Gamma ray spectroscopy: Attenuation of gamma photons and positrons

Week of Oct. 4, 2010

γ

Atomic and Nuclear Physics Laboratory (Physics 4780)

The University of Toledo
Instructor: Randy Ellingson

Error (uncertainty) analysis -- revisited

$$z = f\left(x, y\right)$$

$$\Delta z = \frac{\partial f\left(x, y\right)}{\partial x}\Delta x + \frac{\partial f\left(x, y\right)}{\partial y}\Delta y$$

For uncorrelated errors:

$$\Delta z = \left[\left(\frac{\partial f\left(x, y\right)}{\partial x}\Delta x\right)^2 + \left(\frac{\partial f\left(x, y\right)}{\partial y}\Delta y\right)^2\right]^{\frac{1}{2}}$$

Error (uncertainty) analysis – example using Activity of ^{241}Am source

$$A = \frac{C}{\pi s^2 / 4\pi r^2} = \frac{C(4r^2)}{s^2}$$

Where *C* is count rate, *r* is the distance to the detector, and *s* is the radius of the detector.

$$\Delta A = \frac{\partial}{\partial C}\left(\frac{4Cr^2}{s^2}\right)\Delta C + \frac{\partial}{\partial r}\left(\frac{4Cr^2}{s^2}\right)\Delta r$$

$$\Delta A = \frac{4r^2}{s^2}\Delta C + \left(\frac{4C}{s^2}\right)(2r)\Delta r$$

In quadrature, if these errors are uncorrelated:

$$\Delta A = \left[\left(\frac{4r^2}{s^2}\Delta C\right)^2 + \left(\frac{8Cr}{s^2}\Delta r\right)^2\right]^{\frac{1}{2}}$$

Error (uncertainty) analysis – multiple value r.m.s. approach

Another approach to evaluating the uncertainty relies on a straightforward calculation of the root mean square and the standard deviation. In the case of your Activity measurements, you could compute the RMS value as well as the SD. You should still assess your uncertainty through error propagation, as the uncertainty may very well exceed the SD.

Definition of the root mean square from Wikipedia:

"…the square root of the arithmetic mean (average) of the squares of the original values…"

In the case of a set of *n* values $x_1, x_2, \ldots x_n$, the RMS value is given by:

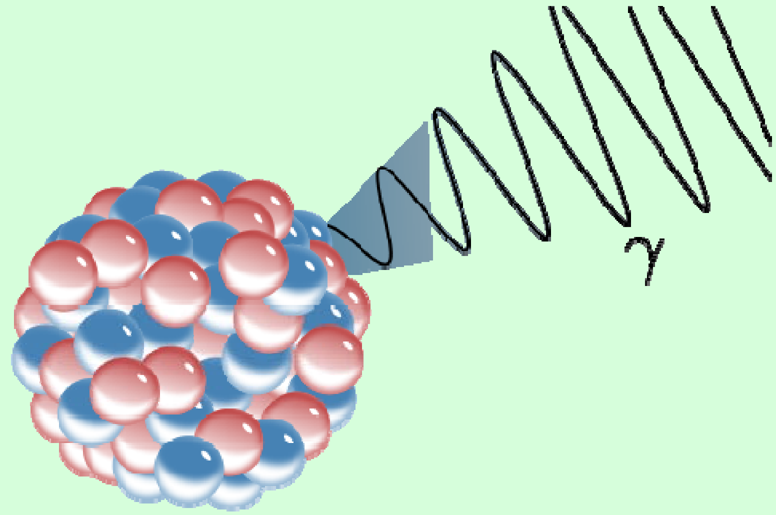
$$x_{rms} = \sqrt{\frac{{x_1}^2 + {x_2}^2 + \cdots + {x_n}^2}{n}}$$

The **standard deviation** is given as follows, where there are *N* values and μ is the arithmetic mean:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$$

Gamma Ray Spectroscopy

Gamma Rays



Photons!

High-frequency electromagnetic radiation.

