PHY127 FS 2026

Prof. Ben Kilminster

Lecture April 24th, 2026

I was asked to show this slide.

Looking for volunteers for a study.

Universität Zürich[UZH]

Institut für Evolutionäre Anthropologie
Department of Evolutionary Anthropology

HEEP
Human Evolutionary Eco-Physiology

Looking for participants!

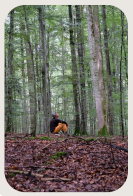
Help us discover how forests and cities influence human biology

Our team studies how the environments in which humans evolved have shaped *Homo sapiens* biology and how modern 21st-century settings affect key biological functions including stress, the immune system and physical performance;
and we want you to be a part of our research!

What are we doing this summer?

In Summer 2026, we're running a unique experimental study exploring how living in different environments influences human health and biology.

You will spend **5 consecutive days** taking part in guided activities in one of two environments:
- Züriberg forest
- Zürich City Centre



What will participants do?

You will take part in:
- Guided walks and light physical activities
- Physiological and psychological measurements
- Group meals and discussions

What you get in return:
- Lunch and dinner provided each day
- Learn how your body responds to the environment
- The chance to contribute to cutting edge research on how our environment affects our health

Get involved! Scan the QR code to learn more and sign up!

If you want to earn credits for your participation (BIO 548) contact: colin.shaw@iea.uzh.ch

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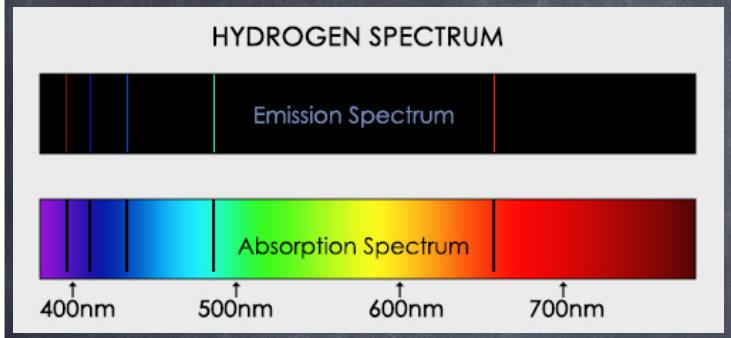
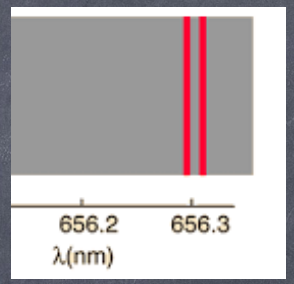
Last week:

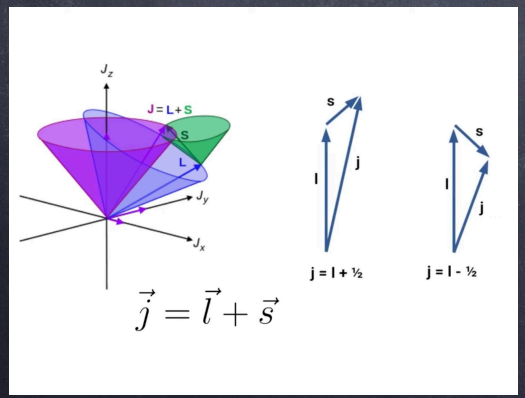
Fine structure is due to 4th quantum number, m_s



correspond to either $m_s = +\frac{1}{2}$ or $-\frac{1}{2}$



visible without a magnetic field.



$$\vec{j} = \vec{l} + \vec{s}$$

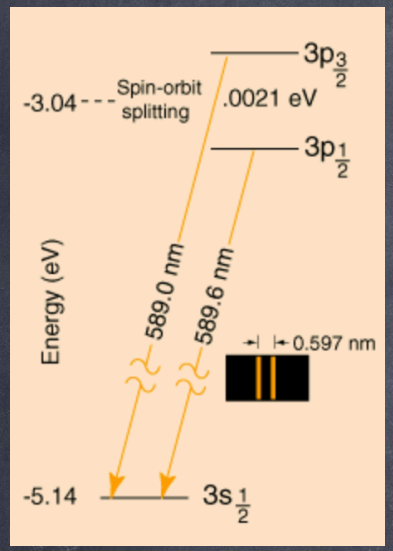
Two lines because of "spin-orbit coupling"

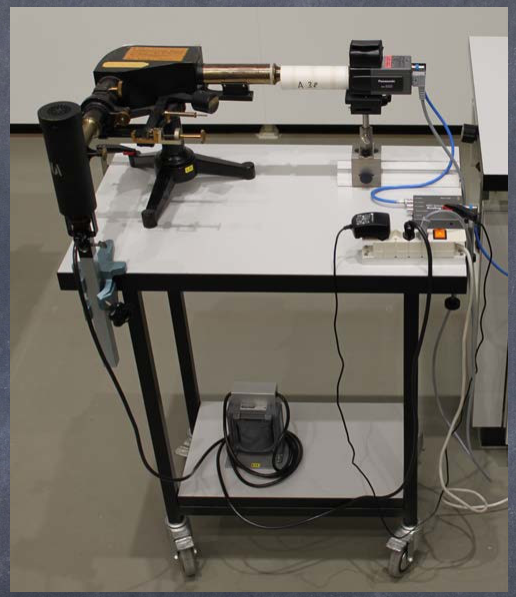
orbital angular momentum: ℓ quantum number

+

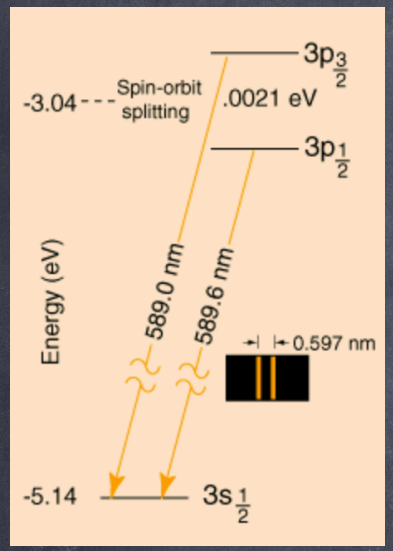
spin: s quantum number

Experiment to see the effect of electron spin-orbit coupling on the energy spectrum of Sodium (Na).





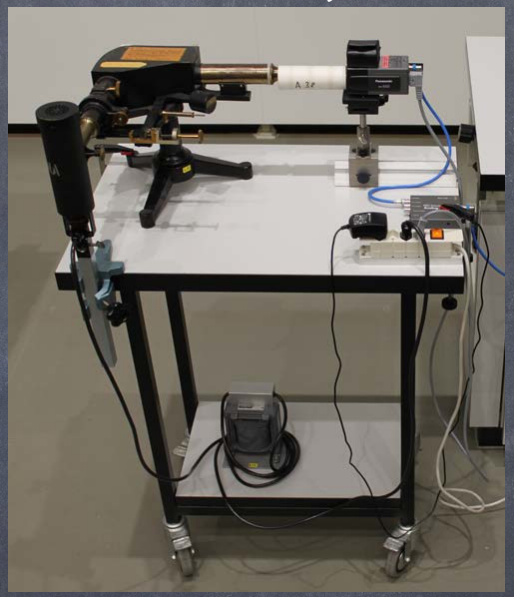
Experiment to see the effect of electron spin on the energy spectrum of Sodium (Na).



