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Holography with resonant quanta

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Atomic resolution holography is a new, emerging field of research. In this paper we give the basic ideas of the inside source/detector holography using short wavelength electromagnetic radiation. The characteristics of γ-ray holography are discussed and the first experimental results of this type are given.

1. Introduction

Holography was put forward by Gabor in 1948 [1]. He intended to improve the resolving power of electron microscopes and tried to get rid of the aberrations caused by the optical elements. His idea was not implemented in electron microscopes for a long time. It became widely used in many areas of science and technology with the introduction of coherent laser light. The most important advantage of holography compared to other imaging techniques is that it stores 3D spatial information on a 2D surface without optical elements, and this information can be retrieved easily. These features would be very advantageous in the study of the spatial order of microscopic objects like molecules or atoms. However, similarly to other methods – based on the interference of the picture forming waves – its spatial resolution is limited by the wavelength. There is another factor which also limits resolution and this is the size of the source or detector element depending on the geometry of the experiment. These two factors prevented researchers to use holography on an atomic scale. In the last three decades there have been many attempts to circumvent the above problems. The wavelength limit can be easily solved by using high energy electromagnetic waves (X- or γ-rays) or electrons as hologram forming waves. However, to produce sources or detectors with a pixel size below a few hundred Angstrom is formidable at the present technological level. This problem can be partially solved by using the atoms or nuclei of the sample as sources or detectors. We will call this idea the "inside source or detector concept". The first experimental realisation of this concept was reported in 1974 [2]. Bartel and Ritz used electrons scattered by the nuclei of a gas as hologram forming waves. They could image the atomic electron cloud with a resolution of 0.08 Å. However, they could only study monatomic gases using their experimental arrangement. More than 10 years after this experiment Abraham Szöke pointed out how the inside source concept could be applied to the study of the atomic order in solids [3]. His idea was first experimentally proved by Barton [4] in 1989. In that experiment the hologram of the near neighbour environment of atoms in a copper single

crystal was measured using electrons as hologram forming waves. The 3D spatial order was successfully reconstructed. This demonstration experiment was followed by many theoretical and experimental studies of electron holography. However, the application of hard X- or γ-rays for holographic imaging was delayed. There are two reasons for this:

1. The long range translational periodicity present in the samples, which produces strong, sharp diffraction lines (Kossel or standing wave lines). These lines mask the holographic oscillations.
2. The small atomic scattering factor of X-rays, which results in a low signal to noise ratio.

The solution of the first problem was given in 1991 by Tegze and Faigel [5]. A few years later the second problem was also solved by careful experimental arrangements, and the 3D order of Sr atoms was reconstructed first in $SrTiO_3$ [6] and then the 2D picture of the Fe atoms in the basal plane of Fe_2O_3 [7] was reported. The latest development in the field of inside source holography was the use of γ-rays for holographic imaging. A Polish group took a γ-ray hologram of ^{57}Fe atoms in an epitaxially grown Fe single crystal [8].

It is clear from the above introduction that holographic studies of the atomic order in solids by X- or γ-rays are a field that has just started. However, it is worth following and understanding its basics since its potential applications are very wide, it goes beyond simple structural studies, especially in the case of nuclear sources and scatterers. It could give information on the 3D magnetic order or one can see selectively the environment of Mössbauer nuclei experiencing different hyperfine fields. In the next few pages we will give the basics of holography with atomic resolution using the inside source or detector concept, especially concentrating on the questions of γ-ray holography. We will avoid a rigorous mathematical treatment in order to facilitate easier understanding. However, references will be given for those who are interested in a more formal description.

2. Holography

The scheme of holographic imaging is shown in figure 1. A wave (with wavelength λ) from a point source illuminates the object as well as the detector directly. The object (elastically and coherently) scatters part of the beam. This scattered wave (often called object wave) interferes with the reference wave and the resulting intensity modulation (called hologram) is measured at the detector surface. Although the intensity of this interference field is detected, it reflects the phase of the scattered waves, since the intensity modulation is determined uniquely by the phase relation between the object and reference waves. If we know the phase of the reference wave the object waves can be reconstructed. Gabor's original suggestion for the holographic reconstruction was the reillumination of the hologram by the inverse of the reference wave (see figure 2).

