

QUANTUM BIOLOGY RESEARCH IN CANADA: DECODING NATURE'S SUBTLEST SECRETS

SUMMARY: Canadian researchers investigate spin- and light-related quantum effects in biological systems.



By **HADI ZADEH-HAGHIGHI**^{1,2}
<hadi.zadehhaghighi@ucalgary.ca>,
TRAVIS J.A. CRADDOCK¹
<travis.craddock@uwaterloo.ca>
and **CHRISTOPH SIMON**²
<christoph.simon@ucalgary.ca>

¹Departments of Biology and Physics & Astronomy, Waterloo Institute for Nanotechnology, University of Waterloo, Waterloo, ON, Canada N2L 3G1

²Department of Physics and Astronomy, Institute for Quantum Science and Technology, Hotchkiss Brain Institute, University of Calgary, Calgary, AB, Canada T2N 1N4

Canada is a global leader in quantum science and technology, with quantum biology emerging as a thrilling frontier. Canadian researchers are unraveling life's deepest mysteries by exploring a key question: how can quantum mechanics, through its unique principles of superposition and entanglement, explain complex biological phenomena that classical approaches cannot?

The radical pair mechanism (RPM) — a quantum-based model that links magnetic fields to the spin dynamics of electron pairs formed transiently during biochemical reactions — has emerged as a leading explanation for magnetosensitive phenomena in biology [1]. So far, the RPM has been investigated primarily in the context of avian magnetoreception — the remarkable ability of birds to perceive and navigate using Earth's magnetic field. However, recent work by Hadi Zadeh-Haghighi and Christoph Simon at the University of Calgary has broadened the scope of this framework, arguing that the RPM may underlie a wide range of magnetic field effects across diverse biological systems, far beyond avian navigation [2]. Motivated by this hypothesis, they initiated a series of interdisciplinary experimental collaborations with research groups across Canada and internationally, aiming to test the broader applicability of the RPM in living organisms. In a recent collaboration with Western Michigan University [3], they investigated the influence of weak magnetic fields on reactive oxygen species (ROS) generation in planarian flatworms. The experimental data showed alterations in ROS levels under hypomagnetic and weak static magnetic field conditions, consistent with RPM-based predictions. These changes in ROS concentrations, particularly superoxide, directly influence tissue regeneration

and healing in flatworms, which are known for their high regenerative capacity, as well as in other organisms. In a collaborative study at the University of Calgary, researchers investigated the impact of weak magnetic fields on pigment formation in *Xenopus* tadpoles, implicating cryptochrome 4 [4,5]. Expanding the scope of their research, Zadeh-Haghighi and Simon also proposed an RPM-based model for the magnetic field effects on microtubule assembly, key components of the cellular cytoskeleton [6]. In this model, RPM influences microtubule polymerization by modulating the spin-dependent recombination of radical pairs formed in tubulin proteins, thereby altering reaction yields that affect the energy exchange processes involved in assembly. Their model predicted that isotope substitution could modulate microtubule polymerization through the RPM. In collaboration with Travis Craddock — then at Nova Southeastern University and currently at the University of Waterloo — they experimentally verified this prediction by demonstrating isotope effects on microtubule assembly consistent with RPM-based mechanisms [7]. Such effects on microtubule dynamics could have profound implications for cellular processes like mitosis, intracellular transport, and cytoskeletal reorganization, potentially linking quantum phenomena to macroscopic biological functions such as cell division or neuronal signaling. These findings further support the role of quantum spin dynamics in mediating magnetic and isotope effects in biology. They also point to microtubules as a novel and highly relevant target for quantum biological investigations, illustrating how subtle quantum effects can propagate to influence essential cellular structures and behaviors in living systems.

