

MAGNETIC SUSCEPTIBILITIES OF TRIVALENT  
LANTHANIDE IONS IN AN OCTAHEDRAL ENVIRONMENT

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MAGNETIC SUSCEPTIBILITIES OF TRIVALENT LANTHANIDE IONS  
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*ABSTRACT* -Magnetic susceptibilities for eight lanthanide ions in  $\text{Cs}_2\text{NaLnCl}_6$  were measured from 2.5°K to ~80°K with a vibrating sample magnetometer. Computer fitting of the data for  $\text{Cs}_2\text{NaCeCl}_6$  gave  $g = 1.43$  for the  $\Gamma_7$  ground level, and  $f^2 = 3.85$  for the  $\Gamma_8$  excited level. These values are in good agreement with values calculated from first-order wave functions. The ground crystal field level for  $\text{Nd}^{3+}$  in  $\text{Cs}_2\text{NaNdCl}_6$  was found to be a  $\Gamma_8$  level. Because of singlet ground levels and small crystal field splitting, no positive information on the ground crystal field levels was obtained for  $\text{Pr}^{3+}$ ,  $\text{Tb}^{3+}$ ,  $\text{Dy}^{3+}$ ,  $\text{Ho}^{3+}$ ,  $\text{Er}^{3+}$ , or  $\text{Tm}^{3+}$  compounds. Based on  $\text{Nd}^{3+}$  and  $\text{Ce}^{3+}$  results, the ratio  $A_4^0\langle r^4 \rangle / A_6^0\langle r^6 \rangle$  was estimated to be about 20;  $A_4^0\langle r^4 \rangle$ , of the order of  $10 \text{ cm}^{-1}$ ; and  $A_6^0\langle r^6 \rangle$ , of the order of  $1 \text{ cm}^{-1}$ .

## INTRODUCTION

Ground states of trivalent lanthanide ions resulting from the splitting of energy terms by spin-orbit coupling are further

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split by the crystalline field of the ion. The type of crystalline field level and the ordering of the levels in energy are determined by the J value of the ion, the symmetry of the crystalline field, and the ratio of fourth- to sixth-order field parameters; the latter represents the details of the field, such as cation-anion distance and the nature of the anions. For lanthanide ions in cubic symmetry, the prediction of type and ordering of levels is greatly simplified; the valuable paper of Lea, Leask, and Wolf<sup>1</sup> (hereafter referred to as LLW) predicts both order and type of level in cubic class symmetries for each J value and for all ratios of field parameters.

The crystalline field levels of the ground state are best measured by magnetic susceptibility or electron spin resonance (ESR). Magnetic susceptibility measurements offer a means to determine the field parameters for the system and also a measure of the magnetic splitting factor, g, for comparison with the theoretical value calculated from point-charge eigenfunctions and the experimental values from ESR measurements.

The series of isomorphous<sup>2</sup>  $\text{Cs}_2\text{NaLnCl}_6$  (where Ln is any  $3^+$  lanthanide ion) are the compounds chosen for this study. The lanthanide ion is in the center of an octahedron of chloride ions in the anionic unit  $\text{LnCl}_6^{3-}$ . This paper reports the results and analyses for  $\text{Ce}^{3+}$ ,  $\text{Pr}^{3+}$ ,  $\text{Nd}^{3+}$ ,  $\text{Tb}^{3+}$ ,  $\text{Dy}^{3+}$ ,  $\text{Ho}^{3+}$ ,  $\text{Er}^{3+}$ , and  $\text{Tm}^{3+}$  in  $\text{Cs}_2\text{NaLnCl}_6$ . A magnetic susceptibility study of  $\text{Cs}_2\text{NaYbCl}_6$  has been previously reported.<sup>3</sup>

## EXPERIMENTAL

Crude anhydrous lanthanide chlorides of 99.9% lanthanide ion purity were purchased and purified by vacuum sublimation in quartz apparatus. The sublimed lanthanide chloride and 5% excess of the stoichiometric quantities of dry cesium chloride and sodium chloride were sealed in quartz tubes, and lowered at 2 cm/hr through a vertical furnace at a temperature about 50°C above the melting point of the lanthanide chloride. Impurities segregated at the top or bottom of the melted  $\text{Cs}_2\text{NaLnCl}_6$ , which was recovered by breaking the quartz tubes. The slight excesses of cesium chloride and sodium chloride were added to ensure against an excess of the lanthanide chloride which, if present, would be a non-octahedral site impurity in the magnetic measurements. The amount of lanthanide ion in the sample was determined by titration with EDTA.<sup>4</sup> The identity of the compounds was established by x-ray powder diffraction patterns.<sup>2</sup> In a few preparations, extra lines appeared in the diffraction patterns, all of which could be accounted for by excess cesium chloride and sodium chloride.

