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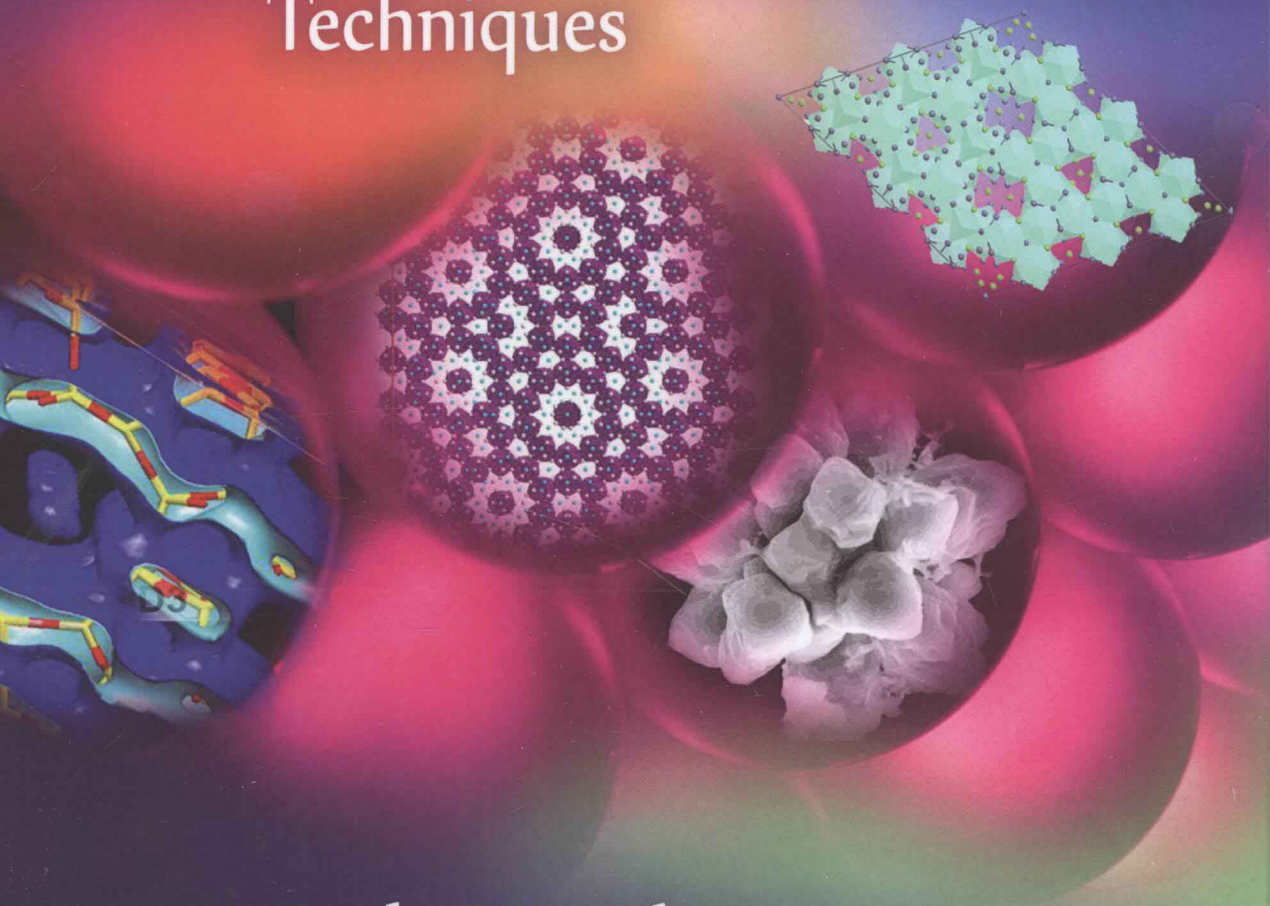
Quasicrystals

Types, Systems, and Techniques



Beth E. Puckermann
Editor

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QUASICRYSTALS: TYPES, SYSTEMS, AND TECHNIQUES

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PREFACE

Quasicrystals are metallic alloys that exhibit atomic scale order, but not periodic order. Atomic scale properties of these materials are different from single crystalline material, for example, extraordinary mechanical properties, electrical and thermal transport properties, and electronic structure. This book presents topical research in the study of quasicrystals, including vacancies in quasicrystals; the formation of quasicrystals in bulk metallic glasses and their effects on mechanical behavior; the electrical transport observed in Al-Pd-Mn quasicrystals; logarithmic periodicity in quasicrystals; and positron annihilation studies of quasicrystals.

