Temperature dependent tunneling spectroscopy in the heavy fermion CeRu\textsubscript{2}Si\textsubscript{2} and in the antiferromagnet CeRh\textsubscript{2}Si\textsubscript{2}

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Abstract

CeRu\textsubscript{2}Si\textsubscript{2} and CeRh\textsubscript{2}Si\textsubscript{2} are two similar heavy fermion stoichiometric compounds located on the two sides of a magnetic quantum critical phase transition. CeRh\textsubscript{2}Si\textsubscript{2} is an antiferromagnet below \(T_N = 36\) K with moderate electronic masses whereas CeRu\textsubscript{2}Si\textsubscript{2} is a paramagnetic metal with particularly heavy electrons. Here we present tunneling spectroscopy measurements as a function of temperature (from 0.15 to 45 K). The tunneling conductance at 0.15 K reveals \(V\)-shaped dips around the Fermi level in both compounds, which disappear in CeRu\textsubscript{2}Si\textsubscript{2} above the coherence temperature, and in CeRh\textsubscript{2}Si\textsubscript{2} above the Néel temperature. In the latter case, two different kinds of \(V\)-shaped tunneling conductance dips are found.

(Some figures may appear in colour only in the online journal)

1. Introduction

Heavy fermion compounds show different ground states, e.g. a paramagnetic (PM) Kondo lattice or antiferromagnetic (AF) Fermi liquid, with low critical temperatures that can be tuned by the application of pressure or magnetic field \([1–3]\). Thus, they are key references for zero-temperature quantum phase transitions. In particular, the so called magnetic quantum critical point (QCP) results when switching at zero temperature from AF to a PM phase at the critical pressure \(P_c\). The parameters needed to describe this transition are the Kondo temperature \(T_K\), the intersite magnetic correlations which appear below \(T_{\text{corr}}\), and the possible lift of the 4f angular momentum degeneracy by the crystal field splitting \(\Delta_{\text{CF}}\). In addition, quasiparticles at the Fermi surface acquire its low-temperature properties only when they are fully dressed below \(T_{\text{coh}}\). During the past three decades, many studies sensing macroscopic and microscopic aspects of these compounds have provided new information about the behavior of a large number of them, especially in 4f (Ce and Yb) and in 5f (U) intermetallic compounds \([1–3]\). However, heavy fermion compounds are usually complex metals with many bands crossing the Fermi surface, often giving ‘spaghetti’-like band structures (see \([4, 5]\) for CeRu\textsubscript{2}Si\textsubscript{2}). Quantum oscillation experiments on the Fermi surface demonstrate that heavy fermions coexist with light itinerant carriers. The topology of the Fermi surface is generally described well by band structure calculations \([5]\). However, the derived calculated effective masses are often one or two orders of magnitude smaller than those experimentally found in the areas of the Fermi surface with heavy quasiparticles \([4]\). It is now believed that a large number of interesting effects appearing in these compounds are intimately related to the Fermi surface with mixed heavy and light electrons, notably for Ce heavy fermion systems. Calculation methods have recently been improved and are able to deal in more detail with band structure experiments, and to help to understand atomic scale scanning tunneling microscopy (STM) \([6]\).
Figure 1. (a) Sketch of the location of CeRu$_2$Si$_2$ and CeRh$_2$Si$_2$ within the $T$–$\delta$ phase diagram of heavy fermions, where $\delta$ is the tuning parameter which describes the competition between the local Kondo effect and the magnetic intersite interactions. Néel ($T_N$) and coherence ($T_{coh}$) temperatures are sketched as dashed black lines. The insets are cartoons of the experiment, with an Au tip tunneling into a Kondo lattice (CeRu$_2$Si$_2$) and into an antiferromagnet (CeRh$_2$Si$_2$). (b) Possible band diagrams for tunneling processes between an Au tip into a system with localized Kondo levels (left panel), and into a Kondo lattice (right panel) at zero temperature. The predominant tunneling channel is represented by blue dashed arrows, and the interaction with quasilocalized states by reddish ones. The corresponding shape of the resulting tunneling conductance curves at $T = 0$ K is represented in the lower panels.

latter opens new perspectives, providing direct information about electronic band structure and correlations. Successful STM measurements have been reported in PrOs$_4$Sb$_{12}$ [7], PrFe$_4$P$_{12}$ [8], YbRh$_2$Si$_2$ [9], URu$_2$Si$_2$ [10, 11] and in CeRhIn$_5$ and CeCoIn$_5$ [12].

