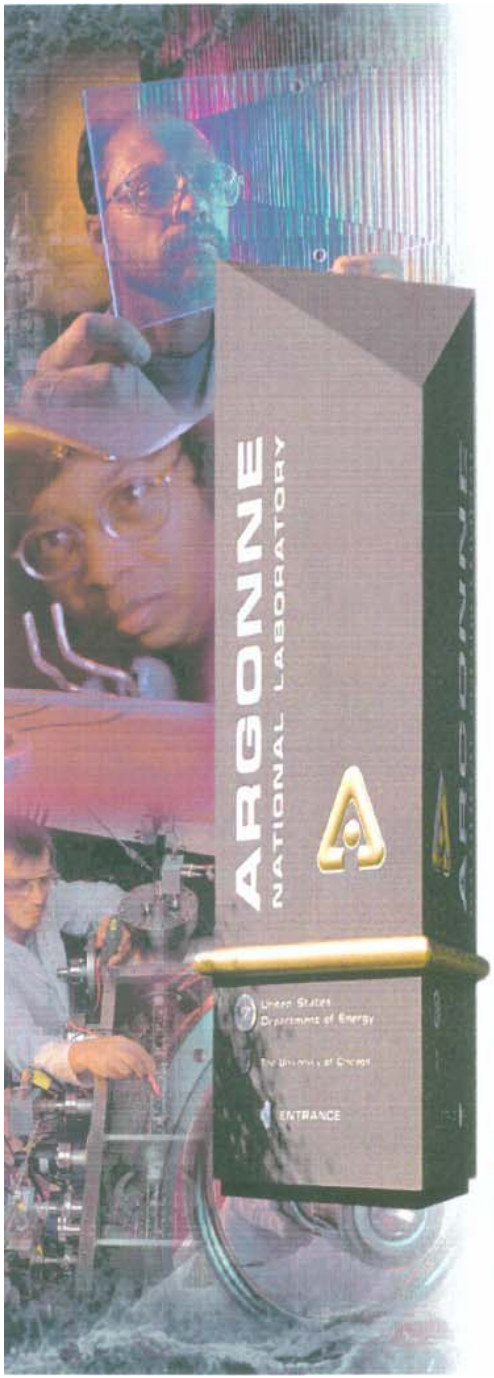

Proton Single-particle States in very Heavy Actinides

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Nuclear Structure at the Limits,
Argonne, July 29, 2004

Argonne National Laboratory

Office of Science
U.S. Department of Energy

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Outline

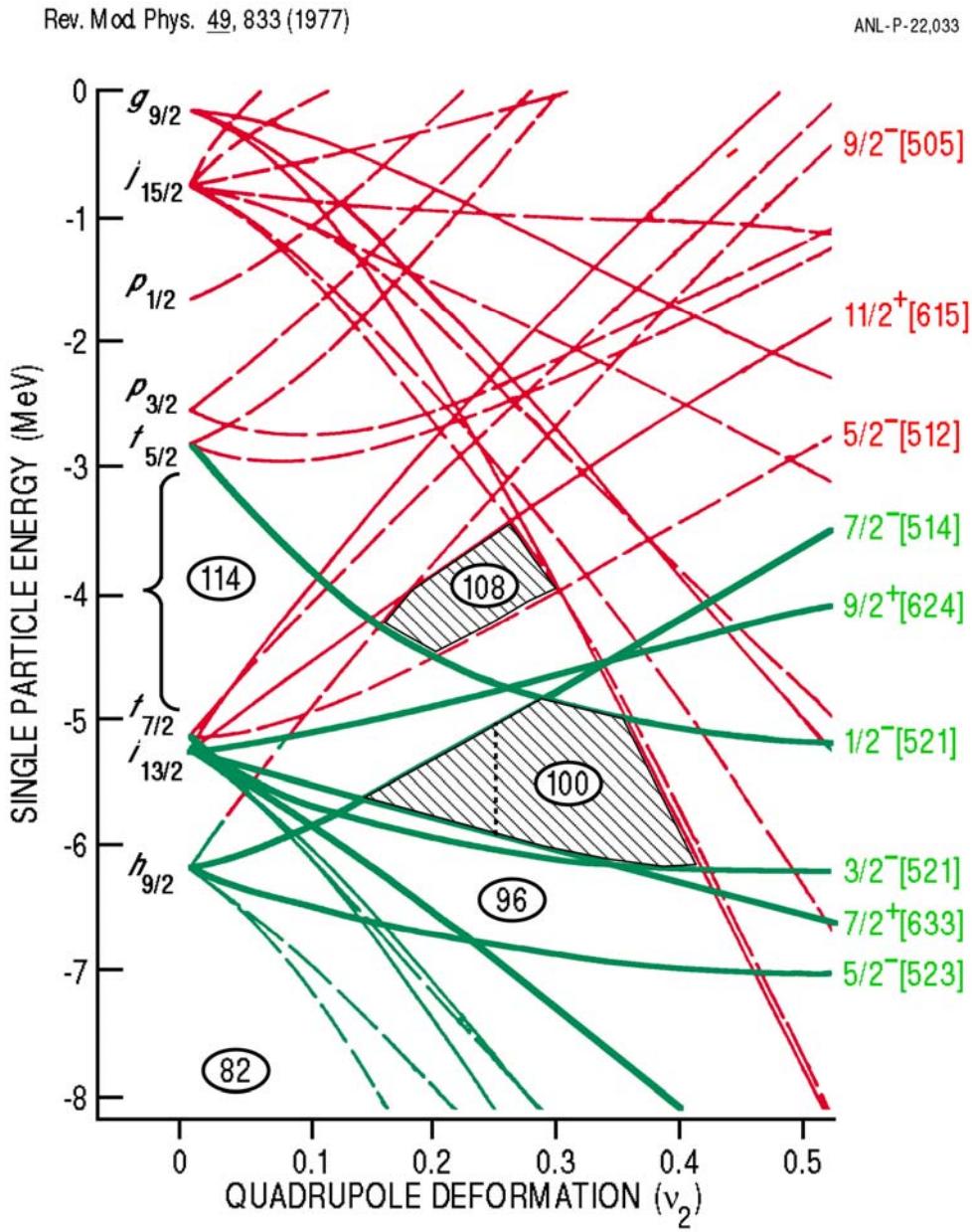
- **Introduction**
- **Identification of proton orbitals**
  - **^{249}Bk (Z=97):**
    - **^{253}Es α decay (gamma singles, coincidences with Gammasphere)**
    - **^{249}Cm β decay**
    - **^{248}Cm(α,t), ^{248}Cm(^{3}He, d)**
  - **^{251}Es (Z=99):**
    - **^{255}Md α decay**
    - **^{251}Fm EC decay**
    - **^{250}Cf(α,t)**
  - **^{253}Es (Z=99):**
    - **^{257}Md α decay**
    - **^{253}Cf β decay**
- **Summary**

