The birth of particle physics? The discovery of the electron

Patrick McCormack

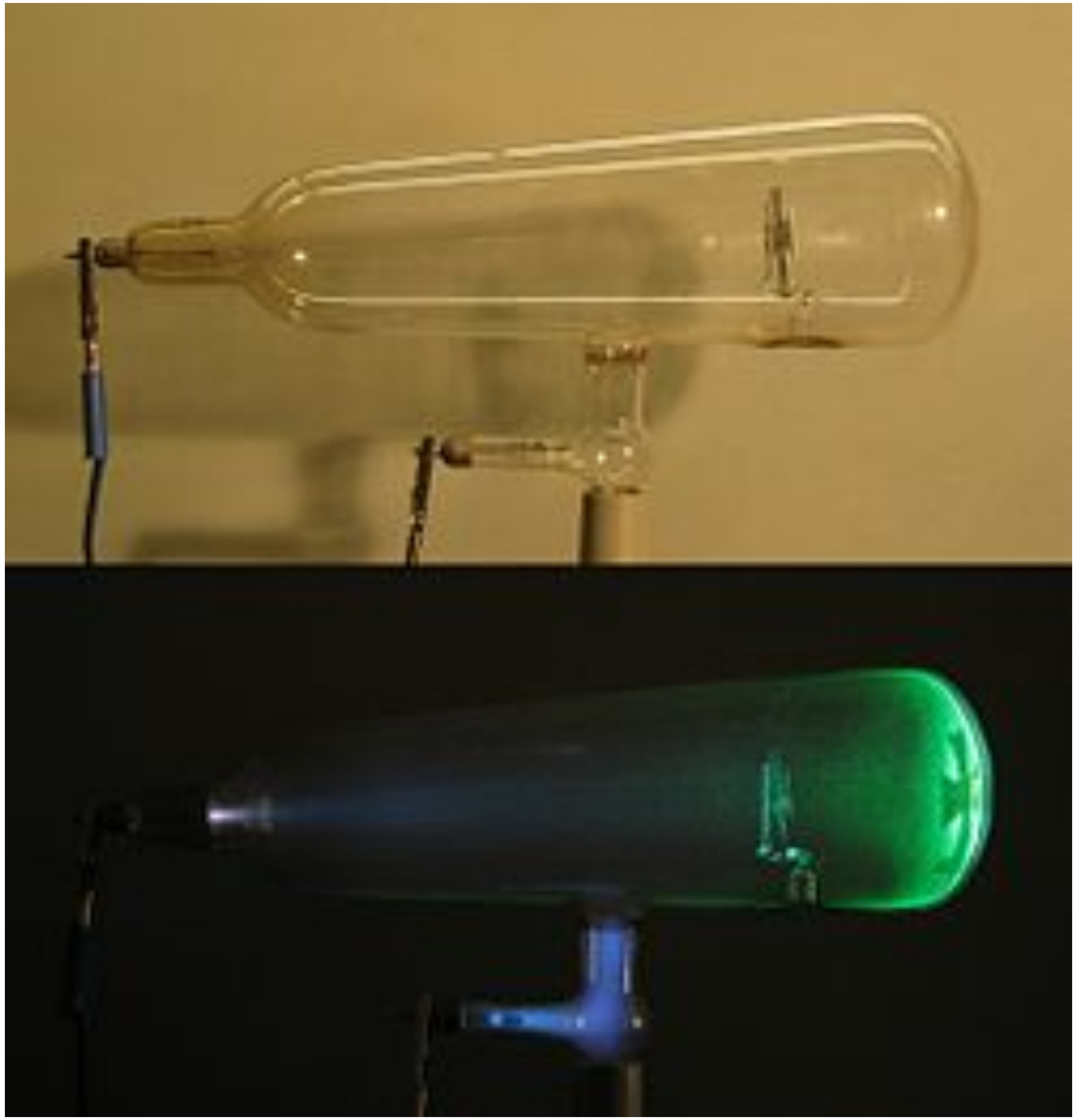
April 15, 2020

290E

J.J. Thompson and child (1897), colorized

Physics circa 1890

- Atoms were considered the smallest physical unit
  - To be fair, there was speculation that the larger elements were essentially conglomerations of hydrogen
- The "hydrogen ion" was known and its m/q ratio had been measured
- The ether was still a thing
- Cathode rays were a hot topic!
  - First observed in 1869
    - You need good enough vacuum such that the mean free path of the …ray... is large-previous vacuum tech hadn't been good enough



