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# Magnetic phase diagrams of dysprosium iron garnet (DyIG) in high dc fields

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**Abstract**

Magnetisation measurements have been performed on spherical single crystals of dysprosium iron garnet ($Dy_3Fe_5O_{12}$) in high dc magnetic fields up to 16 T applied along the three principal crystallographic directions ⟨111⟩, ⟨110⟩ and ⟨100⟩. The magnetic phase transitions near the inversion (or compensation) temperature $T_I$ between the collinear and the field induced canted magnetic structures are observed and the different associated magnetic phase diagrams precisely determined in the ($H$,$T$) plane. The mean exchange field acting on the Dy ions and the effective anisotropy field are deduced to be (12.9±0.2) T and (1.2±0.1) T respectively. Above 228.2±0.5 K, only the collinear magnetic phase exists for all the directions. These results are compared to previous high pulsed magnetic fields data.


*Keywords:* Rare earth iron garnets; High field magnetisation; Magnetic phase transitions; Magnetic phase diagrams; Magnetic anisotropy

## 1. Introduction

Since the first observation on DyIG of the field induced canted phases predicted from the Néel theory of ferrimagnets [ [1], and Refs. herein], a large number of works have been devoted to the study of such phase transitions and the related magnetic phase diagrams. They are observable near the inversion (or compensation) temperature $T_I$, where the spontaneous magnetisations of iron and rare earth sublattices are exactly opposite like in an antiferromagnet. In fact, one of the main interest of these diagrams is that the critical field transition lines $H_{c\alpha}(T)$ depend directly of the magnetic anisotropy and exchange parameters. Apart from the case of YbIG, such canted phases exist only in a narrow range of temperatures around $T_I$ and in very high magnetic fields and so, they have been observed only by pulsed fields in the past [2–4]. Despite of a rather good qualitative agreement with the simple models based on the mean field approximation, their more or less adiabatic conditions and associated time effects could affect the results and may yield to rather large errors. Recently, in some of these rare earth iron garnets, new magnetic transitions have been observed at low temperature [5–8] and a better knowledge of the microscopic parameters which are responsible of the magnetic behaviour of the rare earth ions is needed [9]. Whatever the models, they have to be consistent with the high temperature behaviour, and it is therefore important to have a good description of the magnetic phase diagrams by means of magnetisation measurements with a high degree of resolution both in field and temperature. This work is devoted to settle as precisely as possible the magnetic behaviour of DyIG, which is of special interest for a spin reorientation occurring at 14 K [5,6].

## 2. Experimental

The magnetisation of two spherical single crystals of DyIG grown by standard $PbO/PbF_2$ method (weight: 0.38244 g and 0.20308 g; diameter: 5 mm and 3 mm) have been measured by the extraction technique between 80 K and 250 K in dc magnetic field up to 16 T. The magnetic field of the superconducting magnet was applied along the three main crystallographic directions ⟨111⟩, ⟨110⟩ and ⟨100⟩ which were checked by X-ray Laüe technique to be within a one degree error. The magnetisation is overall

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reported in Bohr magneton for the ($Dy_3Fe_5O_{12}$) formula unit.

## 3. Results and discussion

Two typical isothermal magnetisation curves $M_T(H)$ are reported as a function of the magnetic field for the ⟨100⟩ direction at 204 K (Fig. 1a) and 224 K (Fig. 1b), respectively below and above the inversion temperature. For such non easy directions, in low increasing fields, the magnetic structure become collinear at a first transition field $H_{c1}$ which corresponds to the end of the rotation of the magnetisation from the easy ⟨111⟩ directions toward the ⟨100⟩ direction of the field. After a slightly curved part where the slope varies slowly when the field is increased in the collinear phase, there is a sudden change for a critical field $H_{c2}$ with a jump in the slope. For $H>H_{c2}$, the canted phase is characterised by an almost linear field dependence. In order to see this transition with more evidence and to get a better determination of $H_{c2}$, it is useful to plot the deviation to a straight line. Let remember one feature of the isotropic model: in the canted phase, the field vector **H** is shown to be collinear to the total magnetisation vector **M** and this can be written $\mathbf{H}=\lambda\mathbf{M}$ [10]. The parameter $\lambda$, or inverse susceptibility, which is directly related to the intersublattice exchange, is rigorously constant in the two sublattice model and only slightly temperature and field dependant in the more numerous sublattices models. So, by analogy, for each curve, the reference line $M=H/\lambda$ is taken arbitrarily as the straight line joining the last point of the curve to the origin. As it can be seen on the Figs. 1 and 1b, where the deviations $M_T(H)-H/\lambda$ are plotted together with $M_T(H)$, the transition is rather sharp for $T<T_I$ but become more difficult to locate for $T>T_I$, and vanish at a temperature $T^*\cong 228$ K, above which, only the collinear phases are stable in high fields.

