Magnetisation and magneto-transport measurements on CeBi single crystals

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ABSTRACT
We report the synthesis of CeBi single crystals out of Bi self-flux and a systematic study of the magnetic and transport properties with varying temperature and applied magnetic fields. From these $R(T, H)$ and $M(T, H)$ data, we could assemble the field-temperature ($H-T$) phase diagram for CeBi and visualise the three-dimensional $M-T-H$ surface. In the phase diagram, we identify regions with well-defined magnetisation values and identify a new phase region. The magnetoresistance (MR) in the low-temperature regime shows, above 6 T a power-law, non-saturated behaviour with large MR ($\sim 3 \times 10^5\%$ at 2 K and 13.95 T), along with Shubnikov–de Haas oscillations. With increasing temperatures, MR decreases, and then becomes negative for $T \approx 10$ K. This crossover in MR seems to be unrelated to any specific magnetic or metamagnetic transitions, but rather is associated with changing from a low-temperature normal metal regime with little or no scattering from the Ce$^{3+}$ moments and an anomalously large MR, to increased scattering from local Ce moments and a negative MR as temperature increases.

1. Introduction

In recent years, there has been a revived interest in the properties of low carrier density or semi-metallic materials with large spin-orbit-coupling. When these semi-metals are rare earth bearing, the interaction between local moments and conduction electrons can lead to remarkable magnetic field-temperature ($H-T$) phase diagrams as well as dramatic changes in magnetoresistance (MR) across multiple phase transitions [1–5]. In the RBi, RsB, RBl, RsB, RAgBi, RAgSb ($R =$ rare-earth) and related systems the sometimes large MR, combined with recent computational predictions or models, has lead to interest in possible topological states existing in compounds that can exhibit long-range magnetic order [6–9].

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The rare-earth monopnictides \((RX, R = \text{rare-earth}, X = P, As, Sb, Bi)\) family, which crystallise in the simple NaCl structure, is such a set of compounds. They have been studied in the past for the rich magnetism they host, including the perspective of Kondo lattices and valence fluctuation compounds \([10–16]\). In recent years, new studies have been done on them as candidates for topological materials \([6,17–25]\). An interesting aspect that has been brought to the forefront by recent studies is the existence of large MR in many of the rare-earth antimonides and bismuthides \([19,23,26,27]\).

CeBi, the heaviest member of the CeX family, is known to show multiple metamagnetic transitions in the magnetic field-temperature phase space, with a strong anisotropy arising from crystalline electric field effects and a resultant anisotropic MR \([28–33]\). It thus provides an exemplary candidate to study the effects of magnetic ordering in MR and electronic structure.

Here, we report the crystal growth, magnetic characterisation, and detailed magneto-transport measurements on single crystals of CeBi. We identify regions that are prone to large hysteresis in field as well as temperature, correlating with the existence of many, near degenerate magnetic states. The \(H–T\) phase diagram obtained from decreasing temperature and field sweeps reveals an additional phase line as compared to the complete previous report, but otherwise agrees well with it \([29]\). We also observed a non-monotonic behaviour of MR with temperature, where a low-temperature large MR behaviour slowly diminishes and becomes negative MR with increasing temperatures. This was followed by a shift to positive MR again but with a comparatively small magnitude.

2. Experimental details

Single crystals of CeBi were grown out of Bi self-flux \([34]\), using the current binary Bi–Ce phase diagram \([35]\). Initial composition of \(Ce_{26}Bi_{74}\) was sealed in a welded tantalum tube under an argon atmosphere, followed by sealing under partial pressure of argon into a fused silica ampoule. The thus prepared ampoule was heated up to 1200°C over 8 h and held there for 4 h, followed by slow cooling to 940°C over 60 h, at which temperature, the excess flux was decanted using a centrifuge \([34,36]\). The air-sensitive crystals, of typical dimensions of about \(5 \text{mm} \times 5 \text{mm} \times 3 \text{mm}\), were handled in a nitrogen-filled glove box. The crystal structure as well as phase purity were confirmed by powder X-ray diffraction using a Rigaku Miniflex diffractometer (also in the nitrogen glove box), using Cu \(K\alpha\) radiation.

