The impact of BCS theory on Superconductivity and Condensed Matter Physics

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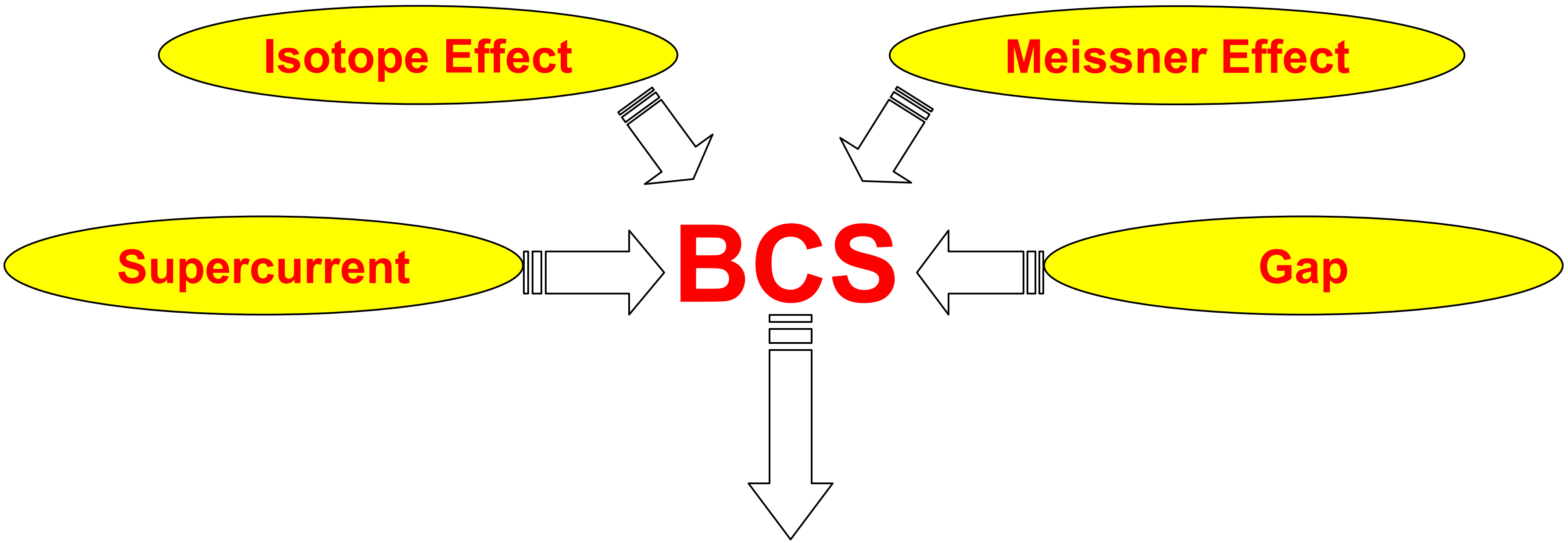


Pairs

"The Mechanism": Electron-Phonon mechanism

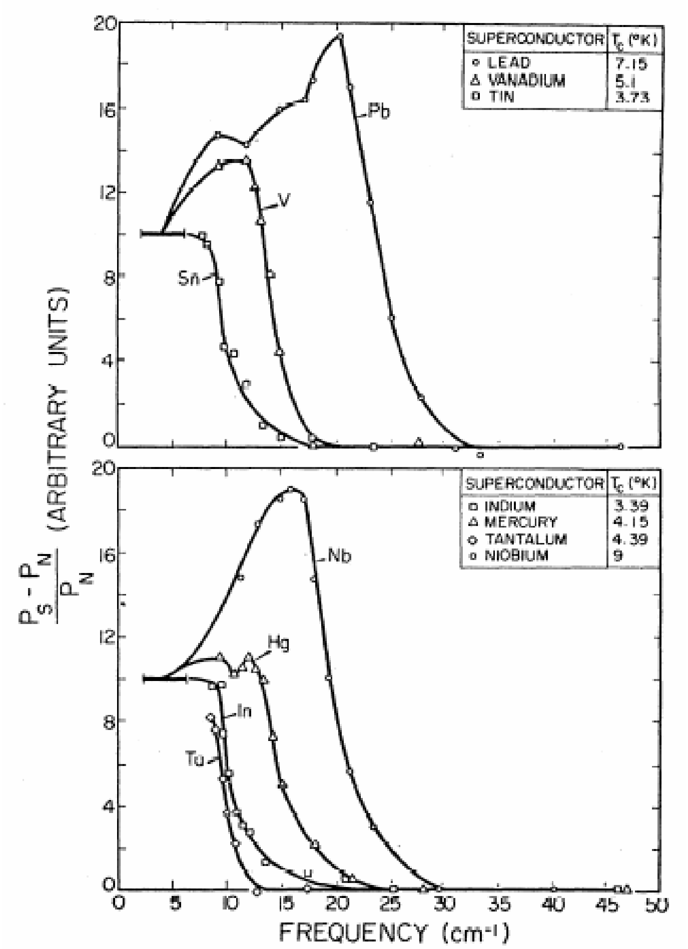
Realization that electrons, behaving collectively, can have most unusual properties: "Correlated electrons"

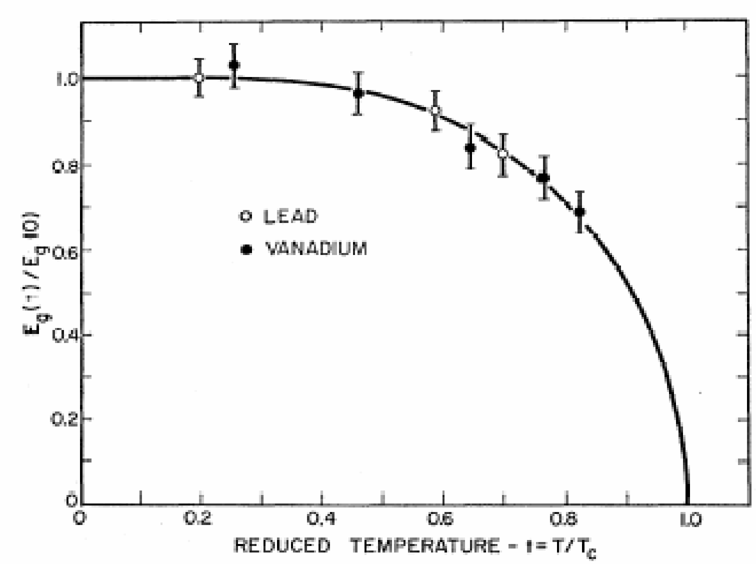
"There is an energy gap for individual-particle excitations which decreases from about $3.5kT_c$ *at* T=0K to zero at T_c."

- J. Bardeen, L.N. Cooper, and J.R. Schrieffer, 1957.

“Probably the most direct method of measuring the superconducting energy gap is by observing the onset of electromagnetic absorption in a bulk sample.”

- P.L. Richards and M.Tinkham





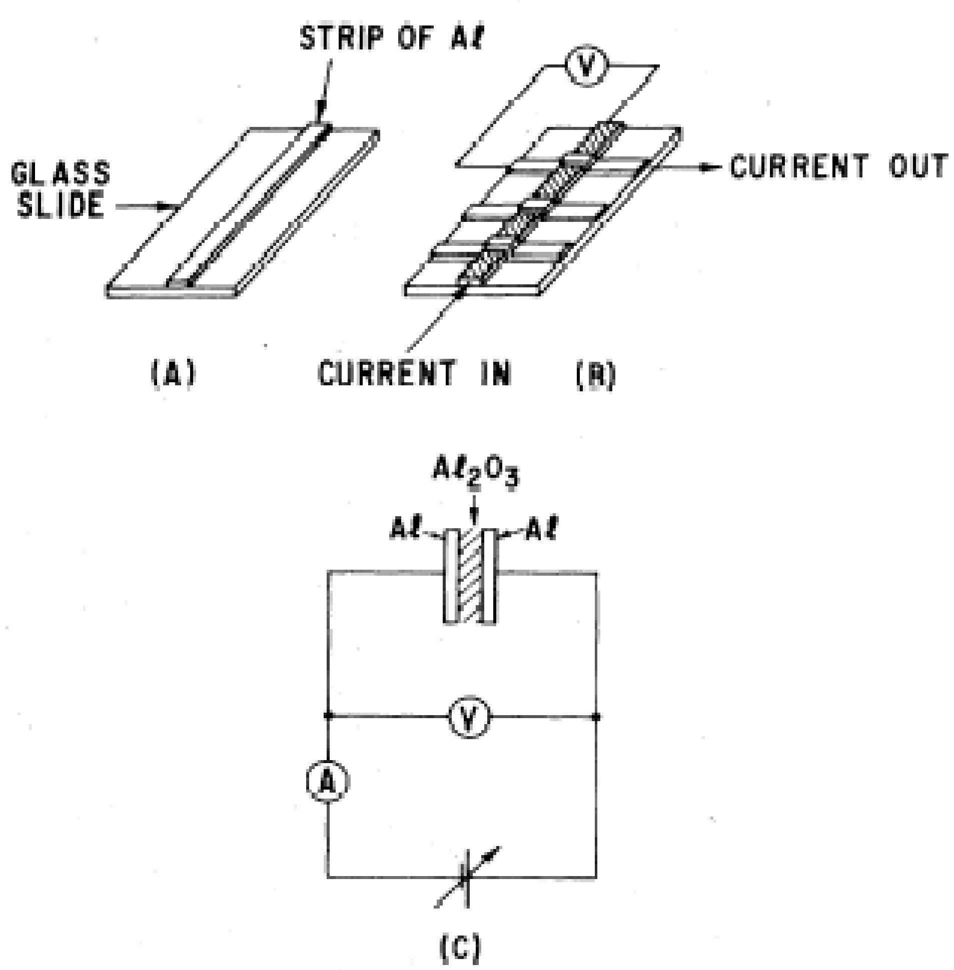
R.E. Glover and M. Tinkham (1957),
P.L. Richards and M. Tinkham (1958),
D.L. Ginsburg and M. Tinkham (1960).