↑ 2 states for l = 1

↓

1 states for l = 0



$\Delta E = 0.0021$ eV

ΔE is due to the magnetic energy from the electron angular momentum difference

$\Delta E = \mu_e B = g \mu_B B$ ($g \sim 2$ for electrons)

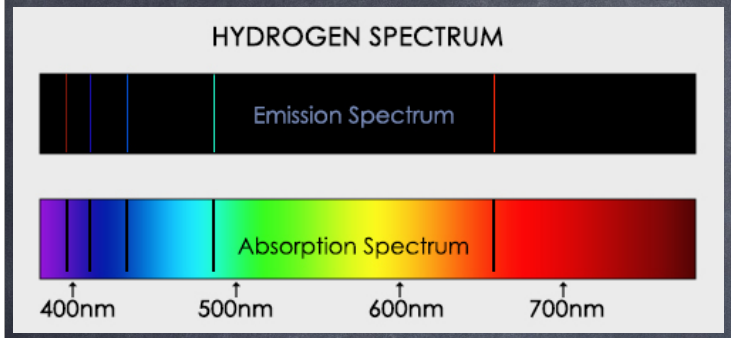
we can find that $B = \frac{\Delta E}{2\mu_B} = 18$ Tesla (very high by lab standards)

This is the internal magnetic field from the electron spin that produces splitting

Last week:

Fine structure is 4th quantum number, m_s

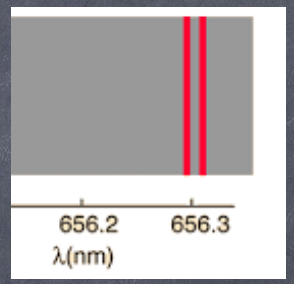
from spin of electron



Coupling of spin with orbital angular momentum causes two lines:

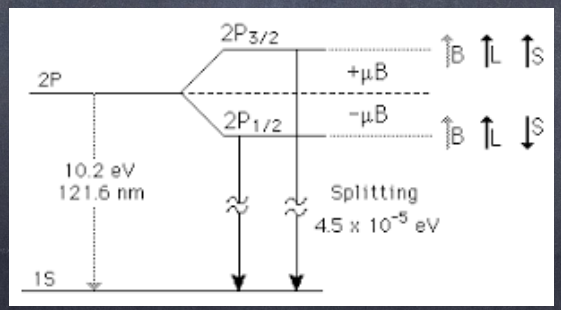
$2p_{\frac{3}{2}} \rightarrow 1s_{\frac{1}{2}}$

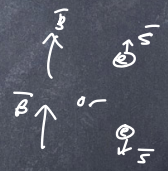
and $2p_{\frac{1}{2}} \rightarrow 1s_{\frac{1}{2}}$



visible without a magnetic field.

In a magnetic field, splitting increases (Zeeman effect)



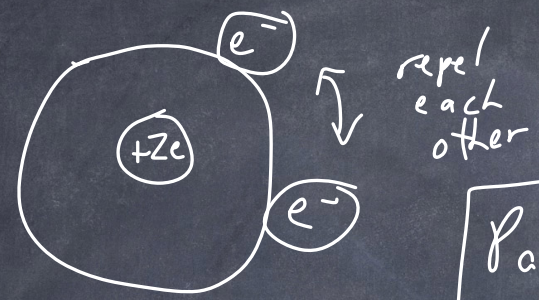


"hyperfine"

Note: there are other effects that further split spectral lines into more than one visible line. (such as the Stark effect - not covered here)

Atoms with many electrons:

He



(cannot be solved exactly with Schroedinger equation)

$$\boxed{\text{Pauli exclusion principle: no two electrons can have the same set of quantum numbers } (n, \ell, m, m_s)}$$

This is a rule that applies to all "fermions": particles that have a spin of $\frac{1}{2}\hbar$

Fundamental fermions (like electrons) have a spin of $\frac{1}{2}$ (often we omit the $\hbar$)

can have a spin of $+\frac{1}{2}$ or $-\frac{1}{2}$

Fermions are the particles that compose matter

fermions: electrons, muons, composite fermions (protons + neutrons)

$+\frac{1}{2}$ $\uparrow$ $\quad$ $-\frac{1}{2}$ $\downarrow$

Applied to the hydrogen atom (with one electron)

ground state: (n, ℓ, m, m_s) : $(1, 0, 0, +\frac{1}{2})$ or $(1, 0, 0, -\frac{1}{2})$ allowed ground states

In the absence of a magnetic field, both have the same energy.

The rules for atomic electron structure:

1) Electrons tend to occupy the lowest available energy levels.

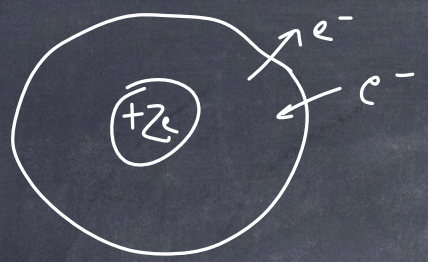
2) Each Electron has a unique set of quantum numbers.

Consider Helium: According to principles.

The first + second electrons occupy:

$(1, 0, 0, +\frac{1}{2})$ and

$(1, 0, 0, -\frac{1}{2})$



Experimental evidence confirms this.
The electrons have spins that anti-align.

This state of 2 electrons anti-aligned forms a rather strong bond with total spin Ø.

Sometimes, we refer to the n-values as "shells".

$n = 1 \quad 2 \quad 3 \quad 4 \quad \ldots$

shell = K L M N ...

And the ℓ values as "sub-shells"

$\ell = 0 \quad 1 \quad 2 \quad 3 \quad \ldots$

sub-shell = s p d f ...

Hydrogen description as: $1s^1$ or $1s$

Helium description as: $1s^2$

After H, He, we get lithium, with $3e^-$

But since only 2 electrons are allowed in the $n=1$ (K-shell) state, the third electron must be in $n=2$ (L-shell) state.

So Li is described as: $1s^2 2s^1$

the third electron can occupy $(2,0,0,+\frac{1}{2})$ or $(2,0,0,-\frac{1}{2})$

How many electrons can be in each sub-shell (and not violate the Pauli exclusion principle)?

For each m: two values of m_s
For each ℓ: $(2\ell+1)$ values of m } $2(2\ell+1)$

ordered by energy

lowest energy states moving to higher energy

n	ℓ	sub-shell	sub-shell capacity	total electrons in all sub-shells
1	0	1s	2	2
2	0	2s	2	4
2	1	2p	6	10
3	0	3s	2	12
3	1	3p	6	18
4	0	4s	2	20
3	2	3d	10	30
...	...	...	...	...

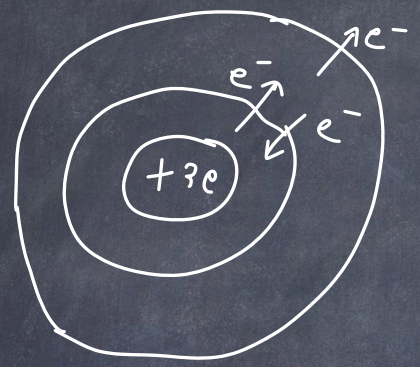
4s lower energy than 3d state due to "screening" & orbital shapes

Note: In hydrogen, 4s is not lower than 3d. (no screening)

E depends only on n (small corrections: fine structure & hyperfine structure)

Screening:

Electrons in higher energy levels see (or feel) a smaller positive charge due to inner electrons.



← Here, the outer electron is screened by the two K-shell electrons. It feels an effective positive charge:

$$Z_{effective} = Z_{eff} = +1e$$

(No screening in hydrogen...)

Ex:

sulfur has $Z = 16$

$$1s^2 2s^2 2p^6 3s^2 3p^4$$

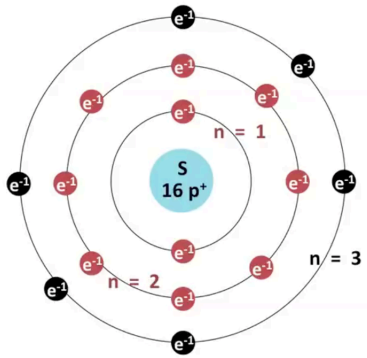
An electron at $n=3$ is shielded from the 16 protons by the inner shell electrons.

$$Z_{eff} = Z - \#\text{ inner shell electrons}$$

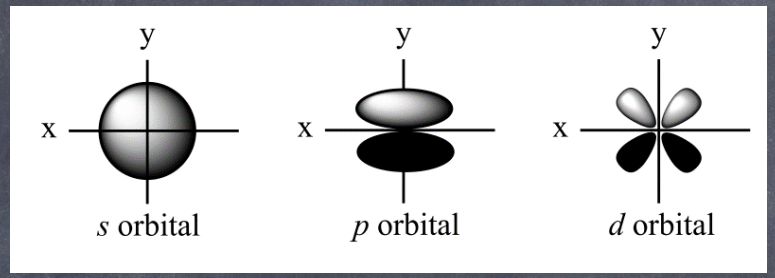
$$= 16 - 10$$

$$Z_{eff} = 6$$

What is the effective nuclear charge felt by an electron in the n = 3 shell of sulfur?