Magnetisation \((M)\), as a function of temperature \((T)\) was measured on two different crystals. An initial measurement of \(M(T)\) at 0.5 T was made in a Quantum Design Magnetic Property Measurement System (MPMS), upon cooling from 300 K to 2 K. This is shown in Figure 2(a). Later more detailed and systematic measurements were carried out in an MPMS 3, in vibrating
sample magnetometer mode, from temperatures 1.8–35 K, and applied magnetic fields \( (H) \) up to 7 T. The magnetic field was applied along one of the \( \langle 001 \rangle \) directions. For \( M(T) \) data acquisition, measurements were done with both zero field cooled (ZFC) sample with increasing temperatures and field cooled (FC) with decreasing temperatures. Similarly, for \( M(H) \) measurements, both increasing and decreasing field isotherms were measured for various temperatures between 3 and 27.5 K.

Resistance measurements were done in the standard four-probe geometry, in a Quantum Design Physical Property Measurement System (PPMS) using a 1 mA excitation with a frequency of 17 Hz. Electrical contacts were made on a cleaved, rectangular bar shaped, crystal, using silver paint (DuPont 4929N). The magnetic field, up to 14 T, was applied along one of the \( \langle 001 \rangle \) directions, and perpendicular to the current which was also along one of the \( \langle 001 \rangle \) directions. For all the measurements, crystals were oriented based on their very clear, natural, cubic morphology and square facets. \( R(T) \) measurements were done partially on warming and partially on cooling. \( R(T) \) curves at 0, 0.5, 1.5, 2, 3.5, 4.2, 4.5, 5.5, 7, 9, and 13.95 T were obtained by measuring resistance on cooling the sample, and the rest while warming up. Similarly, \( R(H) \) at 3.5, 4, 7, 10, 12, 20, 25, 35, 40, and 50 K were measured with decreasing magnetic field, and the rest with increasing fields.

3. Results

Figure 1 shows the powder X-ray diffraction data. The peaks resolved match with the reported peak positions for the cubic \( Fm\overline{3}m \) structure of CeBi [37]. From the \( (hkl) \) indices assigned, by comparison to the reported structure, we calculated the lattice parameter \( a = 6.510 \pm 0.008 \) Å, which is in agreement with Ref. [37]. Weak additional peaks, corresponding to small amounts of residual Bi flux are also identified (marked by arrows in the figure).

3.1. Magnetisation

The magnetic characterisation was done on cleaved and clean crystals handled in a nitrogen-filled glove box. Figure 2(a) shows \( M(T) \) data taken on cooling from 300 to 2 K. The inset shows the 2–35 K range of the \( M(T) \) curve, clearly showing the two transitions, a kink-like anomaly at \( \sim 25 \) K (indicated in Figure 5 by a black circle) and a step-like increase of \( M \) a little below 15 K (indicated in Figure 5 by a square). The transition temperatures are determined by taking the extrema in \( d(\chi T)/dT \) data, which is the criterion for transition temperature in a simple antiferromagnet [38], but has been used to identify multiple transitions as well [39]. Both from the shape of the derivative curves and from the hysteretic behaviour shown in Figure 3, we can identify that the transition around 25 K is a second order transition, and the one below
15 K is first order. This is in agreement with the reported nature of the magnetic transitions [14]. A Curie–Weiss fit for the paramagnetic regime above the transition, as shown in the inset of Figure 3(a), gives an effective moment, $\mu_{\text{eff}} = 2.5 \pm 0.1 \mu_B$, in agreement with the expected effective moment $2.54 \sim \mu_B$ for Ce$^{3+}$ ions, and $\theta = 10.6 \pm 0.1$ K.

Figure 3 shows a representative set of $M(T)$ and $M(H)$ data. $M(T)$, measured on both ZFC and FC sample with warming and cooling, respectively; data for a low field of 0.5 T, at an intermediate field of 2 T and at a higher field of 3.25 T
are shown in Figures 3(a), 3(b) and 3(c). For lower field measurement shown in Figure 3(a), there is a stark distinction between ZFC and FC data, with a notable hysteresis for the transition below 15 K. In addition, the ZFC data go through a cascade of features, some of which are barely resolvable, whereas the FC measurement shows two well-defined features. The features in ZFC data are possibly due to a realignment of domains or may be associated with many closely spaced, near degenerate, ordered states. With increasing fields, the differences in ZFC and FC $M(T)$ data start to disappear and eventually they

