Generation of electron Airy beams

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Within the framework of quantum mechanics, a unique particle wave packet exists1 in the form of the Airy function2–3. Its counterintuitive properties are revealed as it propagates in time or space: the quantum probability wave packet preserves its shape despite dispersion or diffraction and propagates along a parabolic caustic trajectory, even though no force is applied. This does not contradict Newton’s laws of motion, because the wave packet centroid propagates along a straight line. Nearly 30 years later, this wave packet, known as an accelerating Airy beam, was realized4 in the optical domain; later it was generalized to an orthogonal and complete family of beams5 that propagate along parabolic trajectories, as well as to beams that propagate along arbitrary convex trajectories6. Here we report the experimental generation and observation of the Airy beams of free electrons. These electron Airy beams were generated by diffraction of electrons through a nanoscale hologram7–9, which imprinted on the electrons’ wavefunction a cubic phase modulation in the transverse plane. The highest-intensity lobes of the generated beams indeed followed parabolic trajectories. We directly observed a non-spreading electron wavepacket, known as an accelerating Airy beam, was realized4 in the optical domain; later it was generalized to an orthogonal and complete family of beams5 that propagate along parabolic trajectories, as well as to beams that propagate along arbitrary convex trajectories6.

It is then clear from equation (1) that \( |\Psi|^2 \) preserves its shape and follows a parabolic trajectory. The parabolic trajectory is described by\(^22\) \( x(z) = z^2 / 4k_B x_0^2, y(z) = z^2 / 4k_B y_0^2 \). The ideal Airy beam carries an infinite amount of energy, whereas in practice the Airy beam is truncated, having a finite energy. The finite Airy beam is obtained by multiplying the Airy function with an exponential or Gaussian window4. Nevertheless, over a finite distance, the finite Airy beam has all the special characteristics of the infinite Airy beam such as slow diffraction, curved trajectory and self-healing.

In optics, finite Airy beams were experimentally obtained by passing a Gaussian beam through a phase mask imprinting a cubic phase modulation in the transverse direction4, and then doing an optical Fourier transform (the Fourier transform of a function having a cubic phase modulation results in an Airy function). Here we use electrons instead of photons. These electrons pass through a hologram that adds a transverse cubic phase, \( \exp(i\phi(x,y)) = \exp(ic_xx^3 \exp(ic_y y^3)) \), to the wavefunction. Our hologram design method was to construct a binary diffraction grating with the following shape:\(^22\)

\[
h(x,y) = \frac{1}{2} h_0 (\text{sgn} \{ \cos(2\pi x / A + c_xx^3 + c_y y^3) + D_{\text{cycle}} \}) + 1
\]

This way, a cubic phase is imposed on a carrier frequency. The carrier period is \( A, h_0 \) is the ridge height of the binary phase mask and \( D_{\text{cycle}} \) is an arbitrary duty cycle factor. When electrons (or light) diffract from the binary structure, it decomposes into different diffraction orders; the complex amplitude of the \( m \)th-order diffracted beam is proportional to \( \exp(im\phi(x,y)) \). In the special case of a cubic phase modulation, each diffraction order is superimposed with a different cubic phase and so has an amplitude proportional to \( \exp(im(c_xx^3 + c_y y^3)) \). Each order therefore propagates along a different parabolic trajectory with a quadratic coefficient proportional to \( 1/m \) (Supplementary Information, section 1):
section 2). We name this diffraction pattern the ‘Airy lattice’ (Figs 1 and 2). The general parametric equations of the trajectories of order $m$ are

$$x_m(z) = -\frac{1}{f} \frac{1}{m^2 k_B^2} \frac{G}{2} z^2 + mz \frac{G}{k_B} + mz \frac{G}{k_B}$$

$$y_m(z) = -\frac{1}{f} \frac{1}{m^2 k_B^2} \frac{G}{2} z^2$$

(2)

where $G = 2\pi / \lambda$ is the reciprocal lattice vector of the transmission hologram and $f$ is the focal length of the lens. Note that the $y$ trajectories include only a quadratic term, whereas the $x$ trajectories contain both a quadratic term and a linear term, owing to the modulation of the carrier frequency. The Airy lattice is a novel type of lattice that diffracts but does not spread. Although each order diffracts in a different direction, each order stays localized and anomalously bends.

