Implications of an Energy-Dependent Time Definition for Nonlocality in Photons

Johann Pascher

March 24, 2025

Contents

1 Implications of an Energy-Dependent Time Definition for Nonlocality in Photons

This appendix examines the consequences of extending quantum mechanics with an energy-dependent time definition $T = \frac{1}{E}$ for massless particles such as photons, particularly with respect to nonlocality. This extension was developed to improve upon the original models with absolute time (T_0) and intrinsic time ($T = \frac{\hbar}{mc^2}$), which fail for photons with $m = 0$. Planck units ($\hbar = c_0 = G = 1$) are used here to simplify the representation.

1.1 Original Model and Its Limitations

In the standard model of quantum mechanics, nonlocality in entangled photons is described as an "instantaneous" correlation, with the light cone structure, governed by the speed of light ($c_0 = 1$), ensuring causality. Time is relativistically variable, and photons have no rest mass ($m = 0$). The T_0-model with absolute time postulates a constant time, but the mass variability ($m = \gamma m_0$) remains undefined for photons since $m_0 = 0$. Similarly, the intrinsic time $T = \frac{\hbar}{mc^2}$ leads to $T \to \infty$ when $m = 0$, halting time evolution and conflicting with the dynamics of photons.

1.2 Extension of Quantum Mechanics

To overcome these limitations, the time definition for massless particles is extended to $T = \frac{1}{E}$, where $E = p$ for photons (since $E = pc_0$ and $c_0 = 1$ in Planck units). For massive particles, $T = \frac{1}{m}$ remains, and a hybrid definition $T = \frac{1}{\max(m,E)}$ unifies the treatment. This leads to a modified Schrödinger equation:

$$i\frac{\partial\psi}{\partial(t/T)} = H\psi,$$

with $H = p$ for photons and $H = -\frac{1}{2m}\nabla^2 + V$ for massive particles. For a photon with energy $E = 2\pi\nu$ (where ν is the frequency), this yields $T = \frac{1}{2\pi\nu}$, corresponding to the period and enabling finite time evolution.

1.3 Implications for Nonlocality in Photons

The introduction of $T = \frac{1}{E}$ has the following effects on nonlocality:

1. **Finite Time Evolution**: Photons acquire an energy-dependent time scale $T = \frac{1}{E}$, rather than an infinite T. This allows for dynamic evolution dependent on their frequency.

2. **Delays in Entanglement**: For entangled photons with energies E_1 and E_2, the time scales are $T_1 = \frac{1}{E_1}$ and $T_2 = \frac{1}{E_2}$. Different energies (e.g., $E_1 \neq E_2$) result in differing evolution rates, implying a delay $|T_1 - T_2| = \left|\frac{1}{E_1} - \frac{1}{E_2}\right|$ in correlation. This contradicts the instantaneous correlation of the standard model.

3. **Photon with Massive Particle**: In a hybrid system (e.g., photon and electron), the correlation depends on $T_{\text{photon}} = \frac{1}{E}$ and $T_e = \frac{1}{m_e}$. Since E is typically smaller than m_e (e.g., $E = 1\,\text{eV}$ vs. $m_e \approx 5.11 \times 10^5\,\text{eV}$), $T_{\text{photon}} \gg T_e$, implying a significant delay in the photon's state.

4. **Energy-Dependent Nonlocality**: The correlation becomes energy-dependent, making nonlocality appear as an emergent property of the energy-time relationship, analogous to the mass-time relationship in massive particles.

5. **Causality**: The light cone structure remains preserved by $c_0 = 1$, but the time evolution within the cone is scaled for photons by $T = \frac{1}{E}$, altering the dynamics of state changes.

1.4 Experimental Verification

These implications could be tested through Bell tests with photons of different frequencies to detect delays proportional to $\frac{1}{E}$. Similarly, measurements in hybrid systems (photon-electron) could confirm the differing time scales $T = \frac{1}{E}$ vs. $T = \frac{1}{m}$.

1.5 Conclusion

The extension of quantum mechanics with $T = \frac{1}{E}$ for photons consistently integrates massless particles into the model and shifts nonlocality from an instantaneous to an energy-dependent dynamic. This necessitates a reconsideration of correlations in entangled systems and provides new experimental approaches for validation.