**Figure 3.** Representative sets of $M(T)$ and $M(H)$ data. (a) $M(T)$ at a relatively low field of 0.5 T measured ZFC and FC. A clear hysteresis is seen between the two. Inset: A Curie–Weiss fit to the inverse susceptibility data above 50 K. (b) $M(T)$ measured at an intermediate field value of 2 T. Except for the lowest temperatures, ZFC and FC data overlap. The dotted horizontal lines denote values corresponding to 1/2, 1/3 and 1/4 of $\mu_{sat}$, saturated magnetic moment. (c) $M(T)$ measured at 3.25 T where ZFC and FC are overlapping. (d) $M(H)$ at 7.5 K with increasing and decreasing magnetic fields. Below 1.5 T there is a series of metamagnetic transitions which show a clear hysteresis. Dotted lines show 1/2, 1/3 and 1/4 $\mu_{sat}$ and $\mu_{sat}$ values. (e) $M(H)$ at an intermediate temperature of 17.5 K, where the curves almost overlap. (f) $M(H)$ at 22.5 K where the hysteresis has disappeared. Inset: $M(H)$ plotted along with $dM/dH$. The maxima in $dM/dH$ are used as the criteria to determine the transitions from $M−H$ data (Colour online).
fall on top of each other, as shown for $M(T)$ at 2 and 3.25 T in Figures 3(b) and 3(c), respectively.

Similarly, for $M(H)$ data comparison between a low temperature (7.5 K), an intermediate temperature (17.5 K) and a higher temperature (22.5 K) measurement is shown in Figures 3(d), 3(e) and 3(f). At low temperatures, there exists a series of metamagnetic transitions in the low field regime, with a clear hysteresis, as shown for $M(H)$ at 7.5 K. The two, clear, higher field metamagnetic states have locally saturated magnetisations of $\mu_{\text{sat}} = 2.2 \mu_B$/f.u. (as compared to $2.14 \mu_B$ for Ce$^{3+}$) and approximately $1/2 \mu_{\text{sat}} = 1.1 \mu_B$. It should be noted that Figure 3(b) also shows the plateaus in $M(T)$ corresponds to roughly a quarter, a third, and a half of the measured saturated magnetic moment value $\mu_{\text{sat}} = 2.2 \mu_B$/f.u., which are denoted by dotted lines in the figure. As we increase the temperature, this lower-field hysteretic behaviour starts to disappear and the increasing – and decreasing – field $M(H)$ data fall on top of each other with well-defined plateaus, as shown in Figures 3(e) and 3(f) for 17.5 and 22.5 K, respectively. The inset of Figure 3(f) shows both $M(H)$ and $dM/dH$ plotted together. The peaks in $dM/dH$ is identified as the transition fields and are used in plotting the phase diagram shown in Figure 5, which will be discussed later. From here on, all the magnetisation data shown, both in Figures 4 and 6, as well as used for determining the phase diagram in Figure 5 are from FC $M(T)$ and decreasing field $M(H)$ measurements.

Having gained some insight into the hysteretic behaviour of the magnetisation data, we can now look at how various features evolve with temperature and field. Figure 4(a) shows the temperature-dependent magnetisation, $M(T)$, at various magnetic fields up to 7 T. As compared to the 0.5 T measurement, by increasing magnetic fields up to 3.5 T, the kink-like anomaly near 25 K becomes more pronounced and is gradually suppressed to lower temperatures. Whereas the step-like anomaly, initially a little below 15 K, moves to higher

![Figure 4](image-url)

**Figure 4.** (a) Magnetisation as function of temperature, measured with decreasing temperature (FC), at various applied magnetic fields ($\mu_0H$) from 0.1 to 7 T. (b) $M$ as a function of $\mu_0H$ measured at various temperatures from 3 to 27.5 K. All data were taken with decreasing fields (Colour online).
temperature with increasing fields. At about 3.5 T, these two anomalies merge together and evolve into a single, jump-like drop of $M$ for $4 T \leq \mu_0 H \leq 4.5 T$. At even higher fields, all anomalies are suppressed and behaviour of $M(T)$ approaches that of a field polarised (saturated paramagnetic) state. In the intermediate field range ($1.5 T < \mu_0 H < 3 T$), additional step-like anomalies in $M(T)$ appear between 15 and 22 K (corresponding to the series of closely placed transitions shown in Figure 5 using star, hexagon and diamond symbols) which can be associated with additional magnetic transitions. From these transitions, we can start to build a $H-T$ phase diagram as shown in Figure 5. These transition temperatures obtained from $M(T)$ data are shown in Figure 5 as filled symbols (circles, squares, diamonds and stars).

