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Crossover from relativistic to non-relativistic net magnetization for MnTe altermagnet candidate

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We experimentally study magnetization reversal curves for MnTe single crystals, which is the altermagnetic candidate. Above 85 K temperature, we confirm the antiferromagnetic behavior of magnetization M, which is known for α-MnTe. Below 85 K, we observe anomalous low-field magnetization behavior, which is accompanied by the sophisticated $M(\alpha)$ angle dependence with beating pattern as the interplay between $M(\alpha)$ maxima and minima: in low fields, $M(\alpha)$ shows ferromagnetic-like 180° periodicity, while at high magnetic fields, the periodicity is changed to the 90° one. This angle dependence is the most striking result of our experiment, while it can not be expected for standard magnetic systems. In contrast, in altermagnets, symmetry allows ferromagnetic behavior only due to the spin-orbit coupling. Thus, we claim that our experiment shows the effect of weak spin-orbit coupling in MnTe, with crossover from relativistic to non-relativistic net magnetization, and, therefore, we experimentally confirm altermagnetism in MnTe.

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Recently, the concept of spin-momentum locking was extended to the case of weak spin-orbit coupling, i.e. to the non-relativistic groups of magnetic symmetry [1, 2]. As a result, a new class of altermagnetic materials has been added to usual ferro- and antiferro-magnetic classes. For altermagnetics, the small net magnetization is accompanied by alternating spin-momentum locking in the k-space, so the unusual spin splitting is predicted [1, 3]. For example, RuO_2 altermagnet consists of two spin sublattices with orthogonal spin directions. In the k-space, the up-polarized subband can be obtained by $\pi/2$ rotation of the down-polarized subband, so RuO_2 altermagnet is characterized by d-wave order parameter [4, 5]. The probability to scatter between subbands depends both on the electron spin and the propagation direction due to the spin-momentum locking [6].

As a result, altermagnetics are characterized by sophisticated spin structures, which should lead to different physical phenomena. For example, anomalous Hall effect (AHE) is predicted for altermagnetics [7], despite of the zero nonrelativistic net magnetization [2, 8]. It was argued, that the spontaneous nature of the AHE still requires relativistic spin-orbit interaction [6, 9].

Inconsistency between the expected zero non-relativistic net magnetization and ambiguous experimental behavior requires comprehensive magnetization measurements in altermagnetics in wide temperature and magnetic field ranges. This investigation can be conveniently performed for MnTe, which is also characterized by accessible (2–3 T) magnetic field range in contrast to RuO_2 altermagnetic candidate.

For investigation of low magnetic moment, we use MnTe single crystals which is preferable in comparison with thin films to avoid admixture of the substantial signal from the substrate. To investigate magnetic properties, we use Lake Shore Cryotronics 8604 VSM magnetometer, equipped with nitrogen flow cryostat.

The 100 K $M(H)$ curve is nearly linear around zero field. In high fields, $M(H)$ shows two nonlinear branches with small hysteresis above 5 kOe field. This behavior well corresponds to the known antiferromagnetic one for MnTe: in the present field range, we do not reach the Néel vector reorientation field, which is between 2 and 3 T for MnTe [6, 9], so the sample magnetization is mostly compensated in our field range. The small high-field hysteresis is due to the spin flop processes below the reorientation field.

At 80 K, the $M(H)$ curve also consists from two non-linear branches, but the branches are shifted vertically. The branches are just parallel to the high-temperature (100 K) ones, so there is a well-developed step in $M(H)$ around the zero. This step resembles standard ferromagntetic-like behavior. The reported $M(H)$ behavior can be qualitatively reproduced for MnTe samples of different sizes. We should conclude, that for temperatures below 85 K the high-field antiferromagnetic

