Diamagnetism without orbital motion in degenerate exciton condensates

Yuri G. Rubo
Centro de Investigación en Energía,
Universidad Nacional Autónoma de México, Temixco, Morelos, 62580, Mexico

A. V. Kavokin
School of Physics and Astronomy, University of Southampton,
Highfield, Southampton SO17 1BJ, UK

Motivation: recent progress in Bose-Einstein condensation of excitons

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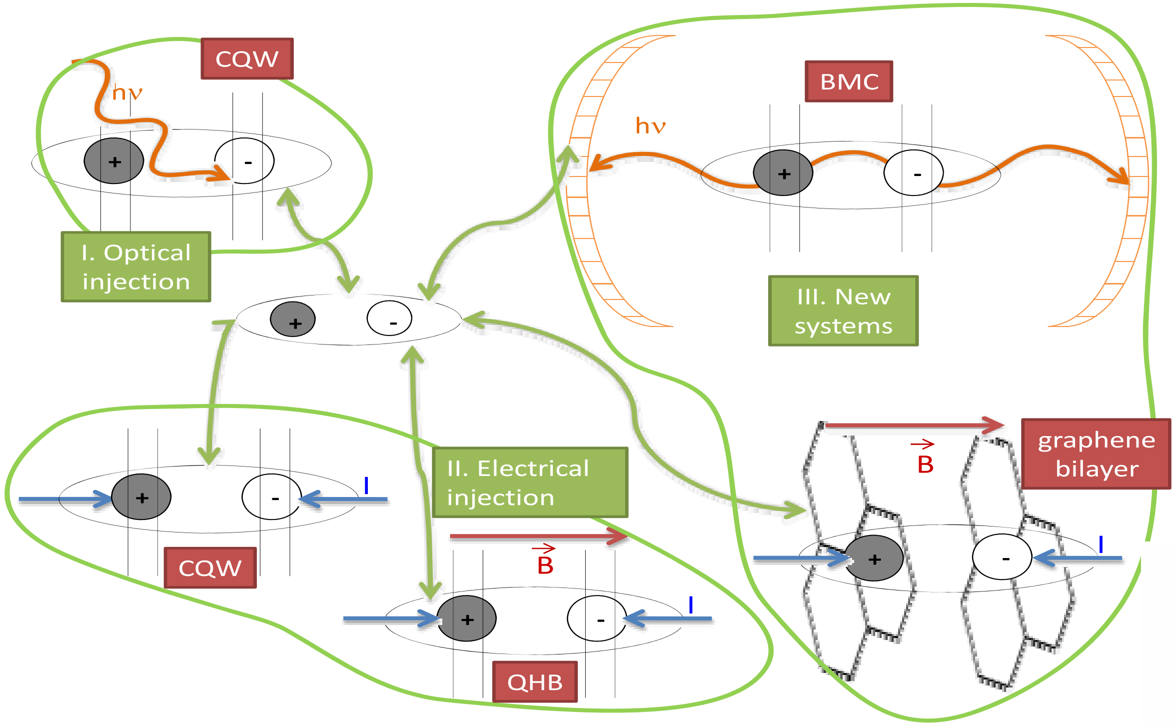
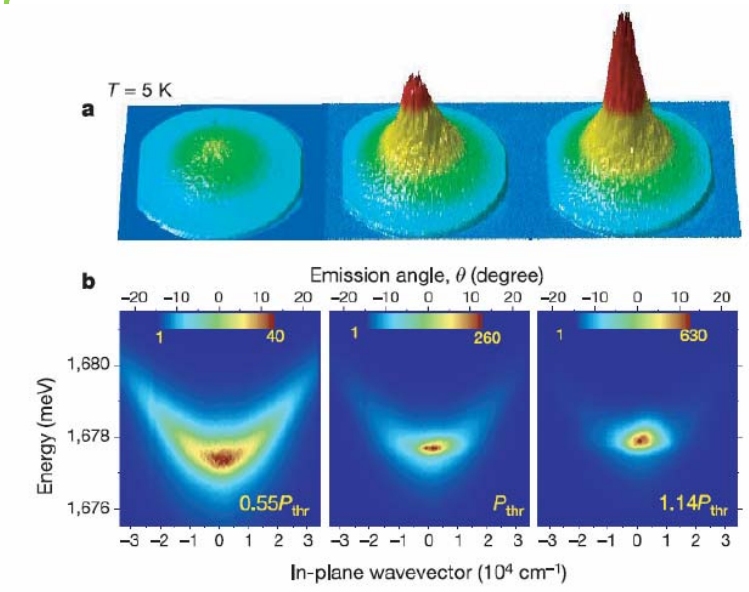
Indirect excitons