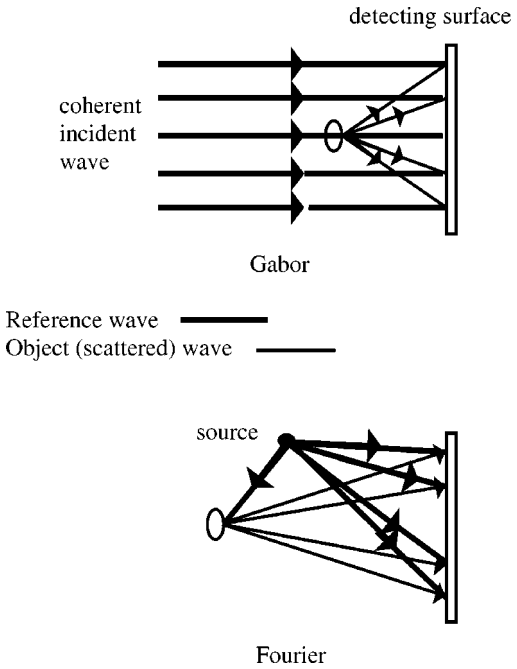

Figure 1. Scheme of holographic imaging. Gabor type arrangement: the reference beam is a plane wave (upper panel). Fourier type arrangement: the reference beam is an outgoing spherical wave (lower panel).

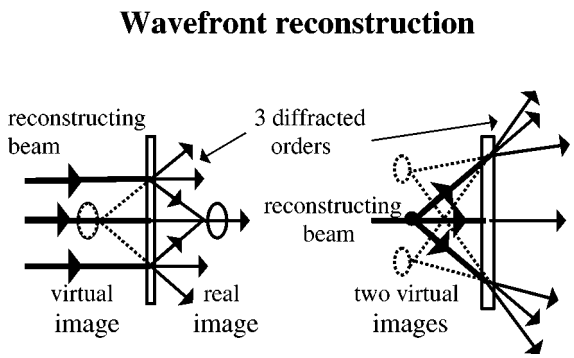

Figure 2. Scheme of holographic reconstruction. The reconstructing beam is a plane wave for Gabor type holography (left panel), or an incoming spherical wave for Fourier type holography (right panel).

In practice the hologram is often stored on a photographic plate and the reference wave is an outgoing spherical while its inverse is an incoming spherical wave. The reconstructing beam is diffracted by the photographic plate and a virtual image of the original object is produced. It can be shown that using a different wavelength λ' for the reconstruction a λ'/λ magnification of the image is produced. The reconstruction can also be done numerically, as pointed out by Wolf [9]. It is appropriate to mention here that after reconstruction we obtain not only an image of the object but also its

twin image (see figure 2). The twin image can be suppressed by taking so called volume holograms. This means that the intensity modulation of the interference field is detected and stored in a volume, not only in a plane. One can imagine this as taking a series of "normal" holograms in parallel planes.

3. Holography using an inside source or detector

As mentioned in the introduction, the resolution of a hologram is limited by the wavelength and by the size of the source or detector element. In this section we show how these two problems can be solved simultaneously.

Let us take a small cluster of atoms. In this cluster there is a single atom which is different from the others. Let us suppose that we can find a way to force this atom to emit short wavelength ($\lambda \sim 1$ Å) radiation. In this case the emitted radiation can reach the detecting surface either directly without interacting with the atoms of the cluster or after scattering from these atoms (see figure 3(a)). We take into account single scattering events only. The scattering can be divided into coherent and incoherent parts. Accordingly, the intensity measured by the detector contains two components:

(1) a continuous background of the incoherent scattering $|A_{\mathrm{I}}|^2$, and

(2) an intensity modulation determined by interference between the direct beam and the coherently scattered part $|A_{\mathrm{D}}+A_{\mathrm{O}}|^2$ (the A's, D and O stand for the amplitudes, direct waves and waves scattered by the object, respectively).

