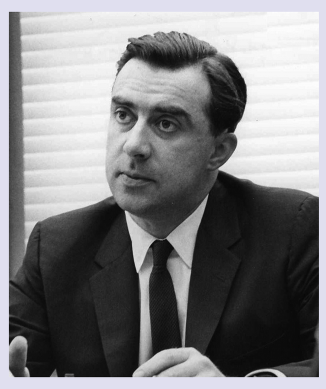
Albert V. Crewe

1927-2009

Brief biography

Born in Bradford, Yorkshire, England, Crewe received bachelor's and PhD degrees from the University of Liverpool where, briefly but inspirationally, his professor was Sir James Chadwick, 1935 Nobelist for discovery of the neutron. Starting in Liverpool, Crewe's early work concentrated on high-energy physics, where he was the first to produce an external beam of protons to study particle interactions; this work continued at the University of Chicago in 1955 where became full professor in 1963, and Distinguished Service Professor in 1977. He was Dean of the Physical Sciences Division at the University of Chicago from 1971 to 1981, and retired as a Professor Emeritus in 1996.

In 1958 he became Director of Argonne National Laboratory's Particle Accelerator Division, where, as the youngest in his group of 100, he supervised the design and construction of Argonne's 12 GeV Zero Gradient Synchrotron. In 1961, he was appointed Director of Argonne National Laboratory, at age 34, still an assistant professor without tenure, and not yet a United States citizen. He left the post in 1967, to return to the University of Chicago and work full-time on the STEM project, having become full professor in 1963.



Crewe took advantage of his prestige and high administrative positions to advocate the need for scientists to take the initiative in helping to solve societal problems (Crewe, 1967) and to urge the Federal government to fund basic research and develop new sources of energy. He often lamented the fact that the US system for awarding grants (perhaps unavoidably) discourages projects that are not likely to succeed, or that are entirely new. Had the funding opportunities at the start of the STEM project been as they are today, the work might never have been done, yet the success of the project led to successful funding for future development.

His honors include:

- Distinguished Scientist Award from EMSA (now MSA)
- Ernst Abbe Memorial Award from the New York Microscope Society
- Albert Michelson Medal from Philadelphia's Franklin Institute
- Duddell Medal from London's Institute of Physics
- Member of the National Academy of Sciences
- Honorary fellow of the Royal Microscope Society

The start of the STEM project

As Director of Argonne National Laboratory, Crewe supervised 5500 people, including 400 biologists. In 1963 he decided to attend a European meeting on biology, to see how "his biologists stacked up". There, he was impressed with the beauty of the electron micrographs. Without ever having seen an electron microscope, or looking into how they worked, he passed time on the long (propeller-driven) flight back by speculating on how an EM might be designed. One of the two designs he came up with (Crewe, 1963; Fig. 1) was entirely new, and became the first STEM.

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A NEW KIND OF SCANNING MICROSCOPE

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Electron microscopes which are in current use are of basically the same design and appear to be limited as regards their ultimate resolving power and the difficulty of achieving sufficient contrast (1). Numerous authors have discussed these limitations and it is apparent that in order to achieve significant improvements it would be necessary to depart from conventional designs.

A clue as to the direction in which to look comes from a study of the scanning X-ray microscope which is being used for the study of metallurgical and other solid specimens (2, 3, 4), albeit, at the moment, with much lower resolution than is achievable by the conventional microscope. The scanning technique is inherently capable of achieving a good resolution in the sense of a very small focused spot. For example, by the use of a tungsten point as the source of electrons and a single lens, it should be possible to focus the electrons onto a spot a few Å in diameter. The disadvantage of this system is, of course, that the total current is small. This disadvantage can, however, be overcome by attempting to detect most of the electrons transmitted through the sample. For example, if a momentum analyzing spectrometer is placed after the specimen, then electrons of one particular energy can be detected by means of standard detecting equipment, such as scintillating counters. The output from this detector can then be displayed on a TV screen whose scanning raster is synchronized with the spot scanning system.

