

Quantum–Biophysical Modeling of Light–Tissue Interaction via Schrödinger–Maxwell Coupling and Relativistic Extensions for Photodynamic Therapy

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ABSTRACT

This study presents a unified quantum–biophysical model for describing light–tissue interaction in photodynamic and diagnostic applications. The framework combines the time-dependent Schrödinger equation with Maxwell's electromagnetic coupling, allowing the representation of photon dynamics, energy localization, and absorption in complex biological media. The optical potential and damping terms are introduced to model refractive and absorptive properties, respectively, leading to analytical expressions for the quantum absorption coefficient (α_a), relaxation time (τ_a), and Photodynamic Therapy Index (PDTI). The model predicts that light intensity decays exponentially with depth, while higher absorption coefficients yield faster relaxation and stronger surface energy deposition—characteristics desirable for shallow photodynamic therapy. A Klein–Gordon relativistic extension is proposed for high-energy photon regimes such as UV or X-ray interactions. The developed theoretical framework provides a data-free, physics-based approach to estimate and optimize biphotonic efficiency. It establishes a foundation for future integration with Physics-Informed Neural Networks (PINNs) to retrieve tissue-dependent parameters from imaging data, bridging quantum theory and medical photonics in a mathematically consistent way.

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1. Introduction

Biphotonic phenomena establish a direct link between quantum physics and modern medical technologies, providing the physical foundation for advanced diagnostic and therapeutic applications such as Photodynamic Therapy (PDT) (Awan & Tarin, 2006; Henderson & Dougherty, 1992; Loewen et al., 2006; Robertson et al., 2009) and Optical Coherence Tomography (OCT) (Fujimoto & Swanson, 2016; Walther et al., 2011). Light–tissue interaction at the microscopic scale involves complex coupling between electromagnetic fields, molecular absorption, and tissue heterogeneity, where classical optical models such as the Beer–Lambert law and diffusion theory (Ishimaru, 2002; Profio, 1989; Saiko et al., 2025) often fail to capture the quantum wave nature of photons within biological media.

Recent advances in quantum optics and biomedical physics have revealed that photon transport inside living tissue cannot be fully described by macroscopic attenuation laws, as quantum coherence, interference, and scattering effects play significant roles in energy localization and dissipation (Ahmed et al., 2025; Boas et al., 2001; BornandE, 1999; Mandel & Wolf, 1995; Tayfor, 2024; Wang et al., 2006). These findings motivate the development of a unified theoretical model that integrates quantum mechanics, electromagnetic theory, and biophysical tissue properties under a consistent mathematical framework.

The present study aims to construct such a quantum–biophysical model based on the time-dependent Schrödinger equation, incorporating the Maxwell–Schrödinger coupling to represent the mutual interaction between the electromagnetic

field and the quantum wavefunction of light in an absorbing biological medium. In addition, a Klein–Gordon correction is proposed to extend the applicability of the model toward short-wavelength, high-energy regimes where relativistic effects become significant (Gordon, 1926; Jackson, 2021; Kaiser, 2005; Klein, 1926; Tamvakis, 2019). Unlike data-driven optical models, the proposed framework is purely theoretical, yet it generates quantitative biophysical parameters—including the quantum absorption coefficient (α_q), relaxation time (τ_q), and the Photodynamic Therapy Index (PDTI)—that can be directly applied to guide therapeutic planning, energy optimization, and quantum-level understanding of light–tissue interactions without requiring experimental datasets (Barsoukov, 2005; Jhunjunwala et al., 2023; Konovalov et al., 2016; Loudon, 2000; Milonni, 1994; Munir et al., 2023; Patel et al., 2024; Ricciarelli et al., 2024; Roorda et al., 2004; Rosencwaig & Griffiths, 1981; Wang, 2024; Yariv, 1997; Zhu et al., 2022).

