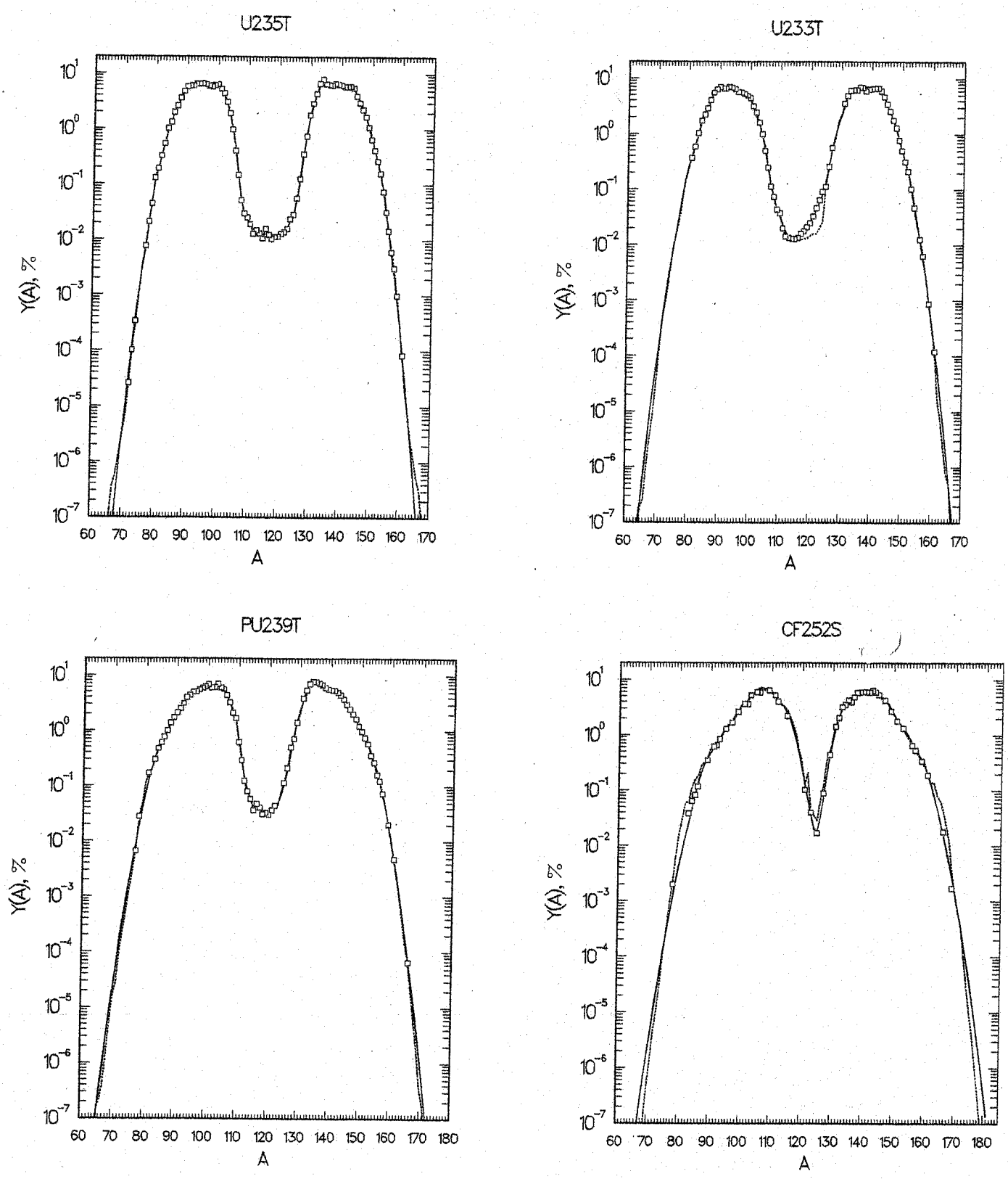
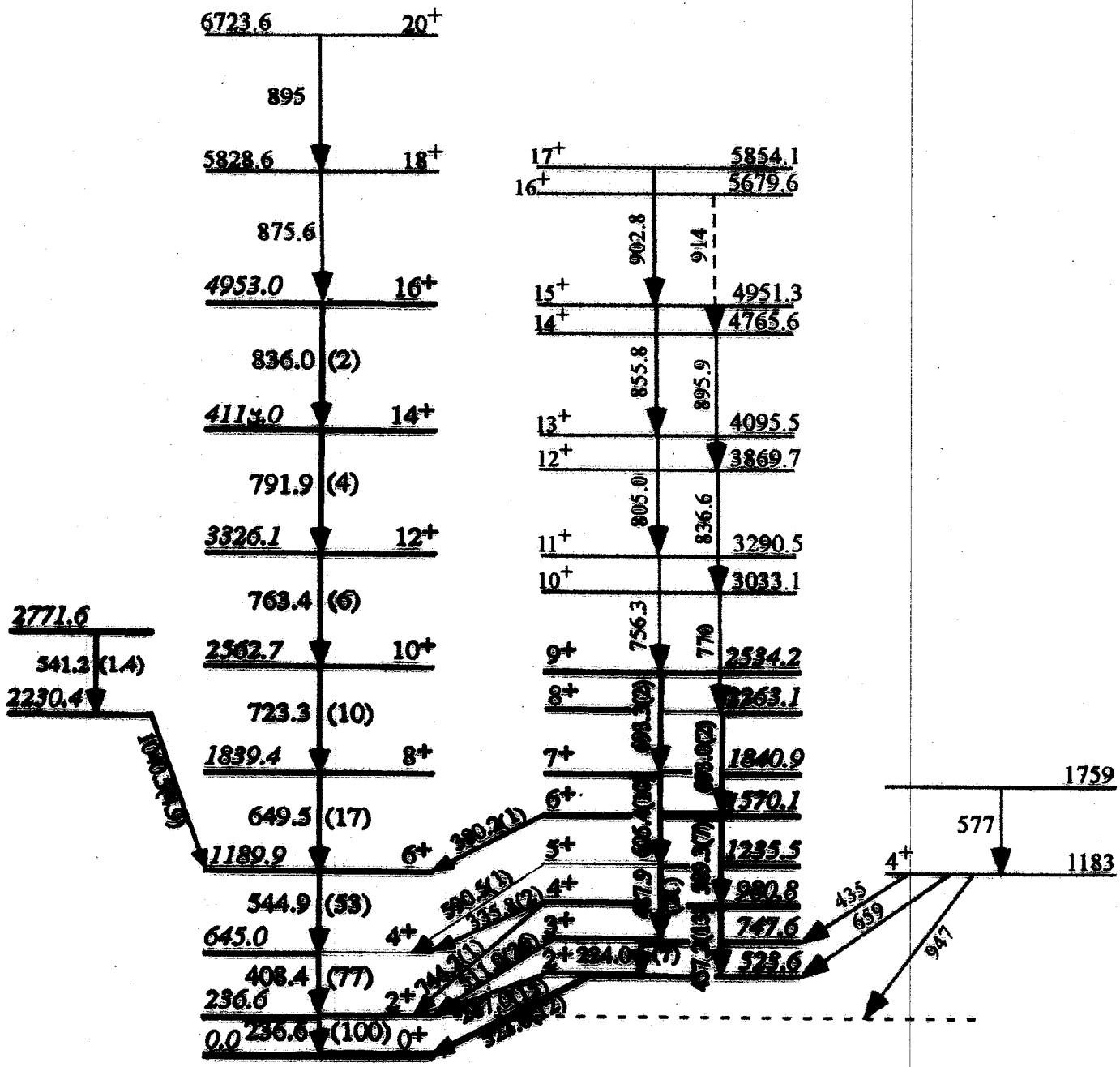


