Crystal Period Vectors under External Stress in Statistical Physics (Version 8)

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For crystal periodic structure prediction, a new and concise approach based on the principles of statistical physics was employed to derive a new form of the equation to determine their period vectors (cell edge vectors), under general external stress. Then the new form is applicable to both classical physics and quantum physics. It also turned out to be the equation of state and the specific explicit equilibrium condition for crystals under external stress and temperature. It should be helpful in piezoelectric and piezomagnetic studies, as the period vectors were changed by the external stress. For linear elastic crystals, it is actually also the microscopic but temperature-dependent form of the generalized Hooke's law, then can be used to calculate the corresponding elastic constants of the law, for given temperatures.

I. INTRODUCTION

For predicting crystal structures, especially before being synthesized, the equations are needed to determine their discrete particle positions and their period vectors (cell edge vectors $\mathbf{h} = \mathbf{a}$, $\mathbf{b}$, or $\mathbf{c}$, forming a right-handed system). Since the particles (atoms, ions, electrons) inside crystals always obey Newton's second law or the Schrodinger equation, the only unknown is the equation for the period vectors, especially when crystals are under general external stress. It has been derived in the framework of Newtonian dynamics in recent years[1], which can be combined with quantum physics by further modeling. Here we will employ a new and concise approach based on the principles of statistical physics to derive it into a new form, then applicable to both classical physics and quantum physics by itself. It also turned out to be the equation of state and the specific explicit equilibrium condition for crystals under external stress and temperature. At the end, the new form and the previously derived one will be shown to verify each other.

II. EXISTING THEORY FOR EXTERNAL PRESSURE

As a matter of fact, in statistical physics, the theory for the same purpose but for crystals under external pressure, a special case of stress, has been established firmly for long time[2]. Now let us recall it briefly.

A. The theory

From microscopic point of view, crystals are made of unlimited periodic arrangements of the same cells in the three-dimensional space. They can be studied by focusing on a "center" cell interacting with the rest cells. Then the external pressure, actually acting only on the surfaces of the macroscopic crystal bulk, can be equivalently described as the action on the surfaces of the "center" cell. The work done by the pressure P on the cell is normally written as

$$dW = -PdV, \qquad (1)$$

where the cell volume $V = (\mathbf{a} \times \mathbf{b}) \cdot \mathbf{c}$. As the cell volume V is the conjugate variable of the pressure P, as shown in Eq.(1), based on the principle of statistical physics[5], the pressure can be derived as in equation (2.96) of the statistical reference book[2]:

$$P = \frac{1}{\beta} \frac{\partial \ln Z}{\partial V}, \qquad (2)$$

where $\beta = 1/(kT)$, and Z, k, and T are the partition function, Boltzmann constant, and temperature respectively. This is essentially the equation of state of crystals under external pressure in equilibrium. In other words, the crystal cell volume can be calculated based on this equation for the given external pressure and temperature. However, it is not for the period vectors explicitly.

B. Expansion with respect to the period vectors

Now let us change these equations slightly. As $dV = \sigma_\mathbf{a} \cdot d\mathbf{a} + \sigma_\mathbf{b} \cdot d\mathbf{b} + \sigma_\mathbf{c} \cdot d\mathbf{c}$, where $\sigma_\mathbf{h} = \partial V/\partial \mathbf{h}$ is the surface area vector of the cell with respect to $\mathbf{h}$, e.g. $\sigma_\mathbf{a} = \mathbf{b} \times \mathbf{c}$, the above work can also be written as

$$dW = -(P\sigma_\mathbf{a}) \cdot d\mathbf{a} - (P\sigma_\mathbf{b}) \cdot d\mathbf{b} - (P\sigma_\mathbf{c}) \cdot d\mathbf{c}, \qquad (3)$$

where $d\mathbf{h}$ ($=d\mathbf{a}$, $d\mathbf{b}$, $d\mathbf{c}$) is now the conjugate variable of the force $-P\sigma_\mathbf{h}$ acting on the cell surface $\sigma_\mathbf{h}$. Then based on the principle of statistical physics, we have

$$P\sigma_\mathbf{h} = \frac{1}{\beta} \frac{\partial \ln Z}{\partial \mathbf{h}} \quad (\mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}), \qquad (4)$$

