Contrast formation in Quantum Electron Microscopy

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For most biological specimen, the present resolution of transmission electron microscopes is more than sufficient. The problem is the sensitivity to radiation damage which results in "dose-limited resolution". The approach called "Quantum Electron Microscopy (QEM)" has tried to reduce the damage by applying principles from "non-demolition", also called "interaction-free" techniques from quantum optics.

In QEM an electron is split into two states, a sample state $|S\rangle$ and reference state. The sample state is used as a STEM focused probe while the reference state passes through empty space. The same electron is cycled through the sample several times. The $|S\rangle$-state experiences phase shift $\delta\phi$ passing through the sample $|S\rangle \rightarrow e^{i\cdot\delta\phi}|S\rangle$. There is also probability for the electron to collapse onto the sample in an (inelastic) interaction. The energy lost by the electron is the damage dealt to the sample. Since the electron was split so that the amplitude of the sample state was small, the probability of damage by the electron is very low.

Previously, we have analysed situations where the amplitude contrast dominated [1], but more recently we have also analysed the effects in samples where phase contrast dominates. The results can be compared to TEM phase contrast with a Zernike phase plate. However, the imaging mode is as in scanning transmission electron microscopy and has features that look like STEM differential phase contrast with a biprism splitter.

To compare QEM with other EM methods we estimate the dose limited phase resolution. Intensity variations in an image occur either deterministically (reflecting the variations in the sample) or stochastically (shot noise). The minimal phase sensitivity $\Delta\phi$ should be so great that the change in intensity is comparable with the shot noise: $\Delta\phi\left|\frac{dC}{d\phi}\right| I = \sqrt{C(\phi)I}$, where $C(\phi)$ is the contrast function and I is the average number of electrons per pixel. Hence for $C(\phi)I$ electrons detected the phase shift of the sample is within interval $\phi \pm \Delta\phi$ with probability of 63%. Note that $\Delta\phi$ is proportional to $\sqrt{I}$ just as SNR in the shot noise limited measurements. For different microscopy techniques phase resolution can be written as $\Delta\varphi = F \cdot \frac{1}{\sqrt{D}}$, where F is a (technique dependent) factor and D is the illumination dose (which is not equal to I in case of QEM). For instance, for TEM with an ideal Zernike phase plate $F_{TEM} = 0.5$. If we use the pessimistic estimate for the dose in QEM $D_{\max} = I \cdot N/2$, then $F_{QEM} \approx \frac{1.6}{\sqrt{N}}$, where N is the number of cycles.

I shall discuss the conclusions we can draw from our work on Quantum Electron Microscopy.

References

[1] S. Thomas et al, Phys. Rev A 90, 053840 (2014), pp. 1-10