"I continued to take formal courses at RPI, and one day in a solid-state physics course taught by Prof. Huntington we got to superconductivity, Well, I didn't believe that the resistance drops to exactly zero – but what really caught my attention was the mention of the energy gap in a superconductor, central to the new Bardeen-Cooper-Schrieffer theory. If the theory was any good and if my tunneling experiments were any good, it was obvious to me that, by combining the two, some pretty interesting things should happen …"

- I. Giaever, Nobel prize lecture 1973.

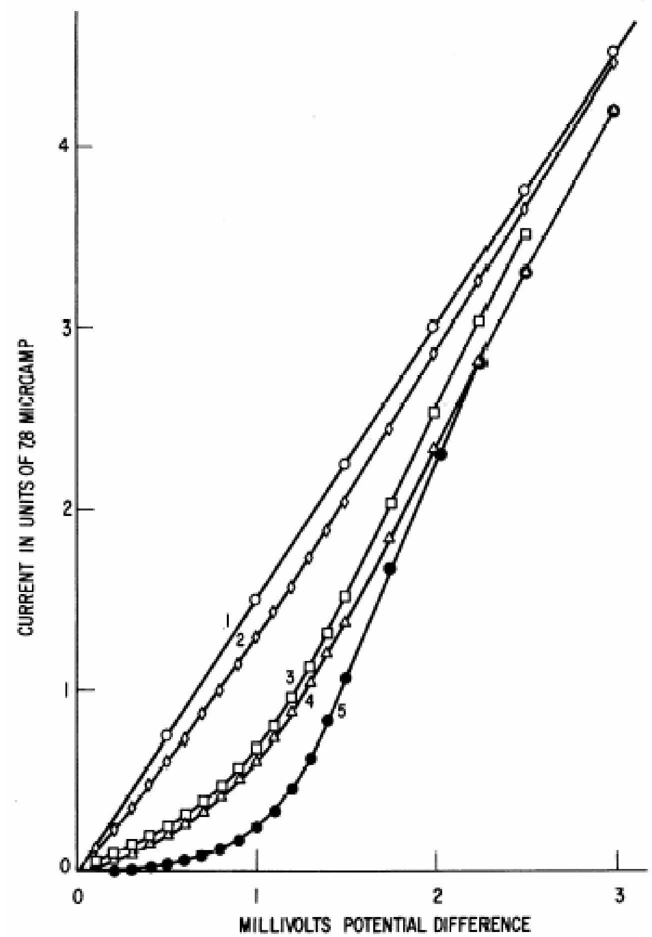
“Friday, April 22 (1960), I performed the following experiment aimed at measuring the forbidden gap in a superconductor”

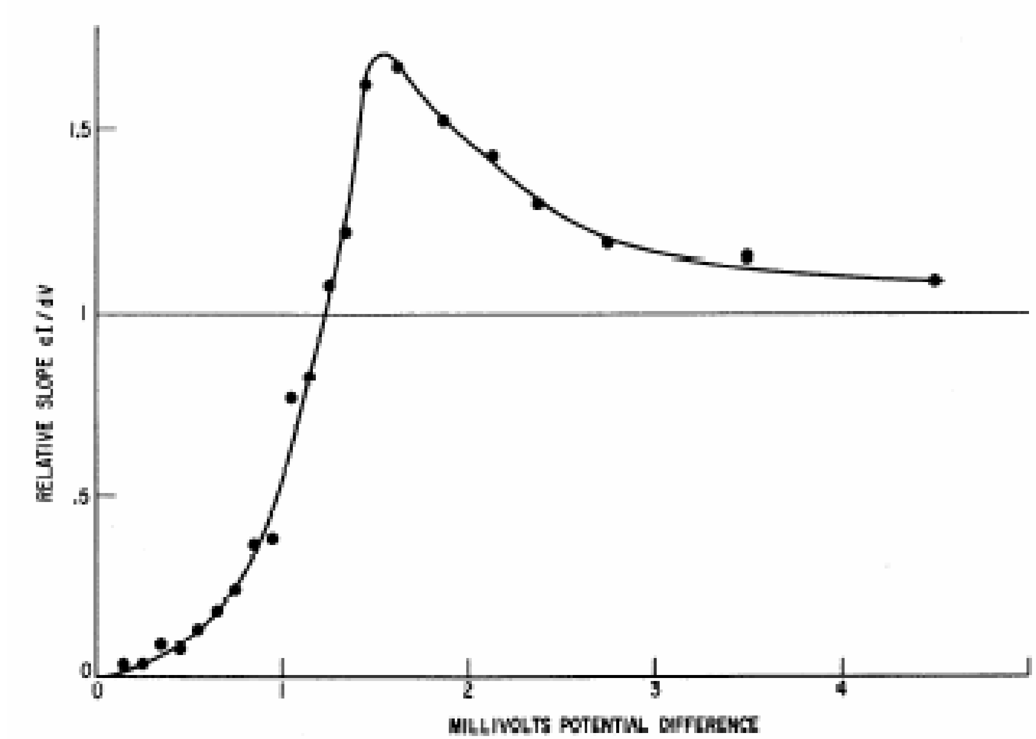
-Notebook entry, I. Giaever, May 2, 1960.



“On the naive picture that tunneling is proportional to density of states, this curve expresses the density of states in superconducting lead - - - -. The curve resembles the Bardeen-Cooper-Schrieffer density of states for quasi-particle excitations. ”

- Ivar Giaever, 1960.

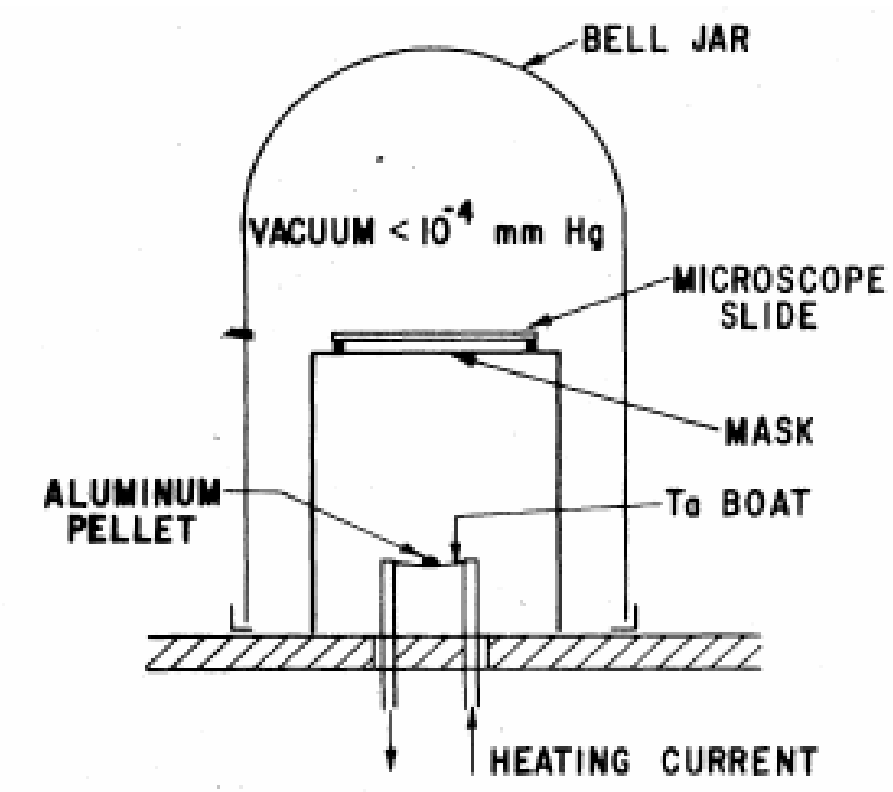


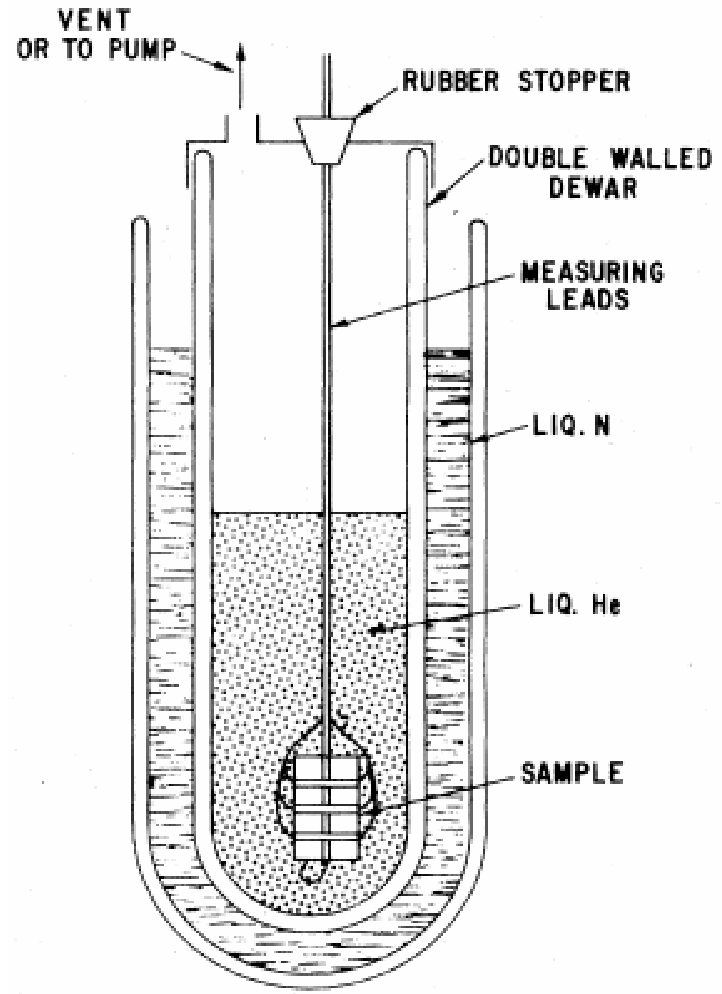


Tunnel current between Al and Pb through Al_2O_3 film as a function of voltage

“..the instruments I used, which were simply a standard voltmeter and a standard ammeter. It is strange to think about that now, only 13 years later, when the laboratory is full of sophisticated x-y recorders. ”