For most of the known incoherent scattering processes the cross-section is low and slightly angle dependent, therefore, we can neglect it.[1] The second part consists of three terms: $I_{\mathrm{D–D}} = |A_{\mathrm{D}}|^2$, $I_{\mathrm{O–O}} = |A_{\mathrm{O}}|^2$ and $I_{\mathrm{D–O}} = 2\mathrm{Re}(A_{\mathrm{D}}A_{\mathrm{O}}^*)$. Re and * stand for the real part and complex conjugate, respectively. This expression is analogous to that of the classical description of traditional holography. The term $I_{\mathrm{D–D}}$ corresponds to the direct beam as if there were only the point source. It gives a smoothly varying intensity. The term $I_{\mathrm{O–O}}$ comes from the atoms surrounding the source atom. It is usually small compared to the two other terms, since in most cases the scattering cross-section is small and this term is quadratic in the scattering factor while the term $I_{\mathrm{D–O}}$ is linear. The term $I_{\mathrm{D–O}}$ gives a spatially oscillating intensity variation, since its value depends on the phase relation between the object and reference wave, which changes from point to point. We call this term the hologram. We have two practical problems with the experiment described above:

1. How can we force atoms to emit short wavelength radiation?

2. How can we produce and maintain a sample consisting of a few atoms only?

The answer to the first question is simple, we have many possibilities: one can excite the electronic system of atoms, which in the relaxation process can emit a fluorescent photon or an Auger electron. The excitation energy and the type of source

[1] However, the validity of this assumption has to be checked for every given scattering process.

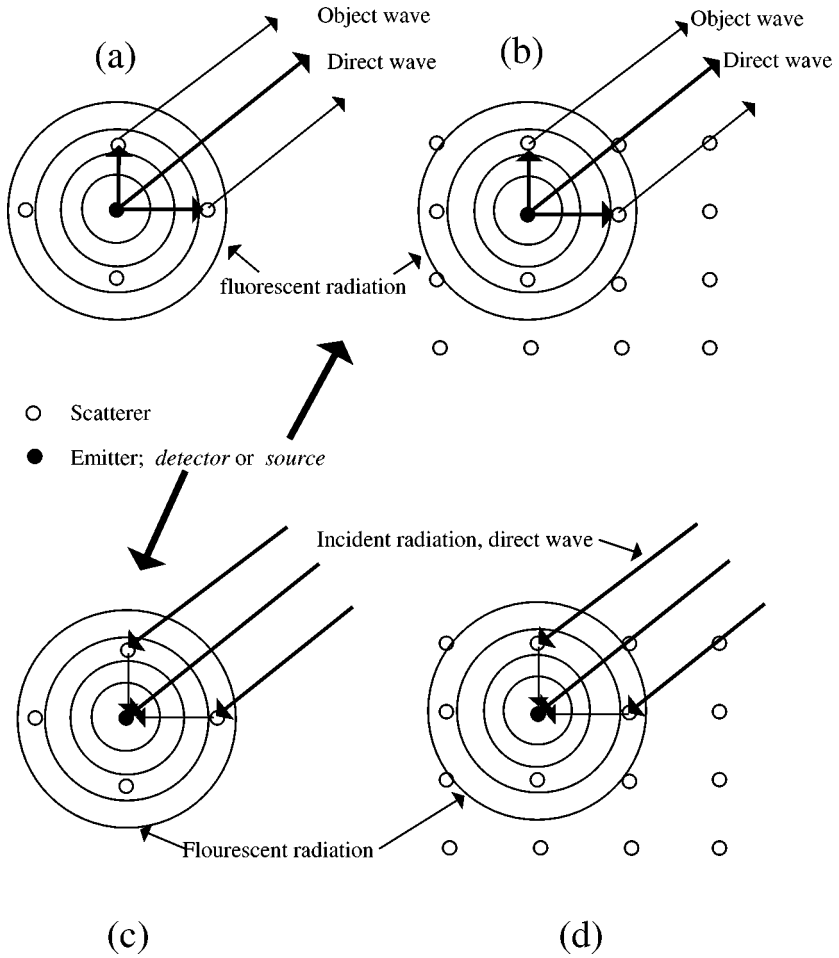

Figure 3. Principles of atomic resolution holography using inside sources or detectors: (a) single source atom with its environment; (b) many sources with identical environment in a crystal which produce the same hologram on the detector surface; (c) single detector atom with its environment; (d) many detector atoms with their identical environment in a crystal. They detect the same scattered intensity from identical neighbours.

atom can be chosen in a way that the wavelength of the photon or electron is below 1 Å, allowing atomic resolution. Electrons can also be produced by photoeffect (photoelectrons) and by slightly inelastic scattering (Kikuchi electrons). All these sources for radiation of short wavelength can in principle be used for holographic imaging. However, there is another way to produce photons of short wavelength, nuclear gamma deexcitation. There are nuclei with low lying nuclear excited states (5–100 keV). These emit photons suitable for holographic imaging.

