Energy level shift of quantum systems via the electric Aharonov-Bohm effect

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Energy-level shift of quantum systems via the scalar electric Aharonov-Bohm effect

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Abstract: A version of the electric Aharonov-Bohm effect is proposed where the quantum system which picks up the Aharonov-Bohm phase is confined to a Faraday cage with a time-varying spatially uniform scalar potential. The electric and magnetic fields in this region are effectively zero for the entire period of the experiment. The observable consequence of this version of the electric Aharonov-Bohmn effect is to shift the energy levels of the quantum system rather than shift the fringes of the two-slit interference pattern. We show a strong mathematical connection between this version of the scalar electric AB effect and the ac Stark effect.

Aharonov-Bohm (AB) Effect: Geometric or Berry Phase

THE PHYSICAL REVIEW

Second Series, Vol. 115, No. 3 — AUGUST 1, 1959

Significance of Electromagnetic Potentials in the Quantum Theory

Y. Aharonov and D. Bohm

Scalar Potential Effect (Electric) — Vector Potential Effect (Magnetic)

486 Y. AHARONOV AND D. BOHM

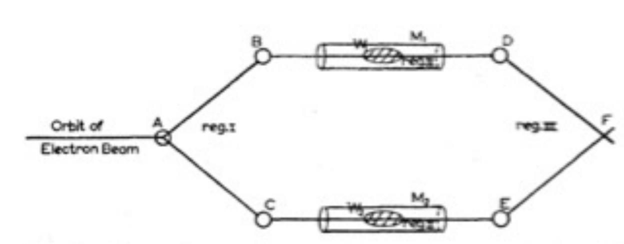


FIG. 1. Schematic experiment to demonstrate interference with time-dependent scalar potential. *A, B, C, D, E*: suitable devices to separate and divert beams. W_1, W_2: wave packets. M_1, M_2: cylindrical metal tubes. *F*: interference region.

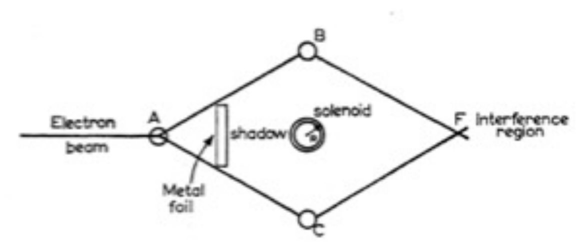


FIG. 2. Schematic experiment to demonstrate interference with time-independent vector potential.

Static AB phase: Vector Magnetic AB Effect

$$\phi_{B_{AB}} = \frac{q}{\hbar}\oint_{\mathcal{P}} \mathbf{A}\cdot d\mathbf{l} = \frac{q}{\hbar}\int_S \nabla\times\mathbf{A}\cdot d\mathbf{S} = \frac{q}{\hbar}\int_S \mathbf{B}\cdot d\mathbf{S}$$

$$\int_S \mathbf{B}\cdot d\mathbf{S} = n\Phi_0$$

for a superconducting system with n Cooper pairs (q=2e)

$= 2n\Phi_0$

normal conductor with free electrons (q=e)

$$\phi_{B_{AB}} = 2n\pi$$

Time dependent AB phase: Scalar Electric AB effect

$$\varphi_E(t) = \frac{e}{\hbar}\int V(t)dt \qquad \mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t} = 0$$

Magnetic Vector AB Effect Verified Experimentally

VOLUME 5, NUMBER 1 — PHYSICAL REVIEW LETTERS — JULY 1, 1960

SHIFT OF AN ELECTRON INTERFERENCE PATTERN BY ENCLOSED MAGNETIC FLUX

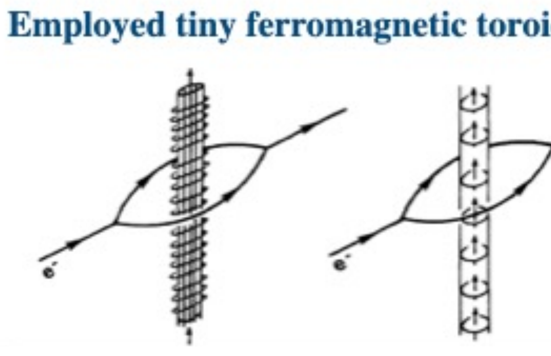
R. G. Chambers
H. H. Wills Physics Laboratory, University of Bristol, Bristol, England
(Received May 27, 1960)

VOLUME 56, NUMBER 8 — PHYSICAL REVIEW LETTERS — 24 FEBRUARY 1986

Evidence for Aharonov-Bohm Effect with Magnetic Field Completely Shielded from Electron Wave

Akira Tonomura, Nobuyuki Osakabe, Tsuyoshi Matsuda, Takeshi Kawasaki, and Junji Endo
Advanced Research Laboratory, Hitachi Ltd., Kokubunji, Tokyo 185, Japan
and
Shinichiro Yano and Hiroji Yamada
Central Research Laboratory, Hitachi, Ltd., Kokubunji, Tokyo 185, Japan
(Received 4 December 1985)

Employed tiny ferromagnetic toroids -> May observe AB effect with solenoid or magnet



DMP Short Course on Magnetic Topological Materials
All Ferromagnets are Topological !

