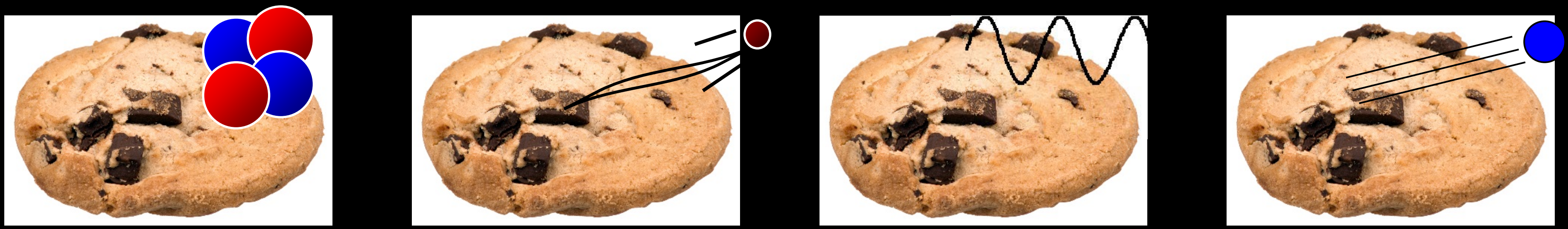
Radiation Basics

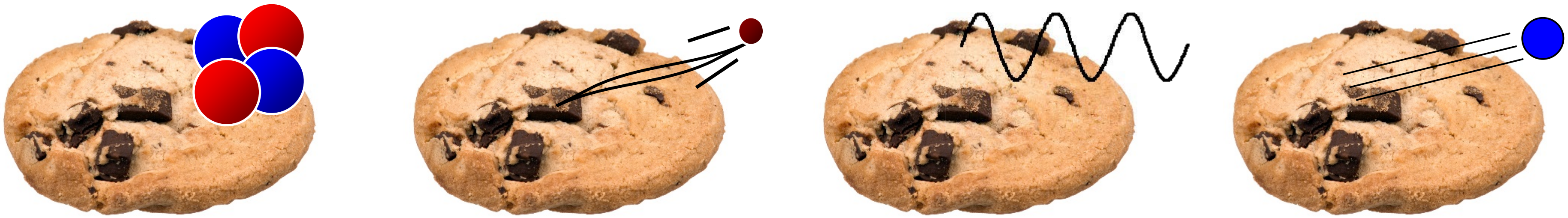


Cookie photo: Public domain.

22.S902 – DIY Geiger Counters
Prof. Michael Short

Old 22.01 Final Exam Question

- You have four highly radioactive cookies:



α **β** **γ** **n**

- You must:

  Put one in your pocket
  Hold one in your hand
  Eat one
  Give one to a "friend"

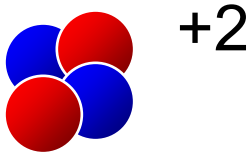
- What do you do?

Motivation

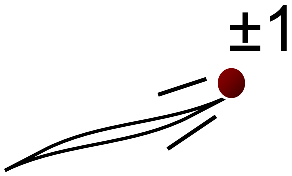
- Introduce ionizing radiation basics
- Establish common notation and terminology
- Understand types of radiation
- Intuitively understand range of radiation
- Derive and use nuclear reaction equations, half lives of common isotopes

Types of Ionizing Radiation

- Alpha (α) – Helium nucleus
  - Heavy, charged

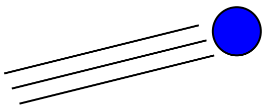


- Beta (β) – A free electron or positron
  - Light, charged



- Gamma (γ) – A nuclear photon (light)
  - No mass, no charge

- Neutron (n) – A free neutron
  - Heavy, no charge



Ranges of Ionizing Radiation

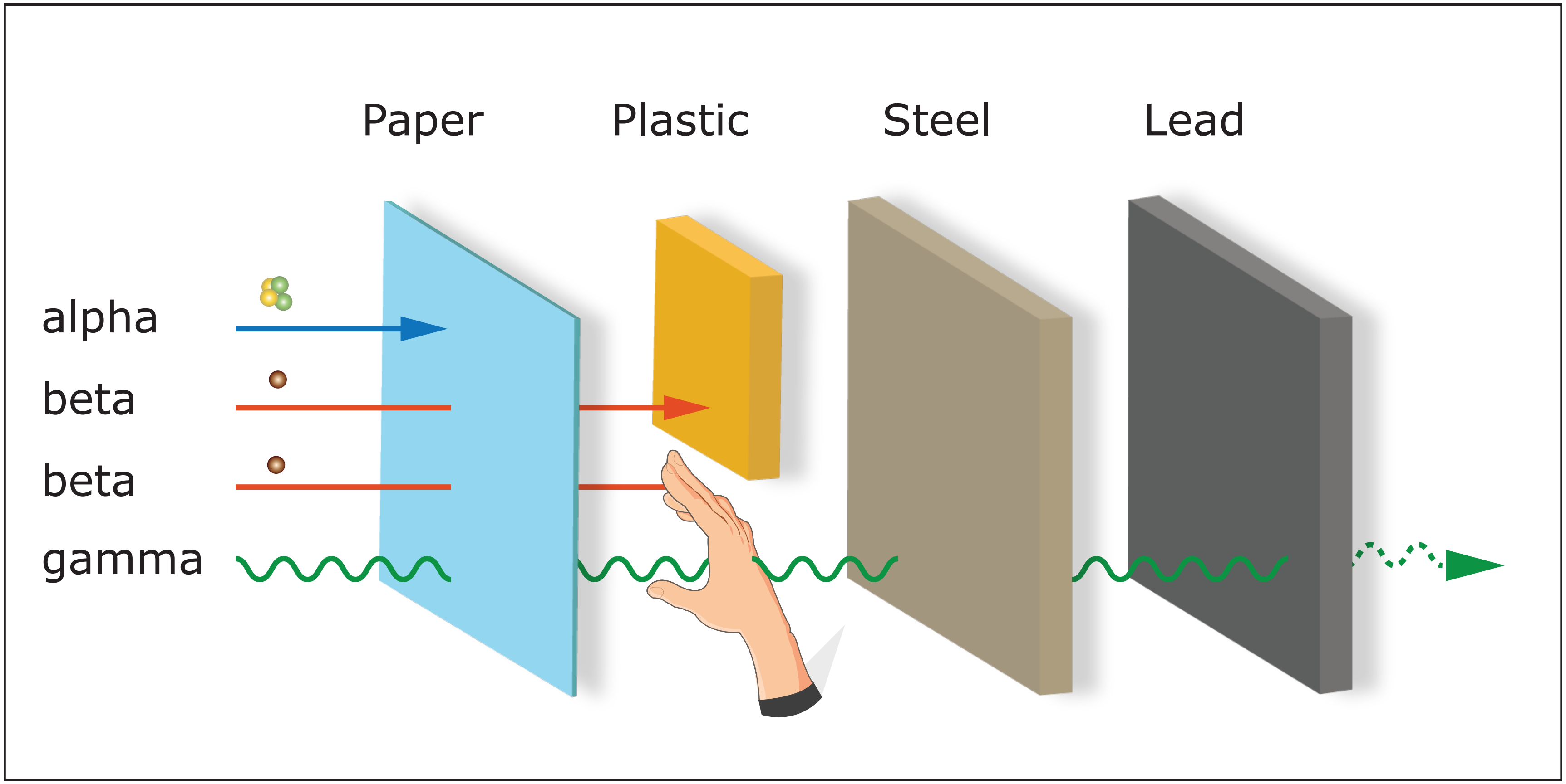
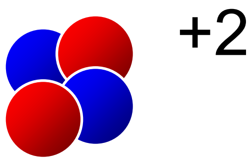


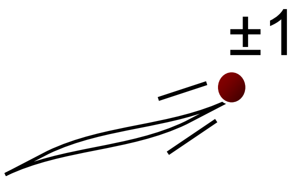
Image by MIT OpenCourseWare.

