A Photon With Wavelength = 0.0590 Nm Is Incident On An Electron That Is Initially At Rest. If The Photon

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The interaction between photons and electrons is a fundamental process in quantum physics, underpinning phenomena such as the photoelectric effect, Compton scattering, and quantum electrodynamics. When a photon encounters an electron initially at rest, various outcomes are possible depending on the photon's energy and wavelength. Understanding these interactions not only sheds light on the behavior of subatomic particles but also plays a crucial role in fields like medical imaging, astrophysics, and particle physics research.

In this article, we explore the scenario where a photon with a wavelength of 0.0590 nanometers (nm) strikes an electron at rest. We will analyze the possible outcomes, including Compton scattering, energy transfer, and whether the photon can cause ionization or other quantum phenomena. Additionally, we will delve into the calculations needed to determine the energy and momentum exchange, the resulting electron's kinetic energy, and the implications of such interactions.

Understanding the Basic Concepts

What Is a Photon?

A photon is a quantum of electromagnetic radiation, carrying energy and momentum but having no rest mass. Its energy E and momentum p are related to its wavelength λ through fundamental equations:

$$
E = \frac{hc}{\lambda}
$$

$$

$$
p = \frac{E}{c} = \frac{h}{\lambda}
$$

where:

- h is Planck’s constant (6.626×10^{-34} Js)
- c is the speed of light in vacuum (3.00×10^{8} m/s)
- λ is the photon’s wavelength

The Electron at Rest

Initially, the electron is stationary, meaning its initial kinetic energy is zero. Its rest mass m_e is approximately 9.11×10^{-31} kg, and its rest energy E_0 is given by Einstein's mass-energy equivalence:

$$
E_0 = m_e c^2 \approx 0.511 \text{ MeV}
$$

Significance of Wavelength 0.0590 Nm

The wavelength of 0.0590 nm falls within the X-ray region of the electromagnetic spectrum. Such high-energy photons are capable of interacting strongly with electrons, leading to phenomena like Compton scattering or even ionization if the energy exceeds the electron's binding energy in atoms.

Calculating the Photon's Energy and Momentum

Photon's Energy

Using the equation $E = \frac{hc}{\lambda}$, we compute:

$$

$$
E = \frac{(6.626 \times 10^{-34} \text{ Js})(3.00 \times 10^{8} \text{ m/s})}{0.0590 \times 10^{-9} \text{ m}}
$$

$$
E \approx \frac{1.9878 \times 10^{-25}}{5.90 \times 10^{-11}} \approx 3.37 \times 10^{-15} \text{ Joules}
$$

Converting Joules to electronvolts (eV):

$$
1 \text{ eV} = 1.602 \times 10^{-19} \text{ Joules}
$$

$$
E \approx \frac{3.37 \times 10^{-15}}{1.602 \times 10^{-19}} \approx 21,040 \text{ eV} \approx 21.04 \text{ keV}
$$

Photon's Momentum

Using $p = \frac{E}{c}$:

$$
p = \frac{3.37 \times 10^{-15}}{3.00 \times 10^{8}} \approx 1.12 \times 10^{-23} \text{ kg·m/s}
$$

This momentum is significant enough to impart noticeable recoil to the electron during interaction.

Possible Outcomes of the Photon-Electron Interaction

1. Compton Scattering

Compton scattering occurs when an incident photon collides with a free or loosely bound electron, transferring part of its energy and momentum, resulting in a longer wavelength photon and a recoiling electron. The key features include:

- The wavelength of the scattered photon increases (redshift).
- The electron gains kinetic energy and recoils.
- Conservation of energy and momentum govern the scattering process.

2. Photoelectric Effect

If the photon's energy exceeds the binding energy of an electron in an atom, it can eject the electron entirely, causing ionization. However, in the context of a free electron, this effect is less relevant unless the electron is bound within an atom.

3. Pair Production

For the photon to produce an electron-positron pair, its energy must be at least 1.022 MeV ($2 \times 0.511 \text{ MeV}$). Since our photon has about 21 keV energy, pair production is not possible in this scenario.

