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<th>Intervley Scattering and Localization Behaviors of Spin-Valley Coupled Dirac Fermions</th>
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We study the quantum diffusive transport of multivalley massive Dirac cones, where time-reversal symmetry requires opposite spin orientations in inequivalent valleys. We show that the intervalley scattering and intravalley scattering can be distinguished from the quantum conductivity that corrects the semiclassical Drude conductivity, due to their distinct symmetries and localization trends. In immediate practice, it allows transport measurements to estimate the intervalley scattering rate in hole-doped monolayers of group-VI transition metal dichalcogenides (e.g., molybdenum dichalcogenides and tungsten dichalcogenides), an ideal class of materials for valleytronics applications. The results can be generalized to a large class of multivalley massive Dirac systems with spin-valley coupling and time-reversal symmetry.

The Bloch bands in many crystals have degenerate but inequivalent extrema in the crystal momentum space, known as valleys. Like the spin index in spintronics, the valley index is a well-defined degree of freedom for low-energy carriers and, thus, can be used to encode information as well. This has led to the concept of valleytronics, a new type of electronics based on manipulating the valley index of carriers [1–5]. The time scale of intervalley scattering determines how long the information represented by valley polarization can be retained. For valleytronics applications to be practical, this time scale shall be long as compared to the typical time for the control of valley dynamics. It is thus crucial to measure the intervalley scattering time for identifying potential valleytronics materials, in particular, in a transport scenario.

Several extensively studied monolayer 2D crystals are promising materials to host valley-based electronics, including graphene, graphenelike crystals such as silicene [6–10], and monolayer group-VI transition metal dichalcogenides [11–14]. In these hexagonal 2D crystals, both the conduction and valence band edges are at the two inequivalent valleys at $K$ points (corners of the first Brillouin zone), which are related by time reversal. In monolayer dichalcogenides, groundbreaking theoretical and experimental progresses on the dynamical control of valleys were recently achieved [15–18]. Unlike graphene, monolayer dichalcogenides are described by massive Dirac fermions, and intrinsic spin-orbit coupling (SOC) gives rise to splitting of valence bands with opposite spins; the splitting must be opposite at the two valleys as required by time-reversal symmetry (see, e.g., Fig. 1). This effective coupling between the spin and valley indices can have two significant consequences for valleytronics: (i) the interplay between spin and valley degrees of freedom and (ii) a unique form of intervalley scattering that must be accompanied by a simultaneous spin flip.

In this Letter, we study the quantum diffusive transport of multivalley massive Dirac fermions with spin-valley coupling. Without loss of generality, we choose the model of monolayer dichalcogenides $MX_2$ ($M = \text{Mo}, \text{W}$; $X = \text{S}, \text{Se}$) for a concrete discussion. This problem is theoretically unique from the conventional 2D electron gas systems or the massless graphene. We show that the spin-valley coupled band edges result in distinct symmetries and localization behaviors in intra- and intervalley scattering dominant regimes. Namely, the spin-conserved intravalley scattering leads to negative quantum conductivity and positive magnetoconductivity from the weak localization (WL) effect, whereas the intervalley spin-flip scattering with time-reversal symmetry gives rise to positive quantum conductivity and negative magnetoconductivity from the weak antilocalization (WAL). The quantum

![FIG. 1 (color online). Low-energy effective band structures of the $MX_2$ monolayer at $K$ and $K'$ valleys. The Fermi surface (at the top edges of the shadowed areas) intersects the highest two valence bands of opposite spin orientations (marked by $\uparrow$ and $\downarrow$). Horizontal dotted arrows indicate the intervalley spin-flip scattering.](image-url)
conductivity and magnetococonductivity have logarithmic
dependence on the ratio between intra- and intervalley
scattering rates, making possible the measurement of the
intervalley scattering in a vastly broad range, from 3
orders of magnitude below to 3 orders of magnitude above
the intravalley scattering rate. Recently, dichalcogenide
field effect transistors became experimentally accessible
[19,20]. Experimental verifications of these phenomena
will reveal the nature of impurities and provide general
guidance on the suppression of intervalley scattering for a
longer valley lifetime necessary for valleytronic applications.
Our approach and results can be readily extended to
spin-valley coupled Dirac fermions with much smaller
masses in monolayers of silicon, germanium, and tin [6],
as they share a similar low-energy band structure.