Relative Energy Deposition

Which do you think deposits the most energy?

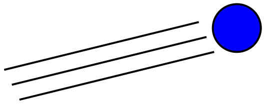


Where? (Over what range?)



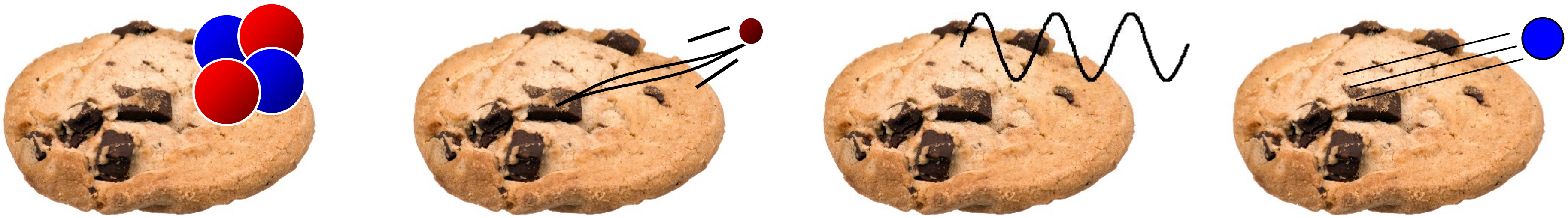
Which type(s) is/are safer outside the body?

Which type(s) is/are safer inside the body?



Old 22.01 Final Exam Question

- You have four highly radioactive cookies:



α β γ n

- You must:

  Put one in your pocket | Hold one in your hand

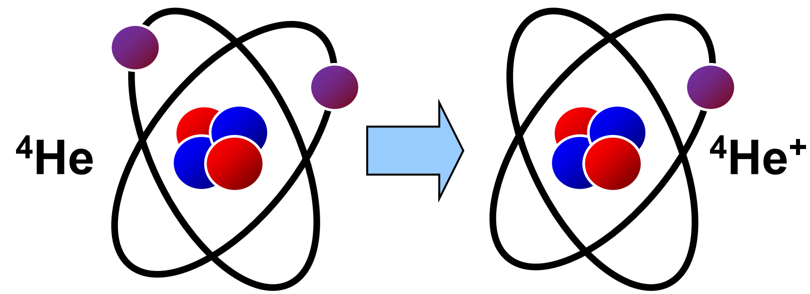
  Eat one | Give one to a "friend"

- What do you do?

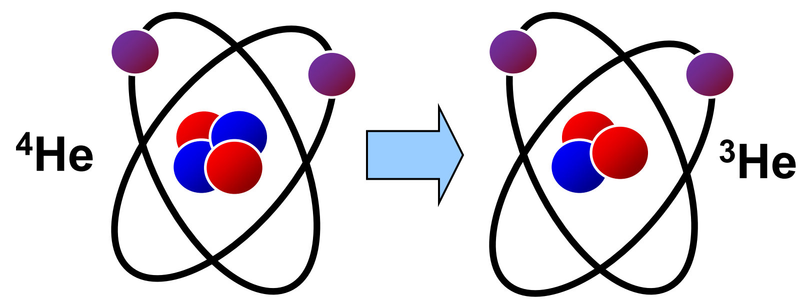
Ions, Isotopes

- Atoms are determined by the number of *protons*
  - Example: Helium ALWAYS has two protons

- Two special types:
  - **Ion**
    - **Same # protons** & neutrons
    - Different # electrons (charge)

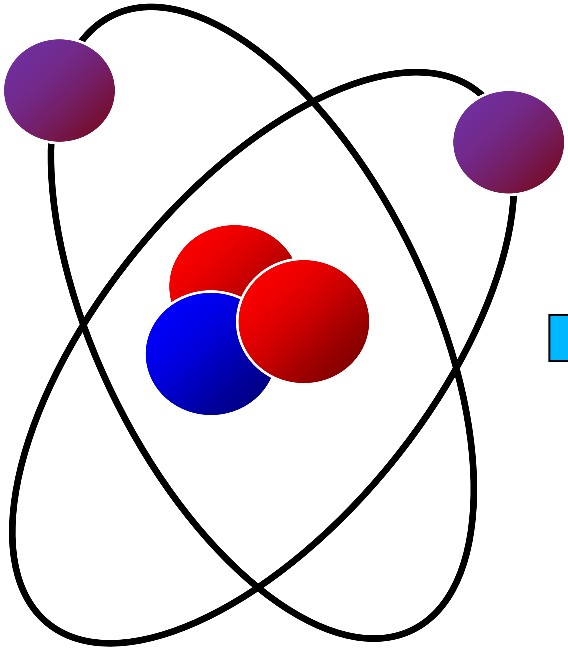


  - **Isotope**
    - **Same # protons**
    - Different # neutrons (mass)



Notation	**Ion** – An atom with a charge (different # of protons & electrons) **Isotope** – An atom with a different number of neutrons (mass)

Isotopic Notation



$$\rightarrow \boxed{{}^{3}\mathrm{He}} \leftarrow {}^{A}_{(Z)}Name^{(\pm c)}$$

Image | **Notation** | Template

Notation	**Atomic Number (Z)** – The number of protons in an atom **Mass Number (A)** – The total number of nucleons in an atom

Notation Examples

$$^{235}_{92}U^{0} = {}^{235}U$$

$$^{235}_{92}U^{+4} = {}^{235}U^{+4}$$

$$^{60}_{27}Co^{0} = {}^{60}Co$$

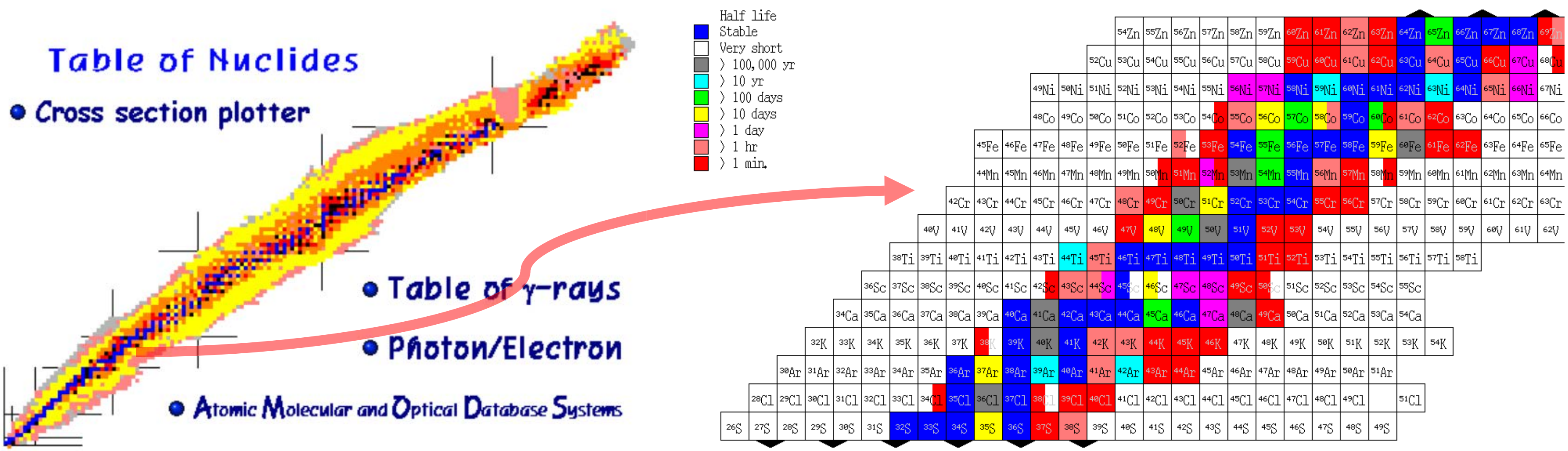
$$^{137}_{55}Cs^{+1} = {}^{137}Cs^{+1}$$

$$^{4}_{2}He^{+2} = {}^{4}He^{+2} = \alpha$$

Stable Isotopes

http://atom.kaeri.re.kr/

- Stable isotopes do not undergo *spontaneous* radioactive decay
- Which are stable? Consult the Table of Nuclides