Microtubules, cylindrical protein polymers composed of tubulin subunits, are critical for maintaining cellular structure, enabling intracellular transport, and orchestrating chromosome segregation during cell division. Their highly ordered lattice, rich in aromatic amino acids such as tryptophan, phenylalanine, and tyrosine, exhibits striking similarities to light-harvesting complexes found in photosynthetic organisms [8], suggesting a potential role in long-range energy transfer and protection against cellular oxidative damage [9]. Research led by Jack Tuszynski at the University of Alberta, in collaboration with Travis Craddock and Gregory D. Scholes of Princeton University, has provided compelling evidence for these functions by observing tryptophan autofluorescence in microtubules. Their studies demonstrated exciton diffusion—energy transfer via excited electrons—across the microtubule lattice, mirroring mechanisms seen in photosynthetic systems [10]. Furthermore, their work revealed that anesthetics, such as propofol, disrupt this energy transfer by altering the electronic properties of aromatic residues, potentially explaining their mechanism of action in modulating conscious awareness. Conversely, certain chemicals, including psychoactive compounds, may enhance this transfer, suggesting a role for microtubules in modulating neural signaling and brain function [11]. The crucial role of microtubules and the quantum effects that govern them could therefore be an avenue for investigating scientific questions around consciousness. Additional experimental evidence from Craddock's and Alfano's lab at City College of New York has identified quantum coupling between the electronic states of aromatic amino acids and vibrational modes within the microtubule lattice, indicating that microtubules may function as quantum-like conduits for energy and information processing in cells [12]. These findings position microtubules not only as structural and transport elements but also as sophisticated optical systems with potential applications in bio-inspired technologies, such as quantum computing and nanoscale energy transfer devices. Ongoing research

continues to explore how these quantum-like properties contribute to cellular processes and neural computation, bridging biophysics, neuroscience, and quantum biology.

Lithium (Li) has been the cornerstone treatment for bipolar disorder since its efficacy was established decades ago, primarily due to its ability to stabilize mood swings. In 1986, pioneering studies on rats uncovered intriguing behavioral differences influenced by lithium isotopes, specifically lithium-6 and lithium-7, which differ in their nuclear spin properties. These findings prompted physicist Matthew P.A. Fisher of the University of California Santa Barbara to hypothesize in 2015 that lithium isotopes could play a role in quantum neural processing within the brain [13]. Fisher proposed that phosphorus nuclear spins in Posner molecules — calcium phosphate clusters potentially present in the brain — could become quantum-entangled, facilitating a form of quantum computation. He suggested that lithium ions, when substituted for calcium in Posner molecules, enhance the molecules' stability. He also posited that these ions influence neurological outcomes through isotope-specific nuclear spin effects, potentially impacting mood regulation at a quantum level. This theory posits that the nuclear spin differences between lithium-6 (spin-1) and lithium-7 (spin-3/2) could modulate the entanglement properties, thereby affecting neural signaling in ways relevant to bipolar disorder treatment. In contrast, Hadi Zadeh-Haghighi and Christoph Simon at the University of Calgary offered an alternative explanation in 2021. They invoked the RPM to account for lithium isotope effects on hyperactivity in rats [14]. They proposed that lithium isotopes differentially affect these radical pair dynamics, altering cellular processes linked to hyperactivity and potentially explaining the behavioral outcomes observed in earlier rat studies.

More recently, in 2023, an international research team — including Zoya Leonenko and Michel Gingras of the University of Waterloo — investigated lithium's isotope-specific effects on mitochondrial calcium handling. This investigation shed light on its cellular mechanisms [15]. Their study explored how lithium isotopes influence mitochondrial function, particularly calcium ion dynamics, which are critical for cellular energy production and signaling. By examining isolated mitochondria, the team found that lithium-6 and lithium-7 differentially affect calcium uptake and release. This differential effect is potentially due to variations in nuclear spin interactions with mitochondrial proteins or membranes. These findings suggest that lithium's therapeutic effects in bipolar disorder may partly stem from isotope-specific modulation of mitochondrial activity, which could influence neuronal excitability and synaptic transmission. This research bridges cellular biology with quantum effects, highlighting the multifaceted role of lithium isotopes in both clinical and theoretical contexts.

These efforts establish Canada as a leader in quantum biology, probing a key question: How deeply do quantum phenomena influence life? This research supports the 2025 International Year of Quantum Science and Technology (IYQ), highlighting quantum science's promise for sustainable health solutions, like magnetic field therapies for cancer or isotope-specific drugs designed to enhance treatment precision.

REFERENCES

1. P. J. Hore and Henrik Mouritsen, The radical-pair mechanism of magnetoreception, *Annu. Rev. Biophys.*, **45**(1), 299-344 (2016).