The possible advantages of this proposed system are numerous. For example, one single lens system is all that is required to achieve good resolution and the lens system must only be capable of taking a small object on the lens axis and forming a small image which is also on the

A.V. Crewe 369

LETTRES A L'ÉDITEUR

JOURNAL DE MICROSCOPIE, VOLUME 2, 1963

lens axis. The restrictions upon lens design are few. Then again, the ability to detect and display electrons in a narrow band of energies allows several types of displays with the inherent possibility of producing good contrast. If the electrons are detected in the main transmitted peak in a small solid angle in the forward direction, then the display would be sensitive to local variations in sample density and atomic number and this sensitivity might very well be increased by selecting the electron energy slightly off the main transmitted peak. Finally, there is the possibility of setting the spectrometer in a momentum range which would detect electrons which have lost a characteristic amount of energy, characteristic, that is, of the energy of a particular X-ray line of a particular chemical element. While it would not be expected that this would enable the selection of only one particular chemical element for display, it would be expected to improve the contrast and indicate in a general way where such an element resided in a specimen.

The details of such a microscope have been calculated and it appears to be feasible. This microscope is now being constructed in this Laboratory. The details of the system which is being constructed are as follows.

The electron source is most conveniently chosen to be a tungsten point because it gives a virtual source only a few Å in diameter. This source can be imaged on to the specimen by a single lens system using a low demagnification. The lens may be a quadrupole doublet because a strong lens is not required. The scanning system will be placed between the lens and the specimen and is a conventional one such as those used in television receivers. Downstream of the specimen is placed the momentum analyzing system which will consist of an electrostatic or magnetic spectrometer of high resolution but conventional structure. The detector will consist of a scintillator and photomultiplier.

It is expected that the microscope will be in operation within the next few months.

BIBLIOGRAPHY

1. ZWORYKIN V.K., MORTON G.A., RAMBERG E.G., HILLIER J. and VANCE A.W., 1945. Electron Optics and the Electron Microscope. Chapter 4, 123-159.
2. ADLER I., 1963. The Electron Probe. *International Science and Technology*, 17, 39-45.
3. BAKISH R., 1962. *Introduction to Electron Beam Technology*, 413.
4. THORNLEY R.F.M., 1960. Recent Developments in Scanning Electron Microscopy. *European Regional Conference on Electron Microscopy*, 1, 173-176.

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370 *New Scanning Microscope*

Fig. 1. Concept for a new type of EM, 1963

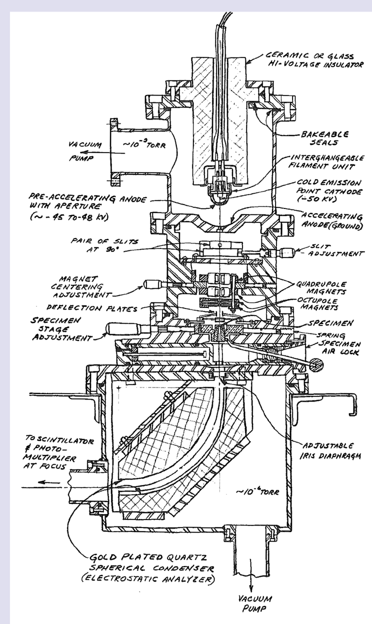

Fig. 2. The first STEM

Development of the field-emission gun

STEM development started at Argonne, where as Director Crewe had the discretion to undertake the project. This was fortunate because, after consulting with relevant experts on each aspect of the project, he was advised that none of his ideas would be feasible. Yet he was confident, and went ahead regardless. He realized that source brightness was limiting the resolution of the scanning EMs, just being developed in the UK, to about 1.5 nm. As a solution, he got the idea of using a field-emission (FE) source from a brief mention in the classic book by the US EM pioneers (Zworykin et al., 1945), although FE had never been used as a source in an electron microscope. He consulted with Robert Gomer, a renowned in-house expert on field emission, and was told that the UHV requirements would make use in an EM impractical.

