Microscopic Origin of the Valley Hall Effect in Transition Metal Dichalcogenides

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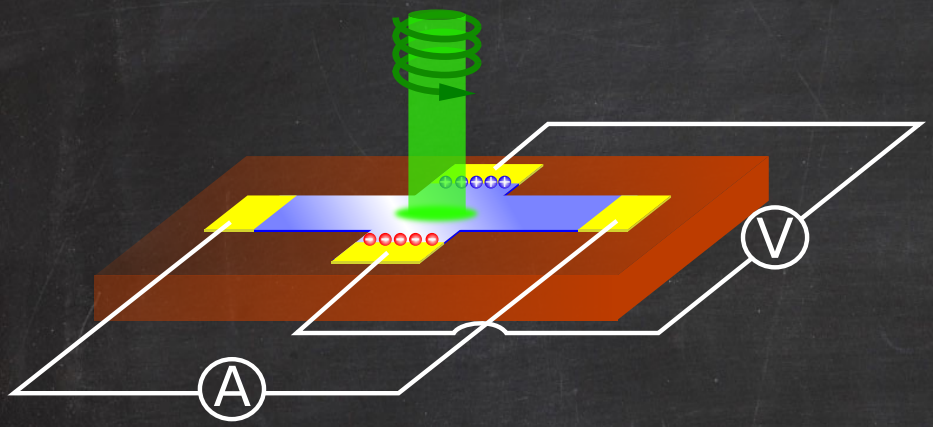
The Valley Hall Effect

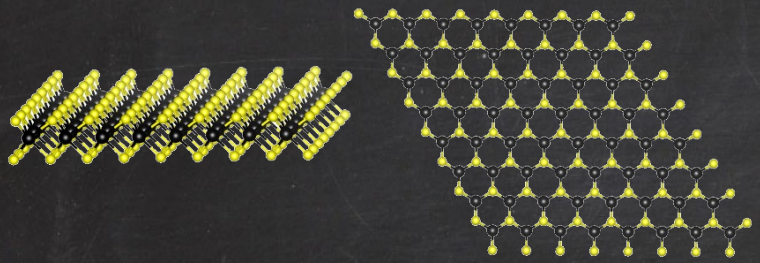


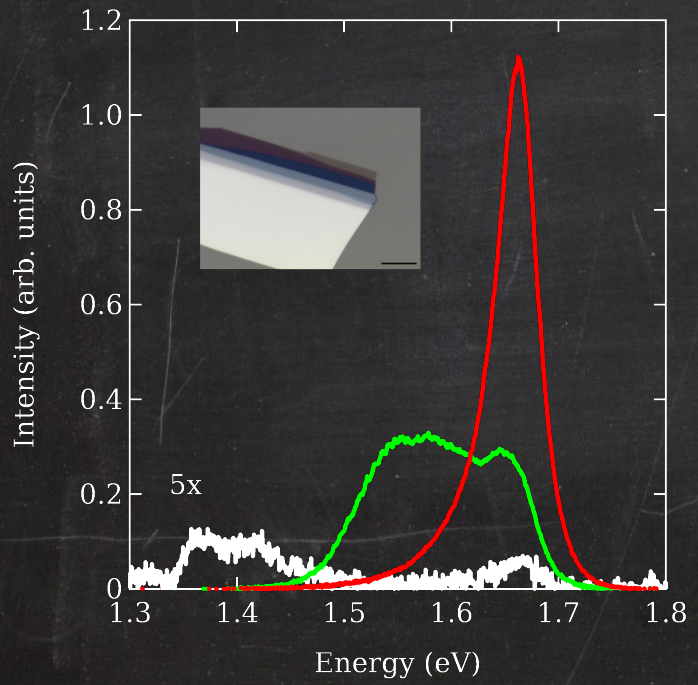
- Hall conductivity can be $\neq 0$ in absence of magnetic field
- Condition: System with broken inversion symmetry and time reversal symmetric
- Valley degree of freedom is of fundamental importance

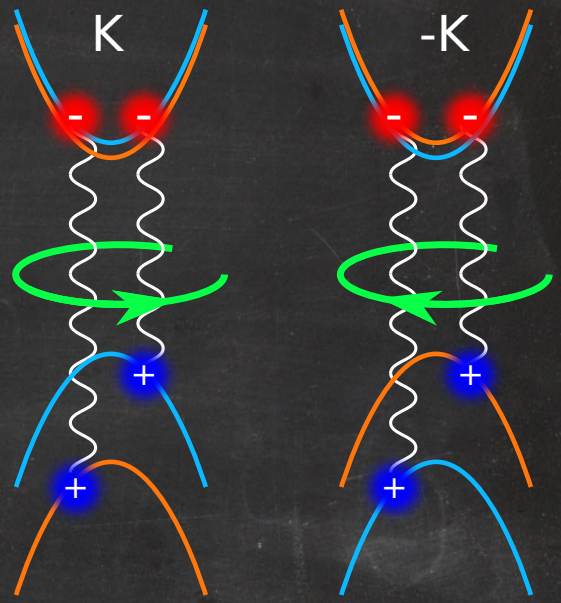
D.Xiao *et al.*, PRL **99**, 236809 (2007)
W.Yao *et al.*, PRB **77**, 235406 (2008)
D.Xiao *et al.*, PRL **108**, 196802 (2012)

