Hybridization and pressure effects in UTX compounds

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The UTX intermetallic compounds (T = transition metal and X = p-electron element) were found to crystallize mainly in two large groups, the orthorhombic TiNiSi and the hexagonal ZrNiAl structure. For both groups, magnetic-ordering phenomena depend sensitively on the 5f-ligand hybridization. The 5f-ligand hybridization is very sensitive to the interatomic distances, which can be effectively controlled by external pressure. Here, we have summarized existing and new pressure studies on various single-crystalline UTX compounds (T = Co, Ni, Ir; X = Al, Ga, Ge). We performed magnetoresistance studies in magnetic fields up to 18 T under external hydrostatic pressure up to 10 kbar. The observed dependencies of the ordering temperatures and the critical fields are compared with the different contributions of the 5f-ligand hybridization, which were deduced from tight-binding calculations. We find relatively weak pressure dependence in compounds, where 5f electrons are more localized, while substantially large pressure effects are found in the more itinerant systems. © 2002 American Institute of Physics. [DOI: 10.1063/1.1456432]

Uranium compounds have attracted a great deal of attention in the past two decades because of the specific nature of U 5f-electron magnetism. The f electrons of U are found to be intermediate between the delocalized d electrons of the transition metal and the well-localized 4f electrons of the lanthanide. Two mechanisms are known to lead to delocalization the 5f electrons, the direct 5f-5f overlap and the 5f-ligand hybridization. Comprehensive studies have revealed a large variety of magnetic phenomena starting from weak paramagnetism to various types of (sometimes unusual) long-range magnetic ordering depending on the degree of the 5f-ligand hybridization. Large 5f-ligand hybridization leads to a delocalization of the f electrons, which ultimately leads to a suppression of magnetic moments. On the other hand, in most cases some 5f-ligand hybridization is needed to promote interionic exchange, which confirms a magnetic order ground state. The 5f ligand hybridization depends on several parameters (geometrical surrounding of the 5f atom, coordination, interatomic distances, etc.), and it is determined by the overlap of the respective wave functions. The interatomic distances and thus the overlap of wave functions can be effectively changed by external pressure.

In this contribution, we have summarized the effect of external pressure on single-crystalline UTX compounds (T = Co, Ni, Ir; X = Al, Ga, Ge) studied to date. The compounds with X = Al or Ga crystallize in the hexagonal ZrNiAl structure, and the compounds with X = Ge crystallize in the orthorhombic TiNiSi structure. UCoGa, UIrAl, and UIrGa are ferromagnets at low temperatures, and UCoGe is a paramagnet. Antiferromagnetic ground states were established in UNiAl, UNiGa, UNiGe, and UIrGe, and UCoAl exhibits metamagnetic behavior at low temperatures. Our pressure studies have been limited to single-crystalline UTX compounds that exhibit antiferromagnetic or metamagnetic ground states.

Electrical resistance and magnetoresistance studies were performed in order to gain information on the pressure dependence of the magnetic-ordering temperature and critical fields, respectively. Most of our experimental studies (UNiAl, UNiGe, UIrGe) were done in the 20 T superconducting magnet at the Pulse Field Facility, NHMFL, Los Alas...
mos National Laboratory, under hydrostatic pressure up to 10 kbar using a Cu–Be pressure cell with mineral oil as the pressure-transmitting medium. The results on UlrGe are shown for the first time, while some of our results on UNiGe and UNiAl have been published previously. Here, we extracted the pressure gradients of the ordering temperatures \(dT_N/dp\) and the critical fields \(dB_c/dp\) as well as the critical pressure \(p_c\) (determined by an extrapolation of pressure to \(T_N=0\) K) for these three compounds and compared them with the published ones on UNiGa (Ref. 5) and UCoAl.\(^6,7\) Here, we are aware of the fact that the results on the values of \(p_c\) can be valid only under the assumption that the compressibility remains constant. In most of the \(d\) materials the compressibility varies (usually getting lower with increasing pressure). Therefore, we propose the values of \(p_c\) to be only a rough estimate for our materials. Direct measurement up to a higher pressure is desired to resolve this issue.

