# 1. CHARACTERIZATION OF AG NM-PARTICLES BY SEM AND DARK FIELD MICROSCOPY

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# 2. OVERVIEW OF THE TECHNIQUES PRESENTED IN THE COURSE

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# 3. PROPOSITION FOR CHARACTERIZATION OF ANOTHER MATERIAL WITH OTHER TECHNIQUES

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1. Characterization of Ag nm-particles by SEM and Dark Field Microscopy

**Introduction**

Gold and silver nanoparticles are objects of active research due to their documented or proposed importance in various nanooptics applications, such as surface-enhanced spectroscopy (SERS)\(^1\), biochemical sensors, near-field scanning optical microscopic (NSOM)\(^2\) and nano-photonics devices\(^3\). The fascinating optical properties originate from localized surface plasmon (LSP) resonances, a class of surface modes that involves the collective excitation of conduction electrons in response to an incident electromagnetic field. Gold and silver nanoparticles are chemically stable and typically exhibit LSP’s in the visible wavelength range, where they can cause a tremendous increase of various optical crossections and an associated enhancement of the electromagnetic fields near the particle surface\(^4\). The latter effect is used in SERS, which enables molecular vibration spectroscopy with unsurpassed detection sensitivity. The resonance frequencies strongly depend on particle shape and size, as well as on the optical properties of the material within the near-field of the particle. Hence, the metal nanoparticles are spectrally selective.

In most nanooptics applications there is a clear demand for nanoparticles with optimised LSP characteristics. For instance, the LSP should coincide with the wavelength of the excitation laser and have a high quality-factor in SERS and NSOM, while many biochemical sensing applications require nanoparticles for which the LSP shift due to a change in surrounding refractive index is maximised.

There are a number of different ways to fabricate noble metal nanoparticles; amongst many, there is laser synthesis from gold-silver colloidal mixtures\(^5\), seed-mediated growth\(^6,9\) and formation and growth of Au nanoparticles inside plants\(^10\).

The goal of this project was to characterise a colloidal silver nm-particle solution that was produced with aqueous reduction at elevated temperatures. In this case sodium citrate serves as a reducing agent, while the solution is kept at boiling temperatures. The amount of reducing agent determines the size of the particles. A detailed description of the protocol is given by H. Xu\(^11\) or Lee and Meisel\(^12\). It is important to consider that the larger the particles become, the broader their size distribution will be. Therefore careful examination and investigation of a colloidal metal particle solution is of highest importance in order to find the optimal LSP characteristics.

Optical measurements on nanoparticles are routinely carried out on large particle ensembles by UV-VIS spectroscopy. The single particle properties are lost due to statistical averaging unless all particles are identical, which is not the case in colloidal solutions. Obviously, it is important to characterize metal nanoparticles by other means, and within this study I would like to investigate and compare the properties of individual silver nanoparticles with scanning electron microscopy (SEM), and dark-field microscopy.

**Optical properties of nm-sized noble metal particles**

In order to develop a simple model to understand the unique properties of noble metal particles it is assumed that they behave as free-electron metals having completely filled valence bands and partially filled conduction bands, which are responsible for most of the electronic and optical properties\(^4\). Their response to an external electromagnetic field with a wavelength \(\lambda_0\) can be described by the dielectric function applying the Drude-Lorentz-Sommerfeld model. If the radius of the totally spherical metal particle is much smaller than
the incident wavelength \( r \ll \lambda_0 \) the model can be simplified using electrostatics. In this case, the positive charges in the particle are assumed to be immobile while the conduction electrons are allowed to move under the influence of an external electric field \( E_0 = |E_0| \exp(i\omega t) \). As a result, a dipole moment \( P = E_0 \alpha \) is induced in the particle, emitting an electromagnetic wave. The resulting internal field can be expressed as

\[
E_i = E_0 \frac{3\varepsilon_m}{\varepsilon + 2\varepsilon_m},
\]

where \( \varepsilon = \varepsilon_1(\omega) + i\varepsilon_2(\omega) \) is the dielectric constant for the particle and \( \varepsilon_m \) is the dielectrical constant for the surrounding medium, which usually is taken to be real. The pointlike polarizability of the sphere can be expressed as

\[
\alpha = 4\pi\varepsilon_0 r^3 \frac{\varepsilon - \varepsilon_m}{\varepsilon + 2\varepsilon_m},
\]