The band edge electrons and holes in monolayer $MX_2$
are well described by the two-valley massive Dirac model
in two dimensions [15]:

$$H = \hbar v(\pm k_x \sigma_x + k_y \sigma_y) + \Delta \tau_z \pm \lambda \tau_z \sigma_z \Delta \tau_z \sigma_z,$$

where $\pm$ stands for $K$ and $K'$ valleys, respectively. The
Pauli matrices $\sigma_x, \sigma_y$ act on the pseudospin indexing the
$A=\sigma_\zeta$ and $B=(\sigma_\zeta - \sigma_y)/\sqrt{2}$ orbitals, while $\zeta=\uparrow, \downarrow$ is the $\zeta$ component of real spin. $(k_x, k_y)$ is the wave vector
measured from $(K(K'))$ points. The Hamiltonian is described
by three parameters: the SOC strength $\lambda$, the band gap
$\Delta$, and the effective velocity $v$. The resulting band structure
consists of four sets of massive Dirac cones, two in $K$
and two in $K'$ valleys. An important feature is the large SOC
splitting [15,21] ($2\lambda \sim 0.15$ eV in molybdenum dichalco-
genides and $2\lambda \sim 0.4$ eV in tungsten dichalcogenides)
between the spin-up and spin-down states at the valence
band top. The conduction band bottoms remain degenerate.
The band dispersion is schematically shown in Fig. 1. The
model, based on a tight-binding analysis, is further con-
firmed by first-principles calculations and well describes the
optical properties of this family of materials (cf., the
recent experiments on valley-dependent optical selection
rule [16–18]). Here, this model is used in a different context
to address the quantum transport phenomena, which are of
relevance for valleytronics applications based on transistor
or other transport devices.

Because of the large spin splitting in the valence bands,
in the following we focus on the localization effect in hole-
doped samples, when the Fermi surface intersects the two
highest valence bands, as shown in Fig. 1. It is instructive
to first consider two limiting regimes when either intra-
or intervalley scattering dominates.

(1) Intravalley scattering dominant regime. As shown
in Fig. 1, the intravalley scattering within each valence
band can only happen between the same spin species.
Meanwhile, because of the large band gap ($\Delta \sim 1.6$ eV),
the orbital pseudospin is almost fully polarized and does not
play a role. The frozen pseudospin can be quantitatively
seen from the Berry phase [22], which for the valence
bands is given by

$$\phi_\nu = 2\pi \frac{V + \Delta - \lambda}{2V + \Delta - \lambda} \sim 2\pi,$$

where $V$ measures the Fermi energy from the valence band
top. $\Delta$ is much larger than $\lambda$ and allowed $V(\in [0, 2\lambda]$ eV)
in $MX_2$ [15]. The conserved spin and pseudospin rotational
symmetries, along with time-reversal symmetry in this
system, belong to the orthogonal symmetry class [23].
The orthogonal symmetry always predicts WL [24], which is
a negative quantum interference correction to electronic
conductivity and usually shows a positive logarithmic
magnetococonductivity.

(2) Intervalley scattering dominant regime. The intravalley
scattering in $MX_2$ must break spin-rotational sym-
bmetry because of the opposite spin splitting at the two
valleys (Fig. 1). The broken spin-rotational symmetry together with time-reversal symmetry leads to the sym-
plectic symmetry [23]. The symplectic symmetry always promises WL [24], which is a positive quantum interference
correction to electronic conductivity and usually shows a negative logarithmic magnetococonductivity.