However, undeterred, he embarked on developing the FE gun, and took on students Joe Wall, Mike Isaacson, and Dale Johnson, in that order. After the first design for the 1964 instrument, the Butler-type gun was the basis for all future work (Crewe et al., 1968). The type of FE studied by Gomer required 10^{-15} Torr vacuum, but they discovered that at 10^{-10} Torr, after a few seconds of intense emission, a monolayer of gas molecules formed and the emission dropped sharply, after which the emission was stable for a long period.

The tips were tested and evaluated in a separate system, then installed in the EM. At first, they lasted about 30 seconds, after which a high-voltage discharge destroyed the tip; after a tip change, two days of pumping were required to get the system back to UHV conditions so that one could try again. However steady progress was made in tip and gun design, and with each new design the tip lasted longer, from days, to weeks, to a year or more.

In 1968, Hitachi had also started to develop a FE gun, and in 1970 Crewe was invited to serve as a consultant for two years. In 1972 Hitachi sold their first FE-SEM, and Vacuum Generators sold their first FE-STEM (which was nearly identical to Crewe's but did not provide atomic resolution until much later).

The STEMs

The first instrument used a rather conventional electron gun design, adapted for field emission, and it employed a quadrupole-octupole arrangement, rather than a solenoid-type post-gun lens (Crewe, 1964; Fig. 2). The detection system was unique because it included an electron spectrometer, which was capable of separating elastically and inelastically scattered electrons. After adoption of the improved FE gun, the system was capable of 0.5 nm resolution. The flexible imaging system of the STEM, with angular- and energy-dependent electron detection, facilitated increased contrast over what could be obtained in TEM, and was key to the impressive results obtained (Crewe and Wall, 1970; Crewe et al., 1970; Fig. 3). The next instrument had only the gun, no lenses at all (Crewe et al., 1969; Fig. 4), yet the resolution was about 10 nm, better than any other scanning EM, and good images were obtained. Very early work was done on low-loss EELS, differentiating the DNA bases (Crewe et al., 1971; Fig 5). Later STEM versions had one or two magnetic lenses following the gun (Crewe et al., 1970; Crewe, 1971), and the acceleration voltage was eventually increased to 100 kV. Crewe also envisioned a million-volt STEM, as early as 1964, He discussed it in the 1970s, but it was never completed, although a very short-lived 1 MeV STEM was built under John Cowley at Arizona State.

