Low temperature electron dephasing time in AuPd revisited

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Abstract

Ever since the first discoveries of the quantum-interference transport in mesoscopic systems, the electron dephasing times, \( \tau_{\phi} \), in the concentrated AuPd alloys have been extensively measured. The samples were made from different sources with different compositions, prepared by different deposition methods, and various geometries (1D narrow wires, 2D thin films, and 3D thick films) were studied. Surprisingly, the low-temperature behavior of \( \tau_{\phi} \) inferred by different groups over two decades reveals a systematic correlation with the level of disorder of the sample. At low temperatures, where \( \tau_{\phi} \) is (nearly) independent of temperature, a scaling \( \tau_{\phi}^{\text{max}} \propto D^{-\alpha} \) is found, where \( \tau_{\phi}^{\text{max}} \) is the maximum value of \( \tau_{\phi} \) measured in the experiment, \( D \) is the electron diffusion constant, and the exponent \( \alpha \) is close to or slightly larger than 1. We address this nontrivial scaling behavior and suggest that the most possible origin for this unusual dephasing is due to dynamical structure defects, while other theoretical explanations may not be totally ruled out.

Key words: Electron dephasing time; AuPd alloys; Dynamical structural defects; Weak localization

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1. Introduction

The electron dephasing time, \( \tau_{\phi} \), in mesoscopic structures at very low temperatures has recently attracted intense theoretical [125] and experimental [45678] attention. One of the key issues under exquisite discussion is whether \( \tau_{\phi} \) should diverge to an infinite value or “saturate” to a finite value as \( T \to 0 \) K. It is known that even very dilute magnetic scattering, if any exists, could eventually dominate over all other kinds of inelastic electron scattering (in particular, the Nyquist electron-electron scattering [9] and the electron-phonon scattering [10]) and control \( \tau_{\phi} \) at sufficiently low temperatures, leading to a seemingly saturated behavior over a certain range of temperature. The magnetic scattering time, \( \tau_m \), in clean metals containing dilute magnetic impurities have very recently been extensively checked theoretically [111213] and experimentally [1415]. On the other hand, it has been argued if intrinsic electron-electron interactions in the presence of disorder might lead to saturation in \( \tau_{\phi}(T \to 0) \) [1]. There are also theories proposing that materials properties associated with specific dynamical structural defects (often modeled as two-level tunneling systems [10]) may cause noticeable dephasing at low temperatures [23]. In spite of these different opinions, one consensus has been reached by several groups, saying that the responsible electron dephasing processes in highly disordered and weakly disordered metals might be dissimilar [61617]. That is, while magnetic scattering is responsible in weakly disordered metals [1118], a different mechanism may be relevant for the “saturation” or very weak temperature dependence of \( \tau_{\phi} \) found in highly disordered alloys [19]. Thus, systematic studies of the temperature and disorder behaviors of \( \tau_{\phi} \) in highly disordered metals should be of great interest, and would provide valuable information complementary to that learned from weakly disordered metals [6171415].

For the convenience of discussion, those samples recently studied in Refs. [4], [6], [7], [14] and [15], where the values of diffusion constant \( D \) are comparatively large (typically, \( D \gtrsim 100 \text{ cm}^2/\text{s} \)), will be referred to as being “weakly disordered,” while the samples with values of \( D \sim 10 \text{ cm}^2/\text{s} \) and smaller to be discussed in this work will be referred to as being “highly disordered.” In the free-electron model, \( D = \sqrt{\frac{3}{2}} \tau \mu = \left( \frac{\nu_F l}{md} \right) \left( k_F l \right) \), where \( \nu_F \) (\( k_F \)) is the Fermi velocity (wave number), \( m \) is the effective electron mass, \( \tau \) (\( l \)) is the electron elastic mean free time (path), and \( d \)
is the dimensionality of the sample. That is, in the following discussion we assume $D \propto k_F l \propto \rho^{-1}$, where $\rho$ is the (residual) resistivity.

We shall survey and discuss the low-temperature electron dephasing times in the concentrated gold-palladium (AuPd) alloys whose resistances, magnetoresistances and $\tau_\varphi$ have previously been extensively measured by several groups \cite{5,19,20,21,22,23,24,25,26}. The reasons for our revisiting the temperature and disorder behaviors of $\tau_\varphi$ of this particular material are discussed below. Here we emphasize that the electron dephasing time $\tau_\varphi = \tau_\varphi(T, D)$ or $\tau_\varphi = \tau_\varphi(T, \rho)$ is both a function of temperature and a function of disorder.