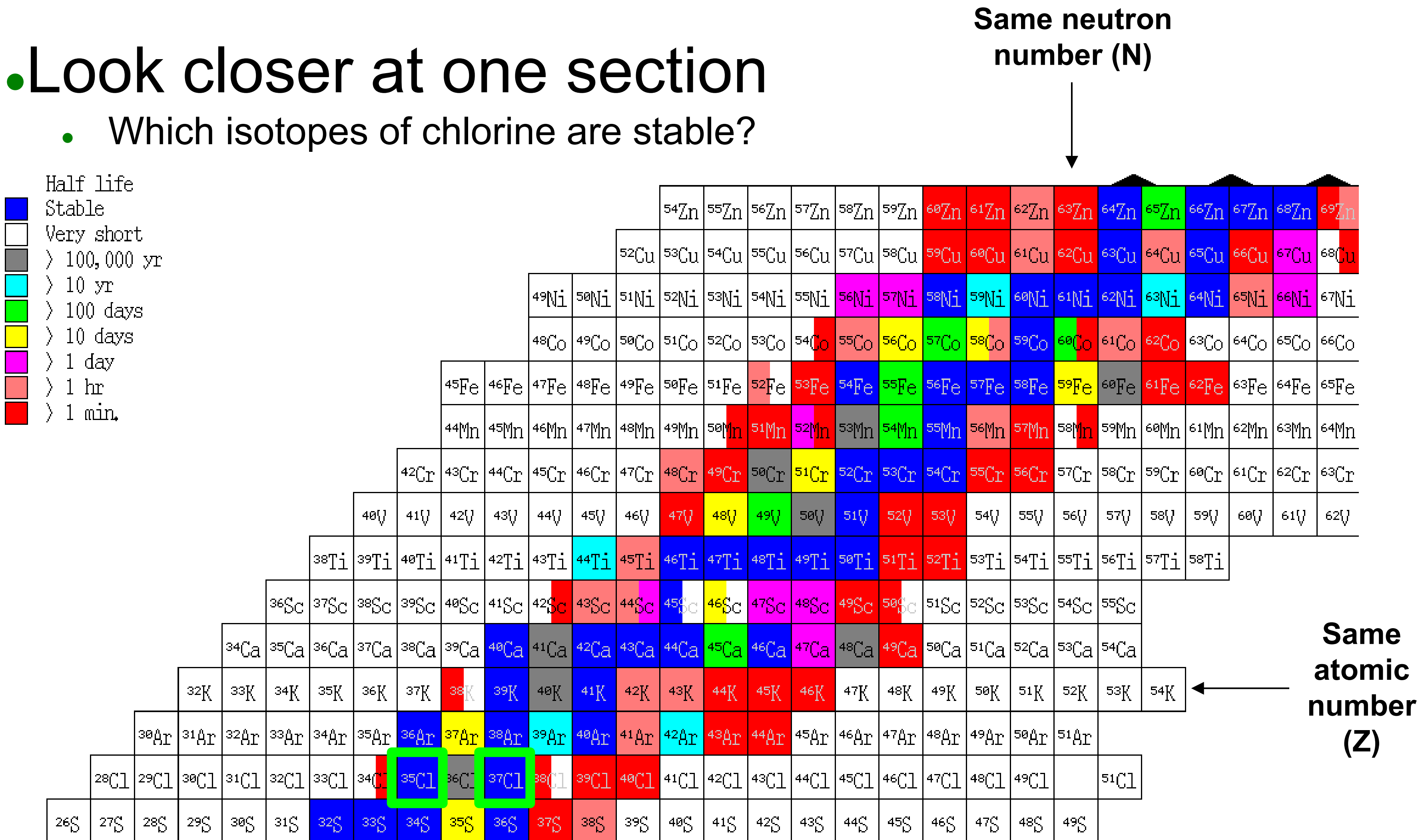


Notation	**Stable Isotope** – An isotope which does not undergo spontaneous, natural radioactive decay

Stable Isotopes, Atomic Weight

http://atom.kaeri.re.kr/

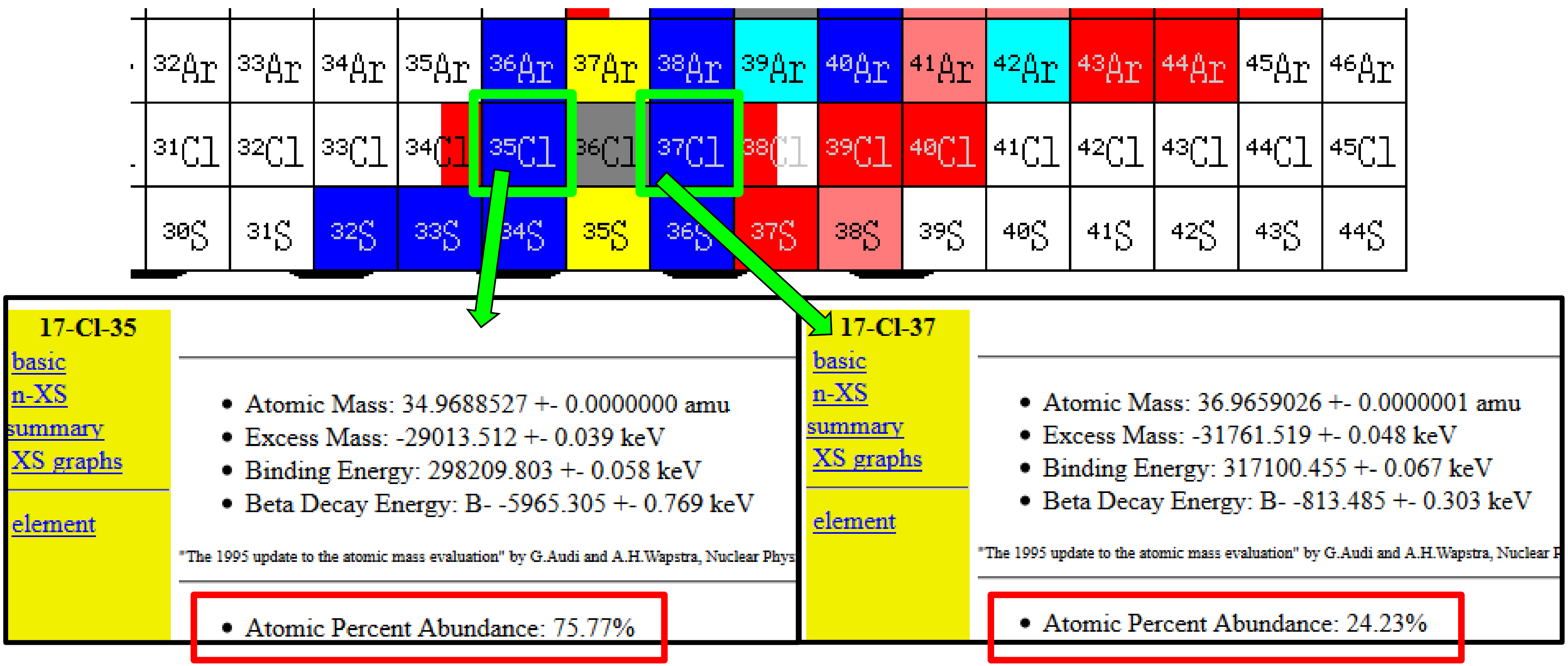
- Look closer at one section
  - Which isotopes of chlorine are stable?



