REMARKS ON THE PRESENT AND FUTURE OF CONDENSED MATTER PHYSICS

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THE PROGRESS OF CONDENSED-MATTER PHYSICS: A SERIES OF (MINI-) PARADIGM SHIFTS?

T. S. Kuhn (The Structure of Scientific Revolutions, 1962):

old paradigm	→	paradigm shift	→	new paradigm
("normal" science)		(scientific revolution)		("normal" science)

(examples: Copernicus, SR, QM ...)

Dictionary definition of Paradigm Shift:

(Merriam-Webster): an important change that happens when the usual way of thinking about or doing something is replaced by a new and different way.

(Cambridge): a time when the usual and accepted way of doing or thinking about something changes completely.

in a scientific context, the paradigm determines

- what are the legitimate/interesting questions
- what kinds of answers to them are allowed
- what kinds of evidence may be adduced

Revolutions in CMP: mostly "velvet"? (old ideas stay around, but no longer shape the field)

WHAT WERE THE PARADIGM SHIFTS 1955 – 2023?

1. Landau Fermi-liquid theory (1956)
   don't even try to calculate from first principles, rather try to relate different physical properties of given system.

2. BCS theory (1957)
   try to identify crucial physical effect (in this case, phonon-induced attraction) and encapsulate in effective low-energy Hamiltonian

3. Renormalization group approach to 2nd – order phase transitions (1963-71)
   universality, broken symmetry
   (L. P. Kadanoff: "The practice of physics has changed… going from solving problems to discussing the relationship between problems")

4. Fractional quantum Hall effect (1983)
   quasiparticles (e.g. anyons) whose character bears no relation to underlying particles or waves

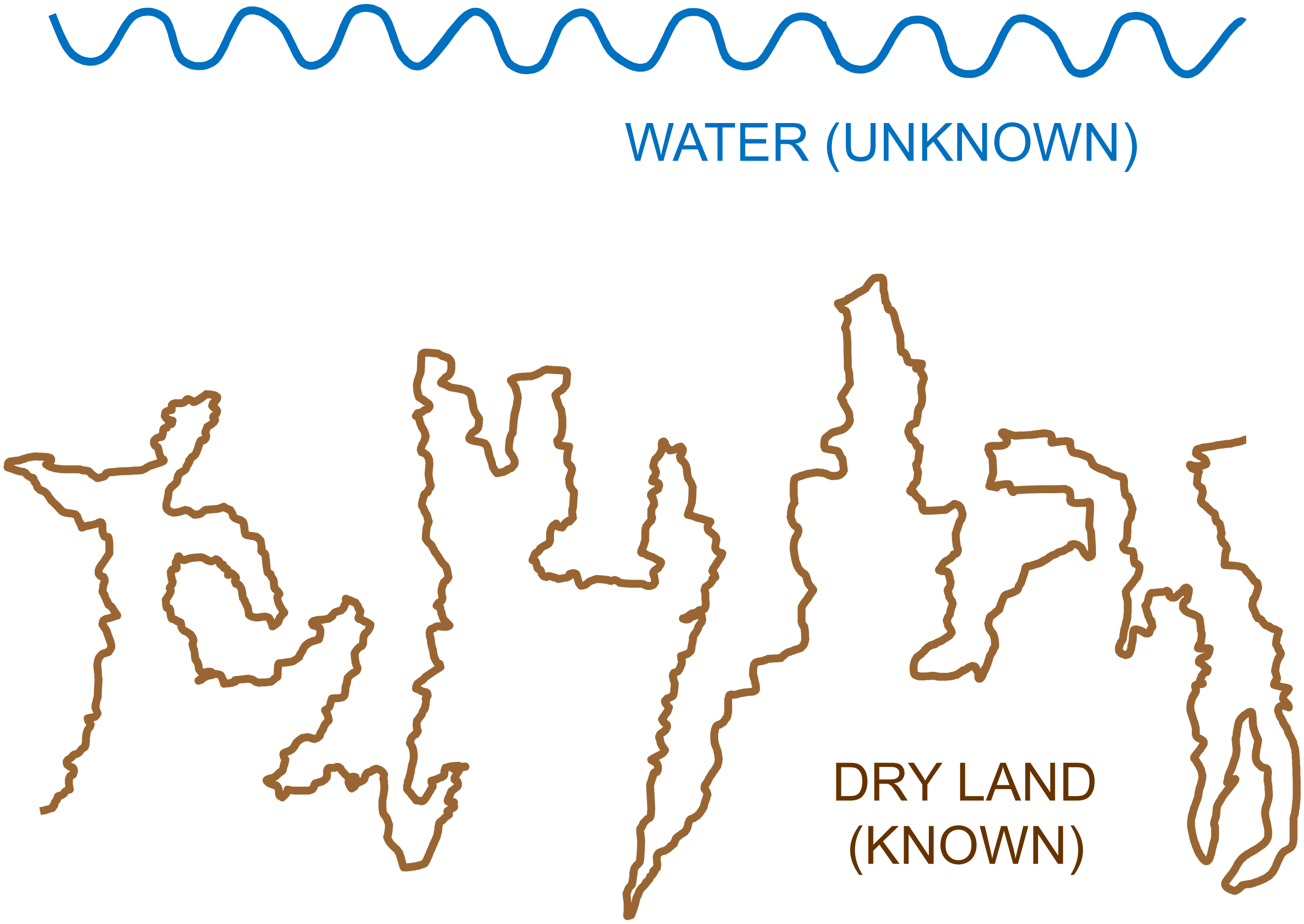
5. Quantum information (2002 -   )
   need to take individual wave functions seriously: emphasis on entanglement.