(i) Ever since the first works of Dolan and Osheroff \cite{27}, and Giordano et al. \cite{28} on the weak-localization and electron-electron interaction effects in 1979 in AuPd, this material has been continuously studied by several groups until nowadays. Narrow wires, thin films, and thick films have been fabricated and studied, corresponding to one- (1D), two- (2D) and three-dimensional (3D) systems, respectively, with regards to the weak-localization \cite{29} and electron-electron interaction \cite{9} effects. Thus far, there already exist in the literature a good amount of data based on this single material. Therefore, a close examination of any possible correlation among those independently measured dephasing times $\tau_\varphi$ should be desirable and insightful.

(ii) In the course of the quantum-interference studies, the source materials used by different groups were obtained from different suppliers, and the molar compositions Au$_{100-x}$Pd$_x$ used were different. In most cases, $x$ varied between 40 and 60 and, thus, the samples fell in the concentrated alloy regime. Moreover, different techniques were employed for the fabrication of samples, including the thermal-flash evaporation, electron-beam evaporation, DC sputtering, and RF sputtering deposition methods. Different substrates such as glass, quartz, and sapphire substrates were also adopted in different experiments; whereas it is known that quartz and sapphire substrates contain far fewer (magnetic) impurities than glass substrates do.

As a consequence, the levels of magnetic impurities contained in the bulk of the samples, if exist, should be different from sample to sample prepared by different groups. Furthermore, in the case of narrow wires and thin films, the amounts of magnetic scattering due to the surfaces and the interfaces between the sample and the substrate, if exist, should also differ from sample to sample prepared by different groups. Therefore, one should expect randomly distributed values of the “saturated” dephasing time $\tau_\varphi^{\text{max}}$ for the various samples, if the measured $\tau_\varphi^{\text{max}}$ should originate from the magnetic scattering due to unintentional magnetic impurity contamination. Notice that, in this work, we denote the highest value of $\tau_\varphi$ extracted at the lowest measurement temperature in each experiment as $\tau_\varphi^{\text{max}}$.

(iii) The measured low-temperature $\tau_\varphi$ in essentially all 1D, 2D and 3D AuPd samples revealed a very weak temperature dependent behavior already at a relatively high temperature of around 1–4 K. That is, for reasons yet to be fully understood, the “saturation” behavior of $\tau_\varphi$ is particularly strong in this material. Therefore, close examination of the properties of $\tau_\varphi$ in this highly disordered alloy material may shed light on our understanding of the puzzling “saturation problem” \cite{130}.

In this paper, we have collected 34 data points of $\tau_\varphi^{\text{max}}$ measured on AuPd samples from the literature. Those values of $\tau_\varphi^{\text{max}}$ were all extracted from the weak-localization magnetoresistance measurements, with only one exception in Ref. \cite{23} where the value of $\tau_\varphi^{\text{max}}$ was determined from the time-dependent universal conductance fluctuation measurements. A set of the $\tau_\varphi^{\text{max}}$ data (10 data points) measured on a series of Ag$_{40}$Pd$_{60}$ samples are also included in the present discussion, because AgPd and AuPd have very similar materials and electronic properties \cite{31}. The relevant parameters for the samples surveyed in this work are listed in Table 1. In addition, we have measured the low temperature thermoelectric powers (the Seebeck coefficient) in both as-prepared and thermally annealed bulk AuPd. We have also fabricated thin and thick AuPd films and measured their resistances in zero field and in (moderately) high magnetic fields down to subkelvin temperatures. These thermoelectric power and resistivity measurements provide useful auxiliary information about the possible existence or not of localized magnetic moments in this alloy material.

2. Results and discussion

2.1. Electron dephasing time

The electron dephasing times $\tau_\varphi$ in AuPd narrow wires \cite{5,21,23,24,26}, thin films \cite{5,22,23,24}, and thick films \cite{19,20} have been extensively measured over the past two decades. In general, a temperature dependent dephasing time is observed at a few degrees Kelvin and higher, which can be satisfactorily attributed to the Nyquist electron-electron scattering and/or the electron-phonon scattering. Between about 1 and 4 K, depending on samples, a crossover to a very weak temperature dependence or a seemingly saturation of $\tau_\varphi$ is found (for example, see Fig. 1 of Ref. \cite{21}, Fig. 1 of Ref. \cite{19}, and Fig. 4 of Ref. \cite{23}). Such a “crossover temperature” of 1–4 K is significantly higher than those recently observed in the weakly disordered metals studied in, for example, Refs. \cite{4,6,7} and \cite{8}.

