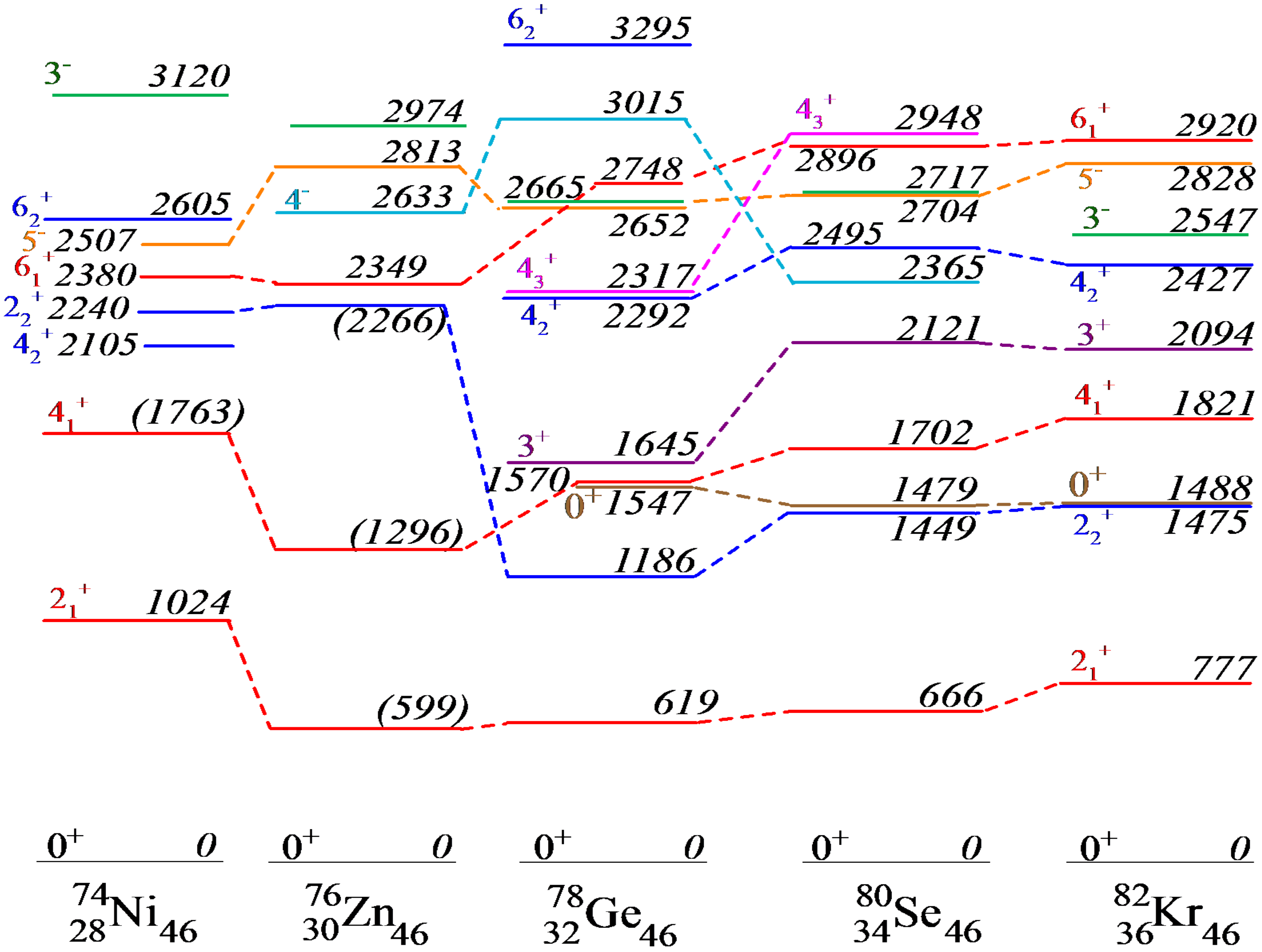

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