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which is in the form of determining the period vectors specifically. Combining Eq.(2) and Eq.(4) leads to

$$
\begin{aligned}
PV &= \frac{V}{\beta}\frac{\partial \ln Z}{\partial V} = \frac{\mathbf{a}}{\beta}\cdot\frac{\partial \ln Z}{\partial \mathbf{a}} \\
&= \frac{\mathbf{b}}{\beta}\cdot\frac{\partial \ln Z}{\partial \mathbf{b}} = \frac{\mathbf{c}}{\beta}\cdot\frac{\partial \ln Z}{\partial \mathbf{c}}.
\end{aligned}
$$

This means that the cell shape must be assumed and kept certain symmetries for external pressure in actual calculation. Under such circumstances, Eq.(4) for any specific period vector, e.g. $\mathbf{h} = \mathbf{a}$, should be equivalent to Eq.(2).

III.   EQUATION DERIVATION FOR EXTERNAL STRESS

Now let us consider crystals under arbitrary external stress $\mathbf{\Upsilon}$, a second-rank tensor (3×3 matrix), to which neither Eq.(2) nor Eq.(4) applies.
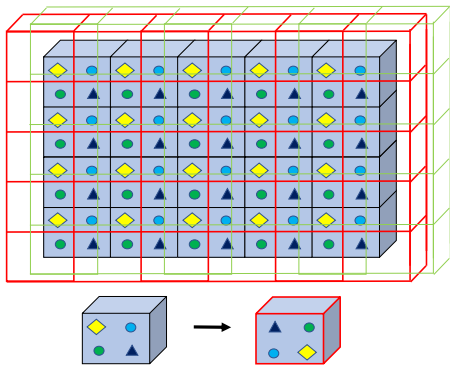

FIG. 1: While the positions of the particles inside a crystal are fixed, all the cells as a whole can be translated anywhere together, then placed in the new position, though only one layer of cells shown here. The red frame is an example of the new cell placement, and the green frame is another. As a result, as shown in the lower part of this figure, the yellow diamond particle in the top-left corner of the old cell on the left, is in the right-bottom corner of the new red-framed cell on the right now, viewed through the front surfaces.

As shown in FIG. 1, while the positions of the particles inside a crystal are fixed, all the cells as a whole can be translated anywhere together, then be placed in the new position. The red-framed and the green-framed ones in the figure are two examples, since the movement of all the cells together can be in any direction and with any distance. All the movements should be equivalent to each other in physics, and also equivalent to the average of them. This can also be described as that while the cells are kept fixed, the particles can be translated as a whole anywhere together. As a result, while the relative positions between the particles are fixed, any individual

particle can appear anywhere in the cell. The above-mentioned average of all the cell movements corresponds to the situation where the fixed "center" cell is made of continuous medium. Then the cell is now an actual object with matter in it everywhere, instead of, as normally described, a vacuum region of three-dimensional space containing some discrete particles. Since the total mass of each cell is never changed, the cell surfaces become physical ones of fixed infinitesimal fraction of the cell mass in an extremely thin layer, from pure geometry planes. Then the force, described by the external stress, acting on the physical surface $\sigma_\mathbf{h}$ of the cell, is a real force and expressed as $\mathbf{\Upsilon} \cdot \sigma_\mathbf{h}$. Further considering that the displacement of the physical cell surface is $d\mathbf{h}$, the work done by the external stress on the crystal cell is

$$
dW = (\mathbf{\Upsilon} \cdot \sigma_\mathbf{a}) \cdot d\mathbf{a} + (\mathbf{\Upsilon} \cdot \sigma_\mathbf{b}) \cdot d\mathbf{b} + (\mathbf{\Upsilon} \cdot \sigma_\mathbf{c}) \cdot d\mathbf{c}. \quad (5)
$$

