# The Serendipitous Road to a Nobel Prize

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# BCS theory of superconductivity (1957)

According to the principles of quantum mechanics, "particles" can be classified into two types:

"fermions"-- very xenophobic

"bosons"– very gregarious

Under appropriate conditions, bosons display the phenomenon of "Bose Einstein condensation (BEC)": all must behave in exactly the same way. ("platoon of well-drilled soldiers")

Electrons in metals are fermions, so cannot undergo BEC directly. However,

2 fermions = 1 boson

So, if electrons can form pairs ("di-electronic molecules") then the pairs can undergo BEC, and are then predicted to show superconductivity..

To form "molecules", electrons must experience an effective attraction.

A second major development in mid-50's: Landau theory of Fermi liquid (set of fermions with strong interactions).

# Liquid helium-3 (“$^3$He”)

Atoms are fermions with strong interactions part of which is thought to be attractive.

Theoretical picture c. 1964:

“Normal” state of liquid thought to be well described by Landau Fermi-liquid theory (good agreement with experiment)

Because part of interaction is attractive, expected to form Cooper pairs like electrons in superconductor, but with important difference:

in superconductors, internal state of pairs (“di-electronic molecules”) is isotropic (spins opposed, no relative rotation).

(conjectured) Cooper-paired phase of $^3$He may be anisotropic (spins possibly parallel, nonzero relative angular motion).

Since $^3$He atoms are electrically neutral, should not be superconducting but should be the neutral analog, “superfluid”.

AJL: after doctoral work with D. ter Haar in Oxford, went to UIUC as postdoc with D. Pines.

First work on "superfluid $^3$He":

put together work of Landau on strong (repulsive) interactions and BCS theory of Cooper pair formation. (at nonzero temperature)

result: temperature-dependence of various quantities ($\chi$,$\rho_s$) interestingly different from simple BCS theory.

⇧: serendipity 1: What I didn't know ….

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1965, second postdoc with T. Matsubara in Kyoto, worked inter alia on "2-band" superconductors…

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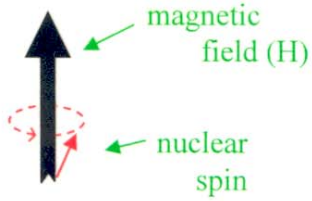
1967→…: work at U. of Sussex (UK) on various topics in low-temperature physics, including "normal" liquid $^3$He; contact with Bob Richardson (Cornell U., U.S.). But seduced by foundations of quantum mechanics….

early summer of 1972:
serendipity no. 2: Bob Richardson's visit to Sussex
serendipity no. 3: phone call from Scotland

What Bob told me that day permentally changed my career.

# NUCLEAR MAGNETIC RESONANCE

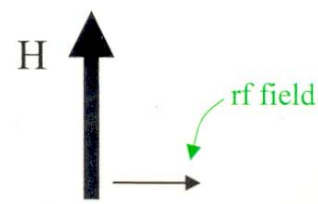



Rate of "precession"