Figure 1 shows the variation of the measured value of $\tau_\varphi^{\text{max}}$ with diffusion constant $D$ collected from ten independent studies previously reported in the literature. The symbols are the experimental data, as indicated in the caption.
Table 1

Relevant measured parameters for the AuPd (AgPd) samples whose highest measured values of the electron dephasing time $\tau_{\varphi}^{\text{max}}$ are collected in Fig. 1. The maximum electron dephasing length $L_{\varphi}^{\text{max}} = (D\tau_{\varphi}^{\text{max}})^{1/2}$. The values of electron diffusion constant were computed using the 3D form $D = v_{\text{pl}}/3$ for all narrow wire, thin film and thick film samples. For sample groups A to J, the parameters are taken from Refs. [20], [19], [32], [21], [22], [5], [23], [24], [25] and [29], respectively. All sample groups indicate AuPd alloys except the sample group C which indicates AgPd alloys. In the last column, the letter “y” indicates that the experimental $\tau_{\varphi}^{\text{max}}$ is already saturated, the letter “w” indicates that the experimental $\tau_{\varphi}^{\text{max}}$ already reveals a much weaker temperature dependence than theoretically expected, the letter “n” indicates no saturation at the lowest measurement temperature in that particular experiment, and the symbol “-” indicates that the temperature behavior of $\tau_{\varphi}$ was not demonstrated in the cited reference.

| Sample Group | $l$(nm) | $\tau_{\varphi}^{\text{max}}$(ns) | $L_{\varphi}^{\text{max}}$(nm) | $\tau_{\varphi}^{\text{max}}$(ps) | Saturation |
|--------------|---------|-------------------------------|-------------------------------|--------------------------------|------------|
| A (3D-AuPd)  | 0.57    | 58                            | 2.65                          | 12.7                           | y          |
|              | 0.76    | 69                            | 3.54                          | 13.5                           | y          |
|              | 1.87    | 56                            | 8.72                          | 3.56                           | y          |
|              | 1.00    | 68                            | 4.66                          | 10                             | y          |
|              | 1.82    | 74                            | 8.49                          | 6.40                           | y          |
|              | 1.14    | 85                            | 5.31                          | 13.5                           | y          |
| B (3D-AuPd)  | 1.05    | 94                            | 4.9                           | 18                             | y          |
|              | 0.28    | 105                           | 1.3                           | 85                             | y          |
|              | 0.28    | 107                           | 1.3                           | 88                             | y          |
|              | 0.74    | 86                            | 5.3                           | 14                             | y          |
| C (3D-AgPd)  | 0.18    | 88                            | 0.85                          | 91.7                           | y          |
|              | 0.24    | 106                           | 1.1                           | 103                            | y          |
|              | 0.30    | 108                           | 1.4                           | 83.6                           | y          |
|              | 0.21    | 120                           | 1.0                           | 145                            | y          |
|              | 0.12    | 116                           | 0.57                          | 236                            | y          |
|              | 0.21    | 116                           | 1.0                           | 135                            | y          |
|              | 0.096   | 139                           | 0.45                          | 430                            | y          |
|              | 0.075   | 110                           | 0.35                          | 347                            | y          |
|              | 0.118   | 141                           | 0.55                          | 362                            | y          |
|              | 0.092   | 69                            | 0.43                          | 111                            | y          |
| D (2D-AuPd)  | 0.47    | 42                            | 2.2                           | 8                              | y          |
|              | 0.47    | 81                            | 2.2                           | 30                             | y          |
|              | 0.47    | 65                            | 2.2                           | 19                             | y          |
| E (2D-AuPd)  | 0.17    | 62                            | 0.8                           | 48.5                           | y          |
| F (1&2D-AuPd)| 2.57    | 147                           | 12                            | 18.1                           | n          |
|              | 2.57    | 108                           | 12                            | 9.8                            | n          |
|              | 3.21    | 112                           | 15                            | 8.3                            | n          |
|              | 3.21    | 130                           | 15                            | 11.3                           | n          |
|              | 3.21    | 115                           | 15                            | 8.8                            | n          |
|              | 3.21    | 147                           | 15                            | 14.4                           | w          |
|              | 3.21    | 176                           | 15                            | 20.7                           | w          |
|              | 3.21    | 151                           | 15                            | 15.3                           | w          |
|              | 3.21    | 139                           | 15                            | 12.8                           | w          |
|              | 3.21    | 143                           | 15                            | 13.6                           | w          |
| G (1&2D-AuPd)| 2.87    | 190                           | 13.4                          | 26.94                          | y          |
|              | 2.87    | 189                           | 13.4                          | 24.18                          | y          |
|              | 1.69    | 150                           | 7.9                            | 28.48                          | y          |
| H (1D-AuPd)  | 4.9     | 80                            | 23                            | 2.8                            | y          |
|              | 4.9     | 61                            | 23                            | 1.6                            | y          |
|              | 4.9     | 96                            | 23                            | 4                              | y          |
| I (1D-AuPd)  | 4.8     | 98                            | 19.2                          | 5                              | y          |
| J (1D-AuPd)  | 1.2     | 27                            | 1.7                            | 1.04                           | –          |
|              | 1.2     | 38                            | 5.6                            | 2.58                           | –          |
|              | 2.5     | 81                            | 12                            | 5.47                           | –          |