To test the above picture, we generalize the diagram-
matic techniques [25–29] to these spin-valley coupled
multivallley massive Dirac cones. The method is based on
expanding the Kubo formula of conductivity, with Eq. (1)
as the unperturbed part and scattering potentials as pertur-
bations. The spin-conserved intravalley scattering is model-
ed by

$$U^0_{k,k'} = \sum_R u^R \delta^{(k'-k)^R},$$

where $u^R$ is the potential of an impurity at position
$R, k, k'$ are electron wave vectors. Although the intravalley scattering should be related to long-range potentials,
the short-range potential and the delta correlation used for
$U^0$ have been justified numerically [30]. In the basis of
$\{+ A\}, \{- A\}, \{- B\}$, the spin-flip inter-
valley scattering that preserves time-reversal symmetry
can be in general modeled by

$$U^l_{k,k'} = \begin{pmatrix} U^A_z & 0 & U^A_{+} & 0 \\ 0 & U^B_{+} & 0 & U^B_z \\ U^A_{+} & 0 & -U^B_{+} & 0 \\ 0 & U^B_{+} & 0 & -U^B_z \end{pmatrix},$$

$$U^{A/B}_{z} = i \sum_{R \in A/B} u^R e^{i(k'-k)^R},$$

$$U^{A/B}_{\pm} = i \sum_{R \in A/B} e^{-i(k'-k)^R}(u^R_+ + iu^R_-),$$

where $\hat{x}, \hat{y}, \hat{z}$ are the unit vectors. The $i$ in front of $U^l_{k,k'}$
protects time-reversal symmetry as $i$ and spins formed by
$\{+ A\}, \{- A\}$ and $\{+ B\}, \{- B\}$ change sign under
time reversal. For two possible spin-flip mechanisms, the magnetic scattering and spin-orbit scattering, the latter preserves time-reversal symmetry and is likely to exist in the materials. For the spin-orbit scattering (\(u_{i}^{R}, u_{i}^{R'}, u_{i}^{R}) = u_{i}^{R}k \times k' \cdot (\hat{x}, \hat{y}, \hat{z})\), where \(k\) and \(k'\) also change sign under time reversal.

The total conductivity is given by
\[
\sigma = \sigma^D + \sigma^F, \tag{5}
\]
where \(\sigma^D\) is the semiclassical (Drude) conductivity following the Einstein relation
\[
\sigma^D = e^2 N_F D, \tag{6}
\]
where \(N_F = E_F/(\pi \hbar^2 v_F^2)\) is the two-valley density of states of at the Fermi energy \(E_F\) measured from the Dirac point, \(D = \eta_v v_F^2 \tau/2\) is the diffusion constant, \(\eta_v\) is the ladder diagram correction to the velocity of Dirac fermions [31], \(v_F\) is the Fermi velocity, and the total scattering time is given by \(\tau = (1/\tau_0 + 1/\tau_1)^{-1}\). \(\tau_0\) and \(\tau_1\) are intravalley and intervalley scattering times, respectively. Since \(\sigma^D\) is a function of the total scattering time, it cannot distinguish the contributions from intervalley and intravalley scattering. Besides, \(\sigma^D\) is insensitive to magnetic field.

The quantum interference correction to the Drude conductivity (quantum conductivity, for short) is found in forms of logarithmic functions
\[
\sigma^F = \frac{\hbar}{e^2} \left( C_0 \ln \frac{X_0^2 + \ell_\phi^2}{X_0^2 + \ell^2} + C_1 \ln \frac{X_1^2 + \ell_\phi^2}{X_1^2 + \ell^2} \right), \tag{7}
\]
where \(C_0\) and \(C_1\) are weight factors for the intravalley and intervalley contributions. \(X_0\) and \(X_1\) are corresponding characteristic lengths that effectively reduce the mean free path \(\ell\) and phase coherence length \(\ell_\phi\). The ratio between the intravalley and intervalley scattering times is incorporated in the expressions for \(C_{0,1}\) and \(X_{0,1}\) [32]. Due to its interference origin, \(\sigma^F\) can be suppressed by a perpendicular magnetic field \(B_z\), giving rise to the magnetic conductivity
\[
\Delta \sigma(B_z) \equiv \sigma^F(B_z) - \sigma^F(0) = \frac{\hbar}{e^2} (C_0 F_0 + C_1 F_1), \tag{8}
\]
where \(F_i = \Psi(\ell_\phi^2/\ell_i^2 + \frac{1}{2}) - \ln(\ell_\phi^2/\ell_i^2), 1/\ell_i^2 = 1/\ell_\phi^2 + 1/X_i^2\), \(\Psi\) is the digamma function, and \(\ell_R = \sqrt{\hbar/(4e|B_z|)}\) is the magnetic length [32]. Considering the low mobility in \(MX_2\) [19], we have assumed short \(\tau\) and \(\ell = \sqrt{D/\tau}\); then, the results are not sensitive to \(\ell\) and \(\tau\).