Aside : screening is a bit more complicated than this due to shape of orbits :



4p
3d
4s
3p
3s
2s
1s

energy

Note: 4s is bound with less energy than 3d

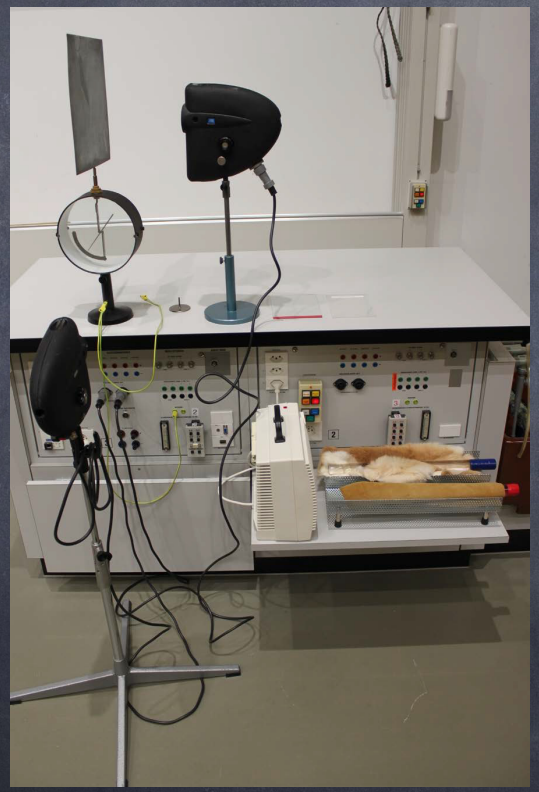
This is because of the shape of the electron orbit, which changes the amount of screening that happens.

Electrons with higher ℓ are more screened.

Lower-ℓ orbits are less screened because the orbits are more eliptical.

A bit of a detour on
detecting radiation

Photoelectric effect we already learned :

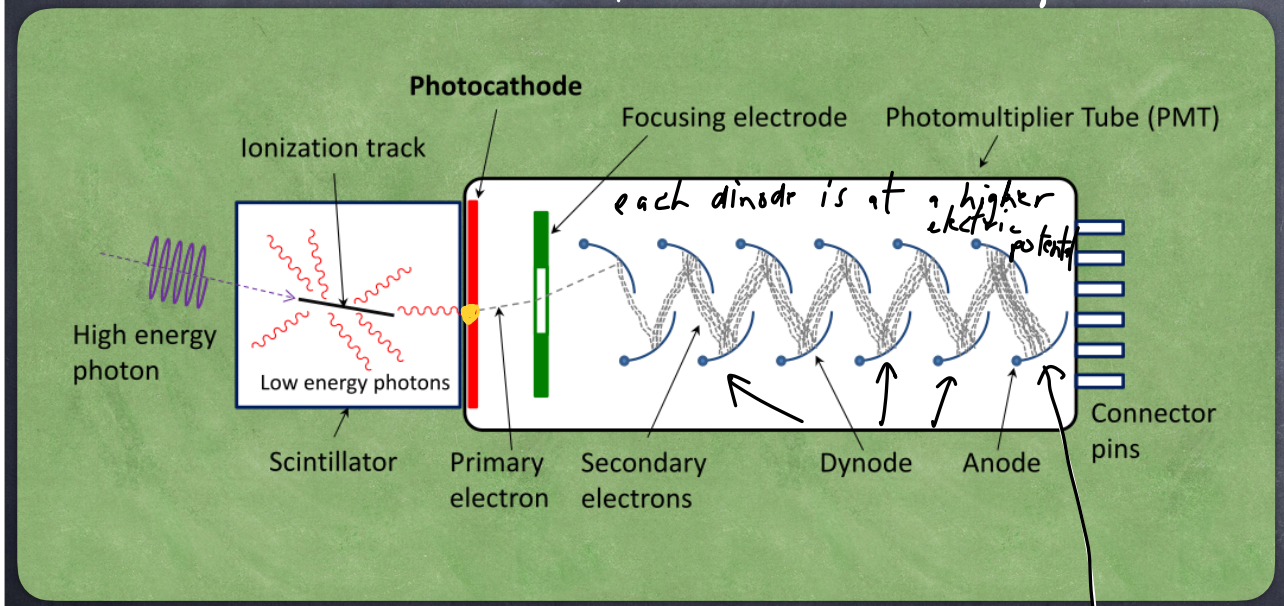


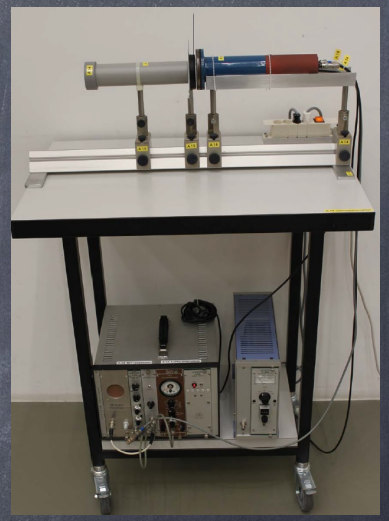
Light can free electrons if photons have enough energy to overcome binding energy

Radiation: we start with visible light detection

(PMT)

Photo multiplier tube causes cascade of electrons from one photon.



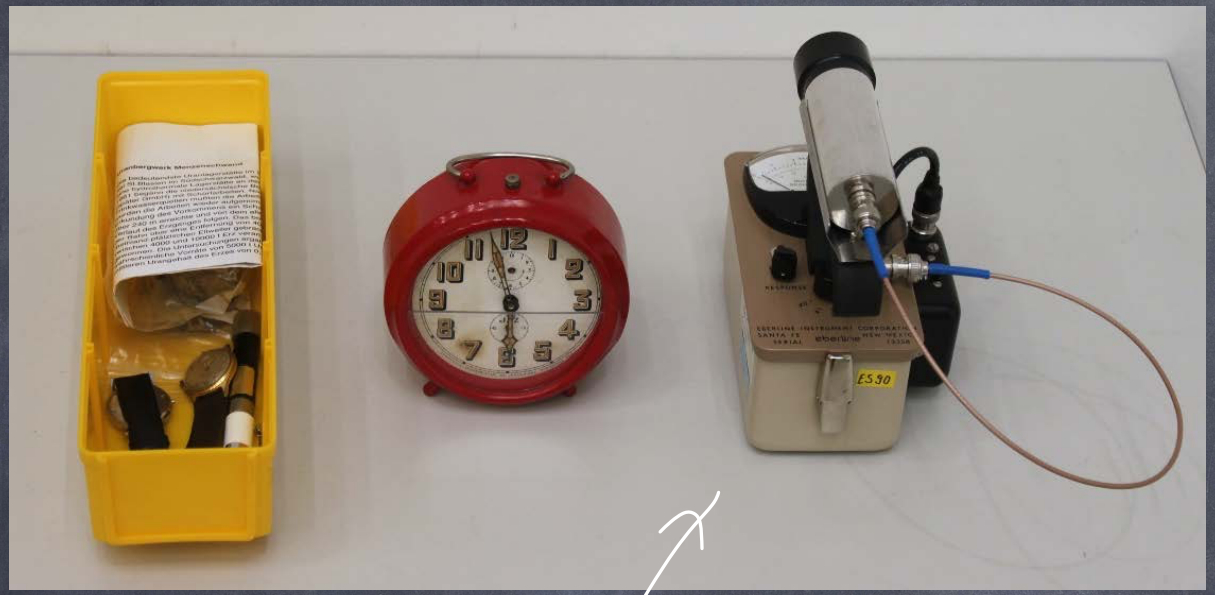


- photoelectric effect

pulse of charge

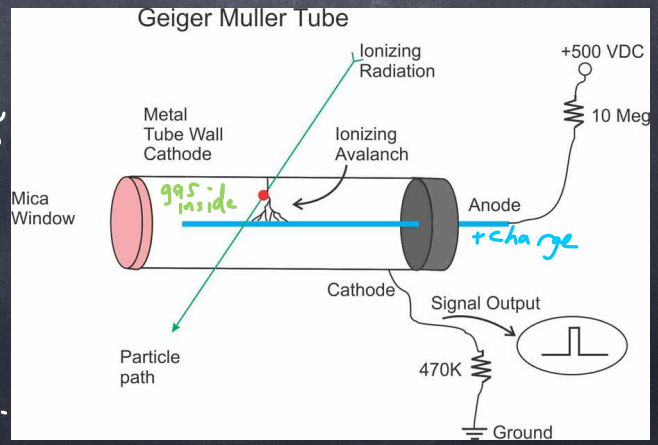
Charged particle radiation

Radium & Uranium decay producing charged radiation (alpha particles or Helium nuclei)



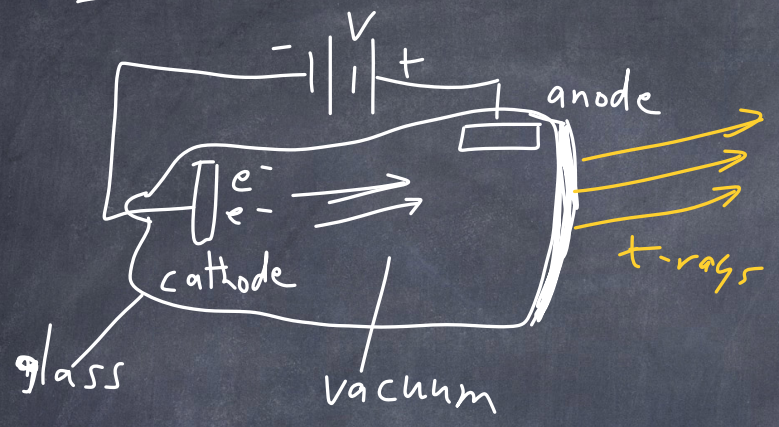
Geiger counter:

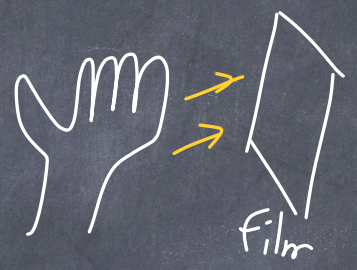
charged particle ionizes a gas inside producing electrons & ions. As the electrons accelerate to anode, secondary electrons are produced. Record charge pulse as a click.



