Electronic Structure and Magnetic Anisotropy in Lanthanoid Single-Ion Magnets with $C_3$ Symmetry: The Ln(trenovan) Series

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Supporting Information

ABSTRACT: We report the syntheses and the magnetic characterization of a new series of lanthanide complexes, in which the Ce, Nd, Gd, Dy, Er, and Yb derivatives show single-molecule magnet behavior. These complexes, named Ln(trenovan), where $H_3$trenovan is tris((3-methoxysalicylidene)amino)ethyl)amine, exhibit trigonal symmetry and the Ln(III) ion is heptacoordinated. Their molecular structure is then very similar to that of the previously reported Ln(trensal) series, where $H_3$trensal is $2,2',2''$-tris(salicylideneimino)triethylamine. This prompted us to use the spectroscopic and magnetic properties of the Ln(trensal) family (Ln = Nd, Tb, Dy, Ho, Er, and Tm) to obtain a set of crystal-field parameters to be used as starting point to determine the electronic structures and magnetic anisotropy of the analogous Ln(trenovan) complexes using the CONDON computational package. The obtained results were then used to discuss the electron paramagnetic resonance (EPR) and ac susceptibility results. As a whole, the obtained results indicate for this type of complexes single-molecule magnet behavior is not related to the presence of an anisotropy barrier, due to a charge distribution of the ligand around the lanthanoid, which results in highly mixed ground states in terms of $M_J$ composition of the states. The crucial parameter in determining the slow relaxation of the magnetization is then rather the number of unpaired electrons (only Kramers ions showing in-field slow relaxation) than the shape of the charge distribution for different Ln(III).

INTRODUCTION

The discovery of slow relaxation of magnetization on terbium-phthalocyanininate by Ishikawa and co-workers$^1$ was a breakthrough in molecular magnetism, and, since then, mononuclear lanthanide single-molecule magnets (SMMs) have been coming out on top.$^2$ The interesting magnetic behavior of lanthanide ions arises from a strong magnetic anisotropy and a large total angular momentum $J$, which are the fundamental keys to potentially observe single-molecule magnetism.$^3,4$ Indeed, these systems have been proposed as potential candidates for applications in molecular spintronics, high-density storage, and quantum information processing.$^5,6$ However, any future technological achievement is subordinate to a deepened understanding of the behavior of these molecular nanomagnets, starting from the clarifications of the different mechanisms involved in the relaxation of magnetization.$^7$

From an empirical point of view, it is fundamental to use a combined approach of spectroscopic and magnetic characterization, in order to have a detailed picture of the electronic structure in these complexes.$^8,9$ In this context, the Ln(trensal) (where $H_3$trensal, sketched in Scheme 1, is $2,2',2''$-tris(salicylideneimino)triethylamine) series has been recently shown to be a good benchmark, since its luminescence investigation has been known for a few years.$^7$ The phenomenological determination of the symmetry-allowed crystal-field parameters (CFPs), derived from the luminescence spectra, allowed the estimation of the magnetic properties of the family, which were compared with experimental results. In some cases, small discrepancies were found,$^10$ especially for those compounds whose lowest energy levels were not

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spectroscopically observed. This emphasizes the need to take into account also the magnetic and electron paramagnetic resonance (EPR) characterization for an accurate description of the ground-multiplet crystal-field splitting, to which these techniques are more sensitive.

From a theoretical point of view, the CFPs can be calculated using the molecular crystal structures with different approaches. These allow the prediction of spectroscopic and magnetic properties and the rational design of new derivatives exhibiting SMM behavior. The simplest and earliest developed procedure is based on the point charge electrostatic model (PCEM), which was later improved by several semiempirical models. These models, while useful for computationally inexpensive predictions and for determining an initial set of CFPs, also need parametrization to take into account covalency, in order to provide a more realistic description of the system. A computationally more expensive approach is based on the calculation of the energy levels using post Hartree–Fock multiconfigurational calculations, the so-called ab initio methods. In general, this methodology has been widely used for the theoretical characterization of SMMs, as first-principle methods are expected to provide results closer to reality than the more intuitive additive electrostatic methods. Nevertheless, deviations between theoretical and experimental observables have recently been accumulating, revealing that modeling the properties of f-element complexes from first-principles still remains an open problem. This is a particularly compelling issue when comparison between structurally related systems with minor chemical differences are investigated, since the resulting differences in the energy patterns can easily be smaller than the uncertainty provided by the calculations. In such cases the analysis of the magnetic behavior of the complete Ln series may also provide some precious information about the observed trend along the series.

For these reasons we decided to investigate the static and dynamic magnetic properties of a new family of lanthanide complexes, Ln(trenovan) (where H₃trenovan, sketched in Scheme 1, is tris(((3-methoxysaliclidene)amino)ethyl)amine and Ln = Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, and Yb), which only differs in a methoxy-substituted position on the ligand from the above-mentioned Ln(trensal) family. For the latter series we report here the static magnetic characterization, which is used, in combination with the previously reported luminescence data, to obtain an improved description of the electronic structure of the complexes of this series.

