Transport of Indirect Excitons in High Magnetic Fields

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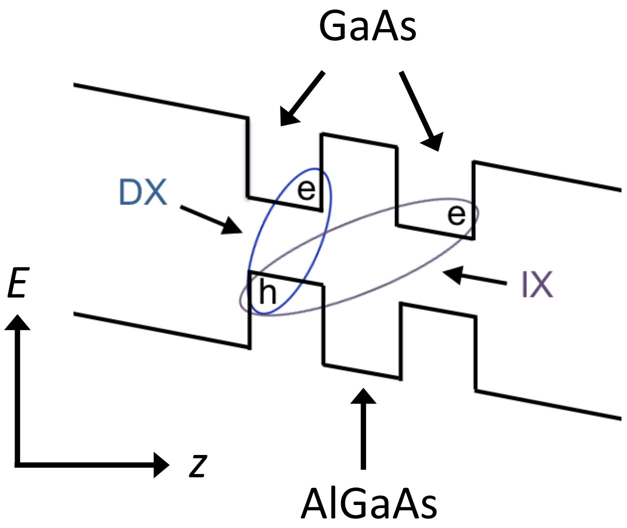
Indirect Excitons

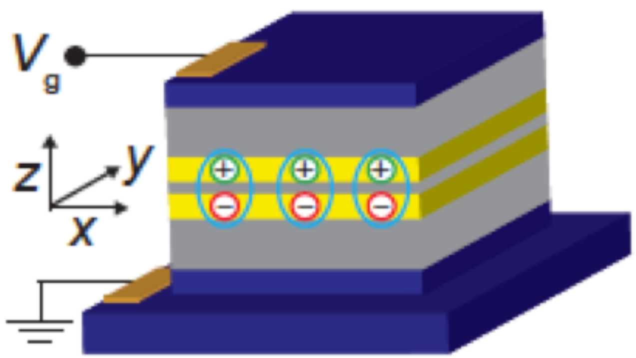


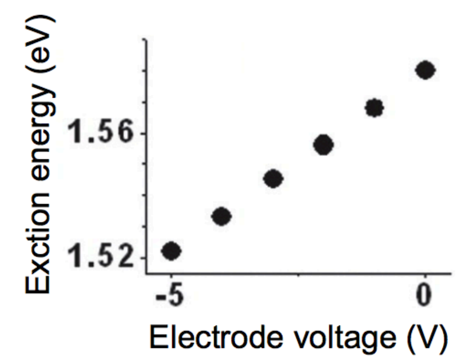
Indirect excitons (IX): bound *e* and *h* pair, *e* and *h* confined to ***spatially separated*** quantum wells

- Long lifetimes → long-range transport
- Oriented dipoles → disorder screening → long-range transport

Oriented dipoles ↓

Can control IX energy with applied voltage: $\boldsymbol{\delta E = -edF_z}$





These properties allow for:

- basic studies: exciton transport, spin transport, interaction, kinetics, coherence, condensation, **composite bosons in strong magnetic field regime**
- development of excitonic devices: excitonic transistors, traps, ramps, lattices, conveyers

High Magnetic Field Regime for Excitons

High magnetic field regime for composite bosons:

$$\hbar\omega_c \geq E_b$$

cyclotron energy ≥ binding energy

This requires:

~ 10^6 Tesla for atoms

Only a few Tesla for excitons

due to large $\hbar\omega_c = \hbar eB/(\mu c)$
and small $E_b \approx (\mu e^4)/(2\varepsilon^4 \hbar^2)$

because of small mass and $\varepsilon > 1$

High magnetic field regime for excitons is achievable in lab

UCSD optical dilution refrigerator
- 40 mK bath temperature
- 16 Tesla magnetic field

IXs are a model system for studying cold bosons in high magnetic fields:

IXs have long lifetimes

(orders of magnitude longer than lifetimes of regular direct excitons)

→

Lifetime long enough for IXs to cool below the temperature of quantum degeneracy

$T_0 = 2\pi\hbar^2 n/(k_B M_x)$

(for a GaAs CQW with n = 10^{10} cm^{-2}, T_0 ~ 3 K)

↓

Long-range transport

can study exciton transport with optical imaging

IX density controlled by laser excitation, **allows the realization of virtually any Landau level filling factor**

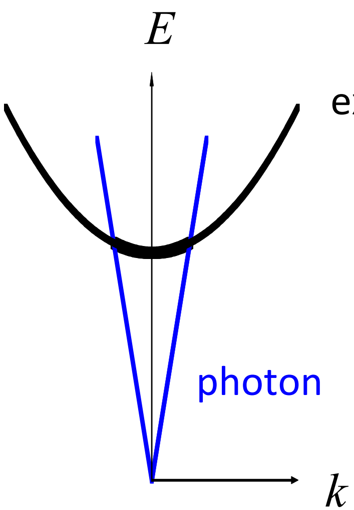
ranging from fractional ν < 1 to high ν, even at fixed magnetic field