Magnetic susceptibilities were measured from about 2.5° to  $\approx 80^\circ\text{K}$  with a Foner-type vibrating sample magnetometer<sup>5</sup> manufactured by Princeton Applied Research Corp. and operated in the field of a 12-inch-diameter pole-face electromagnet. Samples were contained in plastic capsules for magnetic measurements.

Corrections for the diamagnetism of the sample holder and capsule were obtained by measurement of an empty sample capsule. Previous measurements found the diamagnetism of  $\text{Cs}_2\text{NaLnCl}_6$  to be insignificant in comparison with that of the holder and capsule.

Magnetic susceptibilities were measured in magnetic fields of 4 to 10 kOe. Preliminary measurements of signal *vs.* field established that there were no paramagnetic "saturation" effects.<sup>6</sup> The field was calibrated with a nickel standard. Magnetic measurements could be duplicated within  $\pm 2\%$  for a single sample, and the variation between samples was about 5%.

A variable temperature, liquid helium Dewar flask contained the sample and sample rod and provided controlled temperatures from 2.5°K to ~100°K. Temperature was measured with a germanium resistance thermometer mounted directly behind the sample; temperature readings were corrected for the effect of the field on the thermometer.

Magnetic susceptibility readings for each sample were taken first with ascending temperatures and then repeated with descending temperatures to decrease the possibility of temperature drift during measurements. The magnetic readings, corrected for the diamagnetism of the system, were converted to  $\chi^{-1}$  values by multiplication of the appropriate constants (sample weight, molecular weight, field strength) and plotted against temperature to test for consistency. These data were then fitted by a least-squares computer program to the convenient, if empirical, Curie-

Weiss expression  $\chi = C/(T+\theta)$ . The constants obtained in this manner are listed in Table I; values previously obtained for ytterbium<sup>3</sup> and gadolinium<sup>7</sup> trivalent ions in  $\text{Cs}_2\text{NaLnCl}_6$  are also included.

## CRYSTAL FIELD ANALYSIS

The crystalline field on the lanthanide ion in the in the octahedral  $\text{LnCl}_6^{3-}$  anion has the Hamiltonian

$$H_c = B_4(O_4^0 + 50O_4^4) + B_6(O_6^0 - 210O_6^4)$$

where the  $O_n^m$  terms are angular momentum operators transforming like the corresponding spherical harmonics.<sup>8,9</sup> The parameter  $B_n$  is related to the strength of the crystalline field components

$$B_n = a_n A_n^0 \langle r^n \rangle$$

where  $a_n$  is the operator equivalent factor,  $\alpha, \beta, \gamma$  for  $n=2,4,6$ , respectively.  $A_n^0$  are parameters relating the  $n^{\text{th}}$  degree potential on the ion from the ionic charges of the lattice, and  $\langle r^n \rangle$  are the expectation values for the 4f electrons. The product  $A_n^0 \langle r^n \rangle$  is determined to the first order by geometric factors and in principal can be calculated.

LLW have determined the eigenfunction and eigenvalue solutions for the Hamiltonian equation for applicable J values and the full range of  $B_4/B_6$  ratios. They diagram the eigenvalues for crystalline field levels of each J in terms of a quantity x, defined as

$$\frac{x}{1-|x|} = \frac{F(4)B_4}{F(6)B_6} = \frac{F(4)\beta A_4^0 \langle r^4 \rangle}{F(6)\gamma A_6^0 \langle r^6 \rangle} = \frac{b_4}{b_6}$$

where  $-1 < x < 1$ , and  $F(4)$  and  $F(6)$  are multiplicative factors. The eigenfunctions of LLW can be used to calculate theoretical values of g, the magnetic splitting factor. The ground crystalline field levels for  $\text{Ce}^{3+}$  and  $\text{Nd}^{3+}$  are identified by comparing the g values

obtained from magnetic susceptibility results with either the theoretical g values or experimental g values from ESR studies.