The second problem is much more difficult. At the present technological level it seems impossible to produce a sample consisting of a few atoms only. Even if we could

produce one it would be very difficult to find a sample holder which does not disturb the holographic picture by its own scattering. Further, in order to acquire enough photons for a statistically meaningful picture we must measure for very long times (since we have only a single source atom). This would prevent this type of holography in practice. Szöke pointed out [3] that there is a way to circumvent these problems, at least for specifically ordered solids. Let us suppose that we have a macroscopic quantity of identical clusters. All these clusters are located close together[2] and they are oriented in the same way.[3] If we excite this system the separate clusters produce the same hologram. Further, the corresponding parts of all these holograms are located in the same position on the detector. Thus, we measure a single hologram which corresponds to the hologram of one cluster, but its intensity is multiplied by the number of clusters. So the measuring time is drastically reduced. Now the question is: Do we have samples satisfying the above conditions? Yes, for a large class of solids the crystals have these features (see figure 3(b)). The unit cell[4] can be taken as the cluster under study. In the unit cell we can choose a specific site occupied by an atom capable of emitting radiation of short wavelength.

So it seems that our problems are solved, and we have to work out some practical details of the experiment only. However, before we turn to these questions it is worthwhile to think over once more if any unwanted effects occur by introducing many sources and a crystalline order. Having many sources we have to examine if there is any correlation (definite phase relation, coherency) between quanta emitted by different source atoms. If there is, we have to add the amplitudes at the detector, not the intensities. This kind of coherency could wash out the holographic information. In other words, one has to choose emitting processes which are incoherent. Those processes which we have given earlier satisfy this condition. The second effect comes from the long range translational periodic order. As is well known, waves are diffracted by translational periodic systems, which results in high intensities at well defined directions determined by the Bragg law. This applies even in those cases where the sources are located within the sample. The problem of an inside X-ray source located at a crystallographic site was discussed and solved by von Laue long ago [10]. The result is the so called Kossel line pattern. The position and the shape of these lines were calculated by the dynamical theory of X-ray diffraction. It takes into account the interaction between the direct and scattered beams for perfect single crystals applying a multiple scattering treatment. The existence of the pattern was shown shortly after the theoretical prediction [11]. What is the relation between Kossel lines and holograms produced by inside sources? This can be seen from the single scattering description (given in the first part of this section). It was shown that Kossel lines start to form if

[2] Close means that the typical linear size of the volume is much smaller than the detector–sample distance. More precisely, the following relation should hold: $\lambda\pi/2 \cdot R/r \ll D$, where λ, R, r and D are the wavelength, sample–detector distance, typical atomic distance and sample size, respectively.

[3] This means that they can be transformed into each other using translations only.

[4] We chose a unit cell for easy visualisation. However, one can select an arbitrary volume around the source atom.

the number of unit cells is large enough ($>10^5$), and their intensity is given by $I_{O–O}$ and $I_{D–O}$. In a translational periodic system $I_{O–O}$ cannot be neglected since it is large in the Bragg directions. Although this result is not exact, especially in the case of large perfect single crystals, it clearly shows the difference between Kossel line patterns and holograms. The Kossel lines are a direct result of the long range translational order, while the hologram reflects the short range 3D atomic order. It was pointed out by many authors that Kossel lines contain phase information, and this can be used to solve the crystallographic phase problem [12]. That is true in principle; however, in practice this requires a large perfect single crystal, a high angular resolution measurement of the fine structure of Kossel lines and a special evaluation technique. It is not easy to satisfy all these conditions for many materials so this technique has not become widespread.