Chapter1- The critical electronic states originating from the quasiperiodic long-range atomic order make its electrical properties quite unusual. Critical states decay as power-law and hence the temperature dependence of conductivity is expected to follow a power-law i.e. $\sigma \propto T^{a}$. In fact this behavior has been nicely evidenced in some non-magnetic quasicrystals like Al-Pd-Re and Al-Cu-Ru. In this series of Al-based stable quasicrystals Al-Pd-Mn system appears to be the most interesting. It has been reported to contain magnetic Mn sites. Due to its magnetic character, Al-Pd-Mn quasicrystals are expected to show interesting electrical transport properties, which is of basic importance from the "effect of magnetic scattering on the transport of localized electric systems" point of view. We have reviewed and tried to put forward an approach, which describes all the features of the electrical transport observed in Al-Pd-Mn quasicrystals.

To investigate the important role of Mn in these alloys, we changed the concentration of magnetic Mn in $Al_{70}Pd_{20}Mn_{10}$ quasicrystal following three approaches, (i) by exchanging the concentration of Pd and Mn atoms (ii) by replacing Mn by other transition metals like Fe, Cr, Co and Ni and (iii) by replacing aluminum(Al) by boron(B). Studies on these three different compositions have been described in Part-I, Part-II and Part-III. All these stable quasicrystal compositions were investigated using low-temperature (down to 2K) magnetic measurements, embodying magnetization-vs-temperature (M-T) and magnetization-vs-field (M-H) measurements and low-temperature zero-field and in-field magneto-transport measurements using four- probe method.

The σ-T variation of nearly all the studied samples show qualitatively the same behavior i.e. while cooling a σ-T minima is followed by a σ-T maxima. The observed features are all in accordance with the other observations. In the existing literature the occurrence of conductivity minima has been attributed to anti weak localization effect appearing due to strong spin-orbit scattering of conduction electrons by Pd. However, based on strong

arguments as corroborated by other magnetic and magneto-transport measurements, we have shown that although the observed σ-T variation is due to weak-localization the minima may not be due to spin-orbit scattering. We have concluded that the electronic transport in Al-Pd-Mn quasicrystals is fully dominated by quantum interference effects including electron-phonon scattering and Kondo-type magnetic scattering as two competing random dephasing processes. The σ-T minima appear as a result of these two competing scattering processes. The observed σ-T maxima is due to maxima in the spin-flip scattering rate which is expected while spin-flip scattering of electrons is from a system of interacting moments.

Chapter2-'Logarithmic periodicity' refers to three features in quasicrystals: firstly the ideal structure is uniquely icosahedral and infinitely extensive; secondly, the diffraction patterns contain corresponding orders that are geometrically spaced; and thirdly the mathematical description of electronic states is by special Fourier transforms in logarithmic order. This periodicity is driven by the low enthalpy in the subcluster. The model differs from most mathematical models because the three dimensional tiles share edges not faces. Experimental evidence of several types supports the model, beyond its conceptual simplicity. The principal three sources are: electron diffraction; electron microscopy; and diffraction simulations. The variety of properties and predictions are consistent with available experimental data in the binary quasicrystals such as Al_6Mn. Though logarithmic periodicity describes ideal solids with perfect icosahedral symmetry, the structure is defective in realization. While the defects should be expected in rapidly cooled and metastable solids, they imply uncertainties that require further refinement. If dendritic crystal growth depends on deposition of supercluster planar quads, the higher the order, the more nearly icosahedral.

Chapter3- Positron annihilation studies of quasicrystals (QC's) and their related materials (crystalline approximants) are reviewed. We describe why a positron, anti-particle of electron, is suitable for probing vacancies locally in aperiodic QC's. A series of positron annihilation spectroscopy is then briefly outlined. Positron lifetime spectroscopy reveals high concentration of structural vacancies more than 10^{-4} in atomic concentration for QC's and crystalline approximants studied. Chemical environments around the structural vacancies are investigated by coincident Doppler broadening spectroscopy. In addition, the concentration of structural vacancies is discussed based on the positron diffusion data obtained by a variable-energy slow positron beam. Besides the structural vacancy, we refer to other two kinds of vacancies: thermally formed high-temperature vacancy and electron-irradiation induced vacancy. Finally, the structural phase transition in QC's probed through the local atomic and electronic structures around structural vacancies is presented.