More of the CeBi $H-T$ phase diagram can be inferred from $M(H)$ data. Multiple magnetic transitions can also be observed in the field-dependent magnetisation $M(H)$ data as shown in Figures 3(d–f) and 4(b). At 3 K, the $M(H)$ curve shows two sharp jumps at $\sim 4.5 T$ and $\sim 1 T$, and another smaller kink or shoulder at around 0.5 T. At 3 K, and 7 T a saturated moment, $\mu_{\text{sat}} = 2.2 \pm 0.1 \mu_B/\text{f.u.}$ is obtained, which is within the error bar from the expected $2.14 \mu_B$ for Ce$^{3+}$ ions. With increasing temperatures, the higher field transition barely moves (e.g. At 7.5 K, as shown in Figure 3(d), the higher field transition occurs at 4.5 T), but below about 1.5 T one can see a

Figure 5. Field-temperature ($H-T$) phase diagram of CeBi obtained from the magnetic measurements. Solid symbols and open-crossed symbols are obtained from $M$ as a function of $T$ and $H$ data, respectively. Lines are guides to the eye. Regions associated with AFM order as well as plateaus of approximately $\frac{1}{2}, \frac{1}{3}$ and $\frac{1}{4} \mu_{\text{sat}}$ are labelled. The data in the lower temperature, lower field, hysteretic region is not labelled, as the phase boundaries are not clear because of differences in increasing and decreasing field data. Transition temperature, field points in this regime are shown in grey. All the points are determined from FC $M(T)$ and decreasing field $M(H)$ measurements (Colour online).
cascade of closely spaced transitions setting in, which are hysteretic in increasing and decreasing field measurements, as can be seen in Figure 3(d). For 15 K and above, i.e. above the zero-field value of the lower transition temperature, the low field transitions disappear and $M(H)$ curves become simpler, with well defined plateaus Figures 3(e) and 3(f). Above 25 K all the features corresponding to the various transitions disappear, and the $M(H)$ curve resembles that of a typical local moment system in the paramagnetic state. The points for the phase diagram are obtained from $M(H)$ data by evaluating the peaks in derivative $dM/dH$, and are denoted as open-crossed symbols in Figure 5.

A field-temperature phase diagram obtained from our $M(T)$ and $M(H)$ data is shown in Figure 5. This is very similar to the previously reported phase diagrams [28,29,40]. A very early study on polycrystalline CeBi was already able to identify three distinct phase regions in the $H−T$ phase space, which were identified as two antiferromagnetic (AFM) orderings, and a ferrimagnetic ordering with $M = 1/2\mu_{\text{sat}}$, in addition to the field polarised and paramagnetic regimes [11]. Later, more detailed measurements on single crystalline samples were reported, with as many as seven different phases in the same $H−T$ regime [28]. They also observed the hysteretic nature of the transitions, which decreased with increasing temperatures. Followed by this, a neutron scattering study confirmed the AFM ordering and partially assigned magnetic structures to the various phases [29]. They identified the two AFM orderings, the $M = 1/2\mu_{\text{sat}}$ phase and a variety of mixed phases in between, at low temperatures. For $T \geq 12$ K, they identified two phases, but were not able to assign a net magnetisation value. Later, a molecular field model, with Ce moments in [001] direction and having an oscillatory exchange interaction perpendicular to the (001) plane, was shown to calculate the phase diagram agreeing very well with the experimental data [40].