In our experiment, we use a field-emission-gun transmission electron microscope (FEG-TEM), operating at 200 keV. The de Broglie wavelength, including relativistic correction in this case, is approximately 2.5 pm. Therefore, to generate the inner structure of Airy beams as well as the spatial separation of different orders, we used nanoscale holograms (Supplementary Information, section 3). The micrographs of these nanoscale holograms are shown in Fig. 3b, c. The Fourier transform of the modulated wavefunction is done using a set of magnetic lenses, so that an electron Airy beam is obtained in the back focal plane of the FEG-TEM. This method is analogous to the method used to generate optical Airy beams, the only difference being that we manipulate electrons rather than photons. Some of the results from the Airy profiles are shown in Fig. 3d and Fig. 3e. Because the measurement plane is located at a fixed position in our FEG-TEM, we varied the focal lengths of the magnetic lenses to observe the formation and evolution of the electron Airy wave packet in space (Fig. 3a). The experiment details are given in Supplementary Information, section 4.

In the first experiment, we explored the parabolic trajectories of electron Airy beams (Fig. 1). We recorded profiles using an electron beam with a relatively large area (100 μm × 100 μm). Figure 1a shows the numerical (simulated using the beam propagation numerical method) and the experimental transverse profiles of the diffracted electrons at several propagation distances behind the Fourier plane. The viewed diffracting orders are $+1, -1, +2$ and $-2$. As seen, Airy orders $+1$ and $-1$ anomalously converge in $x$ and eventually collide, unlike the normal diffraction of Bragg peaks, which linearly diverge. As expected, the orders diverge in $y$. Unlike orders $+1$ and $-1$, orders $+2$ and $-2$ are almost constant in $x$ and only slightly diverge in $y$. We traced the trajectories of the highest intensity lobe, of orders $+1$ and $+2$. The projections of the deflections of the orders into the $x$–$z$ and $y$–$z$ planes are shown in Fig. 1b. The values of $x(z)$ and $y(z)$ are given by pixel numbers, multiplied by 25 μm per pixel. The measured parabolic

![Figure 1](image_url)

**Figure 1** | Exploring the propagation dynamics of the Airy lattice.

**a.** Comparison of micrographs of the transverse ($x$, $y$) profiles of the Airy lattice with simulation results, revealing the propagation dynamics of orders $+1$, $-1$, $+2$ and $-2$. **b.** The simulated trajectories of multiple Airy orders projected into the $x$–$z$ plane versus the experimental results for orders $+1$ and $+2$ ($y$–$z$ plane also shown). The error bars indicate the range of the estimated systematic error in the measurements. **c.** Propagation of the Airy lattice. **d.** Experimental micrograph revealing the first five Airy orders. **e.** The deflection in $y$ of each order $m$ is proportional to $1/m$. 
trajectories are in the shape given by the analytical trajectories in equation (2). We note that the summation of the deflection of the carrier and the deflection in \( x \) is equal to the deflection in \( y \). Also, the transverse linear coefficient increases by a factor of \( m \), whereas the quadratic term decreases by a factor of \( 1/m \). This is why Airy beams of high order have almost linear trajectories like the Bragg peaks. This also explains the experimental results and the differences in propagation between orders 1 and \( -1 \) (which eventually collide in \( x \)) and orders 2 and \( -2 \). The fitting coefficients for the experimental results are presented in Table 1.

Another way to find the quadratic coefficient of the parabolic trajectory is by using only a single-profile picture at a fixed distance, \( z \), from the Fourier plane (Fig. 1c–e). A single-profile picture reveals several Airy orders. Each Airy order diffracts with a different parabolic trajectory, having a different quadratic coefficient which is proportional to \( 1/m \). The deflection in \( y \) of each order in a single propagation plane \( (z \text{ has a fixed value}) \) is \( \Delta y = C_1/m \), where \( C_1 \) is a quadratic coefficient. This causes the Airy lattice to change its proportions. The diffraction orders that were located equidistantly in the Fourier plane, \( z = 0 \), diverge non-uniformly, and their proportions are not maintained (Fig. 1c and Supplementary Information, section 2). This is another demonstration of the parabolic propagation dynamics, which have been verified experimentally (Fig. 1d). The fitting curve of the experimental results presented in Fig. 1e is \( \Delta y = 193.7/m \), matching the theoretical prediction. Detailed explanation of the parabolic trajectories measurement is given in Supplementary Information, sections 2 and 5. The collision between Airy beams represents a new way of interfering electron beams. The electron beam is separated into two diffraction orders, but these beams re-merge owing to their opposite directions (Fig. 1a, b). The measured deflection in \( x \) and \( y \) was 2.5 mm over an effective distance of 150 m.