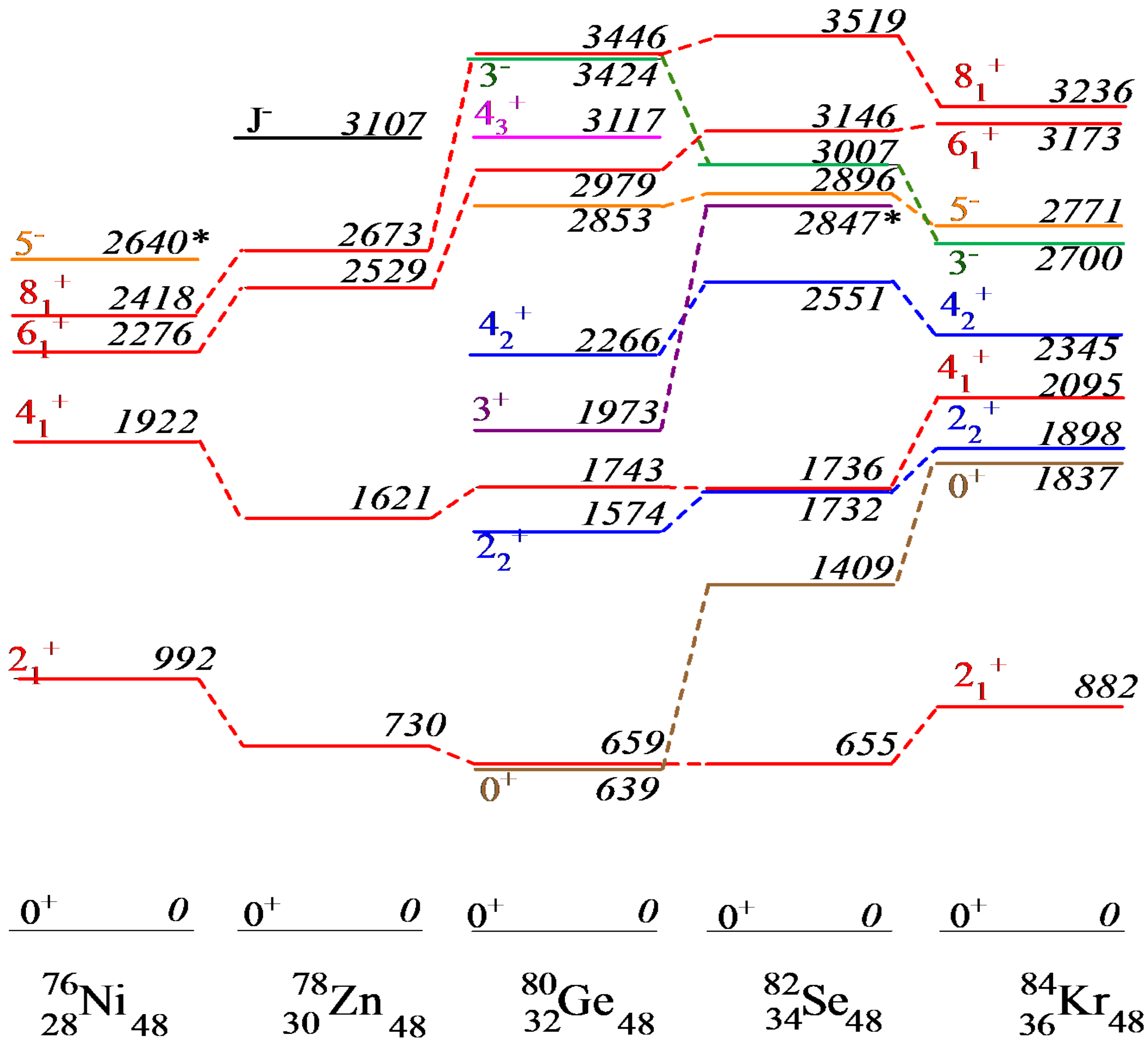
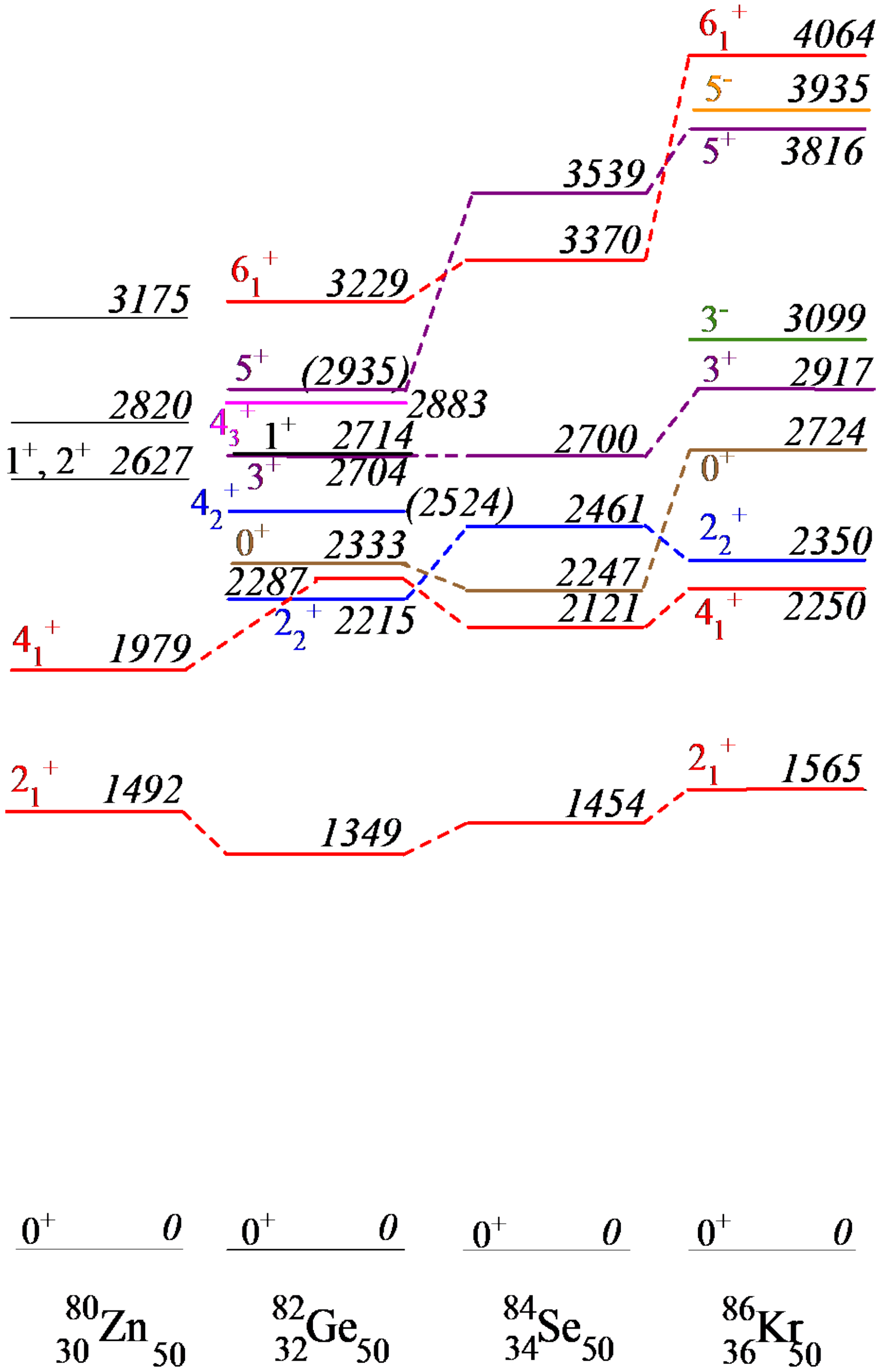

