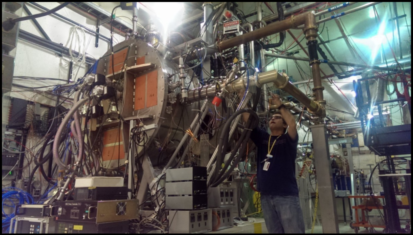
Huge Science

How we build particle accelerators and what we use them for

Daniel Bowring
Fermilab's Ask-A-Scientist
November 9, 2014

Fermilab is huge and complicated. How do you build something like this?

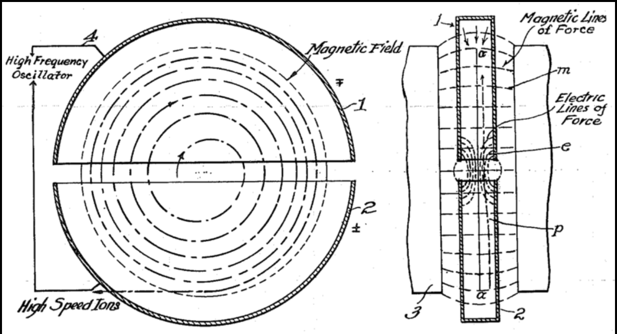


We need to think about particle accelerators in small pieces in order to avoid becoming too impressed.

What are we talking about today?

1. History of particle physics
2. The parts of an accelerator
3. What can you do with an accelerator?

1. An abridged history of particle physics



The whole history of particle physics is fascinating, but we don't have all day.

Let's pick 1900 as a start date. What's going on in 1900?

Boxer Rebellion, China

Carrie Nation, temperance radical, is smashing up bars in the U.S. midwest

First modern hamburger sold in U.S.

What did people know about atoms back in 1900?

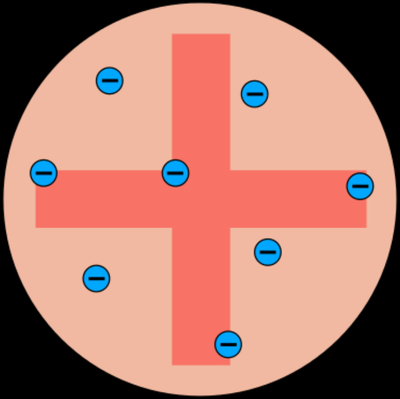
- Things are probably made of atoms.
- Atoms have electrons and some + components too.
- Some materials (radium, polonium, etc.) emit "rays".

- These rays can interact with atoms in interesting ways.

{α-**particle video**}

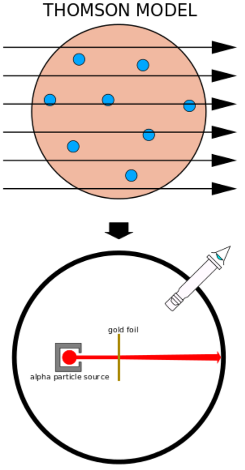
`https://www.youtube.com/watch?v=pewTySxfTQk`

Prior to 1911, J.J. Thomson was pushing his theory that atoms were like blueberry muffins.

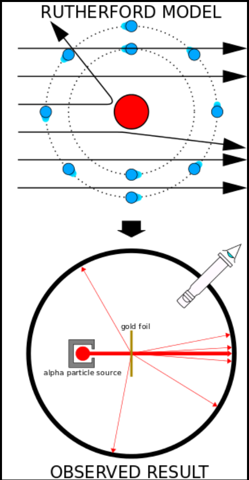


1911: Ernest Rutherford & his students tried **using α-rays as probes to study atoms.**

If the “blueberry muffin” model of atoms was correct, you would expect to see this kind of behavior.



What did Rutherford find instead?

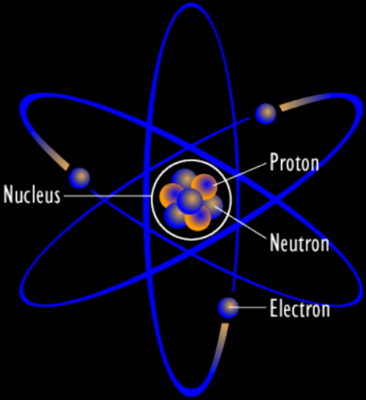


Scattering experiments are a way to learn about the structure of matter.

1911: Where are we now?

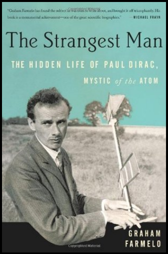
Current events: Amundsen expedition reaches South Pole.

