Journey to the world of elementary particles

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The concept of elementary constituents

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1. The elementary objects mix in varying proportions to produce compound objects.
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    - Example 2: Early theories of elementary constituents of matter adopted this viewpoint: Fire, Water, Air, Earth were the fundamental constituents.

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    - Example 1: Primary colors red, green, blue mix to produce sensation of other colors.
    - Example 2: Early theories of elementary constituents of matter adopted this viewpoint: Fire, Water, Air, Earth were the fundamental constituents.
2. The elementary objects bind with one another to produce compound objects.
    - Note: This is the modern viewpoint. It originated with the atomic theory of Democritus and others.

Atoms and ions

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Binding energy of the electron in a hydrogen atom is 13.6 eV.

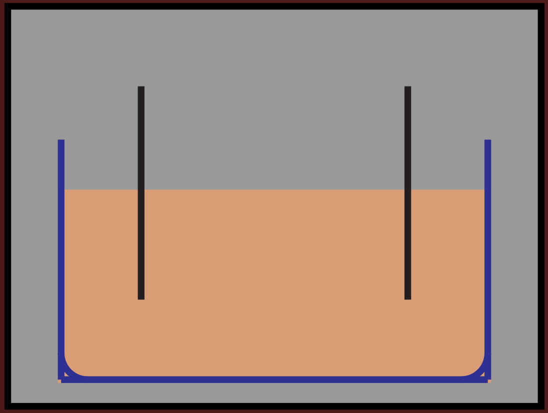
So, if you can put a hydrogen atom in a potential difference larger than 13.6 eV, you can free the electron from the atom and form hydrogen ion.

For other elements, the amount of the energy needed is different.

Discovery of the electron

Take a solution. Put two electrodes in it. Apply an EMF.

If the EMF is high enough, it will strip the atoms of their electrons. The electrons will move towards the positive electrode.



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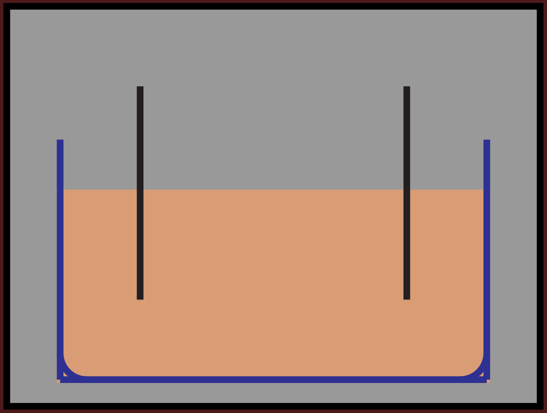

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The nature of the particles moving towards the electrodes was not known until the end of the 19th century.

Thomson (1897) made a hole through the electrode and measured the q/m ratio of particles coming out. Result: the ratio was much larger than that of any ion.

He argued that these are particles of very small mass, carrying electric charge, and called them electrons.

Discovery of the nucleus

Radioactivity was discovered around 1900. The typical energies of alpha particles coming out in a radioactive decay was found to be of the order of MeV.

MeV = Mega (10^6) electron-volt

Rutherford and his associates bombarded atoms with alpha particles with MeV scale energies.

They “saw” the nucleus. The size of the nucleus is of order 10^{-13} cm, down by a factor of 10^5 compared to the atom.

The uncertainty principle

If we shine an object with some kind of waves and want to see substructures smaller than a length ℓ, the wavelength of the wave must satisfy the relation

$$\lambda \lesssim \ell \, .$$

de-Broglie relation between the wave and particle natures:

$$p = \frac{2\pi\hbar}{\lambda} \, ,$$

where p is the momentum of the particles that correspond to the waves. Then,

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Moral: In order to know about smaller and smaller structures, we need to use more and more energetic probes.

Another look

Suppose we have some objects whose lengths are of order ℓ, and we want to know whether they are made up of some building blocks.

The building blocks are somehow confined within a distance of order of ℓ. So,

$$\Delta x \lesssim \ell \,.$$

Heisenberg uncertainty relation:

$$\Delta x \cdot \Delta p \gtrsim \frac{1}{2}\hbar \,.$$

So

$$\Delta p \gtrsim \frac{\hbar}{\ell}, \,.$$

The momentum itself must be greater than its uncertainty. So,

$$p \gtrsim \frac{\hbar}{\ell}, \,.$$

Smaller the object, bigger the momentum of its constituents. Kinetic energy is accordingly bigger.

