Science Open Source Software
for Teaching Learning

Photoelectric Effect

Understanding the Photoelectric Effect and The Particle Behavior of Light

Utpal Anand

Science OpensoUrce Software for Teaching Learning
Free/Libre and Open Source Software for Education
IIT Bombay

Pune, December 2024

Science Open Source Software
for Teaching Learning

Photoelectric Effect

Understanding the Photoelectric Effect and The Particle Behavior of Light

Utpal Anand

Science OpensoUrce Software for Teaching Learning
Free/Libre and Open Source Software for Education
IIT Bombay

Project/Internship

Pune, December 2024

Declaration

I, the undersigned, hereby declare that this handbook, entitled "Photoelectric Effect", has been compiled to serve as a resource for the study of physics. This work brings together knowledge from various scientific contributions to provide a comprehensive guide for students and learners.

This handbook is intended solely as an educational resource and does not claim originality in its entirety, as it is a compilation of existing scientific knowledge curated for academic purposes.

Pune, December 2024

Utpal Anand

Abstract

In this module, we will learn about the photoelectric effect, which was a groundbreaking discovery that expanded our understanding of the nature of light, specifically whether it behaves as a particle or a wave. The photoelectric effect describes the particle-like nature of light: when light strikes a metal surface, it causes the emission of electrons. The number of electrons emitted depends on the intensity of the light, while the emission itself requires the light to have a frequency above a certain threshold.

Einstein's explanation provided a deeper understanding of this phenomenon. We will explore both the philosophical implications and the mathematical formulation of the photoelectric effect. Additionally, we will derive the equation for the kinetic energy of the emitted electrons, $E_{\text{kin}} = hf - W$, where hf is the energy of the photons and W is the work function of the material.

Keywords: Photoelectric effect, work function, particle behavior of light, Einstein, photon

Contents

List of Figures

List of Tables

This page intentionally left blank.

1

Introduction

The **photoelectric effect** is a phenomenon in which light shining on a material, typically a metal, causes the ejection of electrons from that material. This effect has a fascinating history that spans centuries and played a pivotal role in the development of quantum mechanics.

Key Milestones in the History of the Photoelectric Effect

1. Early Observations of Light-Induced Phenomena (19th Century)

- **1839**: *Alexandre Edmond Becquerel* discovered the photovoltaic effect, where light generates an electric current in certain materials.
- **1873**: *Willoughby Smith* discovered photoconductivity in selenium, where the electrical resistance decreased upon exposure to light.

2. Discovery of the Photoelectric Effect (1887)

- **Heinrich Hertz**: Observed that ultraviolet light could cause sparks to jump between two electrodes, demonstrating the photoelectric effect.

3. Quantitative Measurements (1899-1902)

- **Wilhelm Hallwachs**: Showed that a negatively charged zinc plate lost its charge under ultraviolet light.
- **Philipp Lenard**: Conducted experiments showing that the photoelectric effect produced electrons, though the energy relationship remained unclear.

4. Failure of Classical Wave Theory

- The energy of emitted electrons depended on light frequency, not intensity.
- No electrons were emitted if the frequency was below a certain threshold, regardless of intensity.

5. Albert Einstein's Quantum Explanation (1905)

- Proposed light is quantized into packets called *photons*.
- Energy of each photon is $E = h\nu$, where h is Planck's constant, and ν is the frequency of light.
- Explained that if a photon's energy exceeds the metal's *work function*, the electron is emitted.

6. Experimental Verification

- **Robert Millikan (1914)**: Confirmed Einstein's predictions about the photoelectric effect through meticulous experiments.

7. Nobel Prizes and Recognition

- **Albert Einstein**: Awarded the Nobel Prize in 1921 for his explanation of the photoelectric effect.
- **Philipp Lenard**: Awarded the Nobel Prize in 1905 for his work on cathode rays and related phenomena.

8. Impact on Physics

- Pioneered the development of quantum mechanics.
- Confirmed wave-particle duality of light.
- Influenced fields such as semiconductors, spectroscopy, and quantum computing.

Modern Applications

The principles of the photoelectric effect are foundational in:

- Solar panels (conversion of sunlight into electricity).
- Photomultipliers and photodiodes (used in scientific instruments and electronics).
- Advanced imaging techniques like electron microscopy.

Summary Table

Year	Milestone
1839	Becquerel discovered the photovoltaic effect.
1873	Willoughby Smith discovered photoconductivity.
1887	Heinrich Hertz observed the photoelectric effect.
1899-1902	Hallwachs and Lenard made detailed observations.
1905	Einstein explained the effect with quantum theory.
1914	Millikan experimentally verified Einstein's theory.
1921	Einstein received the Nobel Prize.

Table 1.1: *Key Milestones in the History of the Photoelectric Effect*

2

The Classical Wave Theory

Introduction

The **classical wave theory of light**, developed between the 17th and 19th centuries, describes light as a continuous wave phenomenon. It successfully explained many optical phenomena, such as reflection, refraction, diffraction, and interference. However, it encountered significant limitations when faced with quantum phenomena like the photoelectric effect. This document provides an overview of its development, features, and shortcomings.

Development and Foundations

1. Early Ideas of Light as a Wave

- **Christiaan Huygens (1678)** proposed the wave theory of light, suggesting light propagates as waves through a medium called the "luminiferous ether."
- Huygens' principle explained phenomena such as reflection and refraction, as well as the wavefront propagation of light.

