EXCITONIC AHARONOV-BOHM EFFECT IN A TWO-DIMENSIONAL QUANTUM RING

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Workshop GISC 2012

SUMMARY

- Introduction
  - Excitonic Aharonov-Bohm effect
  - Experimental work
- Theoretical model
- Results
  - Exciton energy
  - Oscillator strength
  - Wavefunctions
- Conclusions

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Work done in collaboration with
Prof. Rudolf A. Römer

THE UNIVERSITY OF WARWICK

Centre for Scientific Computing

INTRODUCTION

The Aharanov-Bohm effect

The Refractive Index in Electron Optics and the Principles of Dynamics

By W. EHRENBERG* and R. E. SIDAY†
* Birkbeck College, University of London † I.C.I. Fellow, Edinburgh University

MS. received 23rd February 1948, and in amended form 28th July 1948; read 3rd December 1948

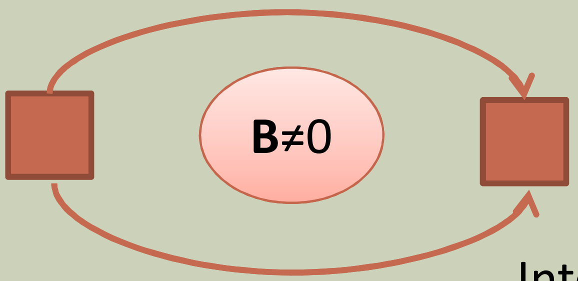
Proc. Phys. Soc. B 62 8 (1949)

Significance of Electromagnetic Potentials in the Quantum Theory

Y. Aharonov and D. Bohm
H. H. Wills Physics Laboratory, University of Bristol, Bristol, England

(Received May 28, 1959; revised manuscript received June 16, 1959)

Physical Review 115, 485-491 (1959)



Electron source

Interference and detection

$$\nabla \times \vec{A} = 0 = \vec{B}$$

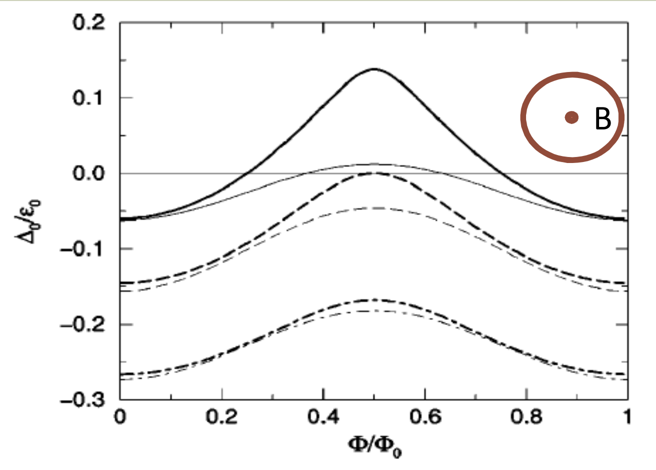
$$\oint d\vec{r}\vec{A} = \Phi$$

Phase difference $\Delta\alpha = 2\pi \frac{\Phi}{\Phi_0}$

$$\Phi_0 = h/e$$

INTRODUCTION

Excitonic Aharanov-Bohm effect



Exciton: neutral particle → no sensitive to AB effect

✓ Finite size and internal motion → It is possible!

1D ring geometry +
perpendicular solenoid magnetic field +
contact electron-hole interaction

R. A. Römer and M. E. Raikh, PRB **62**, 7045 (2000)

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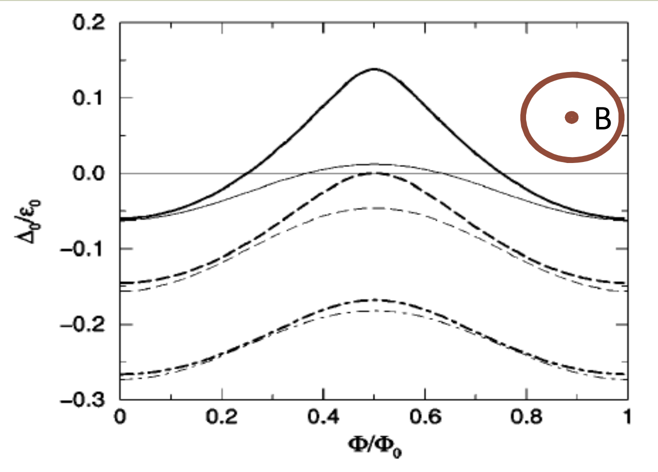

