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OPTICAL AND MAGNETIC PROPERTIES OF URANIUM AND  
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N. Edelstein

June 1983

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OPTICAL AND MAGNETIC PROPERTIES OF URANIUM AND  
NEPTUNIUM BOROHYDRIDES AND TETRAKISMETHYLBOROHYDRIDESK. Rajnak,\* E. Gamp, R. Banks, R. Shinomoto, and N. EdelsteinMaterials and Molecular Research Division  
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The actinide borohydrides possess a number of properties which make them attractive candidates for chemical and spectroscopic studies. The first five members of the series (Th-Pu) have been prepared.<sup>1-3</sup> They are volatile molecules near room temperature which makes it relatively easy to obtain single crystals. High symmetry diamagnetic analogs, Hf or Zr borohydride, are available as diluents.<sup>4,5</sup> In a pioneering study, Bernstein and Keiderling<sup>6</sup> (BK) obtained high resolution optical spectra of  $U(BH_4)_4(U(BD_4)_4)$  in single crystals of  $Hf(BH_4)_4(Hf(BD_4)_4)$  and fit this data to a parameterized Hamiltonian which included the Slater parameters, the spin-orbit coupling constant, and two crystal field parameters reflecting the  $T_d$  symmetry of the host crystals. Subsequently, the molecules Np and Pu borohydride were synthesized and  $Np(BH_4)_4(Np(BD_4)_4)$  diluted in  $Zr(BH_4)_4(Zr(BD_4)_4)$  have been the subject of magnetic and spectroscopic investigations.<sup>7,8</sup>

The actinide borohydrides exhibit two structural types. Th, Pa, and  $U(BH_4)_4$  are isomorphic and increase in volatility with increasing atomic number. Np and  $Pu(BH_4)_4$  are also isomorphic but closely resemble the highly volatile Zr and Hf borohydrides in structure and properties rather than the earlier actinide molecules.<sup>9</sup> All seven compounds contain triple hydrogen bridge bonds connecting the boron atom to the metal. In

addition, the 14 coordinate Th, Pa, and U borohydrides have double-bridged borohydride groups that link metal atoms together in a low symmetry, polymeric structure.<sup>10</sup> The structures of the other four molecules are monomeric and much more symmetric, the 12 coordinate metal is surrounded by a tetrahedral array of  $\text{BH}_4^-$  groups.

The polymeric structure of  $\text{U}(\text{BH}_4)_4$  precludes the possibility of obtaining the magnetic susceptibility of this compound with the same symmetry as found in the host  $\text{Hf}(\text{BH}_4)_4$  crystal used in the optical investigations. However the series of compounds  $\text{M}(\text{BH}_3\text{CH}_3)_4$  ( $\text{M} = \text{Th}, \text{U}, \text{Np}, \text{and Zr}$ ) have recently been synthesized and structurally characterized.<sup>11</sup> All four molecules are monomeric and for each molecule the metal atom is tetrahedrally coordinated to the four methylborohydride groups through tridentate hydrogen bridge bonds. The Zr and Np tetra-kismethylborohydrides belong to the same tetragonal space group with 2 molecules per unit cell. The U and Th compounds are monoclinic and triclinic respectively with 4 molecules per unit cell.

In the following discussion we assume the electronic structures of  $\text{M}(\text{BH}_4)_4$  (for  $T_d$  symmetry) and  $\text{M}(\text{BH}_3\text{CH}_3)_4$  ( $\text{M}=\text{U}$  or  $\text{Np}$ ) are similar so that we can use the data from one system for the analysis of the other.

The magnetic susceptibilities of  $\text{U}(\text{BH}_3\text{CH}_3)_4$  and  $\text{Np}(\text{BH}_3\text{CH}_3)_4$  have been measured in the temperature range 2 K - 330 K. With this additional information concerning the ground state and the low-lying excited states for the tetrahedral  $\text{U}(\text{BD}_4)_4$  systems, the optical data of BK have been reanalyzed. The same procedure has been applied to the optical data for  $\text{Np}(\text{BD}_4)_4$  diluted in  $\text{Zr}(\text{BD}_4)_4$  and the magnetic data for  $\text{Np}(\text{BH}_3\text{CH}_3)_4$ . Electron paramagnetic resonance (EPR) has also been obtained for  $\text{Np}(\text{BH}_3\text{CH}_3)_4$  diluted in  $\text{Zr}(\text{BH}_3\text{CH}_3)_4$  and

compared with similar data for  $\text{Np}(\text{BH}_4)_4$  ( $\text{Np}(\text{BD}_4)_4$ ) diluted in  $\text{Zr}(\text{BH}_4)_4$  ( $\text{Zr}(\text{BD}_4)_4$ ).<sup>9</sup> These topics will be reviewed in this paper.

### Experimental

The syntheses of  $\text{U}(\text{BH}_3\text{CH}_3)_4$ ,  $\text{Np}(\text{BH}_3\text{CH}_3)_4$ ,  $\text{Zr}(\text{BH}_3\text{CH}_3)_4$ , and  $\text{Np}(\text{BH}_4)_4$  ( $\text{Np}(\text{BD}_4)_4$ ) have been described previously.<sup>3,11</sup> Magnetic susceptibility measurements were carried out on a SHE 905 SQUID magnetometer. Powdered samples of  $\text{U}(\text{BH}_3\text{CH}_3)_4$  and  $\text{Np}(\text{BH}_3\text{CH}_3)_4$  were weighed and sealed into calibrated containers in an inert atmosphere box. For  $\text{U}(\text{BH}_3\text{CH}_3)_4$ , several different samples were measured with weights varying from 75 to 130 mg. Only one sample of  $\text{Np}(\text{BH}_3\text{CH}_3)_4$  was measured with a nominal weight of 10 mg. Because of the problems of obtaining an accurate weight on this small, radioactive sample, the weight of the sample was adjusted so that the susceptibilities at low temperatures agreed with the values calculated from the g value obtained by EPR measurements. All data were obtained with applied fields between 0.5 and 40 kGauss and temperatures from 1.8 to 330 K.

Single crystals of  $\text{Np}(\text{BH}_3\text{CH}_3)_4$  diluted in  $\text{Zr}(\text{BH}_3\text{CH}_3)_4$  were grown by first adding approximately 1 mg of  $\text{Np}(\text{BH}_3\text{CH}_3)_4$  to 50 mg  $\text{Zr}(\text{BH}_3\text{CH}_3)_4$  in a pyrex tube in an inert atmosphere box. This tube was removed from the box and evacuated down to  $10^{-4}$  Torr using an oil diffusion pump, and then sealed off under vacuum. Single crystals were obtained by vapor deposition in the upper half of the tube upon heating the lower half at approximately 30°C. These crystals were oriented for EPR measurements by x-ray identification of the faces and edges of the crystals. EPR spectra at 35 GHz were obtained using a Varian E-110 microwave bridge. The magnetic field was produced by an electromagnet

with a 2 inch gap which could be rotated about the vertical axis. The maximum field which could be obtained was approximately 16 kGauss. All samples were run at ~2 K.