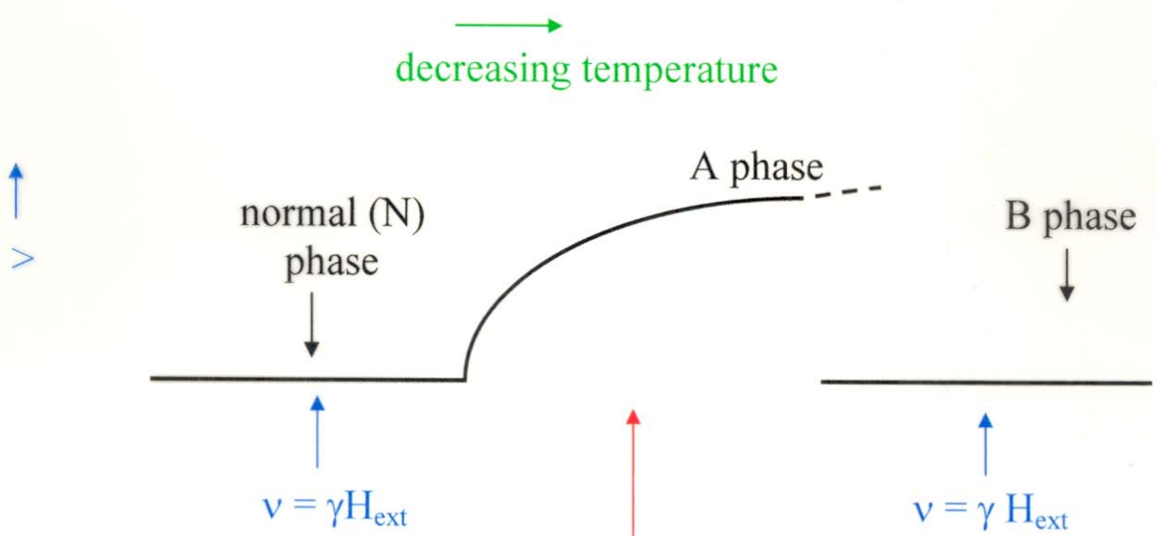
$\nu = \gamma H$

"gyromagnetic ratio"

$\gamma$ is known, (in $^3He$, ~ 3 kHz/gauss)
so, rate of precession ($\nu$) measures magn. field (H)
To measure $\nu$, apply
oscillating (r.f.) field $\perp$ H:
field is strongly absorbed when its frequency is $\nu$.




## NMR IN LIQUID $^3He$ BELOW 3mK:




$\nu = \gamma H_{ext}$

$\nu = \gamma \sqrt{H_{ext}^2 + H_{int}^2 (T)}$

$\nu = \gamma H_{ext}$

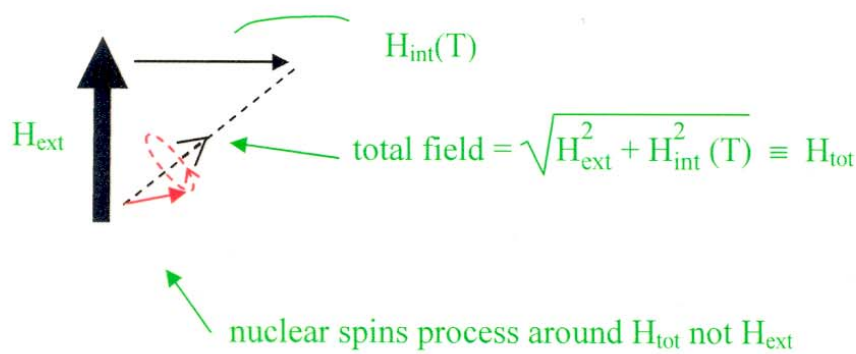
What is going on? (in context of possible Cooper pairing, no-one had thought about NMR at all…)

# THE $^3$HE NMR PUZZLE (cont.)

In A phase, precession freq. $\nu$ is larger than value ($\gamma H_{ext}$) in N phase, and given be expression of form

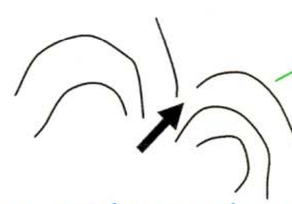
$$\nu = \gamma \sqrt{H_{ext}^2 + H_{int}^2 (T)}$$

Simplest interpretation:




Problem:

Only possible origin of $H_{int}$ (T) is other nuclear spins




Max. value of field of one nuclear spin on another (at distance of closest approach of atoms) < 1 gauss.

But, experimental value of $H_{int}(T)$ is ~ 30 gauss!

FIRST EVIDENCE FOR BREAKDOWN OF QUANTUM MECHANICS?