Discovery of the x-ray

Roentgen, 1895

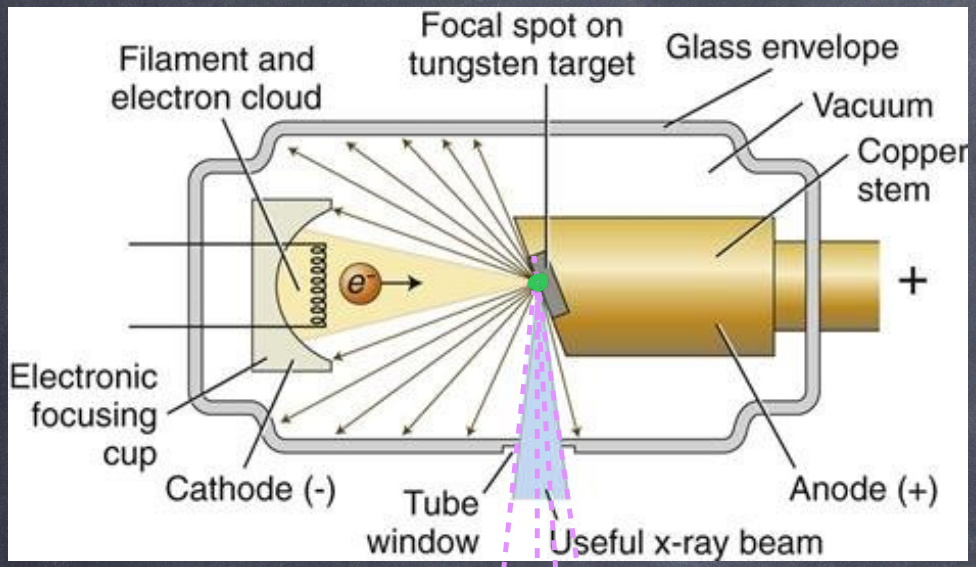


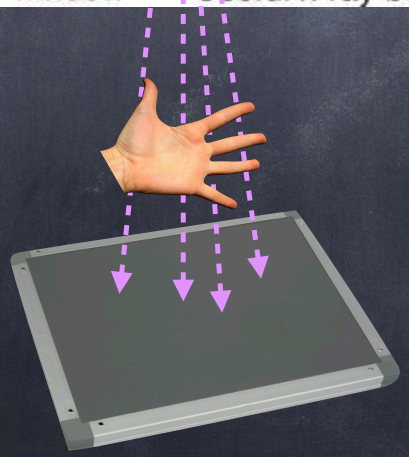


First "medical x-ray"

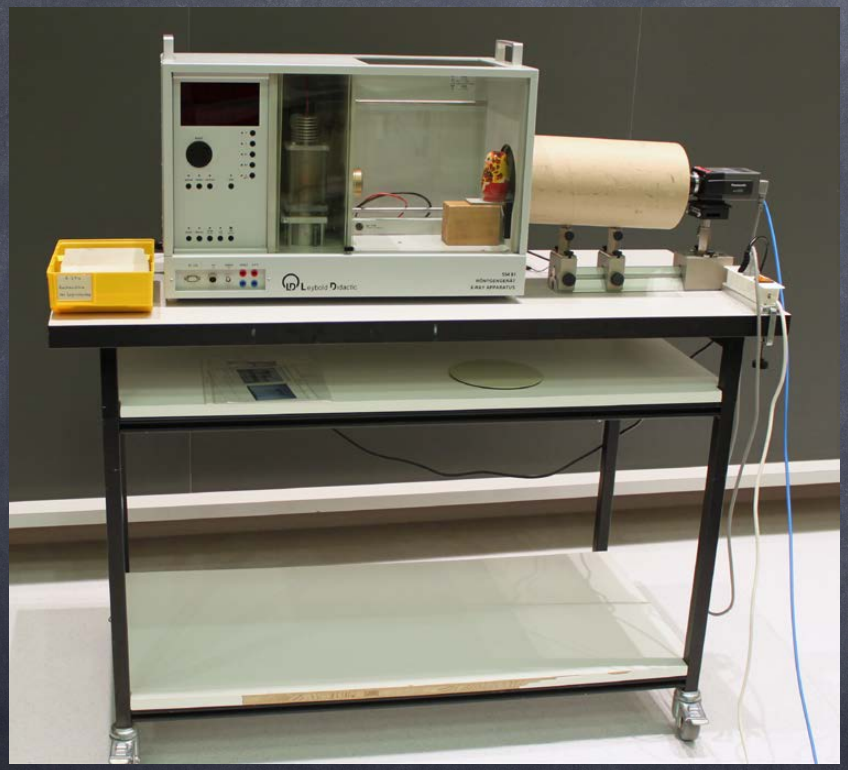
Roentgen's wife:
"I have seen my death"

Modern X-ray tube:

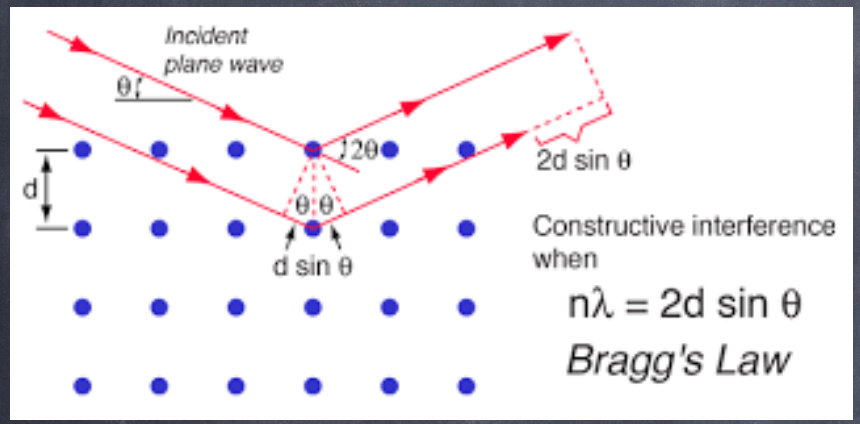


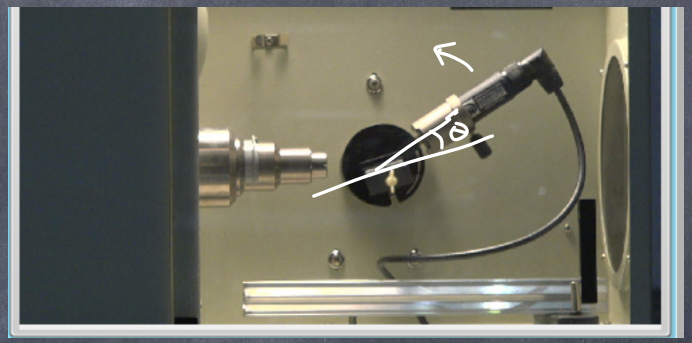


Fun with x-rays in class:



Bragg's Law: we use this to measure the intensity of x-rays at different wavelengths by moving a detector (PMT) at different angles





Experiment in class:

