67th Compton Lecture Series, University of Chicago

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

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Why are we here?

“The purpose of these lectures is to make accessible some of the remarkable recent developments in physical science to the non-specialized public, and to share with laymen some of the intellectual and cultural excitement associated with scientific developments that may affect in some way the lives of all of us and are a significant part of our cultural heritage”

(from the Compton Lectures website)
Why detectors, measurement, and (gasp) *statistics*, of all things??

*I promise the statistics won’t be too mathematical, or unbearably dull, or anything to be afraid of...really! The important thing is how we use statistics for reasoning.*
Measurement anchors even the most exotic physics in concrete observations

A New York Times headline when Dark Energy was first discovered (1998)

Wary Astronomers Ponder An Accelerating Universe

By JOHN NOBLE WILFORD

At their telescopes in the last few years, astronomers have been searching the heavens for evidence that the expansion of the universe is slowing down. The mutual gravitational attraction of all matter in stars, planets and everything else known or hypothesized should be putting a gradual brake on the outward rush of space since the explosive moment of cosmic creation in the theorized Big Bang.

The preliminary results of the search are now in, and they are stunning. The expansion of the universe appears to be accelerating, instead of decelerating.

Based on: images and spectral information about supernovae in the distant universe, collected using CCD cameras mounted on telescopes:

Images from supernova.lbl.gov
Supernova Cosmology Project, Perlmutter et al.
Detectors anchor even the most exotic experiments in the physics of the everyday.

Bizarre phenomenon

radiation

detector

Detectors have to be made out of ordinary stuff that we understand really well.

100,000 gallons of drycleaning fluid!

Used for first detections of neutrinos from inside the sun.
This lecture series, fundamentally, is about detecting radiation.

Energy traveling through space in the form of particles or waves

(and no, I’m not going to get technical about what I mean about particles, waves, energy, traveling, space, ‘through’, ‘in’, or ‘or’)
Where we’re headed....

Next week: The physics in this room

After that:
* Environments in the universe and the types of radiation they produce
* How these types of radiation interact in ordinary matter (like, say, the stuff in your detector)
* What sorts of detector technologies are there?
* How to deal with a random universe
* So you saw something in your detector. Prove it.
* Case studies: looking into the sun from 2km underground, and trying to learn about Dark Energy from the South Pole
Today’s show: Beta decay and the Neutrino, a tale of two detectors

Chadwick, 1914  Reines & Cowan, 1956
What was known by 1914 about radioactivity?

Radioactivity: spontaneous emission of radiation from nuclei (originally thought of as coming from atoms, before nuclei were discovered), first observed by Becquerel in 1896.

A picture like this appeared in Marie Curie’s Dissertation, 1906

**alpha rays:** positively charged, not very penetrating
(now know to be particles- helium nuclei)

**gamma rays:** no charge, very penetrating
(a form of electromagnetic radiation or photons)

**beta rays:** negative charge, somewhat penetrating
(beta “particles” or electrons)

(Already there are some concepts here that we should flesh out in more detail... and it’s only going to get worse!)
How were these things known?

Take a source of radiation, bend it with a magnetic field (if it’s charged anyway), and look at what happens using photographic plates or an electroscope.

Uses ionization: when charged particles go through matter, they can strip electrons off of atoms, making ions.
The contrast between alpha and beta spectra
(a spectrum is an expression of how a physical phenomenon varies with energy)

The question: For a given sample of one single kind of atom, how many alpha or beta particles as a function of energy are emitted from the sample?

Beta spectra were puzzling, but the detector technology was too crude to make progress
Enter the Geiger Counter

The first detector capable of detecting single particles* was famous Geiger Counter, invented in 1908

(*well not exactly – the very first single-particle counters were diligent graduate students staring at fluorescent screens for hours in the dark, including Geiger himself!)
Chadwick’s 1914 beta experiment
Chadwick’s 1914 beta experiment

Why did people believe Chadwick?

1. He measured his “backgrounds”

2. He tested for “detector-related systematic uncertainty” by changing his detector

(Note: the lines on this spectrum are now known to come from a type of nuclear decay called “Internal Conversion”)
A new theory to explain beta decay

Wolfgang Pauli’s ‘desperate way out’ of 1930: invent a particle!

Alpha decay

\[
\text{Original Nucleus} \rightarrow \text{New Nucleus} + \text{alpha}
\]

\[
\text{Energy: } E = E - \Delta E + \Delta E
\]

“\(\Delta E\)” is the energy released in the decay

Beta decay

\[
\text{Energy: } E = (E - \Delta E) + E_\beta + E_\nu
\]

Here, \(E_\beta + E_\nu = \Delta E\)
Could you detect this “neutrino”?

Fermi’s theory, calculations by Bethe and Peierls: There was a mechanism for detecting the neutrino, but you’d have to make your detector more than a *light-year thick* in order to have a decent chance of stopping a particular neutrino inside it!

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"Inverse beta decay" on Hydrogen

\[ \bar{\nu}_e + \text{H} \rightarrow \text{n} + e^+ \]
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Probability to the rescue!

Radiation emission and detection are both random processes.

An individual neutrino is *most likely* to travel through a big chunk of matter without being stopped. But there is a non-zero chance that once in a while, boom! (well, OK, not quite “boom”).

- **Nuclear explosions or sustained reactions:**
  - huge numbers of neutrinos

- **New detector technology (liquid scintillator):**
  - huge detectors

(There’s your boom!)
“Project Poltergeist” (Reines, Cowan 1951)
A slightly saner version, 1956

Images from Los Alamos Science #25, “Celebrating the Neutrino” 1997
The first really big detector (10 tons!)

Whoa!

Inverse beta decay
positron annihilation
neutron capture
gamma rays
scintillation
photomultiplier tubes
delayed coincidence...

(you could fill a whole lecture series with this stuff!)
1956, the triumphant result!

The rate of "delayed coincidence events" in the detector was 5 times higher when the reactor was on!

But ...how to be sure this was a neutrino signal from the reactor?

(1) Test what you see in the detector using a known positron and neutron sources so you believe that’s what you’re really seeing

(2) Change the shielding to reduce the "accidental backgrounds", and see if the neutrino-like signal changes (it shouldn’t)

(3) Change the amount of water and the amount of Cadmium and see if it changes the number of neutrino-like events that you see (it should)

A case of Champagne was consumed by Pauli and his friends... and in 1995 this result finally got the Nobel Prize
Beta decay and the neutrino: from the first single-particle detector to the first ton-scale complex detector

Chadwick, 1914  Reines & Cowan, 1956

We’ve just scratched the surface:

Types of radiation (alpha, beta, gamma, neutrinos, positrons...)

Radiation interaction in matter (ionization, scintillation...)

Random nature of radiation production and detection

Techniques for making convincing arguments that you’ve seen something

See you next week!