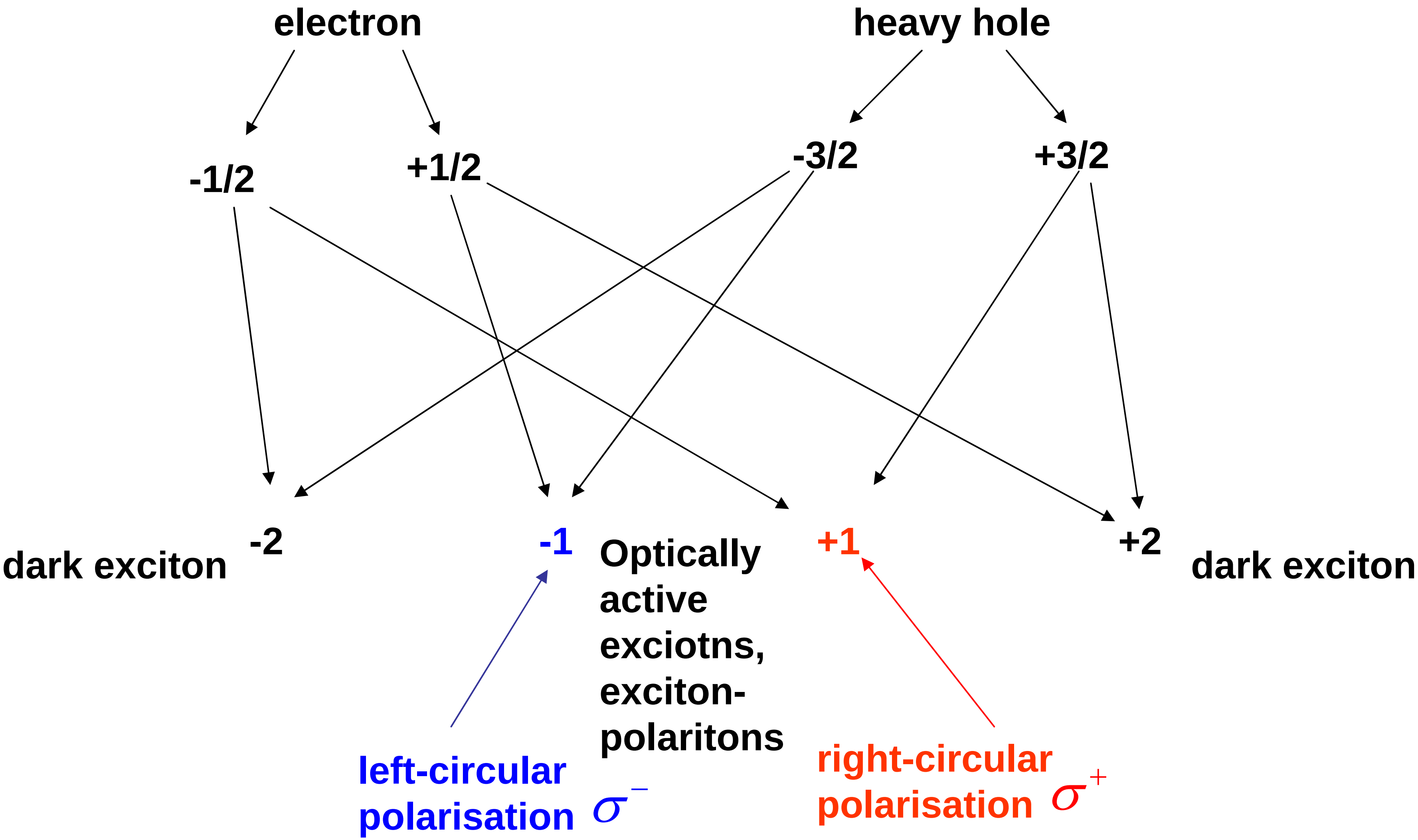


Indirect excitons can be formed by optical injection in coupled quantum wells (CQW) (I) , by electrical injection in CQW (II.1) and quantum Hall bilayers (QHB) (II.2), and in new systems such as biased microcavities (BMC) (III.1) and graphene bilayers (GBL) (III.2)