2. Hadi Zadeh-Haghighi and Christoph Simon, Magnetic field effects in biology from the perspective of the radical pair mechanism, *J. R. Soc. Interface* **19**(193), 20220325 (2022).
3. Rishabh, Jana Vufčkovifá, Hadi Zadeh-Haghighi, Wendy S. Beane and Christoph Simon, Verification of radical pair mechanism predictions for weak magnetic field effects on superoxide in planarians, *bioRxiv [Preprint]*, 2024 Nov 21:2024.11.20.624392.
4. Hadi Zadeh-Haghighi, Gabriel Bertolesi, Christoph Simon and Sarah McFarlane, Weak magnetic field effects on pigmentation in tadpoles, in *APS March Meeting Abstracts 2024*, BB02-002 (2024).
5. Gabriel Bertolesi, Hadi Zadeh-Haghighi, Neda Heshami, Roger-Jan Kutta, Nataliya Archipowa, Christoph Simon and Sarah McFarlane, Cry4 mediated weak magnetic field effects on xenopus pigmentation, 2025. In preparation.
6. Hadi Zadeh-Haghighi and Christoph Simon, Radical pairs may play a role in microtubule reorganization, *Sci. Rep.* **12**(1), 6109 (2022).
7. Hadi Zadeh-Haghighi, Caleb R. Siguenza, Robert P. Smith, Christoph Simon and Travis J. A. Craddock, Tubulin polymerization dynamics are influenced by magnetic isotope effects consistent with the radical pair mechanism, *Sci. Adv.* **12**(7), eady8317 (2026).
8. Travis John Adrian Craddock, Douglas Friesen, Jonathan Mane, Stuart Hameroff and Jack A. Tuszynski, The feasibility of coherent energy transfer in microtubules, *J. R. Soc. Interface*, **11**(100), 20140677 (2014).
9. P. Kurian, T. O. Obisesan and T. J. A. Craddock. Oxidative species-induced excitonic transport in tubulin aromatic networks: Potential implications for neurodegenerative disease, *J. Journal of Photochem. Photobiol., B* **175**, 109-124 (2017).
10. Aarat P. Kalra, Alfy Benny, Sophie M. Travis, Eric A. Zizzi, Austin Morales-Sanchez, Daniel G. Oblinsky, Travis J. A. Craddock, Stuart R. Hameroff, M. Bruce MacIver, Jack A. Tuszynski, Sabine Petry, Roger Penrose and Gregory D. Scholes, Electronic energy migration in microtubules, *ACS Cent. Sci.* **9**(3), 352-361 (2023).
11. Travis J. Craddock, Tatum Hedrick and Isadora De Abreu, Chemical-induced changes in the optical properties of aromatic amino acid lattices in protein polymers, in *Quantum Effects and Measurement Techniques in Biology and Biophotonics*, Clarice Aiello, Sergey V. Polyakov, and Paige Derr, editors, (SPIE, 2024), p 7.
12. Wenxu Zhang, Travis J. A. Craddock, Yajuan Li, Mira Swartzlander, Robert R. Alfano and Lingyan Shi, Fano resonance line shapes in the raman spectra of tubulin and microtubules reveal quantum effects, *Biophys. Rep.* **2**(1), 100043 (2022).
13. Matthew P. A. Fisher, Quantum cognition: The possibility of processing with nuclear spins in the brain, *Ann. Phys.* **362**, 593-602 (2015).
14. Hadi Zadeh-Haghighi and Christoph Simon, Entangled radicals may explain lithium effects on hyperactivity, *Sci. Rep.* **11**, 12121 (2021).
15. Marshall L. Deline, Joshua Straub, Manisha Patel, Pratigya Subba, Martin Grashei, Frits H. A. van Heijster, Philip Pirkwieser, Veronika Somoza, James D. Livingstone, Michael Beazely, Brian Kendall, Michel J. P. Gingras, Zoya Leonenko, Carmen Hvðschen, Gertraud Harrington, Katharina Kuellmer, Wangqing Bian, Franz Schilling, Matthew P. A. Fisher, Matthew E. Helgeson, and Tobias Fromme, Lithium isotopes differentially modify mitochondrial amorphous calcium phosphate cluster size distribution and calcium capacity, *Front. Physiol.* **14**, 1200119, (2023).