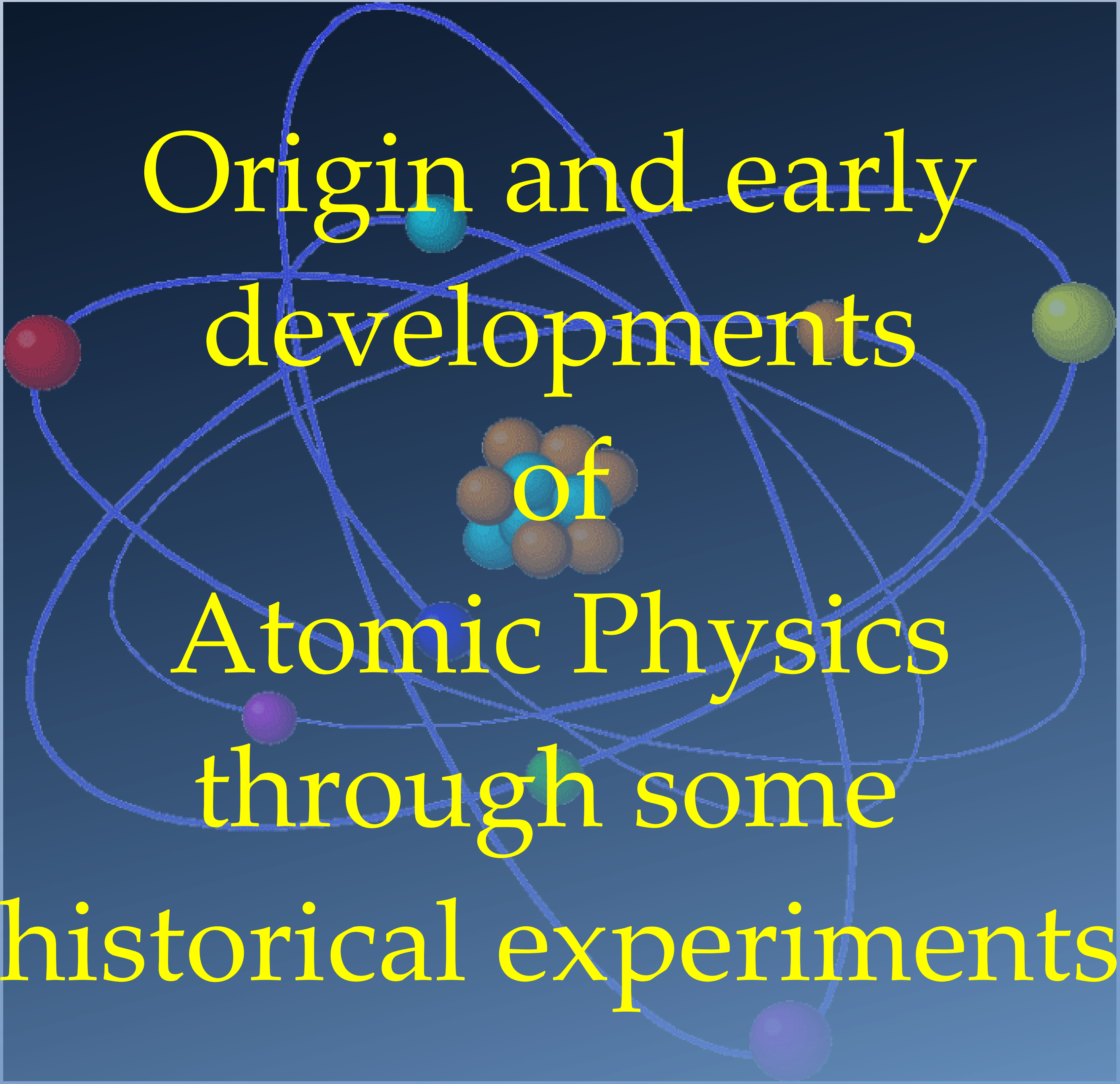
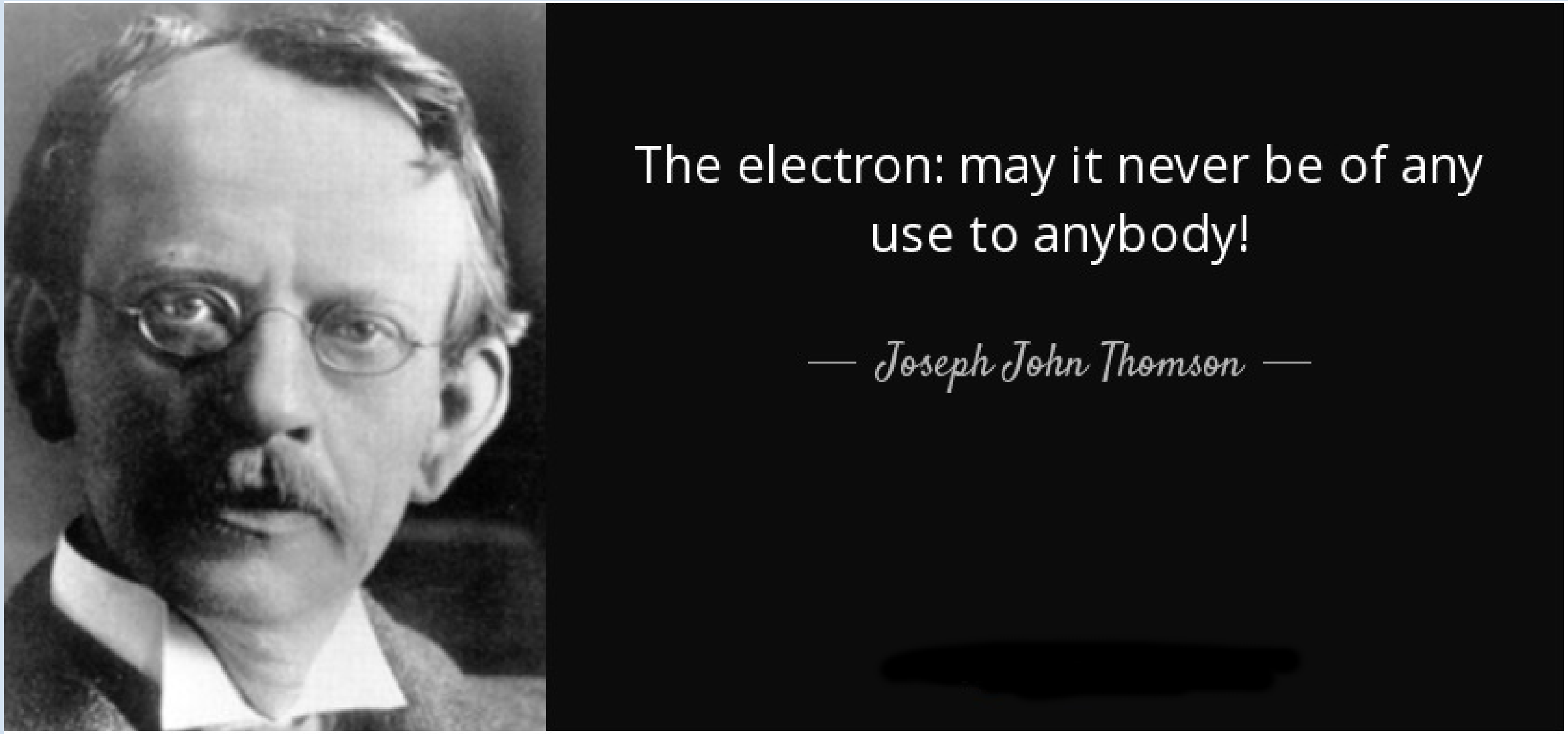


Origin and early developments of Atomic Physics through some historical experiments

John Joseph Thomson
and the discovery of the electron



The electron: may it never be of any use to anybody!

