

The Aharonov-Bohm Effect: Phase Coherence from Physics to Biology

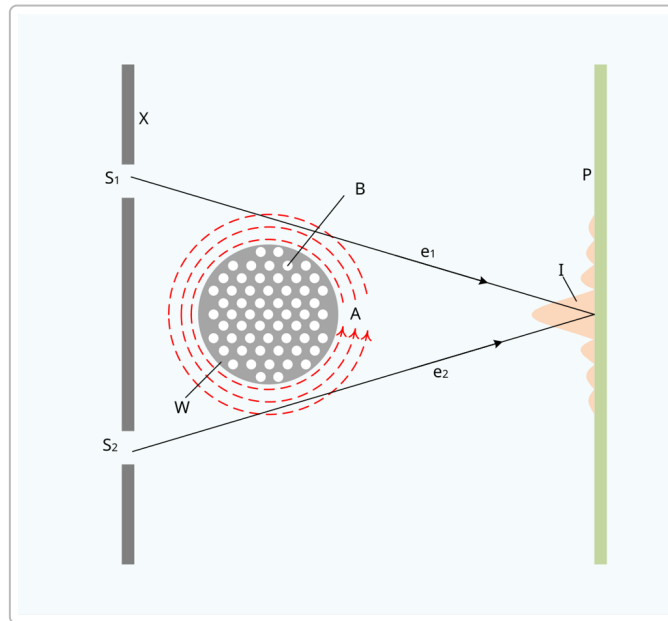


Illustration of the magnetic Aharonov-Bohm (AB) effect: electrons travel through two slits (S_1 , S_2) to a screen (P) while encircling a shielded magnetic flux (at W). No magnetic field \mathbf{B} (red dashed lines) leaks to the electron paths, yet the magnetic vector potential \mathbf{A} (red arrows) shifts the interference pattern (I) by altering the electron waves' relative phase ¹.

Introduction to the Aharonov-Bohm Effect (ABE)

The **Aharonov-Bohm effect** is a quintessential quantum phenomenon demonstrating that **electromagnetic potentials can influence a particle's quantum phase even in regions free of electric or magnetic fields** ² ³. In the classic AB setup (see figure above), an electron beam is split into two paths encircling a **magnetically shielded solenoid**. Although the magnetic field \mathbf{B} is confined (zero field along the electron paths), the **vector potential** \mathbf{A} extends into the field-free region. The striking result is a shift in the interference pattern when the enclosed magnetic flux changes, indicating a **phase difference** $\Delta\phi$ accrued by the electrons due to \mathbf{A} ². Mathematically, this phase shift is proportional to the line integral of the vector potential around the loop:

$$\Delta\phi = \frac{q}{\hbar} \oint \mathbf{A} \cdot d\mathbf{\ell} = \frac{q\Phi}{\hbar},$$

where q is the particle's charge and $\Phi = \oint \mathbf{A} \cdot d\mathbf{\ell}$ is the magnetic flux enclosed. This **gauge-invariant phase** (often a Berry phase in nature) has observable consequences (shifting interference fringes) even though **no classical force acts on the electrons** ⁴. The AB effect thus revolutionized our understanding of potentials: it showed that **the vector potential is not "mere math" but carries physical reality in quantum mechanics**, encoding information that cannot be

dismissed by gauge choice ⁵. Put simply, the AB effect is “the coupling of the electromagnetic potential with the complex phase of a charged particle’s wave function” ² ⁶.

Significance: The AB effect highlights two key points about quantum physics that will guide our exploration into biological systems: **(1)** Information can be conveyed via changes in phase without energy transfer or local forces, and **(2)** Phase effects can be inherently non-local (or topological), depending only on the global topology of field-free loops rather than on local field interactions ³ ⁵. These insights open the door to intriguing theoretical proposals: can **structured vector potentials** influence delicate phase relationships in complex systems (like those in biology) even when classical fields are weak? And might **phase coherence** between distant systems be achieved via shared potentials in analogy to the AB effect’s “action at a distance”? Below, we delve into these questions by examining **phase relationships, coherence, and vector potentials** in both non-biological and biological contexts.

