Large Artificial Magnetic Fields in Strained Graphene

Strain-Induced Pseudo-magnetic Fields Greater Than 300 Tesla in Graphene Nanobubbles

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Application of a magnetic field has long been a standard probe of solids. The strong magnetic field regime is particularly interesting given the appearance of novel phenomena such as the Fractional Quantum Hall effect. Intense efforts has been devoted to generating strong fields - as a result currently the strongest continuous field that can be produced is about 50 Tesla, while pulsed fields that are non-destructive can go to about twice that value. Fields of several hundred Tesla have remained out of reach.

The featured reference describes an experiment, where effective magnetic fields of about 300Tesla were observed in the electronic spectrum of graphene. These are produced, not by circulating currents as in an electromagnet, but simply by straining the graphene sheet. This may be understood as follows - Graphene's Dirac nodes are at crystal moments $\pm K$. Let us focus on the states near K. In the presence of strain, the hopping matrix elements are modified, so that the Dirac Hamiltonian is now

$$H_K \approx v_F \begin{pmatrix} 0 & q+A \\ q^*+A^* & 0 \end{pmatrix} \tag{1}$$

where $q = q_x + iq_y$ is the deviation from the Dirac node, and the additional constant A appears due to the strain induced change in hoppings. In ideal graphene this constant vanishes due to the cancelation amongst the three nearest neighbor hoppings. However, in the presence of modified hoppings arising from spatially varying strain, these cancelations are disturbed. Given the Dirac structure, this term can be interpreted as a gauge potential minimally coupled to the Dirac electrons. Spatially varying $A(r)$ will lead to an effective magnetic field. To achieve a uniform field, an appropriate strain distribution is required. It was theoretically noted previously [1] that a threefold symmetric strain could achieve this rather naturally. At the opposite Dirac point the effective field has the opposite sign, since of course the strain does not break time reversal symmetry. Hence the term 'psuedo' magnetic field.

The featured reference reports a Scanning Tunneling Microscopy (STM) measurement of a sample of graphene, on a Pt substrate, with a topography as shown in Figure 1. While the sheet lies flat for the most part, there are nanometer sized bubbles where the sheet pops up over the substrate. The tunneling spectrum is dramatically different in the bubbles as compared to the flat regions. It is well known that in the presence of a magnetic field B, Dirac

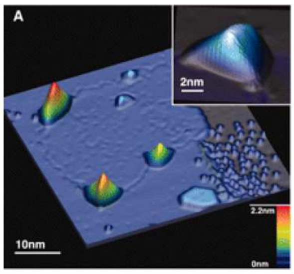

Figure 1: Single layer graphene patch on Pt(111) substrate with nanobubbles. (Inset) High-resolution image of a nanobubble showing the strained honeycomb lattice.

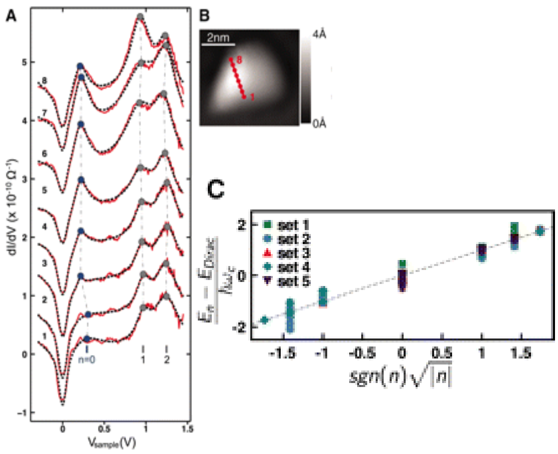

Figure 2: (A) STM spectra taken across a graphene nanobubble as shown in the image in (B). Landau level peaks are labelled. The nearly uniform separation indicates a uniform field (C) Peaks observed on five different nanobubbles can be fitted to expected $E_n \sim \sqrt{nB}$.

fermions Landau levels are spaced according to $E_n \sim \sqrt{nB}$. Precisely such a spectrum was observed when the probe was positioned over a nano-bubble (Figure 2C), despite the absence of an applied magnetic field. A comparison with theoretical estimates for the psuedo-magnetic field arising due to strain in the nanobubble agrees with what is observed - i.e. fields of about 300 Tesla. Also, studying the spectrum on scanning across the bubble reveals a rather uniform profile of magnetic field (Figure 2A,B), as long as one is not too close to the edge of the bubble. An appealing aspect of the current experiments is the rather natural way in which the nano-bubbles are generated. As the Pt substrate and the graphene sheet are cooled, differences in thermal expansivity leads to a lattice mismatch, forcing the bubbles into the graphene sheet. Their triangular shape, arising from the substrate symmetry, is believed to be responsible for the strain pattern that led to uniform field.

It is intriguing to note that with such strong magnetic fields, one could achieve high temperature Fractional Quantum Hall states, which would be of great interest for future experiments. The current experiments however only probe the underlying single particle physics. Several experimental challenges remain before interesting correlated states can be studied. For example, careful filling control will be needed. Also, the graphene bubbles are rather small as seen in Figure 1, meaning that just a few degenerate Landau level states are accommodated. If future work can achieve larger strained domains, with weak substrate coupling, this may open a new window into the properties of matter in ultra large magnetic field.

References

[1] Energy gaps and a zero-field quantum Hall effect in graphene by strain engineering F. Guinea, M. I. Katsnelson, A. K. Geim, Nature Physics 6, 30 - 33 (2009).