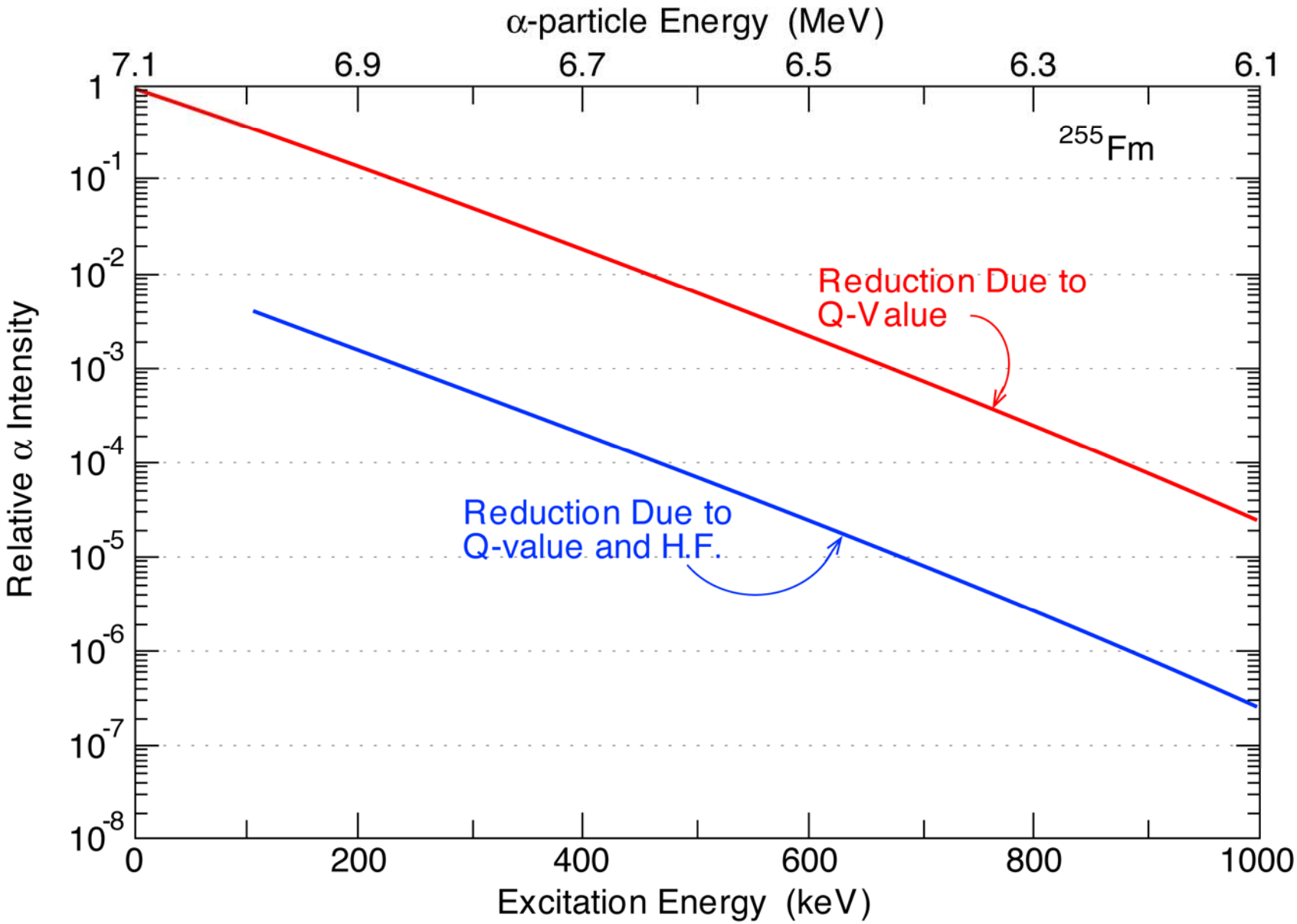
Single-particle Energies and Wave Functions are needed

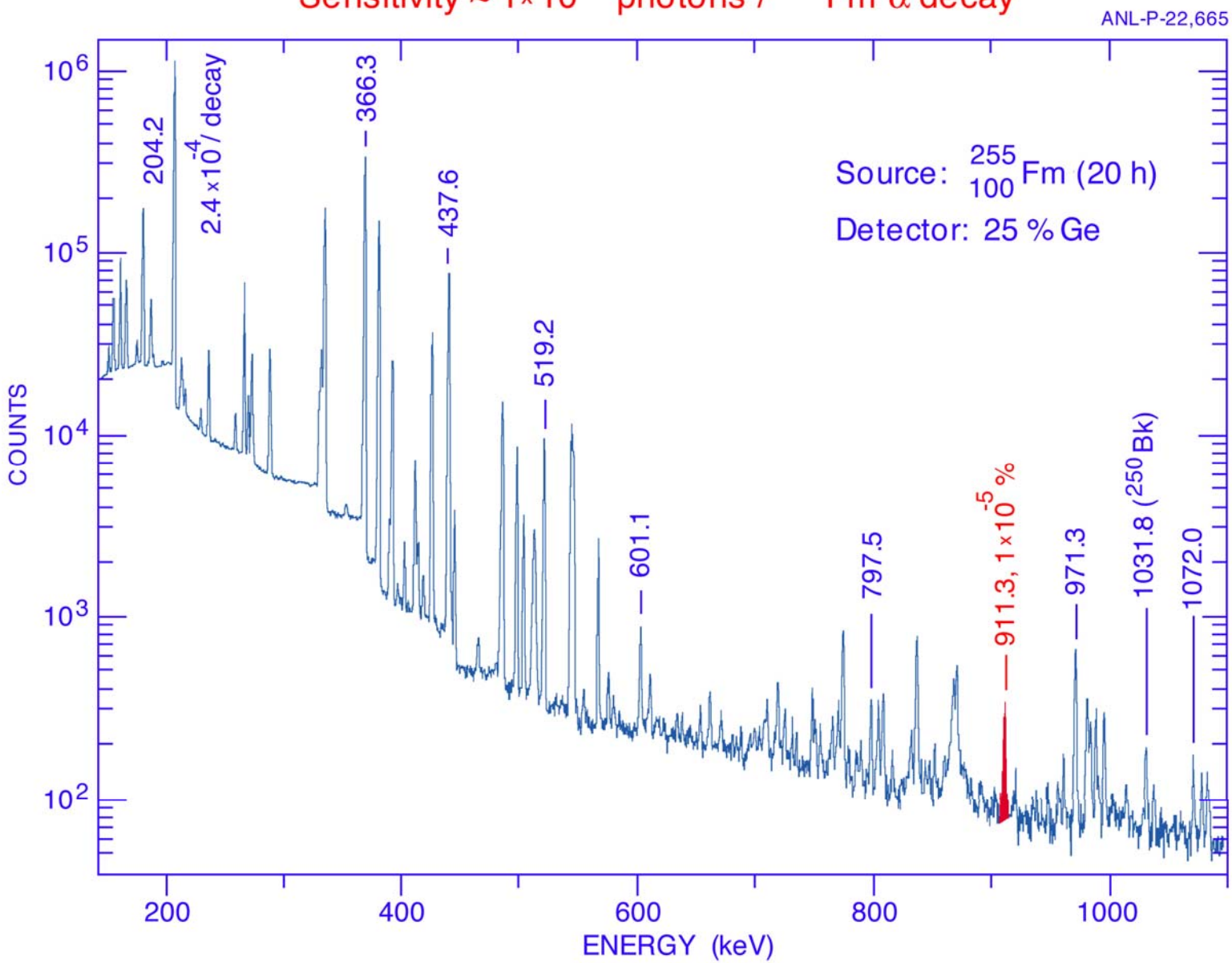
- To understand the observed properties of very heavy nuclei. In particular, the alpha decay of odd-mass and odd-odd nuclei.
- Provide data to test theoretical single-particle models.
  - Nuclei with $Z \leq 100$
    - Sufficient quantities available for decay scheme studies and transfer reactions
    - Detailed spectroscopy possible
  - Nuclei with $Z > 100$
    - Only few atoms produced. Detailed spectroscopy not possible. Theoretical models and data in lower-Z nuclei used to understand their structures.

Best approach for Nuclear Structure Studies

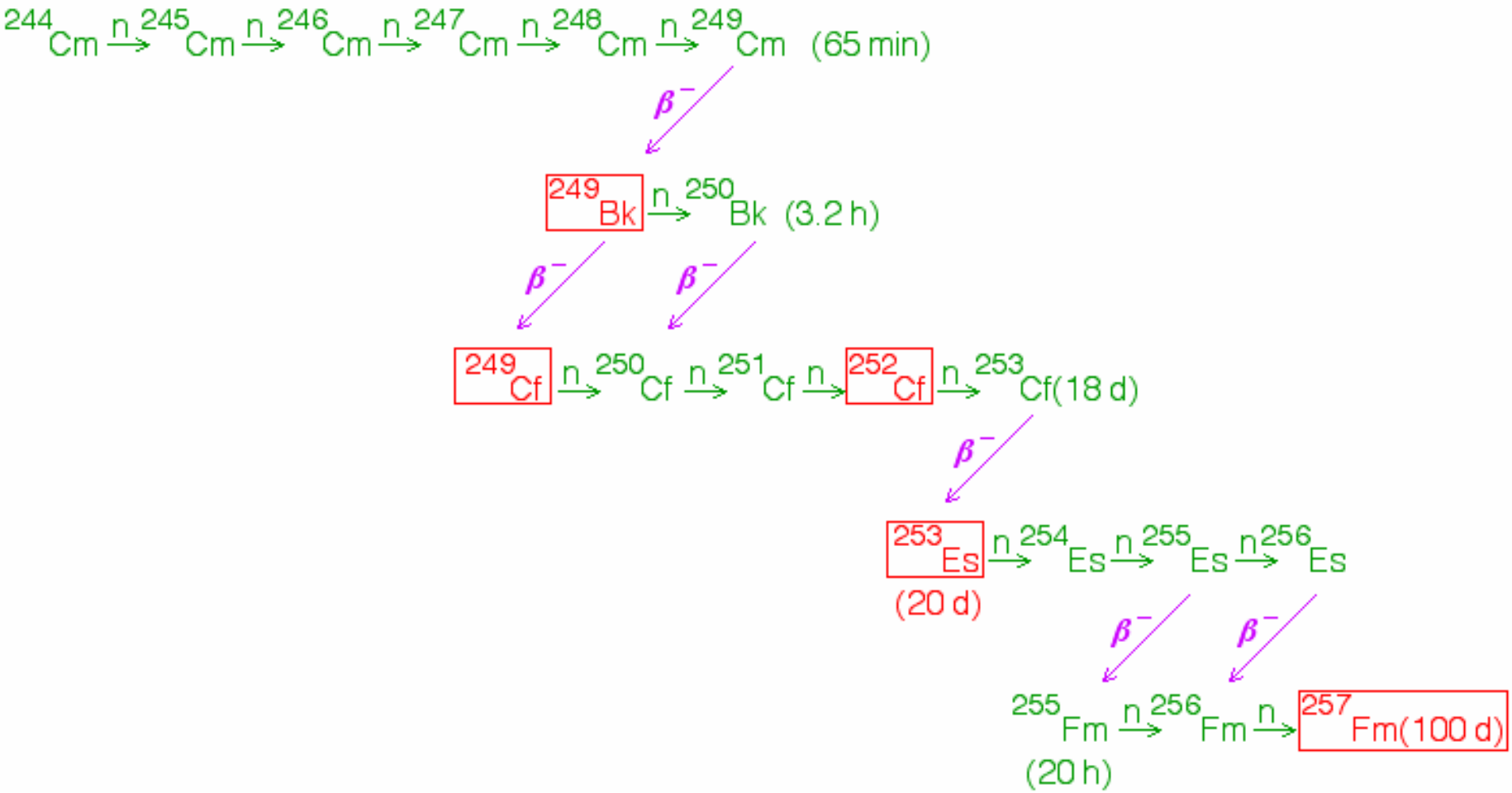
- Combine Decay scheme data and One-nucleon Transfer reaction data
- Decay scheme provides spin, parity, K quantum number, single-particle matrix elements
- One-nucleon transfer reaction gives the amplitudes of the wavefunctions