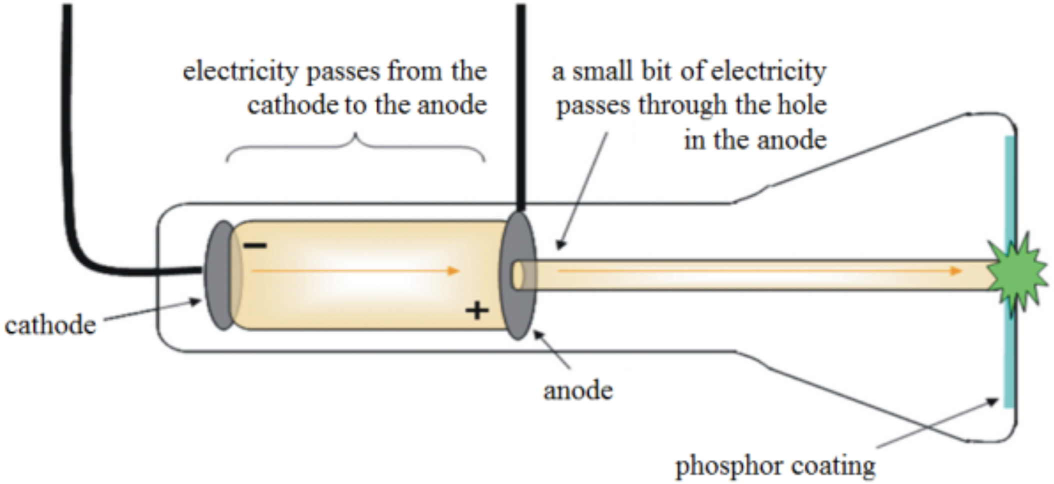
Aren’t cathode rays just electrons?

- Yes!
- But they didn’t know that
- Two main schools of thought

1. Cathode Rays are small negative particles (Thompson was in this group even before 1897)
2. Cathode Rays are a novel phenomenon of the ether (“The almost unanimous opinion of German physicists”- JJ Thompson)

Cathode Ray Tech

- Modern cathode rays are typically of the filament type
  - Heated filament emits electrons (thermionic emission) which are then accelerated across a potential difference
- Old style “Crookes Tubes” just have a large potential difference between anode and cathode
  - Gas gets ionized and accelerated towards the cathode
  - Ions hit cathode emitting electrons
- The rays are invisible (unless there is gas in the tube that gets ionized)
  - A glow can be seen where the rays hit glass though

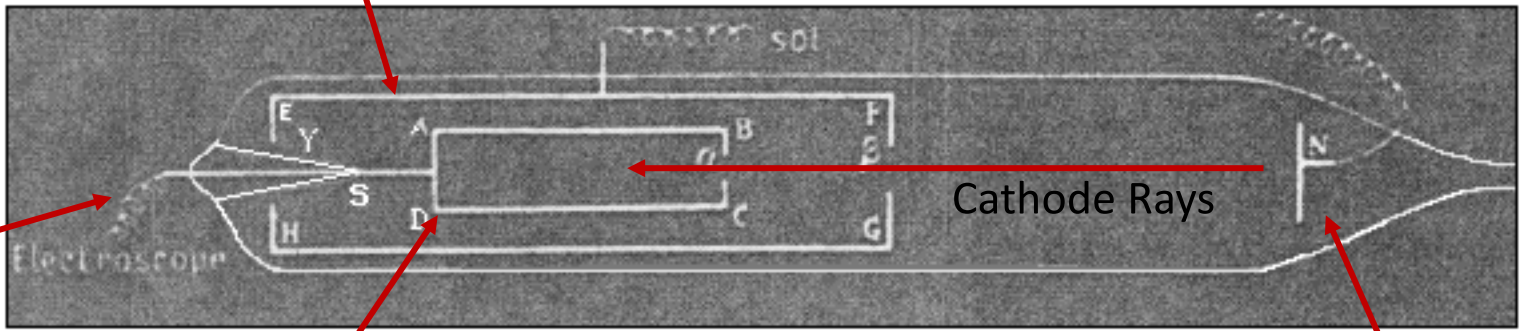


Why did Thompson think cathode rays were particles?