- Things are made of atoms.
- Atoms have a small, $+$ nucleus orbited by $-$ electrons.
- In 1932, James Chadwick discovered the neutron using similar *scattering experiments*. Now we have a complete picture of all regular matter!


Proton
Nucleus
Neutron
Electron

Is that all? Are we done? Well. . .

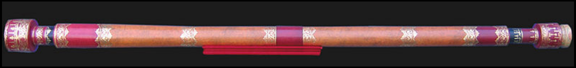
In 1928, Paul Dirac predicts antimatter.

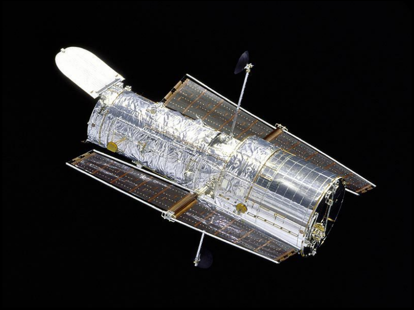


$$i\hbar\gamma^\mu\partial_\mu\psi = mc\psi$$

What is antimatter? An anti-electron is identical to an electron except for its charge. $+$ instead of $-$. When matter and antimatter collide, they annihilate each other.

So far, we're using "rays" to probe other atoms. Amazing progress, but now we need probes with more energy. An analogy:





NASA / SCTI

What keeps the nucleus together?

What about antimatter?

What's our next tool? Cosmic rays!

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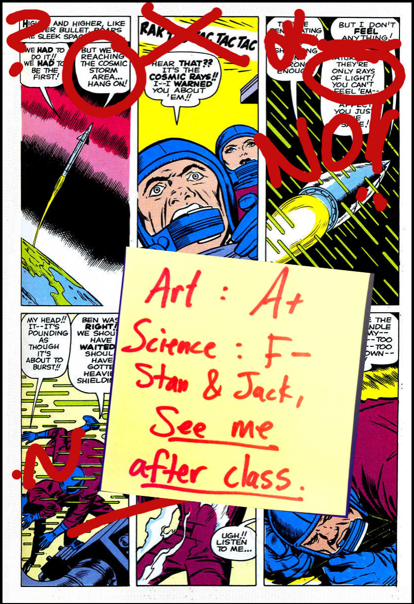


Ok seriously, what are cosmic rays?

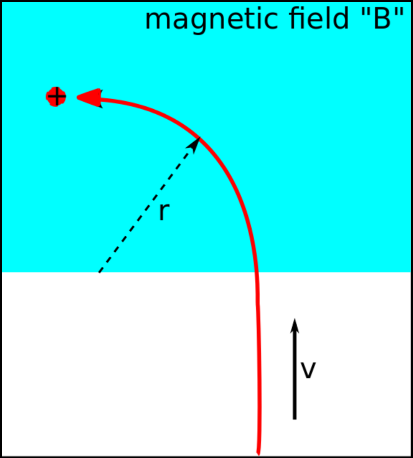
Victor Hess, Austria, 1911

Pic du Midi de Bigorre, in the Pyrenees

Labratoire des Cosmiques, Chamonix, France

Energetic rays measured at high altitudes. Can be used to create, study new forms of matter!

Physics interlude: magnetic fields cause charged particles to curve.

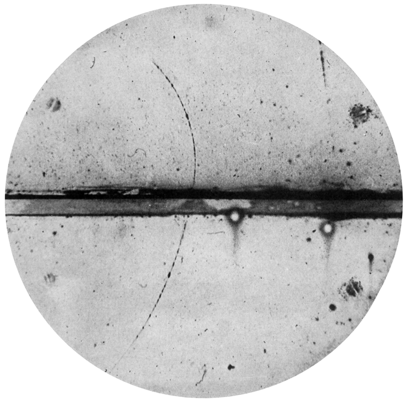


This will be important later!

$$r = \frac{mv}{qB}$$

- r = radius of curvature
- m = particle mass
- v = particle speed
- q = particle charge
- B = applied magnetic field strength
- $+$ curves one way, $-$ curves the other.
- You can measure v if you know r!

