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ABSTRACT

The optical absorption spectra of an easy-plane $NdFe_3(BO_3)_4$ antiferromagnet are measured in the region of the $^4I_{9/2} \rightarrow {}^2H_{11/2}$ transition of the of Nd^{3+} ion. The study is performed in the 2–35 K temperature range, in external magnetic fields of up to 65 kOe directed both along the C_3 axis and the basal plane of the crystal. The splitting values of the Nd^{3+} excited states in the exchange field of the Fe^{3+} subsystem and the g-factors of the $^2H_{11/2}$ multiplet states are determined. The nontrivial dependences of the splitting of some Nd^{3+} states in a magnetic field indicate that these states have anisotropic Fe–Nd exchange interaction.

1. INTRODUCTION

The $NdFe_3(BO_3)_4$ crystal belongs to the family of rare-earth trigonal ferroborates with the general formula $RFe_3(BO_3)_4$ (where R is a rare-earth element), which have lately been the subject of intensive studies. The interest in rare-earth ferroborates is primarily driven by the multiferroelectric properties they exhibit, which suggest the coexistence of magnetic, electric, and elastic ordering.[1–4] The magnetic properties of the crystals belonging to the $RFe_3(BO_3)_4$ family are rather diverse due to the presence of two interacting magnetic subsystems. The exchange interaction in the subsystem of iron ions determines the crystals' magnetic ordering temperature, which for most ferroborates is in the range of 30–40 K.[5] The rare-earth subsystem acquires a magnetic moment due to the f–d exchange interaction with iron ions. The subsystem of Fe^{3+} ions (the ground state is $^6S_{5/2}$) features rather weak easy-plane magnetic anisotropy primarily due to dipole-dipole interaction. As a rule, rare-earth ions exhibit a stronger magnetic anisotropy than Fe^{3+}, and thus determine the type of magnetic structure of the crystal. Ferroborates include both easy-axis and easy-plane antiferromagnets; a spontaneous phase transition from one magnetic state to another occurs in some with a change in temperature.[6,7] Noncollinear and incommensurate[7–9] magnetic structures have been discovered in some ferroborates. All representatives of the $RFe_3(BO_3)_4$ family have a huntite crystal structure that is described by the $R32$ space group at high temperatures. Some ferroborates exhibit a structural phase transition to the lower symmetry phase $P3_121$ with decreasing temperature.[10]

Neodymium ferroborate $NdFe_3(BO_3)_4$ retains its $R32$ crystal structure to a temperature as low as 2 K.[11–13] The rare-earth ion occupies a position with local D_3 symmetry. At a temperature of $T_N \approx 30$–33 K antiferromagnetic ordering of the crystal occurs, and an easy-plane structure is formed as the Fe^{3+} and Nd^{3+} magnetic moments are oriented along one of three second-order axes in the basal plane of the crystal.[14,15] It should be noted that the structure is collinear, despite the presence of many sublattices (no less than 2 Nd^{3+} ions and 6 Fe^{3+} ions) and low positional symmetry of Fe^{3+} ions (C_2). Three equivalent directions in the crystal correspond to three 120° equivalent magnetic domains (excluding antiferromagnetic degeneracy). Below $T_{IC} = 13.5$ K, the collinear magnetic structure transforms into a long-period antiferromagnetic helix that propagates along the C_3 axis, with the orientation of magnetic moments being conserved in the basal plane.[9,16] If a magnetic field is applied perpendicular to the C_3 axis, the helical structure decays, and the antiferromagnetism vectors of the Nd and Fe sublattices

become oriented perpendicular to the external field in the basal plane;[16] this spin re-orientation occurs thus in the form of a first-order transition.[17–19]

The optical absorption spectra of $NdFe_3(BO_3)_4$ were studied in detail in the spectral range 1500–25000 cm^{-1} at temperatures ranging from 4.2 to 300 K, in Ref. 20. The authors calculated the wave functions, energies, and g-factors of the Nd^{3+} states in the crystal field. It was discovered for some states that Kramers doublets split in the process of magnetic ordering of the system as a result of the exchange interaction with the subsystem of Fe ions. It was found, in particular, that the exchange splitting of the Nd^{3+} ground state is 8.8 cm^{-1} at a temperature of 4.2 K.

The optical spectra of the crystal in an external magnetic field were studied for the first time in Ref. 21. A non-trivial behavior of the intensities of the polarized components of the Kramers doublet 15971–15978 cm^{-1} was observed in Nd^{3+}, in the transverse Zeeman geometry in the region of the optical transition $^4I_{9/2} \rightarrow {}^2H_{11/2}$. This phenomenon has been shown to be a reflection of the complex pattern of effective magnetic fields that impact the Nd^{3+} ion. Those fields are a superposition of the external and internal exchange fields, the magnitude and direction of the latter field being different for the ground and optically excited states of the Nd^{3+} ion.