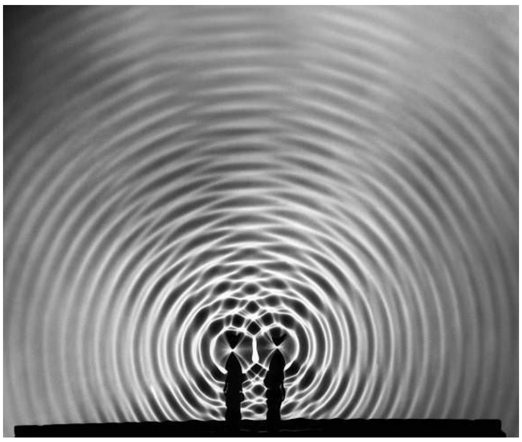

Figure 2.1: *Patterns in water*

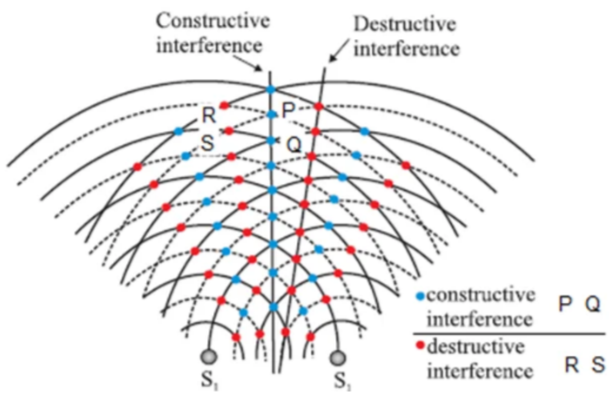

Figure 2.2: *Constructive and Destructive Interference*

2. Wave Nature Confirmed by Interference and Diffraction

- **Thomas Young (1801)** demonstrated light's wave nature through his double-slit experiment, which produced an interference pattern.

- **Augustin-Jean Fresnel** expanded on this work, providing a mathematical framework for understanding diffraction and interference.

3. Electromagnetic Wave Theory (James Clerk Maxwell, 1860s)

- Maxwell unified electricity and magnetism into the electromagnetic wave theory, proposing that light consists of oscillating electric and magnetic fields propagating as transverse waves.
- Maxwell's equations described the behavior of these waves, establishing light as an electromagnetic phenomenon traveling at a finite speed.

Key Features of the Classical Wave Theory

1. Wave Properties

- Light is a transverse wave, with electric (E) and magnetic (B) fields oscillating perpendicular to each other and the direction of propagation.
- The intensity of light is proportional to the square of the wave's amplitude.

2. Continuous Energy Distribution

- Energy is spread continuously across the wavefront, with no quantization.

3. Principle of Superposition

- Light waves combine linearly, producing constructive or destructive interference.

4. Explained Phenomena

- **Reflection**: Light bounces off surfaces, following the law of reflection.
- **Refraction**: Light bends when transitioning between media, as explained by Huygens' principle.
- **Interference**: Coherent light sources produce bright and dark fringes.
- **Diffraction**: Light bends around obstacles, forming patterns.
- **Polarization**: Light waves oscillate in specific directions, confirming their transverse nature.

5. Medium for Propagation

- The theory required a hypothetical medium, the *luminiferous ether*, for light waves to propagate.

Limitations of the Classical Wave Theory

1. **Photoelectric Effect**:
   - Predicted electron energy depended on light intensity, but experiments showed it depended on frequency.
   - No electrons were ejected below a threshold frequency, regardless of intensity.
2. **Blackbody Radiation**:

- Classical predictions led to the ”ultraviolet catastrophe,” resolved by Planck’s quantum theory.

3. **Compton Scattering**:

   - Observations of X-ray scattering revealed particle-like momentum transfer, inconsistent with wave-only behavior.

The classical wave theory of light is a cornerstone of optics and electromagnetic theory, explaining a wide range of macroscopic phenomena. However, its inability to account for quantum effects like the photoelectric effect and blackbody radiation prompted the development of quantum mechanics, introducing the concept of wave-particle duality. This duality remains central to our understanding of modern physics.

Summary Table

Aspect	**Description**
Wave Properties	Transverse waves with E and B fields oscillating perpendicularly.
Continuous Energy	Energy spread uniformly across the wavefront.
Superposition	Waves interfere linearly, producing interference patterns.
Phenomena Explained	Reflection, refraction, diffraction, polarization.
Limitations	Could not explain photoelectric effect, blackbody radiation, Compton scattering.

Table 2.1: *Key Features and Limitations of the Classical Wave Theory*

3

The Photoelectric Effect

Introduction

The photoelectric effect occurs when light strikes a material and causes electrons to be ejected. This seemingly simple phenomenon led to groundbreaking discoveries in physics. It provided key evidence for the quantum nature of light, challenging the classical wave theory of light.

Classical physics predicted that increasing the intensity of light would always eject electrons, regardless of its frequency. However, experiments showed that no electrons are emitted if the light frequency is below a certain threshold, no matter how intense the light is. Albert Einstein resolved this by proposing that light is made of discrete energy packets called *photons*. This idea laid the foundation for quantum mechanics.

Photon Energy

Einstein proposed that each photon carries an energy proportional to its frequency:

$$E = hf, \tag{3.1}$$

where:

- h is Planck's constant ($6.626 \times 10^{-34}\ \mathrm{J \cdot s}$),
- f is the frequency of the light.

The higher the frequency of the light, the more energy each photon carries.

How the Photoelectric Effect Works

When a photon strikes the surface of a material, its energy is transferred to an electron. This energy is used in two ways:

1. A portion of the energy, equal to the *work function* ϕ, is used to free the electron from the material. The work function is the minimum energy required to remove an electron from the material.
2. Any leftover energy becomes the kinetic energy $K_{\max}$ of the emitted electron.

This energy balance can be written as:

$$hf = \phi + K_{\max}, \tag{3.2}$$

where:

- hf is the energy of the photon,
- ϕ is the work function of the material,
- $K_{\max}$ is the maximum kinetic energy of the emitted electron.

