Magnetic circular dichroism in $YBa_2Cu_3O_{7-\delta}$ and estimate of the nonreciprocal optical effects predicted by the anyon model of high-T_c superconductivity

B. B. Krichevtsov, V. V. Pavlov, R. V. Pisarev, and A. B. Sherman
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR, 194021, Leningrad

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The magnetic circular dichroism has been measured in $YBa_2Cu_3O_{7-\delta}$ films in the visible part of a spectrum for the first time. The values found for the specific magnetic circular dichroism are used to estimate the magnitude of the nonreciprocal optical effects predicted by the anyon model of high-T_c superconductivity.

According to the anyon model,[1-5] a phase transition can occur at a certain temperature $T_{tr} \geqslant T_c$ in high-T_c superconductors. It would be accompanied by the simultaneous disappearance of such symmetry elements as spatial inversion, $\bar{I}$, and time reversal, I'. The disappearance of the operation I' would signify the appearance of internal magnetic fields H_{int} or the appearance of a certain magnetic structure in these superconductors. In principle, such changes could lead to the existence of spontaneous nonreciprocal optical effects such as a circular birefringence (the Faraday effect) or a circular dichroism.[3]

Several very recent papers have reported systematic searches for such phenomena in the high-T_c materials.[6-8] Lyons *et al.*[6] have reported observation of a circular dichroism by a polarimetric method in experiments on optical reflection. This dichroism arose at temperatures $T \simeq 200$–300 K and reached values of $(1–3) \times 10^{-4}$ at $T \simeq 55$ K. Weber *et al.*[7] have reported observing a circular dichroism of significantly greater magnitude, $\sim 6 \times 10^{-2}$, in reflection experiments, and also a circular birefringence $\sim 2 \times 10^{-3}$, in transmission experiments on high-T_c single crystals and films. In contrast with Refs. 6 and 7, Spielman *et al.*[8] ended up with a negative result in their search for a nonreciprocal circular birefringence in superconducting $YBa_2Cu_3O_{7-\delta}$ films. Those experiments were carried out on an optical-fiber gyroscope, which eliminated manifestations of reciprocal optical effects. Those experiments demonstrated that there was no nonreciprocal circular birefringence over the temperature range 11-300 K at the sensitivity of the apparatus, $\sim 2 \times 10^{-6}$ rad. Negative results were also found in a search for internal magnetic fields by the method of muon spin rotation (μSR).[9]

Because of the contradictions in the results of Refs. 6–8, it is a matter of fundamental importance to evaluate the magnitude of the possible effects. Although the anyon theory[5] predicts $H_{int} \sim 10$ G as the order of magnitude of the internal magnetic fields, there are no well-grounded estimates of the magnitude of possible nonreciprocal optical phenomena. We believe that such an estimate can be found by working from the magnitude of the nonreciprocal effects which arise in the high-T_c materials when an external magnetic field is applied to them. To the best of our knowledge, there has been no previous study of this sort. In this letter we are reporting the first measurements of magnetic circular dichroism in $YBa_2Cu_3O_{7-\delta}$ superconducting films. We estimate the magnitude of the spontaneous optical phenomena which would be expected according to the anyon model of high-T_c superconductivity.

As the nonreciprocal optical effect to be measured we selected the magnetic circular dichroism $\Delta\alpha = \alpha^+ - \alpha^-$, which is defined as the difference between the optical absorption coefficients for light with a right-hand circular polarization (α^+) and for light with a left-hand circular polarization (α^-) as the light propagates along the magnetic field. This effect occurs in those parts of the spectrum where there is an absorption. Measurements of the magnetic circular dichroism have some very important advantages over measurements of the Faraday effect, which can also be observed in the absence of an absorption. In the latter case it is very difficult to reliably distinguish the Faraday effect which occurs in the thin superconducting film itself ($t \sim 10^{-5}$ cm) from the superimposed Faraday effect from the much thicker substrates, from the cryostat windows, and from other optical elements of the arrangement ($t \sim 10^{-1}$–10^0 cm). A technique which we have developed is capable of measuring the magnetic circular dichroism at a wavelength $\lambda = 0.6328$ μm, at a sensitivity $\sim 2 \times 10^{-6}$ within an error $\pm$ 30%. The technique itself will be described in another publication. As test samples we used $YBa_2Cu_3O_{7-\delta}$ films on MgO (100) substrates. The films were grown

