Seeing and Believing:
Detection, Measurement, and Inference in Experimental Physics

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There is a very wide range of scientific backgrounds in this audience!

(Some of you could give today’s lecture... which is for those of you who can’t!)

There is a very wide range of radiation backgrounds in this room!

Sound, electromagnetic (many varieties and sources), nuclear decay products, neutrinos, cosmic rays, dark matter, [dark energy?], gravity waves...
Today’s topic (slightly revised): What are you radiating?

Otherwise known as a rapid-fire review of (or introduction to) subatomic physics, with applications to understanding some of the challenges of current physics experiments.
Well, first of all, what are you made of?

<table>
<thead>
<tr>
<th>Element</th>
<th>Rough percentage by weight:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen (O)</td>
<td>65%</td>
</tr>
<tr>
<td>Carbon (C)</td>
<td>18.5%</td>
</tr>
<tr>
<td>Hydrogen (H)</td>
<td>9.5%</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>3.3%</td>
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<tr>
<td>Calcium (Ca)</td>
<td>1.5%</td>
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<tr>
<td>Phosphorus (P)</td>
<td>1.0%</td>
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<tr>
<td>Potassium (K)</td>
<td>0.4%</td>
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<tr>
<td>Sulfur (S)</td>
<td>0.3%</td>
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<tr>
<td>Sodium (Na)</td>
<td>0.2%</td>
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<tr>
<td>Chlorine (Cl)</td>
<td>0.2%</td>
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<tr>
<td>Magnesium (Mg)</td>
<td>0.1%</td>
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</tbody>
</table>

Dozens of trace elements make up less than 0.1% ...iron, lead, uranium, strontium...
Let’s get reacquainted with atoms

* The atomic species (element) is determined by the number of protons in the nucleus.

* The number of electrons normally matches the number of protons so that the atom is neutral.

* Atoms are fundamentally quantum mechanical systems:
  
  electrons can only occupy certain ‘energy levels’, and radiation from the atom can only come in certain energies.
Some interesting features of stuff made out of atoms

Observing what frequencies (energies) of light are absorbed or emitted by a material can tell you what’s in it

emission spectrum of Iron:

We rarely take time to appreciate our atoms, but all those macroscopic physical characteristics like solidness, texture, color... all arise from properties of atoms and their interactions
Looking in more detail at the nucleus

Nuclei of the same atomic species with different numbers of neutrons are different *isotopes* of the same element.

Nuclei have *energy levels* similar to those in atoms, and they can only absorb or emit radiation at certain energies.

Breaking things down even more:

The nucleons are not fundamental particles: they are composed of quarks.
The fundamental particles

A few key points:

* There are antiparticles to all of these particles too

* All of ordinary matter is made out of things in the first column

* The force carriers are all at work inside atoms

* Quite a few interesting things are missing here...
The fundamental particles

* Quarks are never found free - Particles made of two are called mesons, of three, baryons.

* Particles on the right decay into those to the left (except for the neutrinos)

* So, to have any particles around from the second or third generation, you need to create them... this takes some kind of high energy event

Bottom line: you don’t contain any mus, taus, or exotic mesons or baryons
The familiar photon (light) is sometimes called ‘electromagnetic radiation’ or ‘electromagnetic energy’ because of its role in carrying the electromagnetic force.
Forces at work inside of ordinary matter

Gravity is too weak to matter much to an atom

The electromagnetic force binds electrons to nuclei and governs interactions between atoms.

It also causes the protons in nuclei to repel.

So you need the strong force (and some neutrons) to keep nuclei bound together.

The weak force allows neutrons and protons to transform into each other to make more stable nuclei.
Ok, we’ve taken you apart all the way to leptons and quarks…
(doi you feel at all exposed??)

So what processes are emitting radiation?
Two facts:

* Any charged particle that changes speed or direction will radiate electromagnetic energy (photons)

* In bulk matter at a non-zero temperature, there are charged particles moving around a lot, and moving more and faster the higher the temperature

Every object is always radiating photons
The hotter it is, the more there will be, and the more energetic they will typically be
The Planck Spectrum

This plot shows a ‘spectrum’ because the energy of electromagnetic radiation is proportional to energy.