This was then used as a starting point for the characterization of Ln(trenovan) complexes. Analogously to Ln(trensal), this new series features crystallographically imposed trigonal symmetry (Figure 1). However, due to the impossibility to obtain crystalline samples and their corresponding single crystal spectroscopic and/or magnetic measurements, we had to follow a different approach. We then resorted to a phenomenological approach, by using the CONDON computational package. This was first used to extract a new set of CFPs for each Ln(trensal) derivative prepared, Ln = Nd, Tb, Dy, Ho, Er, and Tm, by simultaneously fitting all the available spectroscopic and magnetic data. Subsequently, we used these improved sets of CFPs obtained for Ln(trensal) as initial guesses for the determination of the CFPs of Ln(trenovan). Such CFPs are obtained by performing a fit of magnetic susceptibility taking into account the Zeeman splitting of the ground doublet via the g-factors experimentally determined by EPR.

### EXPERIMENTAL SECTION

**Ln(trenovan) Family. Synthesis.** All starting materials were purchased from Aldrich and used without further purification. The H₃trenovan ligand, tris(((3-methoxy)salicylidene)amino)ethyl)amine, resulting from reaction of tris(2-aminoethyl)amine with orthovanillin was obtained as previously described. The different complexes were prepared according to two different experimental pathways. For

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**Scheme 1. Sketches of H₃trensal and H₃trenovan**

**Figure 1.** Left panel: View along the crystallographic axis a of a molecule of Pr(trenovan), as representative of the whole series. The Ln ion (green) is coordinated to three oxygens (red) and four nitrogens (light blues). Right panel: View along the c-axis.
Table 1. Crystal Structure Data for Pr(trenovan), Gd(trenovan), and Tm(trenovan)

<table>
<thead>
<tr>
<th>Compound</th>
<th>Pr(trenovan)</th>
<th>Gd(trenovan)</th>
<th>Tm(trenovan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula</td>
<td>C_{2}H_{12}N_{3}O_{5}Pr</td>
<td>C_{2}H_{12}N_{3}O_{5}Gd</td>
<td>C_{2}H_{12}N_{3}O_{5}Tm</td>
</tr>
<tr>
<td>M</td>
<td>686.5</td>
<td>702.8</td>
<td>714.5</td>
</tr>
<tr>
<td>temp/K</td>
<td>293</td>
<td>293</td>
<td>293</td>
</tr>
<tr>
<td>Wavelength/Å</td>
<td>1.54056</td>
<td>1.54056</td>
<td>1.54056</td>
</tr>
<tr>
<td>Cryst syst</td>
<td>trigonal</td>
<td>trigonal</td>
<td>trigonal</td>
</tr>
<tr>
<td>Space group</td>
<td>P3</td>
<td>P3</td>
<td>P3</td>
</tr>
<tr>
<td>a/Å</td>
<td>14.456(1)</td>
<td>14.240(1)</td>
<td>14.001(1)</td>
</tr>
<tr>
<td>b/Å</td>
<td>14.456(1)</td>
<td>14.240(1)</td>
<td>14.001(1)</td>
</tr>
<tr>
<td>c/Å</td>
<td>8.877(1)</td>
<td>8.121(1)</td>
<td>8.347(1)</td>
</tr>
<tr>
<td>V/Å³</td>
<td>1427.34(1)</td>
<td>1426.25(1)</td>
<td>1417.11(1)</td>
</tr>
<tr>
<td>Z</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Rw p</td>
<td>7.4</td>
<td>5.6</td>
<td>9.7</td>
</tr>
<tr>
<td>Rw w</td>
<td>5.6</td>
<td>4.3</td>
<td>7.9</td>
</tr>
</tbody>
</table>

Simulated annealing was performed with EXPO2013,39 using one-third of the molecule plus the nitrogen and the ion Tm constrained to lie along the C2 axis. Ten runs for the simulated annealing trial were set, and a cooling rate (defined as the ratio $T_n/(T_n-1)$) of 0.95 was used. Best solutions were chosen for Rietveld refinements, which were performed with the software TOPAS. A shifted Chebyshev function with 16 parameters and a pseudo-Voigt function were used to fit background and peak shape, respectively. Soft constraints were applied for all bond distances and angles of the Tm(trenovan) molecule. An overall thermal parameter was adopted for all atoms of the structure. All the hydrogen atoms were fixed in calculated positions. Refinement converged with $\chi^2 = 1.28$ and $\text{Rwp} = 9.68$ (see Table 1). The structures of Pr(trenovan) and Gd(trenovan) were solved starting from the solution obtained for Tm(trenovan) considering the three structures isomorphous. The unit cell parameters, atomic coordinates, and peak shape were refined (see Figure 1 for the molecular structure).

**Determination of Unit Cell Parameters (Pawley Refinement).** Powder diffraction data for 12 different Ln(trenovan) structures were analyzed with the software Highscore Plus. Fifteen peaks were chosen in the $2\theta$ range 3–40°, and unit cell parameters were found thanks to the algorithm DICVOL. Pawley refinement was performed for all 12 unit cell parameters, and results are shown in Table S1.

