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# The Aharonov–Bohm Effect in Biological Systems: Phase, Coherence, and Vector Potentials

## Introduction: Aharonov–Bohm Effect and Phase Influence

The **Aharonov–Bohm effect (AB effect)** is a quantum phenomenon in which charged particles are affected by the **electromagnetic potential** even in regions where classical electromagnetic fields (electric $\mathbf{E}$ and magnetic $\mathbf{B}$) are zero [1]. In the classic AB setup, an electron beam is split into two paths that go around a region containing a magnetic flux (e.g. inside a solenoid) but with the magnetic field confined so that it does not directly touch the electrons. Remarkably, even though the electrons experience no local $\mathbf{B}$ field, the presence of the vector potential $\mathbf{A}$ associated with the enclosed flux shifts the interference pattern on a detection screen. The electron wavefunctions acquire a **phase shift** proportional to the **magnetic vector potential line integral** around the loop [2]:

$$\varphi = \frac{q}{\hbar}\oint_P \mathbf{A}\cdot d\boldsymbol{\ell},$$

where $q$ is the particle's charge and the integral is taken along the particle's path $P$ around the flux region. This phase shift has been observed experimentally, confirming that $\mathbf{A}$ (the **vector potential**) has tangible physical effects despite the classical fields being zero outside the solenoid [1] [3]. In other words, **electromagnetic potentials can influence the** quantum phase** of particles (altering interference outcomes) without imparting force or energy in the classical sense. This contrasts with classical electromagnetism, where only fields have direct physical significance – the AB effect revealed that in quantum mechanics the potentials themselves play a fundamental role [4].

*Mathematically*, the AB phase arises from the coupling of $\mathbf{A}$ to the phase of the particle's wavefunction in the Schrödinger equation. Under a gauge transformation $\mathbf{A}\to \mathbf{A} + \nabla\chi$, the wavefunction gains a position-dependent phase $e^{iq\chi/\hbar}$, which leaves observable predictions invariant. Thus, only the **gauge-invariant** loop integral of $\mathbf{A}$ (related to the enclosed flux $\Phi_B=\oint \mathbf{A}\cdot d\ell$) matters physically. The AB effect is a prime example of a **geometric phase** (or Berry phase) in quantum theory, showing how the "phase landscape" of a system can be shaped by potentials in a *field-free* region. This concept of shaping quantum phase without energy transfer is at the heart of how AB-related ideas might extend to complex systems, including **biological systems**.

## Vector Potentials and Phase Relationships in Biological Systems

In biological contexts, we normally consider electromagnetic influences in terms of field intensities and energy transfer (e.g. induced currents, heating, etc.). However, if certain processes in biology involve quantum coherence – electrons, spins, or other degrees of freedom maintaining phase relationships – then **vector potentials might subtly affect those phase relationships** even at extremely low field strengths. Current research indeed suggests that magnetic vector potentials can play an active role in

biological processes [5]. For example, some studies on **weak magnetic field bioeffects** have found it useful to describe the interaction in terms of vector potential rather than just $\mathbf{B}$ field, especially when direct forces are negligible [5]. The idea is that a *structured $\mathbf{A}$ field* could bias the phases of quantum states in the system without classical force – analogous to the AB effect.

**Quantum systems in biology** that could be sensitive to phase shifts include:

- **Water Coherence Domains:** Water in cells isn't just a random solvent; quantum physicists have hypothesized that water can form **coherent domains** where dipoles oscillate in unison. If such domains exist (as proposed by Preparata, Del Giudice, etc.), they could support collective quantum states. A vector potential spanning a coherent water domain might shift its phase or coherence properties without needing strong fields. Indeed, it has been proposed that the vector potential can modify the quantum states of water [6], potentially altering cascades of biochemical reactions (for instance, those governed by phosphorylating ions with magnetic nuclei [6]). While these ideas are still speculative, they provide a framework where phase, not energy, carries **information**.