Thermal spectrum for an object that absorbs and emits perfectly at all frequencies (a black body)

* All ‘black bodies’ (or approximate ones) radiate over many frequencies

* The hotter the object, the more radiation at all frequencies

* The peak of the spectrum is at higher frequencies for higher temperatures.
You’re always glowing in the infrared

Images from:
http://coolcosmos.ipac.caltech.edu
Why are there unstable nuclei?

* Origin of most nuclei (including unstable ones): nuclear reactions in stars and supernovae

* If the half-life of the isotope is really long, it can persist for billions of years

* It often takes many decays before a stable nucleus is created from an unstable one

* Some high energy nuclear reactions can produce new unstable nuclei (carbon-14 is a good example)
Seeking stability

Most common nuclear ‘chess moves’

The line of stability
Gaining intuition about nuclear instability
(the cartoon version)

Stable

Too many nucleons

Wrong ratio of neutrons to protons

Nucleons have too much energy
Types of nuclear decay

1. Gamma decay: nucleus emits photon(s) to settle down, often after another type of decay

2. Alpha decay: nucleus emits alpha particle to lose some nucleons

3. Beta decay: neutron in nucleus transforms into proton, emitting electron and electron-anti-neutrino

4. Beta + decay: proton in nucleus transforms into neutron, emitting positron and electron-neutrino

5. Fission: really heavy nucleus splits into two lighter nuclei (which then tend to be highly unstable themselves), often emitting neutrons too

(6,7,8 Spontaneous nucleon emission, internal conversion and electron capture – not really related to each other and not nearly as common....)
What nuclear decays are taking place inside you?

Given all the trace elements you seem to pick up, probably some of all of them at some point

**Carbon-14:**
- Produced continuously in the atmosphere
- Half-life: 5700 years
- Makes up 0.0000000001% of carbon atoms
- Decays by beta decay to nitrogen-14
- Used for radioactive dating
- >3000 decays per second in your body!

**Potassium-40:**
- Produced originally in stars
- Half-life: 1.3 billion years
- Makes up 0.01% of potassium atoms
- Decays by beta decay to calcium-40 (90% of decays)
- Decays by electron capture and also beta-plus decay to Argon-40 (10% of decays - hey, you produce antimatter!)
- >4000 decays per second in your body!
Electromagnetic radiation over many frequencies (energies) but peaked in the infrared

An occasional alpha particle (most won’t get out of your body) ...possibly some neutrons from fission once in a long while...

Copious numbers of electrons and electron-antineutrinos (the electrons may not all leave your body, but the neutrinos stream to the end of the universe)

Gamma rays following other decays, or due to positron annihilation

... Gravity waves, sound waves, secondary radiation from reactions caused by radiation you’re absorbing...
### The Electromagnetic Spectrum

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<th>Energy (eV)</th>
<th>10^{-9}</th>
<th>10^{-8}</th>
<th>10^{-7}</th>
<th>10^{-6}</th>
<th>10^{-5}</th>
<th>10^{-4}</th>
<th>10^{-3}</th>
<th>10^{-2}</th>
<th>10^{-1}</th>
<th>1</th>
<th>10</th>
<th>10^2</th>
<th>10^3</th>
<th>10^4</th>
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<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>10^6</th>
<th>10^7</th>
<th>10^8</th>
<th>10^9</th>
<th>10^{10}</th>
<th>10^{11}</th>
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<th>10^{19}</th>
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<tbody>
<tr>
<td>Wavelength (m)</td>
<td>10^3</td>
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<td>10^1</td>
<td>1</td>
<td>10^{-1}</td>
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### Excitations in Neutral Matter:

- Molecular vibrations, rotations
- Atomic transitions
- Nuclear transitions

### Continuous Thermal Emission:

- Cold gas clouds
- Cosmic Microwave Background
- Objects in this room
- The Sun
- Bright stars
- Ionized gas clouds

### Particle Radiation in Our Environment

- Cosmic rays
- Solar neutrinos
- Dark matter (kinetic energy)
- Alphas
- Electrons
- Neutrinos
- Relic neutrinos?
Conclusion: stay away from my detectors!

Two things I’m interested in being able to detect:

**Solar Neutrinos**
Looking for particles at MeV energies
How do you tell them from nuclear decay products or cosmic rays?

**Cosmic Microwave Background Light**
Looking for photons in the microwave
How do you tell them from photons radiated by everything else?

Next week: thinking about radiation signals we’re currently interested in for some of the big questions