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Communication: Structure of magnetic lanthanide clusters from far-IR spectroscopy: \( \text{Tb}_n^+ \) (\( n = 5\)–\( 9 \))

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Small lanthanide clusters have interesting magnetic properties, but their structures are unknown. We have identified the structures of small terbium cluster cations \( \text{Tb}_n^+ \) (\( n = 5\)–\( 9 \)) in the gas phase by analysis of their vibrational spectra. The spectra have been measured via IR multiple photon dissociation of their complexes with Ar atoms in the 50–250 cm\(^{-1}\) range with an infrared free electron laser. Density functional theory calculations using a 4f-in-core effective core potential (ECP) accurately reproduce the experimental far-IR spectra. The ECP corresponds to a \( 4f^8\) trivalent configuration of terbium. The assigned structures are similar to those observed in several other transition metal systems. From this, we conclude that the bonding in Tb clusters is through the interactions between the 5d and 6s electrons, and that the 4f electrons have only an indirect effect on the cluster structures. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4776768]

Small clusters of lanthanide elements are promising materials for molecular magnets, due to their large magnetic moments and strong spin-orbit interaction.1 The magnetism of lanthanide metal clusters originates from the Ruderman, Kittel, Kasuya, Yosida (RKKY) indirect exchange interaction,2 and the magnetic anisotropy is primarily due to the interaction between the asymmetric 4f charge cloud and the local crystal field. Both of these properties are highly dependent on the geometric structure, and the lack of knowledge of the cluster structures is a major barrier to understanding their magnetism. To obtain fundamental insights into their properties, the clusters can be studied in gas-phase molecular beam experiments, which provide an environment free of external influences.

The magnetism of lanthanide clusters has been studied experimentally using the Stern-Gerlach deflection technique.3 These experiments demonstrated that lanthanide clusters3 have large size-dependent magnetic moments and in some cases, Curie temperatures much higher than the corresponding bulk materials. Theoretically, the \( \text{Gd}_{13} \) cluster has been most extensively studied: In Ref. 5, the cluster structures were taken to be fragments of the bulkhcp lattice, and the magnetism was described phenomenologically with a Heisenberg Hamiltonian. The exchange constants which describe the strength of the interaction between local 4f moments due to the RKKY interaction were taken as undetermined parameters, rather than properly estimated from electronic structure calculations. In fact, little to nothing is known about the physics of the RKKY interaction in small sub-nanometer particles. This situation stands in sharp contrast to the present understanding of the bulk lanthanides where many physical properties are well understood with simple models, and first-principles theory can calculate magnetic ordering temperatures with near quantitative accuracy.2,6 The structures of the bulk lanthanides are all known from X-ray diffraction on single crystal and thin film samples, and the lack of such structural information is a major barrier preventing the application of high-level theory to small clusters. A recent theoretical study of the \( \text{Gd}_{13} \) cluster,7 which attempted to include the 4f electrons, concluded that the lowest energy structures were icosahedral, rather than hcp-like, contradicting the previous results of Ref. 5. Despite this, lanthanide clusters have received little or no attention from experimental structural studies.

State of the art computational electronic-structure theory still has many difficulties with reliable prediction of cluster structures and their related properties from first principles. This holds in particular for metals with partially filled d (transition metals) or f (lanthanides, actinides) shells or for heavy elements, such as gold, where relativistic effects are significant. Experimental data are therefore essential for testing the validity of predictions and in motivating methodological developments. To this end, hybrid experimental/theoretical studies with photoelectron spectroscopy,8 trapped-ion electron diffraction,9 and far-IR spectroscopy10–12 have provided invaluable information on the structures of small metal clusters. To identify the cluster structures, we present here experimental far-IR vibrational spectra for cationic terbium clusters in the gas phase, mass-selectively measured by the dissociation of weakly bound Ar messenger complexes. This method has been successfully applied before, e.g., to transition metal clusters.10,11,13–16 Terbium was chosen because there is a single naturally occurring isotope, which is beneficial for mass spectrometric studies, and it can be reasonably expected to behave as a prototype for the heavy lanthanides2,17 (Gd, Tb, Dy, Ho, Er), which are all trivalent and have the same hcp bulk lattice type.

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The Free Electron Laser for Infrared eXperiments (FELIX) in Nieuwegein, the Netherlands, was used as the far-IR source for these experiments. The experimental setup and methods have been described in previous publications\textsuperscript{10, 13} and we only give a brief summary of the relevant details here. Tb clusters are produced in a laser vaporization cluster source, which is in part cooled to 77 K. The He carrier gas is seeded with 5% Ar, which leads to the formation of a small population of weakly bound Ar complexes of the Tb\textsuperscript{+}\textsubscript{n} clusters. The cluster beam is irradiated by the tunable far-IR radiation from FELIX and mass analyzed with a reflectron time-of-flight mass spectrometer. The FELIX beam used in the experiment delivers an energy on the order of $\approx 10$ mJ within a pulse of about 7–9 \(\mu\)s duration. Mass spectra of alternating shots from the cluster source with FELIX toggled on and off are stored into separate channels of a digitizer and in total about 500 mass spectra are averaged per channel and frequency interval. The IR induced relative depletion of the mass signals for the Tb\textsuperscript{+}\textsubscript{n}-Ar complexes is evaluated as a function of IR frequency to obtain the size specific far-IR spectra.