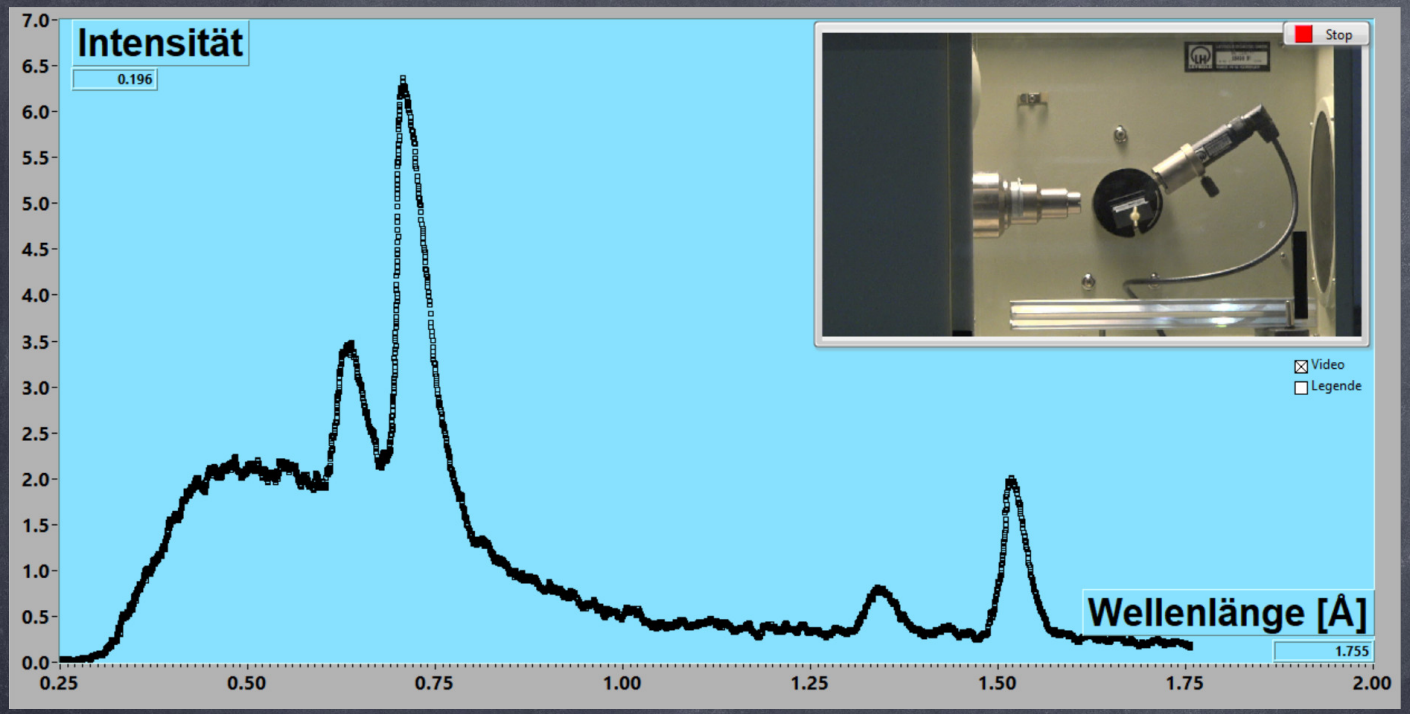
Crystal: Natrium-Chlorid:
Netzebenenabstand 282 pm
Reflexionswinkel für die Molybdän-K α-Strahlung der Wellenlänge 71 pm: $\sigma_B = 7.24°$.

The wavelength probed depends on θ

The detector rotates in θ, $\lambda = \lambda(\theta)$

$$\lambda = \frac{2d\sin\theta}{n}$$

interference maxima
($n=1$ maybe $n=2$?)



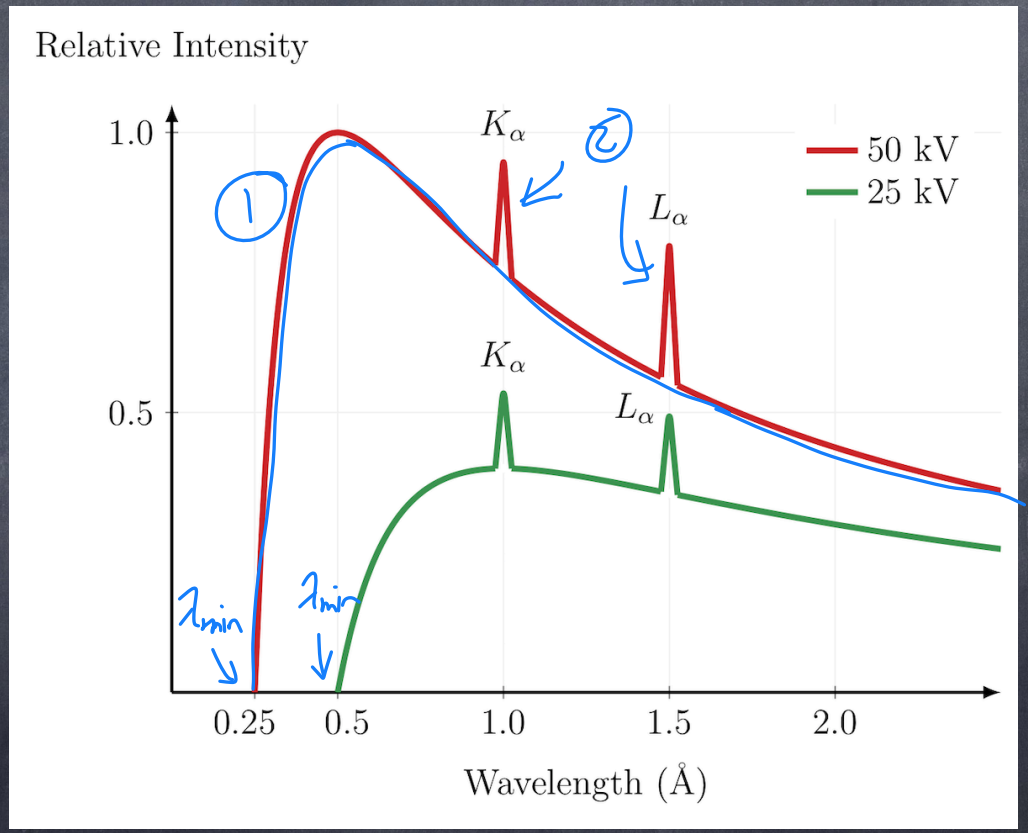
n=1 n=2

what is this structure?

x-ray production: 2 components

1) Bremmstrahlung
2) atomic excitation x-rays (characteristic x-rays)

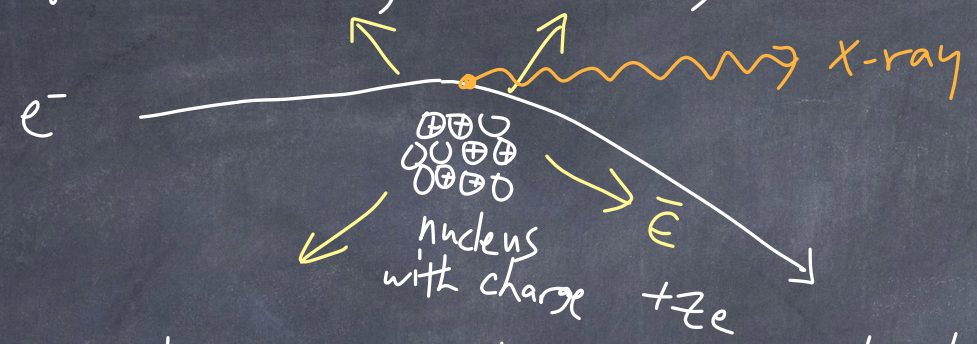
x-ray wavelength spectrum



Å = 1E-10 m
Angstrom

← higher energy is lower wavelength

1) Bremmstrahlung "braking radiation"



when an electron passes closely to a nucleus, it has a large deflection angle, and a photon (or more) is radiated.

Feynman diagrams

Maximum energy from Bremmstrahlung is if all the initial electron energy $(U = eV)$ is converted to an X-ray.

Then $\epsilon = h\nu = \frac{hc}{\lambda} = U = eV$,

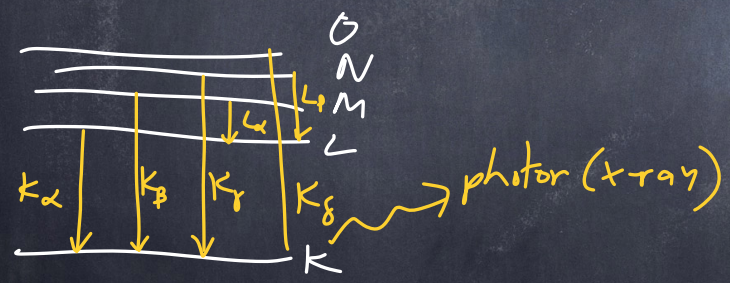
so for a voltage V, the minimum wavelength of the X-ray is $\lambda_{min} = \frac{hc}{eV}$ (This is the cut off wavelength)

② characteristic x-rays:

1) accelerated electron hits an inner orbital electron of an atom, knocking it out.

