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Negative magnetoresistance in Dirac semimetal Cd_3As_2 in the variable range hopping regime

L LIMOUNY[1,*], S DLIMI[2] and A EL KAAOUACHI[3]
[1]ESIM, Physics Department, University Moulay Ismail, BP 509, 52000 Errachidia, Morocco
[2]Physics Department, Faculty of Sciences, 80000 Agadir, Morocco
[3]MPAC Group, Faculty of Sciences, BP 8106, 80000 Agadir, Morocco
*Author for correspondence (limouny@gmail.com)

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Abstract. Cadmium arsenide (Cd_3As_2) is a Dirac semimetal intensively investigated in the last decade due to its stability and high mobility. Cd_3As_2 shows large negative magnetoresistance (NMR) over a wide range of magnetic field. Such NMR has been analysed in the framework of localized magnetic field and quantum interference theories. At low magnetic fields, quantum interference theory is consistent with the experimental data which can be described by variable range hopping (VRH) in the presence of a soft Coulomb gap (Efros–Shklovskii VRH). On the other hand, at moderate magnetic fields, the data are well described by the localized magnetic moment theory and the NMR is well approximated by the Langevin function.

Keywords. Cd_3As_2; Dirac semimetal; negative magnetoresistance; quantum interference; localized magnetic moments; Langevin function.

1. Introduction

Graphene is the most famous Dirac semimetal in two dimensions in which the valence and conduction bands touch in discrete points at the Fermi level [1,2]. In three dimensions, Cd_3As_2 is an alternate of graphene that exhibits the same features. Topological materials and Dirac semimetals, such as Cd_3As_2, Na_3Bi and PbSnSe have received considerable attention and was a subject of intensive investigation recently [3–5]. The negative magnetoresistance (NMR) is among the most studied properties in Cd_3As_2. In this context, several papers regarding the magnetoresistance have been published [6–9]. Recently, magneto-transport in topological materials is widely investigated [10,11]. Special attention has been paid to the study of the NMR behaviour and its origin in these materials [6,12–14].

Magnetoresistance of Cd_3As_2 has been previously measured and NMR at low and moderate magnetic fields which is explained by the chiral anomaly [8]. The observed NMR in some topological materials, such as Dirac and Weyl semimetals, is in most cases, attributed to the chiral anomaly [15,16]. Chiral anomaly mechanism corresponds to the transfer or the pumping of charges from a Weyl node to its partner under application of a magnetic field collinear with an electric field. Nevertheless, the origin of this NMR remains controversial. In this context, the authors of reference [17] claim that magnetoresistance in different systems may have several origins and remains an open question. Moreover, Spivak and Andreev report in reference [18] that NMR can occur in systems without chiral anomaly, in agreement with the work in reference [19], where the authors discuss the effect of orbital moment and Landé 'g' factor in the apparition of NMR.

Furthermore, it was found that the NMR of some materials that display Efros–Shklovskii variable range hopping (VRH) have been negative in some cases [20,21] and positive in other cases [22].

In previous papers [23–29], we have studied transport phenomenon and negative and positive magnetoresistance behaviours on both sides of the metal–insulator transition (MIT) in several 3D and 2D semiconductors, in amorphous and granular alloys systems [30,31]. Magnetoresistance analysis behaviour allows us to highlight different conduction mechanisms.

When the activated conduction is not possible in localized systems, the VRH mechanism takes place. There are two VRH regimes: Mott VRH and Efros–Shklovskii (ES) VRH. In the Mott VRH regime, the density of states (DOS) is supposed to be constant as the electron–electron (e–e) interactions are neglected, and under these conditions, the resistivity (or conductivity) behaves as $\ln\left(\frac{\rho}{\rho_0}\right) \propto \left(\frac{T_0}{T}\right)^{\frac{1}{d+1}}$, where d is the dimensionality of the system, T_0 and ρ_0 are

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parameters that are temperature- and resistivity-dependents [32,33].

When e–e interactions are important, the DOS near the Fermi level is not constant anymore and takes a parabolic form in 3D, following the universal law, $N(E) = \alpha|E - E_F|^{\frac{1}{2}}$ in 3D, therefore: $\ln\left(\frac{\rho}{\rho_0}\right) \propto \left(\frac{T_0}{T}\right)^{\frac{1}{2}}$ [34,35].

In some materials, it was found that the Mott VRH governs the conduction [36], whereas in other materials, ES VRH conduction dominates [37]. In some cases, both Mott and ES VRH coexist and a crossover between these two regimes has been revealed [38–44].