The effect relies on optically generated quasi-particle, i.e. *excitons* and *charged excitons*

Group VI TMD







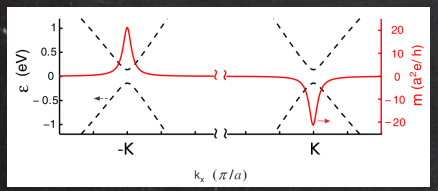
- WS_2, MoS_2, WSe_2, $MoSe_2$, $MoTe_2$
- Direct band gap at K and K' points
- Broken inversion symmetry
- Circular polarization dependent optical selection rules

Berry curvature and Hall effect

Hall conductivity

$$\sigma_{\mathrm{Hall}} = \frac{e^2}{\hbar} \int \frac{\mathrm{d}\mathbf{k}}{(2\pi^2)} f(\mathbf{k})\Omega(\mathbf{k})$$

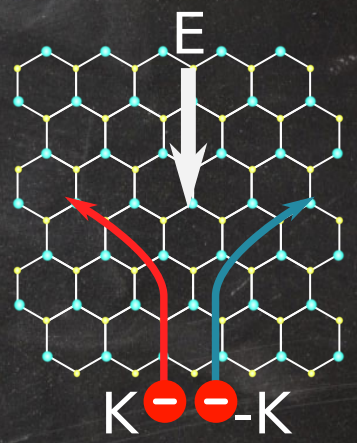
$\Omega(\mathbf{k})$ Berry curvature
$f(\mathbf{k})$ Fermi-Dirac



Xiao *et al.*, PRL **99**, 236809 (2007)

- Berry curvature has opposite sign in K and -K valleys
- In equilibrium Hall conductivities of each single valley cancel out each over