**Ln(trensal) Family. Synthesis and XRPD Measurements.** For both Ln(trenovan) and Ln(trensal) compounds dc magnetic measurements were performed by using a Quantum Design MPMS SQUID magnetometer on powders pressed in a pellet to avoid field-induced orientation of the crystallites. For the Ln(trenovan) series, raw data were rescaled by taking into account the presence of residual DMF lattice solvent, as estimated by thermogravimetric analysis (TGA) (see Table S2). Diamagnetic corrections were calculated using Pascal’s constants and are available in the Supporting Information.

**Magnetic Characterization and Electronic Structure. Magnetic Measurements.** The electronic structures of Ln(trensal) were calculated using Pascal’s constants and are available in the Supporting Information.

**Effect on Crystallinity.** The electronic structures of Ln(trensal) and Ln(trenovan) complexes (Ln = Nd, Tb, Dy, Ho, Er, Tm), where $H_{trensal} = 2,2,2’$-tris(salicylideneimino)trimethylamine, were synthesized as previously described. X-ray powder diffraction patterns of all compounds were measured with a Bruker D8 Advance powder diffractometer equipped with a Cu source ($K_{\alpha} = 1.54 \text{ Å}$).
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local symmetry using the full basis of microstates. In the first family, we have used as an input the parameters of the ligand-field Hamiltonian determined by Flanagan et al. (electron repulsion parameters: \( F_k^\alpha = 2, 4, 6 \)), spin–orbit coupling constant \( \xi_{SO} \), and the non-negligible crystal field parameters for \( C_3 \) symmetry: \( B_2^0, B_4^0, B_6^0, B_4^0, B_6^0, B_8^0 \). In order to model the properties of the series Ln(trensal), all the available luminescence spectra as well as the magnetic susceptibility data have been simultaneously fitted. In the case of Er(trensal) we have also taken advantage of the magnetic properties in the easy axis direction reported by Pedersen et al.\(^{63} \) In the CONDON package, the goodness of the fit (SQX) is defined as follows:

\[
SQX = \sqrt{\sum_{\nu=0}^{n} \left( \frac{1 - \chi_{\text{calc}}}{\chi_{\text{exp}}} \right)^2}
\]

where \( \chi_{\text{calc}} \) and \( \chi_{\text{exp}} \) are the calculated and measured magnetic susceptibility, respectively, \( \sigma \) is a weighting factor, which as standard is 1, and \( n \) is the number of points included in the fit. In the Ln(trensal) family, where spectroscopic information has been included, the same definition of SQX works, but in this case replacing \( \sigma \) by \( E \). In the cases in which experimental energy levels from the ground multiplet were available (Er and Tm), such levels have been weighted using \( \sigma = 0.1 \), giving priority to them in the fitting procedure, in order to obtain a better description of the magnetic properties.

In the compounds of the family Ln(trenovan), for which spectroscopic and single-crystal magnetometry data could not be obtained, we combined the fit of the magnetic susceptibility data with that of the experimental \( g_E \) value determined by EPR, which describes the evolution of the ground doublet under an applied magnetic field. The fitting procedure started from the CFPs calculated for the analogous Ln(trenal) derivatives.

**EPR Spectroscopy.** X-band (\( \nu \approx 9.4 \) GHz) and W-band (\( \nu \approx 94 \) GHz) EPR spectra were recorded using commercial Bruker E500 and E600 spectrometers in the Laboratory of Molecular Magnetism, Florence. Multifrequency high-field EPR spectra were recorded on a homemade instrument at LNCMI, Grenoble.\(^{31} \) All the samples were undiluted except Gd(trenovan) and Dy(trenovan), for which the isostructural complexes YGd(trenovan) and YDy(trenovan) were studied (5.6% and 8.2% Gd(III) and Dy(III), respectively). Simulation of the W-band EPR spectrum of Gd(trenovan) was achieved using the Matlab toolbox Easyspin.\(^{34} \)

**RESULTS AND DISCUSSION**

**Syntheses.** The lighter Ln complexes are prepared according to the previously published two-step process\(^{26} \) in which the first step corresponds to complexation of Ln ions by the outer \( O_3O_3 \) coordination site of the tripodal ligand, with a proton transfer from the phenol function to the imine function. In that complex the ligand is in a zwitterionic phenoxo-iminium form, which implies the presence of nitrate anions as counterions. The resulting complex is isolated and deproto-