Rev. Mod. Phys. 49, 833 (1977)
ANL-P-22,033
SINGLE PARTICLE ENERGY (MeV)
QUADRUPOLE DEFORMATION (ν_2)
$g_{9/2}$
$j_{15/2}$
$p_{1/2}$
$p_{3/2}$
$f_{5/2}$
$f_{7/2}$
$i_{13/2}$
$h_{9/2}$
114
108
100
96
82
9/2⁻[505]
11/2⁺[615]
5/2⁻[512]
7/2⁻[514]
9/2⁺[624]
1/2⁻[521]
3/2⁻[521]
7/2⁺[633]
5/2⁻[523]

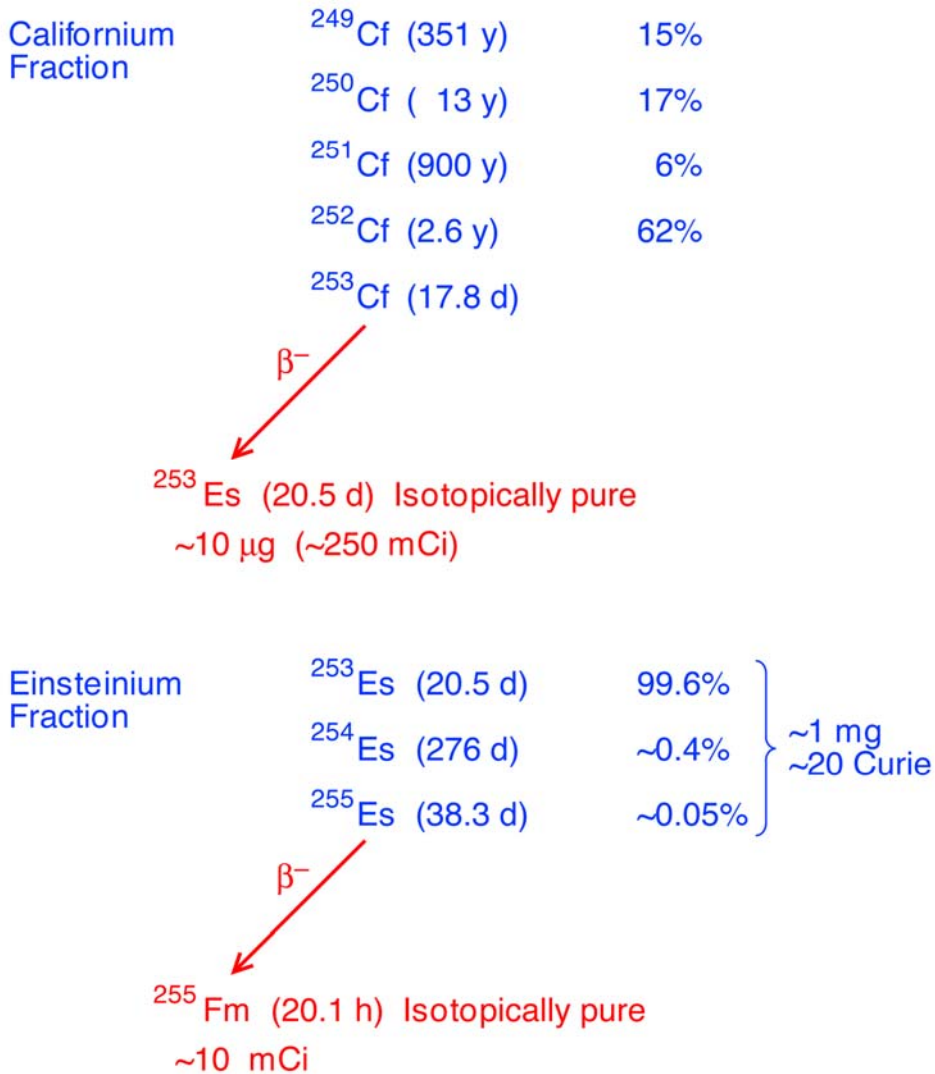

α-particle Energy (MeV)
7.1
6.9
6.7
6.5
6.3
6.1
1
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
Relative α Intensity
255Fm
Reduction Due to
Q-Value
Reduction Due to
Q-value and H.F.
0
200
400
600
800
1000
Excitation Energy (keV)


Sensitivity ~ 1 x 10^-8 photons / 255Fm α decay
ANL-P-22,665
Source: 255 100 Fm (20 h)
Detector: 25 % Ge
COUNTS
ENERGY (keV)
204.2
2.4 x 10^-4 / decay
366.3
437.6
519.2
601.1
797.5
911.3, 1 x 10^-5 %
971.3
1031.8 (250Bk)
1072.0

