Low temperature magnetization of $Pb_{1-x}Ce_xTe$

X. Gratens [a] V. Bindilatti [a,1] N. F. Oliveira, Jr. [a] Z. Golacki [b]

[a] *Instituto de Física – USP, C. Postal 66318, 05315–970 São Paulo SP, Brazil*

[b] *Institute of Physics, Polish Academy of Sciences, Al. Lotniów 32/46, 02–668, Warsaw, Poland*

Abstract

Magnetization measurements on two $Pb_{1-x}Ce_xTe$ single crystals, at $T = 20$ mK and different field orientations, revealed magnetization steps from antiferromagnetic Ce^{3+} pairs. The present data, along with previous ones on $Pb_{1-x}Ce_xS$ and $Pb_{1-x}Ce_xSe$, strongly support the existence of two kinds of nearest-neighbor Ce^{3+}-pairs in this materials: one with isotropic and the other with anisotropic exchange interaction.

Key words: exchange interaction; exchange anisotropy; $Pb_{1-x}Ce_xTe$; dilute magnetic semiconductors

Recent studies[1] on the low temperature magnetization of $Pb_{1-x}Ce_xSe$ and $Pb_{1-x}Ce_xS$ have shown the existence of two kinds of Ce^{3+}–pairs in these diluted magnetic semiconductors. The exchange interaction is antiferromagnetic (AF) for both kinds, giving rise to magnetization steps (MST). For one of them the MST's depend on the field orientation, which has been interpreted as due to exchange anisotropy. In this work, an experimental study on $Pb_{1-x}Ce_xTe$ is presented. The results are qualitatively very similar to the previous ones and give further support to the conclusion that both kinds of pairs are formed by nearest-neighbor (NN) Ce^{3+} ions.

Two Bridgman grown crystals of $Pb_{1-x}Ce_xTe$ were studied. The Ce concentrations, x = 0.0049 and x = 0.0062, were determined from the saturation moments measured at 2 K. The g-factor for the ground doublet (effective spin $S = \frac{1}{2}$), $g = 1.398$, was taken from EPR data. The Ce concentrations for both samples are low enough to prevent crystal inhomogeneities.[2]

The magnetization M of both samples was measured at $T = 20$ mK and magnetic fields H up to 90 kOe, oriented parallel to the three principal directions of the crystals (as the other members of the series, $Pb_{1-x}Ce_xTe$ has the rock-salt structure). For both samples, M is saturated below 20 kOe. Figure 1 shows

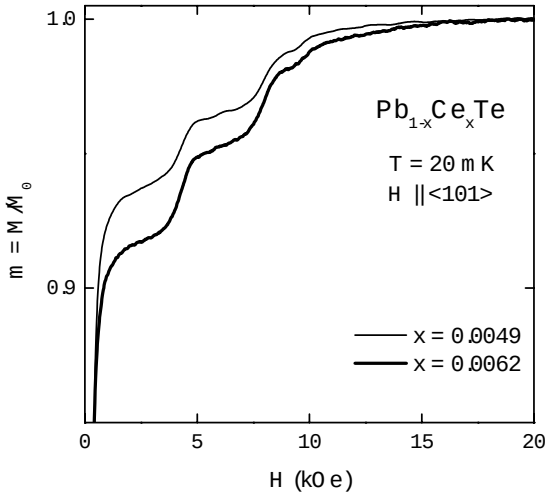

Fig. 1. Relevant part of the magnetization curves measured at $T = 20$ mK with $\mathbf{H} \parallel \langle 101 \rangle$ for two $Pb_{1-x}Ce_xTe$ samples. The magnetization M has been corrected for the lattice diamagnetism and normalized to its saturation value M_0.

the relevant part of the normalized magnetization $m = M/M_0$ (M_0 is the saturation value) below 20 kOe for $\mathbf{H} \parallel \langle 101 \rangle$. After a initial rise, three MST's are observed for this field orientation.

These MST's, as well as the MST's observed for the two other field orientations, are seen as the peaks in the

[1] E-mail: vbindilatti@if.usp.br

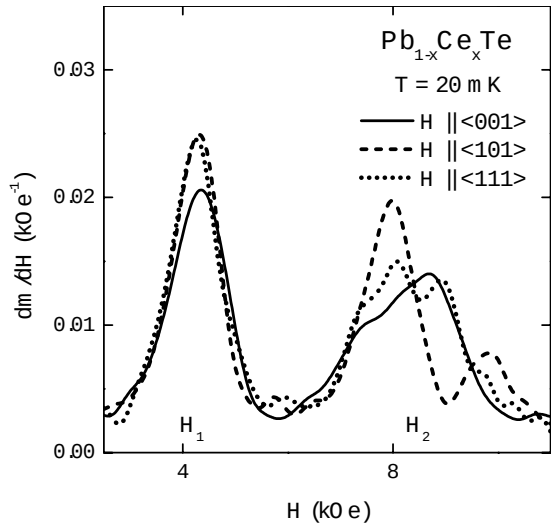

Fig. 2. Numerical field derivative of the magnetization curves at 20 mK for the sample with x = 0.0062 with three different field orientations.

