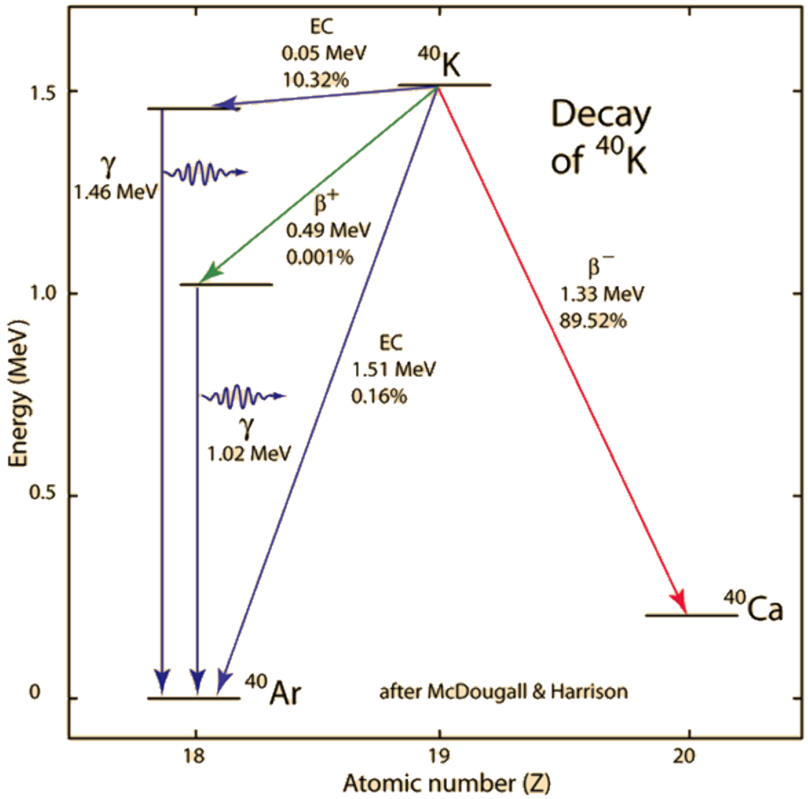
Slides for Radioactive Decay

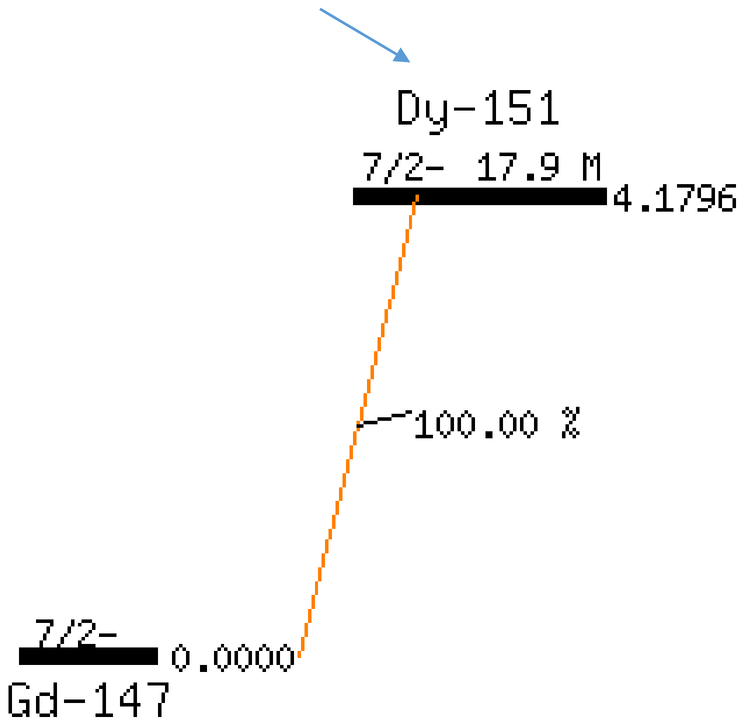
2024

But First… Decay Diagrams

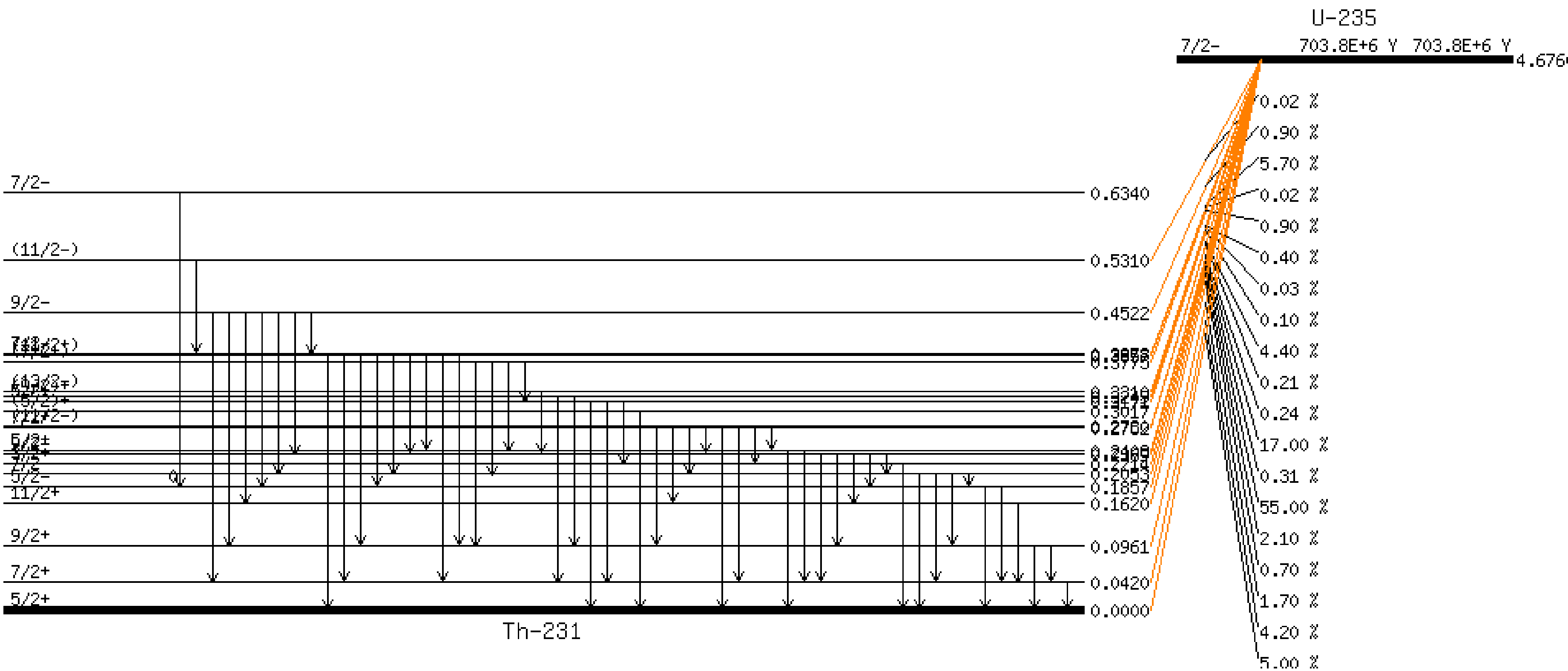
http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/kar.html

