Probing Room Temperature Superconductivity

In A Parallel, Wiser Universe:

Metaphysical Considerations

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Acknowledgment to: Neil Ashcroft
Room Temperature
Superconductivity ND'05
“Matthias’s Rules” for High $T_c$

- 1. Must have d electrons (not just s-p, nor f)
- 2. High symmetry is good, cubic is best
- 3. Certain electron concentrations are favored
- (peak in density of states at Fermi level)

McMillan (1968)

Fig. 10. The theoretical band structure density of states versus energy for tungsten according to Matthias (Ref. 25), together with the empirical (solid-dashed) data for the bcc 5d alloys from Tables III and VI.
Advances in the Critical Temperature
Bruce Friday: **Look on the Bright Side**

![Graph showing the critical temperature (Tc) versus time with a trend line and data points for various materials. The graph includes labels for Pb, Hg, V3Si, NbN, NbC, Nb3Sn, and Nb3Ge. The y-axis represents the maximum critical temperature (K) and the x-axis represents the year ranging from 1910 to 1980. The graph indicates a 2.8 degrees per decade increase. The text on the graph mentions that Tc = 300 in year 2950.](image-url)
“Nitride Offers 30 K Transition?”

MoN: much stronger coupled than Nb(C,N) \([T_c = 17 \text{ K}]\)

“Elastic constants of NbC and MoN: instability of B1-structure MoN.”
Chen, Boyer, Krakauer, Mehl, PR B (1988)

Groups managed to achieve \(T_c = 17 \text{ K}\) in MoN\(_{1-x}\), \(x = 0.9\)

Room Temperature
Superconductivity ND'05
Akimitsu’s Discovery: 2001

MgB$_2$, a common chemical reagent.

Searching for ferromagnetism, superconductivity at $40\ \text{K}$ was discovered.

Quickly reproduced and synthesis techniques were extended by several groups.

Crystal structure is simple. Quasi-2D.

Electronic structure is simple: s-p electrons.

Nagamatsu, Nakagawa, Muranaka, Zenitani, and Akimitsu, Nature 410, 63 (2001)
Four Months Later: Puzzle Solved!

1. MgB$_2$: covalent bonds become metallic
2. Deformation potential $D=13$ eV/Å (amazingly large for a metal)
3. 2D (cylinder) Fermi surfaces focus strength
4. Yet structure remains stable: intrinsic covalency


……more…….
**Prediction of a “better MgB$_2$”: Li$_{1-x}$BC**


Structurally, chemically, similar to MgB$_2$
Semiconductor, so hole-doping is required (de-intercalation of Li)
Deformation potential **50% larger** than MgB$_2$
$T_c = 75$ K might be realistic estimate

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**Not so simple!**

Several reports of inability to prepare Li$_{1-x}$BC

Reports that Li$_{1-x}$BC is not superconducting:
Fogg, Claridge, Darling, Rosseinsky (2003)

But the Li$_{1-x}$BC samples are not well characterized.
Superconducting diamond turns up in Russia

31 March 2004

Physicists at the Russian Academy of Sciences are claiming to have created a form of diamond that superconducts. Vladimir Sidorov and colleagues say that their material, which they made by doping carbon with boron at high temperatures and pressures, exhibits bulk superconductivity below around 4 kelvin and remains a superconductor in strong magnetic fields (E A Ekimov et al. 2004 Nature 428 542). This is the first time that boron-doped diamond -- which is normally a semiconductor -- has shown superconducting behaviour.

\[ T_C = 8 \text{ K} \]

Boeri, Kortus and Andersen, PRL 93, 237002 (2004)
Xiang, Li, Yang, Hou, Zhu, PR B 70,212504 (2004)
Blasé, Adesssi, Connetabable, PRL 93, 237004 (2004)
G. Baskaran, cond-mat/0404286.

Room Temperature
Superconductivity ND'05
Heavy vs. Light Elements

“McMillan’s equation”

\[
T_c = \frac{\langle \omega \rangle}{1.20} \exp\left(-\frac{1.04(1 + \lambda)}{\lambda - \mu^* (1 + 0.62 \lambda)}\right)
\]

Lighter elements can be favorable for raising the critical temperature

\(\text{MgB}_2\): light metal atom, lighter metalloid

Ashcroft (1962----)

Room Temperature
Superconductivity ND'05

Cristina Buzza ¹,² and Kevin Robbie ¹,²

2001-2003: a Paradigm Shift

- What is possible regarding strong coupling in el-ph coupled s-p electron superconductors
- Two-gap superconductivity: a new form of extreme anisotropy

.....in this universe....
MgB$_2$ in 1957

Canfield (2003)
In another universe, developments paralleled those in our universe up to 1957. In that universe, however, Robinson Swift and David White recognized the superconductivity in MgB$_2$, and the two universes went their separate ways………

Through means to be described elsewhere,[1] some of the subsequent developments in this universe have been uncovered….