where \( \varepsilon_0 \) is the dielectric constant for vacuum. Both the internal field and the polarizability show a resonance behaviour when \( |\varepsilon + 2\varepsilon_m| \to 0 \). The resonance condition can also be written as

\[
(\varepsilon_1(\omega) + 2\varepsilon_m)^2 + (i\varepsilon_2(\omega))^2 = \text{minimum},
\]

which is fulfilled when \( \varepsilon_1(\omega) \) has a negative sign and \( |\varepsilon_1(\omega)| \to 2\varepsilon_m \) and \( i\varepsilon_2(\omega) \to 0 \). At this point the real part of \( \alpha \) changes sign, i.e. the phase changes almost abruptly from 0 to \( \pi \). The model is in good agreement with experimental data for small particles \( r \approx 20 \text{ nm} \). For non-spherical particles, the SPR will be modified by the curvature of the surface.

However, the properties of the nm noble metal particles can also be described with the scattering and absorption cross sections

\[
C_{sca} = \frac{k^4}{6\pi} |\alpha|^2 \quad \text{and} \quad C_{abs} = k \text{Im}\{\alpha}\}.
\]

Experimentally, it is straight forward to measure the extinction cross-section

\[
C_{ext} = C_{sca} + C_{abs},
\]

and if the particle concentration \( N \) is known, the extinction cross-section can be directly obtained from Lambert–Beer’s law by measuring the transmitted intensity loss

\[
\Delta I_{ext} = I_0 \left(1 - e^{-NC_{ext}}\right),
\]

where \( z \) is the thickness of the measurement cell.

For particles smaller than 100 nm the polarizability, giving the particle radius, can be calculated using Mie theory, the long wavelength approximation (MLWA) and numerical methods such as discrete dipole approximations (DDA). Thus, by measuring the extinction cross-section and calculating the polarisability, the radius of the particle can be determined.

**Principles of the experimental techniques**

**The principles of scanning electron microscopy**

The electron is a most convenient particle for microscopy since the mass of this subatomic particle is extremely small. It has a quantized negative charge of 1 e (elementary charge = 1.6*10^-19 Coulomb) and since this charge is exactly the same for all electrons, it is possible to precisely predict and control the movement of electrons.
The small and uniform mass to charge ratio of an electron makes its momentum sensitive to electric fields, which exert a force on charged particles. Such fields can be used to accelerate, direct, and focus electrons in the form of an electron beam. Scanning an electron beam over a surface, and measuring its interactions with the surface is a method known as Scanning Electron Microscopy (SEM), which allows nanoscale resolution of conducting surfaces.

The de Broglie wavelength of a particle can be related to its momentum by the relatively simple formula $\lambda = \frac{h}{p}$, where $\lambda$ is the wavelength, $h$ is Plank's constant and $p$ is the momentum of the particle. Electrons differ from photons in that their mass is much larger, which results in a larger momentum and smaller wavelength. While a photon has a wavelength much larger than the size of one atom, the wavelength of an electron is far smaller than an atom. Thus, unlike optical microscopy the far-field diffraction limit is not a barrier to the resolution of electron microscopy or lithography. Rather, other difficulties must be overcome, such as our ability to focus the beam on a spot so small as a single atom. So although the wavelength of the electron in such a microscope is only 1/20 of an ångström it is experimentally not possible to get a better resolution depth than 5-10 nm.

The principles of SEM can be described as follows: A tungsten filament is heated up to a 2700 K, which causes the electrons at the tip of the filament to be released. Thereafter the electrons are accelerated (5~50kV) and focused into a beam that hits the specimen. Emitted secondary electrons are collected by an electron detector and through an amplifier transferred into a signal controlling the brightness of a cathode ray tube (CRT). The specimen surface is scanned in a raster pattern by the focused electron beam synchronously with the spot of the CRT. By doing so an image of the specimen is retrieved onto the CRT. The image magnification is given by the ratio between the width of the CRT screen and the width of the scanned specimen surface. Measurements have to be carried out in vacuum so that the electrons do not collide with air molecules and get knocked before they reach the specimen.
**The principles of dark-field microscopy**

Darkfield illumination can be used to increase the visibility of samples lacking sufficient contrast for satisfactory observation and imaging by ordinary brightfield microscopy techniques. The technique requires blocking out of the central light, which ordinarily passes through and around the specimen, while only oblique rays from every azimuth hit the sample mounted on the microscope slide. In terms of Fourier optics, the zeroth order unscattered light from the diffraction pattern formed at the rear focal plane of the objective is blocked and an image formed exclusively from higher order diffraction intensities is seen. To achieve this, the top lens of the darkfield condenser is spherically concave, and light rays emerging from the surface in all azimuths form an inverted hollow cone of light with an apex centered in the specimen plane. If no sample is present and the numerical aperture of the condenser is greater than that of the objective, the oblique rays cross and will miss entering the objective and the field of view will appear dark. When an uneven sample is placed on the slide, the oblique rays are diffracted, reflected, and/or refracted by the roughness and therefore enter the objective. As a result, the sample will appear bright on an otherwise dark background.