$$\sigma^{K}_{\mathrm{Hall}} = -\sigma^{-K}_{\mathrm{Hall}}$$



Berry curvature and Hall effect

Hall conductivity

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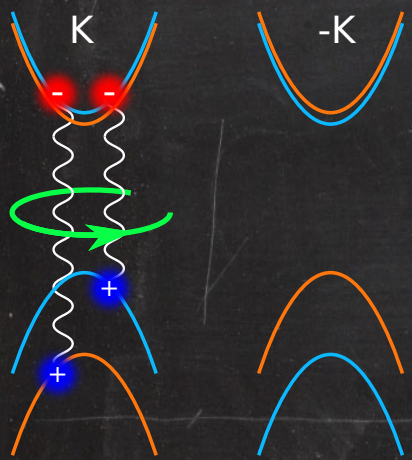
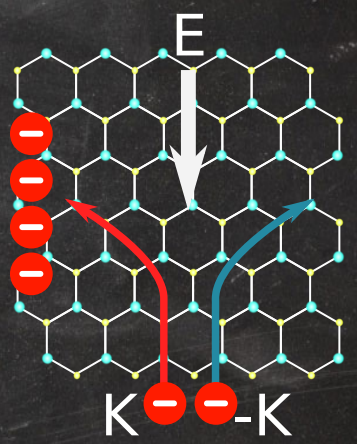
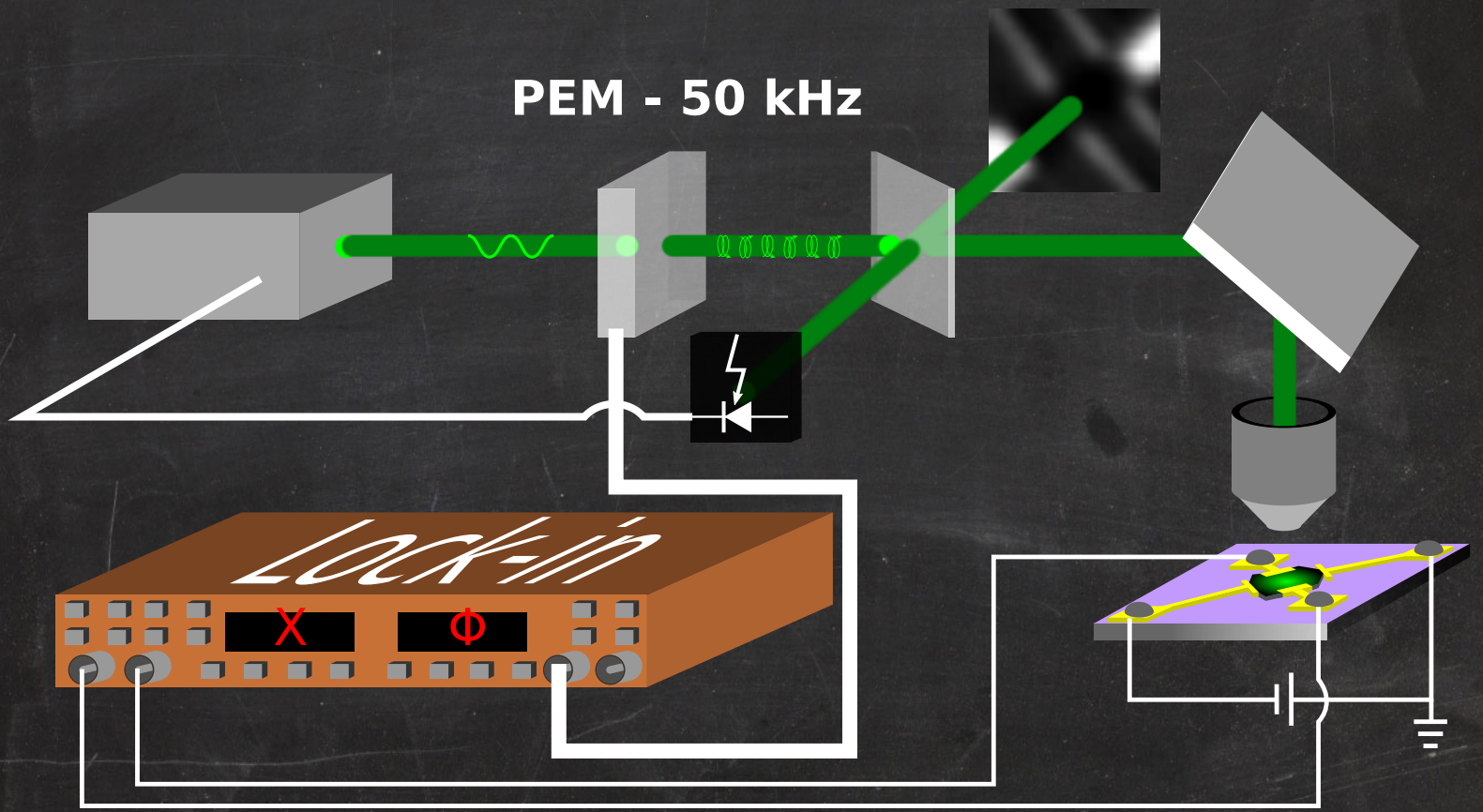


- Circular polarization induces a non-equilibrium distribution between both valley
- Emergence of a light induced Hall voltage without magnetic field

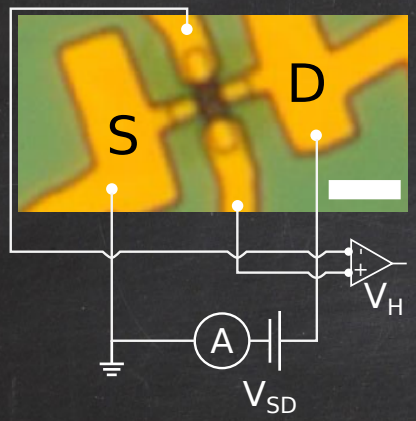


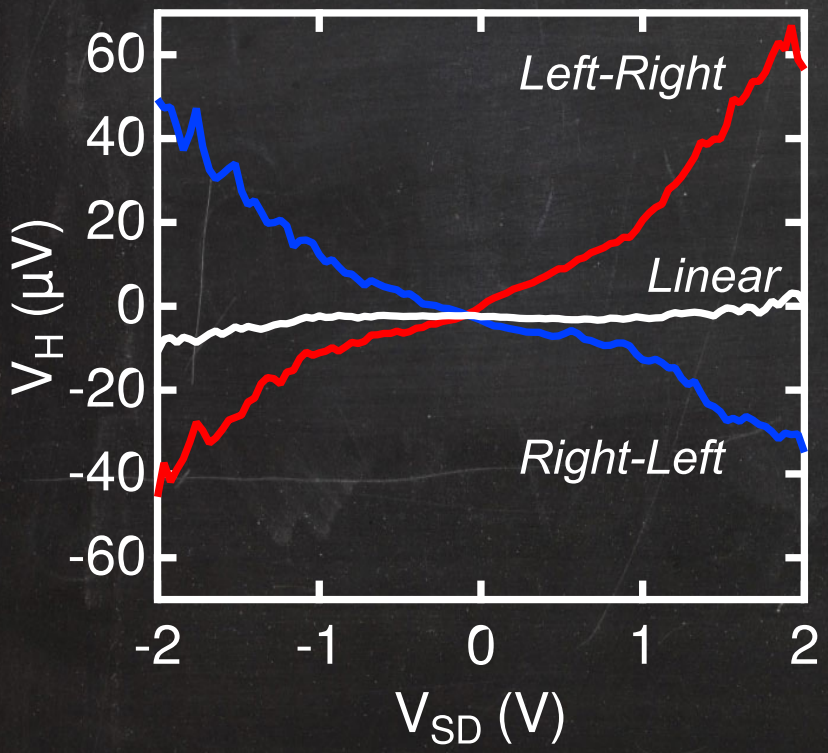
$$\sigma^{K}_{\mathrm{Hall}} > -\sigma^{-K}_{\mathrm{Hall}}$$