Detailed Analysis of Compton Scattering

Compton Wavelength Shift Equation

The change in the photon's wavelength after scattering at an angle θ is given by:

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

where:

- λ' is the wavelength after scattering
- λ is the initial wavelength (0.0590 nm)
- $m_e c / h \approx 2.43 \times 10^{-12} \text{ m}$ (the Compton wavelength of the electron)

Calculating the Energy of the Scattered Photon

The energy of the photon after scattering at angle θ is:

$$
E' = \frac{hc}{\lambda'}
$$

which depends on λ', obtained from the wavelength shift.

Electron Recoil Energy

The energy transferred to the electron (recoil energy K_e) can be expressed as:

$$
K_e = E - E'
$$

or, in terms of scattering angle θ:

$$
K_e = E \left(1 - \frac{1}{1 + \frac{E}{m_e c^2}(1 - \cos \theta)}\right)
$$

where $E \approx 21.04 \text{ keV}$.

Maximum Energy Transfer

The maximum recoil energy occurs at $\theta = 180^\circ$, i.e., backscattering, and can be calculated as:

$$
K_{e,\text{max}} = \frac{2 E^2}{m_e c^2 + 2 E}
$$

Substituting numerical values:

$$
K_{e,\text{max}} = \frac{2 \times (21.04 \text{ keV})^2}{511 \text{ keV} + 2 \times 21.04 \text{ keV}} \approx \frac{2 \times 443.8}{511 + 42.08} \approx \frac{887.6}{553.08} \approx 1.605 \text{ keV}
$$

This indicates the electron can gain up to approximately 1.6 keV of kinetic energy during backscattering.

Implications and Applications

Medical Imaging and Radiation Therapy

High-energy photons like X-rays are employed in medical diagnostics and treatments. Understanding photon-electron interactions helps optimize imaging techniques and radiation doses.

Material Analysis and Crystallography

X-ray scattering techniques rely on photon-electron interactions to analyze material structures at atomic scales. Compton scattering provides insights into electron density and material composition.

Astrophysics and Cosmic Rays

High-energy photons from cosmic sources interact with electrons in space, producing observable phenomena such as gamma-ray emissions and cosmic ray scattering.

Fundamental Physics Research

Studying photon-electron interactions enhances our understanding of quantum electrodynamics, the Standard Model, and potential physics beyond current theories.

Conclusion

The interaction of a photon with a wavelength of 0.0590 nm incident on an electron at rest predominantly involves Compton scattering when the photon’s energy is below the threshold for other processes like pair production. Calculations show that the photon carries approximately 21 keV of energy, capable of transferring a maximum of about 1.6 keV to the electron during backscattering. This energy transfer results in the electron gaining kinetic energy and recoiling with momentum consistent with conservation laws.

Understanding such interactions is crucial across multiple scientific disciplines, from medical physics to astrophysics. Advances in quantum mechanics and experimental techniques continue to expand our knowledge of how light and matter interact at the most fundamental levels.

By analyzing the energy, momentum, and scattering angles associated with such photon-electron interactions, scientists can better interpret experimental data, develop new technologies, and deepen our grasp of the universe's quantum fabric.

Frequently Asked Questions

What is the energy of a photon with a wavelength of 0.0590 nm?

Using the equation $E = hc/\lambda$, where $h = 6.626\times10^{-34}$ Js, $c = 3\times10^{8}$ m/s, and $\lambda = 0.0590$ nm $= 0.0590\times10^{-9}$ m, the energy is approximately 3.37 keV.

What is the significance of a photon with a wavelength of 0.0590 nm in terms of its interaction with electrons?

A photon with this wavelength has enough energy to potentially eject electrons via the photoelectric effect or cause significant electron recoil, indicating high-energy photon interactions.

How do you calculate the momentum of a photon with a wavelength of

0.0590 nm?

Photon momentum p = h/□. Substituting h = 6.626×10$^{□3□}$ Js and □ = 0.0590×10□□ m gives p □ 1.12×10$^{□2□3}$ kg·m/s.

What is the expected change in the electron's kinetic energy after being struck by this photon?

The electron gains kinetic energy approximately equal to the photon energy minus any work function; for free electrons, it is roughly 3.37 keV.

Can a photon with a wavelength of 0.0590 nm cause Compton scattering with an electron?