## RESULTS

### $\text{Cs}_2\text{NaCeCl}_6$

The inverse magnetic susceptibility of  $\text{Cs}_2\text{NaCeCl}_6$  for the temperature range 3.2 to 42°K shows (Figure 1) two Curie-Weiss regions indicating two magnetic crystal field levels. For a  $J=5/2$  ion in  $O_h$  symmetry,  $\Gamma_7$  ground and  $\Gamma_8$  higher levels are predicted. The theoretical expression for the magnetic susceptibility for a ground doublet level and an excited quartet level is<sup>3</sup>

$$\chi = \frac{N\beta^2}{3kT} \left( \frac{g^2 S(S+1) + 2f^2 \exp(-\Delta/kT)}{1 + 2\exp(-\Delta/kT)} \right) + b$$

where g is the magnetic splitting factor for the  $\Gamma_7$  level;  $f^2 = 5/3 g_j F^2$ , where  $F^2$  are the diagonal matrix elements, S is the spin and equal to 1/2;  $\Delta$  is the energy difference between the  $\Gamma_7$  and  $\Gamma_8$  levels; and b is a constant. The experimental values of  $\chi$  were fitted by a least-squares computer program to an equation of the form

$$\chi = \frac{1}{T} \left( \frac{[A+B \exp(-\Delta/kT)]}{1+2 \exp(-\Delta/kT)} \right) + b$$

to determine  $A = 0.1926$ ,  $B = 0.9618$ ,  $\Delta/k = 48.8$ , and  $b = -0.002$ . Values for g and  $f^2$  were obtained from A and B, respectively, by division with appropriate constants, and compared with g and  $f^2$

values calculated from the eigenfunctions of LLW in Table II. The excellent agreement between experimental and calculated magnetic splitting factors indicates that the assumptions involved in the first-order crystalline field analysis are not seriously in error<sup>10</sup> for Ce<sup>3+</sup>.

The  $\Gamma_8$  level is 35 cm<sup>-1</sup> above the ground  $\Gamma_7$  level. For  $J = 5/2$  ions, the sixth-order terms have no effect on the crystal field energy levels. The energy difference between  $\Gamma_7$  and  $\Gamma_8$  is calculated (LLW) to be  $6b_4$  in terms of field parameters; thus,  $b_4 = 5.8 \text{ cm}^{-1}$  or  $A_4^0 \langle r^4 \rangle = 15.3 \text{ cm}^{-1}$ .

#### Cs<sub>2</sub>NaPrCl<sub>6</sub>

The magnetic susceptibility of Pr<sup>3+</sup> in Cs<sub>2</sub>NaPrCl<sub>6</sub> was constant at  $8.12 \pm 0.08 \times 10^{-3}$  emu/mole from 2.5 to 90°K. For  $J=4$ , an octahedral field splits the ground state into  $\Gamma_1$ ,  $\Gamma_3$ ,  $\Gamma_4$ , and  $\Gamma_5$  levels, with  $\Gamma_1$  level predicted to be the lowest for any  $B_6/B_4$  ratios. The absence of temperature-dependent susceptibility is consistent with  $\Gamma_1$  ground level; temperature-independent susceptibility arises from the interaction between the  $\Gamma_1$  and  $\Gamma_4$  levels. The temperature-independent paramagnetism may be calculated from

$$\chi_{\text{TIP}} = \frac{2N\mu_B^2 g_j^2}{hc} \sum_{i \neq j} \frac{|\langle \Gamma_i | J_z | \Gamma_j \rangle|^2}{E_i - E_j}$$

Evaluating the matrix elements (LLW) and substituting numerical values for the constants

$$\chi_{\text{TIP}} = \frac{2.225}{\Delta E_{14}} \quad \text{and} \quad \Delta E = 274 \text{ cm}^{-1}$$

#### Cs<sub>2</sub>NaNdCl<sub>6</sub>

The magnetic susceptibility of Nd<sup>3+</sup> in Cs<sub>2</sub>NaNdCl<sub>6</sub> showed two Curie-Weiss paramagnetic regions,  $\mu_{\text{eff}} = 2.70\mu_{\text{B}}$  from 2.4 to 15°K and  $3.42\mu_{\text{B}}$  from 15 to 70°K (Figure 2). For a J=9/2 ion, either the  $\Gamma_8$  level<sup>2</sup> or the  $\Gamma_6$  level can be the ground level. The theoretical moment for the  $\Gamma_8$  level<sup>2</sup> ranges from  $2.71\mu_{\text{B}}$  to  $2.75\mu_{\text{B}}$  as x varies from 0 to 1; for a  $\Gamma_6$  level,  $\mu_{\text{eff}} = 2.31\mu_{\text{B}}$ . The calculated value for a  $\Gamma_8$  ground level agrees well with the experimental value and indicates a  $\Gamma_8$  ground level for Nd<sup>3+</sup> in the Cs<sub>2</sub>NaNdCl<sub>6</sub>. Above 15°K, the paramagnetism agrees fairly well with the calculated free-ion moment of  $3.62\mu_{\text{B}}$ , indicating that the total crystal-field splitting is 10 to 15 cm<sup>-1</sup>.