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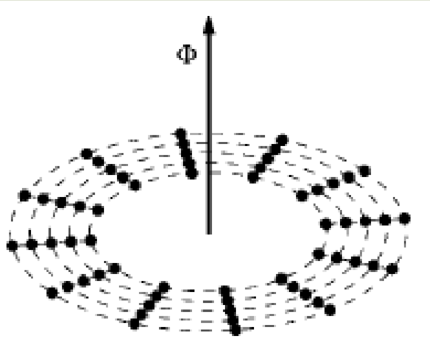
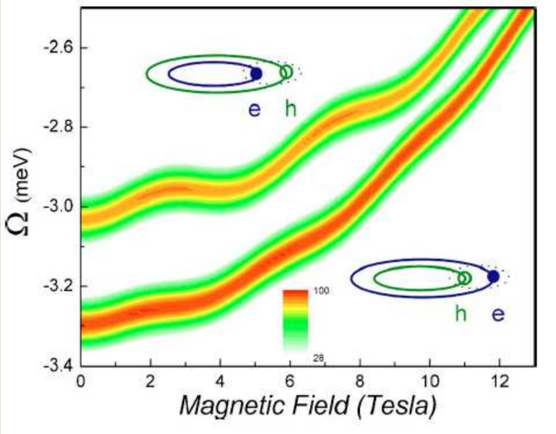
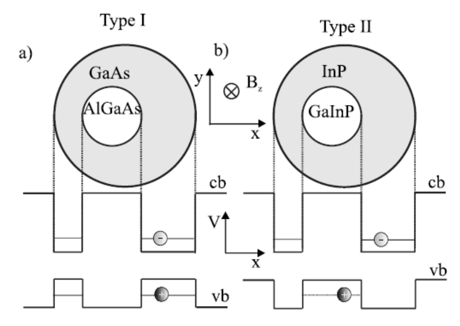
Other models:



PRB **63**, 125302 (2001)



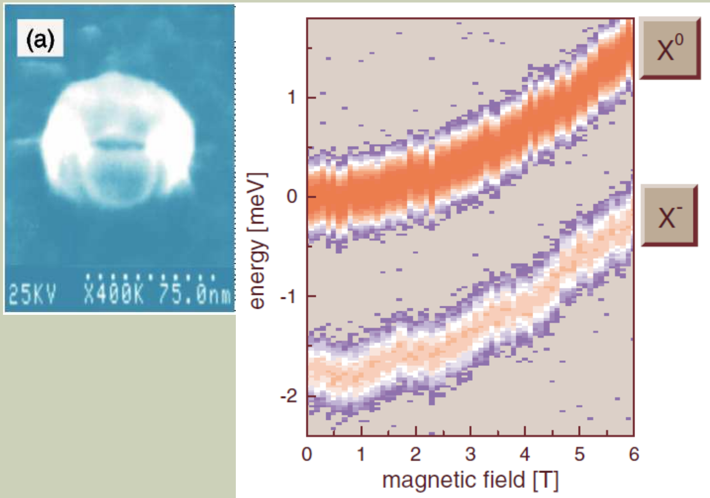
PRB **72**, 125327 (2005)



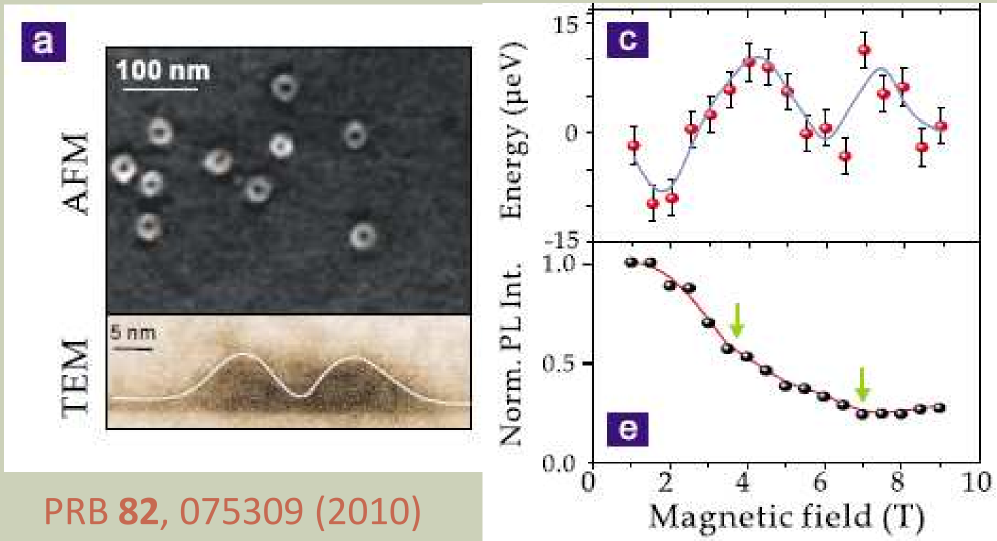
PRB **76**, 195326 (2007)

