Giaever, Nb_3Sn and Josephson

Superconductivity in the Decade after BCS

1957-1967

The Realization of Applied Superconductivity

John M. Rowell

Arizona State University

Bell Labs 1961-83

1935 Mendelssohn's sponge model

1950s Discovery of superconductivity in many alloys & compounds with T_cs up to 18K, e.g., NbTi, NbZr, Nb_3Sn

1952/6 Type II superconductors described by Abrikosov

1954/61 Superconducting magnets made with Nb with fields from 0.7 to 1.5T

1961 Discovery of high critical currents in Nb3Sn at 8.8T

1961 Demonstrations of 5T to 7T magnets using NbZr, NbTi, Nb_3Sn

1962 Appreciation of Abrikosov's work outside Russia

1968 Argonne's 12' bubble chamber magnet - 16' by 10', 50 tons.

1957 Superconducting energy gap measured by millimeter wave and infrared spectroscopy

1960 Tunneling measurement of the energy gap

1962/3 Prediction of the Josephson Effect, observation of the dc and ac effects

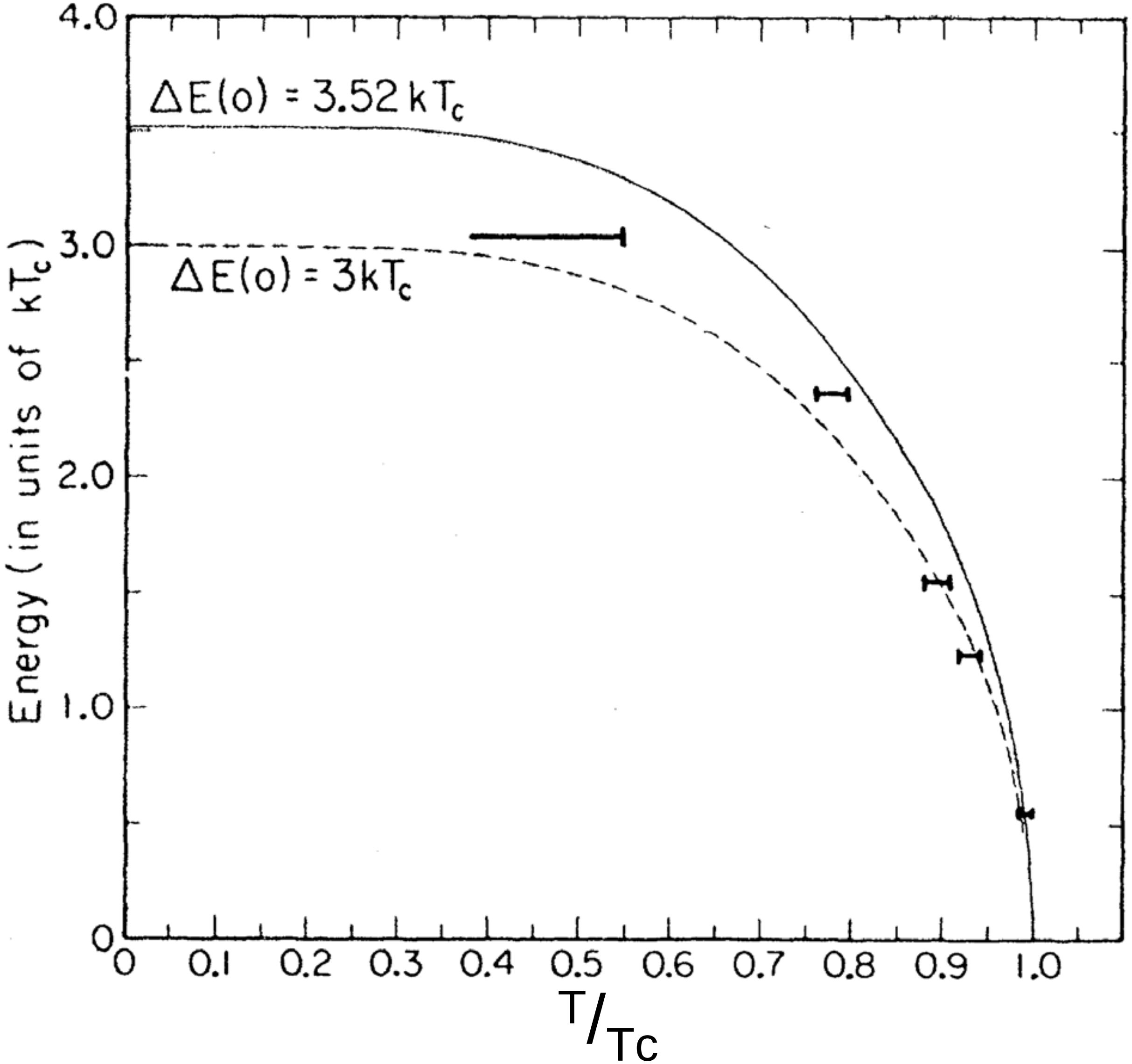
1963/4 Tunneling spectroscopy of the electron-phonon interaction