Our experiments on UlrGe were performed on a single crystal extracted from the same batch as used in previous studies.\(^8\) We performed temperature scans at various pressures in fixed fields and field scans at various pressures with fixed temperatures. As an example, we display the temperature dependence of the magnetoresistance at various fixed pressures of 6 kbar in Fig. 1. In Fig. 2, the low-temperature behavior of the electric resistance in UlrGe is shown for different values of pressure up to 9 kbar. We find that both \(T_N\) and the transition fields (see inset of Fig. 2) decrease slightly with increasing pressure. As an aside, we find that pressure seems to promote a less metallic ground state, i.e., the increase of the low-temperature resistance is more pronounced compared to the ambient-pressure result. This finding could explain the apparent differences in the temperature dependence of the electrical resistance for polycrystalline (metallic behavior below \(T_N\)) and single-crystalline UlrGe (increasing resistance below \(T_N\)). On the other hand, we find that there is no further enhancement of the low-temperature increase of the electrical resistance between 6 and 9 kbar. The curves are almost parallel with slightly lower resistance values in 9 kbar due to the suppression of \(T_N\). For UNiSn, it has been established that the ground-state properties can be altered by the application of relatively small strain fields.\(^9\) It is possible that internal strains also have strong effects in UlrGe. We speculate that internal pressure effects in single-crystalline UlrGe are needed to promote an increase in the low-temperature resistance. In polycrystalline UlrGe, on the other hand, grain boundaries may hamper the propagation of such internal pressure effects, which in turn results in a more metallic resistance behavior.

In Table I, we have summarized the ordering temperatures \(T_N\), the pressure rates \(dT_N/dp\), \(dB_c/dp\) and critical pressure \(p_c\) for various UTX compounds. By inspection of the values in table I, we find that \(dT_N/dp\) is larger in UlrGe and UNiAl compared to UNiGe and UNiGa, which can be taken as evidence that the 5f electrons are more delocalized in these two compounds. UCoAl has a metamagnetic ground state, thus there is no value for \(dT_N/dp\). From the values for \(p_c\), however, we may conclude that UNiAl is more localized

<table>
<thead>
<tr>
<th>Compound</th>
<th>(T_N) (K)</th>
<th>(dT_N/dp) (K/kbar)</th>
<th>(dB_c/dp) (T/kbar)</th>
<th>(p_c) (kbar)</th>
<th>Refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>UlrGe</td>
<td>14.5</td>
<td>-0.34</td>
<td>-0.06</td>
<td>48</td>
<td>this</td>
</tr>
<tr>
<td>UNiGe</td>
<td>41.5(^a)</td>
<td>&lt;-0.10</td>
<td>0.24</td>
<td>&gt;300</td>
<td>4 and this</td>
</tr>
<tr>
<td>UNiAl</td>
<td>17.1</td>
<td>-0.185</td>
<td>-0.062(^b)</td>
<td>105</td>
<td>3, and this</td>
</tr>
<tr>
<td>UNiGa</td>
<td>34.1(^a)</td>
<td>-0.11</td>
<td>0.04</td>
<td>&gt;300</td>
<td>5</td>
</tr>
<tr>
<td>UCoAl</td>
<td>20(^c)</td>
<td>0.27</td>
<td>24</td>
<td>6, 7</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Other transitions occur at slightly higher temperatures.
\(^b\)Derived from extrapolation of pressures below 1 kbar.
\(^c\)UCoAl forms a metamagnetic ground state.
than UIrGe and UCoAl, but more delocalized than UNiGe and UNiGa. While $dT_N/dp$ is negative for all compounds, surprisingly we find opposite signs in $dT_N/dp$ and $dB/dp$ in the two localized representatives, UNiGe and UNiGa. We believe that this originates from a delicate competition of ferromagnetic and antiferromagnetic interactions, which is also reflected by the presence of various magnetic phases in the $B$–$T$ phase diagrams of UNiGa and UNiGe.

In an attempt to discuss the pressure results more quantitatively, we have focussed onto the $5f$-ligand hybridization effects in these compounds. The hybridization causes a delocalization of the $5f$ electrons, but, since the spin polarization is conserved in the hybridization process, it also causes indirect exchange coupling between $5f$ moments. Using the tight-binding approximation, it is possible to get a qualitative and sometimes a quantitative estimate of the importance of the $5f$-ligand hybridization effects in the formation of the uranium magnetic moments.\(^\text{10,11}\) Band-structure calculations within the tight-binding formalism of different compounds have been introduced by Harrison and Froyen for the study of transition-metal compounds.\(^\text{12}\) Later on, they successfully generalized their approach to determine the interaction between $s$, $p$, $d$ and $f$ atomic orbitals.\(^\text{13,14}\) This method in fact a combination of Anderson linear muffin-tin orbital (LMTO) theory\(^\text{15}\) and the transition metal pseudopotential theory\(^\text{16}\) and gives as a result the second moment of the $f$-hybridization band, which can be used as estimate for the delocalization of the $U 5f$ electrons\(^\text{10}\)