— Joseph John Thomson —

[redacted]

First part

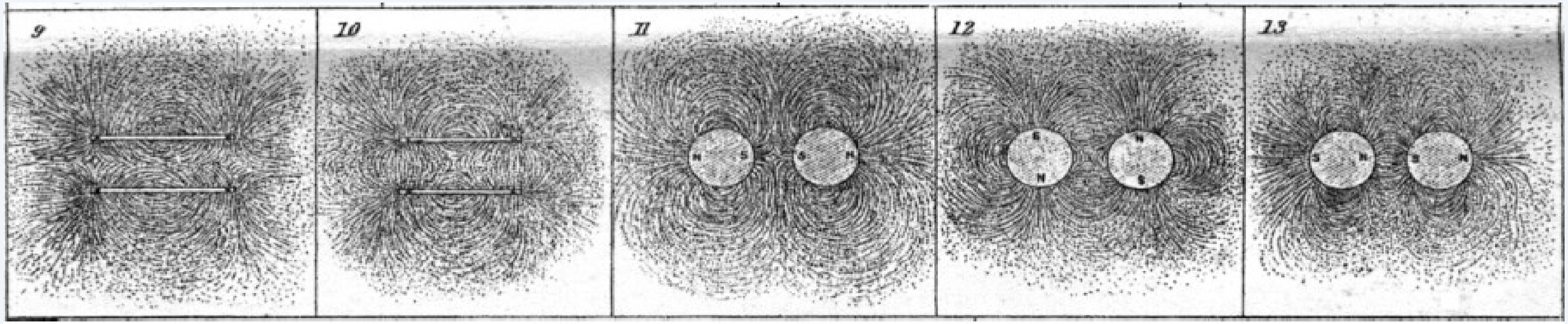
A short introduction: the state of things in Physics during the late XIX century

1865

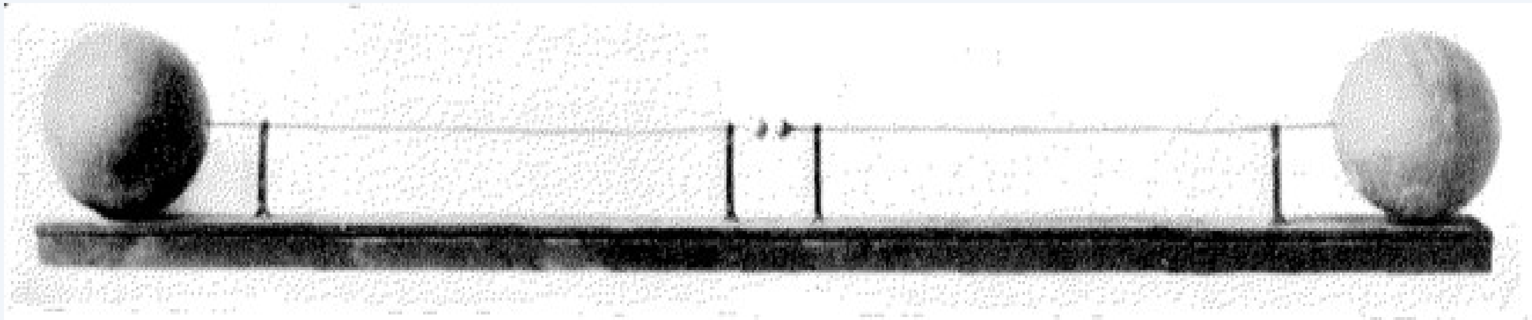
Maxwell's equation

James Clerk Maxwell, with the publication of *A Dynamical Theory of the Electromagnetic Field* demonstrated that electric and magnetic fields travel through space as waves moving at the speed of light.

It's the birth of the
crucial physical concept of
FORCE FIELD
Maxwell's results were largely based
on Faraday's experimental
works about magnetic field lines.



The German physicist **Heinrich Hertz**
between **1886** and **1889** will conduct
a series of experiments
that will prove the effects he was observing
were evidences of Maxwell's predicted
electromagnetic waves.
He will invent a first rough dipole resonator.



1874

A first evaluation of the elementary charge

In 1874 **George Johnstone Stoney**, an Irish physicist,
calculates a first imprecise value of the charge
of the “atoms of electricity”
hypothesized by Helmoltz.
He used Faraday's electrolysis laws and
the number N found by Loschmidt in 1866,
the number you now know as Avogadro's number.

He divided the quantity of electricity
taken for the electrolysis of a cubic centimeter
of hydrogen by the number of atoms that
this volume might contain in normal conditions.
He found out a **10^-20 Coulombs** charge
and suggested to take this value as a unit of measure.

Vacuum tubes

Since XVII century,
as a consequence of Torricelli's
famous experiment,
many scientists had tried
to create vacuum using pumps.
In the early years of 1700 **Francis Hauksbee**
invented a wellworking pump and used it
to study electric phenomena in gases.

These studies did not give significant results till 1855,
when **Heinrich Geissler** invented
a mercury vacuum pump,
that allowed to obtain very rarefacted gases.
Hermann Sprenger in 1865 refined upon it.
His tool made it possible to produce vacuums
with less than one hundredth of an atmosphere
in cathode ray and X-ray experiments.

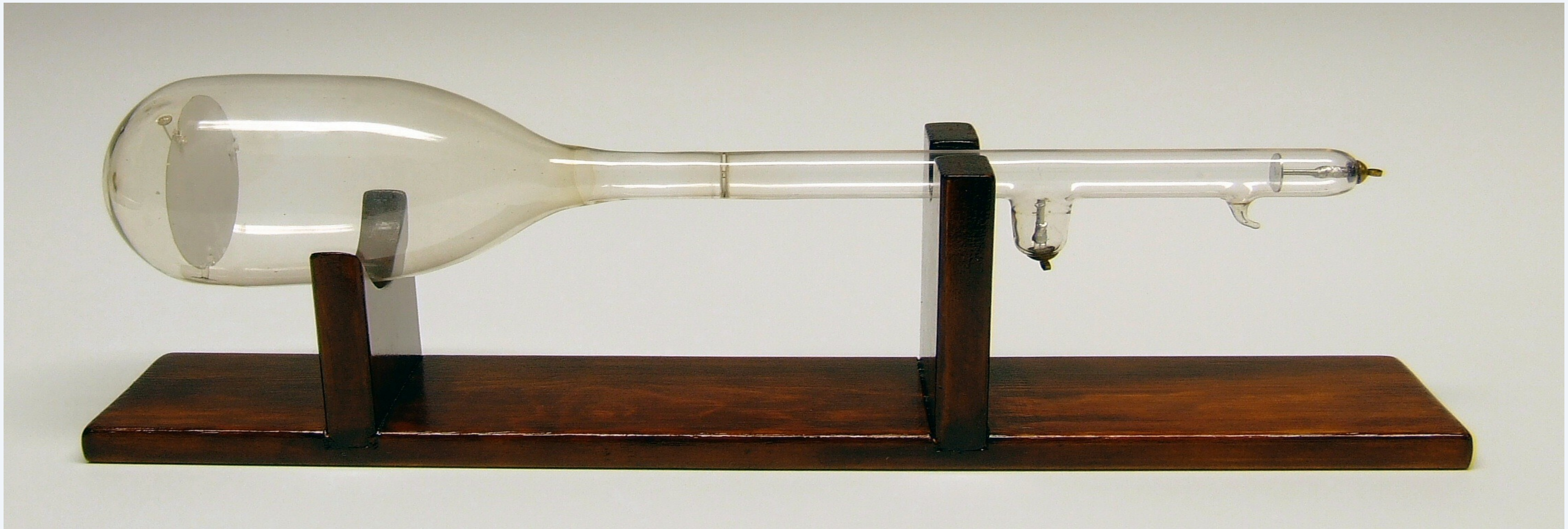
1876

Cathode rays

Many physicists performed experiments
on the electric discharge through gases.
They studied especially the fluorescence
produced on the glass
by the transfer of electricity into the tube.
Cromwell Fleetwood Varley understood that this
fluorescence was caused
by the collision between the glass and
some agents travelling from the cathode.