2. Results

In the present paper, we re-analysed the experimental data of measured NMR of sample Cd_3As_2 carried out by Li *et al* [17] by digitizing data in figure 4a of reference [17]. The sample is a 3D Dirac semimetal, and the experimental details are shown in reference [17]. Recently, it was intensively investigated [7,45–47].

Firstly, we began by analysing experimental data in the framework of localized magnetic moments model. In the second stage, we compare the observed NMR and its possible crossover with magnetic field with quantum interferences theory to deduce that which of the two theoretical models is in agreement with these data of sample Cd_3As_2.

2.1 *Model of localized magnetic moments*

The model of localized magnetic moment was developed for the first time by Toyozawa [48] in 1962. This model takes into account the scattering of the conduction electrons by the magnetic moments localized in centres of impurities. Toyozawa's model provides a good way of investigating negative magnetoresistance. In connection with Toyozawa's studies, the decrease in the magnetoresistance came as a result of reducing scattering by the application of an external magnetic field to the sample, ordering the magnetic moments, thus, resulting in a decrease in magnetoresistance.

In figure 1, NMR of the sample Cd_2As_3 is plotted as a function of magnetic field B for low and moderate values in the range of 0–4 T at different temperatures between 100 and 300 K.

Assuming the existence of magnetic moments, negative magnetoresistance follows the Curie–Weiss law as a function of the field and temperature:

$$\left|\frac{\Delta\rho}{\rho_0}\right|^{-1/2} = K_1\left(\frac{T+\theta}{B}\right) + K_2, \tag{1}$$

where B is the magnetic field and θ represents the Curie temperature of the paramagnetic systems. K_1 and K_2 are constants. Moreover, Yosida [49] has shown that if

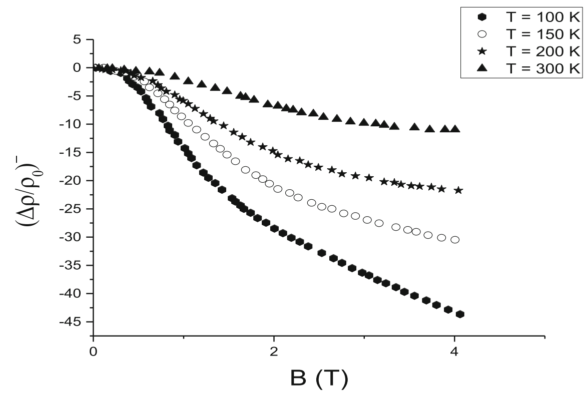

Figure 1. Negative magnetoresistance $\left(\frac{\Delta\rho}{\rho_0}\right)^{-}$ *vs.* magnetic field up to 4 T at four different temperatures.

magnetic moments exist, the magnetoresistance is proportional to the average of the magnetization of the impurities:

$$\frac{\Delta\rho}{\rho_0} \approx M^2 \approx \left(\frac{B}{T}\right)^2. \tag{2}$$

The magnetization of paramagnetic systems is classically described by the Brillouin function B_J as follows:

$$M = N_m g J \mu_B B_J\left[\frac{\mu^* B}{k_B T}\right] \tag{3}$$

Here, μ_B is the Bohr magneton and μ^* the effective magnetic moment of scattering centres, which is proportional to the Landé factor 'g' and the Bohr magneton μ_B, k_B the Boltzmann constant and T the temperature.

N_m represents the concentration of the scattering centers and J indicates the total moment of the localized electrons.

In this case, where N_m is very large, the magnetization can be represented by the Langevin function rather than the Brillouin law. Therefore,

$$L(x) = \coth(x) - \frac{1}{x}, \tag{4}$$

where $x = \frac{\mu^* B}{k(T+\theta)}$ in the case of a paramagnetic system obeying the Curie–Weiss law.

Therefore, the negative magnetoresistance arising from the spin diffusion takes the following form:

$$\left(\frac{\Delta\rho}{\rho_0}\right)^{-} = -\lambda L^2\left(\frac{\mu^* B}{k_B(T+\theta)}\right). \tag{5}$$

As well as:

$$\left|\left(\frac{\Delta\rho}{\rho_0}\right)^{-}\right|^{1/2} = \delta L\left(\frac{\mu^* B}{k_B(T+\theta)}\right), \tag{6}$$

with $\delta = \lambda^{1/2}$ is a constant.

