

MAELAS code

User manual v1.0

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WHAT IS MAGNETOSTRICTION?

Magnetostriction is a physical phenomenon in which the process of magnetization induces a change in shape or dimension of a magnetic material.

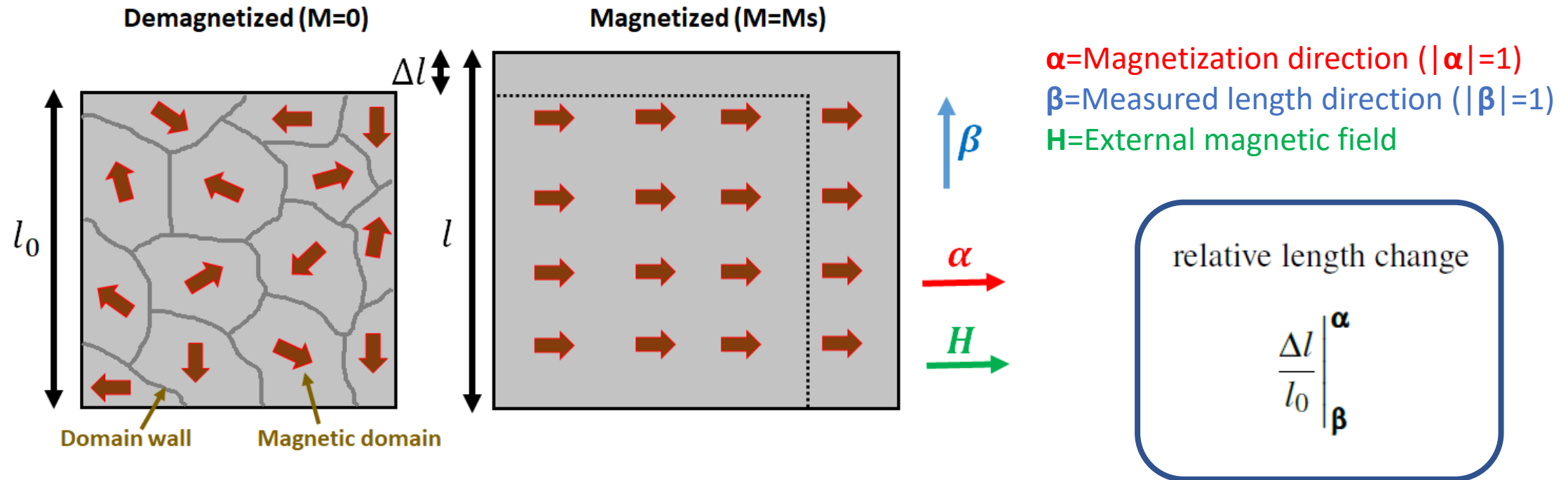


Figure 1: Magnetostriction of a single crystal under an external magnetic field ($\alpha \parallel H$) perpendicular to the measured length direction ($\beta \perp H$). Symbols M and M_s stand for macroscopic magnetization and saturation magnetization, respectively. Dash line on the right represents the original size of the demagnetized material. The magnetostriction effect has been magnified in order to help to visualize it easily, in real materials it is smaller ($\Delta l/l_0 \sim 10^{-3} - 10^{-6}$).

WHAT IS MAELAS CODE?

- MAELAS code is a software to calculate spin-dependent magnetostriction coefficients and magnetoelastic constants up to second order.
- It generates required input files for VASP code to perform Density Functional Theory calculations, and it deduces the value of magnetostriction coefficients from the calculated energies given by VASP.
- If the elastic tensor is provided, then it can also calculate the magnetoelastic constants.
- MAELAS can also be used with other DFT codes instead of VASP, after file conversion to VASP format files.

INSTALLATION

MAELAS code is just one python3 file "maelas.py", so it only requires to have Python3 and imported python libraries. For example, in Ubuntu Linux machine you can check the installed version of python3 by opening a terminal and typing

```
python3 --version
```

In case you need to install it in your machine, you can type

```
sudo apt-get update  
sudo apt-get install python3.8
```

In HPC facilities you may need to load the Python3 module. For example, in Centos 7 Linux you can check all installed Python modules by typing

```
ml avail Python
```

and load the last version of Python3 using command ml

```
ml Python/3.8.2-GCC-8.3.0-2.32-base
```

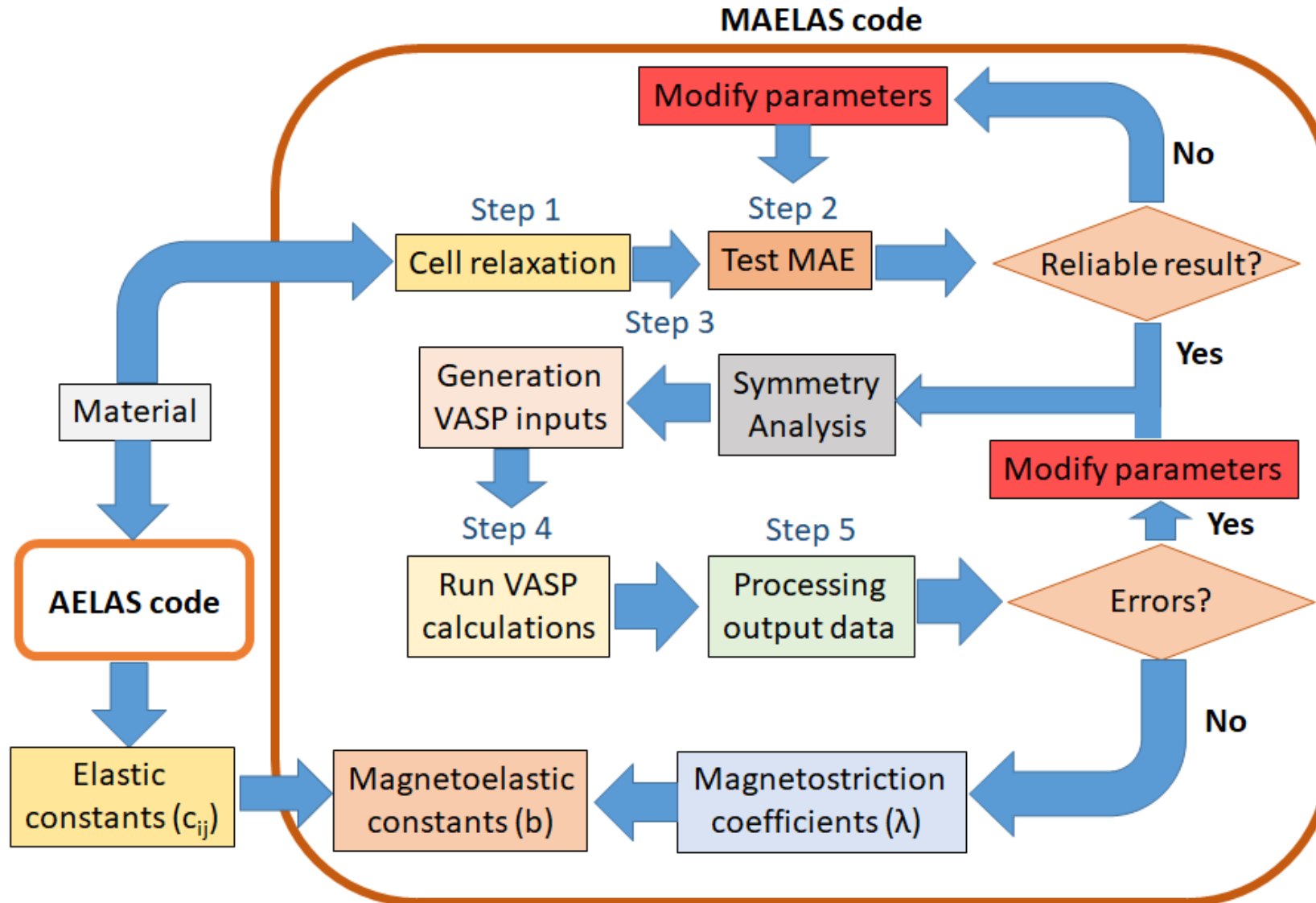
Additionally, MAELAS makes use of the following python libraries: pymatgen, scikit-learn, pyfiglet, argparse, numpy, matplotlib, scipy, math, os and stat. In case you need to install them, you can do it using pip3 as:

```
pip3 install library_name
```

where “library_name” is the name of the python library that you need to install. For example, you should type the following command to install numpy library:

```
pip3 install numpy
```

HOW TO USE MAELAS CODE



HOW TO USE MAELAS CODE

Step 1: Cell relaxation

If your initial POSCAR is not relaxed and you want to perform a cell relaxation before calculating the magentostriction coefficients, then you can use MAELAS code to generate INCAR and KPOINTS files to relax the structure with VASP. To do so, in the terminal you should copy your initial POSCAR and maelas.py files in the same folder where you want to generate the input files for VASP, and after going to this folder then type

```
python3 maelas.py -r -i POSCAR0 -k 40
```

where tag -r indicates that you want to generate VASP files for cell relaxation, -i POSCAR0 is the input non-relaxed POSCAR file (you can name it whatever you want) and -k 40 is the length parameter that determines a regular mesh of k-points. It will generate 4 files: POSCAR, INCAR, KPOINTS and vasp_jsub_rlx. Here, one still needs to copy manually the POTCAR file in this folder in order to have all required files for VASP run. The generated file vasp_jsub_rlx is a script to submit jobs in HPC facilities, one can specify some settings in this script by adding more tags in the command line. For instance,

```
python3 maelas.py -r -i POSCAR0 -k 40 -t 48 -c 24 -q qprod -a OPEN-00-00 -f /scratch/example_rlx
```

where -t 48 indicates that the number of maximum CPU hours for the VASP calculation is 48 hours, -c 24 means that the number of cores for the VASP calculation is 24, -q qprod set to production queue the type of queue in HPC facilities, -a OPEN-00-00 is the project identification number for running jobs in HPC facilities and -f /scratch/example_rlx is the folder where you want to run VASP calculations. All these data are included in the vasp_jsub_rlx file, so one can submit this VASP job immediately in HPC facilities by typing

```
qsub vasp_jsub_rlx
```

This procedure might be helpful for high-throughput routines. More options can be added in vasp_jsub_rlx file through the terminal command line, to see them just type

```
python3 maelas.py -h
```

Note that generated INCAR and KPOINTS files contain standard setting for cell relaxation. The user are free to change this setting either directly on the generated files or in the maelas.py. In case your structure is already relaxed or you do not want to perform a cell relaxation, then you can skip this step and move to step 2.

HOW TO USE MAELAS CODE

Step 2: Test MAE

Copy the relaxed POSCAR, POTCAR and maelas.py files in the same folder where you want to generate the input files for VASP jobs. In the terminal, after going to this folder then type

```
python3 maelas.py -m -i POSCAR_rlx -k 70 -s1 1 0 0 -s2 0 0 1
```

where -m indicates that you want to generate input VASP files for the calculation of MAE, -i POSCAR_rlx is the initial relaxed POSCAR file (you can name it whatever you want), -k 70 is the length parameter that determines a regular mesh of k-points, -s1 1 0 0 is the first spin direction to calculate MAE: s_{1x} s_{1y} s_{1z} and -s2 0 0 1 is the second spin direction to calculate MAE: s_{2x} s_{2y} s_{2z} . It will generate the following files:

POSCAR_0_0 (it is the same POSCAR as)

INCAR_0_C (non-collinear calculation where C=1,2 is the spin orientation case)

INCAR_std (collinear calculation to generate the WAVECAR and CHGCAR files to run non-collinear calculations)

KPOINTS (file for the kpoint generation of VASP)

vasp_mae, vasp_mae_jsub and vasp_mae_0 (interconnected bash scripts to run VASP calculations automatically)

vasp_mae_cp_oszicar (bash script to get the calculated OSZICAR_0_0_C files after VASP calculation is finished)

The generated files vasp_mae, vasp_mae_jsub and vasp_mae_0 are interconnected scripts to submit jobs in HPC facilities. One needs only to execute the file vasp_mae in order to run all VASP jobs automatically. You can specify some job settings in these scripts by adding more tags in the command line. For instance,

```
python3 maelas.py -m -i POSCAR_rlx -k 70 -s1 1 0 0 -s2 0 0 1 -t 48 -c 24 -q qprod -a OPEN-00-00 -f /scratch/example_mag
```

where -t 48 indicates that the number of maximum CPU hours for the VASP calculation is 48 hours, -c 24 means that the number of cores for the VASP calculation is 24, -q qprod set to production queue the type of queue in HPC facilities, -a OPEN-00-00 is the project identification number for running jobs in HPC facilities and -f /scratch/example_mag is the folder where you want to run VASP calculations. This procedure might be helpful for high-throughput routines. More options can be added in these script files through the terminal command line, to see them just type

```
python3 maelas.py -h
```


HOW TO USE MAELAS CODE

Step 3: Generation of VASP files for the calculation of anisotropic magnetostriction coefficients

Copy the relaxed POSCAR, POTCAR and maelas.py files in the same folder where you want to generate the input files for VASP run. In the terminal, after going to this folder then type

```
python3 maelas.py -g -i POSCAR_rlx -k 70 -n 7 -s 0.1
```

where -g indicates that you want to generate input VASP files for the calculation of anisotropic magnetostriction coefficients, -i POSCAR_rlx is the initial relaxed POSCAR file (you can name it whatever you want), -k 70 is the length parameter that determines a regular mesh of k-points, -n 7 means that it will generate 7 distorted states for each magnetostriction mode and -s 0.1 is the maximum strain applied for distorting the structure. It will generate the following files:

POSCAR_A_B (volume-conserving distorted cell where A=magnetostriction mode, B=1,...,n distorted cell for each magnetostriction mode)

INCAR_A_C (non-collinear calculation where A=magnetostriction mode, C=1,2 is the spin orientation case)

INCAR_std (collinear calculation to generate the WAVECAR and CHGCAR files to run non-collinear calculations)

KPOINTSvasp_maelas, vasp_jsub and vasp_0 (interconnected bash scripts to run VASP calculations automatically)

vasp_cp_oszicar (bash script to get the calculated OSZICAR_A_B_C files after VASP calculation is finished)

The generated files vasp_maelas, vasp_jsub and vasp_0 are interconnected scripts to submit jobs in HPC facilities, one can specify some job settings in these scripts by adding more tags in the command line. For instance,

```
python3 maelas.py -g -i POSCAR_rlx -k 70 -n 7 -s 0.1 -t 48 -c 24 -q qprod -a OPEN-00-00 -f /scratch/example_mag
```

where -t 48 indicates that the number of maximum CPU hours for the VASP calculation is 48 hours, -c 24 means that the number of cores for the VASP calculation is 24, -q qprod set to production queue the type of queue in HPC facilities, -a OPEN-00-00 is the project identification number for running jobs in HPC facilities and -f /scratch/example_mag is the folder where you want to run VASP calculations. This procedure might be helpful for high-throughput routines. More options can be added in these script files through the terminal command line, to see them just type

```
python3 maelas.py -h
```

HOW TO USE MAELAS CODE

Step 4: Run VASP calculations

For each generated POSCAR_A_B one should run first a collinear calculation using INCAR_std and use the generated WAVECAR and CHGCAR files to run non-collinear calculations for each INCAR_A_C (C=1,2) using the same POSCAR_A_B. This procedure can be automatically done in HPC facilities just by running the generated bash script

```
./vasp_maelas
```

This will launch independent jobs for each POSCAR_A_B. Each job will run 3 VASP calculations: a collinear one to generate WAVECAR and CHGCAR files, and two non-collinear for INCAR_A_1 and INCAR_A_2. The jobs will be executed in subfolders P_A_B inside the folder indicated by tag -f in the step 2.

Once all jobs are finished, then one can easily get calculated non-collinear OSZICAR files (needed in step 4), by running the bash script

```
./vasp_cp_oszicar
```

it will copy these OSZICAR files and name them as OSZICAR_A_B_C (C=1,2) in the same folder where this script is executed.

HOW TO USE MAELAS CODE

Step 5: Derivation of anisotropic magnetostriction coefficients and magnetoelastic constants

Finally, to derive the anisotropic magnetostriction coefficients one needs to have in the same folder the following files:

maelas.py

POSCAR_rlx (the relaxed POSCAR file used as input in step 2)

POSCAR_A_B (distorted POSCAR generated in step 2)

OSZICAR_A_B_C (non-collinear OSZICAR files calculated in step 3 for each POSCAR_A_B and INCAR_A_C)

Next, in the terminal go to this folder and type

```
python3 maelas.py -d -i POSCAR_rlx -n 7
```

where -d indicates that you want to derive the spin-dependent magnetostriction coefficients from the calculated OSZICAR files, -i POSCAR_rlx is the relaxed POSCAR file used as input in step 2 (you can name it whatever you want) and -n 7 is the number of distorted states for each magnetostriction mode used in step 2.