Threshold Frequency

For electrons to be emitted, the photon energy hf must be greater than or equal to the work function ϕ. This means the light must have a minimum frequency, called the *threshold frequency* f_0, given by:

$$f_0 = \frac{\phi}{h}. \tag{3.3}$$

If the frequency of the light f is below f_0, no electrons are emitted, regardless of the light's intensity. This behavior could not be explained by classical wave theory.

Kinetic Energy of Electrons

When the frequency of the light f exceeds the threshold frequency f_0, the kinetic energy of the emitted electrons is:

$$K_{\max} = h(f - f_0). \tag{3.4}$$

This equation shows that the kinetic energy of the electrons depends linearly on the frequency of the light.

Stopping Potential

In experiments, emitted electrons can be stopped by applying a retarding potential V_s. The stopping potential is related to the maximum kinetic energy of the electrons by:

$$K_{\max} = eV_s, \tag{3.5}$$

where e is the elementary charge $(1.602 \times 10^{-19}\,\mathrm{C})$. Substituting for $K_{\max}$, we get:

$$eV_s = hf - \phi, \tag{3.6}$$

or equivalently:

$$V_s = \frac{hf - \phi}{e}. \tag{3.7}$$

The stopping potential varies linearly with the frequency of the light, confirming Einstein's equation.

Intensity and Current

The intensity of light determines the number of photons incident on the material per second. Since each photon can eject at most one electron, the photoelectric current is proportional to the light intensity, provided the frequency of the light is above the threshold frequency f_0. However, the energy of the emitted electrons depends only on the frequency of the light, not its intensity.

Experimental Evidence

Einstein's theory of the photoelectric effect has been validated by key experimental observations:

- The kinetic energy of emitted electrons depends on the frequency of the light, not its intensity.
- There is a well-defined threshold frequency below which no electrons are emitted.
- The stopping potential varies linearly with the frequency of the light.

The photoelectric effect was pivotal in establishing the quantum theory of light. Einstein's equation:

$$K_{\text{max}} = hf - \phi, \tag{3.8}$$

showed that light behaves as particles (photons) in certain situations. This explanation resolved experimental puzzles and earned Einstein the Nobel Prize in Physics in 1921. The photoelectric effect remains a cornerstone of quantum mechanics, influencing modern technology like solar cells and photodetectors.

4

Explanation with the help of Apps On Physics

We have cathode in two materials, we will illuminate the cathode by yellow (578 nm), green (546 nm), violet (436 nm), and ultraviolet (365 nm or 254 nm) and we will also apply the retarding potential to find the maximum kinetic energy of the electron.

We have two Materials:

a) Cesium (Work function : 2.14 eV)
b) Sodium (Work function : 2.28 eV)

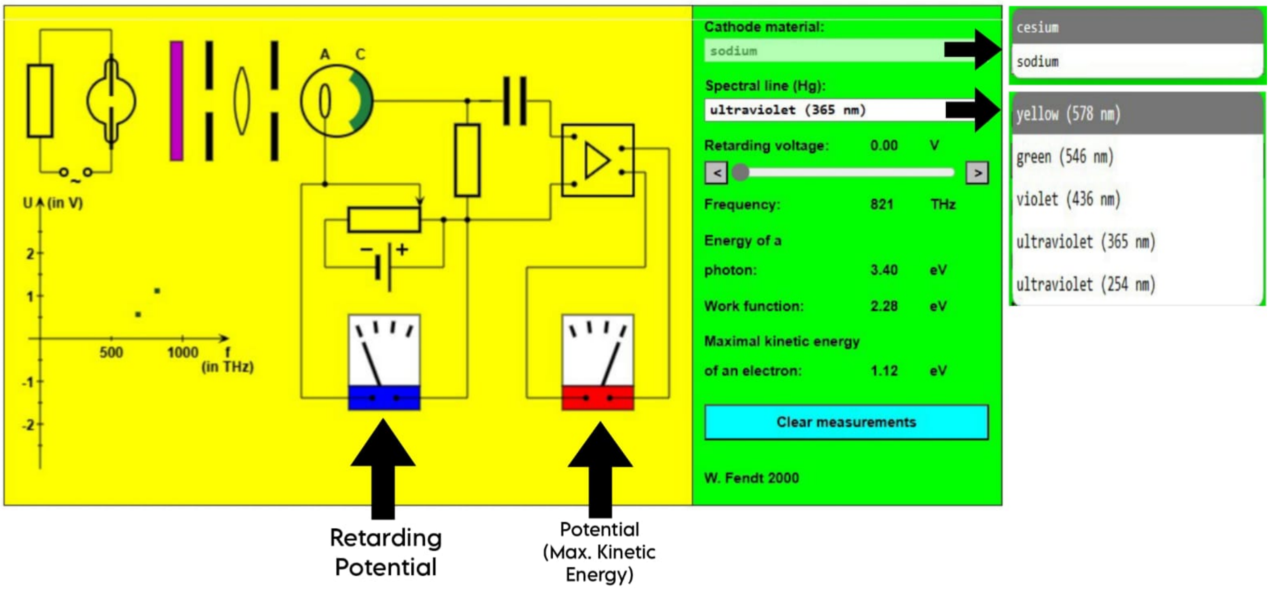

Figure 4.1: *Options and functioning on Apps on Physics*

As shown in Figure 4.1, light of different wavelengths is shone on the material one by one, causing the emission of electrons and the resulting flow of current. The energy of each photon is transferred to the electron. First, the energy is used to overcome the material's work function (the minimum energy required for electron emission). The remaining energy is transferred to the electron as kinetic energy, which is measured in terms of the potential difference.