INTRODUCTION

Experimental work

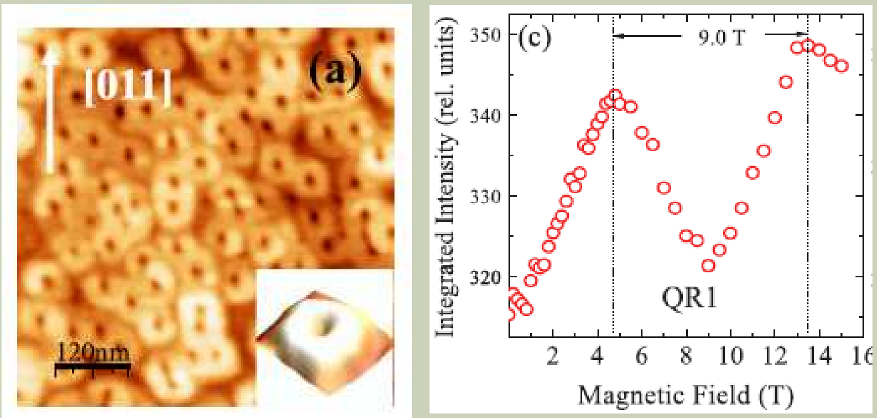


PRL **90**, 186801 (2003) Charged excitons



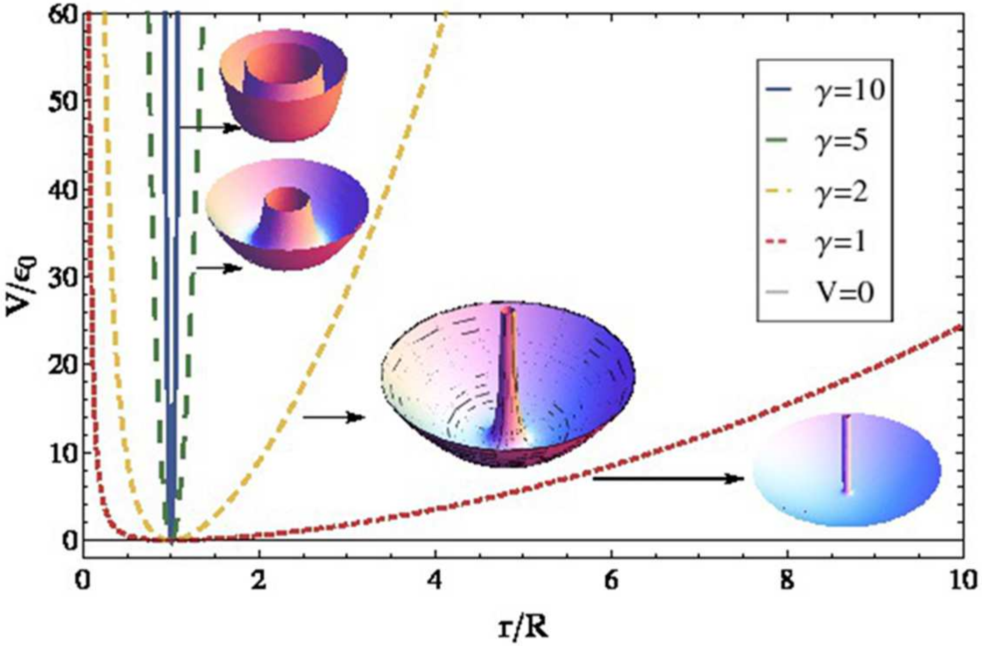
PRB **82**, 075309 (2010)

Molecular beam epitaxy of $AsBr_3$ in InGaAs QD



Self-assembled InAs/GaAs

PRL **104**, 086401 (2010)



$$V(r) = \frac{V_0}{2}\left[\frac{R^2}{r^2} + \frac{r^2}{R^2}\right] - V_0 \qquad \gamma = R/W$$