It will derive and print the calculated anisotropic magnetostriction coefficients in the terminal. If you want to print it in a file (for example, "results.out"), then you can type

```
python3 maelas.py -d -i POSCAR_rlx -n 7 > results.out
```

Additionally, the energy values extracted from OSZICAR_A_B_C files are shown in generated files ene_A_C.dat and fit_ene_A_C.png. The energy difference between the two spin configurations for each magnetostriction mode are shown in Fig. dE_A.png. If the elastic tensor is provided as input, then MAELAS can also calculate the magnetoelastic constants. To do so, one needs to add tags -b and -e with the name of the file containing the elastic tensor with the same format and units (GPa) as it is written by AELAS code (file ELADAT). Hence, you could type

```
python3 maelas.py -d -i POSCAR_rlx -n 7 -b -e ELADAT
```

where ELADAT is the name of the file (it could be whatever name you want) with the elastic tensor data.

Format of the
elastic tensor file

Elastic tensor:

262.03	186.20	186.20	0.00	0.00	0.00
186.20	262.03	186.20	0.00	0.00	0.00
186.20	186.20	262.03	0.00	0.00	0.00
0.00	0.00	0.00	116.63	0.00	0.00
0.00	0.00	0.00	0.00	116.63	0.00
0.00	0.00	0.00	0.00	0.00	116.63

HOW TO USE MAELAS CODE

Full list of arguments in MAELAS code

User can see all possible optional arguments by typing

```
python3 maelas.py -h
```

The optional arguments are the following:

- h, --help Show this help message and exit
- i POS Name of the initial non-distorted POSCAR file (default: POSCAR)
- n NDIST Number of distorted states for each magnetostriction mode (default: 7)
- s STRAIN Maximum value of the parameter epsilon for the strain tensor to generate the distorted POSCAR files (default: 0.01)
- k KP VASP automatic k-point mesh generation to create the KPOINTS file (default: 60)
- g Generation of required VASP files for the calculation of magnetostriction coefficients.
- d Derivation of magnetostriction coefficients from the energy written in the OSZICAR files.
- r Generation of required VASP files for the cell relaxation
- m Generation of required VASP files to test MAE
- s1 s1x s1y s1z First spin direction to calculate MAE
- s2 s2x s2y s2z Second spin direction to calculate MAE
- b Calculation of the magnetoelastic constants from the calculated magnetostriction coefficients and provided elastic tensor.
- e ELAS File with the elastic tensor data in the same format and units (GPa) as it is written by ELAS code (file ELADAT).
- sp SYMPRE Tolerance for symmetry finding (default: 0.01)
- sa SYMANG Angle tolerance for symmetry finding (default: 5.0)
- c CORE Number of cores for the VASP calculation (default: 24)
- t TIME Number of maximum CPU hours for the VASP calculation (default: 48)
- f VASP_FOLD Folder where you will run VASP calculations (default: /scratch)
- mp MPI Command for mpi run of VASP (default: mpiexec.hydra)
- a P_ID Project id for running jobs in HPC facilities (default: OPEN-X-X)
- l LOAD_MODULE Module of VASP that should be loaded (default: VASP/5.4.4-intel-2017c-mkl=cluster)
- q QUEUE Type of queue to be used for VASP calculations in HPC facilities (default: qprod)

HOW TO USE MAELAS CODE

Summary: In a nutshell

Step 1: Cell relaxation

```
python3 maelas.py -r -i POSCAR0 -k 40
```

```
qsub vasp_jsub_rlx
```

Step 2: Test MAE

```
python3 maelas.py -m -i POSCAR_rlx -k 70 -s1 1 0 0 -s2 0 0 1
```

```
./vasp_mae
```

```
./vasp_mae_cp_oszicar
```

Step 3: Generate VASP inputs for calculation of magnetostriction coefficients

```
python3 maelas.py -g -i POSCAR_rlx -k 70 -n 7 -s 0.1
```

Step 4: Run VASP calculations

```
./vasp_maelas
```

```
./vasp_cp_oszicar
```

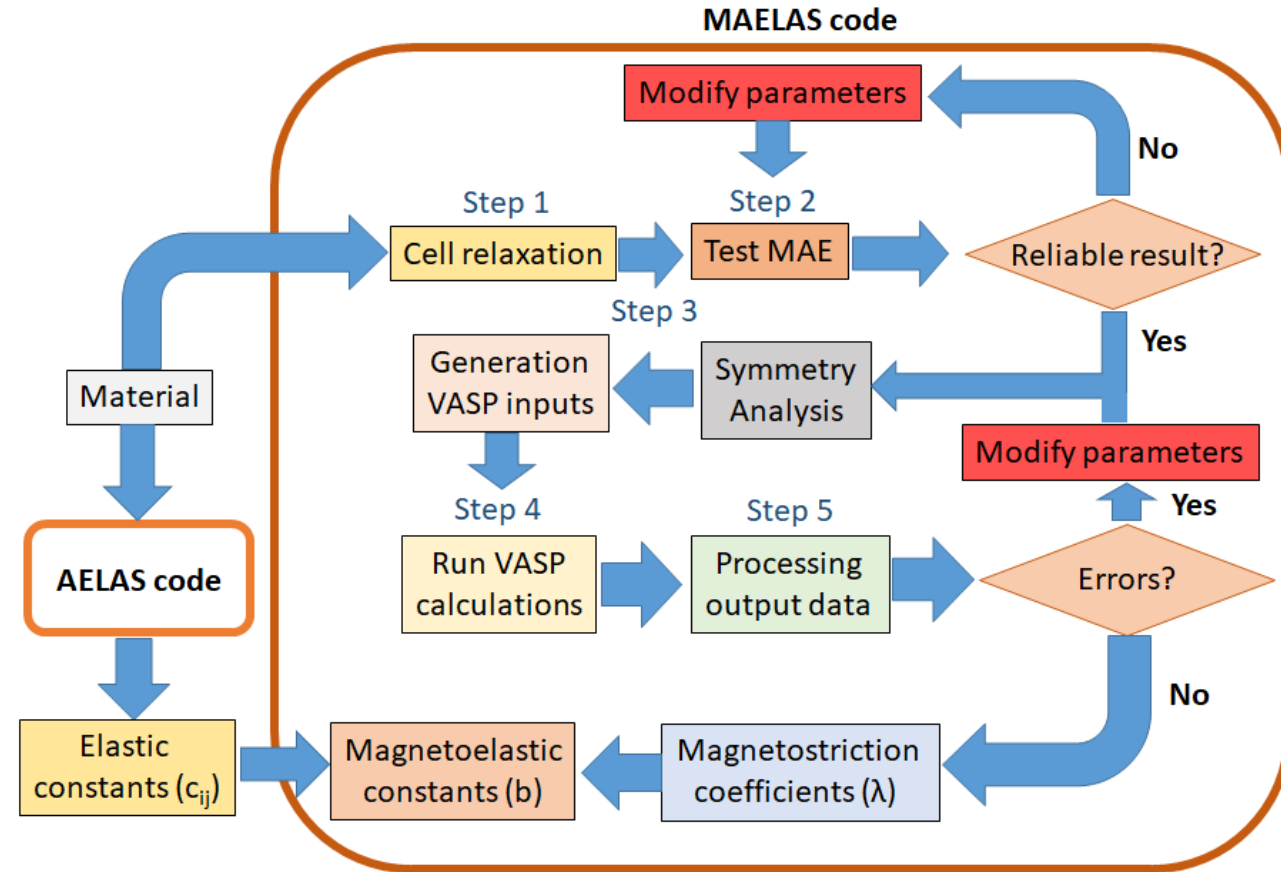
Step 5: Derivation of anisotropic magnetostriction coefficients

```
python3 maelas.py -d -i POSCAR_rlx -n 7
```

Step 5: Derivation of anisotropic magnetostriction coefficients and magnetoelastic constants

```
python3 maelas.py -d -i POSCAR_rlx -n 7 -b -e ELADAT
```

See all optional arguments: `python3 maelas.py -h`



HOW TO USE MAELAS CODE

Using MAELAS with other DFT codes instead of VASP

MAELAS has been designed to read and write files for VASP code automatically. However, it is possible to use MAELAS with other DFT codes instead of VASP, after file conversion to VASP format files. Although, this process might require some extra work for the user. Namely, converting initial and distorted POSCAR files into the other DFT code format, reading the spin direction of each state from INCAR_A_C files (variable SAXIS) and write the calculated energies in a OSZICAR-like file (called OSZICAR_A_B_C) on the penultimate line and third column with same format as in VASP (this is the place where MAELAS reads the energy value of each OSZICAR_A_B_C file). For instance, in the following OSZICAR file, one should write the energy value at "***Energy_DFT_code**":

	N	E	dE	d eps	ncg	rms	rms (c)
DAV:	1	-0.219086777516E+02	-0.21909E+02	0.99185E+02	*****	0.709E+00	
DAV:	2	-0.219092777733E+02	-0.60002E-03	-0.60002E-03	*****	0.452E-01	
DAV:	3	-0.219092846144E+02	-0.68411E-05	-0.68405E-05	*****	0.485E-02	
DAV:	4	-0.219092847670E+02	-0.15258E-06	-0.15274E-06	*****	0.641E-03	
DAV:	5	-0.219092847725E+02	-0.55161E-08	-0.52995E-08	*****	0.117E-03	
DAV:	6	***Energy_DFT_code**	-0.19827E-09	-0.11530E-09	868760	0.143E-04	
1 F=	-0.21909285E+02	E0= -0.21909330E+02	d E =	0.135168E-03	mag=	0.0000	0.0000 2.5077

HOW TO USE MAELAS CODE

Crystal systems supported by MAELAS v1.0

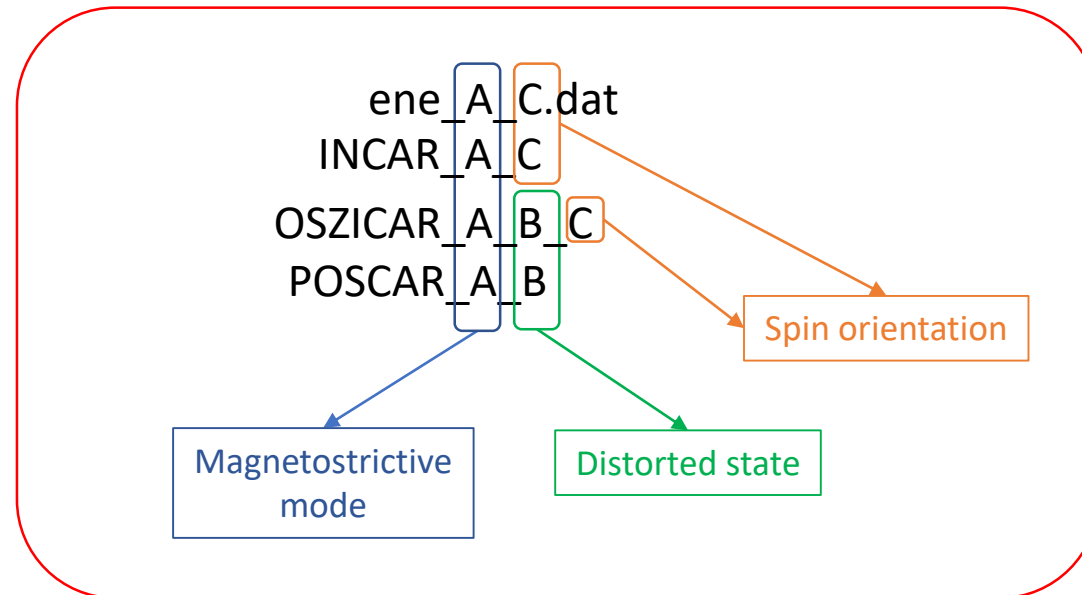
Table 1: Number of independent second-order elastic constants of each crystal system. Number of independent magnetoelastic and magnetostriction coefficients up to second-order of the direction cosine polynomial in the first-order magnetoelastic energy. In the last column we specify which crystal systems are supported by the current version of MAELAS.

Crystal system	Point groups	Space groups	Elastic constants (c_{ij})	Magnetoelastic constants (b)	Magnetostriction coefficients (λ)	MAELAS
Triclinic	$1, \bar{1}$	1 – 2	21	36	36	No
Monoclinic	$2, m, 2/m$	3 – 15	13	20	20	No
Orthorhombic	$222, 2mm, mmm$	16 – 74	9	12	12	Yes
Tetragonal (II)	$4, \bar{4}, 4/m$	75 – 88	7	10	10	No
Tetragonal (I)	$4mm, 422, \bar{4}2m, 4/mmm$	89 – 142	6	7	7	Yes
Trigonal (II)	$3, \bar{3}$	143 – 148	7	12	12	No
Trigonal (I)	$32, 3m, \bar{3}m$	149 – 167	6	8	8	Yes
Hexagonal(II)	$6, \bar{6}, 6/m$	168 – 176	5	8	8	No
Hexagonal (I)	$6mm, 622, \bar{6}2m, 6/mmm$	177 – 194	5	6	6	Yes
Cubic (II)	$23, m\bar{3}$	195 – 206	3	4	4	No
Cubic (I)	$432, \bar{4}3m, m\bar{3}m$	207 – 230	3	3	3	Yes

The crystal systems not supported by MAELAS might be included in the new versions of the code

HOW TO USE MAELAS CODE

MAELAS file notation



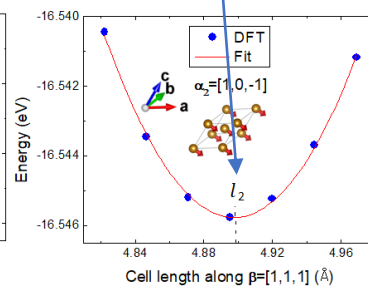
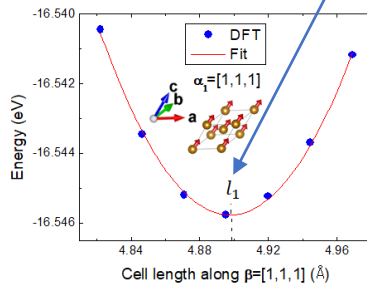
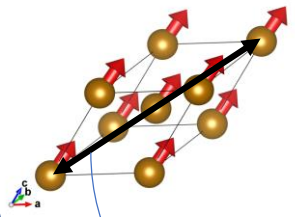
Methodology

$$\frac{\Delta l}{l_0} \bigg|_{\beta^i}^{\alpha_1^i} - \frac{\Delta l}{l_0} \bigg|_{\beta^i}^{\alpha_2^i} = \eta^i \lambda^i$$

$$\begin{aligned} \frac{\Delta l}{l_0} \bigg|_{\beta^i}^{\alpha_1^i} - \frac{\Delta l}{l_0} \bigg|_{\beta^i}^{\alpha_2^i} &= \frac{l_1 - l_0}{l_0} - \frac{l_2 - l_0}{l_0} = \frac{2(l_1 - l_2)}{(l_1 + l_2) \left[1 - \frac{l_1 + l_2 - 2l_0}{l_1 + l_2} \right]} \\ &= \frac{2(l_1 - l_2)}{l_1 + l_2} \left[1 + \frac{l_1 + l_2 - 2l_0}{l_1 + l_2} + \dots \right] \approx \frac{2(l_1 - l_2)}{l_1 + l_2} \end{aligned}$$