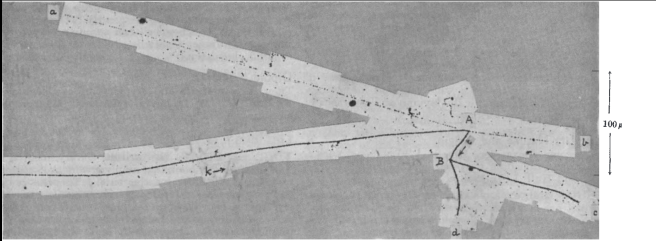
From cosmic rays, we learn that there's a lot more to learn.



1932: Carl Anderson discovers antimatter!
`http://journals.aps.org/pr/abstract/10.1103/PhysRev.43.491`

- **Magnetic fields force charged particles to curve!**
- Slow particles curve more.
- Fast particles curve less.
- $+$ and $-$ curve in different directions.

1948: Powell & co. discover the pion. Not an atom, not a part of an atom, but a whole new thing!



Observer : Mrs. W. J. van der Merwe

http://www.physics.princeton.edu/~mcdonald/examples/EP/brown_nature_163_82_49.pdf

Point being: Enegetic particle collisions can *make new particles*.

Creating particles, thanks to Einstein

$$E = mc^2$$

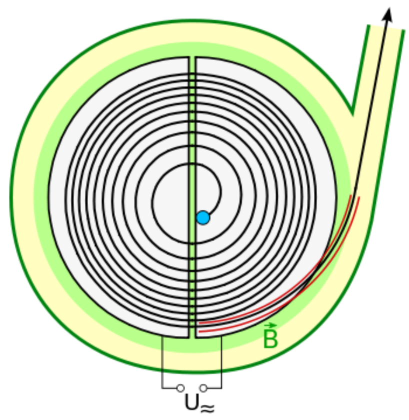
- $E =$ particle energy
- $m =$ particle mass
- $c =$ speed of light (186,000 miles/sec. $= 3 \times 10^8$ m/s)

For a collision of sufficient energy E, you can create particles of mass m.

Now we know everything we need to know to build a particle accelerator!

- Particle collisions are a great way to study particle structure.
- You can also create new particles if you're clever.
- We can (kind of) photograph particle tracks.
- Magnetic fields steer particles.
- Let's build one!

1932: First *cyclotron* operated in California



Notice the magnetic field?
http://www.physics.rutgers.edu/cyclotron/old_papers/phys_rev_50_1131.pdf

- Start particles at the center.
- Give the particles a push (with a **voltage**) as they cross the gap.
- As particles gain speed, they spiral out from the center. Remember, $r = mv/qB$.
- Extract them when they get to a certain v (or r).

What can you do with a cyclotron?

- Create new elements
- Learn things about atoms and isotopes
- Medical physics
- Some contribution to the Manhattan Project too. . .

2. The parts of a particle accelerator

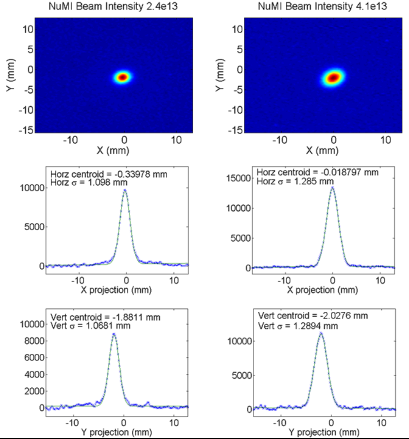
Let's assemble our ingredients.

1. A beam
2. A way to accelerate the beam
3. A way to steer the beam
4. Detectors to study collisions
5. Diagnostics

Every lab is different and these systems can be very *very* different from lab to lab. We're going to use Fermilab as our working example.

Step 1: Make a beam

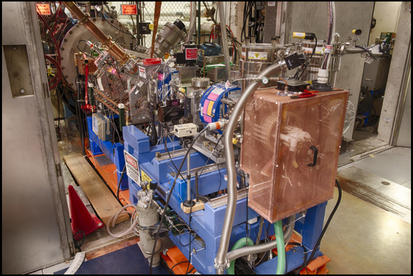
Step 0: Wait, what is a beam?



M. Wendt, "Beam Emittance Measurements at Fermilab"
http://adweb.desy.de/mdi/CARE/Bad_Kreuznach/Reports/FermiEmittance_A4.pdf

- Lots of protons (or anti-protons), all traveling together in the same direction.
- Like charges repel each other. It's like herding cats!
- Not a continuous steam of particles. Bunched like sausage links.
- Runs in a pipe under ultra-high vacuum. (Comparable to interplanetary space.) You don't want your protons scattering off of air molecules.