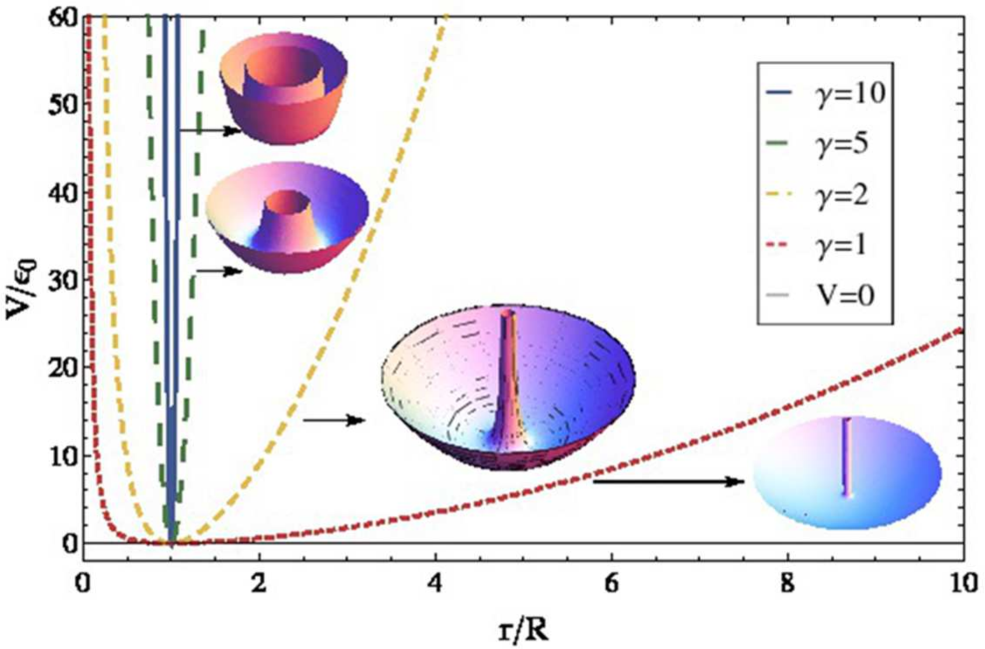
Tan W.-C. and Inkson J. C., Semicond. Sci. Technol., **11** 1635 (1996)

THEORETICAL MODEL

- Confining potential

Anharmonic, axially symmetric potential with a centrifugal core

$\gamma \to \infty$ 1D
$\gamma \to 0$ anti-dot



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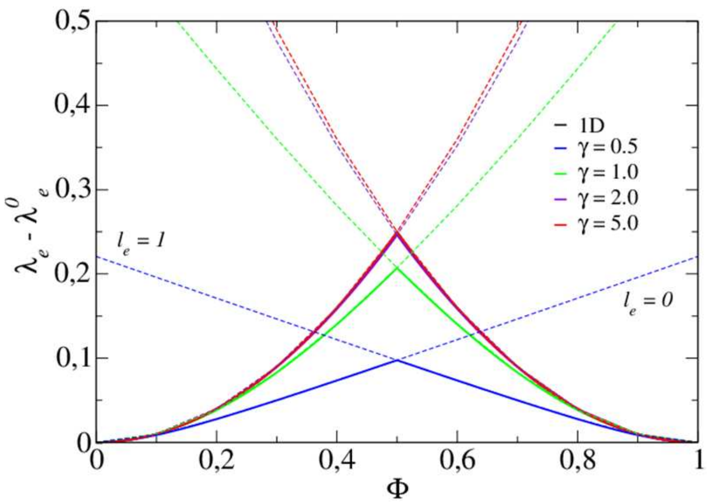


$$\psi_{M_e}(r_e) = \frac{e^{-i\ell_e\theta_e}}{\sqrt{2\pi}}\mathcal{R}_{M_e}(r_e)\ ,$$

$$\mathcal{R}_{M_e}(r_e) = \frac{1}{R}\left[\frac{\Gamma(n_e+1)}{2^{k_e}\Gamma(n_e+k_e+1)}\right]^{1/2} \times (\rho_e\gamma)^{k_e} e^{-\rho_e^2\gamma^2/4} L_{n_e}^{k_e}\left(\frac{\rho_e^2\gamma^2}{2}\right)\ ,$$

THEORETICAL MODEL

- **Confining potential**

Anharmonic, axially symmetric potential with a centrifugal core

$\gamma \rightarrow \infty$ 1D

$\gamma \rightarrow 0$ anti-dot

- **Single particle state in the QR**

THEORETICAL MODEL

- Solution of the excitonic case

$$\mathcal{H} = \mathcal{H}_e + \mathcal{H}_h + \mathcal{H}_{e-h}$$

$$G_{K'} = \sum_K G_K P_{KK'}(\Delta)$$

Values of $\Delta \rightarrow$ eigenvalue $P_{KK'}$ equal to 1

$$\mathcal{H}_{e-h}(\vec{r_e},\vec{r_h}) = (2\pi)^{3/2} v_0 RW \delta(\vec{r_e} - \vec{r_h})$$