Then as seen, this equation was written rigorously based on the original definition of the work, where the subject of the displacement and the object being acted on by the corresponding force should be exactly the same actual object. Eq.(5) becomes Eq.(1) when the stress reduces to the pressure $\mathbf{\Upsilon} = -P\mathbf{I}$ with $\mathbf{I}$ being an identity tensor.

Since, as shown in Eq.(5), the displacement $d\mathbf{h}$ is the conjugate variable of the force $\mathbf{\Upsilon} \cdot \sigma_\mathbf{h}$ acting on the physical cell surface $\sigma_\mathbf{h}$, based on the principle of statistical physics again, we arrived at

$$
\mathbf{\Upsilon} \cdot \sigma_\mathbf{h} = -\frac{1}{\beta}\frac{\partial \ln Z}{\partial \mathbf{h}} \quad (\mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}). \quad (6)
$$

It has the same form on the right side as that in Eq.(4), except the plus/minus sign. However, it is for crystals under external stress.

Supposing the period vectors are the only unknown variables for given external stress and temperature, then can be calculated by solving Eq.(6). During such procedure, different from the above external pressure case, as the period vectors are independent variables with each other, there should be no additional restrictions on the cell shape symmetry. For the special (pressure) case $\mathbf{\Upsilon} = -P\mathbf{I}$, Eq.(6) reduces to Eq.(4), then reduces to Eq.(2), as it should.

However, as a reminder, whatever the cell movement in FIG. 1 or their average being employed, the relative positions between particles should always be kept fixed, thus the interactions between them, the cell energy, the partition function and all other physical quantities are independent of the cell movements. One incorrect idea is that "if the average of all the cell movements is used, since any two particles can appear anywhere, their relative distance can be any value in the cell."

IV.   INTERNAL STRESS AND MECHANICAL EQUILIBRIUM CONDITION

In 2010, Tuckerman expressed the crystal internal stress, also a second-rank tensor, as in Equation (5.6.9)

of his statistical molecular simulation book[3], then applied it in a solid silicon system as an actual calculation example with a success[4]. In fact, this expression can also be written in the following way

$$\mathbf{P}^{(\text{int})} = \frac{1}{\beta V} \sum_{\mathbf{h}=\mathbf{a},\mathbf{b},\mathbf{c}} \frac{\partial \ln Z}{\partial \mathbf{h}} \otimes \mathbf{h}. \tag{7}$$

Let us do three right dot products on Eq.(7) with the cell surface area vectors $(\sigma_{\mathbf{a}}, \sigma_{\mathbf{b}}, \sigma_{\mathbf{c}})$ separately and apply the relationship $\mathbf{h} \cdot \sigma_{\mathbf{x}} = V \delta_{\mathbf{h},\mathbf{x}}$, then

$$\mathbf{P}^{(\text{int})} \cdot \sigma_{\mathbf{h}} = \frac{1}{\beta} \frac{\partial \ln Z}{\partial \mathbf{h}} \quad (\mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}). \tag{8}$$

Bringing Eq.(8) into Eq.(6), then

$$\mathbf{\Upsilon} \cdot \sigma_{\mathbf{h}} = -\mathbf{P}^{(\text{int})} \cdot \sigma_{\mathbf{h}} \quad (\mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}), \tag{9}$$

which is equivalent to

$$\mathbf{\Upsilon} + \mathbf{P}^{(\text{int})} = 0, \tag{10}$$

as the three cell surface area vectors $(\sigma_{\mathbf{a}}, \sigma_{\mathbf{b}}, \sigma_{\mathbf{c}})$ are not in the same plane.