- Crookes saw in 1874 that cathode rays could turn a paddle in their path (they have momentum)
  - He thought they were charged gas molecules in a new state of matter
- It was known that cathode rays bend in a magnetic field
  - Arthur Schuster showed that they could bend in a **large** electric potential and made an estimate of the mass/charge ratio that was mostly ignored, but we now know was fairly accurate (1890)
- Jean Perrin had done an experiment (1896) where he showed that negative charge went in the direction where cathode rays were emitted and that the negative charges could be deflected by B fields

The Perrin Experiment

Grounded conducting cylinder: acts as anode and as Faraday cage



Electroscope measures negative charge captured by the cup

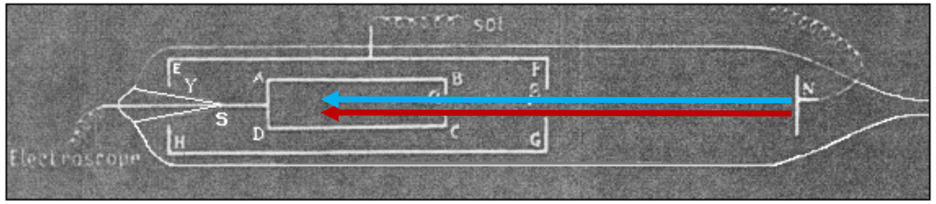
Faraday cup to detect the impending negative charge

The cathode

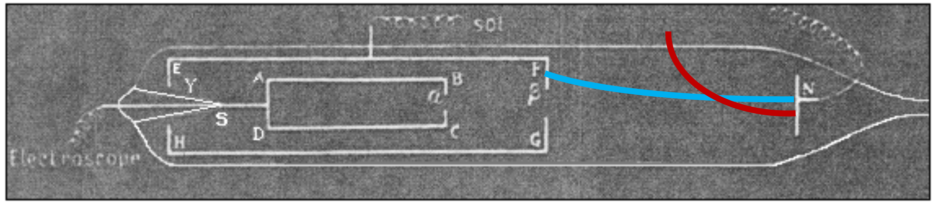
Objections to Perrin

- Apparently, supporters of the ether hypothesis thought the negative charge didn't "have any more to do with the cathode rays than a rifle-ball has with the flash when a rifle is fired" (J.J. Thompson)
- IMPORTANTLY the Perrin experiment did not demonstrate an inexorable link between where the cathode rays ended up and where the negative charge ended up