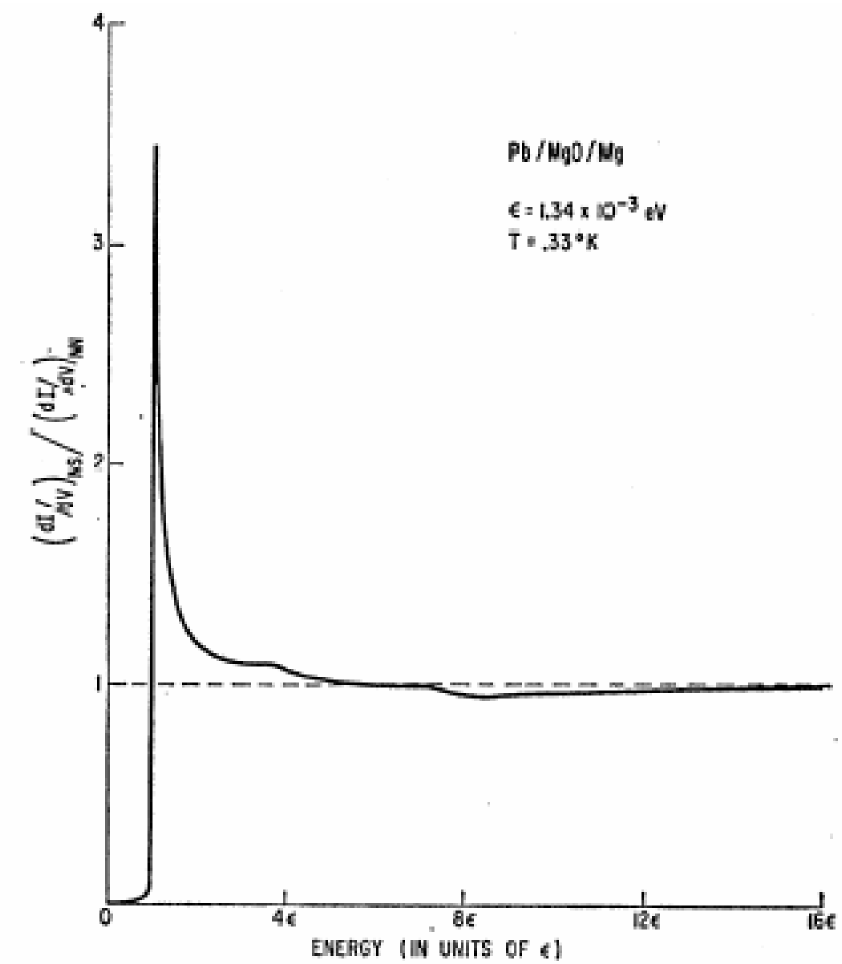
- Ivar Giaever, Nobel prize lecture, 1973.

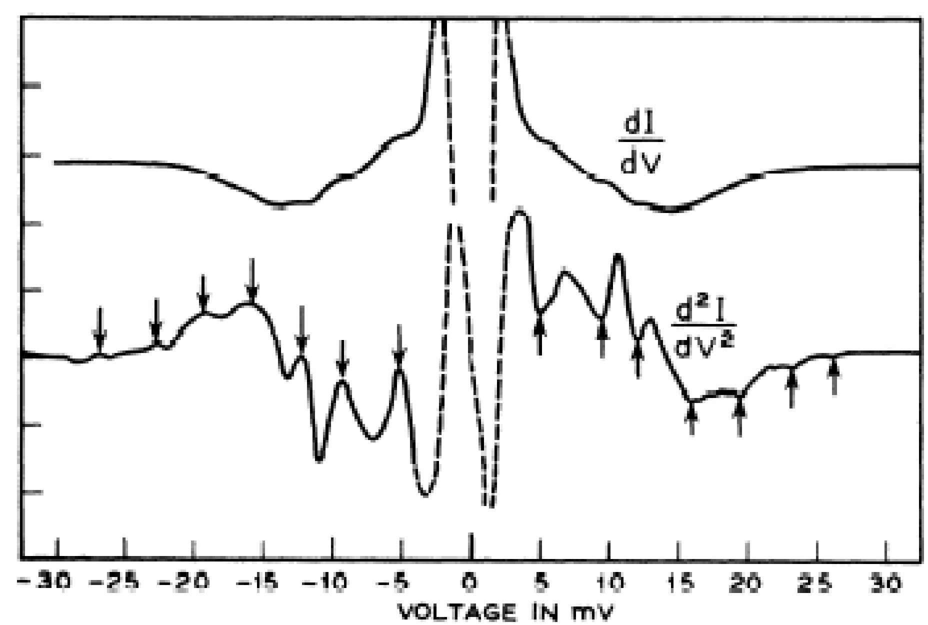




“ At higher energies there are definite divergences from the BCS density of states ---. Note that the crossover point corresponds in energy to the Debye temperature ”

– I. Giaever, H.R. Hart, Jr., and K. Megerle 1962.

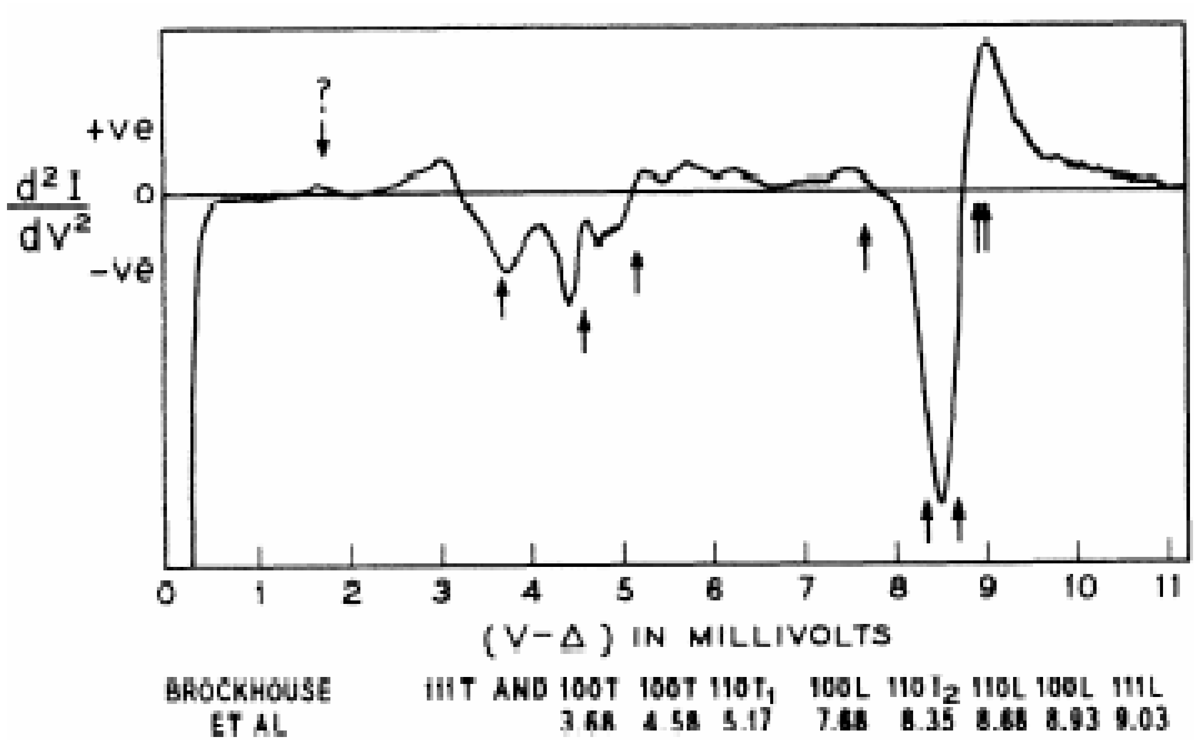




The relative conductance of a Pb-MgO-Mg sandwich plotted against energy.

“ Considerable refinement in experimental technique has allowed us to make a much more detailed quantitative study - - -. We have resolved the structure in detail and can assign much of it to specific Van Hove singularities expected from neutron measurements of the Pb phonon spectrum ”

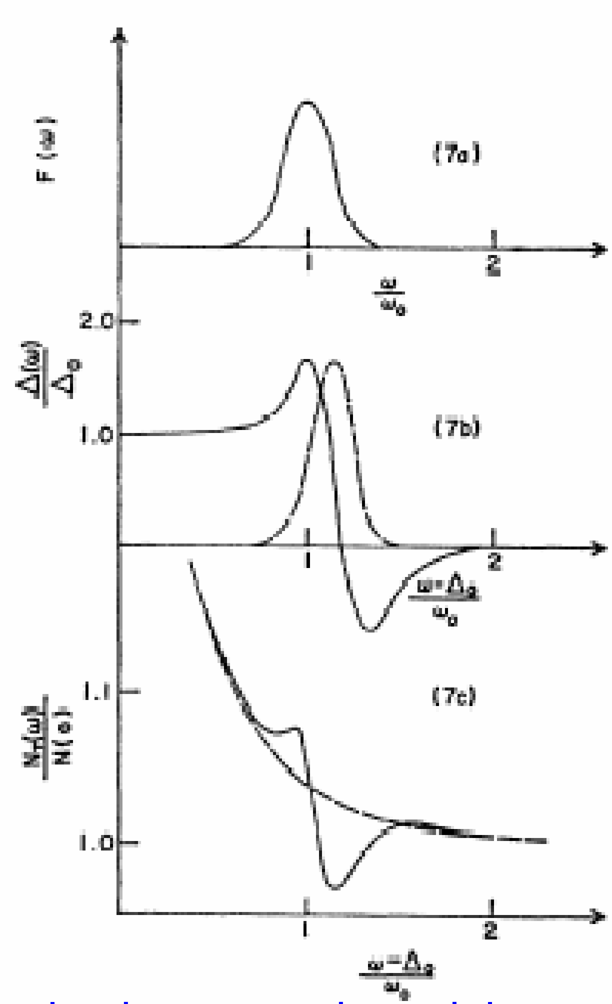
– *J.M. Rowell, P.W. Anderson, and D.E. Thomas 1963.*