Exciton polaritons in microcavities



Spin of excitons in zinc-blend semiconductors



electron

heavy hole

-1/2

+1/2

-3/2

+3/2

dark exciton -2

-1

Optically active exciotns, exciton-polaritons

+1

+2 dark exciton

left-circular polarisation σ^-

right-circular polarisation σ^+

Exciton-exciton interactions are spin-sensitive

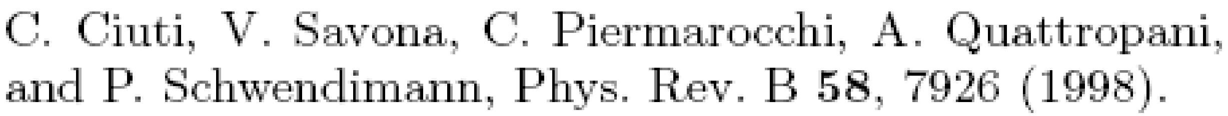
Excitons with parallel spins ↑ ↑ **Strongly repel each other**

α_1

Excitons with antiparallel spins ↑ ↓ **Weakly attract each other (?)**

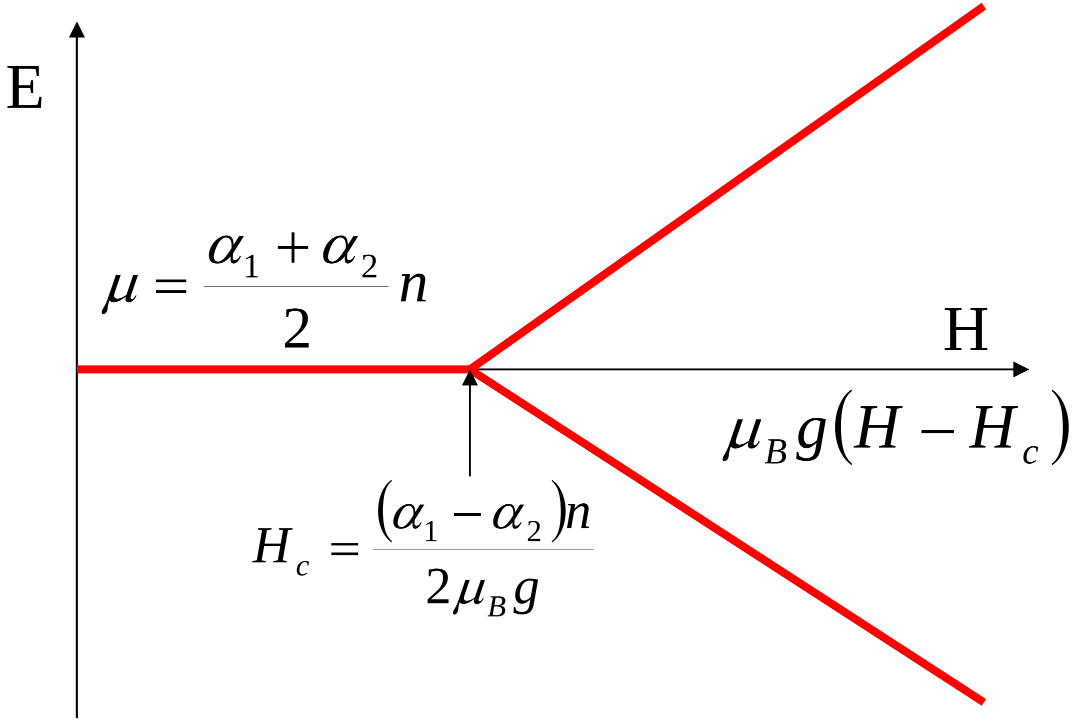
α_2

See e.g.



