Carbon nanotube: A low-loss spin-current waveguide

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We demonstrate with a quantum-mechanical approach that carbon nanotubes are excellent spin-current waveguides and are able to carry information stored in a precessing magnetic moment for long distances with very little dispersion and with tunable degrees of attenuation. Pulsed magnetic excitations are predicted to travel with the nanotube Fermi velocity and are able to induce similar excitations in remote locations. Such an efficient way of transporting magnetic information suggests that nanotubes are promising candidates for memory devices with fast magnetization switchings.

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The time-dependent transverse spin susceptibility is defined as 

\[ \chi_{m,j}(t) = -\frac{i}{\hbar} \Theta(t) \langle \hat{S}_m^x(t), \hat{S}_j^z(0) \rangle \],

where \( \Theta(t) \) is the Heaviside step function, and \( \hat{S}_m^x \) and \( \hat{S}_m^z \) are the spin raising and lowering operators at site \( m \), respectively. The indices \( j \) and \( m \) refer to the locations where the field is applied and where the response is measured, respectively. In our case, a precession of the magnetic moment is induced at site \( j = 0 \), and we wish to observe the spin disturbance at an arbitrary site \( m \). This response is fully described by \( \chi_{m,0}(t) \). Within the random-phase approximation, this susceptibility may be calculated in frequency domain, and in matrix form it is given by \( \chi^0(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} d\omega' f(\omega') \left[ \left( \hat{g}^1_{m,j}(\omega') - \hat{g}^1_{m,j}(\omega')^\dagger \right) \right] \)

\[ \times \left[ \hat{g}^1_{m,j}(\omega' + \omega) + \left[ \hat{g}^1_{m,j}(\omega') - \hat{g}^1_{m,j}(\omega')^\dagger \right] \hat{g}^1_{m,j}(\omega' + \omega) \right] \].

Here, \( \hat{g}^\sigma_{m,j}(\omega) \) represents the time Fourier transforms of the retarded single-particle propagators for an electron with spin \( \sigma \) between sites \( m \) and \( j \), and \( f(\omega) \) is the Fermi function. For a pristine NT \( \hat{g}^\sigma_{m,j}(\omega) \) may be analytically determined and the integration in Eq. (1) performed with great numerical accuracy.

It is instructive to start by calculating \( \chi_{m,0}(\omega) \) given by Eq. (1). A typical result is shown in Fig. 1(a) for a (4,4) armchair NT doped with a single Mn impurity. It depicts \( \chi_{m,0}(\omega) \) which is proportional to the amplitude of the spin disturbance at site \( m \) due to a time-dependent transverse magnetic field applied at site 0. In Fig. 1(a) the site \( m \) is a distance \( x_m = 3a_0 \) from the impurity, where \( a_0 = 2.46 \) Å represents the graphene lattice parameter. A very distinctive peak is evident in the \( \omega \)-dependent susceptibility, reflecting the existence of a resonance close to the Larmour frequency, as expected.

Since we are interested in studying the propagation of magnetic signals, it is illustrative to look at the susceptibility as a function of time rather than frequency. The Fourier transform of the curve depicted in Fig. 1(a) gives the spin disturbance response to an instantaneous \( \delta \)-like pulse \( \hat{h}_0(t) \) applied at site 0. However, for practical reasons, we consider the response to a Gaussian transverse magnetic field pulse given by \( \hat{h}_0(t) = \hbar_0 \exp(-t^2/\sigma^2) \) applied along the \( \hat{x} \) direction (\( \hbar_0 = \hbar_0 \delta \)). Here \( \hbar_0 \) represents the maximum field strength and \( \sigma \) its standard deviation. Figure 1(b) shows how such a magnetic pulse applied at the impurity location affects the spin balance of the NT at a nearby site (\( x_m = 3a_0 \)). The thin solid and dashed lines represent the calculated spin components \( \langle S_m^x(t) \rangle \) and \( \langle S_m^y(t) \rangle \), respectively, and the modulating thick solid line is the magnitude of the transverse spin disturbance given by \( \langle |S_m(t)| \rangle = \sqrt{\langle S_m^x \rangle^2 + \langle S_m^y \rangle^2} \). To avoid congested figures the magnitude will be hereafter used to represent the spin dynamics on the NT.

The fact that the electron spin probed on the NT displays the precessional motion originated at the impurity is a clear indication of a flowing spin current emanating from the impurity into the NT. Earlier calculations have suggested that the existence of this current is sufficient to induce a dynamic magnetic coupling between dispersed impurities in NT, which is far more pronounced and long ranged than any other magnetic coupling of static nature. 

To test how this precession propagates, in Fig. 2 we show \( \langle |S_m(t)| \rangle \) probed at different locations on the NT. The six numbered lines correspond to spin disturbances probed at different sites along a line parallel to the NT axis containing the impurity site 0. The spin disturbance probed on other sites belonging to the same NT ring are virtually identical to the ones displayed in Fig. 2. Small deviations are noticeable when the ring is very close to the impurity but disappear after a short propagation distance. This indicates that the initial omni-directional excitation produced by the applied perturbation
decays very fast into a cylindrical wave front that moves along the NT axial direction with a uniform speed. This propagation speed is found from the slope of the straight line in the inset of Fig. 2 showing the probing position $x_m$ as a function of the time $t$ spent by the pulse maximum to reach $x_m$. We find the propagation velocity $v=1.4 \times 10^5$ m/s, which is precisely the NT Fermi velocity, indicating that the conduction electrons at $E_F$ are the main carriers of the spin current.