^{40}K gives the most generalized example, minus alpha decay

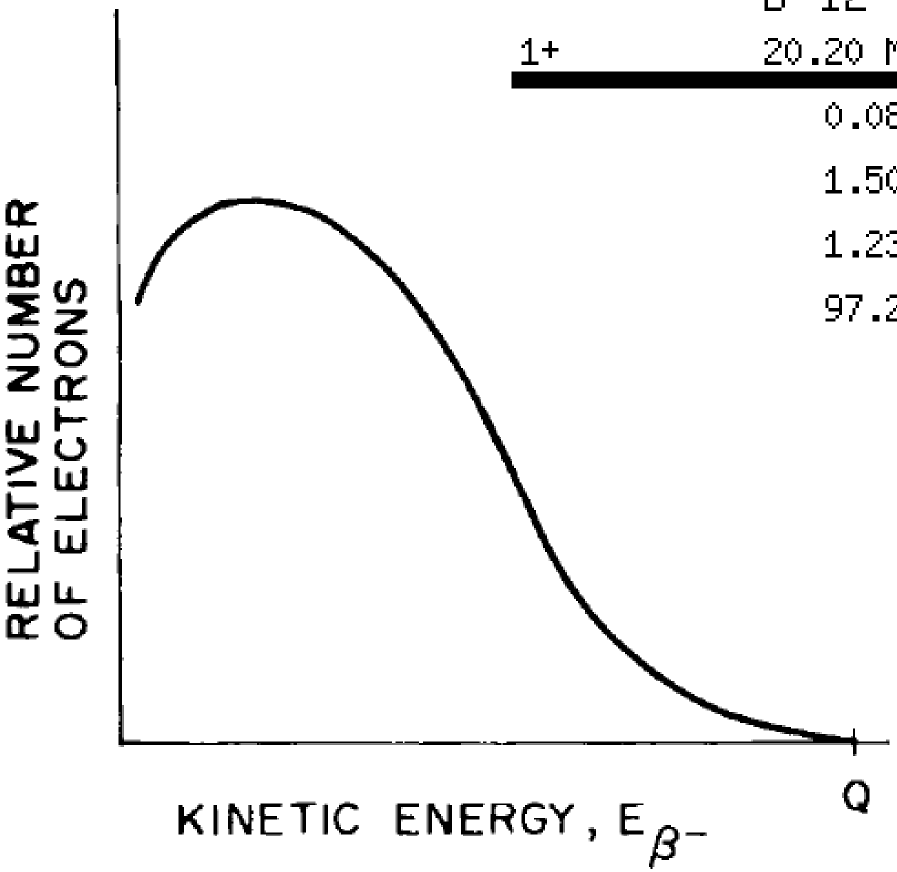


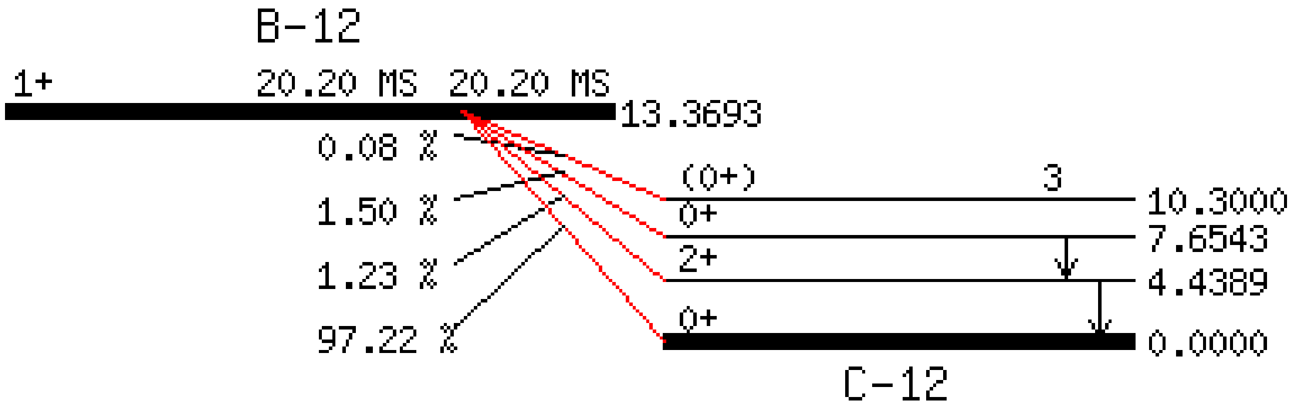


Alpha Decay Diagrams



Beta Decay Diagrams and Energetics

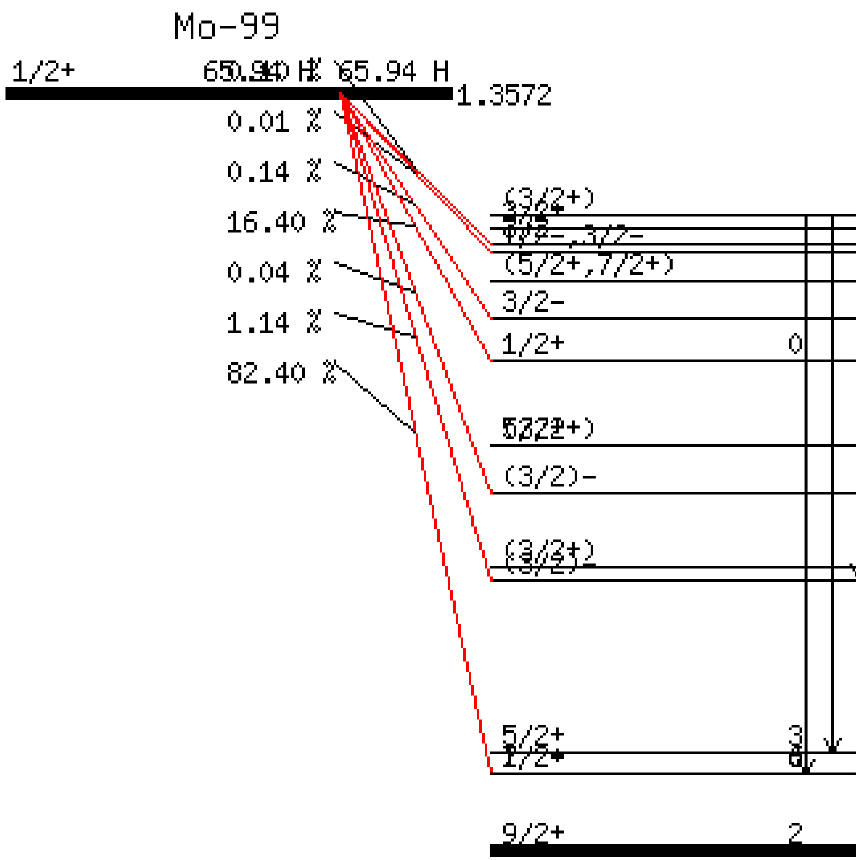


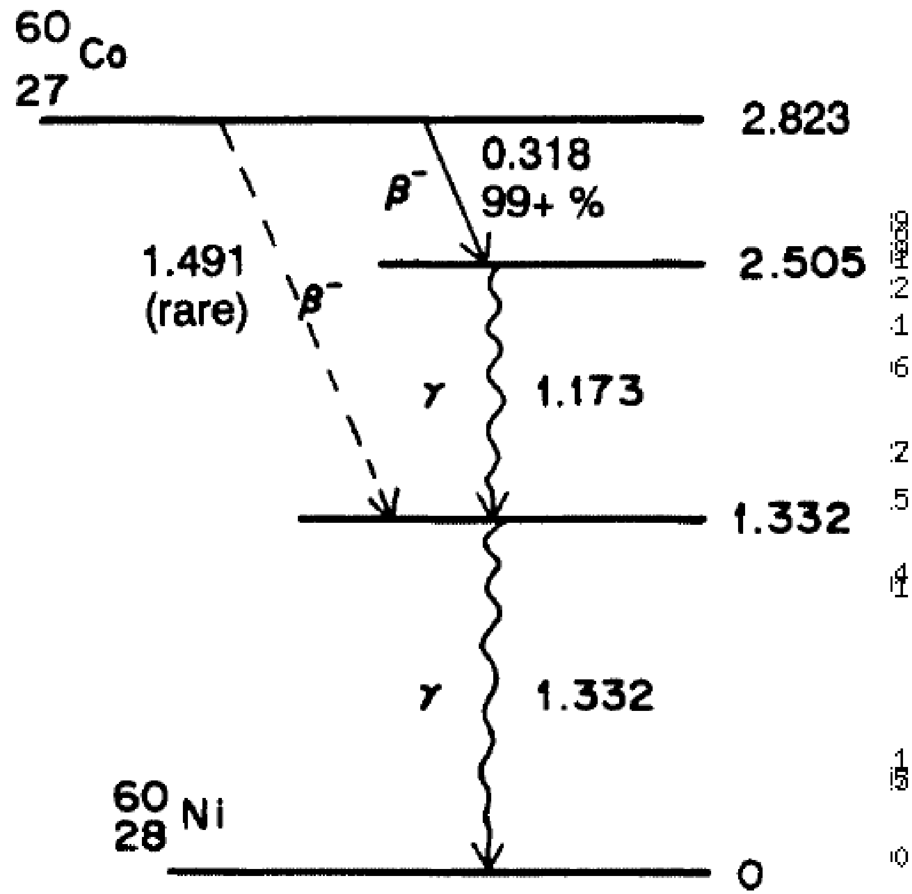


$$^{12}_{5}B \rightarrow \, ^{12}_{6}C + \beta^- + \bar{\nu}$$

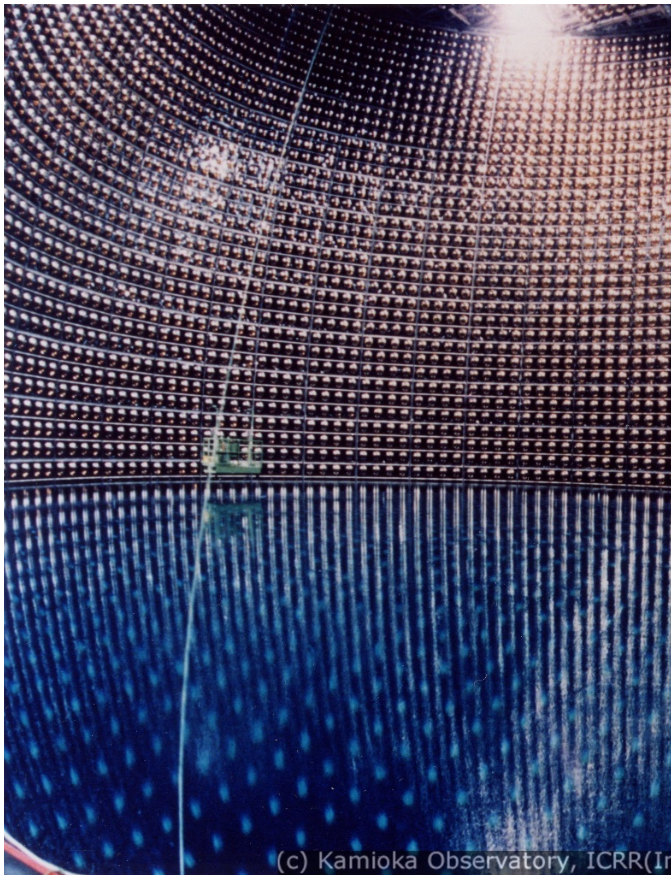
What does the number of antineutrinos vs. energy look like?

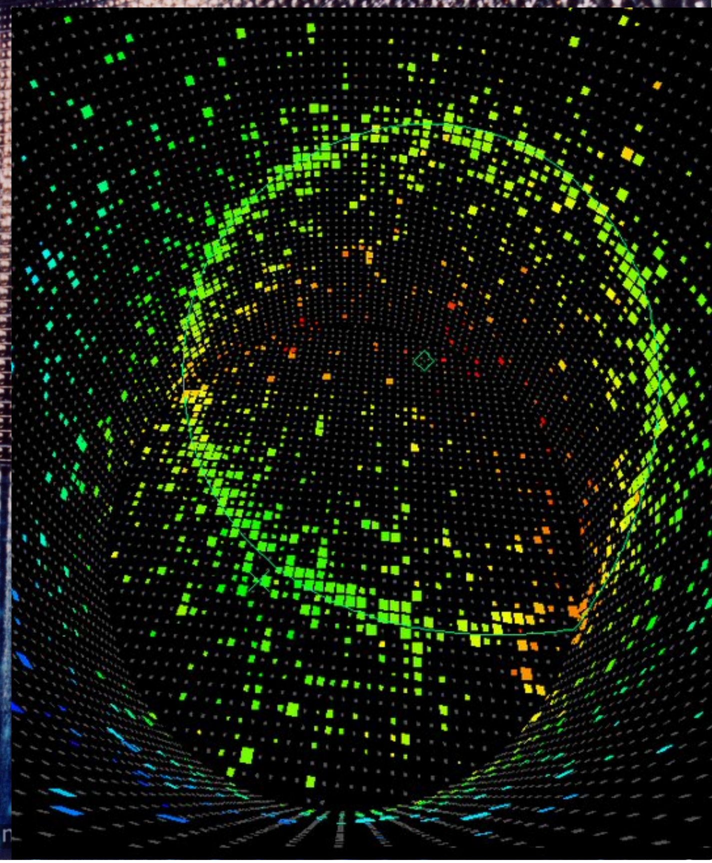
Notable Beta Decay Reactions





Detecting Neutrinos – Super Kamiokande, Japan






news.bbc.co.uk/2/hi/science/nature/1664447.stm

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Monday, 19 November, 2001, 12:49 GMT

Particle physics telescope explodes

A defective photomultiplier tube exploded, setting off a chain reaction

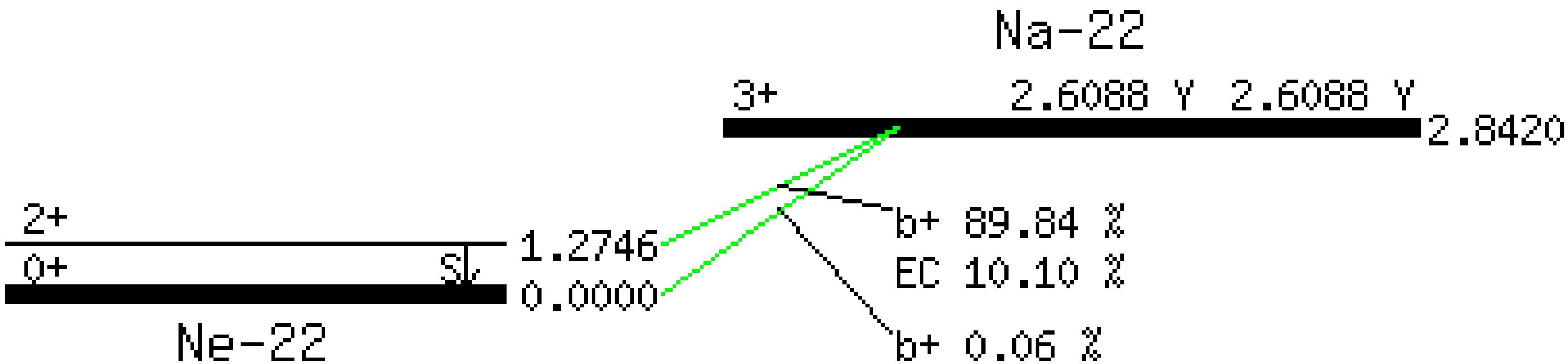
By BBC News Online science editor Dr David Whitehouse

One of the world's leading particle physics instruments has been severely damaged in an accident.

The underground Super-Kamiokande Observatory in Japan detects elusive neutrino particles from space by using photomultiplier tubes to register the flashes of light they produce when they pass through a huge tank of water.

"We will rebuild the detector. There is no question"
Yoji Totsuka, Kamioka Observatory

Positron Decay Diagrams and Required Energetics



$$Q_{\beta^+} = \Delta_P - \Delta_D - 2mc^2. \qquad Q > 1.022 \text{ MeV}$$

Why $2m_ec^2$? We emit one positron (E_{rest} = 0.511MeV) *and* the daughter nucleus must shed one orbital electron to conserve charge.

Introduction to Positron annihilation spectroscopy measurements: Application to Irradiated Fe and some Y-Ti-O clusters in 14YWT

X. Hu, D. Xu, and Brian D. Wirth[1,#],
with significant contributions from
M. Alinger (GE), P. Asoka-Kumar[2], G.R. Odette[3], R.H. Howell[2], P.A. Sterne[2],
Y. Nagai[4], and M. Hasegawa[4]

20 March 2014

Presented at the
U. Michigan Workshop

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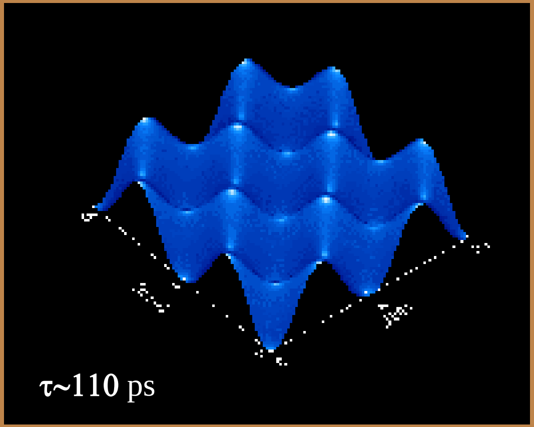
Positron Annihilation Spectroscopy

• **Positrons are a tremendously powerful and self-seeking probe of the chemical, electronic and & magnetic properties of vacancies/vacancy-clusters and locally enriched regions (precipitates) of stronger positron affinity in metallic alloys.**

- localize in open-volume regions (vacancies, voids, other defects) due to lack of positively charged atomic nuclei
- localize in regions of higher positron affinity (elemental specific, eV)

