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Single Atom Imaging and Spectroscopy in a Low-kV STEM

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When operating at voltages low enough to avoid knock-on radiation damage, aberration-corrected scanning transmission electron microscopes (STEMs) allow volumes of matter as small as single atoms to be imaged and analyzed spectroscopically. The instrumental requirement for this type of work is that the STEM needs to be able to produce, at a low operating voltage, an electron probe not much bigger than 1 Å that contains a probe current of 0.1 nA and higher, and preferably has an energy spread of less than 0.4 eV. Such performance is now readily attainable. It has given us clear annular dark field (ADF) images of single atoms as light as boron, and it has identified the chemical type of single atoms in three different ways, sometimes simultaneously1: 1) by the atom's ADF intensity, 2) by its electron energy loss spectrum (EELS) and 3) by its energy-dispersive X-ray spectrum (EDXS). The EELS data typically shows fine structures in spectra from the single atoms, and the structures are often substantially different than when the same kind of atom is bonded in other materials. The fine structures can be used to answer questions relating to charge transfer and atomic coordination numbers, atom-by-atom. Acquiring EELS and EDXS data simultaneously from single atoms also allows theoretical cross-sections to be tested with unprecedented accuracy. Experimental results from materials systems such as single atom impurities in and on graphene and monolayer BN will be shown, and likely future progress will be discussed. Our more recent quest to develop a low to medium kV electron beam analytical instrument that may ultimately be able to identify single atoms of hydrogen by their low energy vibrational spectra will also be described. The new instrument is designed to reach EELS energy resolution down to 10 meV with an atom-sized probe. It uses a monochromator of a new design2 that acts on full-energy electrons and thus minimizes stochastic Coulomb effects that typically limit monochromator performance, and at the same time allows the monochromator and the energy loss spectrometer to be linked together in such a way that both short- and long-term drifts of spectrum energy are largely avoided. References: 1. See for instance O.L. Krivanek, W. Zhou, M.F. Chisholm, N. Dellby, T.C. Lovejoy, Q.M. Ramasse and J.C. Idrobo, "Gentle STEM of Single Atoms: Low keV Imaging and Analysis at Ultimate Detection Limits", in: Low Voltage Electron Microscopy: Principles and Applications (D.C. Bell and N. Erdman, editors, RMS-Wiley) in press. 2. O.L. Krivanek, T.C. Lovejoy, G.J. Corbin, N. Dellby, M.F. Murfitt, N. Kurz, P.E. Batson and R.W. Carpenter "Monochromated STEM with high energy and spatial resolutions", Microscopy and Microanalysis (proceedings 70th annual MSA meeting, Cambridge University Press, 2012), in press.