3446
3519
3⁻ 3424
8_1^+ 3236
J⁻ 3107
4_3^+ 3117
3146
6_1^+ 3173
3007
2979
2896
2853
2847*
5⁻ 2771
5⁻ 2640*
2673
2529
3⁻ 2700
8_1^+ 2418
6_1^+ 2276
2551
4_2^+ 2266
4_2^+ 2345
4_1^+ 2095
3⁺ 1973
4_1^+ 1922
2_2^+ 1898
0⁺ 1837
1743
1736
1621
1574
1732
2_2^+
1409
2_1^+ 992
2_1^+ 882
730
659
655
0⁺ 639
0⁺ 0
0⁺ 0
0⁺ 0
0⁺ 0
0⁺ 0
$^{76}_{28}Ni_{48}$
$^{78}_{30}Zn_{48}$
$^{80}_{32}Ge_{48}$
$^{82}_{34}Se_{48}$
$^{84}_{36}Kr_{48}$


6₁⁺ 4064
5⁻ 3935
5⁺ 3816
3539
3370
3175
6₁⁺ 3229
3⁻ 3099
5⁺ (2935)
2883
3⁺ 2917
2820
4₃⁺ 1⁺ 2714
2700
2724
1⁺, 2⁺ 2627
3⁺ 2704
0⁺
4₂⁺ (2524)
2461
2₂⁺ 2350
0⁺ 2333
2287
2247
2121
4₁⁺ 2250
2₂⁺ 2215
4₁⁺ 1979
2₁⁺ 1565
2₁⁺ 1492
1454
1349
0⁺ 0
0⁺ 0
0⁺ 0
0⁺ 0
$^{80}_{30}Zn_{50}$
$^{82}_{32}Ge_{50}$
$^{84}_{34}Se_{50}$
$^{86}_{36}Kr_{50}$

Conclusions and Questions

- Newly reported transitions in $^{78,80}Ge$ and $^{80,82}Se$
- Clarify doublet at 2323 keV in ^{80}Ge and states in ^{82}Ge
- NuShellX does an adequate job describing states
  - Negative parity states in ^{80}Ge and ^{82}Se
  - Cannot describe cross-shell states in this model space
- DFR best model to describe missing ΔJ=2 transitions in ^{78}Ge
  - The measured half-life of the 4+ level provides assurance that the issue is NOT a super-fast M1 transition.
  - Identified long-sought unique structure rigid nucleus without degrees of symmetry
  - How can a wave function be devised for 4^+ 5^+ and 6^+ levels that do not respond to the quadrupole operator?

Thank you!

- **University of Maryland College Park**: Dr. W.B. Walters, Dr. J. Sethi, Dr. C.J. Chiara (US Army Research Lab), Ms. J. Harker
- **University of North Carolina at Chapel Hill**: Dr. R.V.F. Janssens
- **United States Naval Academy**: Dr. A.D. Ayangeakaa
- **Argonne National Laboratory**: Dr. S. Zhu, M. Carpenter, Dr. M. Alcorta (TRIUMF), Dr. G. Gürdal, Dr. C.J. Hoffman, Dr. B.P. Kay, Dr. F.G. Kondev, Dr. T. Lauristen, Dr. C.J. Lister (University of Massachusetts Lowell), Dr. E.A. McCutchan (Brookhaven National Laboratory), Dr. A.M. Rogers (University of Massachusetts Lowell), Dr. D. Seweryniak
- **Yale University:** Rick Casten
- **Michigan State University:** Alex Brown

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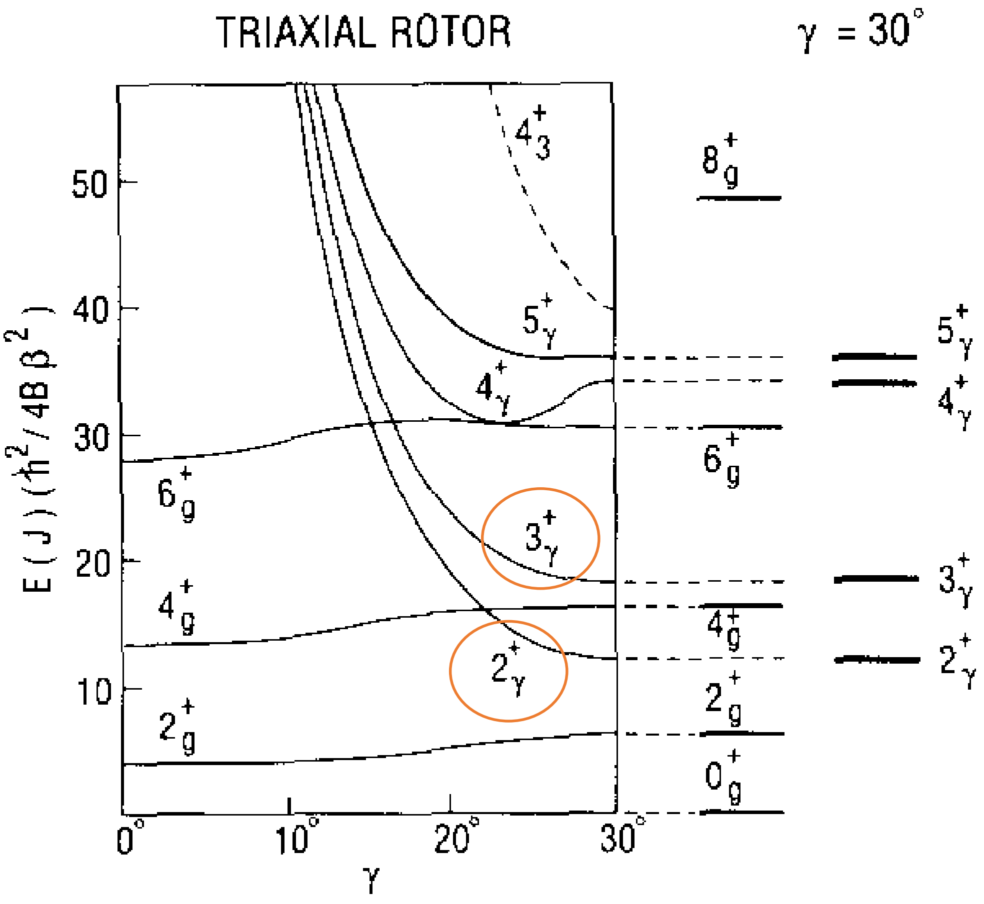
γ deformation:
fixed (rigid) or unstable (soft)?