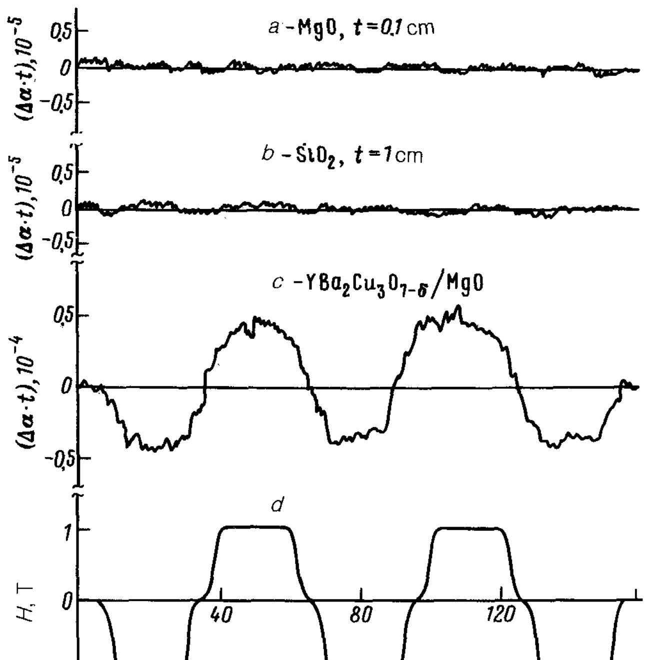

FIG. 1. The magnetic-circular-dichroism signal at a wavelength $\lambda = 0.6328$ μm during a periodic scanning of the magnetic field H (trace d) in various materials at $T = 294$ K. a—MgO; b—SiO_2; c—$YBa_2Cu_3O_{7-\delta}$/MgO.

by magnetron sputtering. Their transition temperature was $T_c = 92$ K, and the transition width was ~ 1 K between the 10% and 90% levels in the resistance. The film thickness t was varied from 1000 to 3000 Å; the absorption coefficient was $\alpha \sim 10^5$ cm^{-1}. The substrate was a wedge with an angle $\sim 1°$; this shape was chosen in order to eliminate interference phenomena in the substrate.

Figure 1 shows the changes in the dichroism signal in various test samples as the magnetic field is varied from $+1$ T to -1 T. The fact that no signal is observed in MgO ($t = 0.1$ cm) or in quartz glass (SiO_2; $t = 1.5$ cm), while there is a signal in the superconducting film on the MgO substrate, implies that the source of the observed magnetic-circular-dichroism signal is the high-T_c film. At $T = 295$ K, the magnitude of the effect observed in a film with $t \simeq 3 \times 10^{-5}$ cm (3000 Å) in a field $H = 1$ T is $(\Delta \alpha t) \simeq 5 \times 10^{-5}$ or $\Delta \alpha \simeq 2$ cm^{-1}. One should recall that the orthorhombic high-T_c modification of $YBa_2Cu_3O_{7-\delta}$ exhibits a pronounced optical anisotropy,[10] which would be capable in principle of reducing the magnitude of the observed magnetic circular dichroism. However, since the size (200–500 Å) of the microscopic grains in the film is much smaller than the wavelength of the light, the film can be thought of as an essentially isotropic medium. This argument is supported by the circumstance that we did not observe a pronounced depolarization of light when we passed it through the film. In epitaxial films of $YBa_2Cu_3O_{7-\delta}$ in contrast, calculations show that the birefringence at $t = 3000$ Å could lower the measured dichroism by a factor of about 2.