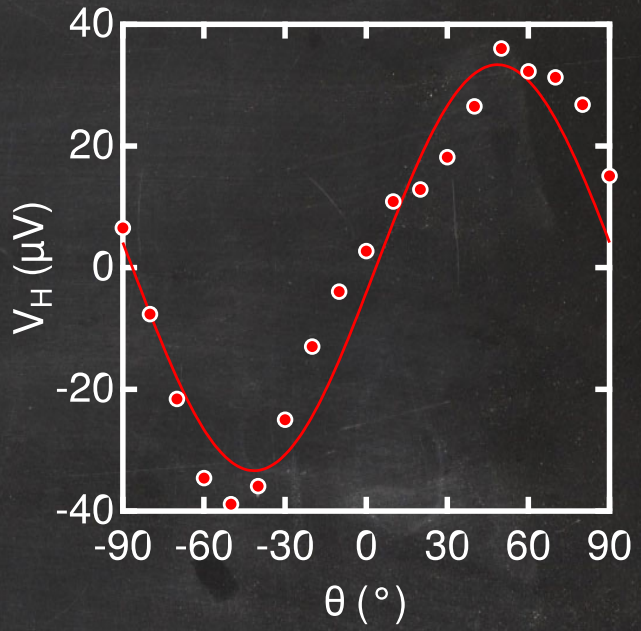
Experimental setup



Valley Hall effect in WS_2

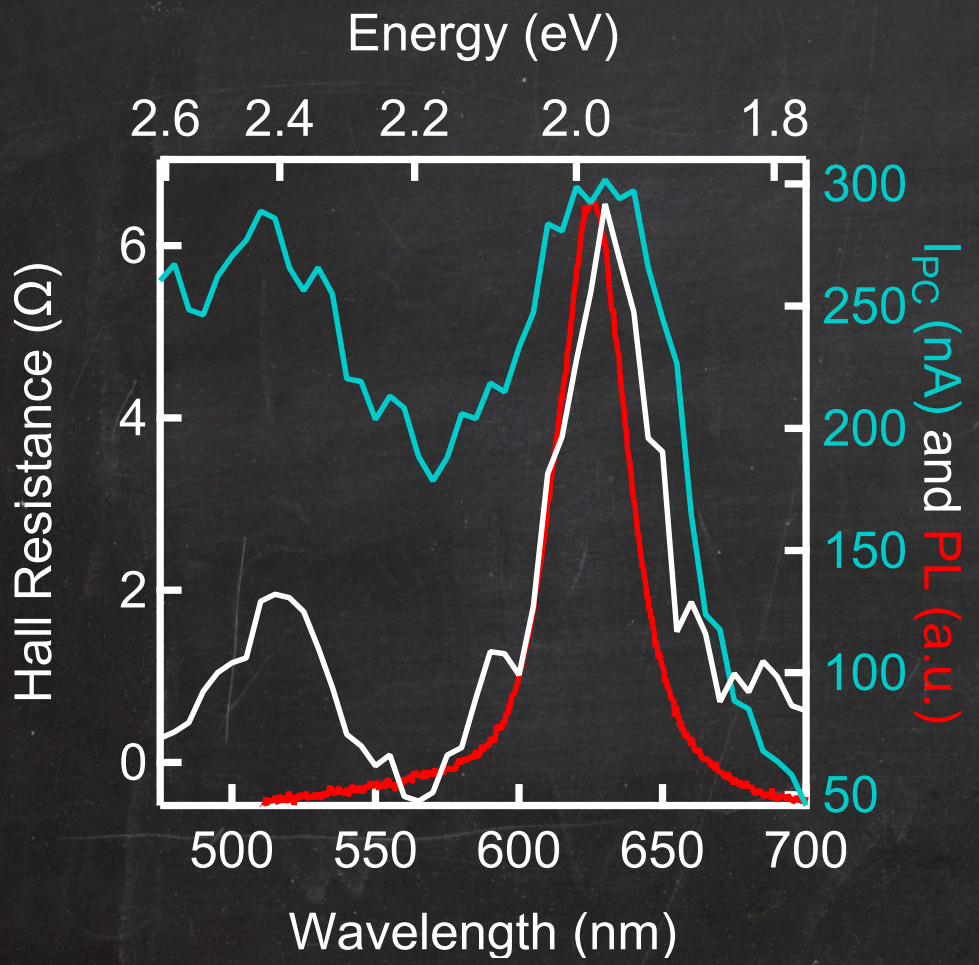






- Shining circular polarized light on a device with a simple geometry
- Signal proportional to the degree of circular polarization

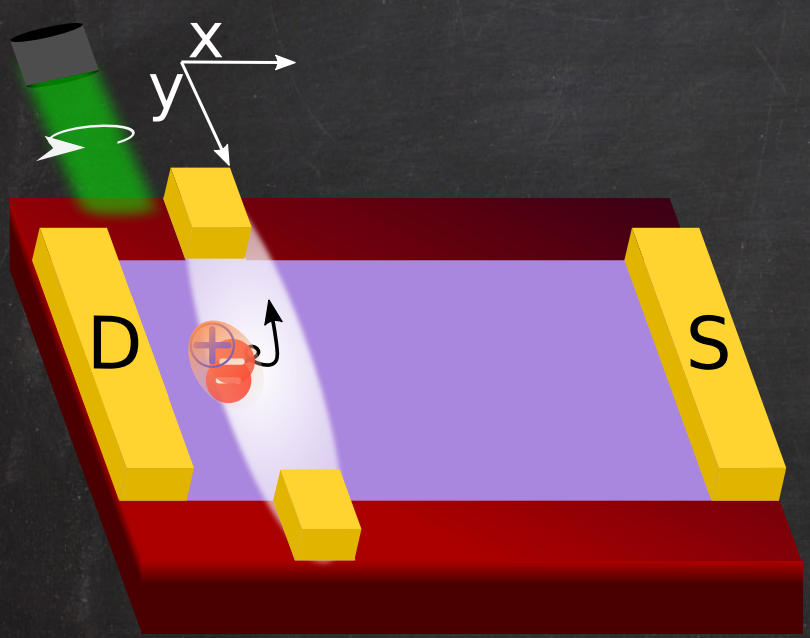
Valley Hall effect in WS_2



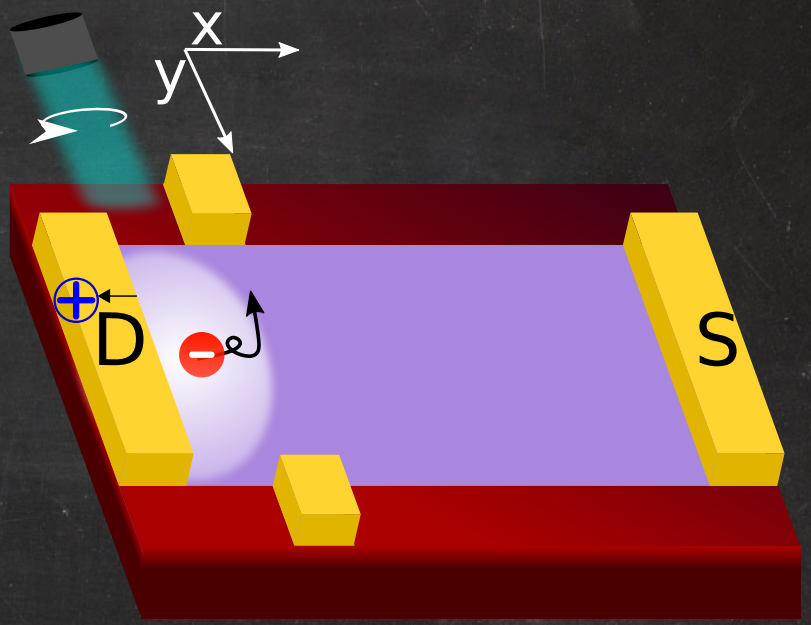
- The key point to understand the effect is the spectral repsonse of the effect
- VHE signal peaks at the same incident energy as PL and photocurrent
- Optical response is governed by quasi-particles with hundred meV binding energy
- Excitons are charge neutral $\rightarrow$ No voltage, even if they accumulate

Valley Hall Effect from Excitons and Trions

VHE from trions (X^A_-)