2. Theoretical Framework

2.1 Quantum Model of Photon Behavior in Biological Media

The quantum state of a photon propagating through an absorbing biological medium can be described by the time-dependent Schrödinger equation with a complex potential

$$i\hbar \frac{\partial \psi(r, t)}{\partial t} = \left[-\frac{\hbar^2}{2m^*} \nabla^2 + V(r) - i\Gamma(r) \right] \psi(r, t) \quad (1)$$

The friction force is given by

$$F_f = \gamma v = -\left(\frac{mv}{\tau}\right)$$

With τ standing for the relaxation time – treating particles as strings

$$x = x_0 e^{i\omega t}$$

$$v = \dot{x} = i\omega x$$

$$V_f = -\int F_f dx = \frac{i\omega x^2}{\tau} \left(\frac{m}{2}\right) = i\Gamma(r)$$

$$V_f = -\frac{imv^2}{\tau\omega} = \frac{-i\hbar(mv^2)}{\tau\hbar\omega} = -\frac{i\hbar}{\tau}$$

Where for the very fast photon

$$\hbar\omega \approx \frac{1}{2} mv^2$$

Thus

$$\tau = \frac{\hbar}{\Gamma}$$

According to eqn (1) for

$$\psi = e^{ikr}$$

$$k = k_1 + ik_2$$

$$v = \frac{\hbar k_1}{m}$$

$$\frac{\hbar^2 k^2}{(2m)} + V + i\Gamma = 0$$

$$\Rightarrow \frac{2\hbar^2}{(2m)} k_1 k_2 = \Gamma$$

$$\alpha = 2k_2 = \frac{2m\Gamma}{(\hbar^2 k_1)} = \frac{2m\Gamma}{\hbar(mv_g)} = \frac{2\Gamma}{(\hbar v_g)}$$

$$|\psi|^2 = A^2 e^{\{-2k_2 x\}}$$

In this representation, $\Gamma(r)$ denotes the optical potential, which depends on the local refractive index $n(r)$. The imaginary term $\Gamma(r)$ accounts for energy loss due to absorption within the tissue. The squared modulus $|\psi|^2$ corresponds to the local photon energy density, describing how optical energy is spatially distributed inside the medium.

$$m^* = \frac{\hbar\omega}{c^2}$$

The parameter represents an effective photon mass, introduced solely for mathematical convenience to express the wave evolution in a Schrödinger-like form. This formulation allows a direct connection between the quantum probability amplitude and measurable optical quantities such as light intensity and absorption rate.

2.2 Photon–Field Coupling (Maxwell–Schrödinger Interaction)

The interaction between the quantum wavefunction and the classical electromagnetic field is described through the Maxwell–Schrödinger coupling. The electric field $E(r, t)$ satisfies the wave equation:

$$\nabla \times \nabla \times E = \left(\frac{1}{c^2}\right) \frac{\partial^2}{\partial t^2} [\varepsilon_r(r)E] + \mu_0 \frac{\partial J_q}{\partial t} \quad (2)$$

where the quantum current density is defined as

$$J_q = \left(\frac{e\hbar}{m^*}\right) \text{Im}(\psi^* \nabla \psi) \quad (3)$$

This coupling expresses the mutual interaction between the electromagnetic field and the quantum state of the photon. Energy is continuously exchanged between the optical field and the absorbing biological medium, allowing the model to capture both the propagation and attenuation of light at the microscopic level.

2.3 Derived Physical Quantities

From the previous equations, several key quantities can be derived that characterize light absorption within biological media.

The local absorption rate is given by:

$$Q(r) = \Gamma(r)|\psi(r)|^2 \quad (4)$$

which represents the optical energy absorbed per unit volume.

The total absorbed energy across the tissue volume V can then be expressed as

$$E_{abs} = \int_V Q(r) d^3r \quad (5)$$

This quantity measures the total energy deposited within the medium due to photon absorption. The quantum absorption coefficient relates the absorption strength to the propagation velocity of photons

$$\alpha_q = \frac{2\Gamma}{(\hbar v_g)} \quad (6)$$

where v_g denotes the photon group velocity in the medium.