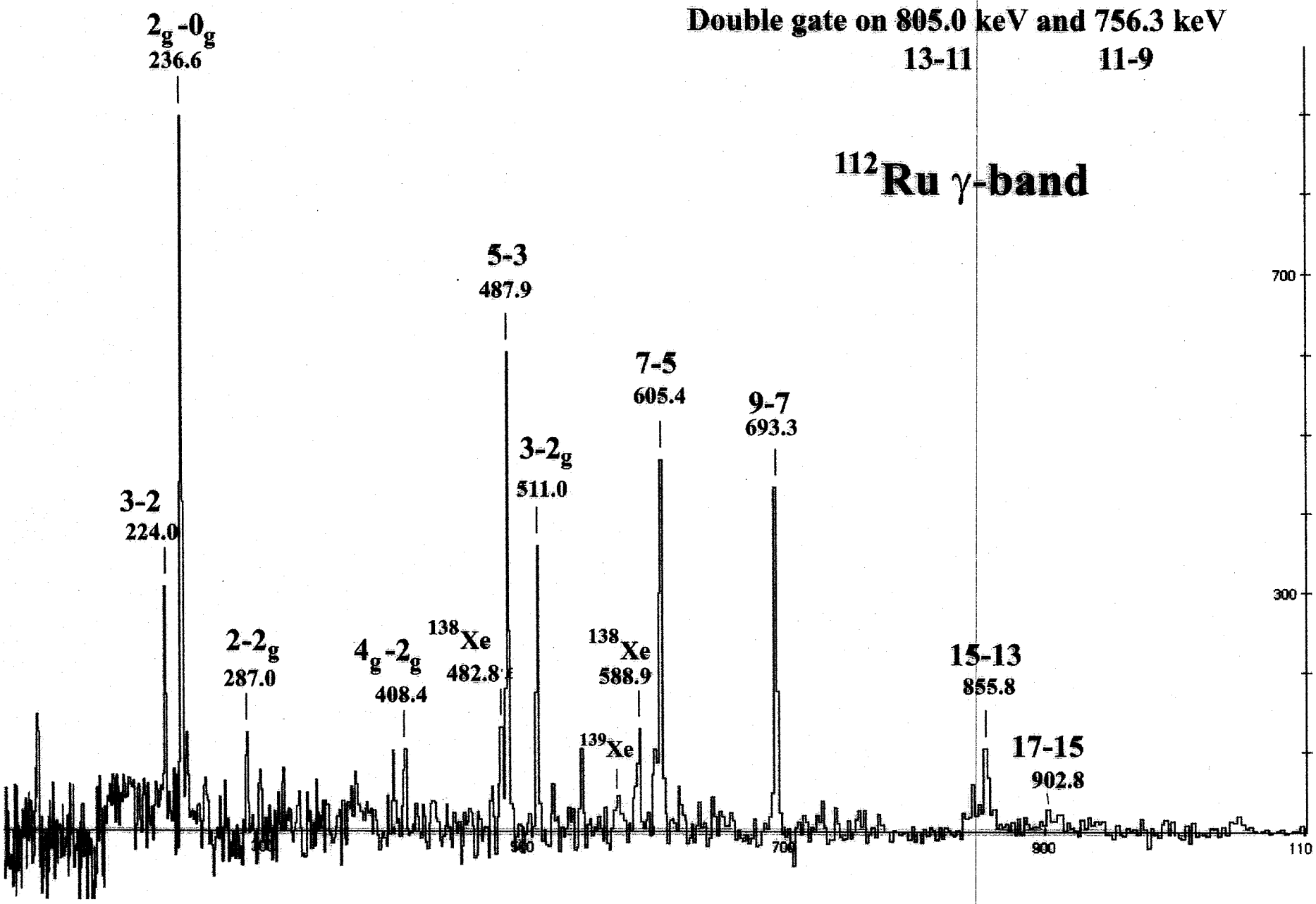

Figure 7. Mass-number yields, $Y(A)$, vs mass number, $A$. □, experimental data for U235T, U233T, and PU239T (Ref. 6) and for CF252S (Ref. 7); ——, calculated from the $A_p'$ model; ---, Rider's mass-number yields.[6]

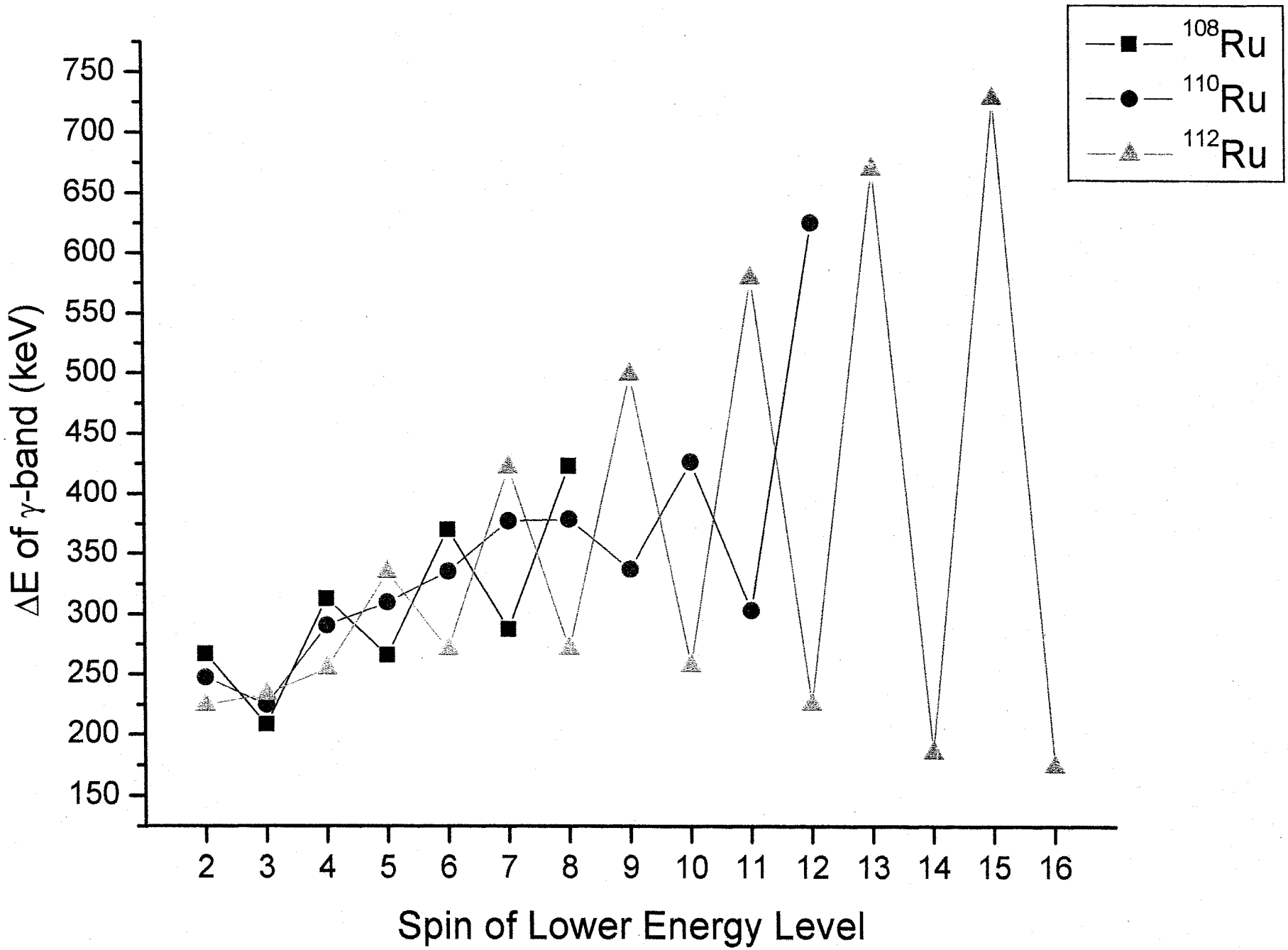
# EXPERIMETAL METHODS

- Lawrence Berkeley National Laboratory
- GAMMASPERE Detector Array
  102 Compton-Suppressed Ge Detectors
- $^{252}Cf$ Source of 62 $\mu$Ci
- Total of 5.7 . $10^{11}$ triple- and higher-fold $\gamma$-$\gamma$-$\gamma$ coincidence events (in cube)
- Radware software package to analyze data


6723.6 20+
895
5828.6 18+
875.6
4953.0 16+
836.0 (2)
4114.0 14+
791.9 (4)
3326.1 12+
763.4 (6)
2562.7 10+
723.3 (10)
1839.4 8+
649.5 (17)
1189.9 6+
544.9 (53)
645.0 4+
408.4 (77)
236.6 2+
236.6 (100)
0.0 0+
2771.6
341.2 (1.4)
2230.4
17+ 5854.1
16+ 5679.6
902.8
914
15+ 4951.3
14+ 4765.6
855.8
895.9
13+ 4095.5
12+ 3869.7
805.0
836.6
11+ 3290.5
10+ 3033.1
756.3
770
9+ 2534.2
8+ 2263.1
7+ 1840.9
6+ 1570.1
5+ 1285.5
4+ 980.8
3+ 747.6
2+ 523.6
390.2(1)
1759
577
4+ 1183
435
659
947

$^{112}_{44}Ru_{68}$


Double gate on 805.0 keV and 756.3 keV
13-11
11-9
112Ru γ-band
2g-0g
236.6
5-3
487.9
7-5
605.4
9-7
693.3
3-2g
511.0
3-2
224.0
2-2g
287.0
4g-2g
408.4
138Xe
482.8
138Xe
588.9
139Xe
15-13
855.8
17-15
902.8
700
300
900
110


$^{108}$Ru
$^{110}$Ru
$^{112}$Ru
ΔE of γ-band (keV)
750
700
650
600
550
500
450
400
350
300
250
200
150
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Spin of Lower Energy Level