In 1876 **Eugen Goldstein** called
these misterious agents
“cathode rays”
believing that this phenomenon
had the same nature as light.

cathode rays tube



Fundamental experiments were performed by **William Crookes**:
he published his results in **1879**. He had verified that cathode rays

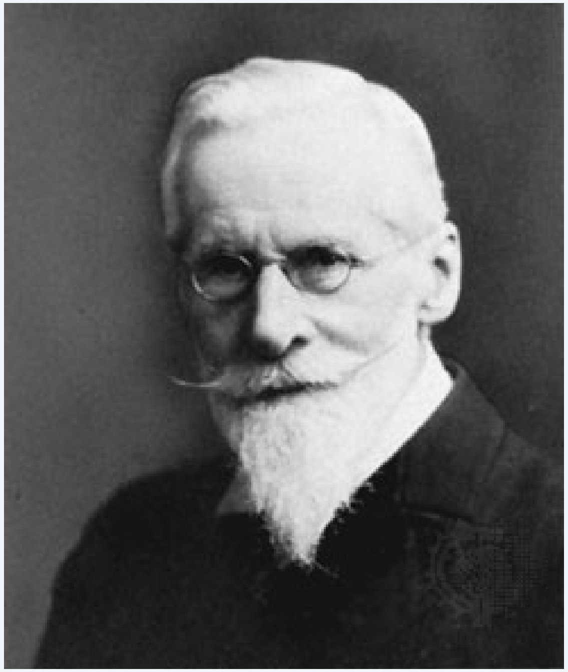
- travel on a straight line

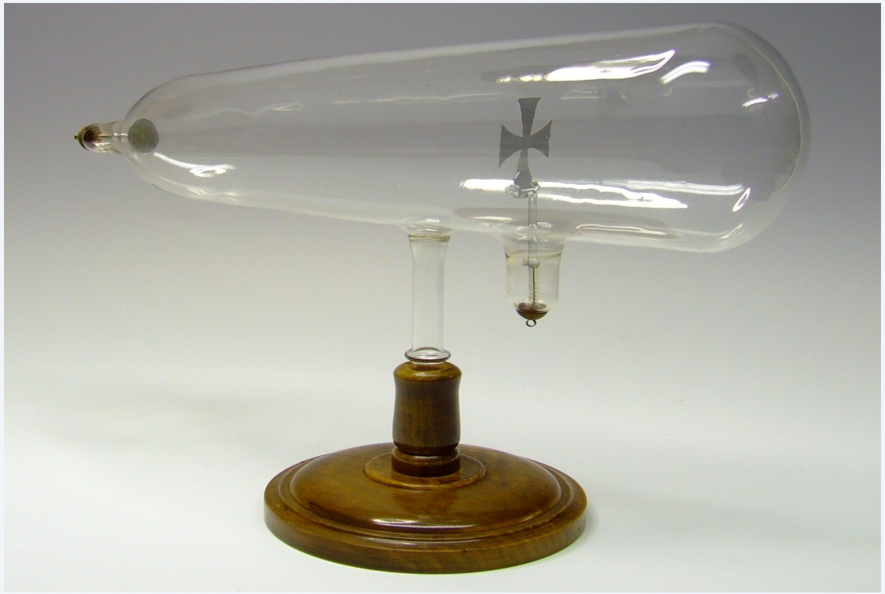
putting a maltese cross between the cathode and the end of the tube, they shaped a geometrically similar shadow on the glass;

- produce a mechanical action

on objects making them move along the tube;

- are deflected by a magnetic field.





Crookes' experiments

Crookes said prophetical words
seeing beyond his experiment results.
He was convinced that cathode rays
were beams of particles,
the building blocks of matter.
He talked about
"the fourth state of matter".
But he had also seen radiant energy
transported by cathode rays.

He guessed the double nature of matter and energy,
object of a physical revolution that
had to wait 30 years to be discovered.
Crookes was sure that the greatest problem
for the future would have been solved
studying this “fourth state of matter”.
Contemporaries did not appreciate these ideas,
perhaps because of Crookes' metaphysical believings.
He practiced spiritualism.

1895 Röngten and X-rays

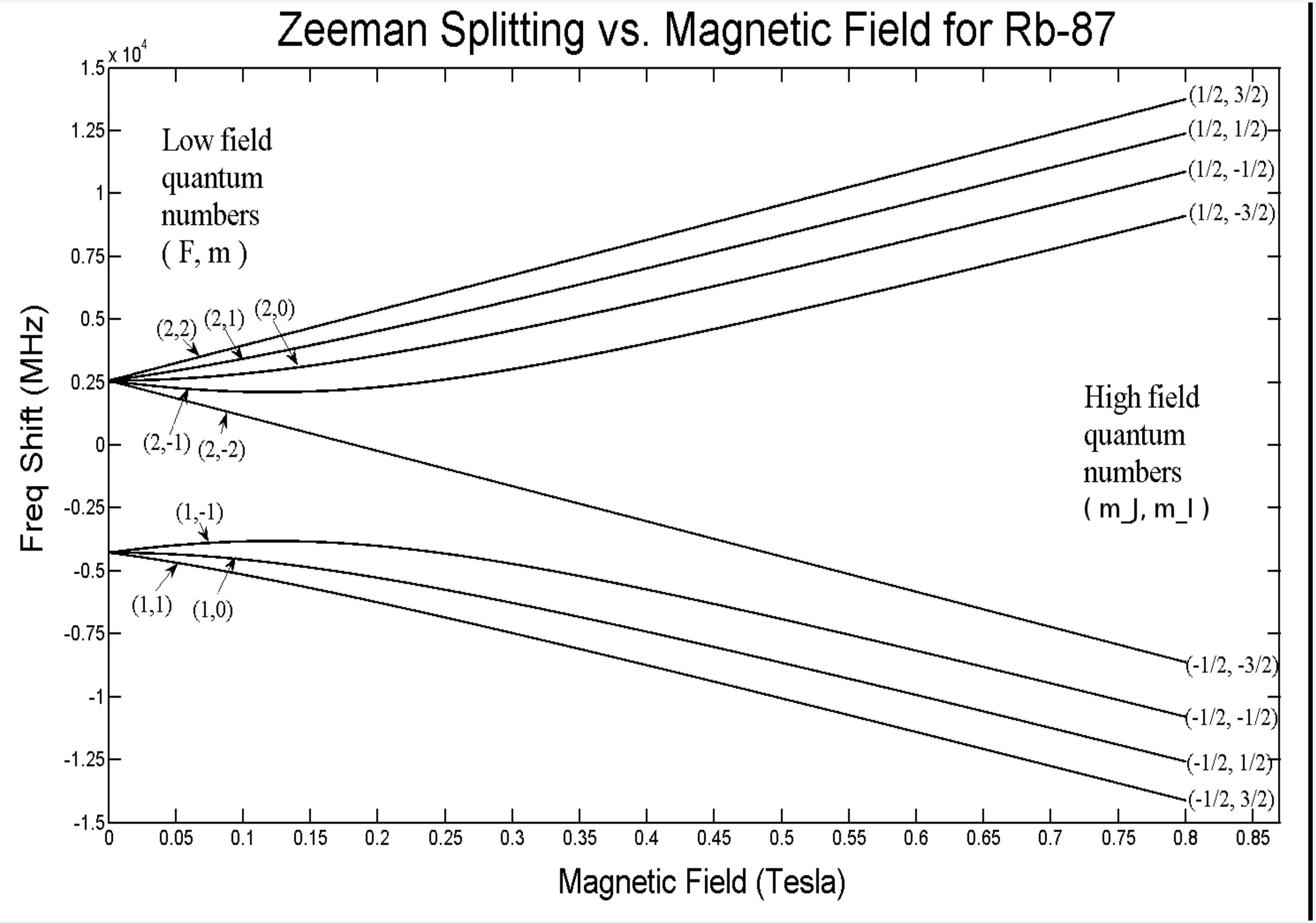
In november 1895 Wilhelm Konrad Röngten
found that, when cathode rays hit
the glass end-side of the tube,
some misterious highly penetrant rays
were issued by the glass.
They could blaken photographic plates and
provoque fluorescence of many substances.
His discovery made a great sensation
among people.

He had placed a tube in front
of a fluorescent screen.
He had completely wrapped up the tube
with black paper for some reason
but he was surprised to see that the screen
became fluorescente just the same.

Cathode rays could not have travelled
the distance from the tube
to the screen.

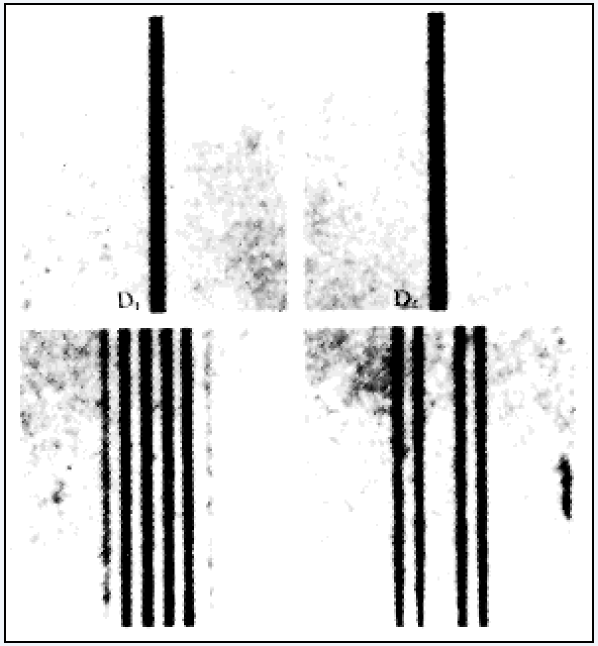
What kind of radiation was that?
He accidentally put his hand
between the tube and the
screen and saw the shadow
of his bones.
Then he made
the first radiography
of the history using
his wife's hand.

