Observation of gold nanoparticles movements under sub-10 nm vortex electron beams in an aberration corrected TEM

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Electron vortex beams have attracted much attention in recent years since their realization in transmission electron microscopes [1-3]. These beams have possible applications in the analysis of magnetic materials, manipulation and trapping of nanoparticles etc. In this respect, we have shown theoretically that electron vortex beams, contrary to the optical vortex counterpart, can exchange orbital angular momentum efficiently with the atomic electrons [4]. In this study we utilise the holographic method, as detailed in [5] for the creation of masks to study the interaction of nanometer scale electron vortex beams with nanosized Au particles.

Figure 1 shows the focused vortex probes attainable at the specimen plane. They are the far field diffraction pattern generated by a forked binary holographic mask [5] placed in the condenser aperture holder at the back focal plane of the condenser aperture in a JEOL 2200FS double-aberration corrected scanning transmission electron microscope operating at 200keV. They are found to be 2.6 nm and 3.4 nm (FWHM) for the first and second order vortex beams, respectively. It is known that aberration and partial coherence are going to broaden the characteristic ring structure; therefore the central dark zones are not observed for the tightly focused first and second order vortex beams in figure 1. To study the interaction of the vortex beam with nanoparticles, the beams were slightly defocused to reveal unambiguous central dark spots and to spread (~5 nm) the ring structure in order to cover the entire particle (Fig. 2a). The possible motion of the nanoparticle under the illumination is monitored by video capturing of the aberration corrected transmission electron microscope images at a refreshing rate of 1.2 second per image. An intermediate spot size 3 was used to compromise the balance between the coherence and intensity of the beams. The investigation of the video images initially showed no evidence of structural change, particle rotation or movement/displacement. But after about 5 minutes beam exposure the particle was observed to be detached from the carbon substrate and displaced while changing its structure occasionally. The displacement, changing the structure and/or rotation of particles under lengthy electron beam irradiation study has been reported in earlier studies [6, 7]. In our study, when the particle is placed under the 1^{st} (Fig. 2a) and 2^{nd} order (Fig. 2b) vortex beams, analysis of the video showed that the particle rotates with a speed of 3.75º/sec., comparably faster than the previously reported studies which use beams with no orbital angular momentum [7]. As an example, four snap shots of a ~5 nm sized Au nanoparticle rotated by a second order vortex beam captured at ~1.2 sec. interval is shown in figure 2b (video available at conference). Tracking of the lattice fringes and the corresponding FFT (insets) of individual images showed that the rotation of the particles was from 99.5º to 84.5º in ~4 sec. duration. Further irradiation causes the particle to be surrounded by/embedded in carbon and the particle is found to be very stable under the vortex beam exposure at this late stage (Fig. 2c).

Although further study is necessary to find the exact mechanism behind this rotation, from the observations we can conclude the following: (i) the displacement or detachment of the particle is observed only after the lengthy beam irradiation both with the centre beam and side vortex beams. (ii) After lengthy beam irradiation most of the substrate carbon film is ablated. At this stage the particle is mostly detached from the substrate and sticking only at one edge/corner of the carbon film, possibly under the influence of van der Walls and viscous forces and rotating while positioned in the vortex core beams.

In summary, we have shown that the manipulation of Au nanoparticles by electron beams carrying orbital angular momentum is possible, but the driving force for the rotation may be competing with other trapping potentials, such as those caused by contamination.

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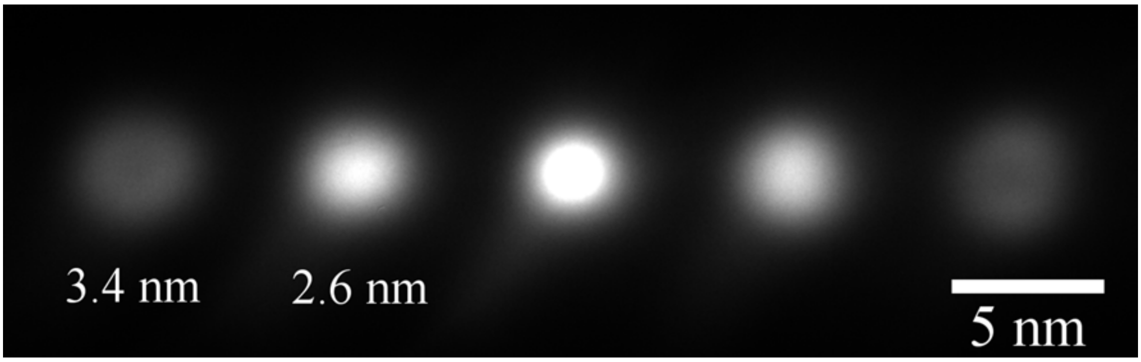