Scalar Effects

PHYSICAL REVIEW A — VOLUME 48, NUMBER 3 — SEPTEMBER 1993

Observation of the scalar Aharonov-Bohm effect by neutron interferometry

B. E. Allman, A. Cimmino, A. G. Klein, and G. I. Opat
School of Physics, University of Melbourne, Parkville, Victoria 3052, Australia
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(Received 12 March 1993)

performed an analogous experiment to the original scalar AB effect

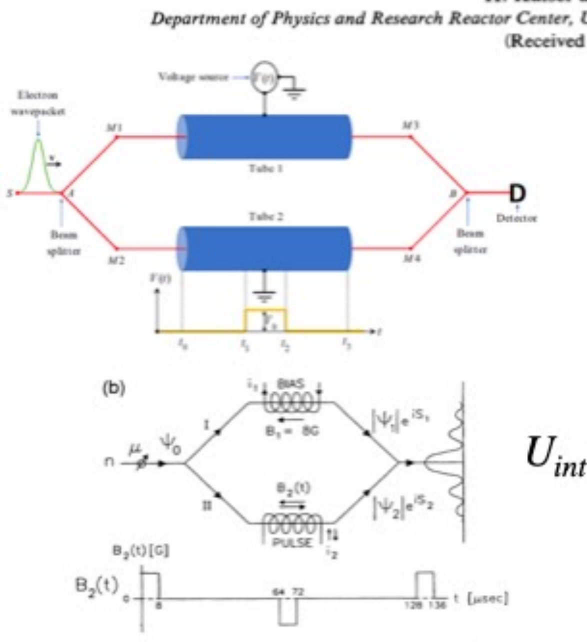


FIG. 2. Schematic diagram of (a) the scalar Aharonov-Bohm experiment for electrons and (b) the scalar Aharonov-Bohm experiment with neutrons. The wave forms of the applied pulses are also shown.

$$U_{int} = qV(t)$$

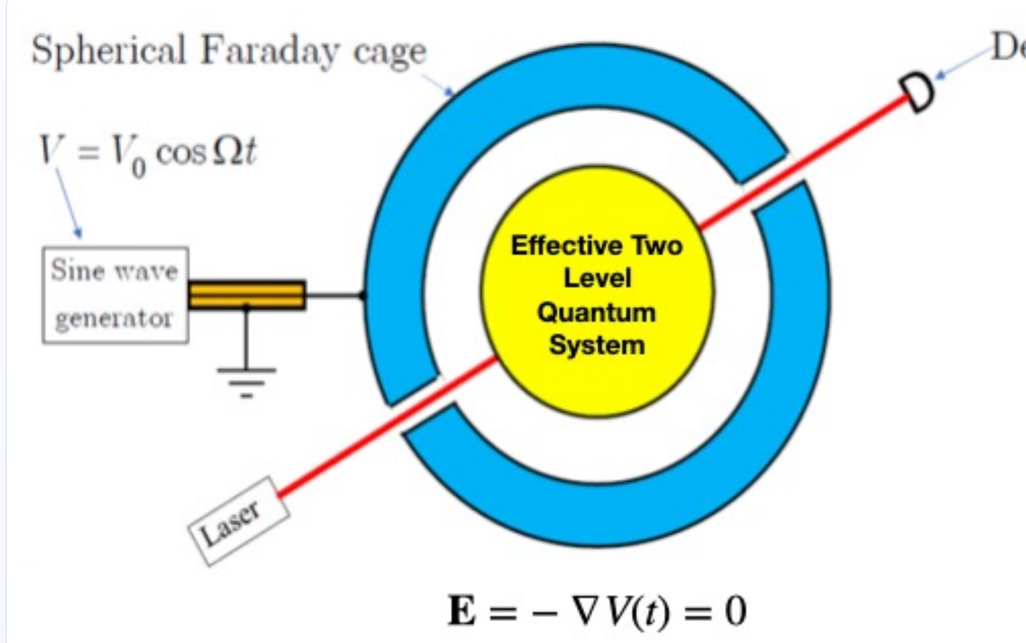
This Experiment has received little attention

To be undertaken cleanly should be in the Absence of fields -> only scalar potential

$$U_{int} = -\mu\cdot\mathbf{B}(t)$$

Note for an electric dipole Could do dual experiment $U_{int} = -\mathbf{d}\cdot\mathbf{E}(t)$

These effects are scalar, but do not show an effect independent of fields as they are proportional to the fields! Similar to the AC vector experiments



$$\mathbf{E} = -\nabla V(t) = 0$$

- We put a quantum system under a time varying, spatially uniform potential, $V(t)$.
- Original proposal had two different static fields.