Vector Potentials and Phase Relationships in Quantum Systems

Phase as a Physical “Landscape”: In quantum mechanics, the **phase of a wavefunction** is not merely abstract – it has observable consequences when comparing multiple paths or components of a system. A structured electromagnetic potential can act like a “phase landscape,” altering the relative phases of quantum states without necessarily imparting energy. The AB effect is the paradigmatic example: a static magnetic vector potential imprints a **phase shift** between two electron paths, shifting where constructive vs. destructive interference occurs ⁴. This phase imprint is gauge-invariant and real – indeed, rigorous analysis shows that the vector potential contains a unique, physical component responsible for the AB phase shift ⁵. **In essence, the potential “sculpts” the phase of the wavefunction in space**, influencing outcomes even though classical forces (which depend on fields \mathbf{E} or \mathbf{B}) are zero in the region of the particle ³.

Phase Coherence and Potentials in Condensed Matter: Many quantum technologies and phenomena exploit this phase landscape concept. For example, in superconducting **SQUID rings**, the current is governed by the phase difference between two paths, which is directly tuned by magnetic flux (an Aharonov–Bohm effect in action). Tiny changes in flux alter the supercurrent via interference, enabling SQUIDS to detect minute fields. Likewise, **mesoscopic electron rings** exhibit conductance oscillations as a function of enclosed flux (hence an AB oscillation), underscoring how a global vector potential pattern influences electron phase coherence and hence measurable currents. Even electron **spin systems** can accumulate geometric phase: in certain magnetic molecules, the quantum spin state picks up a phase when the molecule’s magnetization loops around in “spin space.” In fact, **Wernsdorfer & Sessoli (1999)** observed oscillations in the tunneling rate of a molecular nanomagnet as a function of applied magnetic field orientation – an “Aharonov–Bohm type oscillation in a magnetic system, analogous to oscillations vs. flux in a SQUID ring” ⁷. These oscillations were direct evidence of a **Berry phase (geometric phase) associated with spin**: two different magnetization reversal paths interfered depending on the phase picked up from the vector potential in spin space ⁷ ⁸. This study showed that *phase coherence in a spin system* (with no classical torque difference between paths) can dramatically affect measurable properties like tunnel splitting.

Broader Context: These physical examples illustrate a unifying idea – **structured potentials can carry information and affect outcomes by altering phase relationships**. The AB phase shift or Berry phase is essentially *information transfer via the potential*: the system “learns” about the presence of a flux or field configuration through phase, not force. Notably, this transfer of information occurs *without energy exchange* in the ideal AB setup (no work is done on the particle; only its phase is changed). We can thus imagine designing **modulated potentials** (in space or time) to imprint desired phase patterns on a

quantum system's components, thereby influencing interference outcomes or state probabilities. The question motivating theorists is: *could such phase-based information transfer occur in the complex environment of living systems?* If biological structures support quantum coherence on some level, a subtle external potential might shift their internal phase relationships – much like the AB solenoid shifts electron phases – and thus modulate biological function or signals in a non-classical way.

Phase Coherence in Biological Systems

Quantum Coherence in Biology: It has become increasingly clear that certain biological processes rely on quantum coherent effects. A celebrated example is **photosynthetic light-harvesting**: experiments have shown that excitons (quantum energy carriers) in pigment-protein complexes maintain coherence between pathways, improving energy transfer efficiency (even at physiological temperature). Another is the proposed mechanism of the **avian compass**: migratory birds sense Earth's magnetic field via a **spin-coherent radical-pair reaction** in cryptochrome proteins. In that model, two light-induced radicals in a bird's retina remain quantum entangled for microseconds, and the Earth's weak magnetic field (50 μ T) tilts their spin precession phases, altering chemical reaction yields. This is a genuine quantum phase effect – the bird is effectively measuring a *phase-dependent reaction yield* to perceive direction. While not an Aharonov-Bohm geometry per se, it exemplifies how **weak fields can influence biology by acting on phase of spin states**, rather than brute-force energy effects.

