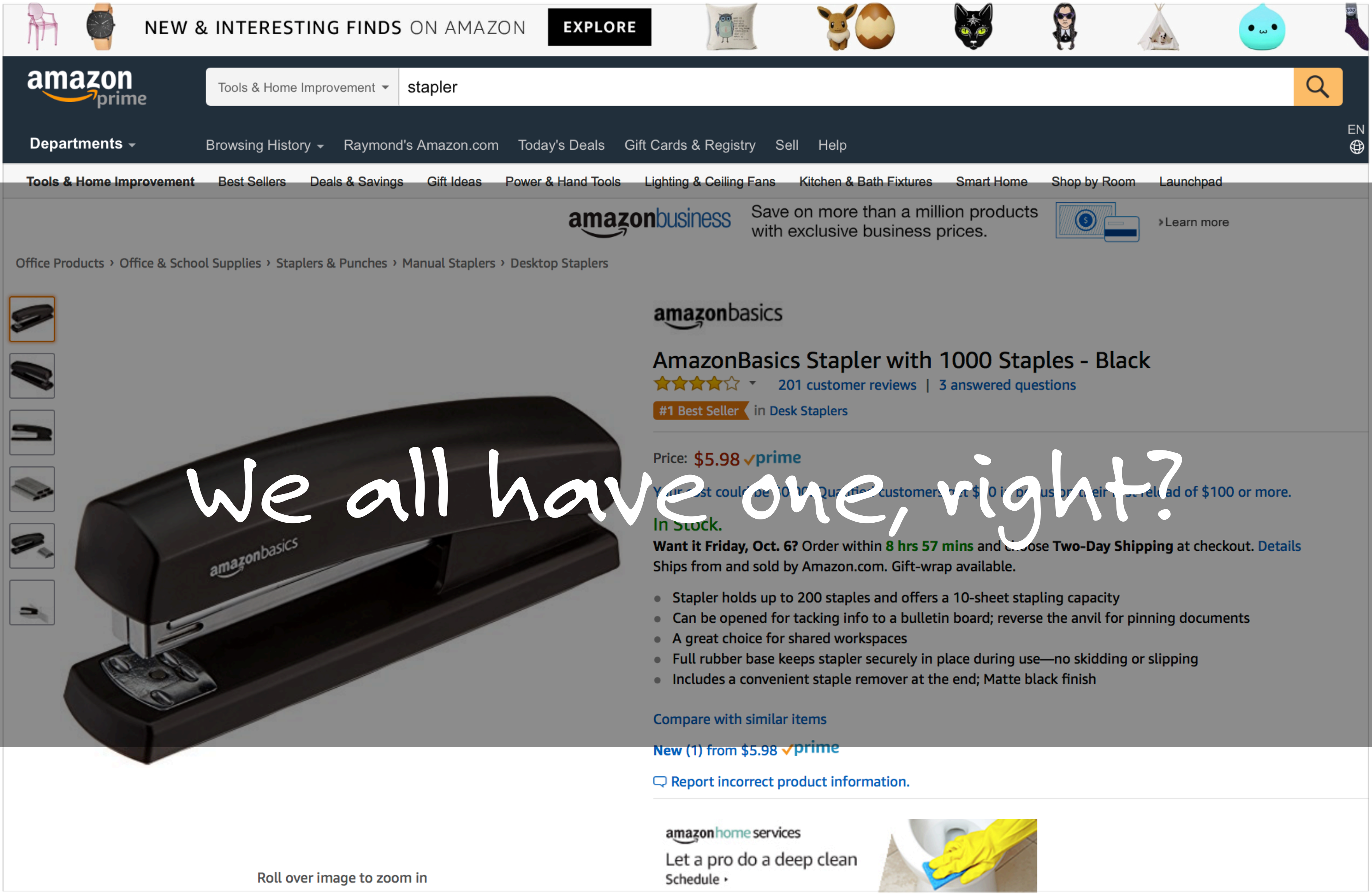
3.
Experimental Basis of Quantum Physics, 4

4.
Structure of the Atom, 1

lecture 16, October 6, 2017



We all have one, right?

AmazonBasics Stapler with 1000 Staples - Black

201 customer reviews | 3 answered questions

#1 Best Seller in Desk Staplers

Price: $5.98 prime

Your cost could be $0.00. Qualified customers get $10 in bonus on their first reload of $100 or more.

In Stock.

Want it Friday, Oct. 6? Order within **8 hrs 57 mins** and choose **Two-Day Shipping** at checkout. Details

Ships from and sold by Amazon.com. Gift-wrap available.

- Stapler holds up to 200 staples and offers a 10-sheet stapling capacity
- Can be opened for tacking info to a bulletin board; reverse the anvil for pinning documents
- A great choice for shared workspaces
- Full rubber base keeps stapler securely in place during use—no skidding or slipping
- Includes a convenient staple remover at the end; Matte black finish

Compare with similar items

New (1) from $5.98 prime

Report incorrect product information.

housekeeping

exam 1 was last friday ;)

- next one: Friday, October 27

Next Tuesday:

- no HW workshop: catch-up lecture…enjoying myself too much

Honors option

- Go to: https://qstbb.pa.msu.edu/storage/PHY215/honors/
- read the MinervaInstructions1_2017_215 document

one more thing

Compton Scattering

one of the most important experiments…ever

COMPTON SCATTERING

Milliken HATED Einstein's idea → worked for decade to kill it @ U of C and beautifully confirmed it by 1913

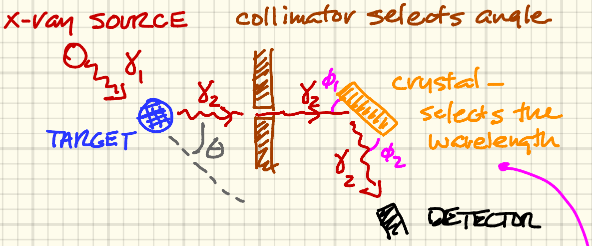
Definite demonstration by Arthur Holly Compton, 1923

imagine

$$\underset{\uparrow \text{ at "rest"}}{\gamma_1 + e} \rightarrow \gamma_2 + \underset{\uparrow \text{ KE}}{e}$$

