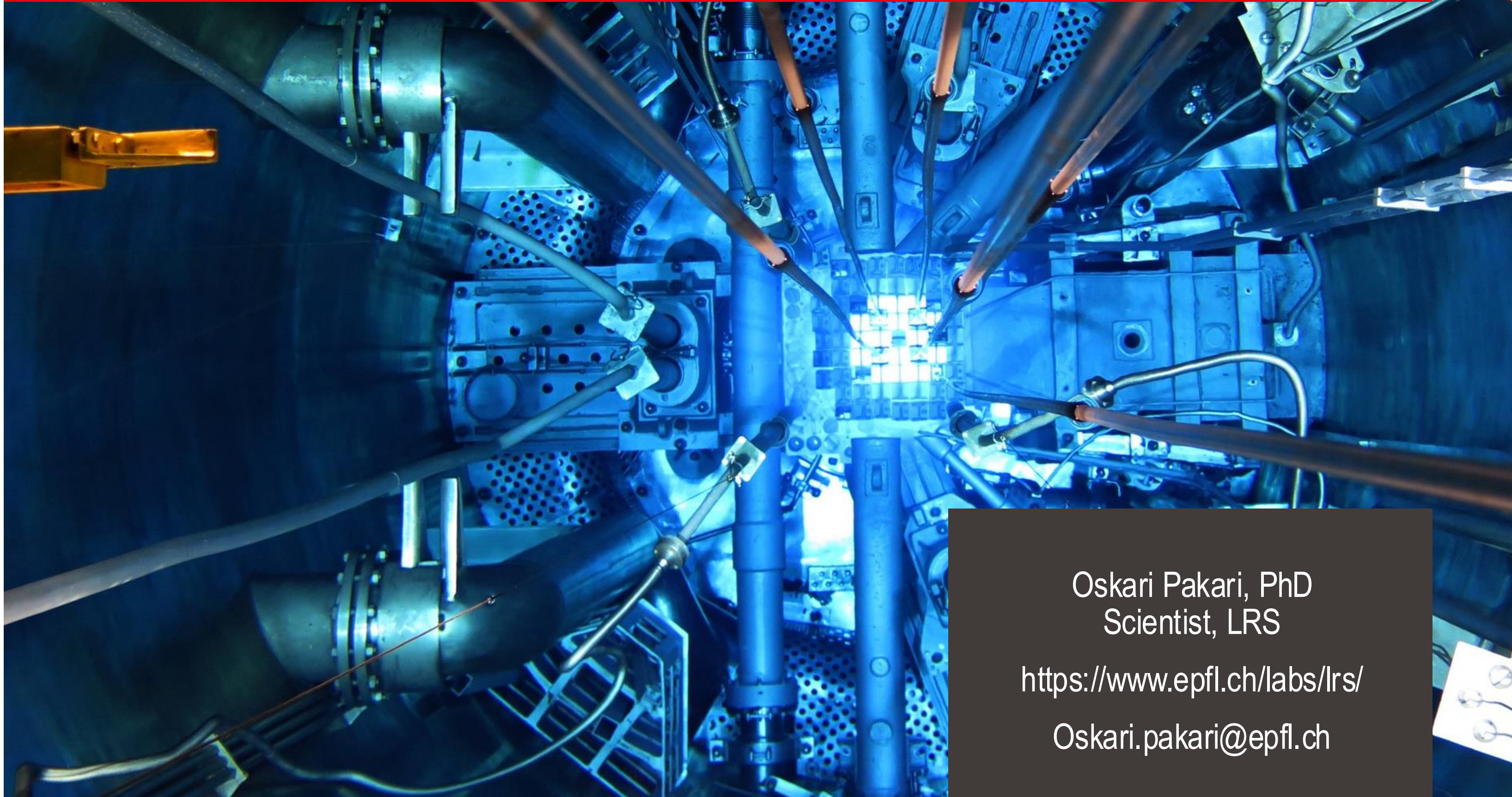
Radiation Biology, Protection and Applications
Week 8: Radiation Sources



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Lecture Plan Nov/Dec

31.10.2025	Radiation sources	Oskari
07.11.2025	Radiation shielding openMC intro	Oskari
14.11.2025	Introduction to Safeguards & the IAEA WARGAME	Uwe, BFE
21.11.2025	Industrial applications of radiation: Cameras, Batteries, Food	Oskari
28.11.2025	Emergency dosimetry, Radiological impact of Chornobyl	Oskari
05.12.2025	Advances in luminescence dosimetry	Jeppe, PSI
12.12.2025	Safeguards and Export control	Uwe, BFE
19.12.2025	Exam example (ONLINE)	Oskari

Radiation Sources: Outline

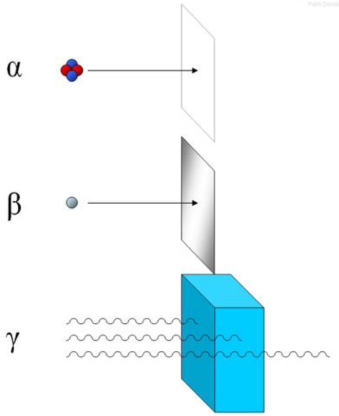
- Basics of radioactivity: See Lecture 1
- Radiation Concepts
- Fast Electron Sources
    - Beta decay
    - Internal conversion
- Heavy Charged Particle Sources
    - Alpha decay
    - Spontaneous fission
- Electromagnetic Radiation (EMR) Sources
    - Gamma rays
    - X-rays, characteristic X-rays
- Neutron Sources
    - Spontaneous fission
    - Neutrons from (α,n)-reactions
    - Photoneutrons
    - Accelerated charged particles

Reminder: Radiation Concepts (1)

- There are four general types of radiation generated in nuclear and atomic processes:
  - **Charged particulate radiation:**
    - Fast electrons: β^{+} and β^{-} from nuclear decay, energetic electrons.
    - Heavy charged particles: all energetic ions with $A \geq 1$ (p^{+}, α^{2+}, fission products, nuclear reaction products)
  - **Uncharged radiation:**
    - Electromagnetic radiation: photons, X-rays (from electron transitions between atomic shells), γ-rays (from nuclear transitions)
    - Neutrons: slow and fast (generated in nuclear reactions.)
- Absolute activity is defined as rate of decay: It measures the source disintegration rate, not the emission rate of radiation.

Reminder: Radiation Concepts (2): “Hardness“

- ☐ Energy range of ionizing radiation:
  - 10 eV: minimum energy for ionization of typical materials.
  - to 20 MeV: upper bound for practical applications.
- ☐ Hard radiation:
  - High penetrating power.
  - Sources are less affected by self-absorption.
  - γ-rays, hard X-rays or neutrons.
- ☐ Soft radiation:
  - Highly ionizing
  - Low penetrating power
  - Sources must be thin to minimize self-absorption.
  - Charged particles, soft X-rays.



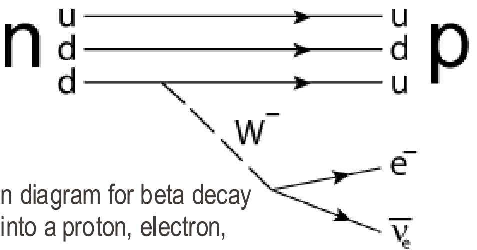
Fast Electron Sources: Beta Decay (1)

- Radioactive decay in which a beta particle (electron or positron) is emitted.
  - electron emission: "beta minus" (β^-),

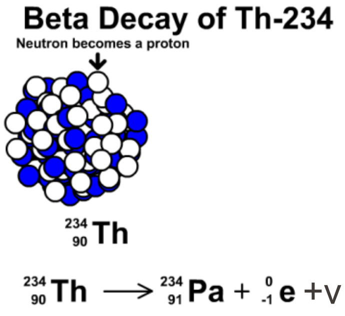
$$\boxed{n^0 \rightarrow p^+ + e^- + \bar{\nu}_e} \qquad \boxed{{}^A_Z X \rightarrow {}_{Z+1}^{A} Y + \beta^- + \bar{\nu}_e}$$

  - positron emission: "beta plus" (β^+).

$$\boxed{Energy + p^+ \rightarrow n^0 + e^+ + \nu_e} \qquad \boxed{{}^A_Z X \rightarrow {}_{Z-1}^{A} Y + \beta^+ + \nu_e}$$

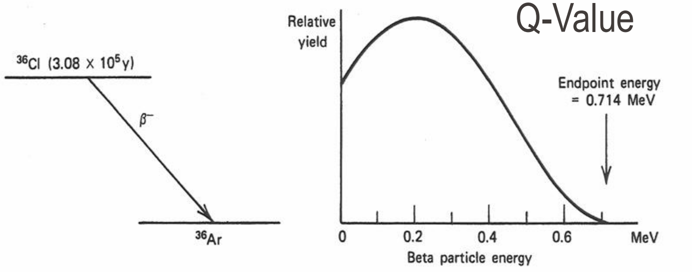


The Feynman diagram for beta decay of a neutron into a proton, electron, and electron-antineutrino via an intermediate heavy W-boson.



$${}^{234}_{90}\mathrm{Th} \longrightarrow {}^{234}_{91}\mathrm{Pa} + {}^{0}_{-1}e + \nu$$

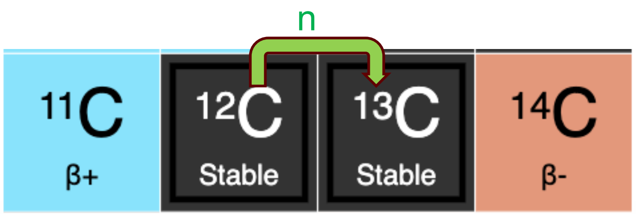
- Beta plus decay cannot occur in isolation:
  - Neutron mass $m_n > m_p$. (proton is stable)
  - Requires available excitation energy from inside nucleus
  - The Q value goes into:
    - the process of converting a proton into a neutron,
    - the positron and the neutrino, and into
    - the kinetic energy of these particles.



The decay scheme of ^{36}Cl and the resulting beta particle energy distribution.

Fast Electron Sources: Beta Decay (2)

- ❑ (Artificial) beta emitters can be produced by neutron irradiation of stable materials in nuclear reactors or high neutron flux facilities.
- ❑ As most beta decays populate an excited state of the daughter nucleus, they are not "pure", i.e., they are accompanied by γ-rays.
- ❑ Examples for beta decays:
  - Beta minus: $^{137}_{55}\mathrm{Cs} \rightarrow\ ^{137}_{56}\mathrm{Ba} + \mathrm{e}^- + \bar{\nu}_e$
  - Beta plus: $^{22}_{11}\mathrm{Na} \rightarrow\ ^{22}_{10}\mathrm{Ne} + \mathrm{e}^+ + \nu_e$
  - Electron capture: $^{22}_{11}\mathrm{Na} + \mathrm{e}^- \rightarrow\ ^{22}_{10}\mathrm{Ne} + \nu_e$



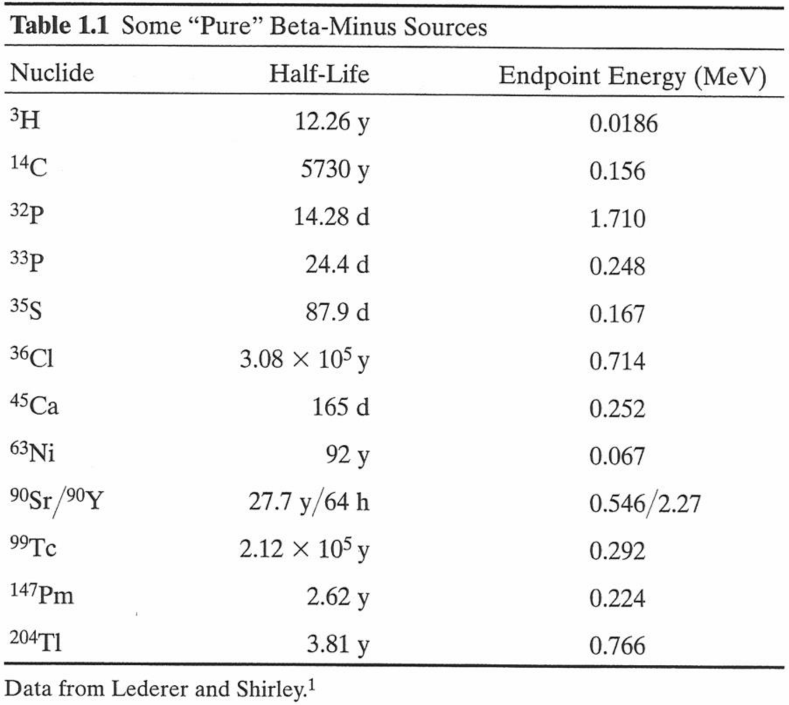
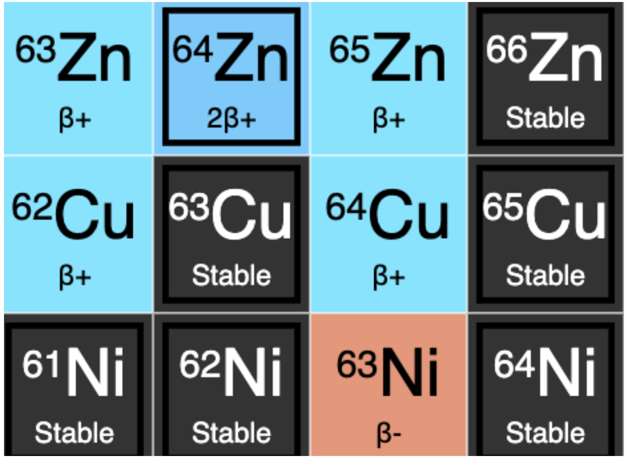


Table 1.1 Some "Pure" Beta-Minus Sources

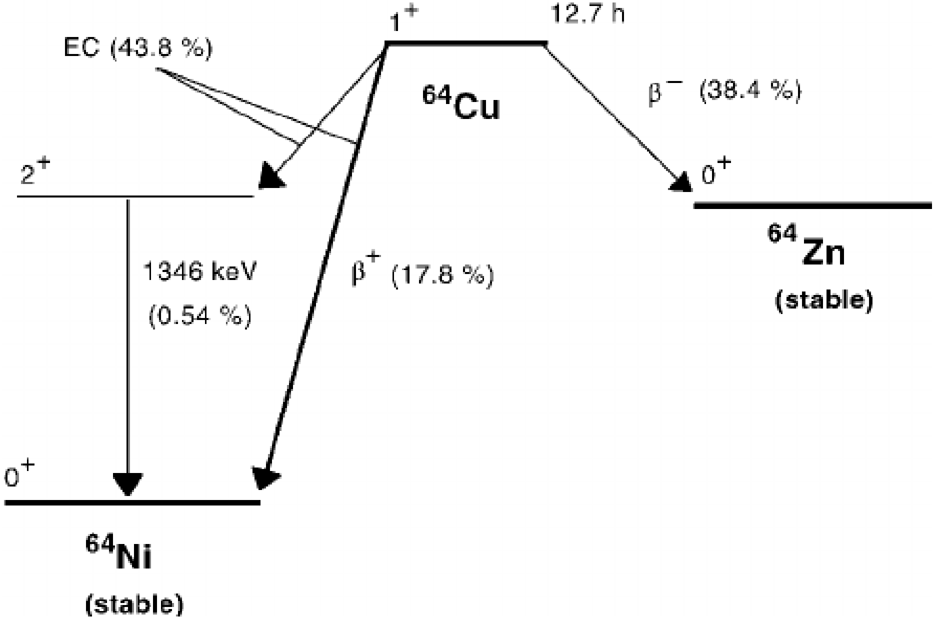
Nuclide	Half-Life	Endpoint Energy (MeV)
^{3}H	12.26 y	0.0186
^{14}C	5730 y	0.156
^{32}P	14.28 d	1.710
^{33}P	24.4 d	0.248
^{35}S	87.9 d	0.167
^{36}Cl	3.08×10^5 y	0.714
^{45}Ca	165 d	0.252
^{63}Ni	92 y	0.067
^{90}Sr/^{90}Y	27.7 y/64 h	0.546/2.27
^{99}Tc	2.12×10^5 y	0.292
^{147}Pm	2.62 y	0.224
^{204}Tl	3.81 y	0.766

Data from Lederer and Shirley.[1]

The curious case of ^{64}Cu



^{63}Zn β+	^{64}Zn 2β+	^{65}Zn β+	^{66}Zn Stable
^{62}Cu β+	^{63}Cu Stable	^{64}Cu β+	^{65}Cu Stable
^{61}Ni Stable	^{62}Ni Stable	^{63}Ni β-	^{64}Ni Stable



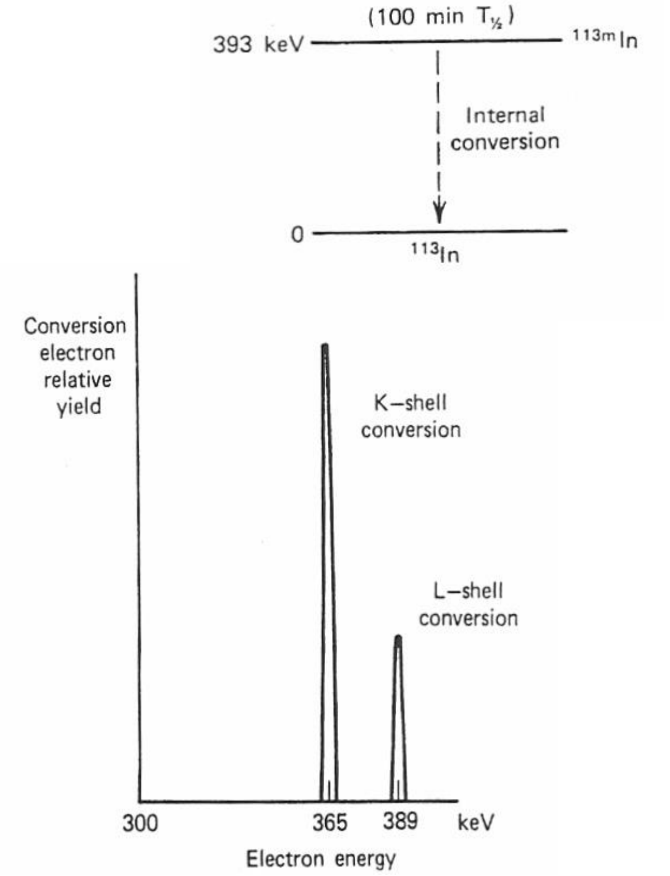
EC = Electron capture

Fast Electron Sources: Internal Conversion (1)

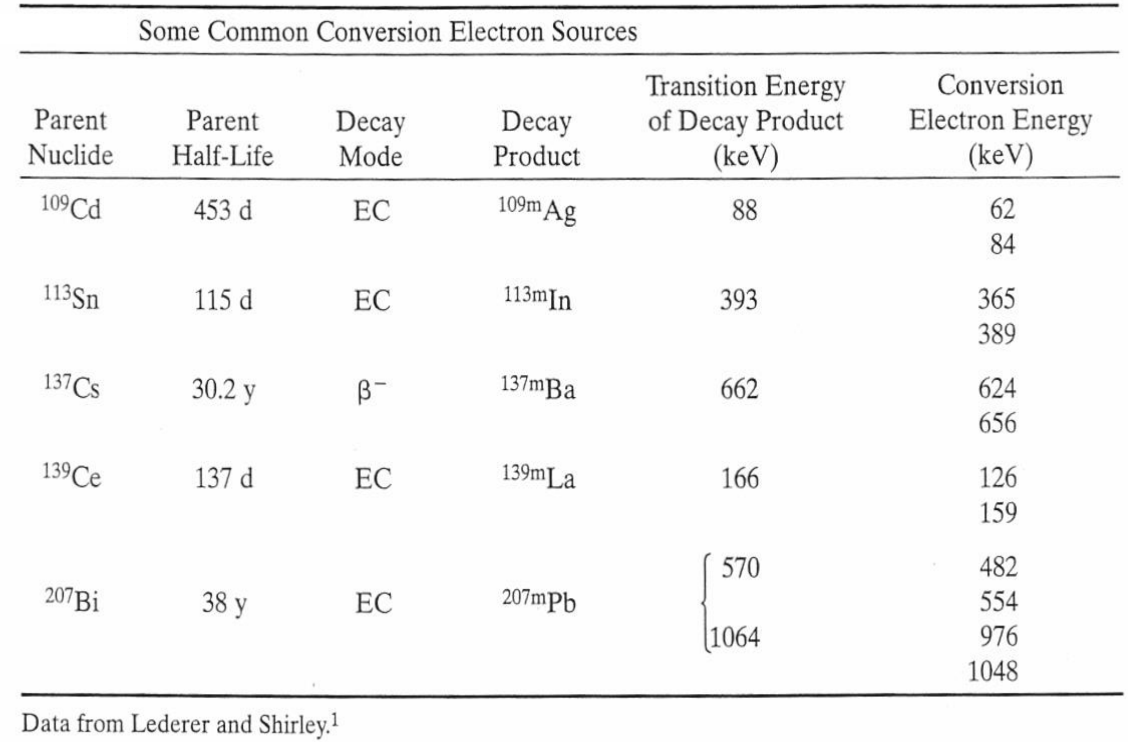
- Source of nearly monoenergetic electrons:

$$\boxed{E_{e^-} = E_{ex} - E_b}$$

- Process:
  - Alternative to de-excitation of an excited nuclear state by emission of a γ-ray.
  - Nuclear excitation energy E_{ex} is transferred to an orbital electron.
  - Discrete energies represent transitions between atomic energy levels (shells).
  - A single excited atom can lead to several groups of electrons with different energies.
  - Sometimes sources have superimposed the β-spectrum of the parent nucleus.



Fast Electron Sources: Internal Conversion (2)



Some Common Conversion Electron Sources

Parent Nuclide	Parent Half-Life	Decay Mode	Decay Product	Transition Energy of Decay Product (keV)	Conversion Electron Energy (keV)
^{109}Cd	453 d	EC	^{109m}Ag	88	62 84
^{113}Sn	115 d	EC	^{113m}In	393	365 389
^{137}Cs	30.2 y	β^-	^{137m}Ba	662	624 656
^{139}Ce	137 d	EC	^{139m}La	166	126 159
^{207}Bi	38 y	EC	^{207m}Pb	570 1064	482 554 976 1048

Data from Lederer and Shirley.[1]

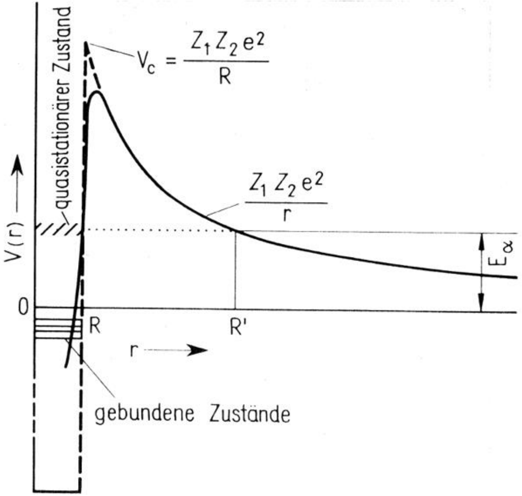
Conversion electrons are the **only practical laboratory-size source** of monoenergetic electron groups **in the high keV to MeV** energy range.

