Torsional optomechanics and quantum simulation with a levitated nanodiamond

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Abstract: We report the observation of the torsional vibration of an optically levitated nanodiamond in vacuum. We propose a scheme to achieve torsional ground state cooling, and utilize the electron spin-torsional coupling to do quantum simulation.
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Diamond nitrogen-vacancy (NV) centers have broad applications in nanoscale sensing and quantum information [1-3]. The NV electron spins can have long coherence times even at room temperature. Combining such NV spin systems with mechanical resonators will provide a hybrid quantum system for many applications [4, 5]. Several authors have proposed to levitate a nanodiamond with a built-in NV center in vacuum as a novel hybrid spin-optomechanical system for studying macroscopic quantum mechanics [6, 7, 8]. Experimentally, nanodiamonds have been optically trapped in liquid [9, 10], atmospheric air [11] and low vacuum [12]. Recently, we optically trapped nanodiamonds in vacuum and demonstrated electron spin control of NV electron spins in a levitated nanodiamond [13]. These results provide a solid foundation for studying spin-optomechanics of levitated nanodiamonds. In this presentation, we will report our observation of the torsional vibration of an optically levitated nanodiamond in vacuum [14]. We also propose a scheme to achieve torsional ground state cooling [14], and utilize the electron spin-torsional coupling to do quantum many-body simulation [15].

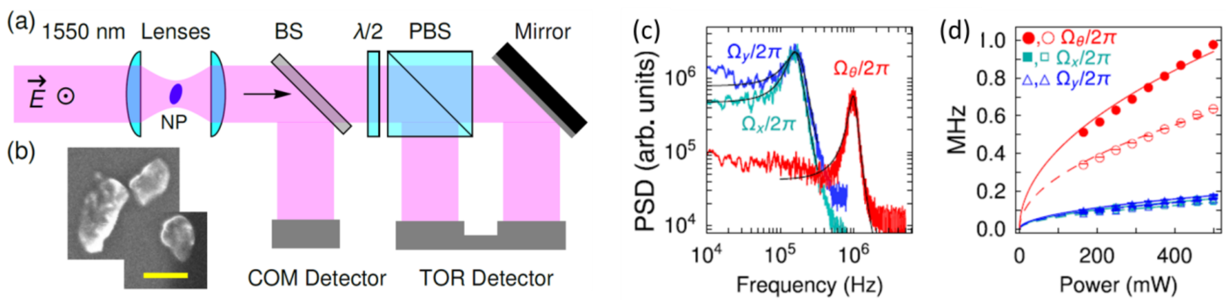

Figure 1. (a) Experimental diagram for detecting torsional (TOR) vibration and center-of-mass (c.m.) motion of a levitated nonspherical nanoparticle (NP). (b) A SEM image of irregular nanodiamonds. The scale bar is 100 nm. (c) Measured power spectrum densities (PSD) of the c.m. motion (labeled with $\Omega_{x,y}/2\pi$) and TOR vibration (labeled with $\Omega_\theta/2\pi$) of an optically levitated nanodiamond. (d) Measured TOR and c.m. frequencies of two different nanodiamonds as a function of the trapping power.

Here we report the first experimental observation of the torsional vibration of an optically levitated nonspherical nanoparticle in vacuum [14]. We achieve this by utilizing the coupling between the spin angular momentum of photons and the torsional vibration of an irregular nanodiamond whose polarizability is a tensor (Fig. 1(a), 1(b)). The torsional vibration frequency can be 1 order of magnitude higher than its center-of-mass motion frequency (Fig. 1(c), 1(d)), which is promising for ground state cooling. We propose a simple yet novel scheme to achieve ground state cooling of its torsional vibration with a linearly polarized Gaussian cavity mode. A levitated nonspherical nanoparticle in vacuum will also be an ultrasensitive nanoscale torsion balance with a torque detection sensitivity on the order of 10^{-29} NmHz$^{-1/2}$ [14]. This sensitivity will be sufficient to detect the torque on a single nuclear spin.

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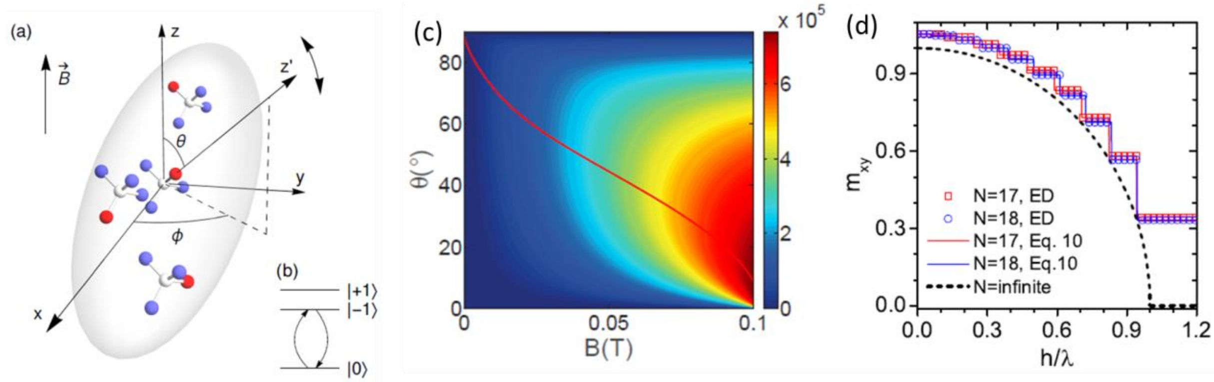

Figure 2. (a) Nitrogen vacancy (NV) centers in a levitated diamond nanocrystal in a uniform magnetic field **B** along the z axis. (b) The energy levels of the electron spin in a magnetic field. (c) NV electron spin-torsional coupling strength $g_N/2\pi$ of a nanodiamond as a function of θ and B. (d) Phase transition of multiple NV spins in a levitated nanodiamond in a magnetic field. A small number of NV centers is sufficient to see the signature of phase transition.

In order to induce strong coupling between an electron spin and the center-of-mass motion of a mechanical oscillator, a large magnetic gradient is usually required [16], which is difficult to achieve. Here we show that strong coupling between the electron spin of a nitrogen-vacancy (NV) center and the torsional vibration of an optically levitated nanodiamond can be achieved in a uniform magnetic field (Fig. 2) [15]. Thanks to the uniform magnetic field, multiple spins can strongly couple to the torsional vibration at the same time (Fig. 2(a)). We propose to utilize this new coupling mechanism to realize the Lipkin-Meshkov-Glick (LMG) model by an ensemble of NV centers in a levitated nanodiamond [15]. The quantum phase transition in the LMG model and finite number effects can be observed with this system (Fig. 2(d)). We also propose to generate torsional superposition states and realize torsional matter-wave interferometry with spin-torsional coupling [15].

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