- **Electron or Dipole Oscillations in Proteins and Microtubules:** Proteins (and cytoskeletal structures like **microtubules**) contain arrays of dipoles and possibly delocalized electrons (e.g. in aromatic amino acids). Quantum models of microtubules suggest they might support excitations or spin states that remain phase-coherent under certain conditions [7] [8]. For instance, dipole coupling between tubulin subunits can be modeled with quantum spin operators in some theories of **quantum computation in microtubules**. If electrons or excitons in such a structure form a collective mode, an external $\mathbf{A}$ field (from an applied electromagnetic signal) could impart a phase shift to these modes. Even without driving an electronic transition, the phase of an electron's wavefunction or a *spin orientation* might be tweaked by a vector potential threading the structure. Over many proteins or tubulin dimers, this amounts to changing the **phase landscape** of the system's state. A subtle phase shift could tip a delicate balance – for example, altering the timing of how certain protein conformational changes synchronize, or modulating reaction rates if quantum tunneling is involved.

- **Spin Systems in Biology:** Biology also hosts numerous spin-bearing particles – electrons in radicals, nuclear spins in certain atoms, even possibly exotic proposals like Posner molecules protecting phosphorus nuclear spin coherence [8]. Magnetic **spin coherence** can survive relatively long in conducive environments (much longer than electronic coherence) [8]. If a biomolecule has two spin states (up/down) in superposition – essentially forming a *qubit* – a magnetic vector potential could shift the relative phase between spin-up and spin-down components if the spins traverse different paths or environments (this is analogous to how a neutron's spin can acquire phase via the Aharonov–Casher effect, a cousin of AB effect). In biology, one prominent spin-coherence example is the **radical pair mechanism** used in bird navigation [9]: a pair of radicals (each with an unpaired electron spin) react differently depending on their spin-singlet vs triplet phase relationship, which is influenced by magnetic fields. While the standard radical pair model emphasizes $\mathbf{B}$-field effects on spin precession, one can also conceive of $\mathbf{A}$-field influence if the geometry allows a loop. In general, if a spin or magnetic moment encircles an area with flux, it could gain an AB phase. Thus, one might speculate that **biomolecules containing ring currents or spin currents** (perhaps electron currents circulating in aromatic rings or ion channels) could be subject to AB-like phase shifts from applied vector potentials. This could modulate reaction yields or signal transduction efficiency in a subtle, non-thermal way.

Crucially, for any of these scenarios, some degree of *quantum coherence* or at least wave-like behavior in the biological system is required. The AB effect is fundamentally an interference phenomenon – you only see an outcome if a particle's wave can split and recombine. In a noisy, wet biological environment at body temperature, maintaining coherence is challenging. Nonetheless, biology has surprised us with quantum effects (e.g. **quantum tunneling in enzymes**, **coherent exciton transport in photosynthetic complexes**, spin coherence in bird compasses). Therefore, theorists have ventured that **if** small pockets of coherence exist in neurons, microtubules, or water clusters, an external vector potential could "tune" their phase relations much like a dial, **without depositing energy** the way a strong field would. This is a form of **information transfer via vector potential**: imparting *phase information* to a system in lieu of energy or force. A "structured" or patterned $\mathbf{A}(t)$ could essentially carry a *signal* into the quantum degrees of freedom of tissue, nudging how processes proceed.

One concrete speculative example is in **migratory birds**: beyond the spin-based compass (cryptochrome radical pairs), birds also incorporate tiny magnetite crystals in their bodies. Bókkon and Salari (2010) hypothesized that these **biomagnetite** crystals might act as biological AB devices, *recording the magnetic vector potential* along the bird's journey [10] [11]. The idea is that as a bird traverses Earth's field, the magnetite (in concert with neuronal electromagnetic activity) could encode phase information corresponding to the Earth's vector potential map of the route [10]. In essence, the bird's brain could be storing a **quantum phase imprint** of its migratory path – a bold idea linking AB-phase memory to navigation. Whether or not this specific mechanism holds, it illustrates how researchers are extending AB effect concepts to explain biological information processing: **phases and potentials as carriers of bio-information**, not just field strengths.