Microtubules and “Phase Landscapes”: Inside neurons, **microtubules** (protein nanotubes of the cytoskeleton) have been speculatively discussed as potential quantum processors. Theoretical models map microtubule subunits (tubulin dimers) to an **array of dipoles or spins** that can exist in bistable states (analogous to qubits). For instance, a one-dimensional ferroelectric pseudo-spin model of the microtubule wall has been developed ⁹, treating each dimer's electric polarization as an up/down pseudospin. Interestingly, this model predicts **nonlinear coherent excitations (solitons)** traveling along microtubules, and it considers the effect of external electromagnetic fields on the dipole alignment ⁹. If such dipole or electron-spin excitations in microtubules can maintain coherence for meaningful times, then an external **vector potential** might influence their collective phase – shifting the system's “phase landscape.” Even water in cells has been hypothesized to form **coherent domains** via quantum electrodynamics, wherein many dipoles oscillate in unison; these could be sensitive to subtle electromagnetic phases. Although these ideas remain theoretical, they set a stage where **biological structures could host phase-coherent states that an external potential might tweak**.

Information via Vector Potentials in Cells: Biókkon and Salari (2010) advanced a fascinating hypothesis that **biogenic magnetite crystals in cells could utilize the Aharonov-Bohm effect for information storage** ¹⁰ ¹¹. Magnetite (Fe_3O_4) nanoparticles are found in various organisms (including the human brain and birds' beaks). The authors argue that as these magnetite crystals form in cells, they could “record” the **magnetic vector potential map** of the environment ¹² ¹³. For a migratory bird, this means imprinting phase information about the Earth's magnetic vector potential during its journey. They suggest that **through the Aharonov-Bohm effect, even very weak geomagnetic fields could influence cellular processes by shifting electron phase** ¹⁰. The concept is that magnetite-bound electrons (or charge carriers) might experience phase shifts due to Earth's vector potential (which is global and cannot be easily shielded) and that these phase shifts modulate the magnetite's electrical properties (e.g. resistance). In fact, magnetite ferromagnets can exhibit quantum interference in electron transport (magnetoresistance oscillations) similar to AB interference ¹⁴. The authors point to an experiment by Wernsdorfer & Sessoli where a **molecular magnet showed AB-like oscillations in its magnetization** – supporting that **magnetic materials can show phase interference effects** ¹⁵. By analogy, a layer of biomagnetite with “frozen-in” phases could later experience an **oscillatory resistance change when exposed to the same vector potential pattern**, much as an AB ring shows oscillating conductance with flux ¹⁶. This oscillating resistance (a quantum

interference effect) could couple into neuronal signaling or other biochemical processes, thus **transducing a phase memory into a functional signal** ¹⁷ ¹⁸ . In this view, **biomagnetites act like phase memory devices**, storing information in the relative phase of electron wavefunctions influenced by the external vector potential. Importantly, because vector potentials (unlike fields) are **not easily screened by intervening matter** – one cannot put a simple shield to remove a static \mathbf{A} without also eliminating the flux that produces it – these phase imprints would be robust to environmental noise ¹¹ . And critically, this mechanism **does not require strong fields to push molecules around**; a subtle potential is enough to bias the quantum phase, which in turn could bias a biological outcome ¹¹ ¹⁹ .

While direct experimental evidence for such AB-based communication in cells is still lacking, these ideas draw on peer-reviewed physics and known biomagnetism. They underscore that **if a biological system can sustain quantum coherence (even briefly), it becomes susceptible to phase manipulations via potentials** just like any quantum system. Neurons, for instance, have endogenous electric oscillations (brain waves) and possibly even **coherent electron currents** in ion channels or microtubules (per some theories). A structured electromagnetic potential – for example, from a **modulated light or electromagnetic signal** – could, *in theory*, **alter the phase relationships among these oscillating charges or dipoles**. This might not manifest as a strong force on any charge (fields could be extremely weak), but rather as a *phase shift* in their ongoing oscillations or quantum states. Over time or across many cells, such phase shifts could synchronize or desynchronize certain processes, effectively transferring information into the biological system without the need for power or heating. It's a bold idea: **using the vector potential as an information conduit into biological tissue**, exploiting the same principle that shifts electron interference in the AB effect. As we've seen, physics provides precedents (phase-dependent effects in solid-state systems) and biology provides potential substrates (magnetite, spin chemistry, coherent excitations) where this could play out.