Fitting to a quadratic function
 $f(l) = Al^2 + Bl + C$

Minimum: $l_{1(2)} = -B_{1(2)}/(2A_{1(2)})$



Cell length along $\beta=[1,1,1]$

Crystal system	Eq.	Magnetostriction coefficient	β	α_1	α_2	η
Cubic (I)	10	λ_{001}	(0,0,1)	(0,0,1)	(1,0,0)	$\frac{3}{2}$
		λ_{111}	$\left(\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}\right)$	$\left(\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}\right)$	$\left(\frac{1}{\sqrt{2}}, 0, \frac{-1}{\sqrt{2}}\right)$	$\frac{3}{2}$
Hexagonal (I)	16	$\lambda^{\alpha 1,2}$	(1,0,0)	$\left(\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}\right)$	$\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0\right)$	$\frac{1}{3}$
		$\lambda^{\alpha 2,2}$	(0,0,1)	(0,0,1)	(1,0,0)	1
		$\lambda^{\gamma,2}$	(1,0,0)	(1,0,0)	(0,1,0)	1
		$\lambda^{\epsilon,2}$	$\left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)$	$\left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)$	$\left(\frac{-1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)$	1
Trigonal (I)	20	$\lambda^{\alpha 1,2}$	(1,0,0)	(0,0,1)	$\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0\right)$	1
		$\lambda^{\alpha 2,2}$	(0,0,1)	(0,0,1)	(1,0,0)	1
		$\lambda^{\gamma,1}$	(1,0,0)	(1,0,0)	(0,1,0)	1
		$\lambda^{\gamma,2}$	$\left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)$	$\left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)$	$\left(\frac{1}{\sqrt{2}}, 0, \frac{-1}{\sqrt{2}}\right)$	$\frac{1}{2}$
		λ_{12}	$\left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)$	$\left(0, \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\right)$	$\left(0, \frac{1}{\sqrt{2}}, \frac{-1}{\sqrt{2}}\right)$	$\frac{1}{4}$
		λ_{21}	$\left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)$	$\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0\right)$	$\left(\frac{1}{\sqrt{2}}, \frac{-1}{\sqrt{2}}, 0\right)$	$\frac{1}{2}$
Tetragonal (I)	24	$\lambda^{\alpha 1,2}$	(1,0,0)	$\left(\frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}, \frac{1}{\sqrt{3}}\right)$	$\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0\right)$	$\frac{1}{3}$
		$\lambda^{\alpha 2,2}$	(0,0,1)	(0,0,1)	(1,0,0)	1
		$\lambda^{\gamma,2}$	(1,0,0)	(1,0,0)	(0,1,0)	1
		$\lambda^{\epsilon,2}$	$\left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)$	$\left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)$	$\left(\frac{-1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)$	1
		$\lambda^{\delta,2}$	$\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0\right)$	$\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0\right)$	$\left(\frac{-1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0\right)$	1
Orthorhombic	27	λ_1	(1,0,0)	(1,0,0)	(0,0,1)	1
		λ_2	(1,0,0)	(0,1,0)	(0,0,1)	1
		λ_3	(0,1,0)	(1,0,0)	(0,0,1)	1
		λ_4	(0,1,0)	(0,1,0)	(0,0,1)	1
		λ_5	(0,0,1)	(1,0,0)	(0,0,1)	1
		λ_6	(0,0,1)	(0,1,0)	(0,0,1)	1
		λ_7	$\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0\right)$	$\left(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0\right)$	(0,0,1)	1
		λ_8	$\left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)$	$\left(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}}\right)$	(0,0,1)	1
		λ_9	$\left(0, \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\right)$	$\left(0, \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}\right)$	(0,0,1)	1

Workflow

CUBIC (I)

SG 207-230

Cubic (I)

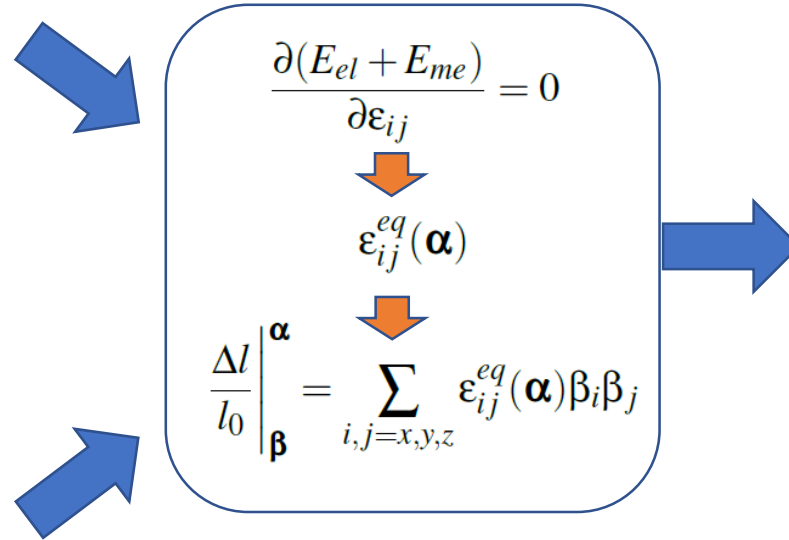
Workflow

Elastic energy

$$E_{el}^{cub} = \frac{c_{11}}{2}(\epsilon_{xx}^2 + \epsilon_{yy}^2 + \epsilon_{zz}^2) + c_{12}(\epsilon_{xx}\epsilon_{yy} + \epsilon_{xx}\epsilon_{zz} + \epsilon_{yy}\epsilon_{zz}) + \frac{c_{44}}{2}(\epsilon_{xy}^2 + \epsilon_{yz}^2 + \epsilon_{xz}^2)$$

Magnetoelastic energy

$$E_{me}^{cub(I)} = b_0(\epsilon_{xx} + \epsilon_{yy} + \epsilon_{zz}) + b_1(\alpha_x^2\epsilon_{xx} + \alpha_y^2\epsilon_{yy} + \alpha_z^2\epsilon_{zz}) + b_2(\alpha_x\alpha_y\epsilon_{xy} + \alpha_x\alpha_z\epsilon_{xz} + \alpha_y\alpha_z\epsilon_{yz})$$



$$\frac{\Delta l}{l_0} \Big|_{\beta}^{\alpha} = \lambda^{\alpha} + \frac{3}{2}\lambda_{001} \left(\alpha_x^2\beta_x^2 + \alpha_y^2\beta_y^2 + \alpha_z^2\beta_z^2 - \frac{1}{3} \right) + 3\lambda_{111}(\alpha_x\alpha_y\beta_x\beta_y + \alpha_y\alpha_z\beta_y\beta_z + \alpha_x\alpha_z\beta_x\beta_z)$$

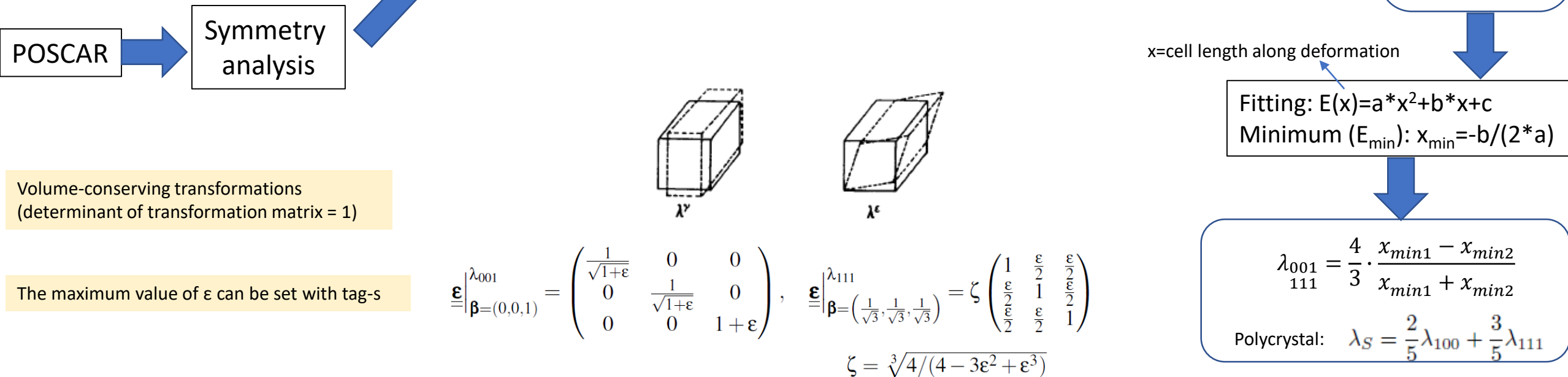
$$\lambda^{\alpha} = \frac{-b_0 - \frac{1}{3}b_1}{c_{11} + 2c_{12}},$$

$$\lambda_{001} = \frac{-2b_1}{3(c_{11} - c_{12})},$$

$$\lambda_{111} = \frac{-b_2}{3c_{44}}.$$

Workflow

$$\left. \frac{\Delta l}{l_0} \right|_{\beta}^{\alpha} = \lambda^{\alpha} + \frac{3}{2} \lambda_{001} \left(\alpha_x^2 \beta_x^2 + \alpha_y^2 \beta_y^2 + \alpha_z^2 \beta_z^2 - \frac{1}{3} \right) + 3 \lambda_{111} (\alpha_x \alpha_y \beta_x \beta_y + \alpha_y \alpha_z \beta_y \beta_z + \alpha_x \alpha_z \beta_x \beta_z)$$



Workflow

HEXAGONAL (I)

SG 177-194

Hexagonal (I)

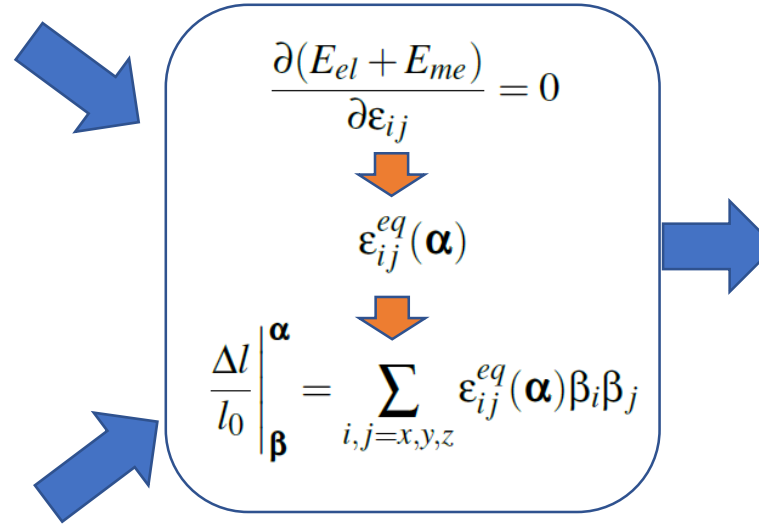
Workflow

Elastic energy

$$E_{el}^{hex} = \frac{1}{2}c_{11}(\epsilon_{xx}^2 + \epsilon_{yy}^2) + c_{12}\epsilon_{xx}\epsilon_{yy} + c_{13}(\epsilon_{xx} + \epsilon_{yy})\epsilon_{zz} + \frac{1}{2}c_{33}\epsilon_{zz}^2 \\ + \frac{1}{2}c_{44}(\epsilon_{yz}^2 + \epsilon_{xz}^2) + \frac{1}{4}(c_{11} - c_{12})\epsilon_{xy}^2.$$

Magnetoelastic energy

$$E_{me}^{hex(I)} = b_{11}(\epsilon_{xx} + \epsilon_{yy}) + b_{12}\epsilon_{zz} + b_{21}\left(\alpha_z^2 - \frac{1}{3}\right)(\epsilon_{xx} + \epsilon_{yy}) + b_{22}\left(\alpha_z^2 - \frac{1}{3}\right)\epsilon_{zz} \\ + \frac{1}{2}b_3[(\alpha_x^2 - \alpha_y^2)(\epsilon_{xx} - \epsilon_{yy}) + 2\alpha_x\alpha_y\epsilon_{xy}] + b_4(\alpha_x\alpha_z\epsilon_{xz} + \alpha_y\alpha_z\epsilon_{yz}).$$

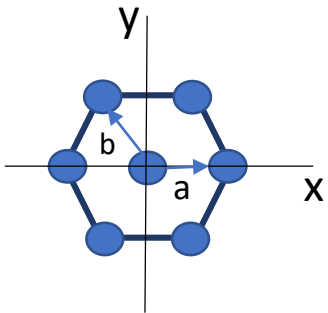
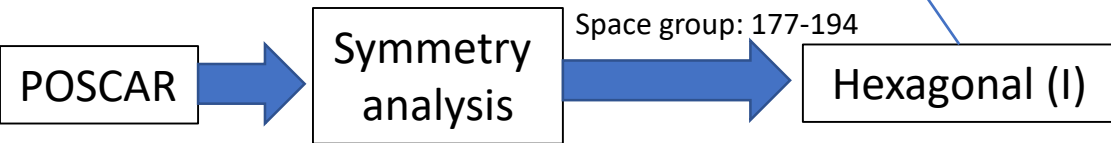
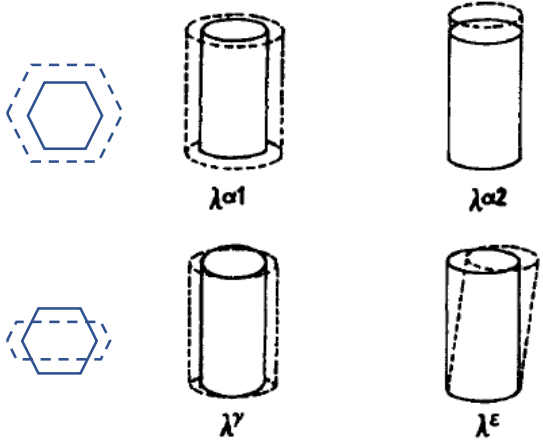


$$\frac{\Delta l}{l_0} \Big|_{\beta}^{\alpha} = \lambda^{\alpha 1,0}(\beta_x^2 + \beta_y^2) + \lambda^{\alpha 2,0}\beta_z^2 + \lambda^{\alpha 1,2}\left(\alpha_z^2 - \frac{1}{3}\right)(\beta_x^2 + \beta_y^2) \\ + \lambda^{\alpha 2,2}\left(\alpha_z^2 - \frac{1}{3}\right)\beta_z^2 + \lambda^{\gamma,2}\left[\frac{1}{2}(\alpha_x^2 - \alpha_y^2)(\beta_x^2 - \beta_y^2) + 2\alpha_x\alpha_y\beta_x\beta_y\right] \\ + 2\lambda^{\epsilon,2}(\alpha_x\alpha_z\beta_x\beta_z + \alpha_y\alpha_z\beta_y\beta_z),$$

$$\lambda^{\alpha 1,0} = \frac{b_{11}c_{33} + b_{12}c_{13}}{c_{33}(c_{11} + c_{12}) - 2c_{13}^2}, \\ \lambda^{\alpha 2,0} = \frac{2b_{11}c_{33} - b_{12}(c_{11} + c_{22})}{c_{33}(c_{11} + c_{12}) - 2c_{13}^2}, \\ \lambda^{\alpha 1,2} = \frac{-b_{21}c_{33} + b_{22}c_{13}}{c_{33}(c_{11} + c_{12}) - 2c_{13}^2}, \\ \lambda^{\alpha 2,2} = \frac{2b_{21}c_{33} - b_{22}(c_{11} + c_{22})}{c_{33}(c_{11} + c_{12}) - 2c_{13}^2}, \\ \lambda^{\gamma,2} = \frac{-b_3}{c_{11} - c_{12}}, \\ \lambda^{\epsilon,2} = \frac{-b_4}{2c_{44}}.$$

Workflow

$$\left. \frac{\Delta I}{I_0} \right|_{\beta}^{\alpha} = \lambda^{\alpha 1,0} (\beta_x^2 + \beta_y^2) + \lambda^{\alpha 2,0} \beta_z^2 + \lambda^{\alpha 1,2} \left(\alpha_z^2 - \frac{1}{3} \right) (\beta_x^2 + \beta_y^2) \\ + \lambda^{\alpha 2,2} \left(\alpha_z^2 - \frac{1}{3} \right) \beta_z^2 + \lambda^{\gamma,2} \left[\frac{1}{2} (\alpha_x^2 - \alpha_y^2) (\beta_x^2 - \beta_y^2) + 2\alpha_x \alpha_y \beta_x \beta_y \right] \\ + 2\lambda^{\varepsilon,2} (\alpha_x \alpha_z \beta_x \beta_z + \alpha_y \alpha_z \beta_y \beta_z),$$



$\lambda^{\alpha 1,2}$

POS_1_X (N POSCAR: Distortion along [1,0,0])
 INCAR_std (1 INCAR: collinear w/o SOC)
 INCAR_1_1 (1 INCAR: non-collinear with SOC, SPIN=[1,1,1])
 INCAR_1_2 (1 INCAR: non-collinear with SOC, SPIN=[1,1,0])

OSZICAR_1_X_1
 OSZICAR_1_X_2

$\lambda^{\alpha 2,2}$

POS_2_X (N POSCAR: Distortion along [0,0,1])
 INCAR_std (1 INCAR: collinear w/o SOC)
 INCAR_2_1 (1 INCAR: non-collinear with SOC, SPIN=[0,0,1])
 INCAR_2_2 (1 INCAR: non-collinear with SOC, SPIN=[1,0,0])

OSZICAR_2_X_1
 OSZICAR_2_X_2

$\lambda^{\gamma,2}$

POS_3_X (N POSCAR: Distortion along [1,0,0])
 INCAR_std (1 INCAR: collinear w/o SOC)
 INCAR_3_1 (1 INCAR: non-collinear with SOC, SPIN=[1,0,0])
 INCAR_3_2 (1 INCAR: non-collinear with SOC, SPIN=[0,1,0])

OSZICAR_3_X_1
 OSZICAR_3_X_2

$\lambda^{\varepsilon,2}$

POS_4_X (N x POSCAR: Distortion along [1,0,1])
 INCAR_std (1 INCAR: collinear w/o SOC)
 INCAR_4_1 (1 INCAR: non-collinear with SOC, SPIN=[1,0,1])
 INCAR_4_2 (1 INCAR: non-collinear with SOC, SPIN=[-1,0,1])

