

# Structure Optimization, Dielectric and Magnetic Properties of Pure Silicon as well as Iron-Doped Silicon and Tin Clusters

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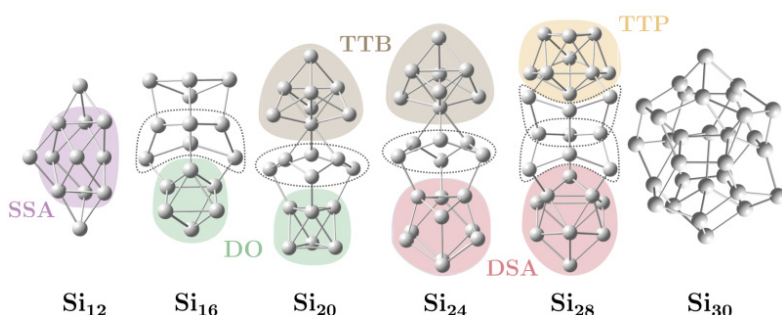


Figure 1: Exemplary selected geometric structures of  $\text{Si}_N$  clusters to indicate the prolate growth pattern up to the cluster  $\text{Si}_{30}$  which is quasi-spherical. The reappearing sub-units are highlighted by different colours: distorted octahedron (DO, green), pentagonal bipyramid (PB, blue), triple-capped trigonal bipyramid (TTB, brown), double-capped trigonal prism (DTP, yellow), triple-capped trigonal prism (TTP, orange), single-capped square antiprism (SSA, purple) and a double-capped square antiprism (DSA, red). Additionally, reoccurring bowl-shaped  $\text{Si}_6$  units are circled with a dashed line.

## Introduction

The previous investigation of  $\text{Sn}_N$  clusters with  $N = 6-40$  showed that below a clusters size of about 30 atoms, a prolate structure growth is dominant. However, larger clusters with  $30 < N < 40$  show again a quasi-spherical shape. Silicon is also a tetrel and the physico-chemical properties of clusters made of silicon and tin are shown to be very similar on the nanoscale. Therefore, it is interesting to investigate the geometric structures of silicon clusters and to compare both systems to get a deeper insight on the growth pattern of tetrel clusters. Additionally, we investigated the magnetic properties of endohedrally doped  $\text{Sn}_{12}\text{TM}$  clusters with  $\text{TM} = \text{Cr}, \text{Mn}$  and  $\text{Fe}$ . It was already observed that  $\text{Sn}_{12}\text{Mn}$  has very special magnetic properties, since it shows a high spin relaxation time within the time scale of the beam deflection experiment. To get a better understanding of the magnetic properties of doped tetrel clusters in general, we investigated the  $\text{Sn}_{12}$  clusters doped by  $\text{Cr}$  and  $\text{Fe}$  which are adjacent to  $\text{Mn}$  in the periodic table experimentally and by quantum chemical calculation.

## Methods

Energetically-favored initial geometries were generated using a plane-wave Density Functional Theory-based (pw-DFT) Genetic Algorithm (GA) developed in our group. These calculations are performed using the Quantum Espresso software package.

Possible candidates are then optimized on the PBE0/def2-TZVPP level of theory. The existence of local minima has been verified by frequency analysis. These calculations were carried out with the quantum chemical program Gaussian16.

Additionally, for the endohedrally doped Sn<sub>12</sub> clusters the magnetic properties are calculated with ORCA v5.0.4 on the DFT level of theory. Since it was shown that the results often do not match the experimental values, complete active space self-consistent field calculations (CASSCF) are carried out, for the first time for such large systems, to get a better description of the electronic structure and, thus, more accurate results on the magnetic properties.

## Results

The comprehensive study of the geometrical structure of Si<sub>N</sub> clusters with N = 12 – 30 shows that for this system the growth pattern is also dominated by prolate structures which are built of reappearing, very stable sub-units. Starting with the cluster Si<sub>27</sub> quasi- spherical shapes appear again. For Si<sub>30</sub> no more prolate shapes are found by quantum chemical calculations.

The calculation on the CASSCF level of theory of the g-factor which represents the magnetic properties revealed that the very different values observed experimentally for the three Sn<sub>12</sub> clusters doped with Cr, Fe and Mn originate from spin-orbit coupling (SOC) between the tin cage and the dopant. Since there is no SOC in Sn<sub>12</sub>Mn, the g-value is equal to the value of the free electron,  $g = 2$ , as already predicted by DFT.

## Discussion

For most of the Si<sub>N</sub> clusters with N = 12 – 30 an assignment of one structural isomer to the experimental data is possible. Additionally, it could be shown that, in contrast to Sn<sub>N</sub>, for no cluster size two isomers are simultaneously present in the molecular beam. However, no distinct assignment of a structural isomer is possible for Si<sub>26</sub> and Si<sub>28</sub> based on our experiment, since the dielectric properties of all found isomers are very similar. Furthermore, it could be seen that a change of the exchange-correlation functional has a huge impact not only on the calculated value of the electric dipole moment but also on the energetic order of the structural isomers.

A more detailed analysis of the electronic excitations in Sn<sub>12</sub>TM with TM = Cr, Mn and Fe, firstly confirmed that no significant spin-orbit effects influence the g-factor of Sn<sub>12</sub>Mn. Because of this, the value for the g-factor was already predicted correctly by DFT calculations. For Sn<sub>12</sub>Cr and Sn<sub>12</sub>Fe the g-factor is slightly lower and much higher, respectively, than the value of the free electron. The much more time consuming CASSCF calculations reveal that the different shifts originate from different kinds of electronic excitations relevant for the g-factor.

## Publications

Rivic, F.; Schäfer, R. Magnetism of single-doped paramagnetic tin clusters studied using temperature-dependent Stern-Gerlach experiments with enhanced sensitivity: impact of the diamagnetic ligand field and paramagnetic dopant. *Phys. Chem. Chem. Phys.* 26, 12982-12992 (2024) <https://doi.org/10.1039/D4CP00890A> Rivic, F.; Lehr, A.; Schäfer, R. Dielectric Behavior and Prolate Growth Patterns of Silicon Clusters SiN with N = 12–30 by Cryogenic Electric Beam Deflection. *J. Phys. Chem. A* 128, 1853-1862 (2024) <http://dx.doi.org/10.1021/acs.jpca.3c08432>

Rivic, F. Influence of size and composition on the dielectric and magnetic properties of pure and doped tetrel clusters. PhD thesis, TU Darmstadt, (2024)

Lehr, A. The Interplay of Geometric and Electronic Structure in (Doped) Tetrel Clusters: A Study of Optical Spectroscopy and Magnetic Deflection in the Molecular Beam. PhD thesis, TU Darmstadt (2023)

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