The magnetic properties of the ion in an optically excited state, as well as properties of its closest crystalline environment, can differ significantly from those of the unexcited ions of the crystal. Exploring the spectra in external magnetic fields makes it possible to determine the specific features of the excited states of the ions.[22–24]

In Ref. 20, for the group of $^4I_{9/2} \rightarrow {}^2H_{11/2}$ absorption lines in $NdFe_3(BO_3)_4$, there is no information on the splitting of states during the magnetic ordering of the crystal. At the same time, a study of low-temperature spectra that we have conducted[21] shows that some of the states exhibit significant splitting in the exchange field. Apart from this, all states of the $^2H_{11/2}$ multiplet exhibit rather significant longitudinal or transverse components of the g-factor.[20] Due to these features, this group of transitions may be used as a kind of "model" for studying the behavior of spectra in magnetic fields. This article presents the temperature dependences of $NdFe_3(BO_3)_4$ absorption spectra in the region of $^4I_{9/2} \rightarrow {}^2H_{11/2}$ transitions at $T \leq T_N$, and explores the spectra in external magnetic fields oriented both along the C_3 crystallographic axis and the basal plane of the crystal.

2. EXPERIMENTAL PROCEDURE

Single crystals $NdFe_3(BO_3)_4$ were grown from the solution-melt using the technique described in Ref. 25. The absorption spectra were measured using samples in the shape of a plane-parallel plates 0.2 to 0.7 mm thick, oriented perpendicular or parallel to the third-order crystallographic axis.

A spectral device, DFS-13, was used to study the absorption spectra; light was recorded using a set of light-sensitive diodes that operated as part of a multichannel optic analyzer. The spectral resolution in the studied region was about 0.5 cm^{-1}. The absorption spectra were recorded when light was propagating perpendicular to the C_3 axis, with the direction of the light-wave **E** vector being parallel (π-spectra) or perpendicular (σ-spectra) to the C_3 axis, and when light was propagating along the C_3 axis (α-spectra).

The magnetic field was created by a superconducting solenoid similar to a Helmholtz coil, which together with the sample was immersed in superfluid helium. Spectra in the magnetic field were recorded at a temperature of 2 K.

3. TEMPERATURE DEPENDENCE OF LIGHT-ABSORPTION SPECTRA OF $NdFe_3(BO_3)_4$ IN THE REGION OF THE OPTICAL TRANSITION $^4I_{9/2} \rightarrow {}^2H_{11/2}$ OF THE Nd^{3+} ION

The states of the Nd^{3+} ion (electron configuration $4f^3$) in the crystal field with D_3 symmetry are Kramers doublets that transform according to two-valued irreducible representations Γ_4 and $\Gamma_{5,6}$. The ground multiplet $^4I_{9/2}$ is split in a trigonal field into five Kramers doublets: $3\Gamma_4 + 2\Gamma_{5,6}$, the lowest state having Γ_4 symmetry.[20] The energy of the first excited state is 65 cm^{-1} and therefore, only the spectral transitions from the ground state are observed in the temperature range under study ($T \leq T_N$). The multiplet $^2H_{11/2}$ explored in this study is split in the crystal field with D_3 symmetry into 6 Kramers doublets in the following way: $^2H_{11/2} \rightarrow 4\Gamma_4 + 2\Gamma_{5,6}$.

Figure 1 shows the absorption spectra that correspond to the optical transitions $^4I_{9/2} \rightarrow {}^2H_{11/2}$ in σ- and π-polarizations at various temperatures in the range $T \leq T_N$. All six possible transitions are observed in the spectrum. They have an electric dipole nature, as is confirmed by the coincidence of spectra in σ- and α-polarizations. In accordance with the selection rules in D_3 symmetry (Table I), transitions $\Gamma_4 \rightarrow \Gamma_4$ should be observed in both σ- and π-polarizations, while transitions $\Gamma_4 \rightarrow \Gamma_{5,6}$, in σ-polarization alone. Table II shows the energies of the observed transitions compared to those calculated in Ref. 20, with symmetry identified using polarization selection rules.

