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# Negative thermal expansion of $\text{ScF}_3$ : first principles vs empirical molecular dynamics

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**Abstract.** The crystal lattice of cubic scandium fluorine ( $\text{ScF}_3$ ) exhibits negative thermal expansion (NTE) over a wide range of temperatures from 10 K to 1100 K. Here the NTE effect in  $\text{ScF}_3$  is studied using atomistic simulations based on empirical and *ab initio* molecular dynamics (AIMD) in the isobaric-isothermal (NpT) ensemble. The temperature dependence of the average lattice constant, the Sc–F–Sc bond angle distribution and the radial distribution functions were obtained. Crossover from the NTE to positive thermal expansion occurring at about 1100 K is reproduced by AIMD simulations in agreement with the known experiment data. At the same time, empirical MD model fails to reproduce the NTE behaviour and suggests an expansion of the  $\text{ScF}_3$  lattice with increasing temperature. However, both MD models predict strong anisotropy of fluorine atom thermal vibration amplitude, being larger in the direction orthogonal to the Sc–F–Sc atom chain.

## 1. Introduction

Materials with a negative thermal expansion (NTE) coefficient were known since the beginning of the twentieth century but attracted the wider attention of researchers recently [1, 2, 3, 4]. The control of thermal expansion of materials is important in the technological areas, where the control of the volume of equipment components with high precision or the invariability of material volume with a change in temperature is required. This task can be solved, for example, by combining materials with positive and negative coefficients of thermal expansion (CTE). Possible areas of applications include electronics, fibre optics, astronomical and optical devices, dental prosthesis, etc [5].

Scandium fluoride ( $\text{ScF}_3$ ) is remarkable among NTE materials due to it exhibits NTE properties in a very wide temperature range from 10 K to 1100 K and has isotropic and high CTE values [6]. Note that a structurally similar  $\text{ReO}_3$  compound possesses NTE effect with a very small CTE and below room temperature [7]. Unlike many other NTE materials as, for example,  $\text{ZrW}_2\text{O}_8$ ,  $\text{HfW}_2\text{O}_8$  [8] or  $\text{ZrV}_{2-x}\text{P}_x\text{O}_7$  [9],  $\text{ScF}_3$  has simple  $\text{ABO}_3$  perovskite-like cubic lattice ( $Pm\bar{3}m$  space group) with the A-site being empty that makes it a useful model object for studying NTE mechanism [10, 11, 12, 13, 14].

Possible mechanisms of the NTE effect were reviewed recently [2, 3, 4] and may have structural and electronic origin. Structural NTE is driven by transverse vibrational motion of the polyhedral units as happens in the case of  $\text{ScF}_3$ , whose structure is built-up by  $\text{ScF}_6$



octahedra connected by vertices. Recently, Lasar et al. [15] showed that *ab initio* molecular dynamics (AIMD) can be used to model the NTE effect in  $\text{ScF}_3$ . They were able to reproduce temperature dependence of the reduced lattice constant, re-normalized at 200 K, using very small  $2a_0 \times 2a_0 \times 2a_0$  ( $a_0$  is the lattice constant of  $\text{ScF}_3$ ) supercell.

In this study, we compare the results of empirical MD and AIMD simulations of  $\text{ScF}_3$  performed for large supercells with the aim to check the limits of applicability of the two methods for a description of the NTE effect.

## 2. Computational details

AIMD simulations based on Kohn-Sham density functional theory (DFT) [16] with exchange-correlation potential PBEsol [17] and empirical MD simulations using the Born–Mayer potential [18, 19] were performed in the isobaric-isothermal (NpT) ensemble at seven different temperatures in the range of 300–1600 K using the CP2K code [20].

