Exotic path effect in interference experiment with matter waves

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Departamento de Física - FCTUC
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Summary

1. Born’s Rule Violation versus Exotic Looped Trajectory
2. Gouy phase and Exotic Looped Trajectory
3. Exotic Looped Trajectory and Fringe Visibility
4. Exotic Looped Trajectory Via Quantum Markin

Overview

- Higher-order interference and Born's rule violation in a triple-slit experiment. U. Sinha et. al., Science **329**, 418 (2010)

  $P_{AB} = |\psi_A + \psi_B|^2 = P_A + P_B + I_{AB}$

  $P_{ABC}^{Born} = |\psi_A + \psi_B + \psi_C|^2 = P_A + P_B + P_C + I_{AB} + I_{AC} + I_{BC}$

- Born's rule violation and Sorkin parameter

  $\kappa = P_{ABC} - P_{ABC}^{Born}$

  R. D. Sorkin, Mod. Phys. Lett. A **09**, 3119 (1994)

- Maybe the Born's rule is not violated. There is exotic path (non-classical path)

  $\psi = \psi_A + \psi_B + \psi_C + \psi_{A,B} + \psi_{A,C} + \psi_{B,A} + \psi_{B,C} + \psi_{C,A} + \psi_{C,B}$ (A, B, C open)

  $\psi = \psi_A + \psi_B + \psi_{A,B} + \psi_{B,A}$ (A, B open)

  $\psi = \psi_A$ (A open)

  $\kappa = P_{ABC}^{T} - P_{ABC}$

  $\kappa \approx 2Re[\psi_A^*(\psi_{B,C} + \psi_{C,B}) + \psi_B^*(\psi_{A,C} + \psi_{C,A}) + \psi_C^*(\psi_{A,B} + \psi_{B,A})]$

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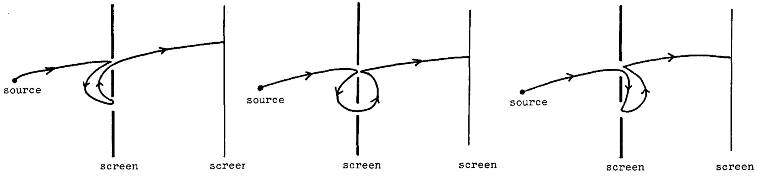
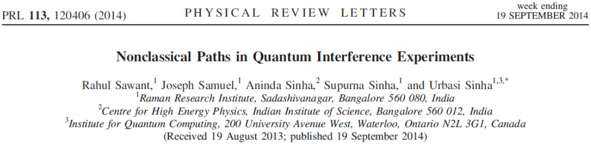
Born’s Rule Violation versus Exotic Looped Trajectory

- H. Yabuki, Int. J. Theor. Ph. **25**, 159 (1986)




PRL **113,** 120406 (2014) PHYSICAL REVIEW LETTERS week ending 19 SEPTEMBER 2014

Nonclassical Paths in Quantum Interference Experiments

Rahul Sawant,[1] Joseph Samuel,[1] Aninda Sinha,[2] Supurna Sinha,[1] and Urbasi Sinha[1,3,*]
[1]*Raman Research Institute, Sadashivanagar, Bangalore 560 080, India*
[2]*Centre for High Energy Physics, Indian Institute of Science, Bangalore 560 012, India*
[3]*Institute for Quantum Computing, 200 University Avenue West, Waterloo, Ontario N2L 3G1, Canada*
(Received 19 August 2013; published 19 September 2014)


SCIENTIFIC REPORTS

OPEN **On the superposition principle in interference experiments**

Aninda Sinha[1], Aravind H. Vijay[1,2] & Urbasi Sinha[2,3]

Born's Rule Violation versus Exotic Looped Trajectory

- We confirm the validity of Born's rule and present the first experimental observation of exotic trajectories as additional paths for the light by directly measuring their contribution to the formation of optical interference fringes

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Exotic looped trajectories of photons in three-slit interference

Omar S. Magaña-Loaiza[1,*], Israel De Leon[2,3,*], Mohammad Mirhosseini[1], Robert Fickler[3], Akbar Safari[3], Uwe Mick[4], Brian McIntyre[1], Peter Banzer[3,4], Brandon Rodenburg[5], Gerd Leuchs[3,4] & Robert W. Boyd[1,3]