## Phase Coherence and Non-Local Coupling: From Physics to Biology

One hallmark of the AB effect is that it introduces a sort of **non-local influence** – the particles are influenced by a field (or rather a potential) in a region they never visit. This raises an intriguing question: could *phase coherence* induced by vector potentials lead to **coupling between separate systems** without energy exchange, even at a distance? In physics, we have analogies like two distant superconductors connected only by a shared electromagnetic mode: e.g. in a SQUID (superconducting quantum interference device), the superconducting currents in two arms of a ring remain phase-coherent through the enclosed flux. If two spatially separated quantum systems share the same **global vector potential structure**, they might exhibit **phase locking** relative to each other – somewhat like two pendulum clocks synchronized by a long belt.

In a thought experiment, imagine two identical setups that are shielded so that no classical EM field passes between them, yet each is subjected to the *same time-varying vector potential pattern*. This could be achieved, for example, by synchronizing coil currents in both locations in an identical manner. From a classical view, if perfectly shielded, neither system gets energy from the other. But from a quantum phase perspective, each system's internal phase might be evolving according to the same $\mathbf{A}(t)$ influence. If those systems had some quantum correspondence initially (say similar entangled states or simply identical preparedness), they could evolve in a **phase-coherent fashion** with each other. In other words, their quantum states could remain correlated in phase as if part of one larger interferometer that spans two labs. This scenario is highly speculative, but it resonates with the AB principle: **phase coherence established via potentials, not forces**.

Some experimentalists have reported puzzling **non-local effects in biology-like setups** that evoke this idea. For instance, S. Kernbach and colleagues conducted "mirrored" experiments with electronic

devices and found that **two spatially separated devices could behave as a single phase-coherent system under certain conditions** [12]. In one set of experiments, an LED-based signal generator was influencing a nearby water-based detector; when a second, identical setup was placed in another room (tens of meters away or more) and driven in synchrony with the first, the distant detector showed subtle responses *as if* it were still coupled to the original generator [12]. Even with electromagnetic shielding in place, the phase influence appeared to persist for some time after the systems were separated. The researchers interpreted this in terms of an **entanglement-like or phase-coupled field** linking the devices [12]. One could speculate that a common *vector potential structure* (from the synchronized modulation) was effectively "bridging" the two setups, maintaining a degree of phase coherence (a concept akin to AB effect but on a macroscopic scale). It's important to note these observations are controversial and not yet widely reproduced; however, they provide a provocative theoretical picture: that **phase information** (as opposed to energy) might be shared across distances via non-classical fields.

From a broader perspective, **non-local phase coupling** is not entirely foreign to physics. Aside from entanglement in quantum mechanics, even classical wave systems can show phase synchronization without direct contact if they are driven by a common source. For example, two radio antennas fed by the same oscillator emit waves in phase; two separate atomic clocks disciplined by the same reference signal stay in phase. By analogy, if two biological or electronic systems each receive a *phase reference* from the same patterned $\mathbf{A}(t)$ field, they could oscillate in unison. The novelty in the AB-like scenario is that this reference might be provided by a potential that does not register as a classical field in the space between the systems – thus appearing "non-local" in effect.

In summary, the AB effect teaches us that **phase coherence can be influenced through potentials in subtle ways**. Applying this lesson to biology suggests that nature might exploit similar tricks: organisms could use not just energy flows but phase synchronization to coordinate processes at a distance. This could be part of what some authors term *"quantum non-locality in biology"*. While highly speculative, it stretches our imagination of communication in biological networks – perhaps cells or neurons could be "phase-entangled" by fields in a way that standard biochemistry alone cannot explain. Any robust theory here must, of course, respect quantum decoherence and known physics; thus, ongoing research is focused on whether **certain biological structures can preserve coherence long enough** and whether **electromagnetic potentials can indeed orchestrate functional changes** at biological scales.

## Dynamic Modulation vs Static Fields: The Significance of Acceleration

A recurring theme in bioelectromagnetics is that **time-varying signals** have very different effects from static fields. The phrase "accelerating rhythms cut through static fields" reflects the observation that a *changing or modulated field* can produce responses where a steady field does not. There are several theoretical reasons why the *acceleration (time variation) of a field* is significant:

- **Inducing Electric Fields:** Maxwell's equations tell us that a time-varying magnetic vector potential $\mathbf{A}(t)$ induces an electric field since $\mathbf{E} = -\nabla \Phi - \frac{\partial \mathbf{A}}{\partial t}$. A *static* $\mathbf{A}$ (as in the static AB effect) might shift quantum phases without forces, but it won't drive currents or polarization in classical media. The moment $\mathbf{A}$ is varied in time (i.e. an accelerating change), a nonzero $\partial \mathbf{A}/\partial t$ creates an $\mathbf{E}$ field that can *directly interact* with charges. **Biological tissue strongly responds to electric fields** (nerve stimulation, ion transport, etc.), so a dynamic vector potential can have a dual effect: imparting phase information and also exerting small forces via

induced $\mathbf{E}$. This means an oscillating or pulsed signal can “get through” where a static offset might be inert. It’s akin to how a **radio signal (AC)** passes through a circuit via capacitive/inductive coupling, whereas a DC (static) bias might be blocked by a capacitor – **the AC changes bypass barriers** that stop DC. In biological terms, static magnetic fields often show minimal or no immediate effect (cells can adapt or ignore a steady field), whereas time-varying fields (especially with specific frequency content) can resonate with cellular processes (e.g. membrane ion channel kinetics, or cyclotron resonance of ions as some have hypothesized [13]).

- **Overcoming Shielding and Adaptation:** Many biological and experimental setups include shielding or homeostatic mechanisms that cancel out static influences. For example, a static magnetic field might be compensated by organisms (they habituate to Earth’s steady field). However, an *accelerating or pulsed field* can produce transients that these shields or adaptive responses cannot cancel instantly. If you imagine a "static field environment" as a sort of equilibrium, a sudden change (an **acceleration**) is a non-equilibrium perturbation that can penetrate. In practical terms, even a well-shielded Faraday cage that blocks static electric fields will develop induced currents on its walls when exposed to a rapid pulse, which can momentarily create internal fields. Likewise, biological membranes that are insulated to DC might allow AC or pulses to pass signals (this principle is used in **electric pulse-mediated drug delivery** and nerve stimulation). Therefore, a *rhythmic acceleration* of a signal can **“cut through” static conditions by exploiting the system’s finite response time**. The faster or more abrupt the change, the harder it is for the system to fully negate it.

- **Selective Resonance:** An accelerating rhythm (for instance, a frequency sweep or a pulse train) can excite specific dynamical modes in a target system. Static fields have no frequency; they’re like a constant bias. But life is dynamic – cells and tissues have numerous oscillatory activities (heartbeat, brain waves, oscillating chemical reactions, etc.). By tuning the modulation frequency of a field, one might **match a resonance** of the biological system, greatly amplifying the effect. For example, certain calcium ion fluxes or enzyme reaction cycles could respond at particular frequencies. If a modulated electromagnetic signal “accelerates” at just the right rate (say, pulses at a gamma-band frequency that neurons use, or at a frequency matching a microtubule vibration mode), it may induce a disproportionately large response compared to a static or off-resonance field. This is essentially **driving the system in sync with its natural rhythms**, slicing through the background noise. In contrast, a static field is like a DC input – easily filtered out by the inherent AC nature of biological signaling (neurons communicate in spikes, not sustained DC level differences).

In the context of the AB effect and phase, a *time-varying vector potential* is also interesting because it could modulate quantum phase **dynamically**. Instead of giving a one-time static phase offset, a changing $\mathbf{A}(t)$ might continuously tweak phases – potentially even causing *oscillations in interference patterns*. However, one must be cautious: a *slowly* varying $\mathbf{A}(t)$ within a single coherent system would produce a **time-dependent AB phase** which is equivalent (through gauge choice) to a mix of AB phase and real induced fields. If varied too fast, the system might not remain coherent to follow the phase adiabatically. Thus, in designing “phase signaling” via $\mathbf{A}$, one might choose modulation speeds commensurate with the coherence times of the system (more on this below). The key point is that adding **acceleration (change)** to the signal opens up channels of interaction (both quantum and classical) that a static situation lacked.

In summary, acceleration in the context of fields and potentials is significant because it is the gateway between **pure phase effects** and **tangible force effects**. It allows a potentially “stealth” channel like a vector potential to actually interface with noisy biological matter by periodically nudging it. The AB effect at heart doesn’t require a time-varying flux – it’s usually demonstrated with static flux producing a

static phase difference. But in a biological setting, to leverage AB-like effects, one might employ *modulated fields* so that there is both a **coherent phase imprint** and enough **temporal structure to avoid being lost in static noise**.