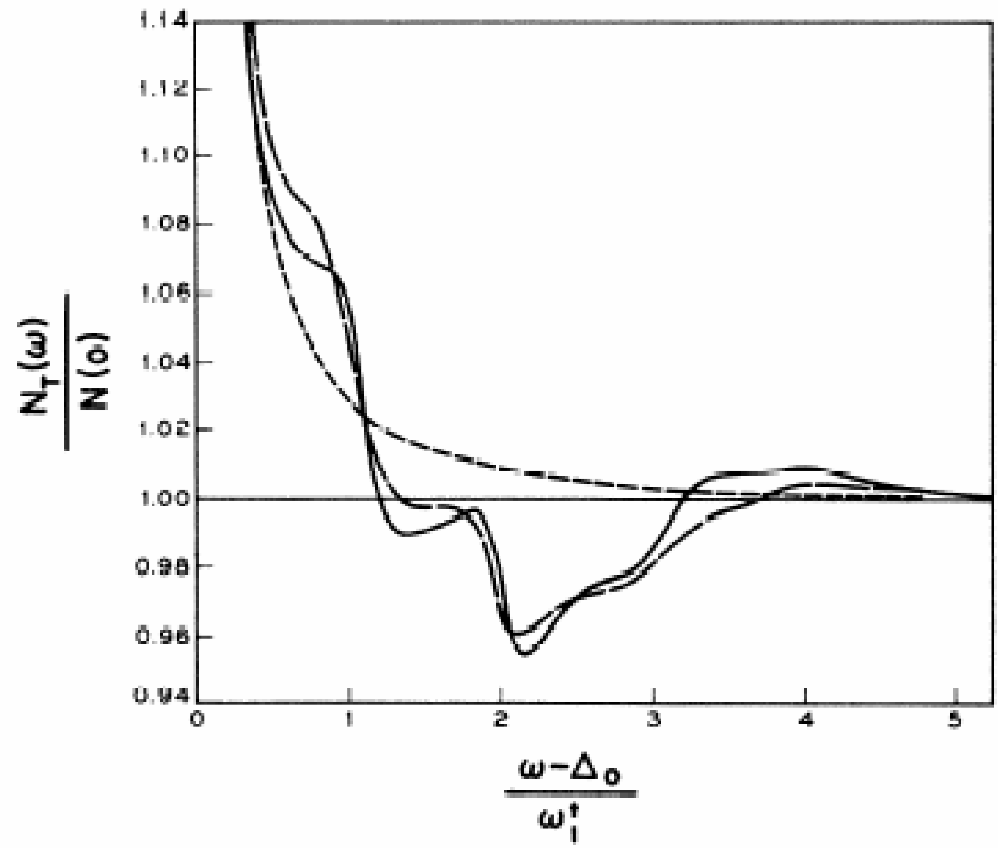
d^2I/dV^2 vs V (measured from Δ) for a Pb-Pb junction at 1.3K.

"Equations (9) and (10) have been solved by an on-line computer facility for a simplified model devised to represent the phonon spectrum of Pb. "

\- *J.R. Schrieffer. D.J. Scalapino, and J.W. Wilkins, 1963.*



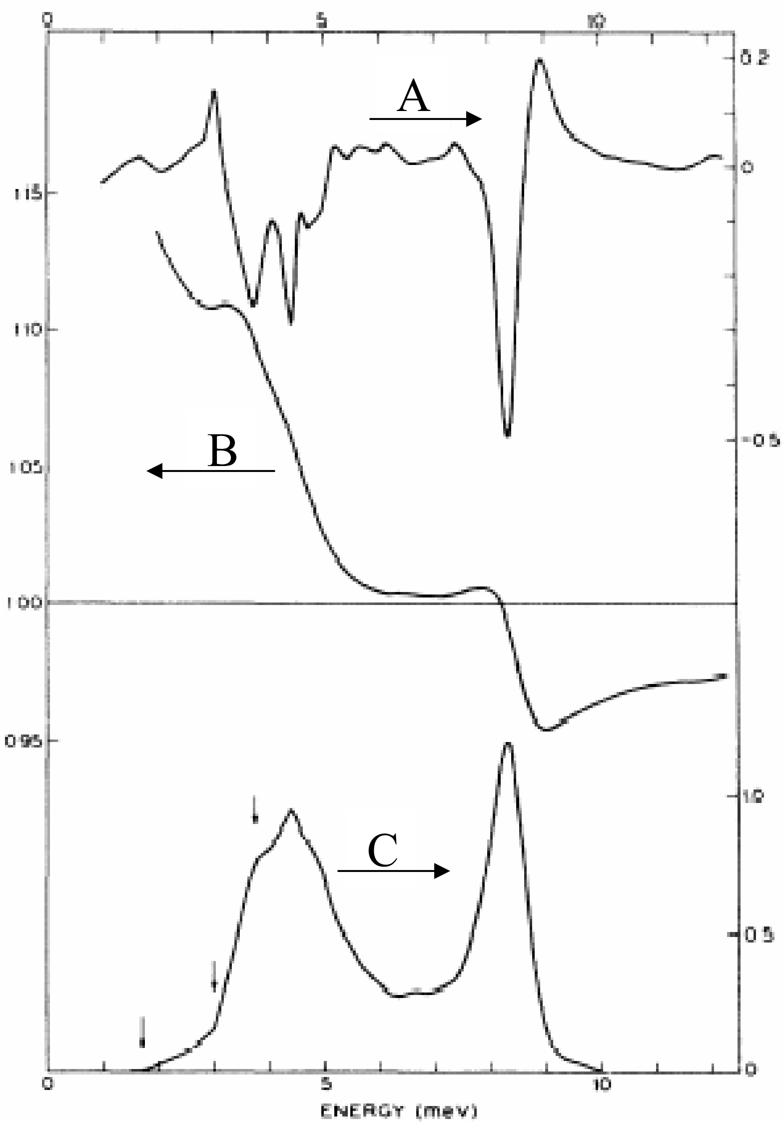
Single phonon peak model as an illustration of the manner in which the phonon density of states is reflected in the gap and the effective tunneling density of states.



The effective tunneling density of states $N_T(\omega)/N(0)$ vs $(\omega-\Delta_0)/\ \omega_1 t$ (solid) and the density of states of the simplified BCS model $\omega/(\omega^2-\Delta_0^{\ 2})^{1/2}$ (short dash)

"Looking into superconductors. The tunneling experiment is unique in probing the dynamical structure of the superconducting state and has provided a confirmation of the correctness of the strong coupling theory."

- *W.L. McMillan, London Prize lecture, 1978.*

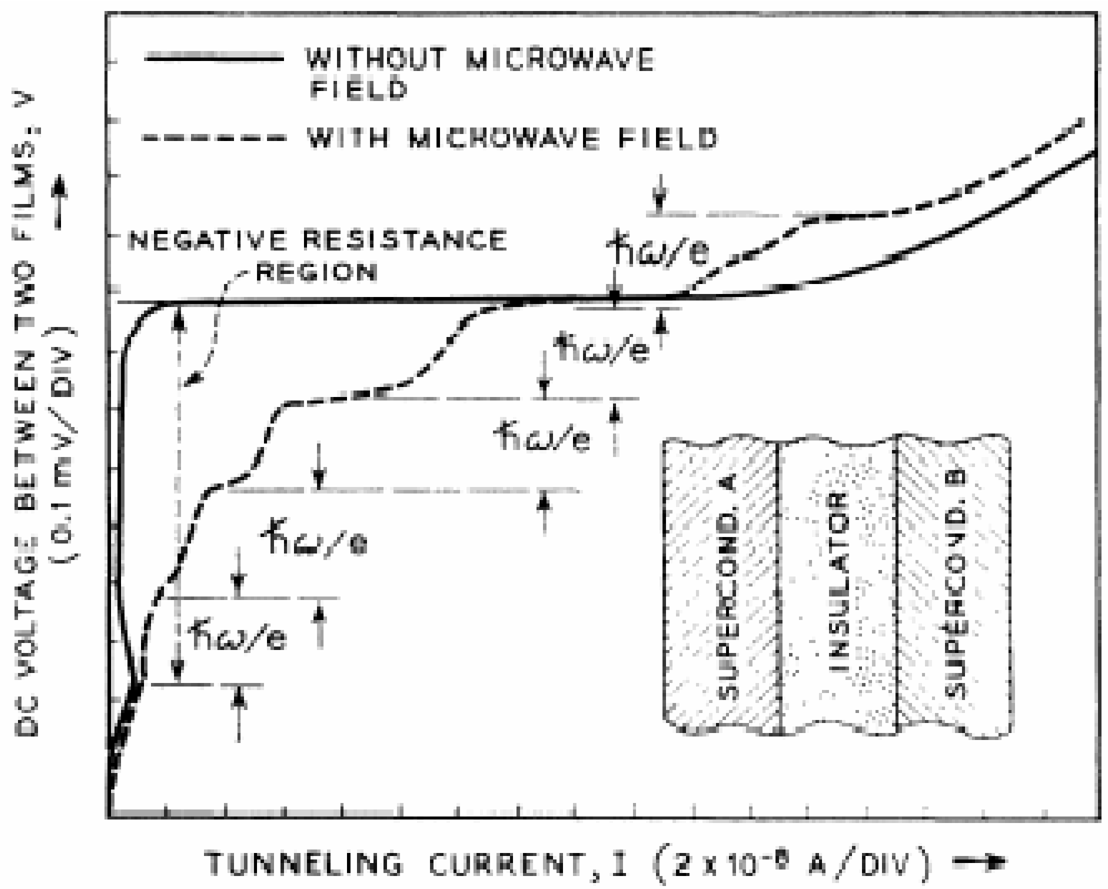


Curve A is the normalized second derivative, $(d / dV)[(dI / dV)_s/(dI / dV)_n]$ (in units of meV^{-1}) for a Pb-I-Pb junction at 0.8K as a function of $V-2\Delta_0$. Curve B is the ratio of the (tunneling) electronic density of states of superconducting and normal lead as a function of $\omega-\Delta_0$.

Curve C is $\alpha^2(\omega).F(\omega)$ versus ω

"These considerations suggest the use of "low-voltage" tunneling in M/B/S and S/B/S structures for quantum detection of microwave and submillimeter-wave radiation - - -."

- *E. Burstein, D.N. Langenberg, and B.N. Taylor, 1961.*



"Bias voltage vs tunneling current of a superconducting Al-Al2O3-In diode with and without the microwave field. $\hbar\omega/e$ = 0.16mV."