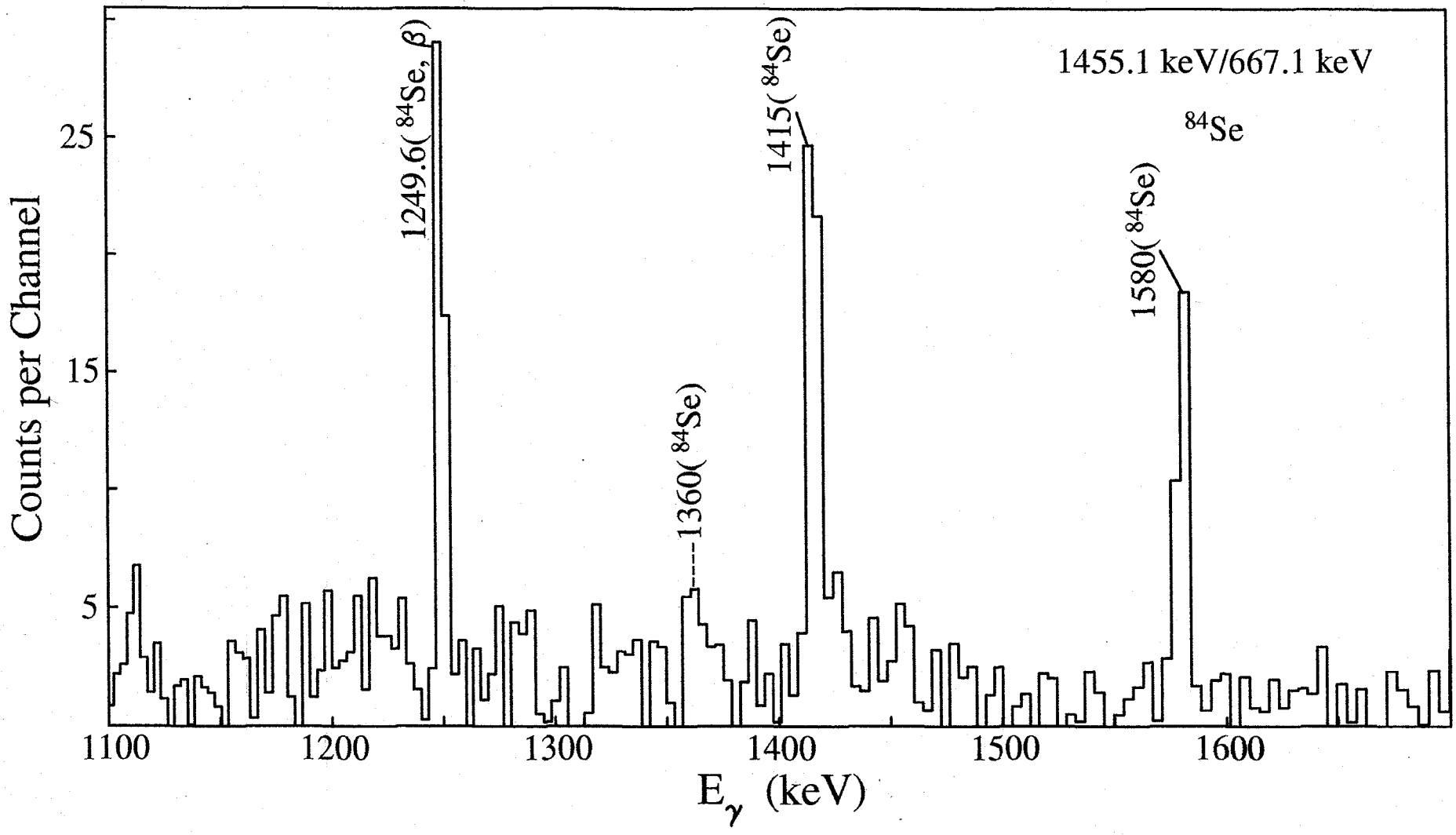
# Recommended Independent Yields for $^{235}U(n)$, $^{239}Pu(n)$ and $^{252}Cf$

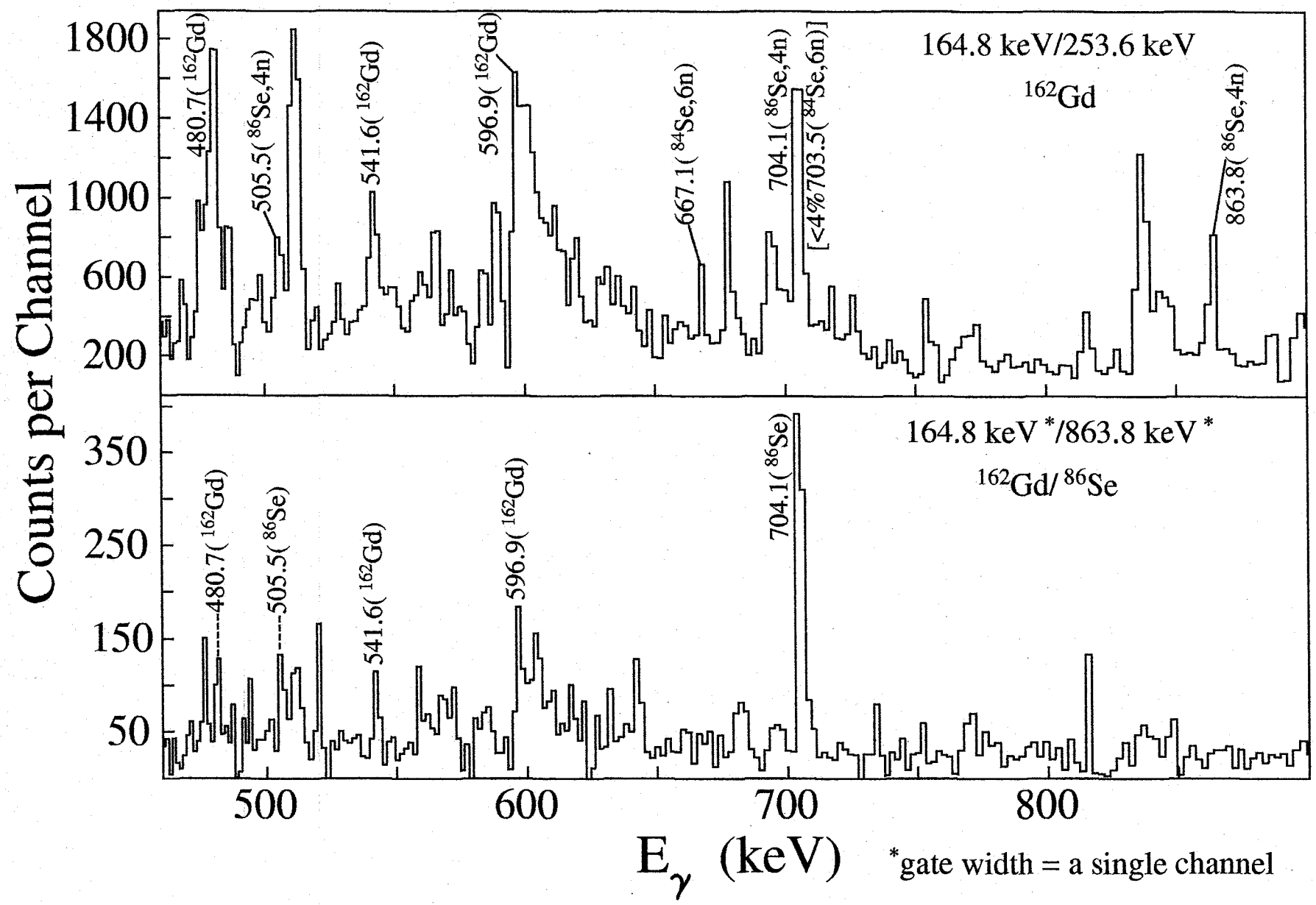
| Isotope | Element | 78 | 80 | 82 | 84 |
|---|---|---|---|---|---|
| $^{235}U+n$ | $_{32}Ge$ | 5.9(-3) | 1.0(-1) | 1.3(-1) | 1.3(-2) |
| $^{239}Pu+n$ | $_{32}Ge$ | 1.5(-2) | 5.9(-2) | 2.2(-2) | 1.6(-3) |
| $^{252}Cf$ SF | $_{32}Ge$ | 9.6(-4) | 2.4(-3) | 2.6(-3) | 7.6(-4) |
| # Neutrons past last stable nucleus | | 2n | 4n | 6n | 8n |