High magnetic field regime for excitons is achievable in lab

Indirect Excitons in High Magnetic Fields

B = 0

Hydrogen-like exciton



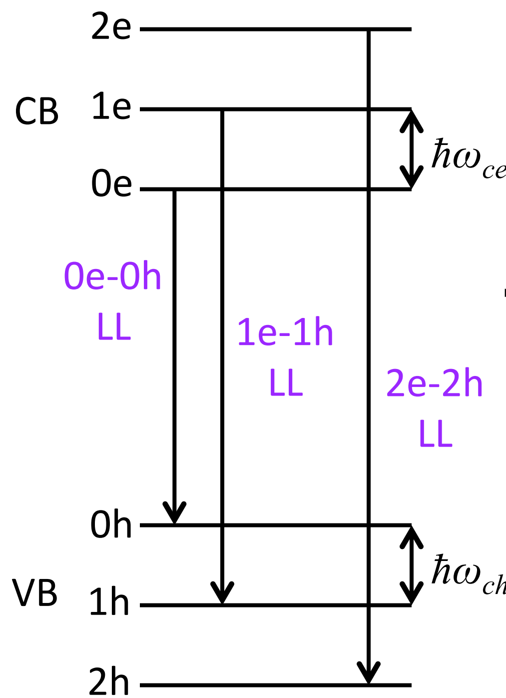
- quadratic dispersion

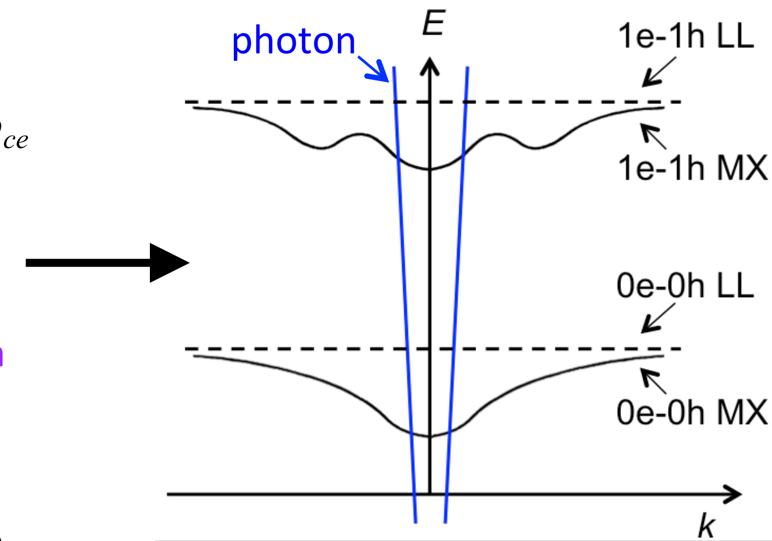
  $E_x(P) = P^2/2M - E_b$

- $M = m_e + m_h$

High B limit

Magnetoexciton (MX)





Optically active IMX:

$N_e = N_h$

$k \lesssim k_0 \approx E_g \varepsilon^{1/2}/\hbar c$

$J_z = \pm 1$

- MXs formed from e-h Landau levels (LL)
- dispersion determined by coupling induced by magnetic field $\quad \boldsymbol{r}_{e,h} = \boldsymbol{k} l_B^2$, $\quad l_B = (\hbar c/eB)^{1/2}$
- M depends on B, independent of m_e and m_h $\quad M(B) \propto B^{1/2}$