1964 Interference observed between two Josephson junctions, hence SQUIDS

1964 Josephson Effect extended to weak links

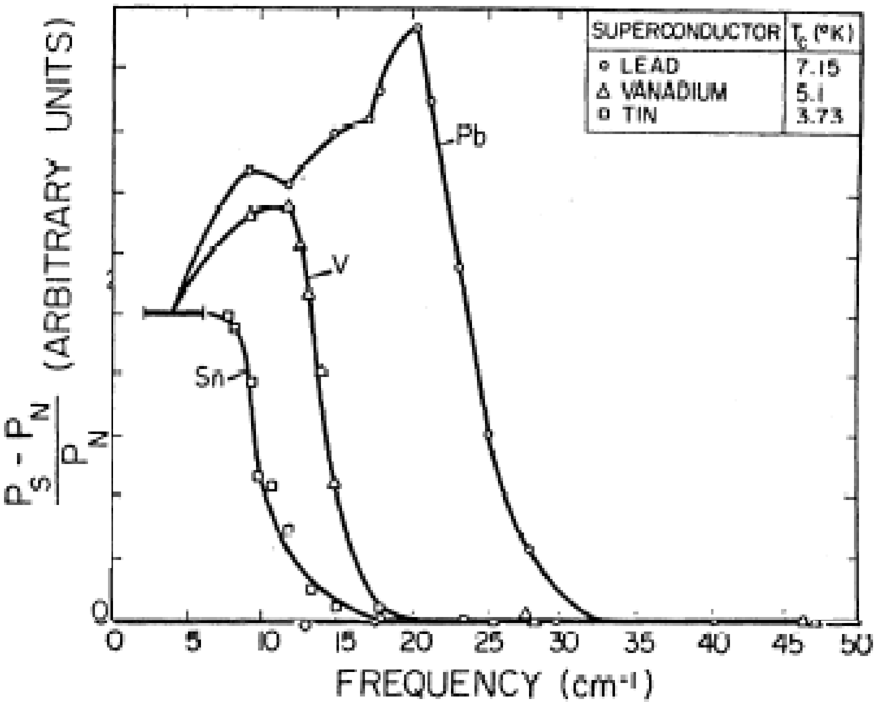
“There is an energy gap for individual-particle excitations which decreases from about $3.5kT_c$ *at* T=0K to zero at T_c.”

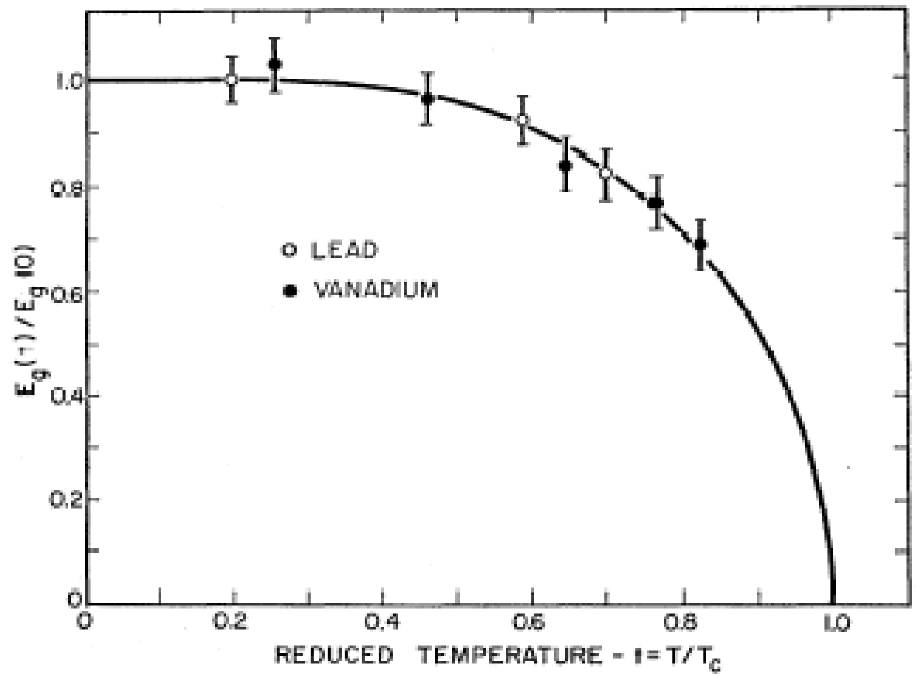
Bardeen, Cooper, and Schrieffer, U. Illinois, 1957.



