A quantum phase transition seen from 0 to 600 K

We are accustomed to attributing phase transitions from an ordered state towards a disordered state to a temperature increase that agitates the atoms till the order is totally broken at a critical temperature T_c. However, this type of transition can also occur at strictly zero absolute temperature, when a parameter such as pressure or magnetic field or (in the case of an alloy) the proportion *x* of one component is varied. The "agitation" is now furnished by quantum fluctuations originating from Heisenberg's Uncertainty Principle, which allows the system to explore beyond its stability region. Such a transition is called a quantum phase-transition and the transition point is called the quantum critical-point. Quantum phase transitions have been studied previously only in systems with low values of T_c (<30 K). In fact, surprisingly, the effects of a quantum critical point can be visible up to arbitrarily high temperature in certain systems.

An interesting material to study in this respect is the alloy of the elements chromium and rhenium ($Cr_{1-x}Re_x$). Pure chromium is antiferromagnetic (*i.e.* it has an antiparallel ordering of neighbour atoms' magnetic moments) up to a critical temperature (called in this case the Néel temperature T_N) of 311 K. With 5-10% of rhenium added, it is antiferromagnetic up to temperatures as high as 600 K.

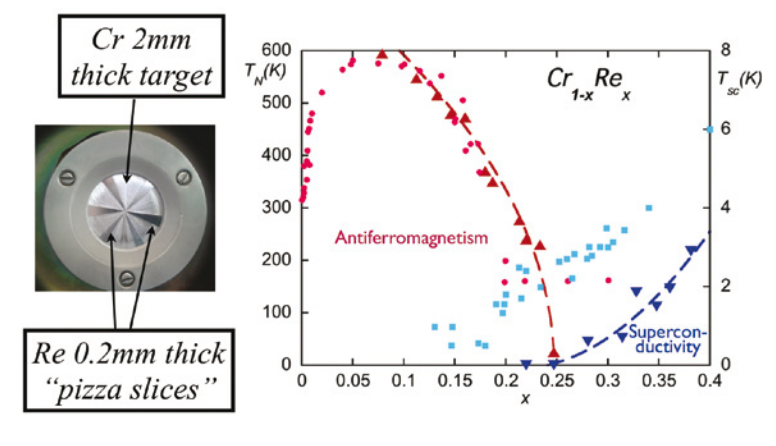

***Fig. 1 - Left Panel**: Compound sputtering target made of a bulk chromium disk and a thin rhenium foil. **Right panel:** Phase diagram of $Cr_{1-x}Re_x$ alloy as a function of Re content. Previous determinations of T_N are mauve circles. Our data are red triangles. The previously reported superconducting transition temperatures are shown (light blue squares) together with our data (blue inverted triangles). Our more homogenous samples show clearly that superconductivity does not coexist with antiferromagnetism, precluding a nonconventional superconductor. From 600 K down to the quantum critical point at 0 °K, x=0.248, the decrease of T_N follows the power law $718[(0.248 - x)/0.248]^{0.5}$.*

Another interesting property of these materials was reported 30 years ago: At very low temperature they are superconducting for concentrations *x* near the value 0.25 where the antiferromagnetic order disappears. Superconductivity has often been observed around a quantum critical point, but its origin remains mysterious even if quantum fluctuations are suspected to some extent.

Unfortunately, chromium evaporates at the melting point of rhenium, making it very difficult to manufacture chromium-rhenium alloys with accurately defined compositions: They tend to be uncontrollably Rhenium rich. We have circumvented this obstacle by using a sputtering (*pulvérisation*) technique. A plasma having the desired proportions of Cr and Re is generated by sputtering a combined target (see Fig. 1, left), and the plasma constituents deposit onto a substrate. Annealing and high temperature electrical resistivity measurements were done simultaneously in a fast optical furnace developed at the Institut NÉEL. Low temperature measurements were done in ^3He and ^4He cryostats.

As concerns the low-temperature superconductivity, we found that – contrary to the old data obtained with less well controlled samples – superconductivity appears only in the rhenium-rich region beyond the quantum critical point at x_c= 0.25. So that property is due to the addition of rhenium to the cubic crystal structure, and not to quantum antiferromagnetic fluctuations from chromium as has been suspected in the past.

Our low temperature measurements established the precise position of the quantum critical point for this alloy to be at x_c= 0.25. We found that the Néel temperature increased continuously from this critical point up to the highest obtained value of T_N =600 K, see Fig. 1. (The anomalous, old data for 160 K, red points in Fig. 1, are again clearly due to the limited quality of the alloys available at that time.) As a function of the alloying parameter x, the parameter T_N followed a power law with a 1/2 exponent, *i.e.* T_N is proportional to $(x_c - x)^{1/2}$. This power law is a defining characteristic of a quantum phase transition. It undoubtedly means that the quantum critical point, i.e. quantum fluctuations, control the transition to the antiferromagnetic phase all the way from *T*= 0 K to *T*= 600 K, a very unexpected result .

We have compared this Cr-Re alloy system to other alloy systems in order to understand why this material is affected by the quantum critical point up to such unusually high temperatures. Systems with long coherence lengths have a more usual exponential dependence far from the QCP, and the 1/2 power law installs itself only near to this point, while systems with short coherence lengths show a quantum-controlled behaviour at all temperatures.

Using the known dependences for T_c and coherence lengths, we have determined a general criterion for the crossover, as a function of an external parameter such as concentration, from the region controlled solely by thermal fluctuations to the region where quantum effects become observable. It shows that the properties of materials with low coherence lengths will be altered far away from the quantum critical points, up to unexpected high temperatures.

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FURTHER READING...

"Experimental consequences of quantum critical points at high temperatures"
D. C. Freitas, P. Rodière, M. Núñez, G. Garbarino, A. Sulpice, J. Marcus, F. Gay, M. A. Continentino and M. Núñez-Regueiro
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