Production of Heavy Elements in HFIR Reactor

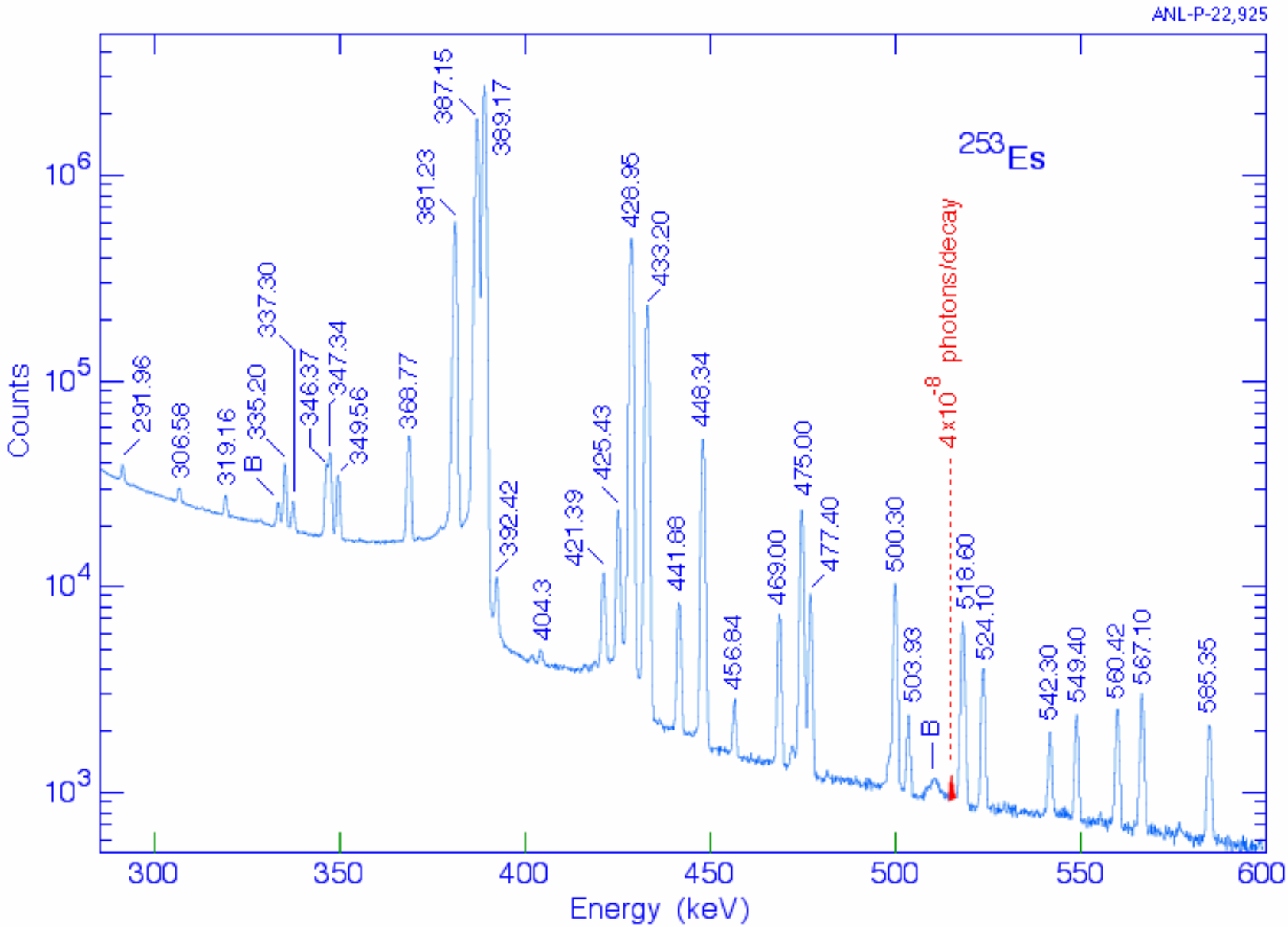


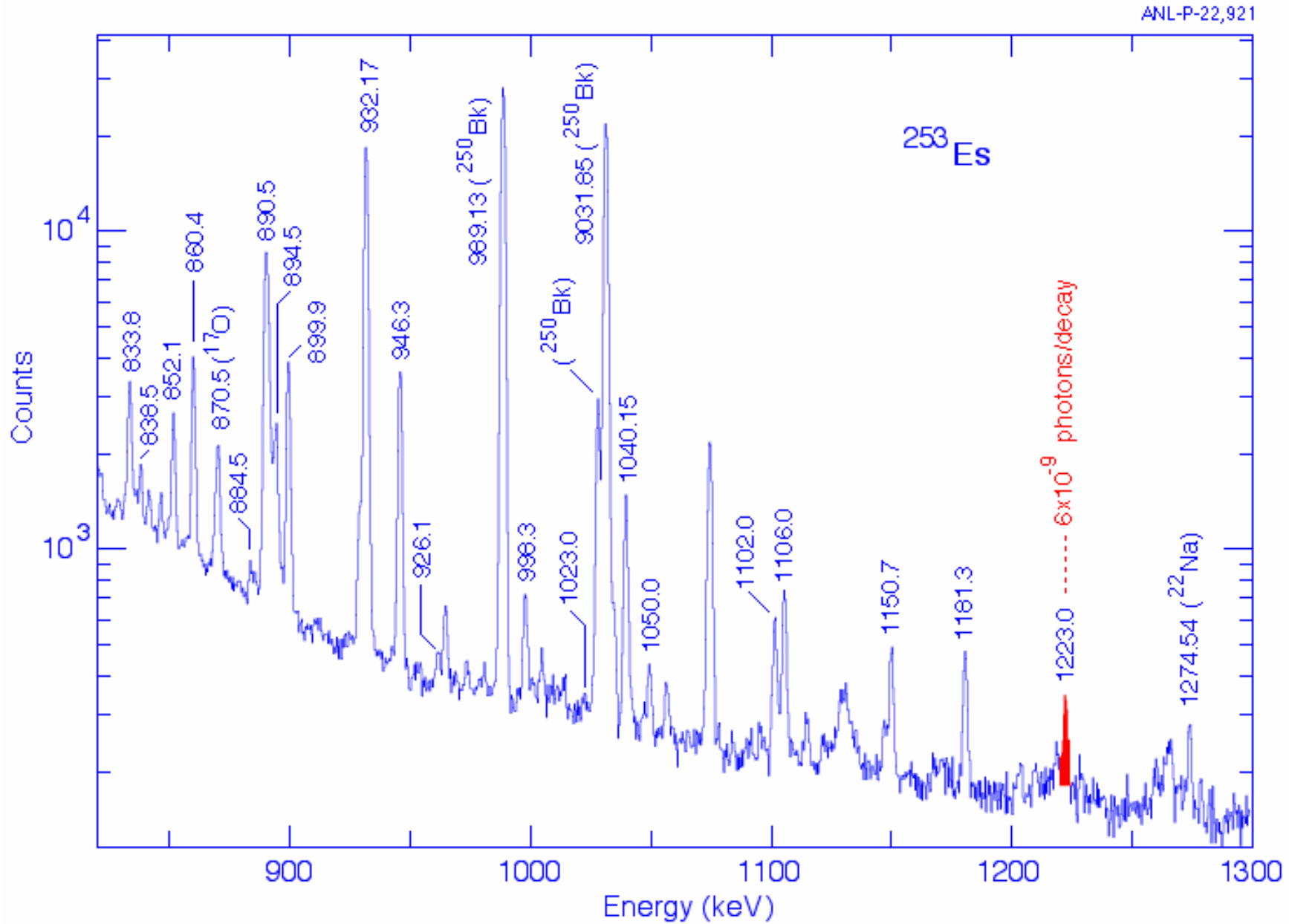
Production of Actinide Elements at High Flux Isotope Reactor (HFIR) at ORNL



Experiments

- Three samples of ^{255}Fm (20 h) ~1 mCi each
- One sample of ^{253}Es (20 d) ~20 mCi (~1 GBq)
  - Obtained from ORNL in 1998, 2000, and 2003
- Measured:
  - Gamma singles with Ge and LEPS detectors
  - Gamma-gamma coincidences with GAMMASPHERE at ANL:
    - ^{255}Fm in 1998
    - ^{253}Es in 2003


ANL-P-22,925
^{253}Es
Counts
Energy (keV)
4x10^{-8} photons/decay
291.96
306.58
319.16
B
335.20
337.30
346.37
347.34
349.56
368.77
381.23
387.15
389.17
392.42
404.3
421.39
425.43
428.95
433.20
441.86
448.34
456.84
469.00
475.00
477.40
500.30
503.93
B
518.60
524.10
542.30
549.40
560.42
567.10
585.35


ANL-P-22,921
^{253}Es
Counts
Energy (keV)
10^4
10^3
900
1000
1100
1200
1300
833.8
838.5
852.1
860.4
870.5 (^{17}O)
884.5
890.5
894.5
899.9
932.17
946.3
926.1
969.13 (^{250}Bk)
998.3
(^{250}Bk)
1023.0
9031.85 (^{250}Bk)
1040.15
1050.0
1102.0
1106.0
1150.7
1181.3
1223.0 ------ 6x10^{-9} photons/decay
1274.54 (^{22}Na)

Gamma single spectrum

- Can see gamma rays with intensities about 1×10^{-8} photons per decay

  Interference
- Gamma rays from fission branch of ^{253}Es
- Gamma rays from (α, p) reactions on light elements like ^{14}N, ^{19}F, ^{23}Na, ^{28}Si.
  - These gamma rays were identified by placing Es on different materials.