1896 Zeeman Effect

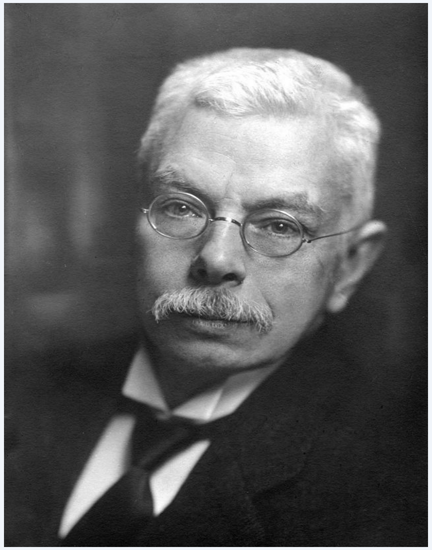


Pieter Zeeman had studied under Hendrick Lorentz at the university of Leiden and there he became "privat Dozent".

In 1896 he disobeyed the direct orders of his supervisor and used laboratory equipment to measure the splitting of spectral lines due to a strong magnetic field.



His discovery has now become known
as the *Zeeman effect*:
a spectral line is split
into several components
in the presence of a magnetic field
and the shift is proportional to the
magnitude of the magnetic field.



Hendrick Lorentz
first heard about Zeeman's
observations on Saturday 31 October 1896
at the meeting of the Royal Netherlands
Academy of Arts and Sciences in Amsterdam.

The following Monday, Lorentz called Zeeman into his office and discussed with him about an explanation of the observed phenomenon, based on his theory of electromagnetic radiation.
The Zeeman effect clearly showed the presence of **moving electric charges in atoms.**

Lorentz calculates e/m

It is astonishining that
Lorentz was able to calculate
the charge-to-mass ratio of these particles.
He understood that
the moving charges were negative
and derived a value of e/m
from the relation between
the split of frequencies due to the Zeeman effect
and the magnitude of the magnetic field.

Lorentz's theory described
the frequencies issued by matter
as a consequence of the **harmonic motion of “ions”.**

Agreeding to a Larmor's theorem,
if a magnetic field is applied, **the shift of frequency**
is proportional to the magnitude of the field,
and inversely proportional to the mass-to-charge ratio.
You can calculate the charge to mass ratio,
for example in this way:

$$\frac{e}{m} = \frac{4\pi}{B} \cdot \frac{c}{\lambda^2} \left| d\lambda \right|$$

This result by Zeeman and Lorentz was obtained
1 year before Thomson's discovery of electrons,
15 years before Rutherford's discovery of nucleus,
17 years before Bohr's atomic model
(Bohr's theory will explain why
the frequencies of light emitted by atoms
are related to the energy of orbitating electrons).

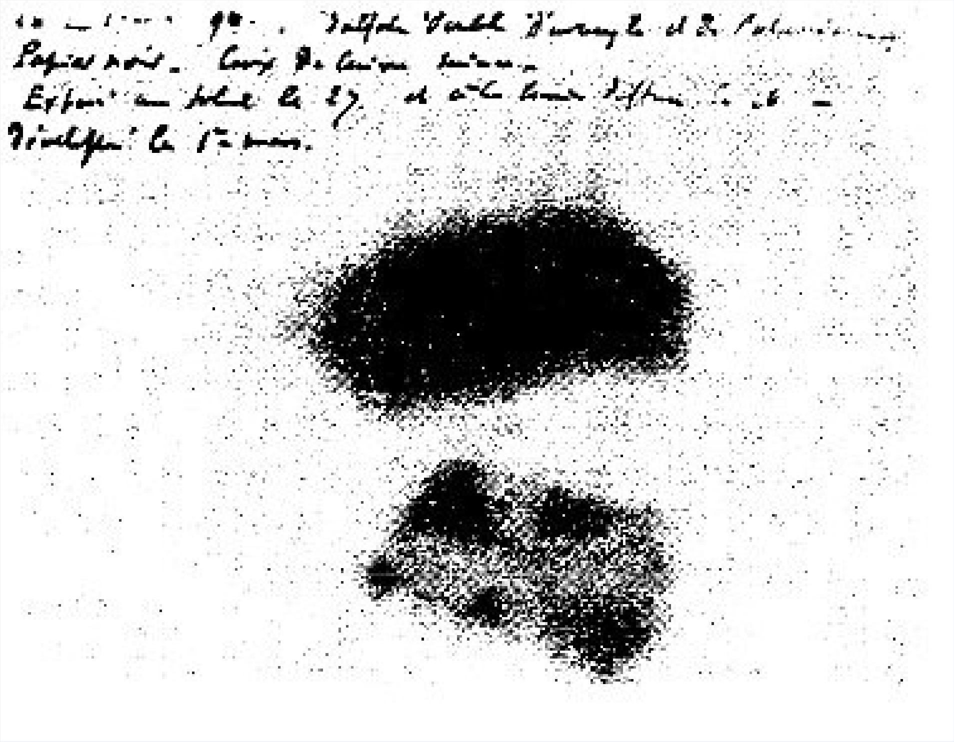
Zeeman and Lorentz did not provide
any significant interpretation of the value e/m.
This is the reason why the “discovery of the electron”
has to be ascribed to another physicist.

1896 Radioactivity

In the same year, while Zeeman and Lorentz
were thinking about Zeeman effect,
Henry Becquerel announced
in Paris a new discovery.
He was working on the possibility
that the sun light could make crystals emit a
penetrating radiation like Röngten's X-Rays.
By chance one of the crystals
contained uranium salts.

The weather was bad and Becquerel
had put away some photographic plates
in a drawer, far away from light,
and had left the crystals at their place.
He found out that
the photographic plates were impressed.
Quickly he could understand
that all crystals containing **uranium**
issued an intense radiation.

This is what he saw having placed a copper cross between the crystals and the plate.



This was the state of things at the very end of the XIX century.

After two hundreds years
of experiments and studies,
scientists were working hard
because they felt to be close to understand
the microscopic nature of matter.

Some experiments had given an evidence
of the presence of electric charges in atom.

Some other experiments showed the emission
of penetrating misterious radiation by matter.

In Europe many physicists were performing experiments with cathode-rays tubes.

What was the real nature of these cathode rays?

Were they some kind of radiation?

Did they have any relation with X-Rays?

Were they vibrations of the aether as light is?

Were they beams of particles?

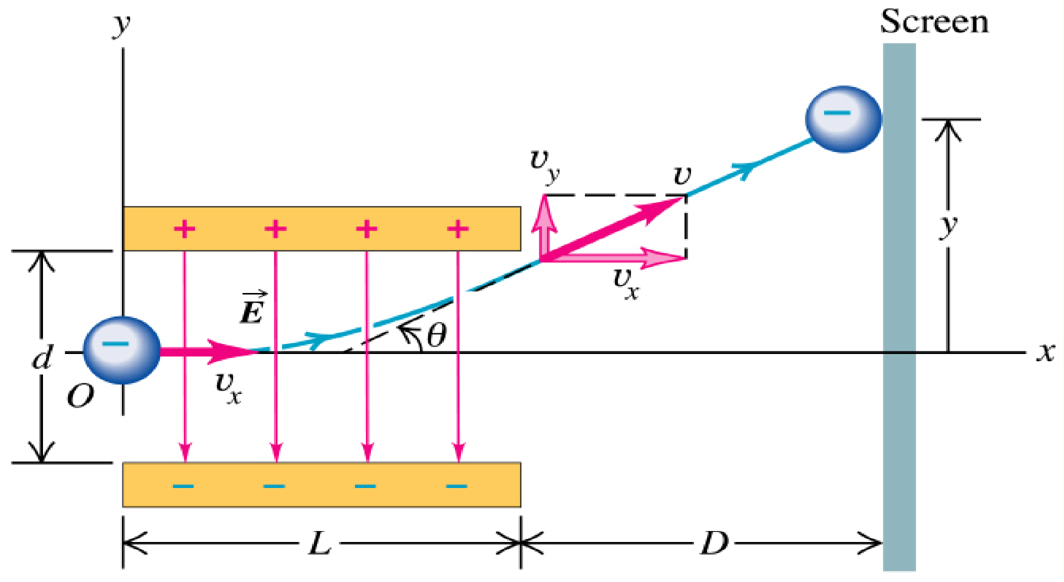
Were they neutral or charged particles?