Millimeter wave measurements of the energy gap of Al versus temperature

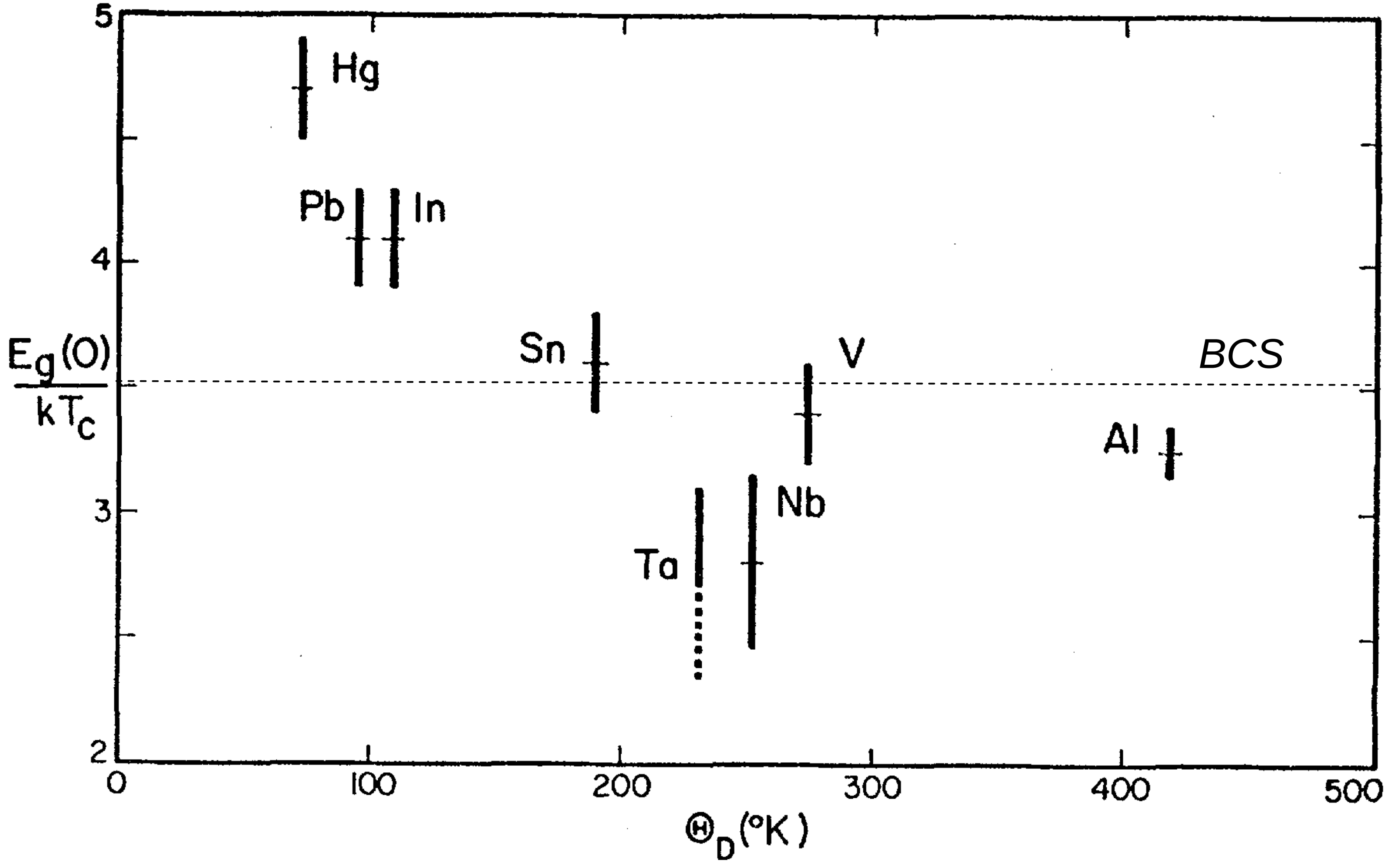
***Biondi, Garfunkel, and McCoubrey, Westinghouse, 1957*.**





