Excitonic Aharonov-Bohm Effect in Type-II Quantum Dots

Igor L Kuskovsky
Department of Physics
Queens College of CUNY, Queens, NY 11367
Acknowledgements

- B. Roy (QC)
- H. Ji (QC)
- S. Dhomkar (QC)
- M. C. Tamargo (CCNY)
- D. Smirnov (NHMFL)
- Y. Kim (NHMFL)
- J. Ludwig (NHMFL)
- L. Mourokh (QC)
- A. O. Govorov (Ohio U.)
- F. Peeters (U. Antwerp)
- M. Tadic (U. Belgrade)
- I. C. Noyan (Columbia U)
- U. Manna (Columbia U)
Aharonov-Bohm Effect

- **Classical electrodynamics:** the vector potential, $A$, is considered a mere mathematical auxiliary -- convenient for calculations, but having no direct physical meaning.

- **Quantum mechanics:** the potential(s) play a more significant role, for the Hamiltonian is expressed in terms of $\varphi$ and $A$, not $E$ and $B$:
  - Nevertheless, it was taken for granted that there could be no electromagnetic influences in regions where $E$ and $B$ are zero.

- In 1959 Aharonov and Bohm showed that the vector potential can affect the quantum behavior of a charged particle even in regions where electromagnetic field is zero (a magnetic flux exists, while no effects of the classical Lorentz force are present).
Consider an electron on a circular orbit with and without presence of a Solenoid (the bound Aharonov-Bohm Effect)

- Solenoid lifts two-fold (direction of rotation) degeneracy
- The energy of a [positive] particle moving along the current of the solenoid ($l > 0$) is lowered
- *The energy now depends on the magnetic filed inside the solenoid, although the magnetic filed at the particle’s location is ZERO*
Macroscopic Test of the Aharonov-Bohm Effect

Adam Caprez, Brett Barwick, and Herman Batelaan*
Department of Physics and Astronomy, University of Nebraska-Lincoln, Lincoln Nebraska 68588, USA
(Received 14 August 2007; published 19 November 2007)

The Aharonov-Bohm (AB) effect is a purely quantum mechanical effect. The original (classified as type-I) AB-phase shift exists in experimental conditions where the electromagnetic fields and forces are zero. It is the absence of forces that makes the AB effect entirely quantum mechanical. Although the AB-phase shift has been demonstrated unambiguously, the absence of forces in type-I AB effects has never been shown. Here, we report the observation of the absence of time delays associated with forces of the magnitude needed to explain the AB-phase shift for a macroscopic system.
Excitonic-AB Effect in Magneto-PL

- The Excitonic [“Optical”] AB Effect refers to manifestation of the Aharonov-Bohm phase in the optical emission of polarized excitons [“dipoles“] – overall neutral quasi-particle
  - Quantum Rings and Type-II Quantum Dots

As the flux increases, $|L|$ changes from 0 to 1, 2, 3 ...

Two important outcomes:

- Energy Oscillation(s) (“known”)
- PL Intensity Oscillation(s) - due to selection rules
  - Multiple Oscillation in strong confinement or weak coupling
  - A single ‘peak’ in strong coupling regime

$$E_{exc} = E_{exc0} + \frac{\hbar^2}{2MR_0^2} \left( L + \frac{\Delta \Phi}{\Phi_0} \right)^2$$

$$\Delta \Phi = 2\pi (R_e - R_h) R_0 B$$

$$L = l_e + l_h \quad R_0 = (R_e + R_h) / 2$$

$$M = \frac{(m_e R_e^2 + m_h R_h^2)}{R_0^2}$$

Excitonic-AB Effect in Magneto-PL

The 1st transition of the electron orbital number to non-zero value occurs at the magnetic field $B_{\text{AB}}$ for which, \[
\pi R_0^2 B_{\text{AB}} = \frac{\Phi_0}{2} \]

\[
E_{\text{exc}} = E_{\text{exc0}} + \frac{\hbar^2}{2MR_0^2} \left( L + \frac{\Delta\Phi}{\Phi_0} \right)^2
\]

\[
\Delta E_{\text{exc}} = \frac{\hbar^2}{8MR_0^2} \sim 0.5 \text{ meV}
\]
Excitonic-AB Effect in Magneto-PL

- The ground state for a QR,

\[
\Delta^0_0 \propto \left[ 1 + \cos \left( \frac{2\pi}{\Phi_0} \frac{\Phi}{\Phi_0} \right) e^{-2\pi\rho\gamma} \right]
\]

- No transition to dark states is expected without external fields, e.g., electric field*

---

Romer and Raikh, PRB 62 7045 (2000); *Fischer, et al., PRL 102, 096405 (2009)
Type-II Heterosturctures

- In Type-II heterostructures, the charge carriers are spatially separated.