Chapter4- The structures of many quasicrystals have still remained unknown since the publication of the first icosahedral quasicrystal in rapidly solidified Al-Mn alloys in 1982. The main obstacle is that the quasicrystals always contain defects and it is difficult to synthesize high quality single crystals which are needed for a good structure determination by single crystal X-ray diffraction. In most cases, quasicrystals coexist with several complex quasicrystal approximants. These approximants have similar local atomic structures as the quasicrystals and many of them also contain defects that make diffraction spots from quasicrystals and different approximants overlapped and the whole diffraction pattern blurred. Meanwhile, some less complicated approximants in the same system can be synthesized as large single crystals with fewer defects, and their atomic structures can be determined. Due to the similar local atomic structures, a quasicrystal and its approximants always show similar intensity distribution and phase relationships for the strong reflections in reciprocal space.

Thus, the structure factors with both amplitudes and phases can be calculated from a known approximant for strong reflections and after re-indexing them, they can be used to calculate a 3D electron density map for more complex approximants by inverse Fourier transformation. The structure model can be deduced from this 3D electron density map since the strongest reflections mainly determine the atomic positions in a structure. In principle, the perfect quasicrystal structure model can be obtained by this approach. The strong reflections approach avoids a direct structure determination from quasicrystals containing defects but takes the advantage of using the common features of quasicrystals and approximants. The model deduced from this approach will be an ideal model for the quasicrystal, free of defects.

Chapter5- The dominant cluster in the Ti/Zr-based quasicrystals is a Bergman-type cluster possessing a large number of tetrahedral interstitial sites; this makes these quasicrystals attractive as potential hydrogen storage materials. This paper summarizes our recent research results on the hydrogen absorption and desorption properties of the Ti-Zr-Ni and Ti-Hf-Ni quasicrystals and related amorphous or crystal phases produced by a combination of mechanical alloying and subsequent annealing. The effects on the microstructures and hydrogenation properties of the substitution of Zr for either Ti or Hf in alloys based on the $Ti_{45}Zr_{38}Ni_{17}$ compositions are investigated. Comparisons between results reported for samples prepared by rapid quenching or annealing are also made.

Chapter6- The annealing of bulk metallic glasses (BMGs) at elevated temperatures usually leads to partial or full crystallization. The crystallization in several systems starts with the formation of metastable quasicrystalline (QC) particles and then the material can be regarded as a composite of QC and amorphous phases. The appearance of QC particles significantly affects the mechanical properties of BMGs. In this chapter, the morphology, structure and chemical composition of QC particles formed during heat-treatment of BMGs are reviewed according to the relevant literature. Special attention is paid to the influence of the formation of QC particles on the mechanical behavior at room and high temperatures. It was found that during heat-treatment of a commercial ZrTiCuNiBe BMG above the glass transition temperature nanosized spherical QC particles containing smaller grains were formed. Depending on the annealing temperature the volume fraction of the QC phase varied between 25 and 37%. The QC particles contain Ti, Zr and Ni in high concentration, while the amorphous matrix is enriched in Be. The high temperature viscosity increases mainly due to the hard QC particles but there is also a slight contribution from the compositional changes of the supercooled liquid matrix. The bending strength measured at room temperature decreases in consequence of QC formation, most probably mainly due to the loss of free volume in the amorphous matrix.

Chapter7- The atomic structure of the 2-fold decagonal Al-Ni-Co quasicrystal surface has been investigated using scanning tunneling microscopy (STM). Decagonal quasicrystals are made of pairs of atomic planes with pentagonal symmetry periodically stacked along a 10-fold axis. It is, therefore, expected that the 2-fold surfaces exhibit a periodic direction along the 10-fold axis, and an aperiodic direction perpendicular to it. The surface shows rough and cluster-like structures at low annealing temperatures ($T<1000K$), whilst annealing to temperatures in excess of 1000K results in the formation of step-terrace structures. The surface consists of terraces separated by steps of heights 1.9, 4.7, 7.8, and 12.6 Å. Ratios of step heights can be properly assigned to different τ powers, suggesting a well defined quasiperiodic long-range order. At the annealing temperature ($1100K < T < 1150K$), atomically resolved STM images of the 2-fold plane reveal atomic rows along the 10-fold

direction with a periodicity of 4 Å. The spacing between the parallel rows is aperiodic, with distances following a Fibonacci sequence. We found that the quasiperiodic order in the sequence of atomic rows is destroyed by the presence of phason defects. Above the heating temperature of 1200K, formation of second phase structures was observed. The formation of a second phase could be associated with the preferential evaporation of Al at the elevated temperature.