Typical visible light frequency:

$\nu = c/\lambda = (3 \times 10^8 \text{ m/s})/(500 \times 10^{-9} \text{ m})$,

$\nu = 6 \times 10^{14} \text{ s}^{-1}$ (600 THz, or
0.6 PHz (petahertz)).

Typical gamma ray frequency: $\nu > 10^{19} \text{ s}^{-1}$, or $\nu > 10$ exahertz.

$\rightarrow \lambda < c/10^{19} \text{ s}^{-1} \rightarrow \lambda < 3 \times 10^{-11}$ m, or $\lambda < 30$ pm. Size of an He atom = 32 pm.

Paul Villard, a French chemist and physicist, discovered gamma radiation in 1900, while studying radiation emitted from radium. Alpha and beta "rays" had already been separated and named by the work of Ernest Rutherford in 1899, and in 1903 Rutherford named Villard's distinct new radiation "gamma rays."

Gamma ray interactions with matter

Gamma Ray – matter interaction

When a gamma ray passes through matter, the probability for absorption in a thin layer is proportional to the thickness of that layer. This leads to an exponential decrease of intensity with thickness.

$$I(d) = I_0 e^{-\mu d}$$

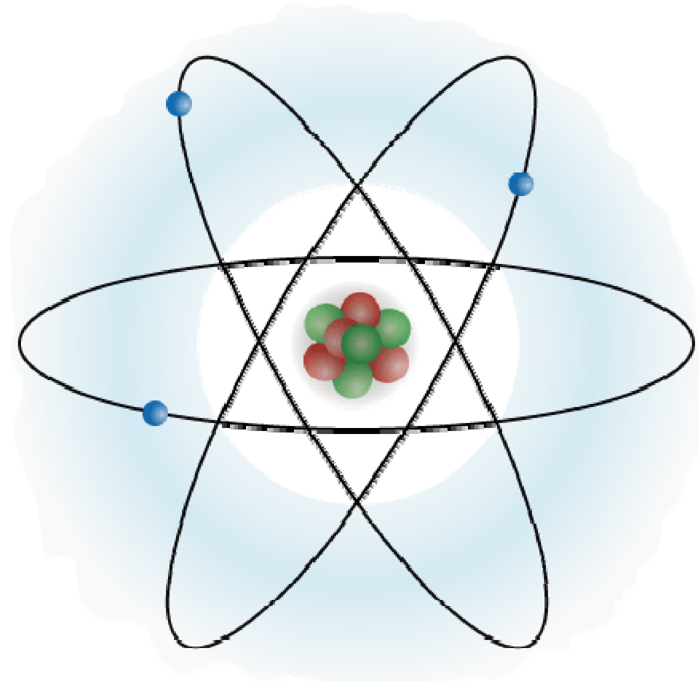
Here $\mu = n\sigma$ is the linear attenuation coefficient (an absorption coefficient), measured in cm^{-1}, n the number of atoms per cm^3 in the material, σ the absorption cross section in cm^2 and d the thickness of material in cm.

Note: the probability that a particle will travel no farther than distance *d* is given by $1-e^{-\mu d}$.

μ depends on both the gamma ray energy as well as the atomic number of the absorber.

Brief Review of Atomic Structure

- Each atom consists of a positively charged core (the *nucleus*, containing protons and neutrons, held together by nuclear forces) surrounded by negatively-charge shells (electrons).
- Electrons exist in specific energy levels (orbits) around the nucleus.
- Element is determined by # of protons. I.e., atoms of the same element have the same # of protons, but can differ in the number of neutrons. Atoms of the same element (same # or protons) with different # of neutrons are *isotopes*. Since # of protons identifies the element, remember that # of protons is referred to as the *atomic number* (Z).