gamma-gamma coincidences with Gammasphere

- Very sensitive
- Can see gammas with intensities

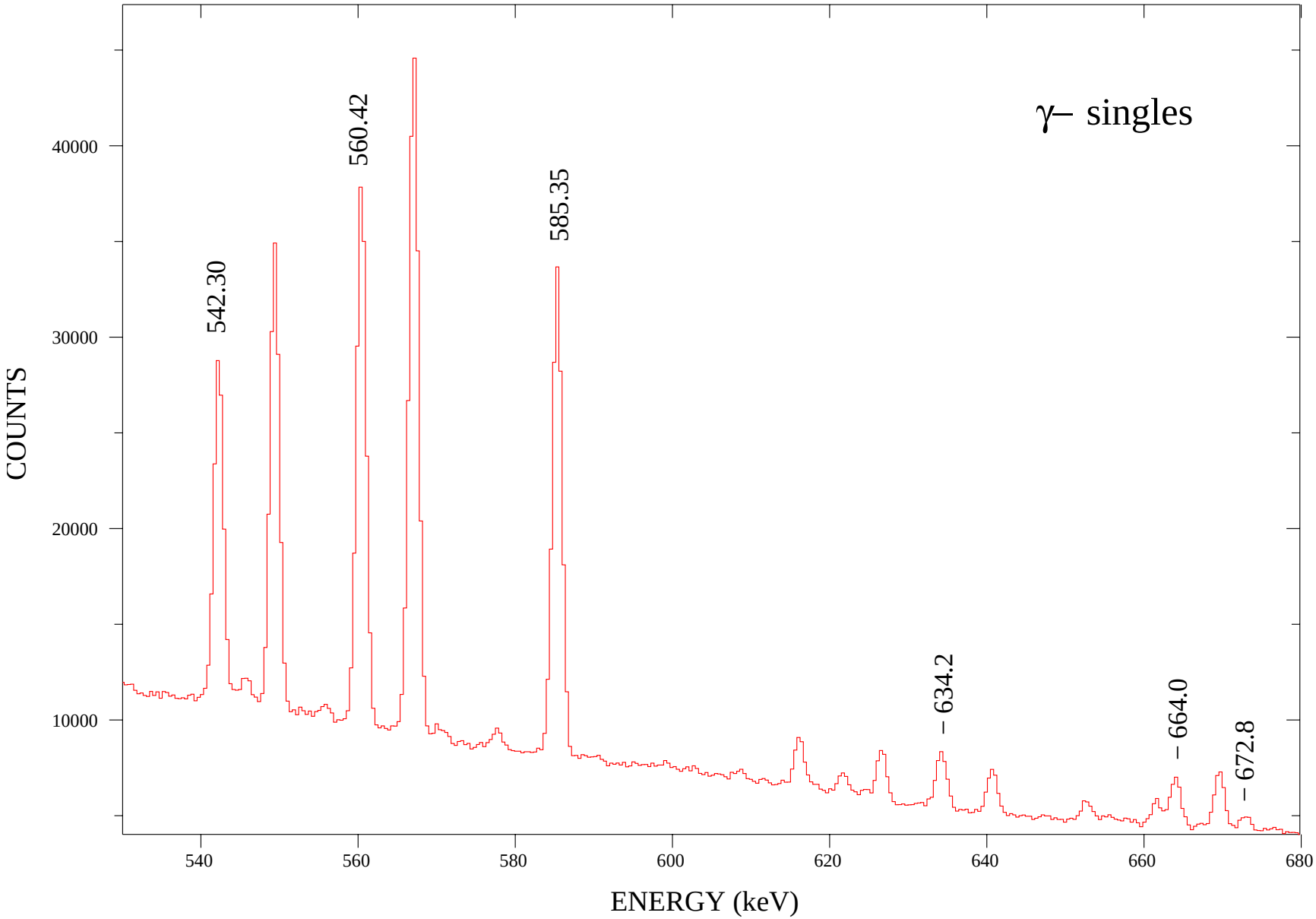
  $\sim 1 \times 10^{-8}$ photons per decay

But!

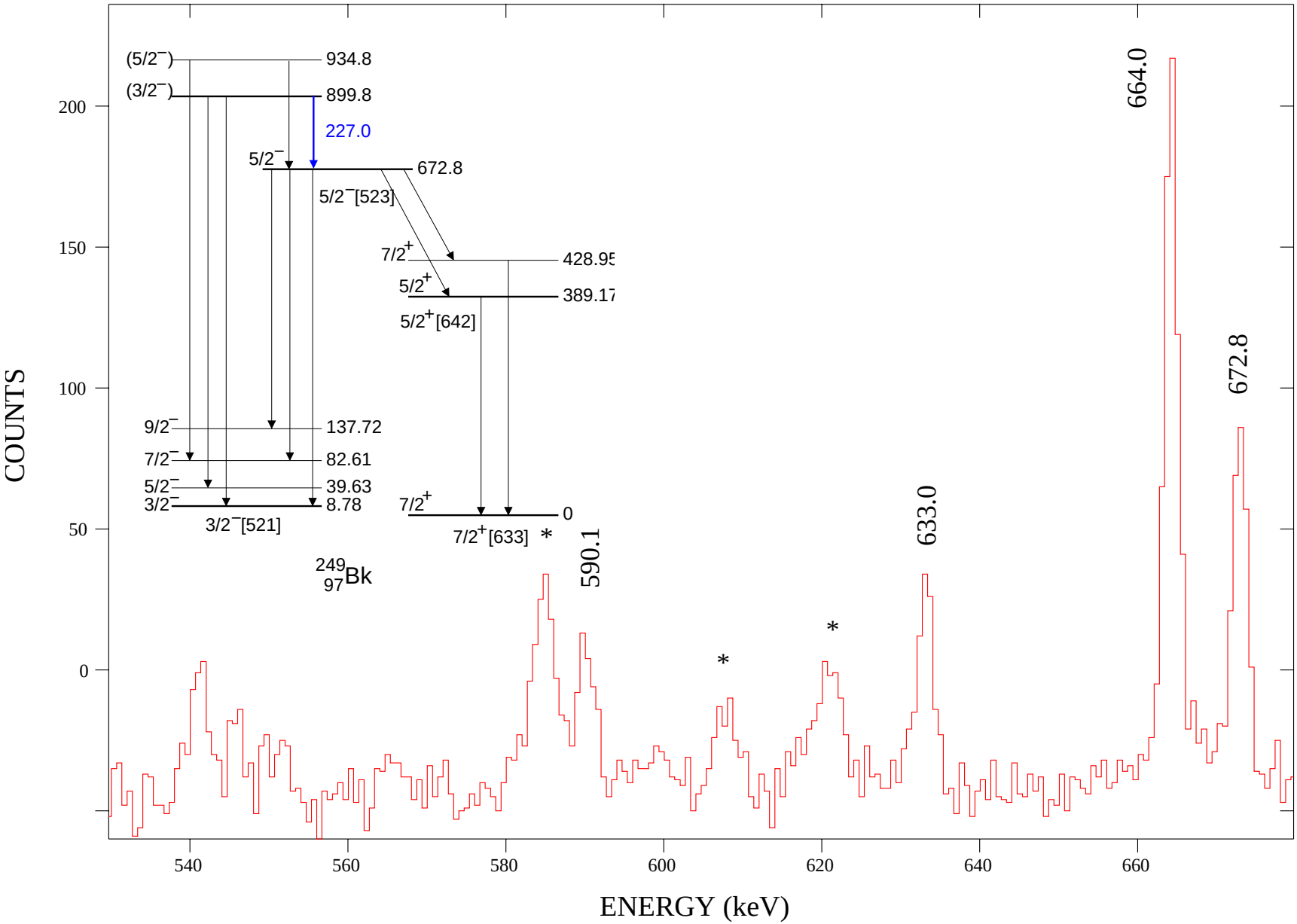
- Residual activities from previous in-beam experiments.

  ^{48}V, ^{52}Mn, ^{56}Co, ^{56}Ni, ^{58}Co
- Strong Compton-Compton peaks from higher energy gamma rays