#### Cs<sub>2</sub>NaTbCl<sub>6</sub>

The magnetic susceptibility of Tb<sup>3+</sup> in Cs<sub>2</sub>NaTbCl<sub>6</sub> above 25°K has  $\mu_{\text{eff}} = 9.65\mu_{\text{B}}$ , in good agreement with the calculated free-ion moment of  $9.72\mu_{\text{B}}$ , and indicated a total crystal field splitting of  $\sim 20 \text{ cm}^{-1}$ . Below 30°K, the magnetic susceptibility approaches a horizontal asymptote indicating that the lowest level has TIP only (Figure 3). LLW predicts either a  $\Gamma_1$  singlet or a  $\Gamma_2$  singlet for the lowest level; the magnetic susceptibility results are con-

sistent with either. Taking a limiting value of  $\chi_{\text{TIP}} = 0.50$ , the splitting between either a  $\Gamma_1$  ground level and an interacting  $\Gamma_4$  higher level or a  $\Gamma_2$  ground level and a higher  $\Gamma_5$  level is calculated to be  $\sim 30 \text{ cm}^{-1}$ .

#### $\text{Cs}_2\text{NaDyCl}_6$

$\text{Dy}^{3+}$  in  $\text{Cs}_2\text{NaDyCl}_6$  has a strong temperature-dependent magnetic susceptibility ( $\mu_{\text{eff}} = 10.77\mu_{\text{B}}$ ), which agrees well with the free-ion moment,  $10.65\mu_{\text{B}}$ , over the temperature range 10 to  $90^\circ\text{K}$  (Figure 4). Below  $10^\circ\text{K}$ , there is a 10% decrease in the moment, suggesting that the crystal field levels lie below  $7 \text{ cm}^{-1}$ .

#### $\text{Cs}_2\text{NaHoCl}_6$

The magnetic susceptibility of  $\text{Ho}^{3+}$  in  $\text{Cs}_2\text{NaHoCl}_6$  from 15 to  $80^\circ\text{K}$  is strong and temperature-dependent,  $\mu_{\text{eff}} = 10.40\mu_{\text{B}}$ , in fair agreement with the theoretical free-ion moment of  $10.61\mu_{\text{B}}$ . Below  $15^\circ\text{K}$ , the susceptibility data approaches a horizontal asymptote indicating TIP below the temperature range of the measurements (Figure 5). The predicted lowest level for a  $J=8$  ion in  $O_h$  site symmetry is either  $\Gamma_3$  (non-magnetic doublet in  $O_h$ ) or a singlet  $\Gamma_1$ , both of which have non-zero matrix elements when combining with each other or the  $\Gamma_4$  level. For a TIP due to  $\Gamma_1$ - $\Gamma_4$  interaction, and  $\chi_{\text{TIP}} = 1.74$ ,  $\Delta E_{14} \approx 10 \text{ cm}^{-1}$ .

Cs<sub>2</sub>NaErCl<sub>6</sub>

The magnetic susceptibility of Er<sup>3+</sup> in Cs<sub>2</sub>NaErCl<sub>6</sub> follows a simple Curie-Weiss dependence from 2.5 to 75°K, with  $\mu_{\text{eff}} = 8.95\mu_{\text{B}}$  (Figure 6). The calculated free-ion moment is  $9.58\mu_{\text{B}}$ , in fair agreement with the experimental value. The crystal field splitting is inferred to be less than  $5 \text{ cm}^{-1}$ .

Cs<sub>2</sub>NaTmCl<sub>6</sub>

The magnetic susceptibility of Tm<sup>3+</sup> in Cs<sub>2</sub>NaTmCl<sub>6</sub> is similar to that of Tb<sup>3+</sup> and Ho<sup>3+</sup> in the corresponding Cs<sub>2</sub>NaLnCl<sub>6</sub> compounds: a strong Curie-Weiss paramagnetism at high temperatures (40 to 70°K), and nearly TIP at very low temperatures (Figure 7). In the region 40 to 70°K,  $\mu_{\text{eff}} = 7.94\mu_{\text{B}}$ ; the calculated free-ion moment is  $7.56\mu_{\text{B}}$ . The predicted ground level for Tm<sup>3+</sup> in O<sub>h</sub> site symmetry is either  $\Gamma_1$  or  $\Gamma_2$ , both singlet levels. At 2.5°K,  $\chi$  approaches a value of 0.34 emu/mole. Assuming  $\chi_{\text{TIP}} = 0.34 \text{ emu/mole}$ , the splitting of the Tm<sup>3+</sup> levels is 40 to 50  $\text{cm}^{-1}$ , depending on an interaction between a  $\Gamma_1$  ground level and a higher  $\Gamma_4$  level or interaction between a  $\Gamma_2$  ground level and a higher  $\Gamma_5$  level is assumed to be responsible for  $\chi_{\text{TIP}}$ .