$$E_2 > \underset{=}{<} E_1 \ ?$$

so $\lambda_2 \underset{=}{>} < \lambda_1$

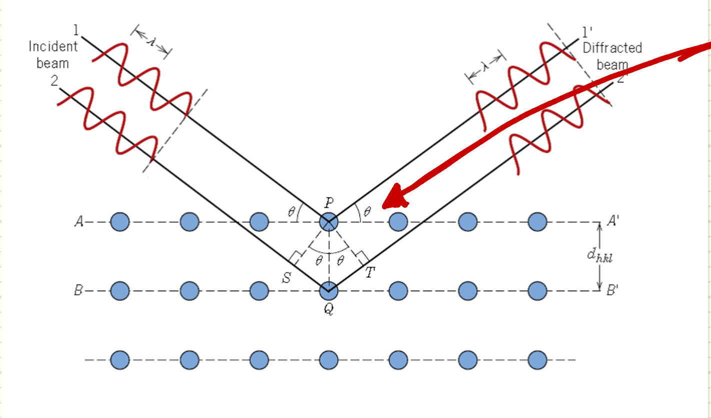


measurable: λ_2

known: λ_1, θ

"Bragg Spectrometer"
measuring ϕ's → λ →

BRAGG SPECTROMETER



$n\lambda = 2d\sin\theta$

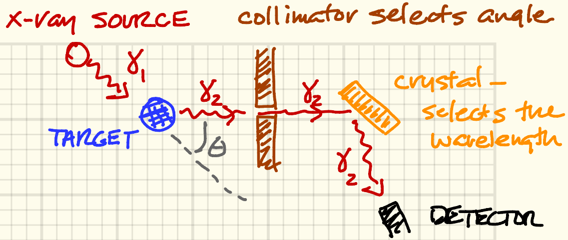
so measuring θ ≡ determining λ

spacing of crystal must be ~ λ light

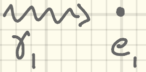
NaCl, calcite, mica, quartz, etc

↳ $d \sim 2.8\,\text{Å}$ $\lambda(\text{Mo}) \sim 1\,\text{Å}$

back to the story:

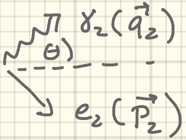


Before



$\gamma_1(\vec{q}_1)$ $e(\vec{p}_1)$

After



TOTALLY A PARTICLE INTERPRETATION!

Billiard Balls!

Conserve momentum:

① $\vec{q}_1 + \vec{p}_1 = \vec{q}_2 + \vec{p}_2$

Conserve Energy:

② $E_{\gamma_1} + E_{e_1} = E_{\gamma_2} + E_{e_2}$

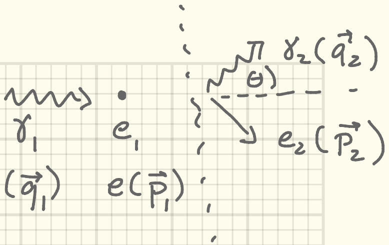
$$E^2 = p^2c^2 + m^2c^4$$

$$E_1^2 = p_1^2c^2$$

$$p_1 = \frac{E_1}{c} = \frac{hf_1}{c} \quad \& \quad p_2 = \frac{hf_2}{c}$$

TOTALLY A WAVE INTERPRETATION!

$$\vec{p}_2 = \vec{q}_1 + \underset{\overset{\uparrow}{=0}}{\vec{p}_1} - \vec{q}_2$$



$$\vec{p}_2 = \vec{q}_1 - \vec{q}_2$$ trick

$$p_2^2 = \vec{p}_2 \cdot \vec{p}_2 = (\vec{q}_1 - \vec{q}_2)^2 = q_1^2 + q_2^2 - 2\vec{q}_1 \cdot \vec{q}_2$$

$$p_2^2 = \left(\frac{hf_1}{c}\right)^2 + \left(\frac{hf_2}{c}\right)^2 - 2\left(\frac{hf_1}{c}\right)\left(\frac{hf_2}{c}\right)\cos\theta \quad ③$$

from ②

$$E_{\gamma_1} + E_{e_1} = E_{\gamma_2} + E_{e_2}$$

$$hf_1 + mc^2 = hf_2 + \sqrt{p_2^2c^2 + m^2c^4}$$

$$(hf_1 + mc^2 - hf_2)^2 = p_2^2c^2 + m^2c^4$$

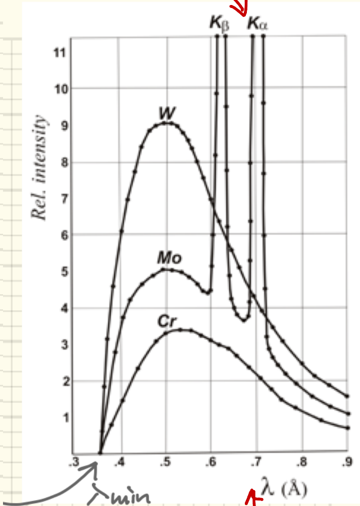
from ③

$$(hf_1)^2 + (hf_2)^2 - 2(hf_1)(hf_2) + 2mh(f_1 - f_2) + m^2c^4 = p_2^2c^2 + m^2c^4$$

$\vdots$

$$2\left(\frac{hf_1}{c}\right)\left(\frac{hf_2}{c}\right)(1-\cos\theta) = 2mhc\left(\frac{f_1}{c} - \frac{f_2}{c}\right) \xrightarrow{\text{measure } \lambda} \cdots$$

Used K_α x-rays from Mo



λ_{min}

$\lambda_1 = 0.7\ \text{Å}$

$$\underset{\text{measure}}{\lambda_2} - \underset{\text{set-up}}{\lambda_1} = \frac{h}{mc}(1 - \cos \underset{\text{set-up}}{\theta})$$

Consider back-scattering $\Rightarrow$ $\theta = \pi$, so $\lambda_2 - \lambda_1$ largest.

$$\lambda_2 - \lambda_1 = \frac{h}{mc}(2)$$

$$= \frac{2hc}{mc^2} \qquad m_e = 0.511\ \text{MeV}$$

$$= \frac{(2)(1241\ \text{eV}\cdot\text{nm})}{(0.511 \times 10^6\ \text{eV})}$$

$$= 0.0049\ \text{nm} = 0.0049 \times 10^{-9}$$

$$\Delta\lambda = 0.049\ \text{Å}$$ tiny but measurable

for $\theta = \pi/2$: $\Delta\lambda = 0.024\ \text{Å}$

original x ray

2nd peaks → scattered x-rays → longer $\underline{\underline{\lambda}}$

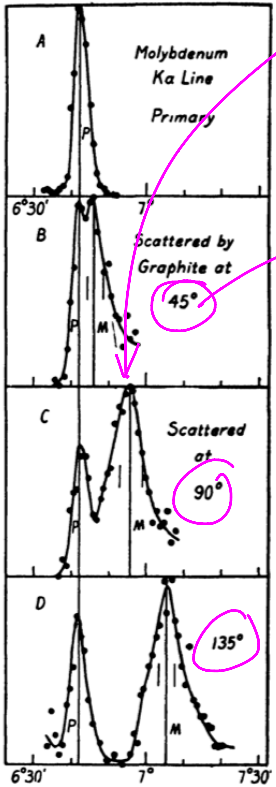


FIG. 108.