Indirect Excitons in High Magnetic Fields

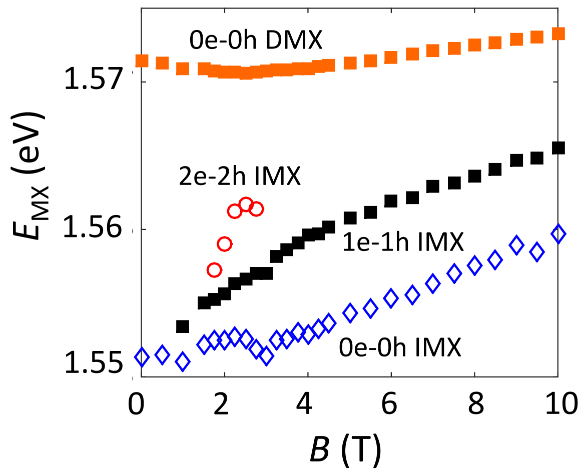
long IX lifetimes

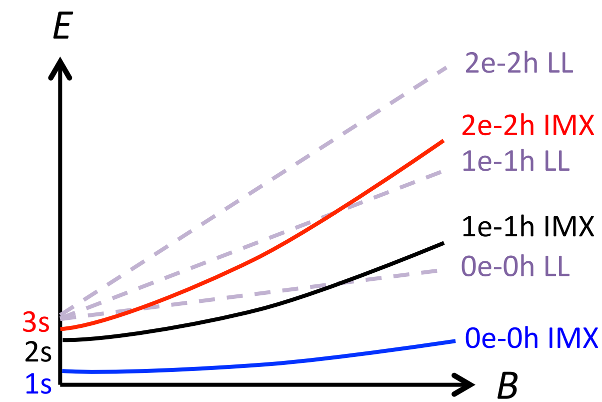
↓

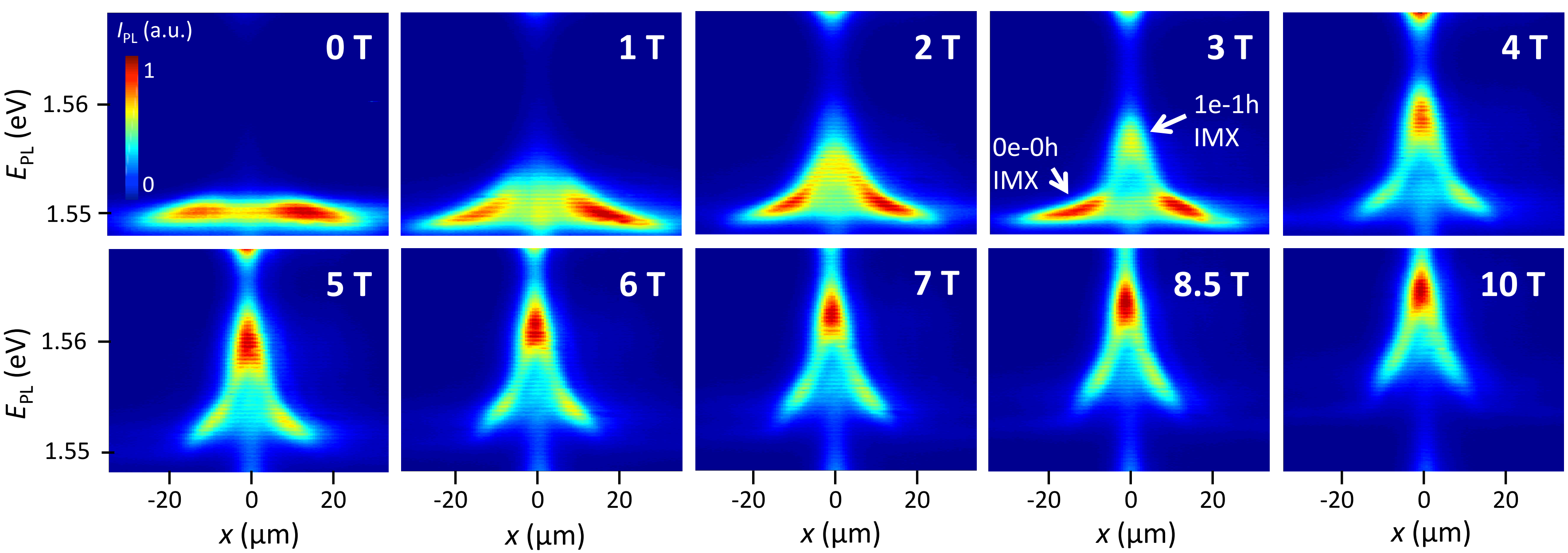
long-range transport and cooling to low T