## DISCUSSION

Magnetic splitting factors extracted from magnetic susceptibility results compared well with values calculated from first-order wave functions (LLW) for  $\text{Ce}^{3+}$ , and were sufficiently good to identify the  $\Gamma_8$  lowest crystal field level of  $\text{Nd}^{3+}$ . Although in principle the splitting factors for the  $\Gamma_8$  ground level of  $\text{Nd}^{3+}$  can be used to calculate the ratio of the fourth- to sixth-order field parameters, the experimental accuracy required is extremely difficult to achieve. Magnetic results for the other six ions did not allow a determination of the ground crystal field level because of the small crystal field splitting for the  $J=15/2$  ions;  $\text{Dy}^{3+}$ ,  $\text{Er}^{3+}$ , and the other four ions have either  $\Gamma_1$ ,  $\Gamma_2$ , or  $\Gamma_3$  ground levels, none of which have a first-order Zeeman effect in an octahedral field.

From the eigenvalues of first-order theory (LLW), the range of  $A_4^0\langle r^4 \rangle / A_6^0\langle r^6 \rangle$  ratios that allows particular ground crystal fields for each  $\text{Ln}^{3+}$  ion can be calculated (Figure 8). The ratio of fourth- to sixth-order field parameters has been found<sup>11</sup> to vary slowly with  $Z$  for  $\text{Ln}^{3+}$  ions in cubic calcium fluoride sites, with the fourth-order term about 10 times greater than the sixth-order term. A similar behavior can be reasonably assumed for the variation of crystal field of the  $\text{LnCl}_6^{3-}$  ion with  $Z$ , and the dominance of the fourth-order parameter was found for  $\text{Yb}^{3+}$  in  $\text{Cs}_2\text{NaYbCl}_6$ .<sup>3</sup> From the determination of a  $\Gamma_8$  ground

level for  $\text{Nd}^{3+}$ , the ratio ( $A_4^0\langle r^4 \rangle / A_6^0\langle r^6 \rangle$ ) is less than 28 for  $\text{Nd}^{3+}$ . The ratio ( $A_4^0\langle r^4 \rangle / A_6^0\langle r^6 \rangle$ ) in the range of 10 to 30 predicts  $\Gamma_1$  ground levels for  $\text{Tb}^{3+}$  and  $\text{Tm}^{3+}$  ions,  $\Gamma_6$  for  $\text{Dy}^{3+}$ , and  $\Gamma_8$  for  $\text{Er}^{3+}$  and  $\Gamma_3$  for  $\text{Ho}^{3+}$  in  $\text{Cs}_2\text{NaLnCl}_6$  compounds. The value of  $A_4^0\langle r^4 \rangle$  of  $15 \text{ cm}^{-1}$  for  $\text{Ce}^{3+}$  suggests that  $A_4^0\langle r^4 \rangle$  is of the order of  $10 \text{ cm}^{-1}$  and  $A_6^0\langle r^6 \rangle$  of the order of  $1 \text{ cm}^{-1}$  in these compounds.

EPR investigations of  $\text{Er}^{3+}$  and  $\text{Dy}^{3+}$  in  $O_h$  sites in potassium magnesium trifluoride ( $\text{KMgF}_3$ ) found ground levels  $\Gamma_8$  and  $\Gamma_6$ , respectively, for these ions.<sup>12</sup> For  $\text{Er}^{3+}$  in  $\text{KMgF}_3$ , the ratio ( $A_4^0\langle r^4 \rangle / A_6^0\langle r^6 \rangle$ ) was  $\sim 23$ , and in  $O_h$  sites in  $\text{MgO}$ ,<sup>13</sup>  $\text{CaO}$ , and  $\text{SrO}$ ,<sup>14</sup> this ratio was 28 to 30. Although the crystal field is considerably stronger in these lattice sites, the ratio of the fourth-to-sixth order parameters is consistent with those estimated for the  $\text{Cs}_2\text{NaLnCl}_6$  compounds. Magnetic or EPR measurements on  $\text{Cs}_2\text{NaPmCl}_6$  could serve to provide a lower limit for the ratio.