Fig. 1. (Color online) Variation of $\tau_{\varphi}^{\text{max}}$ with diffusion constant $D$ for concentrated AuPd and AgPd alloys. The measured $\tau_{\varphi}^{\text{max}}$ are taken from: closed squares (Ref. [20]), closed circles (Ref. [19]), open squares (Ref. [32]), open up triangles (Ref. [21]), closed up triangles (Ref. [22]), open circles (Ref. [5]), closed diamonds (Ref. [23]), closed down triangles (Ref. [24]), open diamonds (Ref. [25]), and open down triangles (Ref. [26]). The long straight line indicates the empirical scaling $\tau_{\varphi}^{\text{max}} \propto D^{-1}$ given by Eq. (1). The short straight line drawn between $D \approx 0.3$ and $3 \text{ cm}^2/\text{s}$ indicates the scaling $\tau_{\varphi}^{\text{max}} \propto D^{-1.6}$. The values of $\tau_{\varphi}^{\text{max}}$. On the contrary, we find that there is a strong correlation among the experimental values of $\tau_{\varphi}^{\text{max}}$ with the levels of disorder contained in the samples, independent of how and where the samples were made. In Fig. 1 the long straight solid line is drawn to guide the eye and is given by

$$\tau_{\varphi}^{\text{max}} \approx 0.08 D^{-1} \text{ [ns]},$$

where $D$ is in cm$^2$/s. Figure 1 suggests an approximate empirical scaling $\tau_{\varphi}^{\text{max}} \propto D^{-1}$, which holds for over two decades of the $D$ value from about 0.3 to 30 cm$^2$/s, corresponding to $\tau_{\varphi}^{\text{max}}$ varying roughly from $3 \times 10^{-10}$ to $3 \times 10^{-12}$ s. Equivalently, $\tau_{\varphi}^{\text{max}} \propto (k_{\text{pD}})^{-1}$ or $\tau_{\varphi}^{\text{max}} \propto \rho$ in this alloy system, and thus the “saturated” dephasing time is longer in more disordered samples. This result is intriguing, which should be suggestive of some unusual and yet to be understood electron dephasing mechanism operating in this particular (and maybe also other) highly disordered materials. We notice that Eq. (1) implies a relatively short and (almost) constant saturated dephasing length $L_{\varphi}^{\text{max}} = \sqrt{D\tau_{\varphi}^{\text{max}}} \sim 900 \text{ Å}$ in AuPd.

We would like to mention that the values of the experimental $\tau_{\varphi}^{\text{max}}$ considered in Fig. 1 and Table 1 are all already saturated or already reveal a much weaker temperature dependence than theoretically expected. There is only in one case involving 5-nm wide AuPd wires [5] where no saturation in $\tau_{\varphi}$ was envisaged down to the lowest measurement temperature of 80 mK in that experiment. In addition, we...
should point out that it cannot be totally ruled out that the variation in Fig. 1 may be described by the approximation $\tau_\varphi^{\text{max}} \propto D^{-\alpha}$ with an exponent $\alpha$ slightly larger than 1 [30,32], especially if we were to concentrate on the most strongly disordered regime of, e.g., $D \lesssim 3 \text{ cm}^2/\text{s}$.

As mentioned, the AuPd samples shown in Fig. 1 are either narrow wires, thin films, or thick films, which are 1D, 2D, or 3D with respect to the weak-localization effects. Nevertheless, with regard to the classical Boltzmann transport (the Drude conductivity $\rho^{-1}$), all the samples studied are 3D, because the elastic electron mean free path $l$ is short in AuPd, as compared with the narrow wire diameter or the film thickness. (For the alloys collected in Fig. 1, the value of $l$, varies approximately between 2 and 49 Å, see Table I.) Therefore, it is justified to discuss the measured $\tau_\varphi^{\text{max}}$ for all the narrow wire, thin film and thick film samples on an equal footing in terms of the 3D form of the electron diffusion constant $D = \tau_\varphi l/3$.