$$v_0 = -\alpha/\pi^2$$

$$\Psi(\vec{r_e},\vec{r_h}) = \sum_{M_e M_h} A_{M_e M_h} \psi_{M_e}(\vec{r_e}\,)\,\psi_{M_h}(\vec{r_h}\,)$$

$$G_{M_e' M_h'} = \sum_{M_e M_h} G_{M_e M_h} P_{M_e M_h M_e' M_h'}(\Delta)$$

$$G_{M_e M_h} = \int d^2\,\vec{r}\Psi(\vec{r},\vec{r})\psi_{M_e}(\vec{r_e}\,)^{\dagger}\psi_{M_h}(\vec{r_h}\,)^{\dagger}$$

$$P_{M_e M_h M_e' M_h'} = -\frac{(2\pi)^{3/2} v_0 RW}{\lambda_{M_e} + \lambda_{M_h} - \Delta}$$

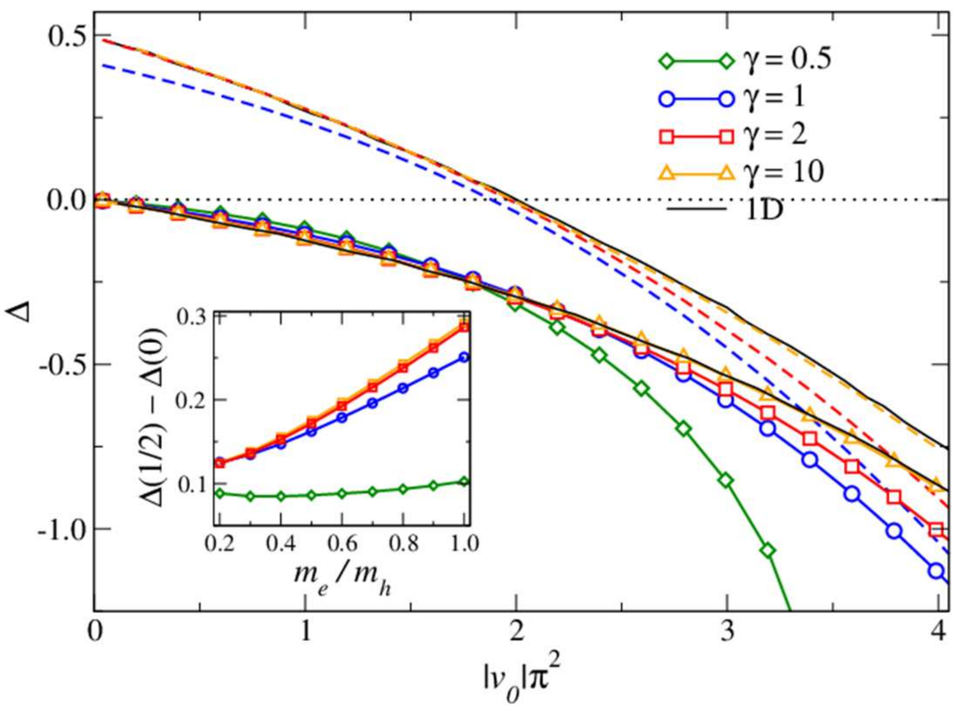
$$\times \underbrace{\int d^2\,\vec{r}\psi_{M_e}(\vec{r}\,)\psi_{M_h}(\vec{r}\,)\psi_{M_e'}(\vec{r}\,)^{\dagger}\psi_{M_h'}(\vec{r}\,)^{\dagger}}$$