Permanent

Elastic

Davydov Filippov

1958



γ - unstable

(Wilets - Jean)

1956

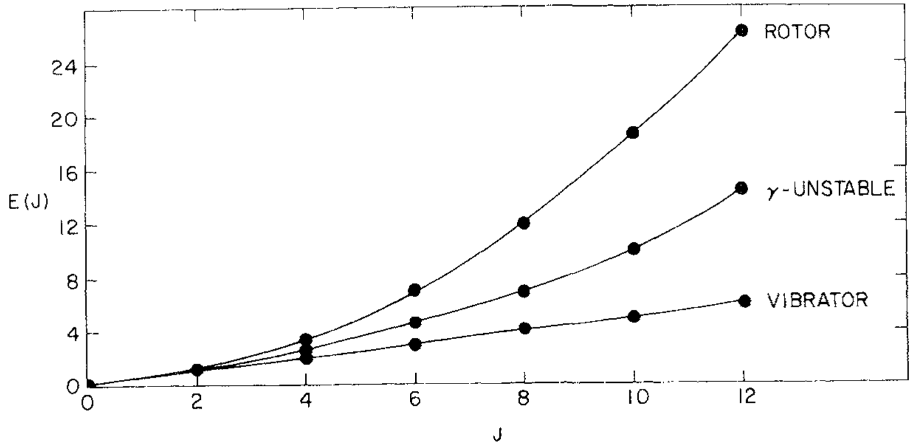
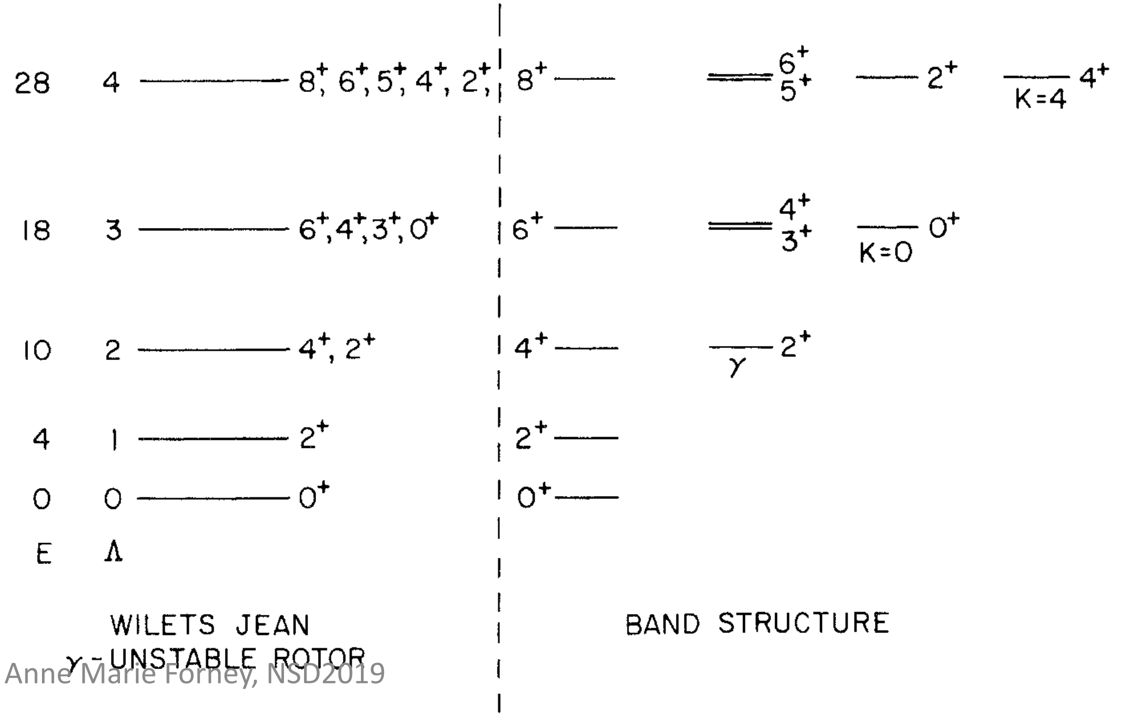
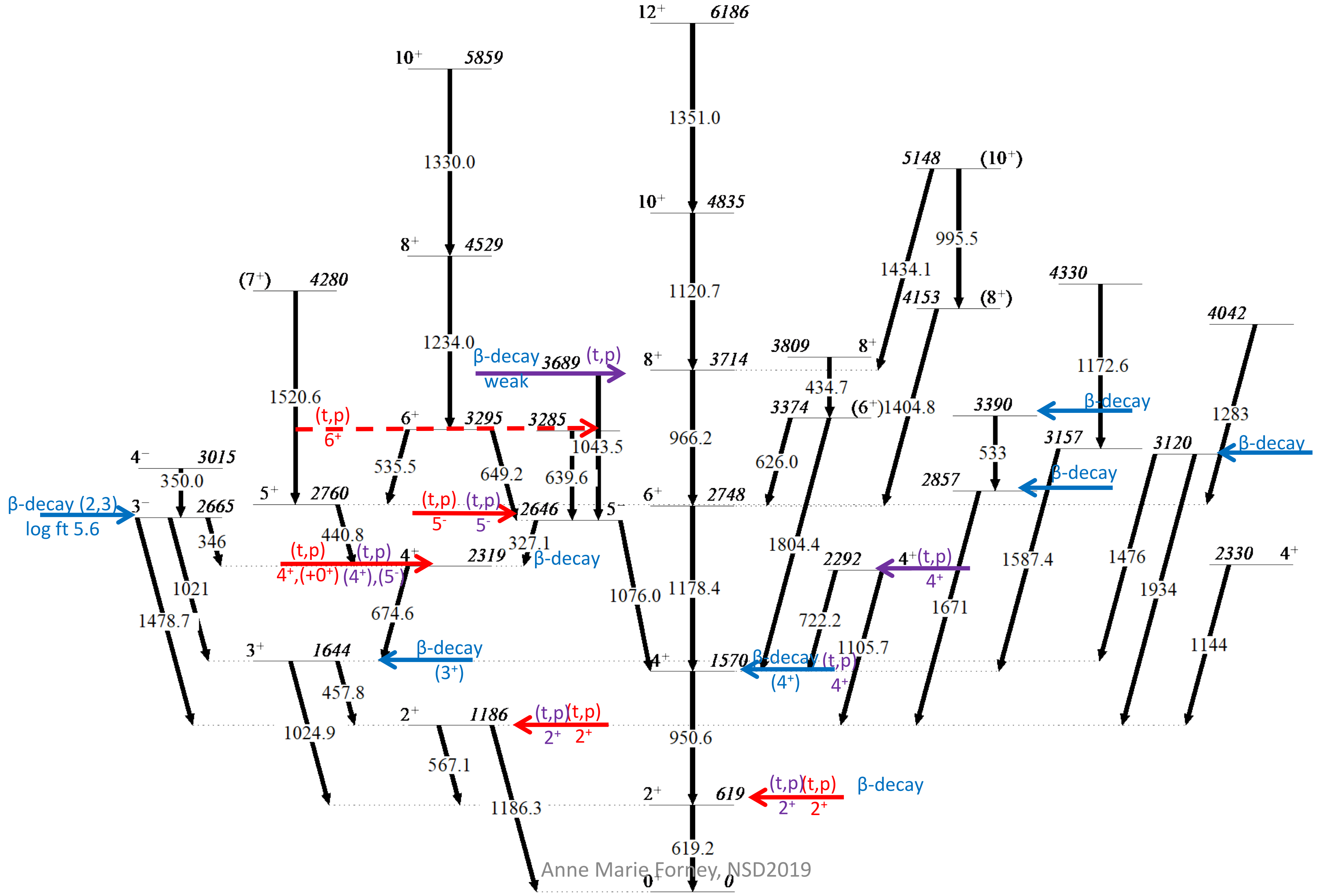


