Locality and the Aharonov-Bohm effect

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Locality of quantum theory

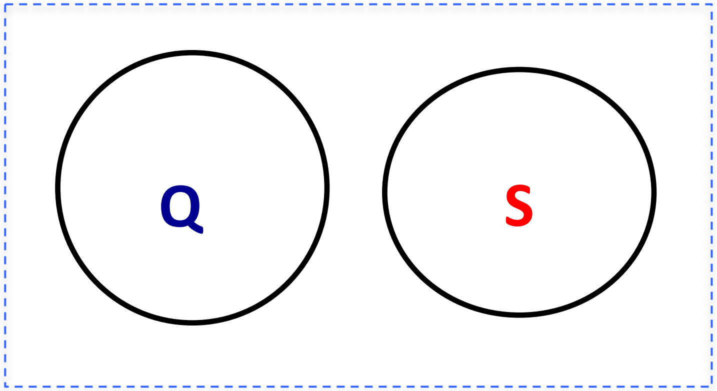
Two subsystems A and B, with algebra of observables $\{A_i\}$ and $\{B_i\}$

- *For any two subsystems A and B, a unitary that operates on A only, but not on B, can only change A's observables, not B's.*

No-signalling follows.

It also follows that for A to induce a change on B, or viceversa, A and B have to directly interact, or to interact through a mediator.

A problem



Is it possible to have a hybrid system composed of a quantum system interacting with one that is not quantum?

A theory-independent argument for Quantum Universality

DeWitt's idea: the 'totalitarian' property of quantum theory (D. Deutsch, Quantum, forthcoming.)

'If a quantum system Q couples to another system S, then S must be quantum'

BUT: the argument assumes far too much…

A theory-independent argument for Quantum Universality

A system is 'non-classical' if it has at least two non-commuting variables X and Z

'Non commuting' means that X and Z cannot be 'copied' simultaneously to perfect accuracy.

D. Deutsch, C. Marletto, Proc. R. Soc. A, 2015.
C. Marletto, Proc. R. Soc. A, 2016.

A theory-independent argument for Quantum Universality

Assume these general principles:

1) Locality

2) 1:1

3) Interoperability of information

A theory-independent argument for Quantum Universality

This system is assumed to have two non-commuting observables, say X, Z.