Some other developments:

superfluid ^{3}He (1972)
integral quantum Hall effect (1980)
cuprate superconductivity (1986)
topological insulators (2004)
room-temperature superconductivity (2022)(?)

$\Bigg\}$ exciting, but didn't shift paradigm.

Condensed-Matter Physics in 2023: The “Rugged-Seashore” Analogy



Examples:

“KNOWN”	versus	“UNKNOWN”
crystalline solids		glasses (amorphous materials)
“classical” superconductivity		high-temperature superconductivity
laboratory photovoltaics		natural photosynthesis

Given that CMP (like most other areas of physics) seems to be overall in a Kuhnian "normal" phase, how can we make "interesting" progress?

A possible answer: think up new questions (ideally yes/no ones)which we can answer by experiment, with only minimal reliance on microscopic theory.

Some examples from specific subfields:

(a) Cuprate superconductivity:

i) Can we understand the macroscopic properties without a detailed microscopic theory?

A: Yes, use generalized Ginzburg-Landau theory
(success story of late 80's)

ii) What is the symmetry of the Cooper-pair wave function (order parameter)? (s/d)

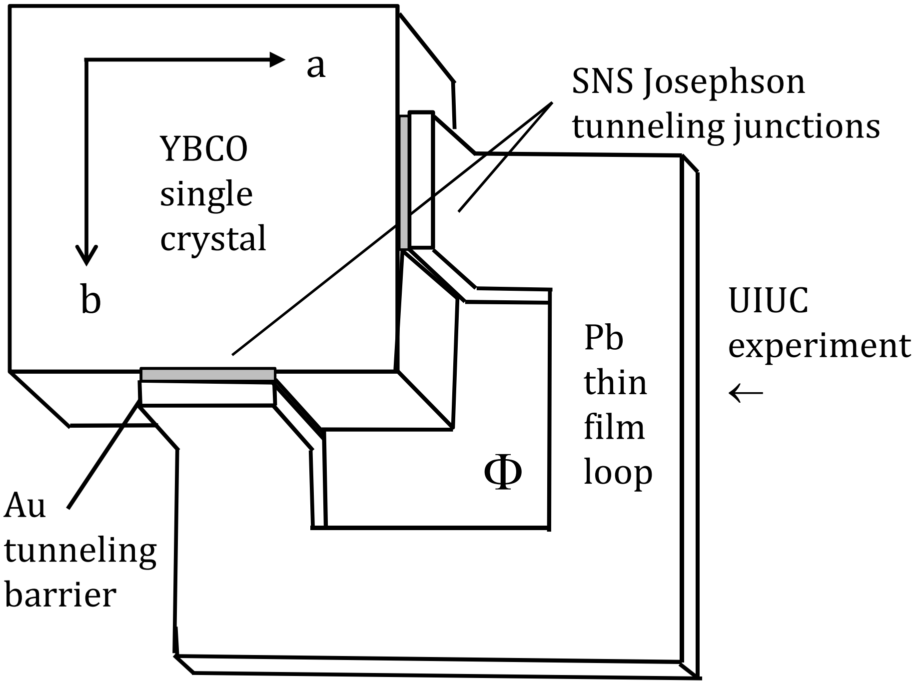
A: Use Josephson circuit* ⇒ d
(success story of 90's)

iii) Where in the space of (q, ω) is the inter-conduction electron Coulomb energy saved (or expended) in the $N \to S$ transition?

A: EELS / optical experiments
(unfinished story of 2010's)

iv) Are we "spoiled" by success of BCS? Is it always possible to discuss low-T ($T \lesssim T_0$) behavior in terms of low-ε ($\varepsilon \lesssim kT_o$) states?