in $(1-\cos\theta)$ formula

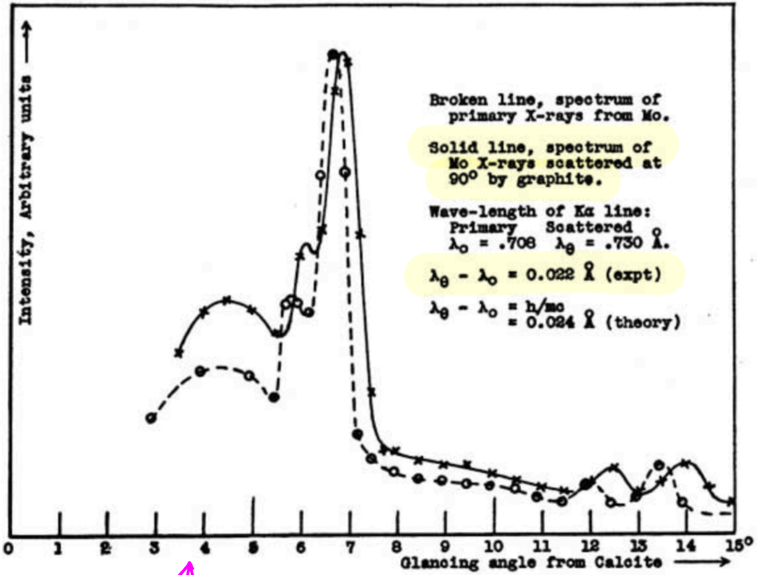
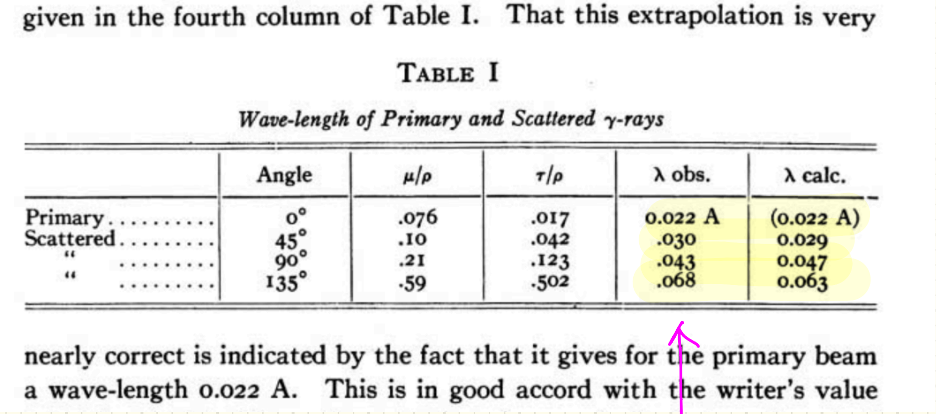


Fig. 4. Spectrum of molybdenum X-rays scattered by graphite, compared with the spectrum of the primary X-rays, showing an increase in wave-length on scattering.

Bragg Sepctrometer angles ≡ λ's



given in the fourth column of Table I. That this extrapolation is very nearly correct is indicated by the fact that it gives for the primary beam a wave-length 0.022 A. This is in good accord with the writer's value

TABLE I

Wave-length of Primary and Scattered γ-rays

	Angle	μ/ρ	τ/ρ	λ obs.	λ calc.
Primary..........	0°	.076	.017	0.022 A	(0.022 A)
Scattered.........	45°	.10	.042	.030	0.029
"	90°	.21	.123	.043	0.047
"	135°	.59	.502	.068	0.063

actually $\Delta\lambda$

I think of this as the discovery of the photon

One more thing $\Delta\lambda = \frac{h}{m_e c}(1-\cos\theta)$

$$E = hf = \frac{hc}{\lambda} \rightarrow m_e c^2$$

$$\frac{hc}{\lambda} = m_e c^2$$

$$\boxed{\frac{h}{m_e c} = \lambda_c}$$

"Compton wavelength" of electron

BEST STAND-IN FOR THE "SIZE" OF AN ELEMENTARY PARTICLE

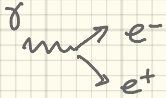
$\lambda_c = 0.002426$ nm

Compton wavelength of proton:

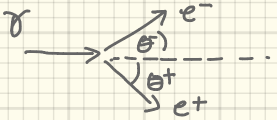
$$\lambda_c(p) = \frac{h}{m_p c} = \frac{hc}{m_p c^2} = \frac{1241 \text{ eV}\cdot\text{nm}}{938\times10^6 \text{ eV}}$$

$$\lambda_c(p) = 1.3\times10^{-6} \text{ nm} = 1.3\times10^{-15} \text{ m}$$

Pair production & annihilation



"pair production"



① $p_\gamma = p_x^- + p_x^+ = p^- \cos\theta^- + p^+ \cos\theta^+$

② $0 = p_y^- - p_y^+ = p^- \sin\theta^- - p^+ \sin\theta^+$

③ $E_\gamma = E^- + E^+ = hf$

remember $E_\gamma = p_\gamma c$

④ $p_\gamma = \frac{E_\gamma}{c} = \frac{hf}{c}$

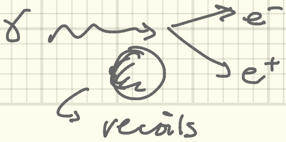
④ → ① $hf = p^- c \cos\theta^- + p^+ c \cos\theta^+$ ⑤

③ $hf = \sqrt{p^{-2}c^2 + m^2c^4} + \sqrt{p^{+2}c^2 + m^2c^4}$ ⑥

max hf from ⑤ $hf_{max} = p^- c + p^+ c$ can't

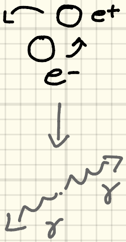
But $hf > p^- c + p^+ c$

problem: momentum cst.

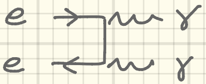


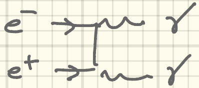
only in matter does $\gamma \to e^+e^-$

Positronium



a little atom

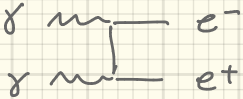




$$E_\gamma + E_\gamma = m_e c^2 + m_e c^2$$

$$E_\gamma = m_e c^2 = 0.511 \text{ MeV}$$

BTW



does happen ... and did.

go back about a decade

Rutherford on the loose

on faculty at McGill University, 1900–1903

on nuclear decay

meanwhile

McGill University in Montreal, 1900-1903

chemists still held to the (new) notion that atoms were indivisible

physicists were becoming convinced that atoms had structure and maybe made of constituents

Rutherford had made his own career

Rutherford was convinced that matter was transmutating from one element to another...somehow

He entered into a heated debate with chemist Frederick Soddy....

> "Perhaps Professor Rutherford may be able to convince us that matter as known to him is really the same matter as known to us... I feel sure that chemists will retain a belief and reverence for atoms as concrete and permanent identities, if not immutable, certainly not yet transmuted"

Instead...they collaborated.

