What Is The Cutoff Frequency Of Light If The Cathode In A Photoelectric Tube Is Made Of Iron? The Work

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Understanding the cutoff frequency in photoelectric phenomena is fundamental to comprehending how light interacts with matter, particularly in devices such as photoelectric tubes. When the cathode material is specified—as in the case of iron—the intrinsic properties of that material, especially its work function, critically determine the minimum frequency of incident light required to liberate electrons. This article explores the concept of cutoff frequency, the work function of iron, and how these factors interplay to define the threshold for photoelectron emission.

Fundamentals of the Photoelectric Effect

What is the Photoelectric Effect?

The photoelectric effect refers to the emission of electrons from a metallic surface when it is illuminated by electromagnetic radiation of sufficient energy. Discovered by Heinrich Hertz and explained by Albert Einstein in 1905, this effect provided pivotal evidence for the quantum nature of light.

Key Concepts in Photoelectric Emission

To understand the cutoff frequency, it is essential to grasp the following concepts:

- **Work Function (φ):** The minimum energy required to liberate an electron from the surface of a material.
- **Photon Energy (E):** The energy of incident light, given by $E = hf$, where h is Planck's constant, and f is the frequency of light.
- **Threshold or Cutoff Frequency (f_0):** The minimum frequency of incident light needed to produce photoelectrons, corresponding to the photon energy equal to the work function: $hf_0 = \varphi$.

Determining the Cutoff Frequency

Mathematical Relationship

The cutoff frequency is derived from the fundamental relation:

- $hf_0 = \varphi$

where:
- $h \approx 6.626 \times 10^{-34}$ Joule·second (Planck's constant),
- φ (work function) is expressed in Joules.

Rearranged, it gives:

$f_0 = \varphi / h$

This formula indicates that knowing the work function of the cathode material allows us to compute the cutoff frequency directly.

Work Function of Iron

What Is the Work Function?

The work function (φ) is a material-specific property that depends on the surface condition, purity, and crystalline structure. It signifies the minimum energy needed to free an electron from the surface.

Work Function Values for Iron

For iron, the work function varies slightly based on surface conditions but generally falls within a known range:

- Typical value: $\varphi \approx 4.7$ eV
- Range: approximately 4.5 eV to 5.0 eV depending on surface treatment and purity

Since these values influence the cutoff frequency, selecting the most representative value (≈4.7 eV) provides a solid basis for calculations.

Calculating the Cutoff Frequency for Iron

Conversion of Work Function to Joules

Given φ in electronvolts (eV), convert to Joules:

- 1 eV = 1.602×10^{-19} Joules

Therefore:
$\varphi \approx 4.7 \text{ eV} \approx 4.7 \times 1.602 \times 10^{-19} \text{ J} \approx 7.53 \times 10^{-19} \text{ J}$

Applying the Formula

Using the relation:
$f_0 = \varphi / h$

Plugging in the values:
$f_0 = (7.53 \times 10^{-19} \text{ J}) / (6.626 \times 10^{-34} \text{ Js})$

Calculating:
$f_0 \approx 1.137 \times 10^{15}$ Hz

This frequency represents the minimum photon frequency needed to eject electrons from an iron cathode.

Implications of the Cutoff Frequency

Wavelength Corresponding to Cutoff Frequency

The cutoff wavelength (λ_0) can be found from the relation:

$$\lambda_0 = c / f_0$$

where $c \approx 3.0 \times 10^8$ m/s (speed of light).

Calculating:
$\lambda_0 = (3.0 \times 10^8 \text{ m/s}) / (1.137 \times 10^{15} \text{ Hz}) \approx 2.635 \times 10^{-7}$ m or 263.5 nm

This wavelength falls within the ultraviolet (UV) region of the electromagnetic spectrum.

Significance for Photoelectric Devices

Since visible light has wavelengths longer than ~400 nm, it cannot cause electron emission from iron cathodes. Only UV radiation with wavelengths shorter than approximately 263.5 nm can induce photoelectric emission.

Additional Factors Affecting the Cutoff Frequency

Surface Condition and Purity

The work function can vary with surface oxidation, contamination, and crystalline structure, which in turn affects the cutoff frequency.

Temperature Effects

While temperature primarily influences thermionic emission, extreme temperatures might slightly alter surface work functions.

Material Purity and Crystalline Structure

Impurities and crystal defects can modify the work function, leading to minor variations in cutoff frequency.