- An alternative parameter to quantify the Born rule violation [J. Quach, Phys. Rev. A 95 (2017) 042129]

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\begin{aligned}
P_{AB} &= |\psi_A + \psi_B + \psi_{AB}|^2 \\
P_{D_A} &= |\psi_A + \psi_{AB}|^2 + |\psi_B|^2 \\
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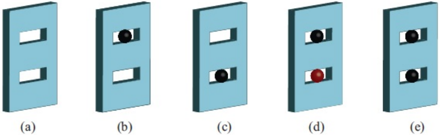

- $\mathcal{I}_{AB} = P_{AB} - P_{D_A} - P_{D_B} - P_{D_{AB}} + 2P_{D_A,D_B}$

-

  Interference on a single spin in solids by F. Jin et. al., Phys. Rev. A **95**, 012107 (2017)

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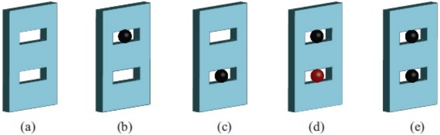

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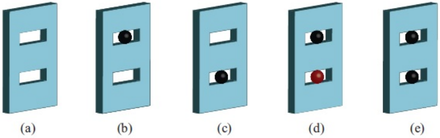

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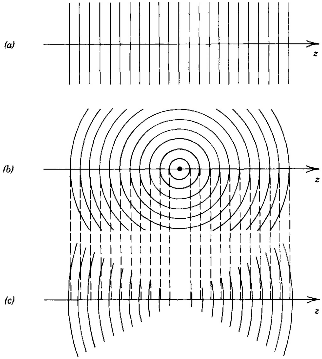
Gouy phase

When a wave light is focused, it acquires a phase equal to $\pi/2$ for cylindrical waves (line focus), and π for spherical waves (point focus) [L. G. Gouy (1890)]



B. E. A. Saleh, and M. C. Teich, *Fundamentals of Photonics* p. 86 (John Wiley Sons, New York, 1991)

- Gouy phase and matter waves (I. G. da Paz et al. Journal of Physics. Conference Series, 2007)
- Indirect evidence for the Gouy phase of matter waves (I. G. da Paz et al. Physics Letters. A, 2010)
- Experimental proposal to measure the Gouy of matter waves (I. G. da Paz et al. New Journal of Physics, 2011)
- Visibility and Gouy phase in the double-slit experiment (I. G. da Paz et al. Annals of Physics, 2015)
- Gouy phase for relativistic quantum particles (I. G. da Paz et al. Phys Rev A, 2015)
- Poisson's Spot and Gouy phase (I. G. da Paz et al. Phys Rev A, 2016)
- Gouy phase in nonclassical path interference experiment (I. G. da Paz et al. Phys Rev A, 2016)

Exotic Trajectory in a Triple Slit Experiment

PHYSICAL REVIEW A **93**, 033621 (2016)

Gouy phase in nonclassical paths in a triple-slit interference experiment

I. G. da Paz,[1] C. H. S. Vieira,[1] R. Ducharme,[2] L. A. Cabral,[3] H. Alexander,[4] and M. D. R. Sampaio[4]
[1]*Departamento de Física, Universidade Federal do Piauí, Campus Ministro Petrônio Portela, CEP 64049-550, Teresina, Piauí, Brazil*
[2]*2112 Oakmeadow Place, Bedford, Texas 76021, USA*
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[4]*Departamento de Física, Instituto de Ciências Exatas, Universidade Federal de Minas Gerais, Caixa Postal 702, CEP 30161-970, Belo Horizonte, Minas Gerais, Brazil*

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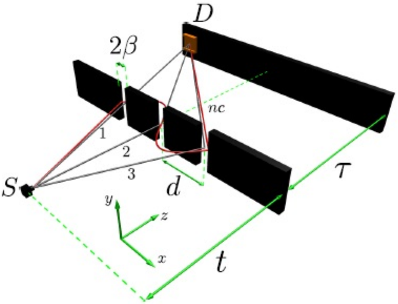