C. Ciuti, V. Savona, C. Piermarocchi, A. Quattropani, and P. Schwendimann, Phys. Rev. B **58**, 7926 (1998).

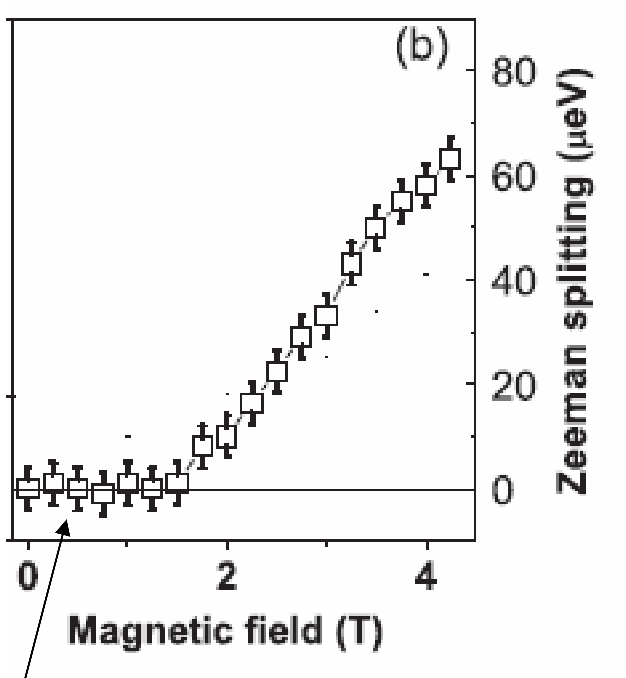
Magnetic field effect on a polariton condensate:



$$\mu = \frac{\alpha_1 + \alpha_2}{2} n$$

$$\mu_B g \left(H - H_c \right)$$

$$H_c = \frac{\left(\alpha_1 - \alpha_2 \right) n}{2 \mu_B g}$$



Spin Meissner effect: full paramagnetic screening of the external magnetic field

$$F = -\mu n - \mu_B g B S_z + \frac{1}{2} \left(\alpha_1 + \alpha_2 \right) n^2 + \left(\alpha_1 - \alpha_2 \right) S_z^2$$

Theory:

Y.G.Rubo, A.V.Kavokin, I.A. Shelykh, Phys.Lett. A 358, 227 (2006).

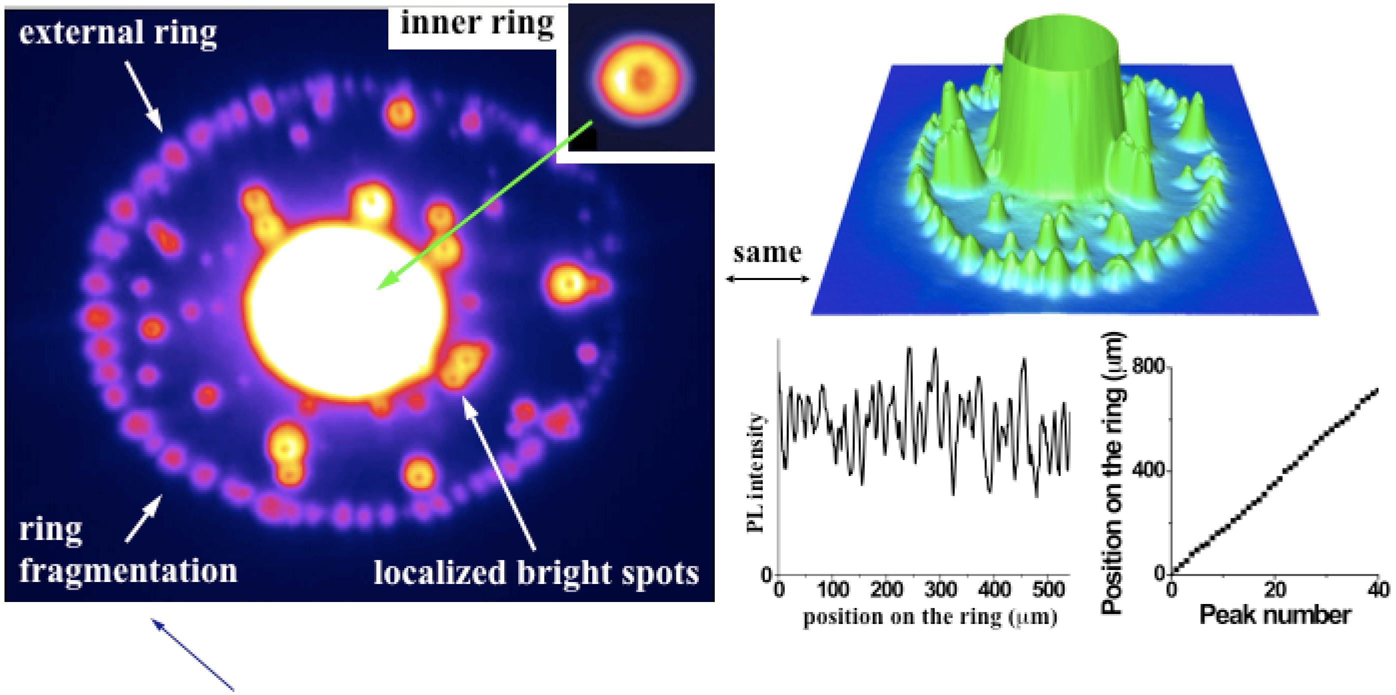
Observation:

A.V. Larionov, V.D. Kulakovskii et al, Phys. Rev. Lett., 105, 256401 (2010).

Coupled quantum wells: Four component exciton condensates:

-2, -1, +1, +2 states are degenerate

Pattern Formation



exciton state with spatial order on macroscopic lengths –

Macroscopically Ordered Exciton State (MOES)

L.V. Butov, Cold exciton gases in coupled quantum well structures,
J. Phys.: Condens. Matter 19, 295202 (2007).

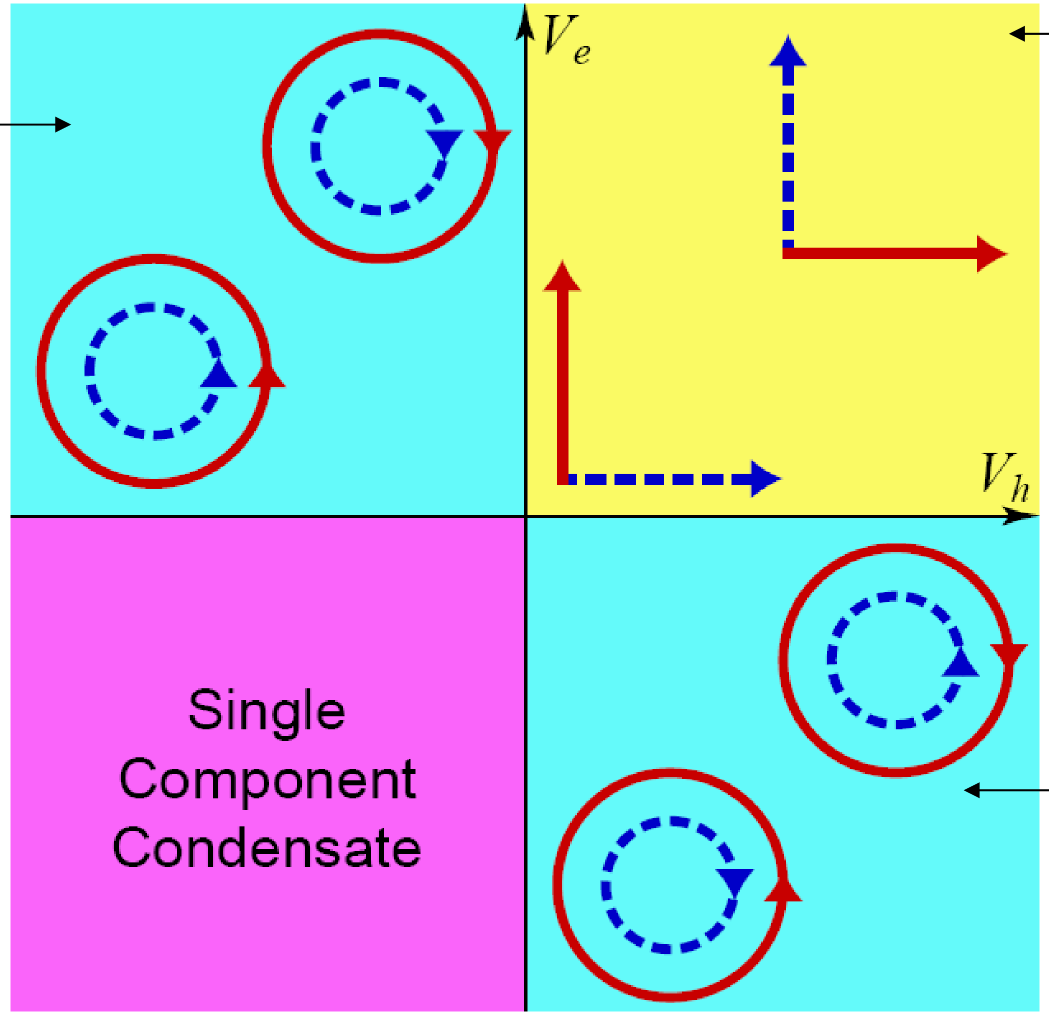
Hamiltonian density (free energy at T=0)