Were they atoms?

Were they something much smaller than an atom?

In the year **1897**
an English physicist,
J.J. Thomson,
will give an answer to these questions
and will build a bridge
between old and new physics.

Second Part



Thomson's experiment

The discovery of the electron

After Crookes', Rongten's
and Becquerel's findings,
everyone in Europe was doing
experiments with cathode rays tubes.
And everyone was making hypothesis
on the real nature of cathode rays.

There were two main
schools of thought.

In Germany the scientist
of greatest influence was Hertz
who had proved
the existence of electromagnetic waves.
In 1883 he performed some experiments
with vacuum tubes
to study the behaviour
of cathode rays in an electric field.

If they had been charged particles
they would have been attracted
by a charged plate of a capacitor.
But **he had not observed**
any deflection of the rays
and he had concluded that
cathodic rays were waves
just like the electromagnetic waves
he had discovered.
But he wasn't right...

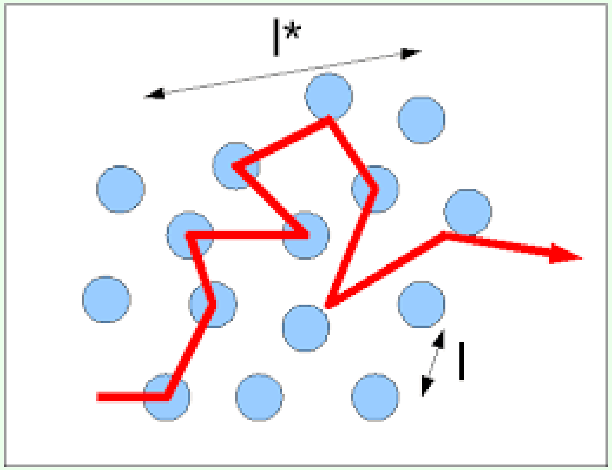
Hertz did not see any deflection because of two main reasons:

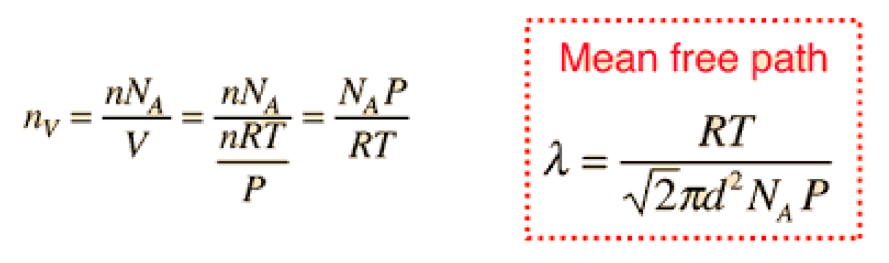
a) the speed ot the rays was too high
and the electric field too weak
to produce a measurable deflection.

b) In fact the gas in the tube was not
so highly rarefacted and the remaining air
was ionised by the electricity.
Ions covered the plates of the capacitor
significantly reducing
the intensity of the electric field.

While in Germany the inclination to think
cathode rays as waves was prevaling
(with some exception like Helmoltz),
in England scientists were more
disposed to believe that
they were beams of particles.
Crookes stated that rays were gas molecules,
which were strongly rejected away
from the cathode, having captured
a negative charge from it.

Eugen Goldstein refused Crookes' idea.
In a vacuum tube, with a pressure
less than 1/100000 atmospheres,
the **mean free path** of a gas molecule,
according to kinetic theory,
would have been around 0.6 centimeters.
The cathode rays traveled 90 centimeters!



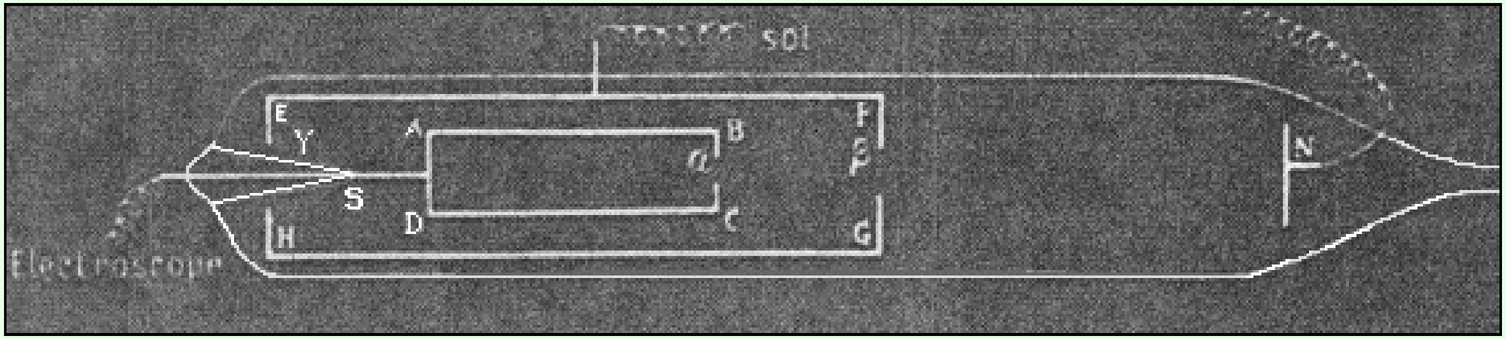


$$n_V = \frac{nN_A}{V} = \frac{nN_A}{\frac{nRT}{P}} = \frac{N_A P}{RT}$$

Mean free path

$$\lambda = \frac{RT}{\sqrt{2}\pi d^2 N_A P}$$

In **1895** the French **Jean Baptiste Perrin**
showed that the cathode rays
left a negative charge on a charge collector
he had placed into the tube.
But when he applied a magnetic field, the
electroscope did not sign any electric charge.
This fact meant that the rays carried a negative
charge and were deflected by a magnetic field.