A.H. Dayem and R.J. Martin, 1962

A search on Google Scholar for "SIS detector telescopes" produced 5040 references.

“We here present an approach to the calculation of tunneling currents between two metals that is sufficiently general to deal with the case when both metals are superconducting. In that case new effects are predicted, due to the possibility that electron pairs may tunnel through the barrier.”

“Our theory predicts that:

i) At finite voltages the usual DC current occurs, but there is also an AC supercurrent of amplitude $|J_1|$ and frequency 2eV/R.

ii) At zero voltages, J_0 is zero, but a DC supercurrent up to a maximum of $|J_1|$ can occur.”

- B.D. Josephson, 1962.

"We have observed an anomalous dc tunneling current at or near zero voltage in very thin tin oxide barriers between superconducting Sn and Pb, which we cannot ascribe to superconducting leakage paths across the barrier - - -"

\- *P.W. Anderson and J.M. Rowell, 1963.*

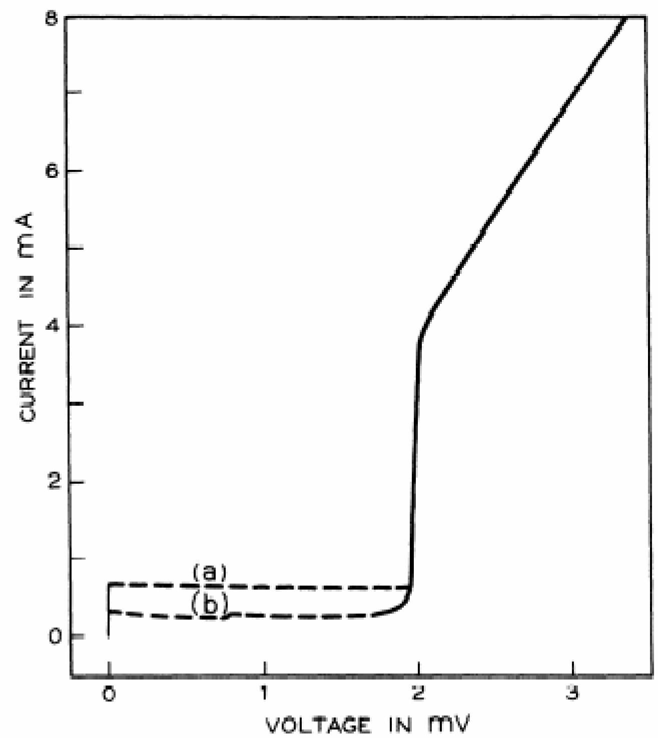
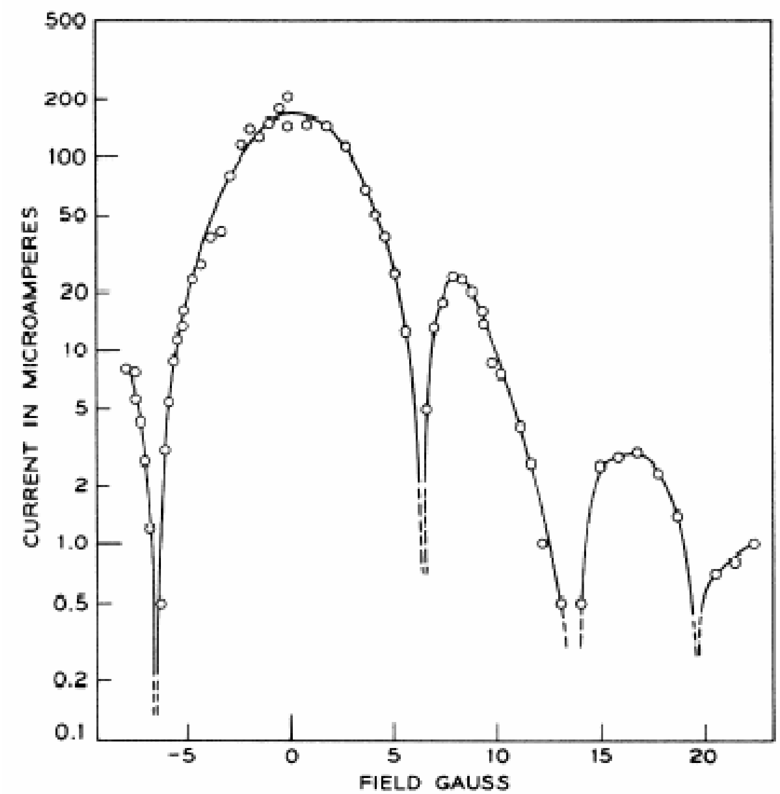


Fig. 1.Current-Voltage characteristics for a tin-tin oxide-lead tunnel structure at ~1.5K, (a) for a field of 6×10^{-3} gauss and (b) for a field 0.4 gauss.



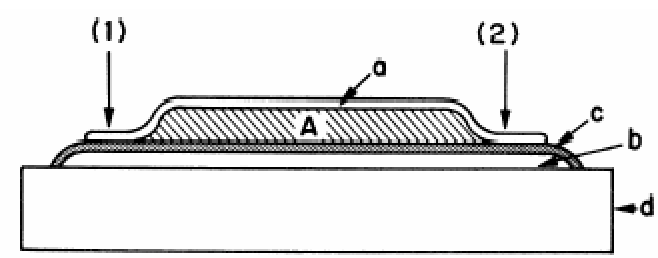
The field dependence of the Josephson current in a Pb-I-Pb junction at 1.3K.

"You could hardly find two people whose minds worked on more different lines than Brian Josephson and myself, so that I was never able to understand what he was talking about."

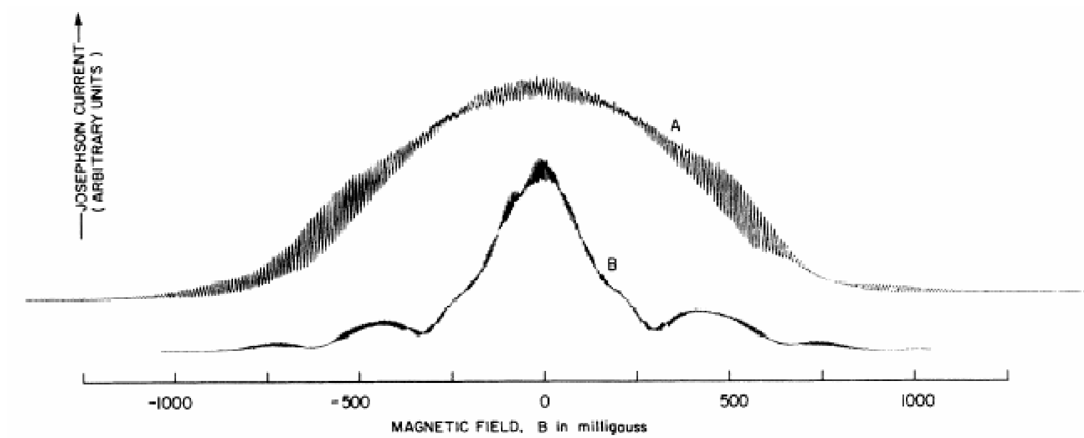
- A.B. Pippard, 1966.

"This second period involves a quantum mechanical interference between the currents flowing through separate junctions in direct analogy with double-slit electron beam interference effects "

- *R. C. Jaklevic, J. Lambe, A.H. Silver, and J.E. Mercereau, 1964.*



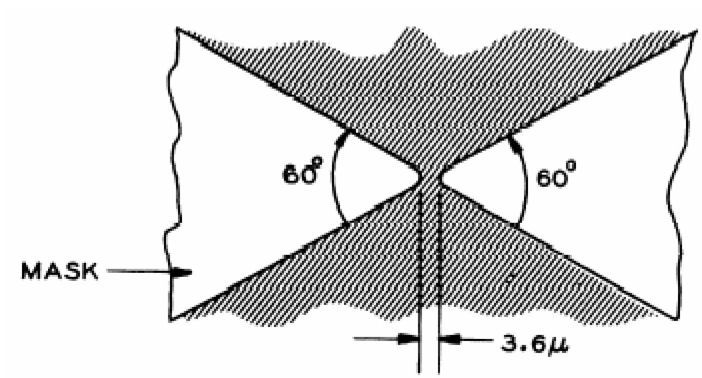
Cross section of a Josephson junction pair vacuum-deposited on a quartz substrate.

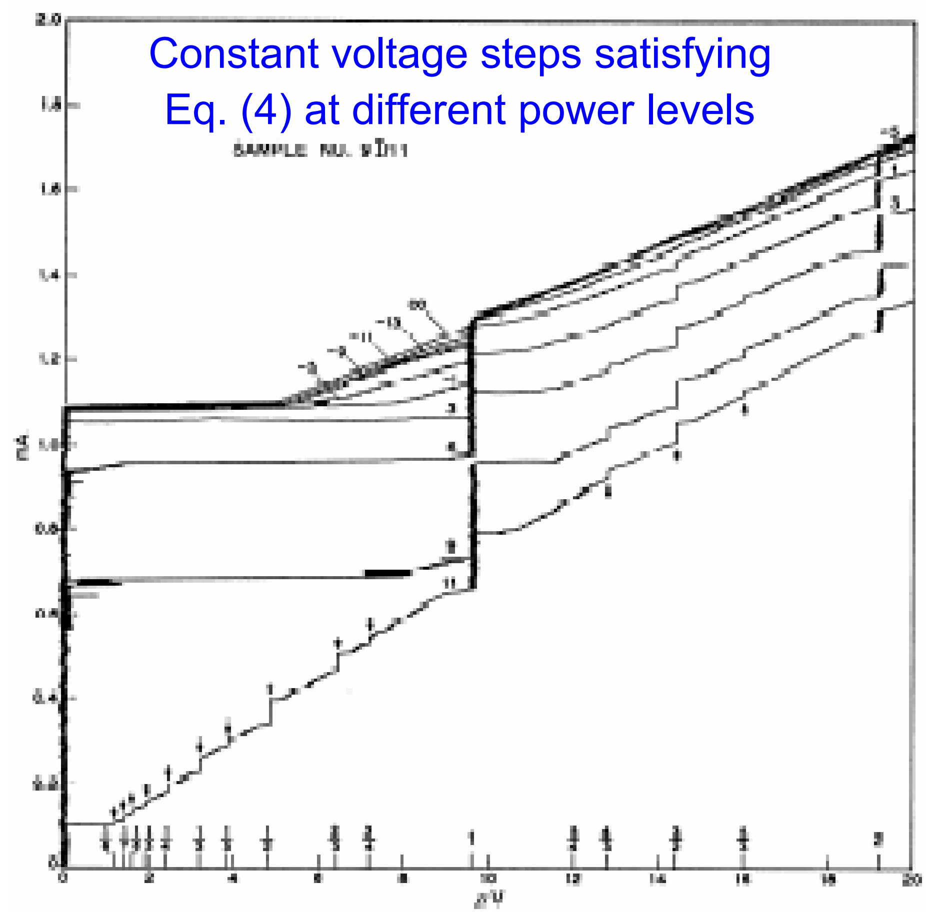


Josephson current vs magnetic field for two junctions in parallel showing interference effects.