$$\langle (E_k - v_f)^2 \rangle = \sum_{i} \frac{n_i}{2l_i + 1} \times \left( V_{ll'}^{2\uparrow\sigma} + 2V_{ll'}^{2\uparrow\uparrow} + 2V_{ll'}^{2\uparrow\delta} + 2V_{ll'}^{2\uparrow\phi} \right),$$

where

$$V_{ll'} = \langle \eta_{ll'} \rangle = \langle \hat{h} \rangle \langle m_i \rangle \left[ \sqrt{(r_{l,l'}^{2l_1^2 + 1} / r_{l,l'}^{2l_1^2 - 1})/d^{l_1^2 + 1}} \right]$$

are the general hybridization elements between two ions with radii at $r$ and $r'$ at distance $d$. The indexes are the angular moments $l, l'$ ($l = 0, 1, 2,$ and $3$ for $s, p, d,$ and $f$ orbitals) and the symmetry of the bond $m$ ($m = 0, 1, 2,$ and $3$ for $\sigma$, $\pi$, $\delta$, and $\phi$ bonds). $m_i$ is the mass of the electron, $n_i$ is the number of the nearest neighbors with orbital quantum number $l'$, and $\eta_{ll'}$ is the general hybridization which are given by:\(^\text{17}\)

$$\eta_{ll'} = \frac{(1)^{l_1 + 1} (l + l')! (2l)! (2l')!}{6 \pi 2^{l_1 + l'} l_1 l_1!} \times (-1)^{m_g} \left[ \frac{(2l + 1)(2l' + 1)}{(l+m)! (l-m)! (l+m)! (l-m)!} \right]^{1/2}.$$

We used the above formalism to calculate the different contributions to hybridization energy for the UTX compounds studied here. As can be seen in Table II, the $V_{ff}$ contribution is much smaller than the other contributions, which indicates $5f$-$p$ and $5f$-$d$ hybridization govern the magnetism in these compounds. For the ZrNiAl compounds, our data are in reasonable agreement with the results published in Ref. 10. Comparing Table II with table I, we find that $p_c$ and $dT_N/dp$ scale reasonably well with the total hybridization, ranging from the local-moment compounds UNiGa and UNiGe with lower total hybridization values, passing the more itinerant systems UIrGe and UNiAl, toward UCoAl that exhibits the largest degree of itineracy.

In conclusion, we have studied and summarized the effect of pressure on the ordering temperatures and critical fields of various antiferromagnetic UTX compounds by means of magnetoresistance studies in magnetic fields up to 18 T. The studies were performed on single crystals under hydrostatic pressure up to 10 kbar. By comparing the results with different contributions of the $5f$-ligand hybridization, which were deduced from tight-binding calculations, we find relatively weak pressure dependence in compounds, where $5f$ electrons are more localized, while substantially large pressure effects are found in the more itinerant compounds.

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TABLE II. Hybridization energy of UTX compounds. $V_{ll'}$ denotes the different types of contributions (see text). In the last column, the sum over all contributions is given.

<table>
<thead>
<tr>
<th>Compound</th>
<th>$V_{ff}$ (meV)</th>
<th>$V_{dd}$ (meV)</th>
<th>$V_{sd}$ (meV)</th>
<th>$(\Sigma V_{ll'})^{1/2}$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UIrGe</td>
<td>128.4</td>
<td>615.8</td>
<td>749.1</td>
<td>0.978</td>
</tr>
<tr>
<td>UNiGe</td>
<td>147.1</td>
<td>287.4</td>
<td>179.3</td>
<td>0.816</td>
</tr>
<tr>
<td>UNiAl</td>
<td>166.0</td>
<td>527.1</td>
<td>828.0</td>
<td>0.995</td>
</tr>
<tr>
<td>UNiGa</td>
<td>165.8</td>
<td>458.7</td>
<td>778.1</td>
<td>0.918</td>
</tr>
<tr>
<td>UCoAl</td>
<td>172.7</td>
<td>536.43</td>
<td>872.1</td>
<td>1.04</td>
</tr>
</tbody>
</table>


\(^3\)O. Mikulina et al., J. Appl. Phys. 87, 3152 (2000).