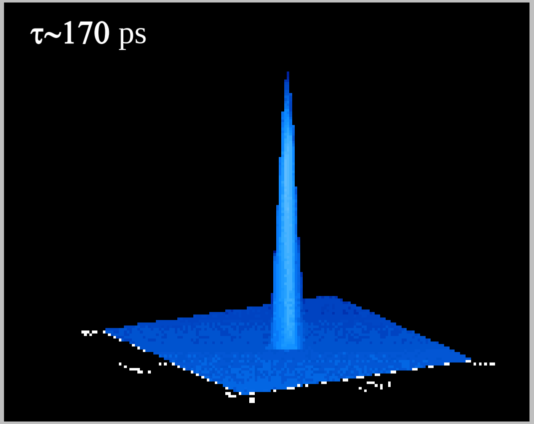
Cr: -2.62 Mn -3.72 Fe:-3.84 Cr:-2.62 Ni:-4.46 Cu: -4.81 Zr: -3.98

Bulk metal without defects

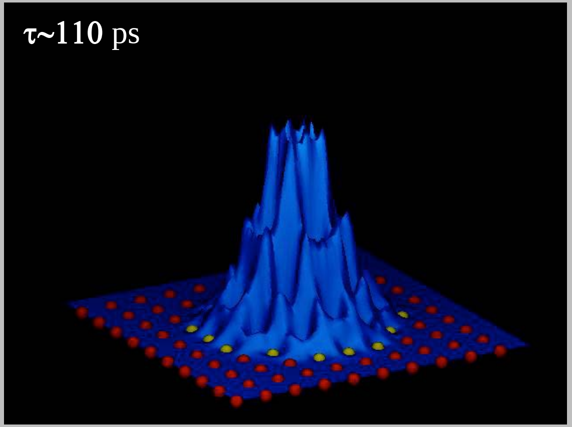


Delocalized positron density

Vacancy defects



Embedded particles of stronger positron affinity

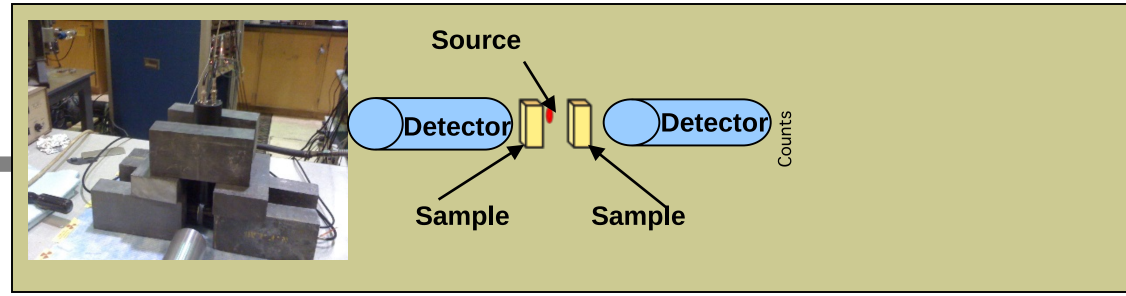


Strongly localized positron density

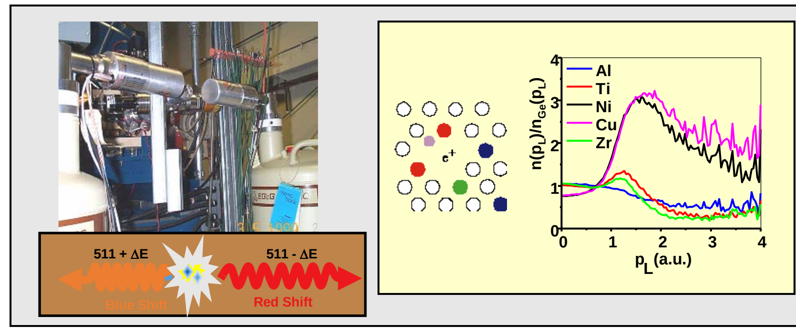
• **Positron annihilation experiments must be carefully analyzed, but strong theoretical foundation exists; especially when combined with complementary techniques (3DAP, SANS, TEM, PIA, mechanical properties, …)**

Positron Annihilation Spectroscopy Methods

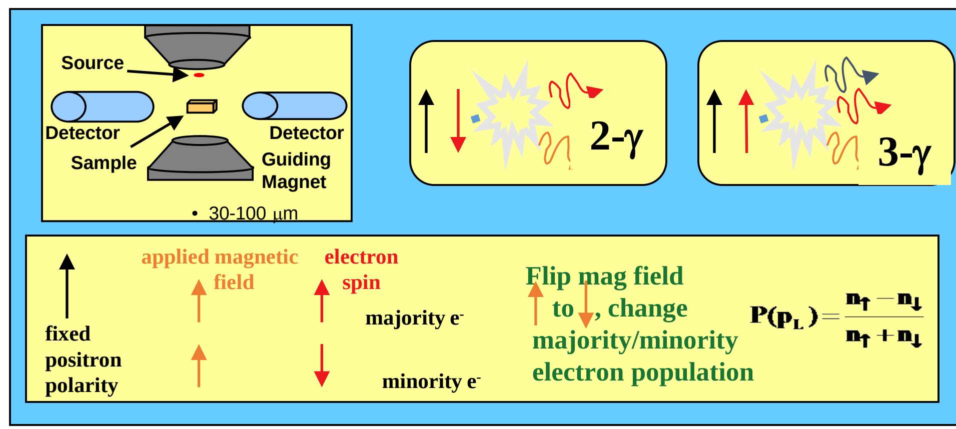
Methods:



- Positron lifetime (*correlates with electron density; vacancies & vacancy cluster size*)



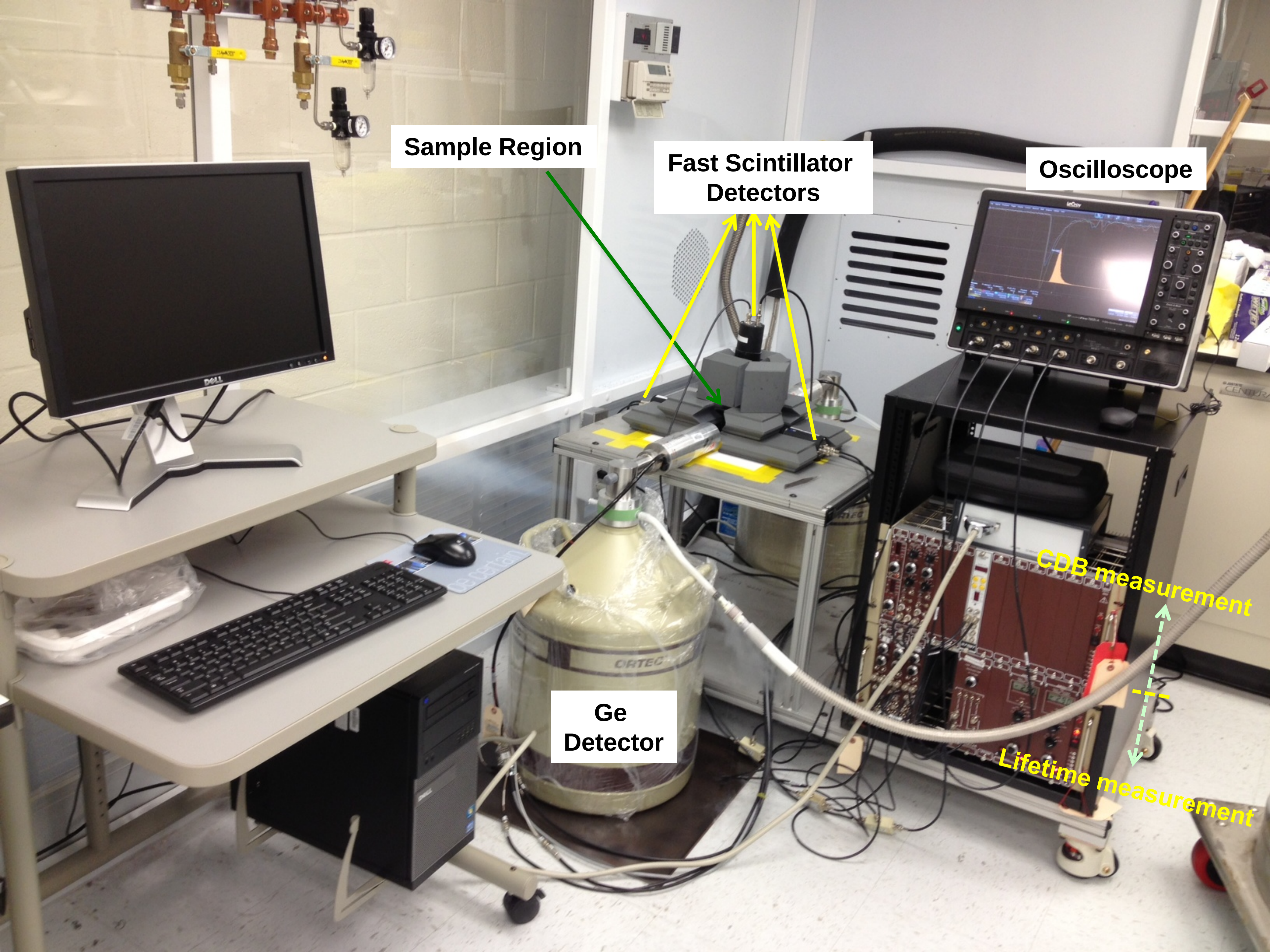
- **Coincidence Doppler Broadening, CDB/OEMS* (*e*$^-$ *momentum; composition - Vacancies influence low momentum; chemical variations generally observed at high momentum*)**



- **Magnetic, polarized CDB/OEMS (*majority & minority e*$^-$*; magnetism*)****

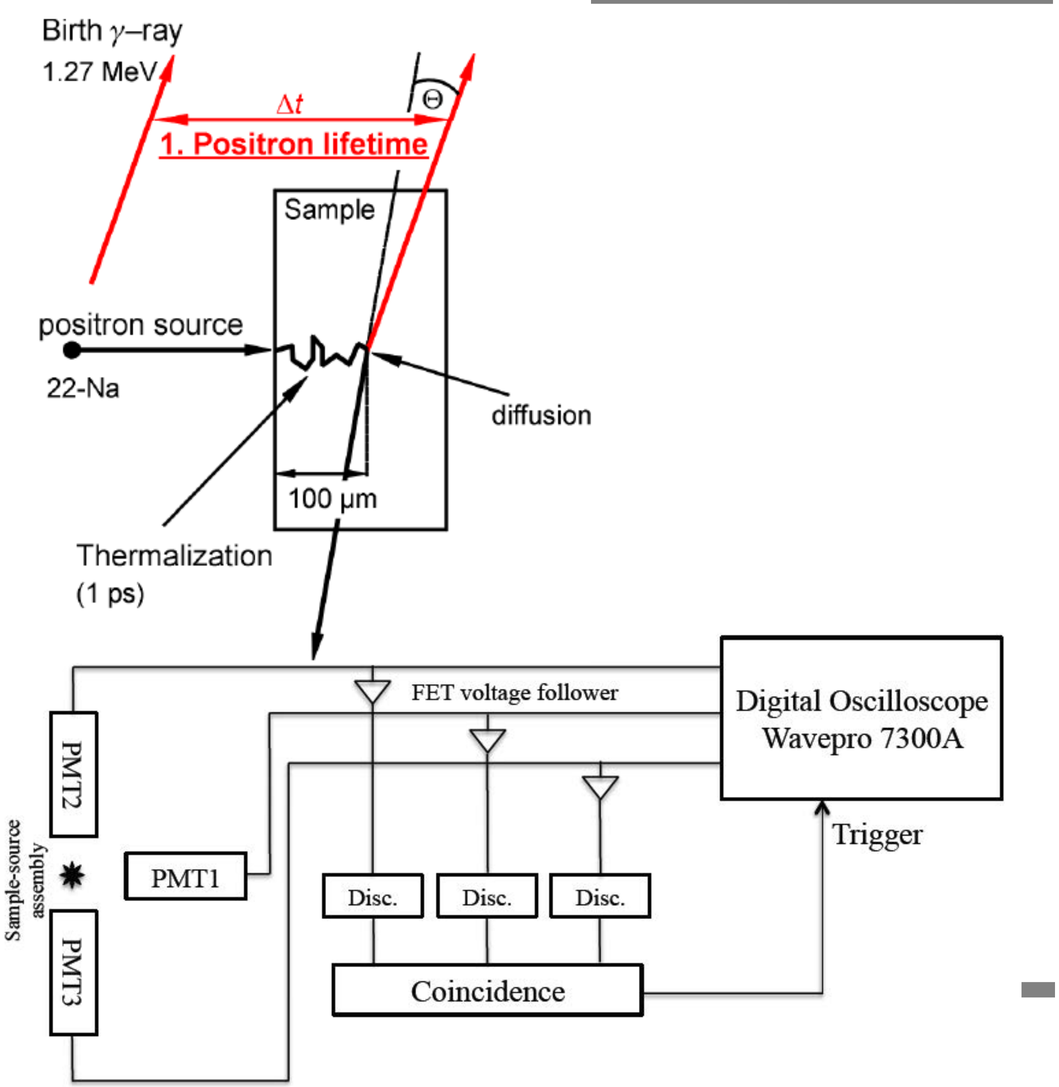
- **2D ACAR (*Fermi surface*)**
- **Age Momentum Correlation, AMOC (*distinguish copper vs vacancy trapping*)**