Optical spectra have been obtained from the near infra-red region through the visible region on a Cary 17 spectrophotometer. Single crystals of  $\text{Np}(\text{BH}_4)_4$  or  $\text{Np}(\text{BD}_4)_4$  (approximate dimensions 1 cm x 2 cm x 25 microns) were grown by simply cooling the liquid borohydrides very slowly in a quartz sample holder of the above dimensions in the optical dewar. When the sample temperature reached ~150 K in about 8 hours, liquid helium was added and the spectra were recorded at approximately 2 K. Mixed crystals of  $\text{Np}(\text{BH}_4)_4/\text{Zr}(\text{BH}_4)_4$  or  $\text{Np}(\text{BD}_4)_4/\text{Zr}(\text{BD}_4)_4$  were grown from the vapor according to the method of BK.<sup>8</sup>

$\text{U}(\text{BH}_4)_4$  and  $\text{U}(\text{BH}_3\text{CH}_3)_4$

Review and Magnetic Susceptibility Data

The  $\text{U}^{4+}$  ion in  $\text{U}(\text{BH}_4)_4/\text{Hf}(\text{BH}_4)_4$  and  $\text{U}(\text{BH}_3\text{CH}_3)_4$  is at a site of  $T_d$  symmetry. The ground term of the  $\text{U}^{4+}$  ion has  $J = 4$  (nominally  $^3H_4$ ) which will split in a tetrahedral crystal field into four states, a singlet  $A_1$ , a doublet E and two triplets,  $T_1$  and  $T_2$ . BK found no EPR spectra for  $\text{U}(\text{BD}_4)_4/\text{Hf}(\text{BD}_4)_4$  at 2 or 77 K nor any Zeeman splitting in the 4000-7500Å region. This fact plus the assignment of at least 11 forced electric dipole transitions led them empirically to assign the ground state as the E state. Their analysis of the optical spectra resulted in a calculated ground state of  $T_2$  symmetry with the E state  $14 \text{ cm}^{-1}$  above it.

The  $T_d$  symmetry about the  $U^{4+}$  in  $U(BH_3CH_3)_4$  allows us to use magnetic susceptibility measurements from 2 K to room temperature to supplement the data of BK. We assume the electronic structure of  $U(BH_3CH_3)_4$  and  $U(BH_4)_4$  are similar. The optical spectra of  $U(BH_4)_4$  and  $U(BH_3CH_3)_4$  obtained in  $C_6D_6$  at room temperature are shown in Fig.

1. As seen from Figure 1 the spectra are similar, although most bands appear to be shifted to higher energies for  $U(BH_3CH_3)_4$ . The susceptibility of  $U(BH_3CH_3)_4$  is shown in Fig. 2. The ground state shows temperature independent paramagnetism consistent with the assignment of the E state as the ground state. This data was initially analyzed considering only the  $^3H_4$  term. Several fits are shown in Fig. 2 with the splittings given in Table 1. From these fits it is clear that the splitting between the ground E state and the first excited  $T_1$  or  $T_2$  state must be on the order of or greater than  $150\text{ cm}^{-1}$ . Finally it should be noted that a reasonable fit could not be obtained without the introduction of an orbital reduction factor.<sup>12</sup>

### Optical Analysis

The energy levels within an  $f^n$  configuration in  $T_d$  symmetry can be written in terms of the matrix elements of atomic ( $E_F$ ) and crystal field ( $E_{CF}$ ) interactions as follows:<sup>13</sup>

$$E = E_F + E_{CF}$$

where

$$E_F = \sum_{k=0,2,4,6} F^k(nf,nf) f_k + \zeta_f A_{SO} + \alpha L(L+1)$$



$$+ \beta G(G_2) + \gamma(R_7) + T^i t_i (i=2,3,4,6,7,8) + E_M$$

and

$$E_{CF} = B_0^4 [C_0^{(4)} + \sqrt{5/14}(C_{-4}^{(4)} + C_4^{(4)})] + B_0^6 [C_0^{(6)} - \sqrt{7/2}(C_{-4}^{(6)} + C_4^{(6)})].$$

The  $F^k(nf, nf)$  and  $\zeta_f$  represent the radial parts of the electrostatic and spin-orbit interactions between  $f$  electrons, respectively, while  $f_k$  and  $A_{SO}$  are the angular parts of the interactions whose matrix elements can be evaluated.  $\alpha$ ,  $\beta$ , and  $\gamma$  are the parameters of the two-body configuration interaction operators and the  $T^i$  are the corresponding parameters of the three-body configuration-interaction operators. The  $t_i$  matrix elements are equal to zero for an  $f^2$  configuration.  $E_M$  represents relativistic effects such as spin-spin and spin-other-orbit interactions [ $M^k(k=0,2,4)$ ] and the effects of higher configurations to produce the electrostatically correlated spin-orbit interaction [ $P^k(k=2,4,6)$ ]. The crystal field interaction for  $T_d$  symmetry can be represented by two parameters  $B_0^4$  and  $B_0^6$ , while the angular matrix elements of the  $C_q^{(k)}$  tensor operators can be readily evaluated.<sup>14</sup>

BK used a parameterized Hamiltonian which included only the  $F^k$ ,  $\zeta$ ,  $B_0^4$ , and  $B_0^6$ . Their best fit for  $U(BD_4)_4/Hf(BD_4)_4$  assigned 11 levels with an rms deviation of  $62 \text{ cm}^{-1}$  between experimental and calculated levels. However their calculated ground state was a  $T_2$  level with the E level lying  $14 \text{ cm}^{-1}$  higher in contradiction with experiment. Furthermore when they assigned 18 energies, their rms deviation increased to  $158 \text{ cm}^{-1}$ .

Recently, the  $U^{4+}$  free-ion spectrum has been completely analyzed.<sup>15</sup> With this additional information it is now possible to

set certain limits for the allowable range of both the free-ion parameters and their ratios. In addition, 26 levels of  $U^{4+}/ThBr_4^{16}$  have been fit with an rms deviation of only  $42\text{ cm}^{-1}$ , thus providing some guidelines for the changes in the free-ion parameters in going from the free ion to the crystal. From assignments of the infra-red and Raman spectra of  $Np(BH_4)_4(Np(BD_4)_4)$ , a normal coordinate analysis of these molecules has been carried out,<sup>17</sup> which has resulted in a reliable list of frequencies with which to assign vibronic bands in the optical spectrum of  $U(BD_4)_4/Hf(BD_4)_4$ . For these reasons a reanalysis of the data of BK has been undertaken.