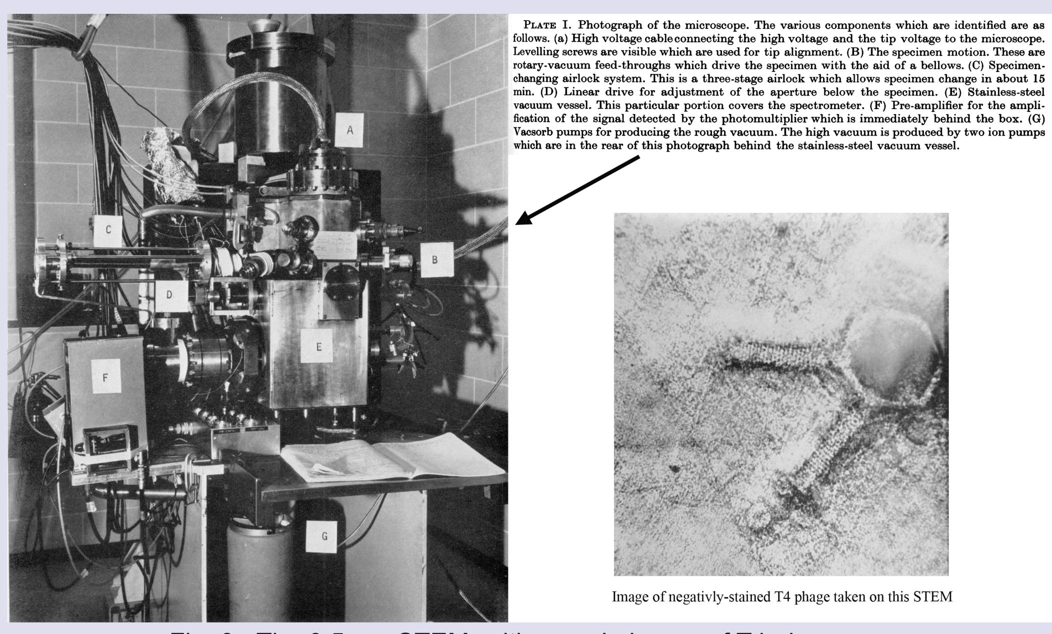

Fig. 3. The 0.5-nm STEM, with sample image of T4 phage

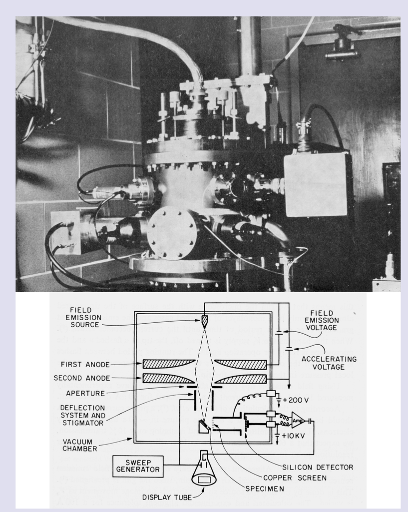

Fig. 4. The lens-less STEM

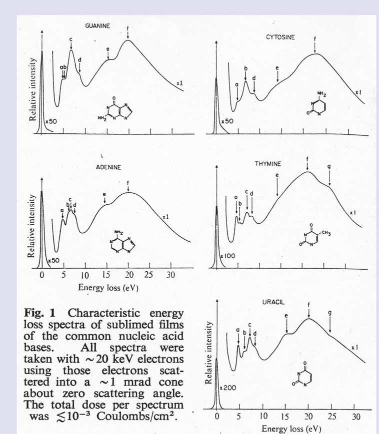

Fig. 5. EELS of DNA bases

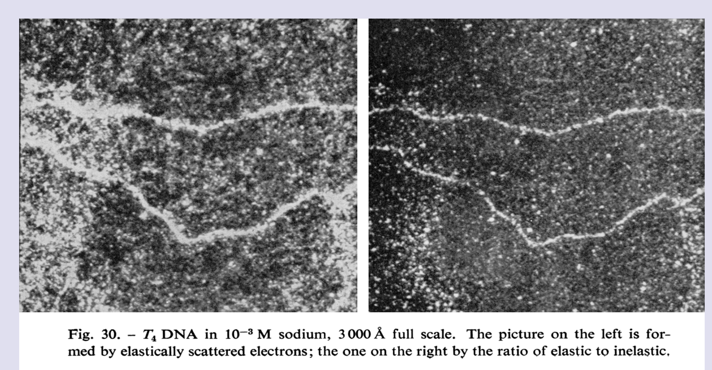

Fig. 6. Single strands of DNA

The first atomic-resolution EM

The probe size of the two-lens STEM brought the resolution down to about 0.25 nm, as good as the best TEMs of the day. It should be noted that TEM and STEM are "reciprocal", and that the objective lens has the same characteristics (and limitations) in both cases, except that the aperture can be very small in STEM since a wide image field is not needed. The images of single DNA strands taken by Wall (Crewe 1971; Fig. 6) led Crewe to calculate the visibility of single atoms, and he realized that he "could not possibly fail" to image single heavy atoms. However, the problem was to convince people that the "dots" seen were actually atoms. This problem was solved by Michael Beer of John Hopkins. He had been working on trying to visualize atoms in the TEM, and he had way to make chains of thorium atoms. He brought his specimens along and, sure enough, every specimen they looked at had chains of dots (Crewe et al., 1970; Fig 7). After looking at many such specimens, Joe Wall found it was getting boring, saying "when you've seen one atom, you've seen them all"; they turned of the EM and went home. Subsequently, they recorded atomic images of several other elements, (Wall et al, 1974) and even recorded atoms in motion (Isaacson et al., 1976, 1977).