After some algebraic manipulations the wave functions corresponding to the classical and non-classical paths are given by

$$\psi_1(x,t,\tau) = A\exp(-C_1x^2 - C_2x + C_3) \times \exp(i\alpha x^2 - i\gamma x - i\theta_c + i\mu_c),$$

$$\psi_2(x,t,\tau) = A\exp(-C_1x^2)\exp(i\alpha x^2 + i\mu_c),$$

$$\psi_3(x,t,\tau) = A\exp(-C_1x^2 + C_2x + C_3) \times \exp(i\alpha x^2 + i\gamma x - i\theta_c + i\mu_c),$$

and

$$\psi_{nc}(x,t,\tau) = A_{nc}\exp(-C_{1nc}x^2 + C_{2nc}x + C_{3nc}) \times \exp\left(i\alpha_{nc}x^2 + i\gamma_{nc}x - i\theta_{nc} + i\mu_{nc}\right).$$

Sorkin parameter

The intensity at the screen including non-classical path reads

$$\begin{aligned} I_T &= |\psi_1 + \psi_2 + \psi_3 + \psi_{nc}|^2 \\ &= I_c + |\psi_{nc}|^2 + 2|\psi_1||\psi_{nc}|\cos\phi_{1nc} \\ &+ 2|\psi_2||\psi_{nc}|\cos\phi_{2nc} + 2|\psi_3||\psi_{nc}|\cos\phi_{3nc}, \end{aligned}$$

where

$$\phi_{1nc} = (\alpha - \alpha_{nc})x^2 - (\gamma + \gamma_{nc})x - (\theta_c - \theta_{nc}) + (\mu_c - \mu_{nc}),$$

$$\phi_{2nc} = (\alpha - \alpha_{nc})x^2 - \gamma_{nc}x + \theta_{nc} + (\mu_c - \mu_{nc}),$$

and

$$\phi_{3nc} = (\alpha - \alpha_{nc})x^2 + (\gamma - \gamma_{nc})x - (\theta_c - \theta_{nc}) + (\mu_c - \mu_{nc})$$

$$\begin{aligned}\kappa I_0 &= I_T - I_c \\ &= |\psi_{nc}|^2 + 2|\psi_1||\psi_{nc}|\cos\phi_{1nc} \\ &+ 2|\psi_2||\psi_{nc}|\cos\phi_{2nc} + 2|\psi_3||\psi_{nc}|\cos\phi_{3nc},\end{aligned}$$

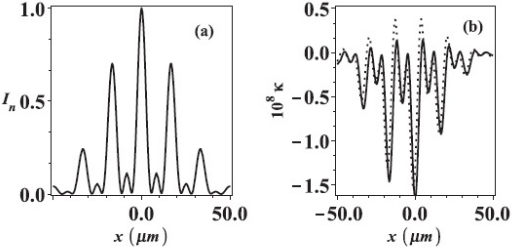
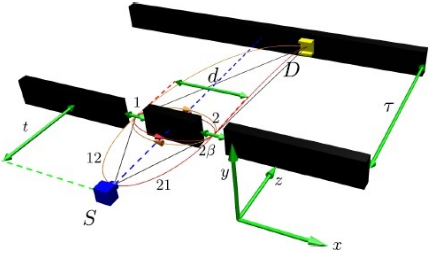


Figure: (a) Normalized intensity and (b) Sorkin parameter for electron wave.

Electron parameters: $\lambda \approx 50\ \mathrm{pm}$ ($v_z \approx 1.46 \times 10^7\ \mathrm{m/s}$), $m = 9.11 \times 10^{-31}\ \mathrm{kg}$, $d = 650\ \mathrm{nm}$, $\beta = 62\ \mathrm{nm}$, $\sigma_0 = 62\ \mathrm{nm}$, $t = 18\ \mathrm{ns}$ ($z_t \approx 26.3\ \mathrm{cm}$) and $\tau = 15\ \mathrm{ns}$ ($z_\tau \approx 21.9\ \mathrm{cm}$).