With this information in hand, we can try to interpret the phase diagram we have obtained. The various features in Figure 5 could be understood as follows: Existence of an envelope denoting paramagnetic to antiferromagnetic at higher temperatures, and a full saturation into field polarised state at lower temperatures, with phase boundaries agreeing very well with the existing reports, within which one can see multiple other regions. For $T$ above 15 K, one can see a well-defined region of antiferromagnetic order, and two narrow regimes corresponding to roughly $1/4$ and $1/3\mu_{\text{sat}}$ values. There also exists a narrow phase in between these, which was not identified in the previous reports [28,29]. We were not able to assign a locally saturated magnetisation value to this phase, given its very limited extent. In the lower temperature regime, between 1.5~$T$ and 4.5~$T$ we have an extended region which corresponds to $M = 1/2M_{\text{sat}}$, which agrees well with the previous reports, whereas, at lower fields, we have plethora of transitions with ill-defined and hysteretic phase boundaries, once again agreeing well with reported mixed phases from the neutron study [29]. Nevertheless, we were not able to assign any specific net
magnetisation values to phases here either, as opposed to Ref. [29], because of the large hysteresis and irreversible nature of the increasing and decreasing field data.

Magnetisation both as a function of temperature and magnetic field are plotted in Figure 6 by combining the data presented in Figure 4(a,b). As shown in the figure, data from two sets of measurements agree with each other very well and together they depict various magnetic transitions and plateaus. Figures 3, 4 and 6 also emphasise that whereas for low temperatures the magnetic plateaus are well saturated at well-defined values, as temperature increases, the plateaus-like regions have (i) decreasing extent, (ii) developed finite slopes and (iii) have their values decrease from their lowest temperature values.

3.2. Resistance

The temperature-dependent electrical resistance in zero field on a cleaved crystal of CeBi is shown in Figure 2(b). The resistance remains relatively invariant at high temperatures, followed by an ∼20% upturn and then a sharp decrease at ∼25 K, associated with loss of spin disorder. The RRR was calculated to be 968. Similar behaviour is observed for CeSb as well, but with a

![Figure 6. Magnetisation as a function of both temperature and magnetic field combining Figure 4(a) and (b) showcasing various metamagnetic transitions and plateaus. All data are from FC $M(T)$ and decreasing field $M(H)$ measurements (Colour online).](image)
much less pronounced upturn [16]. The near 1000 RRR value attests to the high purity of the CeBi samples. This is further born out by the fact that (i) the MR at low temperatures is huge and follows Kohler’s rule and (ii) Shubnikov–de Haas oscillation are detected. The inset of Figure 2(b) shows the low-temperature region with the transitions clearly seen. The first one is around 25 K, and another transition, observed as a relatively small jump in $R$ is seen around 12.5 K. The transition temperatures are determined by taking the local maxima of the derivative $dR/dT$ [39,41].

Figure 7 shows the temperature and magnetic field dependence of electrical resistance. The temperature dependence of $R$ with various applied fields is shown in Figure 7(a) for $T \leq 40$ K. Figure 7(b) shows the intermediate temperature regime where the various transitions are seen. Here, we have denoted the transition temperatures with open symbols (circles, squares, diamonds and stars) with the same shape and colour, as those used for the corresponding transitions from magnetisation data, in the phase diagram. When magnetic fields are applied, the first transition, denoted by black open circles in Figure 7(b), shifts to lower temperatures, and the second transition, denoted by open squares in Figure 7(b), move to higher temperatures before merging into one, at around 4.5 T. Between 2 and 4 T, two other anomalies appear, as a small jump in $R(T)$ data, denoted by open stars and diamonds in Figure 7(b). Similarly, the metamagnetic transitions could be observed in $R(H)$ data as well. The evolution of various features from $R(T)$ and $R(H)$ data follows the behaviour in magnetisation data and agree well with the phase diagram in Figure 5. As temperature decreases both Figures 7(a) and 7(c) show that once spin disorder (or magnon) scattering from the Ce$^{3+}$ is suppressed by field or temperature, a growing and large positive MR emerges.

Figure 7(c) shows the MR, defined as $MR\% = \frac{R(H) - R(H=0)}{R(H=0)} \times 100$, as a function of $H$. A sharp feature in $MR$ vs. $H$ is seen around 4.8 T, at 2 K, coinciding well with the feature obtained in $M(H)$ data. At low temperatures, there is a power-law like behaviour with an experimentally determined power $n=1.6$ for fitting MR at 2 K, above 6 T with $MR = aH^n$. At 2 K and 13.95 T, MR reaches a value of $2.9 \times 10^5\%$. Shubnikov–de Haas (SdH) oscillations are also observed at low temperatures and high fields. With increasing $T$ the quantum oscillations die away and the magnitude of MR decreases, as expected. Above 12 K, a negative MR regime is observed. The step-like features in $MR$ vs. $H$ curves are associated with the metamagnetic transitions, as shown in the inset of Figure 7(c). At even higher $T$, above 100 K, MR becomes positive again, but with comparatively small values. For instance, MR at 100 K and 13.95 T is 0.84%.