The values of  $F^2$  and  $\zeta$  obtained by BK were  $42008$  and  $1910\text{ cm}^{-1}$  respectively. The corresponding free-ion parameters have recently been determined as  $51938$  and  $1968\text{ cm}^{-1}$ . The observed reduction in  $F^2$  to 81 percent of the free-ion value is similar to that found for some  $Cr^{3+}$  compounds,<sup>18</sup> but the decrease in  $\zeta$  of only 3 percent seems very small by comparison. In the reanalysis we initially assumed that the ratios  $F^4/F^2$  and  $F^6/F^2$  should lie somewhere between their free ion values (.82 and .53) and their values for  $U^{4+}/ThBr_4$  (.96 and .64). We further assumed that the values of  $F^2$  and  $\zeta$  should be reduced from the free-ion values in the same ratio as found for  $U^{4+}/ThBr_4$ . Initial values of  $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $M^k_s$ , and  $P^k_s$  were taken from the  $U^{4+}/ThBr_4$  analysis. Even though the sparseness of the data does not allow a determination of all these parameters, it is important to include them at reasonable values. The distortion of the calculated level scheme due to errors of 20-30 percent in the values of these parameters is less than that caused by setting them equal to zero. This is particularly important for the tetravalent actinides because the spin-orbit coupling and crystal field interactions

are both large. The states are so mixed that a number of different sets of parameters will produce moderately good fits (rms deviation  $\sim 100 \text{ cm}^{-1}$ ). Only a very good fit that allows further assignments of missing levels can guarantee a unique set of parameters. Finally, in our reanalysis we took account of the magnetic susceptibility data by forcing the first excited state to be greater than  $150 \text{ cm}^{-1}$  above the ground E state.

With the above assumptions it was immediately obvious that some of BK's uncertain origins could not be fit with our parameter values. Two of the original 11 levels have been reassigned and we kept only three of the less certain ones. The seven new assignments were verified by the identification of vibronic bands based on the electronic origins. Vibronic lines based on origins we discarded have been reassigned. Our final fit included all 19 of the allowed transitions (selection rules  $E \rightarrow T_1, T_2$ ) with an rms deviation of  $73 \text{ cm}^{-1}$ . The parameter values for this fit are given in Table 2 along with those of BK and for  $\text{U}^{4+}/\text{ThBr}_4$ , and the  $\text{U}^{4+}$  free ion. It is interesting to note that our crystal field parameters are not much different than for those of BK,  $B_0^4$  is somewhat smaller while  $B_0^6$  is somewhat larger. It is the free-ion parameters that have been markedly changed and which are now more consistent with other available  $\text{U}^{4+}$  data.

The magnetic susceptibility,  $\chi$ , has been calculated from the above parameters and is also shown in Figure 2. The calculated values of  $\chi$  are too large and the introduction of an orbital reduction factor  $k = 0.93$  gave a better fit, which is also shown in Figure 2. As will be shown later, this parameter is also necessary for the  $\text{Np}(\text{BH}_4)_4$  molecule.

Np(BH<sub>4</sub>)<sub>4</sub> and Np(BH<sub>3</sub>CH<sub>3</sub>)<sub>4</sub>

Magnetic and Optical Data

The EPR data for Np(BD<sub>4</sub>)<sub>4</sub>/Zr(BD<sub>4</sub>)<sub>4</sub> and Np(BH<sub>3</sub>CH<sub>3</sub>)<sub>4</sub>/Zr(BH<sub>3</sub>CH<sub>3</sub>)<sub>4</sub> can be summarized in terms of the parameters of a spin Hamiltonian<sup>19</sup>

$$H = \beta H(g_x H_x S_x + g_y H_y S_y + g_z H_z S_z) + A_x S_x I_x + A_y S_y I_y + A_z S_z I_z$$

where the effective spin  $S = 1/2$ , the nuclear spin  $I = 5/2$ ;  $\beta$  is the Bohr magneton;  $g_k, A_k, k = x, y, z$ ; are the principal axes of the  $g$  and  $A$  tensors. The values are given in Table 3. The resonance spectrum from Np(BD<sub>4</sub>)<sub>4</sub> is isotropic ( $g_x = g_y = g_z, A_x = A_y = A_z$ ) while that from Np(BH<sub>3</sub>CH<sub>3</sub>)<sub>4</sub> is slightly anisotropic. A model to explain this anisotropy will be discussed later. The magnitude of the  $g$  value for Np(BH<sub>4</sub>)<sub>4</sub>(Np(BD<sub>4</sub>)<sub>4</sub>) is 1.894 while the average value for Np(BH<sub>3</sub>CH<sub>3</sub>)<sub>4</sub> is 1.800. The susceptibility of Np(BH<sub>3</sub>CH<sub>3</sub>)<sub>4</sub> is shown in Figure 3.

The ground term for an  $f^3$  system is a  $J = 9/2$  (nominally  $^4I_{9/2}$ ) which will split in  $T_d$  crystal field into a doubly degenerate  $\Gamma_6$  state and two quadruply degenerate  $\Gamma_8$  states. Only the  $\Gamma_6$  state will give an isotropic  $g$  value so that we can assign the observed EPR spectrum to a  $\Gamma_6$  ground state.

Part of the optical spectra of Np(BH<sub>4</sub>)<sub>4</sub> is shown in Figure 4. Unfortunately, there are no reliable free-ion or crystal data for Np<sup>4+</sup> from which we can obtain reasonable starting parameters. However the low lying energy levels (below 10000 cm<sup>-1</sup>) are reasonably well separated and can be assigned on the basis of parameters extrapolated from U(BD<sub>4</sub>)<sub>4</sub>/Hf(BD<sub>4</sub>)<sub>4</sub> and fixed ratios of  $F^4/F^2$  and  $F^6/F^2$ . Starting from

this basis a number of further assignments can be made. In a preliminary analysis we have assigned 30 levels which can be fit with an rms deviation between the calculated and experimental energies of  $83 \text{ cm}^{-1}$ . In contrast with the  $\text{U}^{4+}$  case, we find  $B_0^4 \sim B_0^6 \sim -5000 \text{ cm}^{-1}$ .

Considering only the  $^4I_{9/2}$  ground term the magnetic susceptibility of  $\text{Np}(\text{BH}_3\text{CH}_3)_4$  was calculated as a function of temperature. This curve is labelled A in Figure 3. In order to obtain this curve an orbital reduction factor of 0.82 was needed. The optical analysis described above yielded a g value for the ground  $\Gamma_6$  state of 2.3 and the magnetic susceptibility calculated from the intermediate coupled wavefunction obtained from the preliminary analysis without an orbital reduction factor gave curve B in Figure 3. Inclusion of an orbital reduction factor of 0.87 in this calculation gave curve C.

#### Anisotropic Magnetic Properties of $\text{Np}(\text{BH}_3\text{CH}_3)_4/\text{Zr}(\text{BH}_3\text{CH}_3)_4$

The single crystal EPR spectrum of  $\text{Np}(\text{BH}_3\text{CH}_3)_4/\text{Zr}(\text{BH}_3\text{CH}_3)_4$  clearly indicates the presence of two inequivalent sites (see Figure 5) in the  $\text{Zr}(\text{BH}_3\text{CH}_3)_4$  at 2 K. By following the EPR spectrum as a function of the angle of the magnetic field with respect to the crystal axes, the principal axes of the g and A tensors may be determined. The change in the resonance field with magnet rotation angle in the plane perpendicular to the c axis is shown in Figure 6.

The room temperature crystal structure of  $\text{Zr}(\text{BH}_3\text{CH}_3)_4$  is tetragonal with two molecules per unit cell. From the EPR data it was determined that two of the principal g values lie in the a-a plane (perpendicular to the c axis); the  $g_x$  and  $g_y$  axes are parallel to the projections of the Zr-B bonds on the a-a plane. The  $g_x$  and  $g_y$  axes of the first

molecule in the unit cell are rotated by  $90^\circ$  with respect to those of the second molecule. This is shown in Figure 7. The  $g_z$  axis for both molecules is parallel to the c axis of the unit cell.