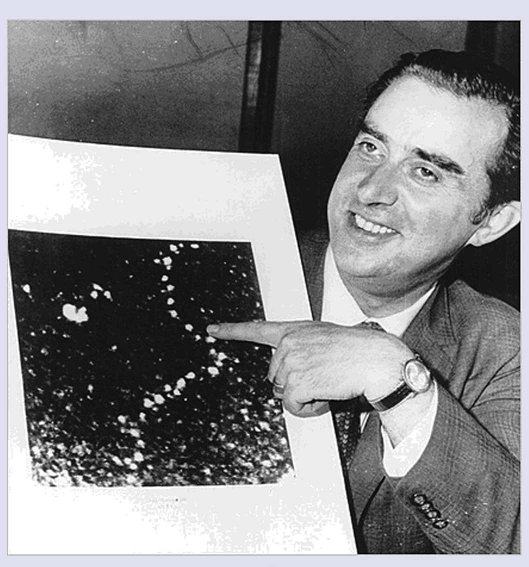

Fig. 7. A chain of thorium atoms

Aberration correction

Greatly impressed by the theoretical and practical work of Scherzer and colleagues, Crewe's lab embarked on their own efforts to correct the unavoidable aberrations of round electron lenses. The first attempt was a quadrupole-octupole corrector, as designed by Scherzer and first tested for feasibility (although not in a microscope) by Deltrap (1964). Crewe already had experience with such elements from his work with high-energy accelerators (note their use in the first STEM, above). The polepieces of the corrector (Beck, 1977; Fig 8) were machined with one-micrometer tolerance, a rare feat, carried out by Walter Mankawich, yet adequate alignment could not be achieved even with the use of trimming coils. This may have been due to inhomogeneity of the iron, or to instability of the power supplies. Next, a simpler arrangement, consisting of sextupoles, was tried (Crewe et al., 1982; Fig. 9), but funding was insufficient to complete the project (funding also prevented complete success of aberration correction during Scherzer's lifetime). The design of the sextupole corrector was refined (Shao and Crewe, 1987), and later proof-of-concept was realized on an SEM column (Chen and Mu, 1990). Finally, an even simpler solution was proposed: use of a mirror corrector (Crewe 1992; Crewe and Tsai, 1998; Fig. 10). The corrector was built (Crewe et al., 2000; Tsai, 2000), but funding ran out before the entire STEM system could be completed.