(in reality, $E \sim N\varepsilon$ is played off against Nk_BT)
(not really started)



Back to (ii):

Result (d) largely accepted for cuprates.
But: what about analogous experiments* for Sr_2RuO_4?
These appear to unambiguously favor "*p*+*ip*" ("Γ_s") triplet state (not just as regards orbital, but as regards spin part)

However, Knight-shift (and neutron) experiments unambiguously indicate spin singlet! ⇒ major prima facie inconsistency.
Is the Bloch-wave analysis somehow misleading?

*Geshkenbein et al. 1985 (for heavy-fermion superconductors)

(b) Amorphous systems (“glasses”)

General observation: the overall properties of glasses are much more universal than those of erysrals, yet we have a much worse understanding of them!

A particularly striking quantitative universality*

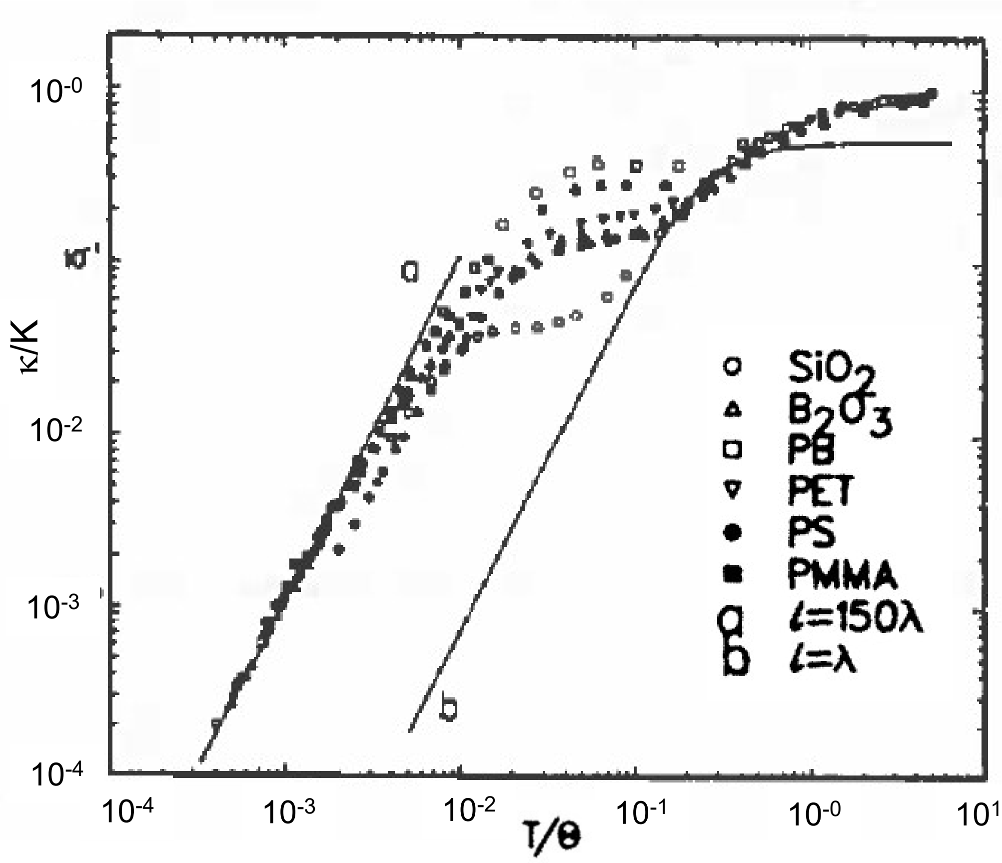


FIG. 2. Thermal conductivities for the same six amorphous solids as in Fig. 1, scaled as explained in the text. The solid lines here and in Figs. 3-5 were computed from Eq. (2) using either ℓ=150λ (line a) or ℓ=λ (line b).

This is essentially a graph of phonon mean free path (ℓ) versus to de Broglie wavelenth (λ) of thermally dominant phonons. We see ℓ / λ is constant and ~ 150 for $T \lesssim 1\text{K}$($\lambda \gtrsim 300$Å) and constant and ~1 at $T \gtrsim 10\text{K}$ ($\lambda \lesssim 30$Å) , irrespective of microscopic nature of system.

*Freeman & Anderson, Phys. Rev. B 34, 5684 (1986)

The standard tunnelling two-level system (TTLS) model = noninteracting two-level systems with energy E: density of states $P(E)$~ const. $\equiv P(0)$ for $E \rightarrow 0$. Couple to phonons & thereby determine ℓ.