The room temperature crystal structure of  $Zr(BH_3CH_3)_4$  shows the two molecules per unit cell are structurally equivalent within the standard deviations of the bond distances and angles. It is possible that the crystal undergoes a phase transition on cooling from room temperature to 2 K or upon the inclusion of the impurity  $Np(BH_3CH_3)_4$ . In order to obtain an idea of the sensitivity of the g value to the geometry of  $Np(BH_3CH_3)_4$  we performed the following calculation. First we arbitrarily determined a set of crystal field parameters which would give the correct ground state g value assuming  $T_d$  symmetry. Using these parameters, the point charge model,<sup>20</sup> and the bond lengths and angles determined from the x-ray structure, we calculated the charge q in the point charge model. We then introduced a distortion by increasing the angle between the Np-H bonds and the c-axis by an angle  $\delta$  thus reducing the symmetry from  $T_d$  to  $D_{2d}$ . Using the empirically determined q, we recalculated new crystal field parameters from the point charge model. These yielded a new wavefunction from which  $g_{||}$  and  $g_{\perp}$  were calculated. The changes in the g values and in the splitting of the first  $\Gamma_8$  state vs. the distortion angle  $\delta$  are shown in Figure 8. A distortion of approximately 0.5 degrees (within the error limits of the x-ray structure analysis) is enough to account for the observed anisotropy. A similar result was obtained for a rhombohedral distortion model. This approximate calculation suggests that g value anisotropy is a sensitive probe of small structural distortions.

### Summary

The optical and magnetic properties of  $M(\text{BH}_3\text{R})_4$  ( $M = \text{U, Np}$ ;  $\text{R} = \text{H, CH}_3$ ) have been determined and the data fit with the parameters of an empirical Hamiltonian. Reasonable fits to the optical data are obtained, but in order to fit the magnetic susceptibility and EPR data, orbital reduction factors of  $\sim 0.8 - 0.9$  must be used.

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Table 1

$U(\text{BH}_3\text{CH}_3)_4$  parameters and energy levels for fits  
considering only the  $^3\text{H}_4$  ground term

	$A^a$	$B^a$
$B_0^4(\text{cm}^{-1})$	-4442	2473
$B_0^6(\text{cm}^{-1})$	-2186	-1410
k	0.79	0.79
Energies ( $\text{cm}^{-1}$ )	0 E 141 $T_2$ 982 $T_1$ 2094 $A_1$	0 E 270 $T_1$ 748 $A_1$ 977 $T_2$

<sup>a</sup>As in Figure 2.

Table 2  
Parameter Values<sup>a</sup> ( $\text{cm}^{-1}$ ) for  $\text{U}^{4+}$

	$\text{U}(\text{BD}_4)_4$ in		$\text{U}^{4+}:\text{ThBr}_4^b$	Free Ion <sup>c</sup>
	BK	This Work		
$F^2$	42008	$41560 \pm 241$	$42643 \pm 142$	$51938 \pm 39$
$F^4$	37679	$40144 \pm 1096$	$41319 \pm 544$	$42708 \pm 100$
$F^6$	28048	$23046 \pm 845$	$26971 \pm 429$	$27748 \pm 68$
$F^4/F^2$	.90	.97	.97	.82
$F^6/F^2$	.67	.55	.63	.53
$\alpha$	-	$40 \pm 3$	$31.3 \pm 1.5$	$33.5 \pm 0.4$
$\beta$	-	$[-648]$	$-641 \pm 83$	$-664 \pm 25$
$\gamma$	-	$[800]$	$[800]$	$744 \pm 26$
$\zeta$	1910.8	$1807 \pm 16$	$1787 \pm 7$	$1968 \pm 2$
$p^2$	-	$[500]$	$[500]$	$573 \pm 66$
$p^4$	-	$[500]$	$[500]$	$524 \pm 144$
$p^6$	-	$[500]$	$[500]$	$1173 \pm 321$
$B_0^4$	-3484	$-2498 \pm 174$	$1380 \pm 166$	
$B_0^6$	-4240	$-5282 \pm 115$	$-2986 \pm 424$	
$B_4^4$	-	-	$-2271 \pm 92$	
$B_4^6$	-	-	$643 \pm 276$	
$B_0^2$	-	-	$-1086 \pm 88$	
Number				
Levels	11	19	26	13
$\sigma$	62	73	41	9.8

<sup>a</sup>Parameters in [ ] were held fixed. In all cases  $M^0 = 0.987$ ,  
 $M^2 = 0.550$ ,  $M^4 = 0.384$ .

<sup>b</sup>Reference 15.

<sup>c</sup>Reference 14.

Table 3  
Spin Hamiltonian Parameters for  $^{237}\text{Np}:\text{Zr}(\text{H}_3\text{B}-\text{R})_4$

Host	$\text{Zr}(\text{H}_3\text{B}-\text{H})_4$	$\text{Zr}(\text{H}_3\text{B}-\text{CH}_3)_4$
$g_x$	1.894(2)	1.7739(4)
$g_y$		1.8292(4)
$g_z$		1.7961(5)
$A_x(\text{cm}^{-1})$	0.1140(10)	0.1079(2)
$A_y(\text{cm}^{-1})$		0.1153(2)
$A_z(\text{cm}^{-1})$		0.1135(2)
$g_{\text{ave}}$	1.894	1.7997(4)
$A_{\text{ave}}(\text{cm}^{-1})$	0.1140	0.1122(2)

