

## 1.10. Tensors in quasiperiodic structures

BY T. JANSSEN

### 1.10.1. Quasiperiodic structures

#### 1.10.1.1. Introduction

Many materials are known which show a well ordered state without lattice translation symmetry, often in a restricted temperature or composition range. This can be seen in the diffraction pattern from the appearance of sharp spots that cannot be labelled in the usual way with three integer indices. The widths of the peaks are comparable with those of perfect lattice periodic crystals, and this is a sign that the coherence length is comparable as well.

A typical example is  $\text{K}_2\text{SeO}_4$ , which has a normal lattice periodic structure above 128 K with space group  $Pcmm$ , but below this temperature shows satellites at positions  $\gamma\mathbf{c}^*$ , where  $\gamma$  is an irrational number, which in addition depends on temperature. These satellites cannot be labelled with integer indices with respect to the reciprocal basis  $\mathbf{a}^*$ ,  $\mathbf{b}^*$ ,  $\mathbf{c}^*$  of the structure above the transition temperature. Therefore, the corresponding structure cannot be lattice periodic.

The diffraction pattern of  $\text{K}_2\text{SeO}_4$  arises because the original lattice periodic *basic structure* is deformed below 128 K. The atoms are displaced from their positions in the basic structure such that the displacement itself is again periodic, but with a period that is *incommensurate* with respect to the lattice of the basic structure.

Such a *modulated structure* is just a special case of a more general type of structure. These structures are characterized by the fact that the diffraction pattern has sharp Bragg peaks at positions  $\mathbf{H}$  that are linear combinations of a finite number of basic vectors:

$$\mathbf{H} = \sum_{i=1}^n h_i \mathbf{a}_i^* \quad (\text{integer } h_i). \quad (1.10.1.1)$$

Structures that have this property are called *quasiperiodic*. The minimal number  $n$  of basis vectors such that all  $h_i$  are integers is called the *rank* of the structure. If the rank is three and the vectors  $\mathbf{a}_i$  do not all fall on a line or in a plane, the structure is just lattice periodic. Lattice periodic structures form special cases of quasiperiodic structures. The collection of vectors  $\mathbf{H}$  forms the *Fourier module* of the structure. For rank three, this is just the *reciprocal lattice* of the lattice periodic structure.

The definition given above results in some important practical difficulties. In the first place, it is not possible to show experimentally that a wavevector has irrational components instead of rational ones, because an irrational number can be approximated by a rational number arbitrarily well. Very often the wavevector of the satellite changes with temperature. It has been reported that in some compounds the variation shows plateaux, but even when the change seems to be continuous and smooth one can not be sure about the irrationality. On the other hand, if the wavevector jumps from one rational position to another, the structure would always be lattice periodic, but the unit cell of this structure would vary wildly with temperature. This means that, if one wishes to describe the incommensurate phases in a unified fashion, it is more convenient to treat the wavevector as generally irrational. This experimental situation is by no means dramatic. It is similar to the way in which one can never be sure that the angles between the basis vectors of an orthorhombic lattice are really  $90^\circ$ , although this is a concept that no-one has problems in understanding.

A second problem stems from the fact that the wavevectors of the Fourier module are dense. For example, in the case of  $\text{K}_2\text{SeO}_4$  the linear combinations of  $\mathbf{c}^*$  and  $\gamma\mathbf{c}^*$  cover the  $c$  axis uniformly. To pick out a basis here could be problematic, but the intensity of the spots is usually such that choosing a basis is not a problem. In fact, one only observes peaks with an intensity above a certain threshold, and these form a discrete set. At most, the occurrence of scale symmetry may make the choice less obvious.

#### 1.10.1.2. Types of quasiperiodic crystals

One may distinguish various families of quasiperiodic systems. [Sometimes these are also called incommensurate systems if they are not lattice periodic (Janssen & Janner, 1987).] It is not a strict classification, because one may have intermediate cases belonging to more than one family as well. Here we shall consider a number of pure cases.