OSZICAR_4_X_1
 OSZICAR_4_X_2

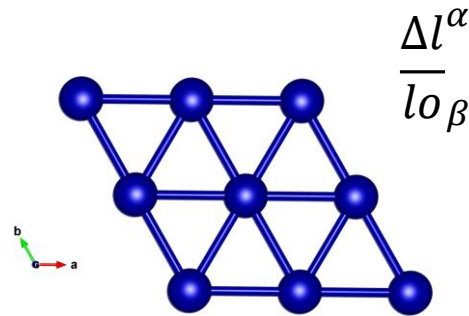
x=cell length along deformation

$$\lambda^{\alpha 1,2} = 6 \cdot \frac{x_{min1} - x_{min2}}{x_{min1} + x_{min2}} \quad \lambda^{\alpha 2,2} = 2 \frac{x_{min1} - x_{min2}}{x_{min1} + x_{min2}} \quad \lambda^{\gamma,2} = 2 \frac{x_{min1} - x_{min2}}{x_{min1} + x_{min2}} \quad \lambda^{\varepsilon,2} = 2 \frac{x_{min1} - x_{min2}}{x_{min1} + x_{min2}}$$

Fitting: $E(x) = a \cdot x^2 + b \cdot x + c$
 Minimum (E_{min}): $x_{min} = -b/(2 \cdot a)$

Hexagonal (I)

Distorted states

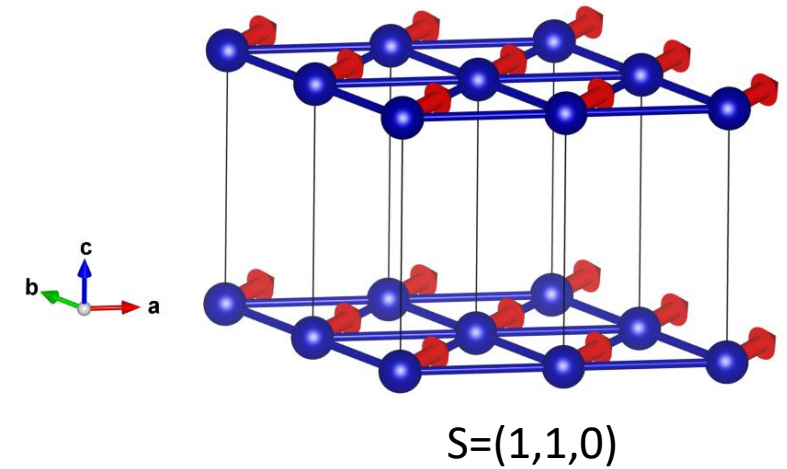
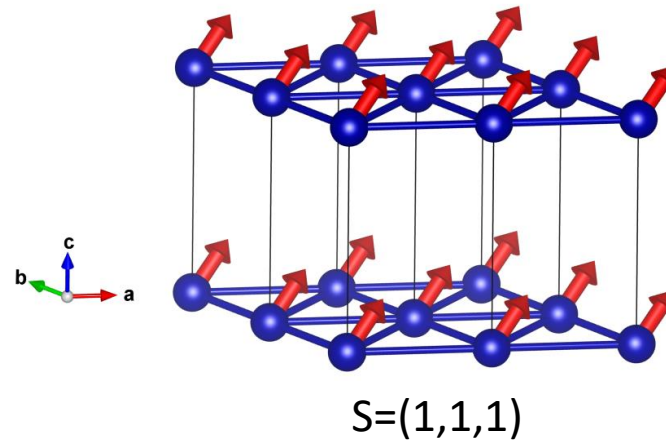
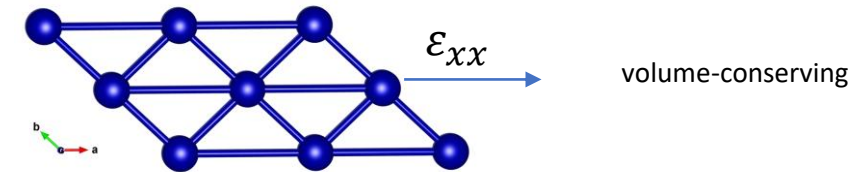


$$|\alpha| = 1, |\beta| = 1$$

strain along x-axis: $\beta = (1,0,0)$

$$\epsilon \Big|_{\beta=(1,0,0)}^{\lambda^{\alpha 1,2}} = \begin{pmatrix} 1+\epsilon & 0 & 0 \\ 0 & \frac{1}{\sqrt{1+\epsilon}} & 0 \\ 0 & 0 & \frac{1}{\sqrt{1+\epsilon}} \end{pmatrix}$$

$$\lambda^{\alpha 1,2}$$

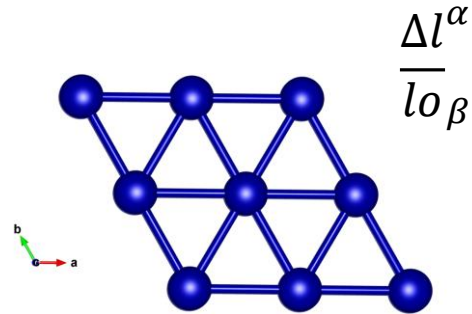


$$A = \begin{pmatrix} a1 & 0 & 0 \\ b1 & b2 & 0 \\ 0 & 0 & c3 \end{pmatrix}$$

$$\lambda^{\alpha 1,2} = 6 \cdot \frac{x_{min1} - x_{min2}}{x_{min1} + x_{min2}}$$

Hexagonal (I)

Distorted states



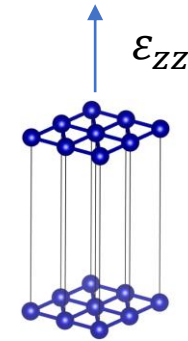
$$\frac{\Delta l^\alpha}{l o_\beta}$$

$$|\alpha| = 1, |\beta| = 1$$

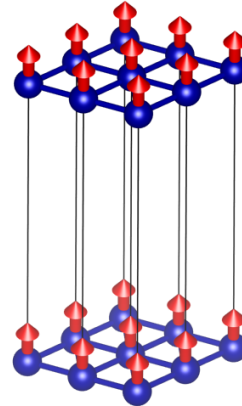
strain along z-axis: $\beta = (0,0,1)$

$$\epsilon \Big|_{\beta=(0,0,1)}^{\lambda^{\alpha 2,2}} = \begin{pmatrix} \frac{1}{\sqrt{1+\epsilon}} & 0 & 0 \\ 0 & \frac{1}{\sqrt{1+\epsilon}} & 0 \\ 0 & 0 & 1+\epsilon \end{pmatrix}$$

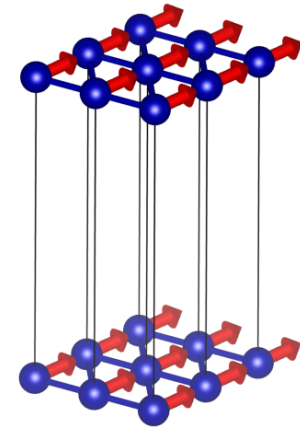
$$\lambda^{\alpha 2,2}$$



volume-conserving



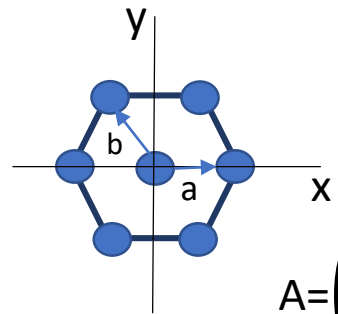
$$S=(0,0,1)$$



$$S=(1,0,0)$$

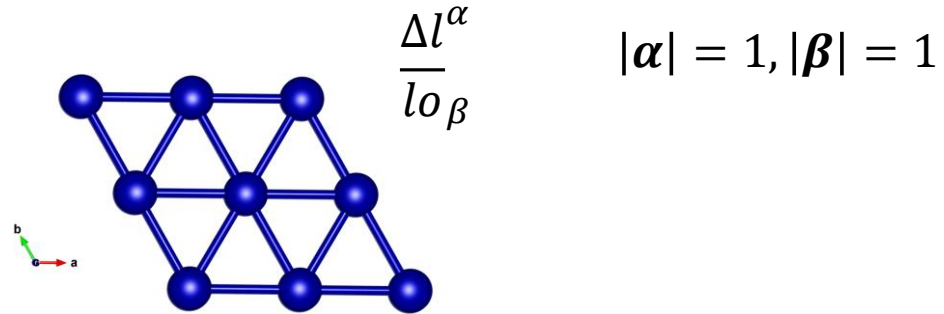
$$A = \begin{pmatrix} a1 & 0 & 0 \\ b1 & b2 & 0 \\ 0 & 0 & c3 \end{pmatrix}$$

$$\lambda^{\alpha 2,2} = 2 \frac{x_{min1} - x_{min2}}{x_{min1} + x_{min2}}$$



Hexagonal (I)

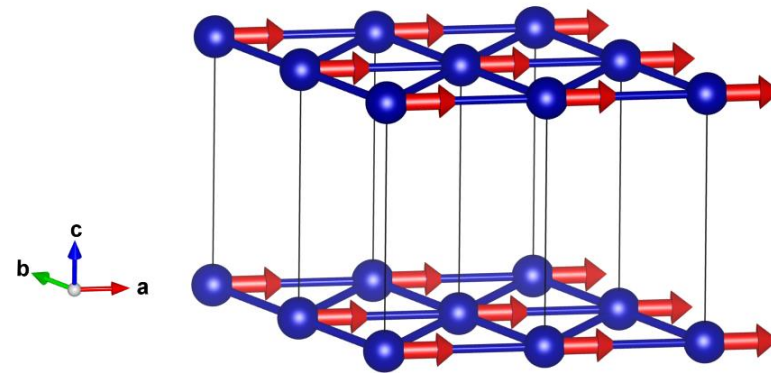
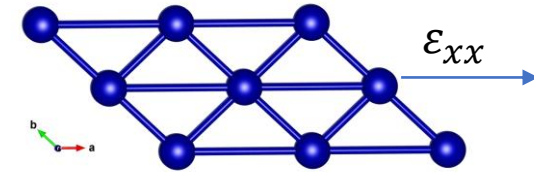
Distorted states



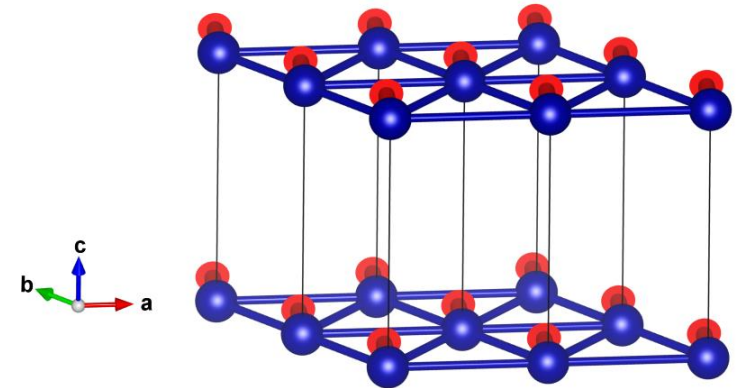
$$\epsilon_{\beta=(1,0,0)}^{\lambda^{r,2}} = \begin{pmatrix} 1+\epsilon & 0 & 0 \\ 0 & \frac{1}{\sqrt{1+\epsilon}} & 0 \\ 0 & 0 & \frac{1}{\sqrt{1+\epsilon}} \end{pmatrix}$$

volume-conserving

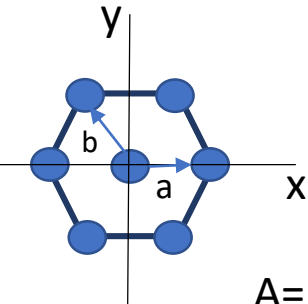
$\lambda^{r,2}$



$S=(1,0,0)$



$S=(0,1,0)$

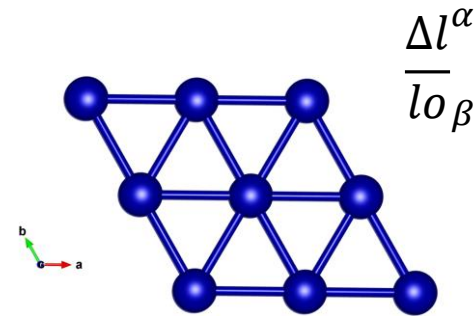


$$A = \begin{pmatrix} a1 & 0 & 0 \\ b1 & b2 & 0 \\ 0 & 0 & c3 \end{pmatrix}$$

$$\lambda^{r,2} = 2 \frac{x_{min1} - x_{min2}}{x_{min1} + x_{min2}}$$

Hexagonal (I)

Distorted states



$$|\alpha| = 1, |\beta| = 1$$

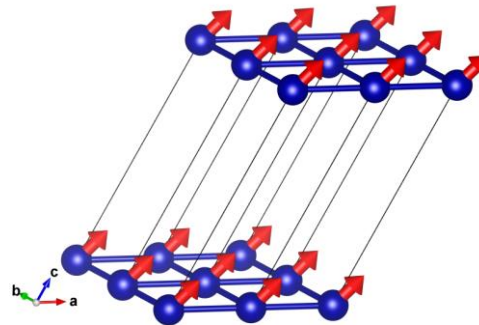
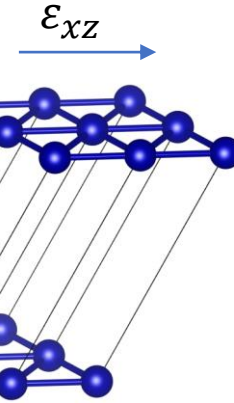
shear along xz: $\beta = (\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}})$

$$\lambda^{\varepsilon,2}$$

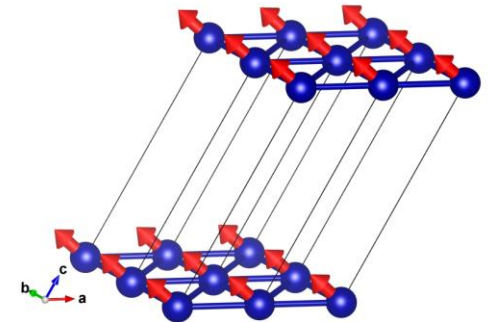
$$\varepsilon \Big|_{\beta = (\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}})}^{\lambda^{\varepsilon,2}} = \omega \begin{pmatrix} 1 & 0 & \frac{\varepsilon}{2} \\ 0 & 1 & 0 \\ \frac{\varepsilon}{2} & 0 & 1 \end{pmatrix}$$

$$\omega = \sqrt[3]{4/(4 - \varepsilon^2)}$$

volume-conserving



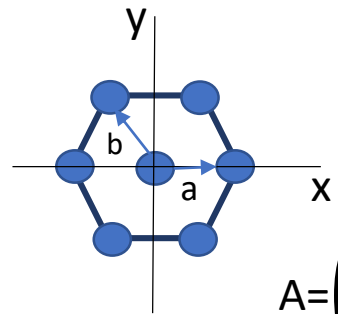
$$S = (1, 0, 1)$$



$$S = (-1, 0, 1)$$

$$A = \begin{pmatrix} a1 & 0 & 0 \\ b1 & b2 & 0 \\ 0 & 0 & c3 \end{pmatrix}$$

$$\lambda^{\varepsilon,2} = 2 \frac{x_{min1} - x_{min2}}{x_{min1} + x_{min2}}$$



Relation between different notations

Clark

Hexagonal system

PHYSICAL REVIEW
VOLUME 138, NUMBER 1A
5 APRIL 1965

PHYSICAL REVIEW
VOLUME 139, NUMBER 2A
19 JULY 1965

Callen

$$\lambda_{11}^{\alpha} = 2\lambda_1^{\alpha,0} + \lambda_2^{\alpha,0} + 2\lambda_1^{\alpha,2} + \lambda_2^{\alpha,2}$$

$$(\sqrt{3}/2)\lambda_{12}^{\alpha} = 2\lambda_1^{\alpha,2} + \lambda_2^{\alpha,2},$$

$$2\lambda_{21}^{\alpha} = -\lambda_1^{\alpha,0} + \lambda_2^{\alpha,0},$$

$$\sqrt{3}\lambda_{22}^{\alpha} = -\lambda_1^{\alpha,2} + \lambda_2^{\alpha,2}.$$

$$\lambda^{\epsilon} = \lambda^{\epsilon,2}$$

$$\lambda^{\gamma} = \lambda^{\gamma,2}$$

Gauge direction			Magnetization direction						Magnetostriiction coefficients		
β_x	β_y	β_z	Initial			Final			$\lambda(x,y)_0 - \lambda(x,y)_f$	Eq. (3)	Birss ^b
1	0	0	1	0	0	0	1	0	$\lambda(a,a) - \lambda(b,a)$	$\lambda^{\gamma,2}$	Q_8
0	0	1	0	0	1	1	0	0	$\lambda(c,c) - \lambda(a,c)$	$\lambda_2^{\alpha,2}$	$-Q_2 - Q_4$
1	0	0	1	0	0	0	0	1	$\lambda(a,a) - \lambda(c,a)$	$-\lambda_1^{\alpha,2} + \frac{1}{2}\lambda^{\gamma,2}$	$-Q_2$
$\sqrt{2}$		$\sqrt{2}$	$\sqrt{2}$		$\sqrt{2}$	$\sqrt{2}$		$\sqrt{2}$			
$\frac{1}{2}$	0	$\frac{1}{2}$	$\frac{1}{2}$	0	$\frac{1}{2}$	$\frac{1}{2}$	0	$\frac{1}{2}$	$\lambda(d,d) - \lambda(e,d)$	$\lambda^{\epsilon,2}$	$\frac{1}{2}Q_6$
2		2	2		2	2		2			

^a W. P. Mason, Phys. Rev. **96**, 302 (1954).
^b R. R. Birss, *Advances in Physics* (Francis & Taylor, Ltd., London, 1959), Vol. 8, p. 252.

