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Coherence and Inelastic Scattering in Electron Microscopy

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Aspects of coherence have profoundly shaped the body of JCH Spence's scientific contributions.[e.g. 1-3] In particular, the coherence of x-ray and electron waves is of interest and commonly described by a temporal (longitudinal) coherence length $l_t = \lambda^2/\Delta\lambda$ and a spatial (transverse) coherence length $l_s = \lambda/2\pi\theta$, where λ is the de Broglie wavelength and ΔE, θ are the energy and angular spread of the probing beams. Traditionally, partial coherence is used to describe wave properties of the ensemble of scattered particles collected on a detector, which affects the formation of high-resolution phase contrast images by introducing damping functions to the Contrast Transfer Function.[4] Surely, the scattering of electrons differs from x-ray scattering because of the existing electron charge e. Moreover, the deposition of a total charge C during recordings can be described by the number of delivered electrons C = N*e or, alternatively, by the beam current C = I*t.

Advanced electron microscopy techniques [5,6] allow investigating how variations of the irradiated area F_I and the recording time t affect both descriptions experimentally as shown in Figure 1. An outstanding contribution of the approach includes the ability to address beam-sample interactions in the limit of single electron self-interferences to better understand the dose and dose rate dependences of irradiated matter.[5-7] For this purpose we assume that quantum theory is universally valid so that observable properties emerge from inelastic interactions among wave functions with energy loss ΔE that degrade phase relations because they change the Broglie wavelength by $\Delta\lambda$ and create wave packages of finite size. Specifically, we consider the case of self-interferences where a phase shift $\varphi = 0.5$ rad equals $(2\pi/\lambda - 2\pi/(\lambda+\Delta\lambda))*l$ [5] to show in Figure 2 how the resulting coherence lengths l (ΔE) relate to the coherence times $l_t = l(\Delta E) / c$, where c is the speed of light. Thus, introducing a decoherence phase of $\varphi = 0.5$ rad, the obtained relation closely matches Heisenberg's Uncertainty Principle because the slope of the line reflects $\hbar/2 = 3.3\ 10^{-16}$ eVs. From the plot it is seen that coherent elastic electron scattering or incoherent inelastic scattering are quantum mechanical approximations. Available experimental data, however, are fully compatible with the view that electron scattering is coherent but inelastic with a coherence length that is energy dependent as indicated in Figure 2. Obviously, it is desirable to directly measure the suggested dependence. Such measurements are currently pursued. [8]

References
[1] J.H.C. Spence, High-Resolution Electron Microscopy, Oxford University Press, UK 2013
[2] J.H.C. Spence, H.N. Chapman, Phil. Trans. R. Soc. B 369 (2014) 20130309
[3] D. van Dyck, J.H.C. Spence, H. Lichte, Ultramicroscopy 81 (2000) 187-194
[4] C. B. Carter, D.B. Williams (eds.), TEM, Capter 7, Springer, Switzerland 2016
[5] C. Kisielowski, P. Specht, B. Freitag, E.R. Kieft, et al., Adv. Func. Mater. 29 (2019)1807818

[6] C. Kisielowski, P. Specht, S. Rozeveld, et al. Microscopy and Microanalysis 27 (2021) 1420-1430
[7] C. Kisielowski, P. Specht, B. Freitag, E.R. Kieft, et al., Adv. Func. Mat., (2022) in review
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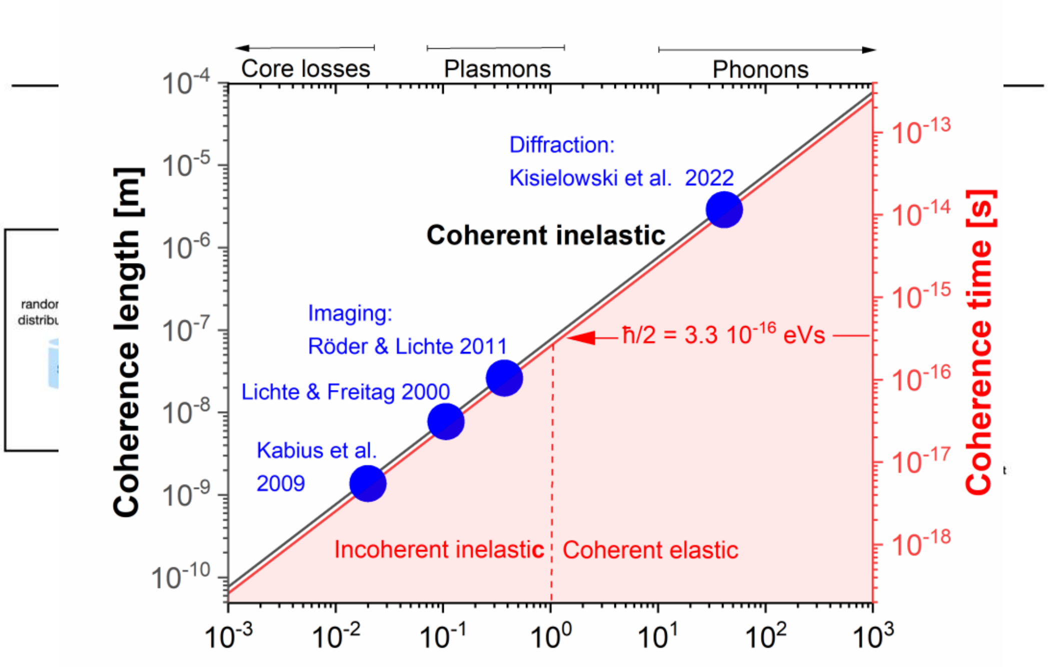

Figure 1: Advancing electron microscopy to access dependences on irradiated area F_I and on time t.[5,6]
Figure 2: Coherence length and time for self-interfering electrons. Blue: Available experimental data.[7]