Fig. 6.21. Dependence of ground band energies on spin for different models. An identical set of curves is obtained in the U(5), O(6), and SU(3) symmetries of the IBA (see Eq. 6.72).



The three previous experimental works overlaid.



Calculating B(E2) of unobserved 1133-keV γ ray 2319 keV level in ^{78}Ge

$t_{1/2}$ = 43.0 (5.5) ps (Chou)

1133 keV B.R. < 2 %

Partial half-life: >2.15 (28) ns = 43 ps *100/2

>2,150 ps

From Weisskopf estimate it is 15.3 ps

B(E2)= $t_{1/2}$ (theo)/ $t_{1/2}$ (obs)

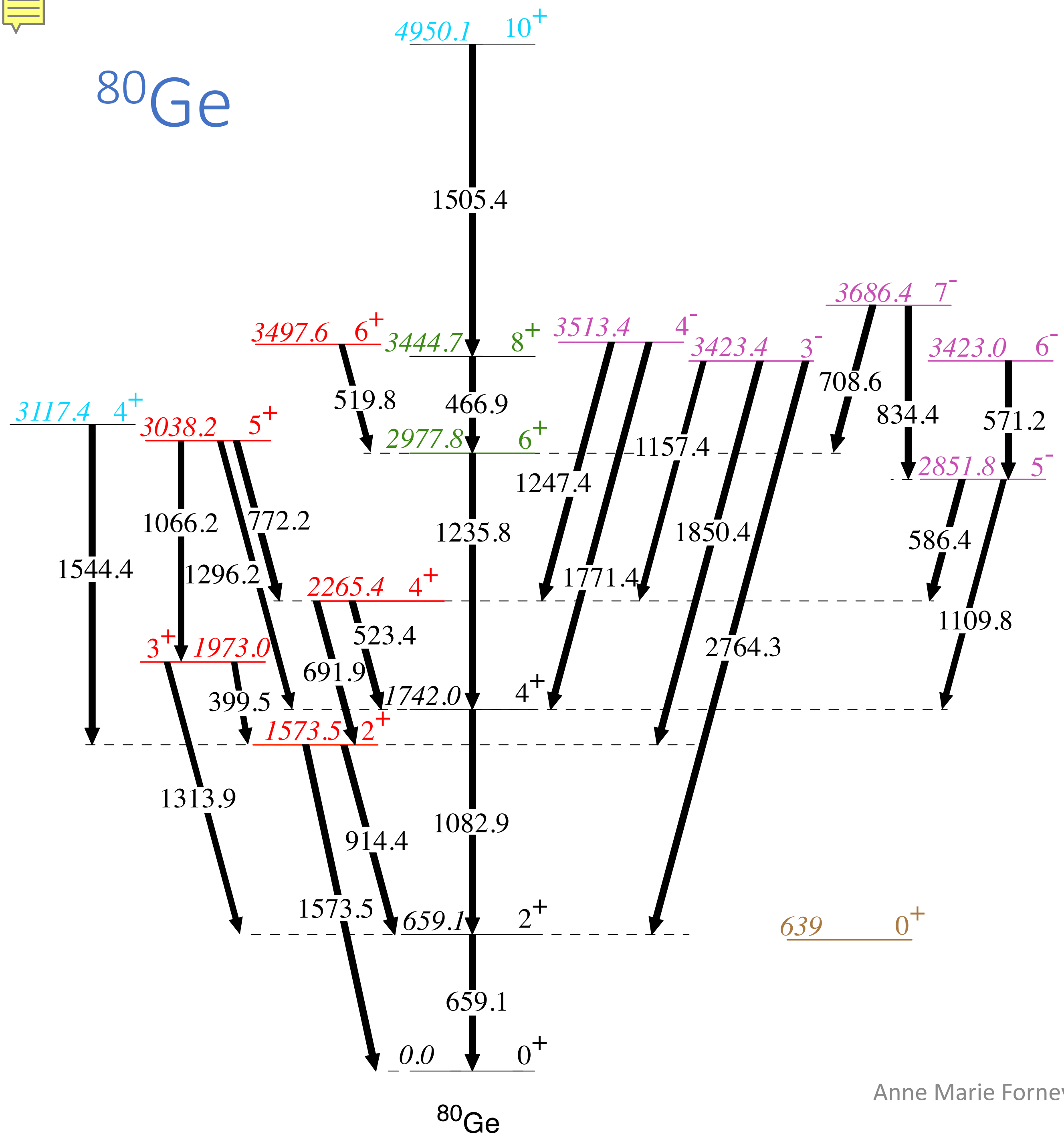
B(E2) < 0.007 (1) W.u.