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TABLE I. Summary of magnetic susceptibility results for Cs<sub>2</sub>NaLnCl<sub>6</sub>

Ln	J	Temp. Range, °K	C, <sup>a</sup> emu-deg/mole	Θ, <sup>a</sup> °K	$\mu_B^{\text{eff}}$ / molecule	χ, emu/mole
Ce	5/2	3.2-27	0.206	1.45	1.28	
		27-42	0.228	2.20	1.54	
Pr	4	2.5-90	TIP <sup>b</sup>			0.00812
Nd	9/2	2.4-15	0.950	0.76	2.76	
		15-70	1.46	10.4	3.42	
Gd	7/2	2.5-50		-	7.64	
Tb	6	2.5-25	TIP <sup>b</sup>			0.50
		25-75	11.6	7.51	9.65	
Dy	15/2	11-90	14.49	4.07	10.7	
Ho	8	2.5-15	TIP <sup>b</sup>			1.74
		15-80	13.40	1.66	10.38	
Er	15/2	2.5-75	10.0	1.63	8.95	
Tm	6	3.2-42	TIP <sup>b</sup>			0.336
		42-65	7.88	16.20	7.94	
Yb	7/2	2.5-20	0.113	0.95	2.46	
		45-100	2.50	70.0	4.47	

a. Constants from Curie-Weiss equation,  $\chi = \frac{C}{T + \Theta}$

b. Temperature-Independent Paramagnetism

TABLE II. Magnetic splitting constants for Ce<sup>3+</sup> in Cs<sub>2</sub>NaCeCl<sub>6</sub>

	Exptl.	Calc.	Ratio, exptl./calc.
g, Γ <sub>7</sub> ground level	1.43	1.428	1.00
f <sup>2</sup> , Γ <sub>8</sub> level	3.85	4.422	0.87
f	1.96	2.103	0.93