Conclusion

The cutoff frequency of light for a photoelectric tube with an iron cathode is fundamentally determined by the work function of iron. Using the typical work function value of approximately 4.7 eV, the cutoff frequency is calculated to be around 1.137×10^{15} Hz, corresponding to a wavelength of roughly 263.5 nm in the ultraviolet spectrum. This means that only incident electromagnetic radiation with frequencies higher than this threshold can eject electrons from the iron surface and induce the photoelectric effect.

Understanding this cutoff frequency is essential not only for designing photoelectric devices but also for applications in spectroscopy, UV detection, and surface science. When selecting light sources for such devices, ensuring the photon energy exceeds the material's work function is critical for efficient operation.

Summary Points:
- The work function of iron ($\approx$4.7 eV) determines the cutoff frequency.
- The cutoff frequency for iron is approximately 1.137×10^{15} Hz.
- The corresponding cutoff wavelength is around 263.5 nm, in the UV range.
- Surface conditions and purity influence the work function and thus the cutoff frequency.
- Only photons with energy greater than the work function can cause photoelectron emission from iron cathodes.

Frequently Asked Questions

What is the cutoff frequency of light for an iron cathode in a photoelectric tube?

The cutoff frequency depends on iron's work function. Since the work function of iron is approximately 4.5 eV, the cutoff frequency is about 1.09 × 10^15 Hz, calculated using $f = \varphi / h$.

How is the cutoff frequency related to the work function of iron in photoelectric emission?

The cutoff frequency is directly proportional to the work function; light must have a frequency higher than the cutoff frequency ($f > \varphi / h$) to eject electrons from iron in a photoelectric tube.

Why does the work function of iron determine the cutoff frequency in the photoelectric effect?

Because the work function represents the minimum energy needed to free an electron from iron's surface, only photons with energy exceeding this threshold (corresponding to the cutoff frequency) can cause photoemission.

What is the significance of the cutoff frequency in photoelectric experiments involving iron?

It indicates the minimum frequency of incident light required to initiate photoemission from iron, helping to analyze the photoelectric properties and the energy levels involved.

How can the cutoff frequency be experimentally determined for an iron cathode?

By gradually increasing the frequency of incident light until photoelectrons are emitted, the threshold frequency at which electrons just start to eject corresponds to the cutoff frequency.

If the energy of incident photons is less than the work function of iron, what happens in the photoelectric tube?

No photoelectrons are emitted because the photon energy is insufficient to overcome the work function, meaning the photon frequency is below the cutoff frequency.

Can the cutoff frequency of iron change with temperature or surface condition in a photoelectric tube?

Yes, variations in temperature or surface cleanliness can alter the work function slightly, thereby affecting the cutoff frequency.

What is the practical importance of knowing the cutoff frequency of iron in photoelectric devices?

It helps in selecting appropriate light sources for efficient photoelectron emission and in designing sensitive photoelectric detectors and sensors.

Additional Resources

What Is The Cutoff Frequency Of Light If The Cathode In A Photoelectric Tube Is Made Of Iron? The Work Function

Understanding the cutoff frequency of light in the context of the photoelectric effect is fundamental for grasping how photoelectric tubes operate, especially when the cathode material, such as iron, plays a significant role. This detailed review explores the concept thoroughly, covering the physics behind the work function, the determination of cutoff frequency, and relevant practical considerations.

Introduction to the Photoelectric Effect and Cutoff Frequency

The photoelectric effect is a phenomenon where electrons are emitted from a material's surface when incident light possesses sufficient energy. It served as crucial evidence for the quantum nature of light and is the foundation of many photoelectric devices, including photoelectric tubes.

Key Concepts:

- Photoelectric Effect: When photons strike a material (cathode), they transfer energy to electrons. If the energy exceeds the work function, electrons are emitted.
- Work Function (Φ): The minimum energy needed to liberate an electron from the surface of a material.
- Cutoff Frequency (f_0): The minimum frequency of incident light required to eject electrons from the cathode surface. Below this frequency, no photoelectrons are emitted regardless of light intensity.

The relationship between photon energy and frequency is given by Planck's equation:

$$E = hf$$

where:

- E = photon energy
- h = Planck's constant ($\sim 6.626 \times 10^{-34}$ Js)
- f = frequency of incident light

To emit electrons, the photon energy must be at least equal to the work function:

$$ hf \geq \Phi $$

The cutoff frequency f_0 is thus:

$$ f_0 = \frac{\Phi}{h} $$

Material Dependence of Work Function and Its Significance

The work function is a material-specific property, influenced by the material’s electronic structure and surface conditions.