> "I am expected to do a lot of original work and to form a research school to knock the shine out of the Yankees."
>
> Rutherford
>
> to his fiancée upon his appointment at McGill University in Montreal, 1898

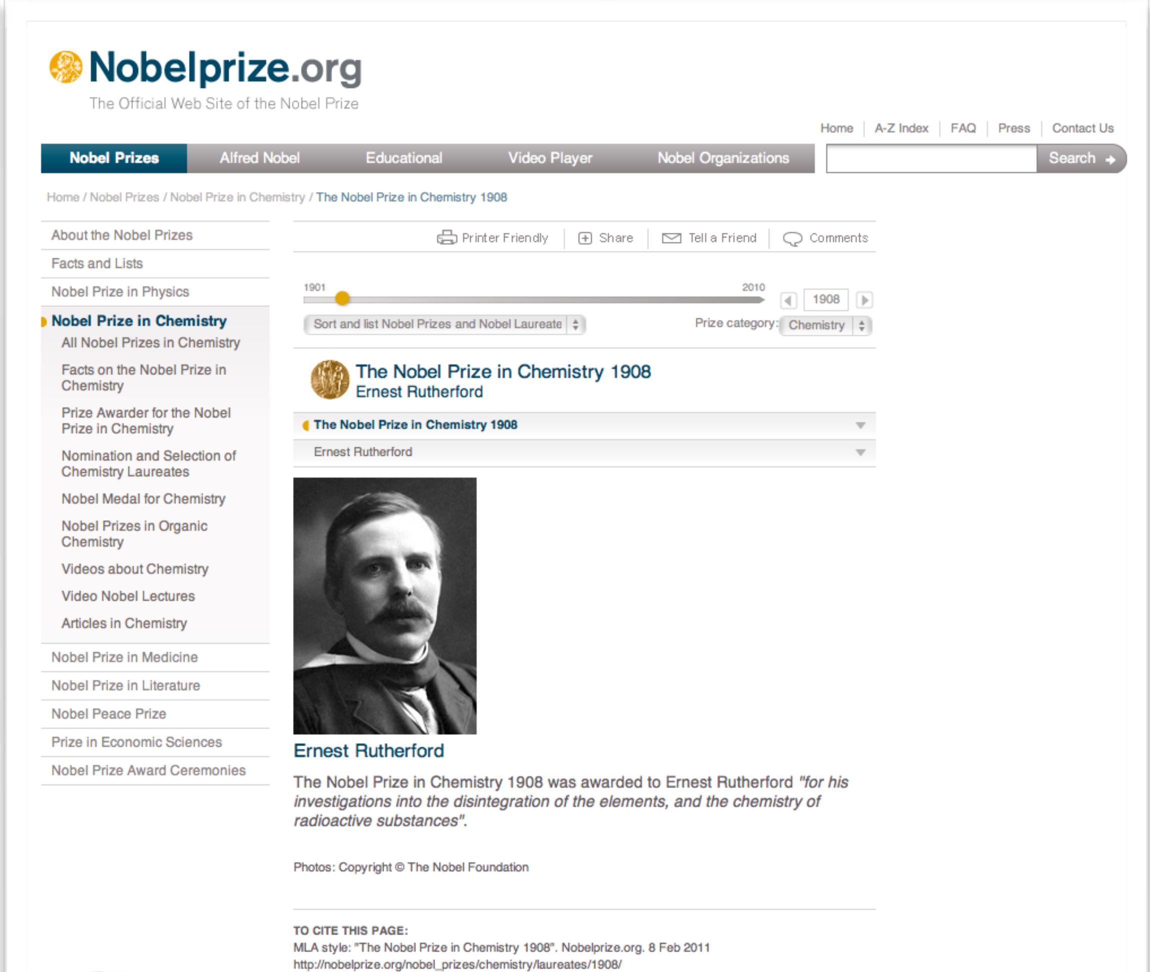
Nobel Prize in Chemistry

1908

which greatly amused him

and went on

to do his best work after his Nobel...very unusual



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1901 2010 1908

Sort and list Nobel Prizes and Nobel Laureate

Prize category: Chemistry

The Nobel Prize in Chemistry 1908
Ernest Rutherford

The Nobel Prize in Chemistry 1908

Ernest Rutherford

Ernest Rutherford

The Nobel Prize in Chemistry 1908 was awarded to Ernest Rutherford *"for his investigations into the disintegration of the elements, and the chemistry of radioactive substances"*.

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so, what's in the atom

from a 1910 perspective?

Look what people were contending with:

electrons produced at the cathode of a cathode ray tube.

electrons seemed to spontaneously pop out of some nuclei.

yet, bulk matter is not electrically charged...so there is some positive charge somewhere

JJ had a model:

"Plum-pudding" model of atom

pudding: a continuous + charge and mass distribution

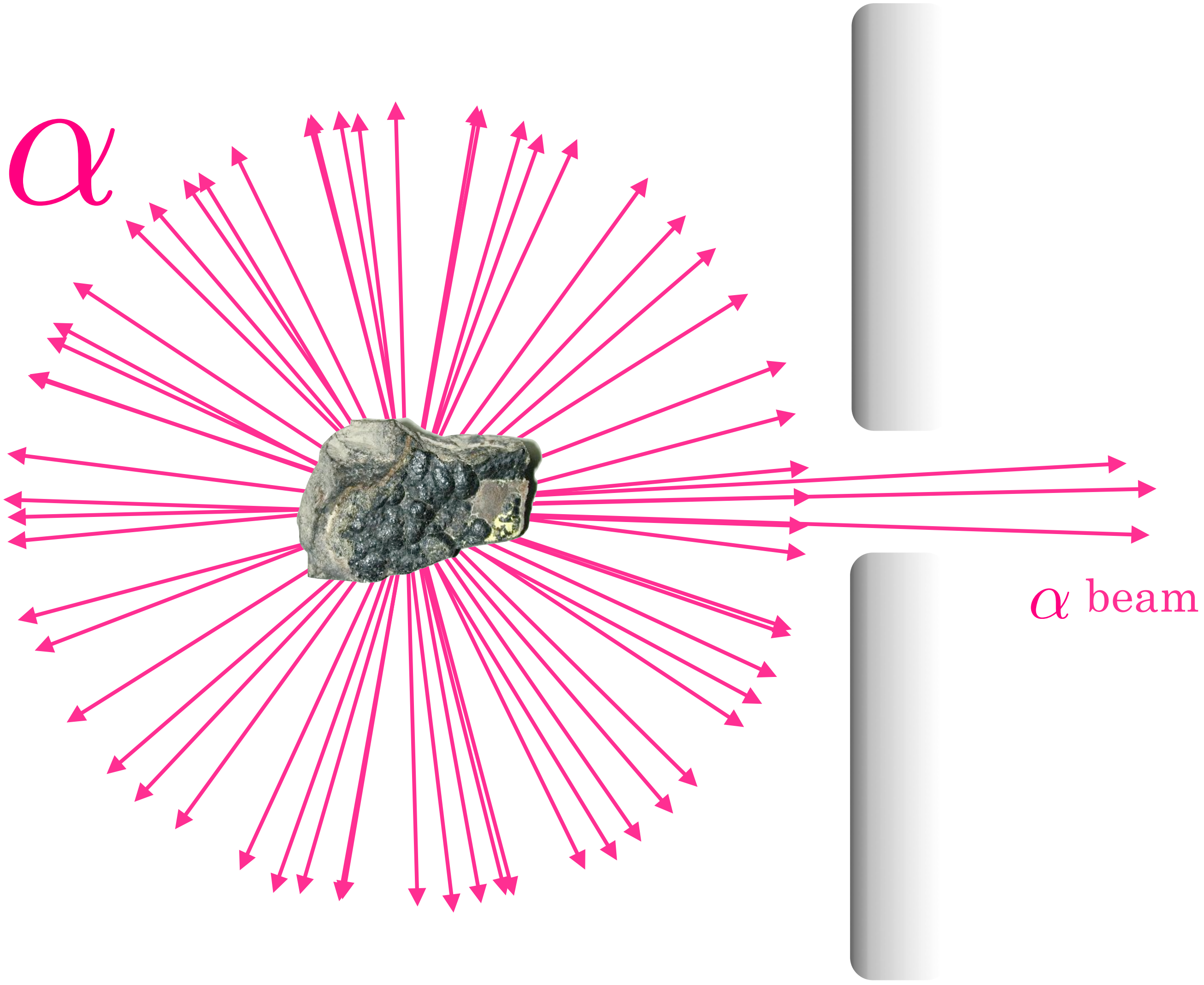
raisins: specks of – electrons

Scattering experiments...

Rutherford went back to Britain

1907, Chair of Physics at University of Manchester

made “beams” of alpha particles using highly radioactive sources



post doc

undergraduate student

Hans Geiger and Eugene Marsden studied

α particle scattering from Gold 1909

1908 Geiger experiment

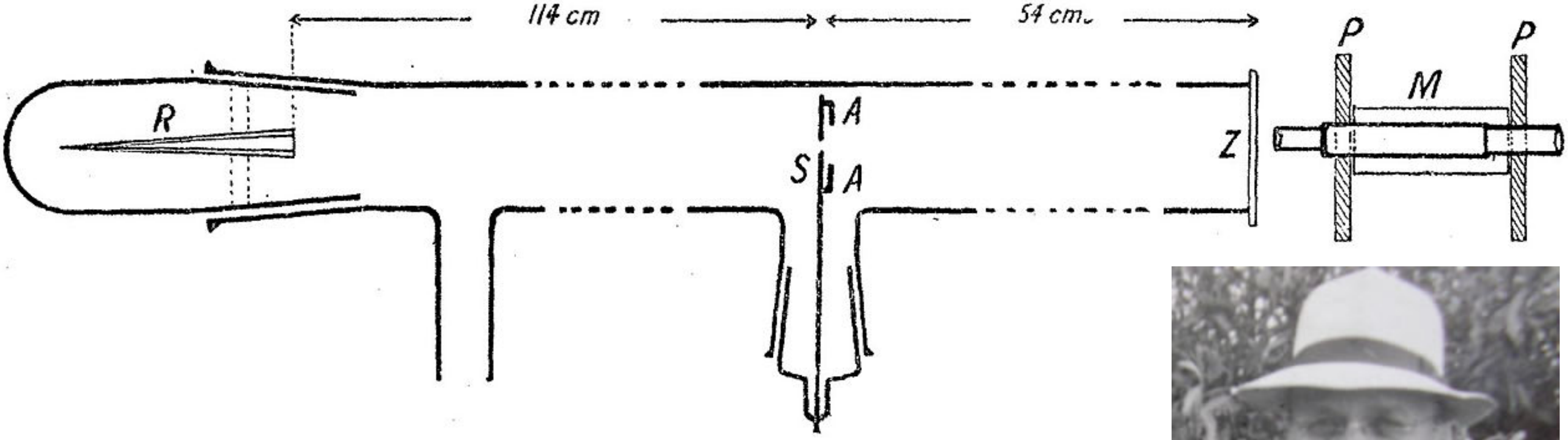


Fig. 1.

1909 Geiger-Marsden experiment

1/8000 at 90°

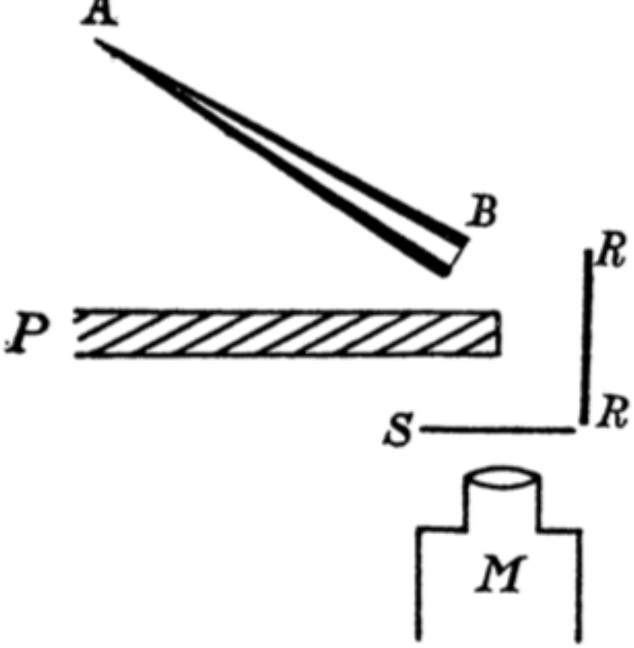


Fig. 1.