Masses:

$m_e = 9.11 \times 10^{-31}$ kg

$m_n = 1.67 \times 10^{-27}$ kg

$m_p = 1.67 \times 10^{-27}$ kg

Brief Review of Atomic Structure (continued)

- Charges: electrons (-1*e*), protons (+1*e*), and neutrons (0).
- Magnitude of the charge on an electron = 1.602 x 10^{-19} Coulombs.
- Electrons are bound to the atom's nucleus through the Coulomb force, in which opposite charges attract ("electrostatic force").
- Ions: basically, an atom is uncharged if the # of electrons = # of protons, and if not, you've got an *ion* (a charged atom).
- Terminology for atoms, generalized to isotopes: (what is a nuclide?) A specific nuclide can be annotated as follows:

$$ {}^{A}_{P}X $$

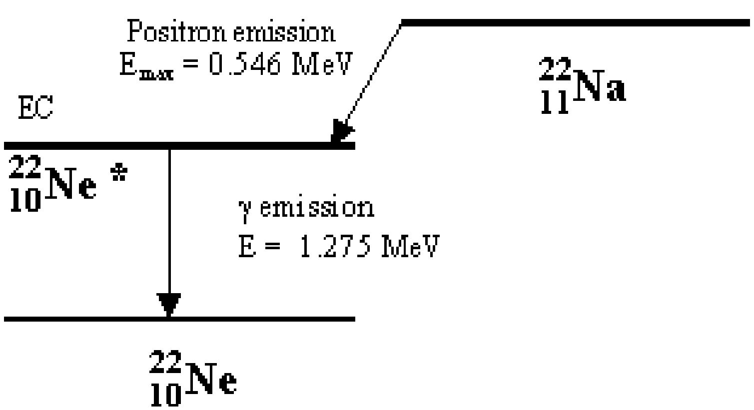
where *A* is the atomic mass number (# of protons + # of neutrons), *P* is the # of protons, and *X* is symbol for the element. Examples:

${}^{1}_{1}H$ ("hydrogen-1") ${}^{4}_{2}He$ ("helium-4")

Na-22: Source for positrons (antimatter for the electron)

Positron = β^+, discovered by Carl Anderson, 1932

In beta plus decay, a proton is converted, via the weak force, to a neutron, a positron (also known as the "beta plus particle", the antimatter counterpart of an electron), and a neutrino.

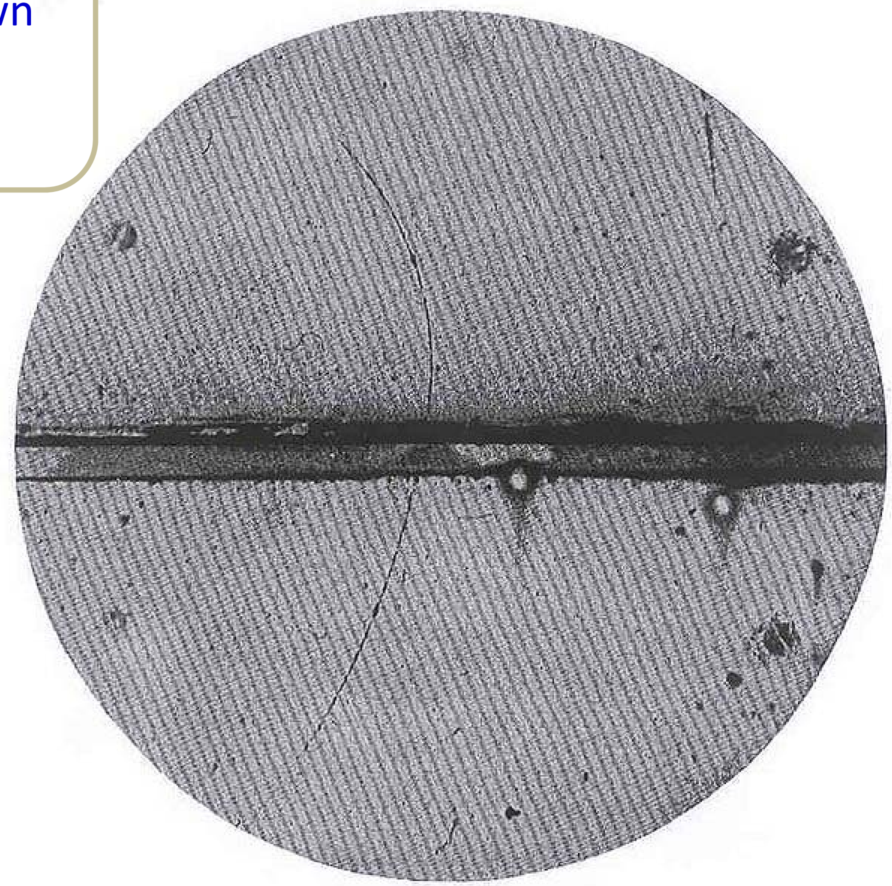


(β⁻ decay)