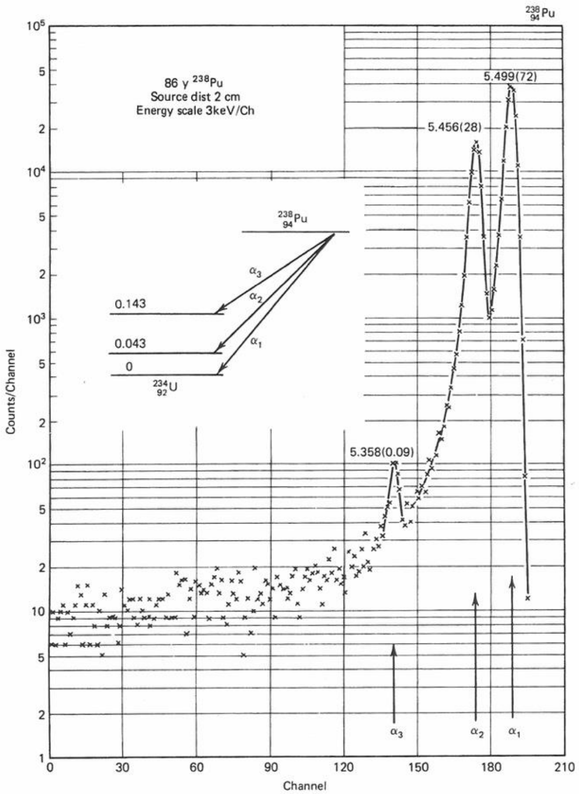
Heavy Charged Particle Sources: Alpha Decay (1)

- Decay by emission of an alpha particle (or $^{4}He^{2+}$ nucleus):

$$\boxed{{}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha}$$

- Alpha decay can be described in the framework of Quantum Mechanics: 'tunneling' through a potential barrier
- Probability of emission increases with the energy of the alpha particle E_α ($\sim e^{-G}$, G=Gamow-Factor).





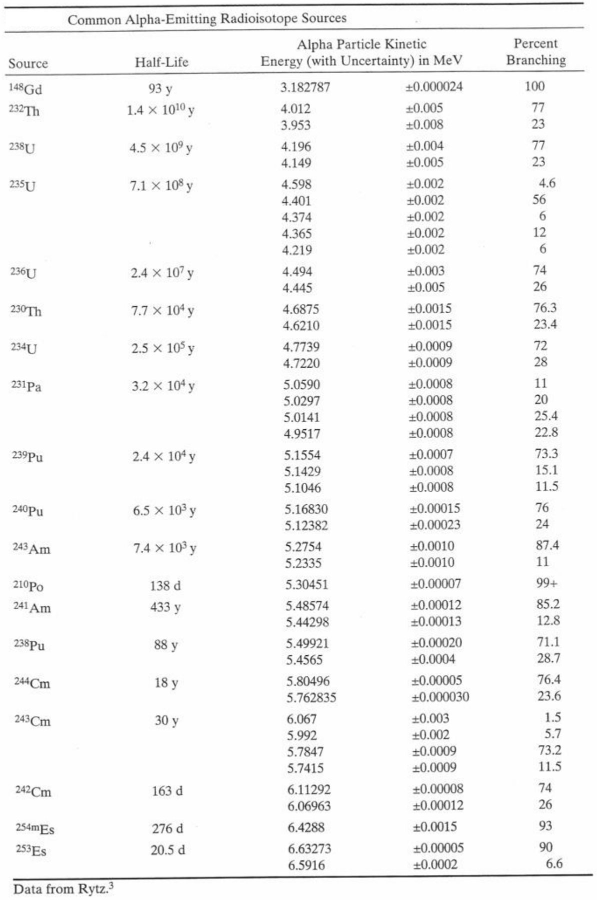
gure 1.3 Alpha particle groups produced in the decay of ^{238}Pu. The pulse height spectrum shows the three groups as measured by a silicon surface barrier detector. Each peak is identified by its energy in MeV and percent abundance (in parentheses). The insert shows the decay scheme, with energy levels in the product nucleus labeled in MeV. (Spectrum from Chanda and Deal.[2])

Heavy Charged Particle Sources: Alpha Decay (2)

- ❑ Each α particle shares the energy with the recoil nucleus in a unique way (Q=Q-value of the decay):

$$E_\alpha = Q\,(A - 4)/A$$

- ❑ Alpha particles appear in one or more (essentially) monoenergetic energy groups.
- ❑ Typical kinetic energy E_α ~ 5 MeV with a speed of 15,000 km/s.
- ❑ **Alpha particles are among the most hazardous forms of internal radiation:**
  - Energy loss takes place within a very short distance.
  - Significant damage to surrounding biomolecules.
- ❑ External alpha irradiation is not harmful:
  - Completely absorbed by a very thin (μm) dead layer of skin as well as by a few centimeters of air.

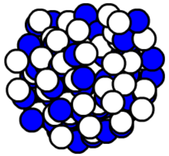


Common Alpha-Emitting Radioisotope Sources

Source	Half-Life	Alpha Particle Kinetic Energy (with Uncertainty) in MeV		Percent Branching
^{148}Gd	93 y	3.182787	±0.000024	100
^{232}Th	1.4 × 10^{10} y	4.012	±0.005	77
		3.953	±0.008	23
^{238}U	4.5 × 10^{9} y	4.196	±0.004	77
		4.149	±0.005	23
^{235}U	7.1 × 10^{8} y	4.598	±0.002	4.6
		4.401	±0.002	56
		4.374	±0.002	6
		4.365	±0.002	12
		4.219	±0.002	6
^{236}U	2.4 × 10^{7} y	4.494	±0.003	74
		4.445	±0.005	26
^{230}Th	7.7 × 10^{4} y	4.6875	±0.0015	76.3
		4.6210	±0.0015	23.4
^{234}U	2.5 × 10^{5} y	4.7739	±0.0009	72
		4.7220	±0.0009	28
^{231}Pa	3.2 × 10^{4} y	5.0590	±0.0008	11
		5.0297	±0.0008	20
		5.0141	±0.0008	25.4
		4.9517	±0.0008	22.8
^{239}Pu	2.4 × 10^{4} y	5.1554	±0.0007	73.3
		5.1429	±0.0008	15.1
		5.1046	±0.0008	11.5
^{240}Pu	6.5 × 10^{3} y	5.16830	±0.00015	76
		5.12382	±0.00023	24
^{243}Am	7.4 × 10^{3} y	5.2754	±0.0010	87.4
		5.2335	±0.0010	11
^{210}Po	138 d	5.30451	±0.00007	99+
^{241}Am	433 y	5.48574	±0.00012	85.2
		5.44298	±0.00013	12.8
^{238}Pu	88 y	5.49921	±0.00020	71.1
		5.4565	±0.0004	28.7
^{244}Cm	18 y	5.80496	±0.00005	76.4
		5.762835	±0.000030	23.6
^{243}Cm	30 y	6.067	±0.003	1.5
		5.992	±0.002	5.7
		5.7847	±0.0009	73.2
		5.7415	±0.0009	11.5
^{242}Cm	163 d	6.11292	±0.00008	74
		6.06963	±0.00012	26
^{254m}Es	276 d	6.4288	±0.0015	93
^{253}Es	20.5 d	6.63273	±0.00005	90
		6.5916	±0.0002	6.6

Data from Rytz.[3]

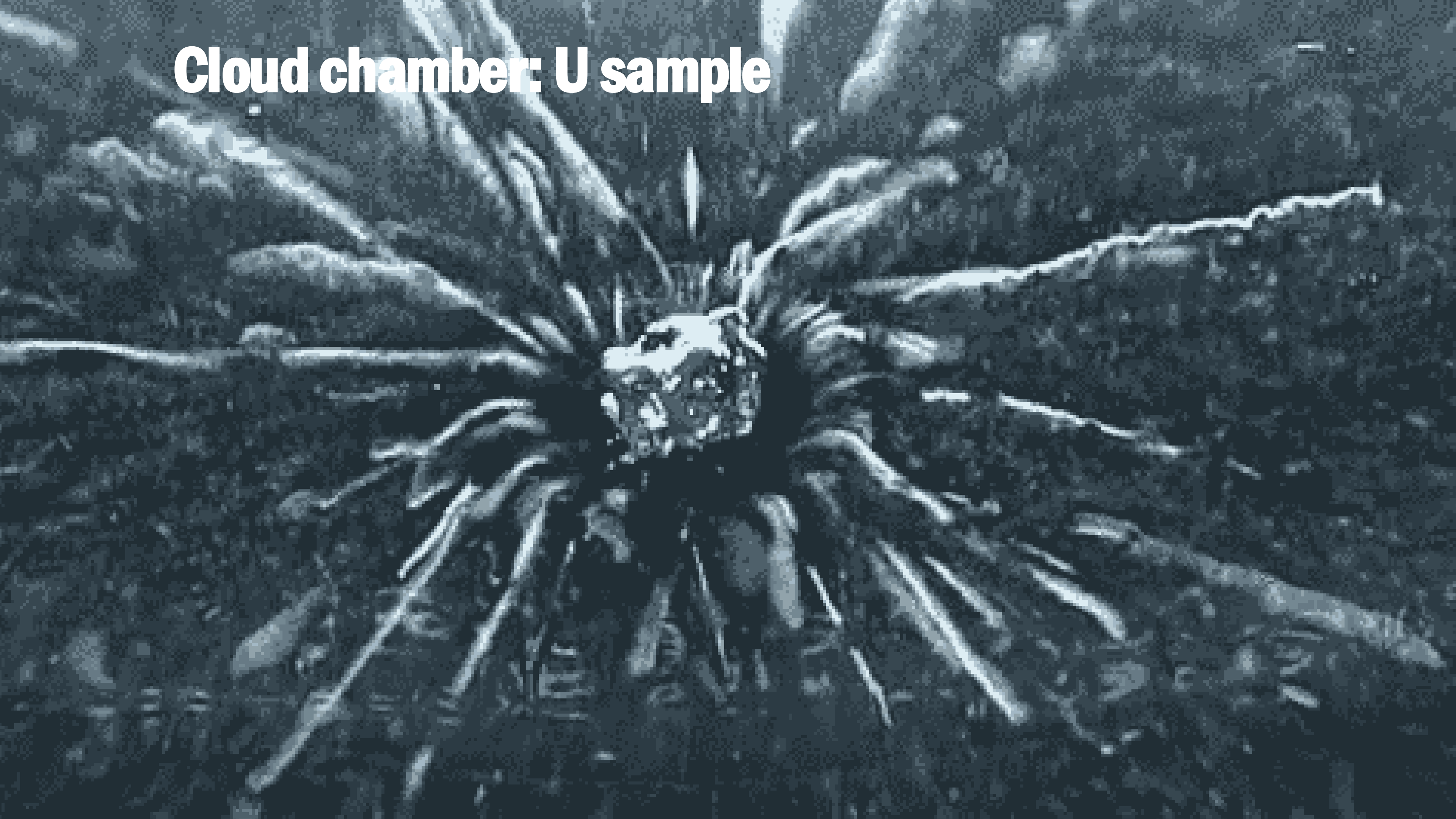
Alpha Decay of U-238

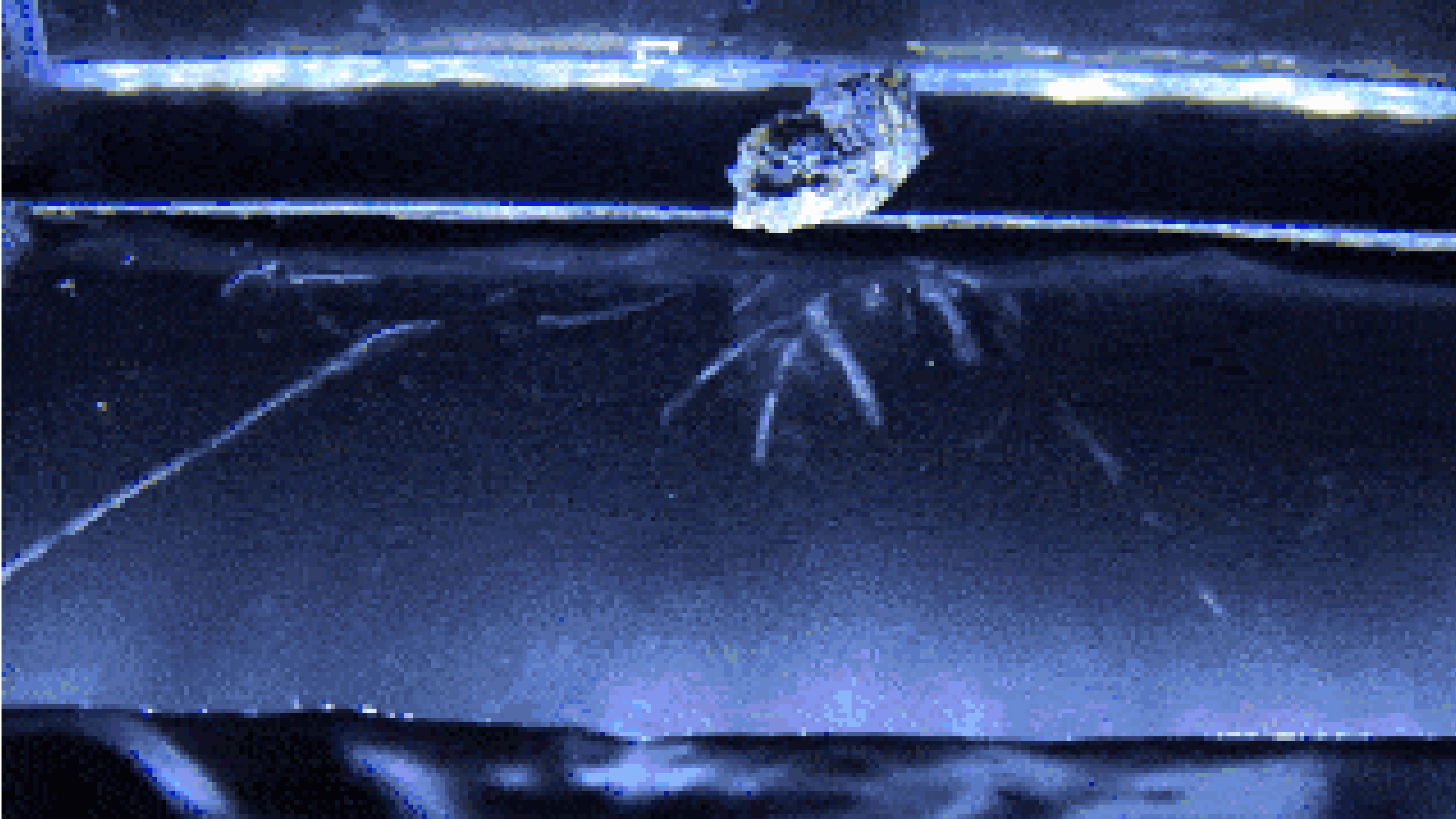


$^{238}_{92}$U

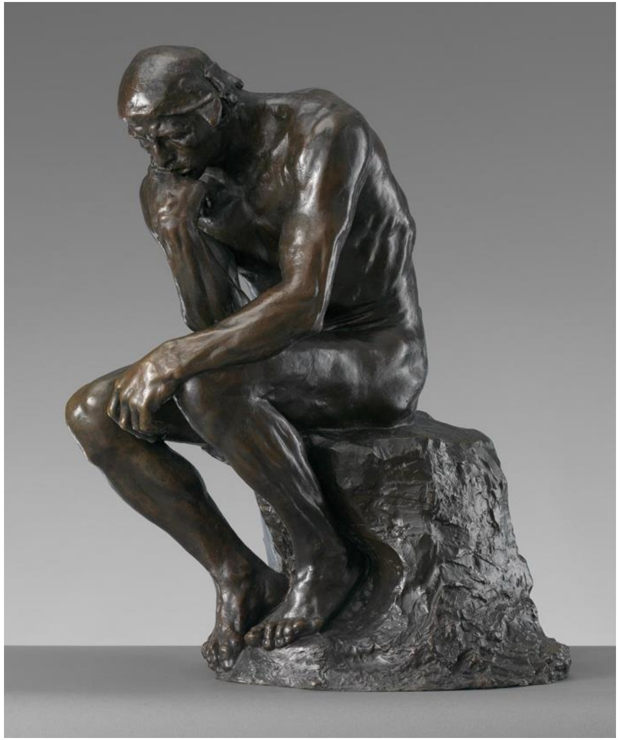
$$^{238}_{92}\mathrm{U} \longrightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$

Cloud chamber: U sample

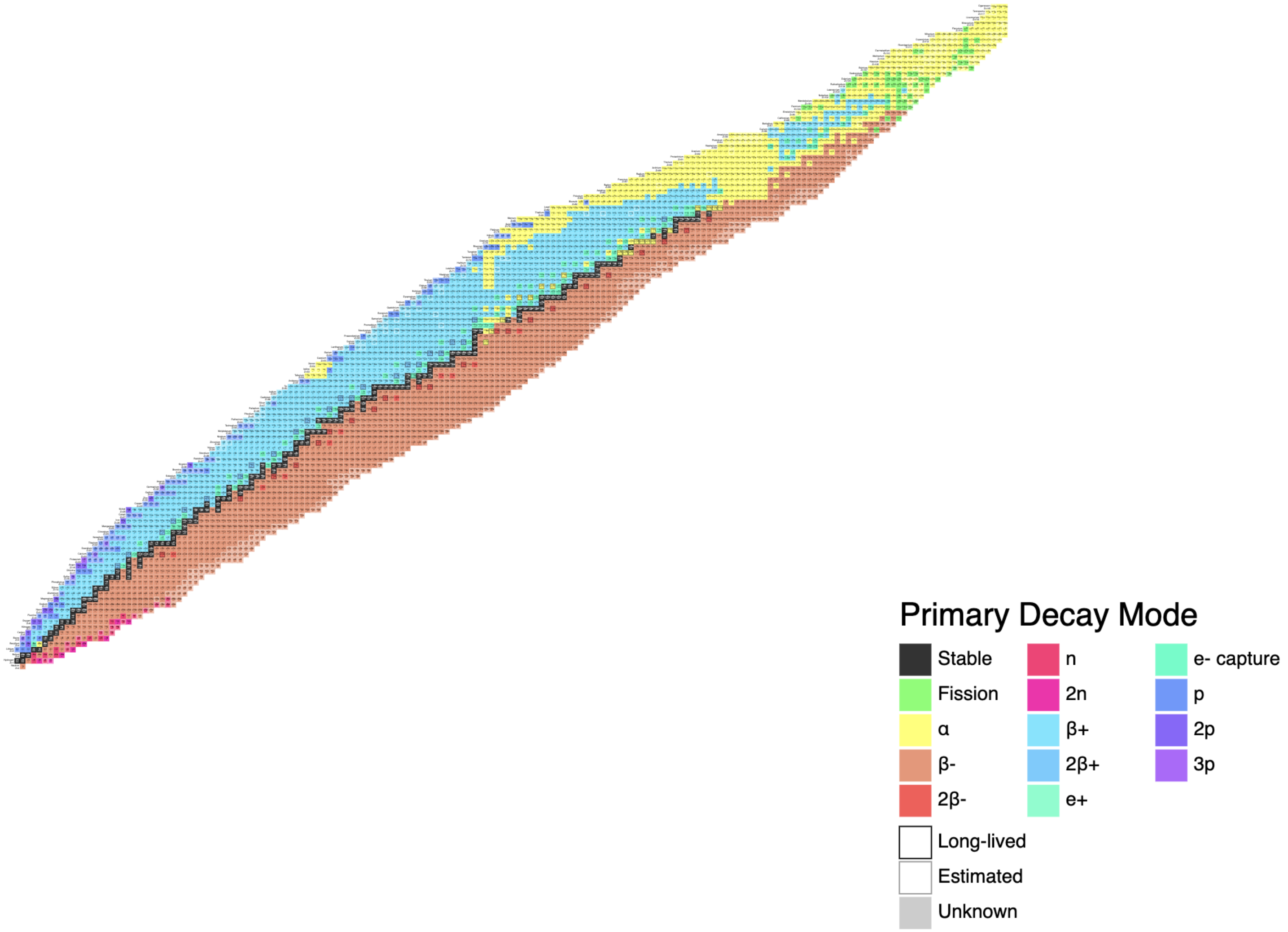


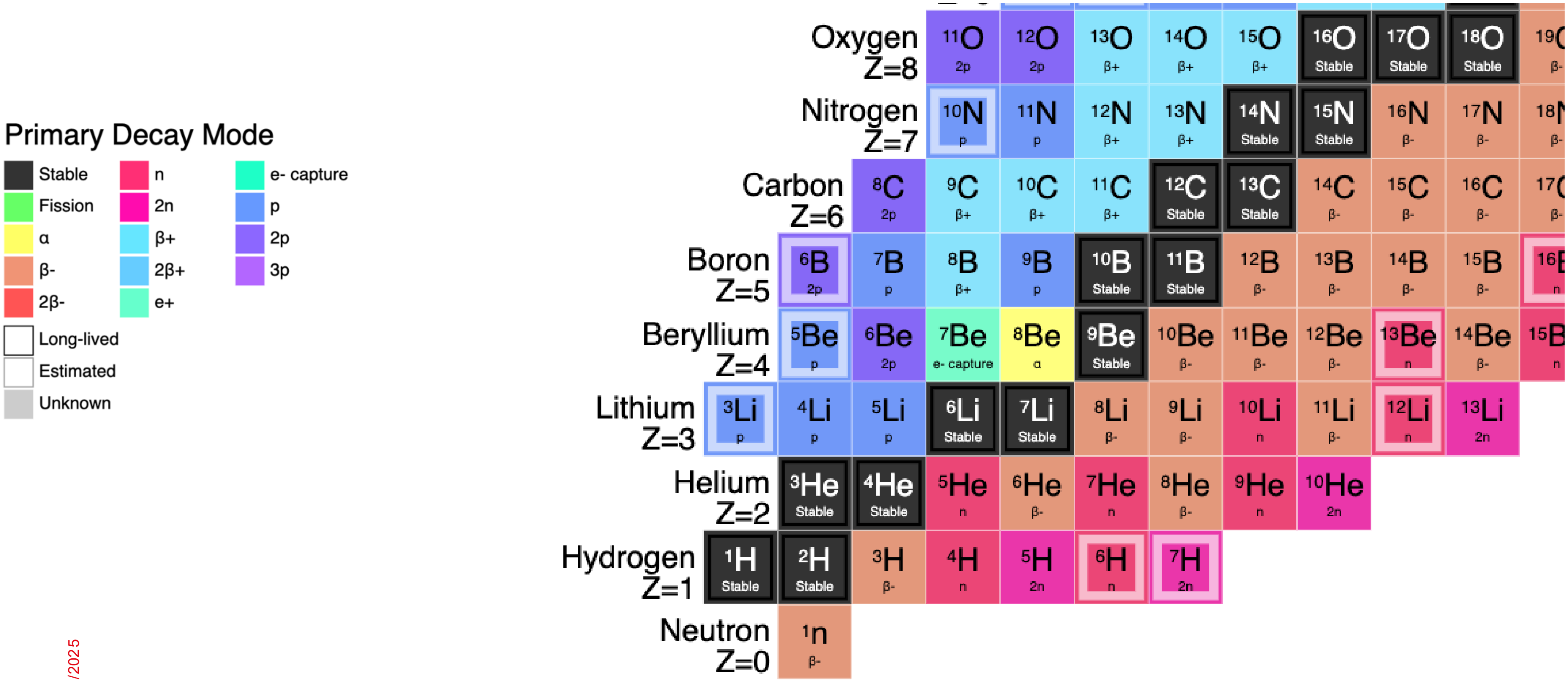


How can we get even heavier charged particles?