No B Field



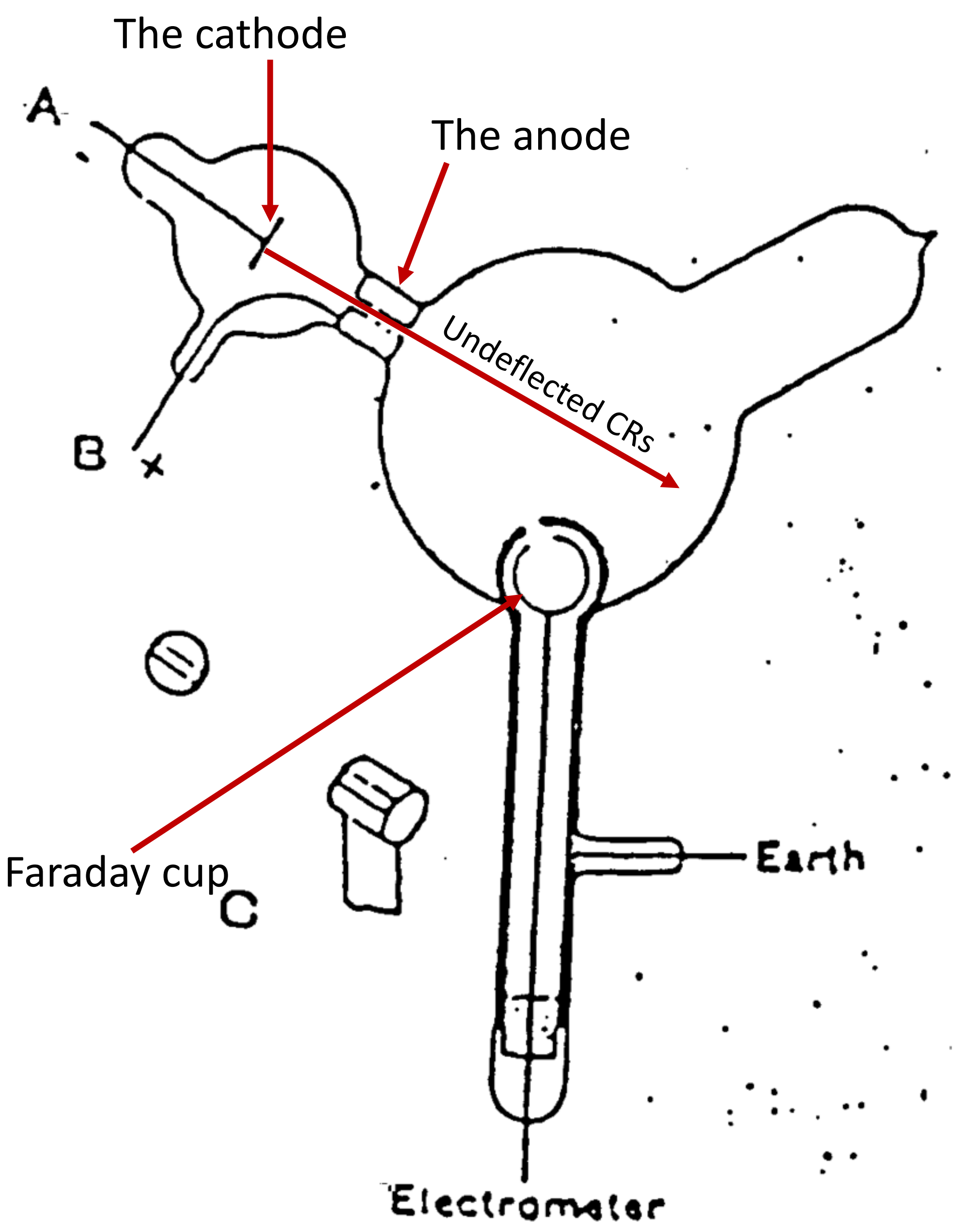
With B Field



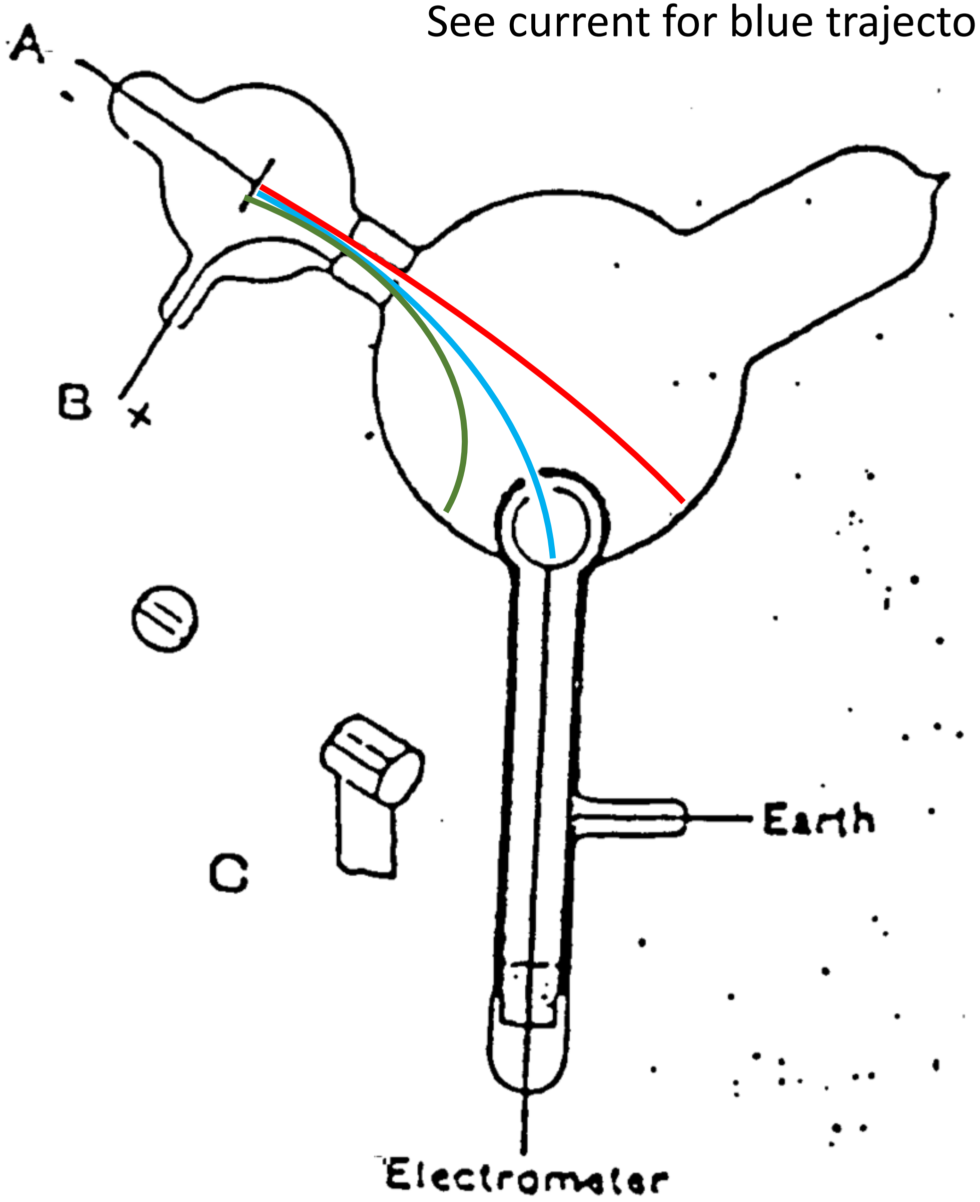
The idea behind the Perrin objections, that the cathode rays (blue) and negative charges (red) were not necessarily the same. Both were known to be deflected by B fields, and both were expected to travel in the cathode-to-anode direction

Thompson’s magnetic deflection setup

- Thompson wanted to see if the negative charge and the cathode rays were ***deflected*** in the same way