“Phil (Anderson) suggests that the structures of Parks and Mochel – narrow superconducting constrictions- should (in low H) be weak coupling regions between bulk superconductors so should exhibit Josephson effects. In fact he considers Parks’ results are Josephson measurements. ”

- Notebook entry, J.M. Rowell, February 1964.



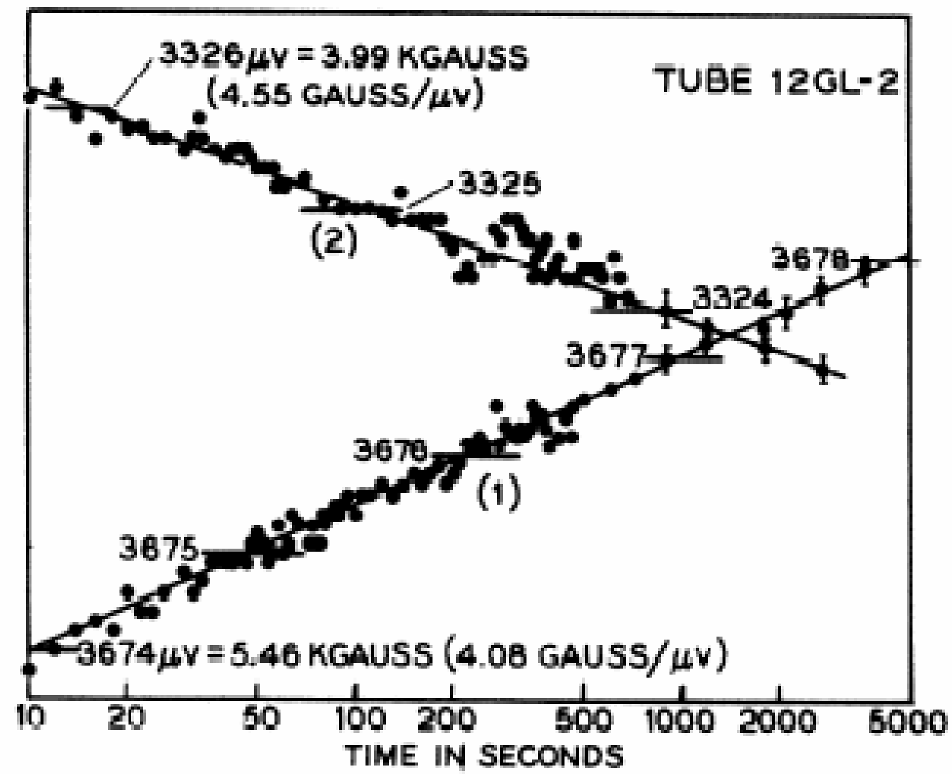


“ A resistive effect in a fully superconducting sample”

- P.W. Anderson and A.H. Dayem, 1964.

"Nowhere in Goodman or Abrikosov is there any appreciation of the importance of motion of the flux line structure: resistance was a concept completely foreign to superconductivity until Josephson's equation, and until Kim and I applied it to flux creep and flux flow."

- *P.W. Anderson, letter to J. Bardeen, 10/31/1973.*

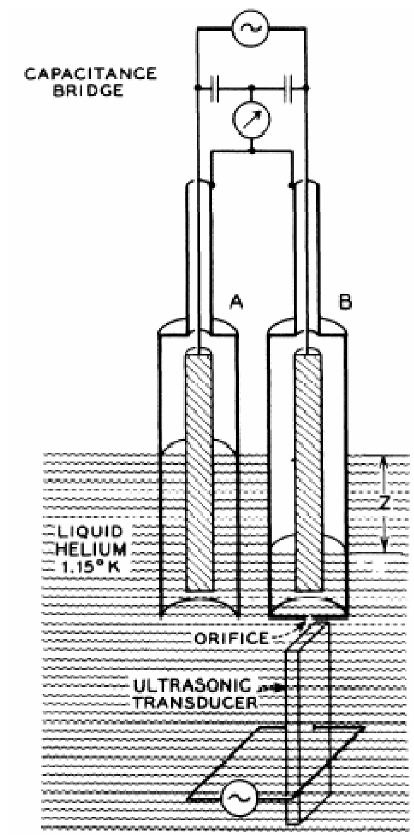


Decay rate measurements of "persistent" currents induced in a 3Nb-Zr tube. Digital voltmeter readings of *H'* probe are displayed as a function of log *t*.

- *Y.B. Kim, C.F. Hempstead, and A.R. Strnad, 1962.*

“We report the first observation of the effect in superfluid helium analogous to the alternating-current Josephson effect in superconductivity.”

- *P.L. Richards and P.W. Anderson 1965.*



The two coaxial capacitors A and B form two arms of a capacitance bridge which measures the helium head difference z. Helium flow through the orifice is modulated by a quartz ultrasonic transducer.

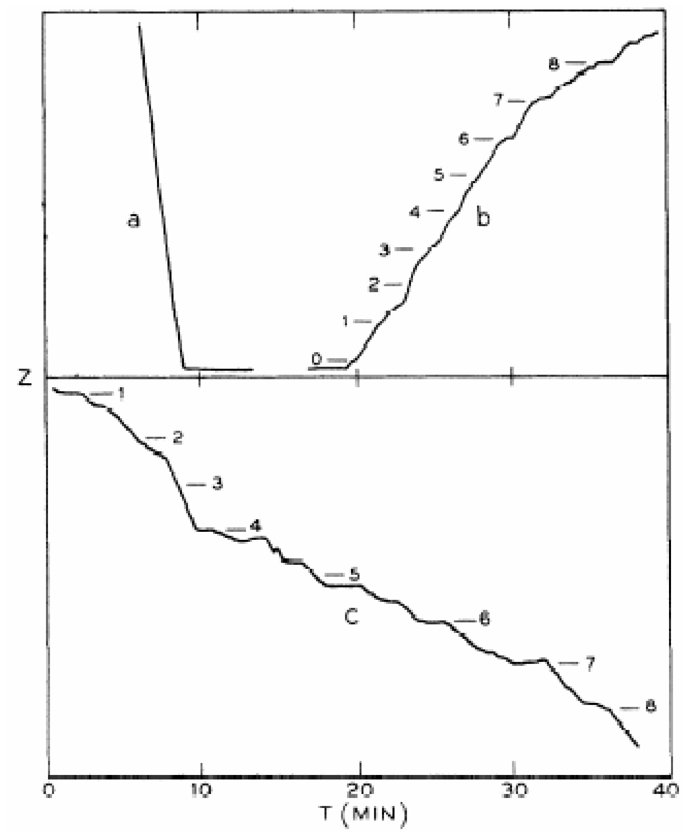


Chart recordings of head difference versus time.

(a) Decay of a head with no ultrasonic modulation;

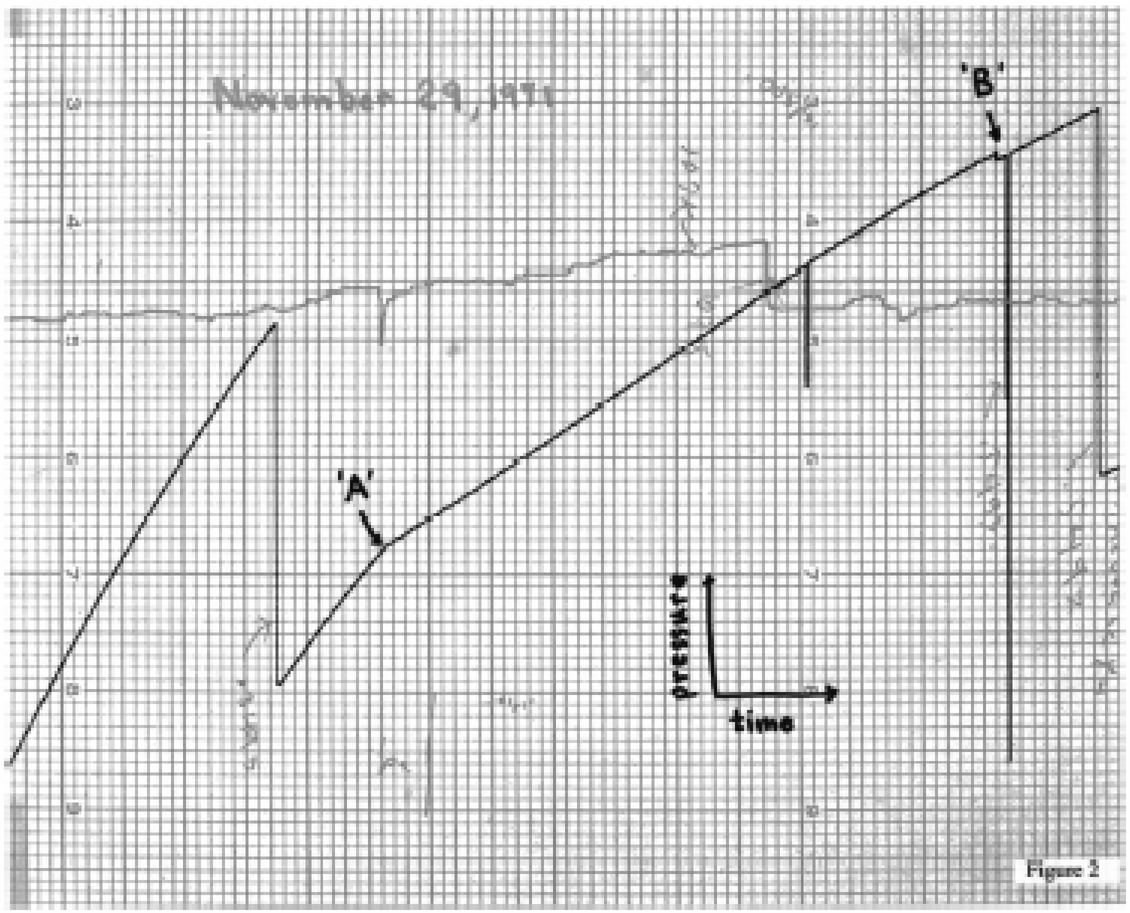
(b) increasing head produced by pumping action of a 69.3-kc/sec transducer;

(c) Decay of a head with ultrasonic modulation.