We can also apply a retarding potential to stop the electron flow. When the current flow ceases, the retarding potential corresponds to the maximum kinetic energy possessed by the electron. Hence, we derive the relationship: the total energy (E) of the photon is the sum of the work function (Φ) and the maximum kinetic energy ($K.E.$) of the emitted electron.

Under ideal conditions, where there is no resistance or disturbance, the kinetic energy is at its maximum. Therefore, we conclude:

$$K.E_{\max} = E - \Phi$$

4.1 Cesium Cathode Material (ϕ = 2.14 eV)

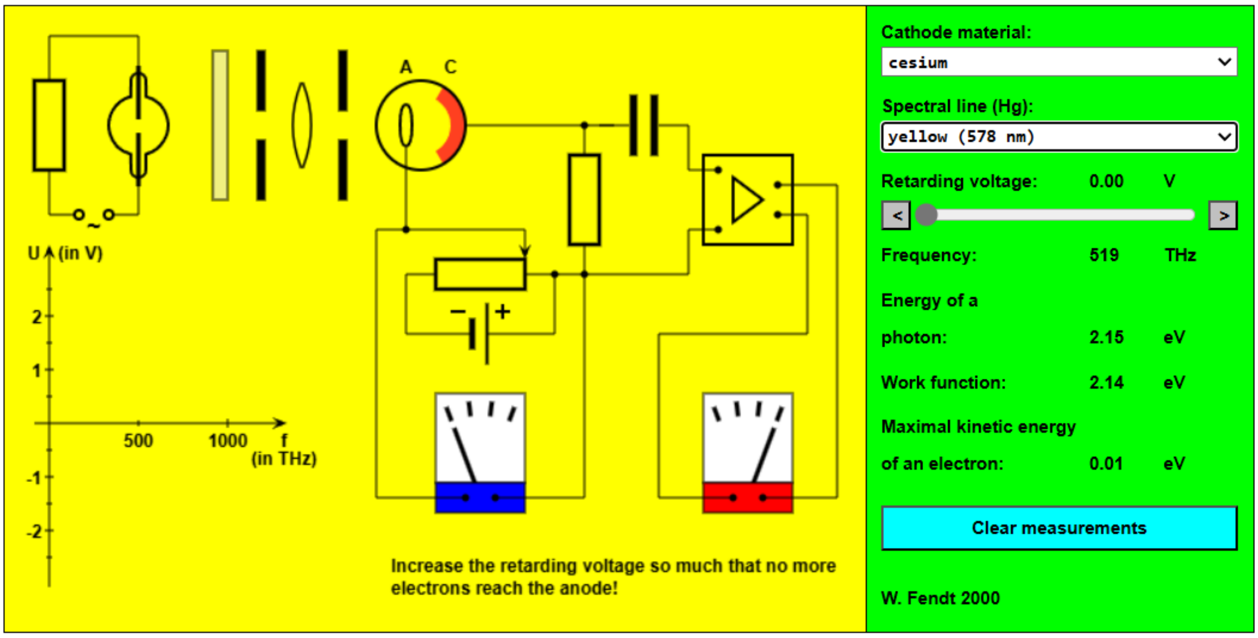

Figure 4.2: *Yellow light (578 nm)*
Photon Energy: 2.15 eV
Max Kinetic Energy: 0.01 eV

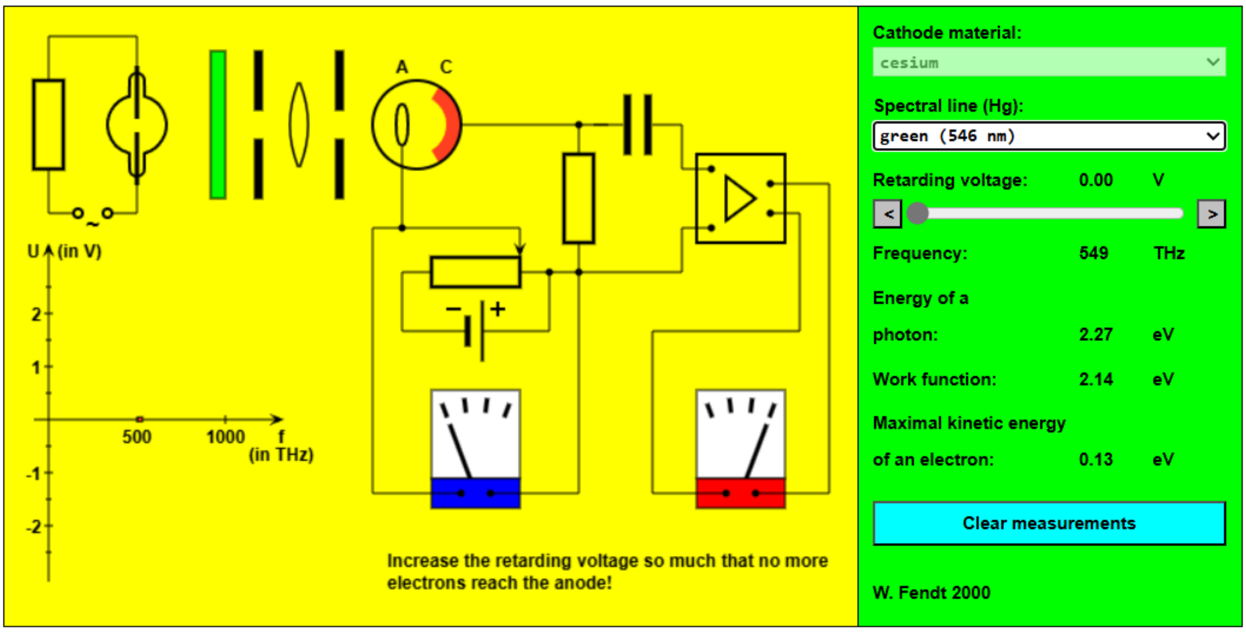

Figure 4.3: *Green light (546 nm)*
Photon Energy: 2.27 eV
Max Kinetic Energy: 0.13 eV