$$H = \frac{1}{2M}\sum_{m} |\nabla\psi_m|^2 - \mu n$$

$$+ \frac{1}{2}\sum_{,} V_{m,m'}|\psi_m|^2|\psi_{m'}|^2$$

$$+ W(\psi^*_{+2}\psi^*_{-2}\psi_{+1}\psi_{-1} + \psi^*_{+1}\psi^*_{-1}\psi_{+2}\psi_{-2}).$$

Phase diagram: No magnetic field



Two
component
condensate

Four
component
condensate

Single
Component
Condensate

Two component
condensate

Relation between single carrier concentration and components of the exciton condensate

$$n_{+1/2} = \left|\Psi_{-1}\right|^2 + \left|\Psi_{+2}\right|^2$$

$$n_{-1/2} = \left|\Psi_{-2}\right|^2 + \left|\Psi_{+1}\right|^2$$

$$n_{+3/2} = \left|\Psi_{+2}\right|^2 + \left|\Psi_{+1}\right|^2$$

$$n_{-3/2} = \left|\Psi_{-2}\right|^2 + \left|\Psi_{-1}\right|^2$$

Accounting for only interactions of electrons with parallel spins and holes with parallel spins:

$$E_e = \frac{1}{2}V_e\left(n_{+1/2}^2 + n_{-1/2}^2\right) + \frac{1}{2}g_e\mu_B B\left(n_{-1/2} - n_{+1/2}\right)$$

$$E_h = \frac{1}{2}V_h\left(n_{+3/2}^2 + n_{-3/2}^2\right) + \frac{1}{2}g_h\mu_B B\left(n_{-3/2} - n_{+3/2}\right)$$

The free energy (T=0):

$$\begin{aligned}\mathfrak{h}_M \quad = \quad & \mathfrak{h}_0 + E_e + E_h + W = \\ & \mathfrak{h}_0 + \left(V_e + V_h + V_e' + V_h'\right)\frac{n^2}{4} + \\ & \frac{V_e - V_e'}{4}S_e^2 + \frac{V_h - V_h'}{4}S_h^2 + \\ & \frac{1}{2}g_e\mu_B B S_e + \frac{1}{2}g_h\mu_B B S_h.\end{aligned}$$