↓

can measure **cold IMX transport** by optical imaging

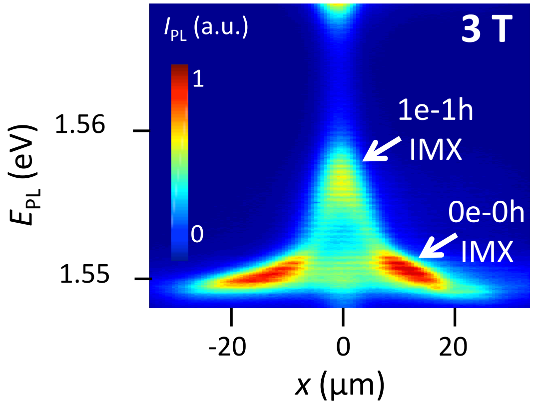


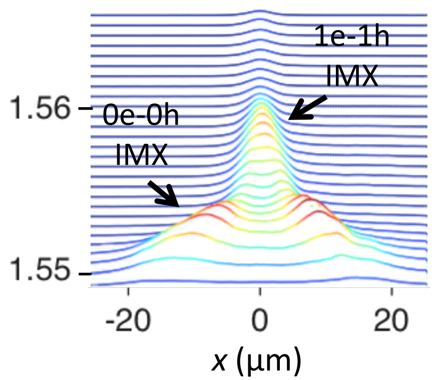


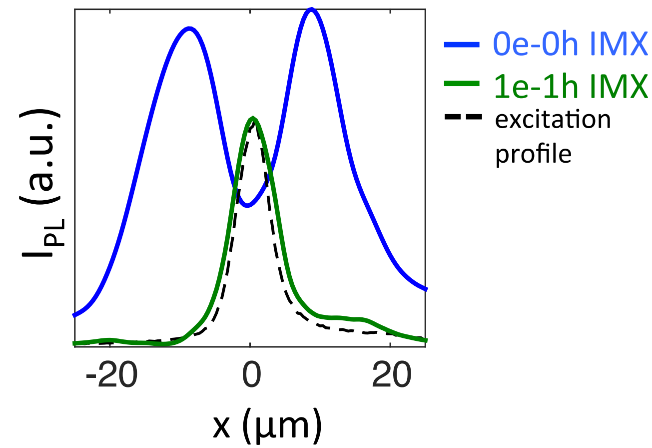


laser excitation centered at x = 0

Transport of 0e-0h IMX



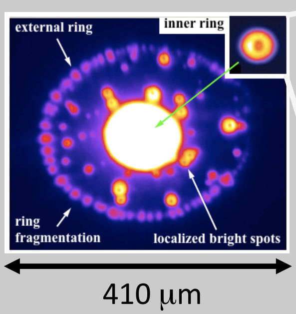




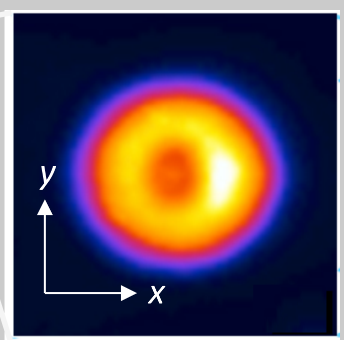
0e - 0h IMX PL intensity enhanced outside the excitation spot

➔ **IMX inner ring**

Exciton emission pattern



Exciton inner ring



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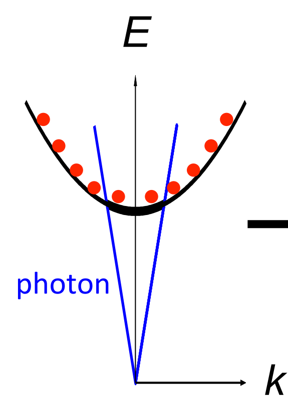
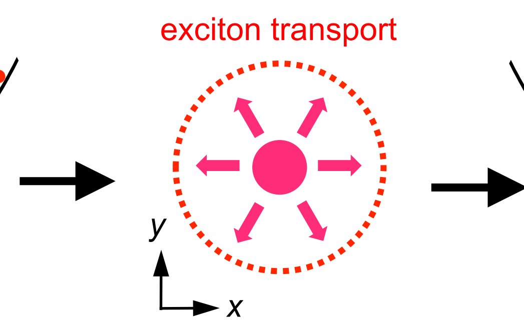
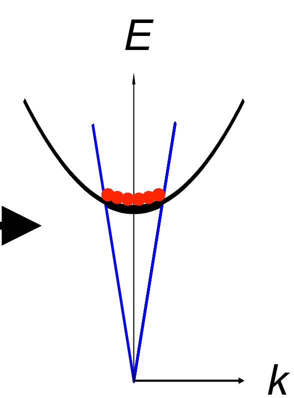