The method is ideal when imaging nanometer sized silver particles in a solution. With normal brightfield illumination the silver particles are seen as diffraction limited gray spots. When applying a darkfield set-up, the particles are still seen as diffraction limited spots, but the size dependent visible light scattering caused by the LSP resonances is revealed.

*Fig. 1) Schematic of a scanning electron microscope.*
**Experimental preparation and results**

**Production of nm-sized Ag particles with citrate reduction**

The Ag hydrosol was prepared according to a citrate reduction protocol in which the reaction times had been slightly modified in order to obtain Ag-particles with an average size of around 90 nm. AgNO₃ (90mg) was dissolved in 650 ml of purified H₂O. 500 ml of this solution was heated to the boiling point. A solution of 1% weight sodium citrate (10 ml) was added. After 30 min the remaining AgNO₃ solution was divided into three parts and added every 15 minutes. The solution was kept boiling for 1.5 hours. The final volume was about 500 ml¹¹,¹².

**Sample preparation for SEM and DF**

In order to obtain a good DF and SEM image the colloidal solution was diluted 10 times with distilled water. For DF imaging 200 µl of the solution was put between two cover-glasses and mounted onto the microscope stage. The darkfield configuration consists of a white light source (100 W halogen lamp) illuminating the sample at large angles from above through a darkfield condenser (Nikon dry 0.95 - 0.80) and an objective with tuneable NA (Nikon 100×/0.5-1.3 oil) set to 0.7. The numerical aperture of the objective is set smaller than that of the condenser so that light transmitted directly through the sample is blocked and darkfield conditions are fulfilled.

---

*Fig. 2) Schematic of a dark field configuration*
For SEM imaging 10 μl of the diluted colloid solution was put on a sample holder consisting of a plate of ~1mm radius, having a copper grid on one side and a perforated carbon film with holes of 200-800 nm on the other. Since the sample has to be dry for SEM imaging, the grid was placed on a tissue so that the water from the colloidal solution was sucked up. The grid was put onto a sample holder with a carbon tape on it in order to immobilize the sample. The sample was put in the scanning electron microscope (LEO Geminus Ultra 55) and the electron beam was set to 5kV.

**Experimental results from the Dark Field measurements**

Fig. 3 shows a typical Dark Field image taken with a Nikon E2000 microscope equipped with a dark field configuration. The Ag particles are seen as diffraction limited spots emitting light of various wavelengths according to the surface plasmon resonances, which are size and shape dependent. This tells us that we in fact are dealing with a very inhomogeneous colloidal solution of Ag particles with a size range between 30-200 nm.

![Fig. 3) Typical DF image of a diluted colloidal solution of Ag particles.](image)

**Experimental results from the SEM measurements**

Below three figures taken with the SEM are shown. Each figure has a different magnification factor and is the mean value of several images in order to get a good enhanced contrast. In the first figure (fig. 4) the copper grid of the sample holder is seen and in the background the perforated carbon film with the adsorbed Ag particles is visible. The SEM image very clearly
Fig 4) SEM image of silver particles on the sample holder. The copper grid is nicely seen as well as the perforated coal film with the adsorbed Ag particles on it.

Fig 5) SEM image of Ag particles. The size distribution of the particles seen here is from 160 nm to 400 nm.
Discussion

The results from the DF images and the SEM images give very complementary results and information. In the DF images the surface plasmon resonances of the Ag particles are revealed and by looking at the polarizability of the particles an idea of the size can be estimated. SEM images however give a picture of the exact size and shape of the particles. Strangely enough the DF image shows surface plasmon resonances from the blue to the white, which corresponds to a size distribution of 30 nm to 400 nm. However, no particles of 30 nm could be seen in the SEM images. A possible explanation could be that the smaller particles were washed away while pipetting the colloidal solution onto the sample holder or that the particles were small enough to diffuse through the perforated coal film and were out of focus.