Stable Isotopes, Atomic Weight

http://atom.kaeri.re.kr/

- Look closer at one section
  - Which isotopes of chlorine are stable? In which percentages?



Stable Isotopes, Atomic Weight

http://atom.kaeri.re.kr/

- Look closer at one section
  - Which isotopes of chlorine are stable? In which percentages?

17-Cl-35

basic
n-XS
summary
XS graphs

element

- Atomic Mass: 34.9688527 +- 0.0000000 amu
- Excess Mass: -29013.512 +- 0.039 keV
- Binding Energy: 298209.803 +- 0.058 keV
- Beta Decay Energy: B- -5965.305 +- 0.769 keV

"The 1995 update to the atomic mass evaluation" by G.Audi and A.H.Wapstra, Nuclear Phys

- Atomic Percent Abundance: 75.77%

17-Cl-37

basic
n-XS
summary
XS graphs

element

- Atomic Mass: 36.9659026 +- 0.0000001 amu
- Excess Mass: -31761.519 +- 0.048 keV
- Binding Energy: 317100.455 +- 0.067 keV
- Beta Decay Energy: B- -813.485 +- 0.303 keV

"The 1995 update to the atomic mass evaluation" by G.Audi and A.H.Wapstra, Nuclear P

- Atomic Percent Abundance: 24.23%

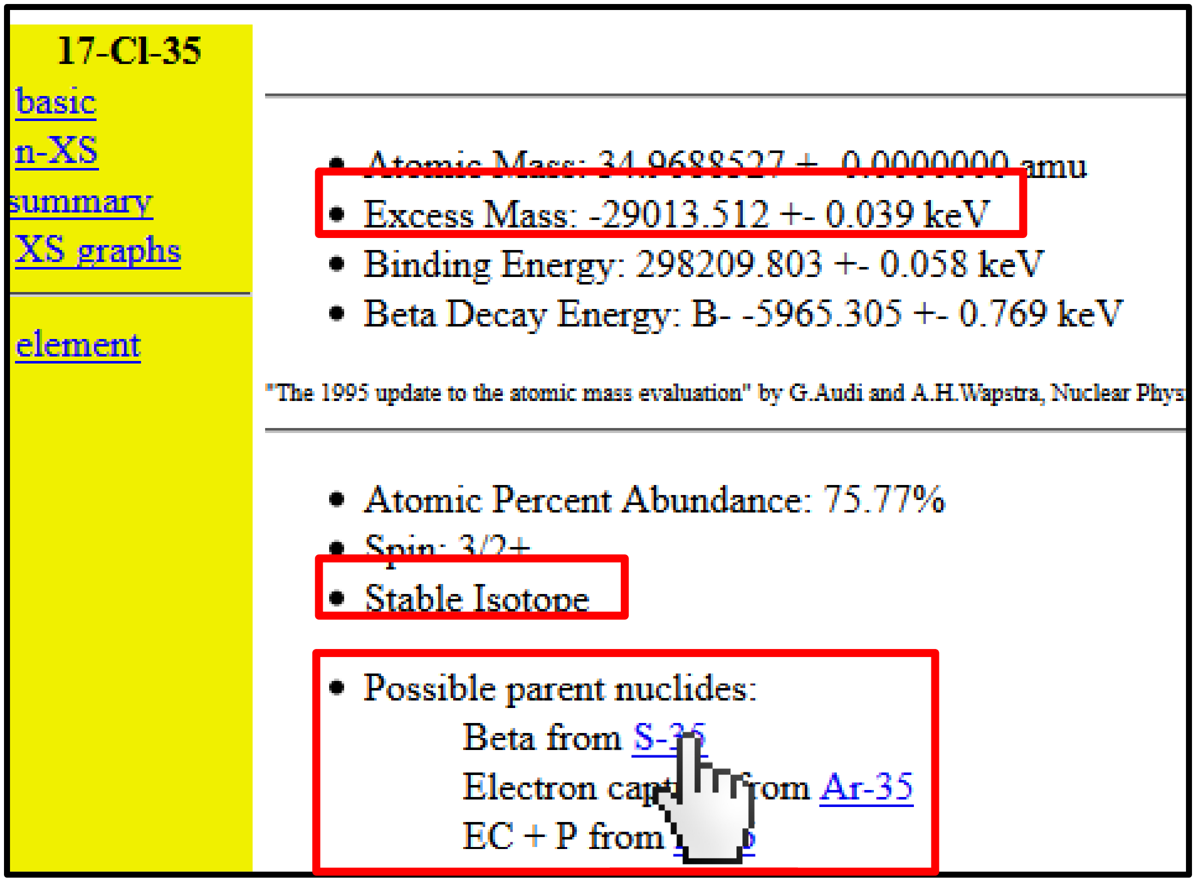
$$Mass_{Cl} = (0.7577 * 34.98) + (0.2423 * 36.97) = 35.46\ amu$$

Literature value: $35.453 \pm 0.002\ amu$

Notation	
	Atomic Weight – The average stable element isotopic weight **Atomic Mass Unit (amu) –** *Exactly* $^1/_{12}$ the weight of ^{12}C

More Features of the Nuclide Table

http://atom.kaeri.re.kr/



Courtesy of Korea Atomic Energy Research Institute. Used with permission.

- Excess mass
  - Yields energetics and nuclear reaction information
- Stability
  - Yields half life and specific activity information
- Parent nuclides
  - Yields nuclear reaction mechanism information

Notation	**Excess Mass (Δ) –** The mass of a nucleus not accounted for by the weight of its protons and neutrons alone

More Features of the Nuclide Table

http://atom.kaeri.re.kr/

16-S-35

basic

XS graphs

element

- Atomic Mass: 34.9690321 +- 0.0000001 amu
- Excess Mass: -28846.371 +- 0.092 keV
- Binding Energy: 298825.015 +- 0.103 keV
- Beta Decay Energy: B- 167.141 +- 0.084 keV

"The 1995 update to the atomic mass evaluation" by G.Audi and A.H.Wapstra, Nuclear Phy

- Spin: 3/2+
- Half life: 87.51 d
- Mode of decay: Beta to Cl-35
  - Decay energy: 0.167 MeV
- Possible parent nuclides:
  Beta from P-35

- Excess mass
  - Yields energetics and nuclear reaction information
- Stability
  - Yields half life and specific activity information
- Mode of decay
  - Yields nuclear reaction mechanism information

Notation

Half Life – The time it takes 50% of an isotope to decay
Decay Energy – The total energy involved in this radioactive decay

Next Three Topics

- Writing nuclear reactions
- Quantifying energetics of reactions
- Predicting radiation type and energy

Nuclear Reactions

- Radioactive Decay – Natural process

Today's focus

- Fission – Splitting atoms
  - Thermal energy is collected from kinetic energy (recoil energy) of fission products
- Fusion – Combining atoms
  - Thermal energy is collected from multiple sources

Notation	
Notation	**Decay** – The natural process of unstable isotope change **Fission** – The process of splitting an isotope into *fission fragments* **Fusion –** The process of combining two isotopes into a new one

Nuclear Reaction Principles

- CONSERVE (almost) EVERYTHING
  - Mass (number of nucleons)
  - Charge
  - Energy
  - NOT necessarily protons and neutrons

- Example: Tritium decay

$$^{3}H \rightarrow {}^{3}He + ???$$

$$\alpha^{+2}$$

$$\beta^{\pm}$$

$$\gamma$$

Nuclear Reaction Principles (β)

- CONSERVE (almost) EVERYTHING
  - Mass (number of nucleons)
  - Charge
  - Energy
  - NOT necessarily protons and neutrons

- Example: Tritium decay

$$^{3}H \rightarrow {}^{3}He^{+} + \beta^{-} + E_{rxn}$$

- What is E_{rxn}? What else is missing?