# RESULT OF MORE SOPHISTICATED APPROACH:

A. Simple classical argument too naive.

(no "transverse" internal field)

B. Nevertheless, indeed predict formula

$$\nu = \gamma \sqrt{H_{ext}^2 + H_o^2(T)}$$

where $H_o^2(T)$ is proportional to average value of nuclear dipole interaction energy $E_{dip}(T)$.

Experimental value of $H_o(T) \rightarrow E_{dip}(T) \sim 10^{-3}$ ergs/cm$^3$

Why is this a problem?


— energy difference ($\Delta E$) between "good" and "bad" orientations $< 10^{-7}$ K per pair.

— thermal energy ($E_{th}$) ($= k_B T$) $\sim 10^{-3}$ K.

$\Rightarrow$ preference for "good" orientation over "bad"

only $\sim \Delta E/E_{th} < 10^{-4}$

$\Rightarrow$ resulting value of $E_{dip}(T)$ much too small to fit experiment.

Need preference for "good" over "bad" $\sim 1$ not $\sim \Delta E/E_{th}$!

$\Rightarrow$ many sleepless nights in late June 1972…

# SPONTANEOUSLY BROKEN SPIN-ORBIT SYMMETRY:

## the analogy with ferromagnetism

### FERROMAGNET


difference in energy per spin = $\Delta E$ (small)

Above Curie temp. ("paramagnetic" phase), spins behave independently ⇒ thermal energy $E_{th}$ competes with $\Delta E$ ⇒ polarization only $\sim \Delta E/E_{eth} \ll 1$

Below $T_c$ ("ferromagnetic" phase): strong (exchange) forces constrain all spins to lie parallel:

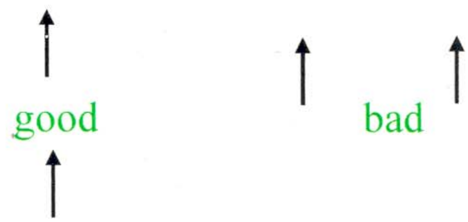
↑↑↑↑↑... or ↓↓↓↓↓...

"good" "bad"

$E_{good} - E_{bad} \sim N\Delta E \gg E_{th}$

⇒ polarization ~ 1

### LIQUID $^3$HE




difference in energy per pair ≡ $\Delta E < 10^{-7}$ K

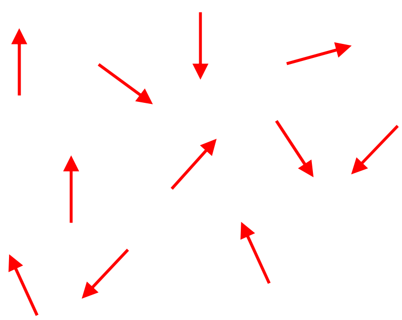
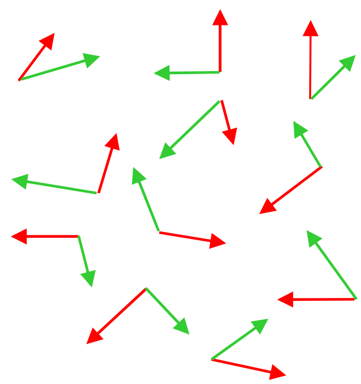
In normal phase, pairs behave independently ⇒ $E_{th}$ competes with $\Delta E$ ⇒ "polarization" (pref. for good orientation over bad) only $\sim \Delta E/E_{th} \ll 1$.

In A phase, assume: strong (kinetic-energy, VDW) forces constrain all pairs to behave in same way ⇒ either all "good" or all "bad"

$E_{good} - E_{bad} \sim N\,\Delta E \gg E_{th}$ ($N \sim 10^{23}$!)