<u>excitation spot</u>
higher T_X,
lower occupation of radiative zone



excitons travel away from excitation spot
cool via phonon emission

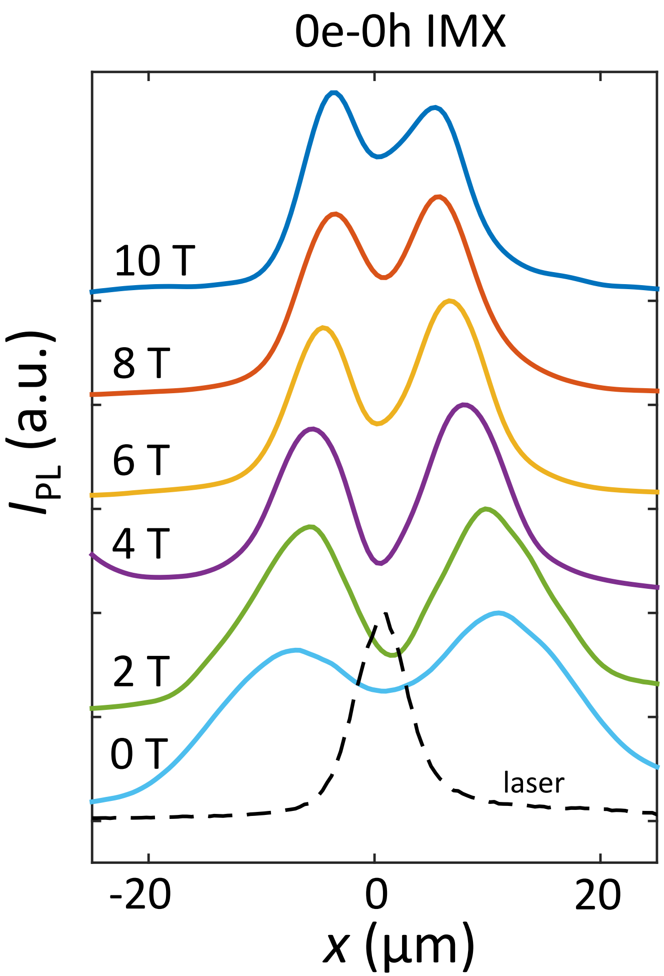


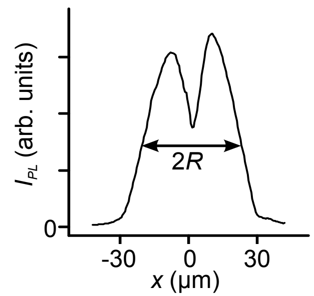
<u>inner ring</u>
lower T_X,
higher occupation of radiative zone

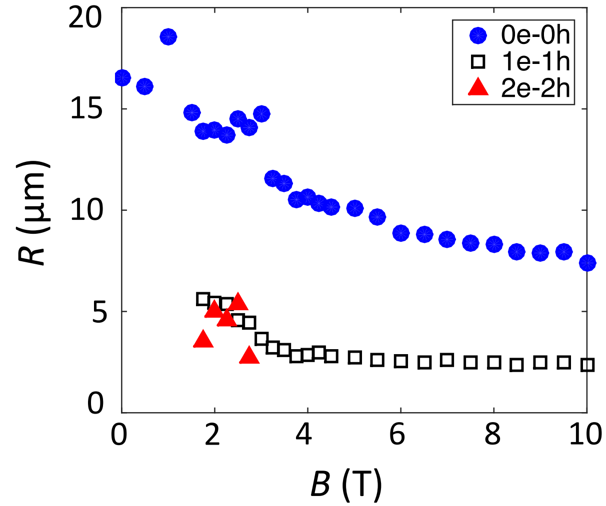
Transport of 0e-0h IMX

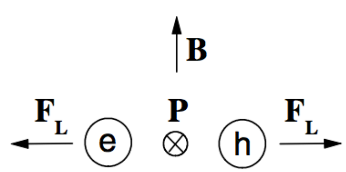
0e - 0h IMX transport length decreases with increasing magnetic field