However in order to verify the dependence of the surface plasmon resonances upon size and shape it would be of considerable value to be able to take a DF and SEM images of the same particles. Such information could lead to enhanced understanding of the fascinating optical properties of the nanometer sized Ag particles. To my current knowledge, nobody has achieved that so far since it is very difficult to find the same spot and particle on the same sample when it has to be moved between different apparatus.
2. Overview of the techniques presented in the course

For all the methods described in this chapter, the sources are if not noted the course book “Material Science and Characterisation” as well as the lecture notes.

**SIMS**

Secondary ion mass spectrometry (SIMS) is a technique that measures elements at a surface with detection sensitivity as low as a few parts per billion\(^{13}\). The surface is bombarded with a beam of energetic oxygen or cesium ions. The bombarding ions force atomic and molecular particles to be sputtered from the surface. Since some of these sputtered particles carry a charge, a mass spectrometer can be used to measure their mass and charge. Continued sputtering measures the elements exposed as material is removed to construct elemental depth profiles. SIMS instruments can produce two-dimensional elemental maps of the original surface or at a particular depth (after sputtering).

This technique is interesting when a surface and its constituents need to be examined. In my study it is rather the shape that is important, thus the technique is not suitable for this project.

**EDX**

In Scanning Electron Microscopy a primary electron beam is scanned over the sample surface. However, different phenomena such as generation of secondary electrons (SE), backscattering of the incident electrons (BSE) and emission of X-rays take place. These signals are used by the corresponding detectors for image formation. Backscattered electrons occur after elastic or quasi-elastic scattering of the primary electrons. The intensity of the BSE signal depends on the average atomic number of the area illuminated by the impinging beam. Inelastic scattering of the incident electrons gives rise to the emission of X-rays with energies characteristic of the atoms in the specimen. X-ray detectors provide qualitative and quantitative information about the elemental composition\(^{14}\).

Same as above, since it is not the elemental composition of the particles that is of interest, this method provides complementary information that is not entirely necessary.

**TEM**

In this technique, the electrons from an electron gun are highly accelerated (~100 kV), focused and thereafter directed towards a thin sample (< 200 nm). These highly energetic incident electrons interact with the atoms in the sample, which results in a characteristic radiation. The transmitted electrons, providing valuable information for material characterization, are focused by an objective lens into an image. The image is passed down a column through intermediate and projector lenses in order to be magnified. The image hits a phosphor image screen.

This technique gives even a more detailed information about the structure of the nanometer sized Ag-particles and is thus worthwhile trying. It can though be compared to using a Ferrari to drive on a bumpy forest road.

**ESCA and AES**

Auger Electron Spectroscopy (AES) is typically utilized for major and minor elemental identification, line scans, and mapping at the surface. FE-AES is also a reliable technique for selected element depth profiling in thin films. Field Emission Auger Electron Spectroscopy (FE-AES) is the energy analysis of Auger electrons generated by a sub-micron electron beam. This technique allows for the imaging of secondary or backscattered electrons and sputtering
with an auxiliary ion beam for depth profiling. The advantage of AES is the small beam size, which permits analysis of areas down to 20nm in diameter\(^1\).

Electron Spectroscopy for Chemical Analysis (ESCA), a close relative of Auger, is the energy analysis of photoelectrons generated by x-ray irradiation. ESCA as well as AES are equipped with a sputtering equipment providing an auxiliary ion beam for depth profiling. Typically ESCA is used in major and minor elemental identification and chemical bonding information at the surface. Like FE-AES, ESCA is also used for selected element depth profiling in thin films, particularly insulators.

AES and ESCA are both powerful techniques for surface analysis. Both techniques provide elemental composition, except for hydrogen and helium, of approximately the top 100 Å of a surface.

Both methods are initiated by exposing the solid sample contained in ultra-high vacuum to an excitation source of a few kV in energy, ESCA using x-rays and AES using electrons. In both cases electrons are ejected from the surface. Energy analysis of the emitted Auger electrons and photoelectrons generates spectra. These spectra provide elemental identification, and, in many cases, chemical bonding information at the surface. AES and ESCA may also be used to determine the elemental composition of a sample as a function of depth.

The advantages of ESCA are the ability to analyze non-conducting materials, such as ceramics and plastics, with minimum charging effects and the ability to relate small shifts in the ESCA signal to differences in the chemical state or bonding of the elements.