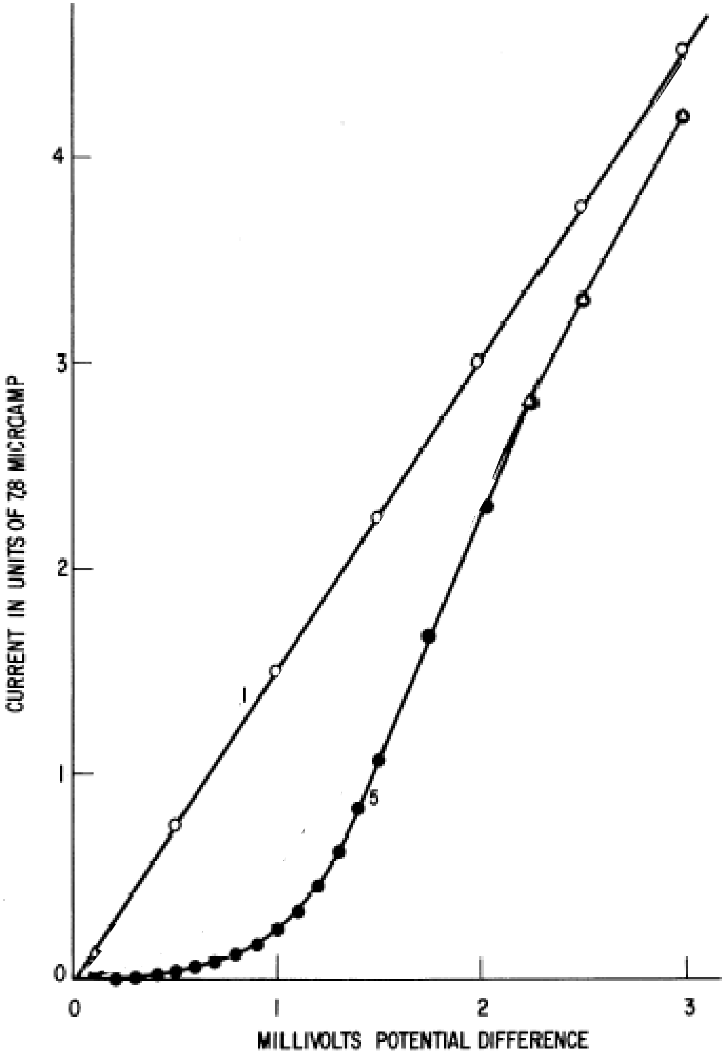
Energy gap by Far Infrared Measurements

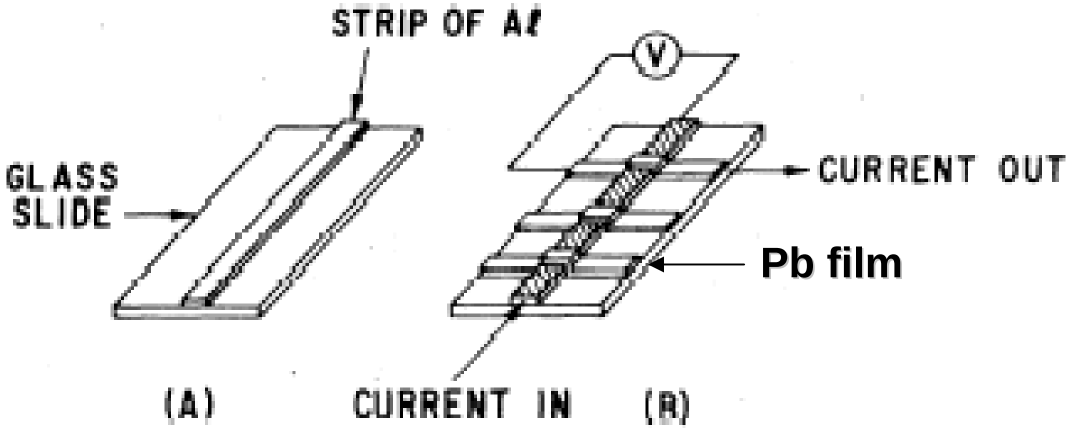
Glover, Richards, Ginsburg, and Tinkham, U.C. Berkeley, 1957-60.



Deviations from $2\Delta = 3.5\ kT_c$

Richards and Tinkham, U.C. Berkeley, 1960.