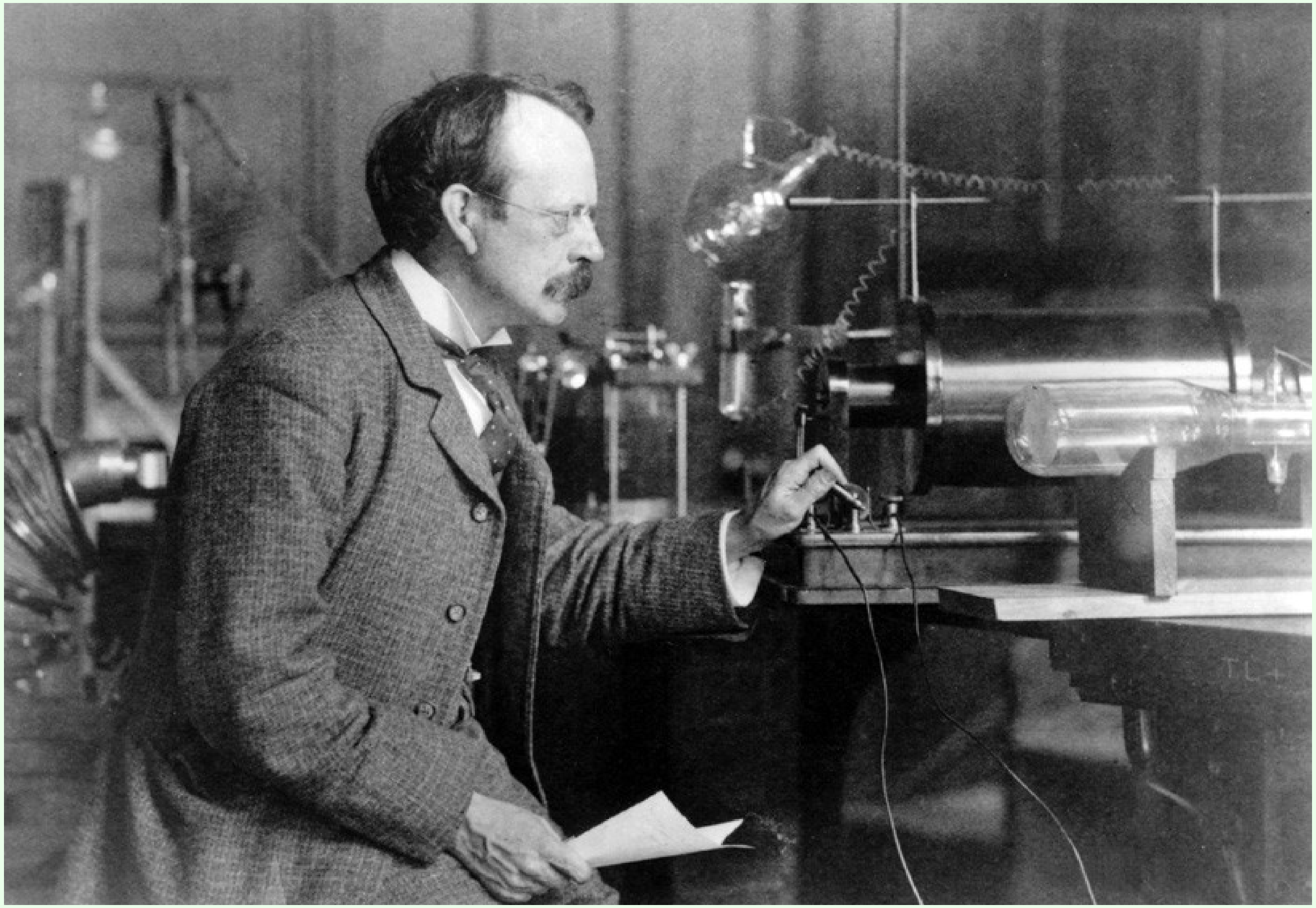


The supporters of the “aether theory”
criticized Perrin's experiment.
In the tube used by Perrin
the collector of charge
was in front of the anode.
They were convinced that the negative
charge revealed by the electroscope
was due to gas ions
rejected by the cathode.

They said that...

"...these charged particles have any more to do with the cathode rays than a rifle-ball has with the flash when a rifle is fired"

This is the moment for J.J. Thomson to make his entrance

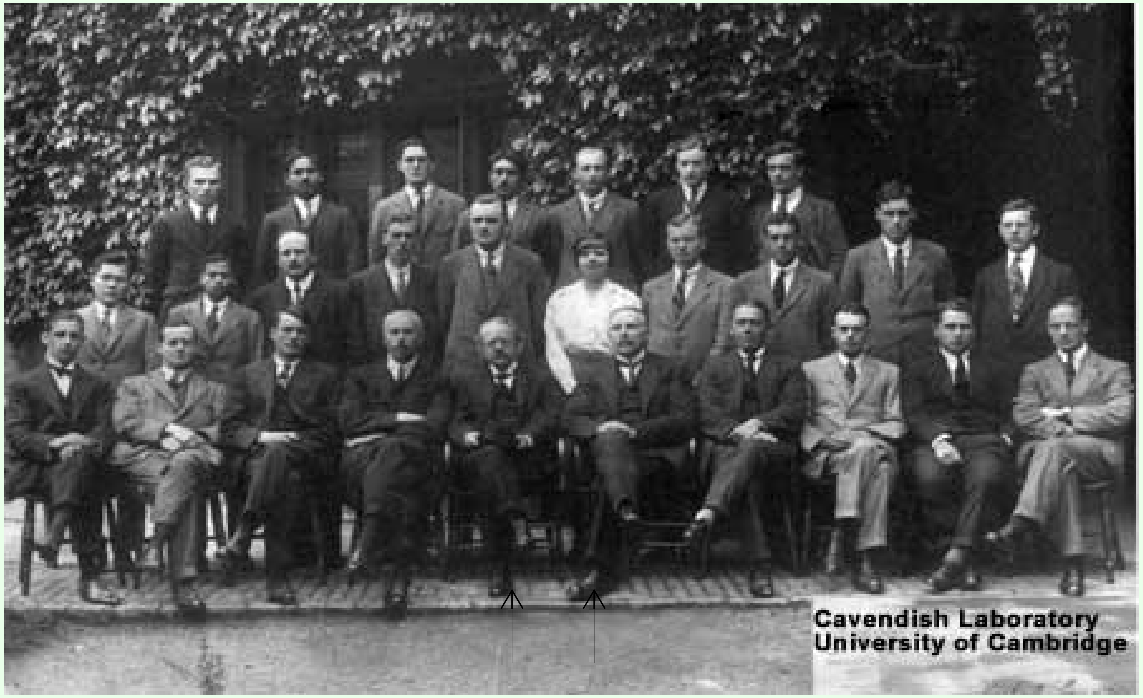


John Joseph Thomson (1856-1940)
studied at the Trinity College, Cambridge.
In 1880, he obtained his BA in mathematics.
He had been Second Wrangler in the Tripos,
the terrible exam that Trinity students
must overcome to gain *honours degree*.
He applied for and became a
Fellow of Trinity College as of 1881.
Thomson received his MA
(with Adams Prize) in 1883.

On 22 December 1884 Thomson was chosen
to become **Cavendish Professor of Physics**
at the University of Cambridge.
He accepted to direct the famous **Cavendish Laboratory,**
that had been guided by Maxwell, who has been
the first Cavendish professor.
He was very surprised
to have been chosen.
He was fundamentally
a mathematician.
Anyway he accepted;
on the contrary Sir William Thomson
(Lord Kelvin)
had refused for three times.

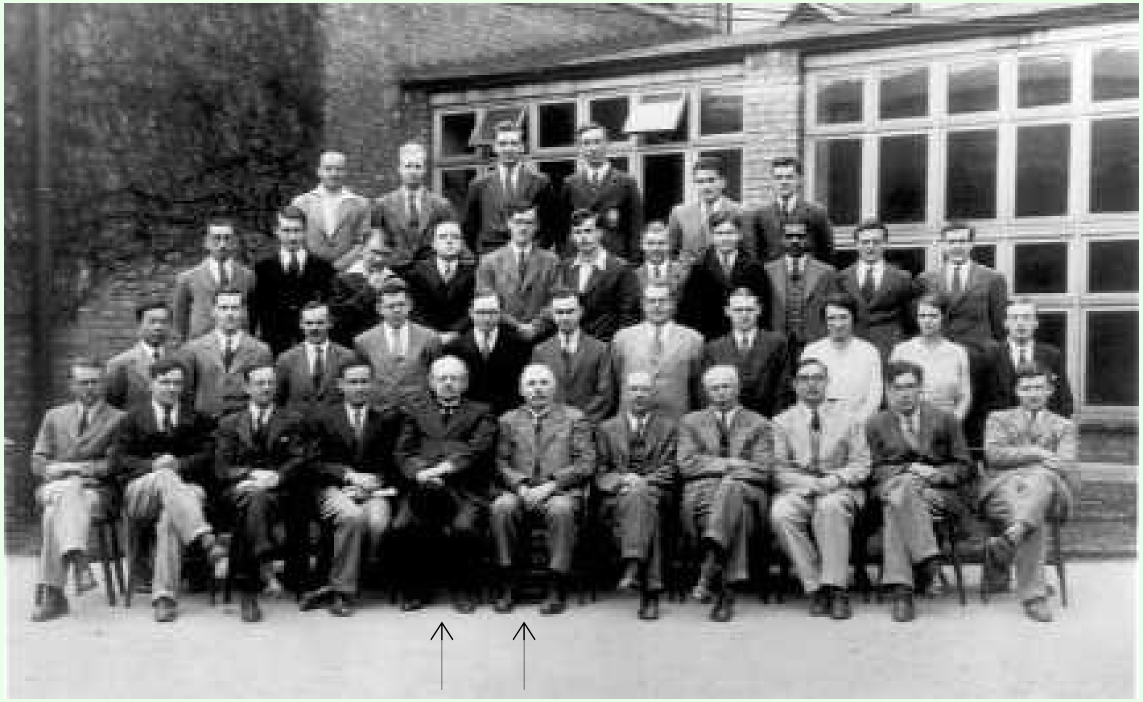
CAVENDISH LABORATORY
1874–1974
Established by the Duke of Devonshire
and extended by Lord Rayleigh (1908) and
Lord Austin (1940), the Cavendish Laboratory
housed the Department of Physics
from the time of the first Cavendish Professor,
James Clerk Maxwell, until its move to
new laboratories in West Cambridge

1922



Thomson Rutherford

1932



Thomson Rutherford

CAVENDISH PROFESSORS

James Clerk Maxwell (1871-1879)