Figure 2 shows that, as the pulse moves, it is initially deformed but it quickly reaches a form that remains unaltered for asymptotically long distances. This can be seen when we focus on two features of the pulsed signals, namely, their maximum amplitude $|\langle S_m \rangle|_{max}$ and their corresponding width, here represented by the midheight separation $\Delta$. Figure 3(a) plots $|\langle S_m \rangle|_{max}$ and $\Delta$ as a function of the probing position $x_m$ in the case of an excitation pulse whose frequency spectrum is centered at the same frequency as used for obtaining Fig. 1(b). Both quantities saturate after a short distance and are stationary for $x_m>10^4a_0$. This is a remarkable result showing that the information contained in the magnetic pulse can be transported across very long distances without distortion. Surely, the asymptotic value for $|\langle S_m \rangle|_{max}$ is not the same as the one probed near the impurity but it still has a sizable magnitude indicating that a considerable fraction of the energy contained in the magnetization precession can be used elsewhere.

Furthermore, we can also control the fraction of the original pulse that reaches this asymptotic regime by selecting the central frequency in the excitation pulse. Figure 3(b) displays $|\langle S_m \rangle|_{max}$ and $\Delta$ for the case of a pulse whose spectrum is centered at an off-resonance frequency $\omega=0.24$ THz. In this case the asymptotic value for $|\langle S_m \rangle|_{max}$ is much reduced when compared with its counterpart in Fig. 3(a). The existence of this nondecaying asymptotic contribution to the spin current has been demonstrated recently for NT and atomic chains, but here we explicitly show that this can be actually controlled by an appropriate selection of excitation frequencies. All the features presented so far indicate that NT can carry spin-current information contained within pulsed excitations without dispersing their form. This can be explained by the peculiar electronic structure exhibited by NT, which is notoriously dispersionless at the Fermi level. In other words, extended states at the Fermi level have a linear dependence on the electronic wave vectors. In this case, group and phase velocities are interchangeable, meaning that every single frequency component comprising a pulse will travel with the same speed, thus preventing any distortion of the pulse shape. If NT are to be used as spin-current waveguides, these features must be tested in the presence of structural disorder.

In fact, we have simulated the presence of isolated Boron substitutional impurities to explore their effect in the propagation of the spin disturbance pulse. We find that the pulse preserves its shape and amplitude, except very close to the impurity, where it becomes slightly distorted. We notice that at larger distances, however, the pulse shape is restored as if no impurity is present. This suggests that the spin-current waveguide features reported so far are robust against the presence of nonmagnetic disorder in NT.

Finally, finding small values for the pulse amplitude at asymptotically large distances [see left axis of Figs. 3(a) and 3(b)] does not imply that the magnetic information is lost. To make this point more explicit we add a second magnetic impurity a long distance apart ($x_m=6 \times 10^4a_0$) and see whether the excitation produced at the origin can be transported to the new location. Figure 4 shows the spin disturbance $|\langle S_m' \rangle|$ probed on both impurities. The solid line shows the magnetization precession at the origin whereas the dashed line represents the spin disturbance as a function of time measured at the second impurity. Both lines have equally spaced peaks that are a time interval $\Delta t=2x_m/v$ apart but are shifted by half that amount. This is easily explained by the fact that precessing magnetic moments will always emit spin current to the surrounding conduction electrons which will induce further precessions when interacting with other magnetic moments. Therefore, the induced precession probed at the origin appears as the first peak in Fig. 4. The subsequent pulse is seen to occur after the spin current has traveled all the way to excite the second impurity at site $m$. Once excited, this impurity precesses also emitting spin current, which will again induce another pre-
cession at the origin. This process is repeated indefinitely each time with smaller amplitudes. The amplitude reduction is inevitable because half of the energy stored in the pulsed precession will travel away from the other impurity. But the fact that the pulse produced at the origin reappears a long distance apart means that the energy stored in the precession of magnetic moments can be noiselessly transported across the conduction electrons of NT, which confirms that these materials are ideal spin-current waveguides.

In summary, we have shown that metallic NT are excellent spin-current waveguides and are able to transport magnetic information across long distances with minimum dispersion and with very little loss. Spin disturbances induced by localized magnetic excitations are shown to propagate throughout the length of a metallic NT with speeds on the order of $10^5$ m/s. Moreover, we show that the energy stored in a magnetic precession can be used elsewhere when the spin current traveling through NT interacts with other magnetic objects. These features turn NT into ideal components for fast-response memory devices. The experimental testing of our predictions requires the generation and detection of spin currents. One possibility is to excite a spin with a laser pulse and monitor a second spin located somewhere downstream with a scanning tunneling microscope (STM) tip. Since the STM current can be modulated by a coherent spin precession, one should be able to observe the second spin being excited by the spin current in the NT.