  - You can tell where the cathode rays are going by the florescence on the glass, and you can tell where the charge is going with an electrometer
  - Thompson used off-axis electrometer
- By adjusting B field, he could change where the cathode rays fell
- Electrometer only read charge when the cathode rays fell in the faraday cup

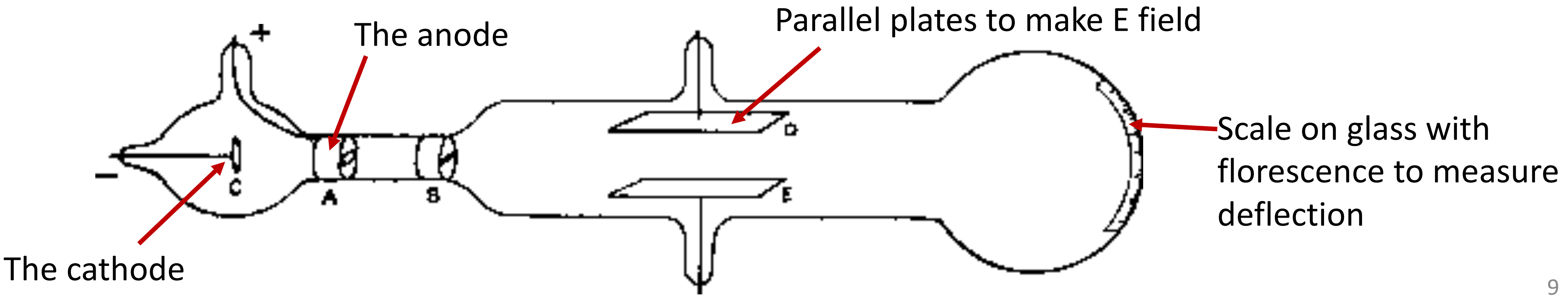


See florescence on the glass for green and red trajectories.
See current for blue trajectory.