Lord Rayleigh (1879-1884)

J. J. Thomson (1884-1919)

Lord Rutherford (1919-1937)

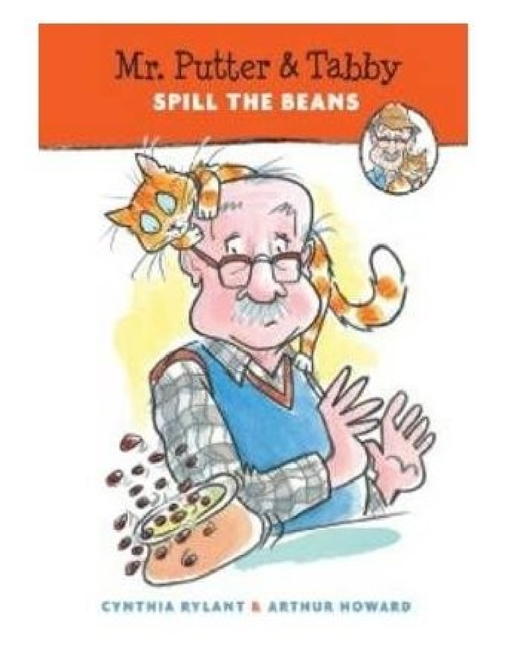
William Lawrence Bragg (1938-1953)

Nevill Mott (1954-1971)

Brian Pippard (1971-1984)

Sam Edwards (1984-1995)

Richard Friend (1995-)

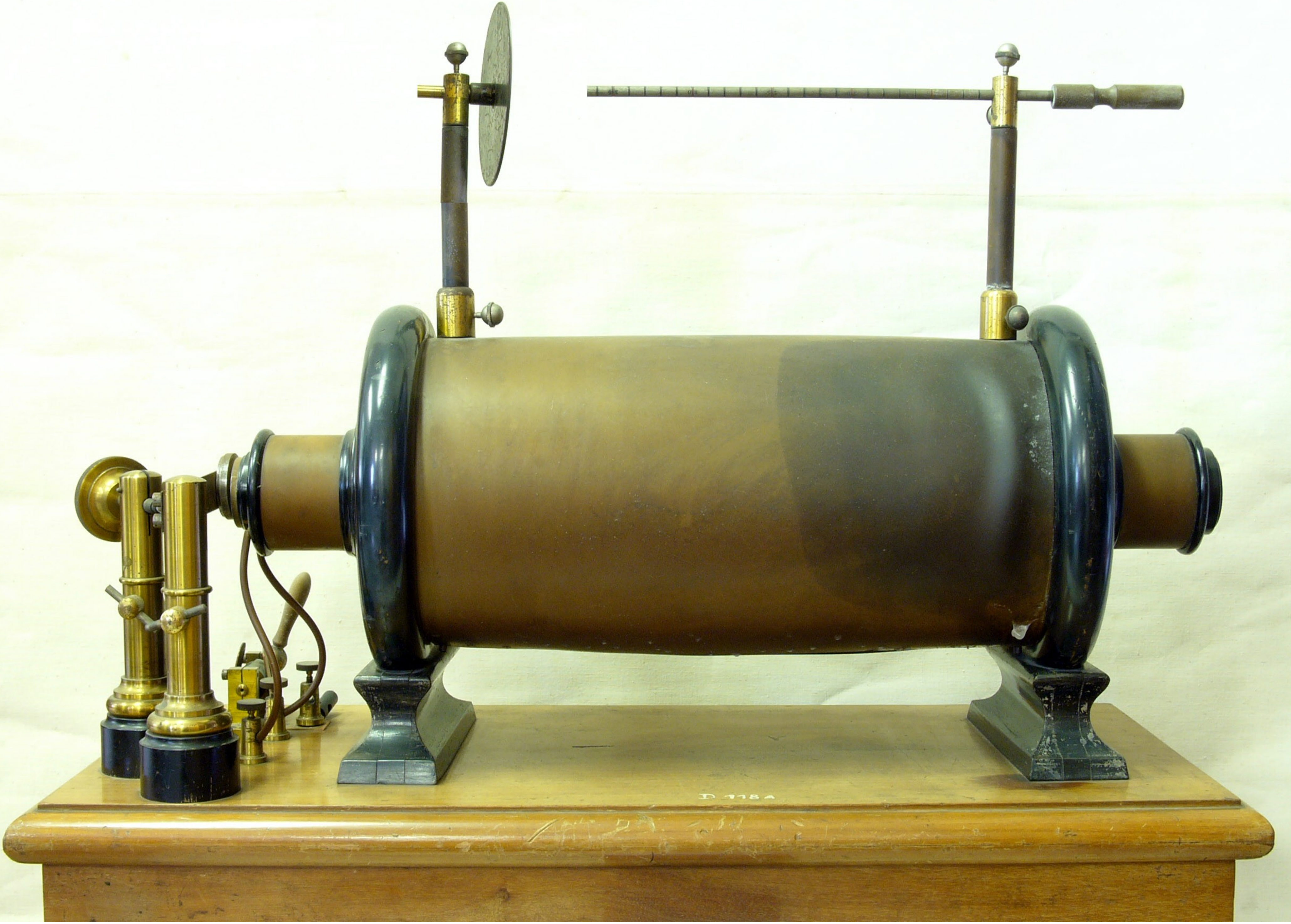


Thomson was told
to be a little bumbling
in manual work...
but he was very keen
on understanding the functioning
of his devices and any problem
that turned up with them.

At that time a laboratory
was not equipped as nowadays...
There was not electric light
because there was not yet a
national electricity distribution system.

A good laboratory had to possess
two essential things:

- a powerful vacuum pump
- a powerful Ruhmkorff coil


D 118A

In 1894 Thomson had already measured
the speed of cathode rays.
His values were not precise but, however,
he had found that
these **rays traveled slower than light.**
So he had confirmed his idea that
cathode rays were not electromagnetic
waves, but beams of “**corpuscles**”,
as he called them.

Let's watch a video about the functioning
of a cathode ray tube

Cathode rays tube

Then we will do a reading
in order to go into details of
Thomson's experiment...
and how he solved the objections
to Perrin's experiment

Evidence for a New Entity: J.J. Thomson and the Electron

Thomson's 1897 experiment on cathode rays is generally regarded as the "discovery" of the electron. The purpose of J.J. Thomson's experiments was clearly stated in the introduction to his 1897 paper.

> The experiments discussed in this paper were undertaken in the hope of gaining some information as to the nature of Cathode Rays. The most diverse opinions are held as to these rays; according to the almost unanimous opinion of German physicists they are due to some process in the aether to which—inasmuch as in a uniform magnetic field their course is circular and not rectilinear—no phenomenon hitherto observed is analogous: another view of these rays is that, so far from being wholly aetherial, they are in fact wholly material, and that they mark the paths of particles of matter charged with negative electricity
>
> (Thomson 1897, p. 293).

Thomson's first order of business was to show that the cathode rays carried negative charge. This had presumably been shown previously by Perrin. Perrin placed two coaxial metal cylinders, insulated from one another, in front of a plane cathode. The cylinders each had a small hole through which the cathode rays could pass onto the inner cylinder. The outer cylinder was grounded. When cathode rays passed into the inner cylinder an electroscope attached to it showed the presence of a negative electrical charge. When the cathode rays were magnetically deflected so that they did not pass through the holes, no charge was detected. "Now the supporters of the aetherial theory do not deny that electrified particles are shot off from the cathode; they deny, however, that these charged particles have any more to do with the cathode rays than a rifle-ball has with the flash when a rifle is fired" (Thomson 1897, p. 294).

Thomson repeated the experiment, but in a form that was not open to that objection. The apparatus is shown in Figure 14. The two coaxial cylinders with holes are shown. The outer cylinder was grounded and the inner one attached to an electrometer to detect any charge. The cathode rays from A pass into the bulb, but would not enter the holes in the cylinders unless deflected by a magnetic field.

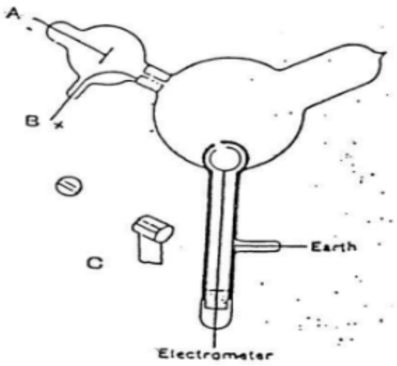


Figure 14. Thomson's apparatus for demonstrating that cathode rays have negative charge. The slits in the cylinders are shown. From Thomson (1897).