Figure 2 shows the temperature dependence of the magnetic circular dichroism. Within the experimental error, we observed no anomalies of any sort, either at $T_c = 92$ K or at higher temperatures, at which the anomalies of the circular dichroism were observed in Refs. 6 and 7. A field $H = \pm 1$ T penetrates into the film both above and

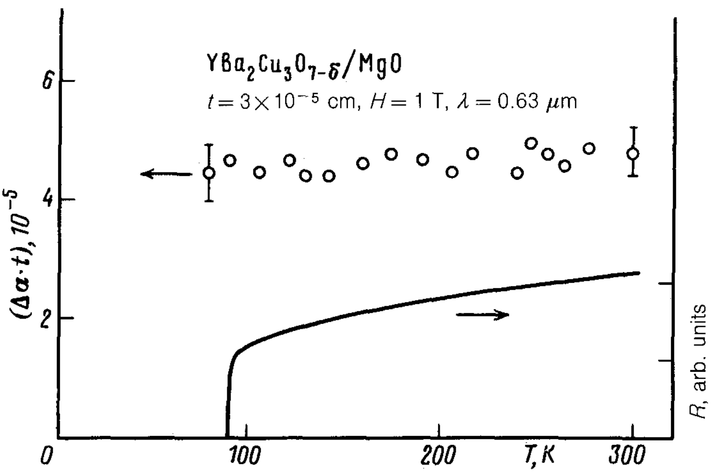

FIG. 2. Temperature dependence of the magnetic circular dichroism at the wavelength $\lambda = 0.6328$ μm in a $YBa_2Cu_3O_{7-\delta}$/MgO film with a thickness $t \simeq 3000$ Å in a magnetic field $H = 1$ T. Shown at the bottom is the temperature dependence of the resistance of the film, which was measured along with the magnetic circular dichroism.

below T_c, but the superconducting state is not destroyed in the process. This conclusion follows from resistance measurements, which were carried out at the same time as the dichroism measurements.

The value found for the specific magnetic circular dichroism, $\Delta\alpha = 2\ \text{cm}^{-1}$ at $\lambda = 0.6328\ \mu\text{m}$, can be used to estimate the spontaneous nonreciprocal circular dichroism which would be predicted by the anyon theory under the assumption that external and internal fields act identically on the electronic states which determine the optical polarizability of the high-T_c material. With[5] $H_{\text{int}} \simeq 10$ G, for a superconducting film with a thickness $t \sim 3 \times 10^{-5}$ cm, we find the possible spontaneous nonreciprocal circular dichroism to be $(\Delta\alpha t) \simeq 5 \times 10^{-8}$ ($\Delta\alpha \simeq 0.02\ \text{cm}^{-1}$). This figure is more than two orders of magnitude lower than the sensitivity $\sim (1\text{–}3) \times 10^{-5}$ of the optical methods used in Refs. 6–8.

On the other hand, we can work from the value which we found for the specific magnetic circular dichroism to estimate the internal fields H_{int} which would be required to produce the circular dichroism which was observed in Refs. 6 and 7. Specifically, fields $H \sim 2\text{–}200$ T would be required to obtain a circular-dichroism effect $\sim 10^{-4}\text{–}10^{-2}$. Such fields are characteristic of magnetically ordered materials, and there can be no doubt that their presence would be manifested in a variety of physical experiments. However, precise studies, particularly by the μSR method, indicate that the internal fields do not exceed[9] $H_{\text{int}} \simeq 0.8$ G. A calculation shows that the estimates given here are valid for effects seen in both the transmission and reflection arrangements.

In summary, the results of these measurements of the magnetic circular dichroism show that if the operation I' disappeared, we would expect to see nonreciprocal effects at a magnitude $\sim 10^{-8}\text{–}10^{-7}$. It would thus become possible to explain the negative result of the laser-gyroscope experiments,[8] since even in that case the sensitivity of the measurements was lower than the expected effect. One might suggest that the optical effects observed in Refs. 6 and 7 were reciprocal effects, and if so they cannot be regarded as confirmation of the anyon theory.

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