Non-Local Phase Coherence and Aharonov–Bohm Analogies

One of the most intriguing aspects of the AB effect is its *apparent non-locality*. The electron acquires a phase from a region it never directly visits (inside the solenoid). This has prompted discussions that AB is a form of “long-range effect” – though it does **not** violate causality or send signals faster than light (the potential is still a field that propagates normally), it shows that **distant sources can influence quantum phase in a delocalized way** ²⁰ . For two separate electrons traveling on either side of a solenoid, their phases are correlated through the common enclosed flux. By analogy, one might ask: could **two spatially separated biological systems become phase-coherent via a common vector potential structure?**

Imagine two identical setups (say, two containers of water or two biochemical reactors) located far apart but both subjected to the **same time-varying magnetic vector potential pattern** (for instance, through identical coil/solenoid arrangements or LED light pulse patterns). If these vector potential oscillations are **phase-synchronized between the locations**, any quantum processes within each system might evolve in phase with their distant counterpart. In other words, the two systems could become **phase-coupled** via the common applied potential, even if no conventional signal (energy transfer) passes between them. This would be a kind of Aharonov–Bohm-inspired **non-local coupling**, where coherence is maintained by the fact that both systems see what is effectively the same “phase driver.” It's important to clarify that from a standard physics perspective, this still requires some communication mechanism – e.g. the experimenter driving both systems with a synchronized generator, or both systems tapping into a ubiquitous field (like Earth's field). But the end result is unusual: *coherent behavior without local interaction between the two systems*, because each is reacting to the same remote potential pattern.

Some **experimental parapsychology/biophysics researchers** have indeed reported hints of such couplings. For example, **Kernbach (2015–2020)** describes “mirrored experiments” where two identical devices (LED-driven chemical oscillators) in separate locations showed correlated fluctuations when modulated with identical signals (even though electromagnetically shielded) – attributing this to a possible “non-classical information channel.” One interpretation frames this in terms of AB-like effects: if both devices share the same modulated vector potential structure (through some global field or synchronized protocol), they might exhibit **phase coherence at a distance**. The **hallmark of the AB effect is precisely phase coherence induced without energy transfer**, so it provides a tempting framework to describe these anomalies. **Quantum entanglement** is another well-established way to get non-local phase correlations (entangled particles share a quantum state no matter the separation). However, entanglement in biological settings is unproven except for transient chemical spins. The AB approach is different in that it doesn’t require initially entangled particles; it requires a shared potential environment. In practice, establishing a common phase reference between distant bio-systems is challenging, but one could envisage using something like the Earth’s magnetic vector potential as a giant reference frame. (Recall the magnetite hypothesis: all birds under the same sky share the Earth’s \mathbf{A} -field structure at any moment, thus could have subtle phase alignment relative to it ²¹.)

To be clear, conventional science would be cautious here: any true influence at a distance should ultimately be mediated by fields or particles (no magic action-at-distance). If two remote labs see correlations, one must suspect either a shared classical signal (perhaps an unnoticed radio frequency leak, or both being affected by the same environmental fluctuation) or shared initial conditions. **Nonetheless, theoretically, Aharonov-Bohm teaches us that “potentia” (the potentials) can connect separated regions in terms of phase.** If one can create a scenario where two systems form effectively two arms of a single large interferometer (with the “interferometer” extending across space), one might see phase coherence between them. This is analogous to two split beams from the same laser remaining coherent even if sent to different labs – their phase relation is fixed at the source. Similarly, two systems driven by the same coherent potential source could show **phase-locking**. For instance, if both are subject to an oscillating magnetic flux pattern such that each system’s internal quantum states pick up oscillating phases, those phases will be in lockstep between systems. In principle, if those phase modulations affect an observable (say, the impedance of a solution or the firing rate of neurons), one might see correlated changes in both locations’ observables. This speculative mechanism resonates with the idea of “communication via global fields” – not standard electromagnetism (since no strong fields are radiated) but through subtle phase imprints that two separated matter systems share. It remains a **theoretical extrapolation** of the AB effect, but one that motivates further research, especially as we understand more about quantum coherence in biology.