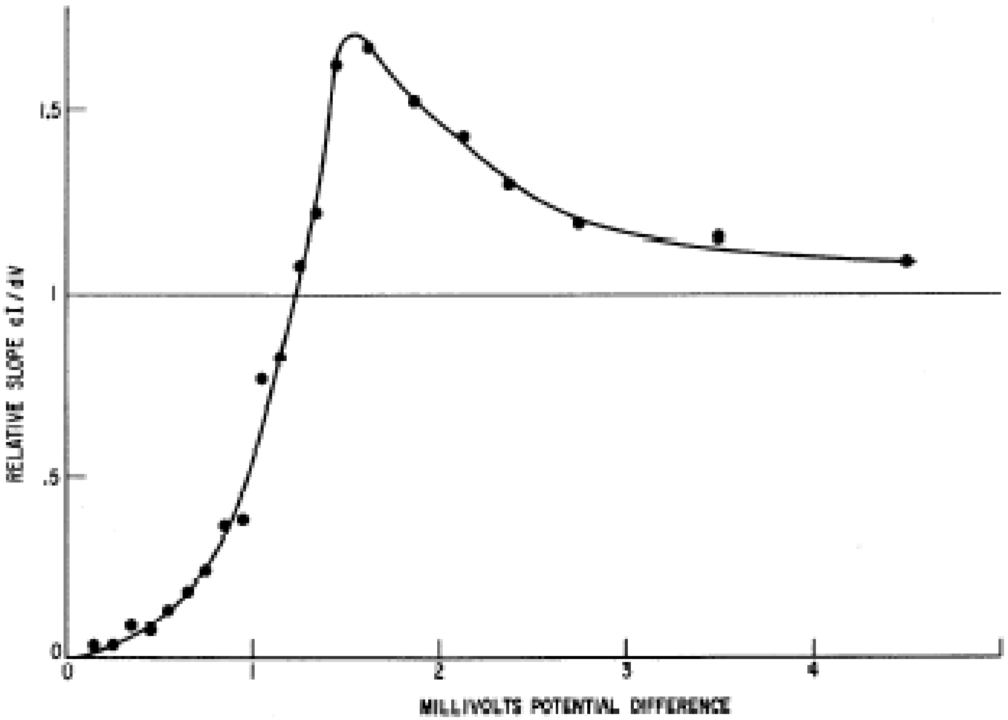




Current versus Voltage for an Al/ I/ Pb junction

Giaever, General Electric, 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. "