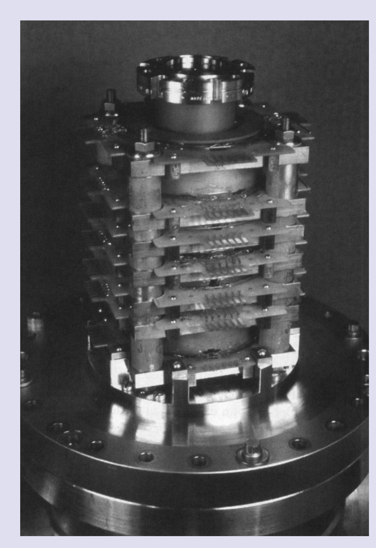

Fig. 8. The quadrupole-octupole corrector

Fig. 9. The sextupole corrector

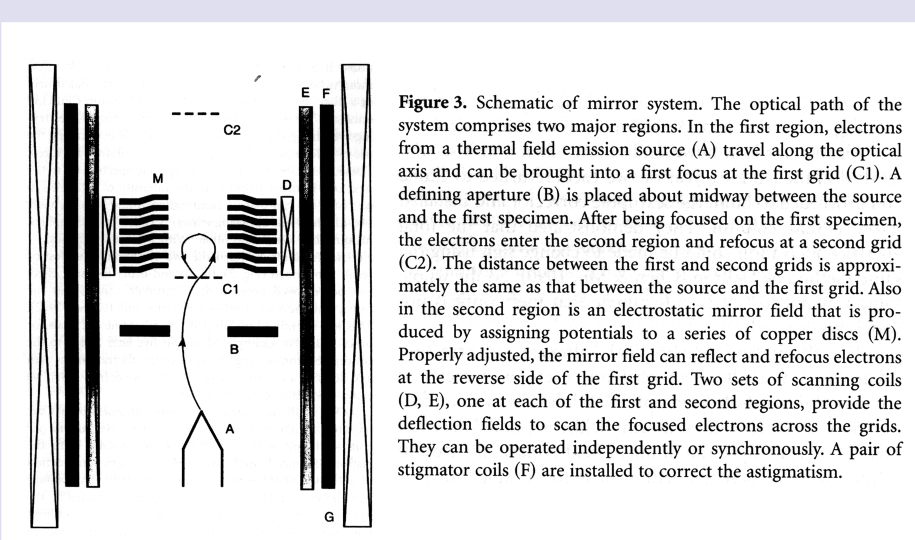

Fig. 10. The mirror corrector

Applications of the STEM

As was generally the case up until the 1980s, the main applications of EM, and the main incentive for its development, was biological research. This was also true of the STEM (e.g. Ohtsuki and Crewe, 1980). Crewe's lab demonstrated that because of much better detection efficiency, the electron dose of the STEM was significantly lower than that of the TEM (Isaacson et al, 1973; Crewe 1973), and this allowed some of the first work on biological macromolecules. Inspired by Unwin and Henderson's work (1975), the Crewe lab realized that if the specimen is not in the form of a 2-D crystal (or helix), multiple views of a molecule would be required to make a 3-D reconstruction. Reducing the problem to the extreme, a scheme was devised to obtain an "inexact" reconstruction from only three views (Crewe et al., 1984; Kapp et al., 1987; Fig. 11).

Joe Wall, recruited from Chicago to Brookhaven National Lab, carried forward the biological applications by building a special-purpose FE-STEM in 1977, which soon became one of the longest-running NIH national microscopy resources. The Brookhaven STEM has an enviable record of producing important and high-quality data (including accurate mass measurements) in structural biology, which could not have been obtained in any other way.

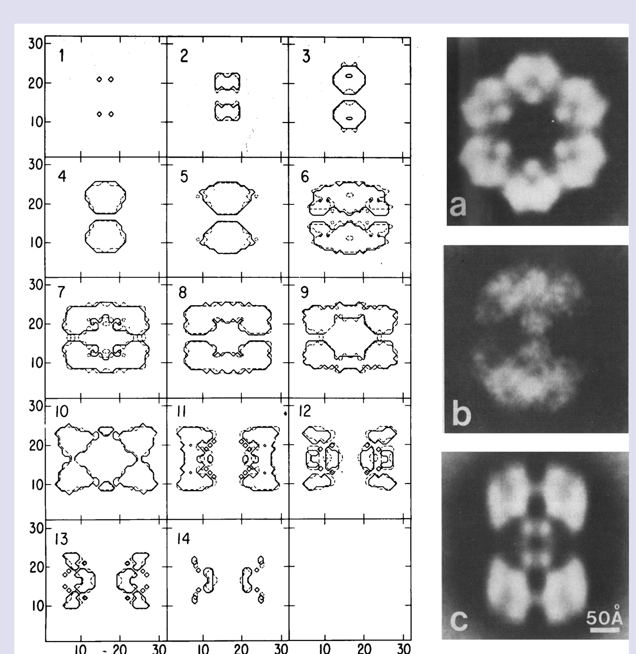

Fig. 11. 3-D reconstruction of hemoglobin molecule

Later work, high-resolution LVSEM

Crewe continued to do basic theoretical work in electron optics (e.g. Crewe 1991a,b) and to consider how the electron microscope could be improved, publishing several theoretical papers. Early on, he realized the advantages of low accelerating voltage for SEM (i.e. surface) imaging (Crewe, 1976), where the lens quality becomes more important than the gun quality. As a result of detailed studies of magnetic and electrostatic probe-forming lenses (Crewe, 1995), he invented a new type of (gapless) focusing lens for low-voltage scanning microscopes (Tsai and Crewe, 1998). He later developed a low-voltage scanning electron microscope using a dipole permanent magnet as a lens (Crewe and Kapp, 2003). Crewe's last two papers appear to have been published in 2006 (Kapp et al., 2006; Crewe and Gorodezky, 2006).

