Spin-Pseudospin Entanglement and Spin Relaxation in Graphene

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Abstract

The extremely small intrinsic spin-orbit coupling (SOC) of graphene and the lack of hyperfine interaction with the most abundant carbon isotope have led to intense research into possible applications of this material in spintronic devices due to the possibility of transporting spin information over very long distances[1, 2, 3]. However, the spin relaxation times are found to be orders of magnitude shorter than initially predicted[4, 5, 6, 7, 8], while the major physical process for spin equilibration and its dependence on charge density and disorder remain elusive. Experiments have been analyzed in terms of the conventional Elliot-Yafet and Dyakonov-Perel processes, yielding contradictory results. Recently, a mechanism based on resonant scattering by local magnetic moments has also been proposed[9]. Here, we unravel a spin relaxation mechanism for nonmagnetic samples that follows from an entanglement of spin and pseudospin degrees of freedom driven by random SOC[10], which makes it unique to graphene and is markedly different to conventional processes. We show that the mixing between spin and pseudospin-related Berry's phases results in unexpectedly fast spin dephasing, even when approaching the ballistic limit, and leads to increasing spin relaxation times away from the Dirac point, as observed experimentally. This hitherto unknown phenomenon points towards revisiting the origin of the low spin relaxation times found in graphene, where SOC can be caused by adsorbed adatoms, ripples or even the substrate. It also opens new perspectives for spin manipulation using the pseudospin degree of freedom (or vice versa), a tantalizing quest for the emergence of radically new information storage and processing technologies.

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Figures

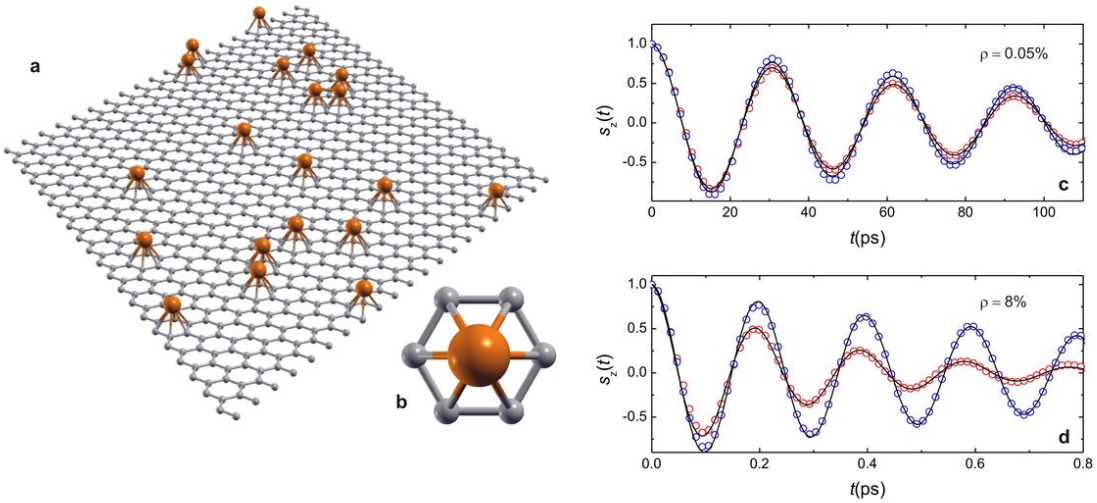

Figure 1: **Spin Dynamics in disordered graphene**. (a) Ball-and-stick model of a random distribution of ad-atoms on top of a graphene sample (b) Top view of the gold ad-atom sitting on the center of an hexagon (c),(d) Time-dependent projected spin polarization $S_z(E,t)$ of charge carriers (symbols) initially prepared in an out-of-plane polarization (at Dirac point (red curves) and at $E = 150$meV (blue curves)). Analytical fits are given as solid lines (see text). Parameters are $V_I = 0.007\gamma_0$, $V_R = 0.0165\gamma_0$, $\mu = 0.1\gamma_0$, $\rho = 0.05\%$ (c) and $\rho = 8\%$ (d).