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Chapter9- The microstructural characteristics of a commercial quaternary AA8090 (Al-2%Li-1.2%Cu-0.8%Mg, by wt.%) alloy reinforced with 15 vol.% SiCp has been examined in detail. The composite material in the form of plate sheets with the thickness about 1600 μm was thinned to electron beam transparent (~ 20 nm thickness) using mechanical polishing and ion beam milling to carry out microscopy observations. In the alloy matrix (α - Al) the presence of δ'-precipitates ($L1_2$ structure, lattice parameter a = 0.401 nm) as tiny spheres of about 50 – 100 nm in size has been delineated. The presence of icosahedral quasicrystalline phase has also been observed in the matrix. In general, a lamellae structure of δ'-precipitate with the layer thickness of about 250 nm has been revealed on the grain boundaries. Adjacent to δ'-precipitate, a prominent region of precipitate free zones with a thickness between 65 – 85 nm is present at the boundaries. The distribution of SiCp in α-Al matrix is uniform with a clear interface exhibiting some dislocations.

Chapter10- The shapes of icosahedral quasicrystalline (IQC) particles in Al-Mn-Be-(Cu) alloys were determined in samples subjected to very wide range of cooling rates: from around 10^6 K/s in very thin melt-spun ribbons down to below 100 K/s in permanent copper dies. Accordingly, the sizes of quasicrystalline particles ranged from few tenths of nanometres up to more than 100 μm. As a consequence, different methods were employed to properly characterize their shapes: projections of quasicrystalline particles using transmission electron microscopy (TEM), cross-sections of IQCs on metallographic polished surfaces, observation of deep etched samples and extracted particles in a scanning electron microscope (SEM). Despite of different sizes and shapes it was discovered that two the most important features are common to all of them:

preferential growth in the three-fold directions

tendency for faceting and adopting the shape of pentagonal dodecahedron.

The evolution of quasicrystalline shapes from apparently spherical particles to very large and highly branched dendrites is systematically presented. Special attention was devoted to the correct interpretation of quasicrystal shapes obtained from 2D-metallographic cross-sections.

CONTENTS

In: Quasicrystals: Types, Systems, and Techniques
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Chapter 1

DOMINANCE OF MAGNETIC SCATTERING IN $AL_{70}PD_{20+X}MN_{10-X}$ (X = 0, 1 AND 2), $AL_{70}PD_{20}MN_8(TM)_2$ (TM=FE, CR, CO AND NI) AND $AL_{70-X}B_X$ $PD_{20}MN_{10}$ (X = 0, 0.5,1, 2 AND 4) STABLE ICOSAHEDRAL QUASICRYSTALS

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ABSTRACT

The critical electronic states originating from the quasiperiodic long-range atomic order make its electrical properties quite unusual. Critical states decay as power-law and hence the temperature dependence of conductivity is expected to follow a power-law i.e. $\sigma \propto T^a$. In fact this behavior has been nicely evidenced in some non-magnetic quasicrystals like Al-Pd-Re and Al-Cu-Ru. In this series of Al-based stable quasicrystals Al-Pd-Mn system appears to be the most interesting. It has been reported to contain magnetic Mn sites. Due to its magnetic character, Al-Pd-Mn quasicrystals are expected to show interesting electrical transport properties, which is of basic importance from the "effect of magnetic scattering on the transport of localized electric systems" point of view. We have reviewed and tried to put forward an approach, which describes all the features of the electrical transport observed in Al-Pd-Mn quasicrystals.