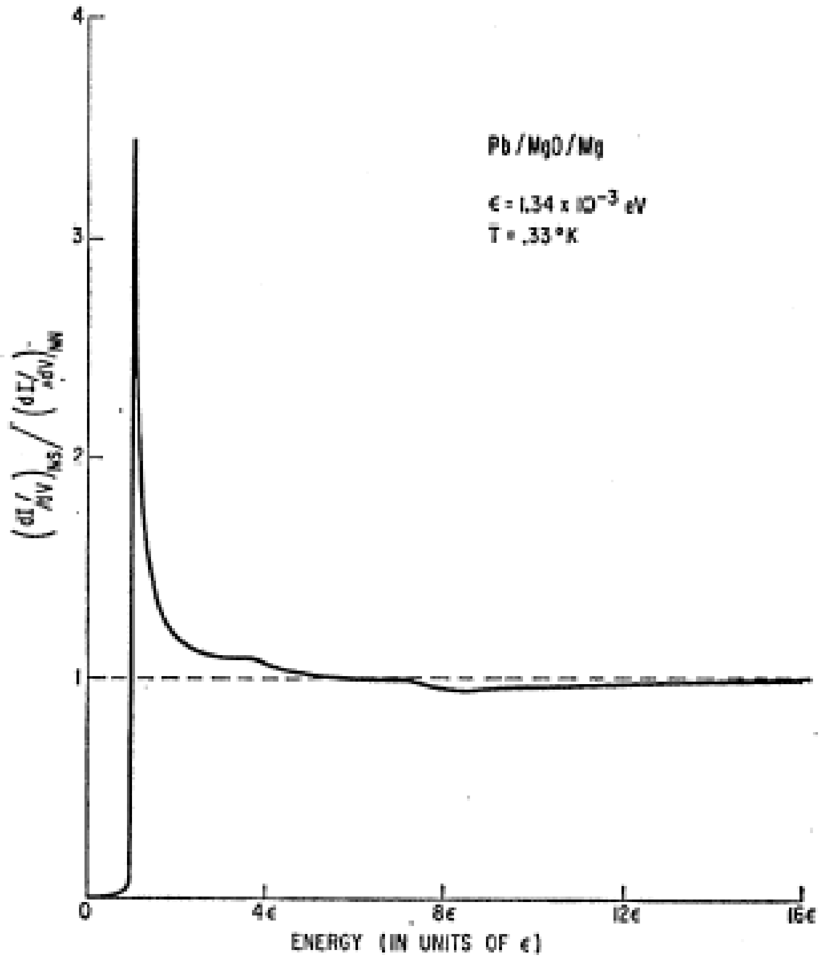


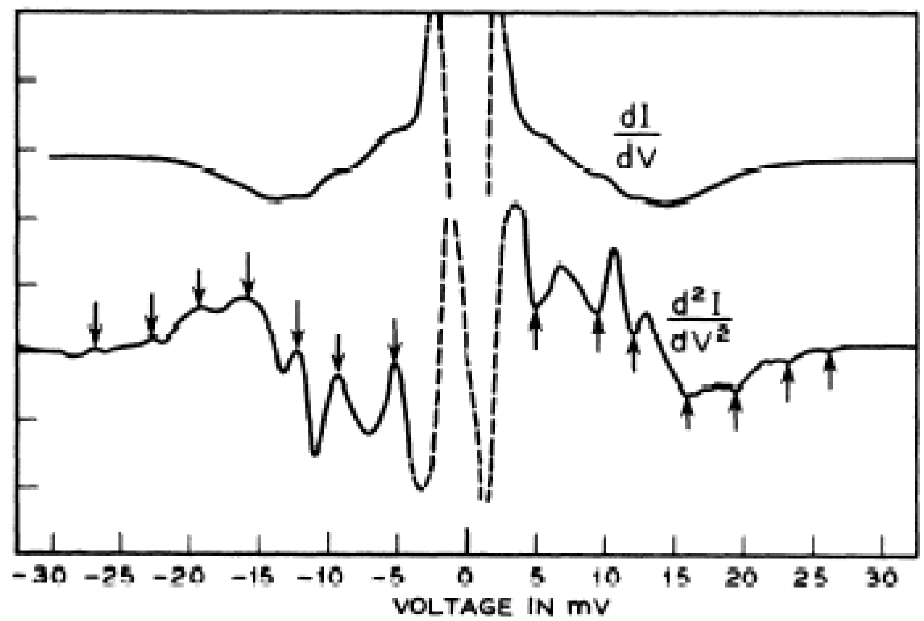
$$\frac{{}^{dI}/_{dV} \text{ with Pb superconducting}}{{}^{dI}/_{dV} \text{ with Pb normal}}$$

Giaever, General Electric, 1960.

“ 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 ”

Giaever, Hart, and Megerle, General Electric, 1962.

