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Epilogue: Superconducting materials past, present and future

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ABSTRACT

Experimental contributors to the field of superconducting materials share their informal views on the subject.

Introduction from the editors

As a closing to this Physica C Special Issue on superconducting materials, dedicated to Ted Geballe on the year of his 95th birthday, we invited selected experimental contributors to the field to share their views on the subject, suggesting that the tone of their contribution be informal, and giving them the following guidelines:

"We suggest that you consider sharing your views on one or more of the following: (i) how the materials class(es) on which you have done experimental work fit in the larger picture of superconducting materials presented in this Special Issue, (ii) your views on any of the classes of materials and their interrelationships, (iii) what are the key unsolved questions in superconducting materials, (iv) what is the most promising route to high T_c, (v) what (if anything) should be done differently from the way it has been done to date, (vi) what you expect or hope the future will bring, e.g. whether and when we will have room temperature superconductivity, and (vii) anything else you would like to say on this topic."

Some of the writers are authors of papers in this Special Issue, others are not. Below are their responses. We hope these unique perspectives from long-time major experimental contributors to the field will be of interest to the reader and a source of inspiration to students and researchers.

Paul Chu

Superconductivity with impacts going far beyond condensed matter physics has lured many of the best and the brightest minds in physics ever since its discovery in 1911. It has created numerous heroes while also humbling many. Although our theoretical understanding of superconductivity in some materials, especially those with high transition temperatures, is still evolving, the experimental properties of superconducting materials have stood a much better test of time. The publication of the Physica C Special Issue on superconducting materials is most timely in view of the recent accelerated development of the field. It is most appropriate to dedicate this Special Issue to Ted Geballe on the year of his 95th birthday for his life-long contributions to superconductivity.

This Special Issue on superconducting materials by Physica C is unique. It is all-encompassing and authored by foremost active practitioners in the field. It summarizes all superconducting materials we know to date: from simple elements to complex compounds, and from conventional to nonconventional superconductors. It even includes the so-called unidentified superconducting objects with unstable and irreproducible superconducting signals. It will serve as a great resource book for experimentalists and theorists, experts and amateurs, and veterans and beginners.

From these seemingly voluminous results accumulated, similarities and differences between different families of superconductors have been drawn, various models have subsequently been

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proposed and further experiments have been suggested to unravel the common origin for superconductivity with high transition temperature. Unfortunately, a commonly accepted microscopic theory remains elusive, leading scientists to ponder: Are we asking the right questions? Are we on right track to getting the right information? Is it possible that high temperature superconductivity is like the common cold with more than one common cause? Is the differentiation of superconductors into different categories with an implied difference in their superconducting mechanisms proper? The most recent report of detection of conventional electron–phonon mediated superconductivity up to 190 K in H_2S under ultrahigh pressures appears to have raised serious challenges to our present understanding in high temperature superconductivity, if proven. At the same time, it reinforces the belief of practitioners in superconductivity that the field is vast and bright, and that more excitements are yet to come.

Issac Asimov once said the content of the future is what people are most insecure about. Indeed, we may not yet know enough about the future superconductors, especially the room temperature superconductors, to ask the right questions to find them. However, we have learned from history that as long as physics does not say it will not happen, it will happen-superconductors at higher temperature will be discovered and new heroes will be found.

Paul Canfield

After roughly 30 years in this field, I think that the best form to summarize my thoughts about new superconducting materials is the limerick. Basically, if you cannot find humor in our fumbling about, then I fear the only alternative is insanity.

History:
Back in the day, superconductivity was rare.
About elements and simplicity you'd care.
  Now most material classes,
  Including oxides and spin glasses,
Go super without any fanfare.

Conventional superconductors:
For traditional T_c's to reach high,
Look for banding that's σ or π.
  Use elements light,
  And bonding that's tight,
And hope critical currents won't die.

High T_c superconductors:
So copper and iron are done,
Now, cobalt or nickel'd be fun.
  While the search must be agile,
  Look for moments quite fragile,
And dimensions of two rather than one.

Bob Dynes

Reflections... and projections

I grew up scientifically just after the BCS theory of superconductivity. In that famous work and in the period following it, the quantitative verification of the role of the time-retarded, electron–phonon interaction as the mechanism responsible for the pairing of the electrons leading to the condensation into the superconducting state was a theoretical and experimental triumph. First-principles interactions described the variation of T_c over a wide range of materials and experiments (tunneling, infrared, heat capacity, ultrasonic, optical light scattering, magnetic properties, electrical and thermal conductivity, NMR and others). We could describe the known phenomena very well inside the BCS framework with no real exceptions. From our knowledge, experience and confidence, we projected that no superconductor with a T_c greater than 30 K would be found.

A variety of new classes of materials were subsequently found by experimental chemists, physicists and material scientists beginning with the cuprates and followed by Fe based, B based and other compounds. They could not have been predicted based on our (we thought thorough) understanding. We tried to force-fit these materials into our existing understanding (BCS and electron–phonon) and it just did not work. A more generic model of pairing which includes the electron–phonon interaction but not exclusively will come. There have been many already described but the sense of triumph after BCS and the electron–phonon interaction is still awaiting. Many of us (me included) keep searching. I look forward to that event when it happens.

Zachary Fisk

One take on superconductivity is that it shows up to solve some problem in a material's electronics: good metals without problems such as Ag and Au are in general not superconductors. The cuprates and pnictides descend from compounds whose prototype compositions make "valence" sense and whose charged layer stacking facilitates introducing carriers. This situation is significantly different from what one finds with most metallic materials where valence is not a particularly useful concept.

In the vicinity of this "valence" border the materials show a variety of low temperature behaviors that suggest, loosely speaking, problems the materials are having taking care of the degrees of freedom coming from the free carriers. These carriers are interacting with a background valence bond structure which seems closer to localized chemistry than free electron physics. From this angle one sees the occurrence of superconductivity as diagnostic of a tension between bonds and bands.

Bertram Batlogg

Phase-diagram-superconductors

While it has become convenient to classify superconductors by the order parameter symmetry or the pairing mechanism as conventional or unconventional, an alternative view of capturing the fascination of superconductors is to realize that many are phase-diagram-superconductors. As an external parameter is tuned, the superconducting ground state forms next to a different electronic ground state: Mott–Hubbard insulator in layered cuprates or spin-density-wave in iron-chalcogenides/pnictides. One of the earliest examples of other electronic instabilities is found in the bismuthate group with perovskite-related structures and transition temperatures above 30 K. Here, a modulation of the charge on the Bi site forms, related to the valence skipping tendency of Bi. A common tuning parameter is the variation of the electron count by aliovalent substitution or by intercalation, and straining the samples by external or chemical pressure can also be a powerful method to map out the phase diagram. The challenge then is to identify the underlying interactions and how the superconducting state emerges.