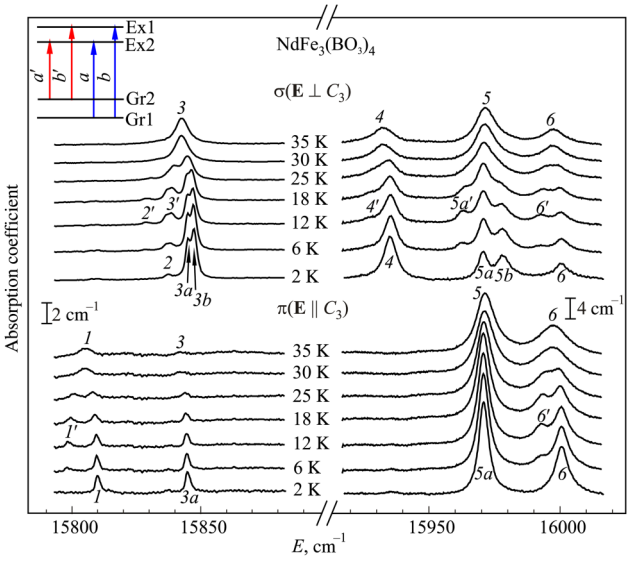

FIG. 1. Light-absorption spectra of $NdFe_3(BO_3)_4$ in the region of the $^4I_{9/2} \rightarrow {}^2H_{11/2}$ optical transition in Nd^{3+} at various temperatures. The insert shows the chart of transitions between splitting components in the exchange field of the ground and excited Kramers doublets.

TABLE I. Selection rules for electric dipole transitions in a crystal field with *D*3 symmetry.

	$E_{1/2}$ (Γ_4)	$E_{3/2}$ ($\Gamma_{5,6}$)
$E_{1/2}$ (Γ_4)	π, σ(α)	σ(α)
$E_{3/2}$ ($\Gamma_{5,6}$)	σ(α)	π

Some of the Kramers doublets, as well as the ground doublet, are split at temperatures $T < T_N$ due to the exchange interaction with the iron subsystem; up to four transitions may be observed in that case, as it is shown in the chart (insert in Fig. 1). At a temperature of 2 K, only transitions from the lowest sublevel of the ground doublet are observed. If the temperature increases to 6 K, transitions from the excited sublevel of the ground doublet also emerge, marked by a "prime" in the chart and spectra (Fig. 1), and their intensity grows with increasing temperature.

The highest value of exchange splitting in the excited state (about 7.5 cm^{-1}) reveals transition "*5*" (lines *5a* and *5b* at $T = 2$ K). Since this value is close to the splitting of the ground doublet (8.8 cm^{-1}), the energies of transitions *5a* and *5b′* are close to each other. As a result, the splitting of line "*5*" into only three components is observed in the spectra below T_N.

The identification of transition "*2*" is complicated by the fact that its energy virtually coincides with that of the "hot" transition "*3′*". It is virtually impossible to separate these transitions along spectra at $T \geq 6$ K. However, the very observation of line "*2*" at 2 K serves as evidence that this is a separate transition from the lowest sublevel of the ground doublet. This observation is also confirmed by the appearance of line "*2′*" with increasing temperature, which is separated from "*3*" by about 16 cm^{-1}; it may not therefore be associated with a transition to levels "*3*" from any excited level. At the same time, the interval E_2–$E_{2'}$ is approximately 8.8 cm^{-1}; line "*2′*" is obviously a transition from the upper component of the ground doublet to level "*2*". It will be shown below that the behavior of lines "*2*" and "*3*" in magnetic fields is significantly different.

4. ABSORPTION SPECTRA IN EXTERNAL MAGNETIC FIELDS H || C_3 AND H ⊥ C_3

Studies in magnetic fields were conducted at a temperature of 2 K, at which the spectra only contain transitions from the lower sublevel of the exchange-split ground Nd^{3+} doublet. Figure 2 shows

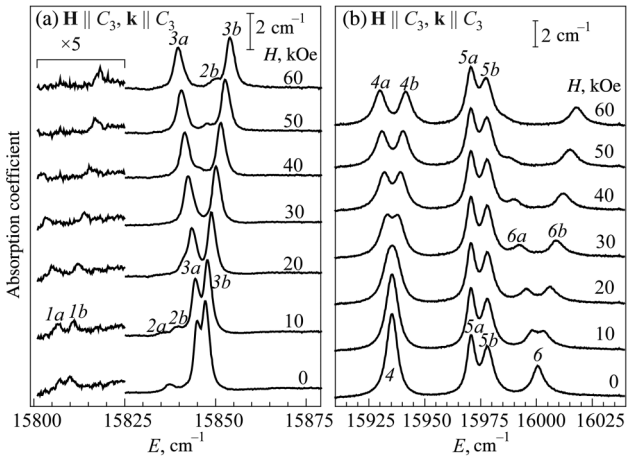

FIG. 2. Absorption spectra of $NdFe_3(BO_3)_4$ in an external magnetic field **H** || C_3 at $T = 2$ K.

a series of spectra as a function of the strength of the magnetic field directed along the C_3 axis. The spectra were recorded in unpolarized light for **k** || C_3 (α-spectra). Significant dichroism of light absorption in the basal plane occurs in the magnetic field directed perpendicular to the C_3 axis of the crystal, in the region of the $^4I_{9/2} \rightarrow {}^2H_{11/2}$ transition.[21] Therefore, in the studies conducted in the field **H** ⊥ C_3, light was directed along the C_3 axis, and the spectra were recorded with two polarizations in the basal plane: **E** || **H** and **E** ⊥ **H** (Fig. 3). Figure 4 shows field dependences of the splitting-component energies of lines *1–6* in magnetic fields **H** || C_3 and **H** ⊥ C_3.