Finally, the quantum relaxation time, representing the duration over which photons retain significant energy before dissipation, is defined as

$$\tau_q = \frac{\hbar}{\Gamma} \quad (7)$$

These parameters serve as fundamental indicators for evaluating the quantum efficiency of light absorption and energy transfer in biological tissues.

2.4 Relativistic Correction (Optional)

In high-intensity or high-energy regimes such as ultraviolet (UV) or X-ray photon interactions the nonrelativistic Schrödinger framework may be extended by incorporating the Klein–Gordon equation, which accounts for relativistic effects in wave propagation

$$\left(\frac{1}{c^2}\right) \frac{\partial^2}{\partial t^2} \varphi - \nabla^2 \varphi + \left(\frac{m^2 c^2}{\hbar^2}\right) \varphi = 0 \quad (8)$$

2.5 Conceptual Illustration

Figure 1 illustrates the interaction between the electromagnetic field and the quantum wavefunction within an

absorbing biological medium. The incoming classical field E transfers energy into the medium through the quantum absorption term (Γ), while part of the absorbed energy may be re-emitted or scattered. This diagram visually represents the coupled Schrödinger–Maxwell dynamics, showing how local absorption and partial re-emission govern photon behavior inside the tissue.

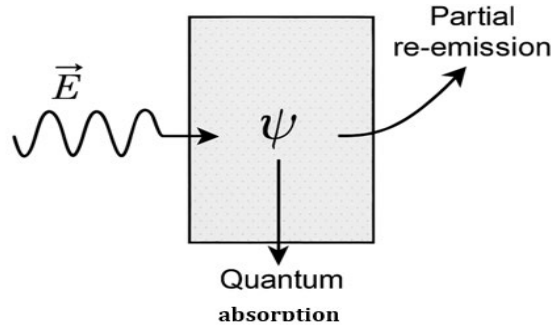


Figure 1: Schematic Illustration of the Interaction between the Electromagnetic Field and the Quantum Wavefunction in a Biological Medium. Energy Is Transferred from the Classical Field E to the Tissue Through Quantum Absorption (Γ), Followed by Partial Re-Emission.

3. Theoretical Results

3.1 Depth Distribution of Light Intensity

From the analytical solution of the Schrödinger equation in a homogeneous medium, the spatial decay of light intensity along the depth (z) is expressed as

$$I(z) = I_0 e^{-\alpha_q z} \alpha_q \quad (9)$$

denotes the quantum absorption coefficient, which increases with the absorption parameter Γ . This exponential relation indicates that as photons penetrate deeper into the tissue, their intensity decreases due to continuous quantum absorption governed by the imaginary potential term in the Schrödinger equation.

As shown in Figure 2, the normalized light intensity $I(z)/I_0$ decreases exponentially with depth, and the rate of decay increases with the absorption parameter Γ , consistent with the quantum absorption model derived in Eq. (9). This behavior illustrates how stronger absorption (larger Γ) leads to faster attenuation and reduced penetration of photons within the biological tissue.

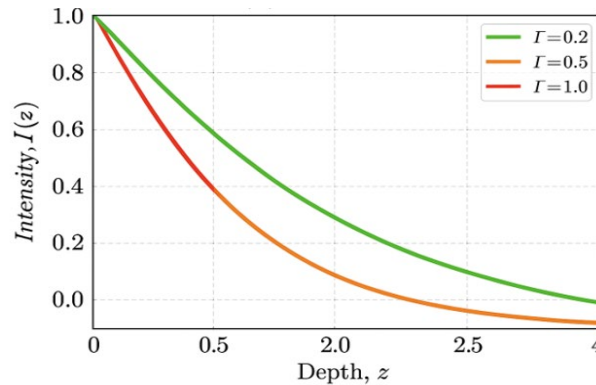


Figure 2: Depth-Dependent Intensity Decay According to Equation 9 for Different Quantum Absorption Parameters ($\Gamma = 0.2, 0.5, 1.0$). The Curves Illustrate that Higher Γ Values Lead to Faster Attenuation of Light Intensity, Reflecting Stronger Quantum Absorption and Shallower Photon Penetration within the Biological Tissue.