Our aim is to realize scanning tunneling spectroscopy in the two cerium tetragonal heavy fermion compounds CeRu$_2$Si$_2$ and CeRh$_2$Si$_2$, which are respectively in the PM and AF ground state [3, 13]. In figure 1(a) we schematically show the situation of both compounds in the phase diagram of heavy fermions in terms of the tuning parameter $\delta$, which describes the competition between the local Kondo effect and the magnetic intersite interactions. In these compounds, the intersite magnetic correlations prevail over the single-site Kondo effect. Furthermore, the crystal field splitting is strong enough to deal with cerium doublet levels. The properties of both compounds are very well documented, including de Haas–van Alphen measurements (see [4, 5] for CeRu$_2$Si$_2$ and [14] for CeRh$_2$Si$_2$).

CeRu$_2$Si$_2$ has a PM ground state and is close to a magnetic QCP. The electronic term in the specific heat, $C/T$, strongly increases when reducing temperature [3, 15, 16]. The Fermi liquid $AT^2$ law is found in the resistivity behavior only below $T_A = 1$ K [17]. Furthermore, the electronic Grüneisen parameter $\Omega_e(T)$ [18] has also a strong temperature variation at very low temperatures. At zero temperature, their respective extrapolations give $\gamma = (C/T)_{T\to0} \sim 350$ mJ mol$^{-1}$ K$^{-2}$, $A \sim 1$ $\mu$cm K$^{-2}$, $\Omega_e(T = 0$ K) $\sim +200$ and $T_{coh} \approx 9$ K. The QCP can be reached by increasing the unit cell size by doping with La or Ge, implying that it is located at a slightly negative pressure of
to the bare electron mass $m_0$. Effective masses range from $120m_0$ down to the bare electron mass $m_0$ [4].

Although the molar volume of CeRh$_2$Si$_2$ is smaller than that of CeRu$_2$Si$_2$ [23], the ground state of CeRh$_2$Si$_2$ is AF, with a rather high Néel temperature $T_N \sim 36$ K [13, 24]. The sublattice magnetization is also rather large ($M_0 \sim 1.3 \mu_B$) [25], generating a large molecular field. $C/T$ decreases on cooling, with a relatively small residual term $\gamma \sim 23$ mJ mol$^{-1}$ K$^{-2}$ [26, 27]. The Fermi liquid $AT^2$ term dominates the resistivity behavior already below 10 K, with $A \sim 1.4 \times 10^{-3} \mu\Omega$ cm K$^{-2}$ [28, 29]. The electronic Grüneisen parameter is negative, with $\Omega_e \lesssim -20$ [26, 30]. Specific heat and thermal expansion have sharp maxima at $T_N$. Fermi surface experiments show effective masses ranging from $6m_0$ to $0.36m_0$ [5, 14, 31]. CeRh$_2$Si$_2$ is a compensated metal with large carrier number, which is also the case for CeRu$_2$Si$_2$ and YbRh$_2$Si$_2$ [2, 32], and with moderately heavy and light electrons.

The effective mass of the heavy carriers scales with the magnitude of $\mathcal{g}$ and roughly with the width of $T_{coh}$. In the PM side of the QCP, the temperature $T_A$ below which the Fermi liquid $AT^2$ law is obeyed is far lower than $T_{coh}$. In CeRh$_2$Si$_2$, antiferromagnetism with a large $T_N$ is the result of a strong interplay between local Kondo fluctuations and magnetic intersite interactions, clearly enhanced by switching from Ru to Rh ions. The effect of pressure is magnified by the proximity to an intermediate valence regime associated with the inefficiency of crystal field splitting ($\Delta_{CF}$) when the Kondo temperature overpasses $\Delta_{CF}$. Antiferromagnetism disappears already below 1 GPa [14, 28–30].

