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Possible Mechanism for Superconductivity in Sulfur—Common Theme for Unconventional Superconductors?

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Abstract

Sulfur has recently been found to be a superconductor at high pressure. At ~93 GPa T_c is 10.1 K, and the sulfur is in a base-centered orthorhombic (b.c.o.) structure. At ~160 GPa T_c is 17 K and sulfur is in a rhombohedral (β-Po) structure. The mechanism for superconductivity in sulfur is not known; in particular, a band-structure calculation does not find superconductivity in sulfur until 500 GPa. Following from work by Anderson, in a 2D strongly interacting, non-fermi liquid system with some degree of disorder at $T = 0$, the only known conducting state is a superconductor. Following this idea it has been suggested that both the HT_c cuprates and 2D electron gas systems are superconductors with planar conducting planes. Similarly, here we suggest that the mechanism for conductivity in sulfur are 2D conducting planes which emerge as the planar rings in sulfur at low pressure pucker at higher pressures (b.c.o. and β-Po). As well, we note some other consequences for study of HT_c materials of Anderson's work.

Recently Struzhkin *et al.* [1] have found that at high pressures sulfur becomes a superconductor. At low pressure sulfur is an insulator with a planar ring structure. Struzhkin *et al.* find that at ~93 GPa sulfur is a superconductor with T_c of 10.1 K. At this pressure sulfur adopts a base-centered orthorhombic (b.c.o.) structure [2] in which the planar rings are now puckered. At ~160 GPa Struzhkin *et al.* find T_c of 17 K. At this pressure sulfur is in a rhombohedral phase (β-Po structure) [3] which also features puckered rings. The mechanism for superconductivity of sulfur is not completely well understood. Indeed, Struzhkin *et al.* note that using band-structure calculations of electron-phonon interactions Zakharov and Cohen [4] found sulfur to be superconducting above 550 GPa, but not at the much lower pressure in which superconductivity was found experimentally. Here we suggest that similarly to proposed mechanisms

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of superconductivity in copper oxide materials, and 2D electron gases at low temperatures [5], (which mechanisms we grant themselves are controversial), is due to conduction in 2D planes, which, in the case of sulfur emerge in puckered rings Fig. 1.

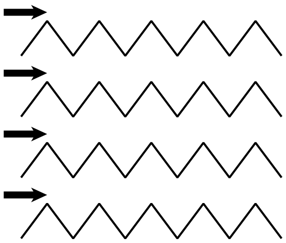

Figure 1: Emergent potential conducting planes in sulfur at high pressure. In this highly schematic figure vertices represent sulfur atoms and lines bonds between the atoms. There are more rows of atoms both in the plane of the paper and in a plane perpendicular to the paper going into the paper. The direction of conduction is indicated by the arrow and the proposed 2D conduction plane is perpendicularly going into the paper. Notice that the proposed conduction plane emerges due to the puckering.

Philips *et al.* [5] seizing upon recent experimental observations [6, 7] finding that in a number of systems 2D electron gases at low temperature are conductors, in contradiction to theory which predicted the electron gas to be an insulator, suggested that not only is the electron gas a conductor, but a superconductor. They provide a number of arguments to support this notion including the features of the transition from insulator to conductor in the electron gas system being reminiscent of an insulator-superconducting transition; there exists a critical magnetic field above which conductivity is destroyed; and the insulating-conducting transition is near an electron crystal state in which large charge retardation effects could possibly lead to Cooper pairing. Furthermore, with reference to a classic paper written by Anderson [8], they note that in 2D at T=0 the only known conducting non-Fermi liquid state in the presence of disorder with zero magnetic field, is a superconductor. In general Anderson's paper [8] emphasizes that often in the presence of some disorder, a superconducting state can be more stable and less likely to be abolished than other conducting states. High pressures may configure sulfur into such a strongly interacting non-Fermi liquid state with emergent planes. A similar mechanism may explain superconductivity in oxygen at high pressure [9]. Experiments consistent with this idea would include the finding of conduction preferentially in the direction indicated in the figure.

The application of the idea of Anderson's paper to unconventional superconducting materials has a number of current and future applications: (1) It has recently been reported that T_c can nearly be doubled in certain superconducting perovskites by making thin films of the material under epitaxial strain [10]. This result may be hard to explain by theories proposing a single mechanism responsible for pairing in the superconducting state. However, assuming, at least *in arguendo* that 2D planes are important for superconductivity in these materials, this result is much easier to understand from the perspective of Anderson's paper: Perhaps there are a number of different contributions to the pairing mechanism, but regardless of the nature or number of such contributions, T_c in a conducting (and thus superconducting) material will rise proportionally to a reduction in the localizing ability of the host state which is accomplished by growth of a material under epitaxial strain. (2) Theoretically and computationally it might be useful to try to find strongly interacting non-Fermi liquid systems which are not superconductors in the presence of some disorder, to help steer experiments from non-productive paths. As well, it would be helpful to try to find other general classes of geometries or materials which are strongly interacting non-Fermi liquids and possible conductors. (3) Experimentalists should appreciate that, especially when studying systems which are predicted to be insulators, if a material is a conductor, it might be a superconductor. As well, it might be possible, for example in 2D systems, to screen large numbers of materials looking for conductors.

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