➔ **IMX mass increase**



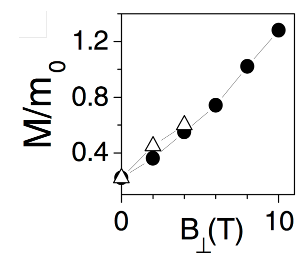






$\boldsymbol{r}_{e,h} = \boldsymbol{k} l_B^{\,2}$

$l_B = (\hbar c/eB)^{1/2}$



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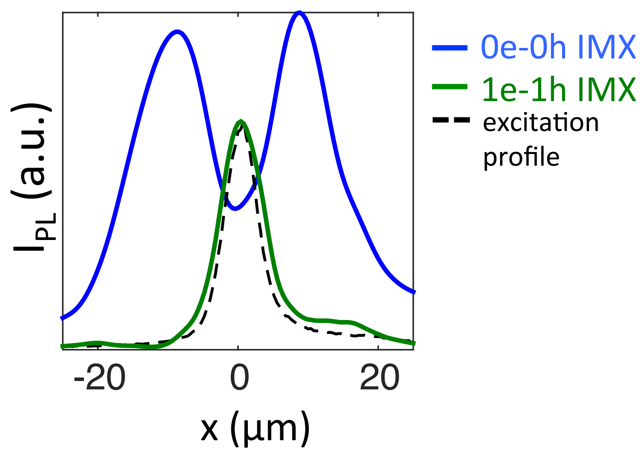
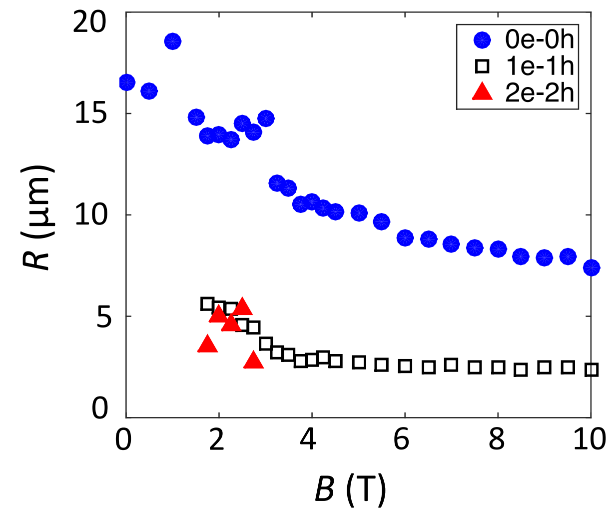
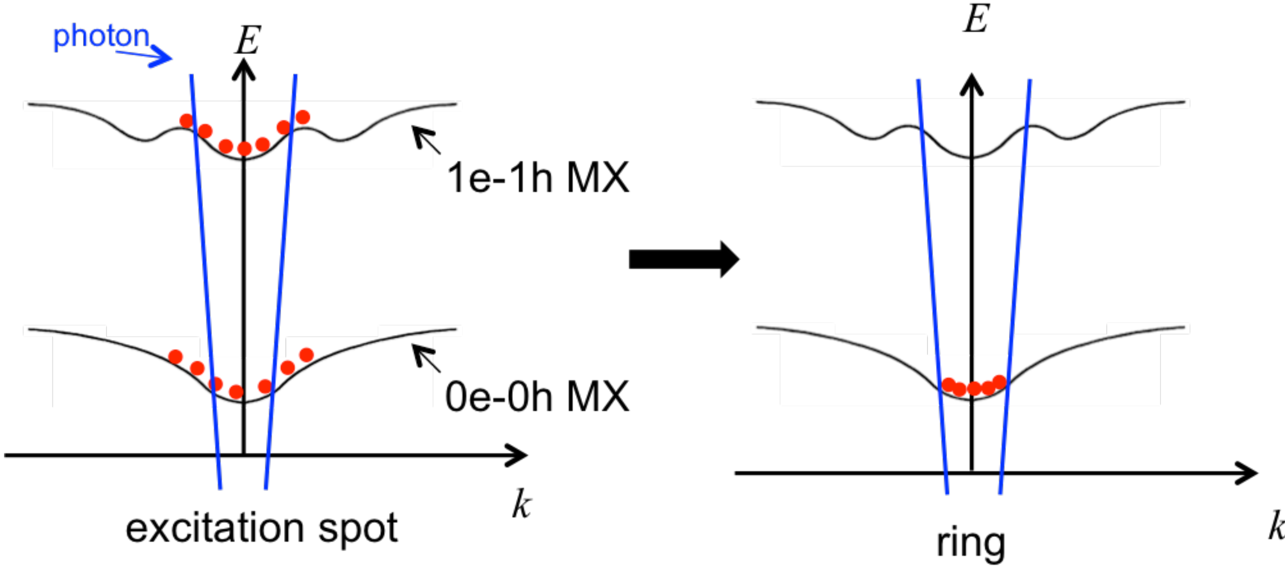
Transport of 1e-1h and 2e-2h IMXs