**Structures and Symmetries.** Upon recrystallization, the consistency of Ln(trenal) complexes (Ln = Nd, Tb, Dy, Ho, Er, Tm) with reported ones was checked by XRPD (Supporting Information, Figures S2). The same technique was used to check for the isostructurality of Ln(trenovan) complexes in the series. The determination of the unit cell on the basis of the powder X-ray pattern reveals that the complexes crystallize in the space group \( P\overline{3} \) (Table 1) and that the cell parameters vary regularly along the series (see Figure S3): the \( c \) axis increases linearly on increasing the atomic number, while \( a \) (h) contracts. Since the rate of variation of unit cell dimension vs \( Z \) is essentially the same for the two directions, the unit cell volume decreases as expected along the series\(^{35} \) (see Figure S3). The structures of Pr(trenovan), Gd(trenovan), and Tm(trenovan) were then determined starting from powder data. As expected on the basis of the structure of complexes with closely similar ligands, the Ln center is heptacoordinated by three equivalent imino nitrogen atoms, three equivalent phenoxy-oxygen atoms, and an axial amionic nitrogen. Furthermore, the Ln ion sits on a \( C_3 \) axis, a point of relevance for the subsequent analysis of the magnetic data (see below). In this respect the coordination geometry around the lanthanide is strictly similar to that observed in the Ln(trensal) series\(^{31,36} \) and complexes of related ligands.\(^{19,41} \) There is however a relevant difference compared to the Ln(trensal) series: as a first point, the Ln–N(ammine) distance is much shorter in the Ln(trenovan) complexes than in the trensal one, ranging from 2.57 Å for Pr(III) to 2.55 Å for the Tm(III) derivative, as compared to 2.8 to 2.71 Å for the Ln(trensal) complexes. This Ln–N(ammine) is extremely short when compared to those observed in similar complexes and suggests that the ligand field strength for Ln(trenovan) might be stronger than in Ln(trensal). It is worth noting that the differences in the Ln–N(imino) and in the Ln–O distances are much less important (see Table S3). Finally, we stress that the oxygens of the methoxy substituent are located at a nonbonding distance ranging from 4.69 to 4.57 Å.

Since the lanthanide ions are lying on a \( C_3 \) site, the number of nonzero CFPs is reduced, and the crystal field splitting over the different multiplets can be described by means of the following CF Hamiltonian (expressed in the Wybourne formalism):

\[
H_{\text{CF}} = B_2^0 C_2^0 + B_4^0 C_4^0 + \text{Re} B_6^0 (C_6^0 - C_4^0) + B_8^0 C_8^0 + \text{Re} B_6^0 (C_6^0 - C_4^0) + i \text{Im} B_6^0 (C_6^0 + C_4^0)
\]

where \( B_2^0 \) are the Wybourne crystal field parameters, which are in general complex, with the exception of \( q = 0 \). The real \( \text{Re} B_6^0 \) and imaginary \( \text{Im} B_6^0 \) parts are by definition real quantities. \( C_q^m \) are the Wybourne operators.\(^{34,45} \)

**Modeling the Static Magnetic Properties.** Compared to the previous investigations on Ln(trensal), we had to follow a different approach to analyze the magnetic and spectroscopic properties of Ln(trenovan). Indeed, syntheses did not provide single-crystal samples but only powders, so that it was not possible to perform a high-resolution luminescence investigation or other single-crystal characterization, like torque magnetometry, which was fundamental in elucidating the electronic structure of Ln(trensal).\(^{11,12} \) A possible path to gain information on the electronic structure, in cases like this one, would have involved performing theoretical calculations using the crystal structures as input. For that we could use \textit{ab initio} methods, but in this case we had to deal with a series of different problems: (1) The molecular structures were obtained from powder X-ray data, which, despite their high quality, provide somehow larger uncertainties on atomic positions than single crystal ones; (2) it was also not possible to use a simplified, or optimized, molecular structure, since this would have amounted to assuming the same structure as Ln(trensal),
making a comparison between the two series meaningless; (3) the calculations for the whole series was quite demanding and their validation on the basis of experimental studies would not have been as strong as for other complexes, due to the reasons outlined above. The latter point is even more relevant if one considers that the calculated CFPs by CASSCF in Er(trensal) and two related complexes by peripheral ligand functionalization were unable to reproduce the energies of the INS transitions nor the g-factors. On the other hand, the application of the semiempirical radial effective charge (REC) model using the SIMPRE computational package was hampered by the lanthanide being coordinated to three types of donor atoms (see Figure 1) and by SIMPRE considering only the ground multiplet. As this parametric model needs to introduce two parameters for each type of donor atom, the use of this approach would result in a total of six REC parameters leading to possible unphysical mathematical fits, whose extrapolation to predict the behavior of other compounds could not be reliable.

Thus, we followed a purely phenomenological approach using the CONDON computational package. This procedure benefited of the large number of energy levels determined by spectroscopic means for Ln(trensal) and of the high and coincident symmetry of the coordination environments in the two families. First, we fitted all the energy levels determined by luminescence for the Nd, Tb, Dy, Ho, and Tm derivatives of the Ln(trensal) series and the temperature dependences of their magnetic susceptibilities, which were determined in the course of this work. In the case of the Er derivative, thanks to the more complete set of experimental information, we could simultaneously fit (a) the 51 spectroscopic Kramers doublets from the different multiplets; (b) the magnetic susceptibility of the ground multiplet with field applied along the trigonal axis, using the product of the series Ln(trensal) (upper panel) and Ln(trenovan) (lower panel) from 2 to 300 K. The dotted lines represent the Curie constants of the corresponding free ions. Color scale: Nd (empty maroon pentagons), Tb (empty cyan triangles), Dy (reversed empty green triangles), Ho (empty orange circles), Er (pink stars), Tm (solid blue circles).