Double Slit Experiment



The total intensity is given by

$$I_T = |\psi_1 + \psi_2 + \psi_{\text{et12}} + \psi_{\text{et21}}|^2$$

The relative intensity is defined by

$$I_r(x,t,\tau) = \frac{I_T(x,t,\tau)}{F(x,t,\tau)},$$

where

$$F(x,t,\tau) = |\psi_1|^2 + |\psi_2|^2 + |\psi_{\text{et12}}|^2 + |\psi_{\text{et21}}|^2 .$$

Fringe Visibility and Sorkin Parameter

At the position $x = 0$ the relative intensity can be written as*

$$I_r(0,t,\tau) \approx 2\{1 + \mathcal{V}_{\mathrm{et}}(0,t,\tau)\cos[\theta_{\mathrm{et}} + \mu_{\mathrm{et}} - (\theta + \mu)]\},$$

where

$$\mathcal{V}_{\mathrm{et}}(0,t,\tau) \approx \frac{2|\psi_{\mathrm{et}12}(0,t,\tau)|}{|\psi_1(0,t,\tau)|}.$$

We can also show that

$$\kappa \approx \mathcal{V}_{\mathrm{et}}(0,t,\tau)\cos[\theta_{\mathrm{et}} + \mu_{\mathrm{et}} - (\theta + \mu)].$$

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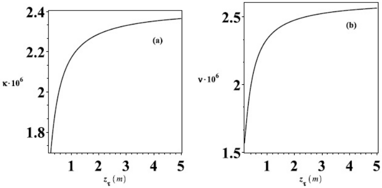
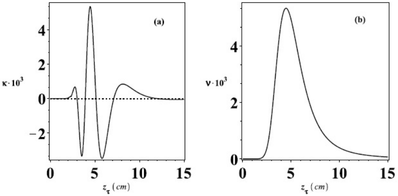
* A. Bramon, G. Garbarino, and B. C. Hiesmayr, Phys. Rev. A, **69**, 022112 (2004).

Fringe Visibility and Sorkin Parameter

Neutron parameters in the Fraunhoffer regime: $m = 1.67 \times 10^{-27}$ kg, $\sigma_0 = 7.0\ \mu$m, $d = 125\ \mu$m, $\beta = 7.0\ \mu$m, $z_t = 5.0$ m, $z_\tau = 5.0$ m and $\lambda = 2$ nm. The Fresnel number for these parameters is $\mathcal{F} = \beta^2/z_\tau\lambda \approx 0.0049$



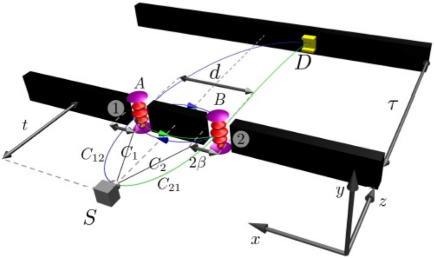
Neutron parameters in the Fresnel regime: $d = 240\ \mu$m, $\beta = 6.0\ \mu$m, $z_\tau = 5.0$ cm and $\lambda = 10$ nm. The Fresnel number for these parameters is $\mathcal{F} = \beta^2/z_\tau\lambda \approx 0.072$

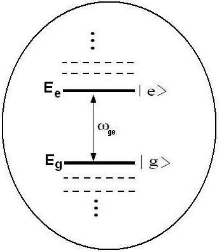


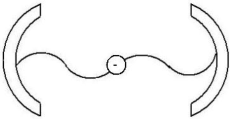
$$\mathcal{V}_T = \frac{I_T^{max} - I_T^{min}}{I_T^{max} + I_T^{min}}$$

$$\mathcal{V}_{et} = 1 - \mathcal{V}_T$$

Interference of only wavefunctions for exotic looped trajectories







The full composite system state at the screen immediately before detection is given by

$$|\Psi\rangle = a_1|\psi_1\rangle \otimes |g\rangle \otimes |10\rangle + a_2|\psi_2\rangle \otimes |g\rangle \otimes |01\rangle$$
$$-a_{12}|\psi_{12}\rangle \otimes |e\rangle \otimes |00\rangle - a_{21}|\psi_{21}\rangle \otimes |e\rangle \otimes |00\rangle \, ,$$