where

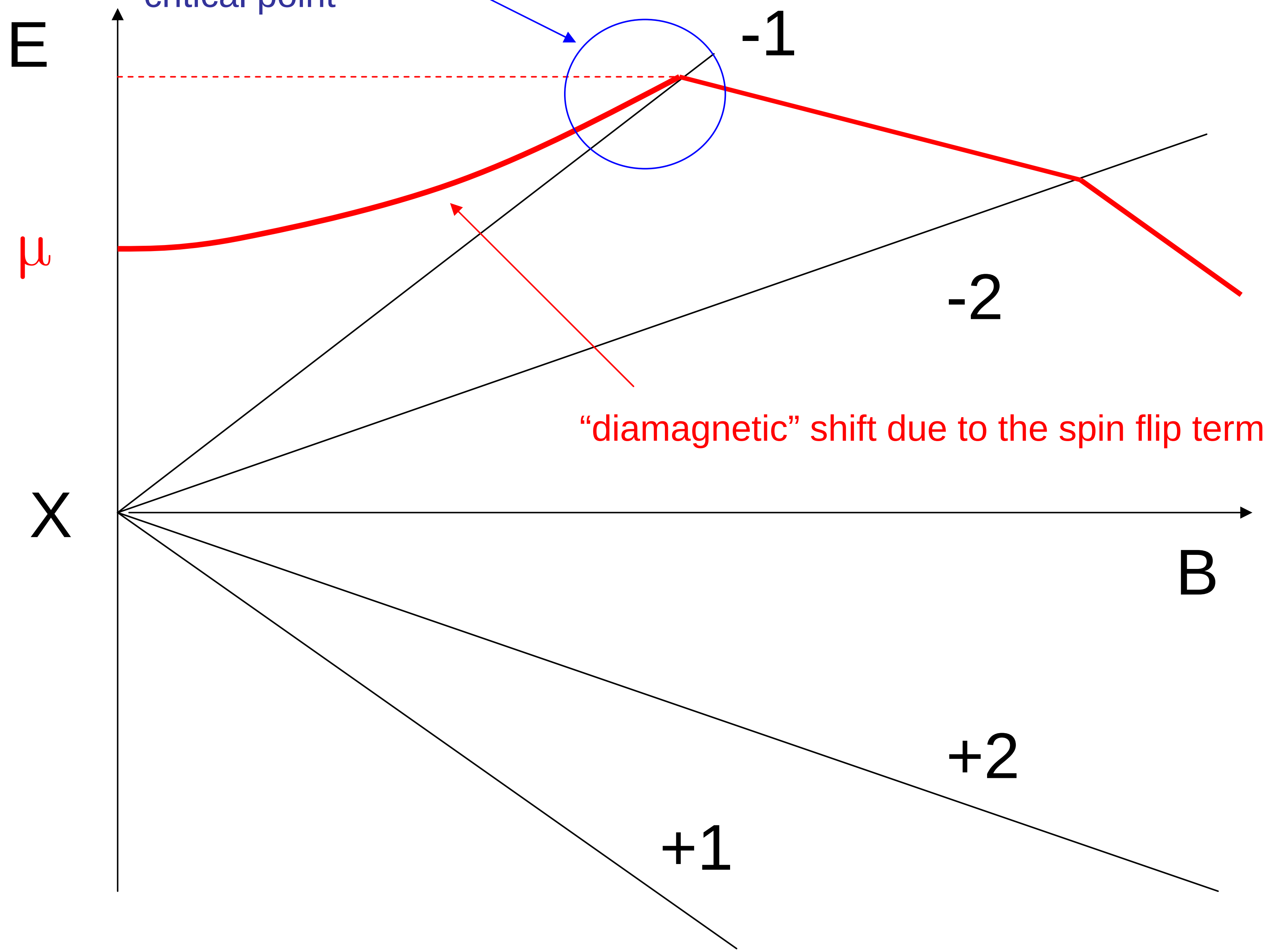
$$S_h = n_{-3/2} - n_{+3/2}, S_e = n_{-1/2} - n_{+1/2}$$

The spin flip term mixes bright and dark exciton states:

+1, -1 ↔ +2, -2

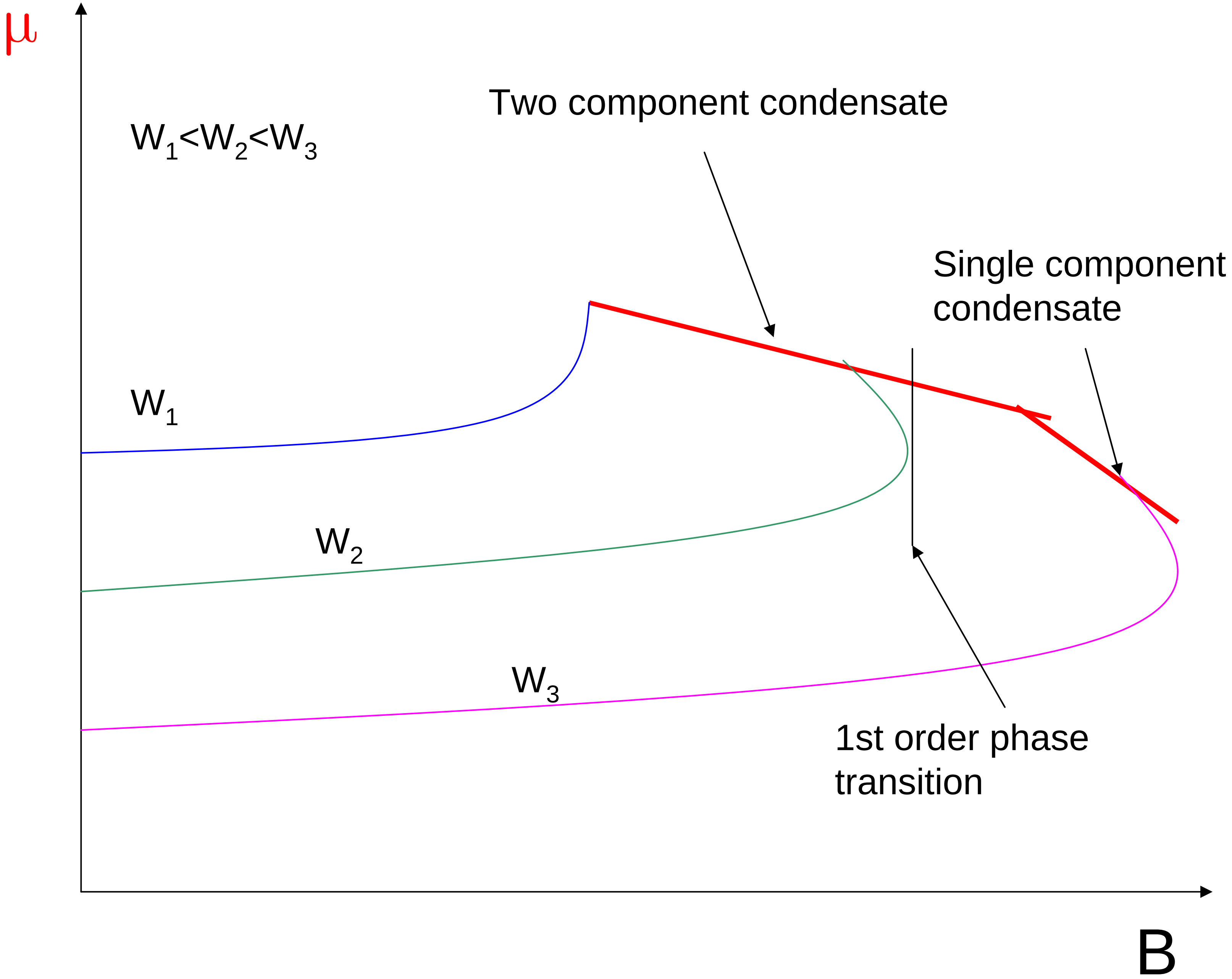
$$W(\psi^*_{+2}\psi^*_{-2}\psi_{+1}\psi_{-1} + \psi^*_{+1}\psi^*_{-1}\psi_{+2}\psi_{-2})$$

It is always negative!



Complex behaviour near the critical point

“diamagnetic” shift due to the spin flip term



Two component condensate

Single component condensate

1st order phase transition

Conclusions:

- The total energy of the condensate is reduced because of spin-flip scattering between +1,-1 and +2,-2 states
- This reduction is suppressed by a magnetic field
- This results in the diamagnetic shift and may lead to a discontinuity of the exciton polarisation dependence on the magnetic field

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DEPARTURE FOR THE BANQUET 19.15 !!!!