The two technique are interesting when a surface and its constituents need to be examined. In my study it is rather the shape that is important, thus the technique is not suitable for this project.

**Diffraction methods**

In diffraction methods like x-rays, neutrons or electrons are used. The incident particles, having a wavevector \(k_i\) and a flux \(F\) (particles per cm\(^2\) and s) are scattered by the sample. Thereafter the backscattered particles are analyzed.

Thermal neutrons and X-rays are well suited to probe the microscopic structure of both crystalline and disordered materials since the wavelengths are comparable with the interatomic distances in liquids and solids. Diffraction is treated as selective reflection where only certain angles of reflection are selected. X-rays of a given wavelength are reflected by the lattice planes of the sample, which gives information about the interplanar distances. X-rays interact with the electrons, thus the scattering cross section is proportional to the atomic number. The scattering of neutrons is a nuclear phenomenon and the scattering cross section is thereby independent of the number of electrons in the material under study but varies between atoms and isotopes. Neutrons are very useful when light materials have to be investigated. Electrons are valuable when studying small samples such as microcrystals in order to investigate grain boundaries and/or local defects.

Powder X-ray Diffraction (XRD) is one of the primary techniques used to examine the physico-chemical make-up of unknown solids.

A powdered sample is placed in a holder and the sample is illuminated with x-rays of a fixed wavelength. The intensity of the reflected radiation is recorded using a goniometer.

Diffraction methods are interesting when the inter-atomic order of a sample has to be characterised or when its constituents need to be examined. Further dynamics caused by temperature differences and phase transitions can be measured. In my study it is rather the shape that is important, thus the technique is not suitable for this project.
In molecular vibrational spectroscopy, the interaction of radiation with matter is used to study the transitions between molecular vibrational levels. In order for a molecular vibration to be IR active, the dipole moment must be changed. A vibrational transition occurs because of an interaction between the incident radiation and the molecular dipole moment. The absorption frequency depends on the molecular vibrational frequency while the absorption intensity depends on how effectively the infrared photon energy can be transferred to the molecule, in other words how big the variation of the dipole moment associated with the molecule is. The Raman effect, on the other hand, is an inelastic scattering process with a simultaneous annihilation of an incident photon and the creation of a scattered photon. The induced dipole moment has to change the polarisability of the molecule to be Raman active.

The selection rules for both methods is that the total symmetric vibrations are absent in the infrared spectrum but not in the Raman spectrum. There are three main types of quantum states for a system involving motions on the atomic scale; i.e. translation, rotation and vibration. The normal modes of vibration involve changes of bond lengths and/or angles can be divided into stretching, bending and torsion. There are 3N-6 normal modes of vibration for a non-linear molecule with N atoms. Since some of the modes are only either Raman or IR active, the two techniques give a complementary picture of the molecules vibration. The silver nanoparticles are used in both methods in order to enhance the weak signals. The reason for their unsurpassed enhancement effect is not totally elucidated yet. Therefore it would be of considerable value if it were possible to identify the exact shape of single particles by means of SEM, TEM, AFM and STEM and then compare it to the enhancement of the vibrational signal.

**AP-FIM**

In the case of the Atom Probe Field Ion Microscopy (AP-FIM) the sample has to be in the form of a sharp tip. A sudden positive potential is applied to the tip such that a very large electric field is present at the tip. The ambient gas surrounding the tip is usually Helium or Neon at a pressure of 1-3 x 10 to the minus 3 millibar. The gas atoms move towards the tip and strike it. The gas atoms can strike the surface many times, before an electron from the gas atom tunnels into the metal tip leaving the gas atom positively ionized. The gas atom is then accelerated away from the tip where it hits a fluorescent screen. The net effect of several gas atoms create a pattern on the fluorescent screen showing spots of light, which correspond to individual atoms on the tip surface. However, the atoms travel down a drift tube where their time of arrival can be measured. The time taken for the atom to arrive at the detector is a measure of the mass of that atom. Thus compositional analysis of the sample can be carried out on a layer-by-layer basis. Since the colloidal Ag particles cannot be formed as a sharp tip this method is not suitable and the information retrieved is not of interest for this project. Further, since the particles are of nanometer size, they would be annealed.