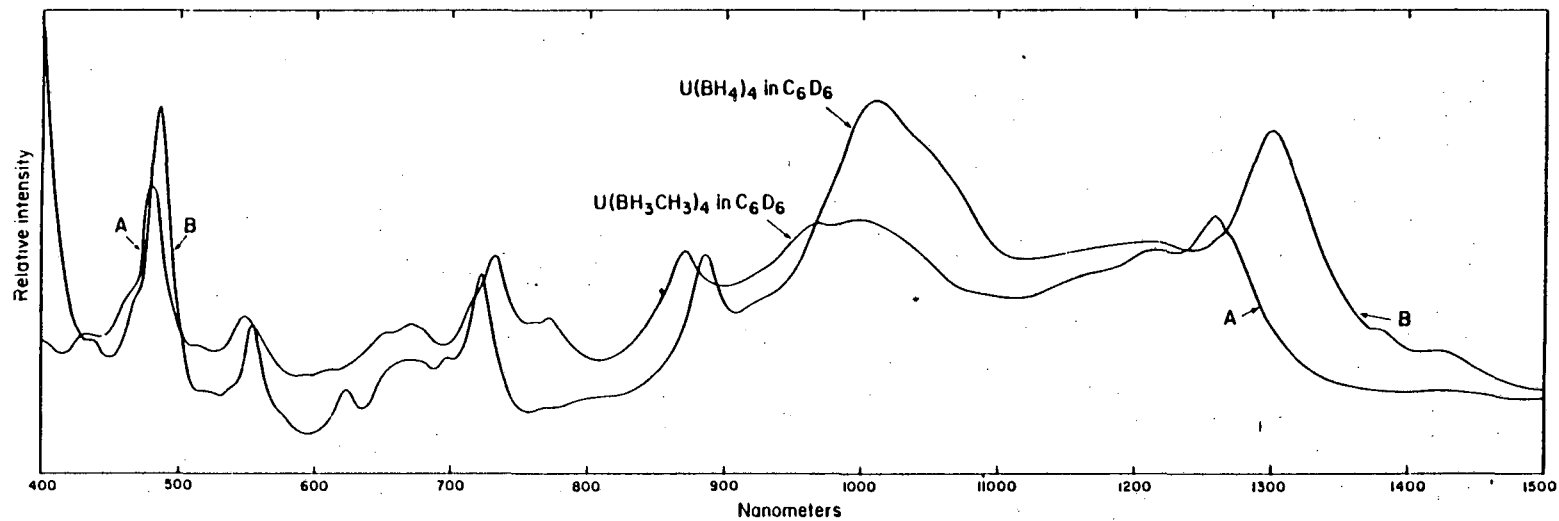


Figure 1. Optical absorption spectra of  $U(BH_4)_4$  and  $U(BH_3CH_3)_4$  in  $C_6D_6$  at room temperature.

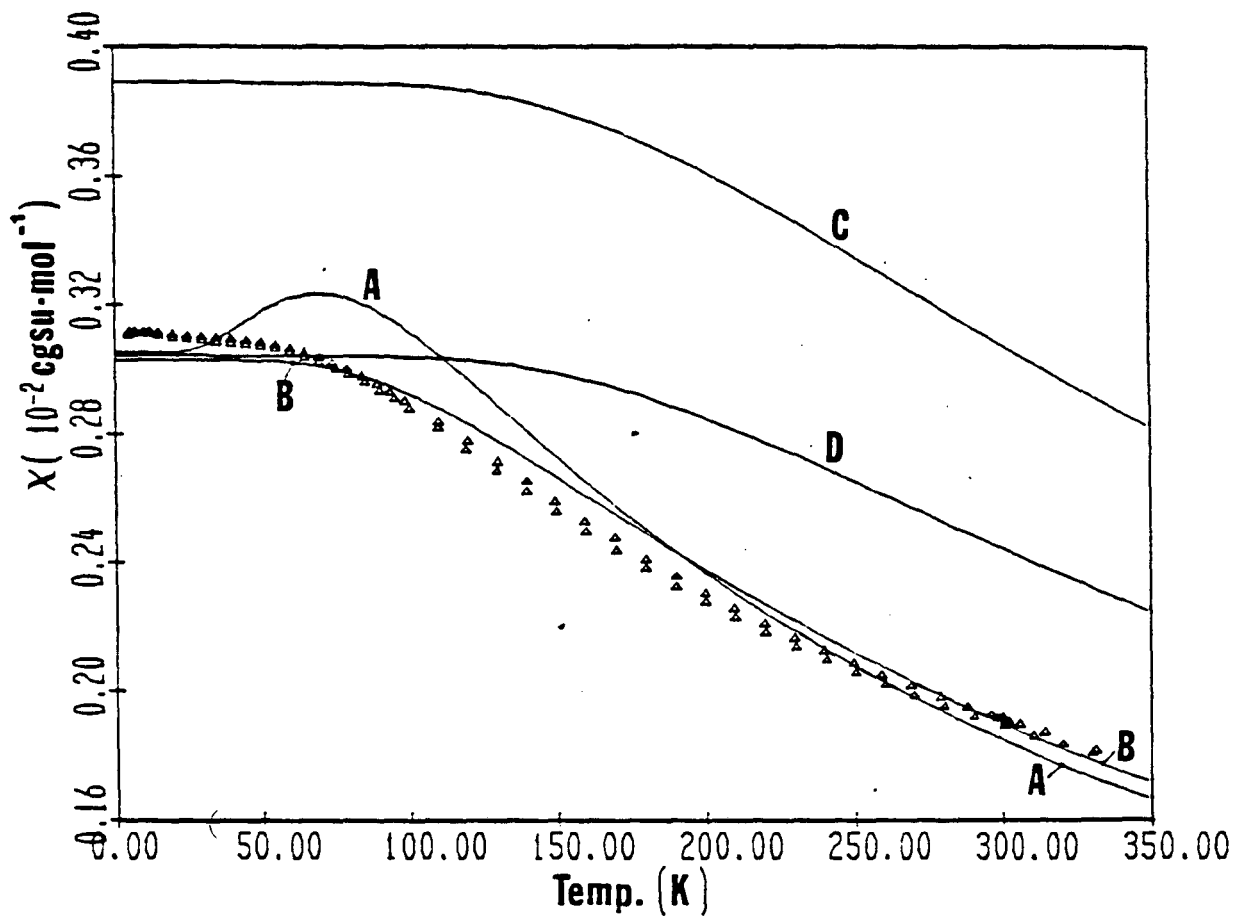


Figure 2

Paramagnetic susceptibility of  $U(BH_3CH_3)_4$ ;

$\Delta\Delta$ : experimental data obtained at 5 and 40 kGauss.

A,B: calculated considering only  $^3H_4$  splittings as in Table 1.

C: calculated from the parameters of the optical analysis  
(Table 2, second column).

D: same as C, but with an orbital reduction factor  $k = 0.93$ .