Since Eq.(10) means the internal and the external stresses balance each other, Eq.(6) is actually the "mechanical" equilibrium condition of the crystal under external stress and temperature, with the aid of the internal stress expressed by Eq.(7). The temperature appears in the partition function. Actually, it also means that Eq.(6) and the internal stress expression verified each other.

V. EQUATION OF STATE AND SYSTEM EXPANSION

In fact, Eq.(6) is an equation about the period vectors, all the particle position vectors in the "center" cell, the external stress, and the temperature variables. In order to solve the whole crystal system, Eq.(6) must be combined with Newton's second law or the Schrodinger equation for motions of all particles in the cell. Since all particle motions can be solved by Newton's second law and/or the Schrodinger equation, for given period vectors as parameters, Eq.(6) can be used to solve the period vectors for given external stress and temperature and the solved particle motions. This process should be repeated till all variables converge. Since Newton's second law and the Schrodinger equation are fundamental principles of physics, which are always available and applicable, the whole procedure can be equivalently regarded as solving the period vectors by Eq.(6) for external conditions. Then Eq.(6) is the equation of state for crystals under external stress and temperature, in the form of the period vectors, instead of the cell volume.

As actually expressed by the period vectors, all kinds of crystal expansions caused by the change of the external stress or the temperature or both of them can be calculated by solving Eq.(6) under all external conditions concerned. Alternatively, as an example, supposing the temperature is fixed but the external stress is changed, one can do partial derivatives of Eq.(6) on both sides with respect to the changed components of the external stress respectively, then gets the isothermal expansion by the external stress.

As another example, let us consider the "isobaric" thermal expansion, in which the external stress is fixed but the temperature is changed. Actually, the particles' motion inside crystals is usually separated into the particles' equilibrium position motion and the harmonic oscillation around it. The harmonic oscillation can be represented by its frequency ω (or frequencies), which is a function of the period vectors and all particle equilibrium position vectors in the cell. For simplicity, let us suppose that there is only one particle in each cell, then its equilibrium position vector can always be set as zero, never changed. Then the partition function Z can be considered as a function of the frequency ω and temperature. When the temperature is changed, the right side of Eq.(6), $-kT\partial \ln Z(\omega, T)/\partial \mathbf{h}$, should change. Then the left side of Eq.(6), $\mathbf{\Upsilon} \cdot \sigma_{\mathbf{h}}$, should also change. Since the external stress $\mathbf{\Upsilon}$ is fixed, $\sigma_{\mathbf{h}}$ should change, then so do the period vectors. This means that the harmonic oscillation causes crystal thermal expansion.

For the special case of external pressure, as said above, the cell shape should keep certain symmetry, then the inside particle (equilibrium) positions should also be assumed accordingly. Then if no structural phase transition happens, the crystal can only expand or contract uniformly. This means that the particle (equilibrium) position vectors and the period vectors should change proportionally, then all the particle (equilibrium) position vectors relative to the period vectors would not change. Then Eq.(6) is only about the period vectors, the external pressure, and the temperature variables, a pure traditional form of the equation of state.

VI. DISCUSSION

A. Piezoelectricity and piezomagnetism

The fascinating piezoelectric and piezomagnetic phenomena are induced when the external pressure on crystals in one direction is changed while those in the other two directions not. Since the external stress is changed, according to Eq.(6), the equation of state, the period vectors should also be changed, then to employ Eq.(6) to calculate the changed crystal structure accurately would be very helpful in these studies.