"It was not superfluidity in ^3He which we were after when we began the experiment that lead to its discovery.- - - - most people doubted that such a state of matter would ever be found. Hopes had been high shortly after the publication of the BCS theory - - -. A similar mechanism would lead to superfluidity in liquid ^3He as well. "

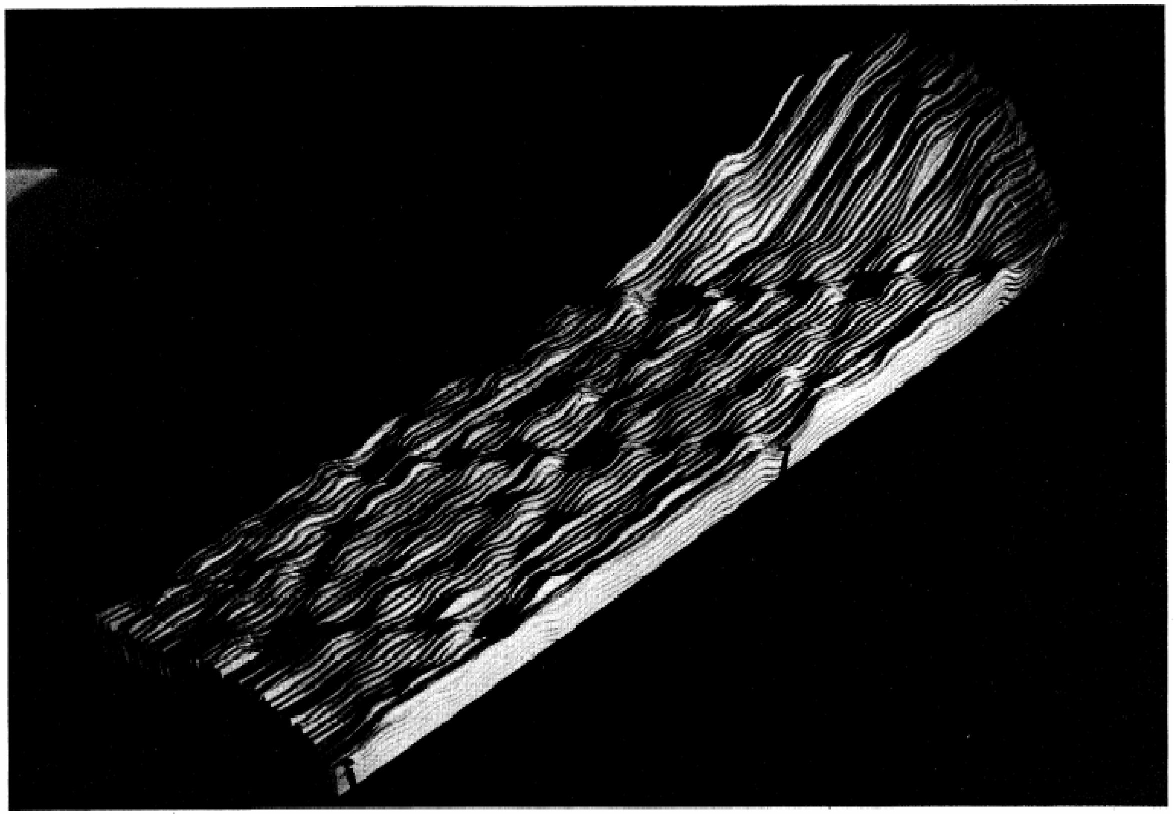
- *D. Osheroff 2000 (Nobel prize 1996).*

[A.J. Leggett, Nobel prize, 2003]



"Tunneling, in one form or another, had intrigued me for quite some time. - - - I watched my colleagues struggle with tolerance problems in the fabrication of Josephson junctions. - - - thoughts on inhomogeneities of surfaces, especially those of thin oxide layers grown on metal surfaces. "

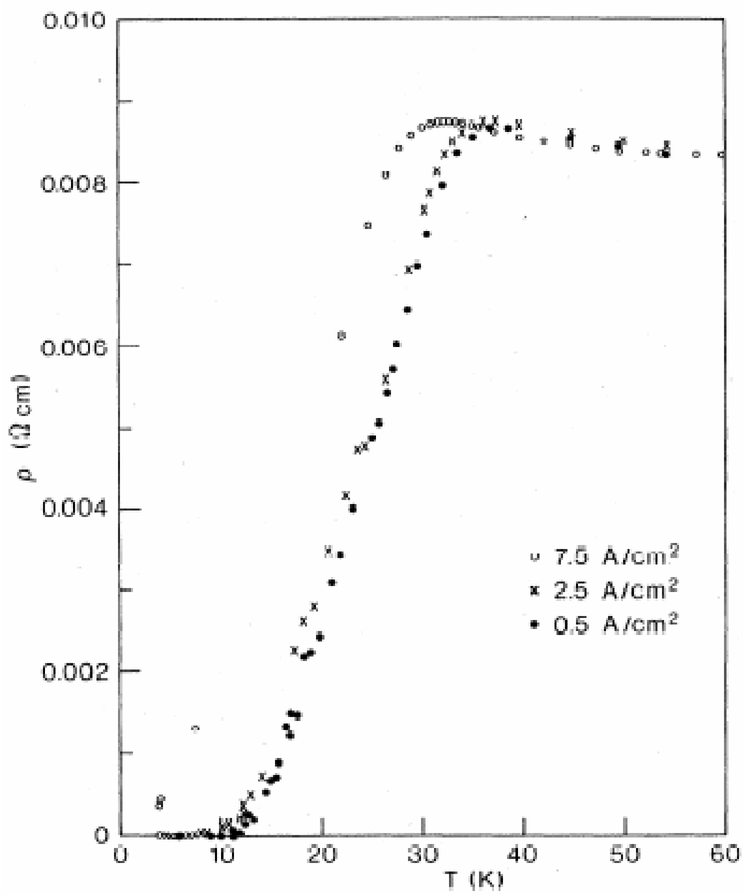
- *G. Binnig and H. Rohrer (Nobel Prize lecture 1986).*



7×7 reconstruction of Si(111). Relief assembled from the original record traces, from Binnig *et al.(1983b)*

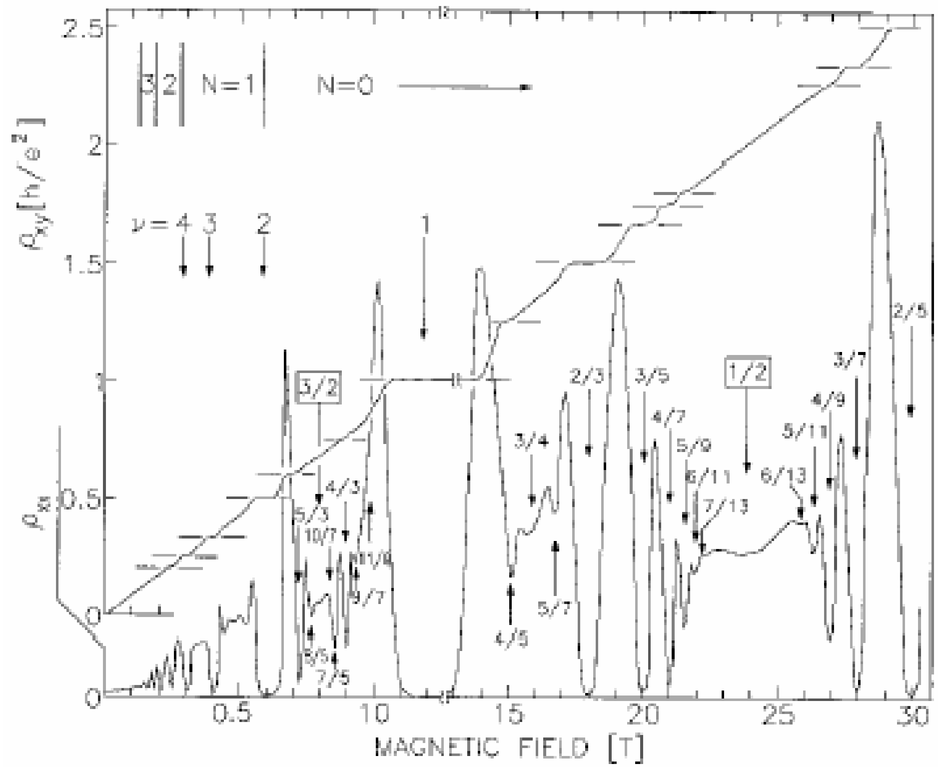
"We expected other metallic oxides to exist where even higher T_cs could be reached by increasing $N(E_F)$ and/or the electron-phonon coupling. Possibly we could enhance the latter by polaron formation."