It is worth noting that a reminiscent scaling $\tau_\varphi^{\text{max}} \propto D^{-1}$ for a good number of 3D polycrystalline metal alloys has previously been reported by Lin and Kao [32]. A related discussion on the correlation between $\tau_\varphi$ at a given temperature and the level of disorder ($k_F l$)$^{-1}$ has been reported for a series of 3D In$_2$O$_{3-x}$ thick films [33], and a dephasing time $\tau_\varphi (4.2 \text{ K}) \propto \rho$ has been reported for a series of 2D In$_2$O$_{3-x}$ thin films [34] by Ovadyahu. (However, it should be noted that in Refs. [33] and [34], the disorder dependent electron dephasing time was inferred for a given temperature where $\tau_\varphi$ is still governed by a strongly temperature dependent dephasing mechanism.) Very recently, in a series of 2D Cu$_{0.93}$Ge$_{0.07}$Au$_3$ thin films, Huang et al. [35] have observed a dephasing time which first “saturates” around 6 K and then crosses over to a slow increase with further decrease in temperature. At 0.4 K, an approximate scaling $\tau_\varphi(0.4 \text{ K}) \propto R_\parallel$ is found, where $R_\parallel$ is the sheet resistance. These abovementioned results seem to suggest that, in certain metals and alloys, strong electron dephasing may originate from specific structural defects in the samples [35,36]. We should also notice that the authors of Ref. [35] have presented measurements that particularly argued against magnetic scattering as a cause for the “saturation” in $\tau_\varphi(T \to 0)$.

2.2. Low temperature thermoelectric powers

The thermoelectric power (thermopower), $S$, is a quantity which is known to be extremely sensitive to the existence of a trace amount of magnetic impurities in an otherwise pure metal [37]. In typical pure nonmagnetic metals, the low temperature thermopower is comprised of two terms: $S = AT + BT^3$, where the first and the second terms represent contributions from electron diffusion and phonon drag, respectively. At temperatures of a few degrees Kelvin, the linear term usually dominates. However, in the presence of a small amount (for instance, $\sim$ a few tenths or a few ppm) of magnetic impurities, a very large $S$ is found (typically, reaching $\sim$ several $\mu\text{V/K}$), which is well more than an order of magnitude larger than that in the corresponding pure metal. In addition, the thermopower now reveals a broad maximum, resulting in a nearly constant $S$ over a wide range of temperature at liquid-helium temperatures. For example, the value of $S(4 \text{ K})$ changes from $+0.03 \mu\text{V/K}$ for pure Au to $-7.2 \mu\text{V/K}$ for the AuFe Kondo alloy containing 13 ppm of Fe [38]. In the case of the Au$_{100-x}$Pd$_x$ alloys, the low temperature thermopowers have been extensively measured by Rowland et al. [39] and Guénault et al. [41] over the whole alloy series. They pointed out that the thermopower can be well described by the expression $S = AT + BT^3 + CT/(T + 0.2)$, in which the third term represents an extra contribution from Fe contamination. Notably, they observed that a finite value of $C$ could only be inferred for the Au-rich ($x \lesssim 20$) alloys; whereas in the concentrated alloys with the compositions ($x \approx 40-60$) pertinent to our discussion, they found $C = 0$, i.e., no magnetic impurities could be inferred from their thermopower measurements. Their studies seem to indicate that Fe atoms may not readily form localized magnetic moments in the concentrated AuPd alloys. This issue deserves further investigation.

In this work, we used two pieces of bulk Au$_{60}$Pd$_{40}$ (0.5-mm diameter and $\sim 1$ cm long, and 99.98% purity) for thermopower measurements between 1.5 and 300 K to check whether magnetic impurities might play important roles in concentrated AuPd alloys. The first bulk Au$_{60}$Pd$_{40}$ was measured twice, once before and once after a thermal annealing at 800°C for 16 h in an oxygen atmosphere of $\approx 5 \times 10^{-3}$ torr [40]. The second bulk sample was first thermally annealed at 800°C for 16 h in a vacuum of $\approx 5 \times 10^{-4}$ torr before its thermopower was measured. Figure 2 shows the variation of thermopower with temperature for our two
bulk AuPd samples, as indicated. To within our experimental uncertainties, the absolute value of the thermopower does not at all decrease after the thermal annealing in oxygen. The thermal annealing in vacuum also does not change the magnitude and the temperature behavior of the thermopower. This result demonstrates that the amount of magnetic (e.g., Fe) impurities, if any exists, in the concentrated AuPd alloys is negligibly small. Otherwise, the magnetic impurities should have become oxidized after annealing, losing their moments, and their contributions to $S$ greatly suppressed. Between 1 and 10 K, our measured thermopower can be well described by the linear expression $S = -0.14T \mu V/K$, as indicated by the least-squares fitted straight solid line in Fig. 2. This result is in consistency with that previously reported by Guénault et al. [11]. In short, no evidence of a huge thermopower with a broad maximum at a few degrees Kelvin signifying the existence of an appreciable level of magnetic impurities is found in the concentrated AuPd alloys. Indeed, to the best of our knowledge, we are aware of no report on the AuPd alloy being a Kondo system. The inset of Fig. 2 shows a plot of the overall temperature behavior of $S$ between 1.5 and 300 K for our as-prepared and annealed bulk AuPd samples.