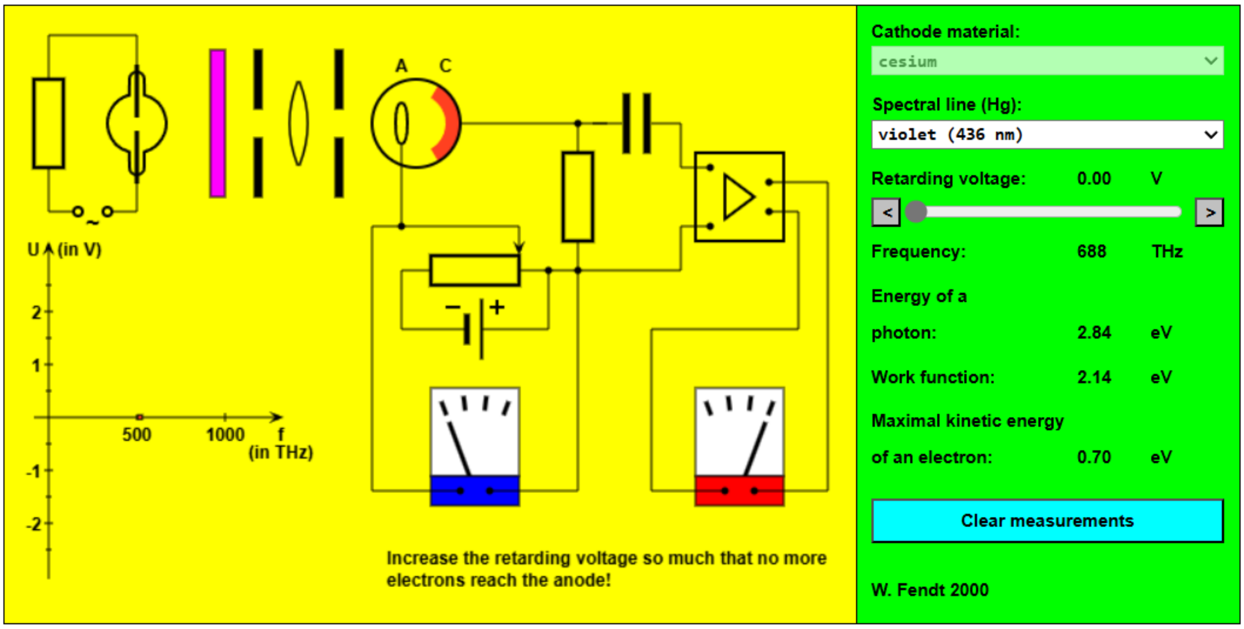

Figure 4.4: *Violet light (436 nm)*
Photon Energy: 2.84 eV
Max Kinetic Energy: 0.70 eV

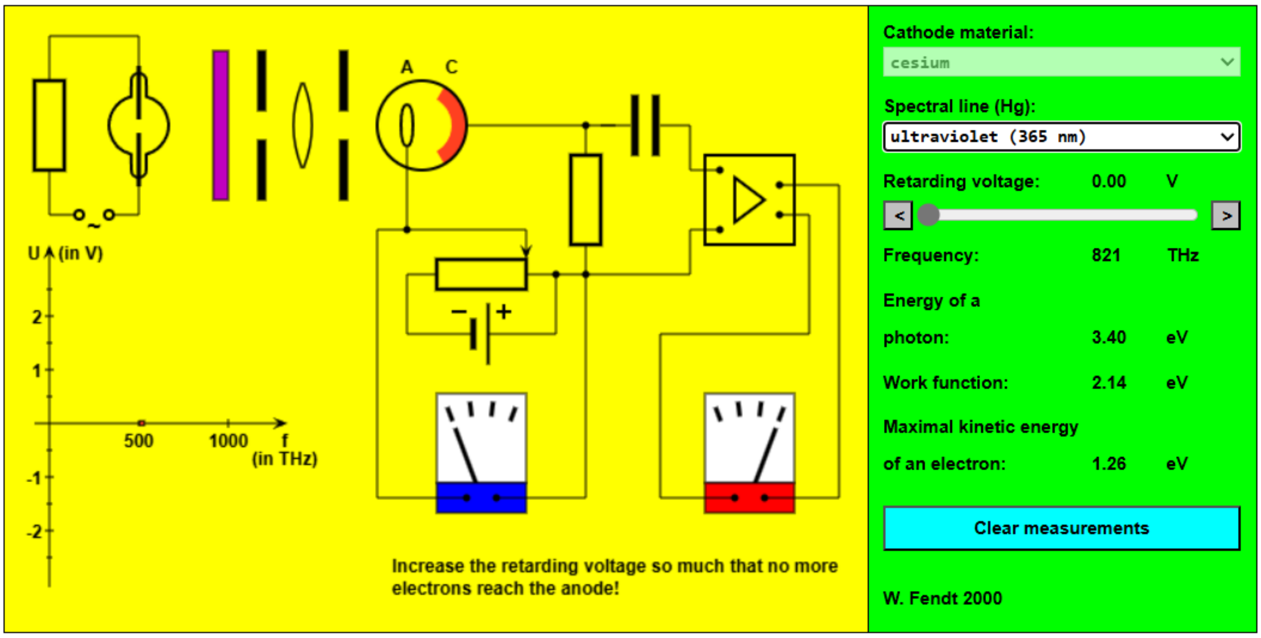

Figure 4.5: *UV light (365 nm)*
Photon Energy: 3.40 eV
Max Kinetic Energy: 1.26 eV