![Figure 2](image)

**Figure 2.** Experimental (symbols) and theoretical fit (solid lines) $\chi T$ product of the series Ln(trensal) (upper panel) and Ln(trenovan) (lower panel) from 2 to 300 K. The dotted lines represent the Curie constants of the corresponding free ions. Color scale: Nd (empty maroon pentagons), Tb (empty cyan triangles), Dy (reversed empty green triangles), Ho (empty orange circles), Er (pink stars), Tm (solid blue circles).
The differences in CFPs obviously result in different wave function composition between Ln(trensal) and Ln(trenovan). If we focus on the ground-state wave function, we see that for Dy(trensal) the ground Kramers doublet is described mainly by a mixture of 34% |±7/2⟩, 32% |±5/2⟩, and 23% |±1/2⟩, whereas Dy(trenovan) is described by 69% |±1/2⟩, followed by 17% |±7/2⟩ and 12% |±5/2⟩. In the case of Er, the |±13/2⟩ contribution to the ground state is enhanced from 77% in Er(trensal) to 92% in Er(trenovan), whereas in the case of the Nd derivatives, the dominant M_z contribution is reduced from 82% |±5/2⟩ in Nd(trensal) to 72% |±5/2⟩ in Nd(trenovan). For the non-Kramers ions, all these investigated are characterized by a ground singlet: in Tm(trensal) this is |±1/2⟩, whereas Dy(trenovan) is described by 69% |±1/2⟩ and 46% |±3/2⟩ contributions, with the excited state closer in energy (11 cm⁻¹, see also Tables S11 and S20).

At this stage it is useful to make a comparison between the series of complexes and its behavior along the series. This can be quantified as described in the paper of Riley and co-workers.⁰¹

\[
\frac{N}{(4\pi)^{1/2}} = \left[ \sum_{k=2,4,6} \left( \frac{1}{2k + 1} \right) (B_0^k)^2 + 2 \sum_{q=1}^6 |B_0^q|^2 \right]^{1/2}
\]

The results, reported both in Table S21 and graphically in Figure S8, confirm that, on increasing Z, the LF strength is decreasing for both series. Furthermore, the LF strength of the Ln(trenovan) series is slightly higher, on average, than for the Ln(trensal) one. While the first, counterintuitive behavior was attributed by Riley and co-workers to the contraction of the f orbitals along the series, resulting in a reduced metal–ligand orbital overlap, the latter point can be traced back to the stronger interaction provided by the aminic nitrogen in Ln(trenovan) as a consequence of the shorter distance (see above). The clear anomalies observed for Ho and Tm trenovan derivatives further suggest that, despite the informed choice of starting values for CFP parameters and the agreement with the experimental properties, the best fit values obtained for these complexes might well be incorrect. This stresses once more that the use of only magnetic data to obtain CFPs should be, in cases more fortunate than this one, avoided and complemented by spectroscopic information.⁰²

**Magnetic Anisotropy.** The magnetic anisotropy of the Ln(trenovan) series at low temperature was investigated by means of CW-EPR spectroscopy and compared to the corresponding analogues of the Ln(trensal) series: this was intended both as a feedback for the phenomenological approach described in the previous section and as a way to evidence any trend in the magnetic anisotropy between the two ligand families.

**Kramers Ions.** For the sake of simplicity, we started our investigation by the Kramers ions of the series, since for these systems resonance condition can be met at reasonably accessible frequency/field combination. The response of the ground doublet to the applied field can indeed be modeled by using an effective Zeeman Hamiltonian, for which the determined g values embody the information about the ground doublet wave function composition. The crystallographically imposed trigonal symmetry of the Ln(III) center in the two series further assures a strict axial symmetry of the obtained effective g factors, with either \( g_{J} > g_{H} \) (easy axis anisotropy) or \( g_{H} > g_{J} \) (easy plane anisotropy). The Ln(trenovan) complexes exhibited both kinds of magnetic anisotropy: Ce, Dy, and Gd derivatives have an easy plane magnetic anisotropy, while Nd, Er, and Yb derivatives have an easy axis anisotropy (see Figure 3 and Table 2).

**Table 2.** Experimental g-Factor and Calculated Ones for the Ln(trenovan) Series Using the CFPs Reported in Table S13

<table>
<thead>
<tr>
<th></th>
<th>( g_{J}(\text{exp}) )</th>
<th>( g_{J}(\text{calc}) )</th>
<th>( g_{H}(\text{exp}) )</th>
<th>( g_{H}(\text{calc}) )</th>
<th>( \Delta g/\sum g(\text{exp}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ce</td>
<td>1.94(1)</td>
<td>not visible</td>
<td>2.24</td>
<td>2.62(1)</td>
<td>0.588(8)</td>
</tr>
<tr>
<td>Nd</td>
<td>0.68(1)</td>
<td>1.60</td>
<td>0.588(8)</td>
<td>2.24</td>
<td>0.588(8)</td>
</tr>
<tr>
<td>YDy</td>
<td>8.7(2)</td>
<td>10.36</td>
<td>1.63(1)</td>
<td>1.88</td>
<td>0.684(4)</td>
</tr>
<tr>
<td>Er</td>
<td>2.37(1)</td>
<td>2.38</td>
<td>13.54(1)</td>
<td>14.32</td>
<td>0.702(1)</td>
</tr>
<tr>
<td>Yb</td>
<td>2.643(6)</td>
<td>4.92(1)</td>
<td>0.301(1)</td>
<td>0.588(8)</td>
<td>0.301(1)</td>
</tr>
</tbody>
</table>