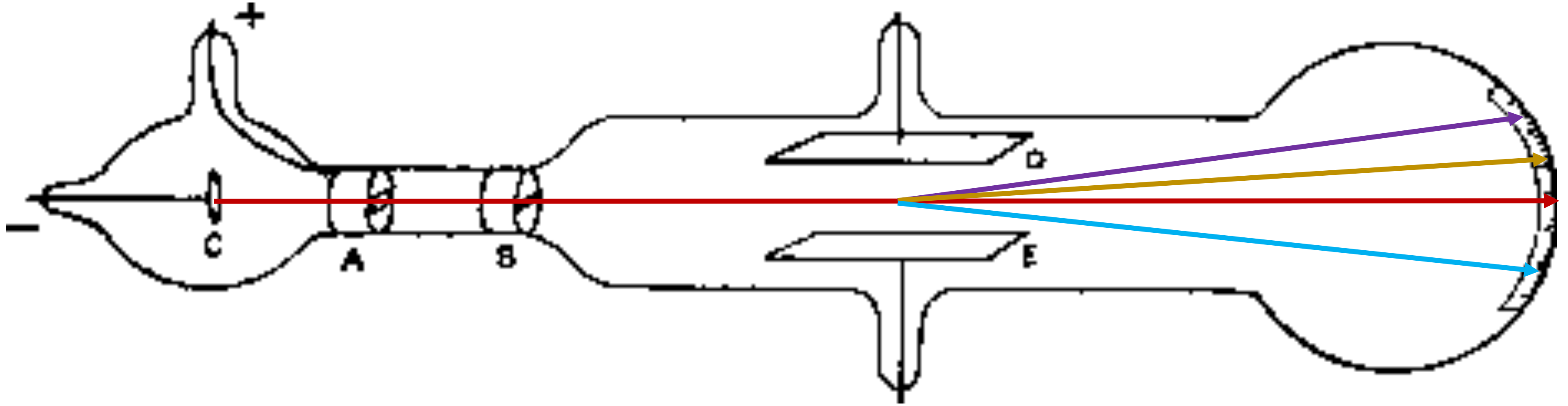


Thompson’s electric deflection setup

- Hertz had looked for deflection of cathode rays by small electrostatic fields, but had not found it
- Thompson realized that the residual gas in the tube was becoming conductive and spoiling the electric field
- By making the vacuum stronger, he saw deflection
  - The direction of the deflection was consistent with negative charge
  - The degree of deflection was proportional to the potential difference