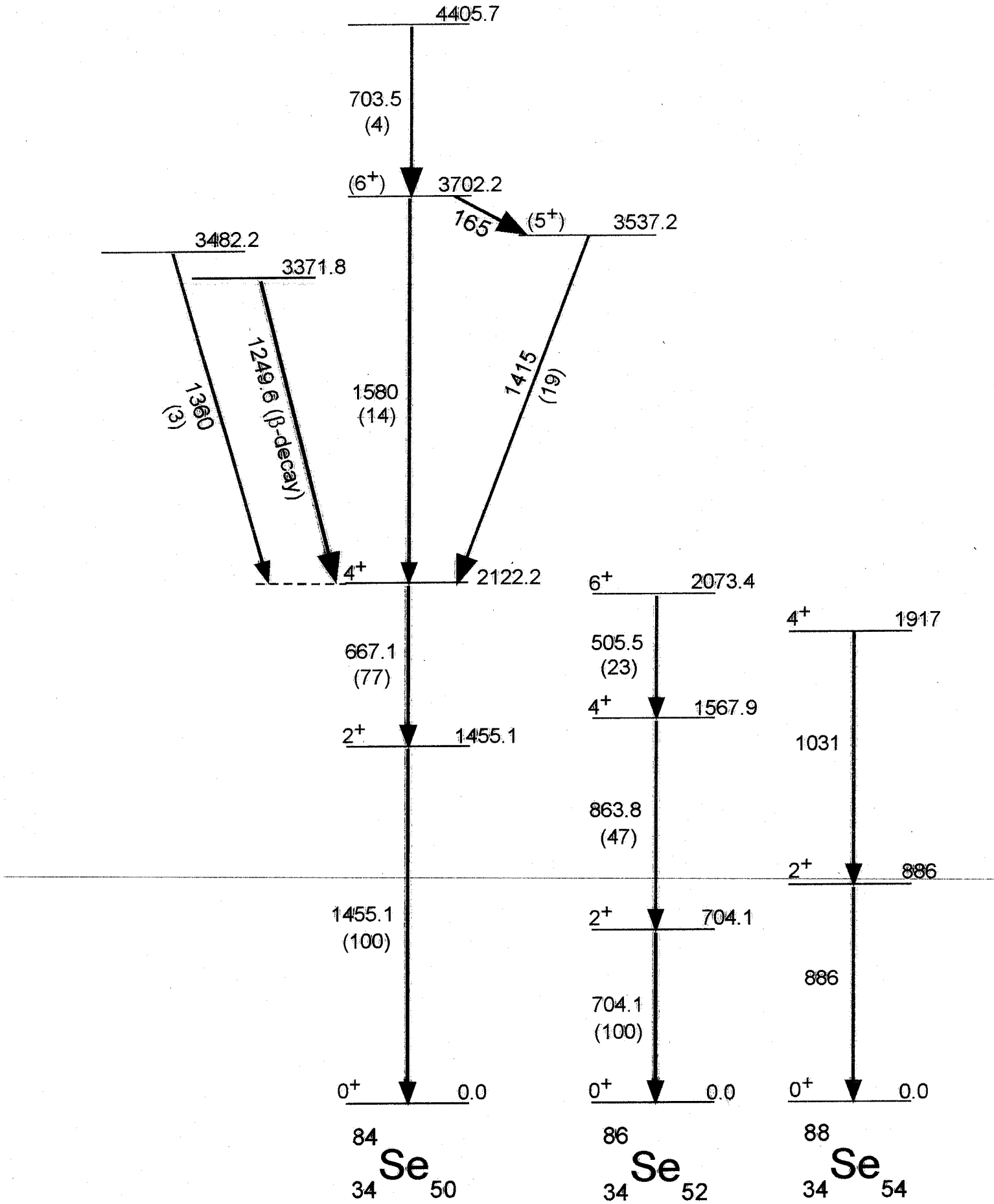
| Isotope | Element | 82 | 84 | 86 | 88 | 90 |
|---|---|---|---|---|---|---|
| $^{235}U+n$ | $_{34}Se$ | 3.9(-2) | 6.5(-1) | 1.2 | 3.1(-1) | 1.0(-2) |
| $^{239}Pu+n$ | $_{34}Se$ | 7.2(-2) | 3.0(-1) | 2.8(-1) | 4.3(-2) | 8.5(-4) |
| $^{252}Cf$ SF | $_{34}Se$ | 3.0(-3) | 3.3(-2) | 4.6(-2) | 2.4(-2) | 2.6(-3) |
| | | stable | 2n | 4n | 6n | 8n |

| Isotope | Element | 84 | 86 | 88 | 90 | 92 | 94 | 96 |
|---|---|---|---|---|---|---|---|---|
| $^{235}U+n$ | $_{36}Kr$ | 3.1(-4) | 1.2(-1) | 1.7 | 4.5 | 1.7 | 1.0(-1) | 8.1(-4) |
| $^{239}Pu+n$ | $_{36}Kr$ | 2.3(-3) | 7.7(-2) | 7.9(-1) | 1.2 | 3.4(-1) | 2.1(-2) | 1.9(-4) |
| $^{252}Cf$ SF | $_{36}Kr$ | 1.1(-4) | 5.1(-3) | 9.5(-2) | 3.4(-1) | 1.7(-1) | 2.9(-2) | |
| | | stable | stable | 2n | 4n | 6n | 8n | 10n |

Jones et al (Vanderbilt) Phys. Rev




Counts per Channel
1800
1400
1000
600
200
350
250
150
50
500
600
700
800
$E_\gamma$ (keV)
164.8 keV/253.6 keV
$^{162}$Gd
480.7($^{162}$Gd)
505.5($^{86}$Se,4n)
541.6($^{162}$Gd)
596.9($^{162}$Gd)
667.1($^{84}$Se,6n)
704.1($^{86}$Se,4n)
[<4%703.5($^{84}$Se,6n)]
863.8($^{86}$Se,4n)
164.8 keV*/863.8 keV*
$^{162}$Gd/$^{86}$Se
480.7($^{162}$Gd)
505.5($^{86}$Se)
541.6($^{162}$Gd)
596.9($^{162}$Gd)
704.1($^{86}$Se)
*gate width = a single channel

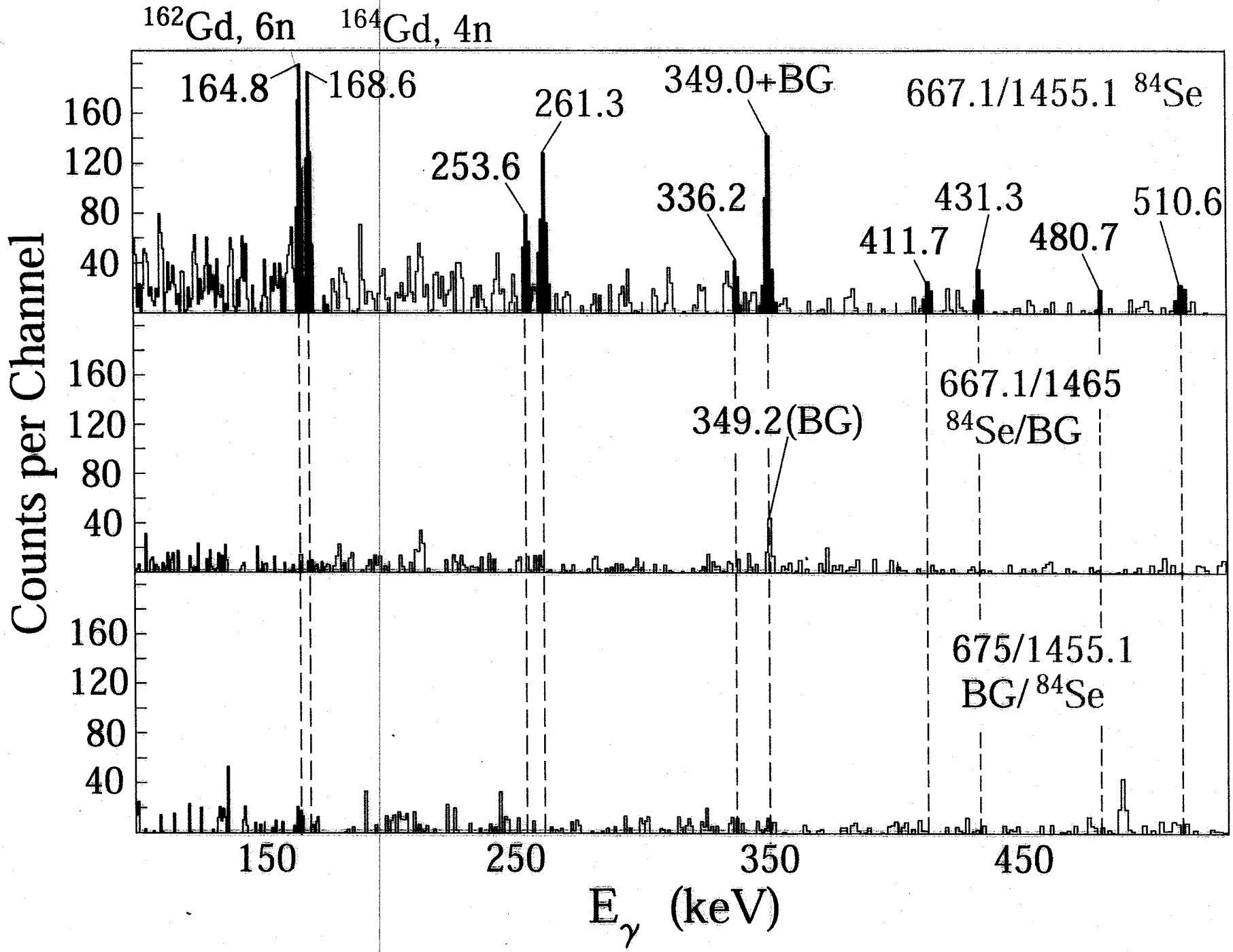

4405.7
703.5
(4)
(6+)
3702.2
165
(5+)
3537.2
3482.2
3371.8
1360
(3)
1249.6 (β-decay)
1580
(14)
1415
(19)
4+
2122.2
667.1
(77)
2+
1455.1
1455.1
(100)
0+
0.0
84
34
Se
50
6+
2073.4
505.5
(23)
4+
1567.9
863.8
(47)
2+
704.1
704.1
(100)
0+
0.0
86
34
Se
52
4+
1917
1031
2+
886
886
0+
0.0
88
34
Se
54