Es253 gamma singles



gate: 227 keV peak



^{249}Bk Levels

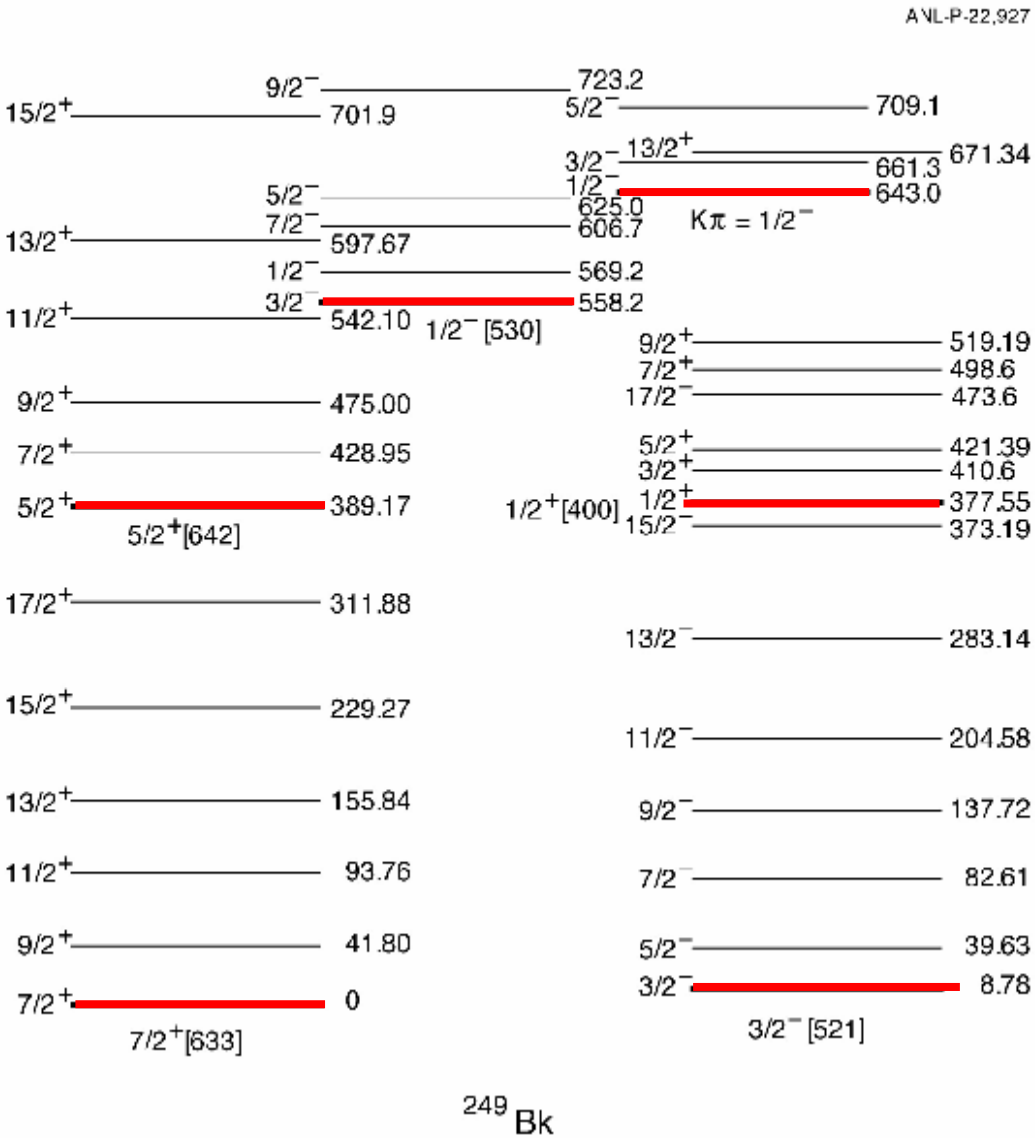
- ^{249}Cm (64 min) decay

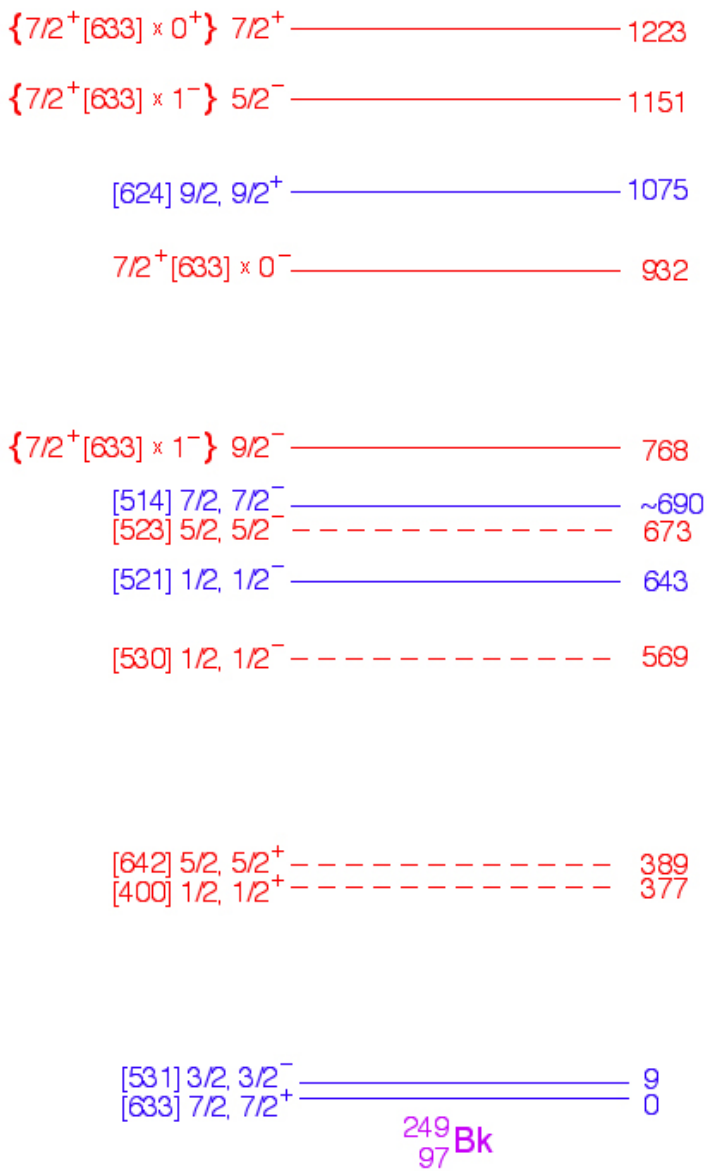
  ground state: 1/2 $^{+}$[620]

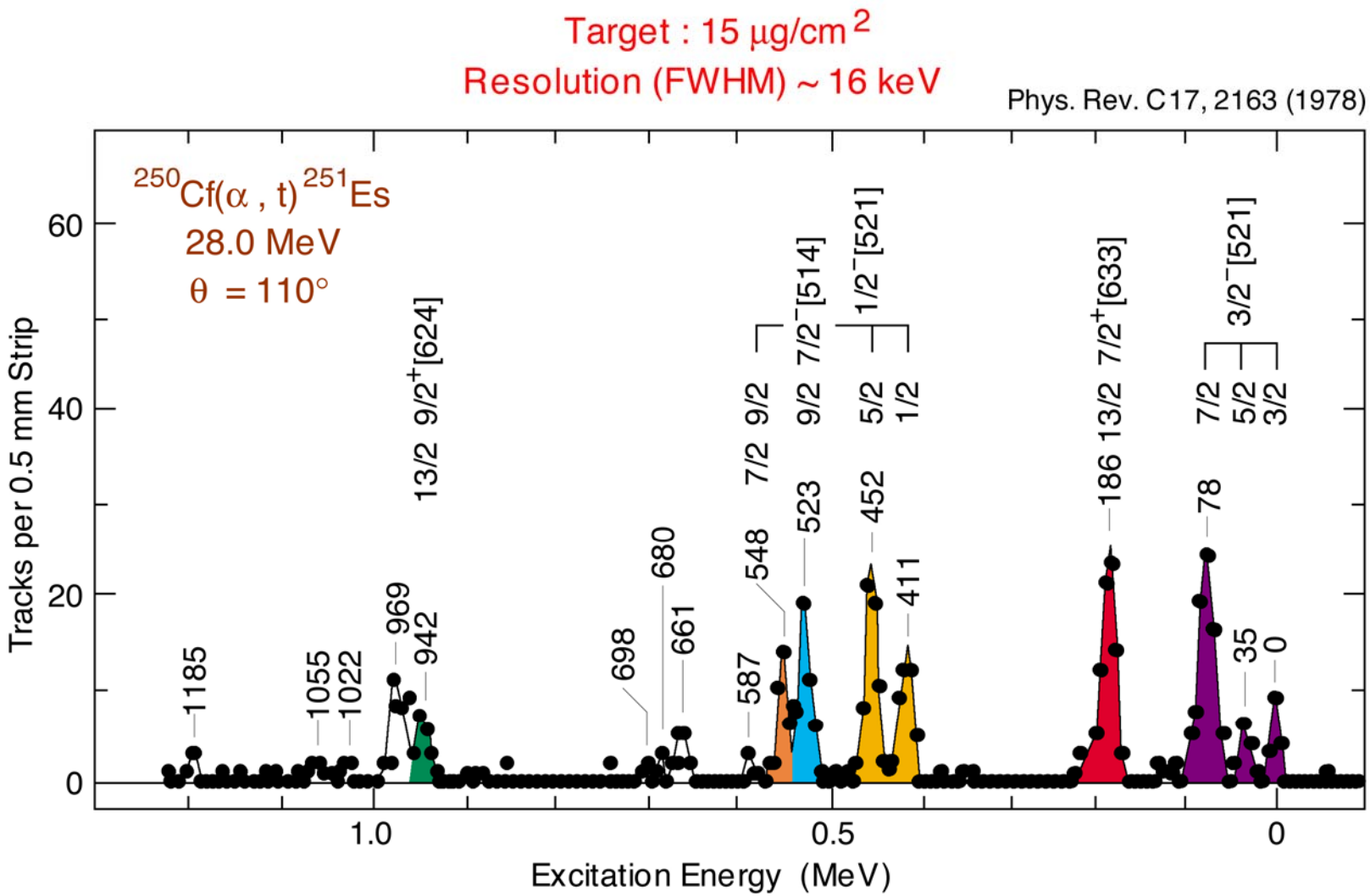
  I=1/2, 3/2 populated
- ^{253}Es (20 d) alpha decay