- *J.G. Bednorz and K.A. Muller (Nobel lecture 1987).*



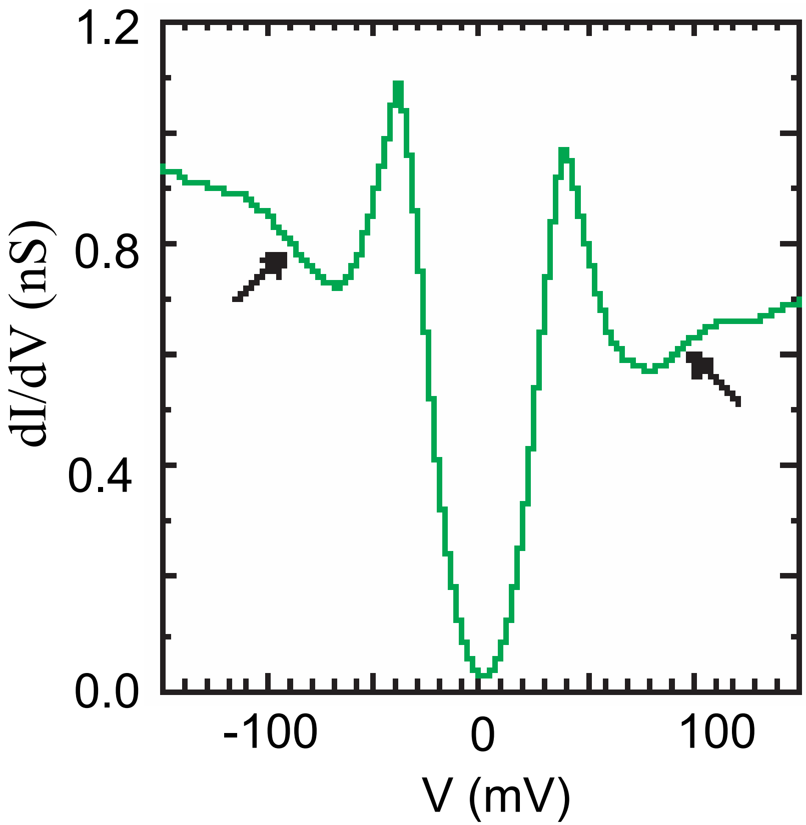
Low-temperature resistivity of a sample with x(Ba) =0.75, recorded for different current densities.

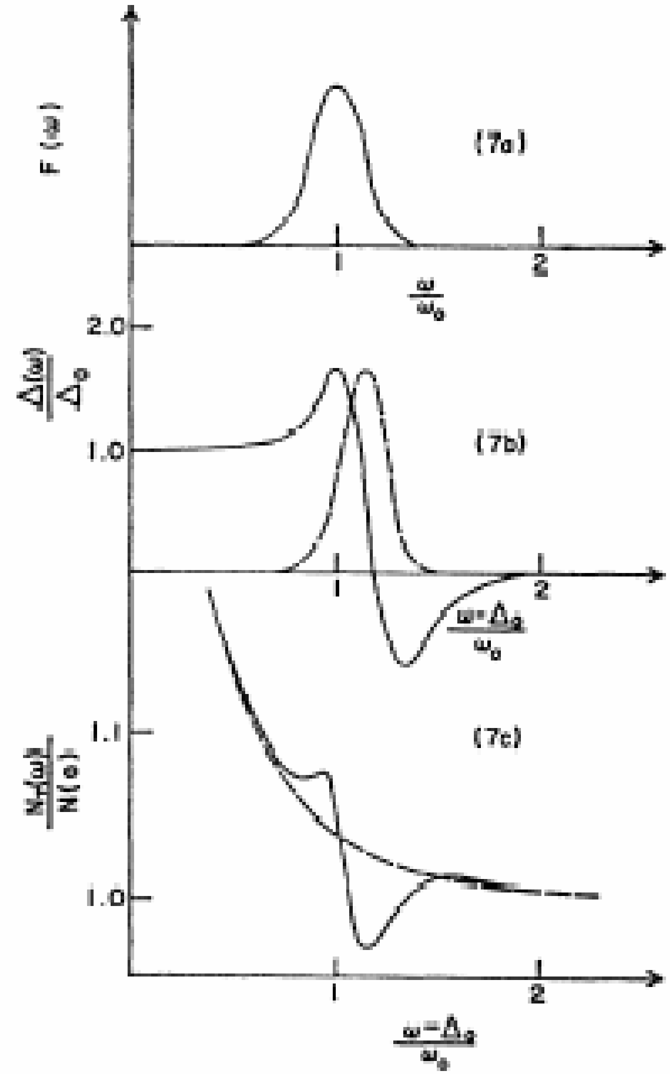
"The fractional Hall effect - - - implies that many electrons, acting in concert, can create new particles having a charge *smaller* than the charge of any individual electron. This is not the way things are supposed to be. - - - If the new particles were doubly charged it wouldn't be so paradoxical- electrons could 'just stick together' and form pairs." - *H.L. Stormer, Nobel prize lecture, 1998, with D.C. Tsui and R.B. Laughlin.*



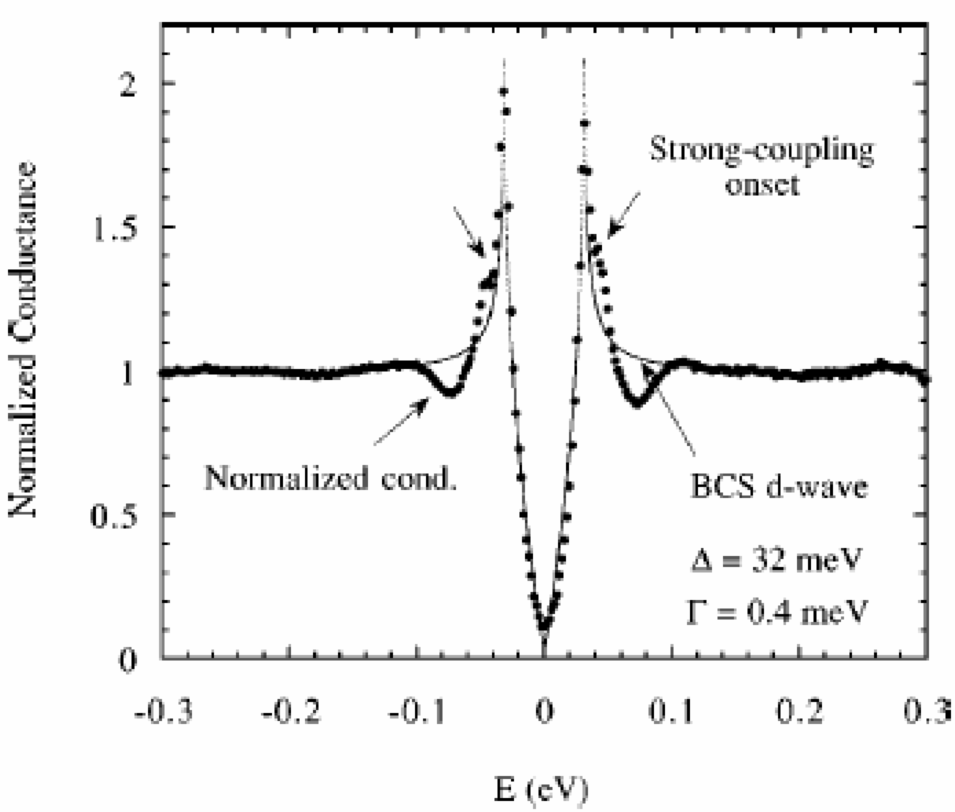
ρ_{xx} *and* ρ_{xy} of a 2DEG in GaAs/$Al_xGa_{1-x}As$ with $n=3.0\times10^{11}/cm^2$ and $\mu=1.3\times10^{6} cm^2/Vs$.

" With the latest advances in d^2I/dV^2 spectroscopy using scanning tunneling microscopy, it has become possible to study bosonic modes directly at the atomic scale." - *Lee et al. 2006*

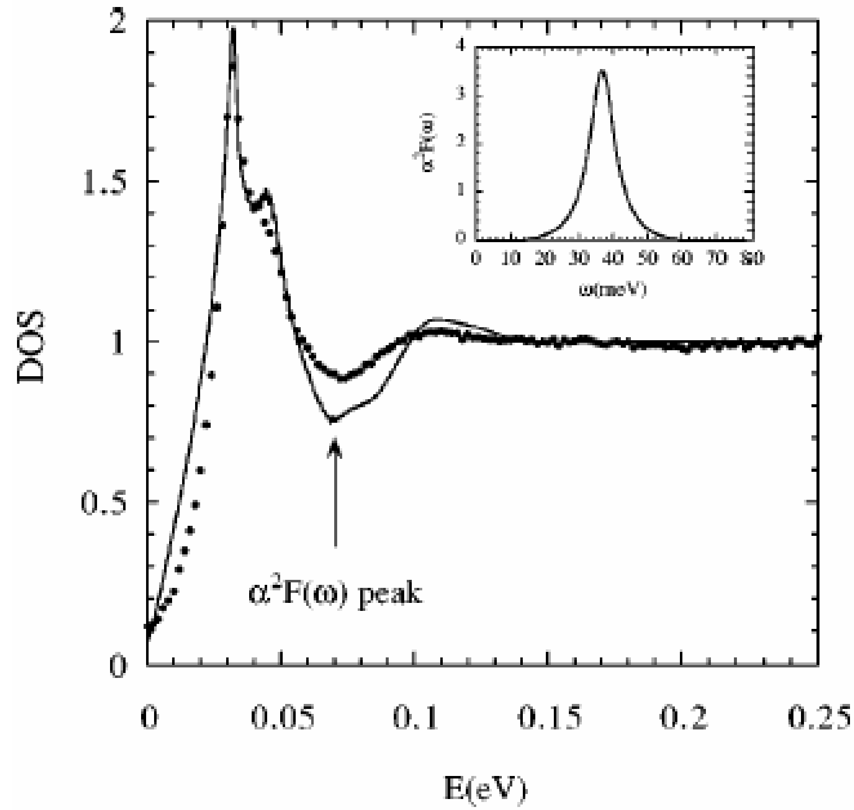




Scalapino, Schrieffer, Wilkins, 1963.



Normalized tunneling conductance data (dots) on Bi-2212. Solid line is a BCS d-wave DOS for comparison.



Positive normalized tunneling conductance data compared with d-wave Eliashberg fit (solid line).

- *J.F. Zasadzinski, L. Coffey, P. Romano, and Z. Yusof, 2003.*

“Although our calculations are based on a rather idealized model, they give a reasonably good account of the equilibrium properties of superconductors.”

“In view of its success with equilibrium properties, it may be hoped that our theory will be able to account for these and for other so far unsolved problems.”

- J. Bardeen, L.N. Cooper, and J.R. Schrieffer, 1957.