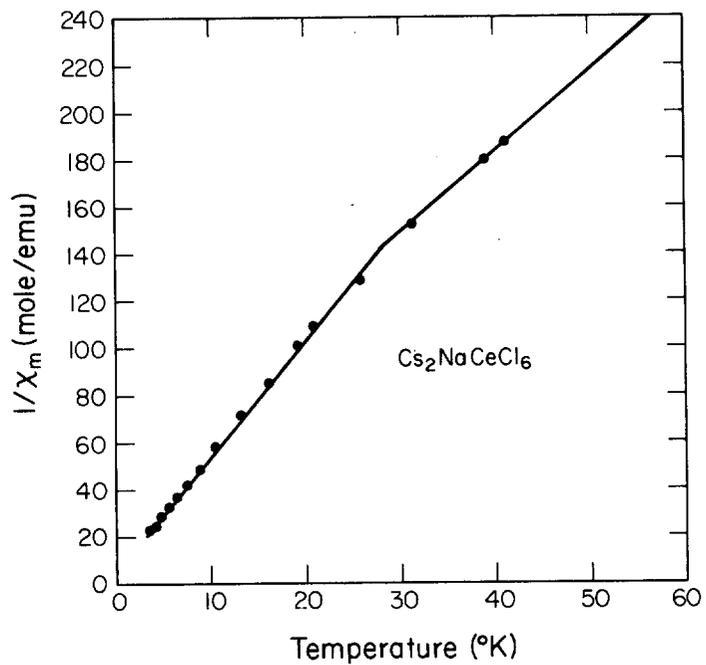


FIGURE 1. Inverse magnetic susceptibility of  $\text{Cs}_2\text{NaCeCl}_6$

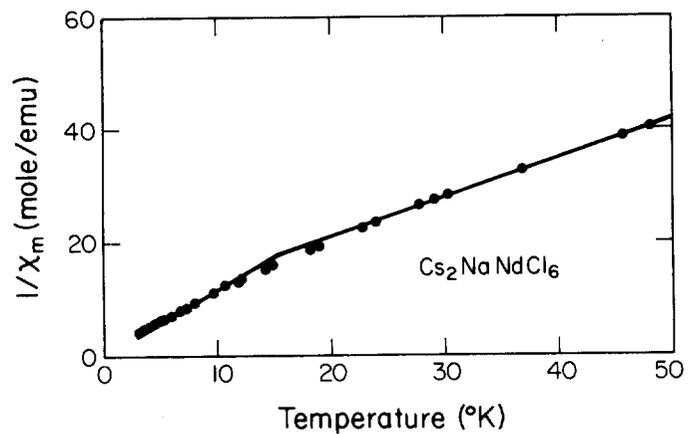


FIGURE 2. Inverse magnetic susceptibility of  $\text{Cs}_2\text{NaNdCl}_6$

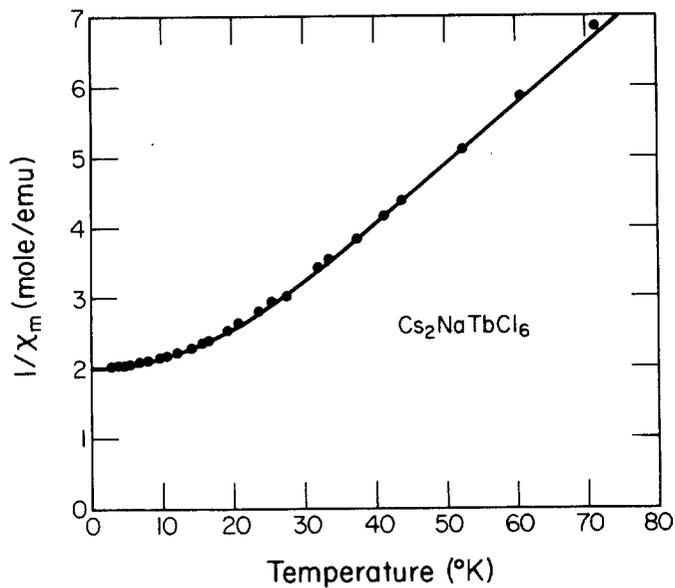


FIGURE 3. Inverse magnetic susceptibility of  $Cs_2NaTbCl_6$

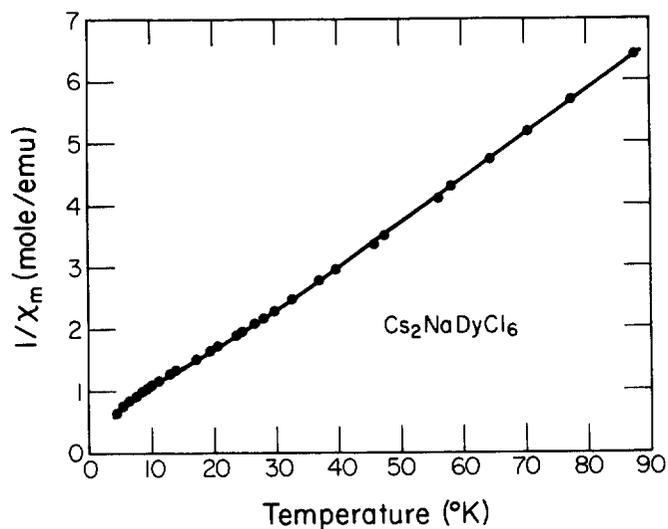


FIGURE 4. Inverse magnetic susceptibility of  $Cs_2NaDyCl_6$