To verify if the localized magnetic moments model is in agreement with the experimental data, we plot $\left|\left(\frac{\Delta\rho}{\rho_0}\right)^{-}\right|^{1/2}$ as a function $B/(T+\theta)$ and check if all data collapse onto a single curve in the range of the magnetic fields studied.

The slope of data representing $\left|\left(\frac{\Delta\rho}{\rho_0}\right)^{-}\right|^{-1/2}$ as a function of the temperature for each value of the magnetic field B yields the Curie temperature θ, as shown in figure 2.

Figure 3 displays slopes by linear fitting of data which, if extended to the low temperature limit, are secant at a $T = -\theta$ and $\left|\left(\frac{\Delta\rho}{\rho_0}\right)^{-}\right|^{-1/2} = -K_2$, thus, we evaluate Curie temperature to be equal to -11 K.

The description of the NMR by the Toyozawa model implies an effective moment between 5 and $10\mu_B$, however, in our case, we have $\mu^* = 23.4\mu_B > 10\mu_B$.

This large value of μ^* is explained by the existence of a large number of paramagnetic sites within the same region.

The large value of μ^* is not consistent with that predicted by Toyozawa [48], and this disagreement can be explained by the high mobility [50,51] of the sample studied in this paper. Apart from the large value of μ^*, the experimental data are well described by the model of localized magnetic moment.

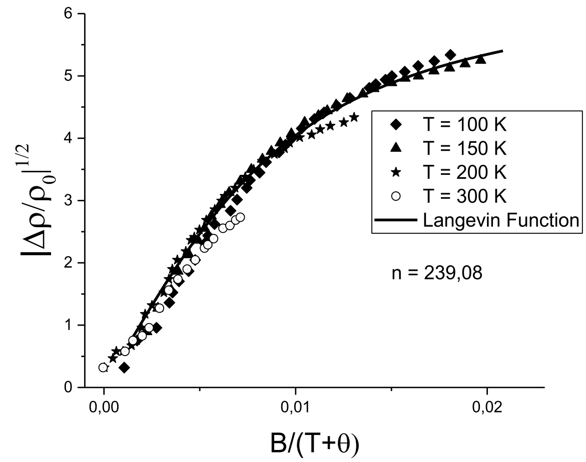

Figure 3. $\left|\left(\frac{\Delta\rho}{\rho_0}\right)^{-}\right|^{1/2}$ *vs.* $B/(T+\theta)$ adjusted by the Langevin function.

2.2 *Model of quantum interference*

The quantum interference model has been proposed to explain the appearance of NMR, valid in the limit of low magnetic fields and low disorder, when the elastic scattering length is larger than Fermi wavelength [52]. This model has analogies with the weak localization theory which gives quantum correction to the classical Drude conductivity. Bergmann [53] proposed that in weak localization regime, the NMR came as a consequence dephasing by a magnetic field of the quantum phase coherence of backscattered trajectories.

Quantum interference was found to be responsible for low field NMR observed in some materials [52].

Nguyen, Spivak and Shklovskii (NSS) were the first to establish a model to explain NMR using quantum interference on percolation paths [54]. In this model, the authors study the effect of the magnetic field on the probability of hopping between two sites separated by a characteristic distance R_h, this probability is determined by the interference between the paths separating these two sites, for more details, see reference [54]. According to this model, the authors have shown that the probability of hopping between two sites is influenced by the interference between all the possible diffusion paths included in an ellipsoidal volume ‘cigar-shaped domain’ of R_h length and width $(R_h\xi)^{\frac{1}{2}}$. With ξ, the localization length.

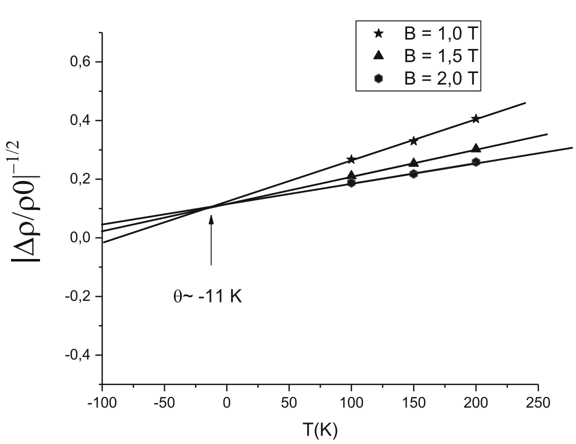

Figure 2. $\left|\left(\frac{\Delta\rho}{\rho_0}\right)^{-}\right|^{-1/2}$ against temperature T for different fixed values of magnetic field B. Deduction of Curie temperature θ as indicated by the arrow.

