NEUTRON TOPOGRAPHY

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Introduction: The preceeding papers in this volume should make it very easy to understand neutron topography: just like its older sister, X-ray topography[1,2], it consists in imaging singularities in single crystals via local variations of reflectivity in Bragg reflections. Because the wavelengths and scattering amplitudes involved are alike[3], the diffraction processes both in perfect and in imperfect enough crystals are very similar for neutrons and for X-rays, and indeed some of the mechanisms responsible for the contrast of defects are the same in either case[1].

There are, however, three major differences[4], and they determine the limitations as well as the value of neutron topography. We will examine them in turn:

- neutrons are few;
- in most materials, their absorption is weak;
- the neutron has a magnetic moment.

1. Neutrons are few

There are rather few neutron beams in the world: this certainly is the reason for the late start[5] of neutron topography. Furthermore the intensities available in a small wavelength range even at a high-flux reactor[6] are small compared to what a conventional X-ray tube offers in a characteristic emission line; consequently, the resolution of neutron topography is poor - no better than $\sim 4 \cdot 10^{-2}$ mm typically - basically because exposure times cannot be increase above an order of magnitude of about a day, and therefore larger beam divergences and wavelength ranges have to be tolerated, leading to a geometrical loss of resolution.

On the other hand, this allows neutron topography to be instrumentally simple: a beam wide enough to illuminate the part of the crystal to be imaged is monochromatized, Bragg diffracted by the specimen and recorded on a neutron-sensitive photographic detector - typically X-ray dental film with a Gd converter foil. Using a thin beam and traversing the specimen, as in Lang's method of traverse X-ray topography [1], is a luxury that would increase the exposure time too much. The geometric resolution, determined by the specimen-detector distance and by the divergence of the Bragg-diffracted beam, can be tailored to a large extent by the choice of the relative setting of the monochromator and specimen as well as by collimation of the primary white beam. One possibility is to work with a low-divergence primary beam: the very clean beam emerging from the end of a curved neutron guide-tube is particularly suitable and, since the massive shielding surrounding the monochromator in "normal" neutron diffractometry becomes unnecessary, the instrument can be compact, flexible and cheap. The instrumentation can even be reduced to its very simplest form, nothing, by using the collimated white beam directly: each Laue spot is then a topograph, just like in synchrotron radiation X-ray topography[1]. Alternatively, neutron topography can be performed on an ordinary thermal neutron beam[7], or a set-up can even be installed behind an existing experiment by pushing back the beam-stop, and using some of the neutrons that would otherwise be wasted.

2. Low absorption of neutrons

The difficulty of low counting rates is of course also encountered in "normal" neutron scattering work, e.g. in structure determinations, and there it is often obviated simply by the use of large specimens, made possible because the absorption of neutrons by most materials is very small indeed[4]. Although it would be futile to hope to improve resolution and/or exposure times in neutron topography by using large crystals, this property of low absorption does make neutron topography very valuable in those situations where X-ray topography is impractical because the X-ray absorption factor, $\mu_x t$ where t is the specimen thickness, is large. This can obviously occur if μ_x is large and/or if t is large, and in both cases boils down to heavy crystals.

The situation is straightforward for thin crystals containing heavy elements (high μ_x): the growth history of natural crystals of lead carbonate $PbCO_3$, cerusite, could thus be, to some extent, reconstructed by observing the growth defects[8] - an investigation that just cannot be done in transmission with X-rays.

For thick crystals, there is an intrinsic difficulty in unravelling the complicated

3-dimensional arrangement of defects from a two-dimensional image. One way out is of course to restrict the study to just a slice of the specimen; neutrons offer the pleasant possibility of looking at a slice without cutting it, just by using the principle of section topography[1], originally developed by Lang for the X-ray case, and which acquires a new dimension with neutrons because really large (cm-thick) crystals can be investigated[9].

Fig. 1 shows a normal (projection) topograph and a section topograph of an as-grown crystal of terbium iron garnet, kindly given by J.P. Remeika (Bell Telephone Laboratories): considerably more detail can be seen on the section topograph, where the investigated region is limited to a slice 1 mm thick. In conjunction with a cruder but much faster Polaroid detector, this technique is now routinely used to select appropriate regions before cutting out monochromators from large crystals.

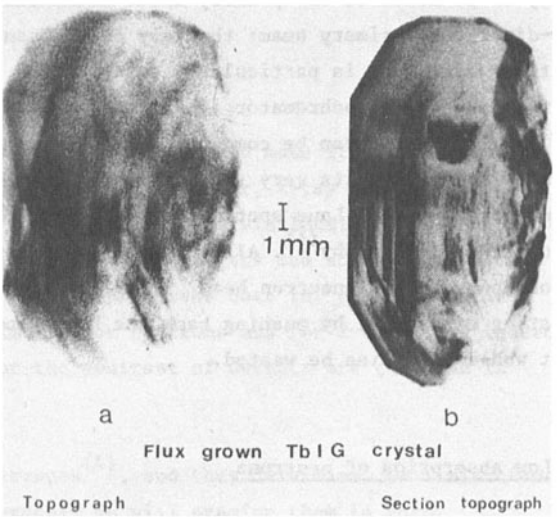

Fig. 1 a) Projection, b) Section topographs of flux-grown TbIG single crystal; λ=4.4 Å. 400 reflection; graphite monochromator using 0002 reflection, mosaic spread 80'. Exposure times a) 1 hour, b) 14.5 hours.

3. The neutron has a magnetic moment

Because neutrons can sense the distribution of magnetic moments they have become the major tool in magnetic structure determination work[4]. In the topographic approach, they can, in principle, provide direct imaging of magnetic domains of all kinds, ferro, ferri, or antiferromagnetic, because different arrangements and/or directions of magnetic moments will lead to different reflectivities in some Bragg reflections[10].