The simple Doniach picture gives a Kondo temperature $T_K = 25$ K for CeRu$_2$Si$_2$ and $T_K = 50$ K for CeRh$_2$Si$_2$ [33, 34]. Specific heat and susceptibility measurements in CeRu$_2$Si$_2$ give a doublet crystal field ground state of Ising character located 200 K below the first excited level [15]. CeRh$_2$Si$_2$ also shows an Ising doublet crystal field ground state. Neutron scattering and susceptibility experiments suggest that the crystal field level is between 200 K and 600 K above the ground state [27, 33]. At first approximation, in the PM phase of Ce heavy fermion compounds, it is assumed that the Kondo temperature governs the high and intermediate temperature properties up to $T_K$ and that the intersite interactions will play a role only below a temperature $T_{corr} < T_K$. However, in CeRu$_2$Si$_2$, microscopic inelastic neutron scattering experiments [19] as well as macroscopic measurements [17] such as magnetoresistivity, give $T_{corr} \sim 60$ K; i.e., higher than $T_K$. Thus the appearance of a resonance due to the interplay between the initial localized 4f electrons and the light itinerant (s, p, d) electrons is already renormalized by the intersite interactions.

Tunneling into a system with localized states such as Kondo ions or electrons with differing associated bands does not follow simple single-particle tunneling theory [6, 9–11, 35, 36]. The tunneling conductance is not proportional to the density of states observed with macroscopic experiments, such as specific heat. Instead, it is the result of interference effects between the quasilocalized state, directly linked to the heavy carriers, and the light electron band, which couples to the tip’s light electron states [9–11]. A first approximation to account for multiparticle tunneling effects is to consider coherent tunneling through two interfering channels (figure 1(b)). The tunneling conductance can then be understood in terms of a Fano lineshape [37–41]. Depending on the dominance of each channel, from preferential tunneling into the quasilocalized states, to tunneling into the itinerant states, different shapes with different asymmetry, ranging from a peak into a dip, can be found in the tunneling conductance. As we show below, here we mainly observe a symmetric dip located at the Fermi level. Symmetric dips have been observed in tunneling experiments on single Ce adatoms [38], and they are interpreted as preferential tunneling into the itinerant electron channel, with a destructive interference to the quasilocalized ones, which reduces the conductance at the resonant level. Therefore, the tunneling conductance is given by an inverted Lorentzian function centered at zero bias voltage $g(V, T) = g_{off} + A \frac{\mathcal{g}^2}{1+(\frac{V}{\mathcal{g}})^2}$, where
The temperature evolution of the tunneling spectroscopy

Figure 3.

The experimental setup consists of a home-made STM in a Oxford Instruments MX400 dilution refrigerator with a positioning system which allows one to change the scanning window of 2 × 2 µm² in situ and without heating [42]. We use tips of Au, which are prepared and cleaned in situ as described in [43]. When taking measurements, bias voltage ramps are applied, and the tunneling current I is measured through the tip electrode, obtaining the tunneling conductance g(V, T) through a numerical derivative dI/dV. g(V, T) is normalized to the value obtained at a bias voltage well above 20 mV. Single-crystal samples of CeRu₂Si₂ and CeRh₂Si₂ were grown by Czochralski method as in previous work (see e.g. [13, 23]). We broke the samples along the basal plane of the tetragonal structure at ambient conditions immediately before mounting them on the STM and cooling them down. Samples with a bright and optically flat surface were selected. In general, we found surfaces with rather irregular shapes (figure 2) showing in some cases modulations at scales comparable to interatomic distances [44, 45]. Of course, some amount of surface contamination is unavoidable. In some particular cases, this could significantly influence tunneling features. The features discussed here are however reproducible, and the observed temperature ranges where they appear coincide with temperature ranges known from macroscopic measurements. Moreover, we have changed the scanning window using the macroscopic positioning system, and present results obtained over clean surfaces showing reproducible imaging.