Nuclear Reaction Energetics (β)

$$^{3}\boldsymbol{H} \quad \rightarrow {}^{3}\boldsymbol{He}^{+} + \ \beta^{-} + \boldsymbol{E_{rxn}}$$

- Total E_{rxn}: Look at differences in *excess mass*

$$Q(MeV) = \Delta_P - \Delta_D$$

- The ***Q*** value gives this amount
  - Parents (*P*) are all species on the left side
  - Daughters (*D*) are all on the right side

Nuclear Reaction Energetics (β)

http://atom.kaeri.re.kr/

~0

$$^{3}H \rightarrow {}^{3}He^{+} + \beta^{-} + E_{rxn}$$

1-H-3

basic

XS graphs

element

Tritium is used for life science and drug metabolism st wrist watches...and to produce luminous paint.

- Atomic Mass: 3.0160493 +- 0.0000000 amu
- Excess Mass: 14949.794 +- 0.001 keV
- Binding Energy: 8481.821 +- 0.004 keV
- Beta Decay Energy: B- 18.591 +- 0.001 keV

"The 1995 update to the atomic mass evaluation" by G.Audi and A.H.Wapstra, Nuclear

- Spin: 1/2+
- Half life: 12.33 years
- Mode of decay: Beta to He-3
  - Decay energy: 0.019 MeV

2-He-3

basic

n-XS

summary

XS graphs

element

- Atomic Mass: 3.0160293 +- 0.0000000 amu
- Excess Mass: 14931.204 +- 0.001 keV
- Binding Energy: 7718.058 +- 0.002 keV

"The 1995 update to the atomic mass evaluation" by G.Audi and A.H.Wapstra, Nuclea

- Atomic Percent Abundance: 0.000137%(3
- Spin: 1/2+
- Stable Isotope

$$Q(MeV) = \Delta_P - \Delta_D = 14.950 - 14.931 = 0.019\ MeV$$

Nuclear Reaction Energetics (β)

$$^{3}H \rightarrow {}^{3}He^{+} + \beta^{-} + E_{rxn}$$

- Total E_{rxn}: Look at differences in *excess mass*

$$Q(MeV) = \Delta_P - \Delta_D = 14.950 - 14.931 = 0.019\ MeV$$

- Not all energy goes to the beta particle
  - Average beta energy: 5.7 keV
  - Some, not all, goes to the daughter nuclide's recoil
- Where does the rest go?

Nuclear Reaction Energetics (β)

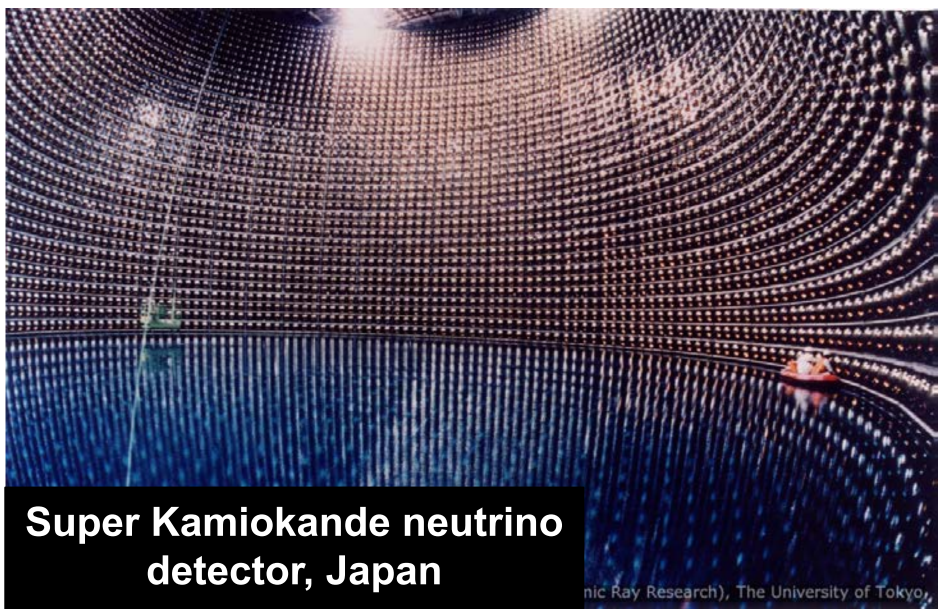
$$^{3}H \quad \rightarrow {}^{3}He^{+} + \beta^{-} + {}^{0}_{0}\overline{\nu} + E_{rxn}$$

- An *antineutrino* carries away the excess energy
- Chargeless, essentially massless particles
- *Extremely hard to detect!*
- *How did we know of their existence? Missing energy in the reaction balance!*

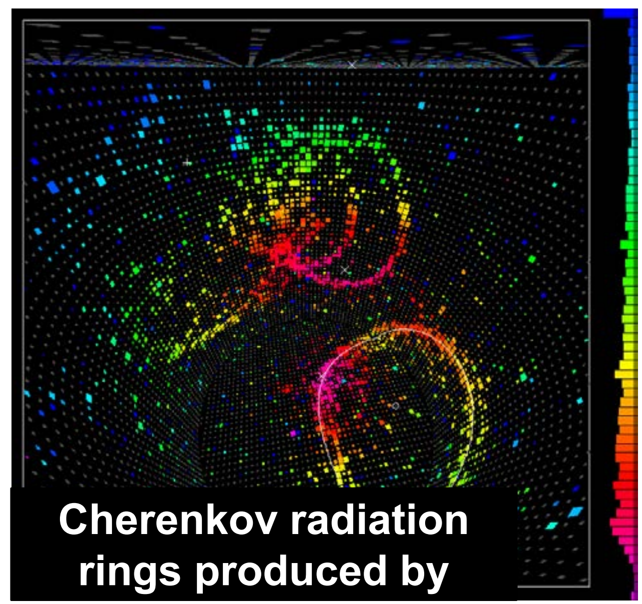
Other Types of Radiation

http://www-sk.icrr.u-tokyo.ac.jp/sk/gallery/wme/sk_01h-wm.jpg
http://www.ps.uci.edu/~tomba/sk/tscan/pictures.html

- Neutrino (ν)
  - Chargeless, nearly massless particle
- Anti-neutrino ($\bar{\nu}$)
  - Antiparticle equivalent of the neutrino



Super Kamiokande neutrino detector, Japan



Cherenkov radiation rings produced by

Nuclear Reaction Principles (γ)

- Sometimes beta decay leaves the nucleus in an *excited state*
- This energy can be lost through *gamma emission*, bringing the nucleus to the *ground state*
- Example: Cobalt-60

Denotes excited state

$$^{60}Co \rightarrow {}^{60^*}Ni^{+} + \beta^{-} + {}^{0}_{0}\overline{\nu}$$

$$^{60^*}Ni^{+} \rightarrow {}^{60}Ni^{+} + \gamma$$

Nuclear Reaction Principles (γ)

http://atom.kaeri.re.kr/

- How to determine gamma energy levels?
- Use *energy level diagrams*

27-Co-60

basic

XS graphs

element

- Atomic Mass: 59.9338222 +- (
- Excess Mass: -61644.218 +- 1
- Binding Energy: 524800.045 +
- Beta Decay Energy: B- 2823.8