3.2 Absorbed Energy and Therapeutic Efficiency

The Photodynamic Therapy Index (PDTI) is defined to quantify the fraction of absorbed optical energy within a specific therapeutic depth range (z_1, z_2):

$$PDTI = \frac{1}{I_0} \int_{z_1}^{z_2} \Gamma(z) |\psi(z)|^2 dz \quad (10)$$

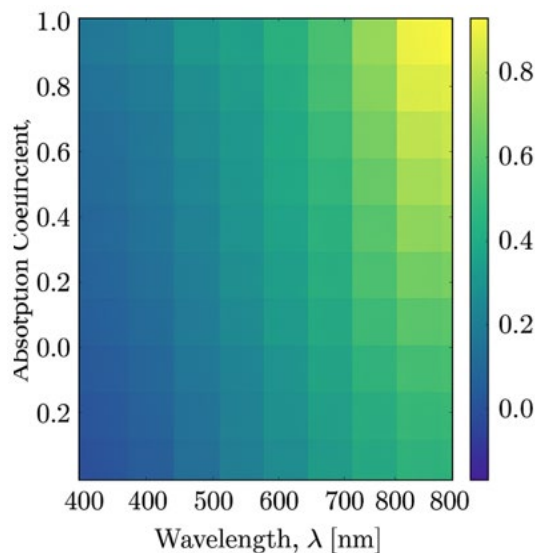


Figure 3: Contour Map of the Photodynamic Therapy Index, PDTI (λ , Γ), Showing the Relationship Between Wavelength λ (400–800 nm) and Absorption Coefficient Γ . The Color Gradient from Blue to Yellow Represents Increasing PDT Efficiency, Where Higher Γ and Longer Wavelengths Enhance Photon Absorption and Tissue Penetration. The Bright Regions Indicate Optimal Therapeutic Zones for Effective Light–Tissue Interaction.

3.3 Quantum Relaxation Time

The quantum relaxation time ($\tau_q = \frac{\hbar}{\Gamma}$) decreases as the absorption coefficient (Γ) increases. This inverse relationship implies that highly absorbing systems dissipate photon energy more rapidly, leading to shorter energy retention within the medium. Such behavior is advantageous for surface-level photodynamic treatments, where rapid energy deposition enhances therapeutic efficiency near the tissue surface. However, it becomes less favorable for deep-tissue applications, where prolonged photon propagation and delayed energy loss are required to achieve effective therapeutic penetration. Hence, optimizing Γ provides a means to tailor the spatiotemporal profile of photon absorption according to the desired medical objective balancing between surface intensity and penetration depth.

As shown in Figure 4, the quantum relaxation time (τ_q) decreases inversely with the absorption coefficient (Γ), confirming the theoretical prediction of Eq. (7). This behavior highlights the trade-off between absorption strength and photon energy retention in biological media, where higher absorption leads to faster energy dissipation and reduced photon lifetime.