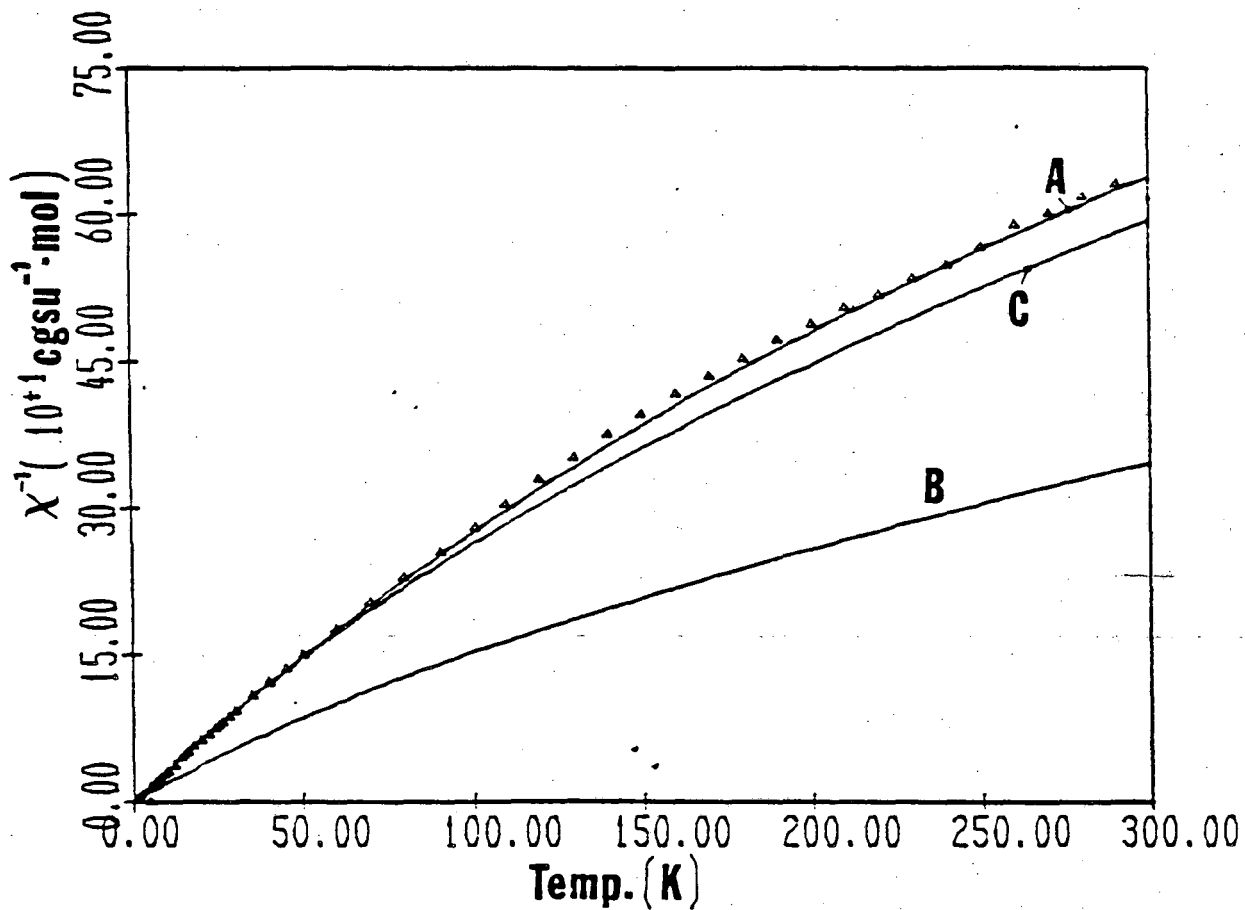


Figure 3. Inverse paramagnetic susceptibility of  $\text{Np}(\text{BH}_3\text{CH}_3)_4$ ;

$\Delta\Delta$ : experimental data obtained at 5 kGauss.

A: calculated considering only  $^4I_{9/2}$ ,  $B_0^4 = -1461 \text{ cm}^{-1}$ ,  
 $B_0^6 = -3274 \text{ cm}^{-1}$ , orbital reduction factor  $k = 0.92$ .

B: calculated from the parameters of the optical analysis.

C: same as B with an orbital reduction factor  $k = 0.87$ .

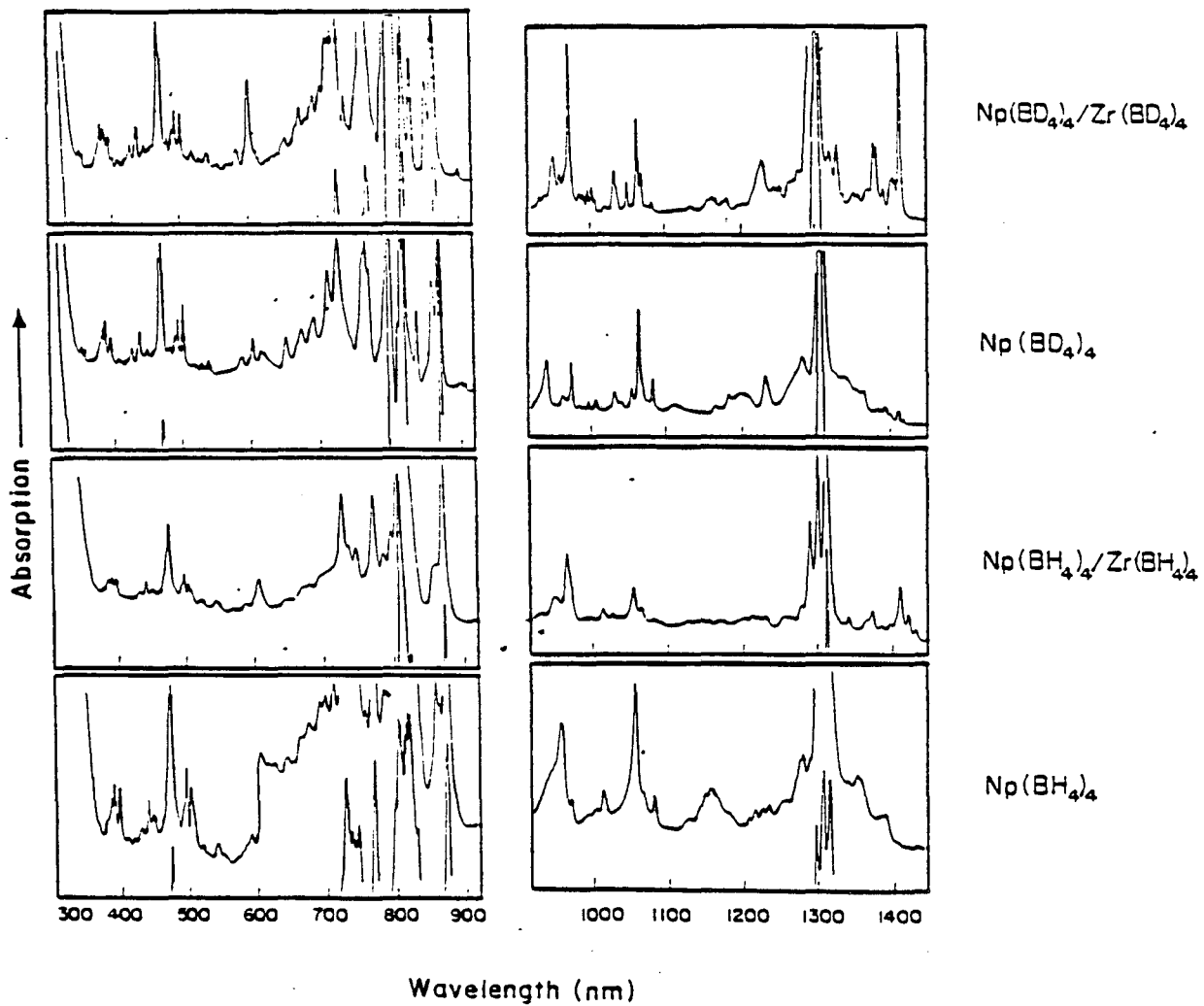
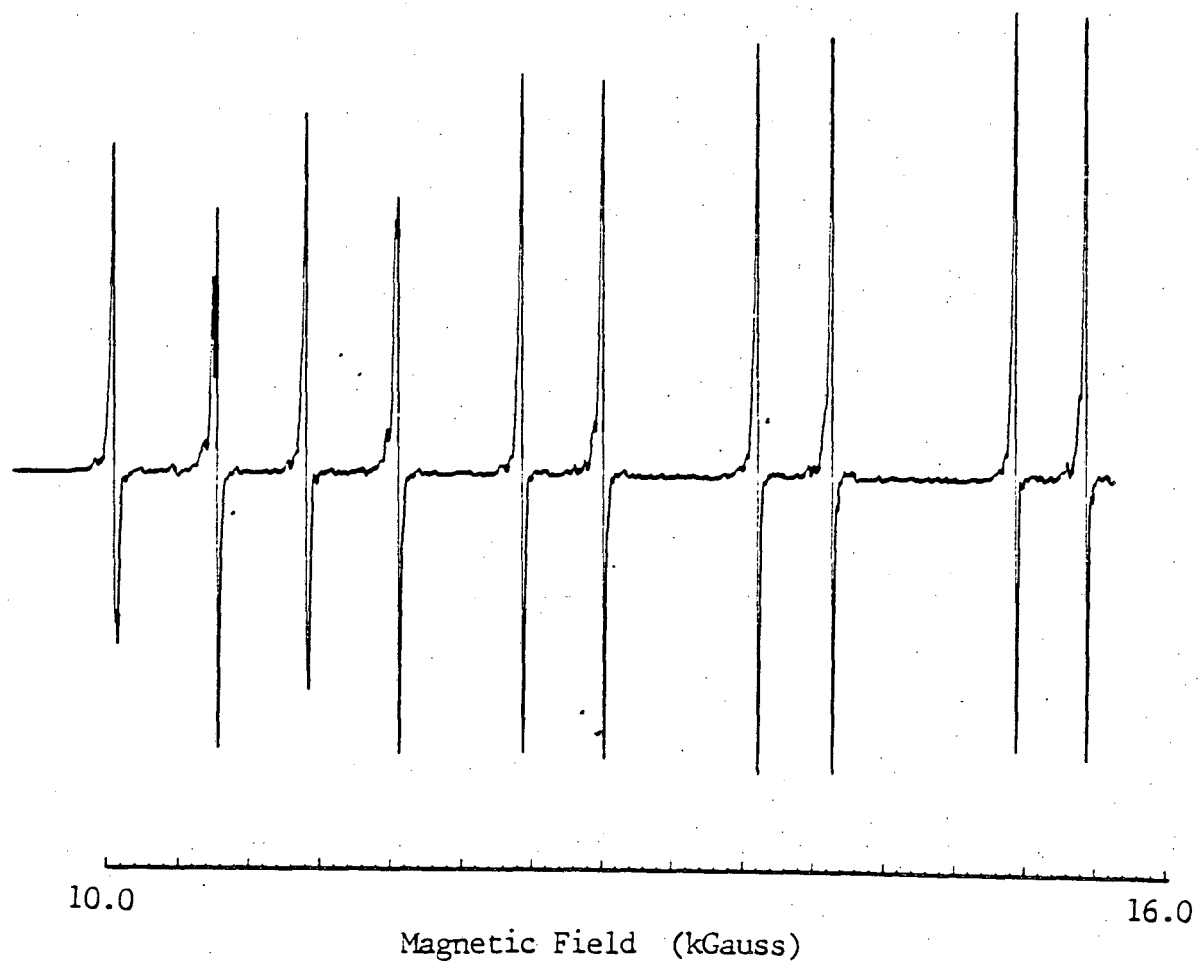