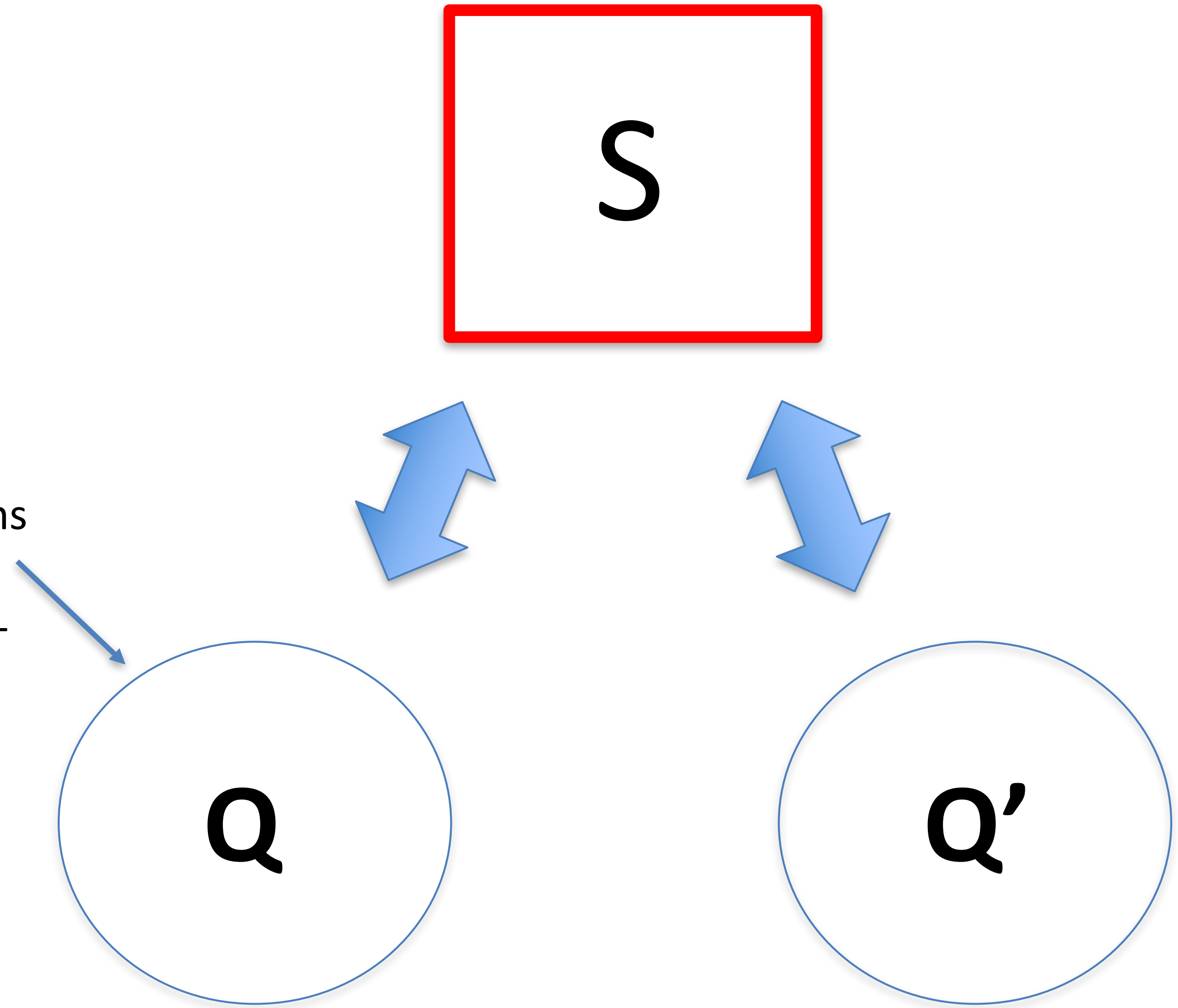
This system is assumed initially to have only one classical observable, say Z.

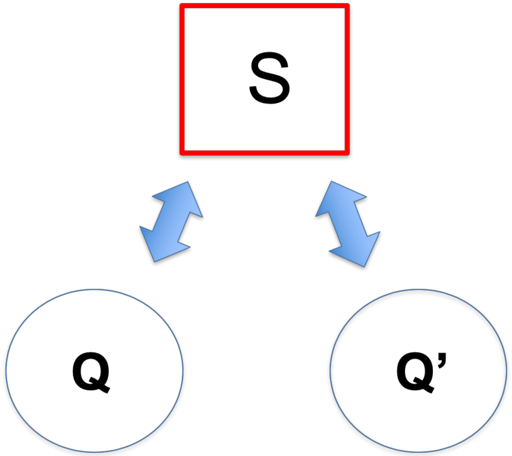
Theorem: if a non-classical system Q couples to another system S via a copy-like interaction, then S must be non-classical as well.

C. Marletto, V. Vedral, npj Quantum Information, 2016

Step two: *indirect* test of non-classicality

We use TWO quantum systems as probes to check if S is non-classical





Theorem

If **S** can locally mediate entanglement between two quantum systems **Q** and **Q’**, **S** is non-classical.