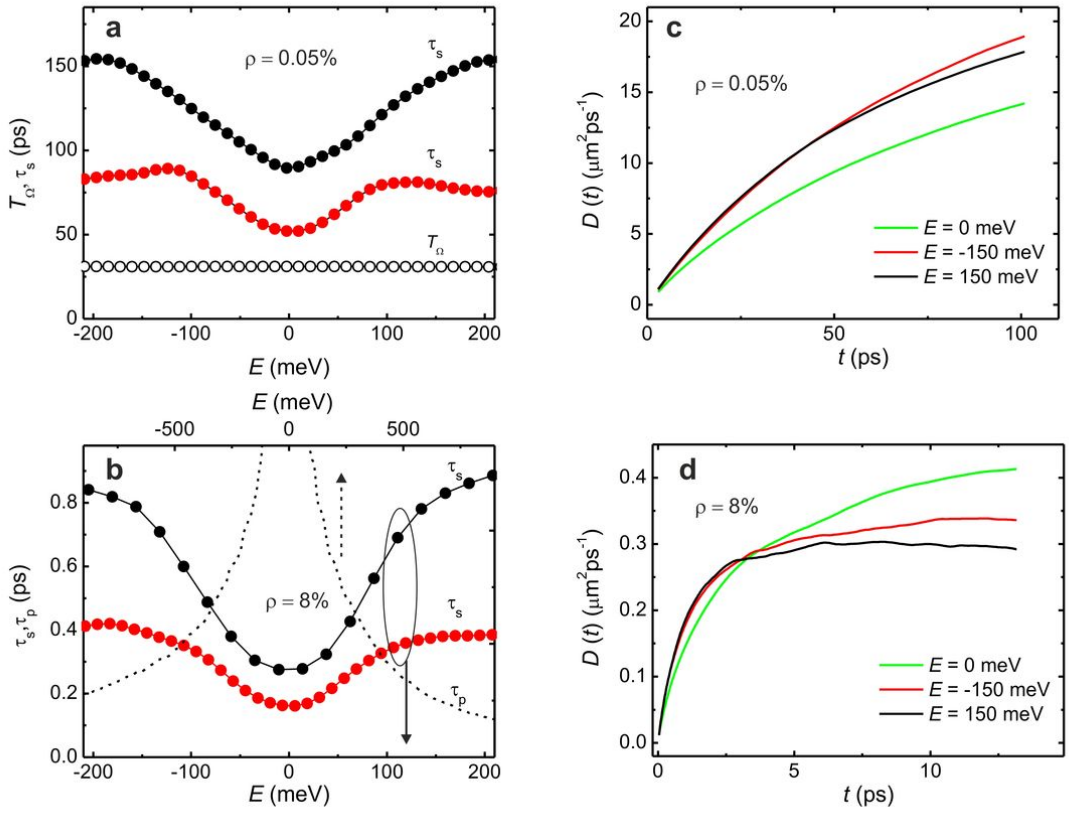

Figure 2: **Spin relaxation times and transport mechanisms**. Spin relaxation times (τ_s) for $\rho = 0.05\%$ (a) and $\rho = 8\%$ (b). Black (red) solid symbols indicate τ_s for $\mu = 0.1\gamma_0$ ($\mu = 0.2\gamma_0$). T_Ω vs. E is also shown (open symbols). τ_p (dotted line in (b)) is shown over a wider energy range (top x-axis) in order to stress the divergence around $E = 0$ ($\mu = 0.2\gamma_0$). We cannot evaluate τ_p below 100 meV, since the diffusive regime is not established within our computational reach. Panels (c) and (d): Time dependent diffusion coefficient $D(t)$ for $\rho = 0.05\%$ and $\rho = 8\%$ with $\mu = 0.2\gamma_0$.