Let us turn back to the hologram ($I_{D–O}$ term). How can we get rid of the effect of translational symmetry which severely distorts the hologram? There are two ways: using radiation with a short mean free path (for example, electrons) or selecting somehow the contribution of the near neighbour atoms of the source. The key to the solution lies in the spatial frequency distribution of the holographic intensity produced by atoms at different distances from the source atoms. First neighbour atoms give a slowly varying intensity while distant atoms produce a higher spatial frequency [5]. Therefore, applying a low pass filter could retain the contribution of atoms close to the source. In practice this can be done either by numerical filtering or by integrating during the measurement, i.e., using low angular resolution. This makes holographic measurements easier than Kossel line experiments. In contrast to Kossel line measurements the ideal sample in a holographic experiment is a highly mosaic crystal, and the detector has a large window (a bad angular resolution covering a few degrees in both directions).

Based on the conditions given in this section, holographic experiments with atomic resolution were performed. First, inside electron [4], then atomic fluorescence sources [6] were used to form holograms. Before we turn to nuclear sources we have to mention one more very important development in the field. The idea is the following: one can turn the experiment using inside sources upside down, i.e., use the atoms not as sources but as detectors. In this case an external source illuminates the sample and the radiation can reach the detector atom directly or by scattering from its environment (see figures 3(c) and (d)). Changing the direction of the incident radiation relative to the cluster, the field changes at the detector atom according to the phase relation of the direct and scattered waves. The excitation of the detector atom is proportional to the field, reflecting the holographic intensity modulation. This method was suggested and experimentally tested by Gog and co-workers [7]. We call it “inverse holography”. In general, it gives the same information as “normal holography”, but it has a practical advantage in that there is no need for any angular resolution at the detector side since the hologram is formed by the incident beam. The best experimental arrangement is to collect radiation in the full solid angle around the sample. This results in a substantial decrease of the measuring time. In the special case of X-ray fluorescent holography

there is an additional possibility offered by inverse holography, the tunability of the energy of the incident beam. This allows one to take holograms of the same sample at various wavelengths, which facilitates the elimination of artifacts like twin image and spurious oscillations caused by a cutoff in the Fourier transformation range.

Now the basic ideas of holography with atomic resolution using inside sources or inside detectors were laid down. Before continuing we call the attention of the reader to three articles: the first two are reviews in which a more detailed description of the topic is given [13,14] and in the third a formal treatment using standard quantum electrodynamics is described [15]. In the next section we concentrate on the special features of nuclear inside sources and detectors.

4. Gamma-ray holography

Isotopes decaying by emitting low energy (10–100 keV) photons can be used as inside sources for holographic experiments. Radioactive decay is incoherent[5] so it satisfies the conditions we set in the preceding section. What are the advantages and disadvantages of nuclear sources as compared to fluorescent X-ray sources? Let us start with the disadvantages. We can use only one special isotope (Mössbauer nuclei or nuclei of their parent isotope) which has to be in the sample in significant concentration. This limits the composition of the samples we can study. By contrast there are many advantages:

(i) Nuclear sources are really point-like. This allows an improvement of resolution by using shorter wavelengths.

(ii) Nuclear levels are sensitive to internal (hyperfine) or external fields. Therefore, non-equivalent source sites can be distinguished.

(iii) Beside electronic scattering photons are scattered with high probability by nuclei via nuclear resonant scattering (by virtue of the Mössbauer effect). This type of scattering has many useful features which electronic scattering does not have.

First, the nuclear form factor is almost angle independent. The angular dependence of the form factor results in a distortion of the weight (brightness) of atoms at the same distance from the source but at positions which result in different scattering angles. This effect is especially large in the case of electrons as hologram forming waves, less severe for fluorescent photons scattered by electrons and it can be neglected in the case of nuclear resonant scattering.

From the experimental point of view one of the most important advantages of nuclear resonant scattering compared with fluorescent photons scattered by electrons is the large scattering cross-section. The holographic term I_{D-O} is linear in the cross-section, so the amplitude of the oscillations grows linearly compared with the direct

[5] Except in those cases when the source nuclei are located on crystallographic sites of a large perfect single crystal and dynamic effects come into play. In holographic experiments one uses highly mosaic crystals, so nuclear decay can be taken as an incoherent process.

beam $I_{\mathrm{D-D}}$ (the background). Since the statistical noise is $\sqrt{N} \sim \sqrt{I_{\mathrm{D-D}}}$ and $I_{\mathrm{D-O}}$ should be equal to or larger than the noise, the measuring time decreases with the inverse square of the cross-section. Another unique feature is that the nuclear levels of the scatterer can be similarly split, as in the sources. This allows the measurement of independent holograms at different energies. In the reconstructed image the intensity (and the phase) of the same nucleus may vary by changing from one line to the other. The actual variation depends on the interplay between the fields and the multipolarity of the transition involved. This offers the possibility to study the spatial variation of hyperfine fields.