To investigate the important role of Mn in these alloys, we changed the concentration of magnetic Mn in $Al_{70}Pd_{20}Mn_{10}$ quasicrystal following three approaches, (i) by exchanging the concentration of Pd and Mn atoms (ii) by replacing Mn by other transition metals like Fe, Cr, Co and Ni and (iii) by replacing aluminum(Al) by boron(B). Studies on these three different compositions have been described in Part-I, Part-II and Part-III. All these stable quasicrystal compositions were investigated using low-

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The σ-T variation of nearly all the studied samples show qualitatively the same behavior i.e. while cooling a σ-T minima is followed by a σ-T maxima. The observed features are all in accordance with the other observations. In the existing literature the occurrence of conductivity minima has been attributed to anti weak localization effect appearing due to strong spin-orbit scattering of conduction electrons by Pd. However, based on strong arguments as corroborated by other magnetic and magneto-transport measurements, we have shown that although the observed σ-T variation is due to weak-localization the minima may not be due to spin-orbit scattering. We have concluded that the electronic transport in Al-Pd-Mn quasicrystals is fully dominated by quantum interference effects including electron-phonon scattering and Kondo-type magnetic scattering as two competing random dephasing processes. The σ-T minima appear as a result of these two competing scattering processes. The observed σ-T maxima is due to maxima in the spin-flip scattering rate which is expected while spin-flip scattering of electrons is from a system of interacting moments.

1. INTRODUCTION

Electronic properties of quasicrystals are expected to be quite unusual. This expectation is due to their critical electronic states [1,2], which are neither exponentially localized like those in disordered materials nor extended like that of crystalline materials. Critical states decay as power-law and hence the temperature dependence of conductivity is expected to follow power-law i.e. $\sigma \propto T^a$ [3,4]. In fact this behavior has been observed in some structurally high quality non-magnetic quasicrystals like Al-Pd-Re and Al-Cu-Ru [4,5 ,6],. In the series of these Al-based stable quasicrystalline alloys, Al-Pd-Mn system, due to the presence of Mn, appears to be the most interesting. It has been reported that only few percent of the total Mn sites are magnetic [28,32,37,46], ,], whose concentration increases with increasing defect [47]. Due to its magnetic character, Al-Pd-Mn quasicrystals are expected to show interesting electrical transport properties, which are of basic importance from "transport in magnetic materials" point of view [7]. The aspect of electrical transport in Al-Pd-Mn quasicrystal has been sparsely studied. We have tried to put forward a universal approach, which describes all the features of the electrical transport in Al-Pd-Mn quasicrystals.

The electrical conductivity σ of icosahedral quasicrystals is unusually sensitive to slight changes in their composition. Such changes shift the position of E_F, which results in a change of the DOS (E_F) and hence a change in σ. Thus, if we dope these quasicrystals by suitable dopants or by internal exchange of relative compositions of their ingredients, we can manipulate the Fermi-level and thus the electrical transport properties. The electronic structure calculations in the case of i-Al-Pd-Mn have shown the presence of structure-induced pseudo-gap at E_F [8]. The sp-d hybridization between Al sp and Mn d states is found to be an important factor in the formation of the pseudo-gap [9,10]. The position and density of Mn states near E_F and hence its magnetic properties are very sensitive to the structural and / or chemical environment of the Mn in the alloy [11]. Looking at the important role of Mn in these alloys, if we change the composition of $Al_{70}Pd_{20}Mn_{10}$ icosahedral quasicrystal by changing the Mn concentration, we can manipulate the DOS of the system. This in turn will affect its magnetic properties. Therefore to investigate the role of magnetic properties of Al-

Pd-Mn quasicrystals on its electrical transport behavior we have changed the concentration of Mn in $Al_{70}Pd_{20}Mn_{10}$ quasicrystalline alloy following three different approaches, (i) by exchanging the concentration of Pd and Mn atoms (ii) by replacing 2% of Mn by other transition metals like Fe, Cr, Co and Ni and (iii) by replacing boron in the place of aluminum. These are separately described in Part I, Part II and Part III.

Part I deals with $Al_{70}Pd_{20+x}Mn_{10-x}$ quasicrystalline samples in which concentration of Pd and Mn have been exchanged, Part II deals with the $Al_{70}Pd_{20}Mn_{10}$ quasicrystalline samples in which 2% of Mn is replaced by other transition metals like Fe, Cr, Co and Ni and finally Part III deals with Al_{70-x} $B_xPd_{20}Mn_{10}$. In these three parts we have studied the magnetic and transport properties of these quasicrystalline alloys.