An *incommensurately modulated structure* or *incommensurate crystal (IC)* phase is a periodically modified structure that without the modification would be lattice periodic. Hence there is a *basic structure* with space-group symmetry. The periodicity of the modification should be incommensurate with respect to the basic structure. The position of the  $j$ th atom in the unit cell with origin at the lattice point  $\mathbf{n}$  is  $\mathbf{n} + \mathbf{r}_j$  ( $j = 1, 2, \dots, s$ ).

For a *displacive modulation*, the positions of the atoms are shifted from a lattice periodic basic structure. A simple example is a structure that can be derived from the positions of the basic structure with a simple displacement wave. The positions of the atoms in the IC phase are then

$$\mathbf{n} + \mathbf{r}_j + \mathbf{f}_j(\mathbf{Q} \cdot \mathbf{n}) \quad [\mathbf{f}_j(x) = \mathbf{f}_j(x + 1)]. \quad (1.10.1.2)$$

Here the *modulation wavevector*  $\mathbf{Q}$  has irrational components with respect to the reciprocal lattice of the basic structure. One has

$$\mathbf{Q} = \alpha\mathbf{a}^* + \beta\mathbf{b}^* + \gamma\mathbf{c}^*, \quad (1.10.1.3)$$

where at least one of  $\alpha$ ,  $\beta$  or  $\gamma$  is irrational. A simple example is the function  $\mathbf{f}_j(x) = \mathbf{A}_j \cos(2\pi x + \varphi_j)$ , where  $\mathbf{A}_j$  is the *polarization vector* and  $\varphi_j$  is the phase of the modulation. The diffraction pattern of the structure (1.10.1.2) shows spots at positions

$$\mathbf{H} = h_1\mathbf{a}^* + h_2\mathbf{b}^* + h_3\mathbf{c}^* + h_4\mathbf{Q}. \quad (1.10.1.4)$$

Therefore, the rank is four and  $\mathbf{a}_4^* = \mathbf{Q}$ . In a more general situation, the components of the atom positions in the IC phase are given by

$$\mathbf{n}^\alpha + \mathbf{r}_j^\alpha + \sum_m \mathbf{A}_j^\alpha(\mathbf{Q}_m) \cos(2\pi\mathbf{Q}_m \cdot \mathbf{n} + \varphi_{j\alpha}), \quad \alpha = x, y, z. \quad (1.10.1.5)$$

Here the vectors  $\mathbf{Q}_m$  belong to the Fourier module of the structure. Then there are vectors  $\mathbf{Q}_j$  such that any spot in the diffraction pattern can be written as

$$\mathbf{H} = \sum_{i=1}^3 h_i \mathbf{a}_i^* + \sum_{j=1}^d h_{3+j} \mathbf{Q}_j \quad (1.10.1.6)$$

and the rank is  $3 + d$ . The peaks corresponding to the basic structure [the combinations of the three reciprocal-lattice vectors  $\mathbf{a}_i^*$  ( $i = 1, 2, 3$ )] are called the *main reflections*, the other peaks are

## 1.10. TENSORS IN QUASIPERIODIC STRUCTURES

*satellites*. For the latter, at least one of the  $h_4, \dots, h_n$  is different from zero.

A second type of modulation is the *occupation* or *composition* modulation. Here the structure can again be described on the basis of a basic structure with space-group symmetry. The basic structure positions are occupied with a certain probability by different atom species, or by molecules in different orientations. In CuAu(II), the two lattice positions in a b.c.c. structure are occupied by either Cu and Au or by Au and Cu with a certain probability. This probability function is periodic in one direction with a period that is not a multiple of the lattice constant. In NaNO<sub>2</sub>, the NO<sub>2</sub> molecules are situated at the centre of the orthorhombic unit cell. There are two possible orientations for the V-shaped molecule, and the probability for one of the orientations is a periodic function with periodicity along the  $a$  axis. In this case, the modulation wavevector  $\alpha\mathbf{a}^*$  has a component  $\alpha$  that strongly depends on temperature in a very narrow temperature range.