1955 $T_c = 18$ K in Nb$_3$Sn

1957 BCS theory

1958 Matthias’s rules: d electrons; high DOS, symmetry is good, cubic is best

1957 BCS theory
Swift & White: $T_c = 40$ K in MgB$_2$

1958 Swift&White rules: s-p electrons are best; DOS is not important; layers are fine

1960 A15 research ramps up (no increase in $T_c$ is found)

1960 Emphasis moves to light atoms; A15 research is cut dramatically

1962 N. Ashcroft predicts $T_c > 100$ K in metallic hydrogen

1962 N. Ashcroft predicts $T_c > 100$ K in metallic hydrogen

1963 A15 research intensifies ………

1963 Intercalated graphite (structural similarity to MgB$_2$) studied, $T_c$ up to 5 K
### Our Universe

1964 W. Little presents case for excitonic sc’y in organic polymers

1966 Structural instabilities in A15s attract much interest and study

1968 Tunneling studies of A15 compounds are hampered by materials difficulties

1970 $T_c = 21$ K in Nb$_3$(Al,Ge). Wow!

1972 BCS win Nobel Prize (Physics)

### That Universe

1964 Polymeric (BeH)$_x$ synthesized, black and flubberlike; has $T_c = 55$ K but transforms to an insulator at 40 K

1966 LiBC, isostructural and isoelectronic to MgB$_2$, is synthesized

1968 LiBC is hole-doped electrochemically, $T_c = 94$ K is achieved

1970 Hexaboride (H$_2$)$_x$B$_6$, 5<x<7, is synthesized; $T_c = 70$ K

1972 BCS win Nobel Prize (Physics)

S&W win Nobel Prize (Chemistry)
Our Universe

1974 $T_c=23.1$ K achieved in Nb$_3$Ge
Disallusionment with A15s settles in
B. Friday tries to encourage with $T_c(t)$

1975 Allen-Dynes theory: there’s not really
any limit to $T_c$, except stability

1978 Theorists argue that structural
instabilities limit $T_c$ to less than 30 K

1986 Ferroelectricity experts Bednorz and
Mueller find $T_c=30$ K in (La,Ba)$_2$CuO$_4$

1987 APS March Meeting “Woodstock
Session” lasts until 5 AM.
Now $T_c = 93$ K in YBa$_2$Cu$_3$O$_7$ (Chu)

Room Temperature
Superconductivity ND'05

That Universe

1975 Mao and Bell achieve Mbar
pressure in Li, find $T_c=20$ K

1978 $T_c=98$ K in Li$_2$H$_3$BeB$_4$
(light atoms, covalent bonding)

1982 Metastable LiBeN$_3$ (perovskite)
becomes ferroelectric at 540 K, then
transforms to sc’ing at 235 K. Current
flow charges the samples, then kills sc’y.
Current relaxes, FE state returns, then
sc’y…. Over and over, at rate of 38 GHz
Æ 3K (temperature units). Interstellar
LiBeN$_3$ becomes the prime candidate for
the cosmic 3 degree background.

1986 Ferroelectricity experts Bednorz and
Mueller find $T_c=30$ K in (La,Ba)CuO$_4$.
Reproducible, but samples are messy and
uninteresting, and are discarded
**Our Universe**

2001 Akimitsu discovers $T_c=40\text{ K}$ in MgB$_2$. APS “Woodstock II” lasts until 2 AM.

2003-4 Three groups find $T_c=18-20\text{ K}$ in Li around 400 kbar

**That Universe**

1996 Superconducting SuperCollider completed on schedule, thanks partly to $600\text{ M}$ saving from HTS (Li$_x$BC) technology at LN$_2$ temperature (77 K)

2005 Janko and collaborators announce an entirely new compound that superconducts at 302 K, it is... **patent pending**...
Insight from a Great Metaphysicist

“There is no question there is an unseen universe. The question is: how far is it from midtown, and how late it is open?”

Woody Allen
Summation

MgB$_2$ introduced a new paradigm in strong-coupling superconductors

[45 years later than it should have]

[A$_3$C$_{60}$ ($A =$ alkaline metal K, Rb, Cs), $T_c$ up to 40 K, represents another new paradigm (vaguely related, but clearly different)]

Great leaps in superconductivity seem to require new paradigms

What we ‘know’ is limited by what we have not yet discovered

What we are, and what we do now, is determined by when we discover it as well as what we discover