Yes, photons of this wavelength can undergo Compton scattering, resulting in a transfer of energy and momentum to the electron, leading to a change in the photon’s wavelength.

What is the Compton wavelength shift for a photon with □ = 0.0590 nm when scattering off an electron?

The Compton wavelength shift □□ = (h/mc)(1 - cos □). For backscattering (□=180°), □□ □ 0.0243 nm, indicating a detectable change in wavelength.

What is the significance of the photon wavelength being 0.0590 nm in terms of X-ray classification?

A wavelength of 0.0590 nm classifies this photon as an X-ray, commonly used in medical imaging and material analysis due to its high energy.

How does the initial rest state of the electron influence the energy

transfer when hit by the photon?

Since the electron is initially at rest, the entire photon energy can be transferred to the electron, resulting in maximum kinetic energy transfer consistent with conservation laws.

What quantum mechanical principles govern the interaction between the photon and the electron in this scenario?

The interaction is governed by conservation of energy and momentum, quantum electrodynamics (QED), and the photoelectric effect or Compton scattering mechanisms.

What practical applications involve photons with wavelengths around 0.0590 nm interacting with electrons?

Applications include X-ray imaging, crystallography, and radiation therapy, where high-energy photons interact with electrons in matter to produce useful diagnostic and treatment effects.

Additional Resources

A Photon With Wavelength = 0.0590 Nm Is Incident On An Electron That Is Initially At Rest. If The Photon

In the fascinating realm of quantum physics, interactions between light and matter often challenge our classical intuitions. One such intriguing scenario involves a photon—an elementary particle of light—with a specific wavelength colliding with an electron initially at rest. This setup opens a window into fundamental processes like Compton scattering, energy-momentum conservation, and the wave-particle duality. Understanding this interaction not only deepens our grasp of quantum mechanics but also has practical implications spanning from medical imaging to astrophysics.

In this article, we explore this scenario in detail, dissecting the physics principles at play, performing key calculations, and elucidating the significance of the phenomena involved. Whether you're a student, a researcher, or simply an enthusiast, this comprehensive overview aims to clarify the intricate dance between photons and electrons in a clear, accessible manner.

Understanding the Scenario: Photons, Electrons, and Wavelengths

The Nature of Photons and Wavelength

Photons are quantum particles that carry electromagnetic energy. They are massless, travel at the speed of light in a vacuum, and are characterized by their wavelength (λ) and frequency (f). The wavelength determines the photon's energy and its interaction with matter.

The photon in question has a wavelength of 0.0590 nanometers (Nm). To put this into perspective:

- Wavelength (λ): 0.0590 Nm = 0.0590 × 10-9 meters = 5.90 × 10-11 meters.

This wavelength falls within the X-ray region of the electromagnetic spectrum, where high-energy photons are capable of penetrating matter and causing ionization.

The Electron at Rest

An electron, a fundamental subatomic particle, possesses a rest mass of approximately 9.11 × 10-31 kg and a charge of -1.602 × 10-19 coulombs. When initially at rest, the electron has no kinetic energy, but it can gain energy through interactions with photons, leading to changes in its momentum and energy states.

Key Concepts: Compton Scattering and Conservation Laws

What is Compton Scattering?

The interaction described resembles Compton scattering, a phenomenon discovered by Arthur Compton in 1923, which involves X-ray or gamma-ray photons colliding with electrons. During this process:

- The photon transfers some of its energy and momentum to the electron.
- The photon is scattered at a different angle with a longer wavelength.
- The electron gains kinetic energy and recoils.

This process demonstrates the particle nature of light and provides experimental evidence for quantum theory.

Fundamental Principles: Conservation of Energy and Momentum

Any interaction between particles must obey the laws of conservation:

- Conservation of Energy: Total energy before and after the collision remains constant.
- Conservation of Momentum: Total momentum before and after the collision remains constant.

Applying these principles allows us to analyze the scattering event comprehensively, determine the change in photon wavelength, and compute the electron's recoil.