C. Marletto, V.Vedral, npj Quantum Information, 2017.
C. Marletto, V. Vedral , Phys. Rev. Lett. 119, 2017.

Two applications:

1) Entanglement-based witness of non-classicality in gravity

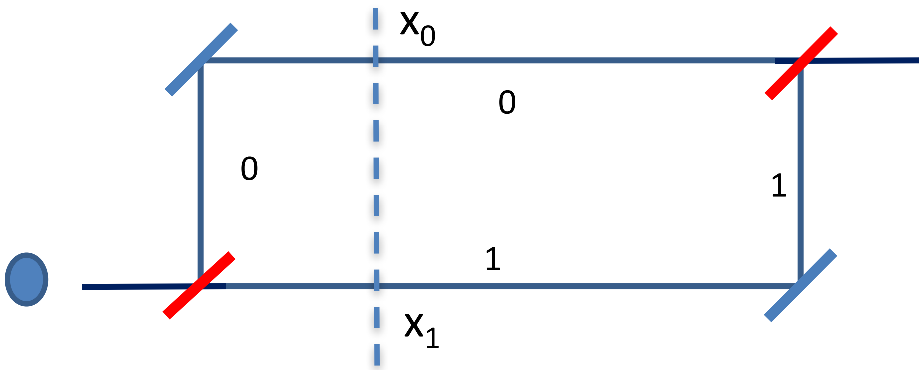
S. Bose et al., Phys. Rev. Lett. 119, (2017).
C. Marletto, V. Vedral , Phys. Rev. Lett. 119, (2017).

2) A local model for the AB effect.

C. Marletto, V.Vedral , arxiv1906.03440

Are all phases locally acquired?

Example: interference in a background field

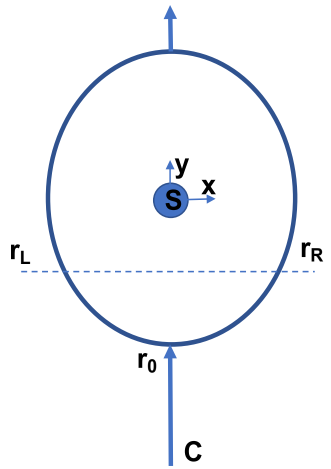


$$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \rightarrow \frac{1}{\sqrt{2}}(e^{i\varphi(x_0)}|0\rangle + e^{i\varphi(x_1)}|1\rangle)$$

$$\Delta\varphi(x_0, x_1) = \varphi(x_0)\text{-}\ \varphi(x_1)$$

The phase difference at each point along the path has a well-defined value, because it is generated by the local action of the field. It is in principle measurable.

The AB effect: the traditional account



$$\varphi_{AB} = \frac{q}{\hbar}\oint A \cdot dl = = \frac{q}{\hbar} B_0 S$$

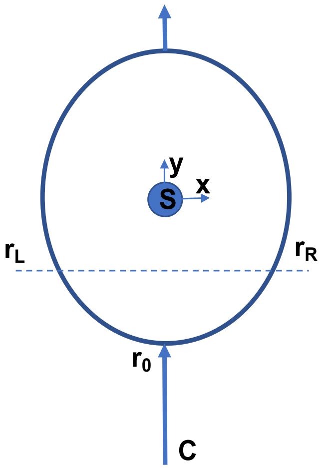
- The phase φ_{AB} observed when closing the interference loop can be accounted for only by local action of the the vector potential on the charge along the path.

- The phase difference $\Delta\varphi(r_R, rL)$ between two points is unobservable.

$$\Delta\varphi(r_R, rL) = \frac{q}{\hbar}\left(\int_{r_0}^{r_L} A \cdot dl - \int_{r_0}^{r_R} A \cdot dl\right)$$

Y. Aharonov, and D. Bohm, *Phys. Rev.* **115,** 485, 1959.
Y. Aharonov, E. Cohen, and D. Rohrlich, Phys. Rev. A, 93, 4, 2016.

Vaidman's idea for a field-based explanation



- The AB phase is in fact due to the interaction between the magnetic field B_S of the solenoid and the magnetic field of the charge B_c *at the solenoid's point.*
- Entanglement between S and Q is needed to mediate the effect

(L. Vaidman, *Phys. Rev. A* **86,** 040101, 2012.)

