

Comment on “Aharonov-Bohm Phase Is Locally Generated Like All Other Quantum Phases”

Introduction—Marletto and Vedral [1] propose a fully quantum model asserting that the Aharonov-Bohm (AB) phase is locally mediated by entanglement between a charged particle and the quantized electromagnetic field, claiming gauge independence for nonclosed paths. In this Comment, we critically analyze their model and demonstrate that the AB phase arises from the interaction with the vector potential $\mathbf{A}$, not from entanglement, which is a byproduct of the quantum electrodynamics (QED) framework. We show that their field-based energy formulation, intended to reflect local electromagnetic interactions, is flawed due to an incorrect prefactor and yields $+q\mathbf{v} \cdot \mathbf{A}_s$ in the Coulomb gauge, conflicting with QED’s $-q\mathbf{v} \cdot \mathbf{A}_s$. This equivalence to $q\mathbf{v} \cdot \mathbf{A}_s$ holds only approximately in the Coulomb gauge under static conditions, failing for time-dependent fields and other gauges, undermining their claim of a gauge-independent local mechanism. Furthermore, we confirm that the AB phase is gauge dependent for nonclosed paths, contradicting their assertion. Our analysis reaffirms the conventional explanation in the semiclassical picture [2], where the AB phase is driven by the vector potential $\mathbf{A}$, with entanglement playing no causal role in its generation (see Ref. [3] for detailed analysis).

Marletto and Vedral’s model—In Marletto and Vedral’s model [1], a charged particle and a solenoid interact via a quantized electromagnetic field, described by an interaction Hamiltonian in the Coulomb gauge. The interaction energy calculated from the second-order term of the transition amplitude is $\mathcal{E} = -q\mathbf{v} \cdot \mathbf{A}$ (the negative sign missed in [1]), yielding the accumulating phase $\phi_{AB} = \int (\mathcal{E}/\hbar) dt = -(q/\hbar) \int \mathbf{A} \cdot \mathbf{v} dt = -(q/\hbar) \int \mathbf{A} \cdot d\mathbf{l}$, which matches the semiclassical AB phase. However, they propose a field-based interaction energy, $\mathcal{E}_{\text{field}} = \frac{1}{2} \int \{[(\mathbf{B}_s \cdot \mathbf{B}_c)/\mu_0] + \epsilon_0 \mathbf{E}_s \cdot \mathbf{E}_c\} d^3\mathbf{r}$, claiming it mediates locally via entanglement the AB phase, which is, thus, gauge independent for nonclosed paths.

Critique of their claims—Discrepancy between field-based and QED interaction energies: First, the $\frac{1}{2}$ prefactor in $\mathcal{E}_{\text{field}}$ is incorrect and should be removed for the interaction energy between two sources (the solenoid and the charged particle). Second, after correction, we can show that $\mathcal{E}_{\text{field}} = q\phi_s(\mathbf{r}_c) + q\mathbf{v} \cdot \mathbf{A}_s(\mathbf{r}_c)$ for static fields in the Coulomb gauge, where ϕ_s is the scalar potential of the source. However, in non-Coulomb gauges and for time-dependent

fields, the equivalence does not hold. Third, $\mathcal{E}_{\text{field}}$ is not equal to QED’s interaction energy, $\mathcal{E}_{\text{QED}}$, even in the Coulomb gauge. In QED, the interaction energy is $\mathcal{E}_{\text{QED}} = q\phi_s(\mathbf{r}_c) - q\mathbf{v} \cdot \mathbf{A}_s(\mathbf{r}_c)$. This energy is valid for both static and time-dependent fields in the nonrelativistic limit. Comparing the two energies, the magnetic term has opposite signs: $-q\mathbf{v} \cdot \mathbf{A}_s$ in QED versus $+q\mathbf{v} \cdot \mathbf{A}_s$ in their model. In the AB setup where $\phi_s = 0$: $\mathcal{E}_{\text{QED}} = -q\mathbf{v} \cdot \mathbf{A}_s$, $\mathcal{E}_{\text{field}} = q\mathbf{v} \cdot \mathbf{A}_s$, highlighting the sign error. Thus, $\mathcal{E}_{\text{field}}$ does not align with $\mathcal{E}_{\text{QED}}$, even in the Coulomb gauge and fails for time-dependent fields. This invalidates the authors’ claim that $\mathcal{E}_{\text{field}}$ universally represents the local interaction driving the AB phase.

Gauge dependence of the AB phase for nonclosed paths: Marletto and Vedral also claim that the AB phase is gauge independent for nonclosed paths. However, this claim results from their incorrect assumption that $\mathcal{E}_{\text{field}}$ universally replaces the QED interaction energy $\mathcal{E}_{\text{QED}}$, ignoring the sign mismatch and its gauge-specific derivation in the Coulomb gauge. In standard QED, the AB phase is derived from the minimal coupling Hamiltonian, yielding the interaction energy $-q\mathbf{v} \cdot \mathbf{A}$. The phase for a path from $\mathbf{r}_1$ to $\mathbf{r}_2$ is $\phi_{AB} = -(q/\hbar) \int_{\mathbf{r}_1}^{\mathbf{r}_2} \mathbf{A} \cdot d\mathbf{l}$, which is gauge dependent for nonclosed paths, only becoming gauge independent for closed paths.

Entanglement is not the primary cause of the AB phase: Marletto and Vedral’s central claim is that the AB phase arises from local entanglement between the charged particle and the photon field. While their model does indeed produce such entanglement, it can be shown that this entanglement: (1) does not determine the AB phase (which is fixed by $\mathbf{A}$); (2) has negligible effect on observables ($\langle \chi_L | \chi_R \rangle_F \approx 1$, where $|\chi_L\rangle_F$ and $|\chi_R\rangle_F$ are photon states associated with each path); and (3) is absent in semiclassical derivations of the effect. Thus, the AB phase remains a manifestation of the vector potential’s role, with entanglement playing no causal role.

Conclusion—Our analysis of Marletto and Vedral’s model [1] reveals critical flaws: an incorrect $\frac{1}{2}$ prefactor in their field-based energy, halving the interaction strength; a sign error yielding $+q\mathbf{v} \cdot \mathbf{A}_s$ instead of QED’s $-q\mathbf{v} \cdot \mathbf{A}_s$, even in the Coulomb gauge; a false claim of gauge independence for nonclosed paths, inconsistent with QED’s gauge-dependent phase; and an unsubstantiated role for entanglement, which is incidental rather than causal. These errors misrepresent the AB effect’s mechanism. This Comment corrects these fundamental flaws, reinforcing the conventional explanation of the AB effect in the semiclassical picture, where the AB phase is driven by the local coupling to the vector potential $\mathbf{A}$. Finally, we note that if Marletto and Vedral’s model were valid, then we would have a gauge-independent explanation of the AB effect. However, it can be shown that such gauge-independent explanations are excluded [4].

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Received 23 April 2025; accepted 11 August 2025;
published 27 August 2025

DOI: [10.1103/v117-v5wn](https://doi.org/10.1103/v117-v5wn)

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