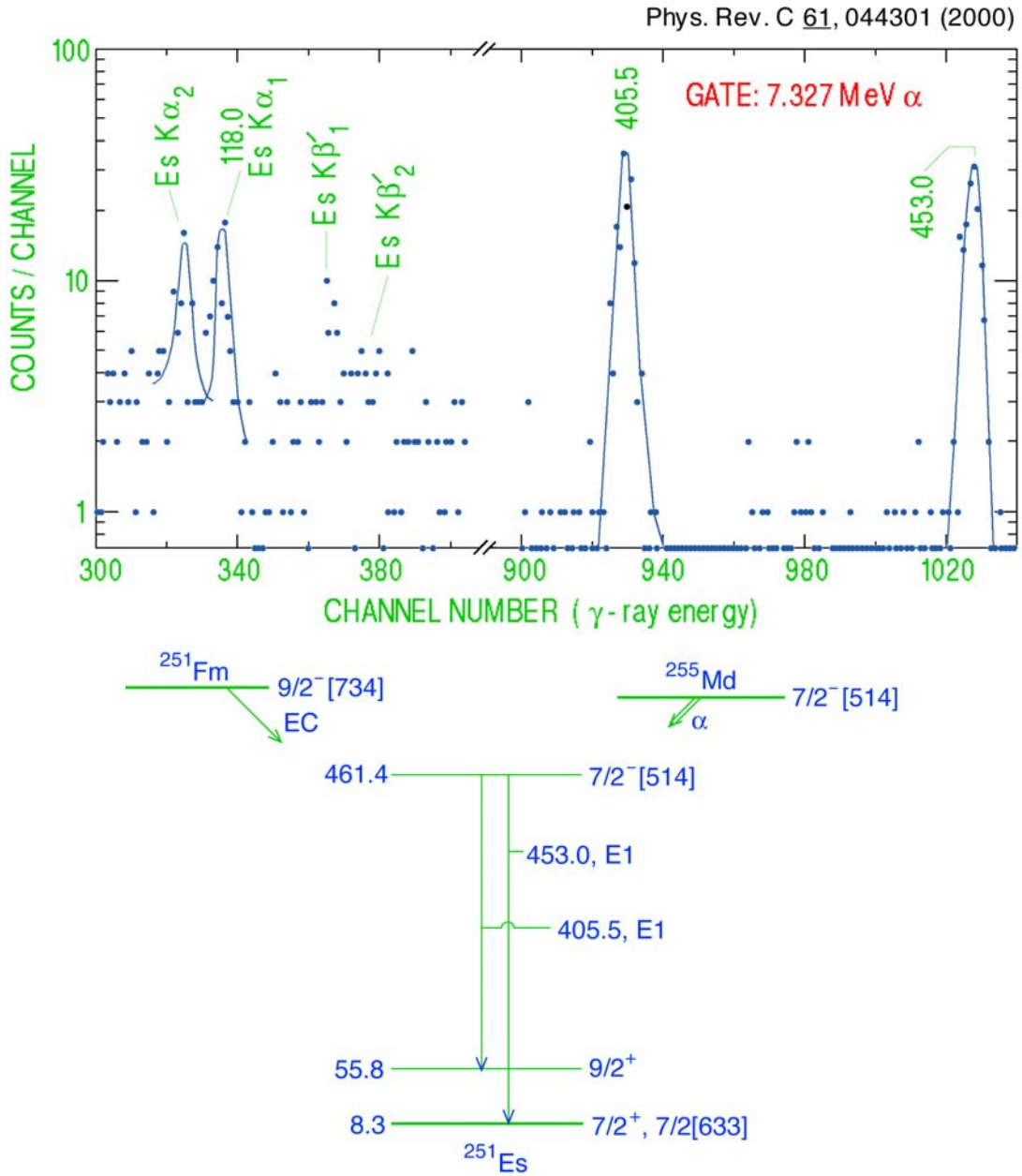
  Spin, parity deduced
- ^{248}Cm (α,t), ^{248}Cm (^{3}He, d) reactions