In the case of the Ce derivative, the EPR investigation did not detect any signal corresponding to a parallel transition. This can be easily rationalized by considering that Ce(III) has a ground multiplet with \( J = 5/2 \) and that the tridgonal site symmetry results in each doublet being either a mix of \( M_J = \pm 5/2 \) and \( M_J = \pm 1/2 \) or a pure \( M_J = \pm 3/2 \) state. For \( g_{H} \neq 0 \), the former situation should occur: further, a simple analysis shows that, for \( g_{H} \) to be consistent with the observed \( g_{J} \), its value should be around 0.40, i.e., beyond the magnetic field limit of

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our X-band spectrometer. We stress here that, among the Kramers ions, the anisotropy of Sm(trenovan) could not be determined; indeed, the sample turned out to contain some Gd(III) impurity, its EPR spectrum featuring a striking similarity to that of Gd(trenosal) diluted in the Y(III) diamagnetic matrix (see Figure S9). We attributed this behavior to the very low magnetic moment of Sm(trenovan) at low temperature, which then acts as an effective “quasi-diamagnetic” matrix for the Gd(III) impurity dopants. No signal intrinsic to Sm(III) could be detected.

As a feedback for the phenomenological approach described in the previous section, the CFPs of Nd, Dy, and Er were employed to get an estimation of their g-factor values by means of the home developed software EVALUCF. 53 The comparison between the experimental and the calculated values is reported in Table 2, evidencing a good qualitative agreement.

The obtained results were further compared to those obtained on corresponding systems of Ln(trensal), for which CFPs have been obtained, i.e., Nd(trensal), Dy(trensal), and Er(trensal). The spectra are reported in Figure S10. In analogy with the Ln(trenovan) compounds, Nd(trensal) and Er(trensal) have easy axis magnetic anisotropy, while Dy(trensal) is easy plane. 54 Also in this case the effective g-factors calculated on the basis of the best fit CFP parameters turned out to be in good agreement with the experimental evidence (see Table 3).

Table 3. Experimental g-Factor and Calculated Ones for the Ln(trensal) Series Using the CFP Reported in Table 246

<table>
<thead>
<tr>
<th></th>
<th>g(exp)</th>
<th>g(calc)</th>
<th>Delta g</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd</td>
<td>0.71(1)</td>
<td>1.07</td>
<td>2.65(1)</td>
<td>2.79 0.582(1)</td>
</tr>
<tr>
<td>Dy</td>
<td>9.4(5)</td>
<td>9.9</td>
<td>1.8(1)</td>
<td>1.4 -0.678(6)</td>
</tr>
<tr>
<td>Er</td>
<td>3.6(1)</td>
<td>4.3</td>
<td>11.8(4)</td>
<td>11.1 0.532(5)</td>
</tr>
</tbody>
</table>

“The EPR investigation of the pure Nd(trensal) complex was conducted with an X-band spectrometer at 5 K, while the values of the g_eff for Er(trensal) and Dy(trensal) originate from a previous EPR W-band experiment on Y(III) diluted samples (3.1% and 5.8% of Dy(III) and Er(III), respectively).”

If we take as a measure of the experimental anisotropy of the ground doublet the ratio \((g_\text{eff} - g_\text{exp})/(g_\text{eff} + g_\text{exp})\), it is easy to note that Ln(trenovan) complexes are slightly more anisotropic than Ln(trensal) ones; the difference, which we essentially attribute to the shorter Ln–N apical distance, is however quite small, so that it cannot be consistently reproduced by the calculated CFPs. Further, the behavior of the magnetic anisotropy in the two series is consistent with the aspherical electron density distributions of the lanthanide ions, pioneered by Sievers and recently made popular by Rinehart and Long. The anisotropies of Ce and Dy derivatives have easy plane anisotropy, while Er and Yb derivatives are easy axis. However, since both CFP analysis and EPR investigation are consistent with all the complexes being characterized by highly mixed ground states, deviation may occur. This is indeed the case of the Nd analogue, for which a weak easy axis anisotropy is observed, whereas a weak easy plane one could be expected on the basis of the Long model. This stresses once more that, even in a relatively high symmetry system, the application of a model conceived for a pure \(M^2\) ground state should be considered with much caution.

Non-Kramers Ions. The EPR investigation of lanthanide-based complexes with integer spin is less straightforward than for Kramers ions, because the resonance condition is more difficult to fulfill and is thus common not to detect a signal. Even when a signal is observed, the more complex energy structure makes the spectrum interpretation not easy. 56,57 The Ln(trenovan) complexes with integer spin do not make an exception: we were able to identify a clear signal in the EPR spectrum of Tm(trenovan) and Tb(trenovan) only, while the spectra of Pr(trenovan) and Ho(trenovan) could not be safely assigned. However, as we will see below, caution should be exerted in the assignment of these signals to Ln(trenovan).