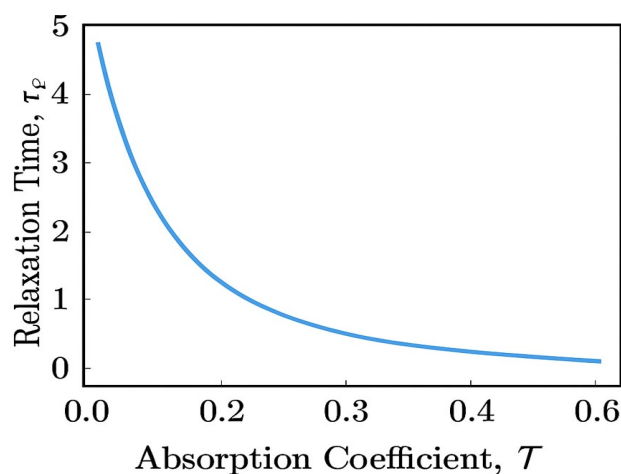


Figure 4: Dependence of Quantum Relaxation Time τ_q on the Absorption Coefficient Γ . The Curve Follows the Inverse Relationship $\tau_q = \hbar / \Gamma$, Indicating That Higher Absorption Leads to Shorter Relaxation Times. This Behavior Implies that Highly Absorbing Tissues Dissipate Photon Energy More Rapidly, Enhancing Surface-Level Photodynamic Efficiency While Limiting Deep Penetration.

4. Discussion

The proposed quantum framework provides a more accurate interpretation of light absorption in biological tissues compared to classical diffusion or Beer–Lambert models. By incorporating the Schrödinger–Maxwell coupling, the model captures interference and scattering effects that shape the spatial energy distribution inside complex media.

The parameters Γ (absorption coefficient) and λ (wavelength) can be tuned to control the therapeutic penetration depth in photodynamic therapy (PDT). Higher Γ enhances surface-level absorption, while longer λ values promote deeper photon penetration allowing precise targeting of specific tissue layers.

Furthermore, the framework naturally explains the phenomenon of photon localization, in which quantum interference leads to spatial confinement of optical energy. This effect becomes particularly important in heterogeneous or highly scattering biological structures.

The inclusion of the Klein–Gordon correction extends the model toward short-wavelength and high-energy regimes, where relativistic effects become non-negligible. Such an extension allows potential applications in ultraviolet or X-ray biophysics.

Finally, the theoretical model can be coupled with Physics-Informed Neural Networks (PINNs) to estimate the spatial variation of $\Gamma(z)$ directly from biomedical imaging data. This hybrid quantum–AI approach may enable real-time, noninvasive characterization of tissue optical properties and personalized optimization of PDT protocols.

5. Conclusions

A unified quantum–biophysical framework has been developed to describe light–tissue interaction using the time-dependent Schrödinger equation coupled with Maxwell's electromagnetic formulation. This theoretical integration provides a consistent foundation for modeling photon behavior, absorption dynamics, and energy transfer within complex biological media.

Analytical expressions for key physical quantities namely the quantum absorption coefficient (α_q), the quantum relaxation time (τ_q), and the Photodynamic Therapy Index (PDTI) were derived. These parameters can guide the design and optimization of light-based therapeutic procedures without requiring direct experimental measurements.

The presented model opens new avenues for applying quantum mechanics in biophotonics and nanomedicine, bridging microscopic photon behavior with macroscopic biological outcomes.

Future extensions may incorporate real experimental data or integrate Physics-Informed Neural Networks (PINNs) to validate and refine the theoretical predictions, leading to more precise and adaptive modeling of optical–biological interactions.

6. Recommendations

Based on the theoretical findings, several future research directions are proposed to extend and enhance the current quantum–biophysical framework

1. Extension to Three-Dimensional Models: Expanding the model to full 3D geometry will allow more realistic simulations of photon transport and spatial energy distribution, especially in heterogeneous biological tissues where scattering and absorption vary with depth and orientation.

2. Incorporation of Fractional Quantum Mechanics: Introducing the Fractional Schrödinger Equation can represent tissue memory effects and nonlocal interactions, providing a more accurate description of anomalous photon diffusion and temporal persistence within complex biological environments.

3. Spectral Adaptation of the Model: Applying the framework across a range of wavelengths will support the design of customized photodynamic therapy protocols, optimizing both penetration depth and energy deposition according to specific tissue optical properties.

4. Development of a Computational Simulation Platform: Building a simplified numerical simulator will enable researchers to test and visualize theoretical predictions before clinical implementation. Such a tool can serve as a bridge between mathematical modeling and experimental validation, promoting efficient optimization of light–tissue therapeutic systems.

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