4. Discussion

We can try to gain a better understanding of the magnetic and transport properties of CeBi by looking more closely at the $H-T$ phase diagram and
Figure 7. (a) Resistance as a function of temperature measured at various applied fields from 0 to 13.95 T, for \( T \leq 40 \) K. (b) A blow-up of (a) with transitions marked with symbols same as in Figure 5. \( \frac{dR}{dT} \) is used as the criterion for evaluating the transition temperatures. (c) Magnetoresistance, \( MR\% = \frac{R(H) - R(H=0)}{R(H=0)} \times 100 \), as a function of applied magnetic field, measured at various temperatures ranging from 2 to 10 K. Inset: MR data for \( T \geq 12 \) K showing negative values. Metamagnetic transitions are clearly visible as step-like features in the MR curves (Colour online).
comparing it with the MR behaviour. In the phase diagram shown in Figure 5, one can observe an envelope of transitions, paramagnetic to antiferromagnetic at higher temperatures and going to field polarised state at lower temperatures but with higher fields. Within this there is a clear and large region between 1.5 to 4.5 T at lower temperatures and reducing in width at higher temperatures above 15 K. This corresponds to a regime with $M = 1/2 \mu_{\text{sat}}$. This is seen as a clear plateau in $M−T−H$ data in Figure 6. Additionally, we have an antiferromagnetic region, existing between the transition at 25 K and the lower one (near $\sim$13 K in lower fields), denoted by squares in the phase diagram in Figure 5. Then there are narrow stretches of magnetic phases existing between squares and stars in Figure 5. The larger two of these regions correspond to phases with a net magnetisation of $M = 1/4 \mu_{\text{sat}}$ and $M = 1/3 \mu_{\text{sat}}$, where $\mu_{\text{sat}}$ is the saturated magnetisation close to $2.14 \mu_{B}/\text{f.u.}$. There exists a third phase in between these two, and that has not been reported earlier. Once we enter the low temperature, low field regime, below 12.5 K and less than 1.5 T, we have multiple closely placed transitions and phases with ill-defined boundaries. This likely corresponds to existence of many near degenerate states, as evidenced by the highly hysteretic behaviour of both $M(T)$ and $M(H)$.

We can compare our $H−T$ phase diagram with the various MR regions, to better understand how MR is being affected by magnetic ordering. This is achieved through a false colour plot of MR as a function of $T$ and $H$, as shown in Figure 8. A change in tone shows the variation from negative to positive large MR.

The most conspicuous feature in the false colour plot is the change from positive to negative MR. Although the lowest field data could suggest that this could be related to the transitions near 10–15 K, the fact that this MR sign change exists to fields 2.5 times larger than the metamagnetic transition to the saturated paramagnetic state indicates that this is not the case. The sign change in MR persists from the high field to low field region, unchanged by crossing the $\mu_{0}H \sim 4.5$ T line. Based on the simpler, higher field $R(T)$ curves, the sign change appears to be associated with a change from a lower temperature, positive MR associated with minimal scattering from the already saturated Ce$^{3+}$ moments to a higher temperature, negative MR that is associated with the increasing applied field suppressing scattering from the Ce$^{3+}$ moments. The negative MR region in the ordered part of the $H−T$ diagram indicates the region where magnetic scattering is most readily suppressed by increased field. One cannot rule out the possible existence of a Lifshitz transition unaffected by the magnetic transitions, which could also cause such a change, but this would be coincidental. In other words, whereas electronic structural changes in zero field have been observed associated with magnetic transitions, both in optical and ARPES measurements [42–44], it is unlikely that this causes such a crossover in MR behaviour, in high fields,
where we are in a saturated paramagnetic regime. This argument is further strengthened by Kohler’s rule analysis in the following paragraph.