The particles must also possess an overall attractive potential energy. In order that the composite system is bound, the total energy must be negative, i.e.,

$$|E_{\text{potential}}| > E_{\text{kinetic}}\,.$$

Virial theorem: The two magnitudes do not differ by huge factors. Hence,

$$|E_{\text{total}}| = |E_{\text{kin}} + E_{\text{pot}}| = |E_{\text{pot}}| - E_{\text{kin}}$$

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The basic problem for elementary particle physics: How to achieve high energies?

Big batteries

Can we use bigger sources of static electricity?

Examples: Cockcroft-Walton generator, van de Graaf generator.

Basic idea:

Particle in

Energy E

Region with

potential difference V

Particle out

Energy $E + qV$

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Problem: It is difficult to maintain huge voltages. Even the best insulators break down beyond the megavolt range, sparks and breakdowns occur.

Cosmic rays

What are cosmic rays?

In the beginning of twentieth century, it was observed that various detectors for charged particles, like the gold-leaf electroscope, give a small but non-vanishing signal even when it is not put near any known source of charged particles.

The flux was seen to increase in balloon-borne experiments.

Conclusion: The signals came from processes taking place outside the earth: cosmic rays. In various astronomical environments, processes involving very high energies take place and produce particles. These particles, on hitting our atmosphere, produces secondary particles.

Opportunity: Free supply of high energy particles. Use it.

Detecting cosmic rays

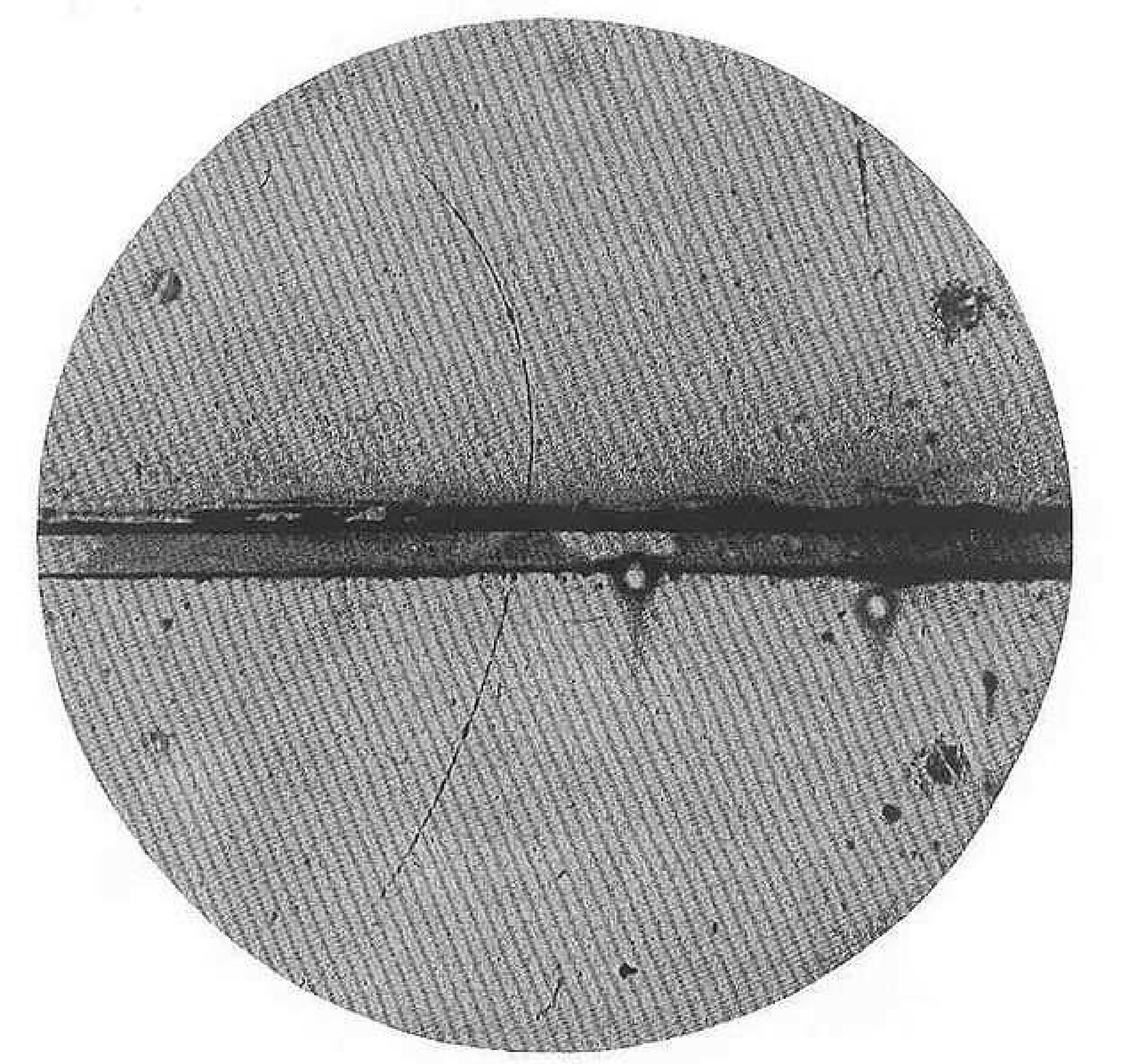
One just needs detectors. Various kinds of detectors were developed in the first half of the twentieth century.