2.3. Resistances in zero field and in magnetic fields

To investigate whether the observed weak temperature dependence or “saturation” of $\tau_{\phi}^{\text{max}}$ in the AuPd samples might be due to magnetic scattering, it is instructive to examine the temperature behavior of resistance in both zero field and in (moderately) high magnetic fields. In this work, we have fabricated thin (2D) and thick (3D) Au$_{50}$Pd$_{50}$ films for low temperature resistance measurements. Our films were made by DC sputtering deposition on glass substrates held at ambient temperature. A background pressure of $9 \times 10^{-7}$ torr was reached before the sputtering was initiated. An argon atmosphere of 20–30 mtorr was maintained during the sputtering process. The resistances as a function of temperature were measured down to 0.3 K. Figures 3(a) and 3(b) show the variations of resistance with temperature for a AuPd narrow wire (taken from Ref. [12]), a thin film and a thick film, respectively, in zero field and in a perpendicular magnetic field, as indicated. These figures indicate that the resistance rises vary with $-1/\sqrt{T}$ and $-\ln T$ all the way down to 0.3 K in narrow wires and thick films, respectively, as would be expected from the electron-electron interaction effects in the presence of disorder [9]. In the case of thick films, the electron-electron interaction effects are comparatively small and the expected $-\sqrt{T}$ dependence [9] is somewhat masked by the intrinsic temperature behavior of resistivity (due to scattering from localized exchange-enhanced Pd d states [34]) of this alloy material. Most importantly, Figs. 3(a) and 3(b) indicate that, in all three geometries in zero magnetic field, there is no any sign of a crossover to a resistivity saturation down to 0.3 K, as would be expected for the Kondo effect [14], even though a very weak temperature dependence of $\tau_{\phi}$ is already set in at temperatures ($\sim 1–4$ K) about an order of magnitude higher. Moreover, in all geometries in the presence of a magnetic field of a few T, there is no any evidence of a detectable negative magnetoresistance signifying the alignment effect of localized magnetic spins [15]. Thus, both the resistance and magnetoresistance behaviors do not seem to suggest the existence of noticeable localized magnetic moments in this alloy material. In fact, a similar conclusion of no Kondo effect in AuPd has previously been drawn by Giordano [12] from comparison of the temperature behavior of resistance in as-sputtered and annealed films.

3. Summary and conclusion

In this work, we survey the low-temperature electron dephasing times in the AuPd (and AgPd) alloys measured...
by several groups over the past 20 years. We show the existence of a nontrivial scaling $\tau_{\varphi}^{\max} \propto D^{-6}$, with $\alpha$ close to or slightly larger than 1, among the various samples made of this alloy material. This intriguing scaling behavior strongly suggests that the observed $\tau_{\varphi}^{\max}$ in AuPd cannot be simply attributed to the magnetic scattering time arising from random amounts of magnetic impurity contamination. To within our experimental uncertainties, the thermopower measurements at liquid-helium temperatures, and the resistance measurements in both zero field and in a (moderately) high magnetic field, indicate no sign of the Kondo effect in this concentrated alloy system. As a matter of fact, it should be noted that previous measurements on as-prepared and then annealed AuPd thin films \textsuperscript{21} and thick films \textsuperscript{19} have also ruled out the magnetic scattering as a plausible explanation for the “saturation” of $\tau_{\varphi}$ found in this material \textsuperscript{16}. In addition, previous studies of AuPd thin films deposited on both glass and quartz substrates indicated no difference in the temperature behavior of $\tau_{\varphi}$, although it was thought that glass substrates should contain more (magnetic) impurities which should in turn contribute to dephasing through electron scattering at the film-substrate interface \textsuperscript{21}.

Theoretically, for highly disordered 3D systems, a $\tau_{\varphi}$ possessing a very weak temperature dependence in a certain temperature interval and then crossing over to a slow increase with decreasing temperature has recently been predicted in a model based on tunneling states of dynamical structural defects \textsuperscript{17}. This model also predicts a ‘counterintuitive’ scaling $\tau_{\varphi} \propto D^{-1}$ in the plateau-like region. Our observation in Fig. 1 essentially mimic these qualitative features. Close comparison between the experiment and theory would require quantitative calculations using realistic material parameters \textsuperscript{16,18}. Finally, we notice that in the weakly disordered regime, the electron-electron interaction theory \textsuperscript{1} predicts a higher saturation value of $\tau_{\varphi}^{\max}$ than in cleaner samples. How this prediction might be modified in the highly disordered regime would be of great interest. Experimentally, in their systematic studies of numerous high-mobility GaAs/AlGaAs quantum wires, Noguchi et al. \textsuperscript{19} have observed a saturated dephasing time which scales approximately with mobility, i.e., $\tau_{\varphi}^{\max} \propto \mu$, which suggests in turn a direct proportionality to $D$. This experimental $\tau_{\varphi}^{\max}$ behavior versus disorder is in line with the prediction of the electron-electron interaction theory \textsuperscript{1} in the weakly disordered regime.