MAELAS notation

The calculated magnetostriction coefficients are written in Clark, Mason, Birss and Callen notation in MAELAS code

Workflow

TRIGONAL (I)

SG 149-167

Trigonal (I)

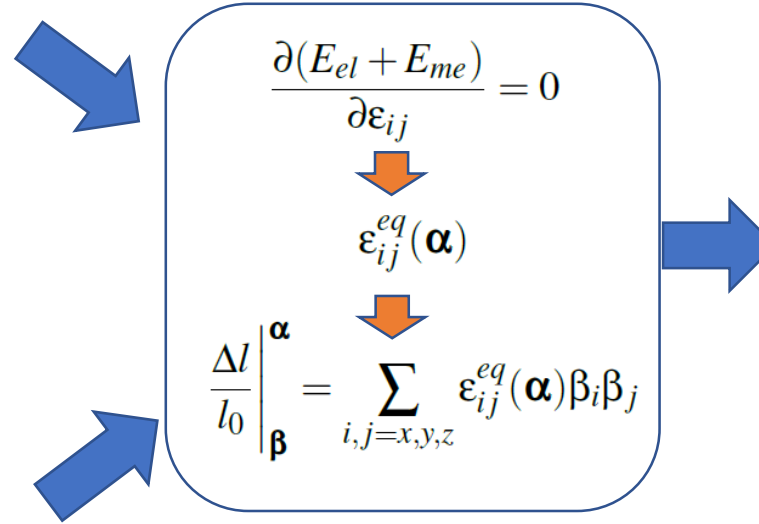
Workflow

Elastic energy

$$E_{el}^{trig(I)} = \frac{1}{2}c_{11}(\epsilon_{xx}^2 + \epsilon_{yy}^2) + c_{12}\epsilon_{xx}\epsilon_{yy} + c_{13}(\epsilon_{xx} + \epsilon_{yy})\epsilon_{zz} + \frac{1}{2}c_{33}\epsilon_{zz}^2 \\ + \frac{1}{2}c_{44}(\epsilon_{xz}^2 + \epsilon_{yz}^2) + \frac{1}{4}(c_{11} - c_{12})\epsilon_{xy}^2 + c_{14}(\epsilon_{xy}\epsilon_{xz} + \epsilon_{xx}\epsilon_{yz} - \epsilon_{yy}\epsilon_{yz})$$

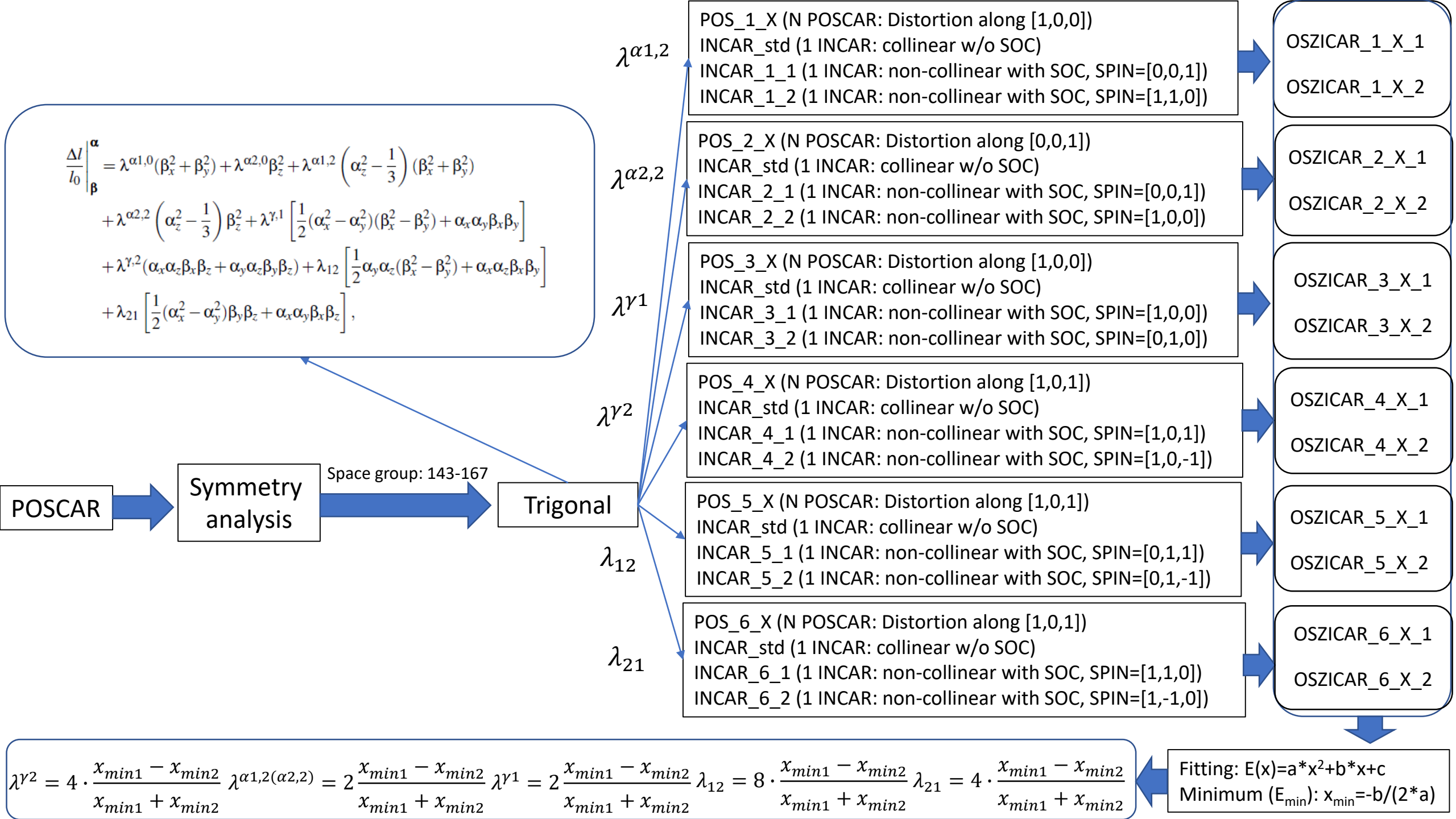
Magnetoelastic energy

$$E_{me}^{trig(I)} = b_{11}(\epsilon_{xx} + \epsilon_{yy}) + b_{12}\epsilon_{zz} + b_{21}\left(\alpha_z^2 - \frac{1}{3}\right)(\epsilon_{xx} + \epsilon_{yy}) + b_{22}\left(\alpha_z^2 - \frac{1}{3}\right)\epsilon_{zz} \\ + \frac{1}{2}b_3[(\alpha_x^2 - \alpha_y^2)(\epsilon_{xx} - \epsilon_{yy}) + 2\alpha_x\alpha_y] + b_4(\alpha_x\alpha_z\epsilon_{xz} + \alpha_y\alpha_z\epsilon_{yz}) \\ + b_{14}\left[\frac{1}{2}(\alpha_x^2 - \alpha_y^2)\epsilon_{yz} + \alpha_x\alpha_y\epsilon_{xz}\right] + b_{34}\left[\frac{1}{2}\alpha_y\alpha_z(\epsilon_{xx} - \epsilon_{yy}) + \alpha_x\alpha_z\epsilon_{xy}\right].$$



$$\frac{\Delta l}{l_0} \Big|_{\beta}^{\alpha} = \lambda^{\alpha 1,0}(\beta_x^2 + \beta_y^2) + \lambda^{\alpha 2,0}\beta_z^2 + \lambda^{\alpha 1,2}\left(\alpha_z^2 - \frac{1}{3}\right)(\beta_x^2 + \beta_y^2) \\ + \lambda^{\alpha 2,2}\left(\alpha_z^2 - \frac{1}{3}\right)\beta_z^2 + \lambda^{\gamma,1}\left[\frac{1}{2}(\alpha_x^2 - \alpha_y^2)(\beta_x^2 - \beta_y^2) + \alpha_x\alpha_y\beta_x\beta_y\right] \\ + \lambda^{\gamma,2}(\alpha_x\alpha_z\beta_x\beta_z + \alpha_y\alpha_z\beta_y\beta_z) + \lambda_{12}\left[\frac{1}{2}\alpha_y\alpha_z(\beta_x^2 - \beta_y^2) + \alpha_x\alpha_z\beta_x\beta_y\right] \\ + \lambda_{21}\left[\frac{1}{2}(\alpha_x^2 - \alpha_y^2)\beta_y\beta_z + \alpha_x\alpha_y\beta_x\beta_z\right],$$

$$\lambda^{\alpha 1,0} = \frac{b_{11}c_{33} + b_{12}c_{13}}{c_{33}(c_{11} + c_{12}) - 2c_{13}^2}, \\ \lambda^{\alpha 2,0} = \frac{2b_{11}c_{33} - b_{12}(c_{11} + c_{22})}{c_{33}(c_{11} + c_{12}) - 2c_{13}^2}, \\ \lambda^{\alpha 1,2} = \frac{-b_{21}c_{33} + b_{22}c_{13}}{c_{33}(c_{11} + c_{12}) - 2c_{13}^2}, \\ \lambda^{\alpha 2,2} = \frac{2b_{21}c_{33} - b_{22}(c_{11} + c_{22})}{c_{33}(c_{11} + c_{12}) - 2c_{13}^2}, \\ \lambda^{\gamma,1} = \frac{c_{14}b_{14} - c_{44}b_3}{\frac{1}{2}c_{44}(c_{11} - c_{12}) - c_{14}^2}, \\ \lambda^{\gamma,2} = \frac{\frac{1}{2}b_4(c_{11} - c_{12}) - b_{34}c_{14}}{\frac{1}{2}c_{44}(c_{11} - c_{12}) - c_{14}^2}, \\ \lambda_{12} = \frac{c_{14}b_4 - c_{44}b_{34}}{\frac{1}{2}c_{44}(c_{11} - c_{12}) - c_{14}^2}, \\ \lambda_{21} = \frac{\frac{1}{2}b_{14}(c_{11} - c_{12}) - b_{34}c_{14}}{\frac{1}{2}c_{44}(c_{11} - c_{12}) - c_{14}^2}.$$



Workflow

TETRAGONAL (I)

SG 89-142

Workflow

Tetragonal (I)

Elastic energy

$$E_{el}^{tet} = \frac{1}{2}c_{11}(\epsilon_{xx}^2 + \epsilon_{yy}^2) + c_{12}\epsilon_{xx}\epsilon_{yy} + c_{13}(\epsilon_{xx} + \epsilon_{yy})\epsilon_{zz} + \frac{1}{2}c_{33}\epsilon_{zz}^2 + \frac{1}{2}c_{44}(\epsilon_{xz}^2 + \epsilon_{yz}^2) + \frac{1}{2}c_{66}\epsilon_{xy}^2.$$

Magnetoelastic energy

$$E_{me}^{tet(I)} = b_{11}(\epsilon_{xx} + \epsilon_{yy}) + b_{12}\epsilon_{zz} + b_{21}\left(\alpha_z^2 - \frac{1}{3}\right)(\epsilon_{xx} + \epsilon_{yy}) + b_{22}\left(\alpha_z^2 - \frac{1}{3}\right)\epsilon_{zz} + \frac{1}{2}b_3(\alpha_x^2 - \alpha_y^2)(\epsilon_{xx} - \epsilon_{yy}) + b'_3\alpha_x\alpha_y\epsilon_{xy} + b_4(\alpha_x\alpha_z\epsilon_{xz} + \alpha_y\alpha_z\epsilon_{yz}).$$

$$\frac{\partial(E_{el} + E_{me})}{\partial\epsilon_{ij}} = 0$$



$$\epsilon_{ij}^{eq}(\alpha)$$



$$\left.\frac{\Delta l}{l_0}\right|_{\beta}^{\alpha} = \sum_{i,j=x,y,z} \epsilon_{ij}^{eq}(\alpha) \beta_i \beta_j$$

$$\left.\frac{\Delta l}{l_0}\right|_{\beta}^{\alpha} = \lambda^{\alpha 1,0}(\beta_x^2 + \beta_y^2) + \lambda^{\alpha 2,0}\beta_z^2 + \lambda^{\alpha 1,2}\left(\alpha_z^2 - \frac{1}{3}\right)(\beta_x^2 + \beta_y^2) + \lambda^{\alpha 2,2}\left(\alpha_z^2 - \frac{1}{3}\right)\beta_z^2 + \frac{1}{2}\lambda^{\gamma,2}(\alpha_x^2 - \alpha_y^2)(\beta_x^2 - \beta_y^2) + 2\lambda^{\delta,2}\alpha_x\alpha_y\beta_x\beta_y + 2\lambda^{\epsilon,2}(\alpha_x\alpha_z\beta_x\beta_z + \alpha_y\alpha_z\beta_y\beta_z),$$

$$\lambda^{\alpha 1,0} = \frac{b_{11}c_{33} + b_{12}c_{13}}{c_{33}(c_{11} + c_{12}) - 2c_{13}^2},$$

$$\lambda^{\alpha 2,0} = \frac{2b_{11}c_{33} - b_{12}(c_{11} + c_{22})}{c_{33}(c_{11} + c_{12}) - 2c_{13}^2},$$

$$\lambda^{\alpha 1,2} = \frac{-b_{21}c_{33} + b_{22}c_{13}}{c_{33}(c_{11} + c_{12}) - 2c_{13}^2},$$

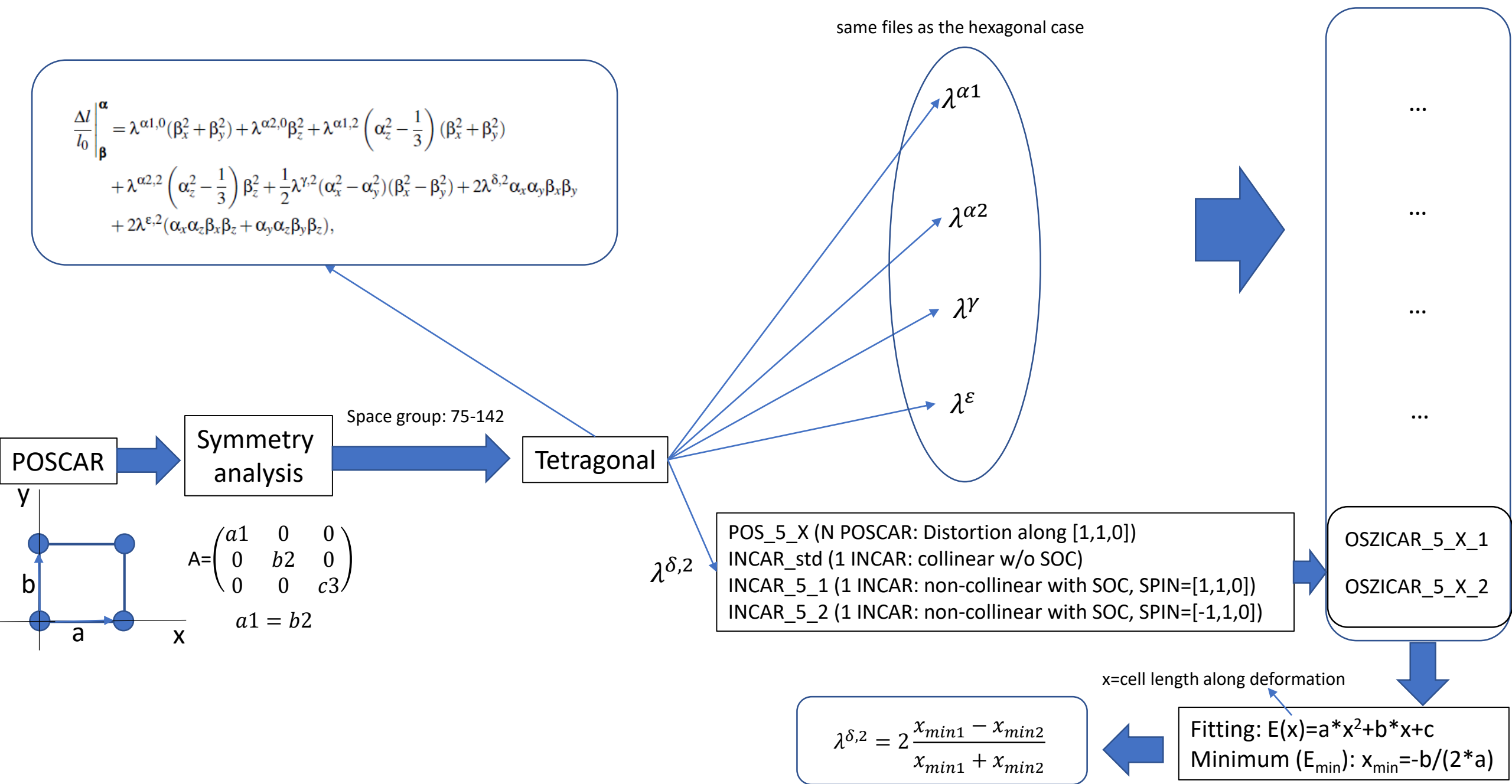
$$\lambda^{\alpha 2,2} = \frac{2b_{21}c_{33} - b_{22}(c_{11} + c_{22})}{c_{33}(c_{11} + c_{12}) - 2c_{13}^2},$$

$$\lambda^{\gamma,2} = \frac{-b_3}{c_{11} - c_{12}},$$

$$\lambda^{\delta,2} = \frac{-b'_3}{2c_{66}},$$

$$\lambda^{\epsilon,2} = \frac{-b_4}{2c_{44}}.$$

Workflow



Relation between different notations

Tetragonal (I)

