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Vortex Beams for Atomic Resolution Dichroism

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It is now possible, using state-of-the-art electron microscopes, to obtain direct chemical identification of individual atoms based on image intensity [1] together with spectroscopic fine-structure information [2]. However, it has not yet been feasible to measure magnetic properties of individual atoms or single atomic columns.

Electron holography, which is a widely used electron microscopy technique to obtain quantitative information on electromagnetic fields (by recovering the phase shifts of electron waves as they pass through the material), has so far only achieved a spatial resolution of about 3 nm [3]. Expected incremental improvements in optics and detectors in the next few years should allow the sensitivity and spatial resolution of electron holography to improve, but imaging magnetic fields with atomic resolution remains a distant goal [4].

Another way to obtain atomic scale magnetic information within an electron microscope would be to *polarize* the electron beam such that each electron carries a specific orbital angular momentum (OAM). Vortex photon beams carrying OAM have been known (and widely used) for almost 20 years in optical physics [5]. For instance, vortex photon beams are used in non-linear optics as optical tweezers, or in quantum computation to produce quantum entangled states [5].

During the last year, research groups in Japan [6], Europe [7], and the U.S.A. [8] have shown experimentally that the interference of an electron plane wave with a fork dislocation grid splits the incident wave into a series of transmitted electron vortex beams that carry OAM. Specifically, by interfering an incident electron beam with a focused ion beam fabricated grid with a fork dislocation Verbeeck *et al.* showed that electron vortex beams can be generated to measure magnetic circular dichroism with a spatial resolution of 250 nm using electron-energy loss spectroscopy (EELS) in TEM [7]. Verbeeck's *et al.* work implies, through the principle of reciprocity, that by using a scanning (S)TEM (see Fig. 1) it may be possible to achieve the goal of atomically resolved measurements of magnetic properties.

By directly evaluating the diffracted pattern formed by a plane wave that has passed through a grid containing fork dislocations, we will present an analytical description of vortex beams carrying OAM. We will show the optical conditions under which small probes with OAM can be achieved and discuss the parameters necessary to design an atomic-resolution scanning transmission microscope using vortex beams [10].

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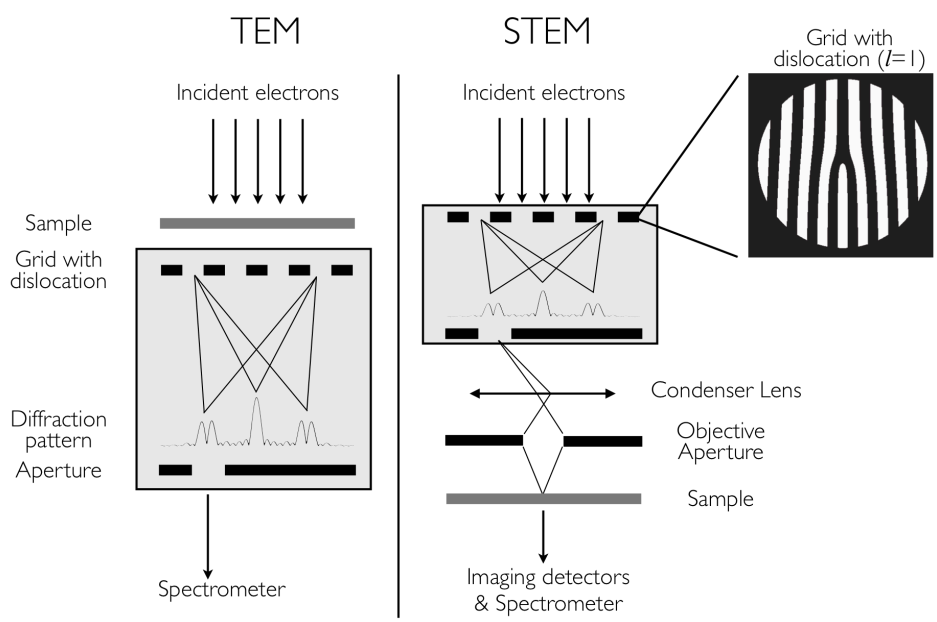

Figure 1: Schematic of how electron vortex beams can be produced in the (S)TEM. In TEM, a grid with fork dislocations is placed after the sample and then an aperture is used to select a single electron vortex beam with the desired OAM [7]. In STEM, the dislocation grid and the beam selecting aperture (highlighted inside the gray rectangle) are placed before the sample. Extra condenser lenses are also required to magnify the electron vortex before the probe forming objective aperture [9]. The resulting electron probe can be used as in any other STEM but with the benefit that since it carries an effective OAM, magnetic properties of the sample could also be studied directly.

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