1e - 1h and 2e-2h IMX transport distance is smaller than for 0e - 0h MX

➔ **energy relaxation**







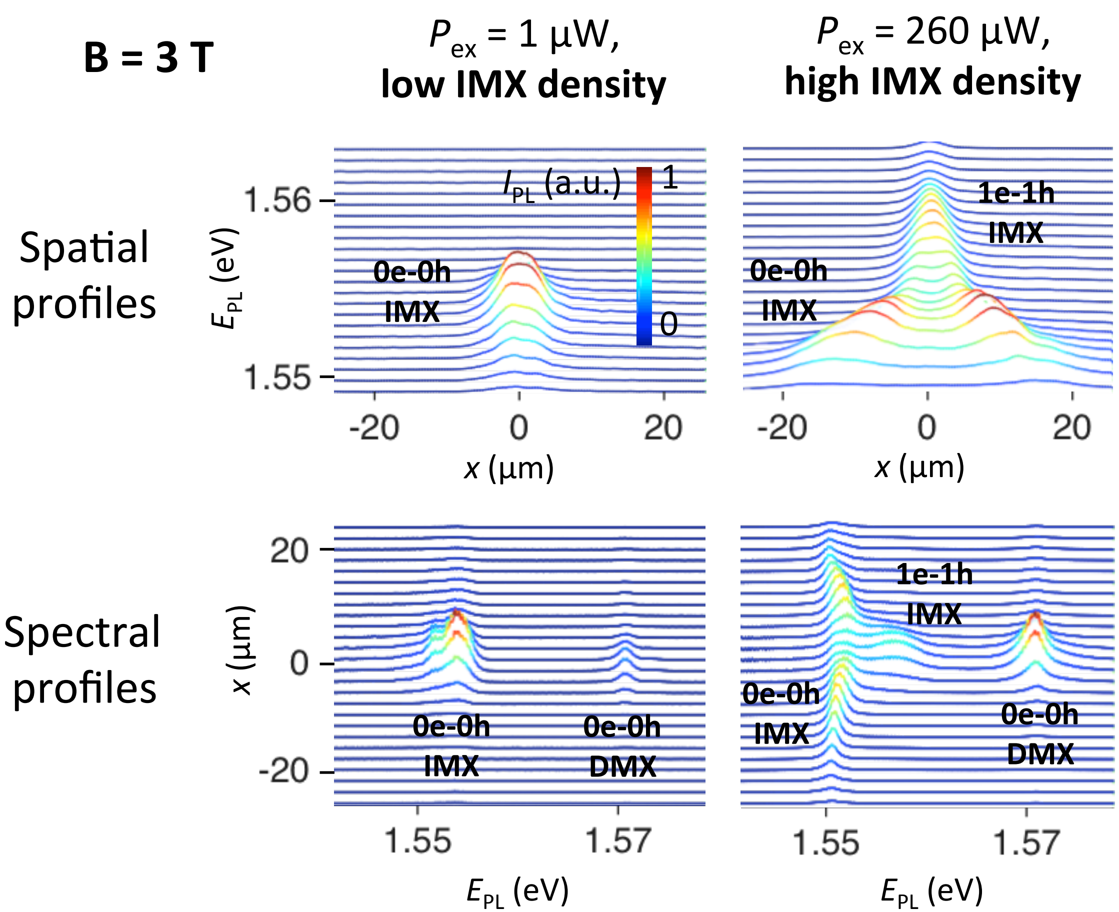
short 1e-1h and 2e-2h MX transport within their energy relaxation time

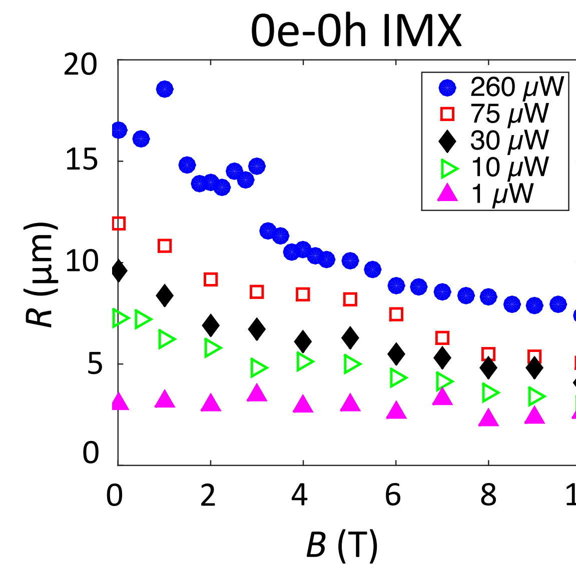
Transport of 0e-0h IMX vs Density

No IMX transport at low P_{ex}

0e - 0h IMX transport length increases with increasing P_{ex}

→ **IMX localization-delocalization transition**





IX have built-in dipole moment

↓

IXs screen disorder

↓

Low densities: IMXs are localized

High densities: IMXs are delocalized

Numerical Simulations of IMX Transport

The exciton system was modeled by solving coupled differential equations:

drift-diffusion equation

$$\frac{\partial n}{\partial t} = \nabla\left[D\nabla n + \mu_{\mathrm{x}} n \nabla(u_0 n)\right] + \Lambda - \frac{n}{\tau}$$

diffusion, drift, exciton generation, optical decay

heat balance equation

$$\frac{\partial T}{\partial t} = S_{\mathrm{pump}} - S_{\mathrm{phonon}}$$

heating due to laser excitation, cooling through phonons

In magnetic field:

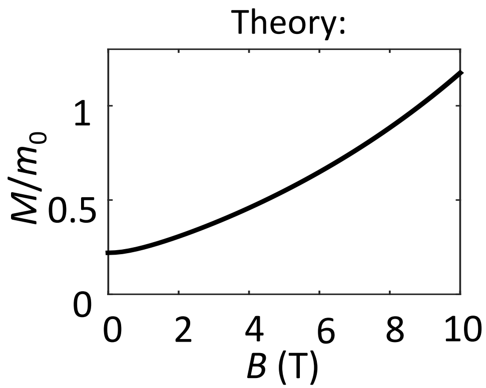
- *D* and μ_x inversely proportional to MX effective mass, *M(B)*