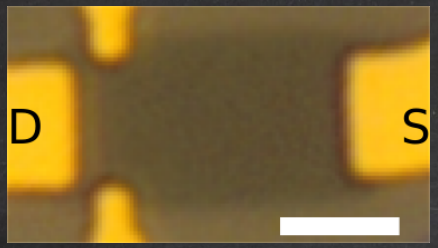


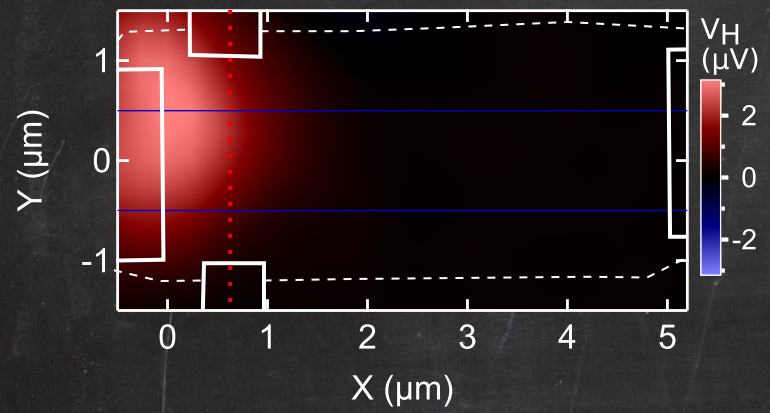
VHE from excitons (X^A_0)

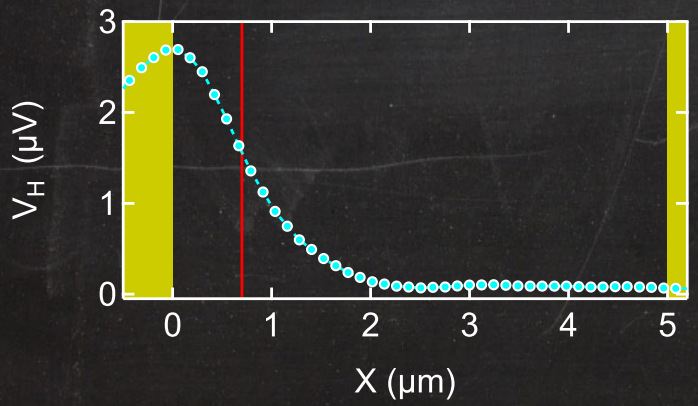


Experimental strategy to discriminate between both mechanisms

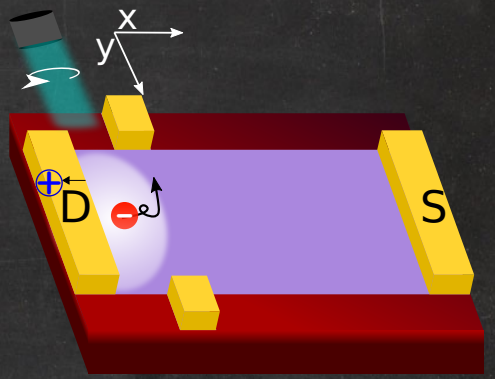
Excitonic Origin of the VHE in WS_2

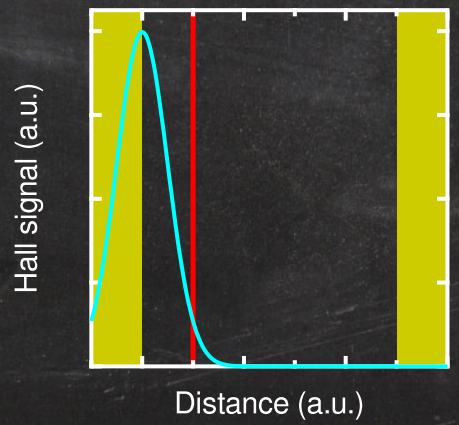






VHE from excitons (X_0^A)