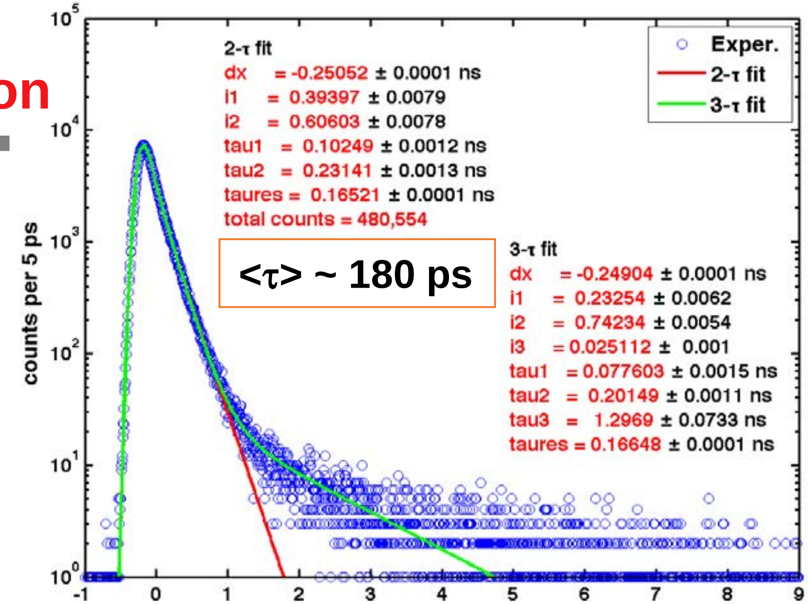
* P. Asoka-Kumar, M. Alatalo, V.J. Ghosh, A.C. Kruseman, B. Nielson, K.G. Lynn, *Phys Rev Let* **77** (1996) 2097.
** P. Asoka-Kumar, B.D. Wirth, et al., *Phil. Mag. Lett.* **82** (2002) 609.

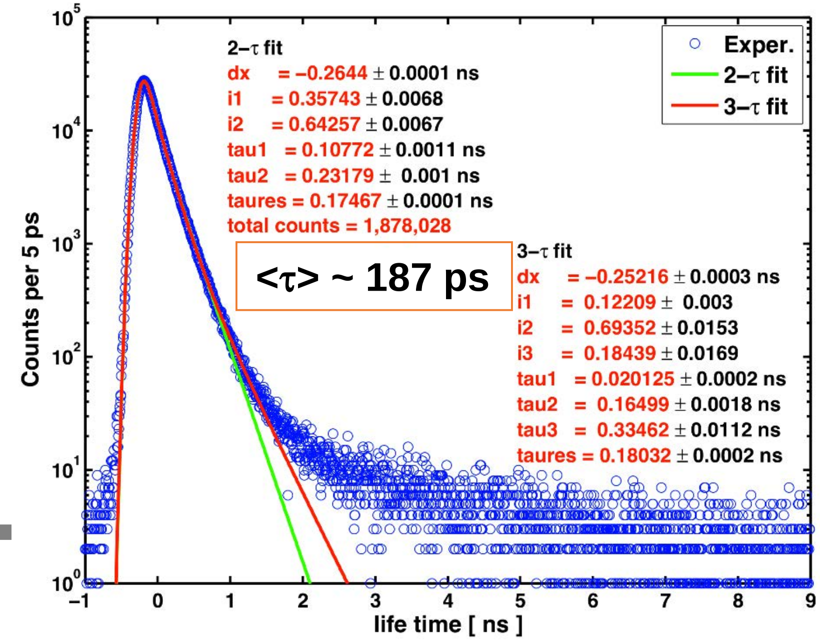

Sample Region
Fast Scintillator Detectors
Oscilloscope
CDB measurement
Lifetime measurement
Ge Detector

Positron Lifetime Measurement

Lifetimes determined by measuring the time between implantation and annihilation

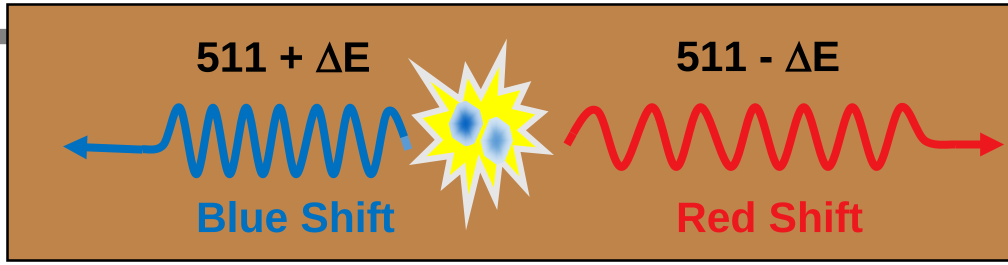






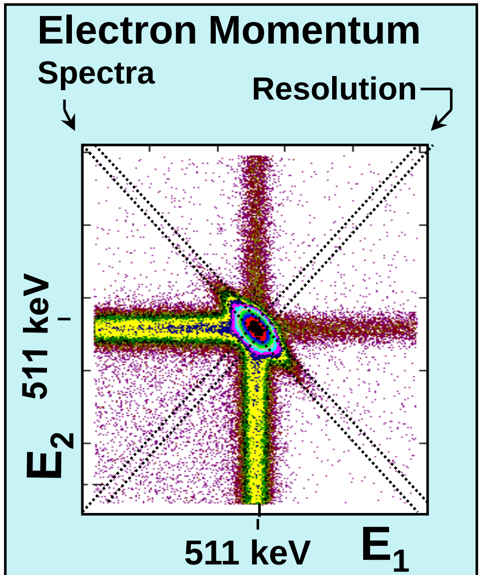
Coincidence Doppler Broadening

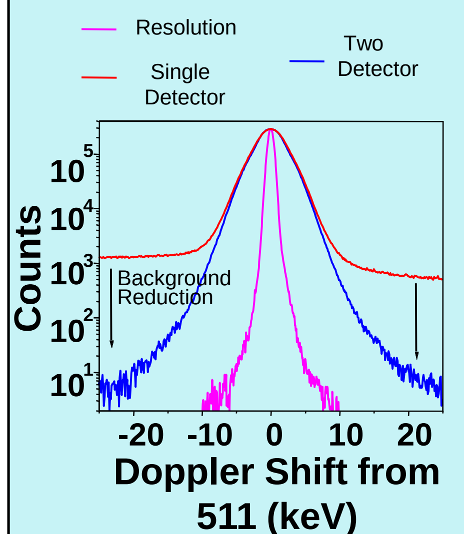
Doppler shift probes the local electron momentum



Doppler shift, ΔE Is proportional to electron momentum, p_L

Sample Position



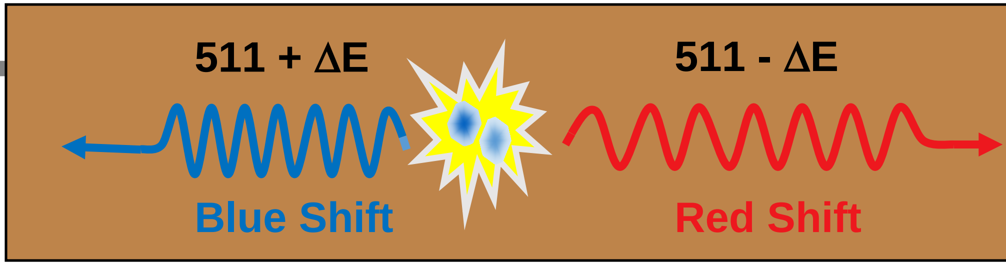


Coincident, two - detector spectroscopy improves signal-to-noise ratio

Kinematic sections provide momentum spectra of orbital electrons, whose momenta are element-specific

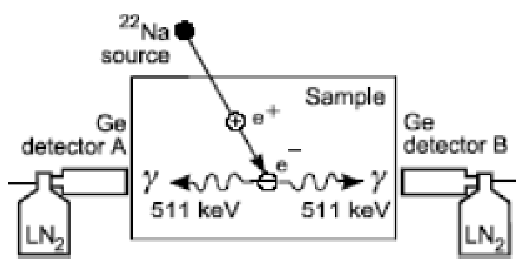
Coincidence Doppler Broadening

Doppler shift probes the local electron momentum



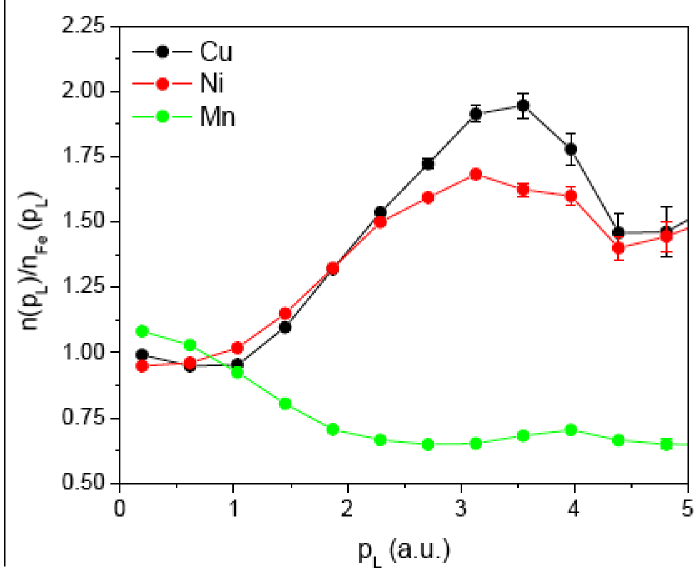
Doppler shift, ΔE Is proportional to electron momentum, p_L

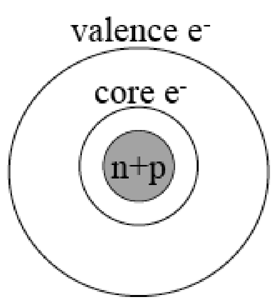
coincidence Doppler broadening (CDB) → Orbital Electron Momentum Spectra (OEMS)



$$\Delta E = \frac{p_L c}{2}$$

1 a.u. = 7.28 mrad × m_0c
m_0 = electron rest mass
c = speed of light





valence e- - low momentum, open-volume character
core e- - high momentum, elemental character

positrons can distinguish different elements with OEMS

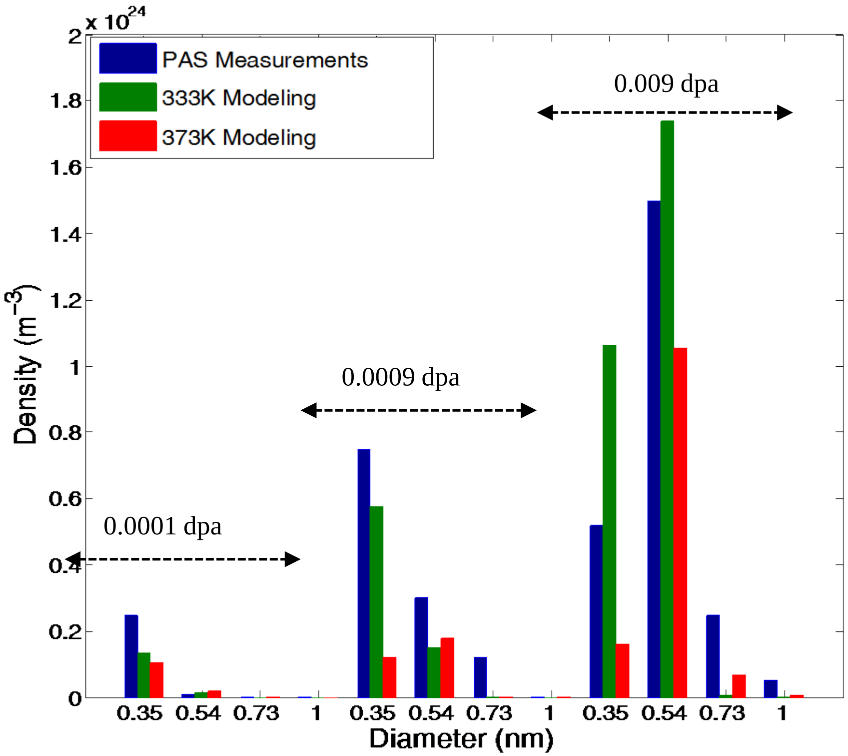
R. Krause-Rehberg and H.S. Leipner, *Positron Annihilation in Semiconductors*, Springer-Verlag, 1999.

