Spin Dependent Scattering in Graphene Systems: From Impurity Characterization to Birefringent Electron Optics

M. M. Asmar[1,2] and S. E. Ulloa[1,2]
[1] Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA
[2] Dahlem Center for Complex Quantum Systems, Freie Universität, Berlin, Germany

An important effect on the dynamics of spins in materials is the spin-orbit interaction (SOI), which reflects/arises from intrinsic lack of inversion symmetry in the lattice structure, or via broken symmetries in the system due to external or interfacial fields (Rashba interaction). Although intrinsic SOI is weak in graphene, the Rashba SOI can in fact be large due to strong local hybridizations by impurities of defects or by manipulation of substrates or applied gates [1]. Indeed, *resonant* scatterers, limiting electron mobility in graphene, appear likely due to impurities such as hydrogen or other adsorbed atoms, molecules, clusters of impurities or vacancies, or can be controllably implemented by metallic islands deposited on (or grown under) graphene. We have studied electron/hole transport in graphene under sizeable SOI and address theoretically some of the anticipated observables due to this effect.

We have developed analytical spinor solutions of the Dirac equation that include spin dependent observables, and use these to examine the role of SOI on scattering cross sections. By calculating the ratio of total to transport cross section at low energy we are able to probe the degree of isotropy of the scattering processes, and consequently probe the nature of the impurities and defects present in the graphene sample. We show that at low energies, this ratio of cross sections (equivalent to the ratio of scattering times obtainable from experiments [2]) can be nearly 1 (instead of 2, as expected with no SOI), to a degree that depends on the Rashba SOI strength. This suggests then a sample specific measurement of the important effective size of the SOI, especially if one is to consider spin transport.

Moreover, we show that Rashba SOI in graphene gives rise to optical *birefringence* in electron optics, which in essence reflects the intrinsic crystal structure even at long electronic wavelengths. This effect requires the presence of Rashba SOI, where different group velocities depend on the chirality of the electronic states, mimicking the light polarization dependence of the group velocities in optical birefringent materials. This can in principle be achieved via gated regions, and result in the formation of spinful cusps and caustics caused by the Veselago lens defined by the gate. Interestingly, this would be evident by the doubling of caustics and cusps produced by circular birefringent lenses, where the spacing between the two different *chiral cusps* is proportional to the strength of the Rashba interaction in the system [3].

[1] D. Marchenko *et al*., Nat. Commun. **3**, 1232 (2012).
[2] M. Monteverde *et al*., Phys. Rev. Lett. **104**, 126801, (2010).
[3] M. M. Asmar and S. E. Ulloa, Phys. Rev. B **87**, 075420 (2013).

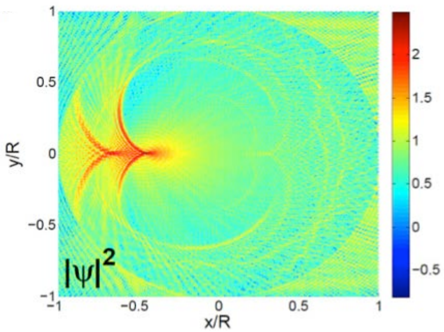

Fig. 1: Probability density patterns (scale bars show log of amplitudes, normalized to incident flux) resulting from the scattering of an incoming spin-up electron wave along the *x* direction towards a circular gate potential covering an area of radius *R*; the normal electric field reverses the carrier character from electron to hole and also generates and a Rashba spin-orbit field. The electronic dispersion in the gated region is modified, and this produces electronic *birefringence*, due to quantum mechanical effects that allow the presence of two chiral states.