2) once the inner electron is removed, an electron from a higher energy level drops down to fill the vacancy.

The energy difference becomes the energy of an emitted x-ray.



To estimate the photon energy of the characteristic x-rays, we can't simply use

$$\Delta E = \frac{hc}{\lambda} \quad \text{where} \quad \frac{1}{\lambda} = R Z^2 \left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right)$$

we instead use Z_{eff} to account for screening.

X-rays

energy for medical applications lies between

30 keV — 150 keV

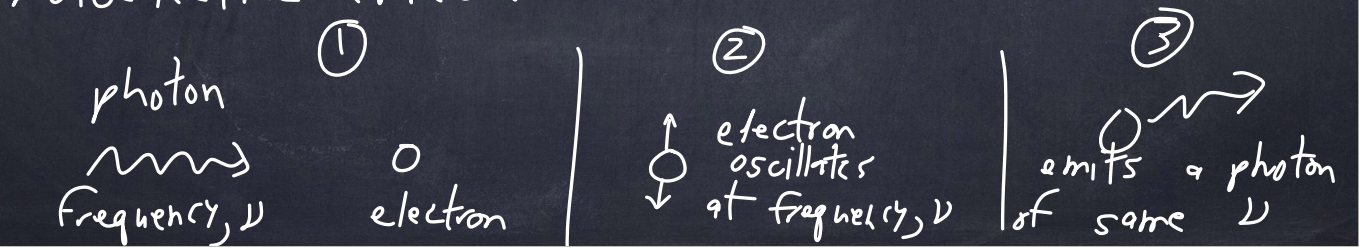
mammography — high-voltage radiology

These correspond to: 10^{-10} m (λ) — 10^{-12} m (λ)

How X-rays interact with matter:

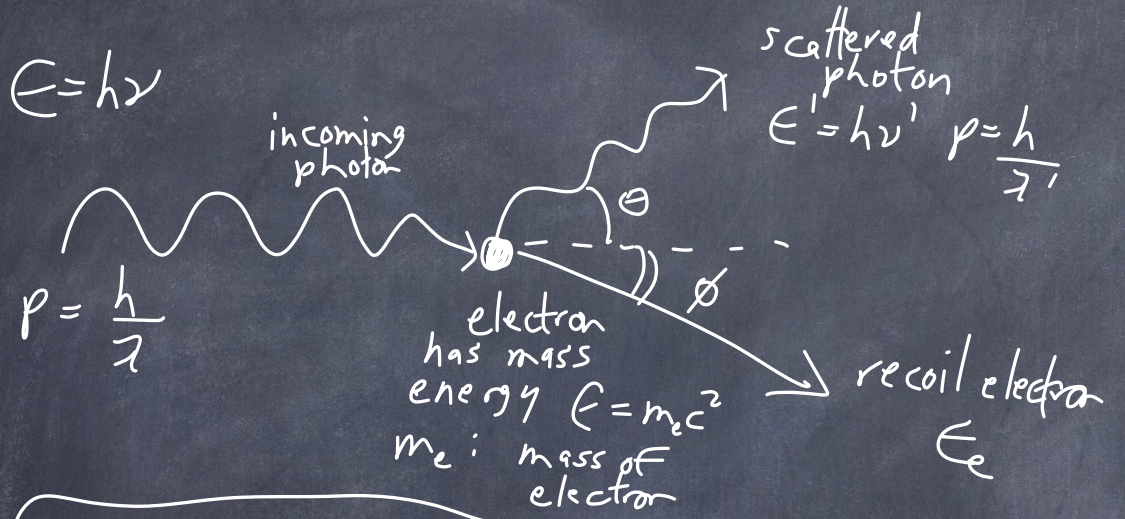
1) Thomson scattering – does <u>not</u> change the photon energy
2) Compton scattering
3) Photoelectric effect.

Thomson scattering:



Compton scattering - process that makes the wavelength larger (reduce the energy ↓ frequency of the ray)

$E = h\nu$



$\nu' < \nu$, $\lambda' > \lambda$

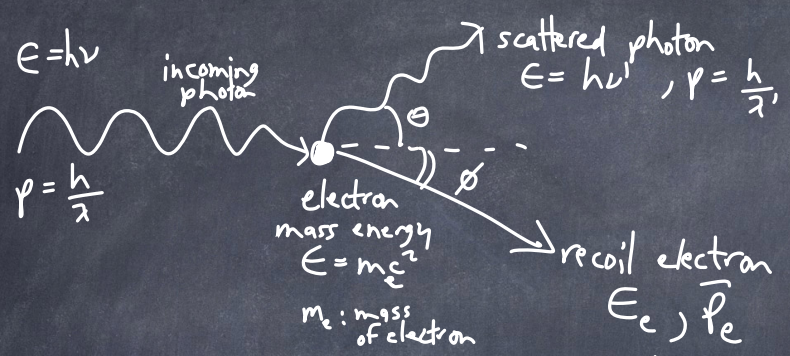
$$\boxed{\Delta\lambda = \lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)}$$

Compton effect

(Derivation of this formula in notes)

start of derivation:

Supplementary: how to derive the Compton effect formula:



we do it using momentum + energy conservation.

	Initial state	Final state
photon energy	$h\nu$	$h\nu'$
photon momentum in x-direction	$\frac{h}{\lambda}$	$\frac{h}{\lambda'}\cos\theta$
photon momentum in y-direction	0	$\frac{h}{\lambda'}\sin\theta$
Electron energy	mc^2	$E_e = m_e c^2 + K$ ← Kinetic energy
Electron momentum in x-direction	0	$p_e \cos\phi$
Electron momentum in y-direction	0	$p_e \sin\phi$

Relativistically, the energy of a massive particle is

$$\boxed{E^2 = \underbrace{(mc^2)^2}_{\text{from rest mass}} + \underbrace{(cp)^2}_{\text{from momentum}}}$$

⓪ True in general!

For our problem

Energy conservation means $E_{initial} = E_{final}$

$$\boxed{h\nu + m_e c^2 = h\nu' + E_e} \quad ①$$

Momentum conservation in x direction:

$$\boxed{\frac{h}{\lambda} = \frac{h}{\lambda'}\cos\theta + p_e \cos\phi} \quad ②$$

in y direction:

$$0 = \frac{h}{\lambda'}\sin\theta - \underbrace{p_e \sin\phi}_{-y \text{ direction}}$$

$$\boxed{\frac{h}{\lambda'}\sin\theta = p_e \sin\phi} \quad ③$$

Now we solve this. First, square ② + ③ and add. This removes ϕ:

$$p_e^2\left(\sin^2\phi + \cos^2\phi\right) = \left(\frac{h}{\lambda}\right)^2 + \left(\frac{h}{\lambda'}\right)^2\left(\cos^2\phi + \sin^2\phi\right) - 2\frac{h}{\lambda}\frac{h}{\lambda'}\cos\theta \qquad ④$$

Now substitute E_e from ① + p_e from ④ into ⓪:
(Setting $\lambda = \frac{c}{\nu}$)

$$\left[h(\nu-\nu') + (mc^2)\right]^2 = m_e^2c^4 + (h\nu)^2 + (h\nu')^2 - 2h\nu(h\nu')\cos\theta$$

Do the squaring of the left side + cancel terms to get:

$$m_ec^2(\nu-\nu') = h\nu\nu'(1-\cos\theta)$$

rearranging: $\frac{h}{m_ec^2}(1-\cos\theta) = \frac{\nu-\nu'}{\nu\nu'} = \frac{\frac{c}{\lambda}-\frac{c}{\lambda'}}{\frac{c^2}{\lambda\lambda'}} = \frac{1}{c}(\lambda'-\lambda)$

end: or $\boxed{\Delta\lambda = \lambda'-\lambda = \frac{h}{m_ec}(1-\cos\theta)}$

Done!

Back to notes...

The quantity $\frac{h}{m_e c}$ is called the Compton wavelength of the electron,

$$\lambda_c = \frac{h}{m_e c} = 2.43 \times 10^{-12}\ \text{m} = 0.00243\ \text{nm}$$

Only for wavelengths of x-rays equal to λ_c or smaller is Compton scattering <u>observed</u>.