3. Results and discussion

The tunneling conductance of CeRu₂Si₂ and CeRh₂Si₂ at 0.15 K reveals features consisting of a sharp V-shaped dip around zero bias voltage (figure 3). We find a different behavior in both materials. The V-shaped dip is wider for CeRh₂Si₂ than for CeRu₂Si₂. In CeRh₂Si₂ we find two differing characteristic behaviors, with deep and shallow minima at zero bias, both showing roughly the same width. The dip disappears at 9.5 K for CeRu₂Si₂, in good agreement with Tcoh measured with thermal expansion. It remains up to a higher temperature, 45 K, for CeRh₂Si₂ (figure 3). Fitting the conductance curves to the expression discussed above g(V, T) = g₀ + A \( \frac{(V - \epsilon_f)^2}{1 + (\frac{V - \epsilon_f}{\Gamma})^2} \), we obtain the parameters discussed in figures 4 and 5. Γ is the resonance width. g₀ and A are the zero bias voltage conductance and the amplitude of the dip, respectively. Both depend on the tip–sample wavefunction coupling and on the density of states of the sample at a given position. In figure 5 we show tunneling conductance curves for both compounds taken at different points of each sample surface, as well as the temperature dependence of the dip size g₀ and width Γ.

The fits of the tunneling conductance curves at the lowest temperature (0.15 K) give a larger width Γ for the dips observed in CeRh₂Si₂ (Γ₁(0.15 K) ≃ 5.5 meV) than in CeRu₂Si₂ (Γ₁(0.15 K) ≃ 4 meV). Moreover, in CeRh₂Si₂ the two characteristic behaviors observed at 0.15 K, with a shallow and a deep V-shaped dip, show roughly the same width Γ₂. The difference between both sets of curves is thus due to a different value of g₀.

In CeRu₂Si₂, g₀ changes with temperature only weakly, but Γ increases. In CeRh₂Si₂ we observe a temperature variation of g₀ which is different depending on the shape

\( \Gamma \) describes its width. This is equivalent to a modified Fano formula [37] with the asymmetry parameter \( q = 0 \) and the energy value where the resonance is centered \( \epsilon_s = 0 \). We take \( \Gamma(T = 0 \text{ K}) \) to be of the order of the width of the heavy band, which inversely scales with the electronic effective mass \( m^* \) of the carriers in the heavy fermion compound.

2. Experimental details

The experimental setup consists of a home-made STM in a Oxford Instruments MX400 dilution refrigerator with a positioning system which allows one to change the scanning window of 2 × 2 µm² in situ and without heating [42]. We use tips of Au, which are prepared and cleaned in situ as
Figure 4. Temperature evolution of the zero bias voltage conductance $g_{\text{off}}$ and the width ($\Gamma$) of the dips revealed in the tunneling spectra normalized to its lowest temperature value for (a) CeRu$_2$Si$_2$ and (b) CeRh$_2$Si$_2$ (triangles for the shallow dips and circles for the strong dips observed in the tunneling conductance curves shown in figure 3). Temperatures have been normalized to the corresponding coherence ($T_{\text{coh}} \sim 9.5$ K) and Néel ($T_N \sim 45$ K) temperature for each compound. In the bottom panels we show (lines) the Fermi liquid fit, using the normalized equation indicated in the text.

Figure 5. Histograms for $g_{\text{off}}$ and $\Gamma$ obtained after fitting tens of tunneling conductance curves to the inverted Lorentzian function discussed in the text, which were taken at several different temperatures and at different positions of the surface of (a) CeRu$_2$Si$_2$ and (b) CeRh$_2$Si$_2$. Lower panels show examples of the different tunneling spectra found at 0.15 K over the surface of (a) CeRu$_2$Si$_2$ and (b) CeRh$_2$Si$_2$.

of the curves. For the shallow dips, $g_{\text{off}}$ does not vary significantly with temperature, as in CeRu$_2$Si$_2$. However, for the deep V-shaped dips, $g_{\text{off}}$ strongly increases. $\Gamma$ increases with temperature similarly in both kinds of curves.

In both systems, despite the different values observed at low temperatures, $\Gamma$ increases similarly with temperature. We can compare the thermal evolution of both $\Gamma_1$ and $\Gamma_2$ with the Fermi liquid prediction for temperature broadening of $\Gamma'$. 
normalized to its zero temperature value, $\Gamma(T = 0)$, which can be written as $\Gamma(T)/\Gamma(0) = \frac{1}{2}(\pi T/\hbar)^2 + 1$ [46]. Here, we take $T^*$ as the temperature for which the V-shaped dip disappears in CeRu$_2$Si$_2$ ($T_{\text{coh}}$) and the Néel ($T_N$) temperature for CeRh$_2$Si$_2$. We observe that the thermal broadening of $\Gamma$ for both compounds roughly follows the Fermi liquid prediction (bottom panel of figure 4). Therefore, the thermal smearing of the tunneling features is only determined by the characteristic energy scales for each compound, which are given by the corresponding values of $\Gamma_1$ and $\Gamma_2$ at 0.15 K. Apart from the different energy scales obtained at the lowest temperatures, the temperature evolution of the tunneling features is roughly the same for CeRu$_2$Si$_2$ and CeRh$_2$Si$_2$.