Reduces to an integral over the radial coordinates

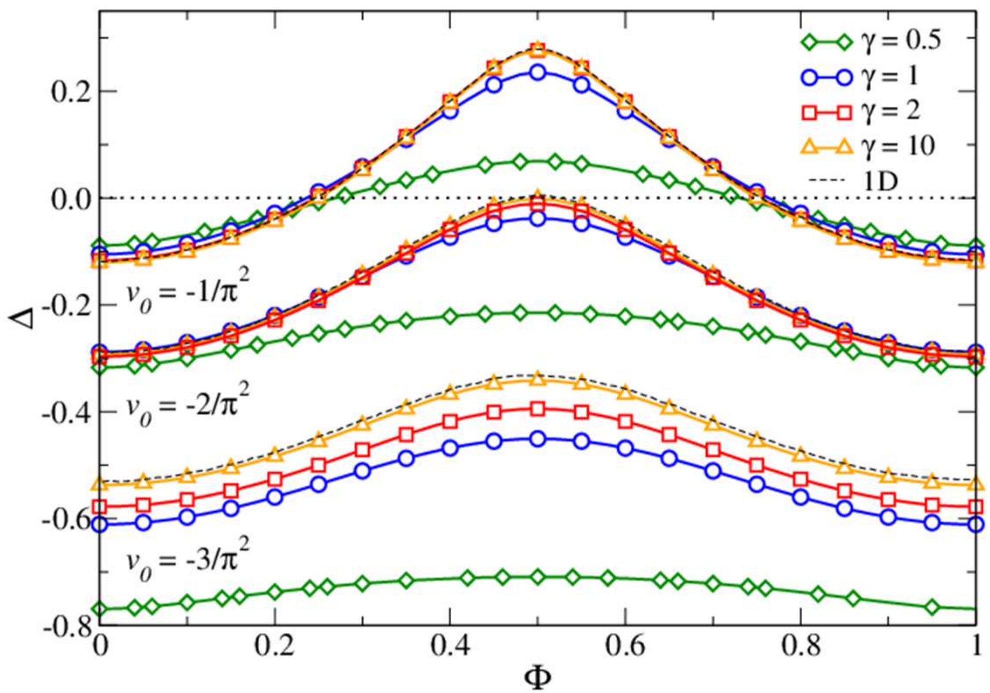
$$L = \ell_e + \ell_h = \mathrm{L}' = 0$$

Dipole approximation

Exciton ground state energy



vs Interaction strength



vs Magnetic flux

RESULTS

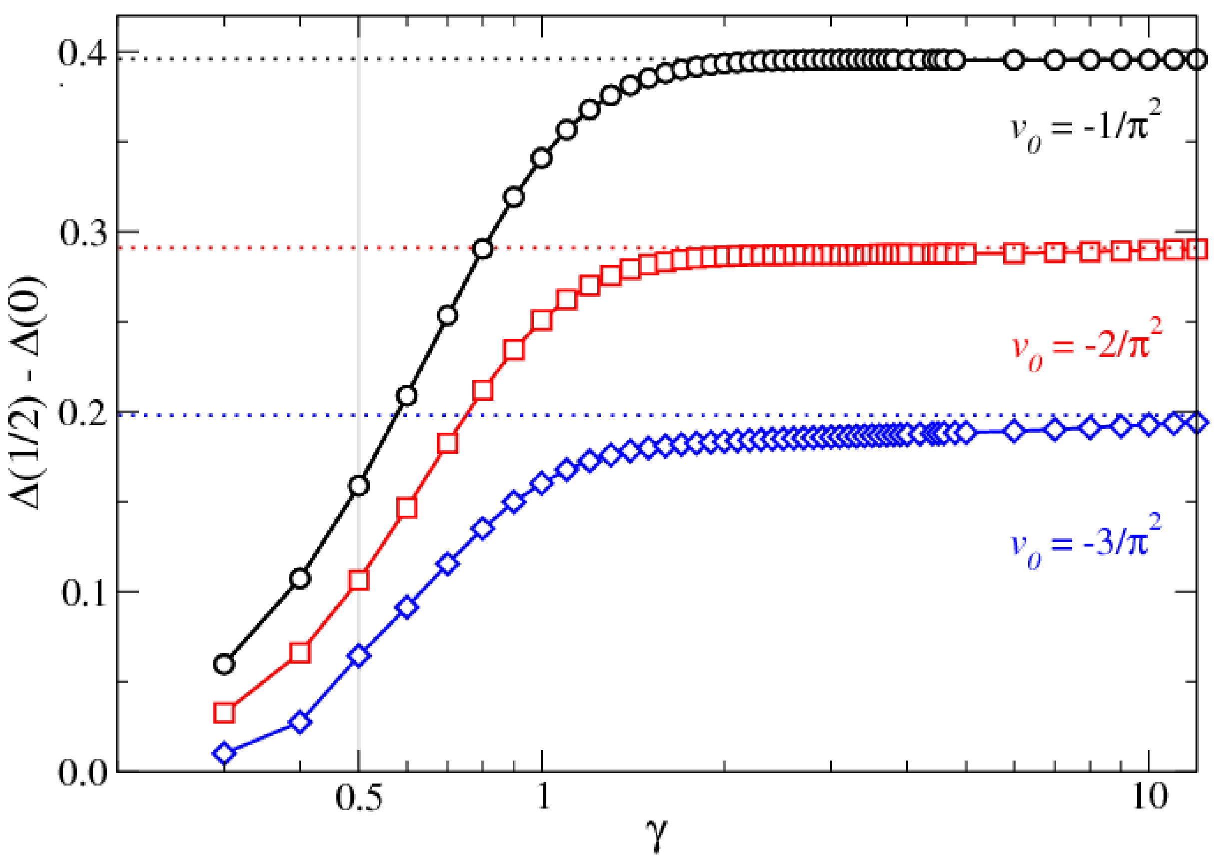
Excitons in 2D QR are also sensitive to magnetic flux

