Introduction: The carbonaceous chondrite (CC) meteorites are among the most primitive materials from the solar system, providing insights into its physical and chemical evolution. The matrices of many carbonaceous chondrite meteorites consists of a C-rich material intimately associated with clays, oxides, and sulfides. The fine-grained nature and heterogeneity of the bulk of the matrix minerals necessitates the use of high spatial resolution imaging techniques and spectroscopies for mineral identification. Electron energy-loss spectroscopy (EELS) with a transmission electron microscope (TEM) is an established spectroscopic technique that provides both qualitative and quantitative chemical information from nanometer scale regions. EELS provides similar information as X-ray absorption spectroscopy (XAS) but from sub-nanometer-sized regions. Analysis of EELS spectral shapes provides information on the coordination, oxidation state, and spin states of atoms in minerals, and the core-loss intensity over a suitable energy window is related to the element concentration. Despite the availability of parallel EELS detectors since the mid 1980s, meteoritical applications are relatively uncommon. Here I illustrate the great potential of EELS for a) determination of the oxidation state of transition elements, b) identification of local coordination and bonding, and c) nanometer-scale element quantification. I will also discuss the problems of electron-beam damage to the samples and techniques for mitigating this damage.

Valence determination: Iron is among the most abundant element in the solar system occurring naturally as Fe$^0$, Fe$^{2+}$, and Fe$^{3+}$. Determination of oxidation state ratios is useful because they can be used to infer the redox conditions under which minerals formed or were last equilibrated. EELS spectra of Fe$^{2+}$- or Fe$^{3+}$-bearing minerals exhibit distinct L$_2$3 edge shapes and chemical shifts, whereas minerals containing Fe$^{2+}$ and Fe$^{3+}$ exhibit two-peak L$_3$ edges that are intermediate in shape between the two single-valence end members. The changes in relative heights of the L$_3$ peaks reflect changes in the Fe$^{3+}$/ΣFe ratio. I will report on Fe valence determination from serpentine group minerals in a range of CM2 chondrites.

Bonding probe: Many EELS spectra exhibit a near-edge structure that is characteristic of the arrangement and number of atoms in the first coordination shell and gives rise to a coordination (also called a bonding) fingerprint. The C K edge provides an excellent example of a coordination fingerprint. Elemental C in meteorites displays a range of bonding environments from the well-known allotropes of diamond, graphite, and fullerenes to a range of amorphous and poorly ordered materials. Bonded C in CC meteorites occurs in a wealth of structures ranging from carbonates, carbides, organic (as in the recently described nanospheres), and intercalated into clays in the CI meteorites. I will illustrate the unique ability of EELS to provide important bonding information by examining the C K edge from a range of materials in CC meteorites.

Element quantification: An often overlooked attribute of EELS is its use for element quantification and when combined with a TEM provides a unique nanometer elemental probe. I show examples of the use of EELS for quantification including serpentine nanotubes in the Mighei (CM2) meteorite and an unusual (for meteorites) Al-S-O phase from the Gujba (CH) meteorite (Fig. 1). I will also briefly discuss some of the difficulties of using EELS for element quantification.

Conclusions: EELS and XAS produce similar sorts of data. Each has its own advantages: big advantages of EELS include its high spatial resolution and element quantification. Additionally, high resolution TEM images, diffraction patterns, and energy dispersive x-ray spectra can be recorded from the same areas, complementing the EELS data. I will discuss the future of EELS research to the meteoritical sciences.
Figure 1. Example using EELS to quantify an unknown material from the Gujba (CB) acid residue. A) TEM image of a cluster of particles from the residue supported on a lacy carbon TEM grid. The lath-shaped crystals are stishovite. The rounded amoeboid crystals are the unknown. The EELS spectrum in B) is from the area indicated by the red dot in A). The EELS spectrum shows O (not shown), Al, and Si only. C) Subtraction of the background from beneath the core-loss edges and extraction of the cross section and edge counts in a 190 eV window. D) Use of the ratio technique gives the corresponding element ratios.

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\frac{C_{A/B}}{I_A} = \frac{I_A(\beta, \Delta_A)}{I_B(\beta, \Delta_B)} \sigma_A(\beta, \Delta_A) \frac{1}{\sigma_B(\beta, \Delta_B)}
\]

Gives

\[
\text{Al}_{1.95}\text{Si} \\
\text{with O} \\
\text{Al}_{1.95}\text{Si}_{1.00}\text{O}_{4.98}
\]