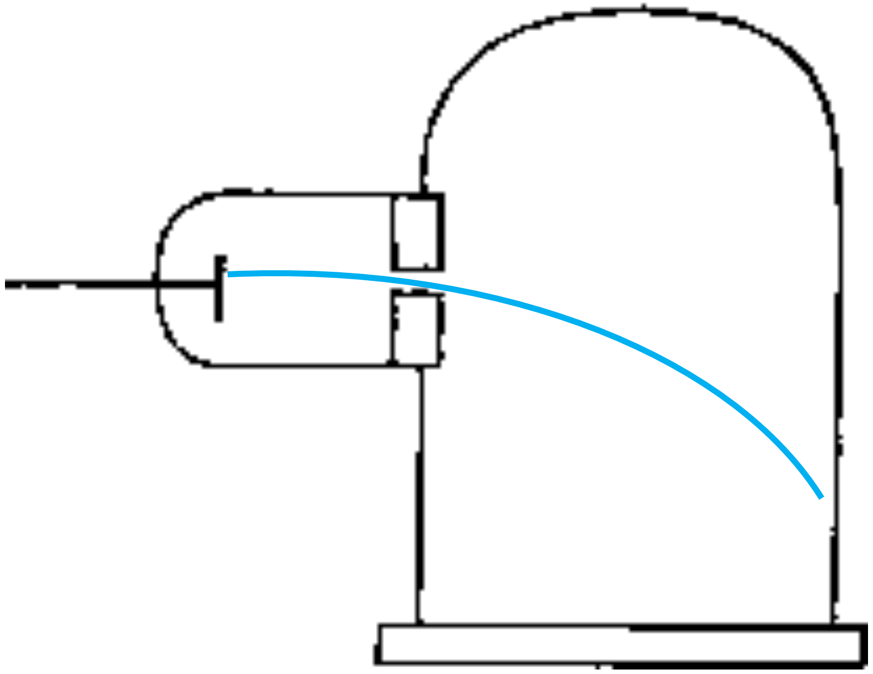


Red: no voltage diff between D and E
Purple: D+ and E-, larger del. V
Gold: D+ and E-, smaller del. V
Blue: D- and E+



Does deflection depend on gas density?

- Thompson filled a bell jar with various gases to see how the density affected the deflection of cathode rays in a magnetic field
- As long as the potential difference between the anode and cathode was the same, the cathode rays followed the same trajectory
  - Didn't depend on the gas used (hydrogen, air, carbonic acid, methyl iodide)
- Supports the idea that if the rays are just negative particles (with the same charge), the deflection should only depend on velocity for a given B strength
  - (Velocity comes from the potential difference)



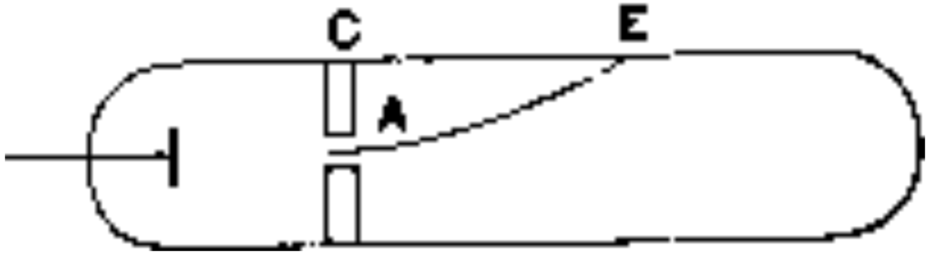
“As the cathode rays carry a charge of negative electricity, are deflected by an electrostatic force as if they were negatively electrified, and are acted on by a magnetic force in just the way in which this force would act on a negatively electrified body moving along the path of these rays, I can see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

-J.J. Thompson

He called the particles “corpuscles”

Measuring velocity and mass/charge

- Thompson measured the rays' velocity and mass/charge in two ways
- In the first method involves the measurement of charge carried by the rays, their kinetic energy, and the radius of curvature in an magnetic field
  - Measure total charge with a Faraday cup and electrometer
  - Measure kinetic energy by assuming that the rays' kinetic energy will be entirely converted into heat when hitting a surface, and measure the temperature increase of a surface with known thermal capacity
  - Measure radius of curvature by measuring where rays hit glass, knowing that it passes through the anode



Math

N ≡number of particles
e ≡ charge of particles
m ≡ particle mass
v ≡ particle velocity
B ≡ magnetic field strength (known)

- Total charge is $\mathrm{Q} = N * e$
- Total kinetic energy is $\mathrm{W} = \frac{1}{2} * N * m * v^2$
- From Newton's second law, we know radius is $\mathrm{R} = \frac{mv^2}{evB}$