- In QDs: one type of carriers is confined within the QD whereas the other is attracted via the Coulomb interaction, creating *spatially indirect (type-II)* exciton.
  - Electrical dipole across interface is formed.

*Blue* = Highest Electron Density

In ideal type-II QDs the ‘barrier’ carrier would locate above-below the QD.

---

Kuskovsky, et al., PRB 76, 035342 (2007)
Type-II Quantum Dots: Examples

- cw PL
  - Emission energy shifts to higher values with increasing excitation

Type-II Quantum Dots: Examples

- Time-resolved PL
  - Long-lived due to weak overlap of the carriers’ wave functions
  - Dependent on $I_{\text{ex}}$, for overlap of the wave functions depends on the concentration of photo-generated carriers

Gu et al., PRB 71, 045340 (2005); Shuvayev et al., PRB 79, 115307 (2009)
Type-II Exciton Lifetimes and Binding Energies from Temperature Dependent TRPL

\[ \frac{1}{\tau} = \frac{1}{\tau_{r0}} [1 - C \exp\left(-\frac{\varepsilon_b}{k_B T}\right)] + \frac{1}{\tau_{nr0}} \exp\left(-\frac{\varepsilon_a}{k_B T}\right) \]

![Graph showing 1/\tau vs 1/k_B T for Sample C at 2.34 eV, with an estimated temperature of ~130 K.]

Type-II Exciton Lifetimes and Binding Energies from Temperature Dependent TRPL

\[
\frac{1}{\tau} = \frac{1}{\tau_{r0}} [1 - C \exp(-\epsilon_b / k_B T)] + \frac{1}{\tau_{nr0}} \exp(-\epsilon_a / k_B T)
\]

<table>
<thead>
<tr>
<th>Sample</th>
<th>Photon Energy (eV)</th>
<th>Exciton Binding Energy (meV)</th>
<th>(\tau_{r0}) (ns)</th>
<th>Activation Energy (meV)</th>
<th>(\tau_{nr0}) (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.48</td>
<td>6.20</td>
<td>64.7</td>
<td>90.7</td>
<td>0.10</td>
</tr>
<tr>
<td>B</td>
<td>2.48</td>
<td>7.34</td>
<td>91.9</td>
<td>103.0</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>2.36</td>
<td>7.44</td>
<td>93.1</td>
<td>111.1</td>
<td>0.18</td>
</tr>
<tr>
<td>C</td>
<td>2.34</td>
<td>11.30</td>
<td>99.9</td>
<td>83.1</td>
<td>1.37</td>
</tr>
</tbody>
</table>

Disk-like Type-II QDs in Magnetic Field

- Blue = Highest Electron Density

- No AB Effect

Kuskovsky, et al., PRB 76, 035342 (2007)
The AB effect was observed in InP/GaAs QDs (Ribeiro, et al., PRL, 92, 126402 (2004)). However, no oscillations were observed by de Godoy, et al., in the same system (PRB 73, 033309 (2006)). Madureira, et al., APL 90, 212105 (2007) showed that the ability to observe it depends on the growth conditions and specifics of the system.
The AB effect was observed in InP/GaAs QDs (Ribeiro, et al., PRL, 92, 126402 (2004)).

However, no oscillations were observed by de Godoy, et al., in the same system (PRB 73, 033309 (2006)).

Madureira, et al., APL 90, 212105 (2007) showed that the ability to observe it depends on the growth conditions and specifics of the system.
Stacked Type-II QDs

- **Blue** = Highest Electron Density
- **No AB Effect Possible**

- **Red** = Highest Electron (Hole) Density at 0 T (upper) and 6 T (lower)
- **AB effect is Possible**
Samples

MEE-MBE Shutter Sequence

Schematic of the Samples

Kuskovsky, et al., PRB 63 155205 (2001); PRB 76, 035342 (2007)
Example: ZnMgTe/ZnSe

- XRD simulations showed
  - A minimal amount of Te (< 1%) inside the spacer
  - ~ 32% of Mg inside the QDs

Manna et al, JAP 111, 033516 (2012)
Quantum Dots Form Stacks, which results in “averaging” out QDs size variations