Possible Systems

- Atom valence electrons
- Ion
- Quantum Dot
- Charge/Transmon Qubit

Scalar Electric AB Effect

Time-independent Schrödinger equation

$$H_0\Psi_i(\mathbf{r}) = E_i\Psi_i(\mathbf{r})$$

Perturbed Hamiltonian

$$H = H_0 + eV(t)$$

$$V(t) = 0 \quad \text{for } t < 0$$
$$V(t) = V_0\cos\Omega t \quad \text{for } t \geq 0$$

Time-dependent Schrödinger equation for this new system

$$i\hbar\frac{\partial\psi}{\partial t} = H\psi = \left(H_0 + eV(t)\right)\psi$$

Solve using Separation of Variables

$$\psi(\mathbf{r},t) = X(\mathbf{r})T(t)$$

Solution

$$\psi_i(\mathbf{r},t) = \Psi_i(\mathbf{r})\exp\left(-\frac{iE_it}{\hbar} - i\varphi(t)\right)$$

Phase Evolution

$$\varphi(t) = \frac{e}{\hbar}\int V(t)dt = \alpha\sin\Omega t$$

Phase Modulation parameter

$$\alpha = \frac{eV_0}{\hbar\Omega}$$

Jacobi-Anger expansion

$$\psi_i(\mathbf{r},t) = \Psi_i(\mathbf{r})\sum_{n=-\infty}^{\infty}(-1)^nJ_n(\alpha)\exp(in\Omega t)\exp\left(-\frac{iE_it}{\hbar}\right) = \Psi_i(\mathbf{r})\sum_{n=-\infty}^{\infty}(-1)^nJ_n(\alpha)\exp\left(-\frac{i\left(E_i - n\hbar\Omega\right)t}{\hbar}\right)$$

- Show a strong mathematical connection between this version of the scalar electric AB effect and the AC Stark effect

$$E_i^{(n)} = E_i \pm n\hbar\Omega \qquad n_{max} \approx \alpha = eV_0/\hbar\Omega \qquad E_i^{(n_{max})} = E_i \pm eV_0$$

- Splitting of energy levels - Scalar AB effect - Almost mathematically identical to the Autler-Townes effect or AC Stark effect
- Only linear with amplitude, Stark Effect has quadratic term as well

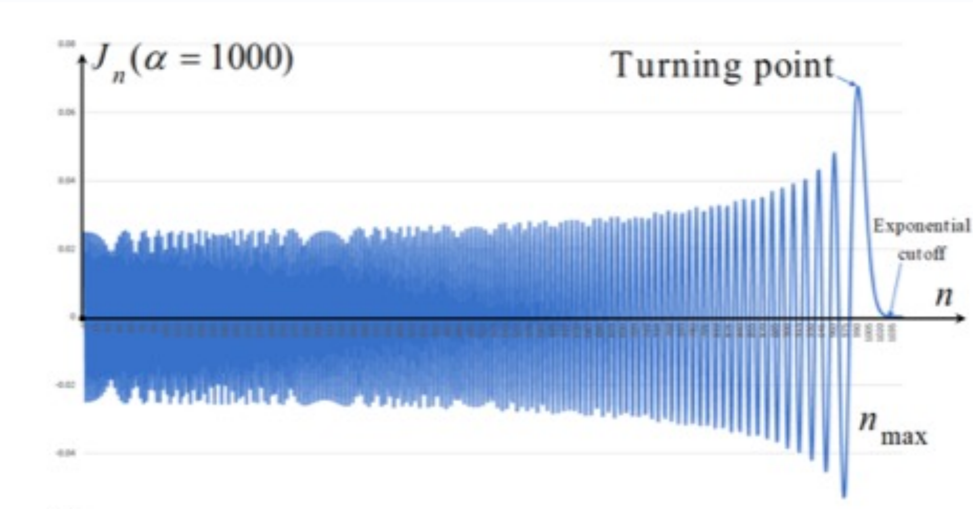


FIG. 3. A plot of $J_n(\alpha)$ vs. n for the case when $\alpha = 1000$. There are sidebands in the energy $E_i^{(n)}$ which occurs up to some maximum index n given by $n_{max} \approx \alpha$. From the plot one can see that the weighting, $J_n(\alpha)$, is largest when $n = n_{max} \approx \alpha$ and it is this state which contributes the most.

Search for level splittings proportional to the applied potential

$$\omega_i^{(n_{max})} = \omega_i \pm \frac{eV_0}{\hbar} = \omega_i \pm \alpha\Omega$$

SUMMARY

- Energy level sidebands can be probed via absorption spectroscopy
- Dominant energy sidebands occur for $n = n_{max} \approx \alpha$, gives level splittings proportional to applied potential
- Mathematically identical to the AC Stark/Autler-Townes effect, Physically very different!
- Big difference, scalar electric AB effect has no quadratic term
- Can show energy side bands are gauge invariant
- Cleaner than the original proposal due to periodic in time (chopping experiment), and no fields

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PHYSICAL REVIEW A 107, 042209 (2023)

arXiv:2212.03437 [quant-ph]