In addition, another suitable way to determine such transitions lines, is to record the magnetisation at constant magnetic field, while the temperature is varied step by step in the 190–240 K range. In Fig. 2, two typical curves are presented for $H=13$ T along ⟨110⟩ (Fig. 2a) and $H=5$ T

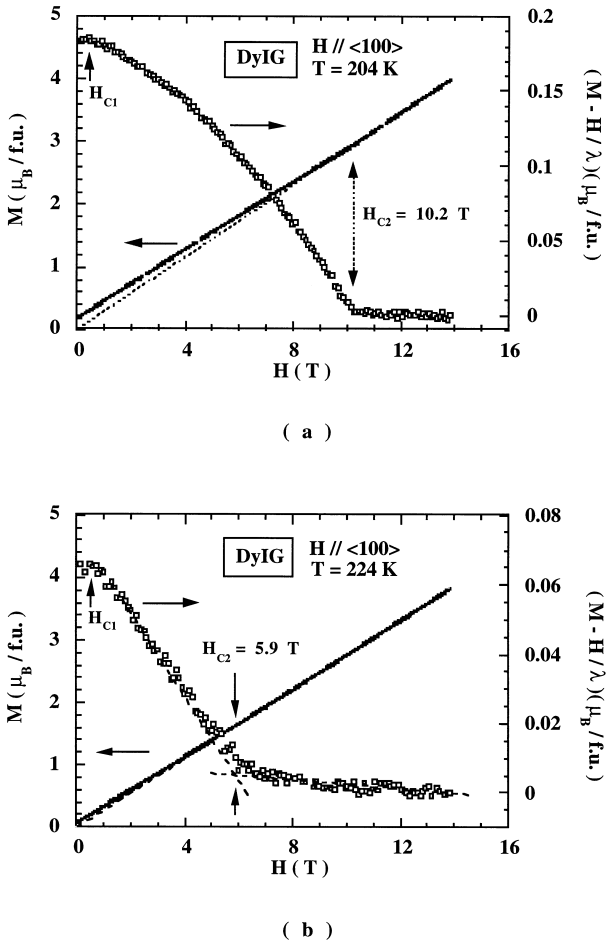


Fig. 1. The ⟨100⟩ isothermal magnetisation curves $M_T(H)$ and their deviation to straight lines $H/\lambda$ at 204 K (a) and 224 K (b).

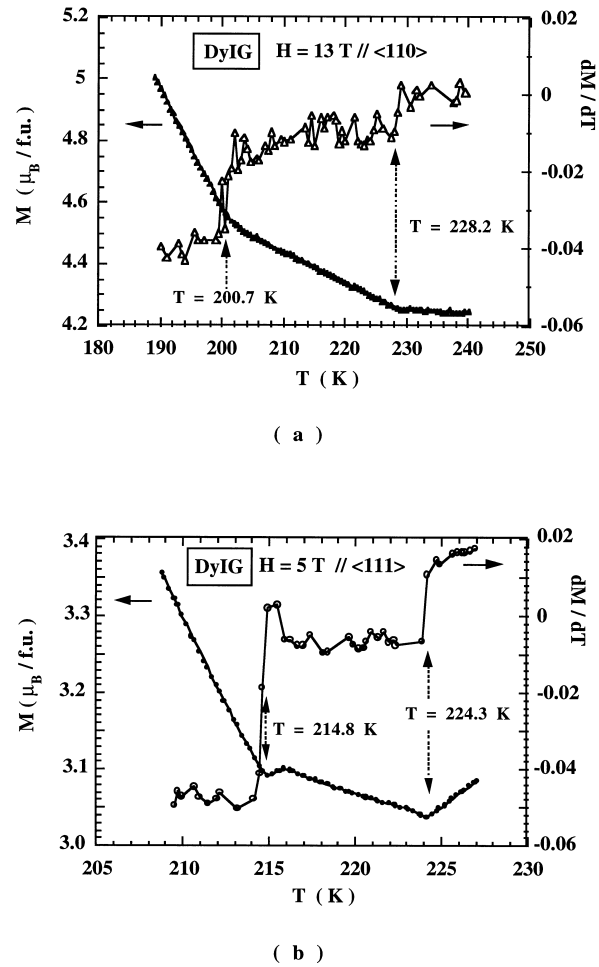


Fig. 2. Thermal dependence of the magnetisation $M_H(T)$ and its derivative $(dM/dT)_H(T)$ at constant external field: $H=13$ T along ⟨110⟩ (a) and $H=5$ T along ⟨111⟩ (b).

along ⟨111⟩ (Fig. 2b). On such curves $M_H(T)$, three almost linear parts can be identified, the canted phase corresponding to the central one, and the two inverse collinear ones on each side. The transition temperatures can be rather well determined within an error of less than 0.5 K by the associated anomalies in the numerical derivative curves $(dM/dT)_H(T)$ plotted on the same figure.