As was mentioned above, two out of six states of the $^2H_{11/2}$ multiplet have the symmetry $\Gamma_{5,6}$. Based on polarization properties of the lines it was hypothesized that transitions "*2*" and "*4*" correspond to those states. States such as $\Gamma_{5,6}$ should not split in the magnetic field directed in the basal plane (for symmetry reasons $g_\perp \equiv 0$). Indeed, line "*4*" in the **H** ⊥ C_3 spectra does not exhibit splitting up to maximum field values, but there is an insignificant mismatch of that line's frequency at 60 kOe for polarizations **E** || **H** and **E** ⊥ **H** [Fig. 3(b)]. This may be indicative of slight splitting of state "*4*". As for the line "*2*", in strong magnetic fields ($H > 40$ kOe) it exhibits a small but quite noticeable splitting [Fig. 3(a)].

TABLE II. The parameters of optical transitions from the ground doublet Γ_4 ($^4I_{9/2}$) of the Nd^{3+} ion to the sublevels of multiplet $^2H_{11/2}$ in $NdFe_3(BO_3)_4$, calculated in Ref. 20 and measured in the experiment.

Line No.	Energy, cm^{-1} (calculation)	Energy, cm^{-1} at 35 K	Symmetry	$g_\perp$ (calculation)	$g_\parallel$ (calculation)	$g_\perp$ (exp.)	$g_\parallel$ (exp.)	ΔE_0, cm^{-1} at 2 K
1	15835	15805	Γ_4	3.7268	5.798	2.21	7.06	3
2	15861	15837 (at 2 K)	$\Gamma_{5,6}$	0	7.931		7.3	1.2–1.8
3	15862	15842	Γ_4	3.482	4.435	1.94	5.07	2.5
4	15946	15932	$\Gamma_{5,6}$	0	5.084	0	4.57	
5	15957	15971	Γ_4	5.259	0.430	5.65	0	7.5
6	15991	15997	Γ_4	1.083	9.728	0	11.58	0

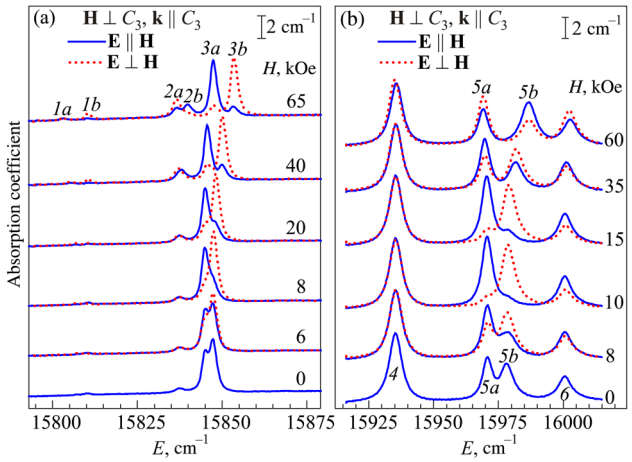

FIG. 3. Absorption spectra of $NdFe_3(BO_3)_4$ in an external magnetic field $\mathbf{H} \perp C_3$ for two polarizations in the basal plane of the crystal. $T = 2$ K.

There is one more line that does not exhibit splitting in the field $\mathbf{H} \perp C_3$: line "6" [Fig. 3(b)]. However, this seems to be caused by the smallness of the transverse component of the g-factor of state "6" (the calculation made in Ref. 20 yields $g_\perp = 1.083$). This line is identified in Ref. 20 as the $\Gamma_4 \to \Gamma_4$ transition, based on its polarization properties.

