67th Compton Lecture Series, University of Chicago

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

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Today’s Question:

What radiation signals do we need to detect in order to learn about the physics of the very small and the very large?

The approach: some historical examples and then reflections on the methods and challenges for today’s experiments
Launching from a question last week

How do we know that some particles are composite, and others are ‘pointlike’?
* In the early 1900s, scattering experiments using alpha particles were done by Geiger and Marsden (working in Rutherford’s lab)
Once in a while, an alpha particle ‘backscattered’

It was almost as incredible as if you fired a fifteen-inch shell at a piece of tissue paper and it came back and hit you

Rutherford, 1909
Alpha particles can only be scattered backwards by a large force.

This apparently required the existence of a dense central positive charge in the atom – the nucleus!
Assumptions that went in (very simple!):
- all positive charge and most of the mass of the atom concentrated in a point
- alpha particles are repelled from the positive charge according to the electromagnetic force law (proportional to $1/r^2$)
- energy and momentum have to be conserved

Predicted the *angular distribution* that was actually observed!
Wait a minute! Nuclei are so not pointlike!

But that took higher energy scattering to discover:

Low Energy

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\uparrow & \downarrow \\
& \text{a} \\
\end{align*} \]

Medium Energy

\[ \begin{align*}
& \text{b} \\
\alpha & \downarrow \\
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High Energy

\[ \begin{align*}
& \text{c} \\
\alpha & \downarrow \\
\end{align*} \]

Smaller angle than you would expect
Scattering allows you to probe structure

...However, you need high energy particles in order to do it

**High energy particle accelerators:**
probe structure
test interactions
create new particles

Example: Fermilab!
* Protons and antiprotons collide
* Energy in each collision is enough to create particles many times the mass of the proton
At very high energies, colliding particles can result in creating new particles.

It’s just $E=mc^2$!

Image from www.fnal.gov
What particles do you need to detect?

Quarks don’t escape – instead they produce ‘jets’

New heavy particles don’t last long – they decay

Mostly:
electrons
muons
pions (mesons made of up and down quarks and antiquarks)
kaons (mesons made of u, d, and s quarks/antiquarks)
...
neutrinos (but those are very hard to see)

High energy charged particles
Requirements for these detectors

Detect high energy charged particles
Measure their energies
Measure their directions
Measure their charge/mass
Get the timing right
The electromagnetic spectrum:

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<tr>
<th>Energy (eV)</th>
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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 and neutrinos from beta decays
- Relic neutrinos?

Notes:
- for electromagnetic radiation, frequency*wavelength=speed of light
- frequency*Planck’s constant=energy
- Energy is expressed in units of ‘electron-volts’, the energy needed to move an electron through 1 Volt
Seeing the very small:

To study structure of matter, test forces/interactions, and produce new particles:

* Need high energy particle interactions
* Need to detect energetic charged particles
* Need to measure their energies, masses, charges, directions, and timing

* Most of the information is in the ‘distributions’ of the measured particles with respect to energy, direction, etc.

(Accelerators aren’t the only sources of high energy particles... Cosmic rays reach much higher energies...

The detectors often look quite different but need the same things)

A Big Challenge:

Searching for subtle signatures amid vast amounts of information

Less of a Challenge:

Local natural background radiation. Generally it is way too low energy.
Shifting gears: the very large

Cosmology asks questions about the origin and evolution of the universe as a whole.

Hubble ultra-deep field. NASA/STScI
The Classic Tools:
1) telescope,
2) eyes, or a camera
Early 20th century: ways of finding out about the stuff that’s out there

1. Locations of objects in the sky...where’s your telescope pointing?

2. What are they made of?....look at the spectral features of the light.
3. How far away are they?  
   ... use brightness of ‘standard candles’

4. How are those objects moving?  
   Look for evidence of redshifts or blueshifts of light
Hubble’s profound discovery, 1929

The more distant the galaxy... the greater its redshift and the more rapidly it is receding from us.
More distant galaxies appear to be moving away faster.

An important (but really hard to believe!) point here: This does not imply that there is any ‘center’ - you’d see the same thing from any galaxy!
If it’s expanding, it used to be small.