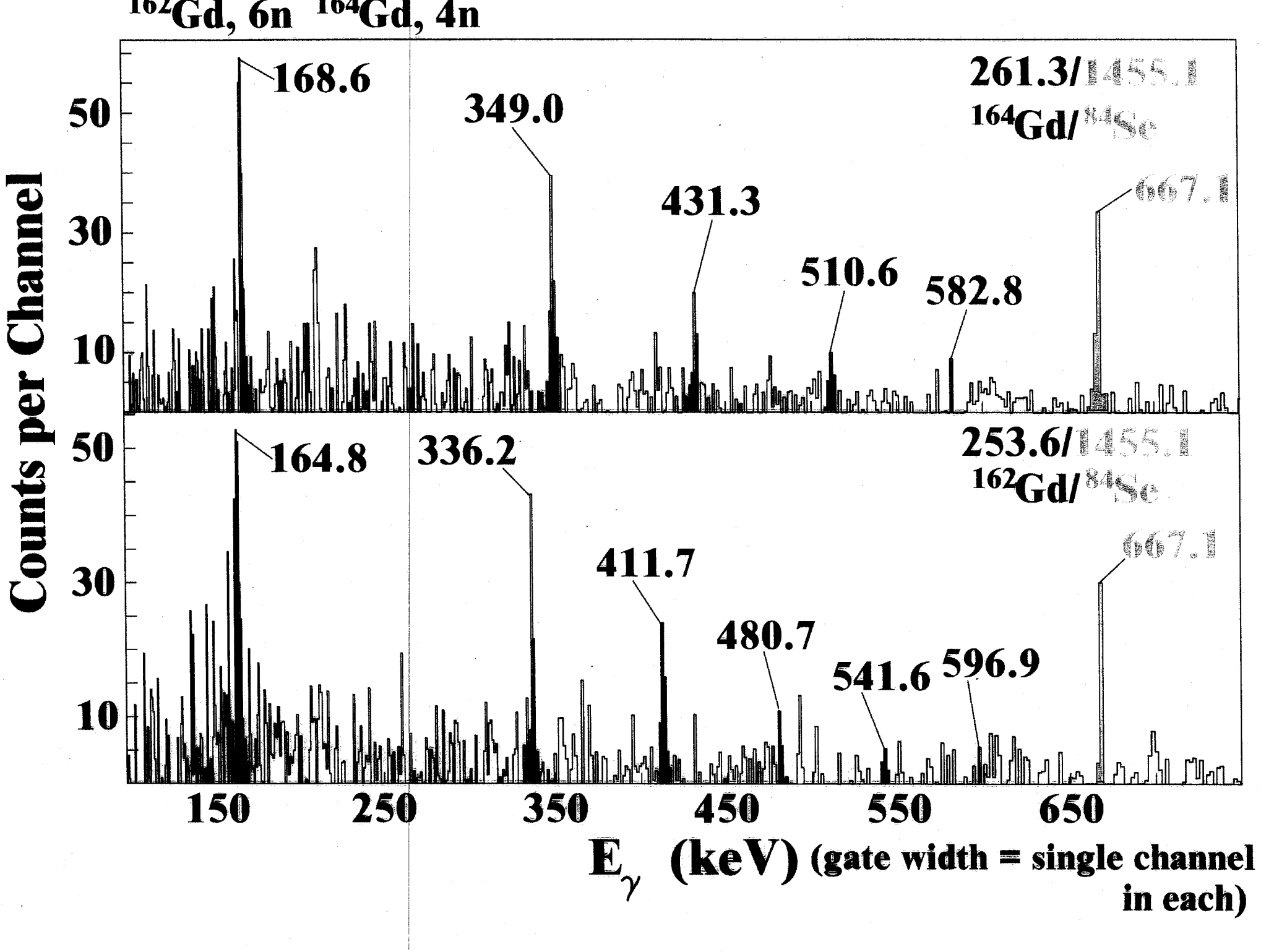
# Recommended Independent Yields for $^{235}U(n)$, $^{239}Pu(n)$ and $^{252}Cf$

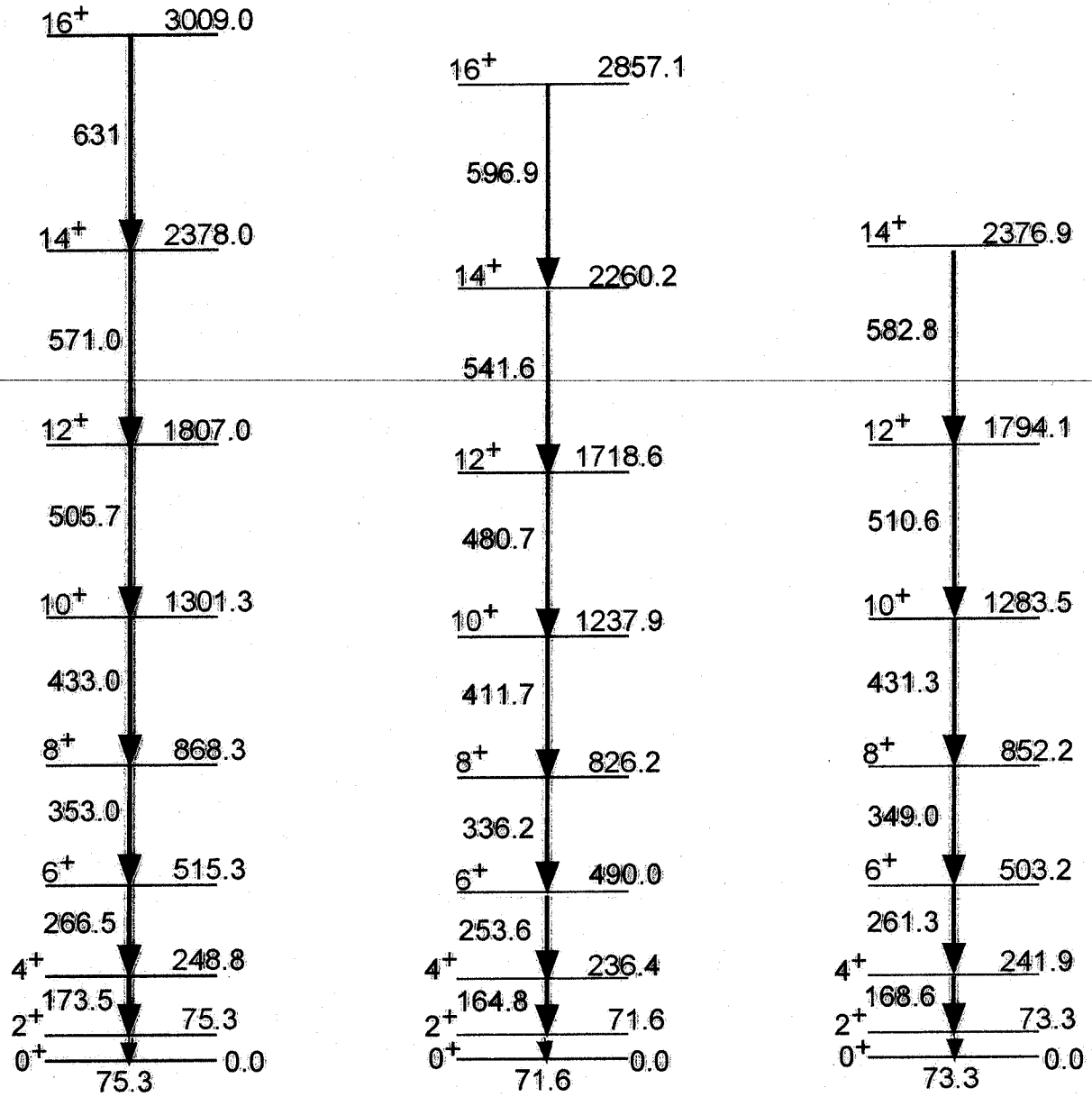
| Isotope | Element | 154 | 156 | 158 | 160 | 162 |
|---|---|---|---|---|---|---|
| $^{235}U+n$ | $_{62}Sm$ | 5.3(-4) | 3.3(-3) | 2.6(-3) | 2.3(-3) | 2.7(-6) |
| $^{239}Pu+n$ | $_{62}Sm$ | 1.0(-2) | 4.9(-2) | 3.1(-2) | 4.3(-3) | 1.3(-4) |
| $^{252}Cf$ SF | $_{62}Sm$ | 4.0(-2) | 1.9(-1) | 3.3(-1) | 8.8(-2) | 5.7(-3) |
| | | Stable | +2m | +4m | +6m | +8m |

| Isotope | Element | 160 | 162 | 164 | 166 | 168 |
|---|---|---|---|---|---|---|
| $^{235}U+n$ | $_{64}Gd$ | 8.1(-6) | 6.4(-4) | 1.5(-6) | 1.9(-7) | |
| $^{239}Pu+n$ | $_{64}Gd$ | 7.6(-4) | 1.3(-3) | 2.0(-4) | 1.4(-5) | 7.9(-8) |
| $^{252}Cf$ SF | $_{64}Gd$ | 2.6(-2) | 5.1(-2) | 2.8(-2) | 4.5(-3) | 1.2(-4) |
| | | stable | +2m | +4m | +6m | +8m |

| Isotope | Element | 164 | 166 | 168 | 170 |
|---|---|---|---|---|---|
| $^{235}U+n$ | $_{66}Dy$ | 5.2(-9) | 5.0(-8) | 3.7(-8) | 3.8(-9) |
| $^{239}Pu+n$ | $_{66}Dy$ | 3.8(-8) | 1.2(-5) | 2.9(-6) | 1.8(-7) |
| $^{252}Cf$ SF | $_{66}Dy$ | 6.4(-4) | 3.3(-3) | 3.0(-3) | 7.8(-4) |
| | | stable | +2m | +4m | +6m |