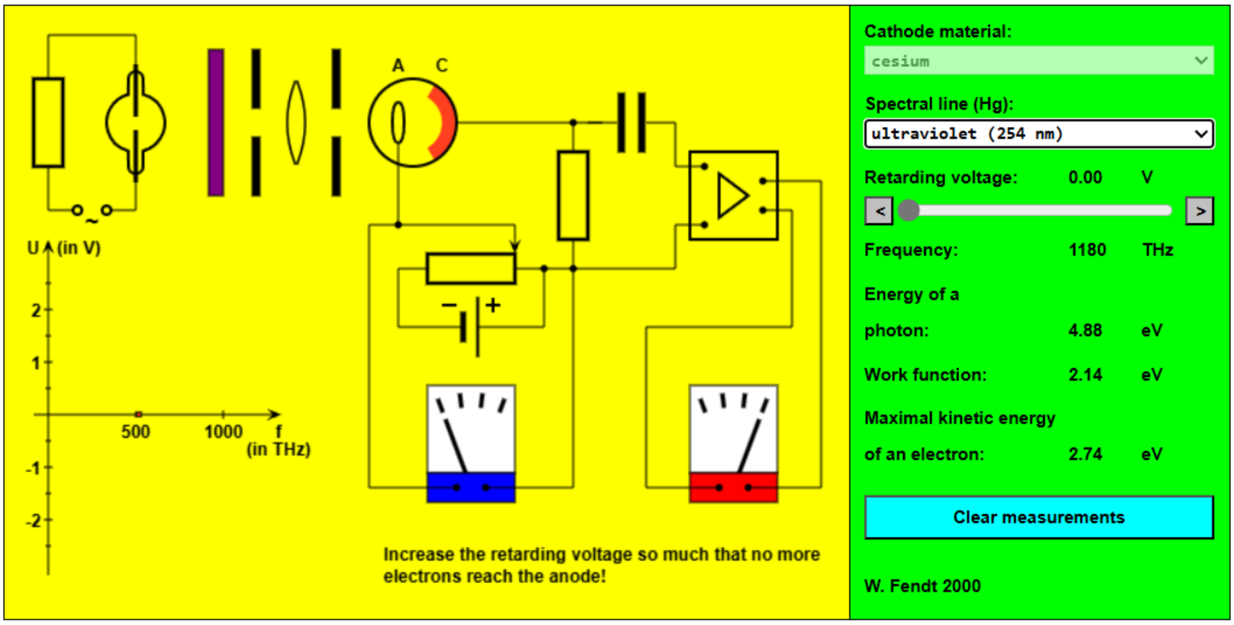

Figure 4.6: *UV light (254 nm)*
Photon Energy: 4.88 eV
Max Kinetic Energy: 2.74 eV

Light Color	Photon Wavelength (nm)	Photon Energy (eV)	Max Kinetic Energy (eV)
Yellow	578	2.15	0.01
Green	546	2.27	0.13
Violet	436	2.84	0.70
UV	365	3.40	1.26
UV	254	4.88	2.74

Table 4.1: *Photon Data for Cesiuim Cathode Material*

4.2 Sodium Cathode Material (ϕ = 2.28 eV)

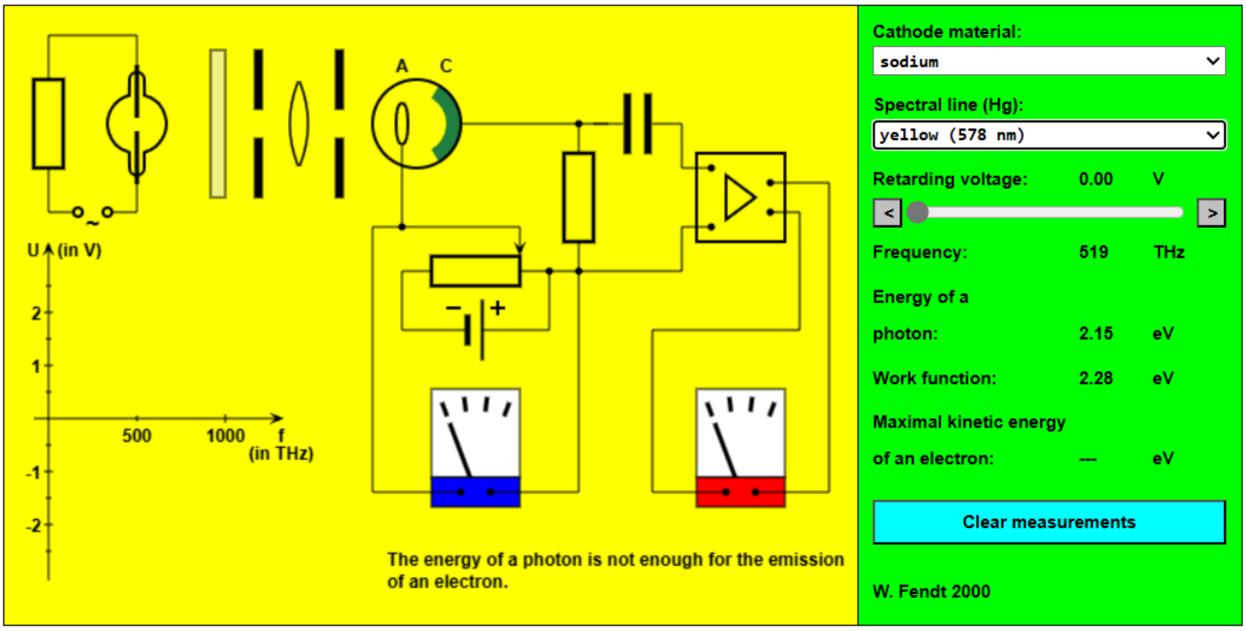

Figure 4.7: *Yellow light (578 nm)*
Photon Energy: 2.15 eV
Max Kinetic Energy: – eV