Figure 4. Optical absorption spectra of  $\text{Np}(\text{BH}_4)_4$  and  $\text{Np}(\text{BD}_4)_4$ , single crystals at 2 K.





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Figure 5. Single crystal EPR spectrum of  $\text{Np}(\text{BH}_3\text{CH}_3)_4/\text{Zr}(\text{BH}_3\text{CH}_3)$  at 2 K. Microwave frequency is 34.700 GHz, orientation of the magnetic field perpendicular to the c axis.

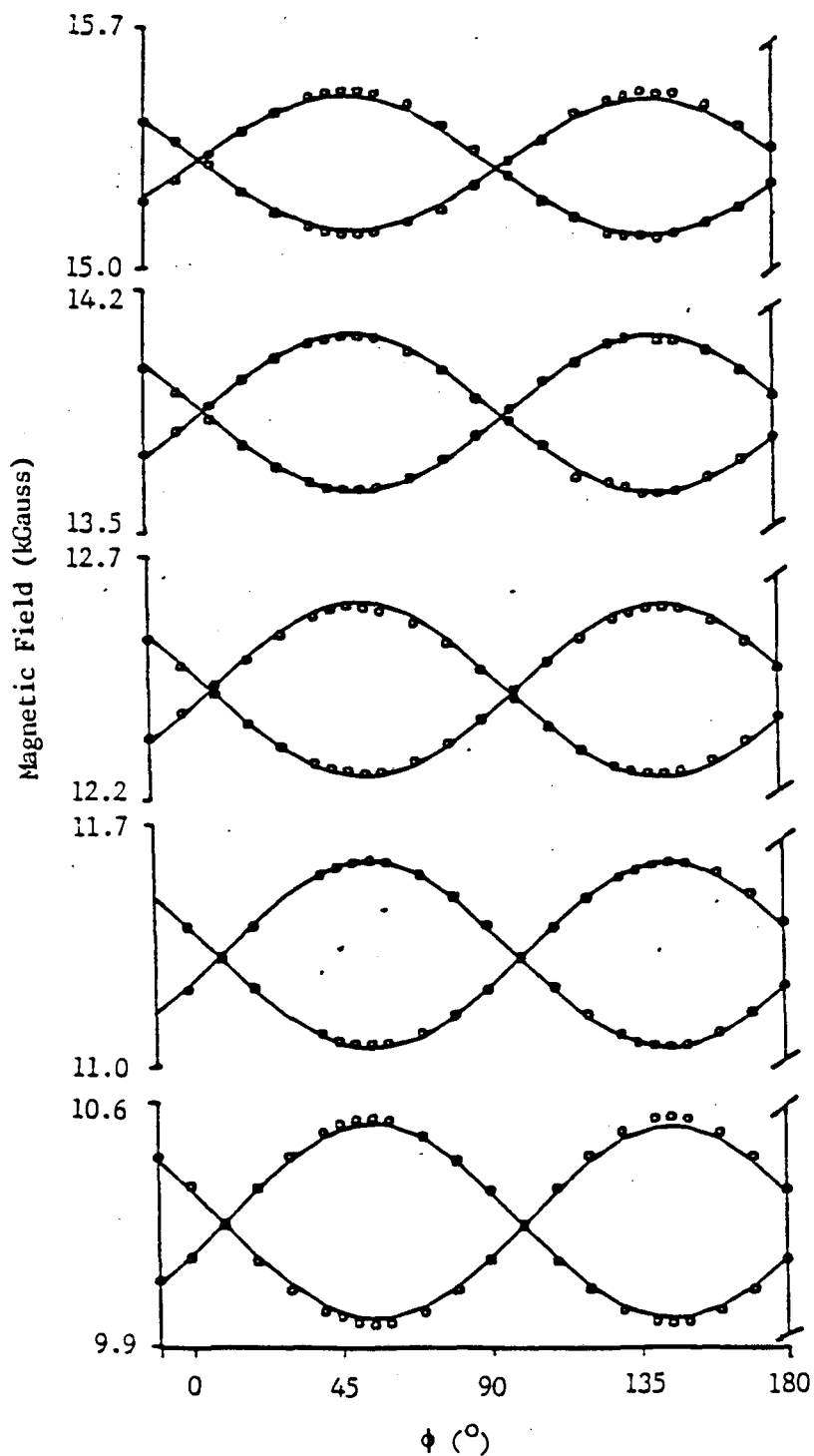


Figure 6.  $\text{Np}(\text{BH}_3\text{CH}_3)_4/\text{Zr}(\text{BH}_3\text{CH}_3)_4$ , angular dependence of resonance fields in the a-a plane.  $\phi$  is the angle of the magnetic field with the crystallographic (110) plane. Solid lines were calculated from the parameters in Table 3.