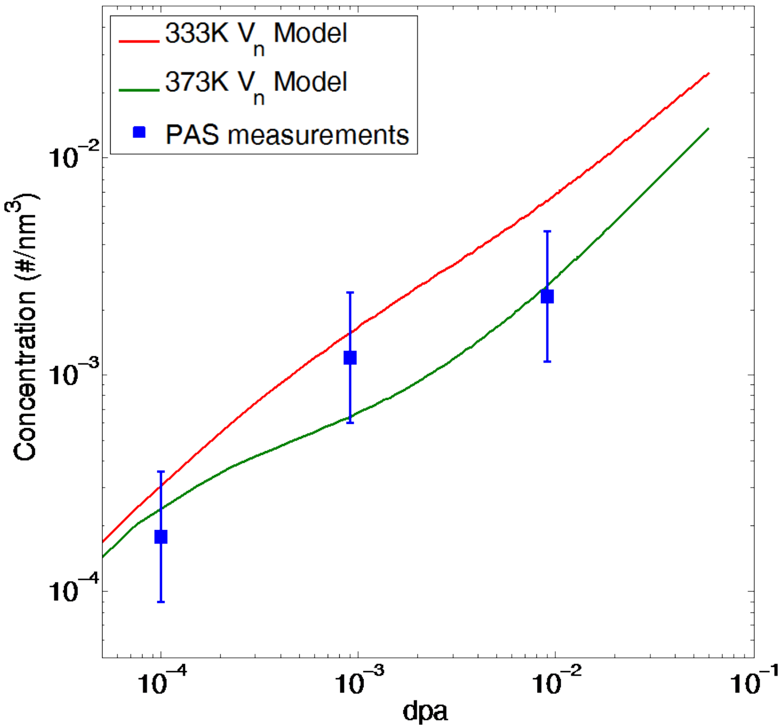
Cluster Dynamics modeling of radiation damage in neutron irradiated Fe: Vacancy cluster comparisons with positrons**

Eldrup etc. applied 'trapping model' to get the rough information of vacancy clusters' distribution at different irradiation levels*

Five-component analysis is used, four of which have fixed lifetimes: 200, 300, 400, and 500 ps, equivalent to three-dimensional vacancy clusters of sizes of about 0.35 (2V), 0.54 (7V), 0.73 (18V) and >1.0 (45V) nm in diameter, respectively.

*M. Eldrup, etc. J. Nucl. Mater. 307-311 (2002) 912-917





Size distribution of vacancy clusters

Total density of vacancy clusters

** X. Hu, D. Xu, T.S. Byun, and B.D. Wirth, *Modeling & Simulation in Materials Science Engineering* (2014) accepted

Interested in PAS? Read More Here!

X. Hu, D. Xu, T.S. Byun, and B.D. Wirth, “Modeling of Irradiation Hardening of Iron after Low Dose and Low Temperature Neutron Irradiation”, *Modeling and Simulation in Materials Science & Engineering* 22 (2014) 0655002

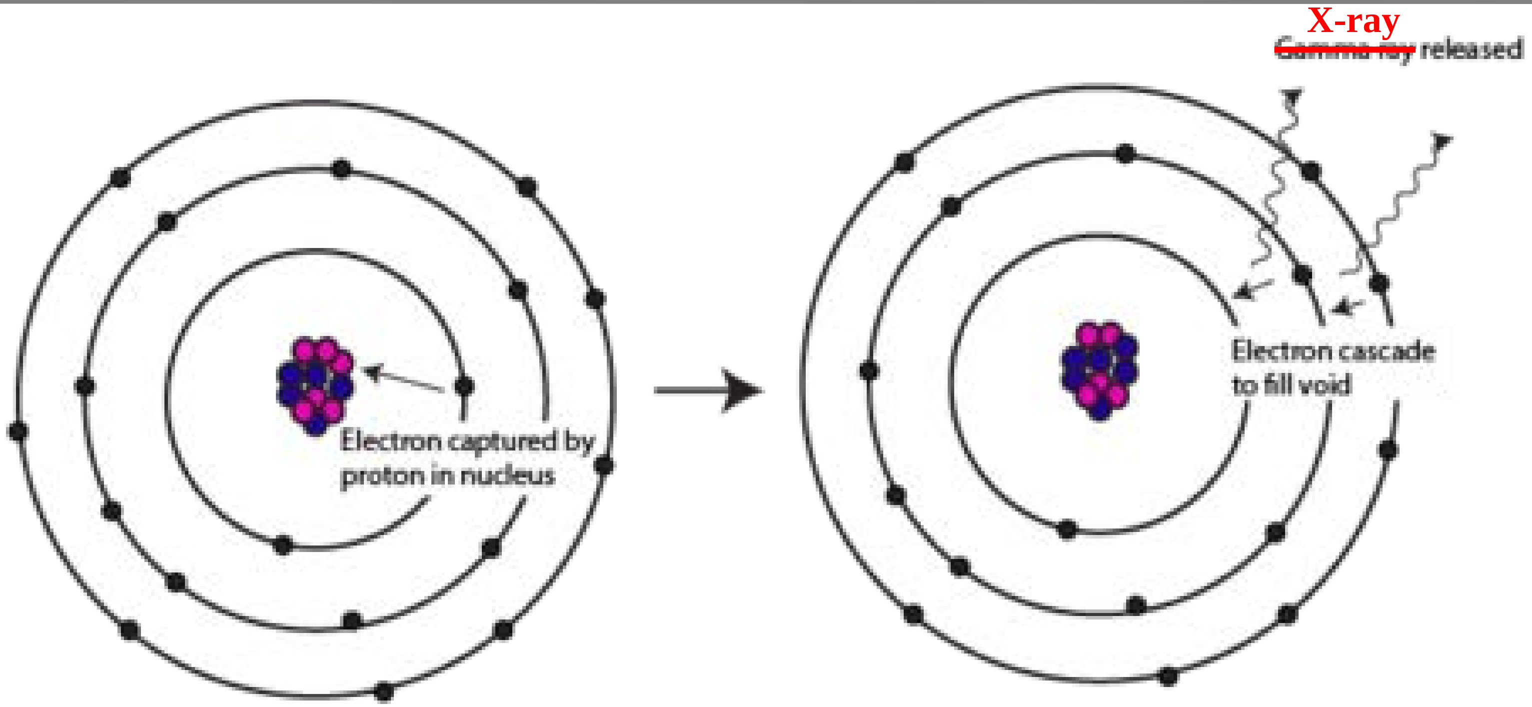
M.J. Alinger, S.C. Glade, B.D. Wirth, G.R. Odette, T. Toyama, Y. Nagai, and M. Hasegawa, “Positron annihilation characterization of nanostructured ferritic alloys”, *Materials Science and Engineering A* 518 (2009) 150-157.

S.C. Glade, B.D. Wirth, G.R. Odette and P. Asoka-Kumar, “Positron Annihilation Spectroscopy and Small Angle Neutron Scattering Characterization of Nanostructural Features in High-Nickel Model Reactor Pressure Vessel Steels”, *J. Nucl. Mater* 351 (2006) 197.

S.C. Glade, B.D. Wirth, G.R. Odette, P. Asoka-Kumar, P.A. Sterne, and R.H. Howell, “Positron annihilation spectroscopy and small angle neutron scattering characterizations of the effect of Mn on the nanostructural features formed in irradiated Fe-Cu-Mn alloys”, *Philosophical Magazine* 85 (2005) 629.

P. Asoka-Kumar, R. Howell, T.G. Nieh, P.A. Sterne, B.D. Wirth, R.H. Dauskardt, K.M. Flores, D. Suh, G.R. Odette, “Opportunities for materials characterization using high-energy positron beams”, *Applied Surface Science* 194 (2002) 160.

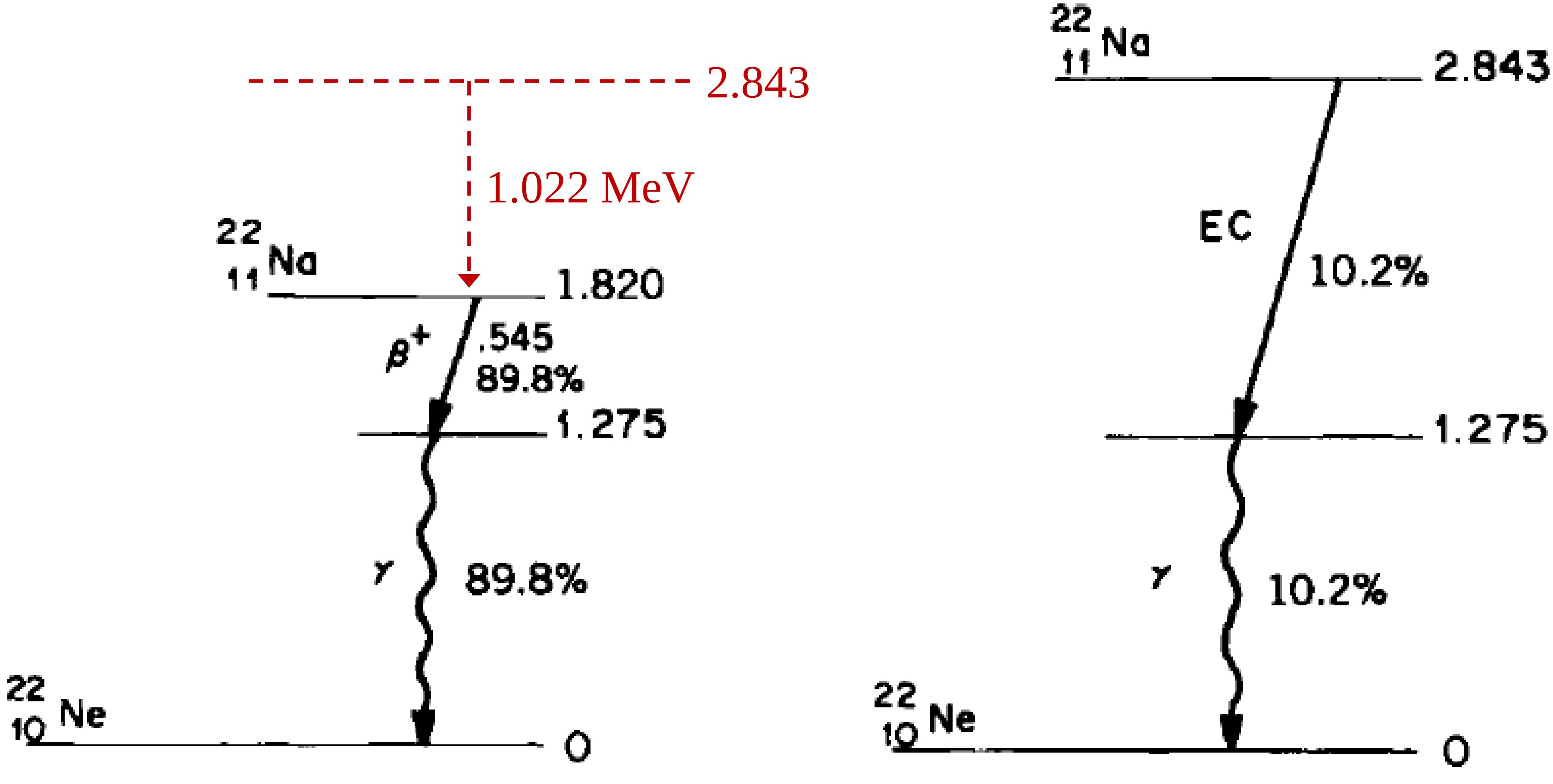
Electron Capture – Competes with Positron Decay