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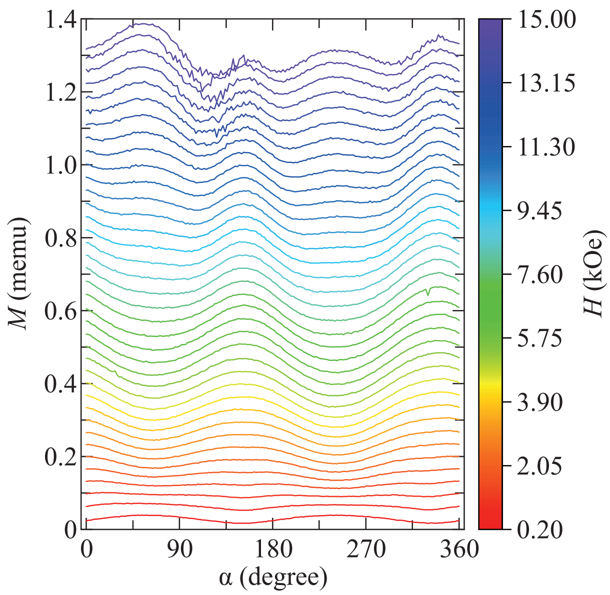

Fig. 1. (Color online) Crossover from ferromagnetic to antiferromagnetic behavior shown as $M(\alpha)$ curves in different magnetic fields. The curves are presented as obtained, without any additional processing, at 80 K temperature for the 4.65 mg MnTe sample. The mean level reflects the $M(H)$ growth, the absolute value of the $M(\alpha)$ modulation is increasing with the magnetic field. In low fields (around 0.2 kOe), $M(\alpha)$ shows ferromagnetic-like 180° periodicity. At high magnetic fields (around 15 kOe), the periodicity is changed to the antiferromagnetic 90° one. For the intermediate fields (around 6 kOe), one can see interplay between the maxima and the minima in $M(\alpha)$ curves

behavior for MnTe is accompanied by the ferromagnetic one in low fields.

The crossover from ferromagnetic to antiferromagnetic behavior is shown in Fig. 1 as $M(\alpha)$ curves in different magnetic fields below the transition temperature. In low fields, $M(\alpha)$ shows ferromagnetic-like 180° periodicity. At high magnetic fields, the periodicity is changed to the 90° one, see, e.g., 15 kOe field curve in Fig. 1, as it is expected for a collinear antiparallel magnetic ordering of Mn moments. For the intermediate fields, one can see interplay between the maxima and the minima in $M(\alpha)$ curves.

The $M(\alpha)$ angle dependence is the most striking result of our experiment, while it can not be expected for standard magnetic classes. In particular, the angle dependence in low fields in Fig. 1 does not correlate with the mean-field susceptibility of a collinear uniaxial antiferromagnet for the cases when the field is perpendicular and parallel to the easy axis.

It is well known, that in altermagnets, spin magnetic moments are fully compensated only when spin-orbit coupling is zero [2, 10]. Nonzero SOC, enabling coupling between spins and alternating local structures, can result in a nonzero net magnetic moment [11]. Thus, we should attribute the observed low-field $M(H)$ hysteresis to the effects of spin-orbit coupling [8].

The effects of spin-orbit coupling in this material has been previously investigated by temperature-dependent angle-resolved photoelectron spectroscopy and by disordered local moment calculations [12]. There were the emergence of a relativistic valence band splitting concurrent with the establishment of magnetic order. It seems to be important, that the observed splitting is well-resolved only below 100 K in [12], which is consistent with our experiment.

In this case, interplay between maxima in low fields and minima in high magnetic fields in $M(\alpha)$ angle dependence in Fig. 1 is the standard beating pattern, similar to one for magnetoresistance oscillations. The nonzero net magnetic moment in low fields (ferromagnetic-like 180° periodicity in Fig. 1) is determined by spin-orbit interaction, which enables coupling between spins and alternating local structures. The spin-orbit splitting can be suppressed by temperature, which is reflected as an abrupt drop of the magnetization around 82–84 K. It can also be suppressed by strong magnetic field, so antiferromagnetic ordering with vanishing net magnetization (90° periodicity in Fig. 1) is dominating in high magnetic fields. While increasing the magnetic field from zero to 15 kOe, we run through the different regimes, which is reflected as beating pattern in Fig. 1.

Thus, in contrast to the AHE investigations, our experiment directly shows the effect of weak spin-orbit coupling in MnTe altermagnet candidate, with crossover from relativistic to non-relativistic net magnetization while increasing the magnetic field.

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Conflict of interest. The authors of this work declare that they have no conflicts of interest.

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