Using atomic fluorescence one can perform two types of holographic experiments, inside source (normal) and inside detector (inverse) holography. The introduction of nuclear decay and/or nuclear resonant scattering leads to more experimental variations. In the following subsections we outline these possibilities.

4.1. Normal holography

4.1.1. Inside radioactive sources

Let us start with normal holography. The simplest experimental situation occurs when we have a single crystal with a radioactive isotope (Mössbauer parent isotope) located in low concentration at equivalent sites, and all other nuclei do not have low lying excited levels close to the γ-energy of the nuclei of the decaying radioactive source. The hologram is determined by elastic electronic scattering and the same information can be obtained as in the case of fluorescent atomic sources. However, the experimental technique changes, since there is no need for external excitation. One puts the radioactive sample on a goniometer and scans with the detector on a hemisphere. The lack of an external source makes this arrangement much simpler then the same experiment with a fluorescent source. One can imitate the detector motion by a single circular motion plus a rotation of the sample within its surface normally aligned perpendicularly to the rotation axis of the detector. This technique had been used in earlier X-ray fluorescent holography measurements [6,7]. However, in those cases part of the inverse (normal) hologram was measured into the normal (inverse) hologram. This was a direct result of the external excitation. In order to get a proper 3D picture of the atoms, the above extra intensity modulation has to be removed. In the case of an inside nuclear source (without external excitation) this effect is not present.

The next case we investigate is similar to the first one, except that there are non-equivalent source sites (from the point of view of hyperfine fields). If different sites can be distinguished in energy (i.e., the Mössbauer transition lines are well separated), one can collect photons of a given line, selecting the source atom and its environment. This can be very useful in the study of the 3D environment of atoms with different valence states or in different magnetic hyperfine fields or in non-equivalent electric field gradients. However, we have to pay for this extra information by a more complicated experimental set-up. In contrast to the previous case, where the energy integrated number of photons had to be collected, here one needs an energy analysis, which

involves a tunable resonant detection system. This leads to lower intensity and a longer measuring time.

So far only electronic scatterers were taken into account. However, our sample usually contains a low concentration of the radioactive source isotope (Mössbauer parent isotope) combined with a high concentration of scatterers capable of nuclear resonant scattering. In this case nuclear resonant scattering cannot be neglected. An extreme example is an ^{57}Fe single crystal in which a small amount of the Fe atoms is replaced by ^{57}Co. Since the nuclear resonant scattering cross-section is usually much larger than the electronic one, the nuclear positions are coded in the hologram. If all nuclear sites are equivalent one cannot gain more information than from a fluorescent hologram. However, the measurement is much easier because of the higher signal to noise ratio, as discussed in the preceding part of this section. To have a feeling for the improvement in the signal to noise ratio, we give here the scattering cross-section for the atomic electrons σ_e and nuclear resonant scattering σ_n in the case of ^{57}Fe. These are in the range of $\sigma_e \sim 10$ b and $\sigma_n \sim 10^4$ b. If we have non-equivalent scatterers, we can select one by tuning the energy to a transition representative of that site only. This way we can study the 3D order of a given set of nuclei separately. This is a unique feature of γ-holography. In practice this might be used to explore magnetic structures or 3D order in mixed valence compounds.

In samples that contain nuclear scatterers in medium concentration the average nuclear scattering cross-section can have a magnitude comparable to the electronic one. Therefore, both contributions have to be taken into account in the formation of the hologram. Basically the same arguments apply as in the preceding paragraphs. However, in general the contrast between non-equivalent sites decreases compared to the previous case because the electronic scattering does not distinguish these sites.