**STM and AFM**

In scanning tunneling microscopy (STM) a sharpened conducting tip biases a voltage between the tip and the sample. The tip is scanned within 10Å over the sample causing the electrons of the sample to tunnel through the gap into the tip or the other way around depending on the sign of the bias voltage. The tunneling current depends on the distance between the sample and the tip and the signal creates an STM image. The sample has to be at least semi conductive to create tunneling and the tunneling current is an exponential function of the
distance giving the STM the remarkable sensitivity. STMs can image the surface of the sample with sub-Ångström precision vertically and with atomic resolution laterally. The STM can scan the surface of a sample in either the constant height of constant current mode. In the constant height mode, the tunneling current varies depending on the topography of the local surface creating a topographic image. In the constant current mode, the height of the scanner is adjusted at each measurement point.

The atomic force microscope (AFM) images atoms, molecules and other very small features of the size of several Angstroms, nanometers and microns. It is most commonly used to measure topography profiles of surfaces. An AFM can also be configured to measure other forces such as magnetic, electrostatic, adhesive and elastic. By measuring very localized forces over a surface, a map of the surface is produced. By associating the force map with topography, structure-property correlations can be drawn. With the ability to sample forces over very small areas of Angstroms or nanometers, the AFM is an important instrument in documenting the scaling of properties from the traditional 'macroscopic' regime down to the regime of collections of several molecules.

Since both methods give structural information they are certainly interesting candidates for this project.

**NMR**

Nuclear magnetic resonance, or NMR, is a phenomenon that occurs when the nuclei of certain atoms are immersed in a static magnetic field and exposed to a second oscillating magnetic field. The nuclei consisting of protons and neutrons of all elements carry a charge.

When the spins of the protons and neutrons are unpaired, the overall spin of the charged nucleus generates a magnetic dipole along the spin axis, and the intrinsic magnitude of this dipole is a fundamental nuclear property called the nuclear magnetic moment, $\mu$. The symmetry of the charge distribution in the nucleus is a function of its internal structure and if it is spherical, analogous to the symmetry of a 1s hydrogen orbital, it is said to have a corresponding spin angular momentum number of $I=1/2$, of which examples are $^{1}\text{H}$, $^{13}\text{C}$, $^{15}\text{N}$, $^{19}\text{F}$, $^{31}\text{P}$ etc.

In quantum mechanical terms, the nuclear magnetic moment of a nucleus can align with an externally applied magnetic field of strength $B_0$ in only $2I+1$ ways, either re-inforcing or opposing $B_0$. The rotational axis of the spinning nucleus cannot be orientated exactly parallel (or anti-parallel) with the direction of the applied field $B_0$, but must precess about this field at an angle with an angular velocity called the Larmor frequency given by the expression;

$$\omega = \gamma B_0.$$ 

The constant $\gamma$ is called the magnetogyratic ratio and relates the magnetic moment $\mu$ and the spin number $I$ for any specific nucleus. NMR is all about how to interpret such transitions in terms of chemical structure.

NMR is interesting when inter-atomic order or bonding of a sample has to be characterised or when its constituents need to be examined. Further dynamics of various kinds can be measured. However only certain atoms have the corresponding spin angular momentum of $1/2$, and Ag is not one of them. Therefore the method is not suitable for this project.

**3. Proposition for characterization of another material with other techniques**
Tin-based glasses are interesting due to their potential as anode materials in Li-ion batteries. However, the mechanism for lithium insertion and extraction process for the glasses is not well understood\textsuperscript{17}. Therefore, a cornerstone for the investigations is to understand the structure of the tin-based glasses. Detailed structural characterisation of disordered material such as glasses is not easy because of the lack of long-range translational order. However, the various local molecular arrangements can be probed with vibrational spectroscopy since on the length scale where structural units consist of only a few atoms vibrational spectroscopy is a sensitive probe. With these techniques the structural ordering as well as clues to the atomic co-ordinations can be found. Thus, vibrations related to all the various elements present in a glass can be probed.

To obtain a more global structural picture, neutron or x-ray diffraction techniques have to be used, since their wavelengths are comparable with the interatomic distance in liquids and solids. The x-rays interact with the electrons and the scattering cross section is therefore proportional to the atomic number, i.e. in a multicomponent sample it is mainly the heavy atoms that are probed. The scattering of neutrons is a nuclear phenomenon and the scattering cross section is thereby independent of the number of electrons in the material under study, but varies between atoms and isotopes. However, no systematic variation can be found between the atomic number and the scattering cross section. Therefore the two techniques are complementary and the choice may depend on the atomic numbers of the elements in the sample. The two main components of tin-based glasses, boron and phosphorous are relatively light elements and well suited for neutron studies.
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