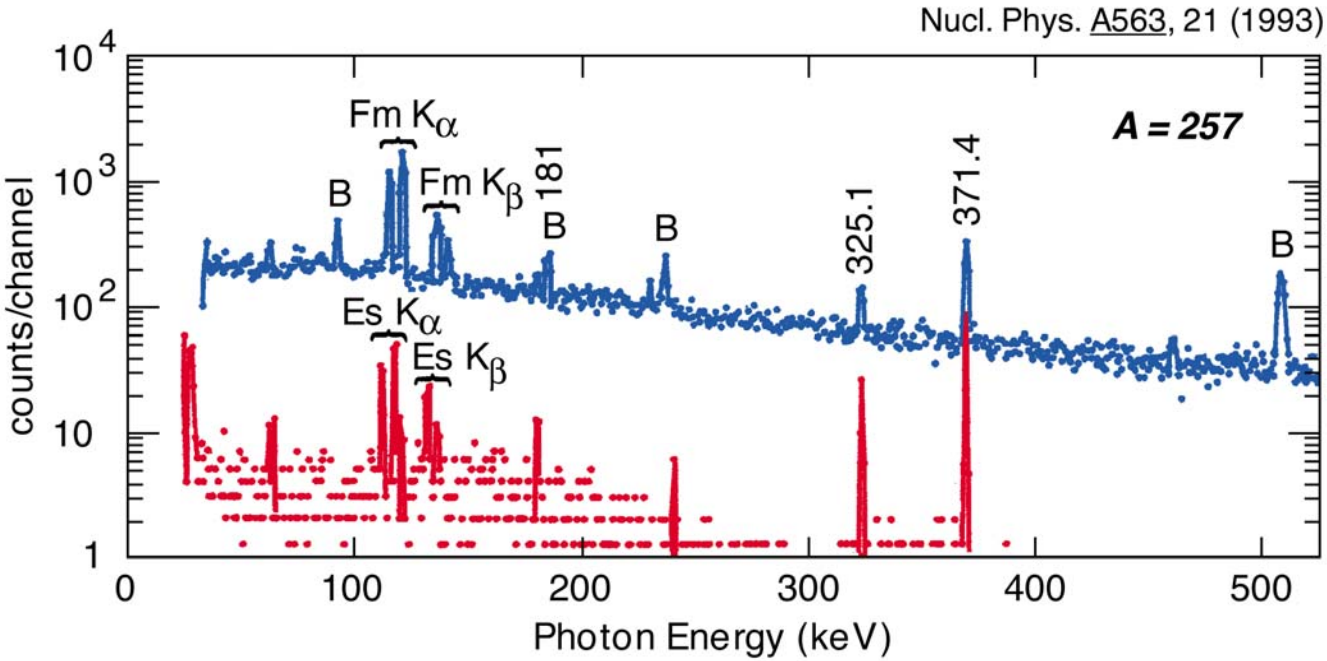
  single-particle character deduced

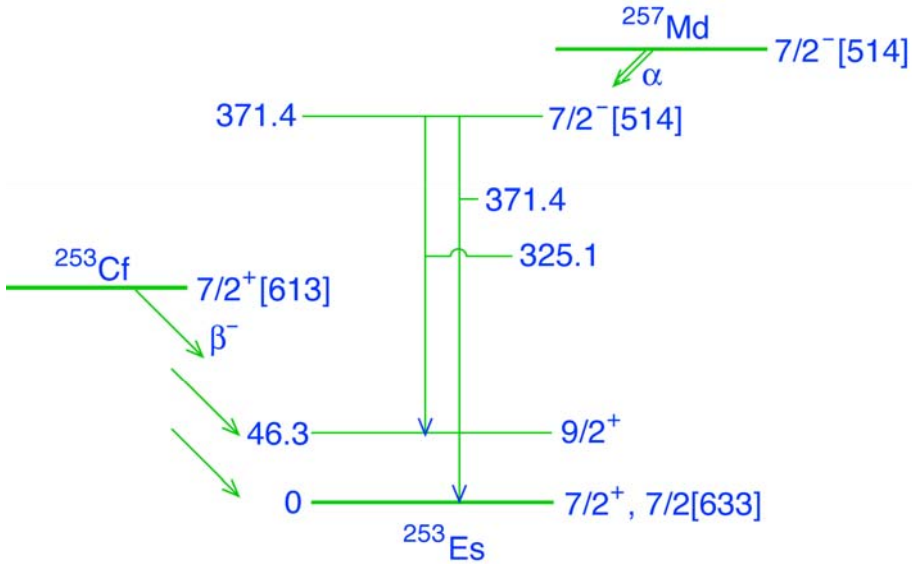

ANL-P-22,927
9/2⁻ 723.2
15/2⁺ 701.9
5/2⁻ 709.1
3/2⁻ 13/2⁺ 671.34
661.3
1/2⁻ 643.0
5/2⁻ 625.0
7/2⁻ 606.7
Kπ = 1/2⁻
13/2⁺ 597.67
1/2⁻ 569.2
3/2⁻ 558.2
11/2⁺ 542.10
1/2⁻[530]
9/2⁺ 519.19
7/2⁺ 498.6
17/2⁻ 473.6
9/2⁺ 475.00
7/2⁺ 428.95
5/2⁺ 421.39
3/2⁺ 410.6
1/2⁺ 377.55
5/2⁺ 389.17
1/2⁺[400]
15/2⁻ 373.19
5/2⁺[642]
17/2⁺ 311.88
13/2⁻ 283.14
15/2⁺ 229.27
11/2⁻ 204.58
13/2⁺ 155.84
9/2⁻ 137.72
11/2⁺ 93.76
7/2⁻ 82.61
9/2⁺ 41.80
5/2⁻ 39.63
7/2⁺ 0
3/2⁻ 8.78
7/2⁺[633]
3/2⁻[521]
249 Bk

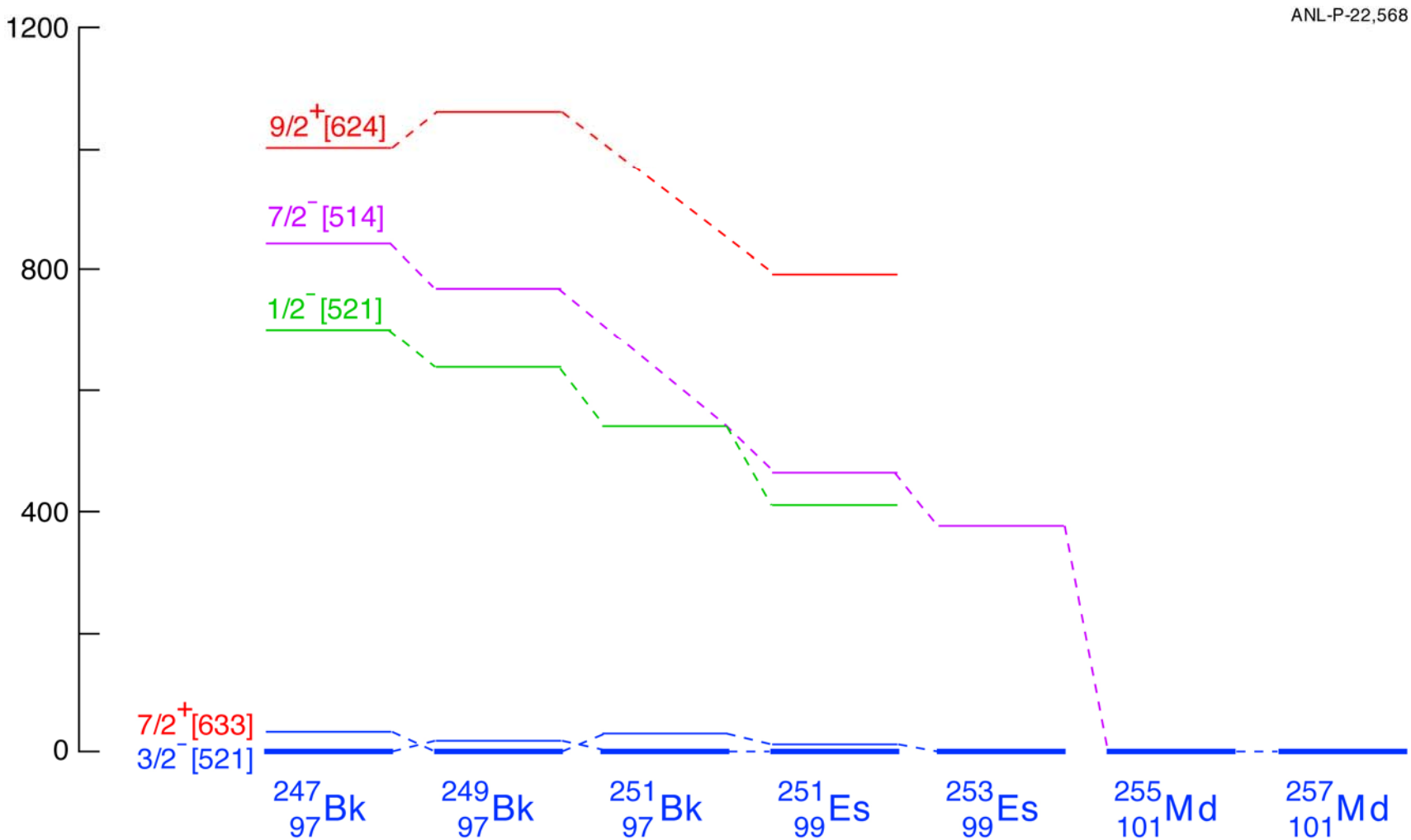

{7/2+[633] x 0+} 7/2+ 1223
{7/2+[633] x 1−} 5/2− 1151
[624] 9/2, 9/2+ 1075
7/2+[633] x 0− 932
{7/2+[633] x 1−} 9/2− 768
[514] 7/2, 7/2− ~690
[523] 5/2, 5/2− 673
[521] 1/2, 1/2− 643
[530] 1/2, 1/2− 569
[642] 5/2, 5/2+ 389
[400] 1/2, 1/2+ 377
[531] 3/2, 3/2− 9
[633] 7/2, 7/2+ 0
249 97 Bk


Target : 15 μg/cm 2
Resolution (FWHM) ~ 16 keV
Phys. Rev. C17, 2163 (1978)
250Cf(α , t) 251Es
28.0 MeV
θ = 110°
Tracks per 0.5 mm Strip
Excitation Energy (MeV)
1185
1055
1022
969
942
698
680
661
587
548
523
452
411
186
78
35
0
13/2 9/2+[624]
7/2 9/2 7/2−[514]
9/2 5/2 1/2 1/2−[521]
13/2 7/2+[633]
7/2 5/2 3/2 3/2−[521]


Phys. Rev. C 61, 044301 (2000)
GATE: 7.327 MeV α
Es Kα2
118.0
Es Kα1
Es Kβ'1
Es Kβ'2
405.5
453.0
COUNTS / CHANNEL
CHANNEL NUMBER (γ-ray energy)
251Fm
9/2⁻[734]
EC
255Md
7/2⁻[514]
α
461.4
7/2⁻[514]
453.0, E1
405.5, E1
55.8
9/2⁺
8.3
7/2⁺, 7/2[633]
251Es


Nucl. Phys. A563, 21 (1993)
A = 257
Fm Kα
Fm Kβ
Es Kα
Es Kβ
B
181
325.1
371.4
counts/channel
Photon Energy (keV)


257Md
7/2⁻[514]
α
371.4
7/2⁻[514]
371.4
325.1
253Cf
7/2⁺[613]
β⁻
46.3
9/2⁺
0
7/2⁺, 7/2[633]
253Es


ANL-P-22,568
1200
800
400
0
9/2+[624]
7/2-[514]
1/2-[521]
7/2+[633]
3/2-[521]
247 97 Bk
249 97 Bk
251 97 Bk
251 99 Es
253 99 Es
255 101 Md
257 101 Md

Summary

- Use of decay data and one-nucleon transfer reaction data have enabled us to determine the single-particle energies and wavefunctions in very heavy actinide nuclei.
  - Neutron orbitals up to N=162 identified
  - Proton orbitals up to Z=101 identified
- The single-particle energies and wavefunctions are reproduced by a single-particle model calculation using a deformed Woods-Saxon potential.

Participants

- ANL: I. Ahmad, F.G. Kondev, E.F. Moore, M.P.Carpenter, R.R. Chasman, J.P. Greene, R.V.F. Janssens, T. Lauritsen, C.J. Lister, D. Seweryniak
- LLNL: R.W. Hoff, J.E. Evans, R.W. Lougheed
- ORNL: L.K. Felker and C.E. Porter
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