$$^{60}_{27}\mathrm{Co} \rightarrow ^{60}_{28}\mathrm{Ni}^* + e^- + \overline{\nu}_e$$

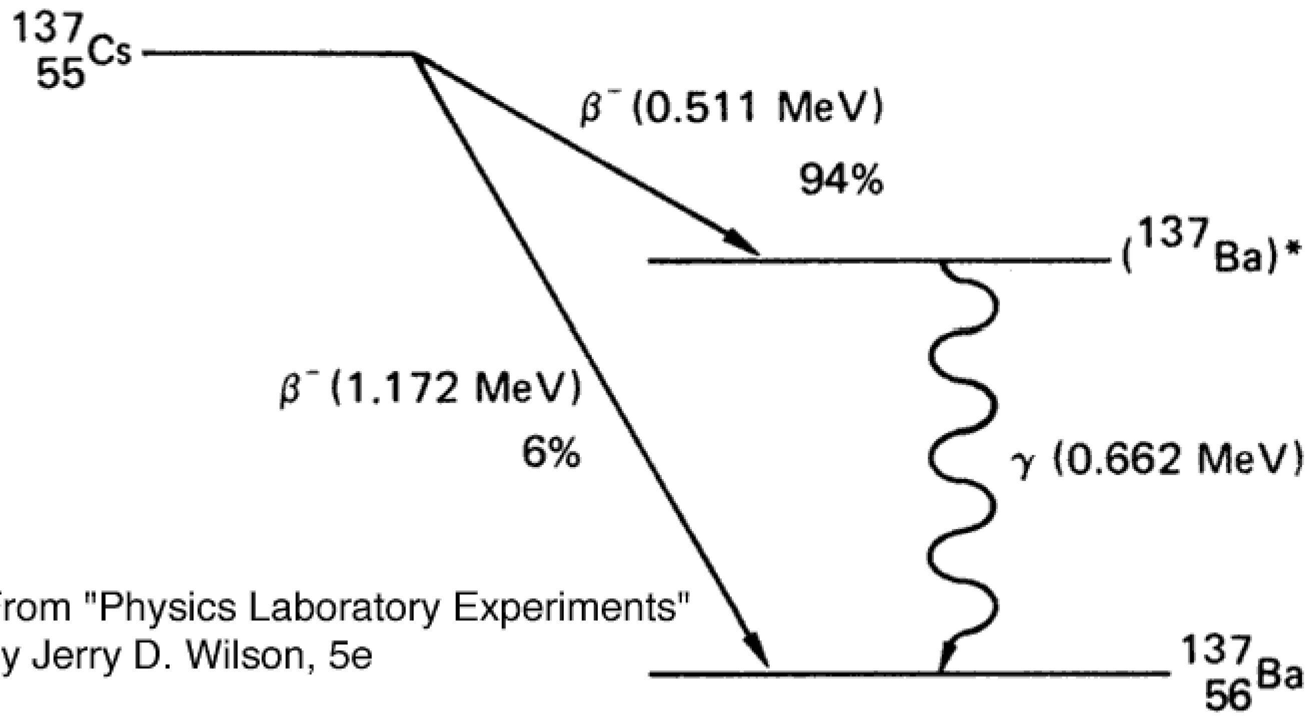
$$^{60}_{28}\mathrm{Ni}^* \rightarrow ^{60}_{28}\mathrm{Ni} + \gamma_1 + \gamma_2$$

(γ emission)