For example, visible light has $\lambda \sim 500$ nm

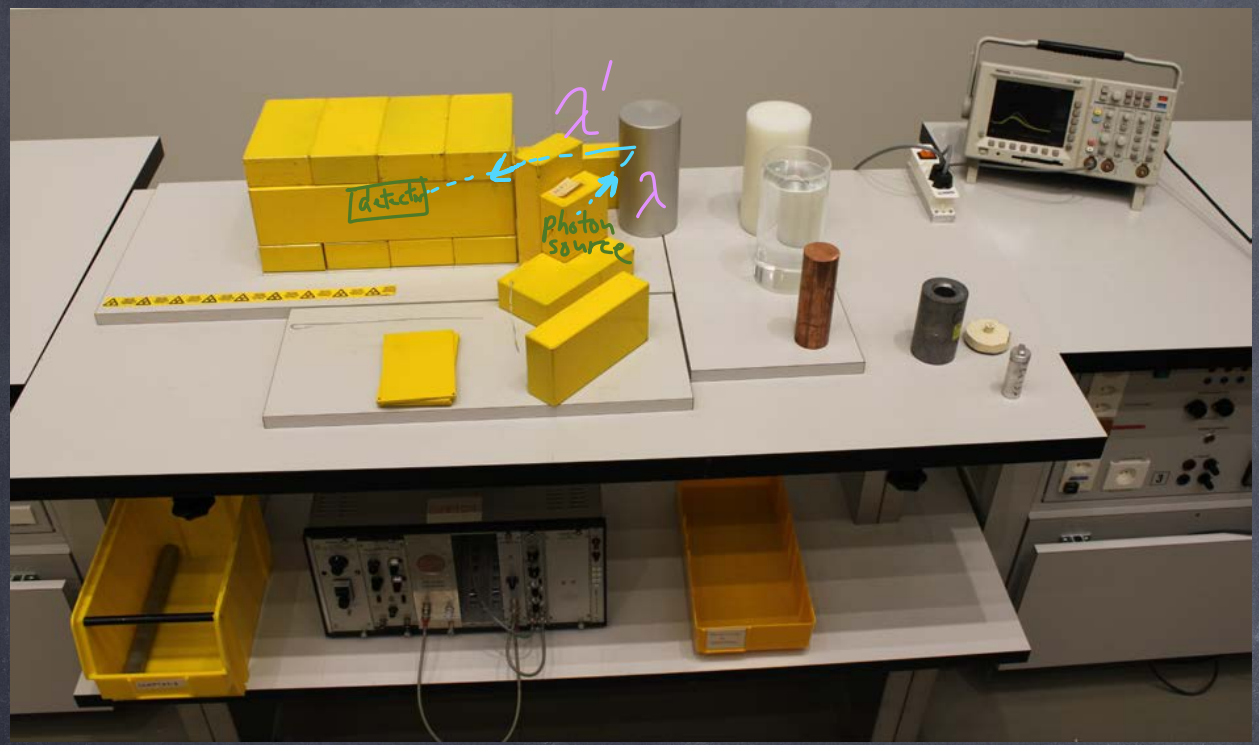
Compton effect happens, but the maximum relative change in λ: $\frac{\Delta\lambda}{\lambda} \sim 10^{-5}$ (too small to see)

For an x-ray, $\lambda \sim 0.07$ nm,

So $\frac{\Delta\lambda}{\lambda} \sim 0.03$ (3%)

So the compton effect is only important for x-rays, gamma energies (not visible, infrared, UV, ...)

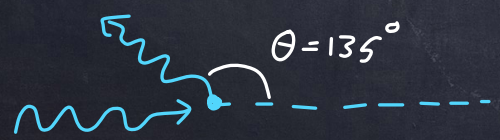
Compton effect experiment



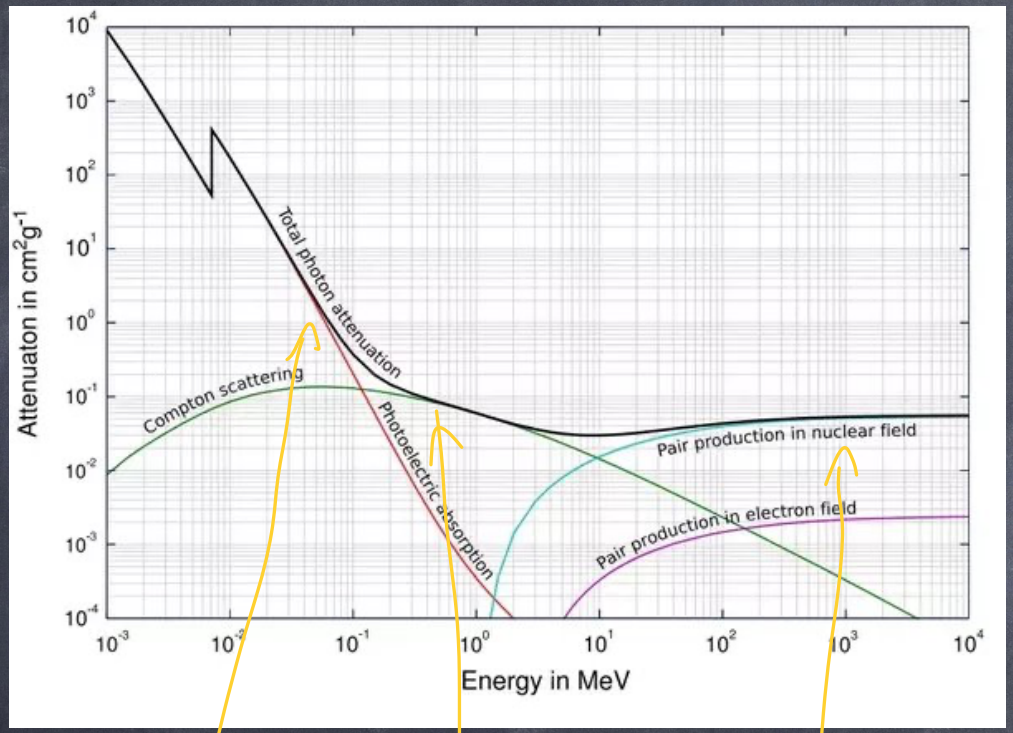
^{137}Cs source emits electrons (512 keV) and photons (662 keV)

we can stop electrons with aluminum

we could calculate λ' based on this angle using formula



Attenuation is $\frac{I}{I_0}$: how the photons lose energy as a function of their initial energy.



Attenuation units $\left[\frac{cm^2}{g}\right]$

if you multiply by the density $\left[\frac{g}{cm^3}\right]$

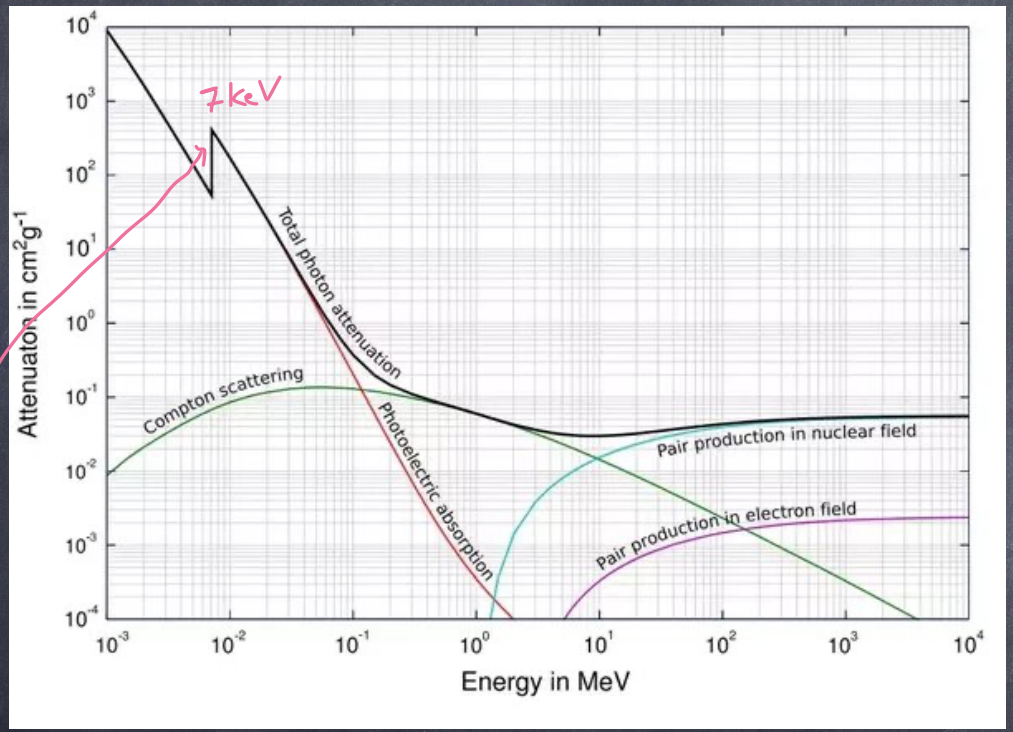
you get attenuation in units cm^{-1}

photoelectric absorption (produces ionization

Compton effect

pair production $\gamma \rightarrow e^+ e^-$

How photons lose energy as a function of their initial energy.