The variations of the critical field $H_{c2}$ versus the temperature in the neighbourhood of the inversion temperature $T_I$ (218.5±0.5 K) are reported in Fig. 3. The slopes $(dH_{c2}/dT)$ of the transition lines at $T_I$ are found to be: 1.02, 0.89 and 0.73 $T\,K^{-1}$ for the ⟨111⟩, ⟨110⟩ and ⟨100⟩ directions respectively. At $T=206$ K, the critical field $H_{c2}$ along ⟨111⟩ is about 1.24 T and 2.41 T much higher than $H_{c2}$ along ⟨110⟩ and ⟨100⟩ respectively. This is consistent with the fact that ⟨111⟩ is the easy direction and it gives an estimation of the effective anisotropy field $H_a \cong 1.2$ T.

The agreement with the previous values of Ref. [2] is found to be rather poor, but it may come mainly from the different definition of the critical fields which are deduced from the anomaly of the magnetostriction observed on powder samples of DyIG in pulsed magnetic field. The agreement is much better with the more recent determinations by both Faraday rotation and magnetisation measurements also performed in high pulsed magnetic fields [4], if their data are translated of 4.6 K toward lower temperature to account for the difference in the observed inversion points. Finally, our value of the slope (1.02 $T\,K^{-1}$) for the ⟨111⟩ phase diagram is slightly higher than that reported in Ref. [4] (0.80 $T\,K^{-1}$). This means that at $H=10$ T there may be a shift of about 2 K between pulsed and static field experiments. This rather large shift is of the right order of magnitude if only the magnetocaloric effect is considered. As a conclusion, this work on DyIG has put a point on the advantages of high static magnetic field magnetisation measurement over high pulsed field experiments for the determination of reliable parameters in the rare earth iron garnets.

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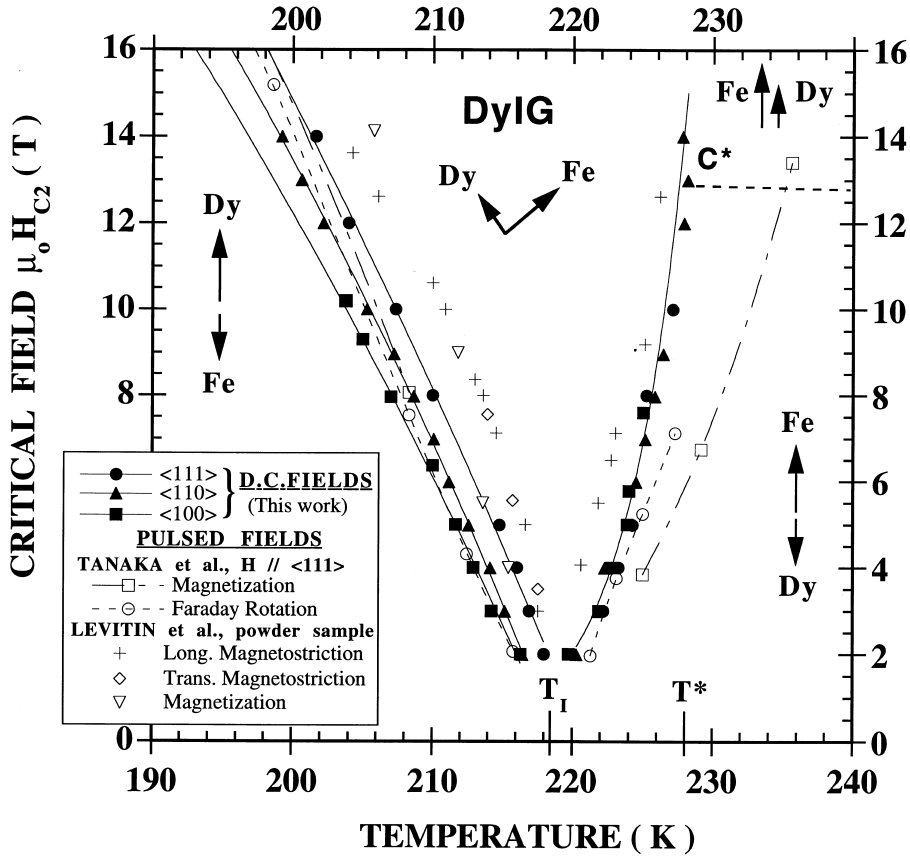


Fig. 3. Magnetic phase diagrams $(H_{c2},T)$ of DyIG for the three principal directions in the neighbourhood of the inversion temperature $T_I$.

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