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Spin splitting in graphene studied by means of tilted magnetic-field experiments

E. V. Kurganova,1 H. J. van Elseren,1 A. McCollam,1 L. A. Ponomarenko,2 K. S. Novoselov,2 A. Veligura,3 B. J. van Wees,3 J. C. Maan,1 and U. Zeitler1∗
1 Radboud University Nijmegen, Institute for Molecules and Materials, High Field Magnet Laboratory, Toernooiveld 7, 6525 ED Nijmegen, The Netherlands
2 School of Physics and Astronomy, University of Manchester, M13 9PL, Manchester, United Kingdom
3 Physics of Nanodevices, Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands
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We have measured the spin splitting in single-layer and bilayer graphene by means of tilted magnetic field experiments. Applying the Lifshitz-Kosevich formula for the spin-induced decrease of the Shubnikov de Haas amplitudes with increasing tilt angle we directly determine the product between the carrier cyclotron mass $m^*$ and the effective $g$-factor $g^*$ as a function of the charge carrier concentration. Using the cyclotron mass for a single-layer and a bilayer graphene we find an enhanced $g$-factor $g^* = 2.7 \pm 0.2$ for both systems.

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The half-integer quantum Hall effect in single-layer graphene (SLG) [1] and the unconventional quantum Hall effect in bilayer graphene (BLG) [2] reveal spin- and valley-degenerate relativistic Landau levels. Due to the extremely large Landau-level splitting [3] [4], completely resolved levels can be observed up to room temperature [5]. However, even at very high perpendicular magnetic fields the Zeeman splitting within one Landau-level is negligible smaller compared to the Landau-level splitting and, more importantly, the Landau-level width generally exceeds the spin-splitting. Exceptionally, the zeroth Landau level in SLG becomes extremely narrow at magnetic fields $B > 20$ T [4], which allows an experimental observation of a spin-related gap opening at magnetic fields $B > 20$ T [7]. Another observation of a spin degeneracy lifting with an effective $g$-factor $g^* = 2$ was reported for $\nu = \pm 4$, in SLG for magnetic fields $B > 30$ T, combined with lifting the valley-degeneracy at $\nu = \pm 1$ [6].

In this paper we determine the spin splitting of broadened Landau levels for SLG and BLG by measuring Shubnikov-de Haas (SdH) oscillations in tilted magnetic fields. This technique allows adjusting the ratio between the spin splitting and the Landau level splitting, by controlling the ratio between a total magnetic field and a component perpendicular to a two-dimensional graphene flake. Using the well-established Lifshitz-Kosevich formula [9] [10] we determine the product of effective $g$-factor and cyclotron mass, $m^* g^*$, from the angular dependence of the SdH amplitudes and we find that $g^*$ is enhanced compared to the free electron value.

We have fabricated field-effect transistors from SLG and BLG, by micromechanically exfoliating graphene flakes from graphite. The flakes were deposited on top of a Si/SiO$_2$ wafer, structured into a Hall-bar and covered with Au/Ti contacts [11]. Charge carriers are introduced by applying a gate voltage on the conducting Si substrate.

We present a detailed analysis on the spin splitting in a SLG sample made from Kish graphite with a mobility $\mu = 0.8$ Vm$^{-2}$s$^{-1}$ and BLG sample originating from natural graphite with a mobility $\mu = 0.3$ Vm$^{-2}$s$^{-1}$. Two other devices, one SLG and one BLG sample, showed qualitatively similar results.

To determine the spin-splitting we have measured the longitudinal resistances $R_{xx}$ as a function of charge carrier concentration $n$ at a constant perpendicular magnetic field. We adjusted the total magnetic field $B_{tot}$ for each tilt angle such that the normal component $B_n$ is the same (inset to Fig.1). The value of $B_n$ was verified by measuring the Hall resistance of the devices in the non-quantized regime.

In Fig.1 we show the experimental $R_{xx}(n)$ dependencies for SLG at $B_n = 6$ T (a) and for BLG at $B_n = 8$ T (b). $R_{xx}$ shows Shubnikov-de Haas oscillations with maxima whenever the Fermi energy is situated in the middle of a spin- and valley-degenerated Landau level $E_N$, $N = 0, 1, 2, ...$ being the Landau-level index. For the higher Landau levels ($N \geq 2$) the longitudinal resistances do not exhibit zero minima indicating that the level broadening is comparable to the cyclotron energy at these perpendicular magnetic fields.