Strain cannot be completely ruled out

The AB Signature in PL Intensity

- The AB peak is only observed in Faraday Configuration, as expected
- The AB signature is ‘masked’ at high excitation intensities
The AB Signature in PL Intensity

- The AB peak is only observed in Faraday Configuration, as expected
- The AB signature is ‘masked’ at high excitation intensities
The AB ‘peak’ appears only in one polarization
- Largest reported magnitude
- Possibly was masked by some background emission
The AB energy peak also becomes evident in polarized PL.

\[
E_{\text{exc}} = E_{\text{exc}0} + \frac{\hbar^2}{2MR_0^2} \left( L + \frac{\Delta\Phi}{\Phi_0} \right)^2
\]

\[
\Delta E_{\text{exc}} = \frac{\hbar^2}{8MR_0^2} \sim 0.5 \text{ meV}
\]
The AB Signature in PL Intensity

- Magnetic field of the 1\textsuperscript{st} angular momentum transition increases with decreasing Te concentration
  - Attribute to ‘size’ of QDs
- Correlating with PL at zero magnetic field, allows to estimate QD density*, binding energy of excitons*, as well as the in-plane size of type-II exciton**

‘Spectral Analysis’

• ‘Double peak’ in the AB oscillation points to at least two different QD stacks, with corresponding type-II exciton sizes of 18.2 & 17.9 nm

• TRPL at B = 0 also confirms two distinct decays in these spectral regions.

• There is a non-monotonic change in the AB oscillation magnitude

Roy, et al., APL, 100, 213114 (2012); PRB, 86, 165310 (2012); *ErJPB 86:31, 1 (2014)
‘Spectral Analysis’

- ‘Double peak’ in the AB oscillation points to at least two different QD stacks, with corresponding type-II exciton sizes of 18.2 & 17.9 nm
- TRPL at B = 0 also confirms two distinct decays in these spectral regions.
- There is a non-monotonic change in the AB oscillation magnitude

Roy, et al., APL, 100, 213114 (2012); PRB, 86, 165310 (2012); *ErJPB 86:31, 1 (2014)
Type-II QDs in Single-Cycle Samples

- Samples that did not exhibit “type-II behavior” at low temperatures at zero magnetic field

Type-II QDs in Single-Cycle Samples

The QD related PL appears at elevated temperatures, and behaves the same as that observed for samples grown with three Zn-Se-Te cycles.

Built-in Electric Field?

- Samples with low amount of Te exhibit relatively narrow AB ‘peak’, which indicates a presence of built-in electric fields.
- Was proposed by Fischer et al., [PRL 102, 096405 (2009)] as caused by an in-plane electric field.

Roy, et al., PRB, 86, 165310 (2012)
Decoherence of the AB Excitons

- Attempt to use excitonic AB effect to study quantum decoherence
- It is inherently a contactless approach
- Decoherence of the AB excitons should be of the same nature as that of AB oscillations observed in transport

![Graph showing the relationship between magnetic field and intensity with temperature as a parameter.](image-url)
Decoherence of the AB Excitons

- $\Delta I_{AB} \propto e^{-L/L_D(T)}$

- Assuming Ballistic regime, $L_D(T) \propto \tau_D(T)$

- $\Delta I_{AB} \propto e^{-\tau/\tau_D(T)}$

- At high temperatures, phonon mediated decoherence dominates, and
  
  $\tau_D^{-1}(T') \propto T^3$
Decoherence of the AB Excitons

\[ \Delta I_{AB} \propto \exp \left[ -\frac{\tau}{\tau_D(T)} \right] \]

- Phonon mediated decoherence
  \[ \tau_D^{-1}(T) \propto T^3 \]
- Below 1÷3 K, carrier-carrier scattering or thermal averaging dominate, so that we assume
  \[ \tau_D^{-1}(T) \propto T \]
Polarized 2D excitons are perfect objects to study Aharonov-Bohm effect of neutral quasi-particles.

Stacked type-II QDs are among the best systems for such experiments as QD size variations are averaged out.

We did observe strong AB signal in PL intensity of in stacked sub-monolayer ZnTe/ZnSe type-II QDs.

Multiple sets of QDs can be detected and size of exciton is measured with sub-nanometer precision.

In some samples, the observed ‘peaks’ are narrow, suggesting presence of in-plane electric fields.

We have attempted to measure decoherence using contactless techniques.

More detailed studies required to verify a non-monotonic behavior at very low temperatures and understand polarized magneto-PL.