The pioneering work in this direction was a very daring and elegant investigation of spin-density-wave domains in antiferromagnetic chromium by Ando and Hosoya[11], who found a disagreement of several orders of magnitude between the domain sizes

observed and those calculated from the then accepted theoretical model.

Later work focused on more classical systems, ferromagnetic and antiferromagnetic. In the case of ferromagnetic domains, the interest was mainly in the optics of neutron propagation in almost perfect magnetic crystals, the theory of which was recently outlined by several authors [references in (12)]; as an example, fig. 2 shows a polarized neutron topograph of ferromagnetic domains in Fe-3% Si.

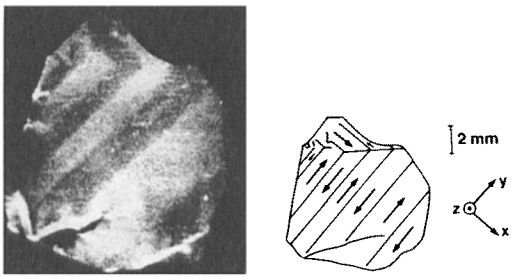

Fig. 2: a) Polarized neutron topograph of Fe-3% Si specimen, 0.1 mm thick. λ = 1.35 Å, 110 reflection; Cu_2MnAl monochromator-polarizer, using 111 reflection. b) schematic diagram of domain structure

In the case of antiferromagnetic domains, a study of the best-known material, NiO, provided direct confirmation[13] of the accepted model of the magnetic moment arrangement; fig. 3 shows the T-domains simultaneously imaged and characterized as to their propagation vector by use of magnetic (superstructure) reflections.

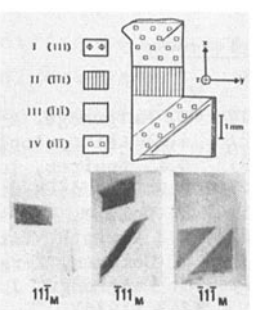

Fig. 3: a) 11$\bar{1}$, b) $\bar{1}$11, c) $\bar{1}$1$\bar{1}$ magnetic (superstructure) reflections from specimen of NiO; d) Diagram of T-domain structure. Note that the 111 reflection could not be found - in agreement with the absence of domains with propagation vector 111.

Recently it was possible using this technique, to directly eliminate one of the suggested possibilities for the magnetic moment direction[14].

The investigation of MnF_2, a case where 180° antiferromagnetic domains appear to be physically distinguishable, is under way; these domains, shown in fig. 4 as seen

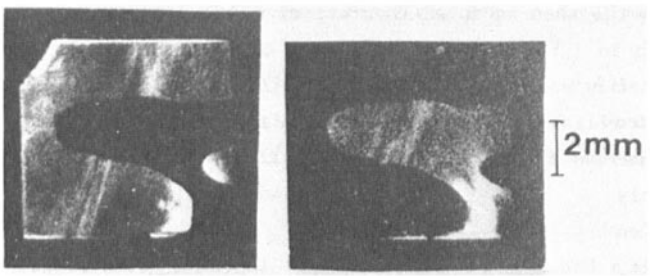

Fig. 4: Polarized neutron topographs of MnF_2 specimen at 20 K. λ=1.35 Å. 210 reflection, with incident neutron polarization reversed. Only one type of domains is visible on each.

by polarized neutron topography, are, to the best of our knowledge, not visible by any other technique; their physics is a completely new field, only poorly understood at the moment.

Conclusion

Neutron topography definitely has poor resolution - it is in this respect closer to the magnifying-glass than to microscopy. But it has the capability of investigating very large single-crystal specimens of most materials - centimeters thick - and to reveal their crystal defects. And it is an invaluable technique in magnetism because it can directly reveal the shape, size and arrangement of magnetic domains of all kinds and at the same time characterize the arrangement of magnetic moments in the domains. New physics is beginning to emerge from such investigations.

References

(1) C. Malgrange, X-ray topography: principles (this volume)
(2) A. Mathiot, Applications of X-ray topography (this volume)
(3) G.L. Squires, Interaction of thermal neutrons with matter (this volume)
(4) G.E. Bacon, Neutron diffraction, 3rd edition, Clarendon Press, Oxford, 1975
(5) K. Doi, N. Minakawa, H. Motohashi, N. Masaki, J. Appl. Cryst., 4, 528 (1971)
(6) J.B Forsyth, Intense sources of thermal neutrons for research (this volume) R. Coisson, X-ray sources (this volume)
(7) C. Malgrange, J.F. Petroff, M. Sauvage, A. Zarka, M. Englander, Phil. Mag. 33, 743 (1976)
(8) J. Baruchel, M. Schlenker, A. Zarka, J.F. Petroff, J. Cryst. Growth 44, 356 (1978)
(9) H. Tomimitsu, K. Doi, J. Appl. Cryst., 7, 59 (1974); J.B. Davidson, J. Appl. Cryst.,7, 356 (1974); M. Schlenker, J. Baruchel, R. Perrier de la Bathie, S.A. Wilson, J. Appl. Phys., 46, 2845 (1975)
(10) M. Schlenker, J. Baruchel, J. Appl. Phys., 49, 1996 (1978)
(11) M. Ando, S. Hosoya, Phys. Rev. Lett., 29,281 (1972), J. Appl. Phys. 49, 6045 (1978)
(12) A. Zeilinger, Perfect crystal neutron optics (this volume)
(13) J. Baruchel, M. Schlenker, W.L. Roth, J. Appl. Phys., 48, 5 (1977)
(14) J. Baruchel, M. Schlenker, K. Kurosawa, S. Saito (to be published)