## The 3 ms vs 5 ms Puzzle: Timing, Coherence, and Resonance

An intriguing empirical observation (noted in the question) is that using **3 ms pulses with pauses** might produce a significant effect whereas 5 ms pulses do not. Let's unpack possible theoretical reasons for why a seemingly small timing difference – pulses separated by 3 ms (~333 Hz repetition) versus 5 ms (200 Hz) – could matter for a phase-mediated mechanism.

**1. Matching Internal Timescales (Coherence Time):** In any system with quantum coherence or even classical oscillators, there is a characteristic **decoherence time or memory time**. If pulses arrive faster than this time, the system can **integrate their effects coherently**. If they come too slowly, the system loses phase memory between pulses, and the effects just wash out. Suppose a population of spins or dipoles in a biological structure has a coherence time on the order of a few milliseconds. Then a 3 ms gap between pulses might be short enough that the phase shift from one pulse is still "remembered" when the next pulse arrives. The phase deviations can accumulate constructively. However, a 5 ms gap might exceed the coherence time – by the time the next pulse comes, the phase of the system has randomized (or the oscillation damped out). In that case, each pulse acts in isolation, and the cumulative effect is much smaller. In essence, **3 ms pulsing could resonate with the system's coherence, whereas 5 ms is too slow, falling into a regime where coherence decays**. It's notable that neural firing and many synaptic processes occur on a few-millisecond scale; 3 ms is roughly the duration of an action potential or the refractory period of a neuron. So a 3 ms pulse pattern could potentially interact with neurons at the upper end of their firing capability (~300 Hz), possibly entraining fast neuronal oscillations or resonating with fast molecular vibrations. 5 ms pulses (200 Hz) are slower and might not hit the same resonance if the system's sweet spot is higher.

**2. Fourier Spectrum and Frequency Content:** A pulse train with a 3 ms interval contains higher-frequency Fourier components than one with a 5 ms interval. In other words, the shorter the pulse repetition, the broader and higher the spectrum of frequencies injected into the system. If the biological target has a frequency-dependent response (as most do), the two pulse trains excite it differently. Perhaps the effective mechanism requires reaching a threshold frequency to trigger a response. For example, imagine a molecular ion channel that responds to oscillating fields above 250 Hz – then a 333 Hz (3 ms) train can stimulate it, while 200 Hz (5 ms) cannot. Some studies on weak-field bioeffects have invoked frequency windows where effects are seen only in certain bands [13] [14]. The **Lednev 1991 model** for weak magnetic field effects, for instance, proposed specific Larmor frequencies of ions that must be matched [13]. It's conceivable that 333 Hz lies near a particular ionic cyclotron or vibrational frequency in the experimental conditions, whereas 200 Hz does not. Additionally, shorter pulses mean sharper "edges" (greater acceleration), which yield stronger high-frequency transients that might momentarily perturb the system more effectively than gentler 5 ms pulses.

**3. Nonlinear Feedback and "Sweet Spots":** Biological systems often respond nonlinearly to stimuli. If one is modulating a complex network (say, a network of spin-coupled molecules or neurons), the output might only spike once the drive exceeds a certain rate. The 3 ms vs 5 ms difference could be analogous to pushing someone on a swing: if you push at the right rhythm, the swing goes higher (resonance), but a slightly off-rhythm push can actually dampen the motion. Perhaps 3 ms pulsing hits a **feedback sweet spot** in which each pulse arrives just as the system begins to relax, giving it another jolt in phase – effectively **pumping the phase coherence** constructively. At 5 ms, each pulse comes too late, by

which time the system might have settled into a less responsive state (or moved out of phase such that pulses add destructively). In quantum terms, 3 ms spacing might coincide with a **2π phase rotation** of some part of the system's wavefunction, so each pulse nudges it further along a preferred direction in Hilbert space. 5 ms could correspond to a non-integer multiple of some natural period, causing pulses to sometimes push against the accumulated phase rather than with it.