5. SPLITTING OF STATES WITH SYMMETRY Γ_4 IN AN EXTERNAL MAGNETIC FIELD

If a magnetic field is applied in the basal plane of the crystal at 2 K, a spin-reorientation phase transition occurs for a field strength of $H_{sf} \approx 9$ kOe, from the long-period helix to a state similar to the spin-flop phase, where the antiferromagnetism vectors of the Nd^{3+} and Fe^{3+} ions are oriented in the basal plane perpendicular to the direction of the external field. The neodymium ion is subject to the concurrent effect of two fields: the exchange field directed along magnetic moments of iron, and the external field. These fields may be considered to be mutually perpendicular at $H > H_{sf}$ (the skew of the magnetic moments of iron may be neglected in the range of fields under consideration, due to strong exchange Fe–Fe interaction.[26,27]) The splitting of the Kramers doublets of Nd^{3+} in the field $\mathbf{H} \perp C_3$ may therefore be described by the equation

$$\Delta E_\perp = \mu_B g_\perp (H_{\mathrm{Fe}}^2 + H^2)^{1/2} = (\Delta E_0^2 + \mu_B^2 g_\perp^2 H^2)^{1/2}, \qquad (1)$$

where H_{Fe} is the effective exchange field for the given excited state and $\Delta E_0 = \mu_B g_\perp H_{\mathrm{Fe}}$ is the initial (exchange) splitting of the doublet at $H = 0$. Strictly speaking, this formula is applicable at $H = 0$ and $H > H_{sf}$.

By the same token, the external and exchange fields in the case of $\mathbf{H} \parallel C_3$ may also be considered to be mutually perpendicular, and the splitting is described by the equation

$$\Delta E_\parallel = \mu_B (g_\perp^2 H_{\mathrm{Fe}}^2 + g_\parallel^2 H^2)^{1/2} = (\Delta E_0^2 + \mu_B^2 g_\parallel^2 H^2)^{1/2}. \qquad (2)$$

Figure 5 shows dependences of splitting of line "3" in magnetic fields $\mathbf{H} \parallel C_3$ and $\mathbf{H} \perp C_3$ and the curves that correspond to the approximations of these dependences with Eqs. (1) and (2). The experimental and calculated data agree best for the following values of the parameters: $g_\perp = 1.94$; $g_\parallel = 5.07$; $\Delta E_0 \approx 2.5$ cm^{-1}; and $H_{\mathrm{Fe}} \approx 28$ kOe.

If there is no initial exchange splitting, Eqs. (1) and (2) reduce to a linear dependence. It is this dependence that is exhibited by line "6" if $\mathbf{H} \parallel C_3$ (see the insert in Fig. 5). The theoretical calculation in

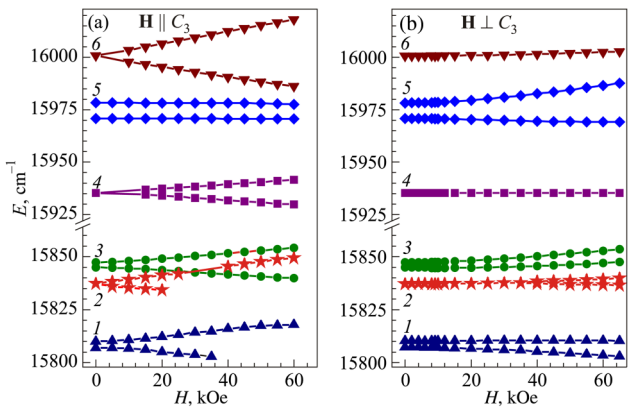

FIG. 4. Energies of the doublet components 1–6 as a function of magnetic field strength, directed along the C_3 crystallographic axis and perpendicular to it.

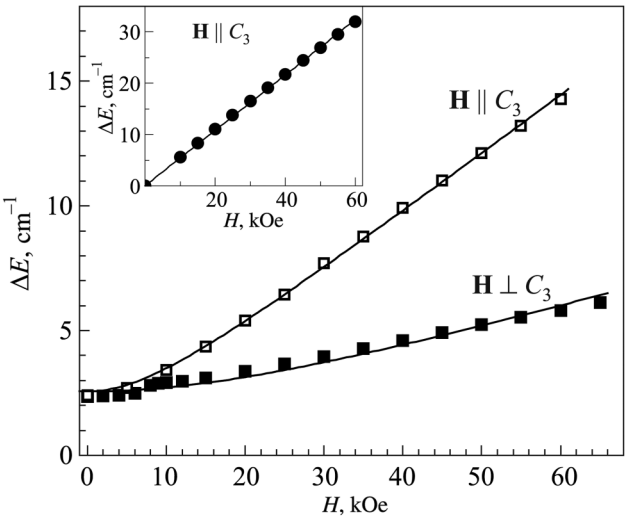

FIG. 5. The splitting of doublet "3" as a function of the magnetic field strength. The insert shows the field dependence of doublet "6" for $\mathbf{H} \parallel C_3$. The points show experimental values, whereas the solid lines are approximations of Eqs. (1) and (2).

Ref. 20 shows that this state has the largest longitudinal g-factor in the $^2H_{11/2}$ ($g_{||} = 9.728$) multiplet; the value we obtained in the experiment is $g_{||} = 11.58$.

