Quantum Biosensing of Neurotransmitters for Real-Time Neural Activity Mapping

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***Abstract*—Recent advances in quantum technologies have opened transformative pathways for neural sensing, enabling unprecedented sensitivity in the detection of biochemical processes underlying brain function. This paper explores quantum biosensing approaches for real-time mapping of neurotransmitter dynamics, focusing on how quantum-enabled sensors can overcome the spatial, temporal, and chemical specificity limitations of conventional neuroimaging and electrochemical techniques. By leveraging quantum phenomena such as spin coherence, superposition, and quantum entanglement, emerging biosensors demonstrate the capacity to detect minute magnetic and electric field variations associated with neurotransmitter release at the synaptic scale. The integration of these sensors with biocompatible platforms enables minimally invasive, high-resolution monitoring of neural activity, offering new insights into fast neurochemical signaling and network-level brain dynamics. This work reviews the principles of quantum biosensing applied to neurotransmitter detection, examines current experimental implementations, and discusses their implications for neuroscience research, neurological disease diagnostics, and brain–machine interfaces. The paper argues that quantum biosensing represents a paradigm shift toward chemically precise, real-time neural activity mapping, with significant potential to reshape both fundamental neuroscience and translational neurotechnology.**

Deciphering the mechanisms underlying neural activity remains one of the most complex challenges in contemporary science. While significant progress has been made in mapping electrical signaling within the brain, neural function cannot be fully understood without accounting for the neurochemical processes that modulate synaptic transmission and network dynamics [10]. Neurotransmitters, including glutamate, γ-aminobutyric acid (GABA), dopamine, serotonin, and acetylcholine, act as the primary chemical mediators of neuronal communication, shaping perception, cognition, emotion, and behavior [8]. Their release, diffusion, and reuptake occur on millisecond timescales and at nanometer spatial resolutions, rendering their real-time observation exceptionally difficult with existing technologies.

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Traditional neuroimaging and neurochemical sensing methods have each contributed valuable insights yet remain constrained by inherent trade-offs. Functional magnetic resonance imaging (fMRI) provides whole-brain coverage but measures indirect metabolic correlates of neural activity with limited temporal resolution [3]. Electroencephalography (EEG) and magnetoencephalography (MEG) capture fast electrical dynamics but lack chemical specificity and spatial precision at the synaptic level [2]. Techniques such as microdialysis and fast-scan cyclic voltammetry offer neurotransmitter-specific measurements, yet they are invasive, spatially coarse, or limited to a small subset of analytes. These constraints hinder the ability to construct a unified, real-time picture of how neurochemical signaling interacts with electrical activity across distributed neural circuits.

In recent years, the emergence of quantum technologies has introduced new paradigms for sensing and measurement that challenge the limits imposed by classical physics. Quantum biosensing leverages quantum mechanical phenomena, such as superposition, coherence, and quantum state sensitivity, to detect extremely weak signals with unprecedented precision [7]. Unlike classical sensors, quantum-enabled devices can respond to minute perturbations in magnetic and electric fields at the nanoscale, making them uniquely suited for probing biological systems where signals are both subtle and transient [1]. When applied to neural environments, these capabilities open the possibility of detecting biophysical signatures associated directly with neurotransmitter dynamics rather than relying on indirect proxies.

Quantum biosensors are particularly promising for neuroscience because they enable chemically informed, minimally invasive measurements within living tissue. Advances in solid-state quantum systems have demonstrated that sensors can be engineered at nanometer dimensions while retaining long coherence times under biologically relevant conditions [11]. This miniaturization allows for proximity to synapses and neural membranes, where neurotransmitter release generates localized electromagnetic and molecular signatures [12]. As a result, quantum biosensing offers a pathway toward observing neural activity not only as an electrical phenomenon but as a chemically resolved, dynamic process.

The implications of real-time neurotransmitter mapping extend beyond fundamental neuroscience. Many neurological and psychiatric disorders, including Parkinson's disease, depression, schizophrenia, and addiction, are characterized by dysregulation of neurochemical signaling rather than gross structural abnormalities [6]. Current diagnostic approaches often detect these conditions only after significant functional impairment has occurred. High-resolution quantum biosensing could enable earlier detection of pathological changes in neurotransmitter dynamics, supporting preventative interventions and personalized treatment strategies [4]. Furthermore, integrating chemically specific neural data into the brain–machine interfaces could dramatically enhance their adaptability, precision, and long-term stability.