We compared the electrons diffracting from an Airy grating with the electrons diffracting from a reference periodic Bragg grating. We simulated the evolution of electrons (Fig. 2a) diffracted from a periodic Bragg grating and from an Airy grating with the same carrier period. (Only in this case did we use different input beam areas for Airy and Bragg lattices, to visualize the trajectories.) As expected, the diffraction from a Bragg lattice is linear and outward; however, the diffraction

### Table 1 | Quadratic fit results

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>( C_1 ) (m⁻¹)</th>
<th>( C_2 )</th>
<th>( C_3 ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m = 1 )</td>
<td>( \Delta x = -1.022e-7 \pm 1.51e-9 )</td>
<td>( 7.141e-6 \pm 2.7e-7 )</td>
<td>( 1.43e-4 \pm 4e-5 )</td>
</tr>
<tr>
<td>( \Delta y = 1.022e-7 \pm 1.51e-9 )</td>
<td>0</td>
<td>( -1.41e-4 \pm 2e-5 )</td>
<td></td>
</tr>
<tr>
<td>( m = 2 )</td>
<td>( \Delta x = -4.869e-8 \pm 1.02e-9 )</td>
<td>( 1.312e-5 \pm 2.7e-7 )</td>
<td>( 2.68e-3 \pm 3.75e-5 )</td>
</tr>
<tr>
<td>( \Delta y = 4.869e-8 \pm 1.02e-9 )</td>
<td>0</td>
<td>( -8.59e-9 \pm 1.42e-5 )</td>
<td></td>
</tr>
</tbody>
</table>

Fits to \( \Delta x, \Delta y = C_1x^2 + C_2x + C_3 \) and 95% confidence intervals calculated from trough curve fitting.
from the Airy lattice is anomalously bent (inwards for low-index diffraction orders). In the second experiment, we recorded profiles from the Airy lattice is anomalously bent (inwards for low-index diffrac-

<table>
<thead>
<tr>
<th>Propagation distance, z (m)</th>
<th>FWHM Bragg (µm)</th>
<th>FWHM Airy (µm)</th>
<th>FWHM Bragg/Airy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.125</td>
<td>102</td>
<td>11</td>
</tr>
<tr>
<td>52</td>
<td>5.785</td>
<td>104</td>
<td>58</td>
</tr>
<tr>
<td>100</td>
<td>8.125</td>
<td>110</td>
<td>81</td>
</tr>
</tbody>
</table>

FWHMs of the diffracted beams.

electron Airy beams suggests a general means of manipulating particles' wave packet trajectories by engineering their initial probability density wave functions. Our experimental results include demonstration of electron wave packet trajectories that show shape and size preservation over an effective length of more than 100 m. Such non-spreading Airy electron wave packets may be useful in improving the resolution properties of TEM imaging, because they have an extremely large depth of focus. Furthermore, we have shown that these electron wave packets self-heal and reconstruct their original shape after passing an obstacle. An interesting feature of these beams is that different diffraction orders with quadratic terms of opposite sign can be merged and possibly used as a new type of electron wave interferometer. The holographic generation of Airy electron beams can be generalized because recent studies have shown that optical Airy beams can be designed with arbitrary spatial shapes and can propagate along arbitrary trajectories. It may also be possible to use these beams to study electron spin–orbit interaction effects in the relativistic regime, similarly to recent studies of electron vortices. Finally, there may be other ways of manipulating and shaping the trajectories and the self-healing properties of Airy beams, based on the ability to externally influence electrons using magnetic or electric potentials.

METHODS SUMMARY

Our analytical method of designing nanoscale holograms for electrons, imposed with any phase, is described in Supplementary Information, section 2. Our technique for determining the propagation dynamics of an electron beam, which we showed can be modelled numerically, is reported in Supplementary Information, section 5. We also developed a way of imaging electron wave packets with high magnification (Supplementary Information, section 4) and a way of manufacturing holographic masks for electrons with high writing resolution (Supplementary Information, section 3).

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Supplementary Information is available in the online version of the paper.

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Author Contributions N.V.-B. conceived the idea and designed the experiments. N.V.-B. and Y. Lereah carried out the experiment. Y. Lilach optimized the production process and fabricated the nanoscale holograms. A.G. and A.A. did the theoretical work and conceived ideas for applications. A.A. and N.V.-B. analysed the experimental results. A.G., A.A. and Y. Lereah provided experimental and theoretical guidance. A.A. and N.V.-B. developed and analysed the Airy lattice. All authors took part in writing the paper.

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