Reminder:
Chart of nuclides





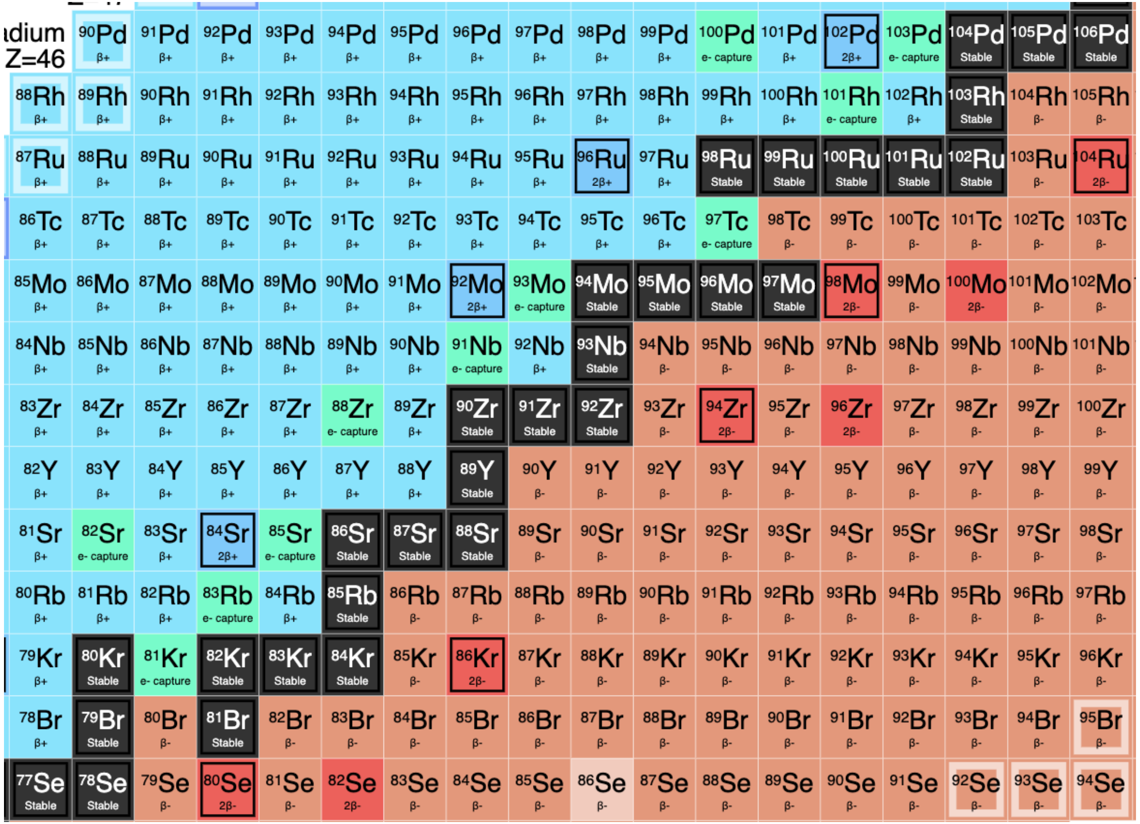
Primary Decay Mode

- Stable
- Fission
- α
- β-
- 2β-
- n
- 2n
- β+
- 2β+
- e+
- e- capture
- p
- 2p
- 3p
- Long-lived
- Estimated
- Unknown

Oxygen Z=8				^{11}O 2p	^{12}O 2p	^{13}O β+	^{14}O β+	^{15}O β+	^{16}O Stable	^{17}O Stable	^{18}O Stable	19 β-
Nitrogen Z=7				^{10}N p	^{11}N p	^{12}N β+	^{13}N β+	^{14}N Stable	^{15}N Stable	^{16}N β-	^{17}N β-	18 β-
Carbon Z=6			^{8}C 2p	^{9}C β+	^{10}C β+	^{11}C β+	^{12}C Stable	^{13}C Stable	^{14}C β-	^{15}C β-	^{16}C β-	17 β-
Boron Z=5		^{6}B 2p	^{7}B p	^{8}B β+	^{9}B p	^{10}B Stable	^{11}B Stable	^{12}B β-	^{13}B β-	^{14}B β-	^{15}B β-	16 n
Beryllium Z=4		^{5}Be p	^{6}Be 2p	^{7}Be e- capture	^{8}Be α	^{9}Be Stable	^{10}Be β-	^{11}Be β-	^{12}Be β-	^{13}Be n	^{14}Be β-	15B n
Lithium Z=3	^{3}Li p	^{4}Li p	^{5}Li p	^{6}Li Stable	^{7}Li Stable	^{8}Li β-	^{9}Li β-	^{10}Li n	^{11}Li β-	^{12}Li n	^{13}Li 2n	
Helium Z=2		^{3}He Stable	^{4}He Stable	^{5}He n	^{6}He β-	^{7}He n	^{8}He β-	^{9}He n	^{10}He 2n			
Hydrogen Z=1	^{1}H Stable	^{2}H Stable	^{3}H β-	^{4}H n	^{5}H 2n	^{6}H n	^{7}H 2n					
Neutron Z=0		^{1}n β-										

Primary Decay Mode

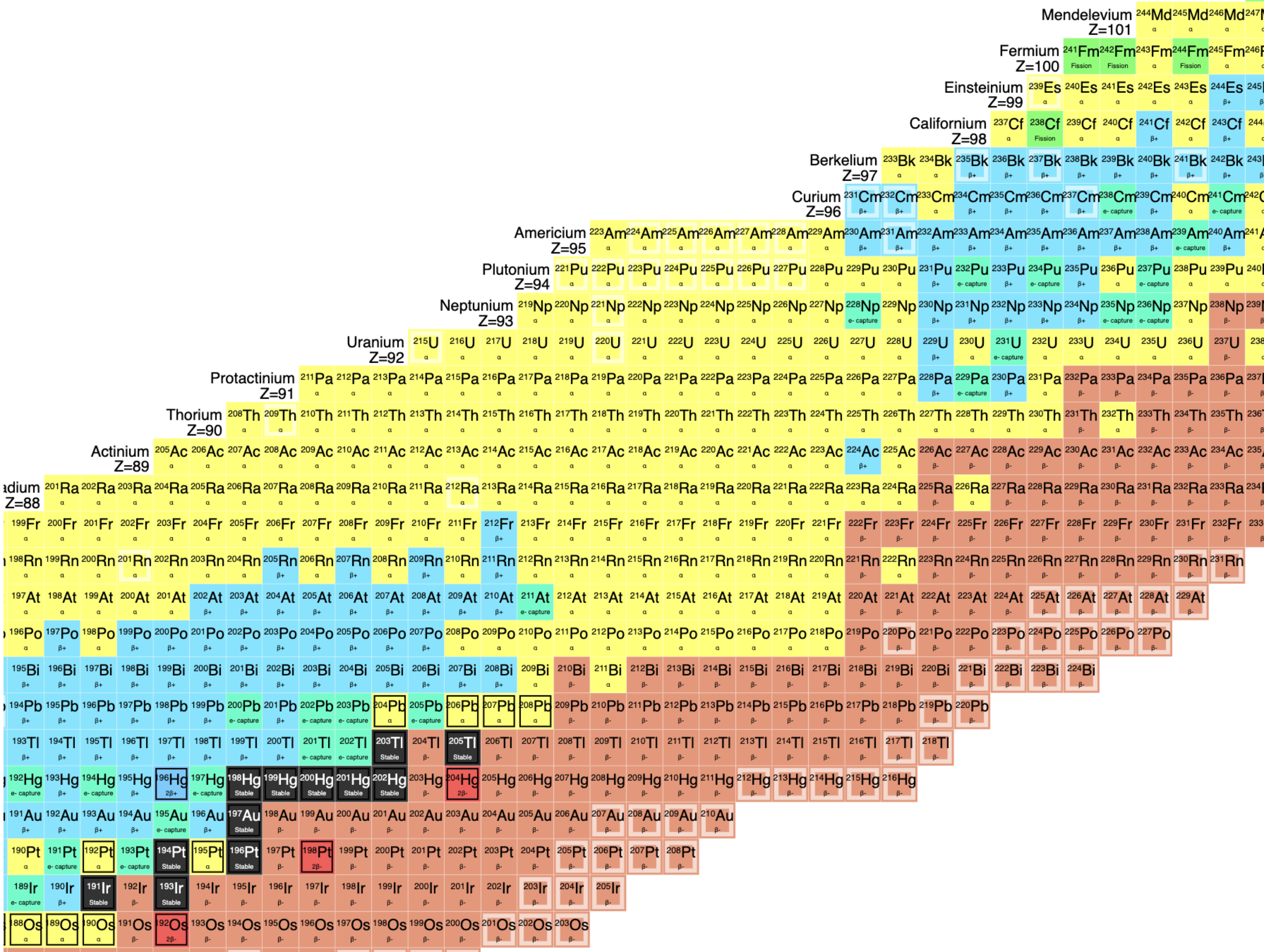
- ■ Stable
- 🟩 Fission
- 🟨 α
- 🟧 β-
- 🟥 2β-
- ☐ Long-lived
- ☐ Estimated
- ☐ Unknown
- 🟥 n
- 🟪 2n
- 🟦 β+
- 🟦 2β+
- 🟩 e+
- 🟩 e- capture
- 🟦 p
- 🟪 2p
- 🟪 3p



ıdium Z=46	^{90}Pd β+	^{91}Pd β+	^{92}Pd β+	^{93}Pd β+	^{94}Pd β+	^{95}Pd β+	^{96}Pd β+	^{97}Pd β+	^{98}Pd β+	^{99}Pd β+	^{100}Pd e- capture	^{101}Pd β+	^{102}Pd 2β+	^{103}Pd e- capture	^{104}Pd Stable	^{105}Pd Stable	^{106}Pd Stable
^{88}Rh β+	^{89}Rh β+	^{90}Rh β+	^{91}Rh β+	^{92}Rh β+	^{93}Rh β+	^{94}Rh β+	^{95}Rh β+	^{96}Rh β+	^{97}Rh β+	^{98}Rh β+	^{99}Rh β+	^{100}Rh β+	^{101}Rh e- capture	^{102}Rh β+	^{103}Rh Stable	^{104}Rh β-	^{105}Rh β-
^{87}Ru β+	^{88}Ru β+	^{89}Ru β+	^{90}Ru β+	^{91}Ru β+	^{92}Ru β+	^{93}Ru β+	^{94}Ru β+	^{95}Ru β+	^{96}Ru 2β+	^{97}Ru β+	^{98}Ru Stable	^{99}Ru Stable	^{100}Ru Stable	^{101}Ru Stable	^{102}Ru Stable	^{103}Ru β-	^{104}Ru 2β-
^{86}Tc β+	^{87}Tc β+	^{88}Tc β+	^{89}Tc β+	^{90}Tc β+	^{91}Tc β+	^{92}Tc β+	^{93}Tc β+	^{94}Tc β+	^{95}Tc β+	^{96}Tc β+	^{97}Tc e- capture	^{98}Tc β-	^{99}Tc β-	^{100}Tc β-	^{101}Tc β-	^{102}Tc β-	^{103}Tc β-
^{85}Mo β+	^{86}Mo β+	^{87}Mo β+	^{88}Mo β+	^{89}Mo β+	^{90}Mo β+	^{91}Mo β+	^{92}Mo 2β+	^{93}Mo e- capture	^{94}Mo Stable	^{95}Mo Stable	^{96}Mo Stable	^{97}Mo Stable	^{98}Mo 2β-	^{99}Mo β-	^{100}Mo 2β-	^{101}Mo β-	^{102}Mo β-
^{84}Nb β+	^{85}Nb β+	^{86}Nb β+	^{87}Nb β+	^{88}Nb β+	^{89}Nb β+	^{90}Nb β+	^{91}Nb e- capture	^{92}Nb β+	^{93}Nb Stable	^{94}Nb β-	^{95}Nb β-	^{96}Nb β-	^{97}Nb β-	^{98}Nb β-	^{99}Nb β-	^{100}Nb β-	^{101}Nb β-
^{83}Zr β+	^{84}Zr β+	^{85}Zr β+	^{86}Zr β+	^{87}Zr β+	^{88}Zr e- capture	^{89}Zr β+	^{90}Zr Stable	^{91}Zr Stable	^{92}Zr Stable	^{93}Zr β-	^{94}Zr 2β-	^{95}Zr β-	^{96}Zr 2β-	^{97}Zr β-	^{98}Zr β-	^{99}Zr β-	^{100}Zr β-
^{82}Y β+	^{83}Y β+	^{84}Y β+	^{85}Y β+	^{86}Y β+	^{87}Y β+	^{88}Y β+	^{89}Y Stable	^{90}Y β-	^{91}Y β-	^{92}Y β-	^{93}Y β-	^{94}Y β-	^{95}Y β-	^{96}Y β-	^{97}Y β-	^{98}Y β-	^{99}Y β-
^{81}Sr β+	^{82}Sr e- capture	^{83}Sr β+	^{84}Sr 2β+	^{85}Sr e- capture	^{86}Sr Stable	^{87}Sr Stable	^{88}Sr Stable	^{89}Sr β-	^{90}Sr β-	^{91}Sr β-	^{92}Sr β-	^{93}Sr β-	^{94}Sr β-	^{95}Sr β-	^{96}Sr β-	^{97}Sr β-	^{98}Sr β-
^{80}Rb β+	^{81}Rb β+	^{82}Rb β+	^{83}Rb e- capture	^{84}Rb β+	^{85}Rb Stable	^{86}Rb β-	^{87}Rb β-	^{88}Rb β-	^{89}Rb β-	^{90}Rb β-	^{91}Rb β-	^{92}Rb β-	^{93}Rb β-	^{94}Rb β-	^{95}Rb β-	^{96}Rb β-	^{97}Rb β-
^{79}Kr β+	^{80}Kr Stable	^{81}Kr e- capture	^{82}Kr Stable	^{83}Kr Stable	^{84}Kr Stable	^{85}Kr β-	^{86}Kr 2β-	^{87}Kr β-	^{88}Kr β-	^{89}Kr β-	^{90}Kr β-	^{91}Kr β-	^{92}Kr β-	^{93}Kr β-	^{94}Kr β-	^{95}Kr β-	^{96}Kr β-
^{78}Br β+	^{79}Br Stable	^{80}Br β-	^{81}Br Stable	^{82}Br β-	^{83}Br β-	^{84}Br β-	^{85}Br β-	^{86}Br β-	^{87}Br β-	^{88}Br β-	^{89}Br β-	^{90}Br β-	^{91}Br β-	^{92}Br β-	^{93}Br β-	^{94}Br β-	^{95}Br β-
^{77}Se Stable	^{78}Se Stable	^{79}Se β-	^{80}Se 2β-	^{81}Se β-	^{82}Se 2β-	^{83}Se β-	^{84}Se β-	^{85}Se β-	^{86}Se β-	^{87}Se β-	^{88}Se β-	^{89}Se β-	^{90}Se β-	^{91}Se β-	^{92}Se β-	^{93}Se β-	^{94}Se β-

Primary Decay Mode

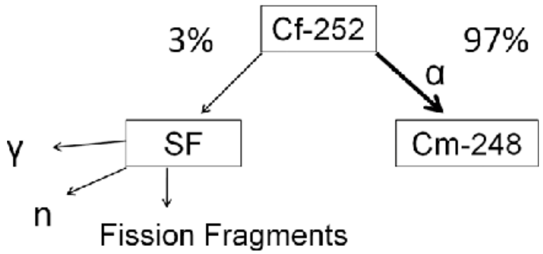
■ Stable	🟥 n	🟩 e- capture
🟩 Fission	🟥 2n	🟦 p
🟨 α	🟦 β+	🟪 2p
🟧 β-	🟦 2β+	🟪 3p
🟥 2β-	🟩 e+	
☐ Long-lived		
☐ Estimated		
⬜ Unknown		



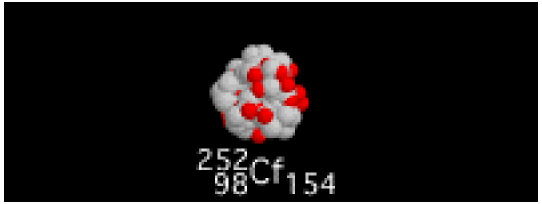
10/31/2025

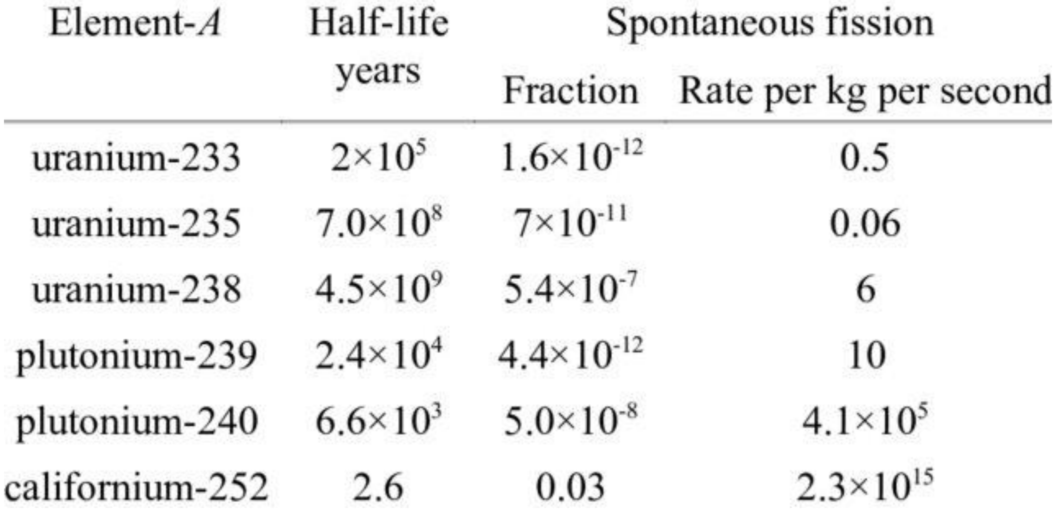
Heavy Charged Particles: Spontaneous Fission (1)

- Form of radioactive decay characteristic of very heavy isotopes.
- Spontaneous fission is only energetically feasible for A > 230
- Same process as induced fission:
  - Releases neutrons, fission products, gamma rays, neutrinos, etc
- Isotopes, for which spontaneous fission is a non-negligible decay mode can be used as neutron sources:
  - ^{252}Cf (half-life 2.645 years)
  - Applied to:
    - Detector calibration (well known spectrum of n)
    - inspect airline luggage for hidden explosives,
    - to gauge the moisture content of soil, materials stored in silos, etc.



