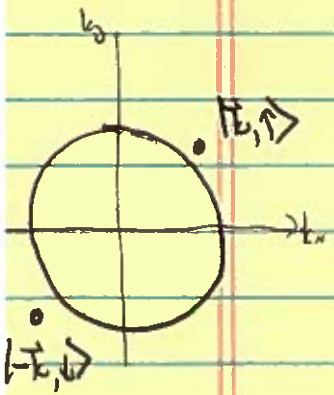
PHYS 460 - LECTURE 26

BCS THEORY

WE END OUR DISCUSSION OF SUPERCONDUCTIVITY WITH BRIEF CONSIDERATION OF THE THEORY OF BARDEEN, COOPER AND SCHRIEFFER (BCS), WHICH UNTIL THE 1980s WAS CONSIDERED THE THEORY OF S.C. NOW, SUPERCONDUCTIVITY IS DISCUSSED AS A MORE GENERAL CONCEPT, BUT BCS STILL DESCRIBES A LARGE NUMBER OF MATERIALS, REFERRED TO AS "CONVENTIONAL SUPERCONDUCTORS".

THE FULL THEORY IS BEYOND THE SCOPE OF THIS COURSE, BUT THE BASIC IDEA IS SIMPLE ENOUGH TO EXPLAIN. SUPERCONDUCTIVITY IS SEEN AS AN INSTABILITY OF THE METALLIC STATE

(1) CONSIDER ELECTRON STATES WITH WAVEVECTOR, $\vec{k}$, AND SPIN, S, DIRECTLY ABOVE THE FERMI ENERGY, ε_F



(2) COOPER SHOWED THAT, AT LOW TEMPERATURES, THESE STATES WERE OCCUPIED IN PAIRS IF THERE EXISTED ANY NET ATTRACTIVE INTERACTION BETWEEN THEM.

i.e. OCCUPATION OF $|\vec{k},\uparrow\rangle \Rightarrow |-\vec{k},\downarrow\rangle$ WAS ALSO OCCUPIED, AND VICE VERSA

$\rightarrow$ "COOPER PAIRS"

(3) THIS COLLECTION OF PAIRS AS EFFECTIVELY A GAS OF BOSONS, WHICH COLLAPSE INTO A "BOSON CONDENSATE"

ALL THE UNINTUITIVE PROPERTIES OF S.C ARE A RESULT OF THIS QUANTUM STATE. IN PARTICULAR, SOME ASPECTS IMMEDIATELY BECAME CLEAR

(1) THE S.C. "GAP" IN NOW UNDERSTOOD. LOW LYING (JUST ABOVE E_F) ARE TIED UP IN PAIRS. ONE NEEDS $\hbar\omega = 2\Delta$ TO "BREAK A PAIR".

(2) THE G.-L. WAVEFUNCTION, ψ, IS NOW INTERPRETED AS THE CENTER-OF-MASS WAVEFUNCTION FOR A PAIR. ξ IS THE SIZE OF THE PAIR. ORIGIN OF $q = 2e$ AND $m^* = 2m$ IN THE EQUATIONS ARE ALSO OBVIOUS.

(3) THE G-L EQUATIONS, AND ALL PREDICTIONS OF G-L THEORY, RESULT FROM A SMALL $|\psi|$ EXPANSION, VALID NEAR T_c

$\xi_0 = \frac{2\hbar v_F}{\pi\Delta}$

(4) THE LONDON EQUATIONS ARE VALID FOR SMALL ξ. → "STRONG COUPLING LIMIT"

IN ADDITION, BCS MADE SEVERAL QUANTITATIVE PREDICTIONS FOR THE JUMP IN C_V AT T_c AND RELATIONSHIP BETWEEN Δ AND T_c, WHICH WERE FOUND TO BE TRUE.