References

Beck V. (1977). Aberration correction in the STEM. Optik 53:241.
Chen EG and Mu CJ. (1990). New Development in Correction of Spherical Aberration of Electro-Magnetic Round Lens. Int. Symp. Electron Microscopy, Beijing, China, Kuo, K. & Yao, J. Eds. pp. 28–35. Singapore: World Scientific.
Crewe AV. (1963). A new kind of scanning microscope. Journal de Microscopie 2:369-370.
Crewe AV. (1964). Scanning techniques for high voltage electron microscopes. AMU-ANL High Voltage Electron Microscope Mtg. Argonne National Laboratory, pp. 68-81.
Crewe AV. (1967). Science and the war on … Physics Today 20(10):25-30
Crewe AV, Eggenberger, DN, Wall J and Welter LM. (1968). An electron gun using a field emission source. Rev. Sci. Instr. 39:4.
Crewe AV, Isaacson MS and Johnson DJ (1969). A Simple Scanning Electron Microscope, Rev. Sci. Instr. 40:241.
Crewe AV and Wall J. (1970). A scanning microscope with 5 A resolution. J. Mol. Biol. 48(3):375-393.
Crewe AV, Wall J and Langmore J. (1970). Visibility of a single atom. Science 168: 1338-1340.
Crewe AV. (1971). High intensity electron soruces and scanning electron microscopy. In: Electron Microscopy in Material Science. U. Valdré ed. Academic Press, New York, pp. 160-207.
Crewe AV, Isaacson M and Johnson D. (1971). Electron energy loss spectra of the nucleic acid bases. Nature. 231(5300):262-263.
Crewe AV. (1973). Considerations of specimen damage for the transmission electron microscope, conventional versus scanning. J. Mol. Biol. 80(2):315-325.
Crewe AV. (1976). Very low voltage electron microscopy. Ultramicroscopy. 1(3):267-269.
Crewe AV. (1982). A system for the correction of axial aperture aberrations in electron lenses. Optik. 60:271-281.
Crewe AV, Crewe DA and Kapp OH. (1984). Inexact three-dimensional reconstruction of a biological macromolecule from a restricted number of projections. Ultramicroscopy. 13(4):365-371.
Crewe AV. (1991a). A new characterization of the magnetic lens. Optik 89:70-74.
Crewe AV. (1991b). The three element electrostatic lens. Optik 90:151-157.
Crewe AV. (1992). Electron motion in tuned fields, II. Some applications. Ultramicroscopy 41:279-285.
Crewe AV. (1995). Limits of electron probe formation. J. Microsc. 178:93-100.

