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Unveiling the OAM and Acceleration of Electron Beams

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Electron beams, specifically in a transmission electron microscope (TEM), are mainly used to investigate biological samples and materials. It was not until recently that investigation of special kinds of beams, namely vortex beams, has begun [1,2]. These beams are especially interesting because they carry orbital angular momentum (OAM) which may be coupled to the atomic wave-function, thus enabling probing of magnetic dichroism [3], for example. In light-optics these beams have long been known, and research into other types of beams, such as accelerating beams, is flourishing. Here we study the well known Airy beam [4,5] in the electron microscope – a shape-invariant, multi-lobed, non-spreading beam whose nodal trajectory follows a parabolic dependence, which has already been exploited in light-optics to overcome the diffraction limit implementing a "super-resolution" technique [6]. Where for the case of vortex beams the OAM property is of utmost importance, in this work* we develop a tool for easy measurement of the Airy's nodal trajectory coefficient, which is the defining property of the Airy beam, derive an elegant analytic model and verify it by fabrication of the relevant amplitude masks and consequent measurement and analysis. Our results agree completely with the proposed model, which is derived without approximations, and nicely relates light- to electron-optics via the geometric ray-tracing technique.

In the optics literature, the familiar form of the Airy beam is given by $Ai[x_0^{-1}(x - z^2/4k_{DB}^2x_0^3)]$, where x_0 is the transverse length-scale, k_{DB} the de-Broglie k-vector and (x, z) the transverse and longitudinal coordinates, respectively. Ai is the Airy function. The quantity $1/(4k_{DB}^2x_0^3)$ is the nodal trajectory parameter, sometimes referred to as the acceleration of the Airy beam, due to the coordinate's parabolic dependence. The Airy beam is easily generated on the optical axis using, for example, the amplitude mask depicted in Fig.1f. This mask, a computer-generated hologram, recreates both the object and image of the encoded pattern in the Fourier (or diffraction) plane, which is why we observe two Airy-like patterns in Fig.1b,d. The nodal trajectory coefficient could be directly calculated by measuring the distance between two lobes and fitting it to the Airy function's zeros; this is difficult, however, since the Airy (a diffraction pattern) must be in focus for an accurate measurement, thus endangering the camera CCD. The accuracy also strongly depends on the resolution. A second method would be to take a focus series and follow the trajectory of the main lobe [5]. Instead, our method involves a cylindrical transformation, easily achieved in the TEM by using the stigmator lenses. It is interesting to note that the same astigmatic transformation is also useful for determining the orbital angular momentum of vortex beams. Mathematically, the cubic phase imposed by the mask on the astigmatic beam is Fourier-transformed, thus yielding the "astigmatic Airy" (see Fig.1), the curve of which is dependent on the nodal trajectory coefficient according to the following formula:

$$(a^2x_0^3)^{-1}\theta_{x(\mp 1)} = \mp(3 + coshu)^{3/2}sinh\frac{u}{2}$$
$$(a^2x_0^3)^{-1}\theta_{x(\pm 2)} = \pm(-3 + coshu)^{3/2}cosh\frac{u}{2}$$

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where $\sqrt{2}\theta_y = (a^2 x_0^3) sinh^2 u$. These curves are marked in both Fig.1 and Fig.2, with $\theta_{x,y}$ the coordinates in Fourier space, a is a measure of the astigmatism and x_0 the afore-mentioned length-scale. The resulting curves of the astigmatic Airy are dependent on the amount of astigmatism and the Airy acceleration, thus allowing flexible, accurate, and safe measurement of Airy beams with nearly-arbitrary acceleration and only one image taken.

In conclusion, we show that the astigmatic transformation provides an easy method to reveal the OAM of vortex beams with integer OAM, and can be exploited to generate an astigmatic Airy and use it to measure the nodal trajectory from one image. While Airy beams have only recently been introduced to electron optics, research in light-optics yielded many interesting applications, the most promising of which could be super-resolution electron imaging.

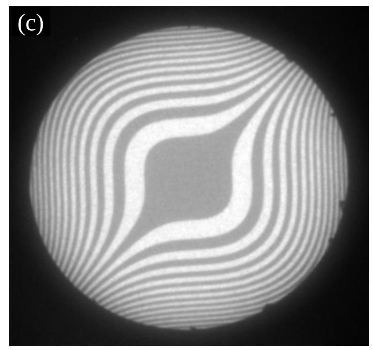

Figure 1. TEM images of (a) Astigmatic Airy, (b) mildly Astigmatic Airy, both with matching curves (blue and magenta) derived from our analytic model. The double-sided pattern is a result of the amplitude nature of the computer-generated hologram: a reconstruction of the object and image. (c) an example of an on-axis amplitude Airy mask (diameter ~ 75um).

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