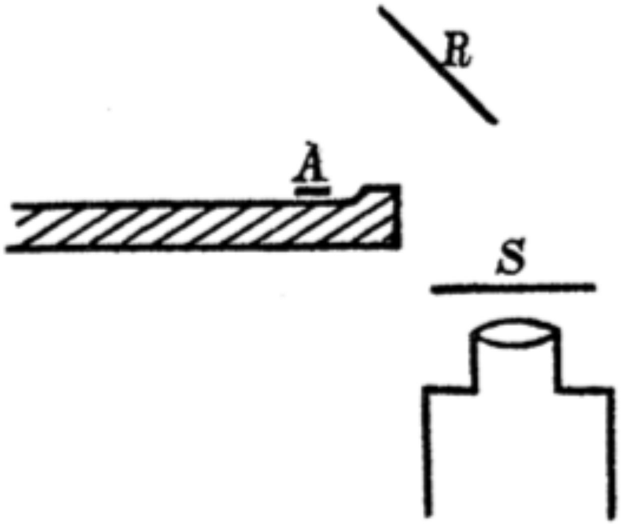
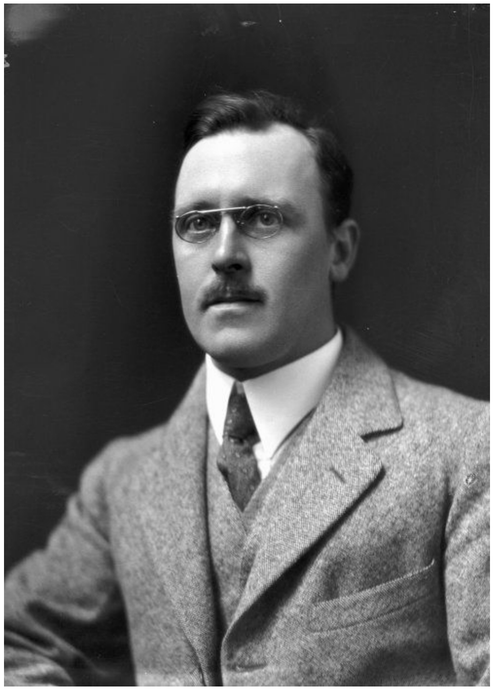
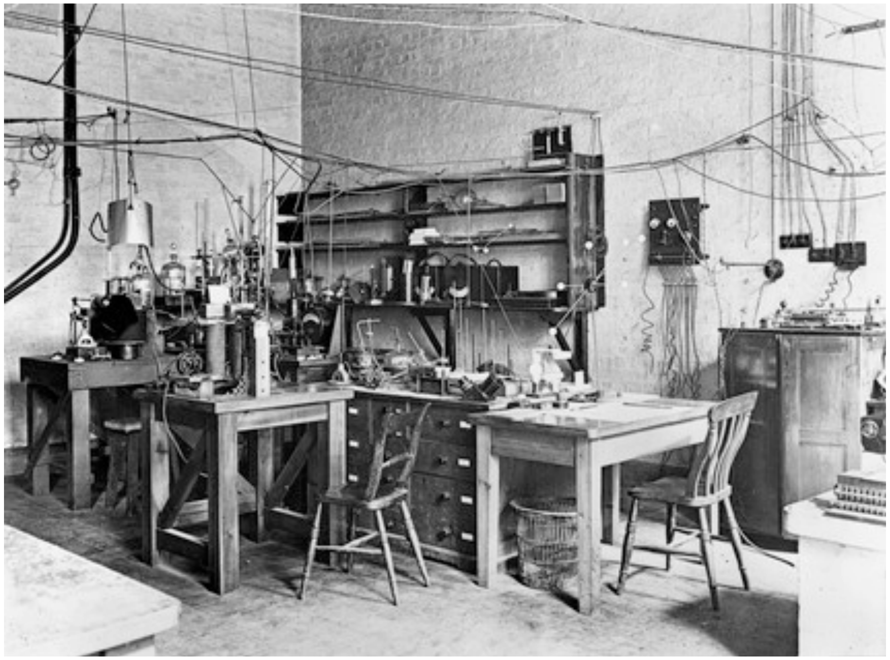
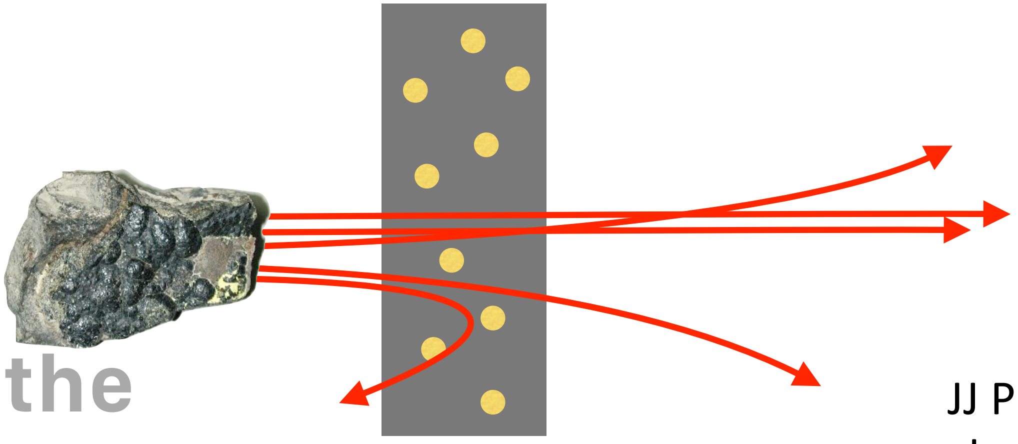


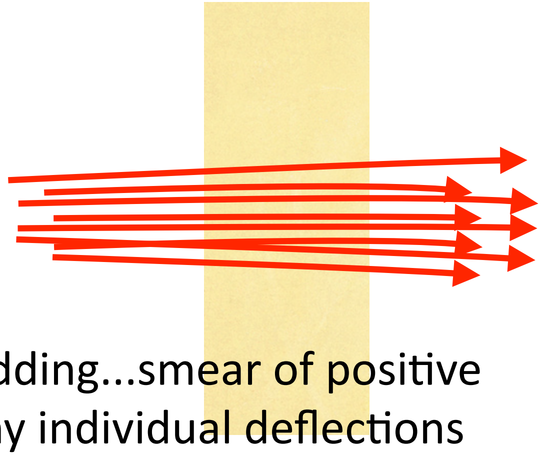
Fig. 3.





> “It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back at you.





JJ Plum pudding...smear of positive charge - tiny individual deflections

He had the solution after 2 years of work

he found:

1911: that the Atomic Number was +Ze

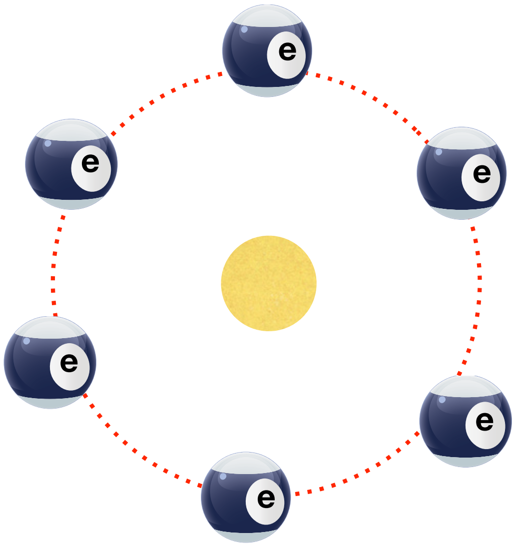
and made a model of the atom...

the Rutherford Model of the atom:

Matter consists of **hard-cores of positive charge**.