The field dependences of the splitting of lines "*1*" and "*5*" are similar in shape to that of line "*3*" and are well described by Eqs. (1) and (2). Table II shows the obtained values of the g-factors of the states in comparison to those calculated in Ref. 20, and their exchange splitting ΔE_0 for $H = 0$, $T = 2$ K.

Ref. 21 reported the phenomenon of "swapping" of the intensities of the polarized components of doublet "*5*" in the magnetic field $\mathbf{H} \perp C_3$. A similar effect is also observed in the components of the exchange-split doublet "*3*" [Fig. 3(a)].

6. SPECIFIC FEATURES OF THE BEHAVIOR OF $\Gamma_{5,6}$ SYMMETRY STATES IN AN EXTERNAL MAGNETIC FIELD

It is not possible to describe the behavior in magnetic fields of lines corresponding to the $\Gamma_4 \rightarrow \Gamma_{5,6}$ transitions using dependences (1) and (2), which assume that the exchange field for the excited states is directed, as is the case in the ground state, in the basal plane along moments of iron. Figure 6 shows the field dependence of splitting of line "*4*" for $\mathbf{H} \,||\, C_3$. The observed dependence is quite different from that of lines "*1*", "*3*", and "*5*". In the single-ion approximation that we use, the simplest way to explain such behavior is by assuming that $\mathbf{H}_{Fe}$ and $\mathbf{H}$ are not strictly perpendicular to each other. Let us introduce an angle α between $\mathbf{H}_{Fe}$ and the C_3 axis, and represent $\mathbf{H}_{Fe}$ as the sum of two components: one directed along C_3 ($\mathbf{H}_{Fe||}$) and another located in the basal plane ($\mathbf{H}_{Fe\perp}$). Thus, we obtain

$$\Delta E_{||} = \mu_B(g_{||}^2(H + H_{Fe||})^2 + g_\perp^2 H_{Fe\perp}^2)^{1/2} = \mu_B(g_{||}^2(H + H_{Fe}\cos\alpha)^2 + g_\perp^2 H_{Fe}^2 \sin^2\alpha)^{1/2}, \quad (3)$$

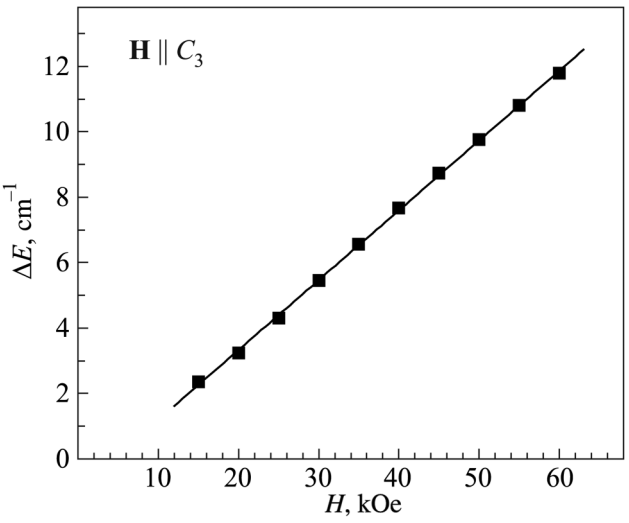

FIG. 6. The splitting of doublet "*4*" as a function of the strength of external magnetic field $\mathbf{H} \,||\, C_3$. The points show experimental data, and the solid curve is the approximation using Eq. (3).

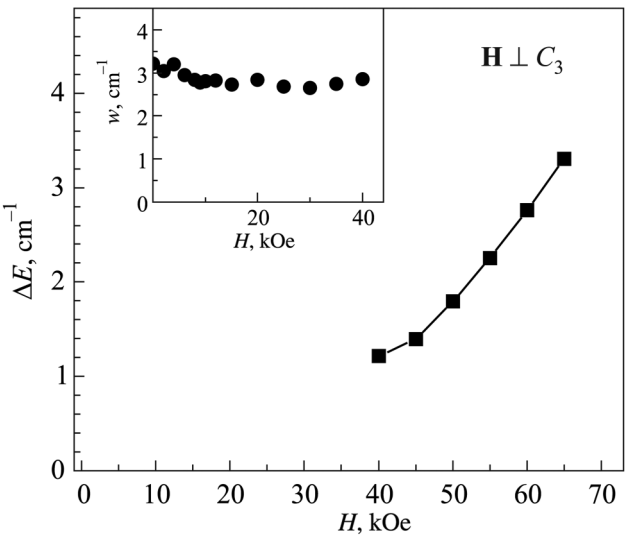

FIG. 7. The splitting of doublet "*2*" as a function of the strength of magnetic field $\mathbf{H} \perp C_3$. The insert shows field dependence of the half-width of line "*2*".

and $g_\perp = 0$ for the given state. Dependence (3) provides a good description of the experimental data for the following parameter values: $g_{||} = 4.57$ and $H_{Fe}\cos\alpha = -4.4$ (it is not possible to unambiguously determine parameters H_{Fe} and α).