To summarize, our result indicates that the intriguing electron dephasing found in the AuPd alloys is very unlikely due to magnetic scattering. It may originate from specific dynamical structure defects in the samples. Other theoretical explanations may also be explored. 

Note added: After the submission of this paper, we have learned that, very recently, Golubev and Zaikin \textsuperscript{50} have developed a universal formula for the saturated electron dephasing time $\tau_{\varphi}^{\max}$ based on a model treating the effect of electron-electron interactions on weak localization in arbitrary arrays of quantum dots. They found that electron-electron interactions always cause a saturated dephasing time, and the saturated value of $\tau_{\varphi}^{\max}$ depends strongly and non-monotonously on the level of disorder in the sample while being insensitive to the sample dimensionality. Their theory has considered the electron dephasing times in all three cases of weakly disordered conductors, strongly disordered conductors and metallic quantum dots in a unified manner. Most notably, their theory predicts that, in weakly disordered systems, $\tau_{\varphi}^{\max}$ increases with decreasing disorder; while, on the contrary, in strongly disordered systems, $\tau_{\varphi}^{\max}$ increases with increasing disorder. Their observation in Fig. 1 is in line with this new theoretical prediction (see the discussion and the Fig. 6 in \textsuperscript{50}). In particular, if we focus on the strongly disordered regime with $D \approx 0.3-3$ cm$^2$/s, the data in Fig. 1 would be best described by $\tau_{\varphi}^{\max} \approx 0.084 D^{-1.6}$ ns, as indicated by the short straight line.