The experimental IR spectra for Tb\textsuperscript{+}\textsubscript{n} (\(n = 5–9\)) are shown in Figs. 1–3. There are well-resolved absorption bands for most cluster sizes. The spectra of the smaller sizes, \(n = 5, 6,\) and 7, are dominated by a single intense feature, which may suggest a highly symmetric structure, while the larger sizes, \(n = 8\) and 9 have more richly featured spectra. For the studied cluster sizes, we find absorption bands in the 50–160 cm\(^{-1}\) range, which is approximately the range where the optical phonon branches of the bulk metal were observed by neutron scattering.\textsuperscript{18} With few exceptions, all observed metal cluster vibrations are below the reported value for the stretching frequency of the neutral Tb\textsubscript{2} of 137 cm\(^{-1}\).\textsuperscript{19}

To identify the clusters’ structures based on the experimental spectra, we perform quantum chemical calculations using density functional theory (DFT). We use the Perdew-Burke-Ernzerhof (PBE) functional\textsuperscript{20} for exchange and correlation as implemented in TURBOMOLE 6.2.\textsuperscript{21} The treatment of the 4\(f\) electrons with DFT remains a challenge because they...
occupy an open shell and are highly localized to their parent atoms, where correlation effects are strong. Their strong localization also implies that they do not directly participate in chemical bonding. Standard DFT functionals are known to falsely delocalize the 4f electrons, and explicit treatment of the 4f states requires corrections such as LDA+U. Alternatively, it is possible to exploit the localization of the 4f states and treat them as a part of the core with an effective core potential. We follow this approach, using the ECP54MWB effective core potential developed by Dolg et al. The valence orbitals are described with the (6s6p5d6f4s4p4d) + 2s1p1d (ECP54MWB-II) basis set. The ECP includes 8 4f electrons in the core. This corresponds to the commonly observed trivalent (4f85d6s2) configuration of the terbium atom, which differs from the 4f65s2 ground state of the neutral gas-phase Tb atom. The trivalent state is most commonly found for the heavy lanthanides in bulk and molecular form because the 4f to 5d promotion energy is dominated by the bonding or cohesive energy of the 3+ state. We investigated the possibility of divalent Tb in our calculations using the ECP55MWB ECP, but found non-bonding or non-convergent structures.

For metal clusters, the interrogation of the configurational space becomes rapidly more complex with growing size and many locally stable arrangements of atoms, in addition to the true global minimum, may be identified for any given cluster size. We investigated a wide range of possible isomers starting with geometries that have been reported for transition metal clusters (after scaling the interatomic distances to values, which match the bulk values for Tb) including those that have been identified in our previous studies, followed by local optimization. In addition, for several sizes, we used Monte-Carlo basin-hopping sampling to locate other local minima. No symmetry constraints have been applied. For all local minima found, the IR spectra have been calculated analytically based on the harmonic approximation; the frequencies are not further scaled. For n = 5–7, alternative isomers are typically much higher in energy. This suggests that the potential-energy surface is quite smooth.

An additional parameter of the calculations is the electronic occupation of the valence states. In all of these calculations, electronic states with different numbers of unpaired 5d6s valence electrons have been considered in order to identify the preferred configuration. The spin states we refer to in the following only relate to the 5d6s occupation as the 4f occupation as the 4f s, d orbitals are always full. (The 4f orbitals are full in our calculations using the ECP55MWB-II fits the experiment better, and the energy difference of 0.1 eV is too small to be considered meaningful.

The lowest energy isomer identified by theory does not always give the best match to the theory, a case illustrated by Tb5+. Tb5+ has 17 (5d6s) electrons, one fewer than the 18 needed to satisfy a spherical shell closing. This would indicate a preference for a low-spin distorted geometry over the octahedral structure. However, the highly symmetric octahedral structure has high density of states at the HOMO, which increases the energy gained by exchange splitting in a high spin state. It is possible for this effect to stabilize a highly symmetric structure against a Jahn-Teller distortion. Indeed, the calculations predict that the S = 5 octahedral structure is 0.3 eV lower in energy than the distorted low-spin (S = 1/2) structure, but appears to match the experimental spectrum better. It is important to note, however, that the geometric difference between 6a and 6c is small, (the bond lengths differ by 2–5%) and their vibrational spectra are very similar. The octahedral structure 6a actually has a triply degenerate vibrational mode located at 100 cm−1, which is close to where an intense feature is observed in the experimental spectrum. However, the IR intensities calculated for these modes are very low. Further investigation is required to understand whether the presence of the Ar, or the inclusion of the 4f
electrons would change the IR intensities of these modes. Thus, our experiment cannot determine conclusively whether Tb$^+$ is a perfect octahedron.

To conclude, we have demonstrated that far-IR spectroscopy allows for structural assignment for small lanthanide clusters. Our theoretical approach, where the 4$f$ electrons are treated as a part of the core, predicts the frequencies and IR intensities of the cluster vibrational modes with remarkable accuracy. This confirms that, such as the bulk materials, the 4$d$ charges are predominantly localized in the metal clusters and do not directly participate in bonding. The structures identified are similar to the geometries found for transition metal clusters. In this sense, heavy lanthanides behave like early transition metals with small d-occupation. It is also highly surprising that the structures can be determined while the magnetic or-der and 4$f$ – (5d-6s) exchange interaction are completely neglected. Knowledge of the cluster structures will enable the application of higher level theory for an explicit treatment of the 4$f$ electrons, which in turn will provide a detailed understanding of lanthanide cluster magnetism.

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4Gd, Tb, Dy, Pr, Ho, and Tm have been studied.
25See http://www.theochem.uni-stuttgart.de/pseudopotentials/ for the ECP and basis set.
27See supplementary material at http://dx.doi.org/10.1063/1.4776768 for atomic coordinates, energies, and calculated IR-spectra of all isomers.