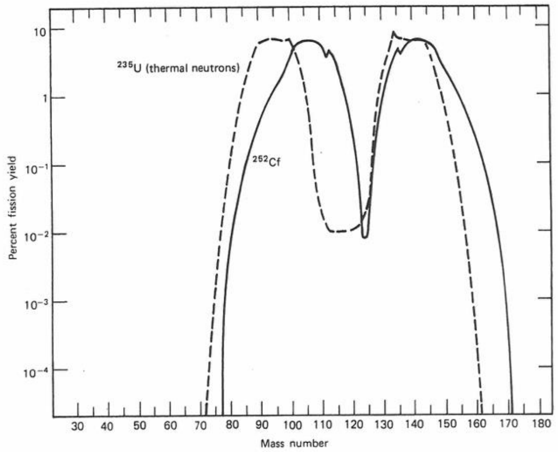
Spontaneous Fission



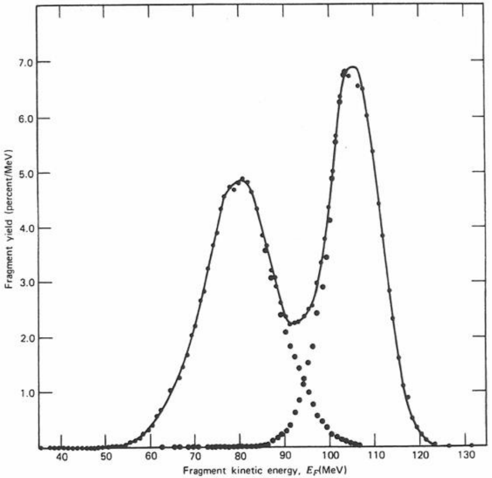


Element-*A*	Half-life years	Spontaneous fission	
		Fraction	Rate per kg per second
uranium-233	2×10^{5}	1.6×10^{-12}	0.5
uranium-235	7.0×10^{8}	7×10^{-11}	0.06
uranium-238	4.5×10^{9}	5.4×10^{-7}	6
plutonium-239	2.4×10^{4}	4.4×10^{-12}	10
plutonium-240	6.6×10^{3}	5.0×10^{-8}	4.1×10^{5}
californium-252	2.6	0.03	2.3×10^{15}

Heavy Charged Particles: Spontaneous Fission (2)



The mass distribution of ^{252}Cf spontaneous fission fragments. Also shown is the corresponding distribution from fission of ^{235}U induced by thermal neutrons. (From Nervik.[4])



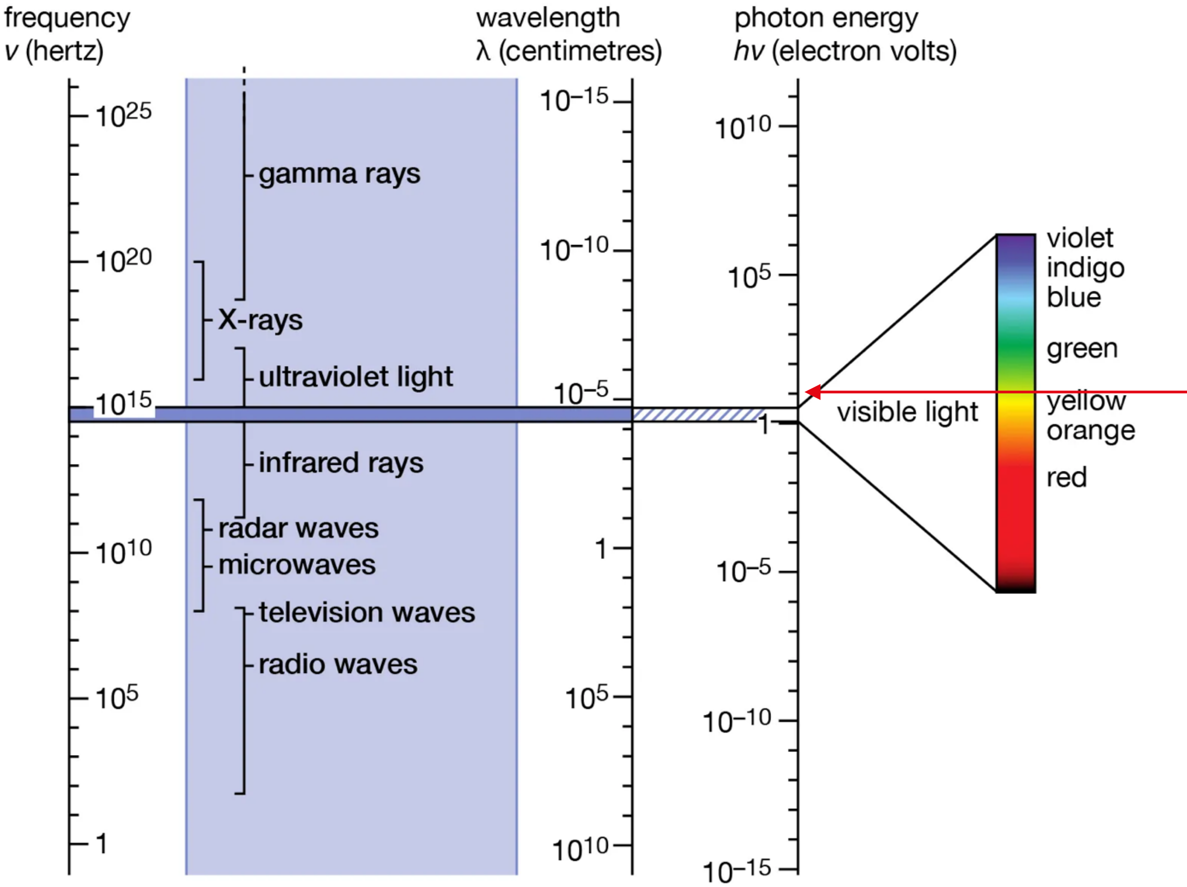
The distribution in kinetic energy of the ^{252}Cf spontaneous fission fragments. The peak on the left corresponds to the heavy fragments, and that on the right to the light fragments. (From Whetstone.[5])

- Fission fragments are medium-weight positive ions.
- Fission is generally asymmetric: clustering into light (A~108) and heavy (A~143) groups.
- Initial charge approaches Z of the fragment and is reduced by interaction with the material.

- Energy shared by the two fragments: ~185 MeV.
- Asymmetric distribution of kinetic energy: light fragments receive the largest.
- Sources must be thin to overcome self-absorption.

5 min break

Reminder: Non-ionizing vs. Ionizing radiation



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Threshold at around 3 - 30 eV

Gamma Rays (following β-decay) (1)

- ❑ Emitted in the transition to lower energy levels in an excited nucleus
- ❑ Excited nuclei are produced by decay of a parent radionuclide:
  - Beta-decay leads to excited nucleus (parent half-life).
  - Energy is emitted as γ-photons (half-life ~ps).
  - The energy level structure reflects that of the daughter nucleus.
  - The γ-emission half-life is effectively that of the parent nucleus.

Energy of photon = $\Delta E_{\text{excited-final}}$

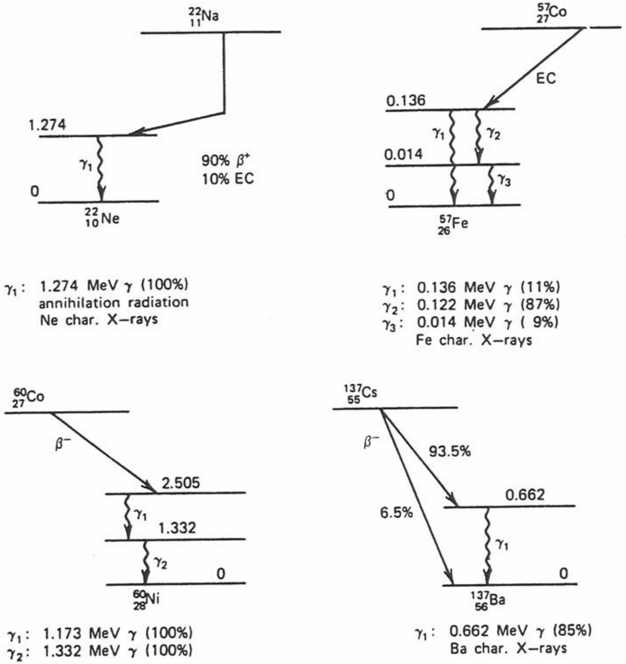
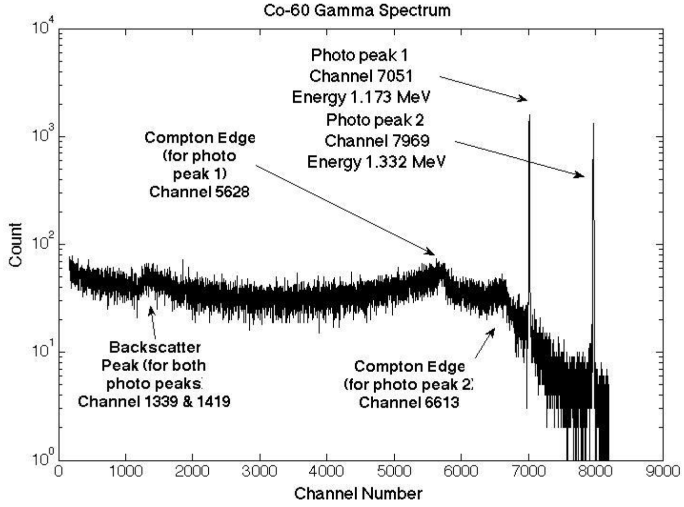


Figure 1.5 Decay schemes for some common gamma reference sources. Only major transitions are shown. The energies and yields per disintegration of X- and gamma rays emitted in each decay are listed below the diagram. (Data from Lederer and Shirley.[1])

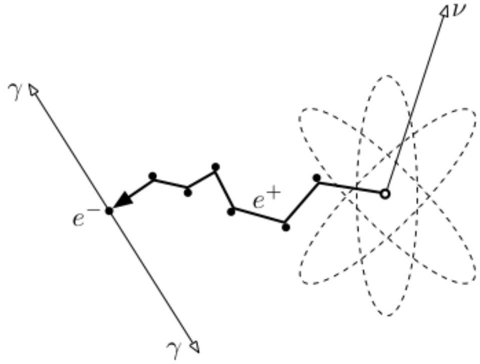
Gamma Rays (following β-decay) (2)

- ❑ Nuclear states have very well defined energies:
  - γ-rays emitted have well defined energies with very narrow peaks (nearly monoenergetic), $E_\gamma = E_i - E_f$.
  - Can be used for detector calibration.
- ❑ Gamma reference sources are essential in radiation measurement laboratories:
  - They consist of samples of β-emitters of a few μCi (~10^5 Bq).
  - Encased in plastic disks or rods and encapsulated to stop particulate radiation.
  - Secondary radiation, annihilation photons or Bremsstrahlung can be significant.
  - Radiation hazard is minimal due to low absolute activity.
- ❑ Energy is limited to about 2.8 MeV. Higher energies from:
  - ^{56}Co (3.55 MeV, half-life 77 days)
  - ^{16}N (6.13 and 7.11 MeV, half-life 7 s).

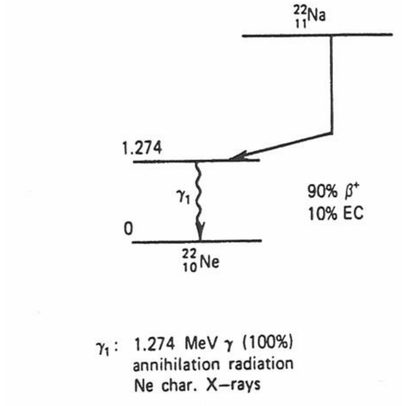


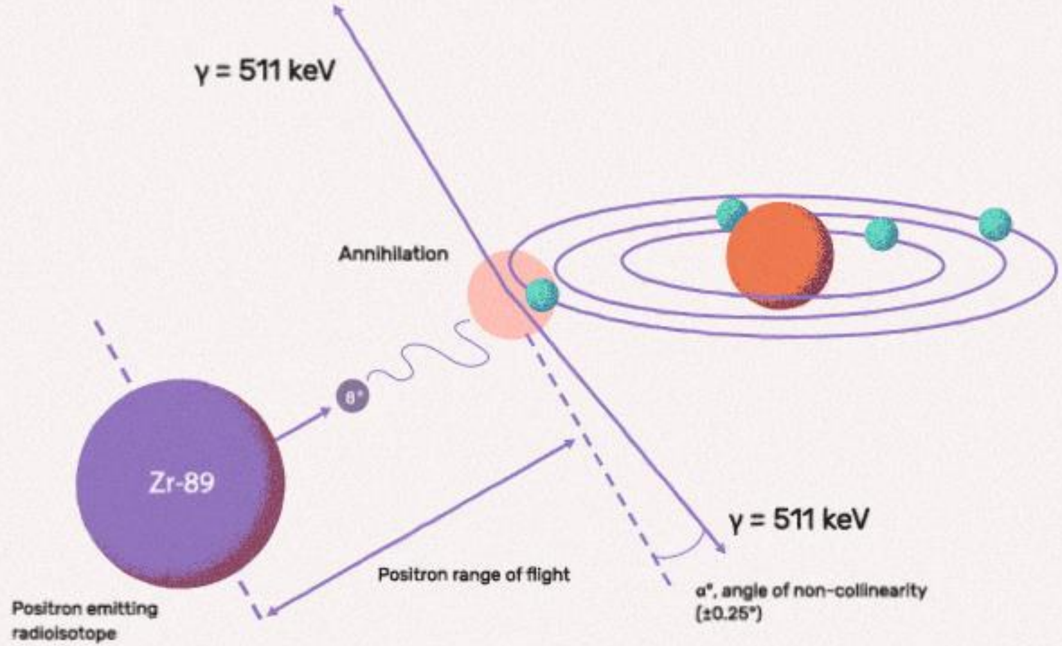
Gamma Rays from Annihilation Radiation

- Produced in nuclei undergoing β⁺decay.
- The positrons travel only a few millimetres before being stopped and annihilated by matter-antimatter interaction.
- This radiation is super-imposed on any gamma radiation emitted in the decay of the daughter nucleus.



$$\boxed{e^+ + e^- \rightarrow 2\gamma (m_e c^2 = 0.511\,\mathrm{MeV})}$$





https://dribbble.com/shots/10852340-Positron-emission

Gamma Rays from Nuclear Reactions

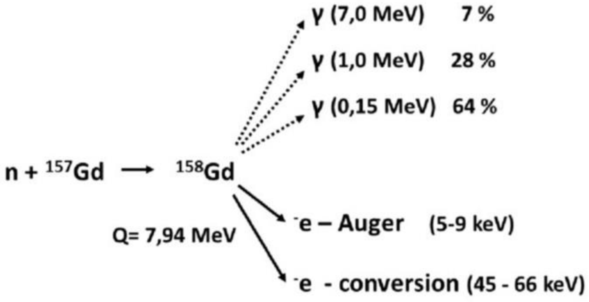
- ☐ High energy γ-rays can be produced from nuclear energy transitions of higher-lying nuclear states.
- ☐ Nuclear reactions provide the needed high energy excited states.
- ☐ Reactions used:
  - **Alpha absorption**:

$$\boxed{{}^{4}_{2}\alpha + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C}^{*} + {}^{1}_{0}\mathrm{n} \xrightarrow{61\,\mathrm{fs}} {}^{12}_{6}\mathrm{C} + \gamma\,(4.44\,\mathrm{MeV})}$$

$$\boxed{{}^{4}_{2}\alpha + {}^{13}_{6}\mathrm{C} \rightarrow {}^{16}_{8}\mathrm{O}^{*} + {}^{1}_{0}\mathrm{n} \xrightarrow{20\,\mathrm{ps}} {}^{16}_{8}\mathrm{O} + \gamma\,(6.130\,\mathrm{MeV})}$$

Sources are a combination of an α-emitter and the target material. Large α-yields must be used for practical intensities: e.g. $6 \cdot 10^9$ Bq of $^{238}PuO_2$ and 200mg of ^{13}C give a source of 770 photons/s of 6.130 MeV γ-rays.

  - **γ-rays from absorption of thermal neutrons** (radiative neutron-capture):
    - Intense flux from nuclear reactors or accelerator facilities.
    - Weaker fluxes from radioisotope sources of neutrons.
    - Gamma energies as high as 9 MeV.



γ (7,0 MeV) 7 %

γ (1,0 MeV) 28 %

γ (0,15 MeV) 64 %

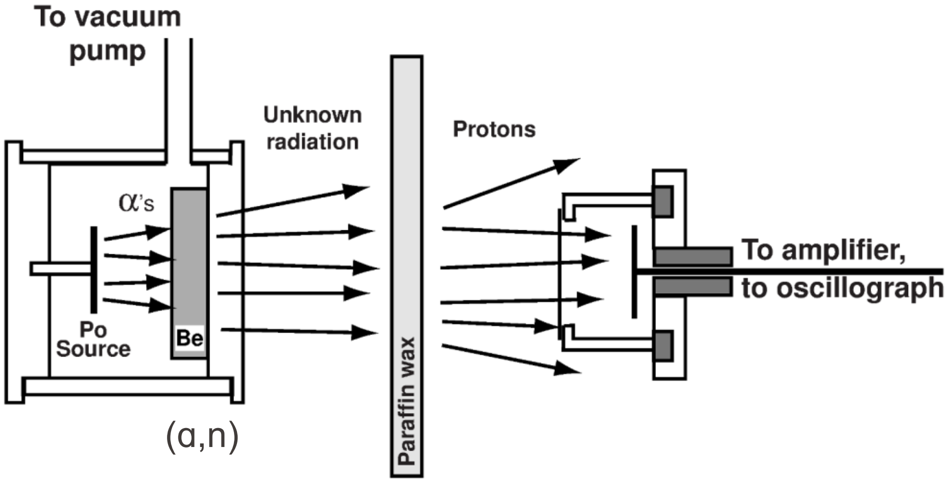
n + ^{157}Gd → ^{158}Gd

Q= 7,94 MeV

e – Auger (5-9 keV)

e - conversion (45 - 66 keV)

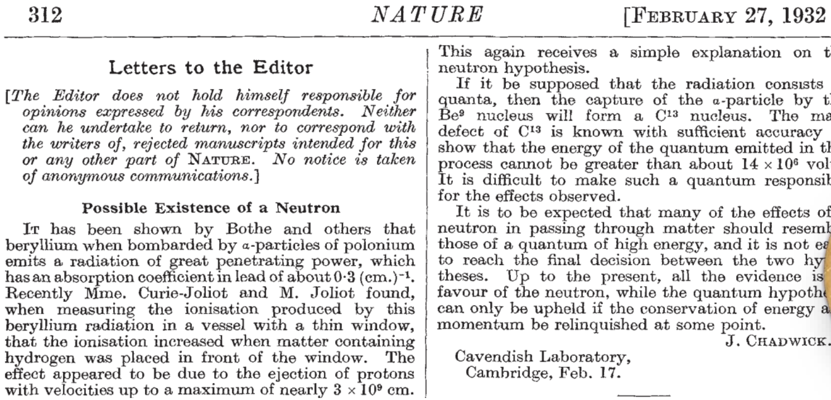
Discovery of the neutron (1932, Chadwick)



(α,n)

(n,p)

1930: No effect in E field
→γ?



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Letters to the Editor

[The Editor does not hold himself responsible for opinions expressed by his correspondents. Neither can he undertake to return, nor to correspond with the writers of, rejected manuscripts intended for this or any other part of NATURE. *No notice is taken of anonymous communications.]*

Possible Existence of a Neutron

IT has been shown by Bothe and others that beryllium when bombarded by α-particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0·3 (cm.)$^{-1}$. Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly 3×10^9 cm. This again receives a simple explanation on the neutron hypothesis.

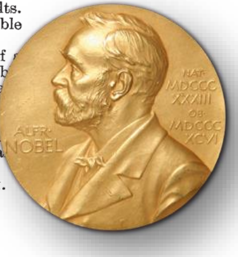
If it be supposed that the radiation consists of quanta, then the capture of the α-particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed.

It is to be expected that many of the effects of neutron in passing through matter should resemb those of a quantum of high energy, and it is not ea to reach the final decision between the two hy theses. Up to the present, all the evidence is favour of the neutron, while the quantum hypothe can only be upheld if the conservation of energy a momentum be relinquished at some point.

J. CHADWICK.

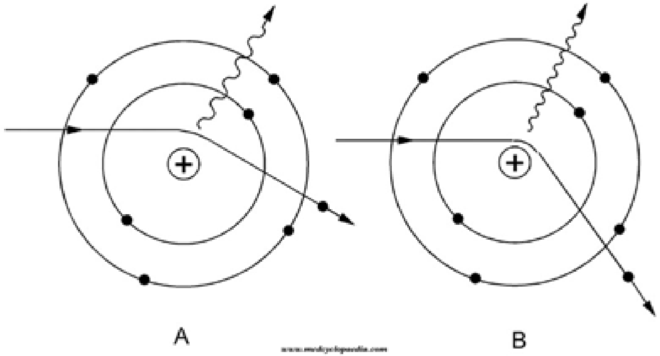
Cavendish Laboratory,
Cambridge, Feb. 17.

1935

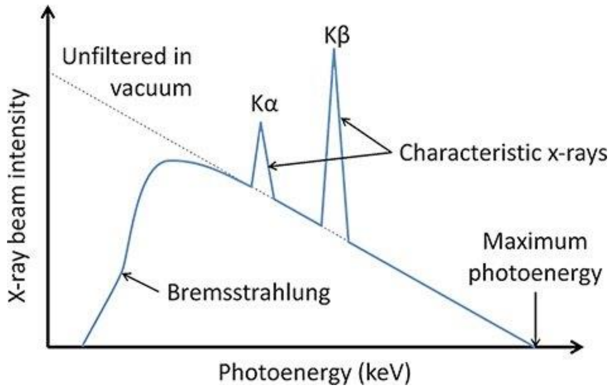


X-Rays from Bremsstrahlung (1)

- ❑ Bremsstrahlung: electromagnetic radiation from acceleration of charged particles, such as e^-
- ❑ Bremsstrahlung has a continuous spectrum:
  - The fraction of e^- energy converted into Bremsstrahlung increases with the electron energy and target Z.
  - The average photon energy is a small fraction of the incident electron energy.

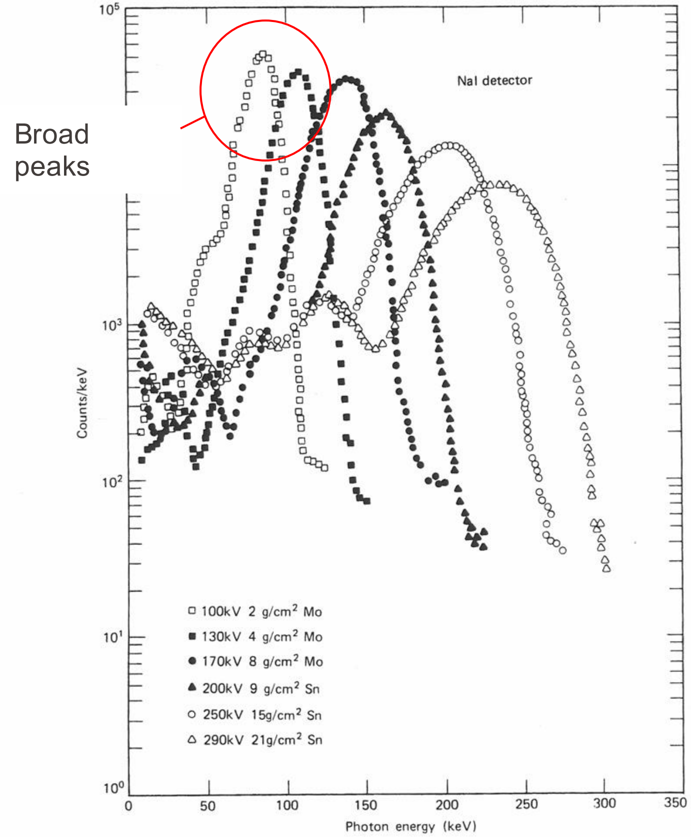


Spectrum produced by X-ray tube



X-Rays from Bremsstrahlung (2)

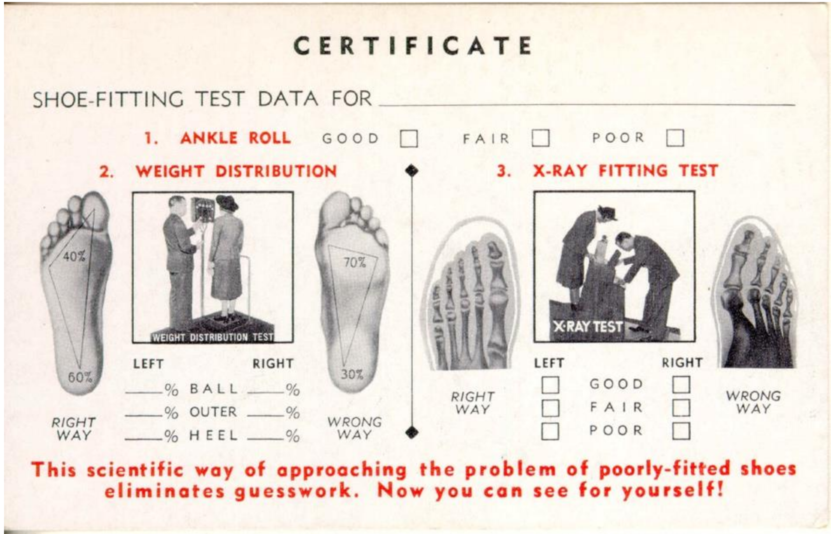
- Bremsstrahlung is used to produce X-rays from conventional X-ray tubes.
  - Continuous spectrum altered by:
    - Filtration with absorber materials.
    - Peaked spectrum can be created by removing lower energy photons.
    - Can be used for calibration of detectors whose response changes only gradually with energy.
- Bremsstrahlung also produced by:
  - β-emitters interacting with shielding.
  - Changes in nucleus electric field during β-decay.