Dynamic Modulation: Accelerating Rhythms vs. Static Fields

A recurring experimental insight in bioelectromagnetics is that **time-varying or pulsed signals can produce effects where static fields do not**. This aligns with both classical and quantum reasoning. Classically, a **static field** tends to simply induce a fixed polarization or force that biological systems often adapt to or shield (e.g. ion redistribution cancels a static electric field in a conductive medium). A **dynamic field or rhythm**, especially if *accelerating or changing*, can break through this adaptation by constantly driving the system. In the context of Aharonov-Bohm and phase, a **static vector potential** would impose a constant phase offset – which might not have any noticeable effect unless you have a long coherent process to accumulate that phase. However, a **time-modulated vector potential** (for example, an oscillating or pulsed magnetic flux) means the phase shift is time-dependent. This can lead to **observable oscillations or beats** in the system’s response. In fact, a *time-varying AB effect* blurs into standard electromagnetic induction – if you change flux fast, you do generate electric fields (Faraday’s law) that can do work. But even moderate oscillations can subtly shake quantum phases without strong forces, effectively **“stirring” the phase landscape so it doesn’t settle**.

Significance of Acceleration: An *accelerating rhythm* (e.g. a chirped frequency or a train of pulses with shortening intervals) is rich in frequency content and can excite resonances across scales. By **sweeping through frequencies**, it can find the natural frequency of a process and amplify it. For instance, if a neural circuit or molecular vibration responds maximally at, say, 200 Hz, then gradually ramping a modulation through that frequency can deposit energy or phase at that sweet spot. In a static field, there is no frequency to speak of – nothing to resonate with. Thus, acceleration can “cut through” because it **prevents the system from reaching equilibrium** under a constant bias; instead, it continuously perturbs phases. In quantum terms, an accelerating or pulsed potential can induce transitions between states (where a static one would just shift energies slightly). If one aims to transmit information via phase modulations, **changing the phase in time (and even changing the rate of change)** is effectively encoding information in the second derivative as well – it’s another channel to influence the system.

3 ms vs 5 ms Pauses – Hitting the Right Timing: The specific observation that **3 ms pauses in a modulated signal are effective whereas 5 ms pauses are not** suggests a resonance or coherence time at play. A 3 ms interval corresponds to a ~333 Hz repetition rate (if we consider it part of a regular cycle). Many biological processes have characteristic timescales in the millisecond range. For example, **neuronal firing and synaptic integration** operate on few-millisecond scales; the absolute refractory period of a neuron is on the order of 1–2 ms, meaning it can fire at most ~500 Hz. A pause of 3 ms between stimuli could be allowing neurons or other excitable elements to recover just enough to respond to the next pulse, whereas 5 ms might be long enough for inhibitory processes or dephasing to dampen the response. In fact, studies in neurostimulation show that **paired pulses separated by ~2–4 ms can produce enhanced responses (facilitation) in cortex, but longer gaps lose this effect** ²². For instance, in transcranial magnetic stimulation research, a second pulse about 2.8–3.0 ms after the first can hit an optimal window to amplify cortical neuron firing (by summing with late EPSPs), whereas at 5 ms the facilitation drops off ²². This implies 3 ms is tapping into an intrinsic circuit rhythm that 5 ms misses. In more general terms, **3 ms could be near the coherence time of a certain quantum or classical mode** in the system. If one imagines, say, a collective oscillation of water molecules or a vibration in a protein, a 3 ms periodic perturbation will reinforce it if it matches the oscillation’s period or a sub-multiple. But a 5 ms perturbation might come out of phase, thus not reinforcing (or even interfering destructively).

Another way to look at it is through the lens of **phase coherence decay**. Suppose a group of spins or dipoles in tissue can maintain phase coherence for, say, ~4 ms before dephasing. If you apply a sequence of pulses separated by 3 ms, each pulse might interact with the system while it’s still phase-coherent with the previous pulse, thereby **cumulatively building a phase effect**. At 5 ms, coherence might have mostly decayed in the interim, so each pulse “starts over” rather than adding coherently. This is analogous to **spin echo techniques** in NMR: you have to send the refocusing pulse before the spins decohere. In a similar vein, if 3 ms is within the memory time of whatever subtle ordering (be it quantum phase or even classical polarization) the system has, then a 3 ms-spaced pattern can drive a progressively bigger response through *phase alignment*. At 5 ms, the memory is lost, so the pattern fails to accumulate effect.