Figure 2(b) shows the magnetic conductivity without intervalley scattering when the Fermi energy intersects with the two highest valence bands. The WL is a quantum interference induced suppression of conductivity; it can be lifted by magnetic field and gives positive magneticconductivity. Figure 2(b) shows that the magnetic conductivity is always positive, corresponding to the WL of the single valence band in the allowed range of the Fermi energy. Increasing the magnetic field and gives positive magnetoconductivity; it can be lifted by magnetic field and gives positive magneticconductivity. Figure 2(b) shows that the magnetic conductivity is always positive, corresponding to the WL of the single valence band in the allowed range of the Fermi energy.
the coefficients \( C \). The characteristic temperature at which \( \sigma^{\text{F}} \) corresponds to WAL (WL). Other parameters are the same as those in Figs. 2(c) and 2(d). The signature that intervalley (intravalley) scattering is stronger than intravalley (intervalley) scattering is given by a positive (negative) \( \sigma^{\text{F}} \), as well as by the fact that \( \sigma^{\text{F}} \) decreases (increases) with decreasing \( T \).

than the mean free path \( \ell \). \( \ell_{\phi} \) increases as the decoherence mechanisms from electron-phonon and electron-electron interactions are suppressed at low temperatures. Empirically, \( \ell_{\phi} = C_{\text{ph}}(T/T^*)^{-3/2} + C_{\text{ee}}(T/T^*)^{-1/2} \), where the coefficients \( C_{\text{ph}} \) and \( C_{\text{ee}} \) are for electron-phonon and electron-electron interactions, respectively. \( T^* \) is a characteristic temperature at which \( \ell_{\phi} = \ell \) and \( \sigma^{\text{F}} \) vanishes, so it defines the boundary between the quantum and classical diffusion regimes. Usually, \( T^* \) ranges between 10 and 100 K [36–38]. In the calculation, we assume that \( \ell_{\phi} = 300 \text{ nm} \) at \( T/T^* = 0.01 \) and \( \ell_{\phi} = \ell \) at \( T/T^* = 1 \). Figure 3 shows \( \sigma^{\text{F}}(T) \) in Eq. (7) for different \( \tau_0/\tau_1 \). The WL (WAL) can be read from a negative (positive) \( \sigma^{\text{F}} \), as well as the fact that \( \sigma^{\text{F}} \) decreases (increases) with decreasing temperature. Note that the total conductivity is \( \sigma(T) = \sigma^0 + \sigma^{\text{F}}(T, B) \), where the Drude conductivity \( \sigma^0 \) may give an extra temperature power law that depends on scattering mechanisms [37,38]. But \( \sigma^{\text{F}} \) from the weak (anti)localization is the contribution most sensitive to magnetic field (because of the logarithmic dependence). \( \sigma^{\text{F}} \) can thus be extracted from the total conductivity by \( \sigma^{\text{F}}(T) = \sigma(T, 0) - \sigma(T, B_c) \), with \( B_c \) a finite magnetic field strong enough to quench the weak (anti)localization of, say, about 1 Tesla.

We can also have some qualitative arguments for the conduction bands. All four conduction bands can take part in transport as they always intersect the Fermi surface together. Therefore, different from the transport in hole-doped samples, both intravalley spin-flip and intervalley spin-conserved scattering are possible in the conduction bands. With time-reversal symmetry, the spin-flip scattering leads to WAL, while spin-conserved scattering leads to WL, as the pseudospin degree of freedom is always frozen. All types of scattering and the resulting WL and WAL are shown in Fig. 4.

The existing experiments on the MX₂ monolayers [19,20] are mainly focused on the on-off characteristics of field-effect transistors, implying that the resistance in the samples still comes mainly from the Schottky barriers between mismatched metal electrodes and monolayers instead of from the monolayers themselves. We expect our theory to inspire more experimental efforts for realizing good Ohm contacts (e.g., by liquid gating) and to explore the spin-valley coupled physics in transport.

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