If the probability of finding species A in position  $\mathbf{n} + \mathbf{r}_j$  or of finding one orientation of a molecule in that point is given by  $P_j(\mathbf{Q} \cdot \mathbf{n})$ , the probability for species B or the other orientation is of course  $1 - P_j(\mathbf{Q} \cdot \mathbf{n})$ . In the diffraction pattern, the spots belong to the Fourier module with basic vectors  $\mathbf{a}^*, \mathbf{b}^*, \mathbf{c}^*$  and  $\mathbf{Q}$ . The analogous expression for a more general situation with more modulation wavevectors, or with more species or orientations, is a straightforward generalization.

The first examples of IC phases were found in *magnetic systems* (see Section 1.5.1.2.3). For example, holmium has a spiral arrangement with a periodicity of the spiral that does not fit with the underlying lattice. For the  $\alpha$  component ( $\alpha = x, y, z$ ) of the magnetic moment at position  $\mathbf{n} + \mathbf{r}_j$  one has in an incommensurate magnetic system a superposition of waves

$$S_\alpha(\mathbf{n}j) = \sum_m M_{m\alpha j} \cos(2\pi\mathbf{Q}_m \cdot \mathbf{n} + \varphi_{m\alpha}). \quad (1.10.1.7)$$

The most general expression is

$$S_\alpha(\mathbf{n}j) = \sum_{\mathbf{H} \in M^*} M_{\alpha j}(\mathbf{H}) \exp(i\mathbf{H} \cdot \mathbf{n}), \quad (1.10.1.8)$$

where  $M^*$  is the Fourier module (1.10.1.1).

A following class of quasiperiodic materials is formed by *incommensurate composite structures*. To this belong misfit structures, intercalates and incommensurate adsorbed layers. An example is Hg<sub>3-x</sub>AsF<sub>6</sub>. This consists of a subsystem of AsF<sub>6</sub> octahedra forming a (modulated) tetragonal system and two other subsystems consisting of Hg chains, one system of chains in the  $x$  direction and one in the  $y$  direction. Because the average spacing between the Hg atoms is irrational with respect to the lattice constant of the host AsF<sub>6</sub> system in the same direction, the total structure does not have lattice periodicity in the  $a$  or  $b$  direction.

In general, there are two or more subsystems, labelled by  $\nu$ , and the atomic positions are given by

$$\mathbf{n}_\nu + \mathbf{r}_{\nu j} + \text{modulation}, \quad (1.10.1.9)$$

where  $\mathbf{n}_\nu$  belongs to the  $\nu$ th lattice, and where the modulation is a quasiperiodic displacement from the basic structure. The diffraction pattern has wavevectors

$$\mathbf{H} = \sum_\nu \sum_{i_\nu=1}^3 h_{i_\nu} \mathbf{a}_{i_\nu}^* = \sum_{i=1}^n h_i \mathbf{a}_i^*. \quad (1.10.1.10)$$

Each of the reciprocal-lattice vectors  $\mathbf{a}_{i_\nu}^*$  belongs to the Fourier module  $M^*$  and can be expressed as a linear combination with integer coefficients of the  $n$  basis vectors  $\mathbf{a}_i^*$ .

Very often, composite structures consist of a host system in the channels of which another material diffuses with a different, and incommensurate, lattice constant. Examples are layer systems in

which foreign atoms intercalate. Another type of structure that belongs to this class is formed by adsorbed monolayers, for example a noble gas on a substrate of graphite. If the natural lattice constant of the adsorbed material is incommensurate with the lattice constant of the substrate, the layer as a whole will be quasiperiodic.

In general, the subsystems can not exist as such. They form idealized lattice periodic structures. Because of the interaction between the subsystems the latter will, generally, become modulated, and even incommensurately modulated because of the mutual incommensurability of the subsystems. The displacive modulation will, generally, contain wavevectors that belong to the Fourier module (1.10.1.10). However, in principle, additional satellites may occur due to other mechanisms, and this increases the rank of the Fourier module.