Step 1: Make a beam



- Hydrogen is easy to get in gas form, but it's paired: H–H (H_2)
- High-voltage abuse separates the hydrogen atoms and gives them each 2 electrons. Now they're H^- ions.
- Electrons are stripped off, leaving bare protons.
- Protons put through structures that "bunch" the beam, focus it, and speed it up.

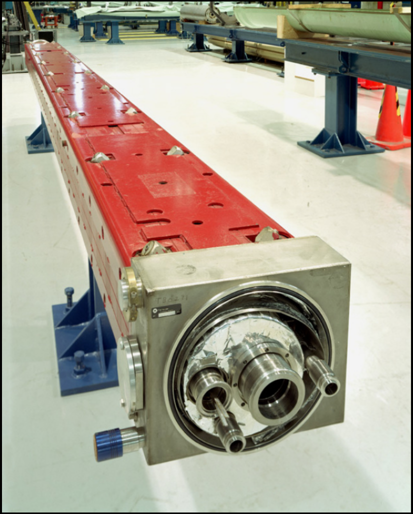
Step 2: Accelerate the beam

Fermilab linac with copper accelerating structures

$$\text{Energy gain} = qV$$

- q = particle charge
- V = applied voltage
- Each of these sections applies about 1 million volts to each particle.
- NOAA says a lightning strike can have 100 million volts. (But much more current than we use in our accelerator.)

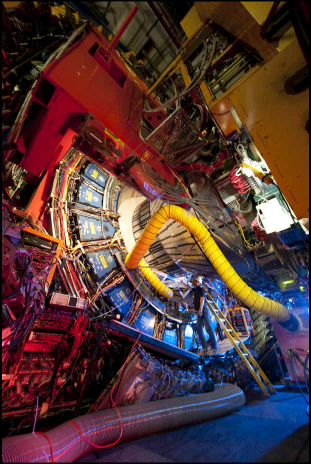
Step 3: Steer the beam



Tevatron dipole bending magnet

- Do you remember $r = mv/qB$? Magnetic fields steer charged particles.
- Bending magnetic field is 3-4 times stronger than a normal MRI magnet.
- About 1 million times stronger than the Earth's magnetic field.

Step 4: Collide your beams inside a detector capable of studying what happens.



Tevatron's CDF experiment

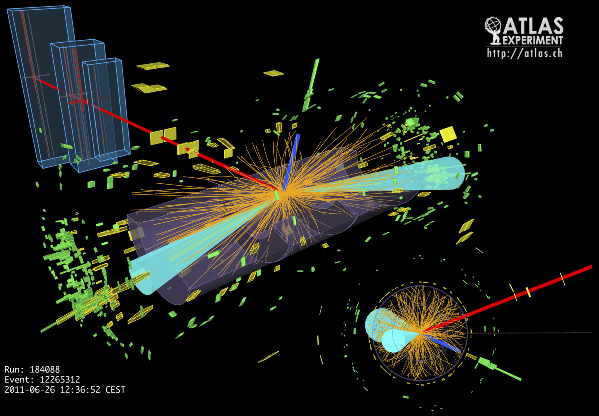
- Detectors built around proton/antiproton collision site.
- Different apparatus for detecting different kinds of particles during/after a collision.
- Handling the raw data coming from this detector is a huge challenge!

Step 5: Carefully control all these systems so they work in concert.

Main control room

A dedicated staff works around the clock to monitor the machine, make improvements, and fix problems.

3. What do we do with accelerators?



Detection of Higgs boson
http://www.atlas.ch/news/images/stories/vp1_Htautau_1muon1electron_run204153_evt35369265_med.jpg

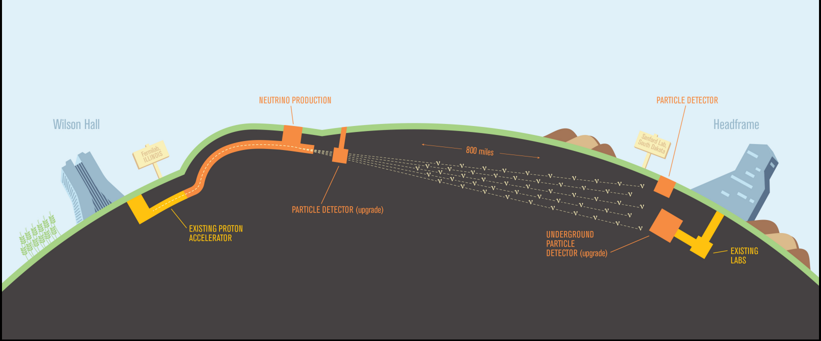
We need to understand neutrinos better.