The nucleus. This matched his alpha-scattering data.

The **electrons**? Somewhere around the outside?



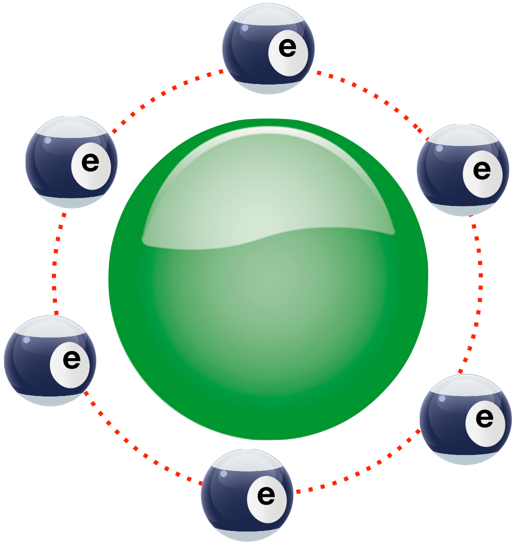
That’s problematic, the electrons would accelerate...and radiate.

a spiral of death.

the minimum size of the nucleus is

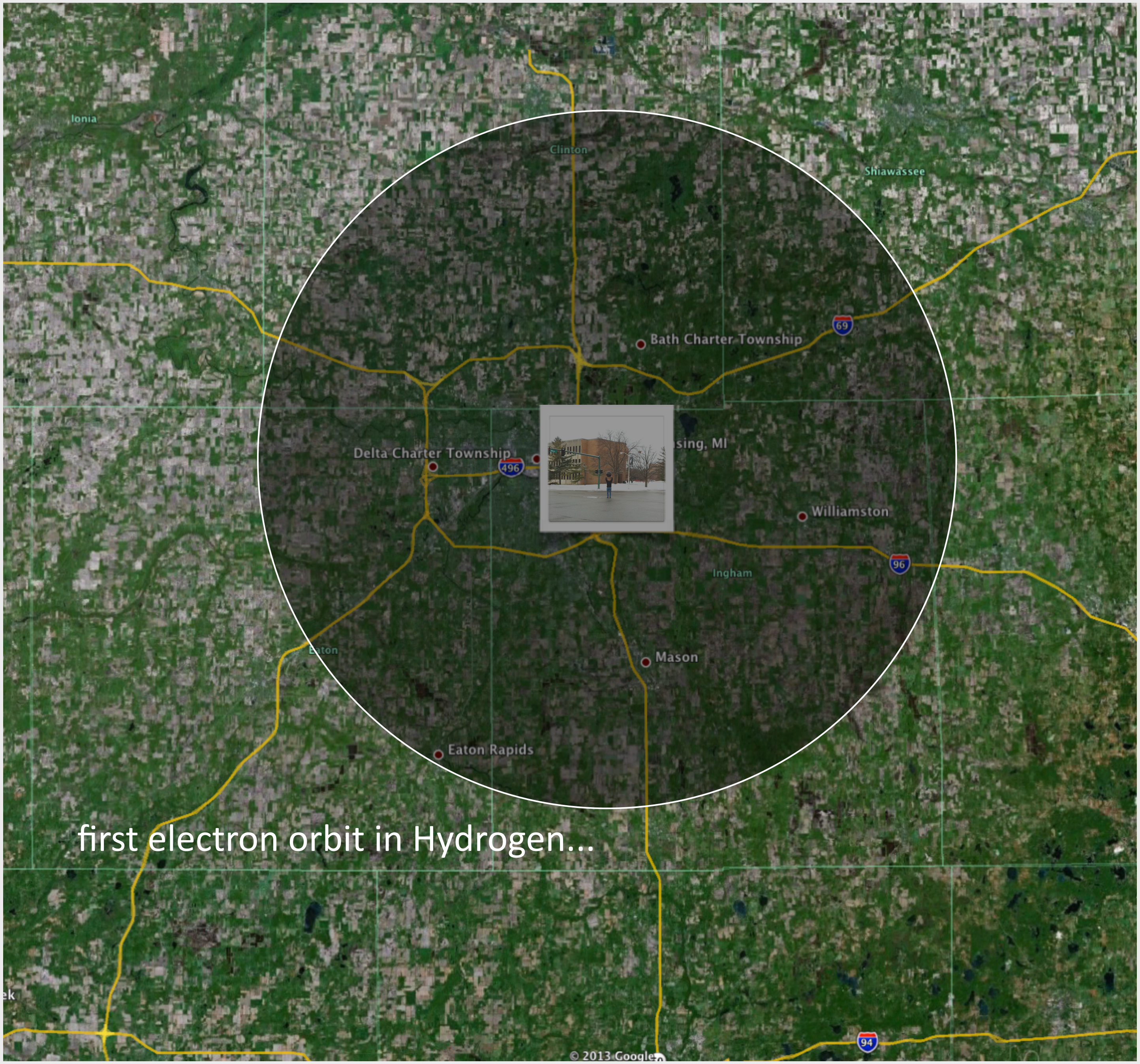
3×10^{-14} m

atom mostly nothing!

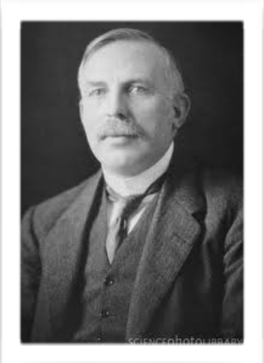


1 meter diameter ball

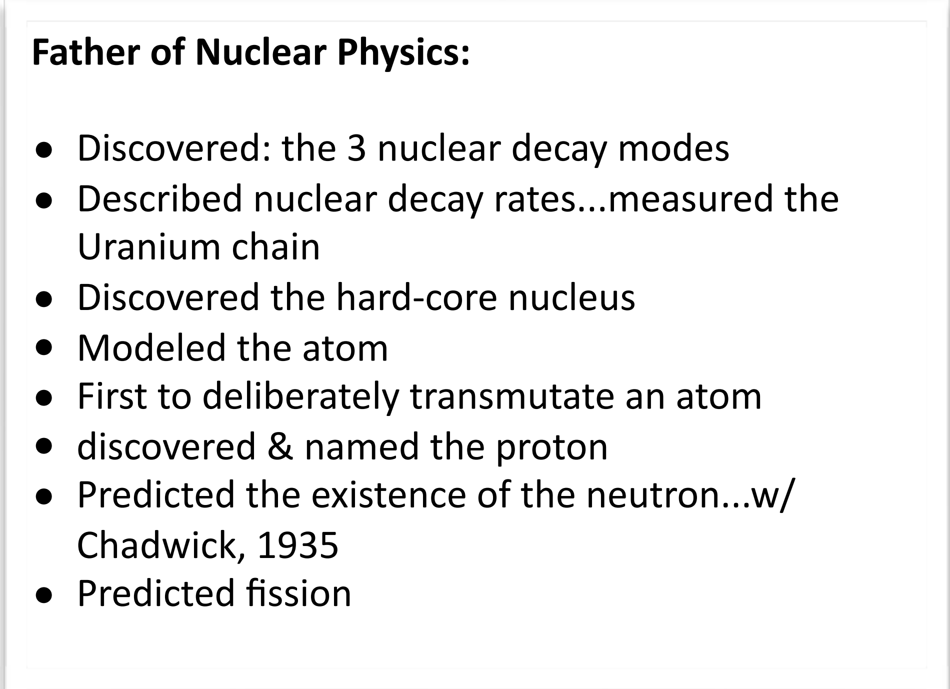
as a proton...



first electron orbit in Hydrogen...