B. Elasticity and plasticity

According to the equation of state, Eq.(6), a crystal, for given external condition A of certain external

stress and temperature, should show fixed period vectors, then crystal structure, representable by its "center" cell structure, denoted with $Cell_A$. Later the external condition is changed to B, the crystal structure is changed to $Cell_B$ accordingly. Then when the external condition changes back from B to A, in principle, the crystal structure should also restore from $Cell_B$ to $Cell_A$, in order to satisfy Eq.(6). This is the general elasticity of crystals. However, there are possibly more than one stable structures in various structural phases satisfying Eq.(6), denoted with $Cell_{A1}$, $Cell_{A2}$, $\cdots$, $Cell_{A100}$, $\cdots$, even for condition A. When the external condition runs from A to B back to A, the structure may go from $Cell_{A25}$ to $Cell_{A8}$. This is an example of microscopic plasticity. Supposing for A to B back to A, the structure goes from $Cell_{A25}$ to $Cell_B$, then back to $Cell_{A25}$, no microscopic plasticity happens. However, further supposing in beginning condition A, the macroscopic crystal bulk has $1000 \times 1000 \times 8000$ cells in the three directions in space, it may becomes $2000 \times 2000 \times 2000$ in B condition. Later when B goes back to ending A, $2000 \times 2000 \times 2000$ may be kept, then macroscopic plasticity happens.

Although Eq.(6) is always satisfied, plasticity may occur in either microscopic or macroscopic or both folds at the same time. Since there is always some potential barrier to be overcome, the less the external condition changes, the less chance for plasticity.

C. Comparison with elasticity theory and the generalized Hooke's law

Since elasticity theory is also about the action of external stress on crystals, it is better to compare it with this work.

First of all, elasticity theory studies macroscopic shapes and properties of crystals mainly, thus regards crystals as continuous medium, then is not interested in crystal period vectors in principle. This work considers continuous medium for cells but only when formulates the work done by the external stress on the crystal cell, and derives the equation for determining the period vectors as the sole purpose. Whatever, let us suppose elasticity theory also studies microscopic structures of crystals in the following.

Second, elasticity theory normally employs a reference state not being acted by any external stress, in which the period vectors $h_0 = a_0, b_0, c_0$, and all the particle position vectors $r_{i,0}(i = 1, \cdots, N)$ in the center cell should be supposed known, where N is the total number of particles in the cell. This work only tries to do something in the current state under any external stress, forgetting all other states completely. In other words, this work regards every state completely independently, with no information from any other state needed.

Third, elasticity theory introduces and widely uses the concept strain u, also a second-rank tensor, to describe crystal deformation caused by the external stress. By

definition, strain means that for any point vector x of the matter in the current state, one has $x = x_0 + u \cdot x_0$, where x_0 is the corresponding point in the reference state, at least within a local macroscopic region of the crystal. Then all the period vectors and particle position vectors in the same local region of the current state under certain external stress are linearly related to the corresponding ones of the reference state in the same form:

$$h = h_0 + u \cdot h_0 \quad (h = a, b, c), \quad (11)$$
$$r_i = r_{i,0} + u \cdot r_{i,0} \quad (i = 1, \cdots, N), \quad (12)$$

as well. Since Eqs.(11 and 12) restrict the crystal structure to change only linearly, then can not describe crystal structural phase transitions caused by the change of the external stress and temperature.

However this work neither use the strain concept nor make the assumption of Eqs.(11 and 12), but regards and uses all the period vectors ($h = a, b, c$) and the particle position vectors $r_i(i = 1, \cdots, N)$ as independent variables with each other, then can describe any new crystal structure being created by the change of the external stress and/or temperature. Typically, external stress may cause structural phase transitions in crystals. Again since it is well-known about how to determine the particle position vectors by applying either Newton's second law or the Schrodinger equation, this work only focuses on how to determine the period vectors.

Furthermore, elasticity theory employs the generalized Hooke's law as a principle, in which the stress and strain are assumed linearly related by introducing the elastic constants, which are usually determined by experiments. This work does not assume any analytical relationship between the crystal period vectors and the external stress. Actually, Eq.(6) is the temperature-dependent relationship between them, but with no additional constants or coefficients introduced, supposing everything in Eq.(6) can be at least calculated numerically. Then Eq.(6) is the microscopic form of the generalized Hooke's law, for the situation where the period vectors and the external stress approximately change proportionally in reality. The elastic constants in the generalized Hooke's law can be calculated by solving Eq.(6) under a series of values of the external stress, for a given temperature.