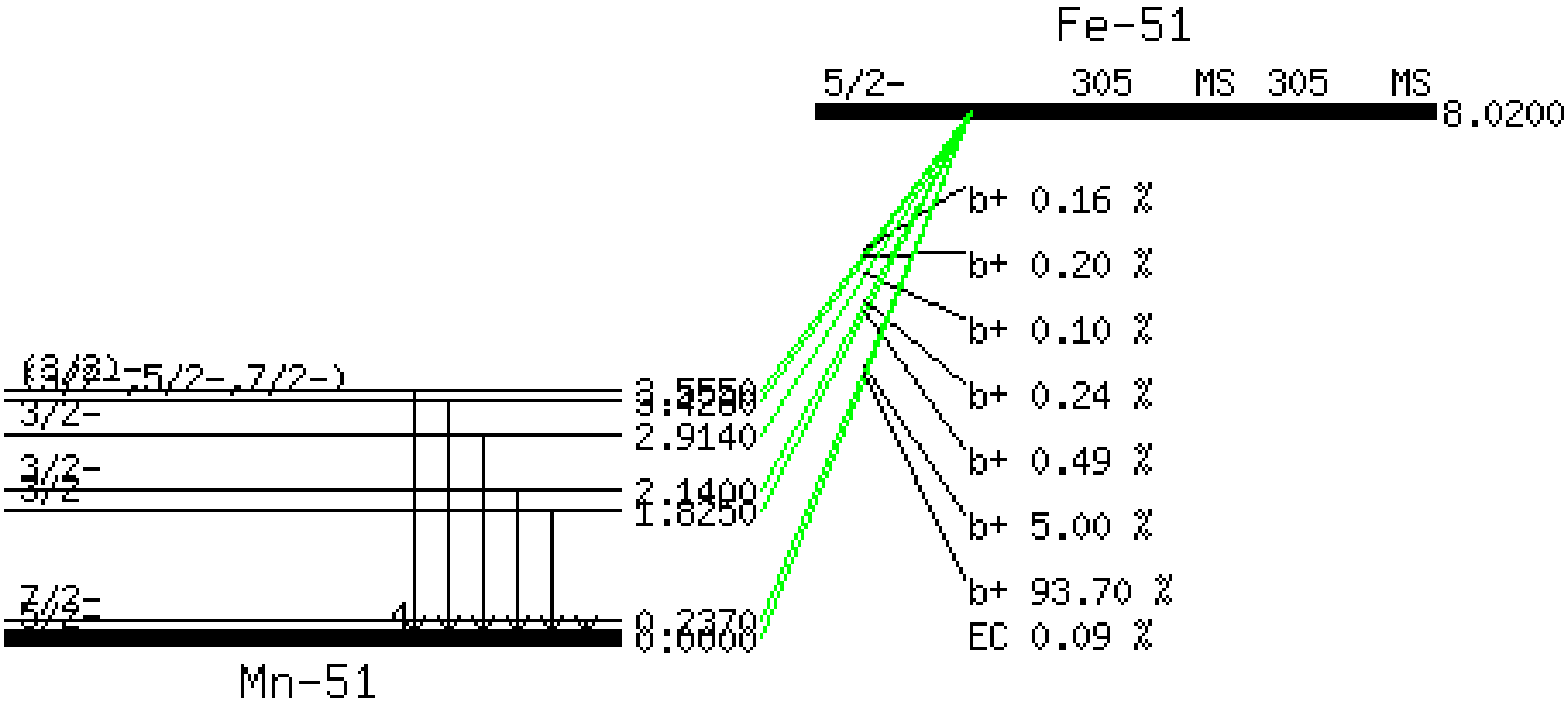
$$^{103}_{46}\mathrm{Pd} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{103m}_{45}\mathrm{Rh} + {}^{0}_{0}\nu.$$

$$Q_{EC} = \Delta_P - \Delta_D - E_B.$$

Electron Capture – Competes with Positron Decay

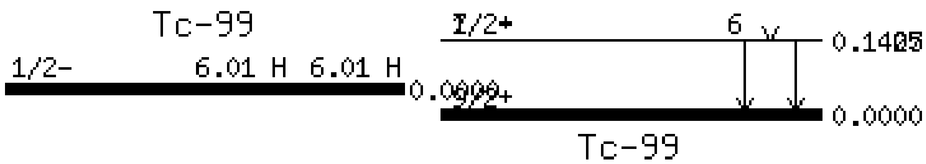


Positron or Electron Capture?

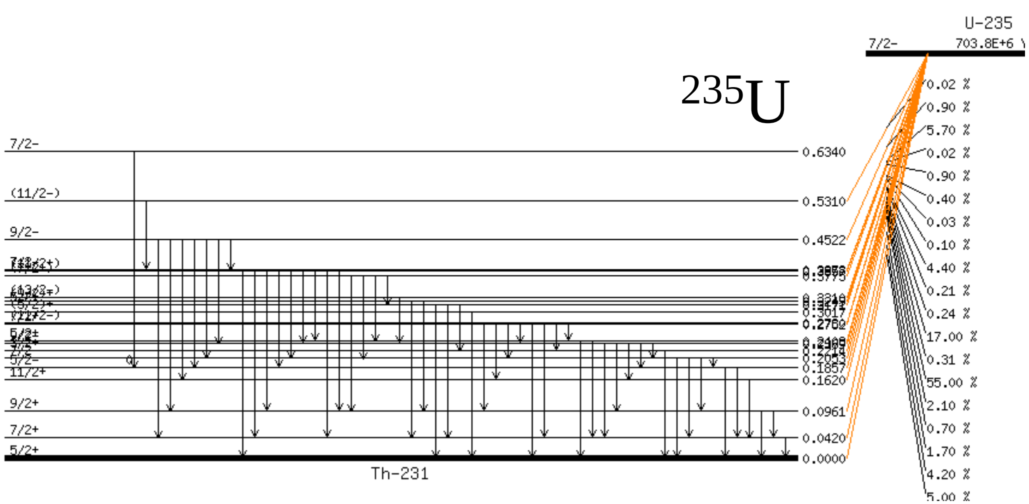


Higher Q-value is more likely to proceed via positron decay

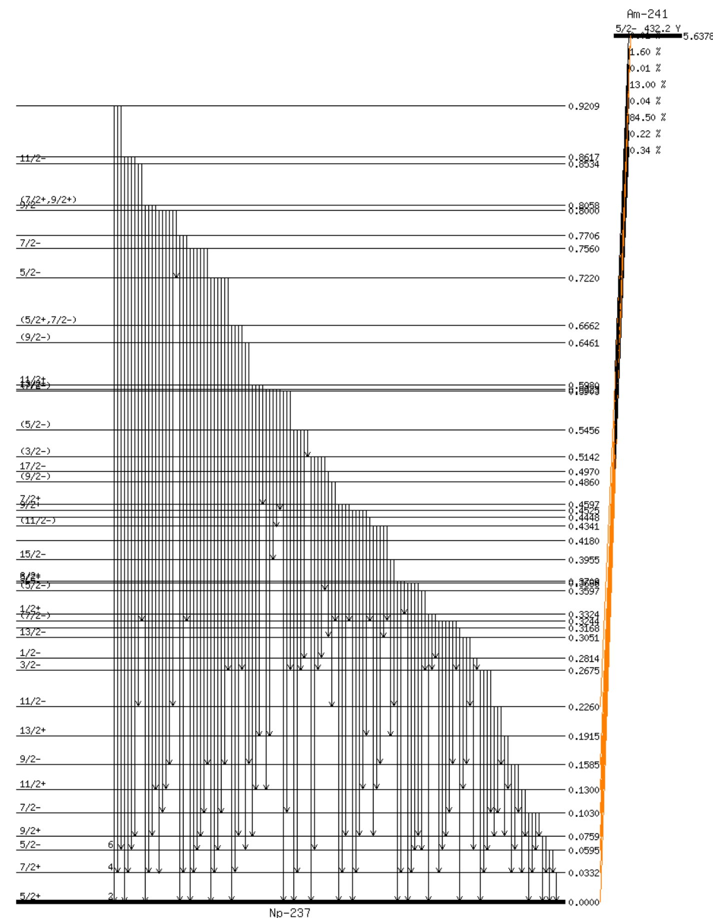
Gamma Decay (Isomeric Transition, or IT)



$$Q = BE_D - BE_P = E_\gamma$$

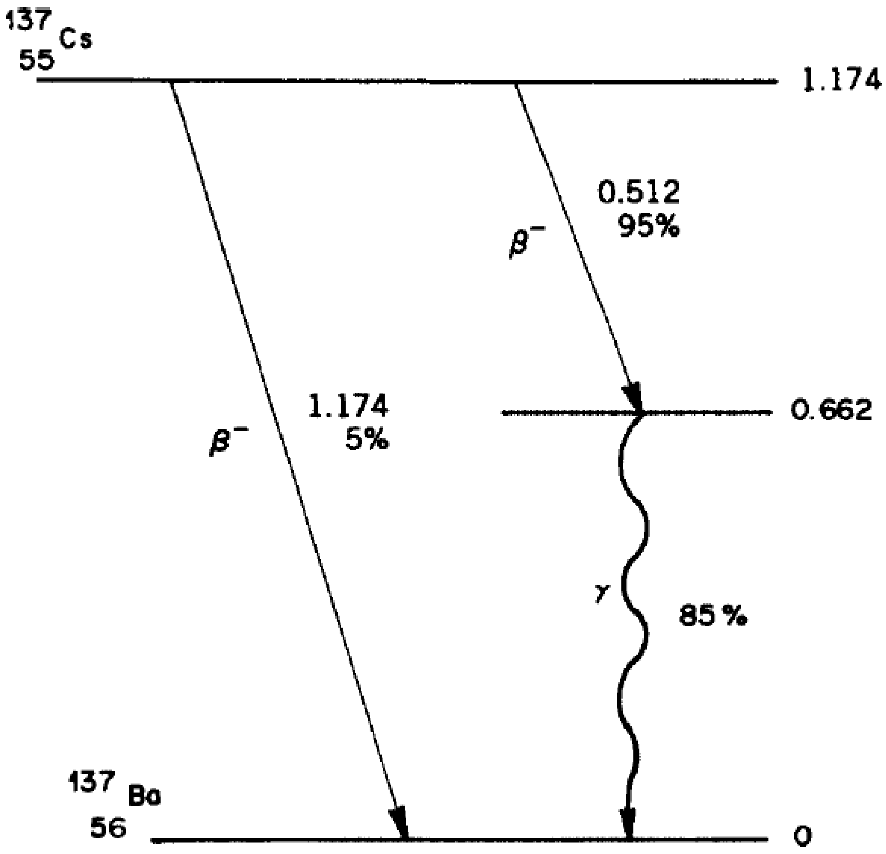


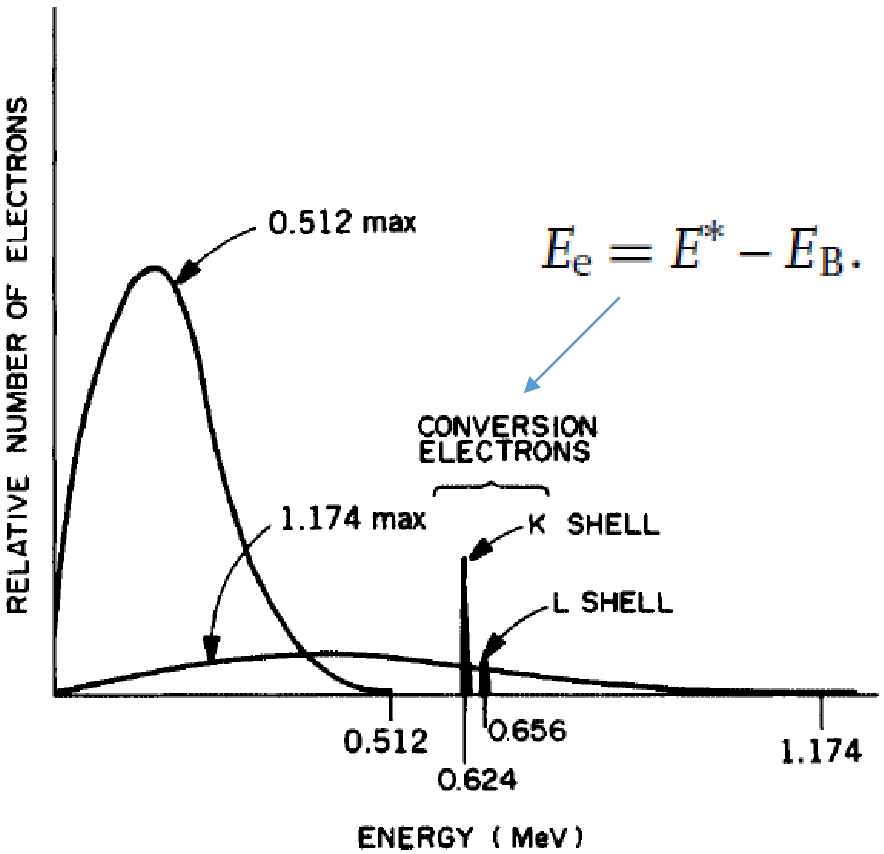
^{235}U



^{241}Am

Internal Conversion (IC) Competes with Isomeric Transition (IT)