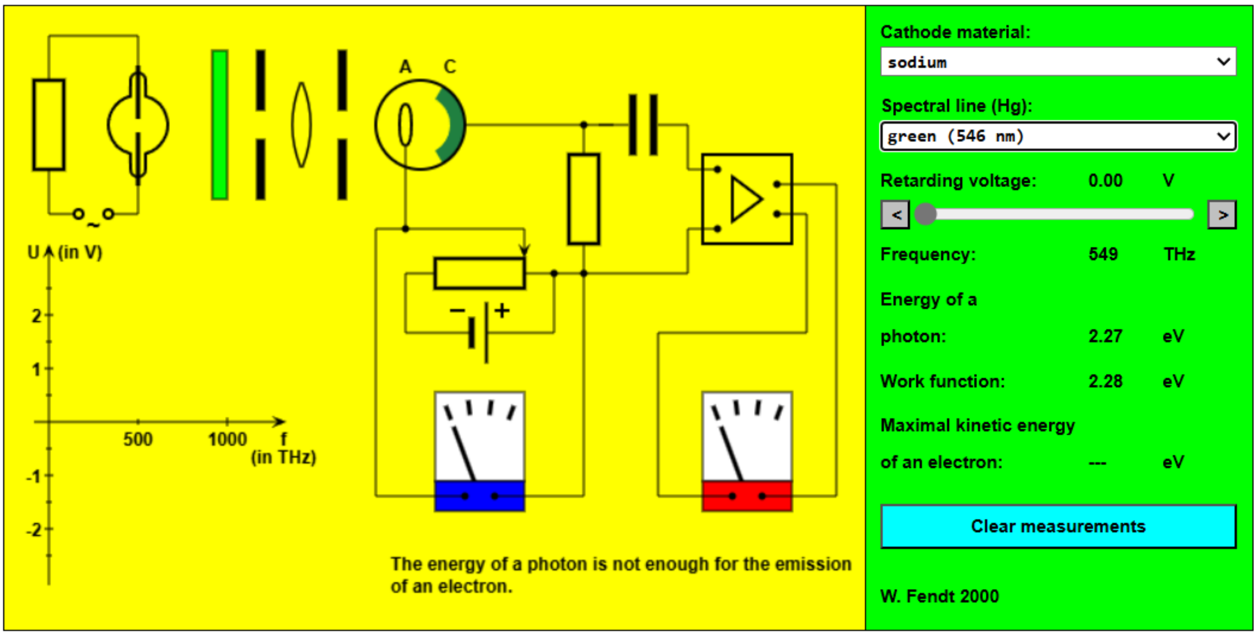

Figure 4.8: *Green light (546 nm)*
Photon Energy: 2.27 eV
Max Kinetic Energy: – eV

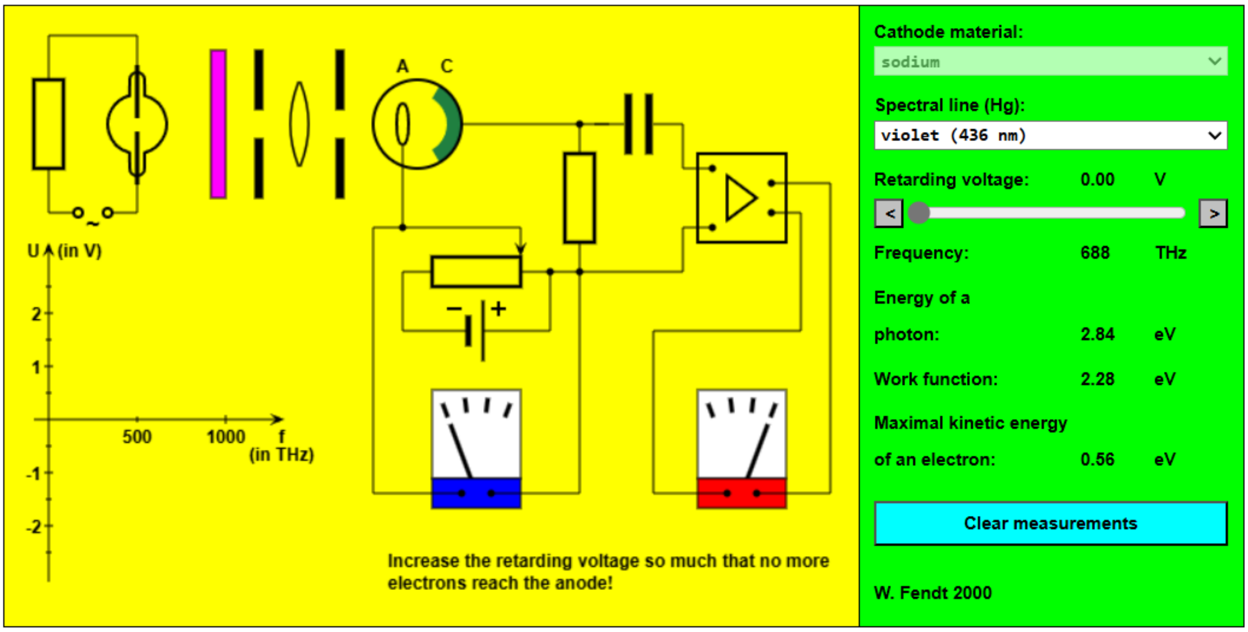

Figure 4.9: *Violet light (436 nm)*
Photon Energy: 2.84 eV
Max Kinetic Energy: 0.56 eV