The last class to be discussed here is that of *quasicrystals*. In 1982 it was found (Shechtman *et al.*, 1984) that in the diffraction pattern of a rapidly cooled AlMn alloy the spots were relatively sharp and the point-group symmetry was that of an icosahedron, a group with 120 elements and one that can not occur as point group of a three-dimensional space group. Later, ternary alloys were found with the same symmetry of the diffraction pattern, but with spots as sharp as those in ordinary crystals. These structures were called quasicrystals. Others have been found with eight-, ten- or twelvefold rotation symmetry of the diffraction pattern. Such symmetries are also *noncrystallographic symmetries* in three dimensions. Sometimes this noncrystallographic symmetry is considered as characteristic of quasicrystals.

Mathematical models for quasicrystals are quasiperiodic *two- and three-dimensional tilings*, plane or space coverings, without voids or overlaps, by copies of a finite number of 'tiles'. Examples are the Penrose tiling or the standard octagonal tiling in two dimensions, and a three-dimensional version of the Penrose tiling, a quasiperiodic space filling by means of two types of rhombohedra. For the Penrose tiling, all spots of the diffraction pattern are linear combinations of the five basis vectors

$$\mathbf{a}_m^* = \{a \cos[2\pi(m-1)/5], a \sin[2\pi(m-1)/5]\} \quad (m = 1, \dots, 5). \quad (1.10.1.11)$$

Because the sum of these five vectors is zero, the rank of the spanned Fourier module is four. The Fourier module of the standard octagonal tiling is spanned by

$$\mathbf{a}_m^* = \{a \cos[(m-1)\pi/4], a \sin[(m-1)\pi/4]\} \quad (m = 1, \dots, 4). \quad (1.10.1.12)$$

The rank of the Fourier module is also four. The rank of the Fourier module of the three-dimensional Penrose tiling, consisting of two types of rhombohedra with a ratio of volumes of  $(\sqrt{5} + 1)/2$ , is six and basis vectors point to the faces of a regular dodecahedron.

An atomic model can be obtained by decorating the tiles with atoms, each type of tile in a specific way. Some quasicrystals can really be considered as decorated tilings.

### 1.10.1.3. Embedding in superspace

A simple example of a quasiperiodic function is obtained in the following way. Consider a function of  $n$  variables which is periodic with period one in each variable.

$$f(x_1, \dots, x_n) = f(x_1 + 1, x_2, \dots, x_n), \dots \quad (1.10.1.13)$$

Now take  $n$  mutually irrational numbers  $\alpha_i$  and define the function  $g(x)$  with one variable as

$$g(x) = f(\alpha_1 x, \alpha_2 x, \dots, \alpha_n x). \quad (1.10.1.14)$$

Because of the irrationality, the function  $g(x)$  is not periodic. If we consider the Fourier transform of  $f(x_1, \dots, x_n)$  we get

## 1. TENSORIAL ASPECTS OF PHYSICAL PROPERTIES

$$f(x_1, \dots, x_n) = \sum_{m_1} \dots \sum_{m_n} A_{m_1, \dots, m_n} \exp[2\pi i(m_1 x_1 + \dots + m_n x_n)] \quad (1.10.1.15)$$

and consequently

$$g(x) = \sum_{m_1, \dots, m_n} A_{m_1, \dots, m_n} \exp\left[2\pi i\left(\sum_{i=1}^n m_i \alpha_i\right)x\right], \quad (1.10.1.16)$$

which proves that the function is quasiperiodic of rank  $n$  with  $n$  reciprocal-basis vectors  $2\pi\alpha_i$  in one dimension.