Cullen

Mason

$$\left. \frac{\Delta I}{I_0} \right|_{\beta}^{\alpha} = \lambda^{\alpha 1,0} (\beta_x^2 + \beta_y^2) + \lambda^{\alpha 2,0} \beta_z^2 + \lambda^{\alpha 1,2} \left(\alpha_z^2 - \frac{1}{3} \right) (\beta_x^2 + \beta_y^2) \\ + \lambda^{\alpha 2,2} \left(\alpha_z^2 - \frac{1}{3} \right) \beta_z^2 + \frac{1}{2} \lambda^{\gamma,2} (\alpha_x^2 - \alpha_y^2) (\beta_x^2 - \beta_y^2) + 2 \lambda^{\delta,2} \alpha_x \alpha_y \beta_x \beta_y \\ + 2 \lambda^{\epsilon,2} (\alpha_x \alpha_z \beta_x \beta_z + \alpha_y \alpha_z \beta_y \beta_z),$$



$$\left. \frac{\Delta I}{I_0} \right|_{\beta}^{\alpha} = \lambda_{Mason}^{\alpha 1,0} (\beta_x^2 + \beta_y^2) + \lambda_{Mason}^{\alpha 2,0} \beta_z^2 + \frac{1}{2} \lambda_1 [(\alpha_x \beta_x - \alpha_y \beta_y)^2 - (\alpha_x \beta_y + \alpha_y \beta_x)^2] \\ + (1 - \beta_z^2)(1 - \alpha_z^2) - 2 \alpha_z \beta_z (\alpha_x \beta_x + \alpha_y \beta_y) + 4 \lambda_2 \alpha_z \beta_z (\alpha_x \beta_x + \alpha_y \beta_y) \\ + 4 \lambda_3 \alpha_x \alpha_y \beta_x \beta_y + \lambda_4 [\beta_z^2 (1 - \alpha_z^2) - \alpha_z \beta_z (\alpha_x \beta_x + \alpha_y \beta_y)] \\ + \frac{1}{2} \lambda_5 [(\alpha_x \beta_y - \alpha_y \beta_x)^2 - (\alpha_x \beta_x + \alpha_y \beta_y)^2 + (1 - \beta_z^2)(1 - \alpha_z^2)].$$

$$\lambda_{Mason}^{\alpha 1,0} = \lambda^{\alpha 1,0} + \frac{2}{3} \lambda^{\alpha 1,2}$$

$$\lambda_{Mason}^{\alpha 2,0} = \lambda^{\alpha 2,0} + \frac{2}{3} \lambda^{\alpha 2,2}$$

$$\lambda_1 = -\lambda^{\alpha 1,2} + \frac{1}{2} \lambda^{\gamma,2}$$

$$\lambda_2 = \frac{1}{2} \lambda^{\epsilon,2} - \frac{1}{4} \lambda^{\alpha 2,2} - \frac{1}{4} \lambda^{\alpha 1,2} + \frac{1}{8} \lambda^{\gamma,2}$$

$$\lambda_3 = \frac{1}{2} \lambda^{\delta,2} - \lambda^{\alpha 1,2}$$

$$\lambda_4 = -\lambda^{\alpha 2,2}$$

$$\lambda_5 = -\lambda^{\alpha 1,2} - \frac{1}{2} \lambda^{\gamma,2}.$$

Workflow

ORTHORHOMBIC

SG 16-74

Orthorhombic

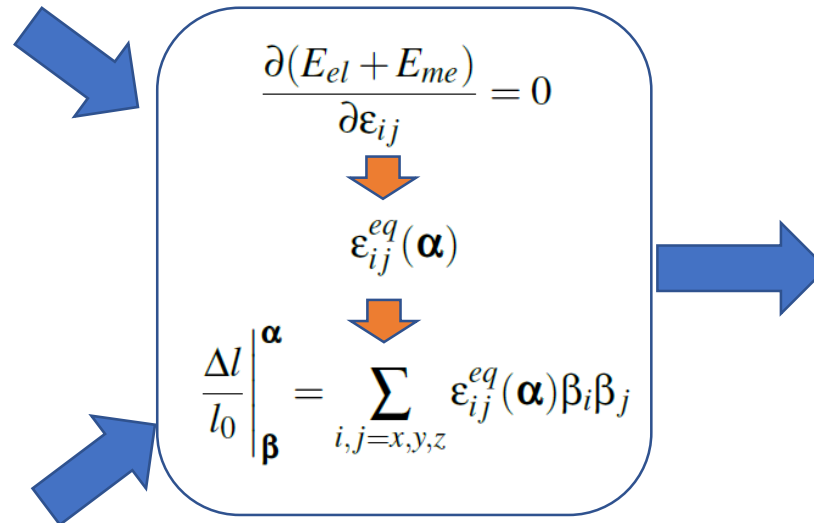
Workflow

Elastic energy

$$E_{el}^{ortho} = \frac{1}{2}c_{11}\epsilon_{xx}^2 + \frac{1}{2}c_{22}\epsilon_{yy}^2 + c_{12}\epsilon_{xx}\epsilon_{yy} + c_{13}\epsilon_{xx}\epsilon_{zz} + c_{23}\epsilon_{yy}\epsilon_{zz} + \frac{1}{2}c_{33}\epsilon_{zz}^2 \\ + \frac{1}{2}c_{44}\epsilon_{yz}^2 + \frac{1}{2}c_{55}\epsilon_{xz}^2 + \frac{1}{2}c_{66}\epsilon_{xy}^2.$$

Magnetoelastic energy

$$E_{me}^{ortho} = b_{01}\epsilon_{xx} + b_{02}\epsilon_{yy} + b_{03}\epsilon_{zz} + b_1\alpha_x^2\epsilon_{xx} + b_2\alpha_y^2\epsilon_{xx} + b_3\alpha_x^2\epsilon_{yy} + b_4\alpha_y^2\epsilon_{yy} \\ + b_5\alpha_x^2\epsilon_{zz} + b_6\alpha_y^2\epsilon_{zz} + b_7\alpha_x\alpha_y\epsilon_{xy} + b_8\alpha_x\alpha_z\epsilon_{xz} + b_9\alpha_y\alpha_z\epsilon_{yz},$$



$$\left. \frac{\Delta l}{l_0} \right|_{\beta}^{\alpha} = \lambda^{\alpha 1,0}\beta_x^2 + \lambda^{\alpha 2,0}\beta_y^2 + \lambda^{\alpha 3,0}\beta_z^2 + \lambda_1(\alpha_x^2\beta_x^2 - \alpha_x\alpha_y\beta_x\beta_y - \alpha_x\alpha_z\beta_x\beta_z) \\ + \lambda_2(\alpha_y^2\beta_x^2 - \alpha_x\alpha_y\beta_x\beta_y) + \lambda_3(\alpha_x^2\beta_y^2 - \alpha_x\alpha_y\beta_x\beta_y) \\ + \lambda_4(\alpha_y^2\beta_y^2 - \alpha_x\alpha_y\beta_x\beta_y - \alpha_y\alpha_z\beta_y\beta_z) + \lambda_5(\alpha_x^2\beta_z^2 - \alpha_x\alpha_z\beta_x\beta_z) \\ + \lambda_6(\alpha_y^2\beta_z^2 - \alpha_y\alpha_z\beta_y\beta_z) + 4\lambda_7\alpha_x\alpha_y\beta_x\beta_y + 4\lambda_8\alpha_x\alpha_z\beta_x\beta_z + 4\lambda_9\alpha_y\alpha_z\beta_y\beta_z.$$

$$b_{01} = -c_{11}\lambda^{\alpha 1,0} - c_{12}\lambda^{\alpha 2,0} - c_{13}\lambda^{\alpha 3,0} \\ b_{02} = -c_{12}\lambda^{\alpha 1,0} - c_{22}\lambda^{\alpha 2,0} - c_{23}\lambda^{\alpha 3,0} \\ b_{03} = -c_{13}\lambda^{\alpha 1,0} - c_{23}\lambda^{\alpha 2,0} - c_{33}\lambda^{\alpha 3,0} \\ b_1 = -c_{11}\lambda_1 - c_{12}\lambda_3 - c_{13}\lambda_5 \\ b_2 = -c_{11}\lambda_2 - c_{12}\lambda_4 - c_{13}\lambda_6 \\ b_3 = -c_{12}\lambda_1 - c_{22}\lambda_3 - c_{23}\lambda_5 \\ b_4 = -c_{12}\lambda_2 - c_{22}\lambda_4 - c_{23}\lambda_6 \\ b_5 = -c_{13}\lambda_1 - c_{23}\lambda_3 - c_{33}\lambda_5 \\ b_6 = -c_{13}\lambda_2 - c_{23}\lambda_4 - c_{33}\lambda_6 \\ b_7 = c_{66}(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 - 4\lambda_7) \\ b_8 = c_{55}(\lambda_1 + \lambda_5 - 4\lambda_8) \\ b_9 = c_{44}(\lambda_4 + \lambda_6 - 4\lambda_9).$$

$$\left. \frac{\Delta I}{I_0} \right|_{\mathbf{\beta}}^{\mathbf{\alpha}} = \lambda^{\alpha 1,0} \beta_x^2 + \lambda^{\alpha 2,0} \beta_y^2 + \lambda^{\alpha 3,0} \beta_z^2 + \lambda_1 (\alpha_x^2 \beta_x^2 - \alpha_x \alpha_y \beta_x \beta_y - \alpha_x \alpha_z \beta_x \beta_z) \\ + \lambda_2 (\alpha_y^2 \beta_x^2 - \alpha_x \alpha_y \beta_x \beta_y) + \lambda_3 (\alpha_x^2 \beta_y^2 - \alpha_x \alpha_y \beta_x \beta_y) \\ + \lambda_4 (\alpha_y^2 \beta_y^2 - \alpha_x \alpha_y \beta_x \beta_y - \alpha_y \alpha_z \beta_y \beta_z) + \lambda_5 (\alpha_x^2 \beta_z^2 - \alpha_x \alpha_z \beta_x \beta_z) \\ + \lambda_6 (\alpha_y^2 \beta_z^2 - \alpha_y \alpha_z \beta_y \beta_z) + 4\lambda_7 \alpha_x \alpha_y \beta_x \beta_y + 4\lambda_8 \alpha_x \alpha_z \beta_x \beta_z + 4\lambda_9 \alpha_y \alpha_z \beta_y \beta_z.$$

POSCAR

Symmetry
analysis

SG: 16-74

Orthorhombic

MAELAS uses the same lattice convention as AELAS code:

$$c < a < b$$

λ_1

POS_1_X (N POSCAR: Distortion along [1,0,0])
INCAR_std (1 INCAR: collinear w/o SOC)
INCAR_1_1 (1 INCAR: non-collinear with SOC, SPIN=[1,0,0])
INCAR_1_2 (1 INCAR: non-collinear with SOC, SPIN=[0,0,1])

λ_2

POS_2_X (N POSCAR: Distortion along [1,0,0])
INCAR_std (1 INCAR: collinear w/o SOC)
INCAR_2_1 (1 INCAR: non-collinear with SOC, SPIN=[0,1,0])
INCAR_2_2 (1 INCAR: non-collinear with SOC, SPIN=[0,0,1])

λ_3

POS_3_X (N POSCAR: Distortion along [0,1,0])
INCAR_std (1 INCAR: collinear w/o SOC)
INCAR_3_1 (1 INCAR: non-collinear with SOC, SPIN=[1,0,0])
INCAR_3_2 (1 INCAR: non-collinear with SOC, SPIN=[0,0,1])

λ_4

POS_4_X (N POSCAR: Distortion along [0,1,0])
INCAR_std (1 INCAR: collinear w/o SOC)
INCAR_4_1 (1 INCAR: non-collinear with SOC, SPIN=[0,1,0])
INCAR_4_2 (1 INCAR: non-collinear with SOC, SPIN=[0,0,1])

λ_5

POS_5_X (N POSCAR: Distortion along [0,0,1])
INCAR_std (1 INCAR: collinear w/o SOC)
INCAR_5_1 (1 INCAR: non-collinear with SOC, SPIN=[1,0,0])
INCAR_5_2 (1 INCAR: non-collinear with SOC, SPIN=[0,0,1])

λ_6

POS_6_X (N POSCAR: Distortion along [0,0,1])
INCAR_std (1 INCAR: collinear w/o SOC)
INCAR_6_1 (1 INCAR: non-collinear with SOC, SPIN=[0,1,0])
INCAR_6_2 (1 INCAR: non-collinear with SOC, SPIN=[0,0,1])

λ_7

POS_7_X (N POSCAR: Distortion along [1,1,0])
INCAR_std (1 INCAR: collinear w/o SOC)
INCAR_7_1 (1 INCAR: non-collinear with SOC, SPIN=[1,1,0])
INCAR_7_2 (1 INCAR: non-collinear with SOC, SPIN=[0,0,1])

λ_8

POS_8_X (N POSCAR: Distortion along [1,0,1])
INCAR_std (1 INCAR: collinear w/o SOC)
INCAR_8_1 (1 INCAR: non-collinear with SOC, SPIN=[1,0,1])
INCAR_8_2 (1 INCAR: non-collinear with SOC, SPIN=[0,0,1])

λ_9

POS_9_X (N POSCAR: Distortion along [0,1,1])
INCAR_std (1 INCAR: collinear w/o SOC)
INCAR_9_1 (1 INCAR: non-collinear with SOC, SPIN=[0,1,1])
INCAR_9_2 (1 INCAR: non-collinear with SOC, SPIN=[0,0,1])

$$\lambda_{1,2,3,4,5,6,7,8,9} = 2 \frac{x_{min1} - x_{min2}}{x_{min1} + x_{min2}}$$

Fitting: $E(x) = a \cdot x^2 + b \cdot x + c$
Minimum (E_{min}): $x_{min} = -b/(2 \cdot a)$