The equilibrium lattice constant of  $\text{ScF}_3$  at  $T=0$  K obtained from preliminary DFT calculations for optimized structure  $a_0=4.027$  Å. The AIMD potential parameters were described previously in [21]. The Born–Mayer interatomic potential was used in empirical MD calculations

$$U(r) = A \exp(-r/B) \quad (1)$$

where  $A$  and  $B$  are potential parameters ( $A=942.4541$  eV and  $B=0.2830$  Å for the F–F atom pairs, whereas  $A=10173.51$  eV and  $B=0.2003$  Å for Sc–F atom pairs). No interaction between Sc atoms was considered. The potential parameters were optimized by fitting to the lattice constant and comparing the phonons given by this potential with phonon calculated in the Ref. [22]

The initial equilibration run was for both empirical MD and AIMD was 15 ps, followed by the production run of 50 ps. The Newton’s equations of motion were integrated with the Verlet leapfrog algorithm, with a time step of 0.5 fs.

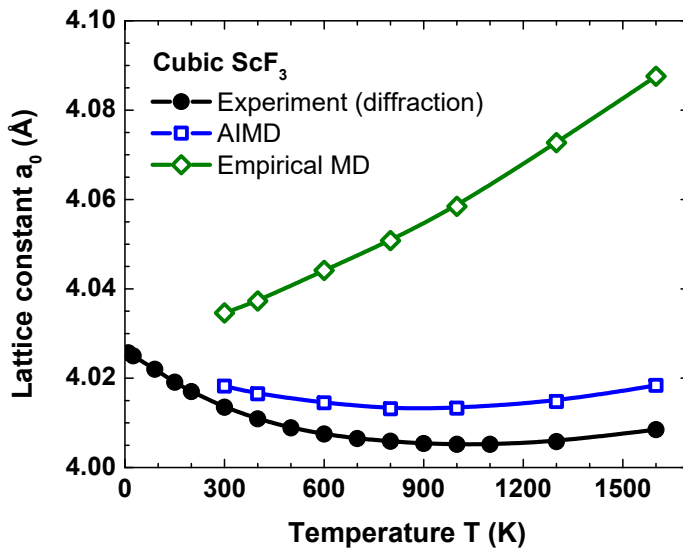
The temperature were controlled using the Nosé–Hoover thermostat. Sets of atomic configurations were generated during the MD simulations performed for  $5a_0 \times 5a_0 \times 5a_0$  supercells with 500 atoms and used further to calculate the lattice constants  $a_0$  (Fig. 1), the radial distribution functions (RDFs) Sc–F and Sc–Sc (Fig. 2) and the bond angle distribution functions (BADFs) Sc–F–Sc (Fig. 3).

## 3. Results and discussion

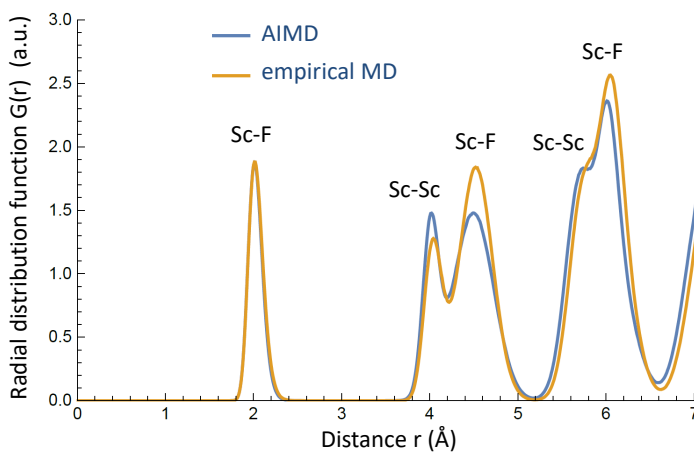
Temperature dependencies of the lattice constant  $a_0$  obtained from empirical MD and AIMD simulations are compared with the experimental diffraction data from [6] in Fig. 1. The AIMD results reproduce the NTE effect in  $\text{ScF}_3$  and agree well with the experimental data, overestimating only slightly (less than 0.01 Å) the absolute values of the experimental lattice constant. On the contrary, empirical MD predicts strong positive expansion of the lattice being always above both the experimental and AIMD data.