C. Anderson's 1932 image from the cloud chamber photograph of the first positron ever observed (published March 1933).

Decay Scheme for Cs-137

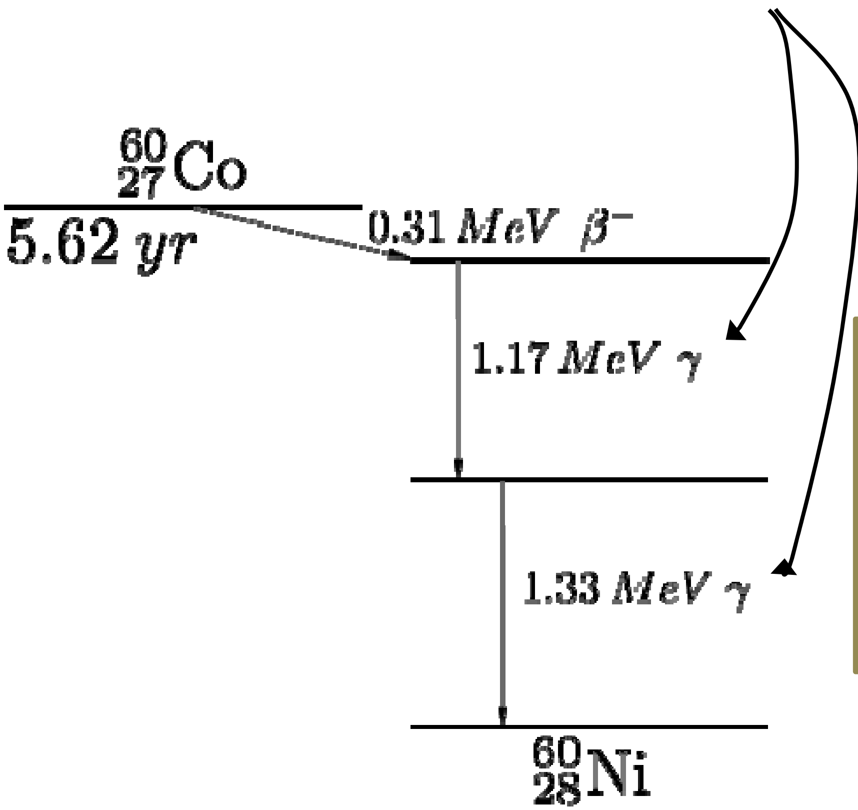


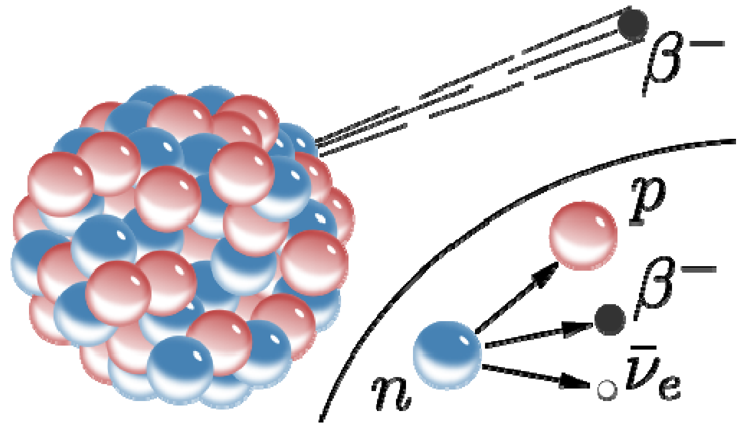
From "Physics Laboratory Experiments"
by Jerry D. Wilson, 5e

Gamma Ray Production: Co-60

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni}^{*} + e^{-} + \overline{\nu}_{e}$$ (β⁻ decay)

$$^{60}_{28}\mathrm{Ni}^{*} \rightarrow {}^{60}_{28}\mathrm{Ni} + \gamma_{1} + \gamma_{2}$$ (γ emission)