D. Classical physics, "algorithm", and combination

In classical statistics, as in equations (3.45-3.47) in the reference book[2], the partition function can be factorized as

$$Z = Z_k Z_u, \quad (13)$$

where Z_k and Z_u are the contributions of the particles' kinetic energy E_k and the cell potential energy E_p respectively as

$$Z_k = \frac{V^N}{N!} \int \int \cdots \int \frac{1}{h^{3N}} e^{-\beta E_k(\mathbf{p})} d\mathbf{p}, \quad (14)$$

where h is Planck constant, and the integration is over all particle' momentum spaces, and

$$Z_u = \frac{1}{V^N} \int_V \int_V \cdots \int_V e^{-\beta E_p(\mathbf{a},\mathbf{b},\mathbf{c},\mathbf{R})} d\mathbf{R}, \qquad (15)$$

where the integration is over all particles position vectors: $\mathbf{R} = \{\mathbf{r}_1, \mathbf{r}_2, \cdots, \mathbf{r}_N\}$, limited in the cell.

Since the integration in Eq.(14) has nothing to do with the period vectors, the derivative

$$\frac{\partial \ln Z_k}{\partial \mathbf{h}} = \frac{N}{V}\frac{\partial V}{\partial \mathbf{h}} = \frac{N}{V}\sigma_\mathbf{h} \quad (\mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}). \qquad (16)$$

But a little more patience is needed for Eq.(15), as the the cell potential energy E_p is a function of all the period vectors and all the particle position vectors $\mathbf{R}$. For every particle in the "center" cell, the position vector can be expanded with respect to the period vectors:

$$\mathbf{r}_i = r_{i,\mathbf{a}}\mathbf{a} + r_{i,\mathbf{b}}\mathbf{b} + r_{i,\mathbf{c}}\mathbf{c} \quad (i = 1, \cdots, N), \qquad (17)$$

where $r_{i,\mathbf{h}}$, in the range of $[0,1)$, can be calculated as

$$r_{i,\mathbf{h}} = \frac{1}{V}\mathbf{r}_i \cdot \sigma_\mathbf{h} \quad (i = 1, \cdots, N; \ \mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}). \qquad (18)$$

Let us perform a similar derivation as in the second half of page 135 of the reference book[2], then the integration regarding $\mathbf{r}_i$ in the cell but per unit volume

$$\frac{1}{V}\int_V \cdots d\mathbf{r}_i = \int_V \cdots \frac{d\mathbf{r}_i}{V}$$
$$= \int_0^1 \int_0^1 \int_0^1 \cdots dr_{i,\mathbf{a}} dr_{i,\mathbf{b}} dr_{i,\mathbf{c}}$$
$$(i = 1, \cdots, N). \quad (19)$$

Then the derivatives of Z_u with respect to the period vectors become only the derivatives of the cell potential E_p inside the integration:

$$\frac{\partial Z_u}{\partial \mathbf{h}} = \int_0^1 \int_0^1 \int_0^1 \int_0^1 \int_0^1 \int_0^1 \cdots \int_0^1 \int_0^1 \int_0^1 \times$$
$$\frac{\partial}{\partial \mathbf{h}} e^{-\beta E_p(\mathbf{a},\mathbf{b},\mathbf{c},\mathbf{R})} dr_{1,\mathbf{a}} dr_{1,\mathbf{b}} dr_{1,\mathbf{c}} \times$$
$$dr_{2,\mathbf{a}} dr_{2,\mathbf{b}} dr_{2,\mathbf{c}} \cdots dr_{N,\mathbf{a}} dr_{N,\mathbf{b}} dr_{N,\mathbf{c}}$$
$$(\mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}). \quad (20)$$