"The 1995 update to the atomic mass evaluation" by G.Auc

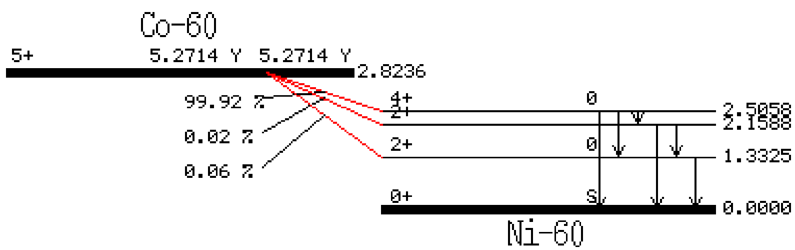
- Spin: 5+
- Half life: 1925.1 d
- Mode of decay: Beta to Ni-60
  - Decay energy: 2.824 Me

Meta state at 0.059 Mev

- Spin: 2+
- Half life: 10.467 min
- Mode of decay: IT
  - Branch ratio: 99.76 %
  - Decay energy: 0.059 Me
- Mode of decay: Beta to Ni-60
  - Branch ratio: 0.24 %
  - Decay energy: 2.883 Me

60CO B- DECAY (5.2714 Y)

```
Parent state: G.S.
Half life: 5.2714 Y(5)
Q(gs): 2823.64(11) keV
Branch ratio:        1.0
```



Beta ray:

Max.E(keV)	Avg.E(keV)	Intensity(rel)	Spin
			5+
1492(20)	625.87(5)	0.057(20)	2+
670(20)	274.93(5)	0.022(LT)	2+
317.88(10)	95.77(4)	99.925(20)	4+

Gamma ray:

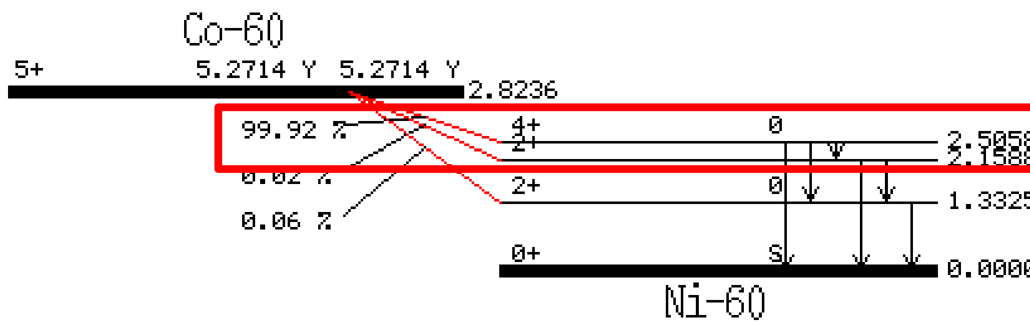
Energy(keV)	Intensity(rel)
346.93(7)	0.0076(5)
826.28(9)	0.0076(8)
1173.237(4)	99.9736(7)
1332.501(5)	99.9856(4)
2158.77(9)	0.00111(18)
2505	2.0E-6(4)

Nuclear Reaction Principles (γ)

http://atom.kaeri.re.kr/

60CO B- DECAY (5.2714 Y)

Parent state: G.S.
Half life: 5.2714 Y(5)
Q(gs): 2823.64(11) keV
Branch ratio: 1.0



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1332.501(5)	99.9856(4)
2158.77(9)	0.00111(18)
2505	2.0E-6(4)

How can this be?

***Internal conversion* – competing process with gamma emission**

Nuclear Reaction Principles (γ)

- Internal conversion (IC)
  - Excited state kicks out an inner-shell electron
- Example: Cobalt-60 most likely mechanism

$$^{60}Co \rightarrow {}^{60^*}Ni^{+} + \beta^{-} + {}^{0}_{0}\bar{\nu} \qquad \beta$$

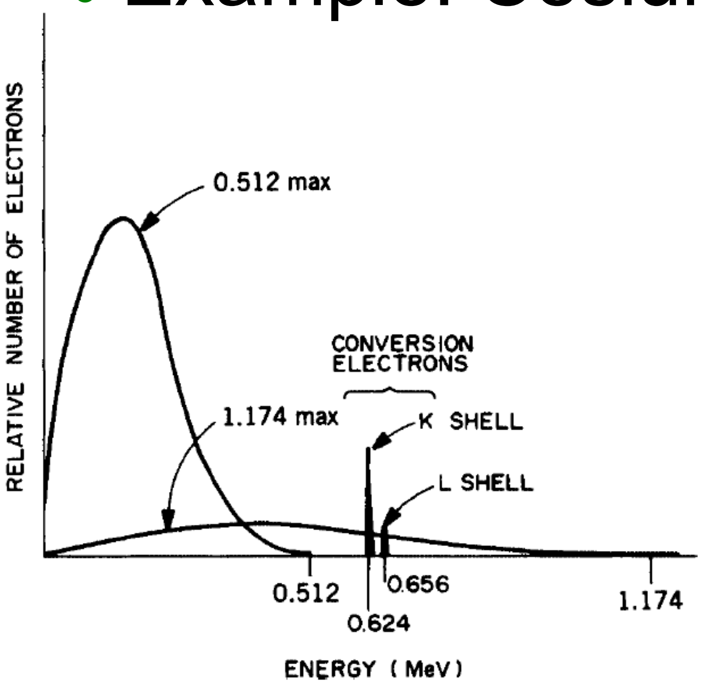
$$60^{2.51\,MeV}Ni^{+} \rightarrow 60^{2.16\,MeV}Ni^{+2} + e^{-} \qquad \text{IC}$$

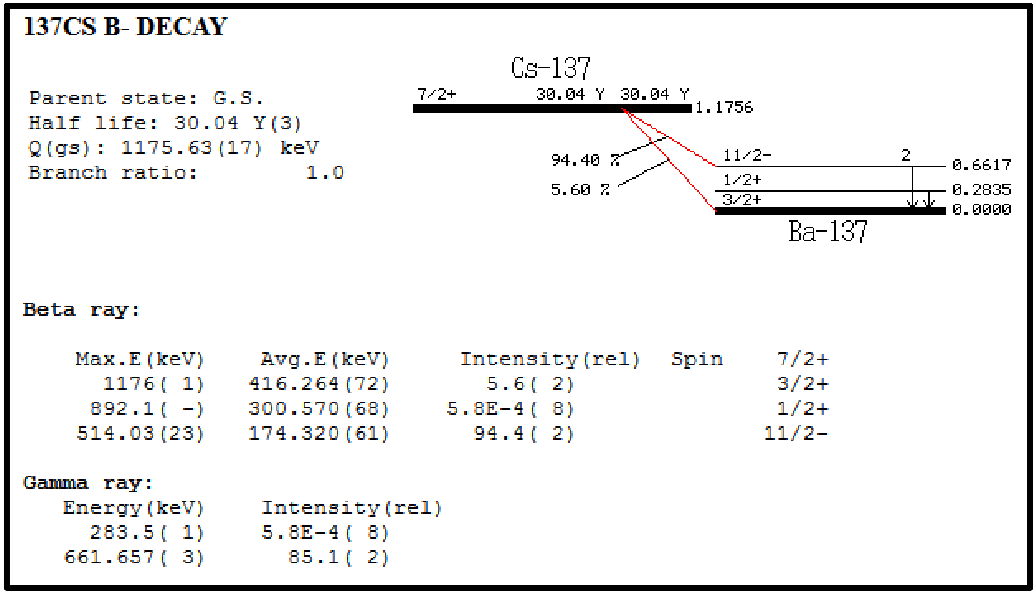
$$60^{2.16\,MeV}Ni^{+2} \rightarrow 60^{1.33\,MeV}Ni^{+2} + \gamma \qquad \gamma$$

$$60^{1.33\,MeV}Ni^{+2} \rightarrow {}^{60}Ni^{+2} + \gamma \qquad \gamma$$

Nuclear Reaction Principles (γ)