162Gd, 6n
164Gd, 4n
164.8
168.6
261.3
349.0+BG
667.1/1455.1 84Se
253.6
336.2
431.3
510.6
411.7
480.7
667.1/1465
84Se/BG
349.2(BG)
675/1455.1
BG/84Se
Counts per Channel
160
120
80
40
150
250
350
450
Eγ (keV)


162Gd, 6n
164Gd, 4n
168.6
349.0
431.3
510.6
582.8
261.3/1455.1
164Gd/84Se
667.1
164.8
336.2
411.7
480.7
541.6
596.9
253.6/1455.1
162Gd/84Se
667.1
Counts per Channel
50
30
10
150
250
350
450
550
650
Eγ (keV) (gate width = single channel in each)




| $^{160}_{64}Gd_{96}$ | $^{162}_{64}Gd_{98}$ | $^{164}_{64}Gd_{100}$ |
|---|---|---|
| 4n $^{88}Se$ | 2n $^{88}Se$ | 0n $^{88}Se$ |
| 6n $^{86}Se$ | 4n $^{86}Se$ | 2n $^{86}Se$ |
| 8n $^{84}Se$ | 6n $^{84}Se$ | 4n $^{84}Se$ |

Asai et al Phys. Rev C59, 3060 (1999)
238U + 20MeV p (1μA); target 4mg/cm²; Mass separated 167,168 Tb as oxide

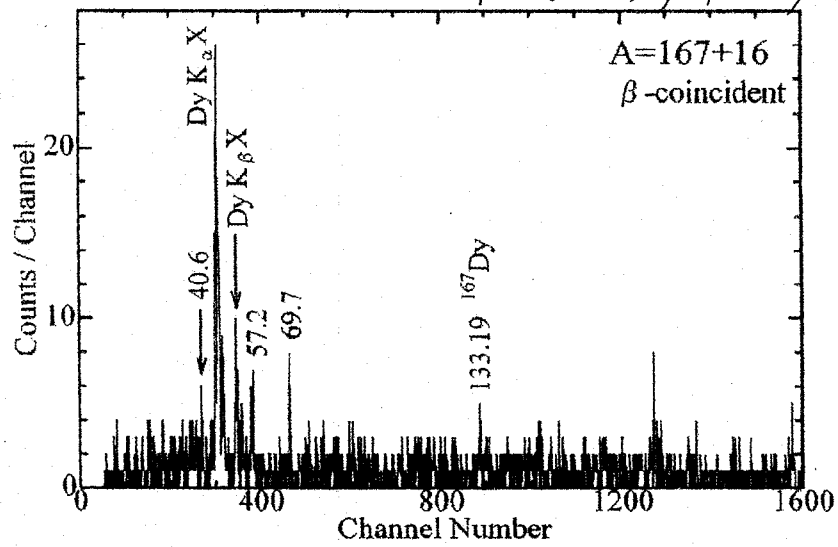



FIG. 1. $\beta$-coincident $\gamma$-ray spectrum for the mass 167+16 fraction.

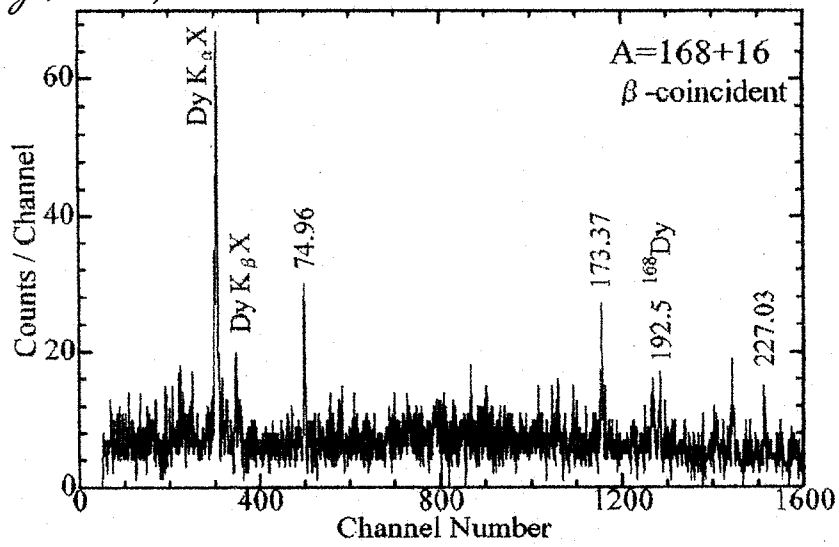



FIG. 3. $\beta$-coincident $\gamma$-ray spectrum for the mass 168+16 fraction.

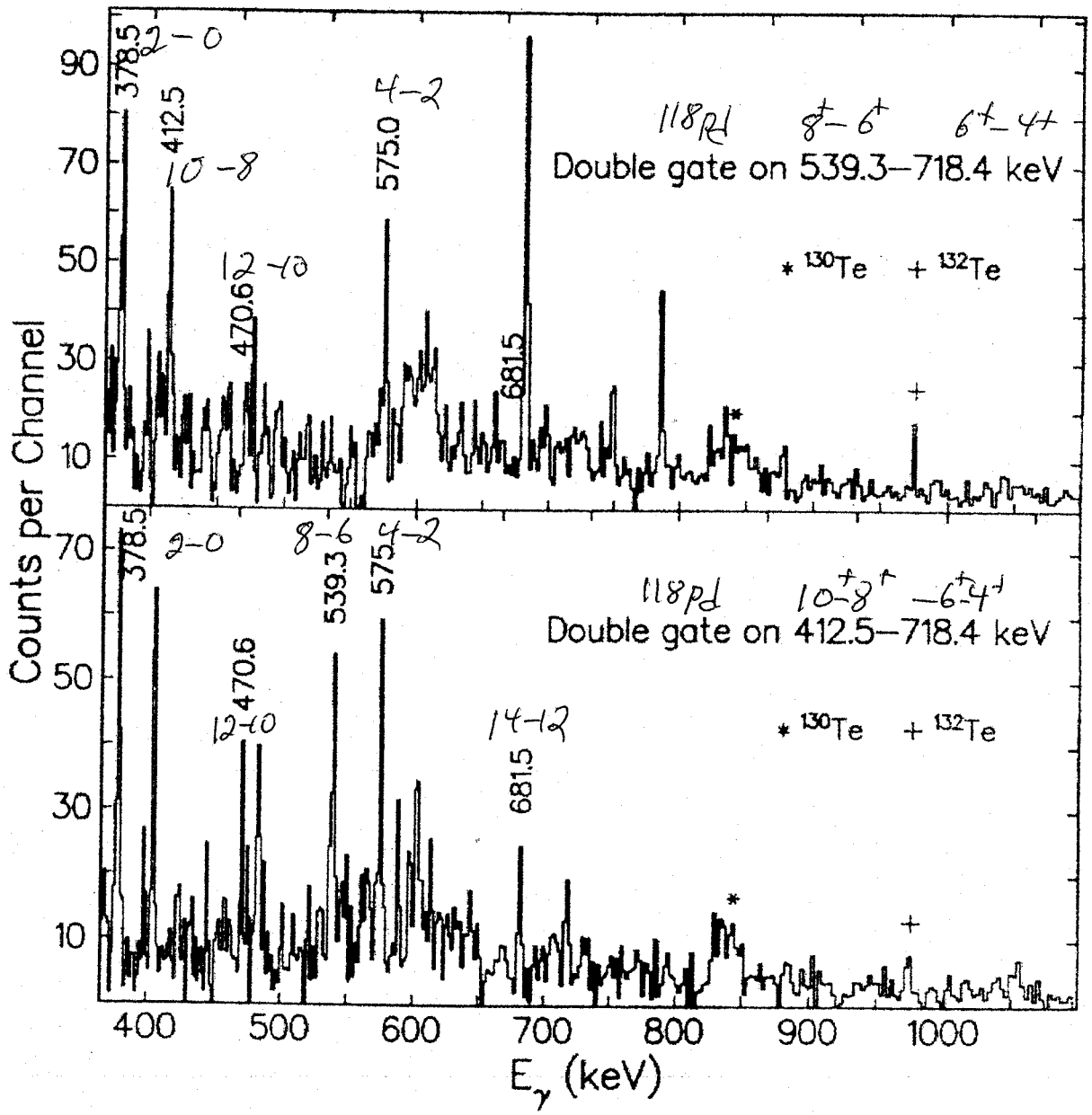
# Recommended Independent Yields for $^{235}U(n)$, $^{239}Pu(n)$ and $^{252}Cf$

| Isotope | Element | 110 | 112 | 114 | 116 | 118 | 120 |
|---|---|---|---|---|---|---|---|
| $^{235}U+n$ | $_{46}Pd$ | | 1.0(-4) | 3.4(-3) | 1.0(-2) | 3.0(-3) | 1.9(-4) |
| $^{239}Pu+n$ | $_{46}Pd$ | | 6.8(-5) | 8.9(-3) | 2.9(-2) | 5.8(-3) | 2.2(-4) |
| $^{252}Cf$ SF | $_{46}Pd$ | 7.2(-2) | 8.0(-1) | 1.9 | 8.2(-1) | 4.6(-2) | 7.5(-6)<br>1.8(-3) |
| | | stable | +2n | +4n | +6n | +8n | +10n |

