# Superconductivity Dome around a Quantum Critical Point

**The interplay between ordered states and the superconductivity that develops when they are destabilized is central in the understanding of subjects as diverse as high temperature superconductors and quantum chromodynamics. In the case of the Heavy Fermion family of compounds, superconductivity develops in a region of the phase diagram enclosed by a dome-shaped boundary. Our measurements show that such "Domes" are not restricted to these antiferromagnetic compounds, but also appear in materials with totally different types of interactions. As a consequence, the theories claiming to explain superconductivity domes should be of universal character.**

A quantum phase transition is a transition from an ordered to a disordered phase (e.g. from a antiferromagnetic to a paramagnetic phase) that is not driven by temperature but by an external parameter, such as pressure, at $T = 0$. Such transitions are unusual, as they are caused not by thermal fluctuations but by quantum fluctuations rooted in the Heisenberg Uncertainty Principle. A huge amount of work on this subject has been done in Heavy Fermion compounds (a class of Rare Earth metal alloys). Intriguingly, very often these compounds develop superconductivity below a dome in their phase diagram, centred at the "Quantum Critical Point" (QCP) i.e. the point where their antiferromagnetic ordering disappears. This suggests that Quantum Critical Points play an important role in promoting superconductivity, e.g. by increasing the quasiparticle interaction.

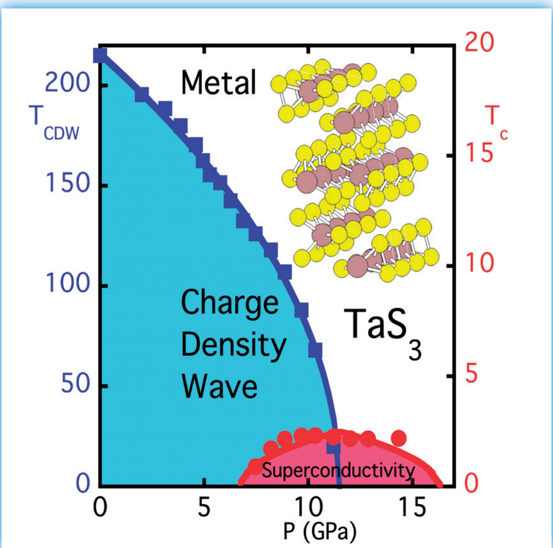


*Fig. 1 : Temperature-pressure phase diagram for o-TaS$_3$. The critical temperature $T_{CDW}$ for the Charge Density Wave phase (left hand y-axis) follows a mean-field power law. The superconductivity critical temperature $T_c$ (right hand y-axis) follows a dome-shaped boundary surrounding the Quantum Critical Point of the CDW phase transition at $P_c$ =11.5 GPa; thus superconductivity coexists with CDWs in a region below $P_c$. (In the linear crystal structure shown, brown and yellow spheres correspond, respectively, to the Ta and S atoms of o-TaS$_3$.)*

The physics of Quantum Critical Points has also been invoked to explain the high-$T_c$ superconductivity in copper-based high temperature superconductors even though a clear ordering under the superconducting Dome has not yet been identified. One possibility is that the important order in cuprates is of the Charge Density Wave (CDW) type (a type of 1 or 2 Dimensional ordering of the electronic density). It is thus of great interest to find clear examples where superconductivity coexists with CDWs, to provide model systems to study this interplay.

Within this context, we have studied the metallic, linear-chain compound Tantalum Trisulphide (o-TaS$_3$), which develops into an insulating, Charge Density Wave phase at $T_{CDW}$ =215 K. We have measured its electrical resistivity from 300 K down to 1 K over a wide range of pressures. These experiments have allowed us to analyze in detail its pressure-temperature QCP and to identify the coexistence of CDWs and superconductivity .

The data show the metal to insulator transition temperature $T_{CDW}$ decreasing monotonically with pressure, and the appearance of a superconducting state at critical temperature Tc under high pressure. Fig. 1 shows the evolution of these two transition temperatures with increasing pressure (note the two very different scales for $T_{CDW}$ and $T_c$). Unexpectedly, $T_{CDW}$ follows a mean-field type power law in the whole pressure range. In contrast, the superconducting phase develops under a dome, as found in the very different Heavy Fermion compounds.

In the field of Heavy Fermion systems, much discussion has been developed about the Dome and whether the superconductivity is due to the existence of a Quantum Critical Point. One hypothesis is that the carriers would forestall the intense critical fluctuations of the QCP by reorganizing themselves into a new stable phase of matter, i.e., superconductivity. On the contrary, in our case of a Charge Density Wave compound, it is natural to expect the appearance of superconductivity as the CDW phase disappears, since both are due to a conventional electron-phonon interaction. What is totally unexpected is the observed, dome-shape of the superconducting phase boundary. This suggests that something not taken into account by existing theories is occurring.

A hint is given by the fact that $T_{CDW}$ follows a power law with pressure, instead of the logarithmic law expected from the Bardeen-Cooper-Schrieffer (BCS) character of the CDW state. Near the Quantum Critical Point we are no longer in what can be called a "classical" BCS regime, but in a critical quantum regime, with different laws and special physics. Our experimental result stresses the fact that superconductivity "domes" are not restricted to Heavy Fermion systems, but also occur in entirely different materials. As a consequence, the laws governing the Domes are definitely very general, as should be the theories proposed to explain them.

## CONTACT


Manuel NUNEZ-REGUEIRO
manolo.nunez-regueiro@neel.cnrs.fr


### FURTHER READING


**Quantum critical point and superconducting dome in the pressure phase diagram of o-TaS$_3$**
M. Monteverde, J. Lorenzana, P. Monceau and M. Núñez-Regueiro
*Phys. Rev. B 88, 180504 (2013)*