The weak temperature dependence of $g_{\text{off}}$ observed in CeRu$_2$Si$_2$ is similar to the one observed in the thermal evolution of the tunneling spectra of URu$_2$Si$_2$ for temperatures above the hidden order transition [11]. In CeRh$_2$Si$_2$ we clearly find two different behaviors for $g_{\text{off}}$ at different positions, which also evolve differently with temperature. This shows that long range magnetic order affects the tunneling signal. In CeRh$_2$Si$_2$ two AF sublattices appear at low temperature [25]. Possibly, additional gap opening or other features can give different tunneling conductance curves on specific surfaces. This can be re-inforced by different behavior in the magnetic correlation lengths, as obtained in neutron scattering experiments. In CeRh$_2$Si$_2$, it will rapidly reach atomic distances on cooling (after its divergence at $T_N$) [47]. In CeRu$_2$Si$_2$, which is closer to the QCP, the magnetic correlation length increases smoothly on cooling being of a few atomic distances at very low temperatures [48]. Therefore, the Rh compound should be prone to show more local size surface dependent effects. It will be interesting to check the variations in the tunneling behavior when doping CeRu$_2$Si$_2$ with Rh [23], because it can unveil electronic features of magnetic interactions close to the quantum critical point.

4. Conclusions

In conclusion, we have measured the features in the tunneling conductance curves of two Ce-based heavy fermion compounds (CeRu$_2$Si$_2$ and CeRh$_2$Si$_2$) as a function of temperature. We find V-shaped dips which signal heavy band formation in CeRu$_2$Si$_2$ and an antiferromagnetically ordered phase in CeRh$_2$Si$_2$. The different temperature evolution of the observed zero bias V-shaped dips reflects the formation of different magnetic heavy fermion ground states.