Can explain $T \lesssim 1\text{K}$ data (only), but at the cost of near-unbelievable degree of coincidence in parameters:

$$\ell/\lambda = \text{const.}\frac{\overbrace{(\rho c^2)}^{\text{bulk modulus}}}{\underbrace{g^2}_{\text{TTLS-phonon coupling}}\underbrace{P(0)}_{\text{TTLS density of states}}}$$

← each factor individually fluctuates by ~6-10

An old idea* which may still have some merit:

At short distances ($r \lesssim 30$Å) phonon-induced interaction $g^2/\rho c^2 r^3$ dominates over original ("bare") TLS energy. On dimensional grounds, if resulting P(0) is constant then it must $\propto \rho\, c^2/g^2$:

$$P(0) = \text{const.}\frac{\rho c^2}{g^2} \qquad \text{with const.} \sim 1$$

But then

$$\ell / \lambda = \text{const.}\ \rho c^2 / g^2\ P(0) = \text{const.} \sim 1!$$

Hence can explain high-temperature (short-distance) behavior.

But what about universal low-temperature behavior? (argt. would require const. ~ 150). No obvious reason for that …

What are we missing? Is scaling of stress-stress response function universal? †

*e.g. AJL, Physica B **169**, 322 (1991)

†D.C. Vural and AJL, J. Noncrystalline Solids **357**, 3528 (2011).

3) Ultracold atomic gases

Legitimately a part of CMP, but untypical in that “Nature is doing exactly what the textbooks tell her to!”
So … what is the (exciting) future?

i) testing conjectures made about more traditional systems, but untestable there (ex: (non)-metastability of supercurrent in superfluid with internal degrees of freedom).

ii) analog computing (e.g. 2D Hubbard model)

iii) instantiation of various quantum-information ideas e.g. new “phases” generated by continuous “measurement”.
one problem: surfeit of possibilities!

e.g. for 100 qubits, Hilbert space is 2^{100}–dimensional: how do we know which parts of it to explore? (traditionally, lowest-energy sector: but are there other “unique” regions, e.g. super-highly-entangled ones)?) cf. G. Baskaran, preprint “Metastable Kitaev Spin Liquids….

But, quite generically, the \$64K (\$64M!) question for the future of condensed matter physics (CMP):

WILL ARTIFICIAL INTELLIGENCE PUT (HUMAN) CONDENSED-MATTER PHYSICISTS OUT OF BUSINESS?

Don’t laugh: look over your shoulder!

Protein folding: > 17K papers in literature
Alphafold program* (2021) may make >50% of them obsolete!

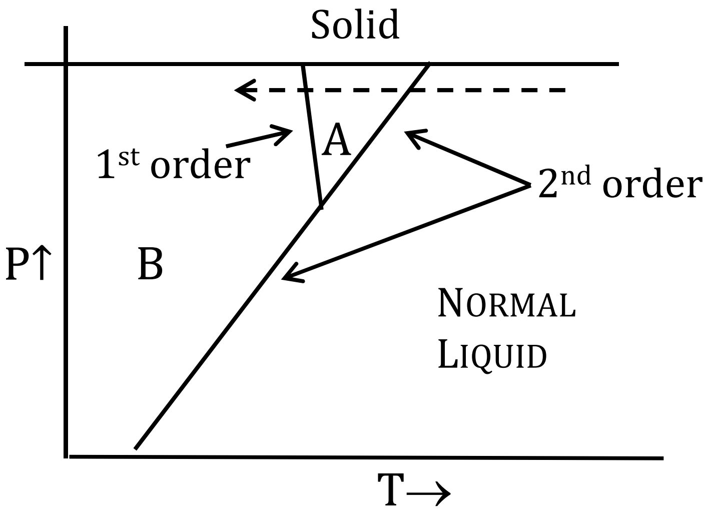
This and similar programs use machine learning to generalize from existing examples, so:

V. likely to be good for materials-genome type operations; may well find robust RT superconductors, new topological insulators…

but …

can it e.g. calculate A →B nucleation rate in liquid ^{3}He?
Why is this question interesting?

The A-B transition
in liquid 3He:



*E. Callaway, Nature Intl. Weekly Journal of Science **604**, 234 (2022)

Theoretically, the Gibbs-Cahn-Hilliard mechanism gives a rate of nucleation of the B phase $o(\text{Myrs})^{-1}$.

Experimentally, it usually takes $\lesssim$ 10–15 mins!

Conjecture*: due to passage of cosmic-ray muon and subsequent “baked-Alaska” temperature distribution.

Experimental confirmation† : laboratory nucleation with γ-rays, neutrons. “What I find particularly pleasing about this explanation of the B-phase nucleation is that in the absence of an explicit instruction to consider cosmic rays, I doubt whether any computer program, however sophisticated, would ever have found it.” (AJL, 2019)

So:

(a) give large-scale AI program access to all of ^{3}He literature. Would it find an alternative, more conventional mechanism?

(b) give it access to all of physics literature. Would it find the “baked-Alaska” mechanism? or something else?

(c) give it a “hint” (“consider possible cosmic-ray effects”). What then?

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*AJL, Phys. Rev. Letters **53**, 1096 (1984)

† P. Schiffer et al. in Prog. Low Temp. Phys. Vol 14.