The high-frequency EPR spectra of Tm(trenovan) were characterized by a single resonance, the magnetic field of which is varying linearly as a function of microwave frequency (see Figure S11). On the assumption that the observed transitions are parallel ones, we can interpret the EPR spectra according to an effective doublet Hamiltonian:

\[ H = g_B S_z + \Delta S_x + \Delta S_y \]

where \(\Delta\) is the energy gap in zero field between the two levels for which the transition is observed and \(S_z\) and \(S_x\), terms arise as a consequence of the transverse terms of the CFP. The resonance field vs frequency plot then allows a lower limit estimate of this energy gap, which is obtained as 9 cm\(^{-1}\); in reasonable agreement with analysis of CFPs. However, the linear dependence of the resonance field, with an estimated effective g value of 8.9, is completely at odds with the results of magnetic characterization, which indicated two low-lying singlets with extremely small effective g values. Further, one has to consider that to get a reasonable transition probability, either the polarization of the microwave should be parallel to the applied field or the local symmetry at low temperature should be lower than trigonal, allowing for further mixing of different \(M^J\) states.

A similar situation occurs for Tb(trenovan), which suggests a roughly linear field/frequency dependence: in this case, the measurements in the X-band evidenced a transition in zero field with four lines, which are attributable to the hyperfine interactions with a \(I = 3/2\) nucleus (see Figure S11), while the analysis of high-frequency data suggests an energy gap of 2 cm\(^{-1}\). None of these results are compatible with a ground singlet in a trigonal symmetry, so that we suggest that, in analogy to what was observed for Tb(trenosal), the observed spectra for Tm(trenovan) and Tb(trenovan) are actually due to an impurity characterized by different CFPs. [We note here that the high-resolution powder X-ray diffractogram of Tm(trenovan) shows some weak extra peak compared to the calculated one, pointing to the presence of an unidentified phase with abundance <5% (see Figure S1). A similar situation occurs for Tb(trenovan). Despite the low abundance of the spurious phase in the two samples, these might well be held responsible for the EPR signal observed, which may be extremely sensitive to the presence of even a small abundance of paramagnetic centers.]

\(\gamma Gd(trenovan)\). The anisotropy of the Gd(trenovan) complex was investigated by measuring the W-band spectrum of the corresponding isostructural and diamagnetic doped Y-phase to obtain a better resolution of the spectrum. The spectrum was interpreted on the basis of the following spin Hamiltonian (in Stevens’ notation):

\[ H_{\text{SH}} = b_0^0 O_2^0 + b_0^0 O_4^0 + \mu_B S \cdot B \]

with \(S = 7/2\) and \(b_0^0 = D/3\), where \(D\) is the commonly employed axial zero-field splitting parameter.
The best simulation of the EPR spectrum gave $D = 0.0615 \pm 0.0005 \text{ cm}^{-1}$, $b^4_z = 4.5 \times 10^{-3} \text{ cm}^{-1}$, and $g = 1.995$. The values of the $D$ and $g$ parameters are consistent with those of other Gd(III)-based complexes;\cite{58,59} these complexes are indeed quite isotropic since Gd(III) has the 4f shell half-filled and the orbital contribution to the angular momentum cancels so that spin–orbit coupling only acts as a second-order perturbation to introduce anisotropy. A few words should be spent on the determination of the sign of the $D$ parameter. It is well established that the determination of the sign of $D$ would require studying the variation of the EPR spectrum as a function of temperature, in order to observe a change in the intensity of the outermost transitions, either parallel or perpendicular.\cite{60} However, this was not feasible for Y:Gd-(trenovan) because only the spectrum collected at 10 K had a signal-to-noise ratio good enough to evidence clearly these transitions, which were further of quite weak intensity. Nevertheless, the analysis of the relative intensity of adjacent parallel transitions, simulated by using either $D = 0.0615$ or $D = -0.0615$ and the fourth-order term of the corresponding sign, strongly supported the choice of $D > 0$ (see also Figure 4). We note here that this is a relevant advantage of the use of a W-band spectrometer compared to the X-band one; indeed, the spectrum could well be observed even at lower field/frequency, but due to the small zero field splitting, all eight levels would have been equipopulated at attainable laboratory temperatures, thus hampering the sign determination. Finally, we note that the spectra were not resolved enough to obtain reasonable estimates of trigonal anisotropy parameters ($b^4_x$, $b^4_y$, and $b^4_z$), which were then not included in the simulation Hamiltonian. With the obtained parameters, the system can be considered to have extremely weak easy plane anisotropy ($D > 0$), and a global energy splitting of the ground multiplet around 1 K ($D(S^2 - 1/4)$).