Examples of measured pulse height spectra [using a NaI(Tl) scintillator] after filtration of an X-ray tube output using the indicated absorbers and tube voltages. (From Storm et al.[15])

Shoe-fitting fluoroscope (1930s-50s)

- Single visits pose little problem (100mSv to the feet)
- Concern mostly for frequent customers (children)
- and machine operators



CERTIFICATE

SHOE-FITTING TEST DATA FOR ______________________

1. **ANKLE ROLL** GOOD ☐ FAIR ☐ POOR ☐

2. **WEIGHT DISTRIBUTION**

3. **X-RAY FITTING TEST**

LEFT		RIGHT
___%	BALL	___%
___%	OUTER	___%
___%	HEEL	___%

LEFT		RIGHT
☐	GOOD	☐
☐	FAIR	☐
☐	POOR	☐

This scientific way of approaching the problem of poorly-fitted shoes eliminates guesswork. Now you can see for yourself!

Characteristic X-Rays (1)

- ☐ X-Rays come from the re-arrangement of orbital electrons from excited atomic energy levels to ground states.
- ☐ Characteristic X-ray series depending on the shell with the vacancies.
- ☐ K-series is the most energetic, energy grows with Z:
  - Na (Z=11) 1 keV,
  - Ga (Z=31) 10 keV,
  - Ra (Z=88) 100 keV.
- ☐ The energy of the characteristic X-rays is unique. They can be used for element analysis.

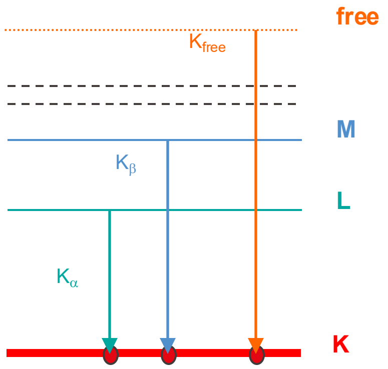
Energies in the K-series:

$$E_{K_\alpha} = E_L - E_K$$

$$E_{K_\beta} = E_M - E_K$$

$$\mathrm{M}$$

$$E_{K\max} = E_{free} - E_K = K_{\text{Binding Energy}}$$



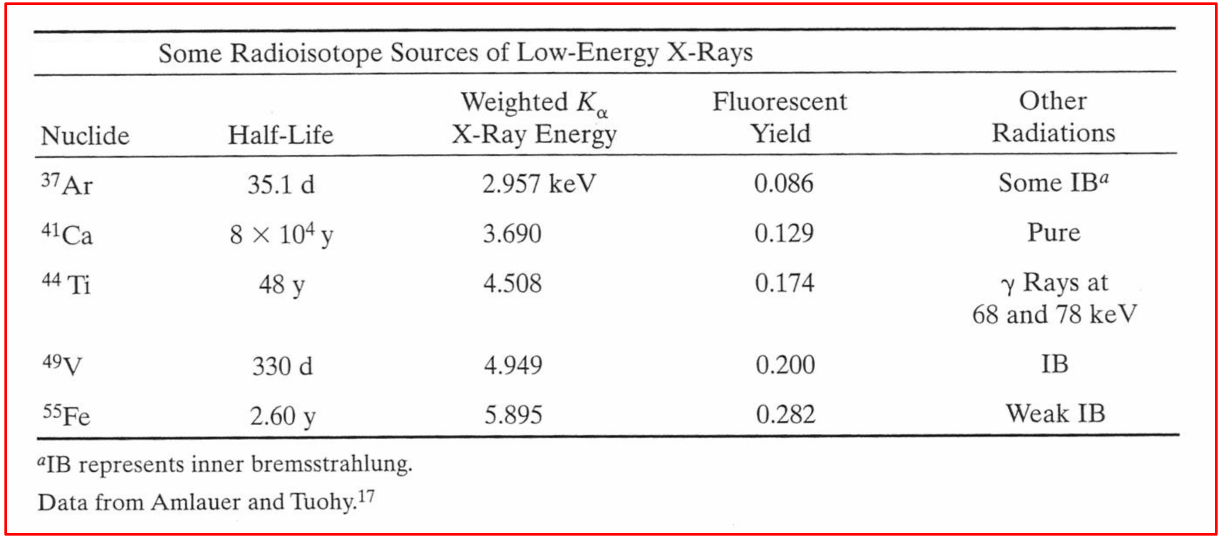
K-series of X-rays

EMR: Characteristic X-Rays (2)

- Excitation by **Electron Capture:** $\boxed{p^{+}+e^{-}\rightarrow n+\nu_e}$
  - Nuclear electron capture from a K-shell electron creates a vacancy.
  - The daughter atom is still neutral (Z-1), but a hole exists in on of the inner shells.
  - The hole is filled by upper-shell electrons and gives a characteristic X-rays.

- Excitation by **Internal Conversion:**
  - K-electrons are the most readily converted: the K-series is the most prominent.
  - Gamma-ray de-excitation competes with this process, thus the K X-rays are produced together with γ-photons.
  - If the energy of the converted electrons is high, Bremsstrahlung is also possible.

Characteristic X-Rays (3)



Some Radioisotope Sources of Low-Energy X-Rays

Nuclide	Half-Life	Weighted K_α X-Ray Energy	Fluorescent Yield	Other Radiations
^{37}Ar	35.1 d	2.957 keV	0.086	Some IB[a]
^{41}Ca	8×10^4 y	3.690	0.129	Pure
^{44}Ti	48 y	4.508	0.174	γ Rays at 68 and 78 keV
^{49}V	330 d	4.949	0.200	IB
^{55}Fe	2.60 y	5.895	0.282	Weak IB

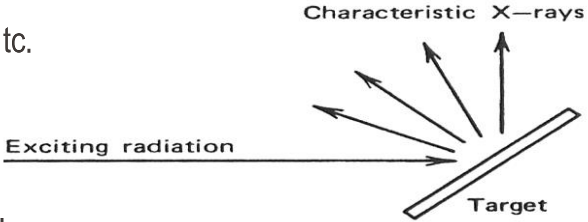
[a] IB represents inner bremsstrahlung.

Data from Amlauer and Tuohy.[17]

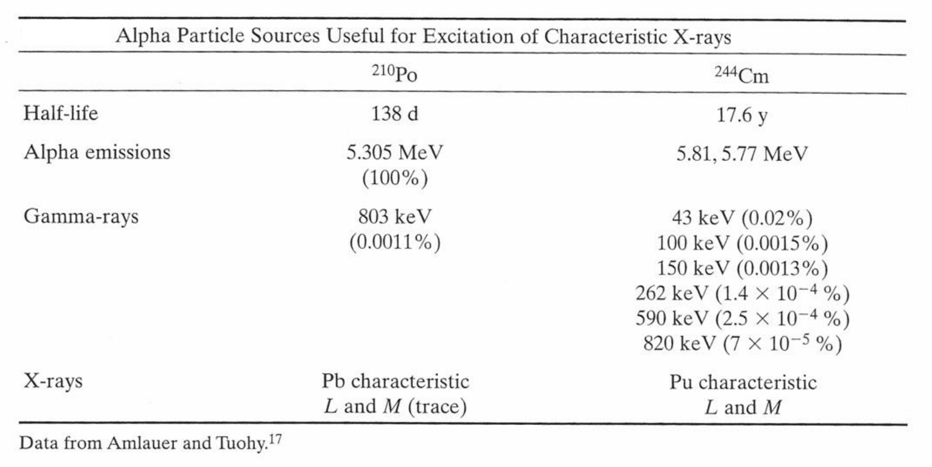
- The yield of high-energy γ-rays from nuclear transitions is large compared to the characteristic Xrays.
- A pure X-ray source needs a radioisotope that decays by electron capture leading directly to a ground nuclear state of the daughter.
- ^{55}Fe is the most used because of its half-life and specific activity, and its nearly pure source of Kseries of Mn at 5.9 keV, with very little Bremsstrahlung.
- Sources must be thin to prevent self-absorption of X-rays and have a high specific activity.

Characteristic X-Rays (4)

❑ Excitation by **external radiation:**
  - external sources of radiation used are: X-rays, e⁻, α, etc.
  - The radiation excites the parent atom which emits characteristic X-rays (isotropically).



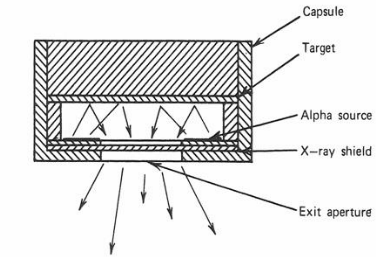
❑ The energy of X-rays depends on the target material: Low Z —> soft X-rays; High Z —> hard X-rays.



Alpha Particle Sources Useful for Excitation of Characteristic X-rays

	^{210}Po	^{244}Cm
Half-life	138 d	17.6 y
Alpha emissions	5.305 MeV (100%)	5.81, 5.77 MeV
Gamma-rays	803 keV (0.0011%)	43 keV (0.02%) 100 keV (0.0015%) 150 keV (0.0013%) 262 keV (1.4 × 10^{-4} %) 590 keV (2.5 × 10^{-4} %) 820 keV (7 × 10^{-5} %)
X-rays	Pb characteristic *L* and *M* (trace)	Pu characteristic *L* and *M*

Data from Amlauer and Tuohy.[17]

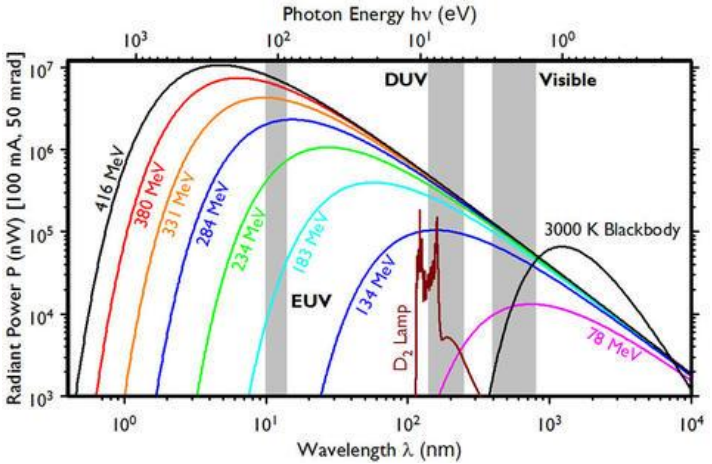


Compact source of characteristic X-rays with α-particle excitation.

No off switch

5 min break

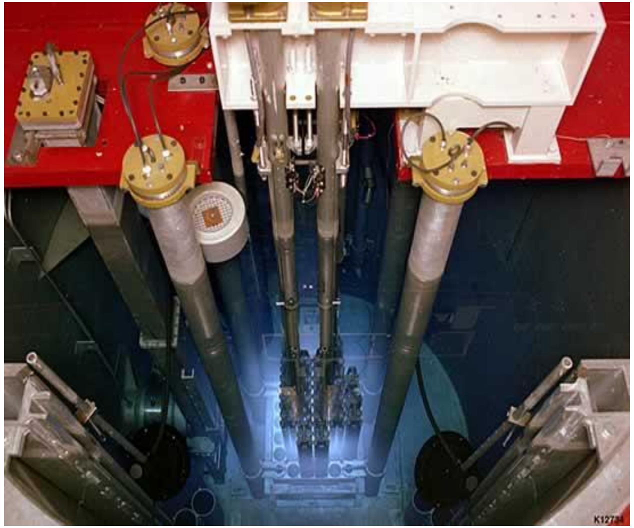
Synchrotron Radiation



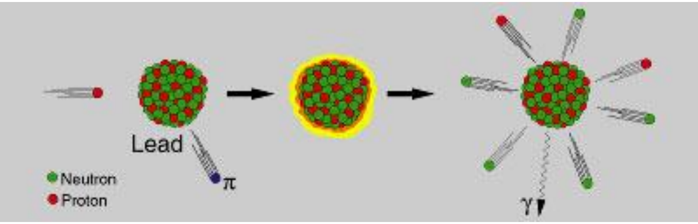
- ☐ Synchrotron radiation:
  - Generated by the B-field acceleration of ***ultrarelativistic e^-***.
  - Artificially by storage rings in a Synchrotron, or naturally by fast electrons moving through magnetic fields in space.
  - The radiation spectrum typically spans from infrared (few eV) to X-rays (10 keV).
- ☐ Characteristics:
  - High brightness and intensity, many orders of magnitude more than with X-rays produced in conventional X-ray tubes.
  - High collimation, i.e. small angular divergence of beam.
  - Low emittance, i.e. the product of source cross section and solid angle of emission is small.
  - Wide tunability in energy/wavelength by monochromatization (sub eV up to the MeV range).
  - High level of polarization (linear or elliptical) .
  - Pulsed light emission (pulse durations at or below 1 ns).
  - See, e.g., http://www.psi.ch/sls/ (Swiss Light Source)

Large Neutron Sources

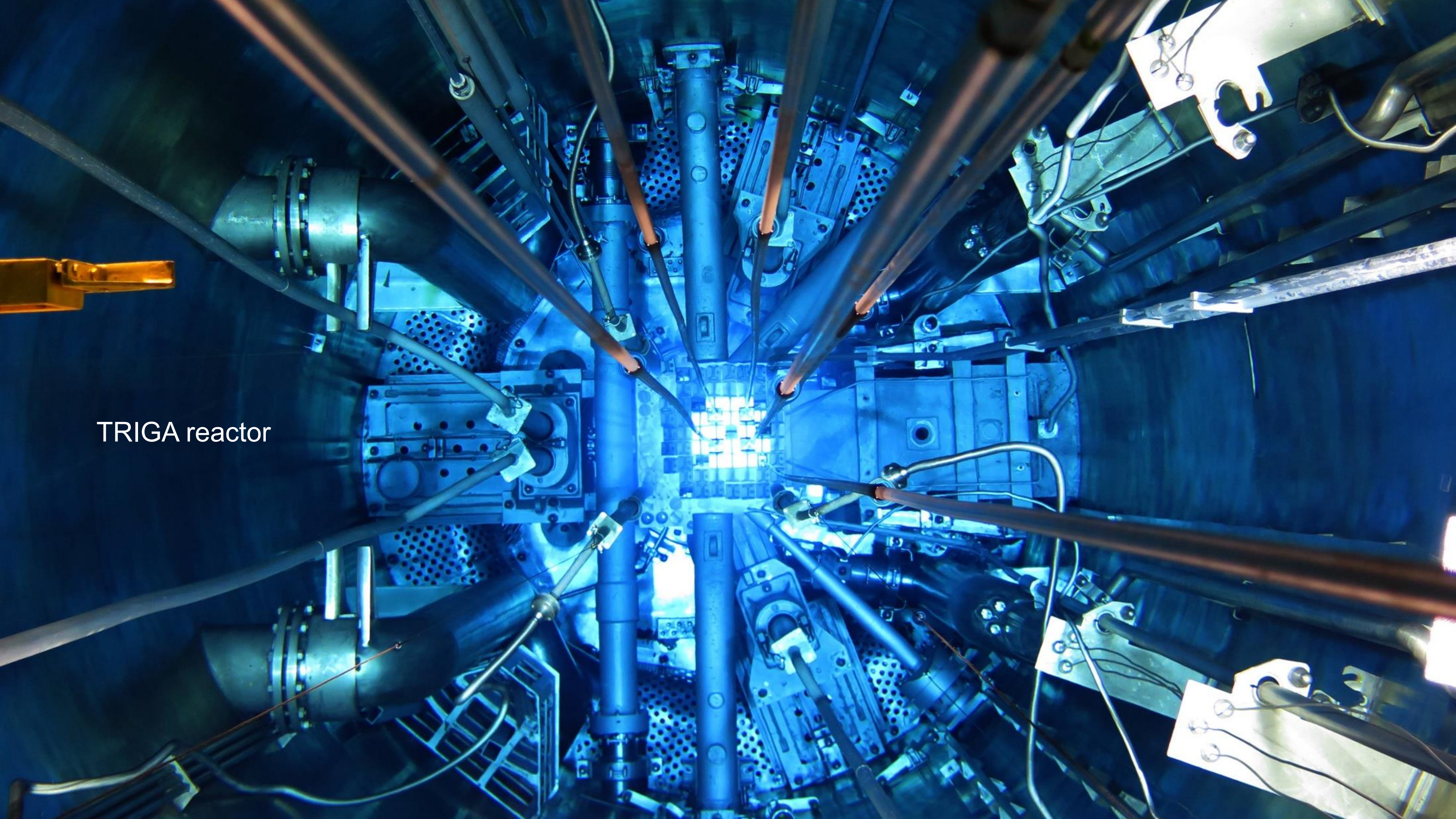
- ☐ **Nuclear reactors** (fission)
- ☐ **Spallation sources**



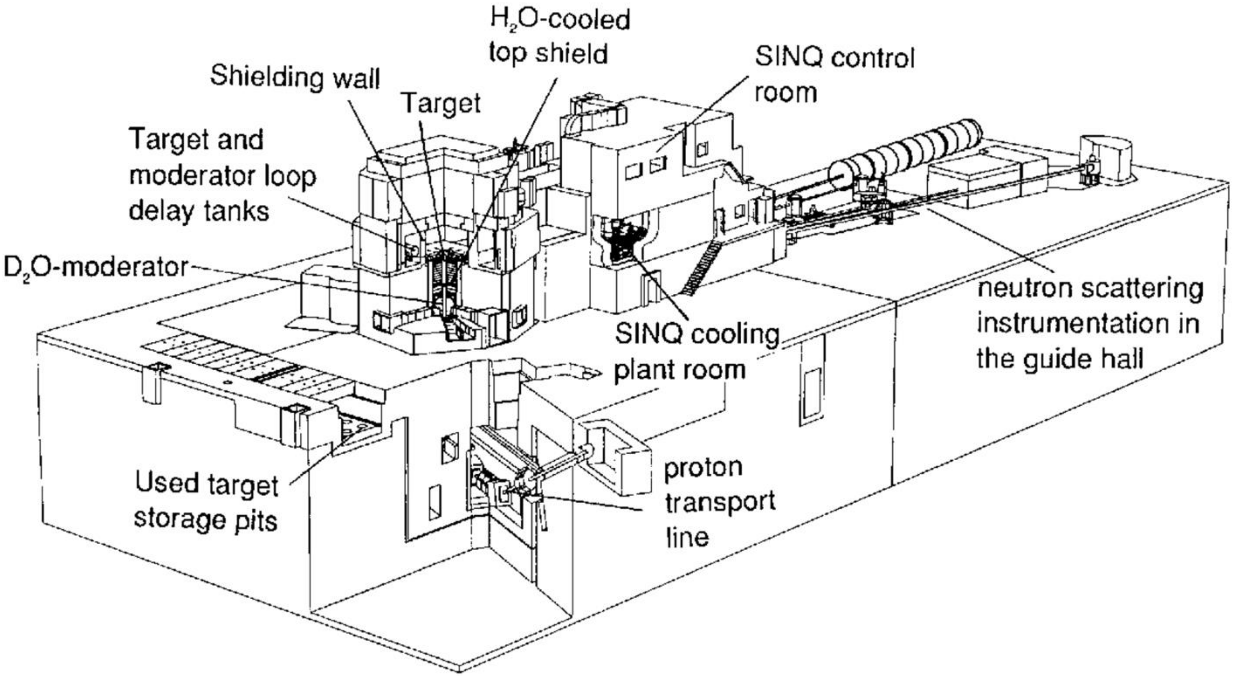
TRIGA Reactor



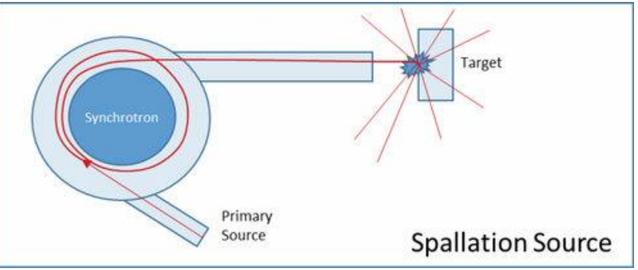
SINQ
Spallation
Source at PSI


TRIGA reactor

Spallation source example:
Swiss Spallation Neutron Source SINQ

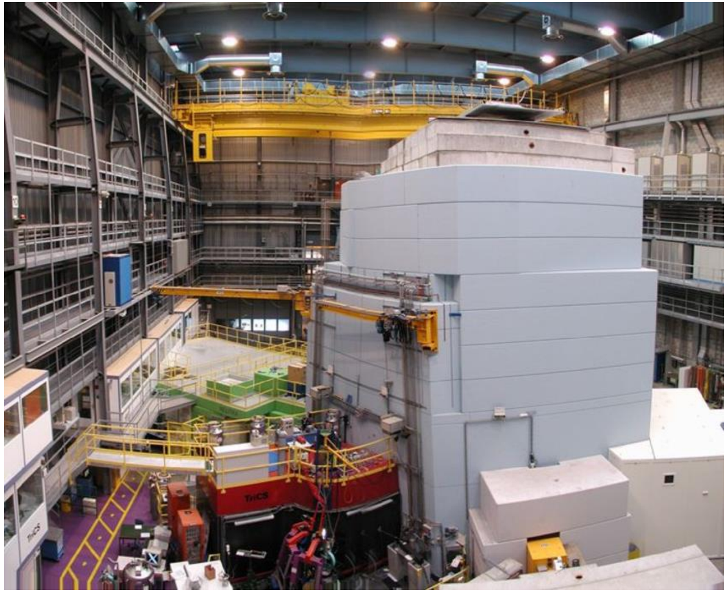


Principle:

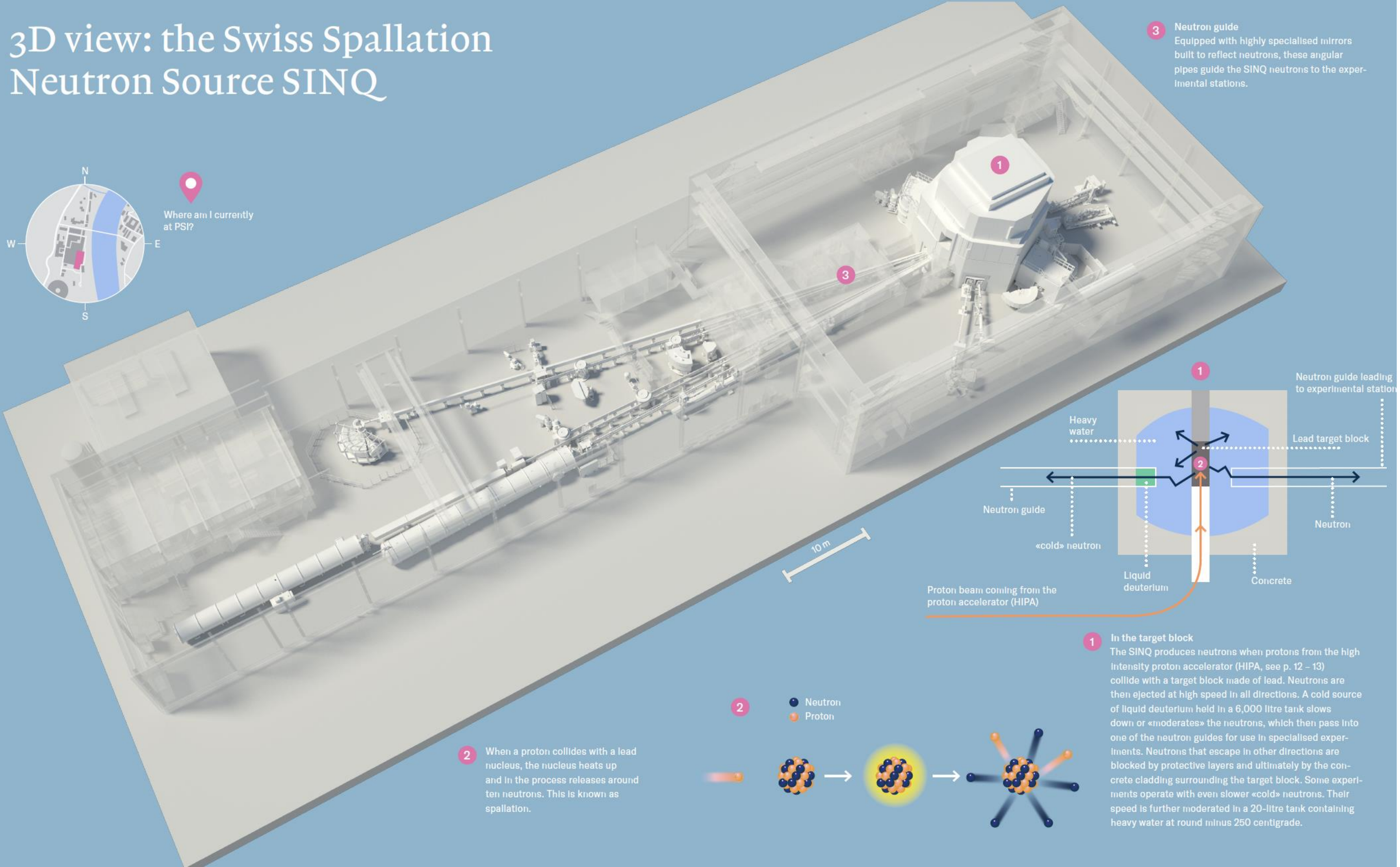


Spallation source example: Swiss Spallation Neutron Source SINQ

PAUL SCHERRER INSTITUT



3D view: the Swiss Spallation Neutron Source SINQ

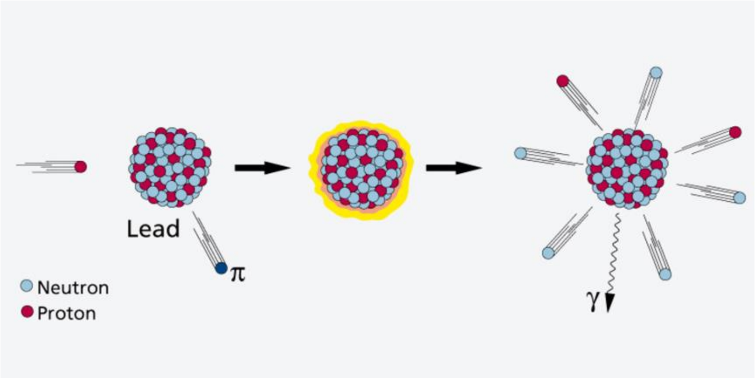


③ **Neutron guide**
Equipped with highly specialised mirrors built to reflect neutrons, these angular pipes guide the SINQ neutrons to the experimental stations.

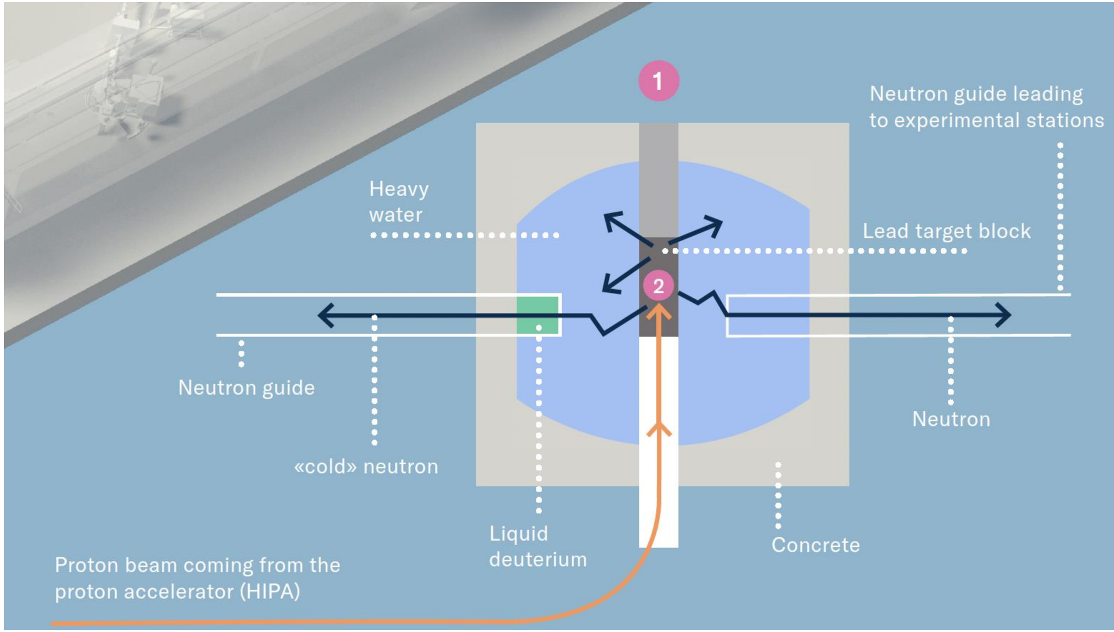
① **In the target block**
The SINQ produces neutrons when protons from the high intensity proton accelerator (HIPA, see p. 12 – 13) collide with a target block made of lead. Neutrons are then ejected at high speed in all directions. A cold source of liquid deuterium held in a 6,000 litre tank slows down or «moderates» the neutrons, which then pass into one of the neutron guides for use in specialised experiments. Neutrons that escape in other directions are blocked by protective layers and ultimately by the concrete cladding surrounding the target block. Some experiments operate with even slower «cold» neutrons. Their speed is further moderated in a 20-litre tank containing heavy water at round minus 250 centigrade.

② When a proton collides with a lead nucleus, the nucleus heats up and in the process releases around ten neutrons. This is known as spallation.

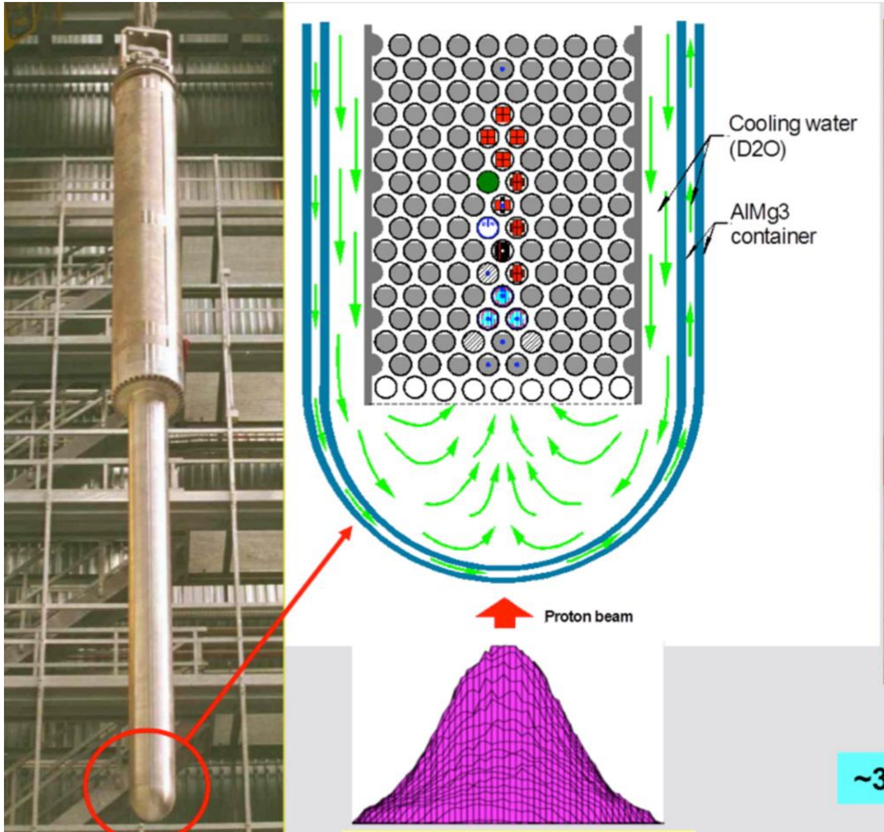
Spallation reaction on Pb nucleus



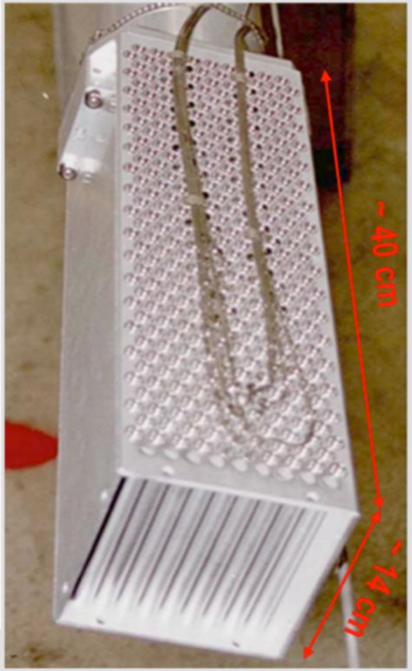
Proton energy at 590 MeV



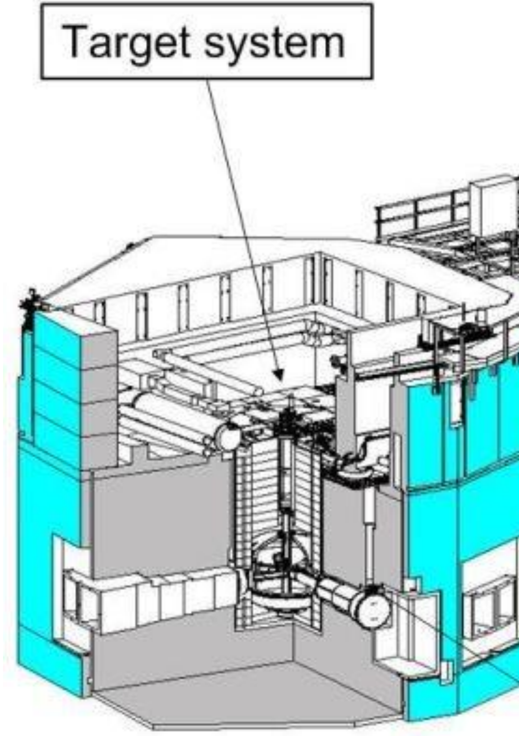
Spallation target



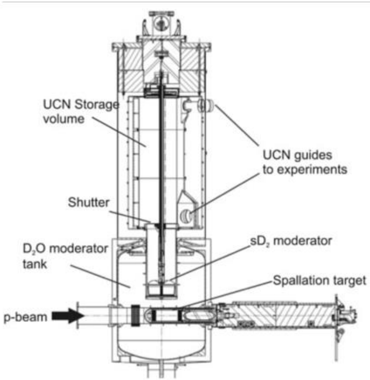
σ_x~3.5cm, σ_y~2cm



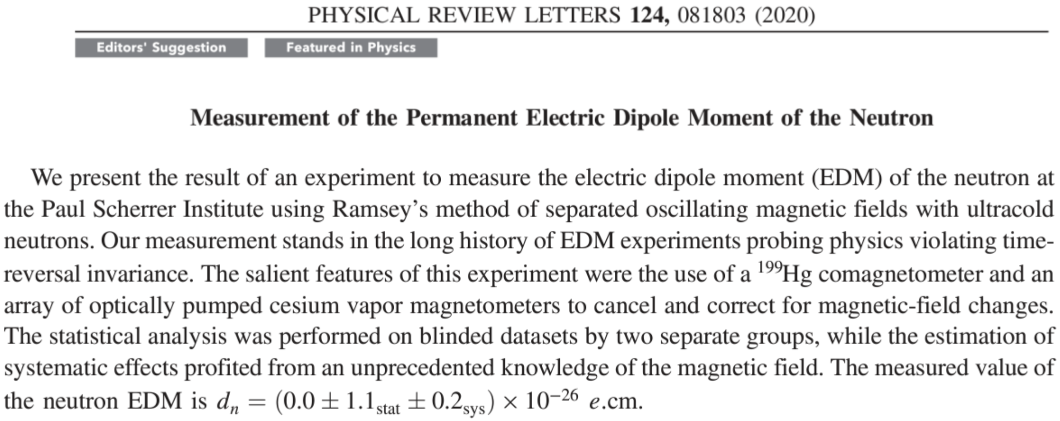
~360 Pb rods with SS / Zy-2 tubes



Application: Neutron science



Cold neutrons via scattering in solid D_2 at 5K
→E_{kin} < 500 neV

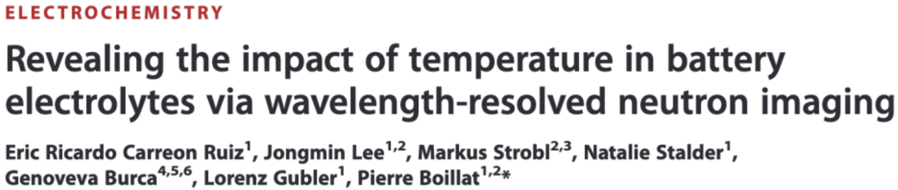

PHYSICAL REVIEW LETTERS **124,** 081803 (2020)

Editors' Suggestion   Featured in Physics

Measurement of the Permanent Electric Dipole Moment of the Neutron

We present the result of an experiment to measure the electric dipole moment (EDM) of the neutron at the Paul Scherrer Institute using Ramsey's method of separated oscillating magnetic fields with ultracold neutrons. Our measurement stands in the long history of EDM experiments probing physics violating time-reversal invariance. The salient features of this experiment were the use of a ^{199}Hg comagnetometer and an array of optically pumped cesium vapor magnetometers to cancel and correct for magnetic-field changes. The statistical analysis was performed on blinded datasets by two separate groups, while the estimation of systematic effects profited from an unprecedented knowledge of the magnetic field. The measured value of the neutron EDM is $d_n = (0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{sys}}) \times 10^{-26}\ e.\text{cm}$.

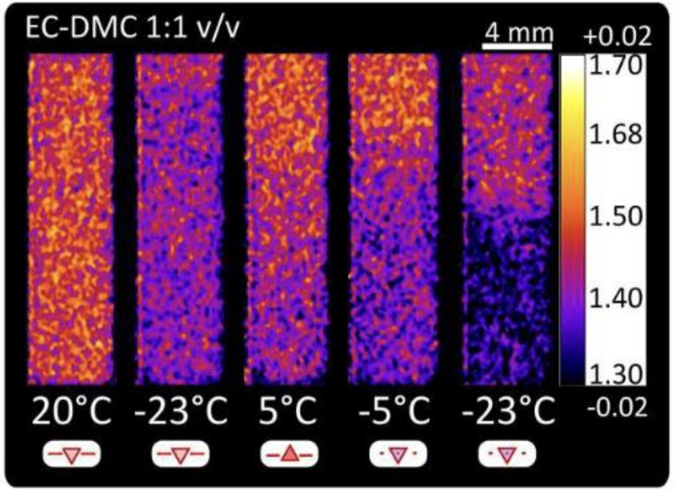
Applications: Neutron imaging and radiography



ELECTROCHEMISTRY

Revealing the impact of temperature in battery electrolytes via wavelength-resolved neutron imaging

Eric Ricardo Carreon Ruiz[1], Jongmin Lee[1,2], Markus Strobl[2,3], Natalie Stalder[1], Genoveva Burca[4,5,6], Lorenz Gubler[1], Pierre Boillat[1,2]*



Relative attenuation

Neutron radiography

5 min break

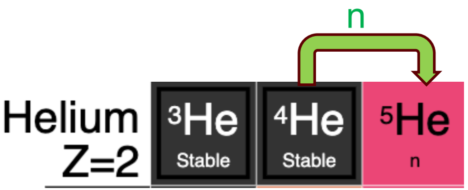
https://youtu.be/NnQdiDVOlvI

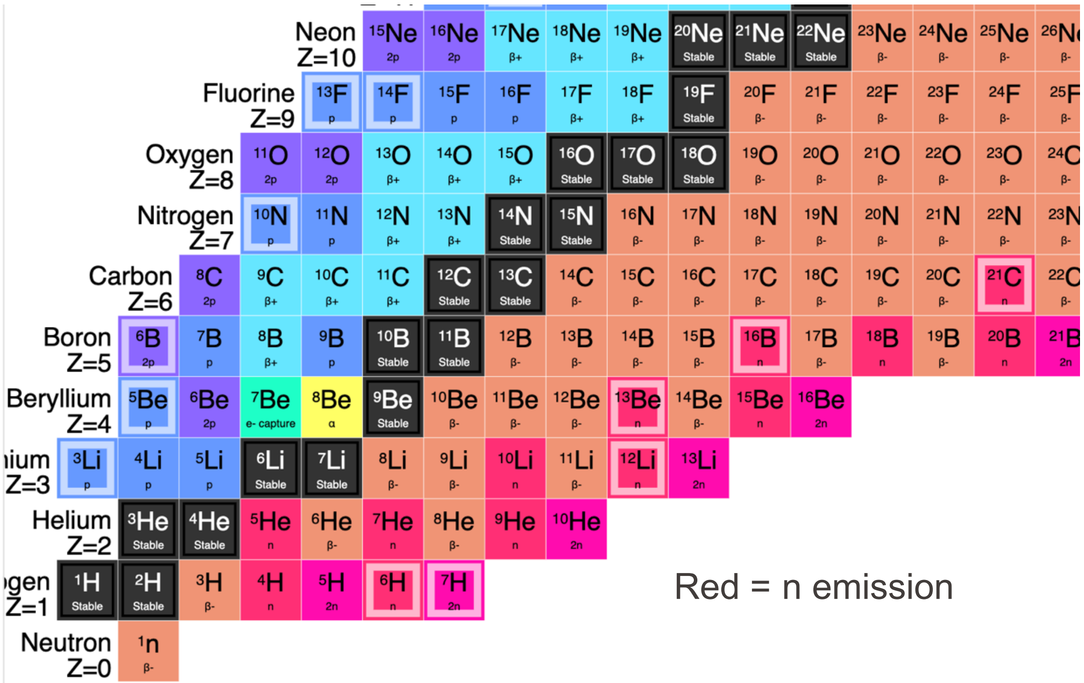
(Don’t brew coffee like that)

Small Neutron Sources: Overview

- Excitation levels with energies larger than the neutron binding energy are **not** produced as a result of any convenient radioactive decay process.
- Small neutron sources can be built based on:
  - Spontaneous Fission (SF).
  - (α,n) nuclear reactions.
  - Neutron ejection of a nucleus induced by gamma radiation (photoneutrons).
  - Photofission: Neutrons are produced when gamma rays with high enough energies cause heavy nuclei to fission.
  - Fusion reactions of deuterium and/or tritium ions (neutron generator)