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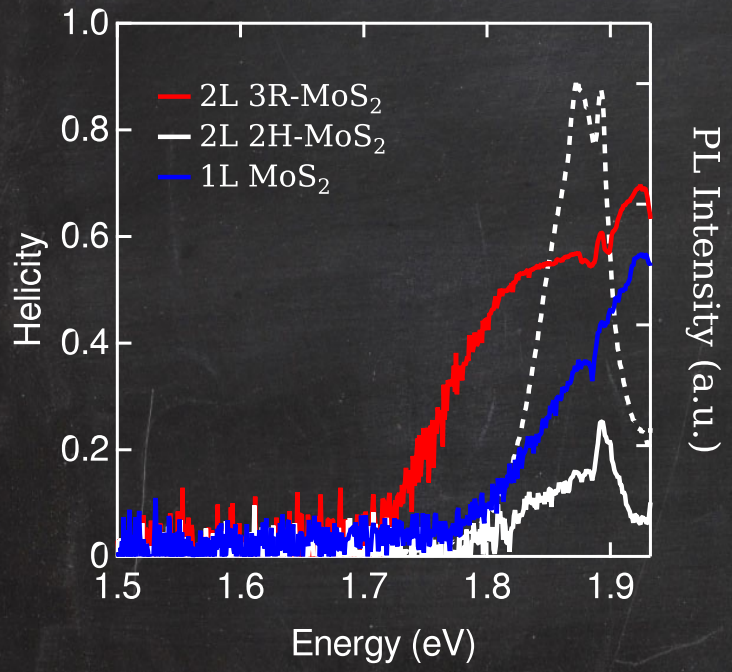
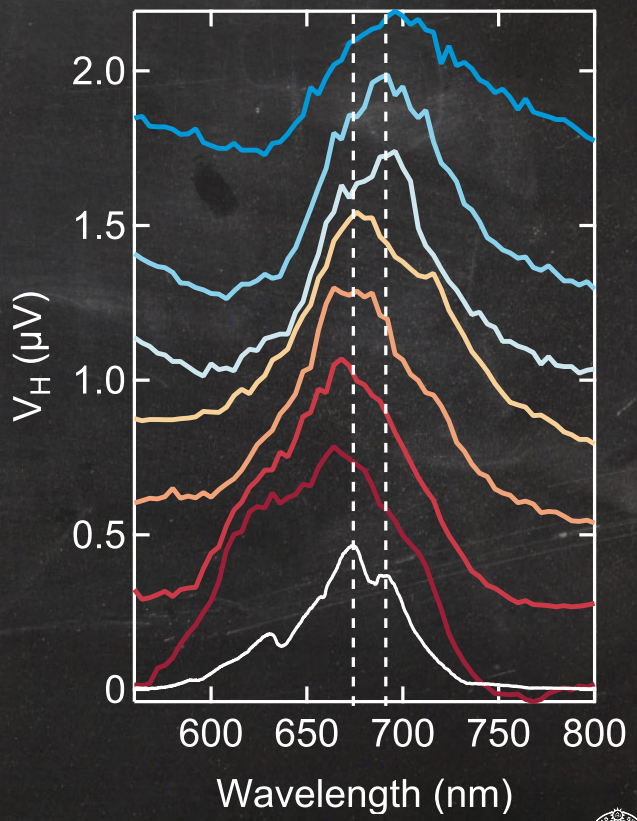
Valley Hall Effect in bilayer 3R-MoS_2

3R type TMDs: Inversion symmetry broken





Suzuki *et al.*, Nat. Nanotech. **9**, 611-617 (2014)

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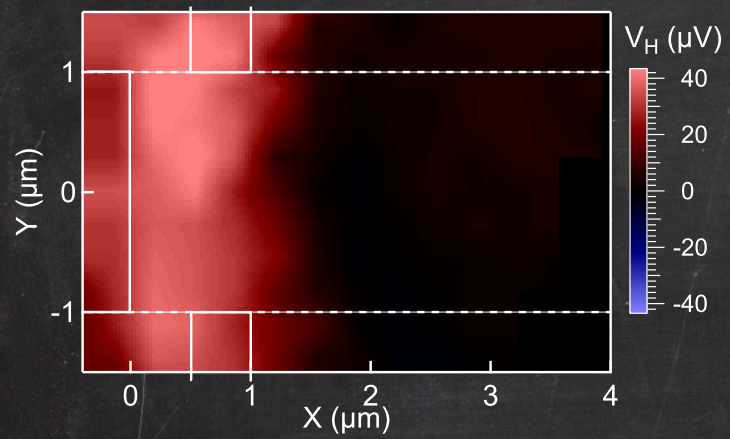
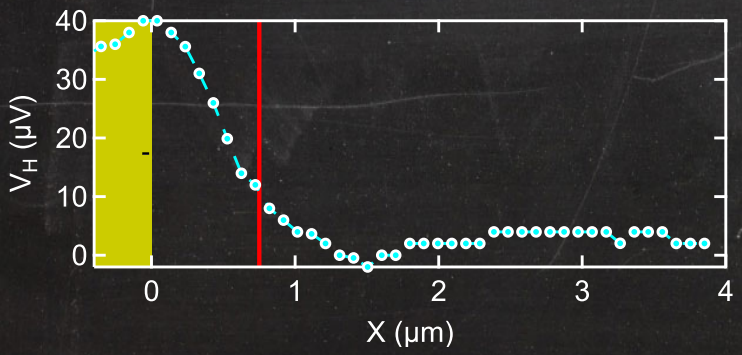
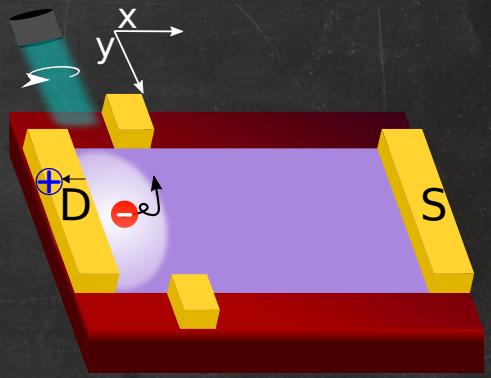
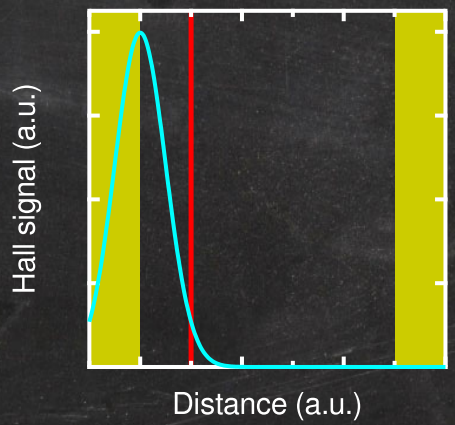
VHE from excitons (X_0^A)