Cloud chamber A chamber of supersaturated vapor of water or alcohol. The vapor cannot condense into liquid because there is nothing like a dust particle that will provide a seed for condensation. If a charged particle passes through it, it ionizes the atoms along the path, and these ions can act as seeds. Condensation of the vapor occurs along the path, and the path has a foggy appearance. This can be photographed and the paths analyzed later.

bubble chamber Roughly the same, except a superheated liquid is used.

scintillation counter Produces light when hit by a particle.

photographic emulsions Photographic plates darken with high energy particle impact.



Achievements

Lots of new particles were discovered through cosmic ray studies. Examples:

- ♣ **Positron:** antiparticle of the electron. Same mass, opposite charge.
- ♣ **Muon:** Properties similar to those of the electron, but is much heavier.
- ♣ **Pion:** Particle conjectured by Yukawa to explain strong interaction between neutrons and protons which bind the nucleus together.
- ♣ **Kaon:** Particles carrying a new property called strangeness.

Limitations

No control over energies and fluxes of the particles.

Elementary vs subatomic

Pions, muons etc are not constituents of the atom. So these are not subatomic.

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The first property is not satisfied if:

1. the particle is unstable (e.g., pions, muons);
2. the particle cannot bind (e.g., photons, neutrinos).

Accelerating particles

Question: Can we build machines where we can accelerate particles and study their behavior at high energies?

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How far can we go up in this dictionary:

	Greek	Latin	English	symbol
10^3	kilo	mille	thousand	keV
10^6	mega		million	MeV
10^9	giga	billio	billion	GeV
10^{12}	tera		trillion	TeV

Cyclotron

Magnetic field perpendicular to the plane of drawing.

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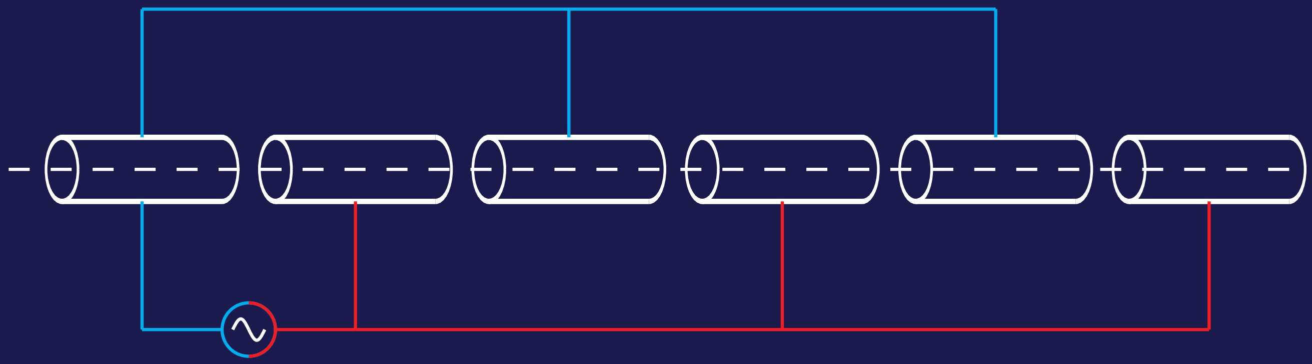
An alternating electric field between the two D's.

