Energy–Momentum Accounting in Photon Interactions: A Relativistic Interpretation of a Conceptual Gap in Standard Physics

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Abstract

In high-energy photon interactions, such as Compton scattering and pair production, a measurable reduction in the energy and momentum of outgoing photons is observed. The principle of energy–momentum conservation requires that this loss be accounted for as a physical quantity that remains within the system. However, in many standard treatments, the fate of this energy is not explicitly formulated and is only stated in the general context of four-momentum conservation.

In this paper, by directly relying on the invariant relation in special relativity, we address this gap by providing a clear, quantitative framework for the fate of lost photon energy and momentum. We show how the reduction in photon momentum corresponds directly to an increase in rest mass, forming the basis for a more detailed energy accounting in photon interactions.

1 Introduction

Energy and momentum conservation is one of the fundamental principles of physics, implemented within special relativity and quantum field theory. Despite this, in the analysis of many photon interactions, the focus is often on the final kinematic outcomes, with little attention given to the physical and locational fate of the lost energy and momentum of the photon.

This paper does not introduce a new theory but aims to fill a specific conceptual gap: while four-momentum conservation is upheld, the local, physical expression of the lost energy in photon interactions is often implicitly neglected. We demonstrate that by returning to the exact structure of the energy–momentum relation, this fate can be clearly and quantitatively accounted for.

2 Practical Definition of a "Closed System"

In this paper, a closed system is practically defined as:

A system that, in the time and spatial scales of the interaction, does not exchange net energy and momentum with degrees of freedom outside the set of involved particles and fields.

In Compton scattering or pair production:
- The interaction time is very short, - Gravitational and background effects are negligible, and - Energy exchange occurs solely between photons and charged particles.
In this framework, the use of a closed system approximation is both justified and standard.

3 Relativistic Energy–Momentum Framework

The invariant relation in special relativity is given by:

$$E^2 - (pc)^2 = (mc^2)^2$$

For a free photon, the rest mass is zero, and the energy appears solely as momentum:

$$E = pc$$

However, once a photon participates in an interaction and transfers part of its momentum, this description is no longer complete.

4 Quantitative Derivation: From Momentum Loss to Rest Mass

For a closed system, differentiating the invariant relation gives:

$$2E\Delta E - 2(pc)\Delta(pc) = 2(mc^2)\Delta(mc^2)$$

Applying the total energy conservation condition:

$$\Delta E = 0$$

This results in:

$$-\Delta(pc) = \Delta(mc^2) \quad \Rightarrow \quad \Delta m = \frac{\Delta p}{c}$$

This relation shows that the reduction in photon momentum corresponds directly to an increase in rest mass.

5 Quantitative Examples

5.1 Compton Scattering

In Compton scattering, the change in photon wavelength is given by:

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

For a scattering angle θ, we have:

$$\Delta\lambda \approx 2.43 \times 10^{-12}\,\text{m}$$

The energy reduction of the photon is:

$$\Delta E = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda + \Delta\lambda}\right)$$

This reduction is exactly reflected by the increase in kinetic energy and effective mass of the electron, consistent with the derived relation.

5.2 Pair Production

In the process:

$$\gamma + \gamma \to e^- + e^+$$

The threshold condition is:

$$E_\gamma \geq m_e c^2$$

In this case, the photon energy is completely and quantitatively converted into the rest mass of the two produced particles and their kinetic energy:

$$2pc \to 2m_e c^2 + K$$

This is a direct, laboratory realization of the derived relation.

6 Formal Connection to QED

In quantum electrodynamics (QED), four-momentum conservation at each vertex is guaranteed:

$$\sum p^\mu_{\text{in}} = \sum p^\mu_{\text{out}}$$

The increase in rest mass in the final state corresponds to the transfer of momentum components to the final particles in the form of invariant energy–momentum. The interpretation provided in this paper is consistent with the QED Lagrangian structure and does not require any modification to the interaction vertices or the field propagators.

7 Testable Predictions

This framework predicts that:

- Any measurable reduction in photon momentum must be accompanied by an increase in rest mass in the final state, - This increase must be quantitatively consistent with the derived relation.

This prediction can be directly tested in:

- High-power lasers, - Photon–photon collisions, and - High-energy plasmas.

8 Conclusion

This paper demonstrates that the reduction in energy and momentum of photons in standard interactions does not imply the disappearance of energy, but rather the result of a precise, calculable transfer to rest mass energy. The innovation of this work lies in providing a clear and quantitative formulation of this transfer, filling a conceptual gap without the need for new physics or unverifiable assumptions.

References

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