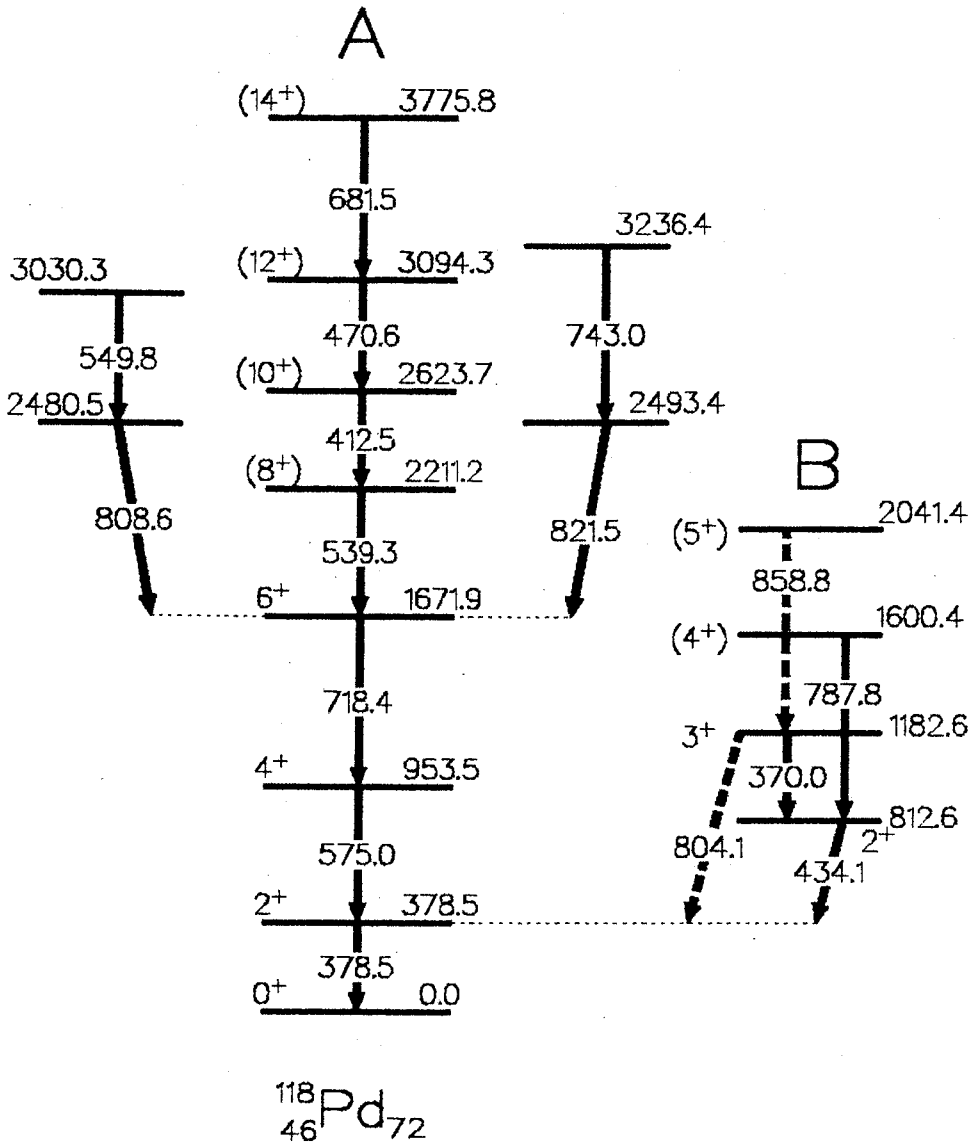
| Isotope | Element | 116 | 118 | 120 | 122 | 124 | 126 |
|---|---|---|---|---|---|---|---|
| $^{235}U+n$ | $_{48}Cd$ | 4.0(-5) | 1.7(-3) | 6.4(-3) | 6.9(-3) | 2.1(-3) | 1.4(-5) |
| $^{239}Pu+n$ | $_{48}Cd$ | 2.0(-4) | 5.5(-3) | 1.9(-2) | 1.4(-2) | 2.6(-4) | |
| $^{252}Cf$ SF | $_{48}Cd$ | 1.4(-1) | 3.3(-1) | 2.0(-1) | 6.6(-2) | 1.3(-2) | 1.1(-5)<br>1.4(-3) |
| | | stable | +2n | +4n | +6n | +8n | +10n |

| Isotope | Element | 130 | 132 | 134 | 136 | 138 | 140 |
|---|---|---|---|---|---|---|---|
| $^{235}U+n$ | $_{52}Te$ | 3.6(-2) | 1.6 | 6.4 | 1.3 | 7.8(-2) | 4.7(-4) |
| $^{239}Pu+n$ | $_{52}Te$ | 2.5(-1) | 2.4 | 4.7 | 6.6(-1) | 1.5(-2) | 8.8(-5) |
| $^{252}Cf$ SF | $_{52}Te$ | 2.9(-2) | 7.3(-1) | 2.0 | 6.7(-1) | 5.4(-2) | 6.9(-4) |
| | | stable | +2n | +4n | +6n | +8n | +10n |

118 Pd Yield = 4.6 x 10^-2/100 SF




(a) Coincidence spectrum obtained by double gating on the 539.3 and 718.4 keV transitions in $^{118}$Pd. (b) Coincidence spectrum obtained by double gating on the 412.5 and 718.4 keV transitions in $^{118}$Pd.