Prior to 1987, all the known quasicrystals were thermodynamically metastable, exhibiting significant structural disorder, as manifested in the broadening of the X-ray diffraction lines. It was argued that this disorder might inhibit some possible novel intrinsic physical properties of quasicrystals. It was therefore of great importance when the first thermodynamically stable icosahedral alloys Al-Cu-TM (M= Fe, Ru, Os) were discovered [12] as they posses a high degree of structural perfection comparable to that found in the periodic alloys. These stable icosahedral phases were found to be chemically ordered and having face centered icosahedral (FCI) structure [12].

In the series of investigations on the formation and stability of the Al-Cu-TM quasicrystals, it was found that quasicrystals of this series form at the compositions with valence electron numbers (e/a) in the vicinity of 1.75. On the basis of this empirical rule, new FCI phases of Al70Pd20Mn10 and Al70Pd20Re10 were discovered [13]. In addition, it was also found that the icosahedral phase forms in a wide composition range, consisting of the simple icosahedra (SI) and FCI phases in different composition regions in the Al-Pd-TM system. The stable icosahedral quasicrystals, which was found in the Al-Pd-Mn alloy system [13,14] are in general free of atomic disorder and phason strains [15]. Structural studies with different techniques show that this phase forms in a perfect icosahedral state [16,17]. Therefore this system is ideal for studying the effects of magnetic impurities on the unusual electrical transport of quasicrystals. Very good structural quality and several centimeters large single grained quasicrystals of Al-Pd-Mn have been obtained by Bridgemann and of Czochralski [18,19] techniques. The most interesting fact about Al-Pd-Mn quasicrystals is that it melts directly into liquid without involving any crystalline phase, which makes the preparation of large single grained quasicrystals easier.

1.1. Phase Diagram

The phase diagram of melt quenched Al-Pd-Mn alloys has been well investigated by Tsai *et al.* [20] and is illustrated in Figure 1. The broken line shows a composition line with e/a = 1.75. It can be noted that the formation composition range of the icosahedral phase (i-phase) elongates along the line of e/a = 1.75, indicating that the electronic structure plays an important role in the formation of the i-phase. The i-phase with FCI structure forms in an wide composition range of 15 to 25 at.% Pd and 7 to 15 at.% Mn. In lower Pd and Mn regions free FCC Al phase exists as contamination.

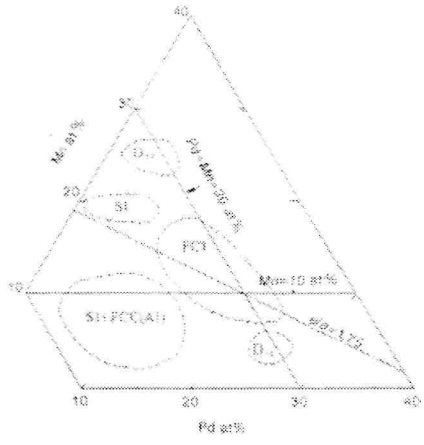

Figure 1. Phase diagram of Al-Pd-Mn alloys.

While an ordered cubic phase occurs in higher Pd and Mn regions, and a decagonal phase exists at the Pd-rich (~25 at.%) and Mn-poor (<5 at. %) regions. It is also expected that a D-phase would be observed in a Pd-poor region with Mn near 20 at. %. Thus, the global concentration of Pd + Mn = 30 at. % seems to be very critical for the formation of quasicrystalline phases. A slight departure from the optimized stoichiometry results in multiphase materials and / or non-perfect icosahedral order.

1.2. Magnetic Properties

Most of the Al-based quasicrystalline alloys show diamagnetic behavior and hence its magnetic susceptibility remains temperature-independent. For instance, diamagnetic behavior is found in icosahedral Al-Cu-Fe and Al-Pd-Re [21] quasicrystals. In contrast, the existence of Curie terms and hence of localized moments, has been reported in stable Al-Pd-Mn quasicrystals. Several experimental studies on polycrystalline [22,23,24] as well as on single grained quasicrystals [25,26,27,28] have shown that the magnetic susceptibility of these Al-Pd-Mn quasicrystals follows the Curie-Weiss law over a wide temperature range with a small and negative value of Curie temperature θ_c, suggesting that the Mn-Mn exchange interaction in these quasicrystals is anti-ferromagnetic in nature [23]. The specific-heat measurements [23,28] suggest that these magnetic moments are coupled through RKKY type of indirect exchange interaction. The observation of small magnetization as compared to the total Mn concentration in these studies [22,23,24,26,27,28] along with the small value of Curie constant C, indicates a very low concentration of moments (~1% or even less) of all the Mn atoms being involved. There exist few other studies [29,30], according to which, Curie-Weiss law cannot account for the susceptibility data in case of Al-Pd-Mn quasicrystals. Their susceptibility as a function of 1/T, exhibits a continuous curvature. According to them the Kondo coupling between the localized moments and the conduction electron spins can explain the anomalous temperature dependence of the susceptibility. Few other studies [23,28] have shown the presence of spin-glass type of transition at low temperatures, indicating high degree of frustration present in the system. Nimori *et al.* [31] gave the cluster-glass type of picture of Al-Pd-Mn quasicrystals. They have suggested the formation of