According to references [55,56], the localization length increases with the magnetic field, hence the observation of the NMR. According to these authors, the magnetic field influences the length of localization without changing the density of the states at the Fermi level.

Sivan *et al* [57] have shown that for low intensities of the magnetic field B, the NMR is proportional to the square of the magnetic crossing an effective surface A as follows: $A = R_M^{3/2}\xi^{1/2}$, thus:

$$\left(\frac{\Delta\rho}{\rho_0}\right)^{-} = \frac{[\rho(B,T) - \rho(0,T)]}{\rho_0} = A^2B^2 = R_{hop}^3\xi B^2, \quad (7)$$

R_h the optimum hopping length temperature-dependent [20], therefore, can be written as:

$$\left(\frac{\Delta\rho}{\rho_0}\right)^{-} = -f_1(T)B^2 = R_{hop}^3 B^2. \quad (8)$$

For three-dimensional systems, where conduction is governed by Mott VRH: $R_h \approx T^{-1/4}$, therefore, the NMR dependence on temperature is given by:

$$\left(\frac{\Delta\rho}{\rho_0}\right)^{-} \propto T^{-3/4}B^2. \quad (9)$$

When the density of states around the Fermi level has a soft Coloumb gap due to the electron's correlations, then we have, $R_h \approx T^{-1/2}$ thus, the NMR is given by:

$$\left(\frac{\Delta\rho}{\rho_0}\right)^{-} \propto T^{-3/2}B^2. \tag{10}$$

For moderate values of magnetic fields, when the quadratic variation of the NMR with the field is no longer observed, Schirmacher [58] predicts a linear dependence of the NMR with the field B:

$$\left(\frac{\Delta\rho}{\rho_0}\right)^{-} = -f_2(T)B^2, \tag{11}$$

with $f_2(T) \approx T^{-7/8}$.

In figure 4, the NMR of sample is plotted as function of the square of magnetic field B^2 for different temperatures as labelled. At low magnetic fields, the NMR is a quadratic function of the magnetic field and the slopes of these straight lines decrease by increasing the temperature as shown in figure 5.

For the low values of the magnetic field B, we adjusted the data representing the NMR of the sample Cd_3As_2 by the relation $\left(\frac{\Delta\rho}{\rho_0}\right)^{-} = -f_1(T)B^2$, $f_1(T)$ is yielded from the slope in figure 5, therefore, one can deduces R_h as: $f_1(T) \approx R_h{}^3 \approx T^{-1.47}$. This value is very close to 3/2 as predicted by the quantum interference model in the presence of a Coulomb gap in the densities of states around the Fermi level and thus, $R_h \approx T^{-1/2}$, and the conduction mode is ES VRH and $\left(\frac{\Delta\rho}{\rho_0}\right)^{-} = -T^{-3/2}B^2$.

For moderate magnetic fields up to 4 T, figure 6 displays NMR *vs.* B for various temperatures. We note that the above characteristic value of the magnetic field B, which we denote as Bc (see figure 6), the NMR is linear by fragment, as a function of the field as predicted by NSS [52] and Schirmacher [58].

On the other hand, Schirmacher [58] established a model for the range of intermediate magnetic fields in which the quadratic variation of the NMR is no longer observed with the field. This model only involves a single diffusion site during the hopping, under these conditions, the NMR varies linearly with the field B as follows:

$$\left(\frac{\Delta\rho}{\rho_0}\right)^{-} = -f_2(T)B, \tag{12}$$

$f_2(T)$ is a temperature-dependent function. In figure 7, we plot the variation of function $f_2(T)$ *vs.* temperature. By fitting data, one can yield $f_2(T) \approx T^{-1.08}$, this value is very close to $-7/8$ predicted by Schirmacher [58] in this model.

At low value of magnetic field, NMR in the VRH regime is quadratic. However, at high value, NMR becomes almost linear in consistence with previous studies [59,60].

Analysis of NMR data in light of the Schirmacher [58] model which considers hopping processes involving only one intermediate site whose energy is located below the Fermi level [58] is in agreement with the experiment taking into account the errors made at depicting the measurements and when analysing the data.