> When the cathode rays (whose path was traced by the phosphorescence on the glass) did not fall on the slit, the electrical charge sent to the electrometer when the induction coil producing the rays was set in action was small and irregular; when, however, the rays were bent by a magnet so as to fall on the slit there was a large charge of negative electricity sent to the electrometer…. If the rays were so much bent by the magnet that they overshot the slits in the cylinder, the charge passing into the cylinder fell again to a very small fraction of its value when the aim was true. *Thus this experiment shows that however we twist and deflect the cathode rays by magnetic forces, the negative electrification follows the same path as the rays, and that this negative electrification is indissolubly connected with the cathode rays* (Thomson 1897, p. 294–295, emphasis added).

This experiment also demonstrated that cathode rays were deflected by a magnetic field in exactly the way one would expect if they were negatively charged material particles.[4]

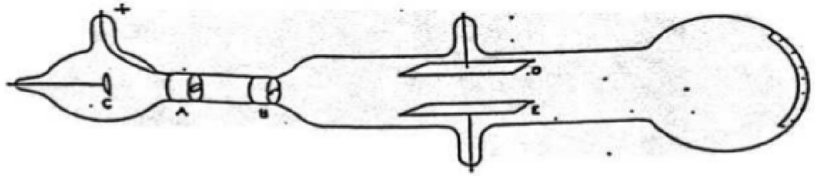


Figure 15. Thomson's apparatus for demonstrating that cathode rays are deflected by an electric field. It was also used to measure *m*/*e*. From Thomson (1897).

There was, however, a problem for the view that cathode rays were negatively charged particles. Several experiments, in particular those of Hertz, had failed to observe the deflection of cathode rays by an electrostatic field. Thomson proceeded to answer this objection. His apparatus is shown in Figure 15. Cathode rays from C pass through a slit in the anode A, and through another slit at B. They then passed between plates D and E and produced a narrow well-defined phosphorescent patch at the end of the tube, which also had a scale attached to measure any deflection. When Hertz had performed the experiment he had found no deflection when a potential difference was applied across D and E. He concluded that the electrostatic properties of the cathode ray are either *nil* or very feeble. Thomson admitted that when he first performed the experiment he also saw no effect. "on repeating this experiment [that of Hertz] I at first got the same result [no deflection], but subsequent experiments showed that the absence of deflexion is due to the conductivity conferred on the rarefied gas by the cathode rays".[5] On measuring this conductivity it was found that it diminished very rapidly as the exhaustion increased; it seemed that on trying Hertz's experiment at very high exhaustion there might be a chance of detecting the deflexion of the cathode rays by an electrostatic force (Thomson 1897, p. 296). Thomson did perform the experiment at lower pressure [higher exhaustion] and observed the deflection.[6]

Thomson concluded:

> As the cathode rays carry a charge of negative electricity, are deflected by an electrostatic force as if they were negatively electrified, and are acted on by a magnetic force in just the way in which this force would act on a negatively electrified body moving along the path of these rays, I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter.
>
> (Thomson 1897, p. 302)

Having established that cathode rays were negatively charged material particles, Thomson went on to discuss what the particles were. “What are these particles? are they atoms, or molecules, or matter in a still finer state of subdivision” (p. 302). To investigate this question Thomson made measurements on the charge to mass ratio of cathode rays. Thomson’s method used both the electrostatic and magnetic deflection of the cathode rays.[8] The apparatus is shown in Figure 15. It also included a magnetic field that could be created perpendicular to both the electric field and the trajectory of the cathode rays.

Let us consider a beam of particles of mass *m* charge *e*, and velocity *v*. Suppose the beam passes through an electric field F in the region between plates D and E, which has a length *L*. The time for a particle to pass through this region $t=L/v$. The electric force on the particle is Fe and its acceleration $a=Fe/m$. The deflection d at the end of the region is given by

$$d = \frac{1}{2}at^2 = \frac{1}{2}\left(\frac{eF}{m}\right)\frac{L^2}{v^2}$$

Now consider a situation in which the beam of cathode rays simultaneously pass through both *F* and a magnetic field *B* in the same region. Thomson adjusted *B* so that the beam was undeflected. thus the magnetic force was equal to the electrostatic force.

$evB = eF$ or $v = \frac{F}{B}$

This determined the velocity of the beam. Thus, $\frac{e}{m} = \frac{2dF}{B^2L^2}$

Each of the quantities in the above expression was measured so the *e*/*m* or *m*/*e* could be determined.

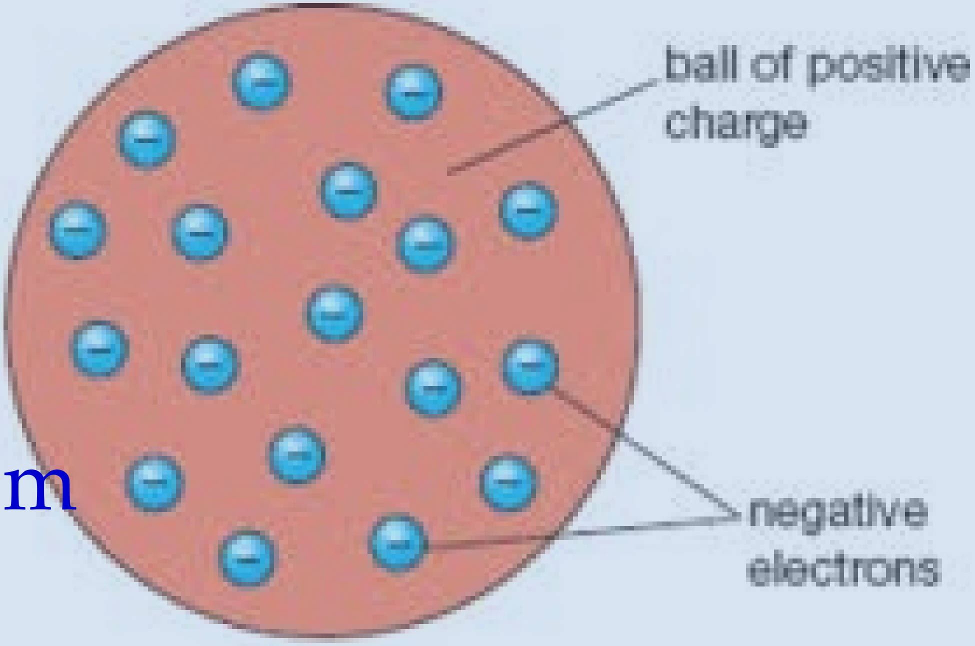
Using this method Thomson found a value of *m*/*e* of (1.29±0.17)×10−7. This value was independent of both the gas in the tube and of the metal used in the cathode, suggesting that the particles were constituents of the atoms of all substances. It was also far smaller, by a factor of 1000, than the smallest value previously obtained, 10−4, that of the hydrogen ion in electrolysis.

Thomson remarked that this might be due to the smallness of *m* or to the largeness of *e*. He argued that *m* was small citing Lenard’s work on the range of cathode rays in air. The range, which is related to the mean free path for collisions, and which depends on the size of the object, was 0.5 cm. The mean free path for molecules in air was approximately 10−5 cm. If the cathode ray traveled so much farther than a molecule before colliding with an air molecule, Thomson argued that it must be much smaller than a molecule.[9]

Thomson had shown that cathode rays behave as one would expect negatively charged material particles to behave. They deposited negative charge on an electrometer, and were deflected by both electric and magnetic fields in the appropriate direction for a negative charge. In addition the value for the mass to charge ratio was far smaller than the smallest value previously obtained, that of the hydrogen ion. If the charge were the same as that on the hydrogen ion, the mass would be far less. In addition, the cathode rays traveled farther in air than did molecules, also implying that they were smaller than an atom or molecule. Thomson concluded that these negatively charged particles were constituents of atoms. In other words, Thomson’s experiments had given us good reasons to believe in the existence of electrons.

After his discovery
Thomson proposed
an atomic model
known as the plum pudding model

He hypothesized that the negative charges are distributed in the atom as plums in a positively charged pudding.



Thomson's 'plum-pudding' model of the atom

This model was supplanted a few years later by Rutherford's model.

The End

Prof.ssa De Bernardi
a.s. 2014-2015