$\lambda = \ln(2)/t_{1/2}$

Weisskopf transition rates

Multipole	E, $\lambda(s^{-1})$	M, $\lambda(s^{-1})$
1	$1.03 \text{ x } 10^{14}\ A_{2/3}\ \mathrm{E}_\gamma^3$	$3.15 \text{ x } 10^{14}\ \mathrm{E}_\gamma^3$
2	$7.28 \text{ x } 10^{7}\ A^{4/3}\ \mathrm{E}_\gamma^5$	$2.24 \text{ x } 10^{7}\ A^{2/3}\ \mathrm{E}_\gamma^5$
3	$3.39 \text{ x } 10^{1}\ A^{2}\ \mathrm{E}_\gamma^7$	$1.04 \text{ x } 10^{1}\ A^{4/3}\ \mathrm{E}_\gamma^7$
4	$1.07 \text{ x } 10^{-5}\ A^{8/3}\ \mathrm{E}_\gamma^9$	$3.27 \text{ x } 10^{-6}\ A^{2}\ \mathrm{E}_\gamma^9$
5	$2.40 \text{ x } 10^{-12}\ A^{10/3}\ \mathrm{E}_\gamma^{11}$	$7.36 \text{ x } 10^{-13}\ A^{8/3}\ \mathrm{E}_\gamma^{11}$

^{80}Ge



- N = 48, 2 neutron holes
  - Adds complexity
  - Purple: neutron states -$g_{9/2}\ p_{3/2}$, $g_{9/2}\ f_{5/2}$, $g_{9/2}\ p_{1/2}$
  - Negative parity
- ^{80}Ga β-decay parent: J=3$^-$ and J=6$^-$
- Yrast 2$^+$, 4$^+$ due to breaking the $f_{5/2}$ proton pair
- Red levels: Two-particle states of $f_{5/2}\ p_{3/2}$
  - γ-band-like structure
  - Drop significantly in energy
- Brown level: intruder state
- Green States: breaking $g_{9/2}$ neutron pair

proton $(f_{5/2}\,p_{3/2})_{1\,2\,3\,4}$ $(f_{5/2}\,f_{5/2})_{2\,4}$ $(p_{3/2}\,p_{3/2})_{2}$