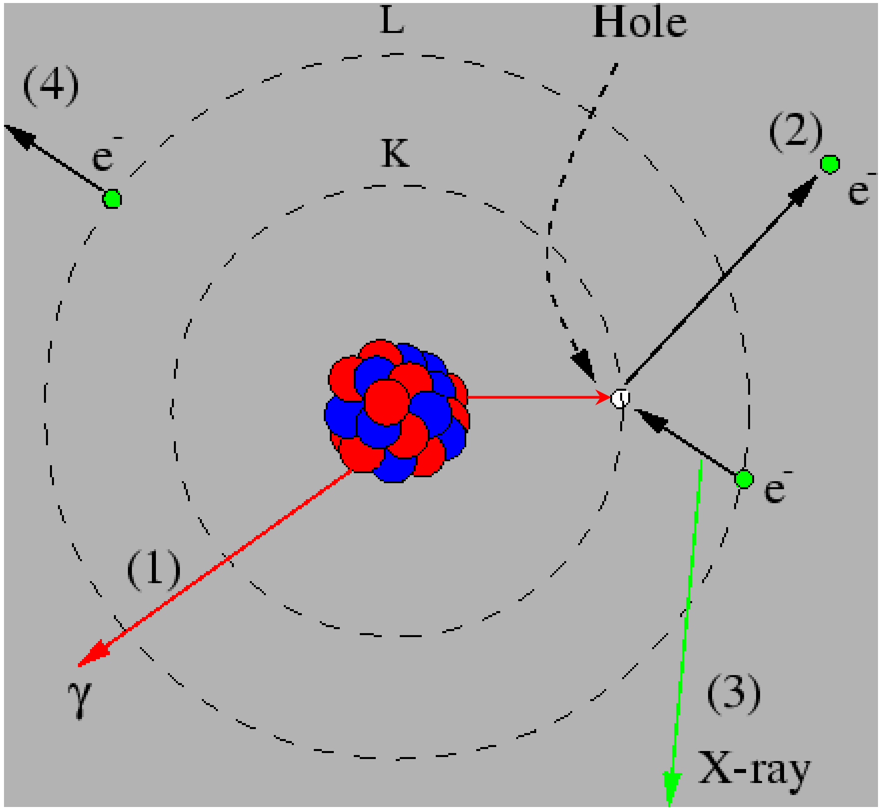




IT-Like Decay Possibilities

Auger electron emission
KE = E_f - E_i - E_{Auger}

Internal conversion
$$E_{e^-} = E_\gamma - E_b$$

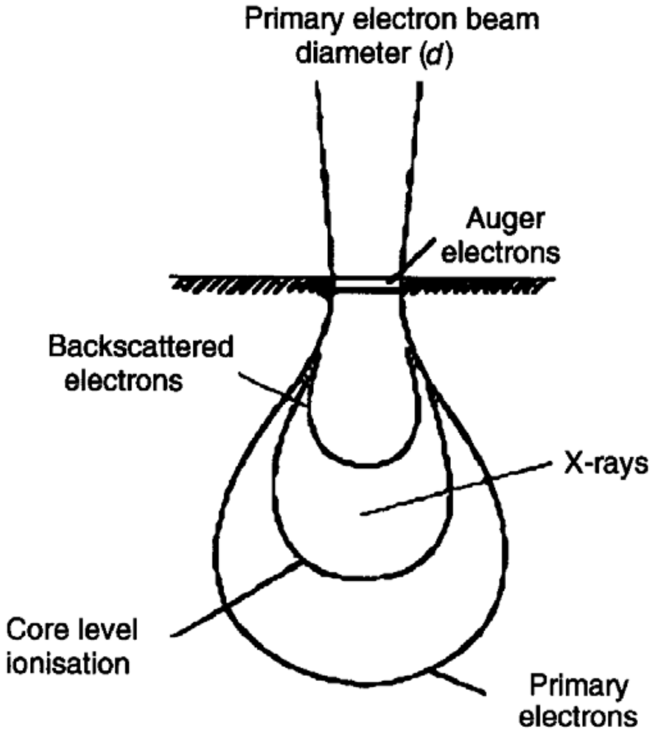


Normal *gamma ray* emission
E_γ = Q

Subsequent *x-ray* emission
(K_α, K_β, L_α …)

Auger Electron Emission

http://www.lpdlabservices.co.uk/analytical_techniques/surface_analysis/aes.php



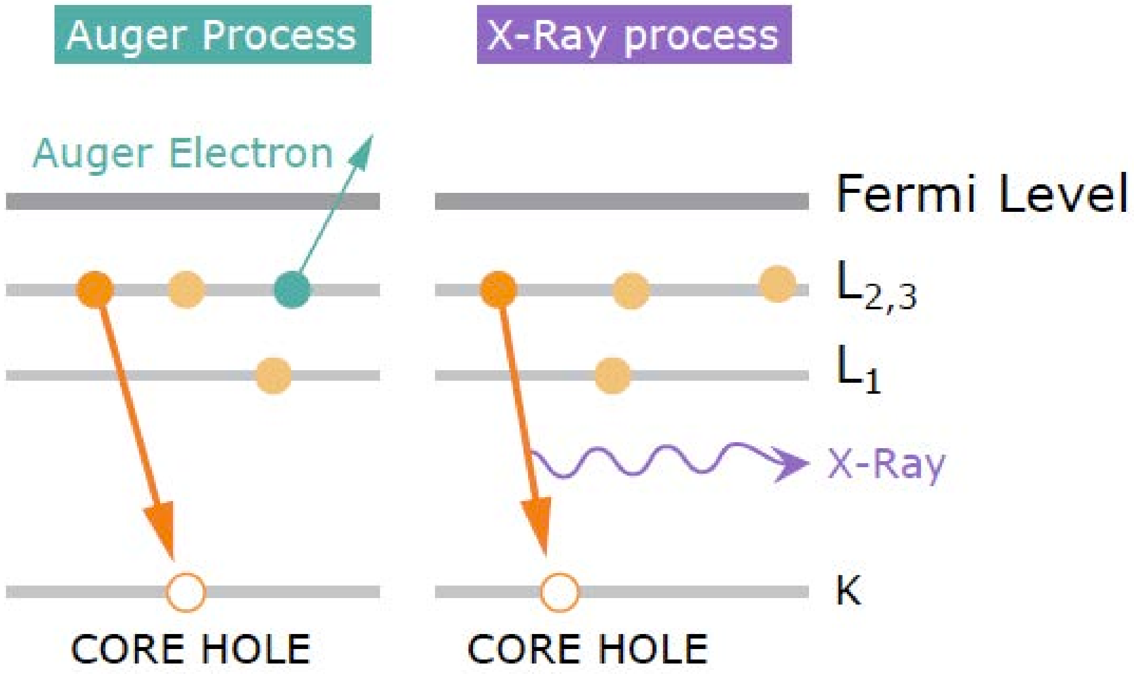
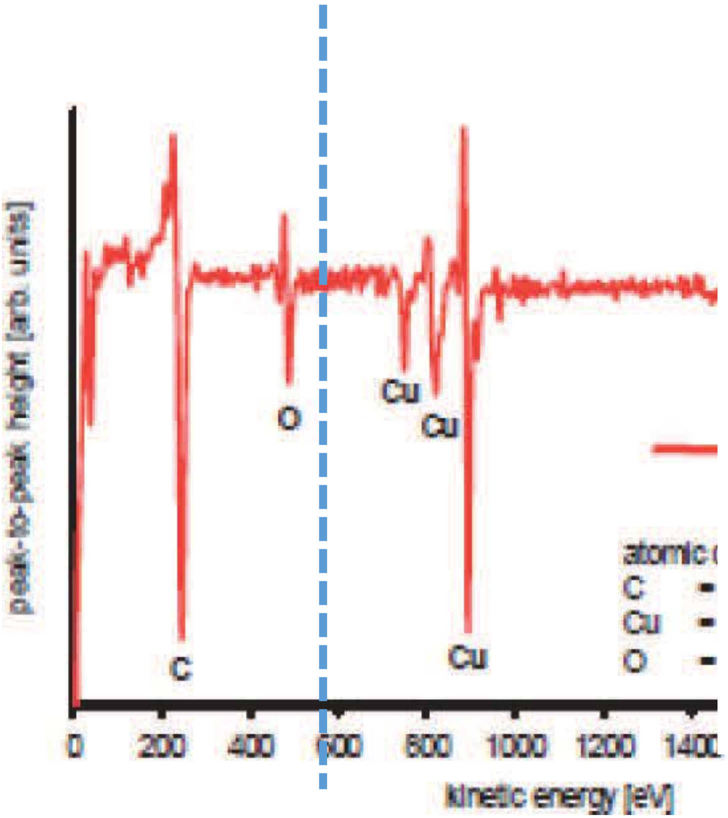


Image by MIT OpenCourseWare.

Auger Electron Spectroscopy

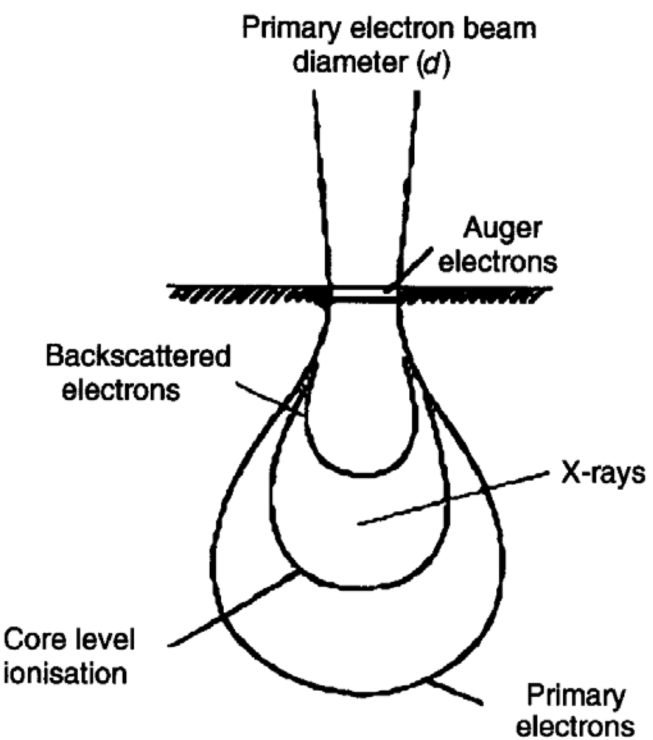
https://www.knmf.kit.edu/AES.php

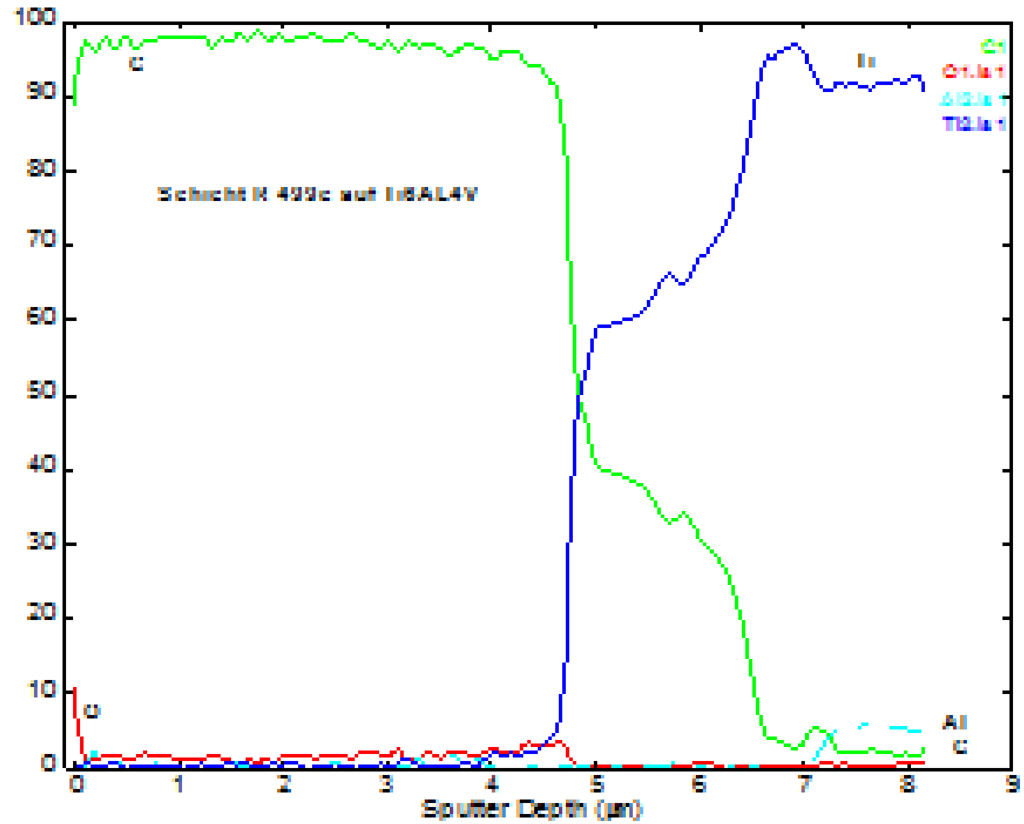


Z	El	$1s_{1/2}$ K	$2s_{1/2}$ L_1	$2p_{1/2}$ L_2	$2p_{3/2}$ L_3
1	H	14			
2	He	25			
3	Li	55			
4	Be	111			
5	B	188			5
6	C	284			6
7	N	399			9
8	O	532	24		7
9	F	686	31		9
10	Ne	867	45		18

Auger Depth Profiling

https://www.knmf.kit.edu/AES.php





Radioactive Decay Summary

Table 3.1 Formulas for Energy Release, Q, in Terms of Mass Differences, Δ_P and Δ_D, of Parent and Daughter Atoms

Type of decay	Formula	Reference
α	$Q_\alpha = \Delta_P - \Delta_D - \Delta_{He}$	Eq. (3.13)
β^-	$Q_{\beta^-} = \Delta_P - \Delta_D$	Eq. (3.25)
γ	$Q_{IT} = \Delta_P - \Delta_D$	Eq. (3.30)
EC	$Q_{EC} = \Delta_P - \Delta_D - E_B$	Eq. (3.35)
β^+	$Q_{\beta^+} = \Delta_P - \Delta_D - 2mc^2$	Eq. (3.41)

Photon Emission Lines of Hydrogen

The visible hydrogen emission spectrum lines in the Balmer series. H-alpha is the red line at the right. The two leftmost lines are considered to be ultraviolet as they have wavelengths less than 400 nm.