Line "*2*" is very low intensity, and if $\mathbf{H} \,||\, C_3$, both its components may only be observed in a range of fields 0–20 kOe. The dependence of its splitting is sufficiently well described by Eq. (2) with the following parameter values: $g_{||} = 7.3$; $\Delta E_0 \approx 1.8$ cm^{-1}. Its splitting in the transverse field only becomes noticeable if the field strength is large [Figs. 3(a) and 7]. In the range of fields where its components are not yet resolved, the half-width of the total contour is almost constant (see the insert in Fig. 7). The splitting of the line does appear to change in the range of fields 0–40 kOe. Similar to line "*4*," Eq. (1) fails to adequately describe the field dependence of the splitting of line "*2*" if $\mathbf{H} \perp C_3$. Moreover, experimental data are not enough to determine its parameters. It should be noted that the splitting of line "*2*" in the both longitudinal and transverse fields significantly differs from that of line "*3*," thus confirming the identification of "*2*" as a separate level.

7. CONCLUSION

All six transitions from the ground state $^4I_{9/2}$ to the $^2H_{11/2}$ multiplet levels of the Nd^{3+} ion are detected and identified in the light absorption spectrum of ferroborate $NdFe_3(BO_3)_4$. The values of Nd^{3+} Kramers doublets' splitting in the exchange field of the Fe^{3+} subsystem during magnetic ordering of the crystal are determined.

The absorption spectra are studied in external magnetic fields directed both along the C_3 axis and in the basal plane of the crystal at a temperature of 2 K. It is found that the field dependences of the splitting of states with symmetry Γ_4 are described well under the assumption that the exchange field is collinear with the

direction of magnetic moments of Fe^{3+}. The character of the splitting of states with symmetry $\Gamma_{5,6}$ is indicative of the presence of an exchange-field component along the direction C_3. This feature may be related to the manifestation of anisotropy of the Fe–Nd exchange interaction for excited states. The g-factors of the $^2H_{11/2}$ multiplet states have been measured and correlate well with the values calculated in Ref. 20.