While we don't have a definitive theory pinned down (since this touches on new science being probed), we can draw a parallel: **NMR (nuclear magnetic resonance) and spin echo techniques** use carefully timed pulse sequences to manipulate phase. A 180° pulse followed by a certain delay can refocus spins (a spin echo) – but timing is critical; a wrong delay gives no echo. Similarly, in **coherent control experiments** in chemistry, femtosecond laser pulse spacing is tuned to steer reactions. By analogy, the 3 ms vs 5 ms could be the difference between building a coherent echo in a biological medium versus letting it dephase. If one treats the modulated field as creating a series of AB-like phase shifts, then 3 ms spacing might allow those shifts to add up in the *same phase*, while 5 ms spacing leads to phase cancellation over cycles.

**4. Physiological Noise Filtering:** Another mundane but relevant factor: a lot of biological electrical noise (from muscles, environment, etc.) is in the 0–200 Hz range. The brain's own dominant rhythms are delta (~1–4 Hz), theta (~5–8 Hz), alpha (~10 Hz), beta (~20 Hz), gamma (~40–100 Hz). A signal at 333 Hz lies above most brain activity, so it might stand out against the "static" of lower-frequency fluctuations. At 200 Hz, the difference is smaller but still above typical neural oscillations. It could be that the experimental detectors or biological receptors have a noise floor that is higher at 200 Hz than at 333 Hz, making the latter easier to detect. In practice, some **electrosensory systems** (like in weakly electric fish or even human brain stimulation techniques) use >300 Hz carriers to avoid interfering with normal neurosignaling and to exploit non-linear envelope detection. The 3 ms pulsing might effectively be a way of delivering a **high-frequency carrier** with some encoded phase pattern, whereas 5 ms is a slightly lower-frequency carrier that maybe gets lost or causes different interference patterns.

In summary, the effectiveness of 3 ms pauses over 5 ms likely points to a combination of **resonance with the system's natural frequencies and coherence times**, and the **spectral differences** in the stimuli. The exact "3 ms" value might not be universally special, but in the context of the specific system studied, it emerged as a critical timescale – hinting at an underlying quantum or classical oscillatory process that has that timescale. Theoretically, one would investigate this by modeling the system's response in the frequency domain and looking for peaks in sensitivity around 300–400 Hz, or by modeling a two-pulse interference effect and seeing at what interval the second pulse constructively interferes with the first.

## Conclusion and Broader Context

The exploration of **Aharonov–Bohm-like effects in biology** sits at a fascinating intersection of quantum physics and life science. We have seen that the AB effect exemplifies how *potentials* (not just fields) can convey physical influence in the form of **phase shifts**, and how this can lead to non-local seeming interactions in purely quantum systems. Extending these ideas to biology, researchers propose that living systems might harness subtle field effects: **vector potentials structuring phases of biomolecules, phase coherence enabling communication or memory, and dynamic modulation to couple with biological rhythms**. While experimental evidence for AB effects in living organisms is not yet conclusive, the **theoretical framework is being built from peer-reviewed advances in quantum biology and bioelectromagnetics**: from the role of **biomagnetite and vector potential maps in bird navigation** [10], to the possibility of **long-lived spin coherences in the brain** [8], and to empirical reports of anomalous long-distance coherence between EM devices [12].

It is important to stress that much of this remains **hypothesis** and frontier science. However, even as a conceptual tool, thinking in terms of phases and potentials broadens our view of biological signaling. It suggests new experiments – for instance, using shielded interference setups to test if organisms can sense potentials, or applying phase-tuned pulse sequences to influence biochemical reactions without significant energy input. It also connects to well-established non-bio analogies: *for example, how AB phases in solid-state nano-rings influence electron transport (a non-biological example), or how Josephson junction arrays maintain phase coherence via gauge fields.* By comparing these, we gain **broader context**: a laser interferometer and a microtubule network might not be so different if both are considered as phase-sensitive systems – one just has more thermal noise and complexity.

Ultimately, this line of inquiry might contribute to a deeper understanding of what one might call the **"quantum information biology"** of cells – how information (in the sense of phase or coherence) could be encoded, transferred, and processed in the wet, warm environment of life. The **Aharonov–Bohm effect provides a guiding principle**: that *not all influences come with energy and force; some come quietly as shifts in phase*. And as we continue to explore accelerating fields, tailored pulses, and quantum sensors in biology, we may yet uncover subtle phase-based communication channels that have been there all along, quietly coordinating the orchestra of life.

