Particle Nature of Light
Exam Details

The exam will be held Wednesday, October 4th during class time.

Steffie will lead the review session on Monday, Oct. 2nd. As a result, there will be no recitations the week of the 2nd.

The practice exam has been posted on the webpage. Please review it, as questions on the actual exam will be quite similar.
Unlike continuous spectra from blackbodies, chemical elements produced discrete spectra.

19th century experiments would excite elements (by applying high voltage) and study their optical spectra.

Johann Balmer noticed that the (particularly simple) hydrogen spectrum had the following form

\[
\lambda = 364.54 \frac{k^2}{k^2 - 4} \text{ nm}
\]
In fact, the Balmer series was only the first of several series to be discovered (first because it was the only series in the visible part of the light spectrum).

Lyman  Balmer  Paschen  etc.
Johannes Rydberg and Walther Ritz found a more general empirical equation for calculating the wavelengths:

\[
\frac{1}{\lambda} = R_H \left( \frac{1}{n^2} - \frac{1}{k^2} \right)
\]

\( R_H = 1.097 \times 10^7 \text{ m}^{-1} \)

\( n \) and \( k \) are integers (where \( k > n \))

- Lyman series: \( n=1, \ k>1 \)
- Balmer series: \( n=2, \ k>2 \)
- Paschen series: \( n=3, \ k>3 \)
- Brackett series: \( n=4, \ k>4 \)
- Pfund series: \( n=5, \ k>5 \)
In fact, what was being observed were transitions between different energy levels. The Lyman series was the transition to the lowest level (i.e. the ground state).
PLANCK’S COMMENT ABOUT EINSTEIN

Max Planck and other senior physicists nominated Einstein for membership in the Prussian Academy of Sciences. In their affidavit they wrote:

“Summing up, we may say that there is hardly one among the great problems, in which modern physics is so rich, to which Einstein has not made an important contribution. That he may have sometimes missed the target in his speculations, as for example in his hypothesis of light quanta (photons), cannot really be held too much against him, for it is not possible to introduce fundamentally new ideas, even in the most exact sciences, without occasionally taking a risk.”

Photoelectric effect quiz. Recall that the stopping potential is proportional to the incident photon energy minus the work function: \( eV_s = h\nu - \phi \)

**PRS Question:** If you double the photon frequency, what happens to the maximum kinetic energy of the released electrons?

A) It **doubles**
B) It **less than** doubles
C) It **more than** doubles
The easy way to see this is to plug in some numbers.
Let $\phi=2 \text{ eV}$ and suppose $h\nu=10 \text{ eV}$. Then $K_{\text{max}}=8 \text{ eV}$. Now suppose $h\nu=20 \text{ eV}$. Then $K_{\text{max}}=18 \text{ eV}$.

$$eV_s = h\nu - \phi$$

PRS Question: If you double the photon frequency, what happens to the maximum kinetic energy of the released electrons?

A) It doubles  
B) It less than doubles  
C) It more than doubles
The photoelectric effect **requires a bound electron**; i.e., the electron cannot be free.

Consider the alternative that the electron is free. In this case:

The photon scatters against an electron at rest. The photon is **absorbed** and the electron is carried away.

Let’s move to the center of momentum frame, where the photon and electron have **equal but opposite** momenta.

In this picture momentum is conserved (p=0, before and after) but **energy is not**! $E_{\text{before}} > m_e c^2$, but $E_{\text{after}} = m_e c^2$. 

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When a photon scatters off of a free electron, the only way to preserve energy and momentum conservation is to allow the photon to be re-emitted during scattering. This is the *Compton effect*.

\[ \Delta \lambda = \lambda' - \lambda = \frac{h}{mc}(1 - \cos \theta) \]

Compton observed longer wavelength photons being re-emitted after scattering with electrons.
As the scattering angle increases, the wavelength of the backscattered photons increases.

Notice that the first peak is preserved. This is because of scatters against tightly bound electrons close to the nucleus.
Notice that by increasing the electron’s mass (equivalent to decreasing the photon’s energy) the difference in wavelength is suppressed.

\[ \Delta \lambda = \lambda' - \lambda = \frac{h}{mc} (1 - \cos \theta) \]

In the limit when \( mc \gg h/\lambda \), then \( \Delta \lambda = 0 \). The photon that is emitted has the same wavelength as the photon that is absorbed.

This is called **Thompson scattering**.

Notice that this is a **wavelength dependent effect**.

For visible light the Compton wavelength shift is one part in \( 10^{-5} \) (i.e. Thompson scattering). Once you have x-rays, the shift is \( \sim 10^{-2} \).
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Is the particle positively charged and moving upward, or negatively charged and moving downward?
1932, C.D. Anderson takes a photograph in a cloud chamber of a cosmic ray particle.

Is the particle positively charge and moving upward, or negatively charged and moving downward?

Tighter circle after particle passes through the lead plate: particle must be going upward. Energy loss is inconsistent with a proton.

Anderson wins Nobel Prize in 1936 for discovering the positron (identical to an electron, but with + charge).
A photon can produce an electron/positron pair by interacting with a nucleus.

PRS Question: A photon is traveling in a vacuum. How much energy is required for a photon to spontaneously produce an $e^+ e^-$ pair?

A) exactly twice $m_e c^2$
B) less than twice $m_e c^2$
C) more than twice $m_e c^2$
D) It is impossible
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D) It is impossible
Go to the center of momentum frame of the electron/positron pair.

In this frame, the total momentum is zero. For momentum to be conserved, the photon would need to have **zero momentum**, also, and consequently **zero energy**. Therefore, this process would **violate energy conservation**.