Since that the dependency of $\mathbf{R}$ on the period vectors must be considered now, as shown in Eq.(17), the following derivatives should be separated as

$$\frac{\partial E_p}{\partial \mathbf{h}} = \left.\frac{\partial E_p(\mathbf{a},\mathbf{b},\mathbf{c},\mathbf{R})}{\partial \mathbf{h}}\right|_\mathbf{R} + \left.\frac{\partial E_p(\mathbf{a},\mathbf{b},\mathbf{c},\mathbf{R})}{\partial \mathbf{h}}\right|_{\mathbf{a},\mathbf{b},\mathbf{c}}$$
$$(\mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}), \quad (21)$$

where

$$\left.\frac{\partial E_p(\mathbf{a},\mathbf{b},\mathbf{c},\mathbf{R})}{\partial \mathbf{h}}\right|_{\mathbf{a},\mathbf{b},\mathbf{c}} = \sum_{i=1}^N \frac{\partial E_p(\mathbf{a},\mathbf{b},\mathbf{c},\mathbf{R})}{\partial \mathbf{r}_i}\frac{\partial \mathbf{r}_i}{\partial \mathbf{h}}$$
$$= \sum_{i=1}^N -\mathbf{F}_i r_{i,\mathbf{h}}$$
$$= \sum_{i=1}^N -\mathbf{F}_i \frac{\mathbf{r}_i \cdot \sigma_\mathbf{h}}{V}$$
$$= -\frac{1}{V}\sum_{i=1}^N (\mathbf{F}_i \otimes \mathbf{r}_i) \cdot \sigma_\mathbf{h}$$
$$(\mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}), \quad (22)$$

where $\mathbf{F}_i$ is the net of all the forces acting on particle i, by any other particles in any cell, including its image particles. Employing Eqs.(20, 21, and 22), it follows

$$-\frac{\partial \ln Z_u}{\beta \partial \mathbf{h}} = -\frac{1}{\beta Z_u}\frac{\partial Z_u}{\partial \mathbf{h}}$$
$$= \frac{-kT}{Z_u V^N} \int_V \int_V \cdots \int_V \frac{\partial}{\partial \mathbf{h}} e^{-\beta E_p(\mathbf{a},\mathbf{b},\mathbf{c},\mathbf{R})} d\mathbf{R}$$
$$= \frac{1}{Z_u V^N} \int_V \int_V \cdots \int_V e^{-\beta E_p(\mathbf{a},\mathbf{b},\mathbf{c},\mathbf{R})} \times$$
$$\left(\left.\frac{\partial E_p(\mathbf{a},\mathbf{b},\mathbf{c},\mathbf{R})}{\partial \mathbf{h}}\right|_\mathbf{R} - \frac{1}{V}\sum_{i=1}^N \mathbf{F}_i \otimes \mathbf{r}_i \cdot \sigma_\mathbf{h}\right) d\mathbf{R}$$
$$(\mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}), \quad (23)$$

Bringing Eqs.(16 and 23) into Eq.(6), we get

$$\boldsymbol{\Upsilon} \cdot \sigma_\mathbf{h} = -\frac{1}{V}NkT\sigma_\mathbf{h} - \frac{1}{\beta}\frac{\partial \ln Z_u}{\partial \mathbf{h}} \quad (\mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}). \quad (24)$$

For "crystals" only containing ideal gases under external pressure, Eq.(24) becomes the ideal gas equation: $PV = NkT$.