⇒ polarization can be ~ 1

# SBSOS: ORDERING MAY BE SUBTLE

| FERROMAGNET | | LIQUID $^3$HE |
|---|---|---|
|  | ⇐ NORMAL PHASE ⇒ |  |
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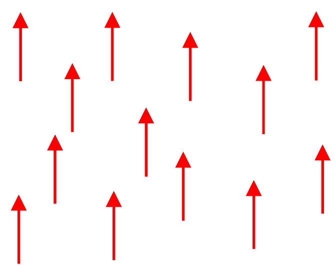
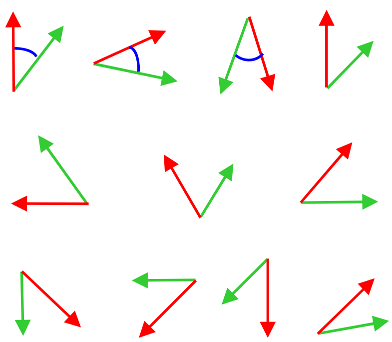
|  | ⇐ ORDERED PHASE ⇒ |  |

 = total spin of pair

 = relative orbital ang. momentum)

$\langle \underset{\sim}{S} \rangle \neq 0$

$\langle \underset{\sim}{S} \rangle = \langle \underset{\sim}{L} \rangle = 0$

but $\langle \underset{\sim}{L} \times \underset{\sim}{S} \rangle \neq 0!$

} For experts only

Relative direction chosen by (ultraweak) nuclear dipole force

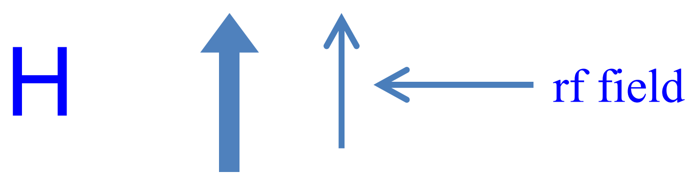
But… what would make all pairs of nuclear spins behave in the same way?

A possible answer: Cooper pairs form and undergo Bose condensation! (then must all behave in exactly the same way, including internal (relative) configuration)

Spring of 1973: 1-month visit to Cornell U. (thanks to Bob Richardson)

serendipity no. 4: Kyoto work on 2-band superconductors plays vital role!

⇒ detailed microscopic theory explained existing data and predicted inter alia: behavior in longitudinal NMR experiment




No such experiments existed, but done in summer of 1974 by Doug Osheroff, confirms theoretical prediction.

Another crucial theoretical development in spring 1973: Anderson-Brinkman theory of stability of A phase (difficult to understand in “naïve” BCS theory).

## Conclusion (by summer of 1973)

Both a priori stability considerations and NMR experimental data are consistent with hypothesis that both new phases are Cooper-paired ("superfluid) phases (and superfluidity later confirmed explicitly) Specifically,

A phase = "ABM"
B phase = "BW"
} Previously conjecture configurations

## What is superfluid $^3He$ good for?

a) Most sophisticated physical system of which we can claim detailed quantitative understanding. E.g. textures, orientational dynamics, topological singularities…
b) Analogies with systems in particle physics, cosmology… (G.E. Volovik)
c) Studies of (some aspects of) turbulence
d) Amplification of ultra weak effects (cfNMR): Example: P-(but not T-) violating effects of neutral current part of weak interaction:

Technical, only for experts!

For single elementary particle, any EDM $\underset{\sim}{d}$ must be of form

$\underset{\sim}{d} = const. \underset{\sim}{J}$ ← violates T as well as P.

But for $^3He - B$, can form

$$\underset{\sim}{d} \sim const. \underset{\sim}{L} \times \underset{\sim}{S} \sim const. \underset{\sim}{\omega}$$

↑ violates P but not T.

Effect is tiny for single pair, but since all pairs have same value of $\underset{\sim}{L} \times \underset{\sim}{S}$, is multiplied by factor of $\sim 10^{23} \Longrightarrow$

macroscopic P-violating effect?

i.e. even at everyday level, nature might know her right hand from her left hand!