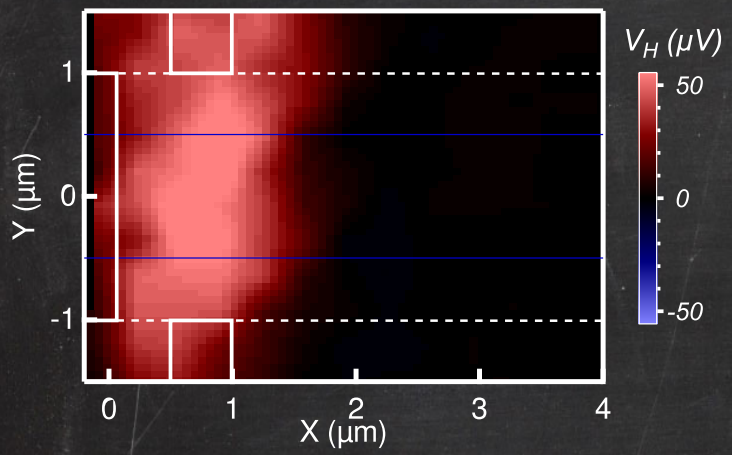


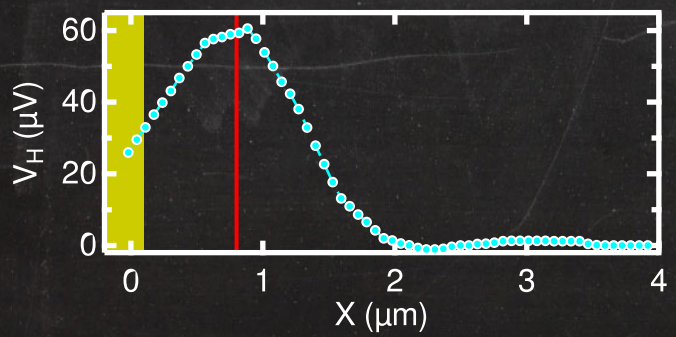


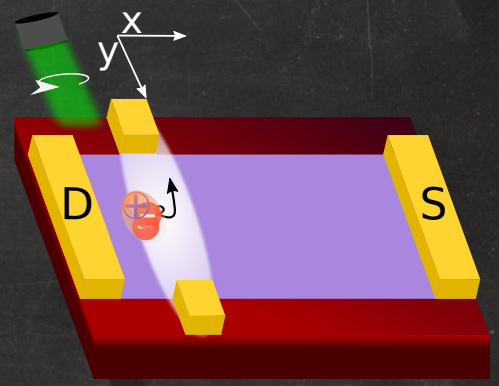


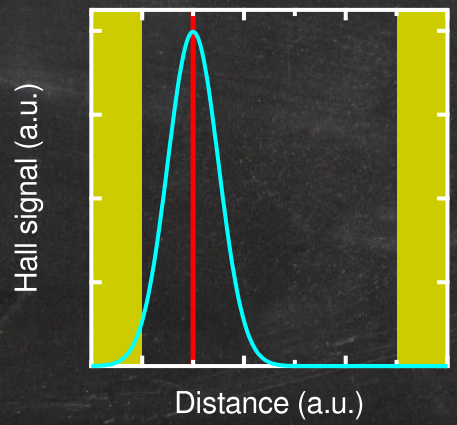


VHE from trions (X^A_-)









Conclusion

- VHE is mainly mediated by excitons and trions
- Demonstration of an experimental strategy to discriminate between exciton and trion contribution to the VHE
- Composite quasi-particles possess a Berry curvature

Outlook

- Se based TMDs narrower linewidth
- Determination of the valley coherence length

NU *et al.*, Nano Letters **17**, 5719–5725 (2017)

Aknowledgements

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