The quasiperiodic function  $g(x)$  is therefore the restriction to the line  $(\alpha_1 x, \dots, \alpha_n x)$  in  $n$ -dimensional space. This is a general situation. Each quasiperiodic function can be obtained as the restriction of a periodic function in  $n$  dimensions to a subspace that can be identified with the physical space. We denote the  $n$ -dimensional space in which one finds the lattice periodic structure (the *superspace*) by  $V_s$ , the *physical space* by  $V_E$  and the additional space, called *internal space*, by  $V_I$ , such that  $V_s$  is the direct sum of  $V_E$  and  $V_I$ . In the field of quasicrystals, one often uses the name *parallel space* for  $V_E$  and *perpendicular space* for  $V_I$ .

On the other hand, one can embed the quasiperiodic function in superspace, which means that one constructs a lattice periodic function in  $n$  dimensions such that its restriction to physical space is the quasiperiodic function. Take as an example the displacively modulated structure of equation (1.10.1.2). Compare this three-dimensional structure with the array of lines

$$(\mathbf{n} + \mathbf{r}_j + \mathbf{f}_j(\mathbf{Q} \cdot \mathbf{n} + t), t) \quad (\text{real } t) \quad (1.10.1.17)$$

in four-dimensional space. The restriction to the three-dimensional hyperplane  $t=0$  gives exactly the structure (1.10.1.2). Moreover, the four-dimensional array of lines is lattice periodic. Because  $\mathbf{f}_j$  is periodic, the array is left invariant if one replaces  $t$  by  $t+1$ , and for every lattice vector  $\mathbf{m}$  of the basic structure the array is left invariant if one replaces simultaneously  $t$  by  $t - \mathbf{Q} \cdot \mathbf{m}$ . This means that the array is left invariant by all four-dimensional lattice vectors of the lattice  $\Sigma$  with basis

$$\mathbf{a}_{si} = (\mathbf{a}_i, -\mathbf{Q} \cdot \mathbf{a}_i) \quad (i = 1, 2, 3), \quad \mathbf{a}_4 = (0, 1). \quad (1.10.1.18)$$

Indeed the quasiperiodic IC phase is the restriction to  $V_E$  ( $t=0$ ) of the lattice periodic function in four dimensions.

The reciprocal basis for (1.10.1.18) consists of the basis vectors

$$\mathbf{a}_{si}^* = (\mathbf{a}_i^*, 0) \quad (i = 1, 2, 3), \quad \mathbf{a}_4^* = (\mathbf{Q}, 1). \quad (1.10.1.19)$$

These span the reciprocal lattice  $\Sigma^*$ . The projection of this basis on  $V_E$  consists of the four vectors  $\mathbf{a}_i^*$  ( $i = 1, 2, 3$ ) and  $\mathbf{Q}$ , and these form the basis for the Fourier module of the quasiperiodic structure.

This is a well known situation. From the theory of Fourier transformation one knows that the projection of the Fourier transform of a function in  $n$  dimensions on a  $d$ -dimensional subspace is the Fourier transform of the restriction of that  $n$ -dimensional function to the same  $d$ -dimensional subspace. This gives a way to embed the quasiperiodic structure in a space with as many dimensions as the rank of the Fourier module. One considers the basis of the Fourier module as the projection of  $n$  linearly independent vectors in  $n$ -dimensional space. This means that for every vector of the Fourier module one has exactly one reciprocal-lattice vector in  $V_s$ . Suppose the quasiperiodic structure is given by some function, for example the density  $\rho(\mathbf{r})$ . Then

$$\rho(\mathbf{r}) = \sum_{\mathbf{H} \in M^*} \hat{\rho}(\mathbf{H}) \exp(i\mathbf{H} \cdot \mathbf{r}). \quad (1.10.1.20)$$

One may define a function in  $n$ -dimensional space by

$$\rho_s(\mathbf{r}_s) = \sum_{\mathbf{H}_s \in \Sigma^*} \hat{\rho}(\mathbf{H}) \exp(i\mathbf{H}_s \cdot \mathbf{r}_s), \quad (1.10.1.21)$$

where  $\mathbf{H}_s$  is the unique reciprocal-lattice vector that is projected on the Fourier module vector  $\mathbf{H}$ . It is immediately clear that the restriction of  $\rho_s$  to physical space is exactly  $\rho$ . Moreover, the function  $\rho_s$  is lattice periodic with lattice  $\Sigma$ , for which  $\Sigma^*$  is the reciprocal lattice.

