VALLEYTRONICS

Divide and polarize

The valley index of an electron is a magnetic moment that can be initialized optically and probed electrically. Now, experiments reveal how magnetic fields can break the degeneracy for states with different valley indices.

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Transition metal dichalcogenides, such as tungsten diselenide (WSe$_2$) and molybdenum disulphide (MoS$_2$), are atomically flat semiconductors when thinned down to one monolayer. In addition to the electron spin, the carriers in these systems also possess a valley magnetic moment that is associated with their valley index in momentum space. Addressing the non-equivalent, degenerate valley states has so far relied entirely on chiral optical selections rules. But now, as they report in *Nature Physics*, two groups have independently shown that the application of a magnetic field introduces a valley Zeeman splitting in monolayer WSe$_2$ — resulting in preferential valley polarization[1,2].

Monolayers of transition metal dichalcogenides are two-dimensional (2D) semiconductors whose light absorption can be as strong as 15% per monolayer due to direct optical transitions[3,4] in the visible range, compared with a light absorption of only 1% for a typical quasi-2D GaAs structure. These materials allow for optical manipulation of the electron valley index, a long-term goal associated with manifestations of Berry phase effects in solid-state physics[5].

Due to the absence of a crystal inversion centre and a strong spin–orbit interaction in these materials, the interband optical transitions are governed by chiral selection rules: the circular polarization (σ^+ or σ^-) of an absorbed or emitted photon can be directly associated with selective carrier excitation in one of the two non-equivalent K-momentum valleys[6] (Fig. 1). In each valley, all of the spin states are non-degenerate. Time-reversal invariance requires that the spin splittings in the two non-equivalent K$^+$ and K$^-$ valleys have opposite signs. Recent optical spectroscopy experiments confirmed this optical initialization of the valley index, based on the observation of strongly polarized photoluminescence following excitation with polarized laser light[7].

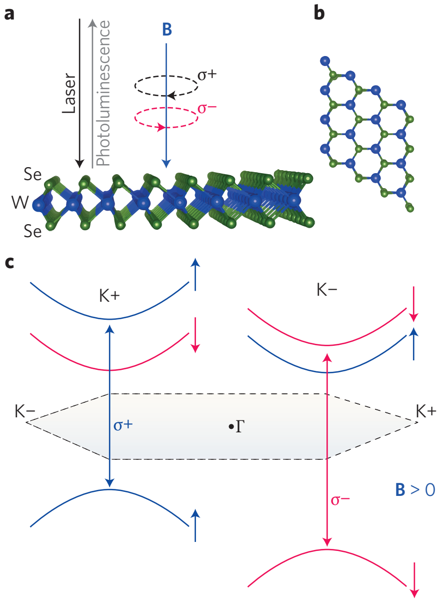

Figure 1 | Valley Zeeman effect. **a**, The magnetic field **B** (blue arrow) is applied perpendicular to the tungsten diselenide (WSe$_2$) monolayer. A circularly polarized (σ^+ or σ^-) laser beam is incident on the surface and the resulting photoluminescence is measured. **b**, Top view of the WSe$_2$ monolayer showing the hexagonal symmetry. **c**, Polarization, σ^+ (blue) and σ^- (red), selection rules and energy shifts of interband optical transitions in the K$^+$ and K$^-$ valley in momentum space in a single particle picture. Γ indicates the centre of the Brillouin zone. Spin up and down states are indicated by short arrows.

In this emerging field of valleytronics, the next step is to control and manipulate the valley index. The two studies published in *Nature Physics* demonstrate that the valley degree of freedom can be manipulated by an external magnetic field applied perpendicular to the 2D layer (Faraday configuration)[1,2]. Both studies clearly demonstrate that the degeneracy of the two valleys in WSe$_2$ monolayers can be lifted. This is achieved by monitoring the energy splitting between the two circularly polarized luminescence components, σ^+ and σ^-, associated with optical recombination in the non-equivalent valleys. As the orientation of the magnetic field is reversed, the sign of the measured valley Zeeman splitting changes and the interaction with the magnetic field is shown to be strongly anisotropic. No such splitting is observed when the magnetic field is applied in the monolayer plane (Voigt geometry) as the orbital magnetic moment of the 2D layer is perpendicular to the plane[8].

These two studies mark only the beginning of investigating optical transitions in monolayer WSe$_2$ and related compounds in magnetic fields. Direct optical transitions in monolayer WSe$_2$ occur at the edge of the Brillouin zone, which mainly consists of strongly localized *d*-orbitals of the transition metal[4]. This is in contrast with GaAs and other conventional semiconductors used in optoelectronics, for which the direct optical bandgap is situated at the centre of the Brillouin zone. In monolayer WSe$_2$ there are several possible contributions to the Zeeman splitting as the emission of circularly polarized light originates from states with contrasting valley index, spin and orbital magnetic moment. As the valleys can now be selectively addressed, these experiments[1,2] will allow the different contributions to the Zeeman splitting to be determined.

Although both research groups measured a clear splitting between the two circularly polarized exciton luminescence components (Coulomb-bound electron–hole pairs) on the order of -0.2 meV T^{-1} for monolayer WSe$_2$, the exact values differ by a factor of two. So, in addition to the contributions intrinsic to WSe$_2$ monolayers, extrinsic factors such as the ratio between the neutral exciton and charged exciton recombination and their respective, optically generated density could play a role. The charged exciton Zeeman splitting is found to be larger than that of the neutral exciton[1,2], confirming the necessity to take into account the strong Coulomb effects in these materials, which yield giant exciton and charged exciton binding energies[9]. Similar results obtained in photoluminescence experiments in another 2D system, namely monolayer molybdenum diselenide (MoSe$_2$)[10,11], confirm that non-equivalent K-valleys can be energetically separated. ❐

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