From this plot, the K-absorption edge is ~7 keV. use this to find out what material this is. website

photoelectric absorption edge (higher interaction rate if photon has almost the same energy as an atomic energy shell.) Here we see the K-shell absorption edge.

Database of K-absorption edges for different materials here :

http://skuld.bmsc.washington.edu/scatter/AS_periodic.html

Follow-up clarification: If energy levels for atoms with a spin-up or spin-down electron are the same,

then why is there splitting of energy levels due to fine structure?

To be clear, energy levels are only the same when $\ell = 0$, such as the <u>ground state</u>, where $n=1, \ell=0$.

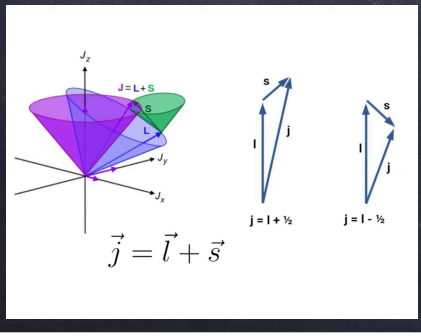
This is because the splitting of energy levels comes from adding the orbital angular momentum (quantum number, ℓ) with the spin, s. (A non-zero ℓ is required)

To add $\bar{\ell} + \bar{s}$, we add or subtract the magnitudes:

$j = |\ell| + |s|$ and $j = |\ell| - |s|$

the total magnitude is $|j|$:

Adding $\bar{\ell} + \bar{s}$



Examples:

If one adds $\ell = 1$ and $s = \pm\frac{1}{2}$,

we get $j = |1| + |+\frac{1}{2}| = \frac{3}{2}$ and $j = |1| - |+\frac{1}{2}| = \frac{1}{2}$

So $|j| = |\frac{3}{2}| = \frac{3}{2}$ and $|j| = |\frac{1}{2}| = \frac{1}{2}$

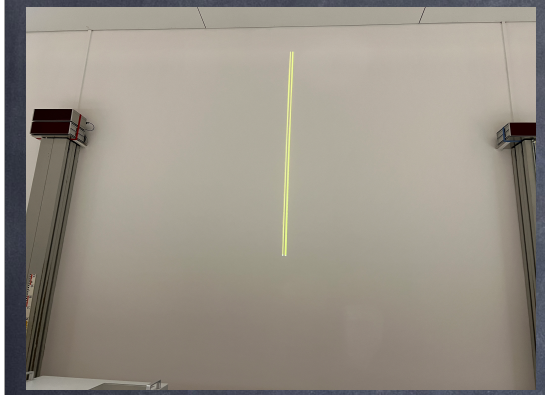
These different $|j|$ have different energy levels.

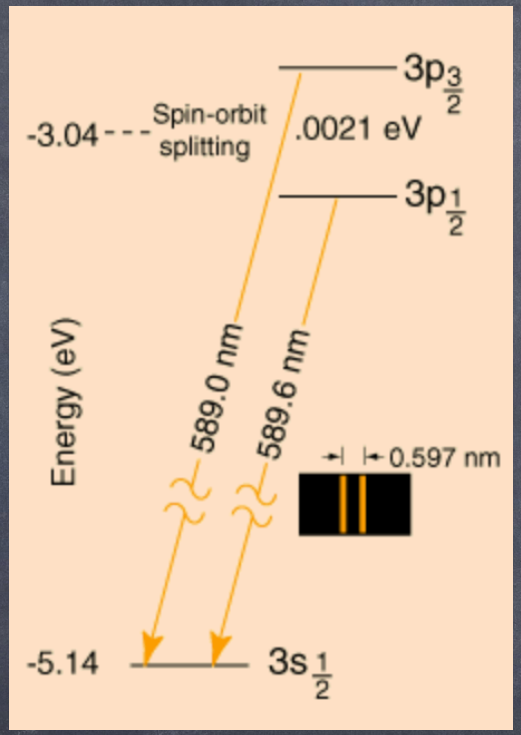
If one adds $\ell = 0$ and $s = \pm\frac{1}{2}$,

we get $j = |0| + |+\frac{1}{2}| = \frac{1}{2}$ and $j = |0| - |+\frac{1}{2}| = -\frac{1}{2}$

These same $|j| = \frac{1}{2}$ have the same energy levels.

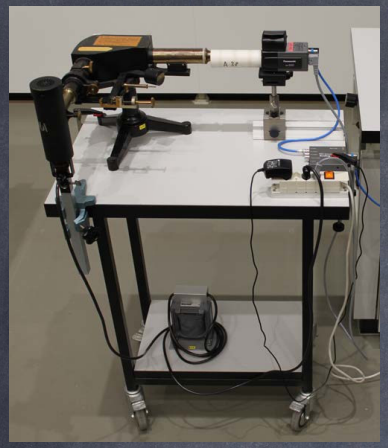
Sodium doublet





2 energy levels for $\ell = 1$ (p subshell)

1 energy level for $\ell = 0$ (s subshell)



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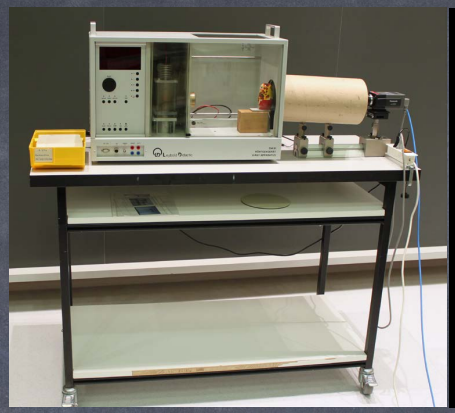

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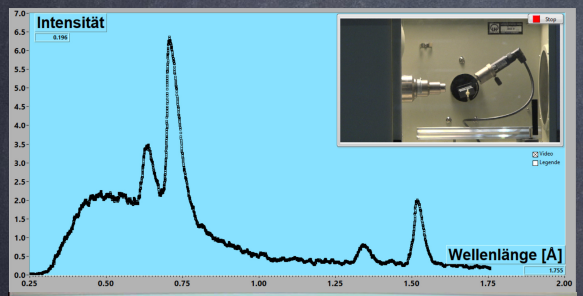

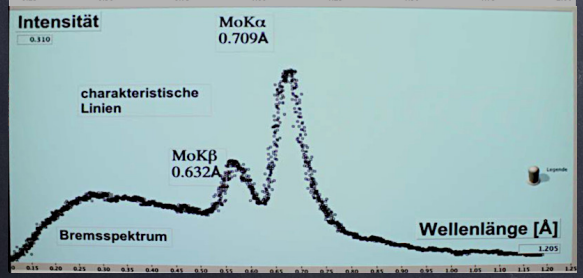

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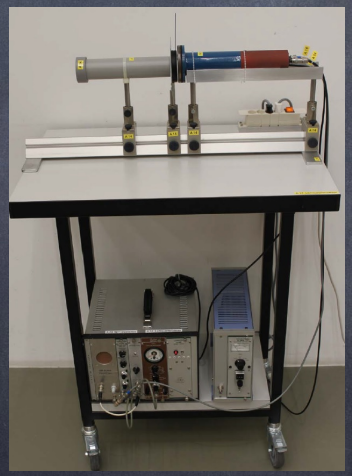

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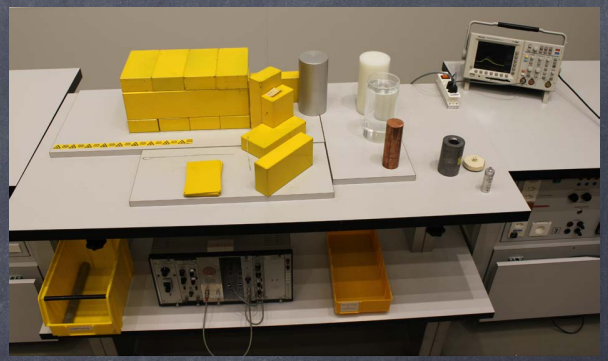

A3

ES90