$$\frac{m}{e} = \frac{(B * R)^2 * Q}{2 * W}$$

$$v = \frac{R * B}{m/e}$$

Measuring velocity and mass/charge

- Thompson's second method involved measuring the deflection by both a magnetic and electric field
  - For both E and B, let $l/v_{\perp}$ denote the time it takes to traverse the region with field (l is length of field region, and $v_{\perp}$ is velocity perpendicular to deflection)
  - Assuming there is 0 deflection without the fields, the impulse is $F * t = m * v_{\parallel}$, where F is force, t is the time, m is the mass, and $v_{\parallel}$ is the velocity in the direction of deflection
    - For E field, $v_{\parallel,E} = \frac{E*l}{v_{\perp}} * \frac{e}{m}$
    - For B field, $v_{\parallel,B} = \frac{v_{\perp}*B*l}{v_{\perp}} * \frac{e}{m}$
  - Small angle of deflection, so angle of deflection is approx. $\theta = v_{\parallel}/v_{\perp}$
- Thompson ended up setting things up so that the E deflection and the B deflection were equal, so:

$$\frac{m}{e} = \frac{B^2 * l}{E * \theta} \qquad v = \frac{E}{B}$$

Results

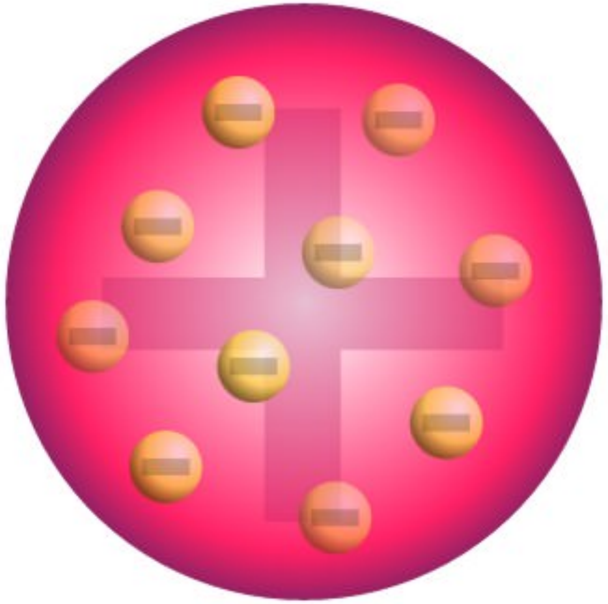
- Ultimately the two methods disagreed by a factor of ~2
  - There were ~20% uncertainties though of course
- Thompson found an m/e that was about 1000 to 2000 times smaller than that found for the hydrogen ion
  - The electron mass is about 1836 times smaller than the proton mass, so he wasn't far off!
  - This was the smallest such ratio ever measured, and suggested a totally new form of matter (the previous smallest had been hydrogen of course)
- He found the velocity of the particles to be about 2-5$\times 10^9$cm/sec
- It was previously known that the mean free path of cathode rays in air was relatively large, and Thompson interpreted this as meaning that the electron was physically small

Things Thompson was right about

- The electron (or corpuscle) exists
- It has negative charge
- The m/e is O(1000) times smaller than that of the hydrogen ion
  - The m/e is independent of the material used as the cathode (he performed his experiments with different cathode types, by the way)
- It is physically much smaller than an air molecule
- It is a component of atoms

Things Thompson was wrong about

- He thought m/e was small because e was large, not because m was small
- He thought electrons were basically the only thing inside the atom
  - He thought they basically spread out throughout the atom (making some analogies to some prior experiments about how magnets arrange themselves)
  - This was the basis of his Plum Pudding model where the electrons spread out within some extended, massless region of positive charge



Aftermath

- Rutherford discovered that radioactive materials emitted alpha and beta particles (1899)
  - Henri Becquerel discovered that the beta particles emitted by Radium had the same m/e ratio as the electron (1900)
- Millikan and Fletcher measured the electron charge in oil-drop experiment (1909)
- Rutherford, Geiger, and Marsden demonstrate nuclear deflection of alpha particles (1909)
  - Rutherford interprets this as atoms having a positive nucleus around which the electrons orbit
- De Broglie postulates that matter has wave-like properties (1924)
- Quantum mechanics developed, etc., etc., etc. (I might have skipped a few steps here)

Aftermath

- Thompson won the 1906 Nobel Prize
- 8 of his research assistants (and his son) ended up winning a Nobel Prize at some point too
  - Among them: Rutherford, Born, Bohr, Bragg, Wilson

References

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