This construction can be performed in the following equivalent way. Consider a point  $\mathbf{r}$  in physical space, where one has the quasiperiodic function  $\rho(\mathbf{r})$ . The Fourier module of this function is the projection on physical space of the  $n$ -dimensional reciprocal lattice  $\Sigma^*$  with basis vectors  $\mathbf{a}_{si}^*$  ( $i = 1, 2, \dots, n$ ). The reciprocal lattice  $\Sigma^*$  corresponds to the direct lattice  $\Sigma$ . A point  $\mathbf{r}$  in  $V_E$  can also be considered as an element  $(\mathbf{r}, 0)$  in  $n$ -dimensional space. By the translations of  $\Sigma$ , this point is equivalent with a point  $\mathbf{r}_s$  with lattice coordinates

$$\xi_i = \text{Frac}(\mathbf{a}_{si}^* \cdot (\mathbf{r}, 0)) = \text{Frac}(\mathbf{a}_i^* \cdot \mathbf{r}) \quad (1.10.1.22)$$

in the unit cell of  $\Sigma$ , where  $\text{Frac}(x)$  is  $x$  minus the largest integer smaller than  $x$ . If one puts  $\rho_s(\mathbf{r}_s) = \rho(\mathbf{r})$ , the function  $\rho$  determines the function  $\rho_s$  in the unit cell, and consequently in the whole  $n$ -dimensional space  $V_s$ . This means that all the information about the structure in  $V_E$  is mapped onto the information inside the  $n$ -dimensional unit cell. *The information in three dimensions is exactly the same as that in superspace.* Only the presentation is different.

In the case in which the crystal consists of point atoms, the corresponding points in  $d$ -dimensional physical space  $V_E$  are the intersection of  $(n-d)$ -dimensional hypersurfaces with  $V_E$ . For displacively modulated IC phases in three dimensions with one modulation wavevector, one has  $n=4$ ,  $d=3$  and the hypersurfaces are just lines in superspace, as we have seen. For more independent modulation vectors the dimension of the hypersurfaces is larger than one. In this case, as often in the case of composite structures, the  $(n-d)$ -dimensional surfaces do not have borders. This in contrast to quasicrystals, where they are bounded. All these hypersurfaces for which the intersection with physical space gives the atomic positions are called *atomic surfaces*.

Physical properties of aperiodic but quasi-periodic structures are partly determined by their symmetry, which can be formulated using the superspace approach. Here we deal mainly with such symmetry-related properties. A more extensive view is given in Janssen *et al.* (2007).

### 1.10.2. Symmetry

#### 1.10.2.1. Symmetry transformations

Because the embedded periodic structure in  $n$  dimensions has lattice periodicity, it has  $n$ -dimensional space-group symmetry as well. It is not *a priori* clear that such a symmetry group in the unphysical  $n$ -dimensional space is relevant for the physical structure, but we shall show here that the superspace description is indeed useful for the description of quasiperiodic systems. First we shall discuss some of the structures of these higher-dimensional space transformations.

Suppose the diffraction pattern has rotational symmetry. Consider for example an orthogonal transformation  $R$  that leaves the diffraction pattern invariant. In particular, any basis vector of the module is transformed into an element of the module, *i.e.* an integral linear combination of the basis vectors.

$$R\mathbf{a}_i^* = \sum_{j=1}^n M_{ji} \mathbf{a}_j^*, \quad i = 1, 2, \dots, n. \quad (1.10.2.1)$$

Because the matrix  $M$  depends on  $R$  and acts in reciprocal space, we denote it by  $\Gamma^*(R) = M$ . The matrix  $\Gamma^*(R)$  has integer entries. Because the intensity of the diffraction pattern is not constant on circles around the origin (that would imply that one can not distinguish separate peaks), the orthogonal transformation  $R$  is of