OSZICAR_1_X_1
OSZICAR_1_X_2

OSZICAR_2_X_1
OSZICAR_2_X_2

OSZICAR_3_X_1
OSZICAR_3_X_2

OSZICAR_4_X_1
OSZICAR_4_X_2

OSZICAR_5_X_1
OSZICAR_5_X_2

OSZICAR_6_X_1
OSZICAR_6_X_2

OSZICAR_7_X_1
OSZICAR_7_X_2

OSZICAR_8_X_1
OSZICAR_8_X_2

OSZICAR_9_X_1
OSZICAR_9_X_2

BRIEF REVIEW OF KNOWN MAGNETOSTRICTIVE MATERIALS

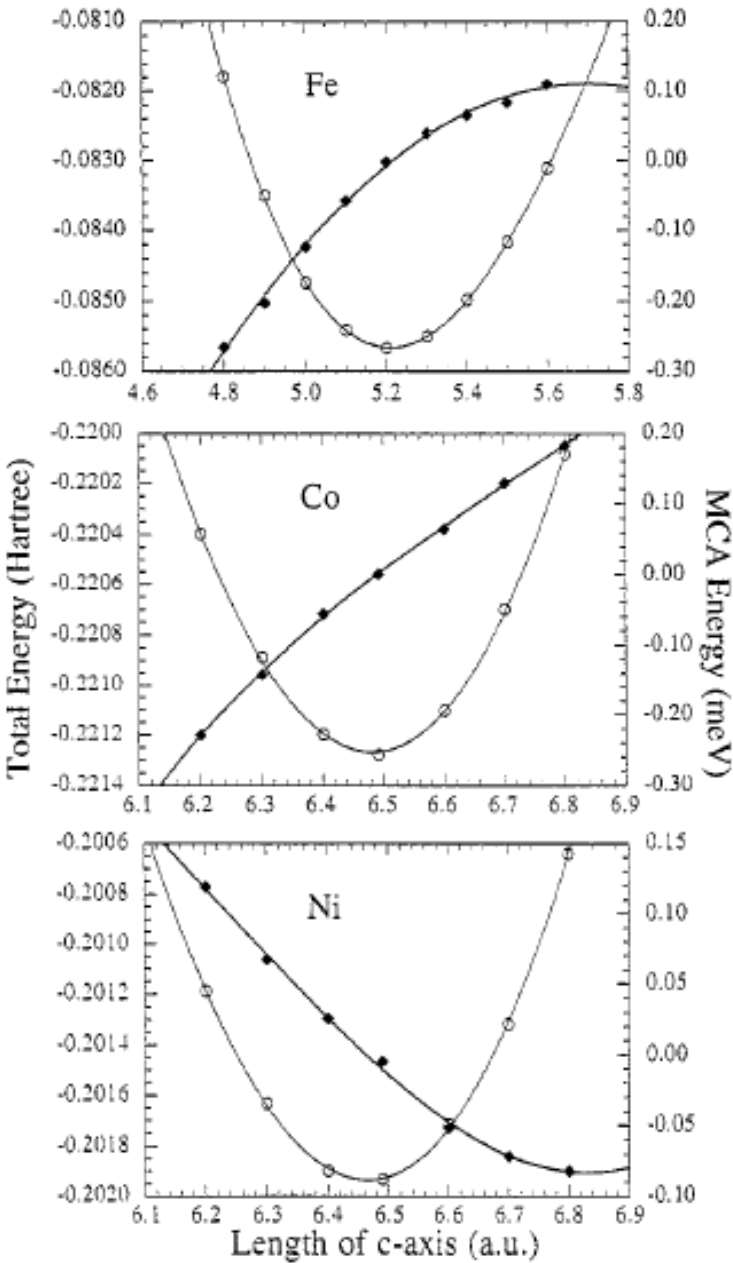
Cubic systems: Itenerant magnets

R.Q. Wu et al. / *Journal of Magnetism and Magnetic Materials* 177–181 (1998) 1216–1219

	a (a.u.)	σ	$M_s(\mu_B)$	$M_L(\mu_B)$	$\lambda_{001}(10^{-6})$
bcc Fe					
LDA	5.20	-0.409	2.05	0.048	52
GGA	5.37	-0.486	2.17	0.045	29
EXP	5.41	-0.368	2.22	0.08	21
fcc Co					
LDA	6.48	-0.374	1.59	0.076	92
GGA	6.67	-0.396	1.66	0.073	56
EXP	6.70	---	1.72	0.12	79
fcc Ni					
LDA	6.46	-0.332	0.62	0.049	-63
GGA	6.64	-0.3376	0.66	0.050	-56
EXP	6.66	-0.376	0.57	0.05	-49

R. C. O'Handley,
Modern magnetic materials,
Wiley, 2000.

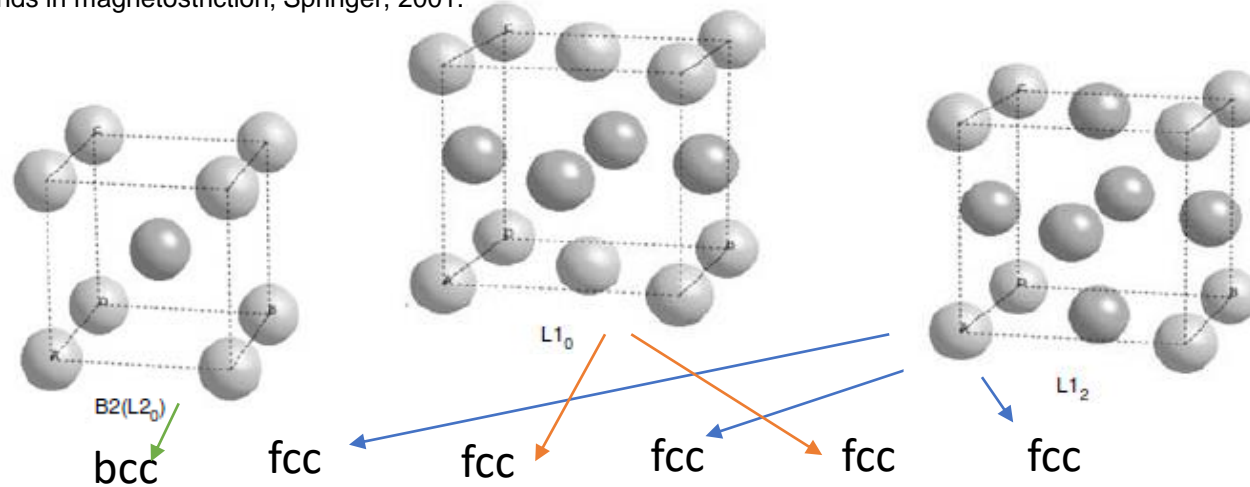
	T = 4.2 K		Room Temperature		
	$\lambda_{100}(\lambda^{r,2})$	$\lambda_{111}(\lambda^{r,2})$	$\lambda_{100}(\lambda^{r,2})$	$\lambda_{111}(\lambda^{r,2})$	Polycrystal λ_s
3d Metals					
BCC-Fe	26	-30	21	-21	-7
HCP-Co ^u	(-150)	(45)	(-140)	(50)	(-62)
FCC-Ni	-60	-35	-46	-24	-34
BCC-FeCo	—	—	140	30	—
a-Fe ₈₀ B ₂₀	48 (isotropic)	—	—	—	+32
a-Fe ₄₀ Ni ₄₀ B ₂₀	+20	—	—	—	+14
a-Cos ₈₀ B ₂₀	-4	—	—	—	-4



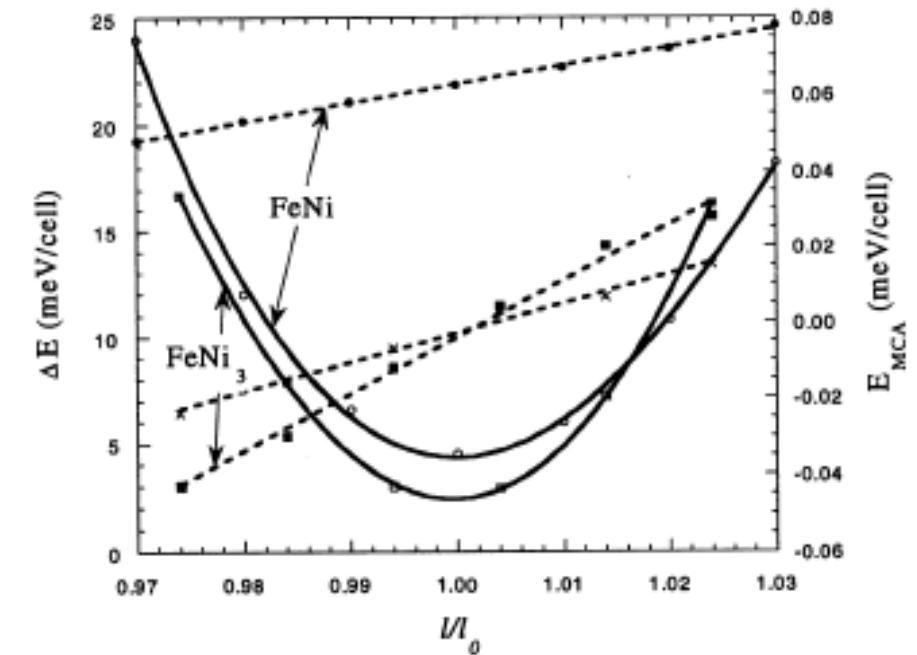
BRIEF REVIEW OF KNOWN MAGNETOSTRICTIVE MATERIALS

Cubic systems: Itenerant magnets

M. Gibbs, Modern trends in magnetostriction, Springer, 2001.



	FeCo	FeCo ₃	FeNi	FeNi ₃	CoNi	CoNi ₃
a (a.u.)	5.38 (5.39)	6.70	6.76 (6.76)	6.70 (6.71)	6.62 (6.67)	6.66 (6.65)
c (a.u.)	5.38 (5.39)	6.70	6.76 (6.76)	6.70 (6.71)	6.78 (6.67)	6.66 (6.65)
E _{MCA} (μeV)	0	0	63	0	143	0
σ	-0.35	-0.36	-0.33	-0.35	-0.34	-0.36
λ ₀₀₁ (10 ⁻⁶)	83 (125)	-68	10 (12)	27 (13)	42 (42-100)	33



BRIEF REVIEW OF KNOWN MAGNETOSTRICTIVE MATERIALS

G. Engdahl, Handbook of giant magnetostrictive materials, Academic Press, 1999

Cubic systems: Rare-Earth magnets

M. Gibbs, Modern trends in magnetostriction, Springer, 2001.

C15 cubic Laves phase

	Theory	Experiment
λ_{001} (GdCo ₂)	-407	-1200
λ_{111} (GdCo ₂)	19	< 10
λ_{001} (SmCo ₂)	-290	---
λ_{001} (ErCo ₂)	-516	-1000
λ_{001} (GdFe ₂)	44	39

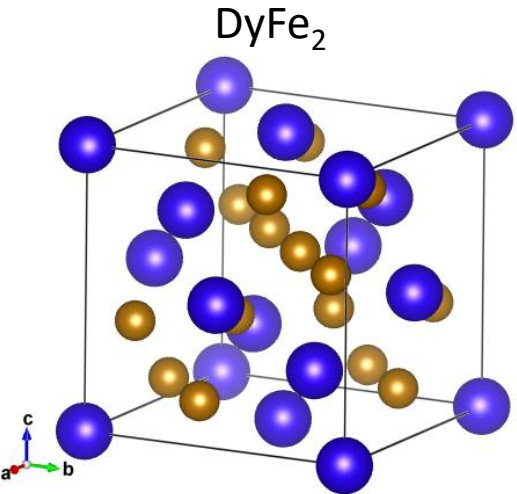
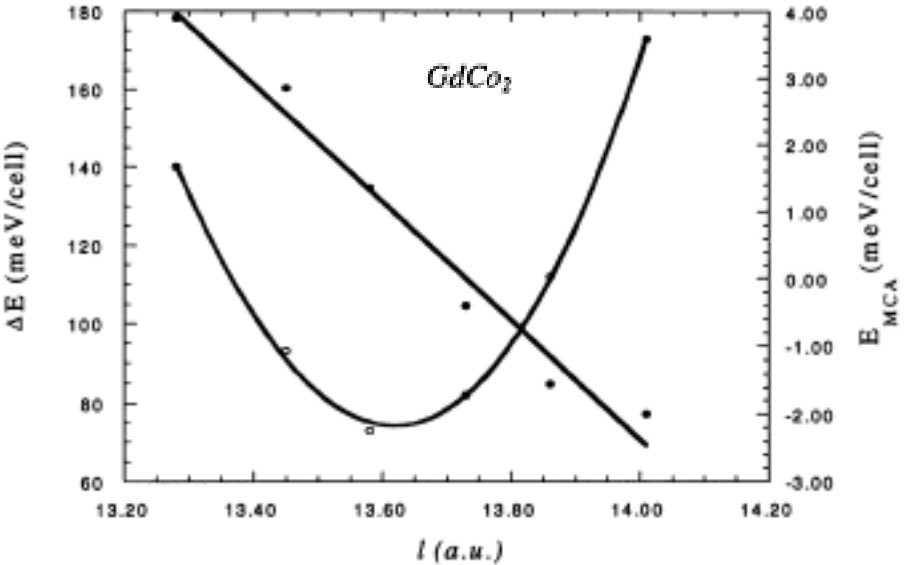


Table 16-10. Low-temperature magnetostriction constants for RCo₂ crystals [from Levitin and Markosyan (1990) unless otherwise noted].

R in RCo ₂	10 ⁶ λ_{111}	10 ⁶ λ_{100}	T _c (K) ^a
Gd	< 10 ⁻⁵	-1200	409
Tb	4500	-1200 ^b	256
Dy	5000 ^{b, c}	-2000 ^d	159
		-1300 ^e	
Ho	300, 600 ^c	-2000	85
Er	-2500	-1000	36
Tm	-4100 ^b	750 ^c	18

Table 1.6. Magnetostriction of Cubic Laves Phase Compounds with Rare Earths at T = 0

Compound	$\lambda_{111}(10^{-6})$	$\lambda_{100}(10^{-6})$	T _c (K)
NdAl ₂	—	-700	61
TbAl ₂	-3000	—	114
DyAl ₂	—	-1700	68
TbMn ₂	-3000	—	40
TbFe ₂	4000, 4500	—	711
DyFe ₂	—	-70	635
HoFe ₂	—	-750	612
TmFe ₂	-3500, -2600	—	610
TbCo ₂	4400	—	256
DyCo ₂	—	-2000	159
HoCo ₂	—	-2200	85
ErCo ₂	-2500	—	36
TbNi ₂	1500	—	45
DyNi ₂	—	-1300	30
HoNi ₂	—	-1000	22

Table 1.7. Magnitudes of Single-Crystal Magnetostriction in Rare Earth-Fe₂ Compounds

Compound	$\frac{2}{3}\lambda_{111}(10^{-6})$ (calculated at 0 K)	$\frac{2}{3}\lambda_{111}(10^{-6})$ (measured at room temperature)	T _c
SmFe ₂	-4800	-3150	676
TbFe ₂	6600	3690	697, 711
DyFe ₂	6300	1890	635
HoFe ₂	2400	288	606
ErFe ₂	-2250	-450	590, 597
TmFe ₂	-5550	-315	560

BRIEF REVIEW OF KNOWN MAGNETOSTRICTIVE MATERIALS

TABLE 6
Magnetostriction coefficients at zero Kelvin in units of 10⁻³

Element	$\lambda_1^{a,2}$	$\lambda_2^{a,2}$	$\lambda^{\gamma,2}$	$\lambda^{\epsilon,2}$	$\lambda_1^{a,0} - \frac{1}{3}\lambda_1^{a,2}$	$\lambda_2^{a,0} - \frac{1}{3}\lambda_2^{a,2}$	$\lambda^{\gamma,4}$
Gadolinium ^{a)}	0.14	-0.13	0.11	0.02	-	-	-
Terbium ^{b)}	-2.6 ^{c)}	9.0 ^{c)}	8.7	15.0 ^{c)}	-0.8	4.3	-2.1
Dysprosium ^{b)}	-	-	9.4	5.5	-2.0	7.3	1.5
Holmium ^{b)}	-	-	2.5 ^{c)}	-	-3.9	7.1	-
Erbium ^{b)}	-	-	-5.1 ^{c)}	-	+0.3	6.2	-

^{a)} After Mishima et al. (1976).
^{b)} After Rhyne (1972).
^{c)} Extrapolated from paramagnetic range using single-ion theory.

	<i>T</i> = 4.2 K		Room Temperature		
	$\lambda_{100}(\lambda^{\gamma,2})$	$\lambda_{111}(\lambda^{\epsilon,2})$	$\lambda_{100}(\lambda^{\gamma,2})$	$\lambda_{111}(\lambda^{\epsilon,2})$	Polycrystal λ_s
	<i>Spinel Ferrites</i>				
Fe ₃ O ₄	0	50	-15	56	+40
MnFe ₂ O ₄ ^u	—	—	(-54)	(10)	—
CoFe ₂ O ₄	—	—	-670	120	-110
	<i>Garnets</i>				
YIG	-0.6	-2.5	-1.4	-1.6	-2

Hexagonal
Rare-Earth

Oxide magnets

MAELAS TESTS

Table 3: Anisotropic magnetostriction coefficients and MAE calculated by the program MAELAS and measured in experiment ($T \approx 0$ K) for a set of magnetic materials. In parenthesis we show the magnetostriction coefficients with Mason’s definitions obtained using the relations given by Eq. A.2.

