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SUPERCONDUCTIVITY IN THE ACTINIDES

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ABSTRACT

The trends in the occurrence of superconductivity in actinide materials is discussed. Most of them seem to show simple transition metal behavior. However, the superconductivity of americium proves that the f electrons are localized in that element and that "actinides" is the correct name for this row of elements. Recently the superconductivity of UBe_{13} and UPt_3 has been shown to be extremely unusual, and these compounds fall in the new class of compounds now known as heavy fermion materials.

Superconductivity in actinide elements, alloys, and compounds has an interesting parallel to the history of actinides. Forty years ago the actinide elements were thought to belong to the d-electron transition metal series, and Th, Pa, and U were placed under Hf, Ta, and W in the periodic table of the elements. For the majority of approximately 200 known actinide-containing materials that are superconducting, the actinides can quite reasonably be treated as transition metals [1]. Indeed, B. T. Matthias never did move the actinides to their modern position in the version of the periodic table that he used to show the occurrence of superconductivity. Perhaps the prettiest demonstration of this point of view is that for Ti alloys containing 10 to 35 at.% of Cr, Mo, W, and U, there occur almost identical maxima in the superconducting transition temperature at around 17 at.% impurity [2]. Clearly all four elements can be considered as hexavalent transition metals.

However, since Seaborg's suggestion of the actinide elements as a 5f-electron series, we have had the modern version of the periodic table. In fact it was the superconductivity of Am that finally convinced Zachariasen that the actinide series settled down to trivalency, just as do the lanthanides. Americium is superconducting because its six 5f electrons are completely localized, and that makes it precisely non-magnetic [3]. This consideration then requires three valence electrons because any other number would lead to a magnetic ground state, which is easily observed and which would suppress superconductivity.

Until rather recently, the most important development in superconductivity (and magnetism) of the actinides was the Hill plot [4].

Fifteen years ago at the Pu 1970 conference in Santa Fe, Hill (as he liked to say) brought order to superconductivity and magnetism of the actinides in the first talk. Previously transition metal- or lanthanide-like behavior (that is, superconductivity or magnetism) seemed to occur randomly in metallic actinide materials. He showed that this decision towards a particular ground state depended only upon the spacing of the actinide atoms. If they were closer than a critical spacing: *f*-electron bands developed; the *f* electrons were bonding; and superconductivity could occur. If the spacing were larger: the *f* electrons tended to localize; magnetic moments could occur; and the ground state could be magnetism. All of this was true for almost any nearest-neighbor atoms. This could be expressed in a Hill plot where actinide spacing is displayed versus ordering temperature. Thus the switch from transition metal to lanthanide behavior could be followed, and predictions made for superconductivity versus magnetism [5].

The most noticeable exceptions on the Hill plots were many compounds with large actinide atom spacings that did not become magnetic. At the time this was recognized to be due to an *f* band formation caused by hybridization with electrons on intervening atoms. Recently superconductivity was discovered in two of these compounds with large actinide spacings, UBe_{13} [6] and UPt_3 [7]. This was simply not understandable by current thinking and this fact alone suggests that the superconductivity could be of a new type. These compounds are now referred to as heavy fermion superconductors following the use of the term for a few Ce compounds. The word heavy arises because the *f*-electron energies occur in such a narrow

band at low temperatures that correlation effects give rise to an electron effective mass at least 100 times as heavy as a free electron.

It is also now clear that magnetism or states of no long range order can occur in other, equally heavy compounds [8]. These compounds all represent a new ground state for metals, one with extremely narrow energy bands. Many theoretical questions have been raised about how such a state can form and about the nature of the superconductivity [9]. However for actinide experimentalists there is much work to do to make more compounds and more measurements.

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