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REFERENCES

[1]A. K. Zvezdin, S. S. Krotov, A. M. Kadomtseva, G. P. Vorobiev, Yu. F. Popov, A. P. Pyatakov, L. N. Bezmaternykh, and E. A. Popova, JETP Lett. **81**, 335 (2005) [JETP Lett. **81**, 272 (2005)].
[2]A. K. Zvezdin, G. P. Vorobiev, A. M. Kadomtseva, Yu. F. Popov, A. P. Pyatakov, L. N. Bezmaternykh, A. V. Kuvardin, and E. A. Popova, JETP Lett. **83**, 600 (2006) [JETP Lett. **83**, 509 (2006)].
[3]A. M. Kadomtseva, Yu. F. Popov, G. P. Vorobiev, A. P. Pyatakov, S. S. Krotov, K. I. Kamilov, V. Yu. Ivanov, A. A. Mukhin, A. K. Zvezdin, A. M. Kuzmenko, L. N. Bezmaternykh, I. A. Gudim, and V. L. Temerov, FNT **36**, 640 (2010) [Low Temp. Phys. **36**, 511 (2010)].
[4]A. A. Mukhin, G. P. Vorobiev, V. Yu. Ivanov, A. M. Kadomtseva, A. S. Narizhnaya, A. M. Kuzmenko, Yu. F. Popov, L. N. Bezmaternykh, and I. A. Gudim, JETP Lett. **93**, 305 (2011) [JETP Lett. **93**, 275 (2011)].
[5]A. N. Vasiliev and E. A. Popova, FNT **32**, 968 (2006) [Low Temp. Phys. **32**, 735 (2006)].
[6]R. Z. Levitin, E. A. Popova, R. M. Chtsherbov, A. N. Vasiliev, M. N. Popova, E. P. Chukalina, S. A. Klimin, P. H. M. van Loosdrecht, D. Fausti, and L. N. Bezmaternykh, Pis'ma v ZhETF **79**, 531 (2004) [JETP Lett. **79**, 423 (2004)].
[7]C. Ritter, A. Vorotynov, A. Pankrats, G. Petrakovskii, V. Temerov, I. Gudim, and R. Szymczak, J. Phys. Condens. Matter **20**, 365209 (2008).
[8]H. Mo, C. S. Nelson, L. N. Bezmaternykh, and V. T. Temerov, Phys. Rev. B **78**, 214407 (2008).
[9]M. Janoschek, P. Fischer, J. Schefer, B. Roessli, V. Pomjakushin, M. Meven, V. Petricek, G. Petrakovskii, and L. Bezmaternikh, Phys. Rev. B **81**, 094429 (2010).
[10]S. A. Klimin, D. Fausti, A. Meetsma, L. N. Bezmaternykh, P. H. M. van Loosdrecht, and T. T. M. Palstra, Acta Crystallogr. B **61**, 481 (2005).
[11]J. A. Campá, C. Cascales, E. Gutiérrez-Puebla, M. A. Monge, I. Rasines, and C. Ruíz-Valero, Chem. Mater. **9**, 237 (1997).
[12]D. Fausti, A. A. Nugroho, P. H. M. van Loosdrecht, S. A. Klimin, M. N. Popova, and L. N. Bezmaternykh, Phys. Rev. B **74**, 024403 (2006).
[13]J. E. Hamann-Borrero, M. Philipp, O. Kataeva, M. v. Zimmermann, J. Geck, R. Klingeler, A. Vasiliev, L. Bezmaternykh, B. Büchner, and C. Hess, Phys. Rev. B **82**, 094411 (2010).
[14]E. A. Popova, N. Tristan, H. Hess, R. Klingeler, B. Büchner, L. N. Bezmaternykh, V. L. Temerov, and A. N. Vasiliev, JETP **132**, 121 (2007) [JETP **105**, 105 (2007)].
[15]I. V. Golosovsky, A. K. Ovsyanikov, D. N. Aristov, P. G. Matveeva, A. A. Mukhin, M. Boehm, L.-P. Regnault, and L. N. Bezmaternykh, J. Magn. Magn. Mater. **451**, 443 (2018).
[16]J. E. Hamann-Borrero, S. Partzsch, S. Valencia, C. Mazzoli, J. Herrero-Martin, R. Feyerherm, E. Dudzik, C. Hess, A. Vasiliev, L. Bezmaternykh, B. Büchner, and J. Geck, Phys. Rev. Lett. **109**, 267202 (2012).
[17]G. A. Zvyagina, K. R. Zhekov, I. V. Bilych, A. A. Zvyagin, I. A. Gudim, and V. L. Temerov, Fiz. Niz. Temp. **37**, 1269 (2011) [Low Temp. Phys. **37**, 1010 (2011)].
[18]V. A. Bedarev, M. I. Pashchenko, D. N. Merenkov, L. H. Bezmaternykh, and V. L. Temerov, UFJ **57**, 650 (2012) [Ukr. J. Phys. **57**, 648 (2012)].
[19]D. V. Volkov, A. A. Demidov, and N. P. Kolmakova, JETP **131**, 1030 (2007) [J. Exp. Theor. Phys. **104**, 897 (2007)].
[20]M. N. Popova, E. P. Chukalina, T. N. Stanislavchuk, B. Z. Malkin, A. R. Zakirov, E. Antic-Fidancev, E. A. Popova, L. N. Bezmaternykh, and V. L. Temerov, Phys. Rev. B **75**, 224435 (2007).
[21]I. S. Kachur, V. S. Kurnosov, V. G. Piryatinskaya, A. V. Yeremenko, and I. A. Gudim, FNT **43**, 738 (2017) [Low Temp. Phys. **43**, 590 (2017)].
[22]A. V. Malakhovskii, S. L. Gnatchenko, I. S. Kachur, V. G. Piryatinskaya, A. L. Sukhachev, and V. L. Temerov, J. Magn. Magn. Mater. **375**, 153 (2015).
[23]A. V. Malakhovskii, S. L. Gnatchenko, I. S. Kachur, V. G. Piryatinskaya, and V. L. Temerov, Opt. Mater. **52**, 126 (2016).
[24]A. V. Malakhovskii, S. L. Gnatchenko, I. S. Kachur, V. G. Piryatinskaya, and I. A. Gudim, Phys. Rev. B **96**, 224430 (2017).
[25]L. N. Bezmaternykh, V. L. Temerov, I. A. Gudim, and N. A. Stolbovaya, Crystall. Rep. **50**(Suppl. 1), S97 (2005).
[26]C. Ritter, A. Balaev, A. Vorotynov, G. Petrakovskiĭ, D. Velikanov, V. Temerov, and I. Gudim, J. Phys. Condens. Matter **19**, 196227 (2007).
[27]A. I. Pankrats, G. A. Petrakovsky, L. N. Bezmaternykh, and V. L. Temerov, FTT **50**, 77 (2008) [Phys. Solid State **50**, 79 (2008)].

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