Transition of *n*	3→2	4→2	5→2	6→2	7→2	8→2	9→2	∞→2
Name	H-α	H-β	H-γ	H-δ	H-ε	H-ζ	H-η	
Wavelength (nm) [2]	656.3	486.1	434.1	410.2	397.0	388.9	383.5	364.6
Color	Red	Blue-green	Violet	Violet	(Ultraviolet)	(Ultraviolet)	(Ultraviolet)	(Ultraviolet)

Half Life vs. Decay Constant

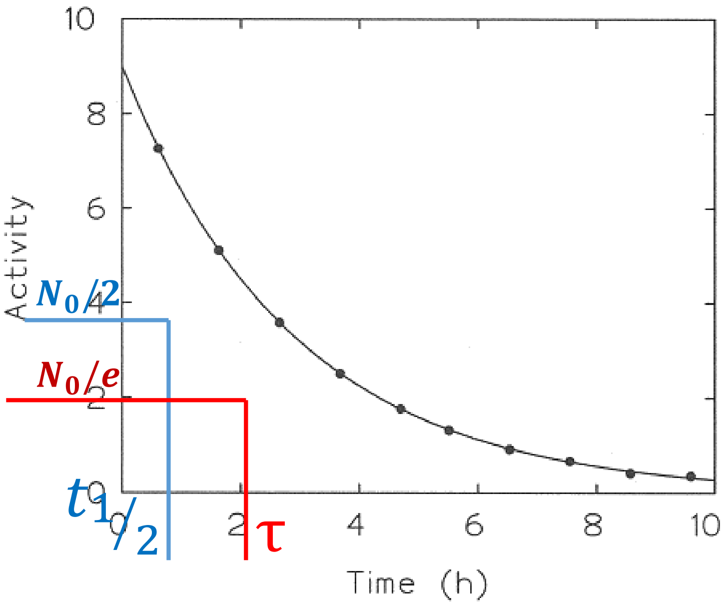


Figure 5.15. The activity of a radioactive sample with a half-life of two hours. At any time on the exponential curve, the activity is one-half of the activity two hours earlier.

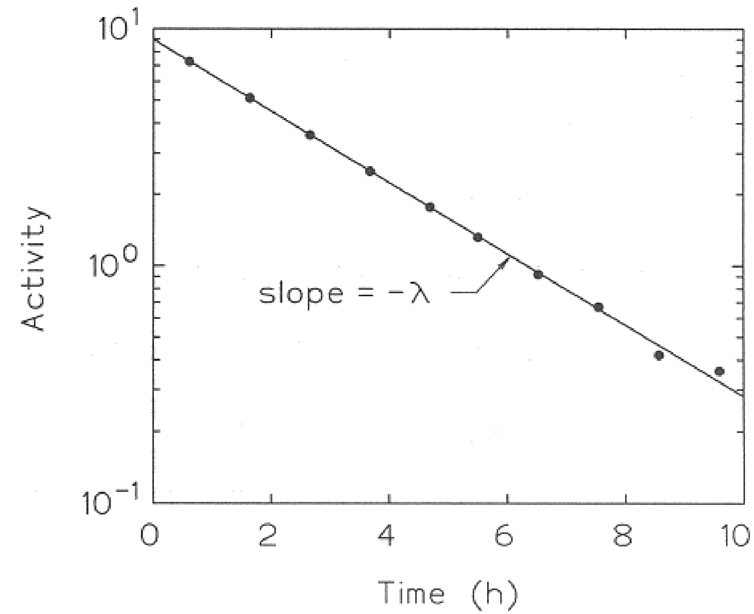
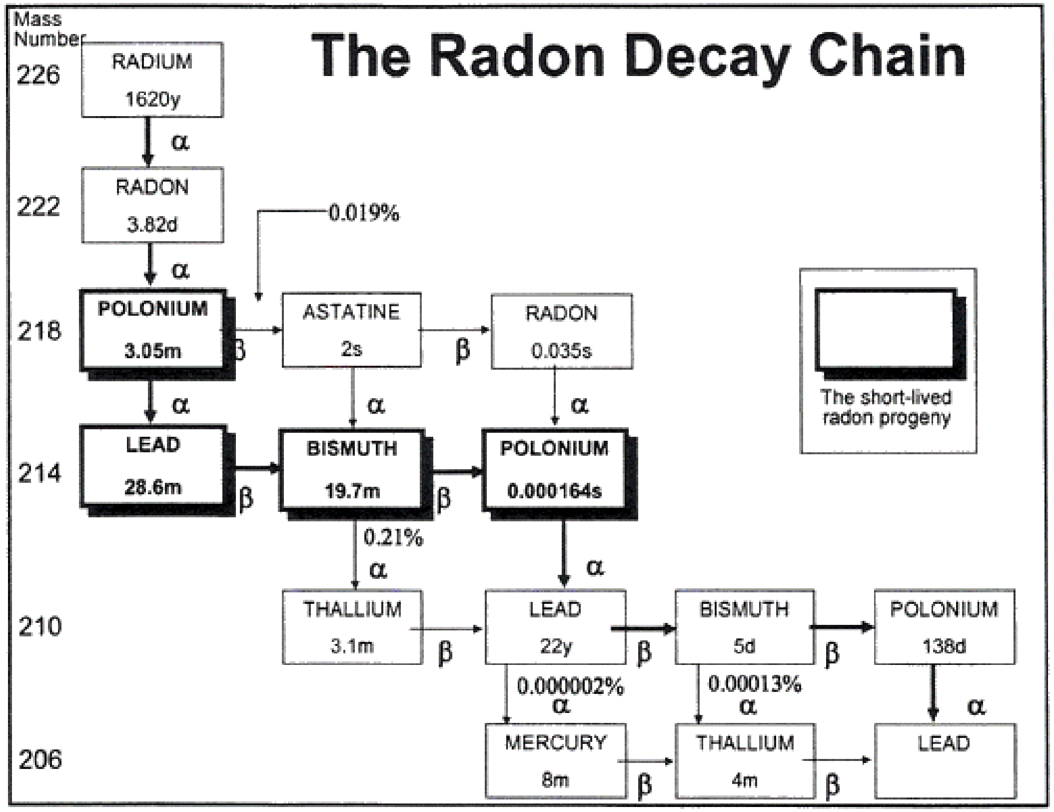


Figure 5.16. Semilog plot of the decay of the sample's activity. The decay curve is a straight line with a slope of $-\lambda$, from which the half-life $T_{1/2} = \ln 2/\lambda$ can be calculated.

The Radon Decay Chain

http://www.omfi.hu/cejoem/Volume13/Vol13No1/CE07_1-01.html



Source: National Research Council. Health Effects of Exposure to Radon: BEIR VI. The National Academies Press, 1999. doi:10.17226/5499.

The Primordial Nuclides

Table 5.2. *The 17 isolated primordial radionuclides. Data taken from GE-NE [1996].*

Radionuclide & the Decay Modes		Half-life (years)	% El. Abund.	Radionuclide & the Decay Modes		Half-life (years)	% El. Abund.
$^{40}_{19}K$	β^- EC β^+	1.27×10^{9}	0.0117	$^{50}_{23}V$	β^- EC	1.4×10^{17}	0.250
$^{87}_{37}Rb$	β^-	4.88×10^{10}	27.84	$^{113}_{48}Cd$	β^-	9×10^{15}	12.22
$^{115}_{49}In$	β^-	4.4×10^{14}	95.71	$^{123}_{52}Te$	EC	$> 1.3 \times 10^{13}$	0.908
$^{138}_{57}La$	EC β^-	1.05×10^{11}	0.090	$^{144}_{60}Nd$	α	2.38×10^{15}	23.80
$^{147}_{62}Sm$	α	1.06×10^{11}	15.0	$^{148}_{62}Sm$	α	7×10^{15}	11.3
$^{152}_{64}Gd$	α	1.1×10^{14}	0.20	$^{176}_{71}Lu$	β^-	3.78×10^{10}	2.59
$^{174}_{72}Hf$	α	2.0×10^{15}	0.162	$^{180}_{73}Ta$	EC β^-	$> 1.2 \times 10^{15}$	0.012
$^{187}_{75}Re$	β^-	4.3×10^{10}	62.60	$^{186}_{76}Os$	α	2×10^{15}	1.58
$^{190}_{78}Pt$	α	6.5×10^{11}	0.01				

Source: Shultis, J. K., and R. E. Faw. Fundamentals of Nuclear Science and Engineering, 2nd Edition. CRC Press, 2007.

Series Decay Chains

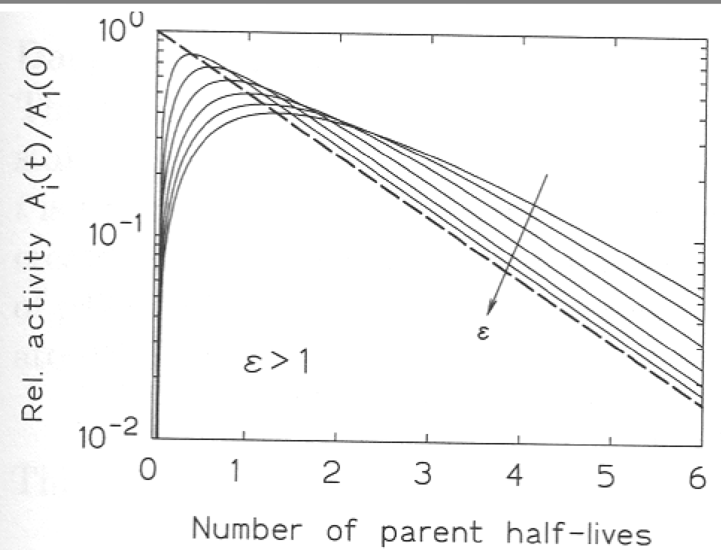


Figure 5.18. Activity of the first daughter with a half-life less than that of the parent, i.e., the daughter's decay constant $\lambda_2 = \epsilon\lambda_1, \epsilon > 1$. The six displayed daughter transients are for $\epsilon = 1.2, 1.5, 2, 3, 5$, and 10. The heavy-dashed line is the parent's activity.

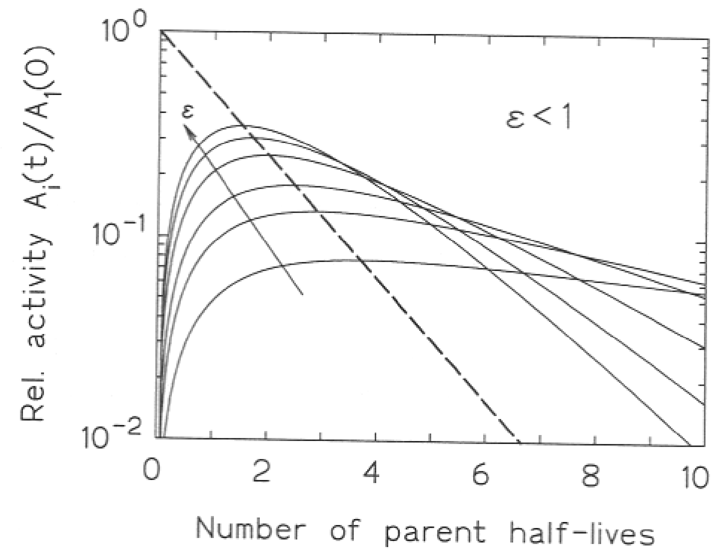


Figure 5.19. Activity of the first daughter with a half-life greater than that of the parent, i.e., the daughter's decay constant $\lambda_2 = \epsilon\lambda_1, \epsilon < 1$. The six displayed daughter transients are for $\epsilon = 0.9, 0.7, 0.5, 0.3, 0.2$, and 0.1. The heavy-dashed line is the parent's activity.