Every time the particle goes from one D to the other, it gets a kick.

Radius of the path keeps on increasing.

Linear accelerators



Alternating cylinders of opposite potentials.

A charged particle is subject to an electric force when it crosses over from one cylinder to the next.

Alternating current source ensures that the direction of the electric field is such that it accelerates the particle.

Synchrotron

Working principle: opposite to that of cyclotron.

Type of machine	Magnetic field	Radius of path
Cyclotron	constant	increases with energy
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Advantages of the synchrotron over the cyclotron:

1. A single tube at the circumference of a circle determines the path. Construction of the ‘D’ for the full circle is not needed.
2. Maintaing a constant magnetic field over a large region is difficult.

Discoveries of the 1950s and 1960s

Particles could be accelerated to several GeVs.

1. Many many hadronic states.
   (Hadrons are particles which have strong interactions.)
2. Antiparticles of several of them, e.g., antiproton.
3. Substructure of the proton in a Rutherford-type experiment.
   Constituents of the proton came to be known as quarks.
4. All other hadrons can be thought of as made of quarks.

Problem with synchrotrons

A particle moving in a circular path is always accelerating. Hence,

Problem 1 Some force has to be applied all the time to keep it in orbit. This force increases with energy. If this is done by applying a magnetic field, high magnetic fields are required. Recall the formula

$$\frac{R}{v} = \frac{m}{|q|\,B}\,.$$

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Problem 2 The particle always radiates and loses energy. This is called synchrotron radiation. For a particle of mass m and energy E moving in a circular path of radius R,

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Solution To obtain larger values of E, build machines with bigger R.

Fixed-target machines vs Colliders

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That is a big waste of energy. Consider production of a heavy particle C from lighter particles A and B:

$$A + B \to C + D \,.$$

For A at rest, one needs (simplified form for small m_B and m_D)

$$E_B > \left[\frac{m_C^2 - m_A^2}{2m_A}\right] c^2 \,.$$

Define $m_C = r m_A$:

$$E_B > \frac{1}{2}(r^2 - 1) m_A c^2 \,.$$

So, to produce a particle 10 times heavier than A, one needs roughly 50 times the mass-energy of A.

Problem occurs because the two initial particles have a net momentum.

In a collider (or storage ring), two beams with equal and opposite momenta are collided. So there is no net momentum in the initial state.

If the two beams have opposite charge, same set-up can accelerate both beams. So e^+-e^- colliders, or $p\bar{p}$ colliders came up.