...when it was small, it had to be hot and dense.

...at some point, it must have been too hot and dense for atoms to exist.
A concrete prediction of the Big Bang model

* A hot soup of charged particles and photons is pretty much a perfect black body (perfect absorber and emitter at all frequencies of light).

* A sea of neutral hydrogen atoms isn’t anymore.

* As soon as atoms started to form, the light from that earlier stage was no longer absorbed, and it should still be around.

* It’s coming from really far away, and should be redshifted a lot.

Everywhere, we should see thermal radiation peaked in the microwave (as if from a 3K blackbody)
...Discovered by accident, Penzias and Wilson 1963

They looked for dung but found gold, which is just opposite the experience of most of us!

Ivan Kaminow, a colleague
Probing the physics of the early universe by mapping the features of the microwave sky:

Image source:
http://arcade.gsfc.nasa.gov/cmb_intensity.html

NASA/WMAP science team
Exploring structure and evolution with optical light

(Sometimes X-ray light is also useful for finding big objects – galaxy clusters - which have hot thermal gas)
Seeing the very large:

To study composition, structure, and evolution of the universe as a whole:

* Look at electromagnetic radiation from every direction in the sky
* Detect electromagnetic radiation in the microwave, optical, x-ray...
* Need to measure the direction it comes from, its energy or spectrum information, and its intensity

* Most of the information is in the statistical properties of the signals across the sky or as a function of distance.

Challenges for CMB experiments:

Detecting tiny variations in intensity across the sky, when many things closer to us contribute larger signals

Challenges for optical cosmology surveys:

Need to get good measurements of huge numbers of objects and look at subtle statistical properties

Complex physics of the objects themselves can confuse you
We know it’s interesting to detect light at high and low energies for cosmology...

And charged particles at high energies for particle physics...

What about charged particles at low energies?

(And what about particles that aren’t electrically charged?)
If a particle isn’t charged, how does it interact?

The weak force allows for scattering of neutral particles, as well as transmutations that can be used as signatures.

Example 1: A solar neutrino (energy ~MeV)
   a) neutrino scatters with an electron via weak force
      (maybe the electron gains enough energy that you see it)
   b) neutrino scatters with nucleus
      (nucleus gains only a tiny amount of energy – hard to see)
   c) neutrino interacts in nucleus and changes nuclear species
      (you might be able to either find these new nuclei or see some secondary radiation caused by this)

Example 2: A dark matter particle (massive, but slow)
   a) dark matter particle scatters via weak force with a nucleus, leaving the nucleus with a tiny kick of energy
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Special challenges for some interesting neutral radiation (e.g. Dark matter, neutrinos):

* Need large, sensitive detectors because weak interactions are rare
* Detect secondary products, often low-energy charged particles or light
* Extra care has to be taken to distinguish your signal from local radiation backgrounds
* Statistics: how to deal with very small numbers of candidate ‘events’?

Fundamental physics experiments we haven’t surveyed:

* Gravity experiments (most typically, use lasers to detect motion)
* Atomic physics experiments/tests of quantum mechanics (also typically lasers)
* Additional experiments with a bearing on cosmology – cosmic rays, light element abundances, ...
* Probably others I’ve just missed!
Early days: measuring simple features of charged particles from scattering, or just the intensities and spectra of a few objects in the sky...

Nowadays: we are still measuring features of charged particles and intensities/spectra across the sky, but it’s gotten bigger, subtler, and more complex.

Detector demands:

Charged particle detectors allowing measurements of energies, directions, masses, and timing
Detectors for wide range of EM radiation, allowing measurements of intensity, spectrum, (and direction)
Good ways of discriminating your signal from your backgrounds
The plan:

1) Advertisement: detectors are cool
2) Subatomic physics background
3) Radiation signals of interest
4) Detectors for electromagnetic radiation
5) Charged particle detectors
6) Randomness and uncertainty
7) Background for case study 1: Solar Neutrinos with SNO
8) Making a convincing case for neutrino oscillations
9) Background for case study 2: the SPT
10) (Hopefully) making a convincing case that we can test Dark Energy