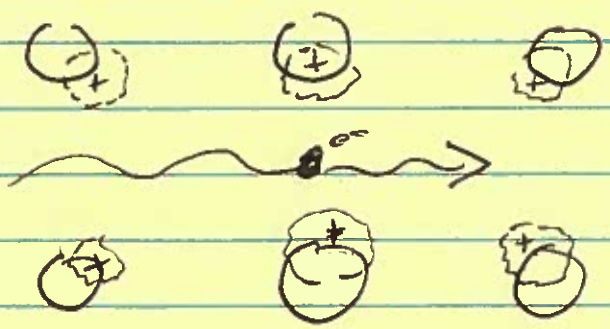
ONE SHOULD BE CAREFUL ABOUT TAKING THE CONDENSATE PICTURE TOO LITERALLY. UPON INSPECTION, IT IS CLEAR THAT $\sim 10^6$ e^- EXIST IN SPACING OF

A SINGLE "PAIR" → THESE ARE NOT NON-INTERACTING BOSONS! ITS MORE LIKE ELECTRONS HAVE GIVEN UP THEIR INDIVIDUAL IDENTITIES TO [redacted] BECOME PART OF A LARGER QUANTUM OBJECT.

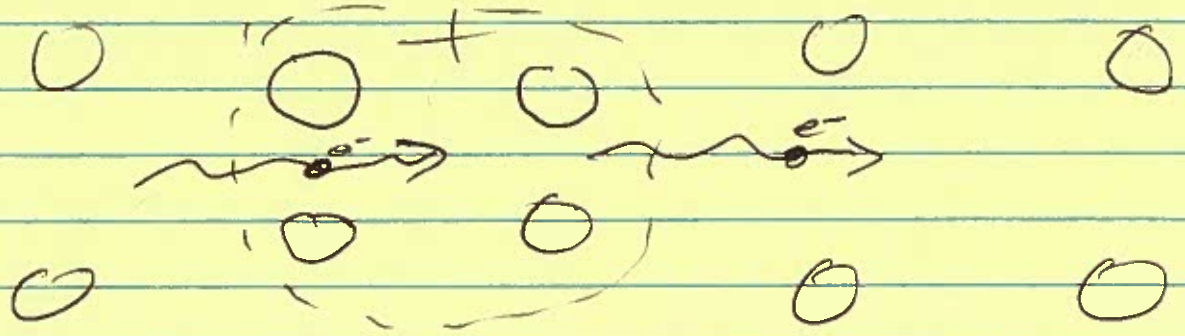
ATTRACTIVE INTERACTION

IT IS IMPORTANT TO NOTE THAT BCS THEORY WORKS FOR ANY ATTRACTIVE INTERACTION. PEOPLE OFTEN CONFLATE THE THEORY WITH A STATEMENT ABOUT THE SPECIFIC ORIGIN OF THE PAIRS. THIS IS NOT CORRECT!

BCS DID SUGGEST ONE POSSIBLE SOURCE OF AN ATTRACTIVE INTERACTION INVOLVING PHONONS, WHICH I DESCRIBE BELOW. IMAGINE A SINGLE ELECTRON TRAVELLING INSIDE A CRYSTALLINE SOLID, COMPRISING A LATTICE OF POSITIVELY CHARGED NUCLEI. THE NUCLEI WILL BE ATTRACTED TO THE ELECTRON, AND MOVE TOWARDS IT. LATTICE MOTION → "PHONONS"



NOW, ON AVERAGE, THE POSITIVE CHARGE OF THE NUCLEI AND SEA OF ELECTRONS IS ZERO. HOWEVER, ELECTRONS MOVE FASTER THAN NUCLEI, SO BY THE TIME THEY REACT TO ITS PRESENCE, IT HAS MOVED ON. THIS CREATES A LOCAL REGION OF NET POSITIVE CHARGE, WHICH CAN ATTRACTED A SECOND ELECTRON, JUST A BIT LATER IN TIME ("RETARDED").