Ernest Rutherford:



Father of Nuclear Physics:

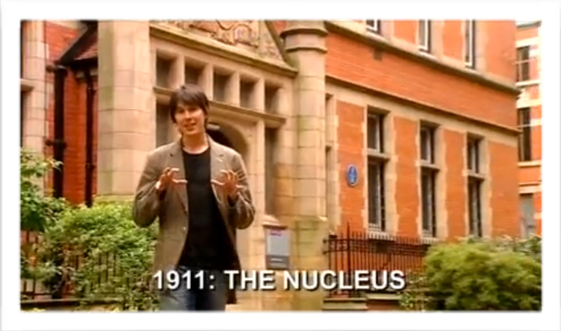
- Discovered: the 3 nuclear decay modes
- Described nuclear decay rates...measured the Uranium chain
- Discovered the hard-core nucleus
- Modeled the atom
- First to deliberately transmutate an atom
- discovered & named the proton
- Predicted the existence of the neutron...w/ Chadwick, 1935
- Predicted fission

Sir Ernest, 1914

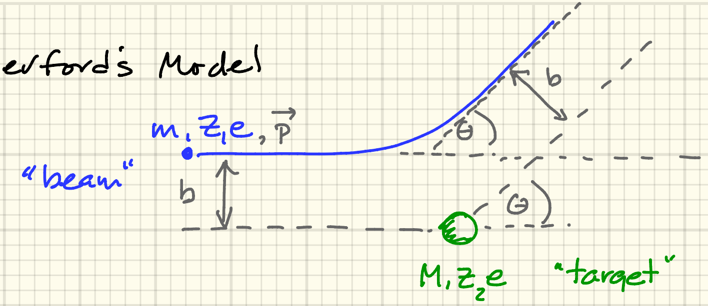
Baron, Lord Rutherford of Nelson, 1931

Died 1937, ashes interred

Westminster Abbey near Newton



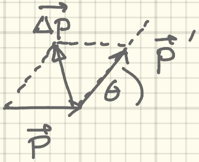
Rutherford's Model



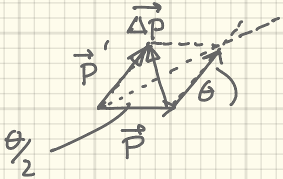
b: "impact parameter"

distance of closest approach.

momentum:

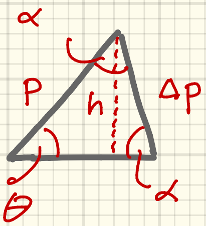


rearrange



some trig:

elastic: $|\vec{p}| = |\vec{p}\,'| = |m\vec{v}_0|$



$2\alpha + \theta = \pi$

$\alpha = \frac{\pi - \theta}{2}$

left: $\frac{h}{p} = \sin\theta$

$h = p\sin\theta$

right: $\frac{h}{\Delta p} = \sin\alpha$

$h = \Delta p \sin\alpha$

$= \Delta p \sin\left(\frac{\pi}{2} - \frac{\theta}{2}\right)$

$h = \Delta p \cos \theta/2$

$$\Delta p = 2mv_0 \sin\theta/2 = \int F\cos\phi \, dt = \frac{z_1 z_2 e^2}{4\pi\epsilon_0}\int \frac{\cos\phi}{r^2}\, dt$$

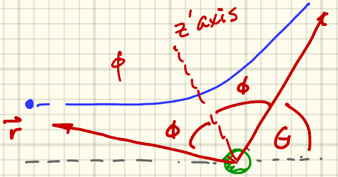
Conserve angular momentum: $\cancel{m} r^2 \frac{d\phi}{dt} = \cancel{m} v_0 b$

$$r^2 = \frac{v_0 b}{d\phi/dt}$$

so

$$2mv_0 \sin\theta/2 = \frac{z_1 z_2 e^2}{4\pi\epsilon_0}\int \frac{\cos\phi}{v_0 b}\,\frac{d\phi}{dt}\, dt = \frac{z_1 z_2 e^2}{4\pi\epsilon_0 v_0 \underset{\uparrow}{b}}\int_{\phi_i}^{\phi_f}\cos\varphi \, d\varphi$$

angle extremes:



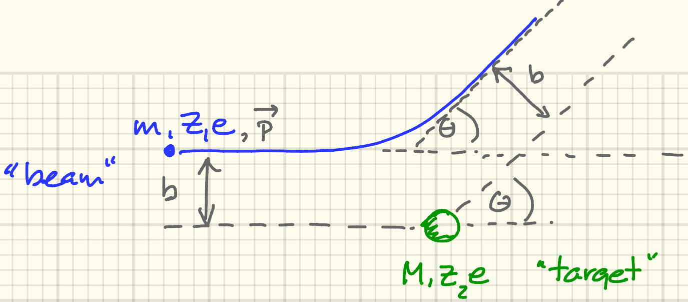
when $r \to \infty$

$\phi + \phi + \theta = \pi$

$\phi = \frac{\pi - \theta}{2}$

$$\int_{\phi_i}^{\phi_f} \longrightarrow \int_{-\left(\frac{\pi-\theta}{2}\right)}^{\left(\frac{\pi-\theta}{2}\right)} \cos\phi \, d\phi = 2\cos\theta/2$$

solve for b: $$b = \frac{z_1 z_2 e^2}{4\pi\epsilon_0 \underbrace{m v_0^2}_{2K}} \cot\theta/2$$



$$b = \frac{z_1 z_2 e^2}{4\pi\epsilon_0 m v_0^2} \cot \theta/2$$

$\theta = 0 \quad \cot \theta/2 = \infty \Rightarrow b = \infty$
forward

$\theta = \pi/2 \quad \cot \theta/2 = 1 \quad b = \frac{z_1 z_2 e^2}{4\pi\epsilon_0 m v_0^2}$

$\theta = \pi \quad \cot \theta/2 = 0 \Rightarrow b = 0$
backward.

smaller b ⇒ larger θ

What's the likelihood of scattering into a particular direction?

glad you asked.

"cross section"