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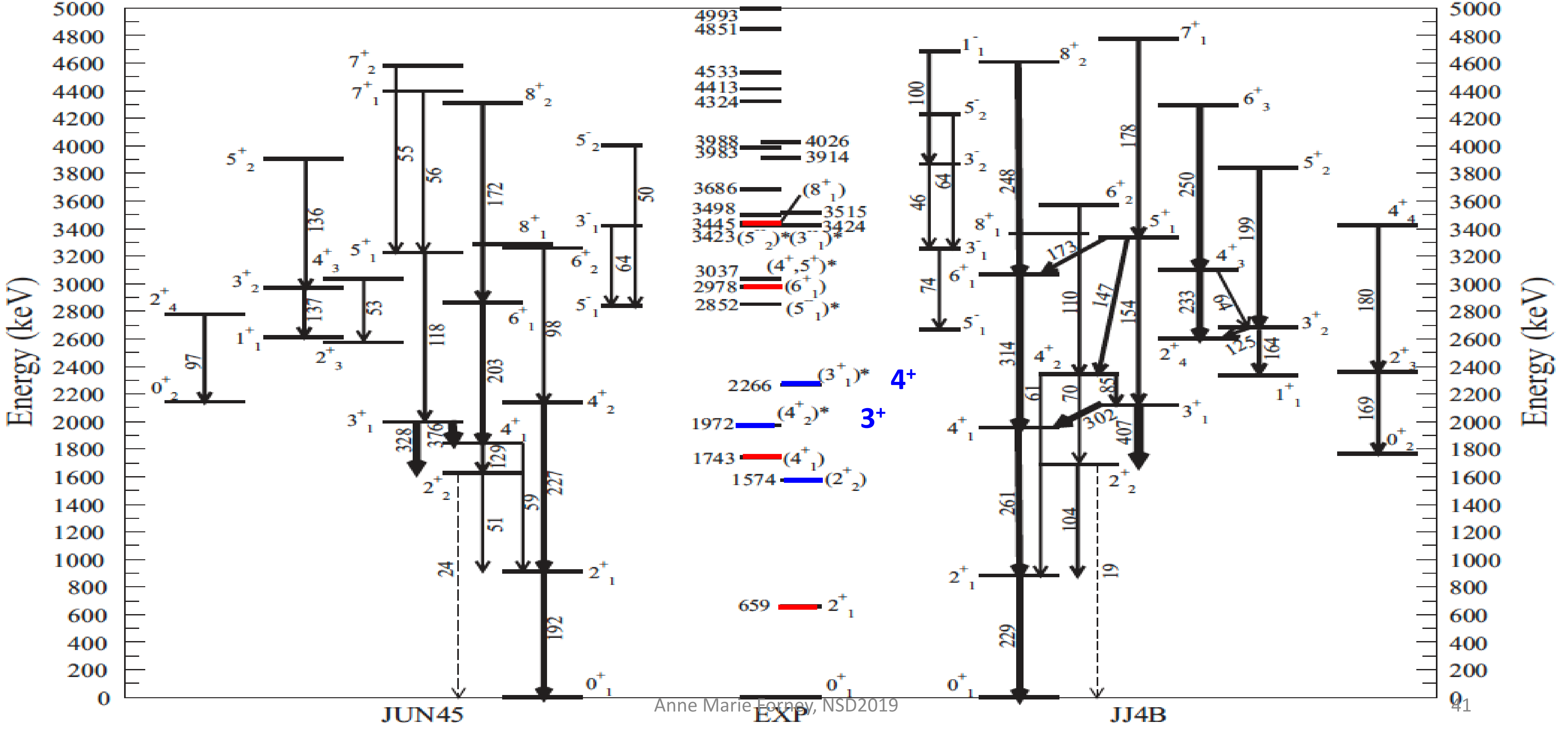
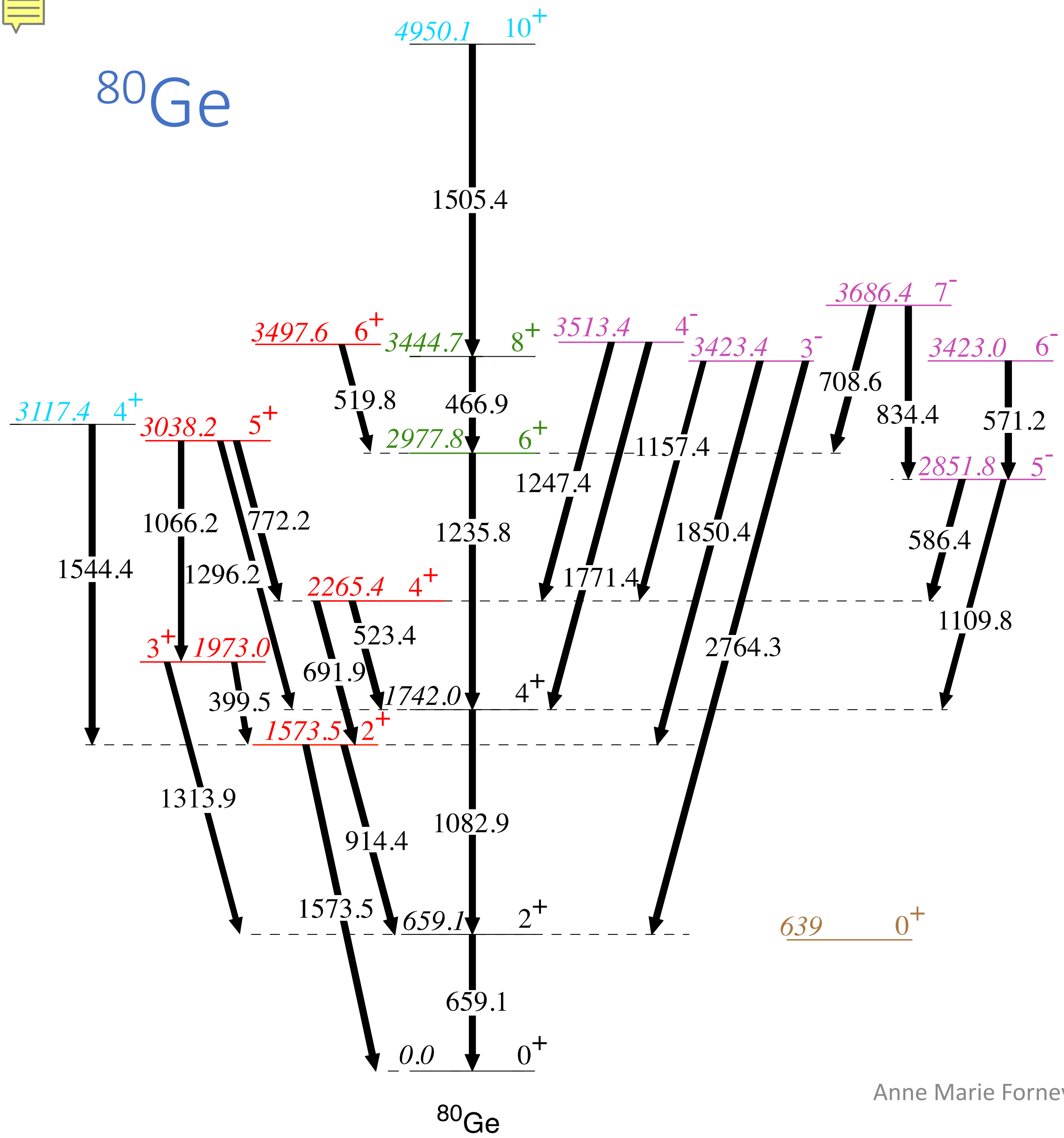