- For γ = 10:

2D behaviour similar to 1D

- AB oscillations retained from γ=0.5 to 10
- Different masses do not destroy the effect

Amplitude Aharanov-Bohm oscillations as a function of radius-to-width ratio



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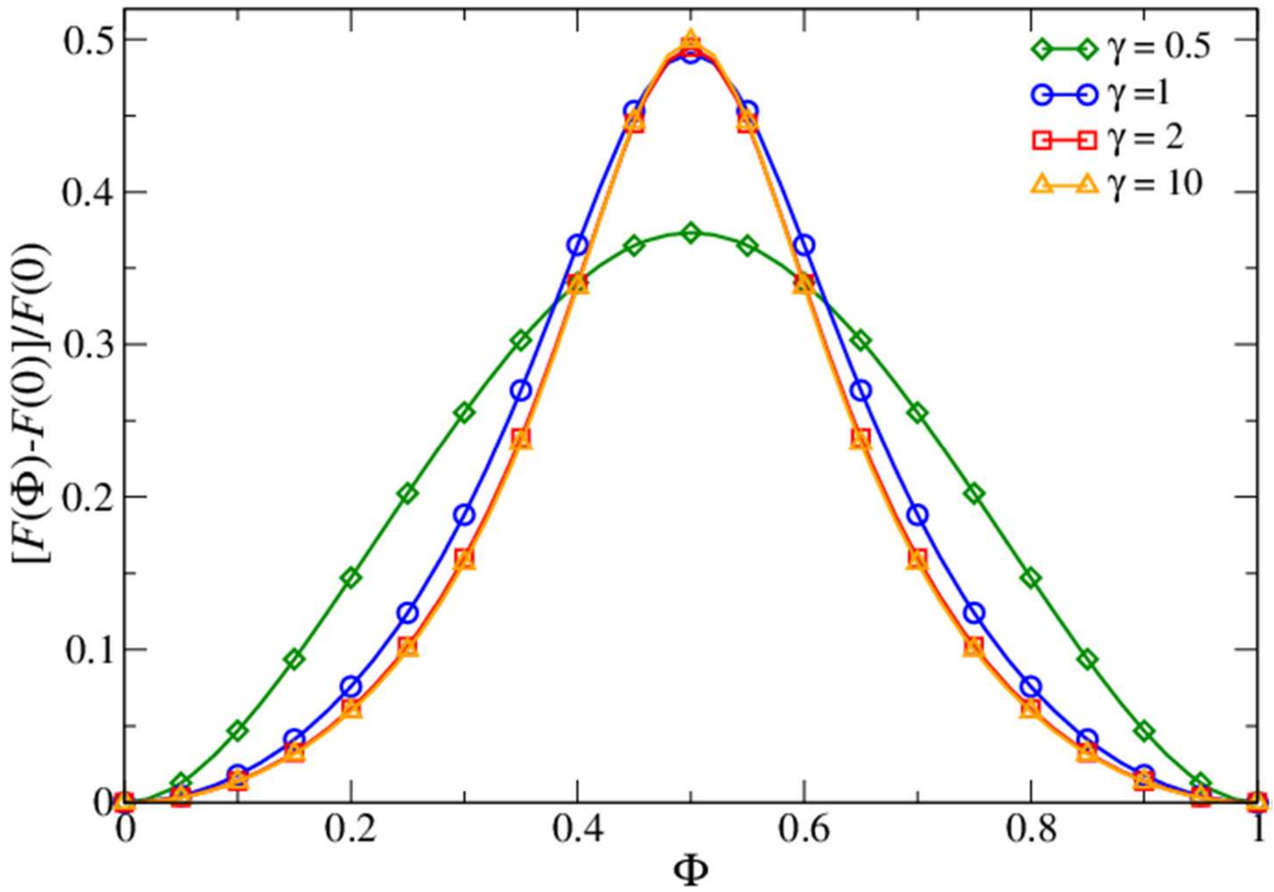
Oscillator strength



$$F = \frac{\left|\int d^2\,\vec{r}\Psi(\vec{r},\vec{r})\right|^2}{\int d^2\overrightarrow{r_e}\int d^2\overrightarrow{r_h}\,|\Psi(\overrightarrow{r_e},\overrightarrow{r_h})|^2}$$