When increasing $B_{tot}$ at a constant $B_n$ the oscillation amplitudes for both BLG and SLG are reduced. From this reduction we determined the spin-splitting. We use the Lifshitz-Kosevich formula for systems with a general dispersion and we specifically include spin-splitting [9] [10] with an effective $g$-factor $g^*$ [12] [13] and tilted magnetic fields [14]. The oscillatory contribution to the longitudinal resistance can be described as [2]:

$$\tilde{R}_{xx} = A \cos \left( \frac{h}{eB_n} S(E)|_{E=E_F} + \pi + \varphi_B \right)$$

where $S(E)|_{E=E_F}$ is a extremal cross section of the Landau orbits in the $k$-space, $A$ is the oscillation amplitude and $\varphi_B$ is Berry phase, $\varphi_B = \pi$ for SLG [1] [2].
The amplitude $A$ contains a monotonic $n$-dependent part, a temperature dependence, a $B_n$-dependent contribution and a damping factor due to spin splitting depending on the total field $B_{tot}$.

For clarity all amplitudes are normalized to $A_0$.

For the spherical Fermi surface in SLG and BLG with a Fermi wave-vector $k_F = \sqrt{\pi n}$, the extremal cross section of the Landau orbits is $S(E)|_{E=E_F} = \pi k_F^2 = n \pi^2$ and Eq. (1) yields the concentration-dependent resistance oscillations as we observe them in our experiments:

$$\tilde{R}_{xx} = A \cos \left( \frac{\hbar \pi^2}{eB_n} n + \pi + \varphi_B \right) = A \cos \left( \frac{\pi}{2} \nu + \pi + \varphi_B \right),$$

where $\nu = (\hbar n)/(eB_n)$ is the filling factor. As expected, the oscillation period, $(2\pi B_n)/(|\hbar \pi|)$, is independent on the band structure of the 2D material and only depends on the filling factor.

To accurately determine the experimental oscillation amplitudes we have fitted our experimental data $R_{xx}(n)$ to Eq. (2) in two steps. First we determined the oscillation period and a smooth background using all oscillations measured for a wide range of the carrier concentrations. Second we fitted the oscillation amplitudes $A$ for each individual oscillation using the above determined period and background as fixed parameters. In Fig. 2 we show the final results of this fitting procedure for the SdH amplitude as a function of the total magnetic field for different Landau levels $N$. For clarity all amplitudes are normalized to $A_0$.

FIG. 1: (color online) Shubnikov de Haas oscillations in SLG (a) at $T = 1.3$ K and in BLG (b) at $T = 0.4$ K as a function of the carrier concentration for different total fields $B_{tot}$ or tilt angles $\theta$, respectively. When varying $\theta$ the total field $B_{tot}$ is adjusted such that the perpendicular field $B_n$ remains constant, i.e. $B_{tot} = B_n \cos \theta$. The oscillation maxima are marked with the corresponding Landau level numbers $N$. The inset schematically shows this tilting configuration.

FIG. 2: (color online) Normalized oscillation amplitudes as a function of total field $B_{tot}$ at a constant perpendicular field $B_n$ in SLG (a) and BLG (b). Error bars represent standard least squares fitting errors in the determination of $A$. Solid lines are fits to Eq. (2) with $m^* g^*$ as a fit parameter.

The experimentally observed reduction of the SdH amplitudes can be qualitatively visualized in a simple density of states (DOS) picture of a Landau level as depicted in Fig. 3a. In a purely perpendicular magnetic field the Landau level width exceeds the spin splitting and the DOS of the spin-down state (orange, horizontally dashed in Fig. 3a) overlaps with the one of the spin-up states (red, vertically dashed) to one broad Landau level. When increasing $B_{tot}$ by leaving $B_n$ constant, these two states move apart yielding an additional broadening of the Landau level with a reduced DOS in the center (green, solid areas in Fig. 3a). Eventually, when the spin splitting exceeds the level width a minimum between two distinct levels starts to develop in the DOS. This scenario is indeed observed experimentally in SLG (Fig. 3b). The SdH maxima corresponding to the $N = 9$ and $N = 10$ Landau levels starts to develop in the DOS. This scenario is indeed observed experimentally in SLG (Fig. 3b). The SdH maxima corresponding to the $N = 9$ and $N = 10$
dau levels at $B_{tot} = B_n = 5$ T do not show any splitting. Increasing of the total field at a constant perpendicular component leads to a reduction of the oscillation amplitude and eventually appearance of spin-resolved peaks at the highest field of 28 T. However, this splitting is not yet enough to determine the energy difference by e.g. activation measurements.

A quantitative analysis of this decrease of the SdH amplitudes with increasing total magnetic field is done by fitting the data to Eq. 3 with $m^*g^*$ as a fitting parameter (solid lines in Fig. 2). The values for $m^*g^*$ obtained are plotted as a function of the charge carrier concentration in Fig. 3 for SLG (a) and BLG (b).