From a theoretical perspective, the integration of quantum biosensing into neuroscience challenges reductionist models that privilege electrical signaling as the primary carrier of neural information [5]. Instead, it supports a more holistic framework in which electrical, chemical, and quantum-sensitive processes interact across scales to produce cognition and behavior. This shift aligns with emerging views of the brain as a complex, adaptive system in which information is distributed across multiple modalities and temporal layers. Quantum-enabled measurement tools provide the sensitivity required to interrogate these interactions directly, rather than inferring them through averaged or delayed signals [9].

This paper investigates the role of quantum biosensing technologies in enabling real-time mapping of neurotransmitter activity and, by extension, neural function. It first outlines the physical principles that allow quantum sensors to achieve exceptional sensitivity in biological contexts. It then examines current experimental approaches to neurotransmitter detection, highlighting both their capabilities and limitations. Finally, the paper discusses future directions for integrating quantum biosensors into neurotechnological platforms, emphasizing their potential to transform basic research, clinical diagnostics, and human–machine interaction. By situating quantum biosensing at the intersection of physics, biology, and neuroscience, this work argues that it represents a foundational step toward a new generation of chemically precise, real-time neural mapping technologies.

REFERENCES

1. Abohmra, A., Zubair, M., Rehman, M. U., Abbas, H., Imran, M. A., & Abbasi, Q. H. (2025). Frontiers in Quantum Antennas: Theoretical Foundations, Practical Applications, and Future Outlook. IEEE Open Journal

of Antennas and Propagation.
2. Chaudhary, U. (2025). Non-invasive Brain Signal Acquisition Techniques: Exploring EEG, EOG, fNIRS, fMRI, MEG, and fUS. In Expanding Senses using Neurotechnology: Volume 1–Foundation of Brain-Computer Interface Technology (pp. 25-80). Cham: Springer Nature Switzerland.
3. Chen, Z., Chen, Y., Gezginer, I., Ding, Q., Yoshihara, H. A., Deán-Ben, X. L., ... & Razansky, D. (2025). Non-invasive large-scale imaging of concurrent neuronal, astrocytic, and hemodynamic activity with hybrid multiplexed fluorescence and magnetic resonance imaging (HyFMRI). Light: Science & Applications, 14(1), 341.
4. Das, S., Mazumdar, H., Khondakar, K. R., Mishra, Y. K., & Kaushik, A. (2024). Quantum biosensors: principles and applications in medical diagnostics. ECS Sensors Plus, 3(2), 025001.
5. Ebrahimi, M. (2025). Homunculus Models in Neuroscience, Immunology, and Quantum Biology: Insights into Cellular Signaling and Communication. International Journal of Innovative Science and Research Technology, 10(2), 1960-1968.
6. Ghallab, Y. K., & Elassal, O. S. (2024). Biochemical and neuropharmacology of psychiatric disorders. In Nutrition and Psychiatric Disorders: An Evidence-Based Approach to Understanding the Diet-Brain Connection (pp. 25-47). Singapore: Springer Nature Singapore.
7. Khorsheed, S., & Altaei, M. (2025). Bridging fundamental physics and practical applications: Advances in quantum-enhanced sensing. Inf. Dyn. Appl, 4(1), 12-22.
8. Ma, M., Zhang, Y., Tao, K., & Lu, Z. (2025). Neurochemical crossroads: exploring the neurotransmitter network in chronic pain and depression comorbidity. Frontiers in Molecular Neuroscience, 18, 1675814.
9. Nguyen, D. C., Uddin, M. R., Shaon, S., Rahman, R., Dobre, O., & Niyato, D. (2025). Quantum federated learning: A comprehensive survey. arXiv preprint arXiv:2508.15998.
10. Roy, A., Kumari, S., Singh, A. K., Gupta, R. K., & Kumar, A. (2025). The Nervous System Decoded: Structural Dynamics, Functional Integration, and Emerging Neuroscientific Frontiers. International Journal of Scientific Research and Technology.
11. Yukawa, H., Kono, H., Ishiwata, H., Igarashi, R., Takakusagi, Y., Arai, S., ... & Baba, Y. (2025). Quantum life science: biological nano quantum sensors, quantum technology-based hyperpolarized MRI/NMR, quantum biology, and quantum biotechnology. Chemical Society Reviews.
12. Zhi, W., Li, Y., Wang, L., & Hu, X. (2025). Advancing neuroscience and therapy: Insights into genetic and non-genetic neuromodulation approaches. Cells, 14(2), 122.