Biological Resonances: It’s worth noting that frequencies in the high hundreds of Hz (periods of a few ms) do pop up in biology: for example, certain high-frequency oscillations in the brain (so-called “ripples” in the hippocampus) occur around 150–200 Hz, and some cortical interneurons can fire at ~200 Hz. While 333 Hz (3 ms) is higher, an accelerating pulse train might excite subharmonics or higher-order modes. Additionally, the **water-protein interface** can support sub-thermal vibrational modes in the kHz-MHz range; a 3 ms pattern (which is 333 Hz fundamental but contains a broad spectrum due to pulsing) might stimulate low-kHz modes (third harmonic of 333 Hz is 1 kHz, etc.), whereas 5 ms (200 Hz fundamental) stimulates a different set. If a specific mode is resonant with 1 kHz, the 3 ms pulsing will

engage it strongly via Fourier components, whereas 5 ms pulsing has a 1 kHz component that might be weaker or out of sync.

In summary, **the efficacy of a 3 ms pause suggests a resonance with the system's dynamics**, ensuring that each cycle of the stimulus constructively interferes with the system's ongoing oscillations or coherence, whereas 5 ms falls out of step. The **acceleration** – i.e. shortening the pauses from 5 ms toward 3 ms – could be seen as tuning through a “critical tempo” at which the system locks on. This notion of *critical tempos* is well-known in neurobiology (brainwave entrainment, where flickering lights at the right frequency induce EEG oscillations) and even in chemistry (oscillatory reactions synchronize when driven at specific frequencies).

Conclusion

From the foregoing analysis, we see a theoretical framework emerging: **electromagnetic vector potentials can influence phase coherence in physical systems without exerting direct force, and this principle may extend to certain bio-systems if they support quantum-like coherence or finely tuned classical oscillations**. The Aharonov-Bohm effect provides the fundamental example in physics – a coil's vector potential shifting electron interference bands – but analogous ideas appear in spin chemistry, condensed matter, and speculative quantum biology. In all cases, the crux is that **altering phase relationships** can alter outcomes (be it an interference pattern, a reaction yield, or a signal) even if energy input is negligible.

In biological contexts, this implies that **living systems might be sensitive not only to the strength of fields, but to the phase structure of fields and potentials**. If neurons, proteins, or water networks have internal oscillatory states, then an external signal structured in the right way (e.g. as **modulated light or EM fields encoding vector potential patterns**) could **entrain or perturb the phase of those states**. The theoretical involvement of Aharonov-Bohm phase factors in, say, magnetite-based sensing or microtubule dynamics, while still unproven, gives a tantalizing glimpse of what might be possible: a form of biological information transfer at a distance, relying on phase coherence rather than power.

Crucially, timing is everything. **Dynamic, accelerating rhythms can succeed where static or slow-varying fields fail**, by tapping into resonances and maintaining coherence. The observation that *3 ms pulsed intervals yield effects that 5 ms do not* is a concrete example, likely reflecting an intrinsic temporal coherence in the system on the order of a few milliseconds ²². This resonates with the broader principle that **to influence a coherent system, the external perturbation must be synchronized to the system's own frequencies** – much as a playground push must match the swing's timing. An accelerating sequence of pulses can effectively “scan” for that timing, breaking through any static-field immunity by hitting the right phase alignment.

In a graduate seminar setting, these concepts tie together physics and biology under the theme of **phase-coherent phenomena**. The Aharonov-Bohm effect is not just a curiosity of electron interferometers; it's a doorway to understanding how *fields and information* intertwine. By comparing solid-state examples (like AB oscillations in nanomagnets ⁷) with biological hypotheticals (magnetite phase memory ¹⁰ ¹⁶, neural response to pulsed fields ²²), we appreciate both the universality of the physics and the unique challenges of the biology. Whether or not nature actually exploits AB-like mechanisms, thinking in terms of **phase landscapes, coherence times, and vector potential coupling** enriches our approach to bioelectromagnetic research. It encourages experimentalists to look beyond field strength and consider **frequency, phase and timing** as critical factors – because as the AB effect teaches, *what you can't feel (as a force), might still affect you (as a phase)*.

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² ⁶ Aharonov–Bohm effect - Wikipedia

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⁷ ⁸ (PDF) Quantum Phase Interference and Parity Effects in Magnetic Molecular Clusters

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