Now let us consider equilibrium states where

$$\ddot{\mathbf{h}} = 0 \quad (\mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}), \qquad (25)$$
$$\ddot{\mathbf{r}}_i = 0 \quad (i = 1, \cdots, N). \qquad (26)$$

Then the previously derived dynamical equation for the period vectors based on the Newtonian dynamics: Equation (27) in the paper[1], becomes

$$\boldsymbol{\Upsilon} \cdot \sigma_\mathbf{h} = -\frac{1}{3V}\sum_{i=1}^N m_i |\dot{\mathbf{r}}_i|^2 \sigma_\mathbf{h} +$$
$$+ \left.\frac{\partial E_p}{\partial \mathbf{h}}\right|_\mathbf{R} - \frac{1}{V}\sum_{i=1}^N (\mathbf{F}_i \otimes \mathbf{r}_i) \cdot \sigma_\mathbf{h}$$
$$(\mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}), \quad (27)$$

where Equations (9, 17, 19, 25, and 26) in the paper[1] were employed, with m_i being the mass of particle i in the cell. The last term $-kT\partial \ln Z_u/\partial \mathbf{h}$ in Eq.(24) as shown

in Eq.(23) is the averaged form of the last two terms $(\partial E_p/\partial \mathbf{h})|_{\mathbf{R}}$ and $-\sum_{i=1}^{N} \mathbf{F}_i \otimes \mathbf{r}_i \cdot \sigma_{\mathbf{h}}/V$ of Eq.(27), then essentially they are the same in physics.

Then, in classical physics, as the corresponding kinetic energy terms in the two equations are normally also regarded the same as each other, Eq.(24) achieved in statistical physics here and Eq.(27) previously derived based on the Newtonian dynamics[1] verified each other.

The previously derived Equation (27) in the paper[1] for the period vectors based on the Newtonian dynamics is a dynamical equation, then can be used as an "algorithm" for solving the equilibrium states. Let us replace its internal stress with Tuckerman's expression, Eq.(7), then get

$$\alpha_{\mathbf{h},\mathbf{h}}\ddot{\mathbf{h}} = \left(\boldsymbol{\Upsilon} + \mathbf{P}^{(\text{int})}\right) \cdot \sigma_{\mathbf{h}} \quad (\mathbf{h} = \mathbf{a}, \mathbf{b}, \mathbf{c}), \qquad (28)$$

where $\alpha_{\mathbf{h},\mathbf{h}}$ is an equivalent mass, then can be chosen with any positive real number. Eq.(28) can be used as an "algorithm" for solving Eq.(6) in both classical physics and quantum physics.

In the Born-Oppenheimer approximation, ions and electrons in crystals are usually solved by Newtonian dynamics and quantum mechanics separately. Then the partition function of the whole crystal should be factorized accordingly, then Eq.(6) is for the combination of classical physics and quantum physics.

VII. SUMMARY

Eq.(6) was derived here for determining crystal period vectors, then predicting crystal structures, by rigorously formulating the work done by the external stress on the crystal and applying the statistical principles. While the previously derived one in the frame work of Newtonian dynamics can be combined with quantum mechanics by further modeling, Eq.(6) applies to both classical physics and quantum physics and their combination by itself. Since the period vectors are only meaningful in equilibrium states, where the external and the internal temperatures should be the same, Eq.(6) is not only the equilibrium condition, but also the equation of state for crystals under external stress and external temperature, expressed on the basis of the period vectors.

Eq.(6) further turned out to be the microscopic but temperature-dependent form of the generalized Hooke's law, for linear elastic crystals, then can be used to calculate the corresponding elastic constants of the law, for given temperatures. It should also play an essential role in piezoelectric and piezomagnetic studies, caused by an increase of the external pressure on crystals but only in one direction. Eq.(6) also concluded that harmonic oscillators can cause crystal thermal expansion at constant external stress.

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[3] M. E. Tuckerman, *Statistical Mechanics: Theory and Molecular Simulation*. Oxford University Press, Oxford, 2010.

[4] Z. Ma, M. Tuckerman, *J. Chem. Phys.* **133**, 184110 (2010). https://doi.org/10.1063/1.3499812 .

[5] If the work done on a system can be written as in the form of $dW = A_1 dB_1 + A_2 dB_2 + \cdots + A_i dB_i + \cdots$, for any pair of A_i and B_i variables, one has $A_i = -kT\partial \ln Z/\partial B_i$.