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References

[1] Lohneysen H, Rosch A, Votja M and Wolfle P 2007 Rev. Mod. Phys. 79 1015
[2] Gegenwart P, Si Q and Steglich F 2008 Nature Phys. 4 186
[3] Floquet J 2005 Prog. Low Temp. Phys. 15 139
[4] Takashita M, Aoki H, Terashima T, Uji S, Maczawa K, Settai R and Onuki Y 1996 J. Phys. Soc. Japan 65 515
[5] Suzuki M and Harima H 2010 J. Phys. Soc. Japan 79 024705
[6] Haule K and Kotliar G 2009 Nature Phys. 5 796
[7] Soderow H, Vieira S, Strand J D, Bud’ko S and Canfield P C 2004 Phys. Rev. B 69 060504
[8] Soderow H, Behnia K, Guillamon I, Crespo V, Vieira S, Kikuchi D, Aoki Y, Sugawara H and Sato H 2008 Phys. Rev. B 77 153101
[9] Ernst S, Kirchner S, Krellner C, Geibel C, Zwicknagi G, Steglich F and Wirth S 2011 Nature 474 362
[10] Schmidt A, Hamidian M, Wahl P, Meier F, Balatsky A, Garrett J, Williams T, Luke G and Davis J C 2010 Nature 465 570
[11] Aynajian P, da Silva Neto E, Pargher C, Huang Y, Pasupathy A, Mydosh J and Yazdani A 2010 Proc. Natl Acad. Sci. USA 107 10383
[12] Aynajian P, da Silva Neto E, Gyenis A, Baumbach R E, Thompson J D, Fisk Z, Bauer E D and Yazdani A 2012 Nature 486 201
[13] Knafo W, Aoki D, Vignolles D, Vignolle B, Klein Y, Jaudet C, Villaume A, Prout C and Floquet J 2010 Phys. Rev. B 81 094403
[14] Araki S, Settai R, Kobayashi T, Harima H and Onuki Y 2001 Phys. Rev. B 64 224417
[15] Besnus M J, Kappler J P, Lehmann P and Meyer A 1985 Solid State Commun. 55 779
[16] Fisher R A, Marcenat C, Phillips N E, Haen P, Lapierre F, Lejay P, Floquet J and Voiron J 1991 J. Low Temp. Phys. 84 49
[17] Haen P, Floquet J, Lapierre F, Lejay P and Remenyi G 1987 J. Low Temp. Phys. 67 391
[18] Lacerda A, de Visser A, Haen P, Lejay P and Floquet J 1989 Phys. Rev. B 40 8759
[19] Knafo W, Raymond S, Lejay P and Floquet J 2009 Nature Phys. 5 753
[20] Kambe S, Floquet J and Hargreaves T E 1997 J. Low Temp. Phys. 108 383
[21] Quezel S, Burlet P, Jacaud I L, Regnault L P, Rossat-Mignod J, Vettier C, Lejay P and Floquet J 1998 J. Magn. Magn. Mater. 176 479
[22] Haen P, Bioul H and Fukutara T 1999 Physica B 259–261 85
[23] Aoki D et al 2012 J. Phys. Soc. Japan 81 034711
[24] Godart C, Gupta L C and Ravel-Krill M F 1983 J. Less-Common Met. 94 187
[25] Kawarazaki S, Sato M, Miyako Y, Chigusa N, Watanabe K, Metoki N, Koike Y and Nishi M 2000 Phys. Rev. B 61 4167
[26] Graf T, Thompson J D, Hundley M F, Movshovich R, Fisk Z, Mandrus D, Fisher R A and Phillips N E 1997 Phys. Rev. Lett. 78 3769
[27] Settai R, Misawa A, Arai S, Kosaki M, Sugiyama K, Takeuchi T, Kindo K, Haga Y, Yamamoto E and Onuki Y 1997 J. Phys. Soc. Japan 66 2260
[28] Aoki S, Nakashima M, Settai R, Kobayashi T C and Onuki Y 2002 J. Phys.: Condens. Matter 14 377
[29] Bourrier V, Villaume A, Lapertot G, Aoki D, Knebel G and Floquet J 2008 Physica B 403 726
[30] Villaume A, Aoki D, Haga Y, Knebel G, Bourrier V and Floquet J 2008 J. Phys.: Condens. Matter 20 015203
[31] Suzuki M 2012 private communication
[32] Knebel G, Aoki D, Brison J P and Flouquet J 2008 J. Phys. Soc. Japan 77 114704
[33] Severing A, Holland-Moritz E and Frick B 1989 Phys. Rev. B 39 4164
[34] Kawasaki Y, Ishida K, Kitaoaka Y and Asayama K 1998 Phys. Rev. B 58 8634
[35] Ternes M, Heinrich A and Schneider W 2009 J. Phys.: Condens. Matter 21 053001
[36] Hamidian M et al 2011 Proc. Natl Acad. Sci. USA 108 18233
[37] Fano U 1961 Phys. Rev. 124 1866
[38] Li J, Schneider W-D, Berndt R and Delley B 1998 Phys. Rev. Lett. 80 2893
[39] Madhavan V, Chen W, Jamneala T, Crommie M F and Wingreen N S 1998 Science 280 567
[40] Wahl P, Diekhoner L, Schneider M A, Vitali L, Wittich G and Kern K 2004 Phys. Rev. Lett. 93 176603
[41] Zhu J, Julien J, Dubi Y and Balatsky A 2012 Phys. Rev. Lett. 108 186401
[42] Suderow H, Guillamon I and Vieira S 2011 Rev. Sci. Instrum. 82 033711
[43] Rodrigo J G, Suderow H, Vieira S, Bascones E and Guinea F 2004 J. Phys.: Condens. Matter 16 R1151
[44] Raymond S, Rueff J P, Shapiro S M, Wochner P, Sette F and Lejay P 2001 Solid State Commun. 118 473
[45] Grier B H, Lawrence J M, Murgai V and Parks R D 1984 Phys. Rev. B 29 2664
[46] Schiller A and Hershfield S 2000 Phys. Rev. B 61 9036
[47] Flouquet J and Harima H 2012 Kotai Butsuri (Solid State Phys.) 2 47
[48] Regnault L P, Jacoud J L, Mignot J L, Rossat-Mignod J, Vettier C, Lejay P and Flouquet J 1990 Physica B 163 606