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Feasibility of an Electron Orbital Angular Momentum Sorter

William Parker[1*], Benjamin McMorran[1]

[1.] Department of Physics, University of Oregon, Eugene, OR, United States of America.
* wparker4@uoregon.edu

Whenever an electron interacts with matter, a range of information about the matter is encoded into the various degrees of freedom of the electron. Recently, free electrons with orbital angular momentum - or electron vortices - have been demonstrated in transmission electron microscopes [1-3], opening the door to a new range of information that could be extracted from samples. Optical vortices have been used to probe chirality in organic and biological samples, and incident electron vortices have been used to probe magnetic chirality [4]. However, optical probes have limited resolution in comparison to the available angstrom resolution of electron probes, and electron vortex probes present numerous experimental difficulties.

An alternative approach to imaging using the orbital angular momentum of electrons would be to scatter plane electron waves through a sample, and directly measure the orbital angular momentum spectrum of the scattered electrons. Such a technique would open the door to angstrom resolution chiral and magnetic imaging [5]. Although various methods exist to generate electron vortices, a practical method to sort and analyze orbital angular momentum spatial modes based on chirality still does not.

We recently proposed a method based on the log-polar coordinate transformation used to sort optical vortices [6]. The sorting device consists of two custom phase elements, each followed by a Fourier-transforming lens. The first phase element, known as a phase unwrapper, maps an azimuthal angle to a vertical position in the back focal plane of the subsequent lens. The second element, known as the phase corrector, corrects for differences in path length. When a vortex state passes through the device, its azimuthally increasing phase is mapped to a linear phase ramp, which is then mapped by the final lens to a transverse position that varies with the chirality of the input state.

The adaptation of this proven optical method to free electrons presents both difficulties and opportunities. Phase elements for electrons are in general not easy to create; thin phase plates have high attenuation rates and are difficult to fabricate. Instead, we have proposed the use of electrostatic phase elements - the tip of a charged needle approximates the unwrapper phase, and a line of alternating diodes reproduces the corrector phase - and are working to realize these phase elements. Their design will also open doors to more general phase manipulation of free electrons.

We are also investigating novel methods to simulate the output of such a device under various input conditions. Ideally, for a given input superposition of vortex states, the output would be a set of spots whose transverse position corresponds linearly to the chirality of each vortex state. However, the actual output is affected by error sources within the device, as well as interference between neighboring states. In addition, scattered electrons may come into the device misaligned and off-axis, and may also be in higher-order Laguerre-Gauss modes, which map not to spots in the output plane but to distributions along one axis.

To determine the feasibility of an electron orbital angular momentum sorter, we simulate the action of such a device on various inputs. We consider inputs that are arbitrary superpositions of off-paraxial Laguerre-Gauss modes, including varying beam waists and non-zero radii of curvature. In addition, we include errors in the device itself, including spherical aberrations, non-ideal phase elements, dispersion, and chromatic aberrations. The resulting output images are typically more complex than the ideal spot pattern, and if the input modes or the device are too noisy, analysis of the output of the device will become non-trivial. In that vein, we are also considering multiple methods to analyze these outputs.

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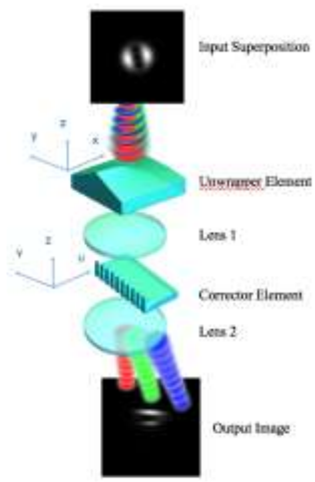


Figure 1. The schematic design of the device to sort electrons. The input is any approximately plane wave free electron, and the output is its orbital angular momentum spectrum.

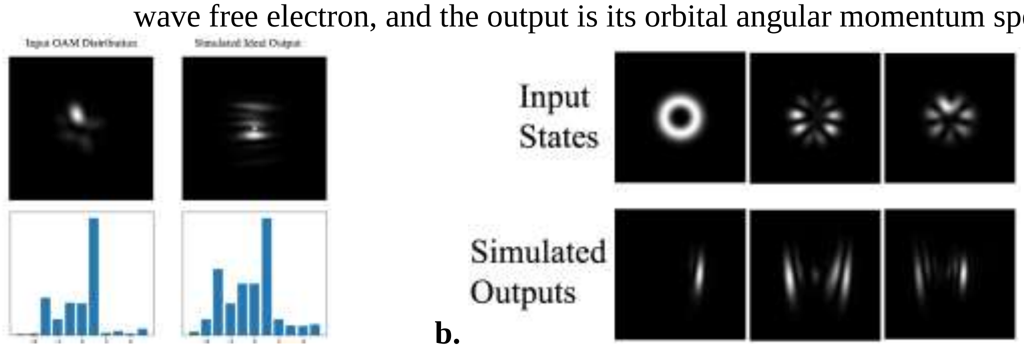
a. 

Figure 2. a. The ideal output of the sorter and corresponding input and output intensity distributions. b. A sample of input radial states and their ideal sorted output intensity distributions.

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