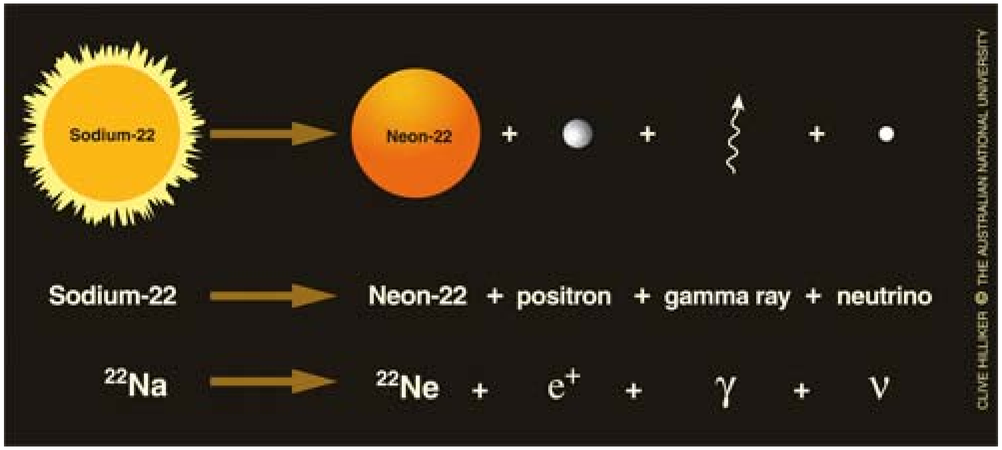




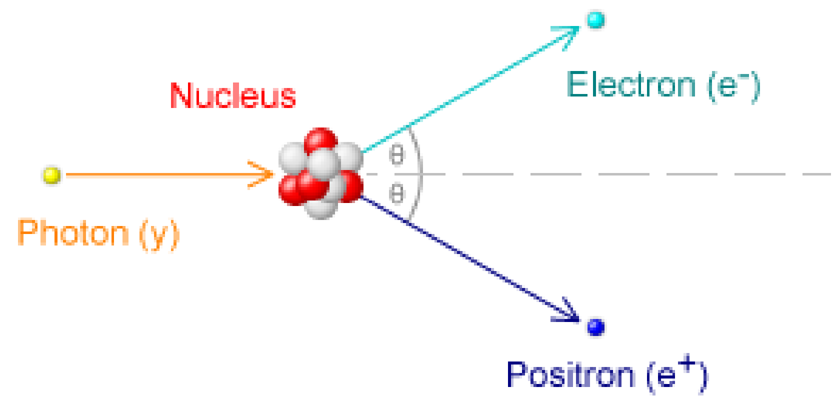
In β⁻ decay, the weak interaction converts a neutron (n) into a proton (p) while emitting an electron (e⁻) and an electron antineutrino (ν_e):

$$n \rightarrow p + e^{-} + \overline{\nu}_{e}$$

Note: some images from Wikimedia Commons: http://commons.wikimedia.org/wiki/Main_Page



Pair production?



What is the minimum photon energy required to produce an electron-positron pair?

Positronium

Positronium: a system consisting of an electron and positron, bound together and orbiting one another. The orbit of the two particles and the set of energy levels is similar to that of the hydrogen atom (electron and proton), with a significantly smaller mass -- associated spectral lines are less than half of those of the corresponding hydrogen lines.

Positron (the 1983 video game)

Health Effects of Gamma Rays

Gamma Rays – Health Effects

A health hazard since they result in ionization when interacting with living tissue (ionizing radiation).

Effects of ionizing radiation on living tissue depends on the amount of energy deposited rather than the charge generated in ionization. Total energy deposited is the **absorbed dose**:

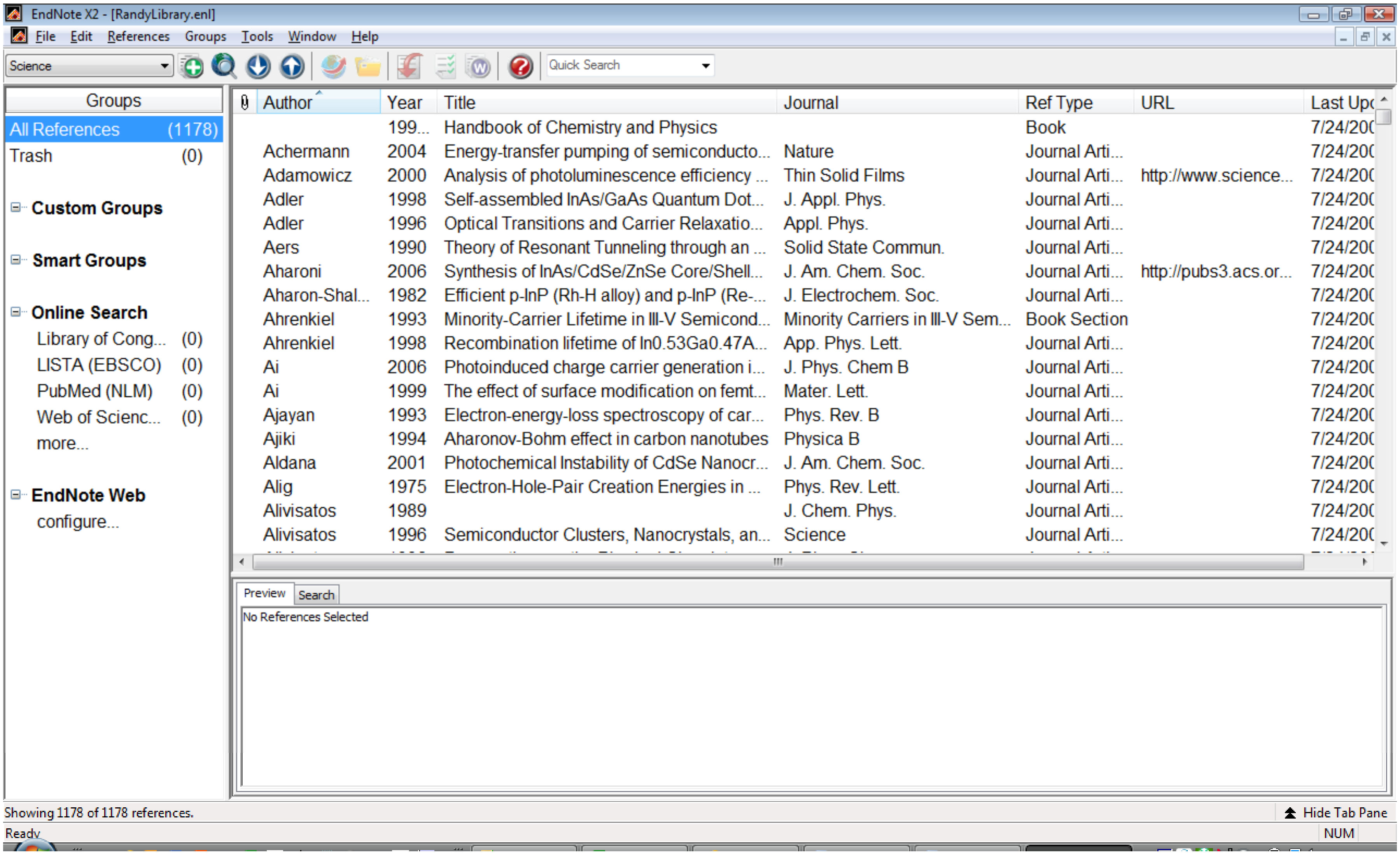
The gray (Gy) has units of (J/kg) and is the SI unit of *absorbed dose*: given by the amount of radiation required to deposit 1 joule of energy in 1 kilogram of any kind of matter.

Equivalent dose? Measures the biological effect of radiation on human tissue. For gamma rays, how does the *equivalent dose* differ from *absorbed dose*?

Shielding: Large amounts of mass. Most important: the total "areal mass density" in the path of the gamma rays. Pb shields only slightly better (20-30%) than an equal mass of another shielding material.

Note that the density (ρ) of lead is 11.35 g/cm^3; $\rho \cong 0.95$ g/cm^3 for polyethylene.

EndNote (more available software)



EndNote (more available software)