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References

[1] D. S. Golubev, A. D. Zaikin, Phys. Rev. Lett. 81 (1998) 1074.
[2] A. Zawadowski, J. von Delft, D.C. Ralph, Phys. Rev. Lett. 83 (1999) 2632.
[3] Y. Imry, H. Fukuyama, P. Schwab, Europhys. Lett. 47 (1999) 608.
[4] P. Mohanty, E. M. Q. Jariwala, R. A. Webb, Phys. Rev. Lett. 78 (1997) 3366; P. Mohanty, R. A. Webb, Phys. Rev. Lett. 91 (2003) 066604.
[5] D. Natelson, R. L. Willett, K. W. West, L. N. Pfeiffer, Phys. Rev. Lett. 86 (2001) 1821.
[6] F. Pierre, N. O. Birge, Phys. Rev. Lett. 89 (2002) 206804; F. Pierre, A. B. Gougam, A. Anthore, H. Pothier, D. Esteve, N. O. Birge, Phys. Rev. B 68 (2003) 085413; N. O. Birge, F. Pierre, arXiv:cond-mat/0401182.
[7] F. Schofer, C. Bäuerle, W. Rabaud, L. Saminadayar, Phys. Rev. Lett. 90 (2003) 056801; C. Bäuerle, F. Malet, F. Schofer, D. Mailly, G. Eska, L. Saminadayar, Phys. Rev. Lett. 95 (2005) 266805.
[8] B. Hackens, S. Faniel, C. Gustin, X. Wallart, S. Bollaert, A. Cappy, V. Bayot, Phys. Rev. Lett. 94 (2005) 146802.
[9] B. L. Altshuler, A. G. Aronov, in: Electron-Electron Interactions in Disordered Systems, Modern Problems in Condensed Matter Science, Vol. 10, ed. A. L. Efros, M. Pollak (North-Holland, Amsterdam, 1985) pp. 1-153.
[10] L. Li, S. T. Lin, C. Dong, J. J. Lin, Phys. Rev. B 74, 172201 (2006).
[11] G. Zarand, L. Borda, J. von Delft, N. Andrei, Phys. Rev. Lett. 93 (2004) 107204.
[12] T. Micklitz, A. Altland, T. A. Costi, A. Rosch, Phys. Rev. Lett. 96 (2006) 226601; T. Micklitz, T. A. Costi, A. Rosch, Phys. Rev. B 75 (2007) 054406.
[13] S. Kettemann, E. R. Mucciolo, Phys. Rev. B 75 (2007) 184407. 
[14] F. Mallet, J. Ericsson, D. Mailly, S. Ünlübayır, D. Reuter, A. Melnikov, A. D. Wieck, T. Micklitz, A. Rosch, T. A. Costi, L. Saminadayar, C. Bäuerle, Phys. Rev. Lett. 97 (2006) 226804.
[15] G. M. Alzoubi, N. O. Birge, Phys. Rev. Lett. 97 (2006) 226803.
[16] O. Ujsághy, A. Zawadowski, J. Phys. Soc. Jpn. 74 (2005) 80.
[17] Z. Ovadyahu, Phys. Rev. B 63 (2001) 235403.
[18] M. G. Vavilov, L. I. Glazman, Phys. Rev. B 67 (2003) 115310.
[19] J. J. Lin, Y. L. Zhong, T. J. Li, Europhys. Lett. 57 (2002) 872.
[20] Y. L. Zhong, J. J. Lin, Phys. Rev. Lett. 80 (1998) 588.
[21] J. J. Lin, N. Giordano, Phys. Rev. B 35 (1987) 1071.
[22] R. A. Webb, P. Mohanty, E. M. Q. Jariwala, Fortschr. Phys. 46 (1998) 779.
[23] A. Trionfi, S. Lee, D. Natelson, Phys. Rev. B 70 (2004) 041304.
[24] J. J. Lin, N. Giordano, Phys. Rev. B 35 (1987) 545.
[25] A. P. Heraud, S. P. Beaumont, C. D. W. Wilkinson, P. C. Main, J. R. OwensBradley, L. Eaves, J. Phys. C: Solid State Phys. 20 (1987) L249.
[26] F. Altomare, A. M. Chang, M. R. Melloch, Y. Hong, C. W. Tu, Appl. Phys. Lett. 86 (2005) 172501.
[27] G. J. Dolan, D. D. Osheroff, Phys. Rev. Lett. 43 (1979) 721.
[28] N. Giordano, W. Gilson, D. E. Prober, Phys. Rev. Lett. 43 (1979) 725.
[29] G. Bergmann, Phys. Rep. 107 (1984) 1.
[30] J. J. Lin and J. P. Bird, J. Phys.: Condens. Matter 14 (2002) R501.
[31] M. Hansen, Constitution of Binary Alloys (McGraw-Hill, New York, 1958), pp. 41 and 224, and references therein; K. Schroder, CRC Handbook of Electrical Resistivities of Binary Metallic Alloys (CRC Press, Boca Raton, Fla., 1983), pp. 61 and 136, and references therein.
[32] J. J. Lin, L. Y. Kao, J. Phys.: Condens. Matter 13 (2001) L119.
[33] Z. Ovadyahu, Phys. Rev. Lett. 52 (1984) 569.
[34] Z. Ovadyahu, J. Phys. C: Solid State Phys. 16 (1983) L845.
[35] Y. Imry, Z. Ovadyahu, A. Schiller, arXiv:cond-mat/0312135
[36] S. M. Huang, T. C. Lee, H. Akimoto, K. Kono, J. J. Lin, to be published.
[37] D. K. C. MacDonald, W. B. Pearson, I. M. Templeton, Proc. R. Soc. Lon. A 266 (1962) 161.
[38] J. Kopp, J. Phys. F: Metal Phys. 5 (1975) 1211.
[39] T. Rowland, N. E. Cusack, R. G. Ross, J. Phys. F: Metal Phys. 4 (1974) 2189.
[40] R. D. Barnard, J. Phys. E: Sci. Instru. 6 (1973) 508.
[41] A. M. Guénault, N. S. Lawson, J. Northfield, Phil. Mag. B 38 (1978) 567.
[42] N. Giordano, Phys. Rev. B 22 (1980) 5635.
[43] A. P. Murani, Phys. Rev. Lett. 33 (1974) 91.
[44] M. D. Daybell, W. A. Steyert, Phys. Rev. Lett. 18 (1967) 398.
[45] P. Monod, Phys. Rev. Lett. 19 (1967) 1113.
[46] J. J. Lin, T. J. Li, Y. L. Zhong, J. Phys. Soc. Jpn. 72 (2003) Suppl. A. 7.
[47] Y. M. Galperin, V. I. Kozub, V. M. Vinokur, Phys. Rev. B 69 (2004) 073102; V. V. Afonin, J. Bergli, Y. M. Galperin, V. L. Gurevich, V. I. Kozub, Phys. Rev. B 66 (2002) 165326.
[48] G. Zaránd, Phys. Rev. B 72 (2005) 245103.
[49] M. Noguchi, T. Ikoma, T. Odagiri, H. Sakakibara, S. N. Wang, J. Appl. Phys. 80 (1996) 5138.
[50] D. S. Golubev and A. D. Zaikin, Physica E (2007), this volume.