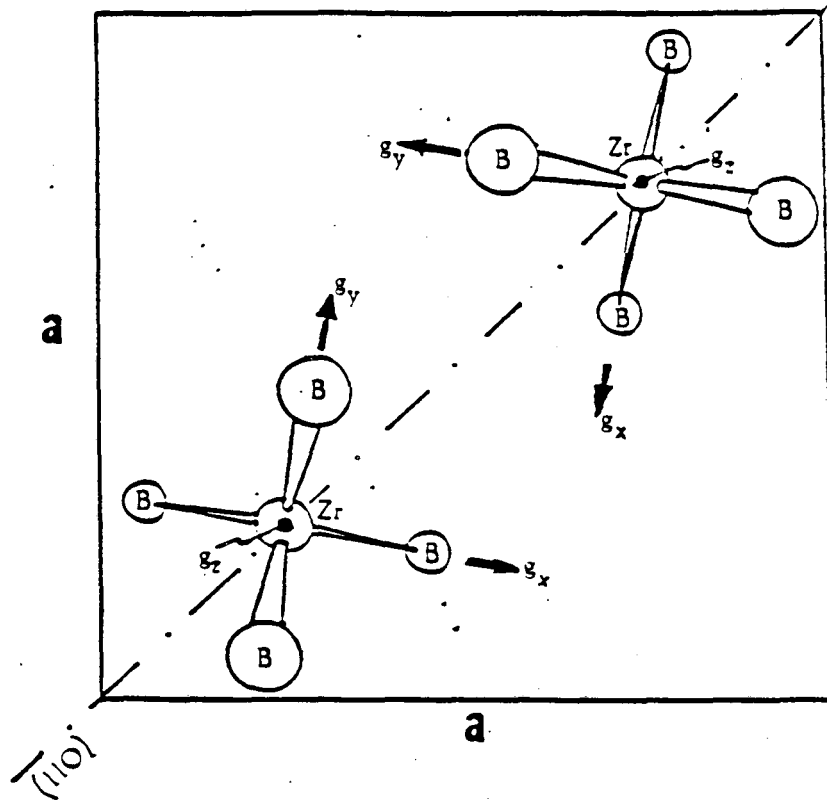


Figure 7.  $\text{Np}(\text{BH}_3\text{CH}_3)_4/\text{Zr}(\text{BH}_3\text{CH}_3)_4$ , orientation of the g-tensor axes in the crystallographic unit cell. The view is along the c axis, the Zr(Np) atoms are located at (0.25, 0.25, 0.25) and (0.75, 0.75, 0.75).

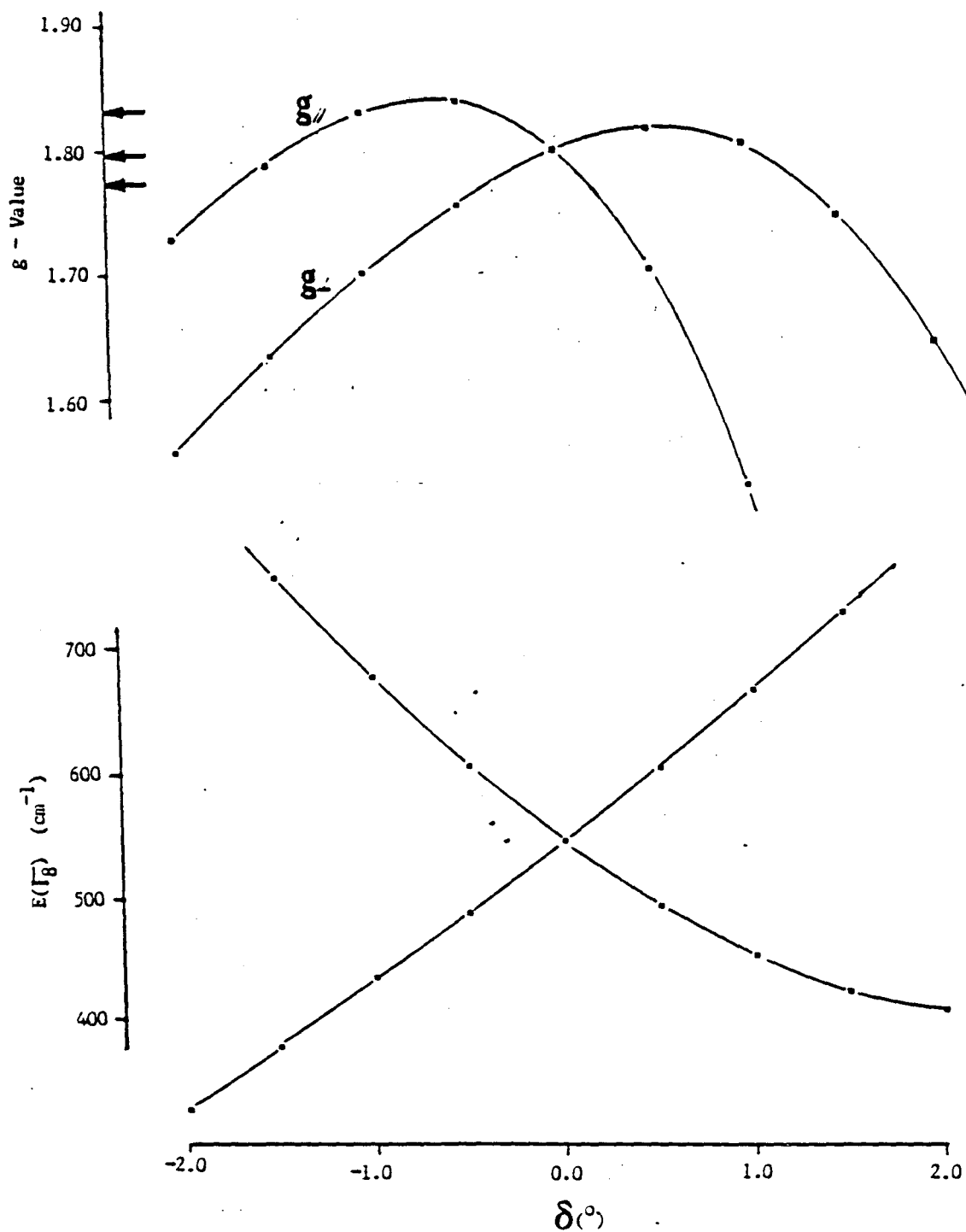


Figure 8. Influence of an axial distortion on the g-value and the energy of the lowest  $\Gamma_3$  state. The arrows indicate the experimental g values.

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