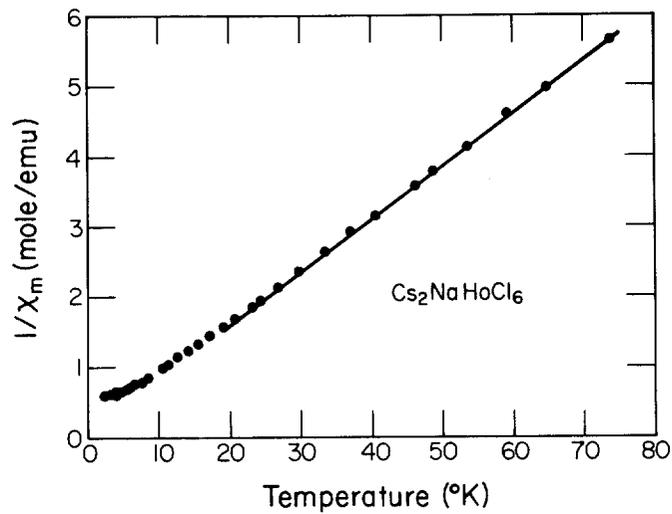


FIGURE 5. Inverse magnetic susceptibility of  $\text{Cs}_2\text{NaHoCl}_6$

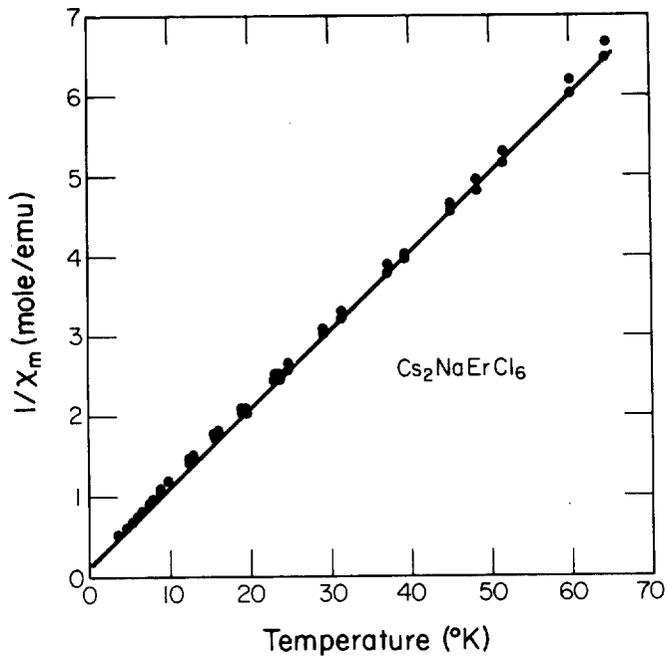


FIGURE 6. Inverse magnetic susceptibility of  $\text{Cs}_2\text{NaErCl}_6$

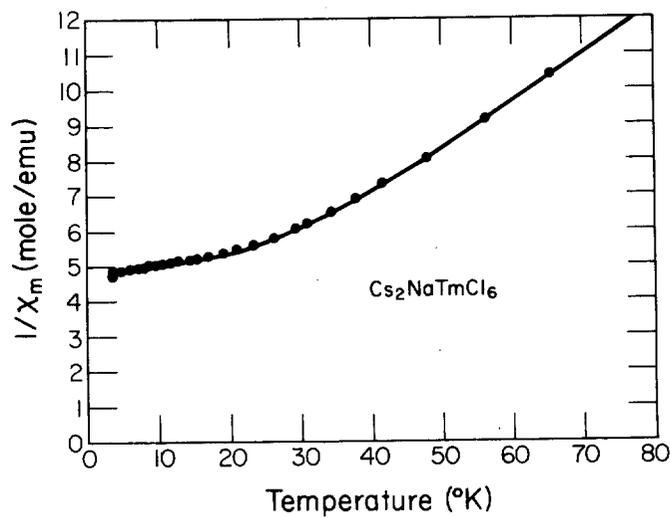


FIGURE 7. Inverse magnetic susceptibility of  $\text{Cs}_2\text{NaTmCl}_6$

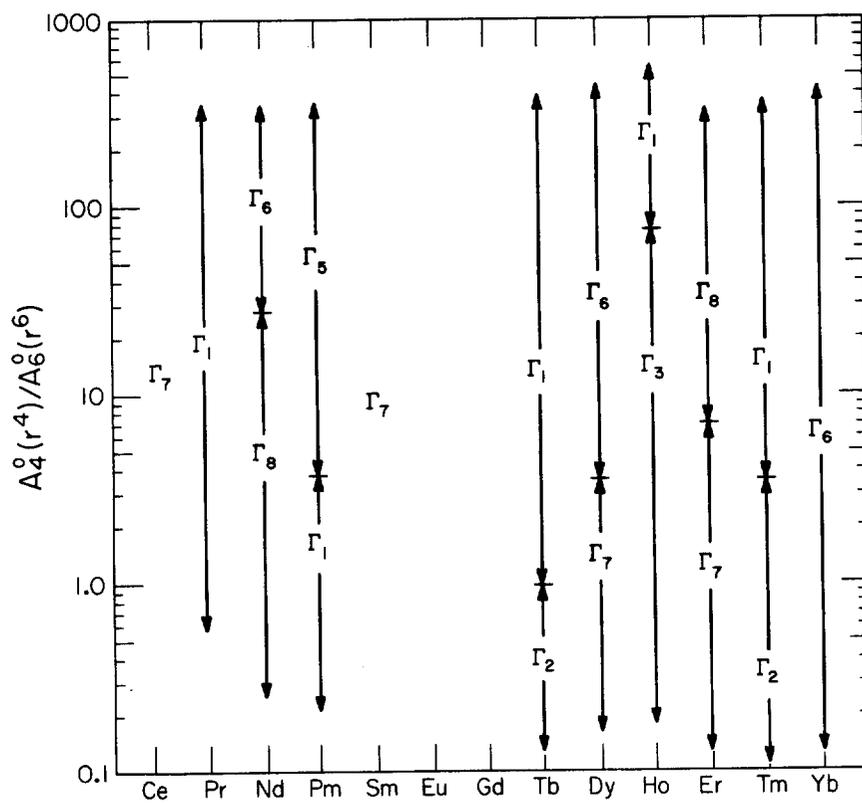


FIGURE 8. Ground crystal field levels of  $\text{Ln}^{3+}$  ions in  $O_h$  symmetry