- Resulting radiation spectrum can be *complex*
- Example: Cesium-137





137CS B- DECAY

Parent state: G.S.
Half life: 30.04 Y(3)
Q(gs): 1175.63(17) keV
Branch ratio: 1.0

Beta ray:

Max.E(keV)	Avg.E(keV)	Intensity(rel)	Spin
1176(1)	416.264(72)	5.6(2)	7/2+
892.1(-)	300.570(68)	5.8E-4(8)	3/2+
514.03(23)	174.320(61)	94.4(2)	1/2+
			11/2-

Gamma ray:

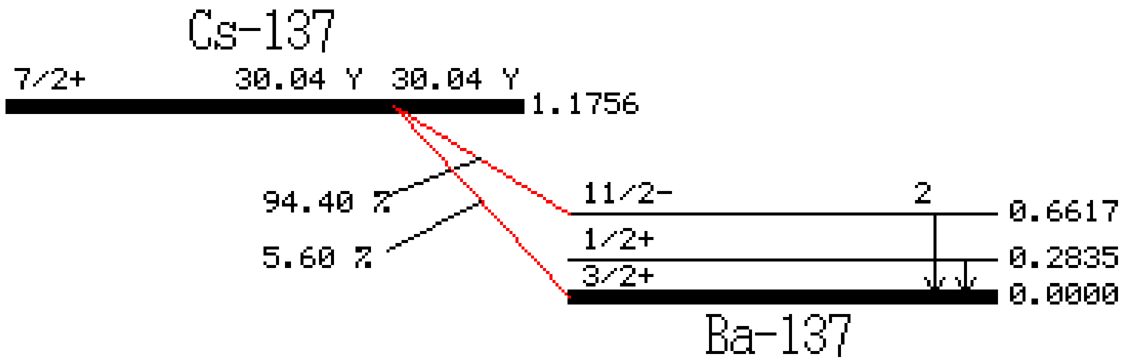
Energy(keV)	Intensity(rel)
283.5(1)	5.8E-4(8)
661.657(3)	85.1(2)

Nuclear Reaction Principles (γ)

http://atom.kaeri.re.kr/

137CS B- DECAY

Parent state: G.S.
Half life: 30.04 Y(3)
Q(gs): 1175.63(17) keV
Branch ratio: 1.0



Beta ray:

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514.03(23)	174.320(61)	94.4(2)		11/2-

Gamma ray:

Energy(keV)	Intensity(rel)
283.5(1)	5.8E-4(8)
661.657(3)	85.1(2)

Nuclear Reaction Principles (α)

- Relatively heavy isotopes can emit a helium nucleus (alpha particle)
- Example: Americium-241

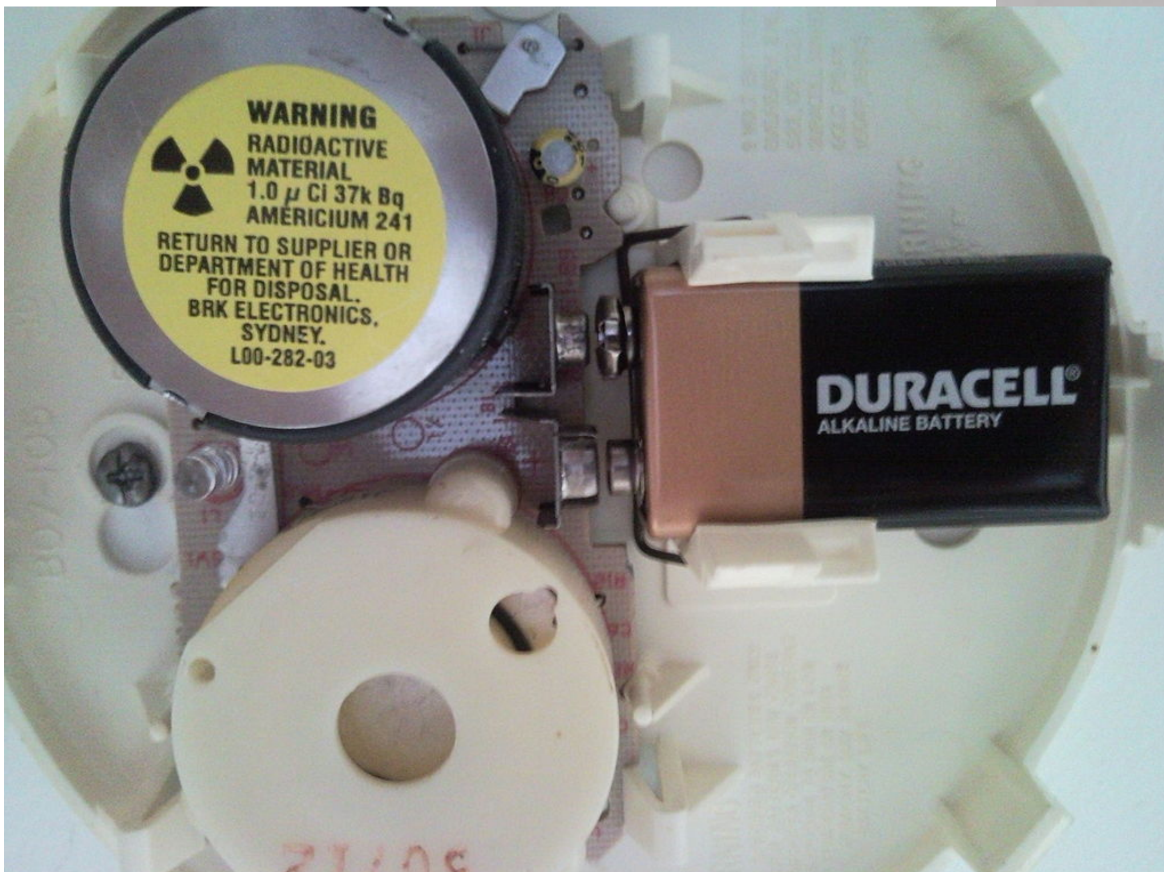
$$^{241}\boldsymbol{Am} \rightarrow {}^{237^*}\boldsymbol{Np}^{-2} + \alpha^{+2}$$

$$^{237^*}\boldsymbol{Np}^{-2} \rightarrow {}^{237}\boldsymbol{Np}^{-2} + \gamma$$

Nuclear Reaction Principles (α)