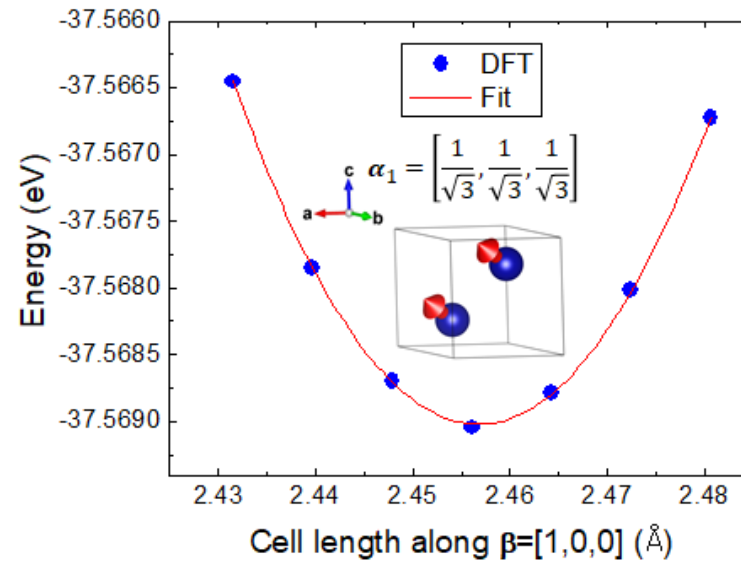
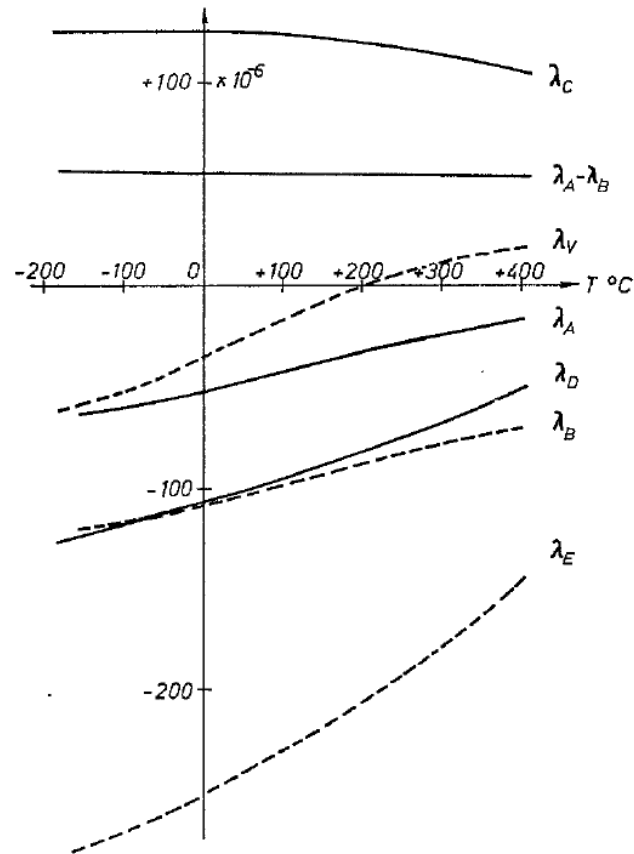
Material	Crystal system	Space group	Magnetostriction coefficient	MAELAS ($\times 10^{-6}$)	Expt. ($\times 10^{-6}$)	MAE	MAELAS ($\mu\text{eV}/\text{atom}$)	Expt. ($\mu\text{eV}/\text{atom}$)
Fe bcc	Cubic (I)	229	λ_{001}	23	26 [44]	$E(110) - E(001)$	0.1	1.0 [43]
			λ_{111}	19	-30 [44]	$E(111) - E(001)$	0.21	1.3 [43]
Co hcp	Hexagonal (I)	194	$\lambda^{\alpha 1,2} (\lambda_A)$	85 (-78)	95 (-66) [47]	$E(100) - E(001)$	53	61 [43]
			$\lambda^{\alpha 2,2} (\lambda_B)$	-115 (-92)	-126 (-123) [47]			
			$\lambda^{\gamma,2} (\lambda_C)$	15 (115)	57 (126) [47]			
			$\lambda^{\varepsilon,2} (\lambda_D)$	-17 (1)	-286 (-128) [47]			
Gd hcp	Hexagonal (I)	194	$\lambda^{\alpha 1,2}$	-67	145 [†] [49]	$E(100) - E(001)$	32	35 [48]
			$\lambda^{\alpha 2,2}$	145	-125 [†] [49]			
			$\lambda^{\gamma,2}$	143	108 [†] [49]			
			$\lambda^{\varepsilon,2}$	-95	22 [†] [49]			
YCo ₅	Hexagonal (I)	191	$\lambda^{\alpha 1,2}$	-90	$ \lambda^{\alpha 1,2} < 100$ [4]	$E(100) - E(001)$	365	567 [50]
			$\lambda^{\alpha 2,2}$	115	$ \lambda^{\alpha 2,2} < 100$ [4]			
			$\lambda^{\gamma,2}$	73				
			$\lambda^{\varepsilon,2}$	147				
FePd L1 ₀	Tetragonal (I)	123	$\frac{-\lambda^{\alpha 1,2}}{3} + \frac{\lambda^{\gamma,2}}{2}$	12	100 [‡] [52]	$E(100) - E(001)$	109	181 [51]
			$\lambda^{\alpha 1,2}$	-23				
			$\lambda^{\alpha 2,2}$	83				
			$\lambda^{\gamma,2}$	8				
			$\lambda^{\varepsilon,2}$	25				
			$\lambda^{\delta,2}$	61				

[†]Terms higher than second-order direction cosine polynomial were included.

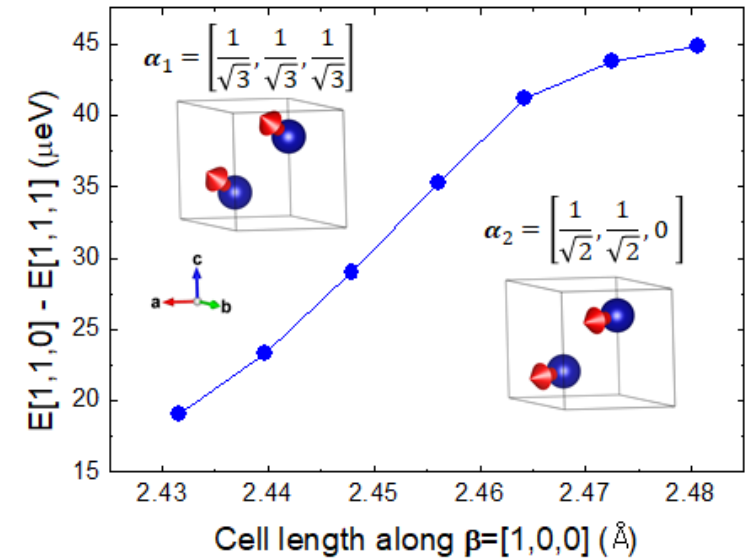
[‡]The experimental measurement corresponds to $\lambda^{\alpha 1,0} + \frac{-\lambda^{\alpha 1,2}}{3} + \frac{\lambda^{\gamma,2}}{2}$ with composition Fe₄₈Pd₅₂.

MAELAS TESTS: Co hcp

Z. Physik 224, 148—155 (1969)



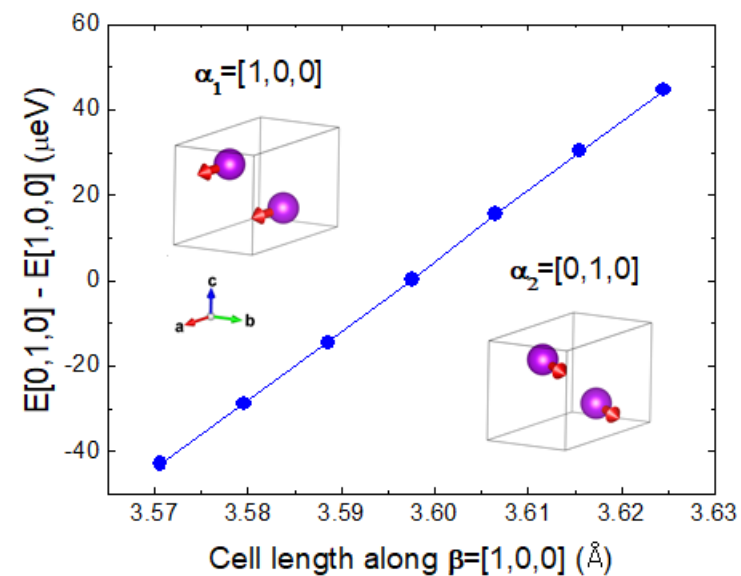
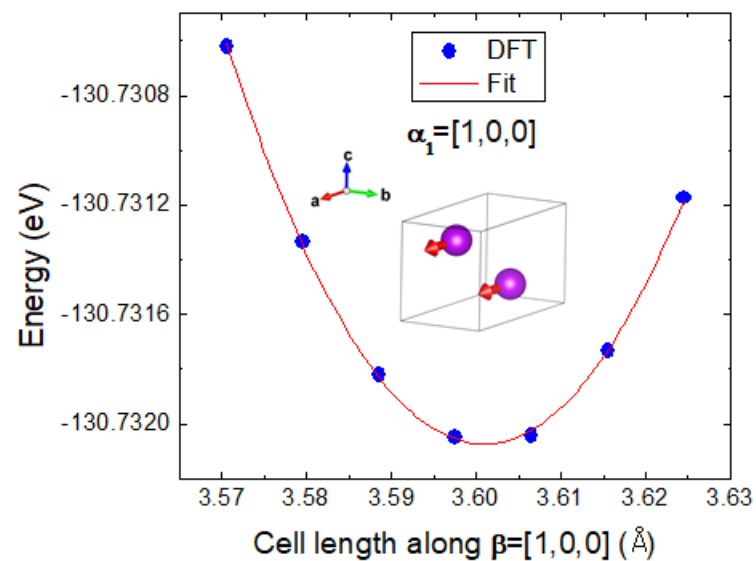
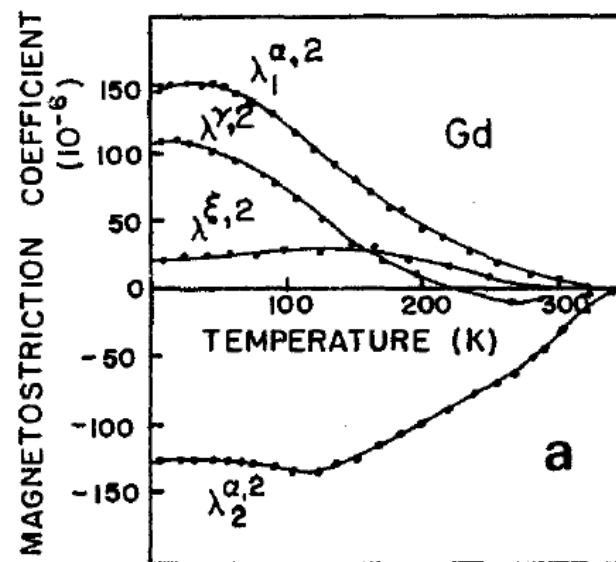
$\lambda^{\alpha_{1,2}}$



MAELAS TESTS: Gd hcp

Mishima, A., H. Fujii and T. Okamoto, 1976, J. Phys. Soc. Jap. **40**, 962.

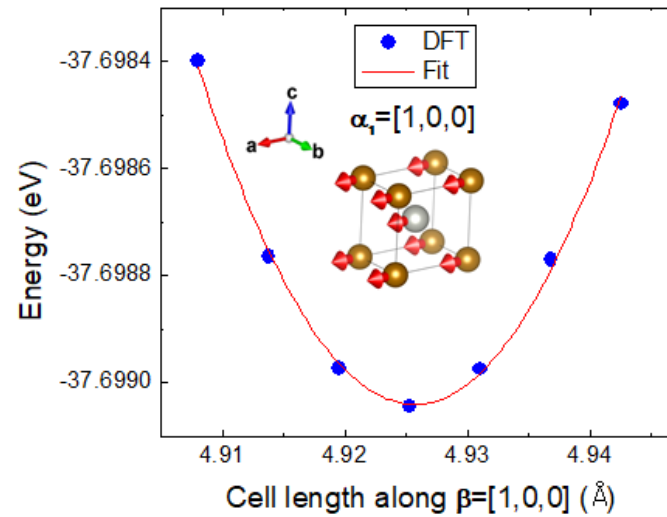
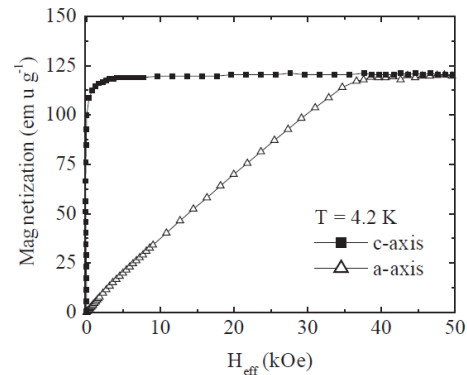
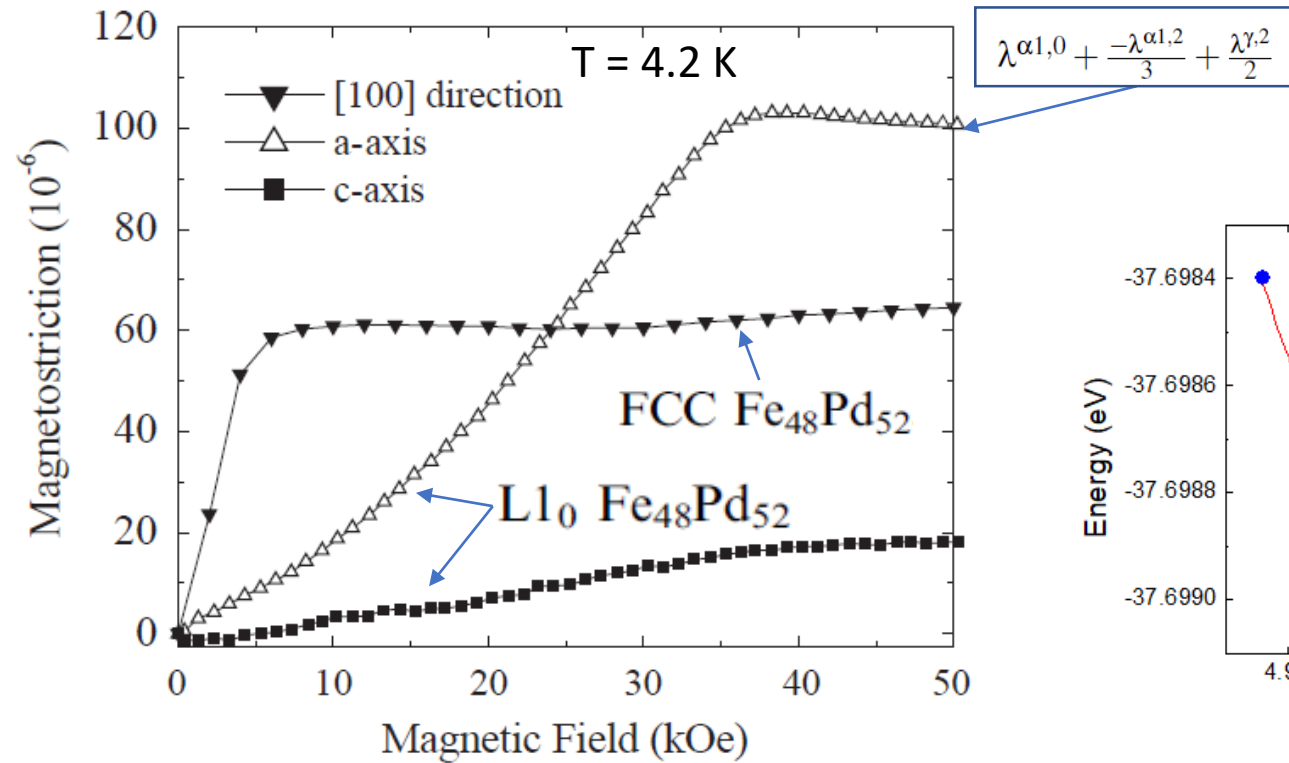
$\lambda^{\gamma,2}$



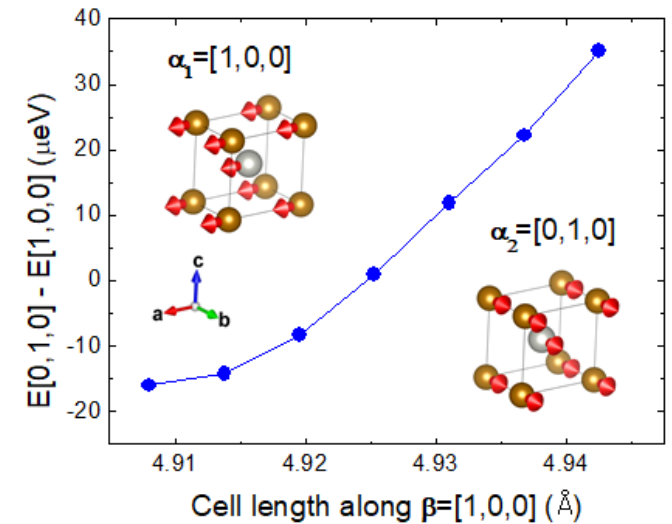
MAELAS TESTS: L1₀ FePd

Experiment

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$\lambda^{\gamma,2}$



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