4.1.2. Inside nuclear souces excited from outside

All the above experimental situations were based on nuclear sources (radioactive parent isotopes) present in the sample. However, there are two possibilities for external excitations; strong radioactive sources or synchrotron radiation. Using one of these the experiments become analogous to holography with electronic fluorescence, except that in the nuclear case the external excitation energy is the same as the energy of the hologram forming waves. This raises an experimental problem, i.e., the separation of holographic information from the external excitation. Now this cannot be done by energy analysis as in the case of X-ray fluorescence. Depending on the type of excitation we have different possibilities to solve the above problem. In the case of a radioactive source, the only solution is collimation of the incident radiation, so that the detector does not see the source directly. However, in this way we cannot separate nuclear scattering from scattering in air and from electronic scattering in the sample. Unfortunately, the background caused by these processes can have a strong spatial variation and mask the holographic information. Putting the sample in vacuum and increasing the nuclear resonant scattering (i.e., by using highly enriched samples) the above effects might be pushed down below the level of the holographic signal.

The situation is very different in the case of excitation with synchrotron radiation. Using the pulse structure of synchrotron radiation and the very different interaction times of nuclear resonant and electronic scattering, one can separate these two processes in time, similarly to the traditional nuclear resonant scattering experiments done at synchrotron sources. However, the distinction between non-equivalent sites becomes more difficult than for radioactive sources combined with energy analysis. We have two options, either to measure the time integrated intensity of delayed quanta, or to take the full time spectra at every point of the hologram. In the first case there is no way to separate the contribution of different sites. However, by Fourier analysis of time spectra it is possible to select contributions from non-equivalent sites, at least in principle.

4.1.3. Inverse holograpghy

Now, the experimental considerations of the "inverse holography" (i.e., the inside detector case) are discussed. In this case the sample does not contain the Mössbauer parent isotope. An external source has to be used. This can be a radioactive source or synchrotron radiation as in the experiments described previously. However, the intensity variation has to be measured as a function of the direction of the incident radiation ($\mathbf{k}_{in}$) and not as a function of the detector position ($\mathbf{k}_{out}$) as in "normal holography". The information is the same as in the case of inside sources. All arguments we used there also apply here, except that sentences like "low concentration

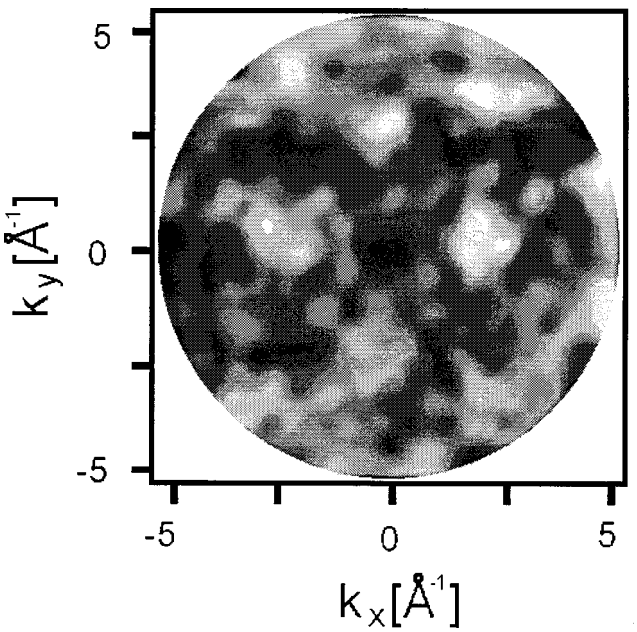

Figure 4. Hologram of an epitaxially grown single crystal of ^{57}Fe taken at the 14.4 keV Mössbauer transition [8].

