Comment on “Interaction-Induced Shift of the Cyclotron Resonance of Graphene Using Infrared Spectroscopy”

In a recent Letter (the Letter), Henriksen *et al.* [1] used the cyclotron resonance (CR) transitions to probe the unusual $n = 0$ Landau level (LL) of monolayer graphene. By varying the gate voltage, they found that the CR peak between $n = 0$ and $n = 1$ LLs exhibits large and non-monotonic shifts as a function of the LL filling factor. Based on the fact that this shift is much bigger than the Zeeman energy and a heuristic view of CR transition, they concluded that this peak shift is due to the electron-electron ($e-e$) interaction-induced energy gap in the $n = 0$ LL. Although we cannot rule out the picture in the Letter, it seems that disorder-induced shift of density of states (DOS) of Landau subbands can, at least, equally explain the observation if it is not more nature and direct.

It is known [2] that the centers of $n \neq 0$ disorder-broadened Landau bands shift toward $E = 0$ while the $n = 0$ band does not if the Zeeman effect is neglected. In the experiment of the Letter [1], change of LL filling factor ν will inevitably change the charging distribution of the defect states in the substrate. Thus the degree of randomness on the electrons in the graphene varies with the LL filling factor [3]. To demonstrate that disorder-induced LL shifts are the more natural cause of the CR peak shifts, we carry out the similar numerical simulations as those in Ref. [2]. Figure 1 is the DOS for various randomness measured by the renormalized disorder strength $W = g/\sqrt{2\pi}l_B$, where l_B is the magnetic length and g is the on-site energy fluctuation as explained in Ref. [2]. It shows that the $n \neq 0$ LLs shift toward $E = 0$ with the increase of disorder. The inset is randomness dependence of the peak shifts ΔE of the $n = 1$ and $n = 2$ bands. It is clear that the peak shifts of the order of tens of meV in the reasonable range of variation of W . It shows that this randomness-induced peak shift could be a more natural cause of what was observed in the Letter [1].

Furthermore, the $\sqrt{n}$ LL spectrum is the result of linear dispersion relation. In the disorders, the dispersion relation is not linear [4], and the group and phase velocities are substantially reduced near the Dirac point while they remain almost the same values as the unrenormalized ones away from the Dirac point. As a result, $(E_2 - E_{-1})/(E_1 - E_0)$ is bigger than $\sqrt{2} + 1$. This is what was observed in the Letter. On the contrary, $e-e$ interaction will enhance both group and phase velocities near the Dirac point [5]. If $e-e$ interaction is the real cause of the observations of the Letter, $(E_2 - E_{-1})/(E_1 - E_0)$ should be smaller than $\sqrt{2} + 1$. Thus, the explanation in the Letter is not consistent with this fact.

In conclusion, the disorder-induced shift of the $n \neq 0$ LLs provides a natural explanation to the observed shift of

FIG. 1 (color online). DOS for various disorder strengths of spin-up electrons. A small Zeeman shift appears in the $n = 0$ band. A large disorder-induced shift clearly shows in the $n = 1$ bands. Inset: The disorder strength dependence of the peak shifts ΔE of the $n = 1$ and $n = 2$ bands.

CR transition. The observed ratio of $(E_2 - E_{-1})/(E_1 - E_0)$ agrees with the disorder effects and is inconsistent with $e-e$ interaction effects.

This work is supported by HK UGC Grants (No. 604109, No. HKU10-HKUST17/CRF/08 and No. SBI07/08.SC09). Q. W. S. is supported by NNSF of China (No. 10974187) and KIP of the CAS (No. KJCX2-YW-W22).

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Received 7 April 2010; published 7 October 2010

DOI: 10.1103/PhysRevLett.105.159703

PACS numbers: 78.30.Na, 71.70.Di, 76.40.+b, 78.66.Tr

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