http://en.wikipedia.org/wiki/Americium

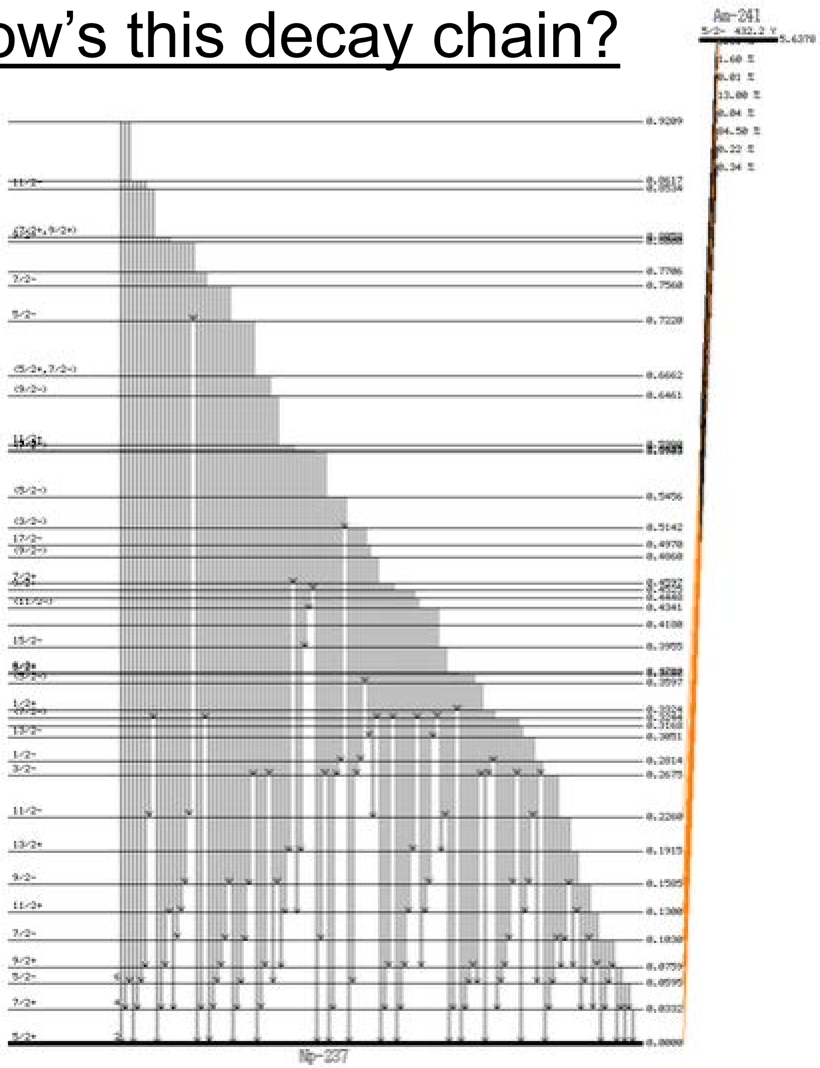
Uses of Americium:



Nuclear Reaction Principles (α)

http://atom.kaeri.re.kr/

How's this decay chain?



Alpha ray:

Energy(keV)	Intensity(rel)	Hindrance
5544.5(16)	0.34(5)	6.9E2(11)
5511.47(13)	0.22(3)	6.9E2(10)
5485.56(12)	84.5(10)	1.27(2)
5469.45(14)	0.04(LT)	2160(GT)
5442.80(13)	13.0(6)	4.7(3)
5416.27(14)	0.01(AP)	4200(AP)
5388.23(13)	1.6(2)	18(3)
5321.90(13)	0.015(5)	750(AP)
5281.01(14)	0.0005	12700
5244.12(13)	0.0024	1560
5232.5(3)	-	-
5225.08(13)	0.0013	2190
5217.27(13)	-	-
5190.4(2)	0.0006	2860
5181.64(13)	0.0009	1680
5179.34(13)	0.0003	4860
5155.16(13)	0.0007	1460
5133(4)	-	-
5117.20(20)	0.0004	1450
5106.71(16)	-	-
5099.09(13)	0.0004(AP)	1110(AP)
5092.05(13)	0.0004(AP)	1000(AP)
5066.22(17)	0.00014	1930
5055.34(14)	-	-
5007.58(20)	0.0001	1100
4963.63(20)	-	-
4961.6(11)	-	-
4956.0(3)	-	-
4888.9(2)	-	-
4834.15(13)	0.0007	10
4800.62(16)	8.6E-5	47
4757.39(16)	0.00004(3)	50(AP)

Half Life

- Time it takes for half of an isotope to decay
- The *decay constant* relates this to an exponential form of the same rule

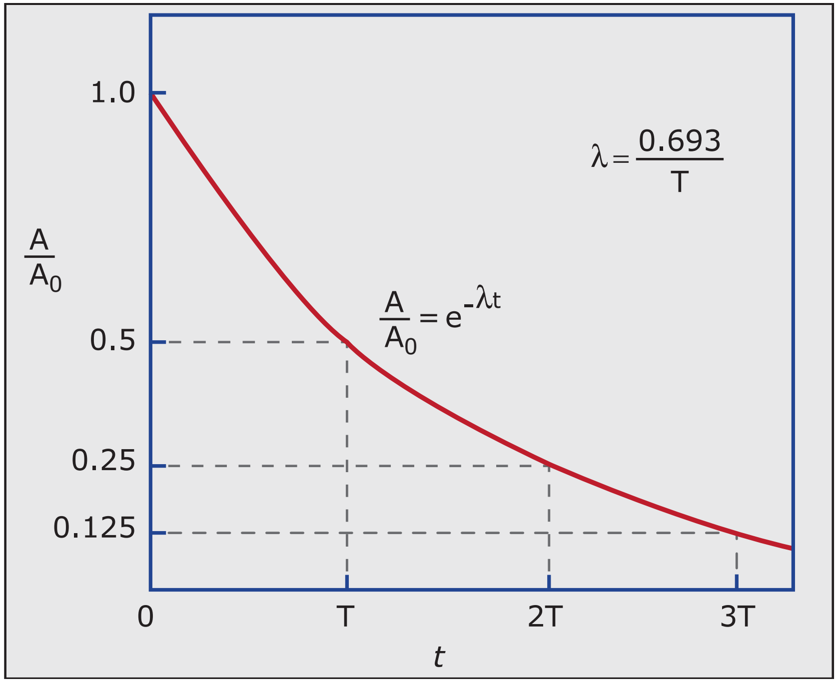


Image by MIT OpenCourseWare.

Half Life

- Define an *activity* in terms of decays per second

$$A = -\frac{dN}{dt} = \lambda N \qquad A = A_0 \text{ @ } t = 0$$

- Solve the ordinary differential equation:

$$\frac{dN}{N} = -\lambda * dt \Rightarrow \ln N = -\lambda t + c \xrightarrow{t=0} \ln N_0 = c$$

$$\ln N = -\lambda t + \ln N_0 \Rightarrow ln\left(\frac{N}{N_0}\right) = -\lambda t \Rightarrow N = N_0 e^{-\lambda t}$$

- *λ* describes how quickly the number of atoms *N* changes by a factor of *e*

Half Life

$$A = -\frac{dN}{dt} = \lambda N \qquad A = A_0 \ @ \ t = 0$$

$$N = N_0 e^{-\lambda t} \quad \rightarrow \quad \frac{A}{\lambda} = \frac{A_0}{\lambda} e^{-\lambda t}$$

Find the half life (***T***):

$$\frac{N}{N_0} = \frac{1}{2} = e^{-\lambda T} \Rightarrow \ln 0.5 = -\lambda T \Rightarrow T = \frac{0.693}{\lambda}$$

Notation	
	Activity – A measure of the number of radioactive decays per second **Decay Constant** – The constant for an activity to decrease by a factor of *e* **Half Life –** The time it takes a sample's activity to decrease by a factor of 2

Measuring Activity

- Activity is measured in Becquerels (Bq)

$$1\ Bq = 1\ Disintegration\ per\ second$$

- A more convenient unit is the Curie (Ci)

$$1\ Ci = 3.7 \times 10^{10}\ Bq$$

- You will often see reduced units (mCi, µCi) on real devices and sources
  - One Curie is *a lot* of radiation!!!

Notation	**Becquerel (Bq)** – The fundamental unit of radioactivity, equal to one disintegration per second **Curie (Ci)** – A more convenient activity unit, 1 Ci = 3.7 x 10^{10} Bq

Activity on Sources and Devices

en.wikipedia.org/wiki/Americium

www.prc68.com/I/Rad_Det.shtml

Thinking Ahead for the Lab

- How do you measure the activity of a source?
- How do you account for older sources?
- What else will make measuring the activity of a source difficult?
  - In other words, what are possible sources of error and/or confusion?

Questions?

22.S902 Do-It-Yourself (DIY) Geiger Counters
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