But wait…





Neon Z=10						^{15}Ne 2p	^{16}Ne 2p	^{17}Ne β+	^{18}Ne β+	^{19}Ne β+	^{20}Ne Stable	^{21}Ne Stable	^{22}Ne Stable	^{23}Ne β-	^{24}Ne β-	^{25}Ne β-	^{26}N β-
Fluorine Z=9					^{13}F p	^{14}F p	^{15}F p	^{16}F p	^{17}F β+	^{18}F β+	^{19}F Stable	^{20}F β-	^{21}F β-	^{22}F β-	^{23}F β-	^{24}F β-	^{25}F β-
Oxygen Z=8				^{11}O 2p	^{12}O 2p	^{13}O β+	^{14}O β+	^{15}O β+	^{16}O Stable	^{17}O Stable	^{18}O Stable	^{19}O β-	^{20}O β-	^{21}O β-	^{22}O β-	^{23}O β-	^{24}C β-
Nitrogen Z=7				^{10}N p	^{11}N p	^{12}N β+	^{13}N β+	^{14}N Stable	^{15}N Stable	^{16}N β-	^{17}N β-	^{18}N β-	^{19}N β-	^{20}N β-	^{21}N β-	^{22}N β-	^{23}N β-
Carbon Z=6			^{8}C 2p	^{9}C β+	^{10}C β+	^{11}C β+	^{12}C Stable	^{13}C Stable	^{14}C β-	^{15}C β-	^{16}C β-	^{17}C β-	^{18}C β-	^{19}C β-	^{20}C β-	^{21}C n	^{22}C β-
Boron Z=5		^{6}B 2p	^{7}B p	^{8}B β+	^{9}B p	^{10}B Stable	^{11}B Stable	^{12}B β-	^{13}B β-	^{14}B β-	^{15}B β-	^{16}B n	^{17}B β-	^{18}B n	^{19}B β-	^{20}B n	^{21}B 2n
Beryllium Z=4		^{5}Be p	^{6}Be 2p	^{7}Be e- capture	^{8}Be α	^{9}Be Stable	^{10}Be β-	^{11}Be β-	^{12}Be β-	^{13}Be n	^{14}Be β-	^{15}Be n	^{16}Be 2n				
ium Z=3	^{3}Li p	^{4}Li p	^{5}Li p	^{6}Li Stable	^{7}Li Stable	^{8}Li β-	^{9}Li β-	^{10}Li n	^{11}Li β-	^{12}Li n	^{13}Li 2n						
Helium Z=2		^{3}He Stable	^{4}He Stable	^{5}He n	^{6}He β-	^{7}He n	^{8}He β-	^{9}He n	^{10}He 2n								
gen Z=1	^{1}H Stable	^{2}H Stable	^{3}H β-	^{4}H n	^{5}H 2n	^{6}H n	^{7}H 2n										
Neutron Z=0		^{1}n β-															

Red = n emission

However:

Helium-5 (Z=2, N=3)

Discovered 1937 [5]

$t_{1/2}$ = 602±22 ys [5]

yocto = 10^{-24}

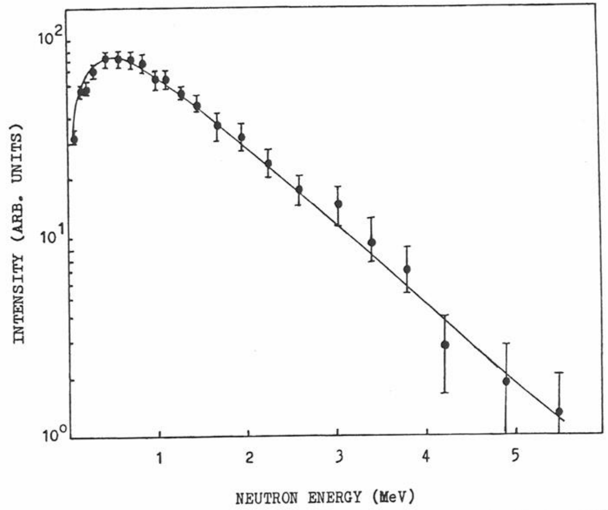
Neutron Sources: Spontaneous Fission (SF) (1)

- ☐ SF appears in many of the transuranic heavy nuclides (Z>92).
- ☐ It produces:
  - Several fast neutrons.
  - Heavy fission products.
  - Prompt fission γ-rays (in ns).
  - β and γ activity of the fission products.
- ☐ The neutron energy spectrum is peaked between 0.5 and 1 MeV and can be approximated by:

$$\boxed{\frac{dN}{dE} = E^{1/2}\, e^{-E/T}}$$

Spontaneous fission rates

U-235	5.60E-03 *f*/s-kg
U-238	6.93 *f*/s-kg
Pu-239	7.01 *f*/s-kg
Pu-240	489,000 *f*/s-kg



Measured neutron energy spectrum from the spontaneous fission of ^{252}Cf. (From Batenkov et al.[18])

Neutron Sources: Spontaneous Fission (SF) (2)

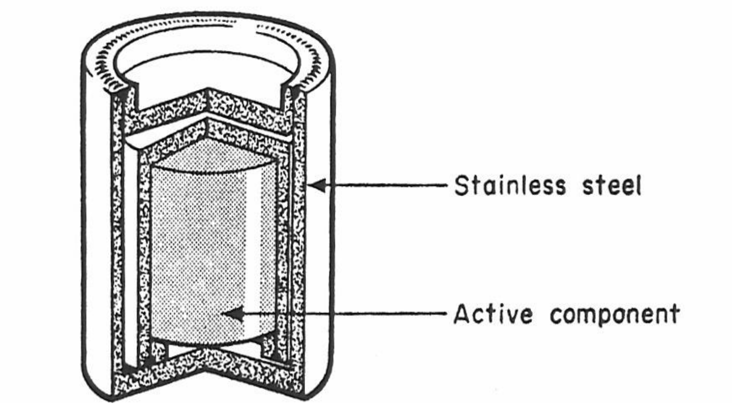
- ☐ The most common SF source is ^{252}Cf (Z=98).
- ☐ Characteristics:
  - **2.6 year half-life**
  - Dominant decay mechanism is α-decay
  - **Extremely radioactive** (1 mg spontaneously emits 170 million neutrons per minute)
- ☐ Produced in nuclear reactors: from irradiation of Cm with α-particles (but how to produce Cm?)
- ☐ ^{252}Cf neutron sources are typically 1/4" to 1/2" in diameter and 1" to 2" in length. The price of a typical ^{252}Cf neutron source : $50,000.
- ☐ Some uses of the ^{252}Cf sources:
  - Neutron start-up source for some nuclear reactors, calibrating instrumentation.
  - Treatment of certain cervical and brain cancers where other radiation therapies are ineffective.
  - Radiography of aircraft to detect metal fatigue.
  - Airport neutron-activation detectors of explosives.
  - Neutron moisture gauges used to find water and petroleum layers in oil wells.
  - Portable neutron source in gold and silver prospecting for on-the-spot analysis.

Neutron Sources: (α,n) Sources (1)

- ❑ Neutrons are produced in (α,n)-reactions.
  - The source of α is a radioisotope.
  - Self-contained sources have a mixture of an α-emitter and a target material.
  - The maximum neutron yield comes from ^{9}Be as a target material.
- ❑ Sources of (α,n) neutrons:
  - All α-emitters are actinides: ^{239}Pu, ^{210}Po, ^{241}Am, ^{244}Cm, ^{226}Ra, etc.
  - Most α-particles are absorbed in the target, only 1 in 10^4 reacts with Be.
  - They form stable alloy of the form MBe_{13} (M=actinide metal), with no intermediate loss of energy for the α-particle.

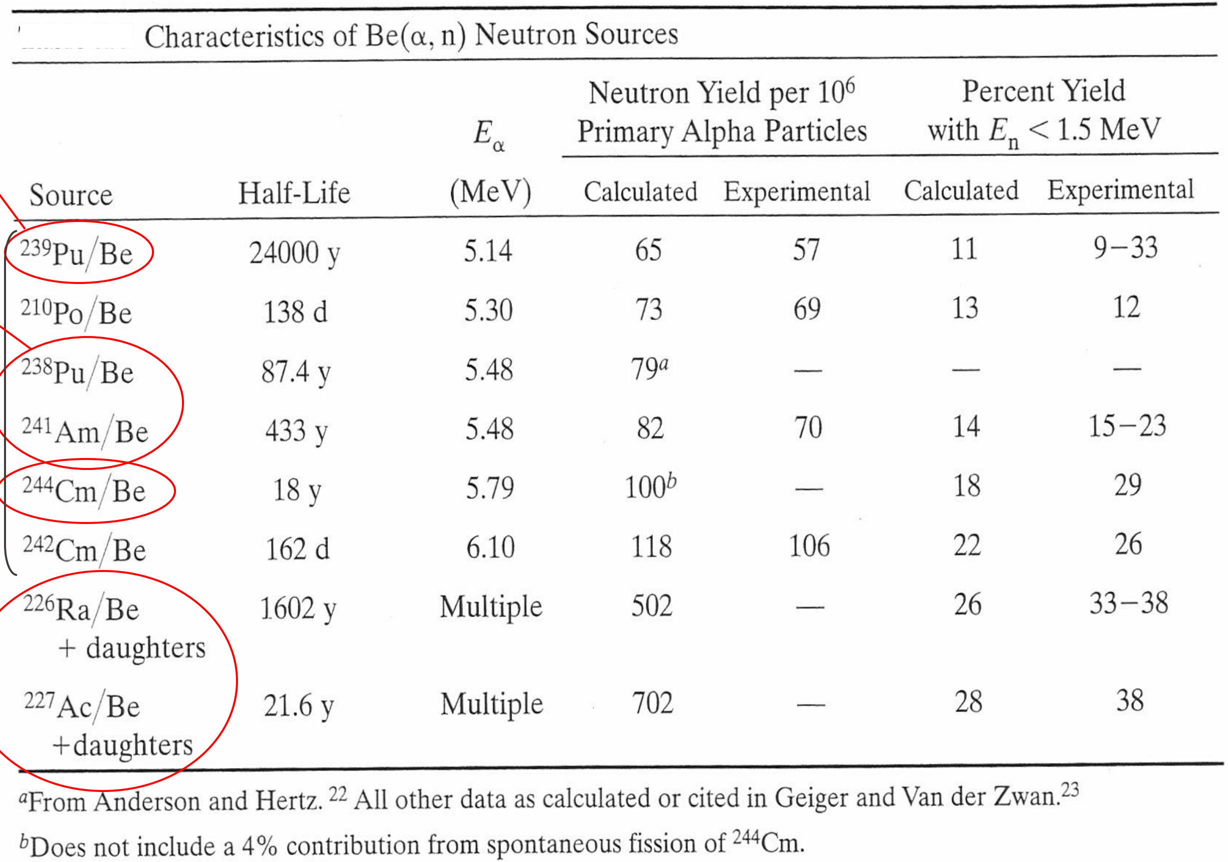
Basic reaction for Be neutron sources:

$$\boxed{{}^{4}_{2}\alpha + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C}^{*} + {}^{1}_{0}\mathrm{n} \xrightarrow{61\,\mathrm{fs}} {}^{12}_{6}\mathrm{C} + \gamma\,(4.44\,\mathrm{MeV})}$$



Typical double-walled Be(α,n) source

Neutron Sources: (α,n) Sources (2)



Characteristics of Be(α, n) Neutron Sources

Source	Half-Life	E_α (MeV)	Neutron Yield per 10^6 Primary Alpha Particles: Calculated	Neutron Yield per 10^6 Primary Alpha Particles: Experimental	Percent Yield with $E_n < 1.5$ MeV: Calculated	Percent Yield with $E_n < 1.5$ MeV: Experimental
^{239}Pu/Be	24000 y	5.14	65	57	11	9–33
^{210}Po/Be	138 d	5.30	73	69	13	12
^{238}Pu/Be	87.4 y	5.48	79[a]	—	—	—
^{241}Am/Be	433 y	5.48	82	70	14	15–23
^{244}Cm/Be	18 y	5.79	100[b]	—	18	29
^{242}Cm/Be	162 d	6.10	118	106	22	26
^{226}Ra/Be + daughters	1602 y	Multiple	502	—	26	33–38
^{227}Ac/Be +daughters	21.6 y	Multiple	702	—	28	38

[a] From Anderson and Hertz.[22] All other data as calculated or cited in Geiger and Van der Zwan.[23]

[b] Does not include a 4% contribution from spontaneous fission of ^{244}Cm.

Most widely used

High n yields, high specific activity

Low γ background, simple α decay process.

Ideal

Intense γ background radiation from daughters

Neutron Sources: (α,n) Sources (3)

- Energy spectra of all sources with ^{9}Be are similar.
  - Differences reflect the small variations in the primary α-particle energies.
  - Thick sources have more „spread“, i.e, the originally discrete α-energy spectrum is washed out.

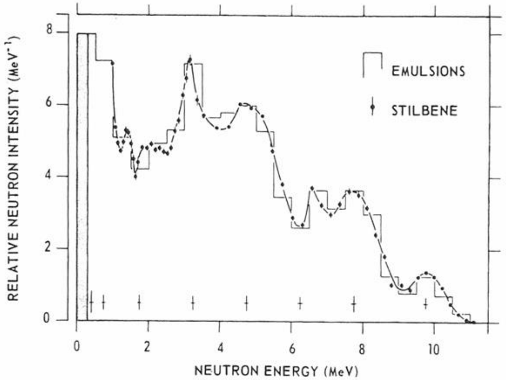
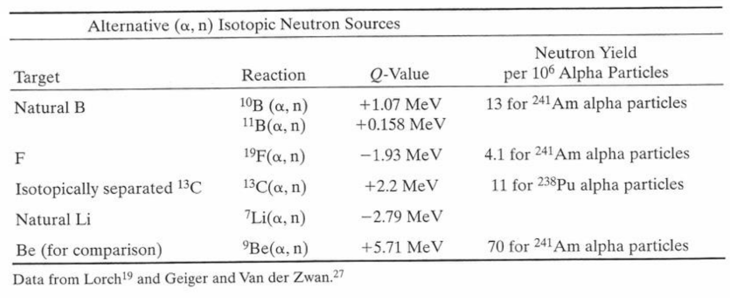


Figure 1.12 Measured energy spectra for neutrons from a ^{239}Pu/Be source containing 80 g of the isotope. (From Anderson and Neff.[25])

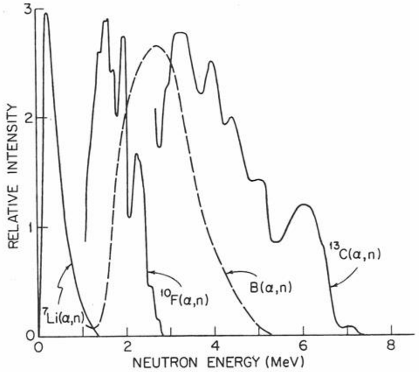
Additonal sources of (α,n)



Alternative (α, n) Isotopic Neutron Sources

Target	Reaction	*Q*-Value	Neutron Yield per 10^6 Alpha Particles
Natural B	^{10}B (α, n) ^{11}B(α, n)	+1.07 MeV +0.158 MeV	13 for ^{241}Am alpha particles
F	^{19}F(α, n)	−1.93 MeV	4.1 for ^{241}Am alpha particles
Isotopically separated ^{13}C	^{13}C(α, n)	+2.2 MeV	11 for ^{238}Pu alpha particles
Natural Li	^{7}Li(α, n)	−2.79 MeV	
Be (for comparison)	^{9}Be(α, n)	+5.71 MeV	70 for ^{241}Am alpha particles

Data from Lorch[19] and Geiger and Van der Zwan.[27]



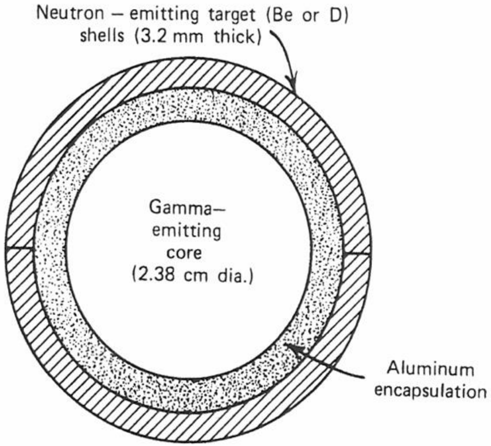
Neutron energy spectra from alternative (α, n) sources. (^{7}Li data from Geiger and Van der Zwan,[27] remainder from Lorch.[19])

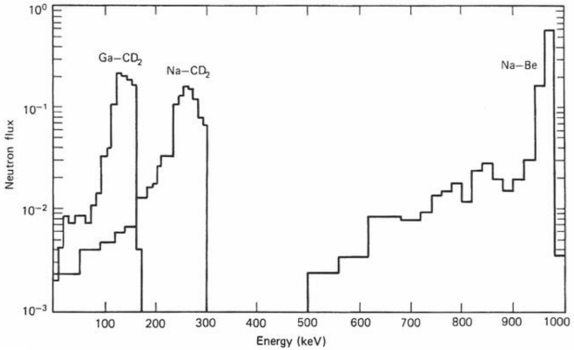
Neutron Sources: Photoneutrons (1)

- Excitation of the nucleus by high energy γ-rays:
  - Photoneutron sources combine a powerful γ-emitter with a target isotope.
  - Only two target nuclei are practical: ^{9}Be and ^{2}H:

$$\begin{aligned} {}^{9}_{4}Be + \gamma &\longrightarrow {}^{8}_{4}Be + {}^{1}_{0}n \qquad -1.666\text{MeV} \\ {}^{2}_{1}H + \gamma &\longrightarrow {}^{1}_{1}H + {}^{1}_{0}n \qquad -2.226\text{MeV} \end{aligned}$$

  - Photoneutron sources produce monoenergetic neutrons (for monoenergetic gammas).
  - They need very large γ-ray activities (1 out of 10^5-10^6 photons produces 1 n).
  - Common emitters are: ^{226}Ra, ^{124}Sb, ^{72}Ga, ^{140}La, ^{24}Na.
  - Very short half-lives require reactivation in a nuclear reactor between uses.
  - Alternative: e^- accelerator + target

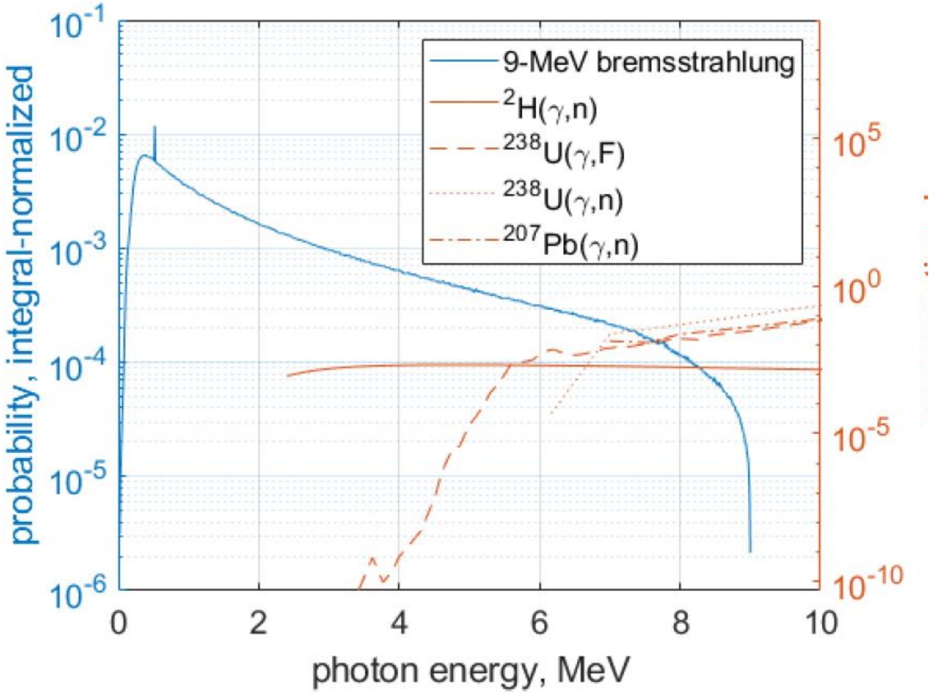




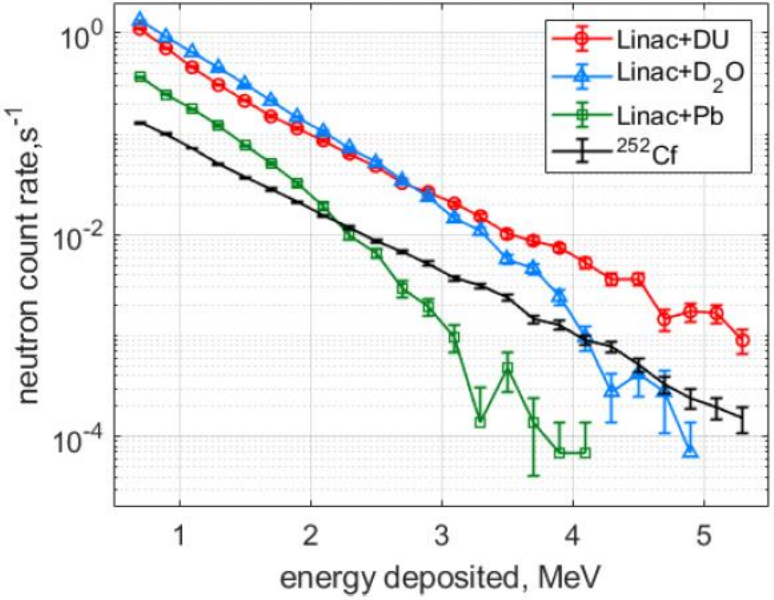
Neutron spectra calculated for the photoneutron source dimensions shown in Fig. 1.15. The gamma emitters are either ^{72}Ga or ^{24}Na. The outer shells are either deuterated polyethylene (CD$_2$) or beryllium (Be).