**Magnetic Relaxation.** The investigation of the magnetization dynamics for the Ln(trenovan) series evidenced that only compounds that contain Kramers ions exhibit a nonzero imaginary susceptibility and only in the presence of an applied magnetic field. The absence of slow magnetic relaxation for non-Kramers ions in Ln(trenovan) is in agreement with the electronic structure derived in the previous sections: all of them are characterized by a ground singlet, for which slow relaxation is not expected. Moreover, the magnetic relaxation is clearly not related to the magnetic anisotropy of the complexes, since both compounds with easy axis and easy plane anisotropy showed a nonzero out-of-phase susceptibility. An analogous behavior had been first reported for Er(trensal) and Dy(trensal)\cite{54} and is now quite commonly reported, being attributed to relaxation processes different from the Orbach ones.

The magnetic relaxation was first studied as a function of the applied magnetic field at 2 K; the field that provided the maximum of the imaginary susceptibility was then chosen as optimum one and used to perform the measurements as a function of temperature (see Figures S12–S17). It is worth noting that the scan in field at 2 K also evidenced a secondary maximum in the imaginary susceptibility for applied fields greater than 2000 Oe; its intensity however decreases very rapidly with temperature, and it is no longer visible above 5 K (Figure S18). Moreover, this peak is completely absent in the diluted samples YGd(trenovan) and YDy(trenovan) (see Figures S19–S21). This behavior suggests that the presence of this secondary peak in $\chi''$ may be due to dipolar interactions between different paramagnetic centers. Indeed, a similar feature was observed also in pure Er(trensal) and Dy(trensal) samples.

The temperature dependence of the relaxation time for the compounds of the series is reported in Figure 5. Although the Sm(trenovan) complex also showed a weak nonzero imaginary susceptibility, we could not exclude that the observation of a slow dynamics might be traced back to the Gd impurity. This stresses once more the importance of an integrated approach to the characterization of slow relaxing lanthanide complexes, where ac susceptibility results are complemented by spectroscopic outcomes.

A quantitative study of the mechanisms involved in the magnetic relaxation was not feasible, since it would have required investigating the diluted analogues of the samples, which were available only for Dy and Gd. However, it is evident from the log–log plot in Figure 5 that the relaxation time of the investigated pure complexes presents two types of regimes that can be attributable to a Raman-like mechanism (at higher temperatures) and a direct process (at lower temperatures).
The different observed behavior between pure and diluted systems for Gd and Dy derivatives clearly shows the dynamic properties in the other systems are not purely molecular in nature and are affected by the spin concentration in the lattice. It is then not to be attributed simply to an Orbach process, as it is also evident by the absence of linearity in the corresponding Arrhenius plots (see Figure S22).

As regards YDy(trenovan), above 2.2 K its dynamics was too fast to be measured with our ac susceptometer: indeed, the corresponding relaxation time, extracted by fitting the $\chi’’$ curves with the Casimir Dupré equation, is available only for three temperatures, and it is thus not suitable for discussion (see Figure 5). In the case of YGd(trenovan), it is possible to confirm that the relaxation is not promoted by an Orbach process, since EPR results showed that the whole $S = 7/2$ multiplet spans only 1 K and the $D$ value is positive. Indeed, a simple check of the YGd(trenovan) relaxation time above 7 K by means of the Arrhenius law would give an energy barrier of 10 cm$^{-1}$, which, in this case, has no physical meaning (see Figure S23).

**CONCLUSIONS**

We have prepared and characterized a new family of lanthanide complexes in which most of the Kramers ions derivatives behave as single-ion magnets (Ce, Nd, Gd, Dy, Er, and Yb). For the study of their magnetic properties we have designed a strategy based on the structurally and chemically related Ln(trensal) family, which has been studied deeply in the literature. We have systematically completed these previous studies by combining spectroscopic and magnetic data to perform a detailed theoretical analysis using the CONDON package. These results have been an excellent starting point to reproduce the magnetic data and discuss the outcome of the EPR experiments.

As a whole, these results indicate once more that this type of complex does not behave as a “real” SMM, if we denote with this term systems for which relaxation can be engineered by varying the anisotropy. This is clearly related to the charge distribution of the ligand around the lanthanoid being not clearly axial nor equatorial, which results in highly mixed ground states in terms of $M_I$ composition. This was also nicely confirmed by the results of EPR spectroscopy on Kramers derivatives, showing that passing from trensal to trenovan ligands, while keeping the same point symmetry at the lanthanides, slightly increases the ligand field strength along the series. The crucial parameter in determining the slow relaxation of the magnetization is then rather the number of unpaired electrons, only Kramers ions showing in-field slow relaxation.

Finally, this study evidences that the analysis of a complete series such as that of Ln(trenovan) can be of help in elucidating trends in electronic and magnetic properties of Ln-based complexes. In this respect it points out that the electronic structures obtained for Kramers ions of the Ln(trenovan) series follow a very reasonable trend, thanks to the observation of clear EPR spectra that imposed relevant constraints on CFP values; on the other hand, the situation is less clear-cut for those system for which no EPR spectra could be safely assigned, such as Tm and Ho derivatives.


(45) Wybourne, B. G. Spectroscopic Properties of Rare Earths; John Wiley and Sons, 1965.