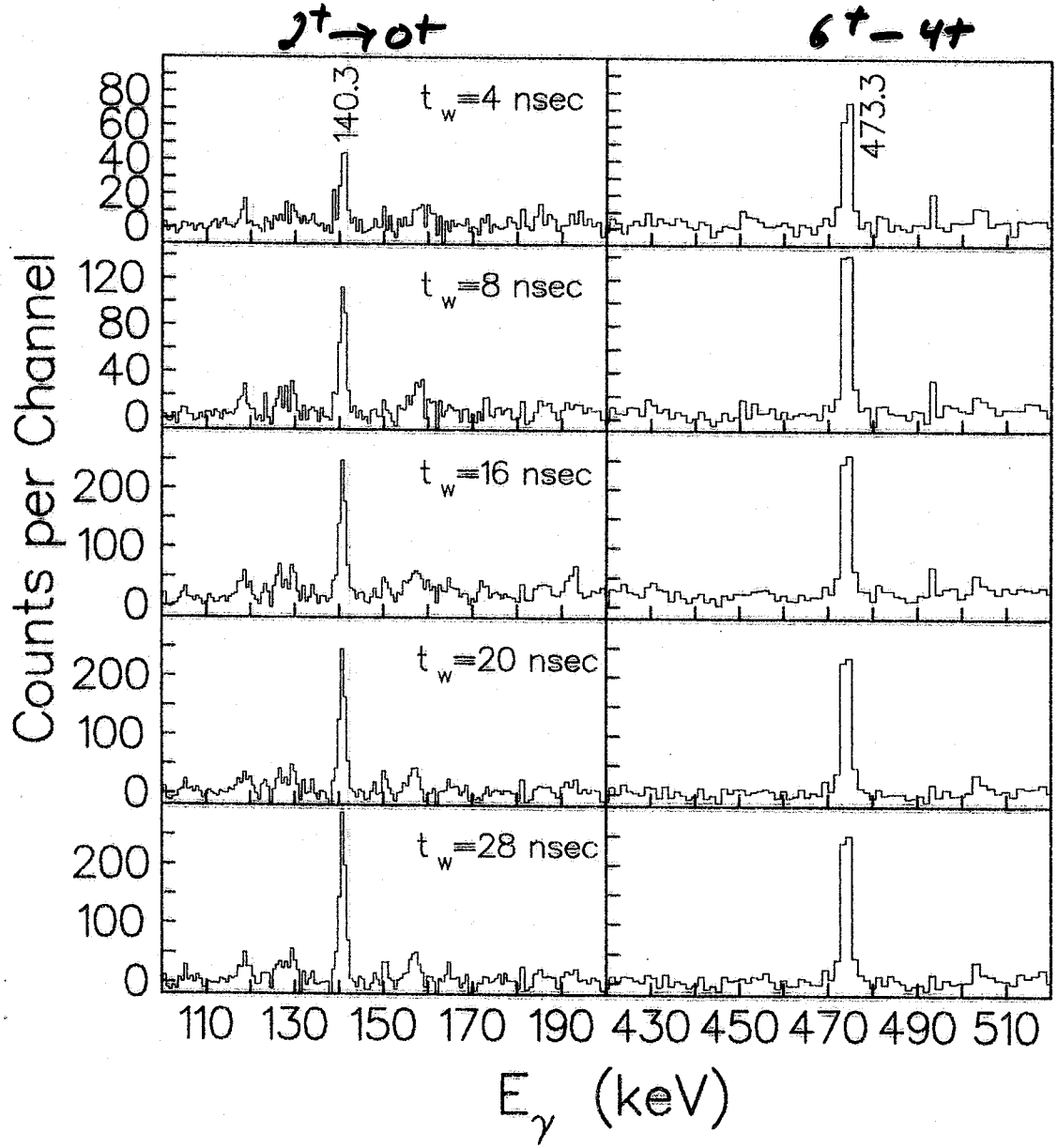

Zhang et al (Vanderbilt) Phys Rev

Level scheme for $^{118}$Pd

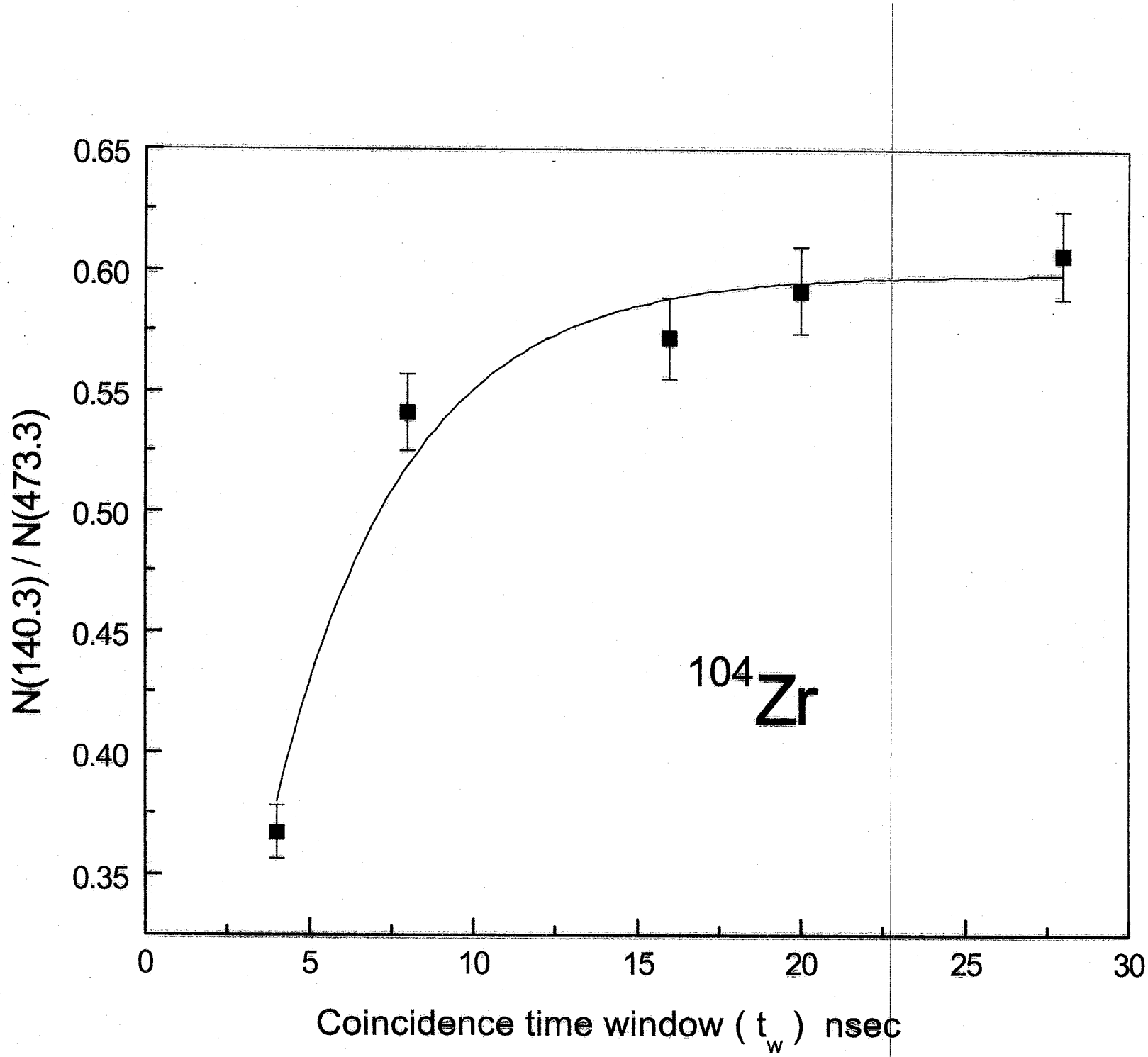
Aysto et al IGISOL first observed 2+, 4+, 6+ in β decay studies

$^{104}$Zn

Double gate on 312 keV $4^+ - 2^+$
624 keV $8^+ - 6^+$




Vanderbilt Collaboration
Hwang et al Phys Rev


0.65
0.60
0.55
0.50
0.45
0.40
0.35
N(140.3) / N(473.3)
0
5
10
15
20
25
30
Coincidence time window ( $t_w$ ) nsec
$^{104}$Zr

Hwang et al Phys Rev Vanderbilt

TABLE I: Half-lives ($T_{1/2}$ nsec) of isomeric states ($E_{IS}$, keV). $E(\gamma_3)/E(\gamma_1)$ are the double-gated transition energies. For $^{97}$Sr, $^{137}$Xe, and $^{158}$Sm, $E(\gamma_3)/E(\gamma_2)$ and $E(\gamma_1)$ are used instead.

| Nuclei | $E_{IS}$ | $E(\gamma_3)/E(\gamma_1)$ | $E(\gamma_2)$ | $E(\gamma_0)$ | Present $T_{1/2}$ | Reference's $T_{1/2}$ |
|---|---|---|---|---|---|---|
| $^{95}$Sr | 555.4 | 682.4/678.6 | 427.1 | 203.7 | 23.6(24)[20] | 24[13], 21[16] |
| $^{97}$Sr | 829.8 | 239.6/272.5 | 205.9 | 522.0 | 265(27)[20] | 382(11)[13], 255(10)[6] |
| $^{99}$Zr | 252.2 | 416.4/415.2 | 142.5 | 130.4 | 316(48) | 292(20)[14], 375(11)[13] |
| $^{108}$Tc | 330.6+x | 123.4/341.6 | 125.7 | 154.0 | 94(10) | 100(10)[3] |
| $^{133}$Te | 1610.4 | 721.1/933.4 | 738.6 | 125.5 | 97(7) | 115[16], 81.6(114)[13] |
| $^{134}$Te | 1691.8 | 2322.0/516.0 | 549.7 | 115.7 | 197(20) | 161(4)[3], 196(7)[15], 175(6)[13] |
| $^{137}$Xe | 1933.2 | 311.3/304.1 | 1046.4 | 314.1 | 10.1(9) | 8.1(4)[8] |
| $^{98}$Sr | 144.3 | 289.0/565.1 | 433.0 | 144.3 | 3.9(4) | 3.6(4)[22], $4.0^{+3.0}_{-1.5}$[18], 4(1)[23], 2.80(8)[24] |
| $^{102}$Zr | 151.8 | 326.2/630.1 | 486.1 | 151.8 | 1.8(4) | 1.71(14)[18], 0.86(18)[5], 2.21(17)[7] 1.7(4)[10] |
| $^{104}$Zr | 140.3 | 312.5/624.5 | 473.3 | 140.3 | 2.1(4) | |
| $^{143}$Ba | 117.7 | 343.3/625.7 | 493.1 | 117.7 | 5.9(8) | 3.8(12)[9], 6(2)[8] |
| $^{150}$Ce | 97.2 | 208.6/375.9 | 300.7 | 97.2 | 3.0(4) | 3.6(10)[7], 3.08(54)[18] |
| $^{152}$Ce | 81.7 | 182.5/355.5 | 274.4 | 81.7 | 4.9(9) | |
| $^{152}$Nd | 73.1 | 164.2/322.2 | 247.4 | 73.1 | 4.8(10) | 4.45(26)[12] |
| $^{158}$Sm | 72.8 | 258.1/344.1 | 167.5 | 72.8 | 1.9(4) | >2[11] |

TABLE II: $B(E2;0^+ \rightarrow 2^+)(e^2b^2)$ values, experimental $\beta_2$, and theoretical $\beta_2(Theory)$. VANDERBILT Hartree-Fock-Bogoliubov Code

| Nuclei | B(E2) | present $\beta_2$ | $\beta_2(Theory)$ |
|---|---|---|---|
| $^{98}$Sr | 0.92(9) | 0.34(2) | |
| $^{102}$Zr | 1.57(35) | 0.42(5) | 0.43 |
| $^{104}$Zr | 1.87(36) | 0.45(4) | 0.45 |
| $^{150}$Ce | 3.29(44) | 0.32(3) | |
| $^{152}$Ce | 2.98(55) | 0.30(3) | 0.32 |
| $^{152}$Nd | 3.45(72) | 0.32(3) | |
| $^{158}$Sm | 8.22(173) | 0.46(5) | 0.37 |

Super Deformation
Reinforcing of
Shell gaps
at $\beta_2 \sim 0.45$
for $Z = 38, 40$.
$N = 62, 64$
$Z = 64$, $N = 98$