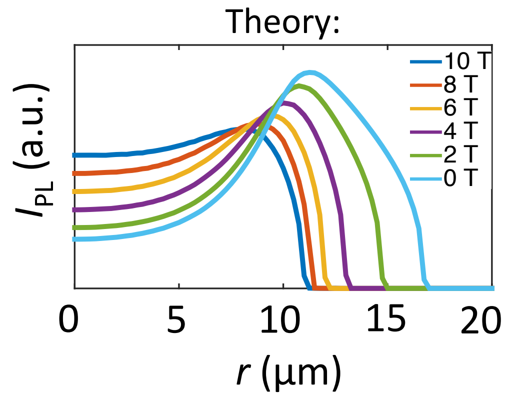
Numerical Simulations of IMX Transport

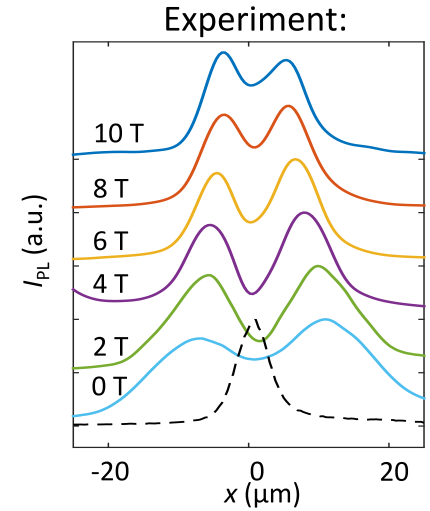
IMX mass increases with increasing *B*

→

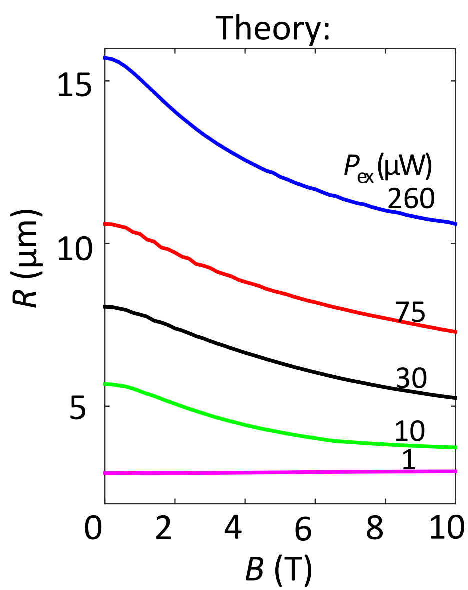
IMX transport distance decreases with increasing *B*

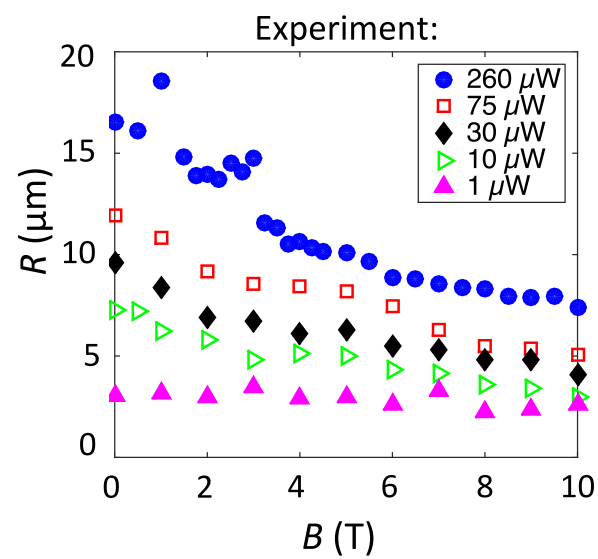






IMX transport distance increases with increasing P_{ex}





Conclusion

- **Transport of cold bosons in the high magnetic field regime was measured in a system of indirect excitons**
- IMX transport length decreases with increasing magnetic field → MX effective mass increase
- 0e-0h IMX PL: ring shape → increased occupation of radiative zone away from excitation spot
- At low densities IMXs are localized, at high densities IMXs are delocalized → disorder screening
- Theoretical model of IX transport is in agreement with experiment

Y. Y. Kuznetsova, C. J. Dorow, E. V. Calman, L. V. Butov, J. Wilkes, E. A. Muljarov, K. L. Campman, and A. C. Gossard, *Phys. Rev. B* 95, 125304 (2017)

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