THE SECOND e^- SURFS ALONG IN THE WAKE OF THE FIRST, ESSENTIALLY FOLLOWING IT AS A BOUND PARTNER → "PAIR"

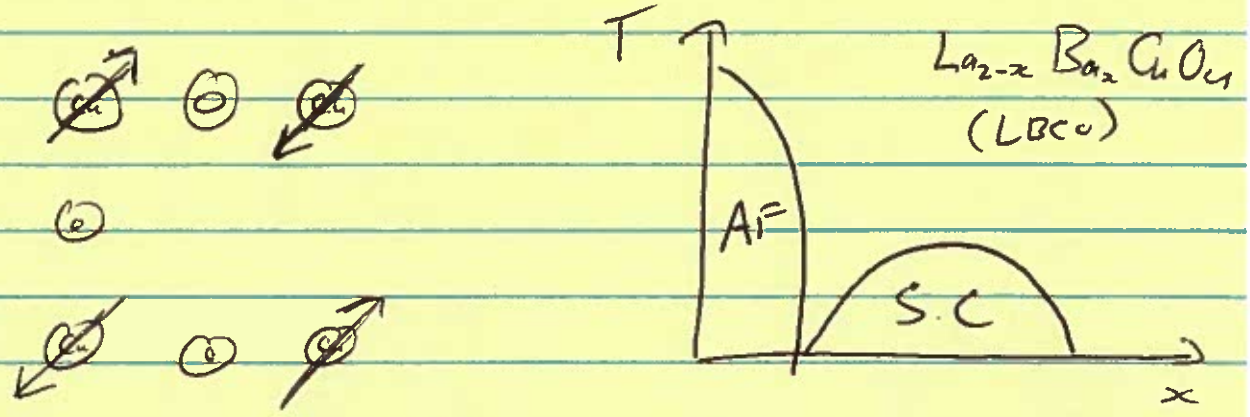
BCS FORMALIZED THIS WITH FIELD THEORY LANGUAGE, BUT THIS IS THE GIST. IT IS KNOWN AS THE "RETARDED PHONON PAIRING MECHANISM" FOR S.C.

THOUGH THERE IS A LARGE BODY OF SCIENTIFIC LITERATURE DEDICATED TO THIS MECHANISM AND MUCH IS BEING DEBATED, THE GENERAL CONSENSUS IS THAT PHONONS CAN'T GIVE T_c's MUCH LARGER THAN 30K. (CURRENT RECORD $T_c = 39$ K FOR MgB_2)

HIGH TEMPERATURE SUPERCONDUCTIVITY

AFTER BCS, PHYSICISTS FELT THEY UNDERSTOOD S.C. TO THE POINT THAT THEY WERE MAKING RULES ABOUT WHERE TO FIND THEM. IN 1986, BEDNORZ AND MUELLER DISCOVERED WHAT HAVE SINCE BEEN NAMED THE "HIGH TEMPERATURE CUPRATE SUPERCONDUCTORS" WHICH DRAMATICALLY BROKE ALMOST ALL OF THESE RULES.

BASICS: TAKE MATERIAL $La_2Cu_1O_4$, WHICH IS A MOTT INSULATING ANTIFERROMAGNET



REPLACE SOME La^{3+} WITH Ba^{3+} TO "DOPE" HOLES $\longrightarrow$ SUPERCONDUCTOR WITH $T_c = 38K$!

THESE SYSTEMS ARE QUASI-2D, POOR METALS, WITH STRONG LOCAL MOMENTS WHERE PHONONS CANNOT BE PLAYING A ROLE. BASED ON LBCO, RELATED MATERIALS WITH T_c UP TO 156K HAVE BEEN DISCOVERED, AND WE HAVE NO IDEA HOW THEY WORK!

AMONG MAJOR TOPICS BEING DISCUSSED: BANDS, ORBITALS, MAGNETISM, PHONONS, INTERACTIONS AND ORDER. WELCOME TO C.M.