Figure 1. *Vortex probes at focus. Sizes of the 1st and 2nd vortex cores at FWHM are 2.6 nm and 3.4 nm, respectively.*

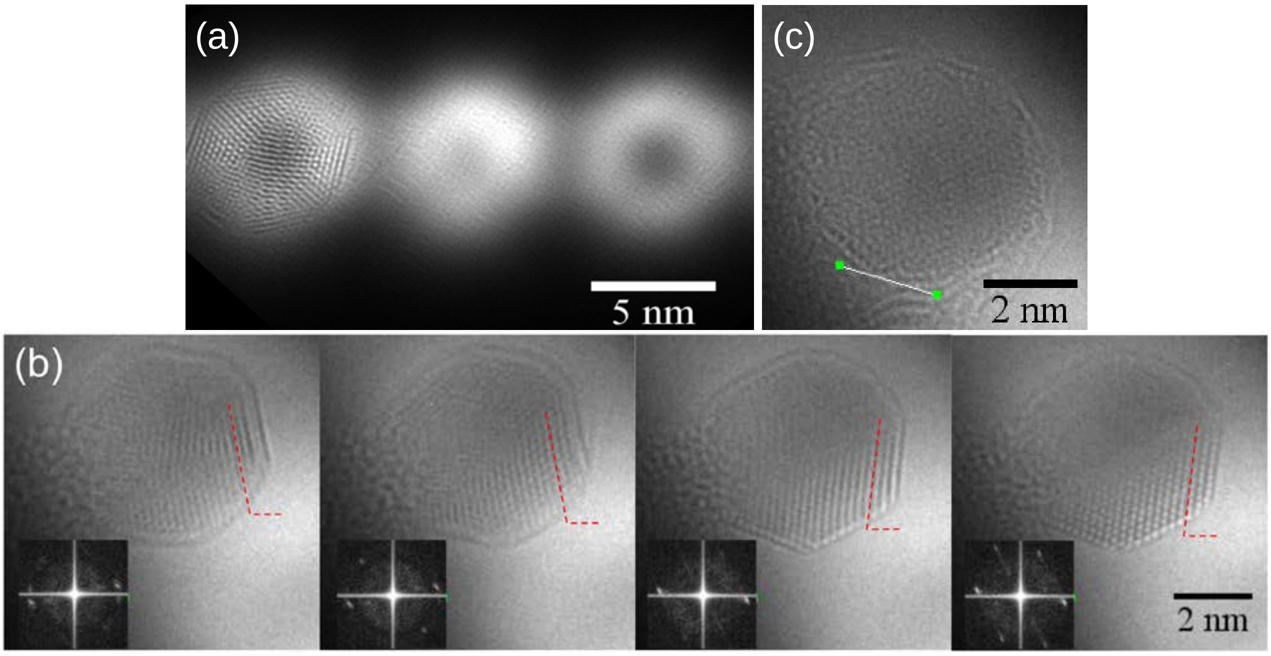

Figure 2. *(a) Au nanoparticle located at the 1st order vortex beams. (b) Four shots of Au nanoparticles rotated by 2nd order vortex beams selected from a video at 1.2 sec. intervals. The centre dark core surrounded by the bright ring of the 1st order vortex beams is partially visible at the bottom right corner. The angles of lattice fringes noted in figure 2b correspond to 99.5, 99.0, 87.0 and 84.5 degrees respectively. Insets show the corresponding FFT. In (c), the particle is found to be covered by a thin layer of carbon and there is no noticeable rotation.*