The existence of a power-law like behaviour of $MR(H)$ at low temperatures calls for Kohler’s rule analysis of this data set. Kohler’s rule provides a simplistic approach, wherein the classical electron motion in an applied magnetic field leads to a scaling behaviour of the form:

$$\frac{\Delta R}{R_0} = F\left(\frac{H}{R_0}\right)$$

Here, $F(x)$ is the scaling function and $\Delta R = R(T, H) - R_0$ where $R_0 = R(T, H = 0)$. Kohler’s rule holds as long as there is a single, dominant scattering mechanism. Given that we think scattering from the Ce$^{3+}$ moment is minimal to the left of crossed line in Figure 8, i.e. in the positive MR region, we can analyse our data in that region of the $H-T$ space. Figure 9(a) shows Kohler’s plot obtained from the resistance $R(T)$ measured at various fields above 5 T, in the temperature range $1.8 K \leq T \leq 10 K$. Figure 9(b) shows Kohler’s plot from different $R(H)$ curves measured at various temperatures up to 12 K. All the curves, except $R(H)$ at 12 K, fall approximately on top of each other signifying the scaling behaviour and its breaking as we approach the magnetic transition. In Figure 9(a), one can see, the various $R(T)$ data roughly fall on top of each other, indicating the MR behaviour at low temperatures being governed by the same physics across a wide range of
applied fields. This also shows that the various magnetic transitions in the low-
temperature low field regime play a less dominant role in electronic transport,
as the effects of these on electronic scattering are small (on the logarithmic
scale) compared to Kohler’s rule behaviour due to very high positive non-satur-
ing MR values observed at low temperatures. This can be emphasised more by
plotting $\Delta R/R_0$ vs. $H/R_0$ using $MR(H)$ data at 2 K. It agrees well with the curves
from various $R(T)$ data as shown in Figure 9(a). But additionally, if we look
carefully at the 2 K curve, shown separately in the inset of Figure 9(a), one
can see small glitches in it (indicated by red arrows in the figure), which corre-
sponds to the field values of 1.1~T and 4.8~T, which are close to the fields
where we observe the magnetic transitions. This clearly shows that the effect
of magnetic transitions on the MR behaviour in this regime is comparatively
small. The slope of data shown in inset of Figure 9(a) is roughly 5/3. Although
the manifolds are shown in the main body of Figures 9(a) and 9(b) have some
spread, they are consistent with this value as well.

Thus, we can say, MR sign change tracks minimum in $R(T)$ close to 12 K and
is most clearly associated with a crossover from low-temperature Kohler’s rule
– like behaviour in $R$ with $H$ associated with a normal metal with an anomalous-
lously large MR to a higher temperature decrease in $R$ with $H$ associated
with saturating the Ce spins and decreasing spin disorder/ magnon scattering.

The anisotropic MR behaviour of CeBi was studied recently [33], and it
suggests a magnetisation governed MR in the temperature regime ~12.8–25
K. This is not inconsistent with our results. Whereas they observe a magnetisation
dependent MR in the temperature regime between $T_N/2 < T < T_N$, we
focus on Kohler’s rule behaviour below that and the shift to negative MR
above that temperature region.

Figure 9. (a) Kohler’s plot obtained from $R(T)$ data taken at various fields above 5 T, in the
temperature range $1.8 \, K \leq T \leq 10 \, K$. In addition, MR data at 2 K is plotted in the same way,
which falls on top of the curves from $R(T)$ data. Inset: Kohler’s plot for MR at 2 K plotted sepa-
ately. Two small features corresponding to the metamagnetic transitions are marked by red
arrows. (b) Kohler’s plot obtained from $R(H)$ data taken at various temperatures from 2 to 12 K.
The breakdown at 12 K as we approach the magnetic transition is clearly seen (Colour online).
5. Conclusion

We measured the magnetic and the transport properties of CeBi, on flux-grown single crystals. From the magnetisation data, we were able to construct a field-temperature phase diagram and identify regions with near degenerate states, as well as those with well-defined magnetisation values. We were also able to identify a new phase region in addition to the ones existing in earlier reports. In addition, we observed a non-monotonic behaviour of MR. A large MR was observed in the low-temperature regime, where it has a power-law, non-saturated behaviour, which obeys Kohler’s scaling rule. This gives way to the onset of a negative MR region with increasing temperatures, when the magnetic scattering plays the dominant role.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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