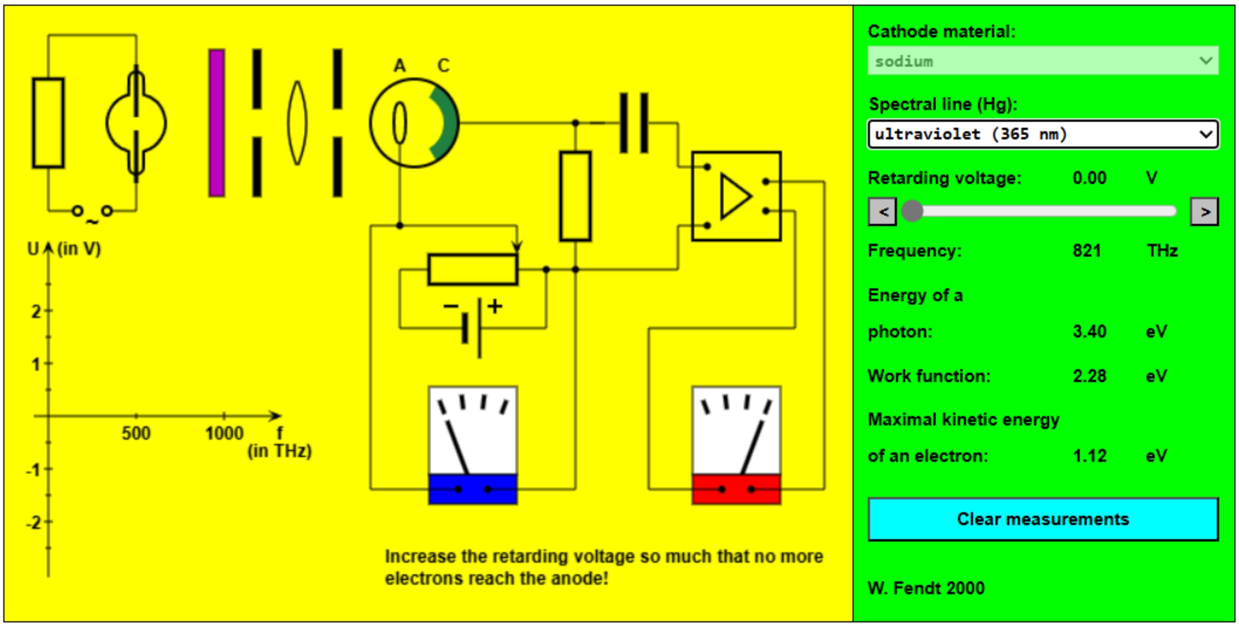

Figure 4.10: *UV light (365 nm)*
Photon Energy: 3.40 eV
Max Kinetic Energy: 1.12 eV

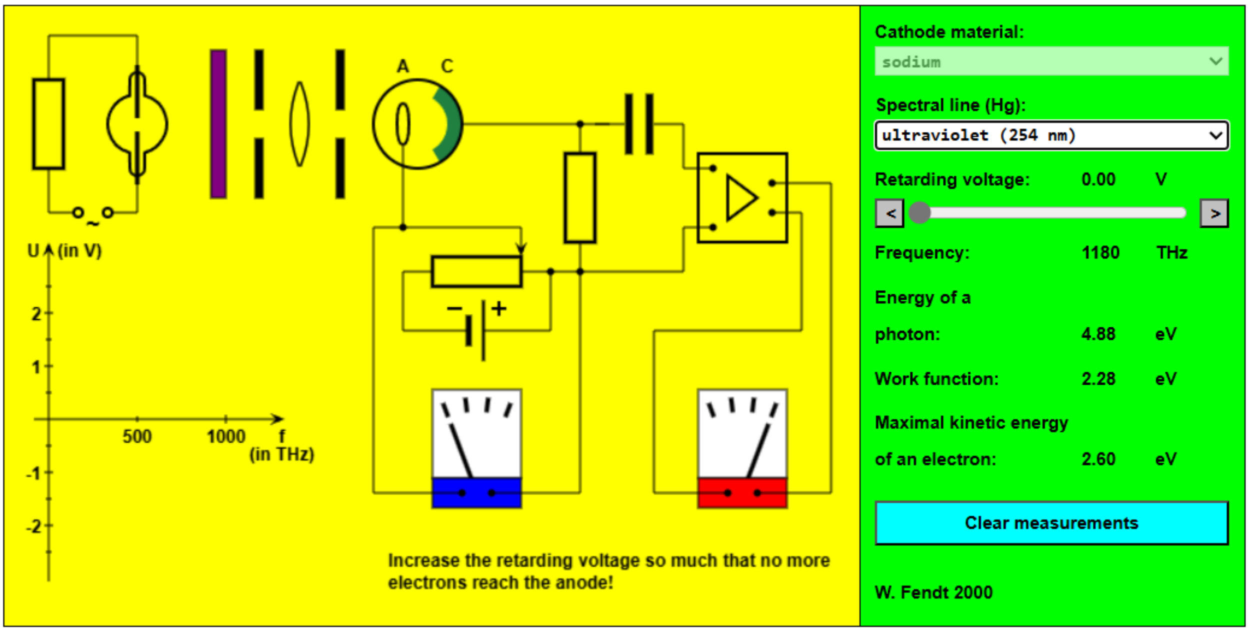

Figure 4.11: *UV light (254 nm)*
Photon Energy: 4.88 eV
Max Kinetic Energy: 2.60 eV

Light Color	Photon Wavelength (nm)	Photon Energy (eV)	Max Kinetic Energy (eV)
Yellow	578	2.15	–
Green	546	2.27	–
Violet	436	2.84	0.56
UV	365	3.40	1.12
UV	254	4.88	2.60

Table 4.2: *Photon Data for Sodium Cathode Material*

This page intentionally left blank.