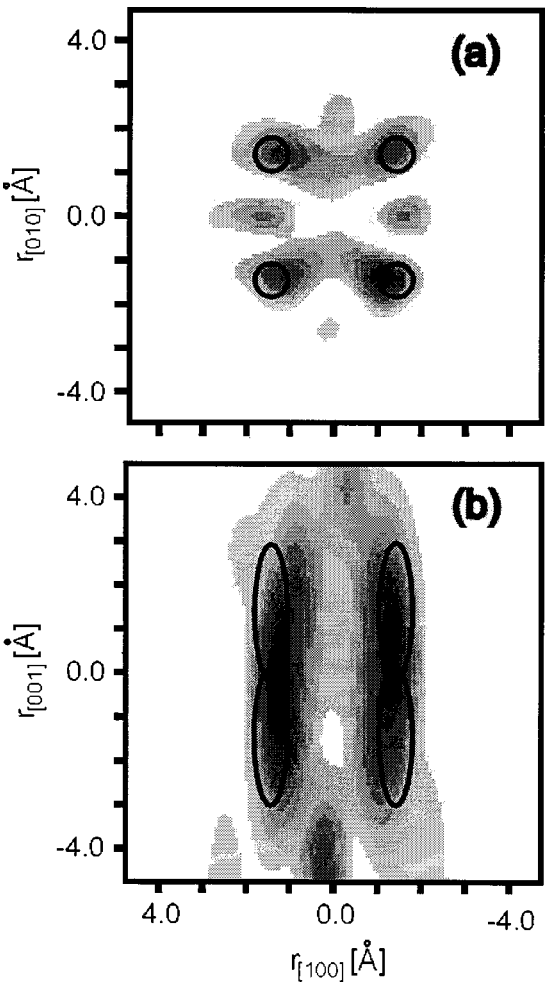

Figure 5. Reconstructed atomic positions from the hologram shown in figure 4. (a) Cross-section in the plane parallel to the physical surface of the crystal ((0 0 1) crystallographic plane) and at 1.43 Å distance from the emitter; (b) cross-section of the (0 1 0) crystallographic plane at 1.43 Å distance from the emitter [8].

of radioactive isotopes (Mössbauer parent isotopes) ...” have to be changed to “low concentration of Mössbauer isotopes (detector atoms) ...”, etc. Therefore, we do not repeat the last few paragraphs, rather we point out the differences between normal and inverse holography. Since in these experiments all photons emitted by the “detector nuclei” have to be collected,[6] the best experimental arrangement is to put the external detector very close to the sample (or put the sample inside the detector). This might increase the counting rate compared to normal holography, resulting in a reduced measuring time. The other effect which we can use is the inelastic decay of excited

[6] In practice, this is not possible, but we have to collect photons from as large a solid angle as possible.

states. In many cases this (internal conversion) channel has much higher probability than radiative γ-decay. For example, for ^{57}Fe there is about a factor of 10 in favour of internal conversion. The number of inelastic events that we have to determine is proportional to the number of excited nuclei. So the holographic information can be obtained by measuring the conversion electron yield as a function of $\mathbf{k}_{\mathrm{in}}$. The disturbing effects of scattering in air and elastic electronic scattering are avoided. Special detectors developed for conversion electron Mössbauer spectroscopy (CEMS) are readily available for these experiments. In principle, this detection technique could be used both for synchrotron and radioactive source excitation. However, in practice the very intense synchrotron pulses prevent the normal operation of CEMS detectors. The timing technique discussed earlier for synchrotron sources can similarly be used by applying fast plastic scintillators or avalanche photodiodes.

At the end of this section the first γ-holography experiment is described. In 1997 Pawel Korecki and his co-workers measured the hologram of an epitaxially grown ^{57}Fe crystal in the inverse mode [8]. The sample was located inside a CEMS detector that could be turned relative to the incident beam direction around two perpendicular axes. The CEMS signal was measured as a function of the detector angle. To facilitate normalisation, intensity data were taken at three constant velocities, at the strongest resonance lines and off resonance. The hologram is shown in figure 4. Since the surface of the sample was parallel to the (0 0 1) plane one expects a fourfold symmetry in the hologram. Within experimental errors this can be recognised. The reconstructed images are shown in figure 5. The atomic positions in the cross-section parallel to the surface are located at about the right places. However, in the perpendicular cross-section they are off-centre. It is clear that the technique has to be improved but this measurement demonstrates the possibility of γ-holography experiments in practice. At the end of this part we would like to call attention to a recent paper of Korecki et al. in which model calculations of γ-ray holograms for pure iron and mathematical formulas of the holographic intensity in the case of resonant scattering are given [16].

5. Summary

In this paper the basic features of atomic resolution holography using inside sources or inside detectors were reviewed. The first steps in the experimental demonstration of this method have been done. The results are encouraging, both in fluorescent holography and in γ-holography. The area of applications seems wide, especially in the case of γ-holography, where one can exploit the unique features of nuclear sources and scatterers. These applications include: the study of magnetic structures, site selective measurement of 3D atomic order in crystals, the mapping of sites with non-equivalent quadrupole interactions, etc. The application of synchrotron radiation for γ-holography appears very attractive for the future.

Acknowledgements

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