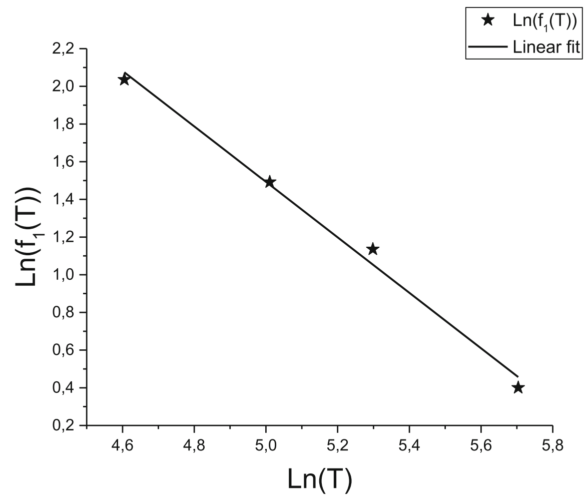

Figure 5. The function $f_1(T)$ against temperature T on a log–log scale.

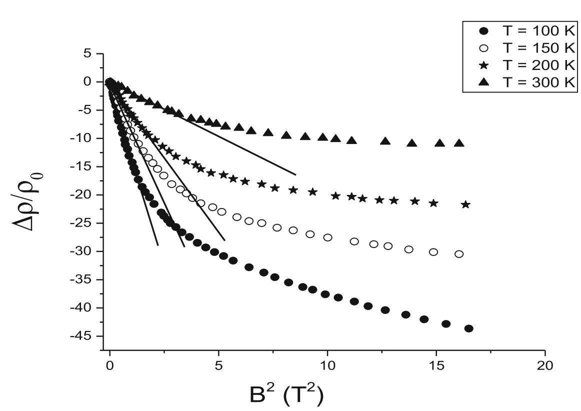

Figure 4. NMR $\left(\frac{\Delta\rho}{\rho_0}\right)^{-}$ *vs.* B^2 at various temperatures.

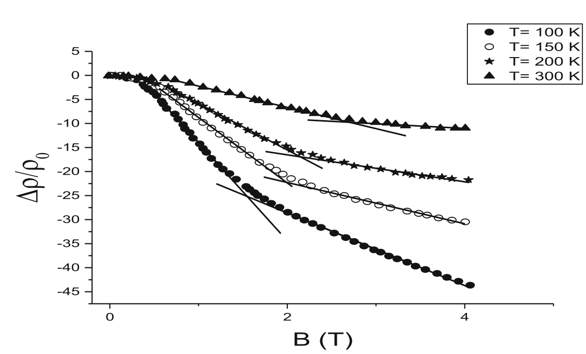

Figure 6. NMR $\left(\frac{\Delta\rho}{\rho_0}\right)^{-}$ *vs.* magnetic field B at various temperatures.

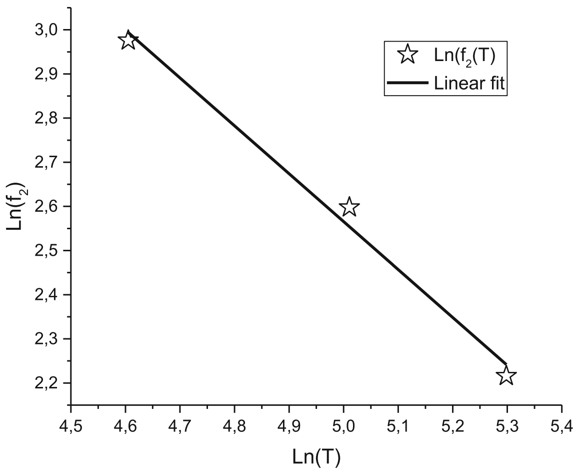

Figure 7. The function $f_2(T)$ against temperature T in logarithmic scale.

3. Conclusion

In summary, negative magnetoresistance of a Dirac semimetal Cd_3As_2 is analysed at low and moderate magnetic fields, in the light of two theories: namely localized magnetic field and quantum interferences theories. Within the model of localized magnetic moment, NMR is well approximated by the Langevin function and the magnetic moment $\mu^* = 23.4\mu_B$. The large value of μ^* than that predicted by theatrical model can be explained by the high mobility of the studied sample.

On the other hand, at low magnetic fields, experimental data are well described by the model of quantum interference and quadratic dependence of NMR is observed. The NMR follows the law, $\left(\frac{\Delta\rho}{\rho_0}\right)^{-} = -f_1(T)B^2 = \mathrm{R}^3_{\mathrm{hop}}B^2$ with $f_1(T) \approx T^{-1.5}$ which is consistent with theoretical expectations for the effect of quantum interference in the hopping regime in presence of Coulomb gap. In the range of moderate magnetic field, the model developed by Schirmacher [58] seems to be in good agreement with the experimental data.

Acknowledgements

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