susceptibility traces shown in Fig. 2. The first MST at $H_1 = 4.3$ kOe is isotropic and the structure of MST's centered near $H_2 = 8.5$ kOe depends on the field orientation. The same feature was observed for the sample with x = 0.0049.

For the low concentration of the studied samples, M is determined essentially by singles and pairs, the larger clusters being in much smaller numbers. For pairs of $S = 1/2$ spins coupled by an AF isotropic exchange interaction, only one MST is predicted, at $H = 2|J|/g\mu_B$. Therefore, the MST's are attributed to two kinds of Ce^{3+}-pairs. One kind, giving the MST at H_1, has isotropic exchange, with $J = -0.20 \pm 0.01$ K. The second kind leads to the orientation dependent structure of MST's around H_2.

To explain the observed structure we assume exchange anisotropy, taking the pair Hamiltonian in the form:

$$\mathcal{H}_p = -2J\mathbf{S}_1.\mathbf{S}_2 \\ -2D(3S_{1z}S_{2z} - \mathbf{S}_1.\mathbf{S}_2) - 2E(S_{1x}S_{2x} - S_{1y}S_{2y}).$$

Here z is the bond direction of the pair and x is the cubic edge perpendicular to z. The exchange anisotropy makes the position of the MST for a pair to depend on the orientation of its axes relative to the applied magnetic field. Differently oriented pairs of the same kind, present in a diluted sample, will then give rise to MST's in different field positions, generating the observed peak structure.

A novel feature for $Pb_{1-x}Ce_xTe$, as compared to the other two materials, is the MST splitting observed for $\mathbf{H} \parallel \langle 111 \rangle$. It means that there are two differently oriented groups of anisotropic pairs for this field orientation. That rules out the possibility that these pairs are formed by next-nearest neighbors Ce-ions. In that case, all pairs would be in equivalent orientations in relation to the field. We conclude, therefore, that the anisotropic pairs are NN-pairs.

Table 1
Exchange parameters for the two kinds of NN Ce-pairs in $Pb_{1-x}Ce_xS$, $Pb_{1-x}Ce_xSe$[1] and $Pb_{1-x}Ce_xTe$ (this work).

	Isotropic	Anisotropic		
Material	J/k_B	J/k_B	D/k_B	E/k_B
$Pb_{1-x}Ce_xS$	-0.32	-0.46	-0.057	$+0.150$
$Pb_{1-x}Ce_xSe$	-0.26	-0.42	-0.028	$+0.155$
$Pb_{1-x}Ce_xTe$	-0.20	-0.40	-0.107	$+0.060$

The exchange parameters for the isotropic and anisotropic kinds of pairs for the three materials of the $Pb_{1-x}Ce_xX$ series are shown in Table 1. We notice that for the anisotropic pairs in $Pb_{1-x}Ce_xTe$, the axial term D is sensibly stronger than for the other two materials. This explains why the $\mathbf{H} \parallel \langle 111 \rangle$ splitting is observed in this case and not in the other two.

For both $Pb_{1-x}Ce_xX$ samples, the total size of the MST's (from both the isotropic and the anisotropic pairs) is quite consistent with the predicted number of NN-pairs with random distribution of the Ce^{3+} ions. This agreement has been observed for every one of the eight samples investigated in the $Pb_{1-x}Ce_xX$ family, with x ranging from 0.0018 to 0.035. Such remarkable agreement strongly indicates that both kinds of pairs are NN Ce pairs. The coexistence of these two kinds of NN-pairs (with about the same population in each of the studied samples) may be due to the presence of local defects in the crystals. This possibility is being investigated by EPR experiments.

Acknowledgements

This work was supported by CNPq and FAPESP (Brazilian agencies) and the Polish Committee for Scientific Research.

References

[1] X. Gratens, V. Bindilatti, E. ter Haar, N. F. Oliveira, Jr., Y. Shapira, Z. Golacki, Physica B **284** (2000) 1519; J. Magn. Magn. Mater. **226** (2001) 2036.

[2] P. Fita, K. Smolinski, Z. Golacki, K. Lawniczak-Jablonska, Appl. Phys. A-Mater. **68** (1999) 681.