Pause for neutrino demonstration.

Why neutrinos?

1. They're hard to study because they're so ephemeral.
2. They help us to understand the "Standard Model" of physics. What's correct? What needs tweaking?
3. Precise measurements of neutrino properties can help us answer an interesting question: why is there matter in the universe?

We can use our proton beam to generate intense neutrino beams.



http://lbne.fnal.gov

Because neutrinos are so "ghostly", we can send them straight through the Earth to South Dakota. No tunnel, no beam pipe, nothing!

This is what a neutrino beam looks like.

The detectors are large because neutrinos are hard to detect.

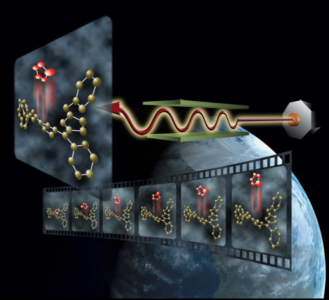
But the beamline is just rocks and dirt.

What else?

1. Other basic science research
2. Environmental applications
3. Medical applications
4. National security applications

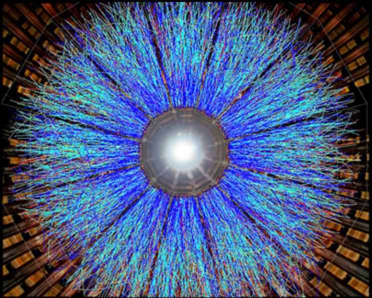
All of this stuff is completely fascinating, but we're almost out of time! I've included links in these slides wherever possible so you can explore on your own, later.

Basic science research



http://lcls.slac.stanford.edu/WhatIsLCLS_1.aspx

You can use accelerators to create lasers so bright and precise, they can study individual molecules and atoms in motion.



http://newsoffice.mit.edu/2010/exp-quark-gluon-0609

You can create and study matter (the "quark-gluon plasma") that was only present in the early universe.

Environmental applications

- You can destroy nuclear waste quickly and cheaply.

  http://science.energy.gov/~/media/hep/pdf/files/pdfs/ADS_White_Paper_final.pdf

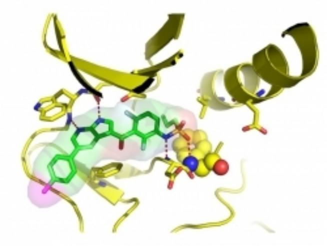
- You can power nuclear reactors safely.

  http://www.theguardian.com/science/blog/2012/feb/09/accelerator-nuclear-reactor

- You can treat flue gas from factories, removing harmful pollutants and creating fertilizer.

  http://ebfgt.com/

Medical applications



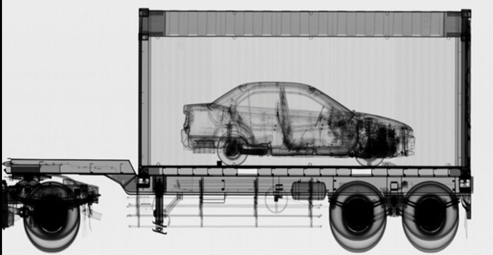
http://energy.gov/articles/light-sources-help-discover-new-drug-against-melanoma

Accelerators used to design anti-cancer drugs, flu vaccines.

http://www-bd.fnal.gov/ntf/reference/hadrontreat.pdf

Proton, neutron, and ion beams can be more effective against some cancers than conventional x-ray radiation treatments.

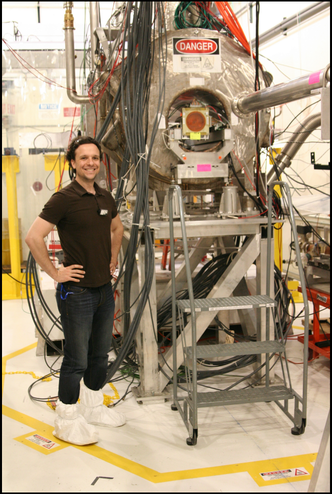
National security applications



http://www.symmetrymagazine.org/article/august-2010/accelerator-apps-cargo-scanning

Accelerators can generate high-energy x-rays for faster, more accurate scanning of cargo containers at ports.

Thanks for your attention!



- There's so much fascinating stuff to talk about. I feel like I barely scratched the surface!
- I look forward to your questions.