For both SLG and BLG the product $m^*g^*$ increases with concentration, which can be mainly attributed to the concentration dependent cyclotron mass $m^*$ of particles with a linear [1] and hyperbolic dispersion [15] as predicted by Eq. 3.

The dashed lines in Fig. 3a show the calculated dependence of $m^*g^*$ for $g^* = 2$ and $g^* = 2.7$ using $m^*(n) = (h/c) \sqrt{\pi n}$ [1]. The shadowed areas represent a 10% uncertainty of this calculation mainly due to the experimental errors and some uncertainty in the Fermi velocity [14].

For SLG (Fig. 3a), the increase of $m^*g^*$ with $n$ is symmetric for electrons and holes (i.e. negative and positive $n$ in the figure). A best fit using $m^*(n)$ for SLG yields $g^* = 2.7 \pm 0.2$ (the error is the standard deviation). This finding is shown directly in the inset of Fig. 3a, where we plot the value of $g^*$ determined in the middle of each Landau level $N$ for different perpendicular fields $B_n$. Within an experimental error $g^*$ does not show any dependence on $N$ or $B_n$.

For BLG (Fig. 3b) the experimental situation is more complex as the observed increase of $m^*g^*$ with $n$ is not symmetric for holes and electrons. Such a behavior is caused by an asymmetry of $m^*$ resulting from an asymmetric band structure of biased BLG, which was already observed experimentally in transport experiments [17], cyclotron resonance [18] and activation-gap measurements [5]. Applying the experimental cyclotron mass from Ref. [17] (depicted as blue crosses in Fig. 3) allows us to estimate $g^*$ to be about 2.5 for both electrons and holes which is, within experimental accuracy, reasonably consistent with the $g$-factor enhancement observed in SLG.

The observed enhancement of the effective spin-splitting compared to its free-electron value can be explained by electron-electron interaction [19] yielding an interaction-enhanced splitting between two spin levels within one Landau level [20] [21].
\[ g^* \mu_B B_{tot} = g \mu_B B_{tot} + E_{cz}^0 (n_\downarrow - n_\uparrow). \]  
\hspace{1cm} (5)

Here \( g = 2 \) is a free-electron \( g \)-factor, \( E_{cz}^0 \) is an exchange interaction, \( \Gamma > g^* \mu_B B_{tot} \), i.e. where the spin splitting is not yet resolved, this relative occupation difference can be approximated using the Taylor expansion of the Gauss error function \( \text{erf}(g^* \mu_B B_{tot}/\Gamma) \):

\[ n_\downarrow - n_\uparrow \approx \sqrt{\frac{1}{2\pi}} \frac{g^* \mu_B B_{tot}}{\Gamma} \]  
\hspace{1cm} (6)

and Eq. (5) yields:

\[ \frac{g^*}{g} = \left( 1 - \sqrt{\frac{E_{cz}^0}{\Gamma}} \right)^{-1}. \]  
\hspace{1cm} (7)

\( E_{cz}^0 \) is of the order of Coulomb interaction, \( E_{cz}^0 \propto \sqrt{B_n} \) [21], and \( \Gamma \propto \sqrt{B_n} \) [22]. Therefore, the ratio \( E_{cz}^0/\Gamma \) remains constant and the \( g \)-factor enhancement is indeed predicted to be constant as we observe experimentally. Using the experimentally found \( g^* = 2.7 \) in Eq. (7) yields \( E_{cz}^0 = 130 \text{ K} \) at 10 T when assuming \( \Gamma = 200 \text{ K} \) [4, 5]. For a completely spin polarized system, i.e. \( n_\downarrow - n_\uparrow = 1 \), one might then speculate that the exchange enhancement in the Eq. (5) would be of same order of magnitude larger than a single particle Zeeman energy at this particular field.

Finally, we note, that the experimentally found enhanced values of \( g^* \) in graphene are close to those observed in transport experiments in graphite [23]. This may suggest that an exchange induced enhancement of \( g^* \) is quite common for graphitic materials. In contrast, no interaction-induced \( g \)-factor enhancement is observed using electron-spin resonance in graphene and graphite [24] since these measurements are not sensitive to many body corrections [25]. Interestingly, measuring the Zeeman splitting of single-electron states in quantum dots, where no exchange enhancement of the \( g \)-factor is expected, also yields \( g \approx 2 \) [27], albeit with a considerable experimental uncertainty.

To conclude, we have experimentally measured and analyzed spin-splitting in SLG and BLG. We have shown that the product between the cyclotron mass \( m^* \) and the effective \( g \)-factor \( g^* \) increases with charge carrier concentration, as expected for a linear dispersion in SLG and a hyperbolic dispersion in BLG. Using the known concentration dependence of \( m^* \) we found that \( g^* \) in graphene is enhanced compared to the free-electron value and we attribute this to electron-electron interaction effects.

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