The difference in the behaviour of lattice constants for two simulation methods is also visible in the RDFs  $G(r)$  in Fig. 2, where the RDF peaks obtained by empirical MD are slightly shifted to larger distances. However, both MD simulations predict anharmonic Sc–F bonding, leading to the visible asymmetry of the first peak in the RDFs at 2 Å. This result supports the importance of anharmonic effects in  $\text{ScF}_3$  [10].

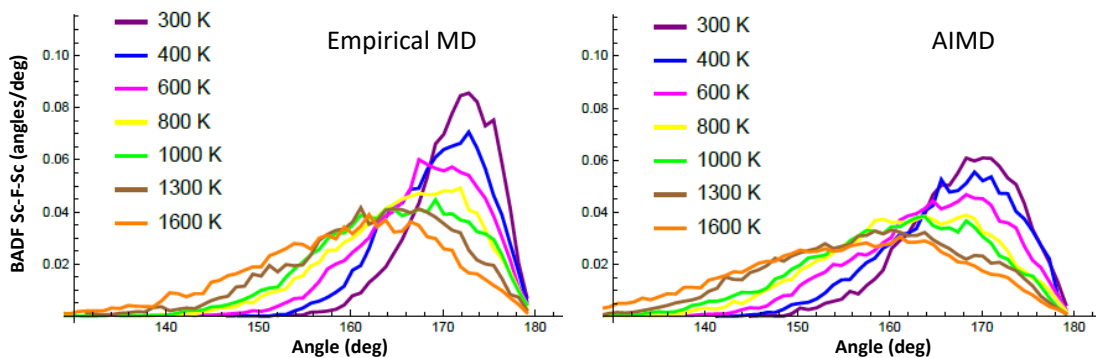
Finally, the temperature dependencies of the average bond angle Sc–F–Sc between two nearest  $\text{ScF}_6$  octahedra are shown in Fig. 3. Note that there is a principal difference between the average bond angle Sc–F–Sc calculated from the instantaneous atomic coordinates, which deviates always from  $180^\circ$  due to transverse atom motion, and the Sc–F–Sc angle calculated from the average atomic positions, which is equal to  $180^\circ$  in cubic  $\text{ScF}_3$ . As one can see, an increase of temperature



**Figure 1.** Temperature dependence of the lattice constant  $a_0$  of cubic  $\text{ScF}_3$  obtained from empirical MD and AIMD simulations in the NpT ensemble in comparison with the experimental data from [6].



**Figure 2.** The total radial distribution functions  $G(r)$  for Sc-F and Sc-Sc atom pairs at 600 K calculated using the results of the empirical MD and AIMD simulations in the NpT ensemble.



**Figure 3.** The inter-octahedral Sc-F-Sc bond angle distribution function calculated using the results of the empirical MD and AIMD simulations in the NpT ensemble.

leads to the broadening of BADF and its maximum shifts to smaller angles due to an increase of the amplitude of transverse vibrational motion of fluorine atoms. This effect is observed in

both empirical MD and AIMD simulations. However, the Sc–F–Sc BADFs obtained by AIMD are always broader than those from empirical MD and extend to smaller angular values. This suggests slightly larger vibration amplitude of atoms in the AIMD simulations.

#### 4. Conclusions

*Ab initio* and empirical molecular dynamics simulations of cubic ScF<sub>3</sub> were performed in the NpT ensemble and using large  $5a_0 \times 5a_0 \times 5a_0$  supercells in the temperature range of 300–1600 K. Both simulations predict anharmonic nature of the Sc–F bonds and large amplitude of fluorine atoms transverse motion, which increases at higher temperatures. The negative thermal expansion of the ScF<sub>3</sub> lattice is well reproduced only by *ab initio* MD simulations, which predict the lattice constant values close to those obtained experimentally by diffraction in [6] and a crossover of thermal expansion from negative to positive around 1100 K upon increasing temperature. Empirical MD simulations fail to predict the NTE effect and shows only positive expansion.

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