Calculations and Analysis

Step 1: Determine the Initial Photon Energy

The energy of a photon is given by:

$$ E = \frac{hc}{\lambda} $$

where:

- h = Planck's constant = $6.626 \times 10^{-34} \, \text{Js}$
- c = speed of light = $3.00 \times 10^{8} \, \text{m/s}$
- λ = 5.90 × 10-11 m

Plugging in the values:

$$
E_{initial} = \frac{6.626 \times 10^{-34} \times 3.00 \times 10^{8}}{5.90 \times 10^{-11}} \approx 3.37 \times 10^{-15} \, \text{J}
$$

Converting to electronvolts (eV), noting $1 \, \text{eV} = 1.602 \times 10^{-19} \, \text{J}$:

\[

$$
E_{initial} \approx \frac{3.37 \times 10^{-15}}{1.602 \times 10^{-19}} \approx 21,000 \, \text{eV} = 21 \, \text{keV}
$$

Thus, the photon’s energy is approximately 21 keV, characteristic of X-ray photons.

Step 2: Determine the Compton Wavelength Shift

The core of Compton scattering involves a change in the photon’s wavelength, described by the Compton formula:

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

where:

- λ' = scattered photon wavelength
- λ = initial photon wavelength
- m_e = electron rest mass = $9.11 \times 10^{-31} \, \text{kg}$
- θ = scattering angle of the photon in the lab frame

The quantity $\frac{h}{m_e c}$ is known as the Compton wavelength of the electron, approximately:

$$
\lambda_C = \frac{6.626 \times 10^{-34}}{9.11 \times 10^{-31} \times 3.00 \times 10^{8}} \approx 2.43 \times 10^{-12} \, \text{m}
$$

This is about 0.0243 nm.

The change in wavelength depends on the scattering angle θ, which can vary between 0° (no scattering) and 180° (backscattering).

Step 3: Find the Wavelength Shift for Specific Angles

Suppose the photon is scattered at an angle θ. The change in wavelength is:

$$
\Delta \lambda = \lambda_C (1 - \cos \theta)
$$

- For forward scattering ($\theta = 0^\circ$):

$$
\Delta \lambda = 0
$$

- For backscattering ($\theta = 180^\circ$):

$$
\Delta \lambda = 2 \lambda_C \approx 2 \times 0.0243\, \text{nm} = 0.0486\, \text{nm}
$$

Adding this to the original wavelength:

$$
\lambda'_{max} = 0.0590\, \text{nm} + 0.0486\, \text{nm} = 0.1076\, \text{nm}
$$

Correspondingly, the photon loses energy as its wavelength increases.

Step 4: Calculate the Recoil Electron Energy

The energy transferred to the electron (recoil energy) can be derived from the change in photon energy, which depends on the initial and scattered photon wavelengths.

The photon energy after scattering:

$$
E' = \frac{hc}{\lambda'}
$$

For backscattering (maximum energy transfer), the initial photon has $\lambda = 0.0590\, \text{nm}$, and the scattered photon has $\lambda' = 0.1076\, \text{nm}$:

$$
E' = \frac{6.626 \times 10^{-34} \times 3.00 \times 10^{8}}{1.076 \times 10^{-10}} \approx 1.85 \times 10^{-15}\, \text{J}
$$

In eV:

$$
E' \approx \frac{1.85 \times 10^{-15}}{1.602 \times 10^{-19}} \approx 11,560\, \text{eV}
$$

Therefore, the energy transferred to the electron:

$$
\Delta E = E_{initial} - E' \approx 21,000\, \text{eV} - 11,560\, \text{eV} = 9,440\, \text{eV}
$$

This indicates the electron gains approximately 9.44 keV of kinetic energy during the collision.

The recoil kinetic energy of the electron:

$$
K_e = \Delta E \approx 9.44 \, \text{keV}
$$

Correspondingly, the electron's velocity v_e can be estimated using classical kinetic energy:

$$
K_e = \frac{1}{2} m_e v_e^2
$$

Solving for v_e:

$$
v_e = \sqrt{\frac{2 K_e}{m_e}} = \sqrt{\frac{2 \times 9.44 \times 10^{3} \times 1.602 \times 10^{-19}}{9.11 \times 10^{-31}}}
$$

Calculating numerator:

\[
2 \times 9.44 \times 10^{3

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