Linear accelerator (linac) + photoneutron target

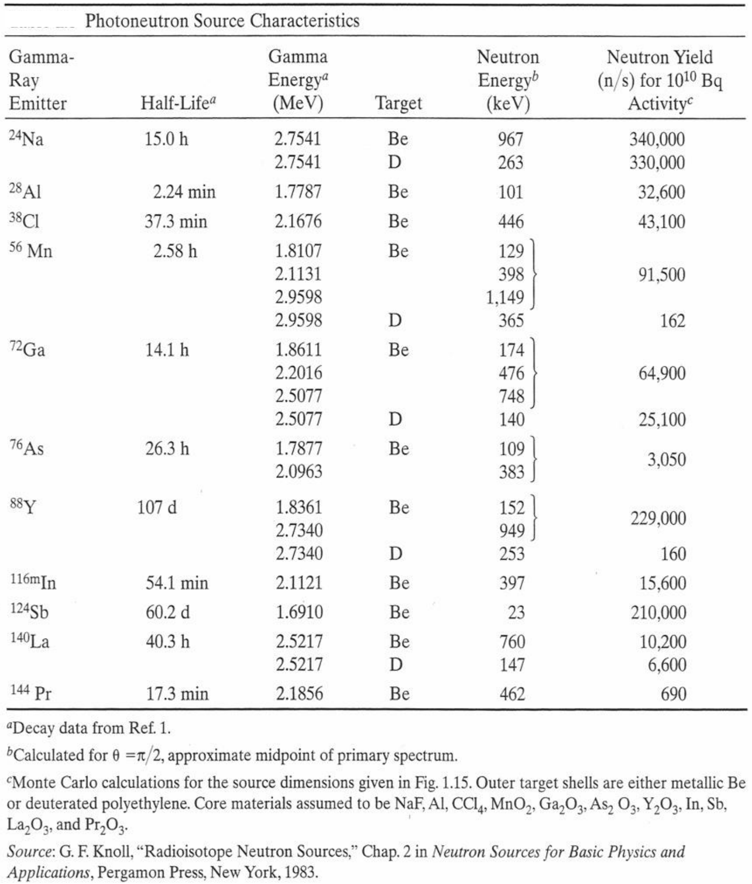
Cross sections for neutron production (orange)
Vs. linac Xray spectrum (blue)



Measured neutron energies for
different targets and sources
DU = depleted uranium



Neutron Sources: Photoneutrons (2)



Photoneutron Source Characteristics

Gamma-Ray Emitter	Half-Life[a]	Gamma Energy[a] (MeV)	Target	Neutron Energy[b] (keV)	Neutron Yield (n/s) for 10^{10} Bq Activity[c]
^{24}Na	15.0 h	2.7541	Be	967	340,000
		2.7541	D	263	330,000
^{28}Al	2.24 min	1.7787	Be	101	32,600
^{38}Cl	37.3 min	2.1676	Be	446	43,100
^{56}Mn	2.58 h	1.8107	Be	129	91,500
		2.1131		398	
		2.9598		1,149	
		2.9598	D	365	162
^{72}Ga	14.1 h	1.8611	Be	174	64,900
		2.2016		476	
		2.5077		748	
		2.5077	D	140	25,100
^{76}As	26.3 h	1.7877	Be	109	3,050
		2.0963		383	
^{88}Y	107 d	1.8361	Be	152	229,000
		2.7340		949	
		2.7340	D	253	160
^{116m}In	54.1 min	2.1121	Be	397	15,600
^{124}Sb	60.2 d	1.6910	Be	23	210,000
^{140}La	40.3 h	2.5217	Be	760	10,200
		2.5217	D	147	6,600
^{144}Pr	17.3 min	2.1856	Be	462	690

[a] Decay data from Ref. 1.

[b] Calculated for $\theta = \pi/2$, approximate midpoint of primary spectrum.

[c] Monte Carlo calculations for the source dimensions given in Fig. 1.15. Outer target shells are either metallic Be or deuterated polyethylene. Core materials assumed to be NaF, Al, CCl_4, MnO_2, Ga_2O_3, As_2O_3, Y_2O_3, In, Sb, La_2O_3, and Pr_2O_3.

Source: G. F. Knoll, "Radioisotope Neutron Sources," Chap. 2 in *Neutron Sources for Basic Physics and Applications*, Pergamon Press, New York, 1983.

Neutron Sources: Accelerated Charged Particles

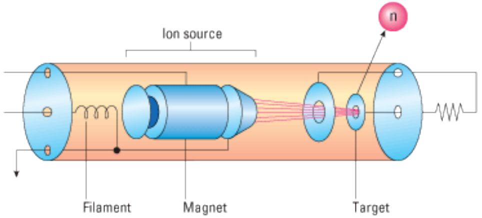
- Two of the most common reactions (with their Q-values) are fusion reactions:

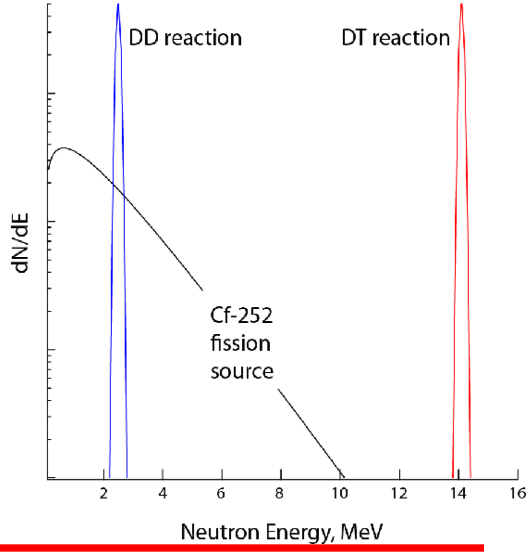
$$D + T \rightarrow n + {}^{4}He \qquad E_n = 14.1\ \text{MeV}$$

$$D + D \rightarrow n + {}^{3}He \qquad E_n = 2.5\ \text{MeV}$$

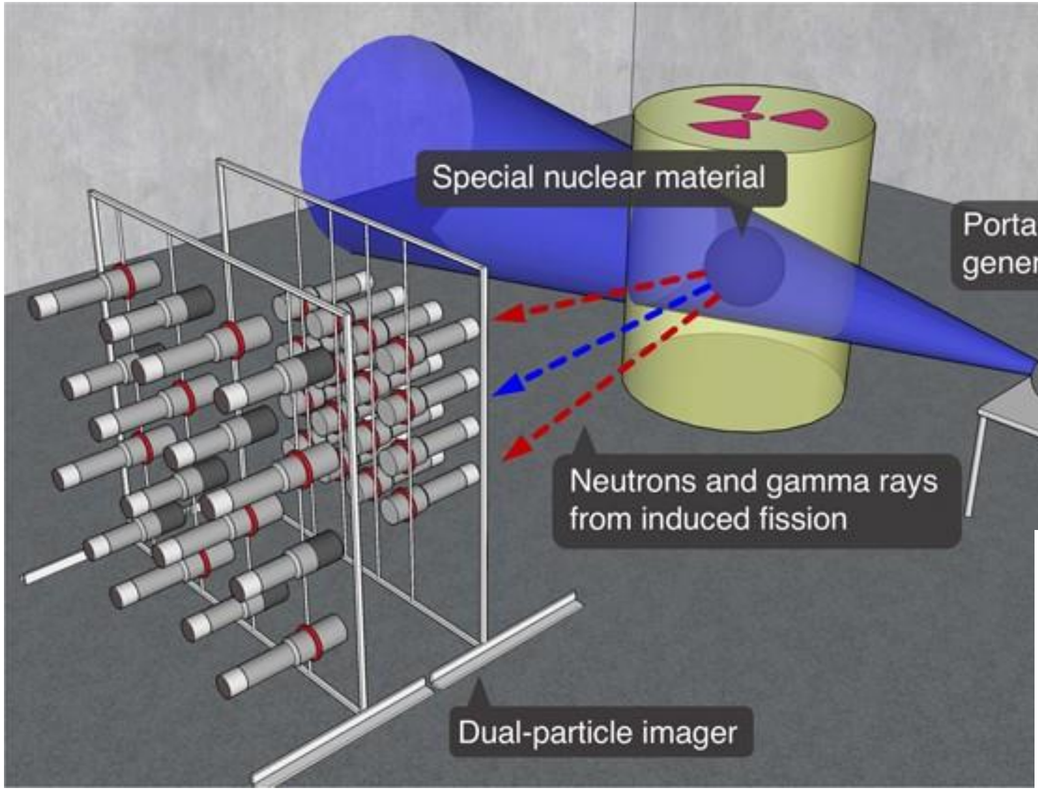
- Characteristics of the sources:
  - Low coulomb barrier (low Z target) requires accelerating potentials of 100-300 kV for the charged particles.
  - All neutrons mono-energetic
  - Typical yields: 1 mA ^{2}H beam will produce 10^{9} n/s for ^{2}H and 10^{11} n/s for ^{3}H targets → compact, portable source
  - Other reactions $^{9}Be(d,n)$, $^{7}Li(p,n)$ and $^{3}H(p,n)$ require large accelerators $(Q < 0)$.

Neutron generator



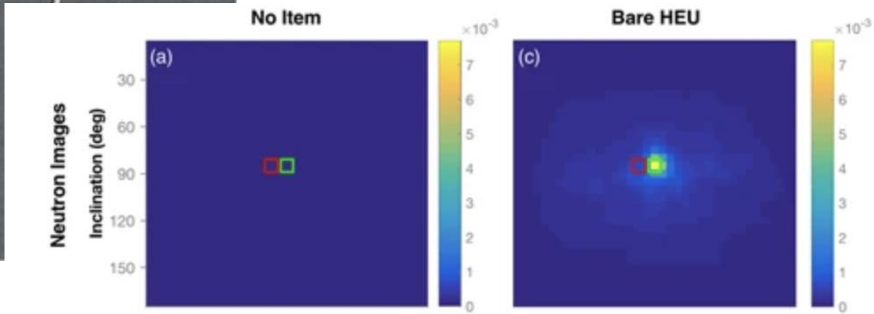


Neutron generator application: Nuclear security

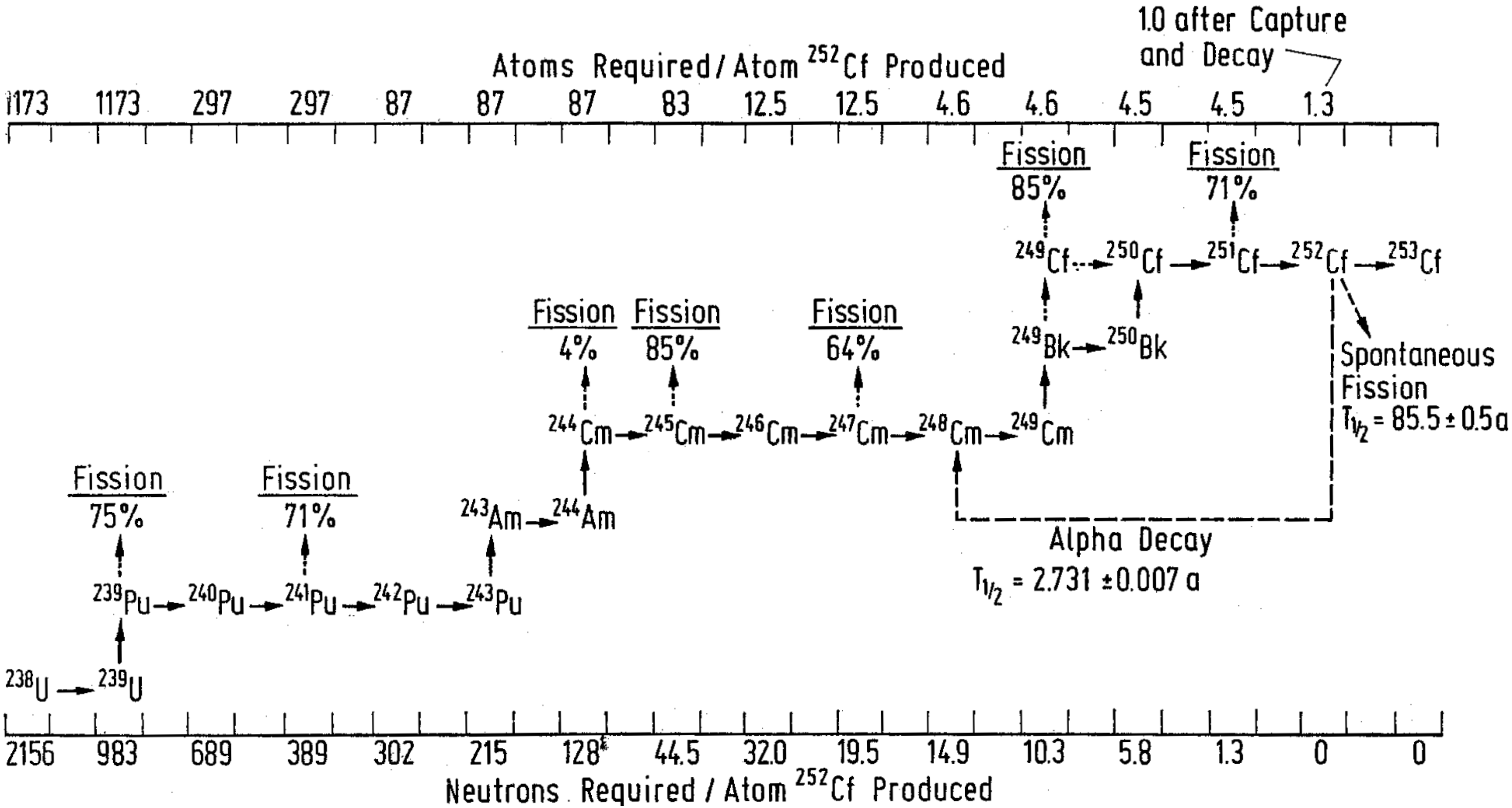


Active neutron and gamma-ray imaging of highly enriched uranium for treaty verification

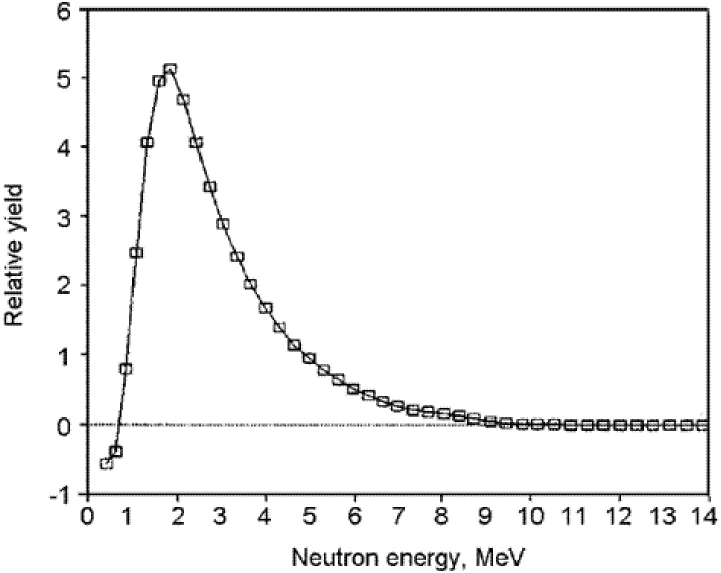
Michael C. Hamel, J. Kyle Polack, Marc L. Ruch, Matthew J. Marcath, Shaun D. Clarke & Sara A. Pozzi



^{252}Cf production in a reactor



^{252}Cf properties



Neutron energy spectrum from ^{252}Cf sf

Californium-252 (Z=98, N=154)

Discovered 1954 [5]

$t_{1/2}$ = 2.645±0.008 y [5]

$J^{\pi} = 0^{+}$ [5]

Decay modes

α = 96.9% [5]

Spontaneous fission = 3.10% [5]

https://people.physics.anu.edu.au/~ecs103/chart/

Uranium-235 (Z=92, N=143)

Discovered 1935 [5]

Natural abundance 0.7204% [5]

$t_{1/2}$ = 704±1 My [5]

$J^{\pi} = 7/2^{-}$ [5]

Decay modes

α = 100% [5]

Spontaneous fission = 7.00e-9% [5]

20Ne = 8.00e-10% [5]

25Ne ~ 8.00e-10% [5]

28Mg = 8.00e-10% [5]

Uranium-238 (Z=92, N=146)

Discovered 1896 [5]

Natural abundance 99.2742% [5]

$t_{1/2}$ = 4.463±0.003 Gy [5]

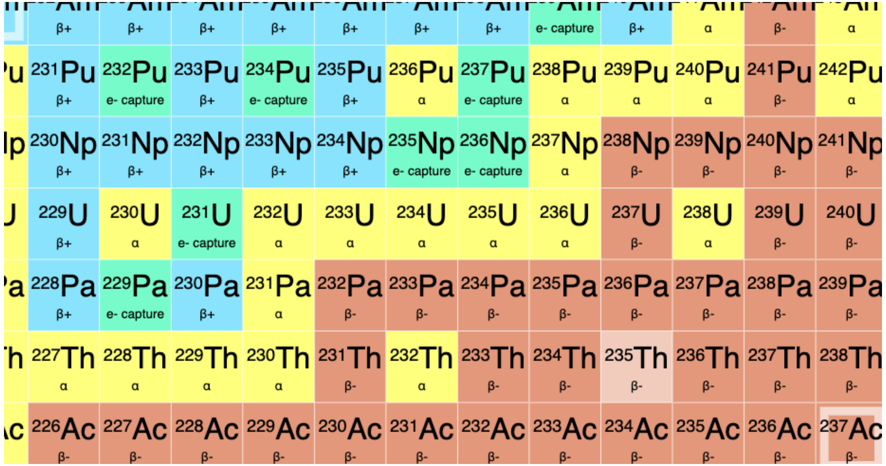
$J^{\pi} = 0^{+}$ [5]

Decay modes

α = 100% [5]

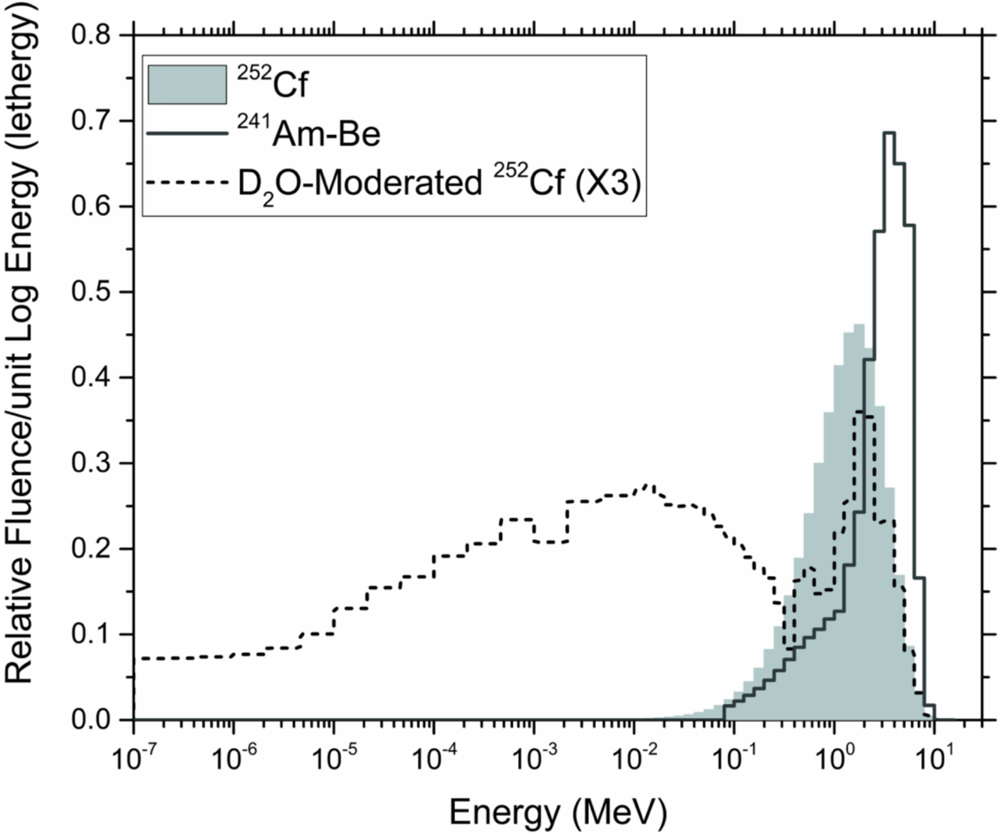
Spontaneous fission = 0.0000544% [5]

$2\beta^{-}$ = 2.20e-10% [5]



β+	β+	β+	β+	β+	β+	β+	e- capture	β+	α	β-	α
^{231}Pu β+	^{232}Pu e- capture	^{233}Pu β+	^{234}Pu e- capture	^{235}Pu β+	^{236}Pu α	^{237}Pu e- capture	^{238}Pu α	^{239}Pu α	^{240}Pu α	^{241}Pu β-	^{242}Pu α
^{230}Np β+	^{231}Np β+	^{232}Np β+	^{233}Np β+	^{234}Np β+	^{235}Np e- capture	^{236}Np e- capture	^{237}Np α	^{238}Np β-	^{239}Np β-	^{240}Np β-	^{241}Np β-
^{229}U β+	^{230}U α	^{231}U e- capture	^{232}U α	^{233}U α	^{234}U α	^{235}U α	^{236}U α	^{237}U β-	^{238}U α	^{239}U β-	^{240}U β-
^{228}Pa β+	^{229}Pa e- capture	^{230}Pa β+	^{231}Pa α	^{232}Pa β-	^{233}Pa β-	^{234}Pa β-	^{235}Pa β-	^{236}Pa β-	^{237}Pa β-	^{238}Pa β-	^{239}Pa β-
^{227}Th α	^{228}Th α	^{229}Th α	^{230}Th α	^{231}Th β-	^{232}Th α	^{233}Th β-	^{234}Th β-	^{235}Th β-	^{236}Th β-	^{237}Th β-	^{238}Th β-
^{226}Ac β-	^{227}Ac β-	^{228}Ac β-	^{229}Ac β-	^{230}Ac β-	^{231}Ac β-	^{232}Ac β-	^{233}Ac β-	^{234}Ac β-	^{235}Ac β-	^{236}Ac β-	^{237}Ac β-

Comparison of neutron source spectra for detector calibration



Beyond Californium – A Neutron Generator Alternative for Dosimetry and Instrument Calibration in the U.S.

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Table 1

Overview of Neutron Calibration Sources and Properties

Neutron source (type)	Radionuclide half-life (years)	Number of sources needed for 15 years[a]	Relative neutron intensity of individual source[a]	Radionuclide nominal specific neutron intensity (s^{-1} g^{-1})	Nominal mass of radionuclide needed for 10^9 s^{-1} source (g)
DD (NG)	n/a	3-5	1.000	n/a	n/a
DT (NG) [b]	12.3	3-5	1.147-1.087	2.28×10^{13}	0.00004
^{252}Cf (SF)	2.645	2	2.285	2.31×10^{12}	0.0004
^{210}PoBe (α,n)	0.378	13	2.409	1.08×10^{10}	0.1
^{244}CmBe (α,n)	18.1	1	1.315	2.06×10^{8}	5
^{238}PuBe (α,n)	87.74	1	1.060	4.12×10^{7}	24
^{248}Cm (SF)	348000	1	1.000	3.94×10^{7}	25
^{226}RaBe (α,n)	1620	1	1.003	1.27×10^{7}	79
^{244}Cm (SF)	18.1	1	1.315	1.11×10^{7}	90
^{241}AmBe (α,n)	433.6	1	1.012	8.23×10^{6}	122
^{239}PuBe (α,n)	24100	1	1.000	1.49×10^{5}	6700

Literature

- Glenn F. Knoll, *“Radiation Detection and Measurement”*, John Wiley & Sons (4th edition, 2010, and 3rd edition, 2000)
- James E. Martin, *“Physics for Radiation Protection”*, Wiley-VCH (2nd edition, 2006)
- James E. Turner, *“Atoms, Radiation, and Radiation Protection”*, Wiley-VCH (3rd edition, 2007)