^{80}Ge



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- ^{80}Ga β-decay parent: J=3$^-$ and J=6$^-$
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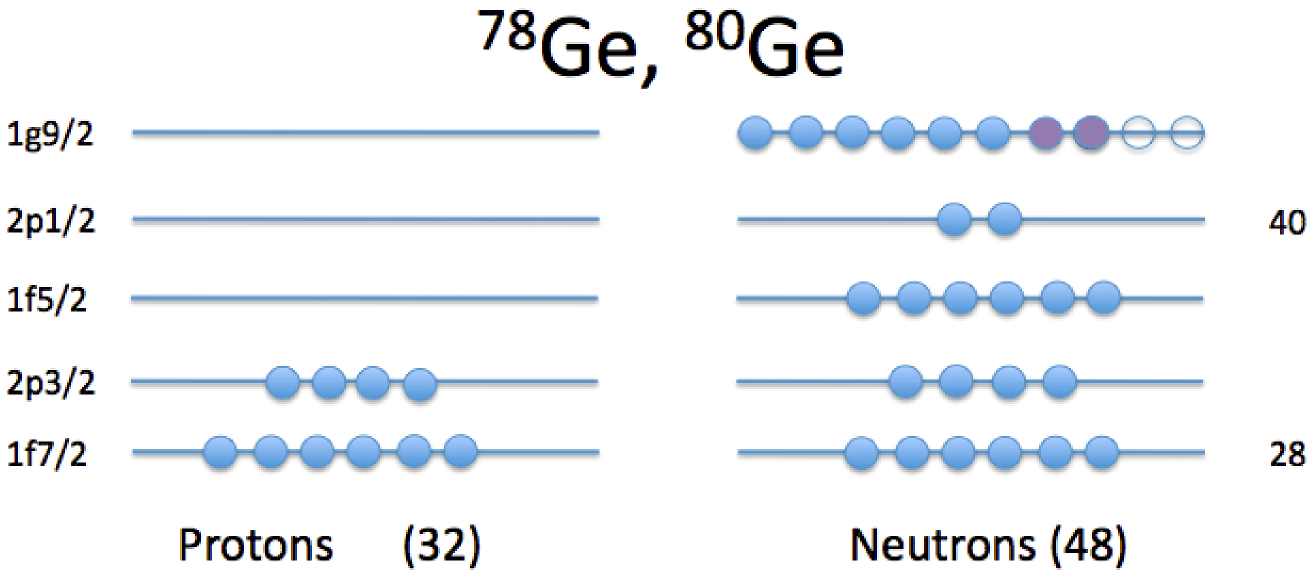
  - Drop significantly in energy
- Brown level: intruder state
- Green States: breaking $g_{9/2}$ neutron pair

^{78,80}Ge

- Triaxiality and shape coexistence in ^{72,74,76}Ge
  - Two triaxial shapes in ^{72}Ge

- Intruder 0+ state in ^{80}Ge
  - Two holes from N=50 shell
- ^{78}Ge four holes from N=50 shell



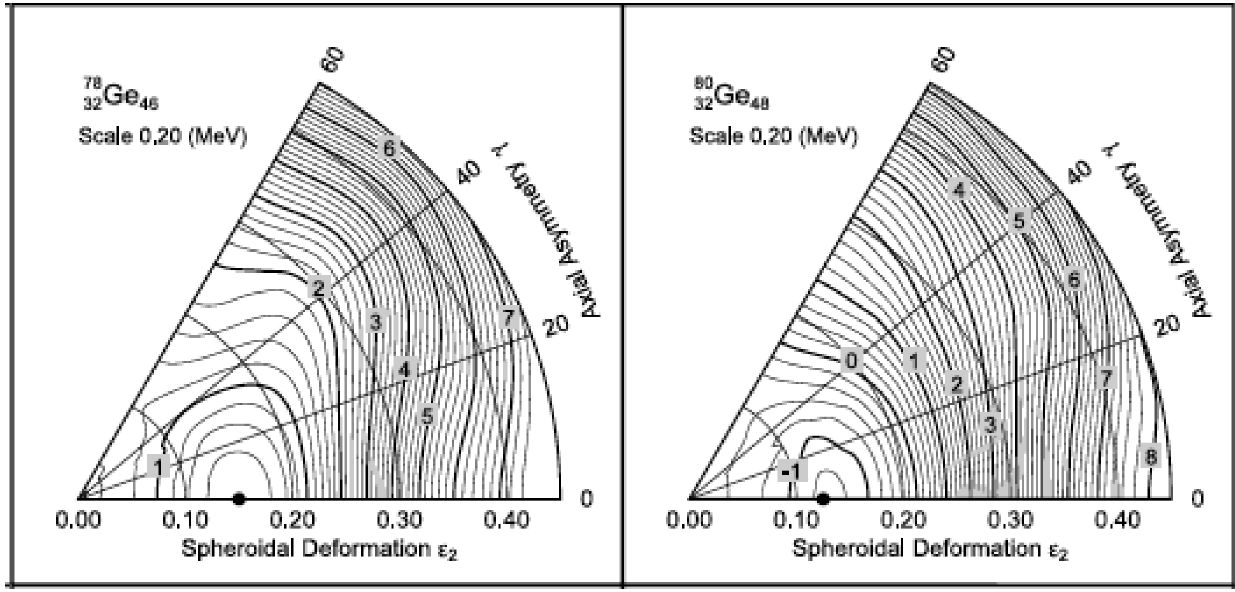


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Table 1. The measured [4] and calculated $B(E2)$ values, given in units of $10^{-3}e^2b^2$. Two set of effective charges are employed: $e^{\pi}_{\rm eff} = 1.5\ e$, $e^{\nu}_{\rm eff} = 0.5\ e$ and $e^{\pi}_{\rm eff} = 1.5\ e$, $e^{\nu}_{\rm eff} = 1.1\ e$, shown separated "/".

Nucleus	Expt.	JUN45	jj44b	fpg
^{70}Ge	36(4)	24.8/47.5	33.7/67.7	55.5/99.5
^{72}Ge	40(3)	26.2/50.8	35.3/71.2	44.3/78.1
^{74}Ge	60(3)	30.7/59.1	36.7/70.6	51.5/94.4
^{76}Ge	46(3)	31.3/56.9	34.8/63.9	53.6/93.7
^{78}Ge	44(3)	28.5/48.0	31.5/53.8	48.9/79.8
^{80}Ge	28(5)	19.2/30.1	22.9/34.8	33.3/47.5
^{82}Ge	25(5)	8.1/8.1	15.9/15.9	22.7/22.7