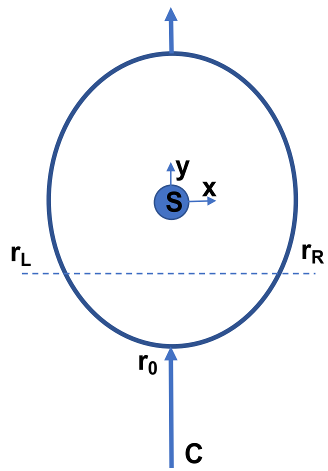
- The value of the phase difference when the charge has not yet closed the loop is a gauge-invariant quantity, in principle detectable.

$$\Delta\varphi(r_R, r_L) = \frac{\mathcal{E}t}{\hbar}$$

$$\mathcal{E} = \frac{1}{2}\int_V \left(\frac{\mathbf{B_s}\mathbf{B_c}}{\mu_0} + \epsilon_0\mathbf{E_s}\mathbf{E_c}\right)\mathrm{d}^3r$$

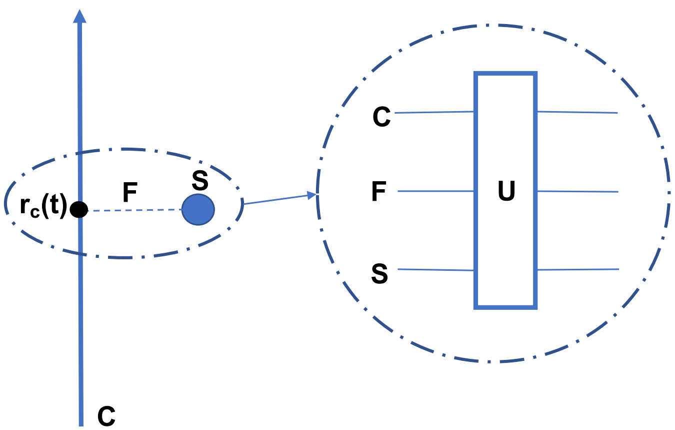
(K. Kang, Journal of the Korean Physical Society, 71, 9, 2017.
M. Kim, K. Kang, N. J. Phys, 20, 2018.)

...But what about locality?

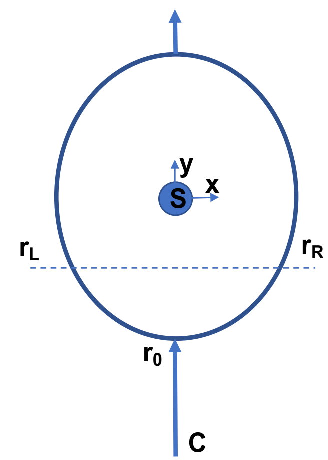


The field-based semiclassical model for the AB phase generation is still non-local: how do the charge's observables come to depend on the phase, if the latter is generated locally at the solenoid through the field-field interaction?

For a local account of the AB phase generation via fields, we need to quantise the mediating field.



$$
\begin{aligned}
H_{AB} &= E_C q_z^{(C)} + E_S q_z^{(S)} + \sum_k \hbar\omega_k a_k^\dagger a_k \\
&+ \sum_k \hbar C_k q_z^{(C)} (a_k e^{i\mathbf{k}\mathbf{r_c}} + a_k^\dagger e^{-i\mathbf{k}\mathbf{r_c}}) \\
&+ \sum_k \hbar G_k q_z^{(S)} (a_k e^{i\mathbf{k}\mathbf{r_s}} + a_k^\dagger e^{-i\mathbf{k}\mathbf{r_s}})
\end{aligned}
$$



C. Marletto, V. Vedral , arxiv1906.03440

AB local quantum model and experimental consequences

- By using local tomography on each of the charge's paths it is possible to measure how the phase difference is building up along the path, without coherently closing the interference loop. (Note issues with superselection rules.).

- If observed, this phase difference would refute the non-local, semiclassical, potential-based model.

Summary for AB phase

- The issue of whether there exists a field-only expression for the quantum theory of interacting charged and EM fields is distinct from the issue of locality of the AB phase.
- There is a fully local quantum model for the AB phase generation, and it can be tested.

Conclusion

Locality is a universal guiding principle, obeyed by all quantum phases -including the AB phase.

It is a fundamental basis to construct future theories of physics that go beyond quantum theory.