ferrimagnetic clusters and have argued that the observed small magnetization as a result of this ferromagnetic ordering. Besides this, the study of magnetic properties of liquids in Al-Pd-Mn systems reveals a very strong increase of the susceptibility on melting [32]. These features were ascribed to the presence of magnetic moments on a large fraction of the Mn atoms in the liquid state. A similar change is observed in neutron scattering measurements, which indicate that localized magnetic moments appear on melting, and disappears in the solid state [32].

The origin of magnetism in Al-Pd-Mn quasicrystals has been widely debated. The moment formation has been shown to be affected by the pseudo-gap in the electronic density of states (DOS) at the Fermi level and also by the hybridization between Al *s-p* and Mn *d* states [33,34,35,36,37]. Spin-polarized band structure calculations on quasicrystalline Al-Pd-Mn models show that the formation of magnetic moments on Mn atoms is extremely sensitive to their local DOS and occurs only on a few Mn sites, which supports the observed low moment concentration [36].

1.3. Electrical Conductivity

In the series of Al-based stable quasicrystalline alloys, Al-Pd-Mn appears to be the most interesting. It has been investigated for its interesting electronic transport properties and reports have been published [22,24,27,38,39,40,41,42,43,44,45,46]. The resistivity $\rho(T)$ of the i-AlPdMn represents a special class amongst quasicrystals. It displays a maximum in $\rho(T)$ between 40K-130K [22,24,40,42,43] and sometimes an additional minimum at lower temperatures between 4K-25K [40,42,43] Such a peculiar behavior of $\rho(T)$ in Al-Pd-Mn quasicrystals is not yet well understood. The presence of Pd atoms along with Mn in this quasicrystalline system has made it more complicated and at the same time interesting also. There are many earlier studies [22,24,38,39,40,41], which, indicate that Pd plays the dominant role in the transport mechanism of Al-Pd-Mn quasicrystals. These studies have shown that the σ-T behavior can be well explained by strong spin-orbit scattering in the presence of Quantum Interference Effects (QIE's) giving rise to the weak anti-localization effect. As will be discussed in detail in following sections, these interpretations do not appears to be appropriate.

However, because of the presence of magnetic moments of Mn atoms, Al-Pd-Mn quasicrystals are magnetic in nature and the role of magnetic Mn cannot be neglected while explaining its transport properties. It may be the most dominant factor. K. Saito [27] *et al.* and S. Matsua [41] have shown that the $\rho(T)$ data gives a poor fit to the weak localization theory including only spin-orbit scattering. But the σ (T) data can be well accounted, below the σ-T minima temperature only, by weak localization theory, if spin scattering along with spin-orbit scattering is considered as the dephasing mechanism. Moreover, there exist few other experimental studies [22,24,29,40,42,46,47] that indicate a one-to-one correspondence between the temperature T_m of the $\rho(T)$ maximum and the concentration of the magnetic Mn moments, suggesting that $\rho(T)$ maximum could be purely a magnetic effect.

The occurrence of $\rho(T)$ minimum has been attributed to the magnetic scattering, i.e., Kondo-effect, since below ~10K, $\rho(T)$ rises very steeply following a lnT dependence [24,40,,48]. Occurrence of negative magneto-resistance [40] at 4.2K also indicates the presence of Kondo effect. C. R. Wang *et al.* [24] have shown that in the $\rho(T)$ curve, T_{min}, which corresponds to the temperature of $\rho(T)$ minimum, increases with increasing Mn concentration. This indicates that the