**Sources:**


- Y. Aharonov and D. Bohm (1959). *Significance of Electromagnetic Potentials in the Quantum Theory*. **Physical Review**, 115(3):485–491 – (Original paper proposing the AB effect, showing that potentials affect quantum phase) [4] [15].

- A. Tonomura *et al.* (1986). *Evidence for Aharonov–Bohm effect with magnetic field completely shielded from electron wave*. **Physical Review Letters**, 56(8):792–795 – (Classic experimental verification of the AB effect influencing electron interference).

- A. Szasz (2021). *Bio-Electromagnetics without Fields: The Effect of the Vector Potential*. **Open J. Biophysics**, 11(2):205–224 – (Discusses how electromagnetic potentials, not just fields, may play roles in biological interactions; notes that vector potentials can modify water's quantum state and biological processes) [5].

- I. Bókkon and V. Salari (2010). *Information storing by biomagnetites*. **Journal of Biological Physics**, 36(1):109–120 – (Hypothesis that biogenic magnetite in organisms can record information via the magnetic vector potential, e.g. birds recording Earth's vector potential during flight) [10] [11].

- M. Ghaderi *et al.* (2022). *Radical pairs may play a role in microtubule reorganization*. **Sci. Reports**, 12:5843 – (Reviews quantum effects in microtubules and neuroscience; notes that quantum **spin coherence** could persist longer than fast electronic coherence, suggesting spins as carriers of quantum information in cells) [8].

- S. Kernbach *et al.* (2013). *Long and super-long range device-device and operator-device interactions*. **Journal of Fundamental and Frontier Sciences** 1(1):24–42 – (Reports anomalous results where synchronized devices exhibit couplings over distances; interpreted in terms of non-classical fields and **persistent entanglement** between the systems) [12].

- V. V. Lednev (1991). *Possible mechanism for the influence of weak magnetic fields on biological systems*. **Bioelectromagnetics**, 12(2):71–75 – (Early theoretical model suggesting that extremely

weak oscillating magnetic fields could affect biological molecules via resonance mechanisms, potentially using vector potential formalisms for explanation) [13].

- A. Buchachenko (2016). *Why magnetic and electromagnetic effects in biology are irreproducible and contradictory?*. **Bioelectromagnetics**, 37(1):1–13 – (Analyzes the challenges and inconsistencies in bioelectromagnetics experiments, pointing to the complexities of spin chemistry and magnetic isotope effects in biology) [16].

- W. E. Smith (2004). *Quanta and coherence effects in water and living systems*. **J. Alt. Comp. Med.**, 10(1):69–78 – (Discusses evidence and theories for coherent quantum processes in water and living systems, providing context for how phase coherence might manifest in biology).

- M. Tegmark (2000). *Importance of decoherence in brain processes*. **Physical Review E**, 61(4):4194–4206 – (A critical look at quantum coherence in the warm brain, estimating very short decoherence times; serves as a counterpoint highlighting the challenge that any AB-like phase coherence mechanism must overcome rapid decoherence in biological conditions).

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[1] [2] [3] Aharonov–Bohm effect - Wikipedia
https://en.wikipedia.org/wiki/Aharonov%E2%80%93Bohm_effect

[4] [5] [6] [13] [14] [15] [16] Bio-Electromagnetics without Fields: The Effect of the Vector Potential
https://www.scirp.org/journal/paperinformation?paperid=108861

[7] [8] [9] Radical pairs may play a role in microtubule reorganization | Scientific Reports
https://www.nature.com/articles/s41598-022-10068-4?error=cookies_not_supported&code=caef9359-e6e4-4410-be81-8a07e5339cb8

[10] [11] (PDF) Information storing by biomagnetites
https://www.researchgate.net/publication/26787386_Information_storing_by_biomagnetites

[12] (PDF) Macroscopic quantum entanglement in local and nonlocal experiments
https://www.researchgate.net/publication/376787293_Macroscopic_quantum_entanglement_in_local_and_nonlocal_experiments