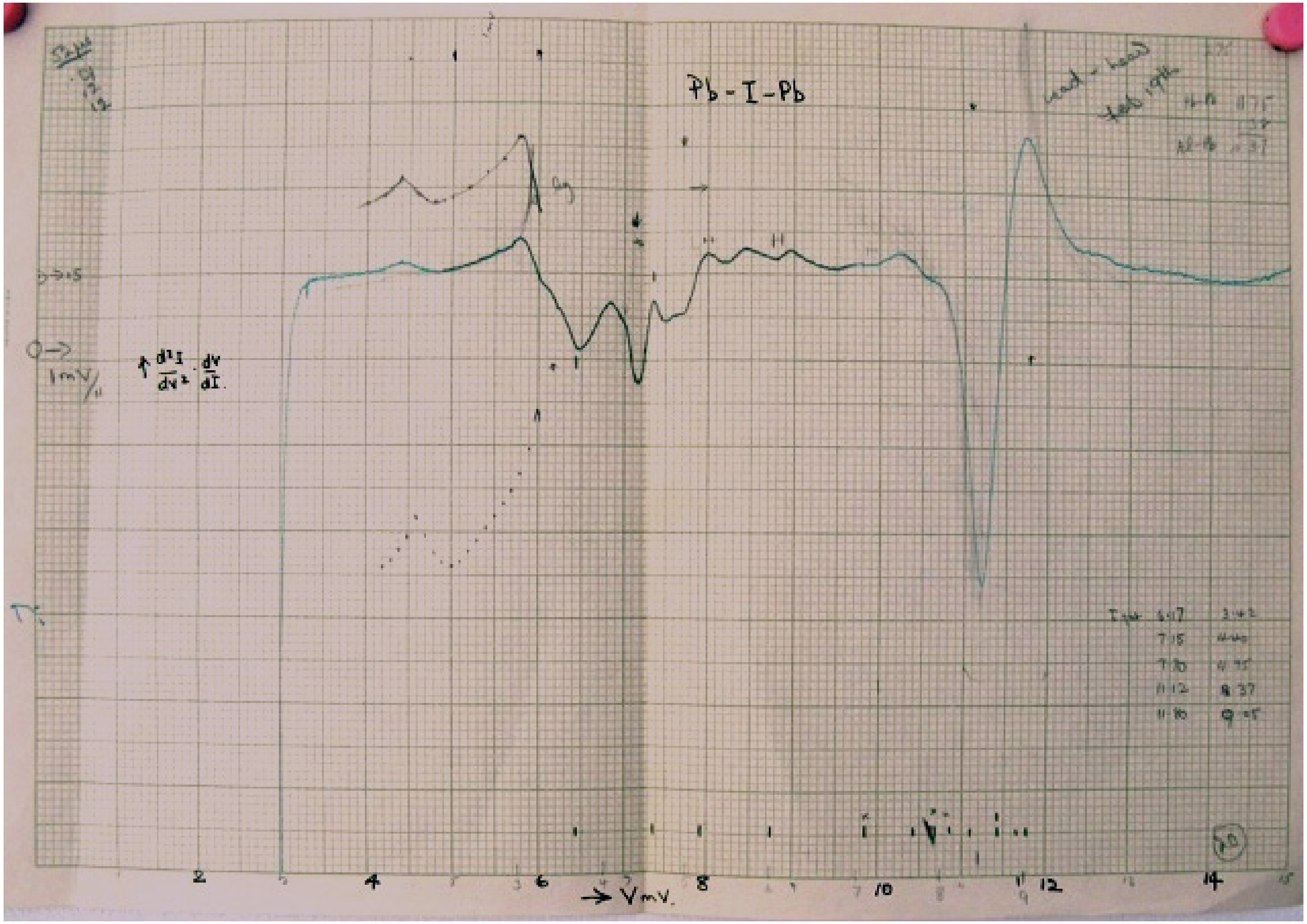




Rowell, Chynoweth, Phillips, Bell Labs, 1962.

“ 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 ”

Rowell, Anderson, and Thomas, Bell Labs, 1963.



.0

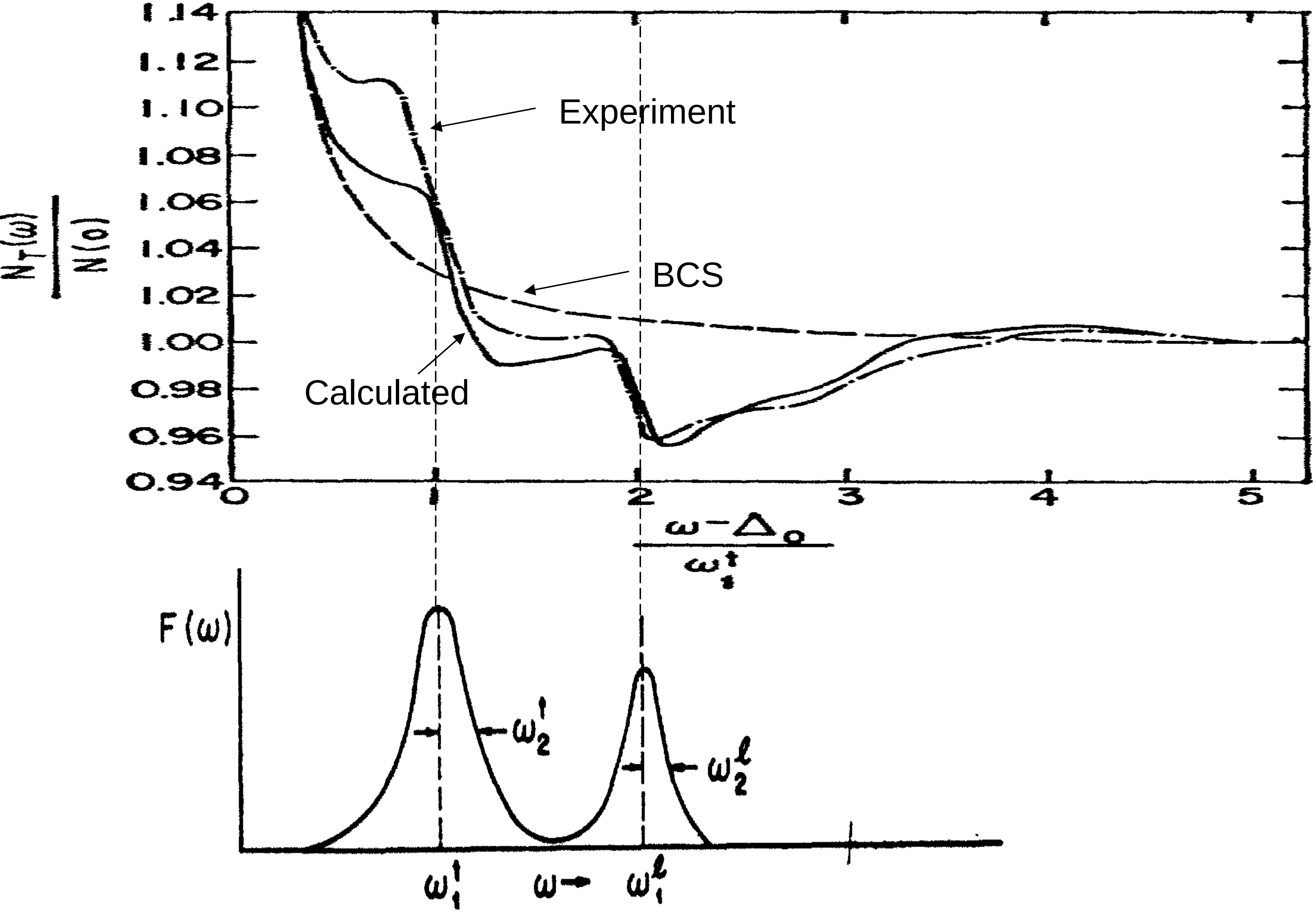
d^2I/dV^2 vs V (measured from 2Δ) for a Pb-Pb junction at 1.3K.