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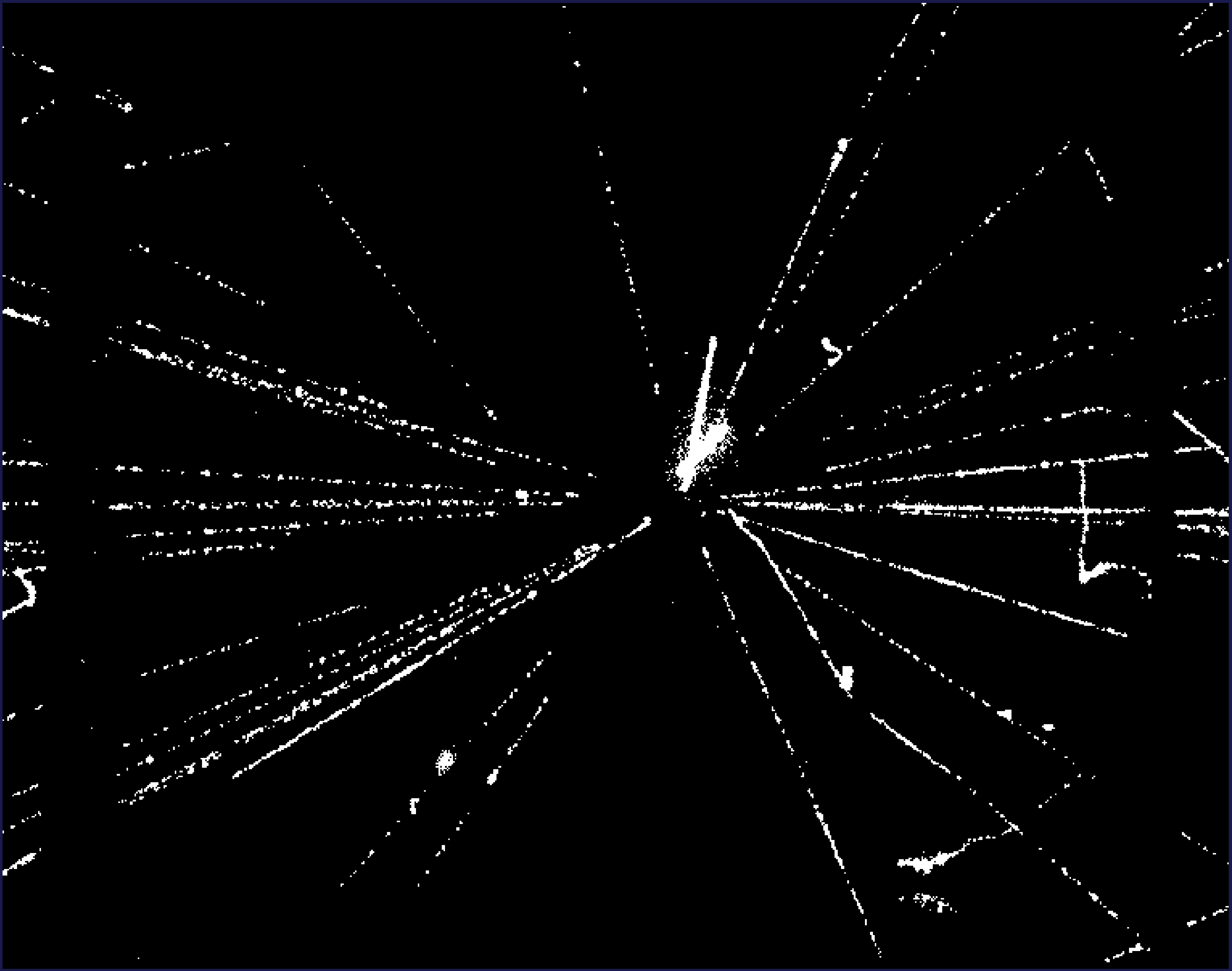
Comparison of e^+-e^- and hadronic colliders:

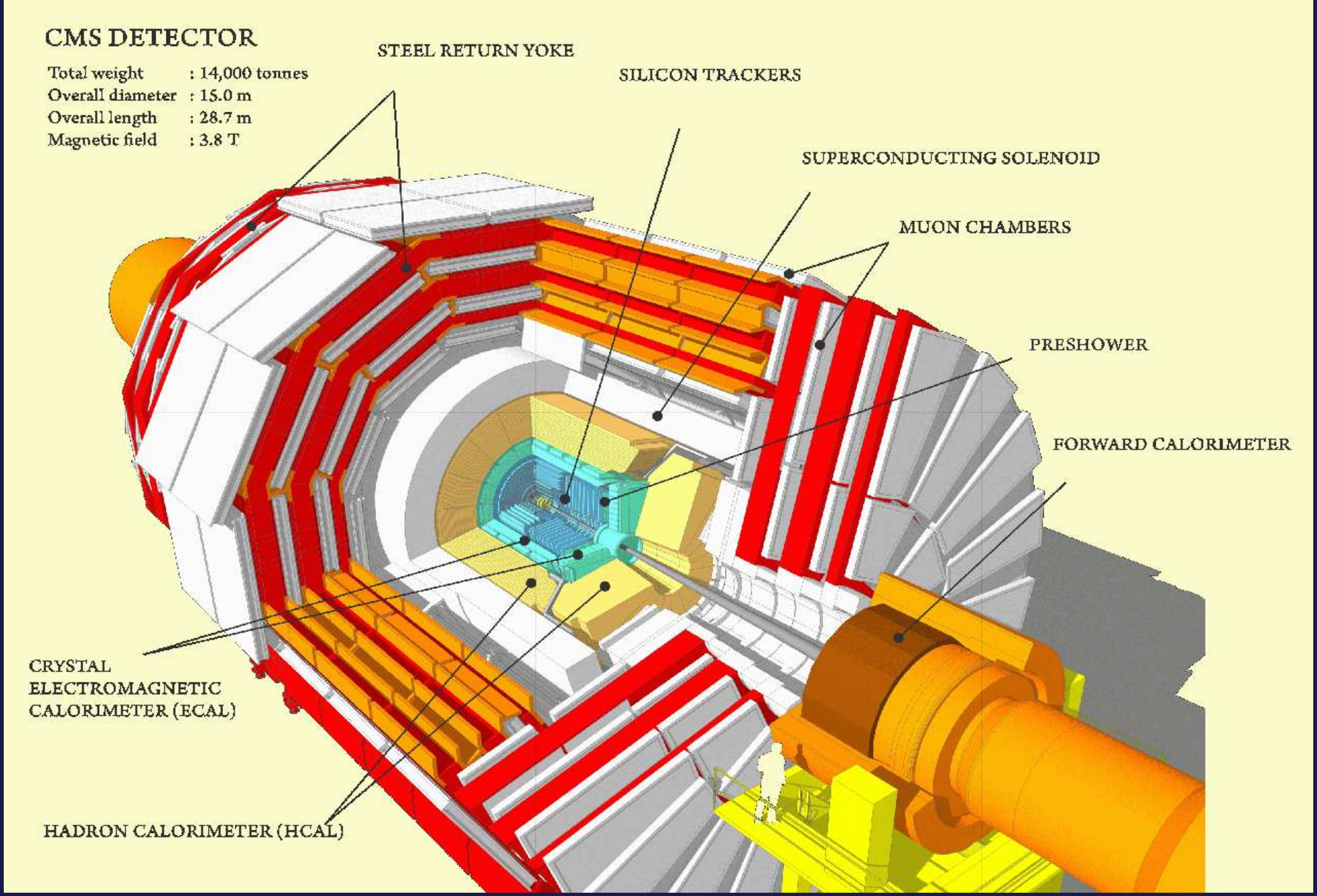
	e^+-e^-	hadronic	reason
Synchrotron radiation	worse	better	$m_e \ll m_p$
reaching high energy	difficult	easier	$m_e \ll m_p$
precision test	yes	no	proton has substructure



Bigger and bigger colliders

Machine			length	energy	beams	discovery
Full Name	Short	Location	(km)	(GeV)		
Super proton Synchrotron	SpS	CERN	6.9	300	$p\bar{p}$	W, Z
Tevatron	—	Fermilab	6.3	1000	$p\bar{p}$	t
Large Electron-Positron Collider	LEP	CERN	27	45	e^+e^-	
Large Hadron Collider	LHC	CERN	27	7000	pp	Higgs boson

A modern detector



The present list of elementary particles

Fermions

	Name	Symbol	Charge		Name	Symbol	Charge
Leptons	Electron	e	-1	**Quarks**	Up	u	2/3
	Electron-neutrino	ν_e	0		Down	d	$-1/3$
	Muon	μ	-1		Charm	c	2/3
	Muon-neutrino	ν_μ	0		Strange	s	$-1/3$
	Tau	τ	-1		Top	t	2/3
	Tau-neutrino	ν_τ	0		Bottom	b	$-1/3$

Bosons

Spin	Name	Number	Symbol
1	Photon	1	γ
	W bosons	2	W^+, W^-
	Z boson	1	Z
	Gluons	8	$\mathtt{G}$
0	Higgs boson	1	H

Non-accelerator experiments

Many properties of elementary particles can be tested without accelerators.

Examples:

Testing proton stability: Huge underground experiments. No instability detected so far.

Solar neutrino detection: Detects neutrinos from the sun. Derived important information about neutrino masses.

Neutrino observatories: Detecting cosmic neutrinos. The experiments have just begun!

Indian neutrino observatory (INO)

News item, 07 Jan 2015

The Indian government has given the go-ahead for a huge underground observatory that researchers hope will provide crucial insights into neutrino physics. Construction will now begin on the Rs15bn ($236m) Indian Neutrino Observatory (INO) at Pottipuram, which lies 110 km from the temple city of Madurai in the southern Indian state of Tamil Nadu. Madurai will also host a new Inter Institutional Centre for High Energy Physics that will be used to train scientists and carry out R&D for the new lab.

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Detection of atomospheric neutrinos. Aim: resolving neutrino mass hierarchies.

Huge project, big opportunities.