where $|a_1|^2 + |a_2|^2 + |a_{12}|^2 + |a_{21}|^2 = 1$.
If the atom is found in the ground state we get

$$|\Psi\rangle \rightarrow |\Psi\rangle_g = \frac{(a_1|\psi_1\rangle|10\rangle + a_2|\psi_2\rangle|01\rangle) \otimes |g\rangle}{r},$$

with probability $r = \mathrm{Tr}[|g\rangle\langle g| \cdot |\Psi\rangle\langle\Psi|]$.
If otherwise the atom is found in the excited state then, we will have

$$\Psi \rightarrow |\Psi\rangle_e = -\frac{(a_{12}|\psi_{12}\rangle + a_{21}|\psi_{21}\rangle) \otimes |00\rangle|e\rangle}{s} \, ,$$

with $s = \mathrm{Tr}[|e\rangle\langle e| \cdot |\Psi\rangle\langle\Psi|]$.

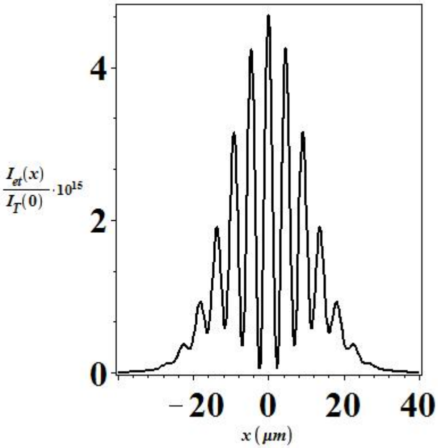
Density matrix

$$\rho_{\text{et}} \equiv \text{Tr}_c[|\Psi\rangle_{e\,e}\langle\Psi|] = \frac{1}{s^2}\Big[|a_{12}|^2|\psi_{12}\rangle\langle\psi_{12}| + |a_{21}|^2|\psi_{21}\rangle\langle\psi_{21}| + \Big(a_{12}a_{21}^*|\psi_{12}\rangle\langle\psi_{21}| + h.c.\Big)\Big],$$

The intensity just before being detected in the screen is obtained from as follows:

$$\begin{aligned} I_{\text{et}}(x,t,\tau) &= \mathcal{N}_{\text{et}}^2\Big\{|\psi_{12}(x,t,\tau)|^2 + |\psi_{21}(x,t,\tau)|^2 \\ &+ 2|\psi_{12}(x,t,\tau)\psi_{21}(x,t,\tau)|\cos(\phi_{12}^{21})\Big\} \end{aligned}$$

Rydberg atom: $m = 1.44 \times 10^{-25}$ kg, life time 30 ms $\omega_{ge} = 51.099$ GHz which is the same of the fields in cavities A and B (resonant interaction). $\lambda = 2\pi c/\omega_{ge}$, $v_z = 30m/s$ $t_i = 0.1$ ms, which corresponds to a width v_z, $t_i = 3$ mm for the field on the cavities. $\sigma_0 = 0.3$ μm, $\beta = 0.3$ μm, $d = 5$ μm, $t = 5$ ms, and $\tau = 5$ ms, $\epsilon = 2.9$ ms.



Annals of Physics ***387*** *(2017) 222*

Conclusions

- We solved exactly a one dimensional model of propagation through a triple-slit and found analytical expressions for the wavefunctions of classical and non-classical paths.
- The Gouy phase difference can not be neglected in the three-slit interference if non-classical paths are presents.
- It is possible to observe effects of non-classical paths through the deviations on the visibility for $x = 0$
- We observed that the non-classical effects can be increased to values experimentally accessible by changing some parameters of the double-slit apparatus in the Fresnel regime.
- It is possible to separate classical and non-classical effects by considering a double-slit experiment with Rubidium atoms and QED cavities.

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- The Gouy phase difference can not be neglected in the three-slit interference if non-classical paths are presents.
- It is possible to observe effects of non-classical paths through the deviations on the visibility for $x = 0$
- We observed that the non-classical effects can be increased to values experimentally accessible by changing some parameters of the double-slit apparatus in the Fresnel regime.
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