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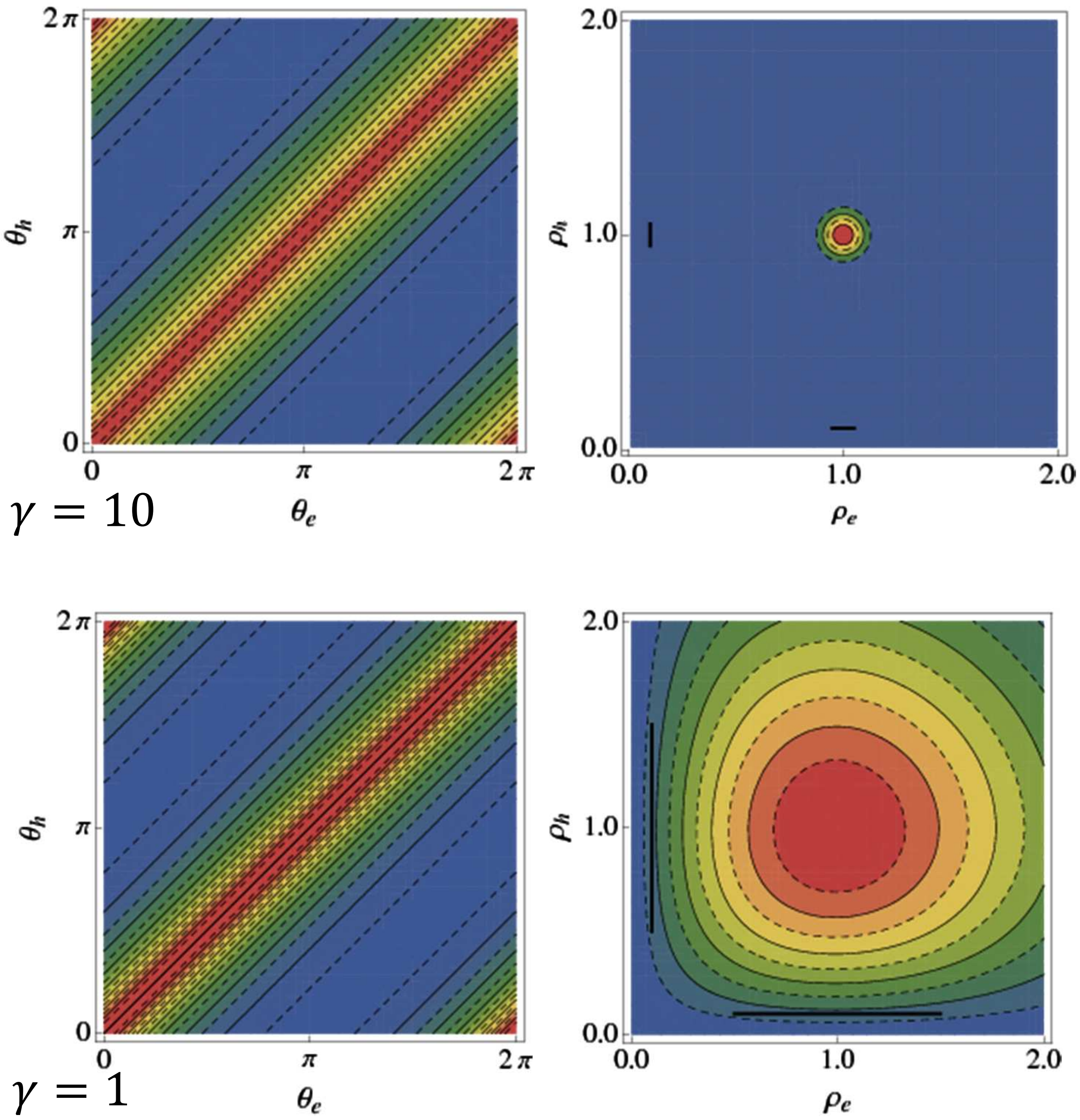
- $F \neq 0 \rightarrow$ experimentally observable?

Local wavefunction probability



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- $F \neq 0$ → experimentally observable?
- Exciton fills QR width

CONCLUSIONS

- Excitonic AB predicted for 1D QR remains essentially unchanged in 2D
- When enlarge the ring width by one order of magnitude, the amplitude of the AB oscillations drops by about 15%
- Non-simply connected confined potential explains the presence of AB oscillations in 2D QR
- The behaviour of oscillations depends on the relative interaction strength to ring radius
- Our results are in good agreement with experimental results

Phys. Rev. B **84**, 235103 (2011)

¡MUCHAS GRACIAS!