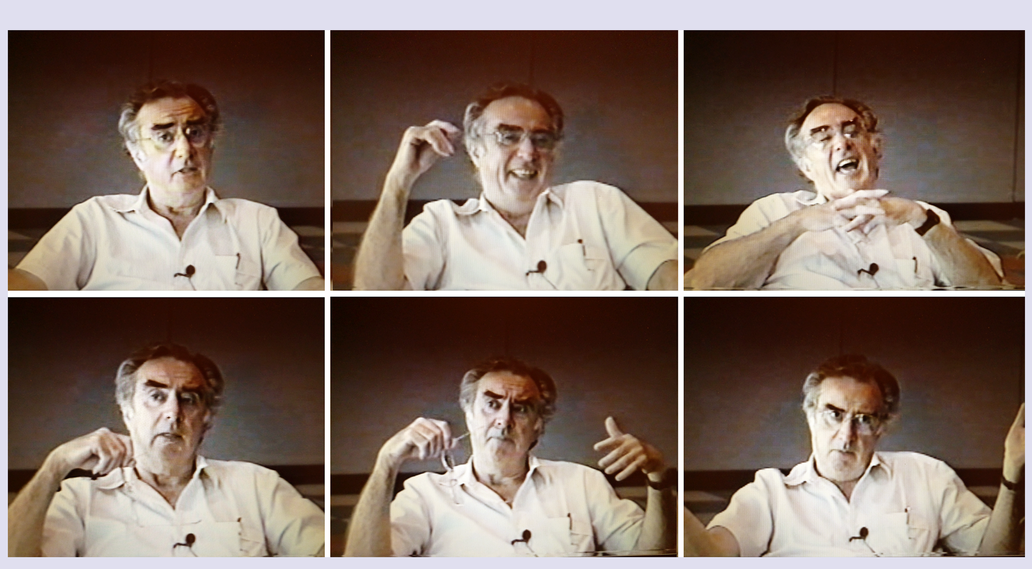

Fig. 12. Frames from 1992 interview by Sterling Newberry

Crewe AV and Tsai FC. (1998). Aberrations of a Magnetically Focused Mirror. J. Microsc. 189(3):185-187.
Crewe AV, Ruan S, Korda P and Tsai F. (2000). Studies of a magnetically focused electrostatic mirror, I. Experimental test of first order properties. J Microsc 197:110-117.
Crewe AV and Kapp OH. (2003). First tests of a dipole lens for a scanning electron microscope. J. Microsc. 209(1):47-55.
Crewe, AV (2004) Some Chicago aberrations Microsc. Microanal. 10:414-419.
Crewe A and Gorodezky I. (2006). Flat electron beams. Optik. 117(1):15-20.
Deltrap JHM. (1964). Correction of spherical aberration with combined quadrupole-octopole units. Proc. EUREM-3, Prague, A:45–46.
Isaacson M. Johnson D. Crewe AV. (1973). Electron beam excitation and damage of biological molecules; its implications for specimen damage in electron microscopy. Rad. Res. 55(2):205-224.
Isaacson M, Langmore J, Parker NW, Kopf D and Utlaut M. (1976). The study of the adsorption and diffusion of heavy atoms on light element substrates by means of the atomic resolution STEM. Ultramicroscopy.1:359.
Isaacson, MS, Kopf, D, Parker NW and Utlaut M. (1976). Observations of surface diffusion at the atomic level by means of microcinematography in the STEM. Proc. 34th Ann EMSA Mtg. 584-585.
Isaacson MS, Kopf D, Utlaut M, Parker NW and Crewe AV (1977). Direct observations of atomic diffusion using a STEM. PNAS USA. 74:1802.
Kapp OH, Mainwaring MG, Vinogradov SN and Crewe AV. (1987). Scanning transmission electron microscopic examination of the hexagonal bilayer structures formed by the reassociation of three of the four subunits of the extracellular hemoglobin of Lumbricus terrestris. PNAS USA. 84(21):7532-7536.
Kapp OH, Smith DR, Jendraszkiewicz G, Gorodezky I, Kim KJ and Crewe AV. (2006). A flexible instrument control and image acquisition system for a scanning electron microscope. J. Microsc. 223(2):140-149.
Ohtsuki M and Crewe AV. (1980). Optimal imaging techniques in the scanning transmission electron microscope: applications to biological macromolecules. PNAS USA. 77(7):4051-4054.
Shao Z and Crewe AV. (1987). Spherical aberrations of multipoles. J. Appl. Phys. 62:1149-1153.
Tsai FC and Crewe AV. (1998). A Gapless Magnetic Objective Lens for Low Voltage SEM. Optik. 109(1):5-11.
Tsai F. (2000). Studies of a magnetically focused electrostatic mirror, II. Aberration correction. J Microsc 197:118-135.
Unwin PNT and Henderson R. (1975). Molecular structure determination by electron microscopy of unstained crystalline specimens. J Mol Biol, 94:425-440.
Wall J, Langmore J, Isaacson M and Crewe AV. (1974) Scanning transmission electron microscopy at high resolution. PNAS USA. 71(1):1-5.
Zworykin VK, Morton GA, Ramberg EG, Hillier J and Vance AW. (1945). Electron Optics and the Electron Microscope. New York: John Wiley & Sons.

Additional sources

Hawkes PW (Ed.) (2010) Cold field emission and the scanning transmission electron microscope. Advances in Imaging and Electron Physics, vol 159. Elsevier/Academic Press, Amsterdam.

MSA Oral History Project video interview by Sterling Newberry, 1992 (Fig. 12).

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