For Iron:

- The work function typically ranges between 4.5 eV to 5.0 eV, depending on factors like surface cleanliness, crystal orientation, and temperature.
- Commonly cited average value: approximately 4.7 eV.

Implications:

- The higher the work function, the higher the minimum photon energy (and thus frequency) needed to eject electrons.
- Materials with lower work functions are more sensitive to longer wavelengths (lower frequencies).

Calculating the Cutoff Frequency for Iron

Given the work function for iron, the cutoff frequency can be computed using the fundamental relation:

$$ f_0 = \frac{\Phi}{h} $$

where:

- Φ is given in electronvolts (eV),
- h is Planck's constant in eV·s for convenience.

Conversion of Constants:

- 1 eV = 1.602×10^{-19} Joules
- h in Joules·seconds: 6.626×10^{-34} Js
- h in eV·s: approximately 4.1357×10^{-15} eV·s

Calculation:

Using $\Phi \approx 4.7\, \text{eV}$:

$$
f_0 = \frac{4.7\, \text{eV}}{4.1357 \times 10^{-15}\, \text{eV·s}} \approx 1.137 \times 10^{15}\, \text{Hz}
$$

Result:

> The cutoff frequency for iron as a cathode material in a photoelectric tube is approximately 1.14×10^{15} Hz.

Understanding the Significance of the Cutoff Frequency

The cutoff frequency essentially delineates the boundary between photons capable of ejecting electrons and those that are not.

Practical Aspects:

- Wavelength Correspondence: The cutoff wavelength λ_0 relates to f_0 via:

$$ \lambda_0 = \frac{c}{f_0} $$

where c is the speed of light (~3.00×10^8 m/s):

$$
\lambda_0 \approx \frac{3.00 \times 10^8\, \text{m/s}}{1.14 \times 10^{15}\, \text{Hz}} \approx 2.63 \times 10^{-7}\, \text{m} = 263\, \text{nm}
$$

- Spectral Range: Light with wavelength shorter than 263 nm (ultraviolet range) can cause photoemission from iron cathodes.

Implication:

- To initiate photoelectric emission from iron, the incident light must have a wavelength less than approximately 263 nm, i.e., in the ultraviolet spectrum.

Factors Affecting the Actual Photoelectric Response

While the theoretical cutoff frequency gives a fundamental limit, real-world factors influence the efficiency and thresholds.

Surface Conditions:

- Oxidation, contamination, or surface roughness can alter the effective work function.
- Cleaner, well-prepared surfaces tend to have work functions closer to the ideal values.

Temperature:

- Elevated temperatures can slightly modify the work function.
- Thermal energy may assist in electron liberation, but the primary threshold remains governed by photon energy.

Photon Intensity:

- Above the cutoff frequency, increasing light intensity increases the number of emitted electrons but does not affect the threshold frequency.

Material Purity:

- Impurities can introduce localized energy states, potentially lowering or raising the effective work function.

Practical Applications and Relevance

Understanding the cutoff frequency is crucial in designing and optimizing photoelectric devices:

- Photodetectors: Selecting materials with appropriate work functions for the target wavelength range.
- Spectroscopy: Using cutoff frequencies to analyze spectral properties.
- Quantum Efficiency: The ratio of emitted electrons to incident photons depends on how well the photon energy exceeds the work function.

In the context of iron:

- Iron is not typically used as a photoelectric cathode material in sensitive detectors due to its relatively high work function and susceptibility to oxidation.
- However, understanding its cutoff frequency helps in academic and experimental setups or in understanding fundamental physics.

Summary and Final Remarks

- The cutoff frequency for light incident on an iron cathode in a photoelectric tube is approximately 1.14×10^{15} Hz.
- This frequency corresponds to a wavelength of about 263 nm, placing the threshold in the ultraviolet region.
- The work function of iron (~4.7 eV) is the key parameter determining this cutoff.
- In practical applications, surface quality, temperature, and purity influence the effective work function and, consequently, the actual cutoff frequency.
- Knowledge of this cutoff is essential for designing photoelectric systems, understanding spectral sensitivities, and conducting fundamental physics experiments.

In conclusion, the cutoff frequency acts as a fundamental boundary, defining the limits of photoelectric emission based on the material properties of the cathode. For iron, this cutoff is firmly in the ultraviolet spectrum, emphasizing the need for UV light sources if photoemission is to be achieved effectively.

References & Further Reading:

- Principles of Quantum Mechanics by R. Shankar
- Introduction to Quantum Mechanics by David J. Griffiths
- Photoelectric Effect – Physics textbooks and online educational resources
- Surface science literature on work function variations in metals

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