The "post BCS" theory of strong coupling superconductors evolved through the contributions of Bogoluibov (1958), Migdal (1958), Eliashberg (1960), Morel and Anderson (1962), Swihart (1962), and Schrieffer, Culler, and Huff, Scalapino and Wilkins (1962-3)

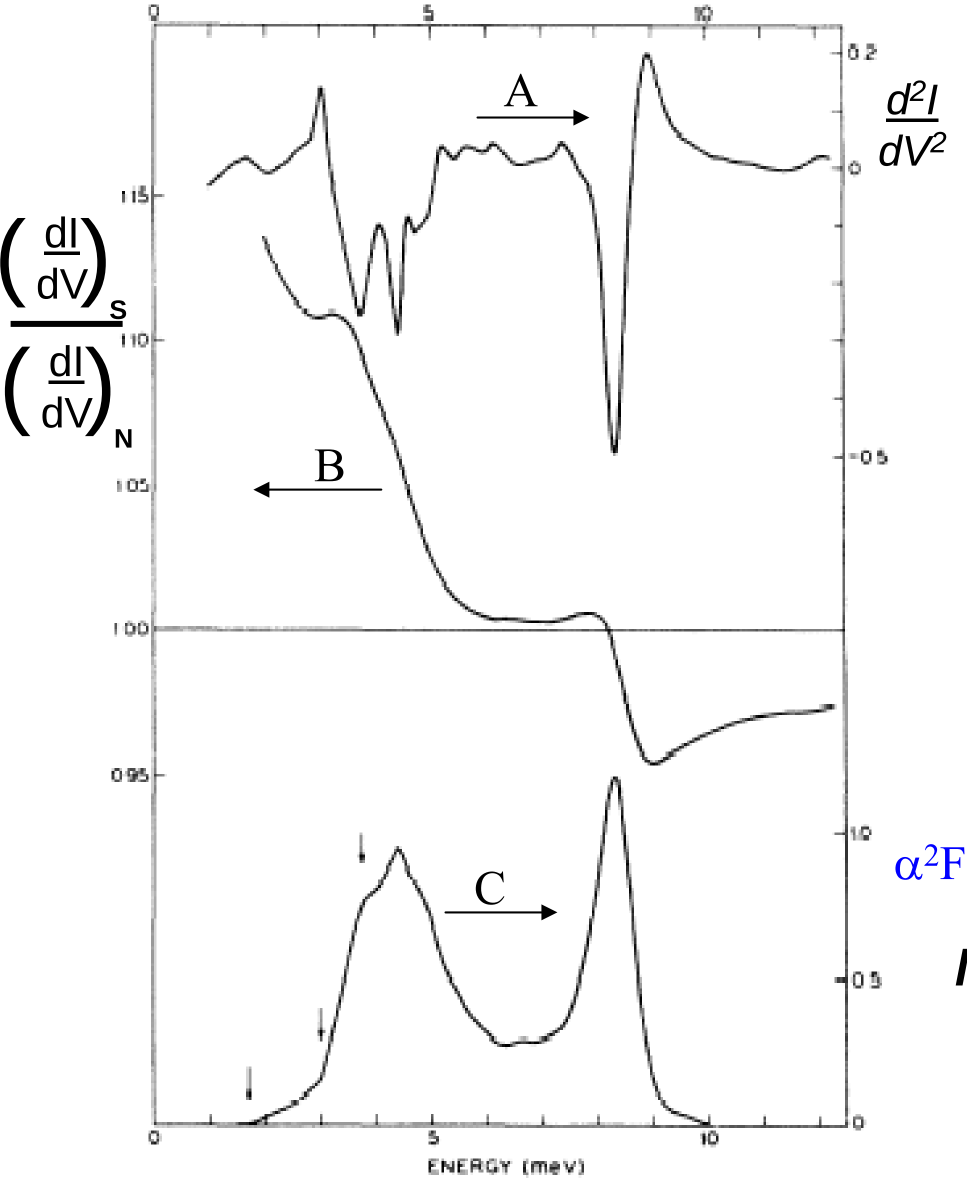
Tunneling into superconductors was described by Cohen, Falicov and Phillips (1962)

Scalapino, Schrieffer and Wilkins (1963) linked the tunneling density of states to the complex energy dependent gap parameter

$$\frac{N(w)}{N(0)} = \mathrm{Re}\left\{ \frac{|w|}{[w^2 - \Delta^2(w)]^{1/2}} \right\}$$



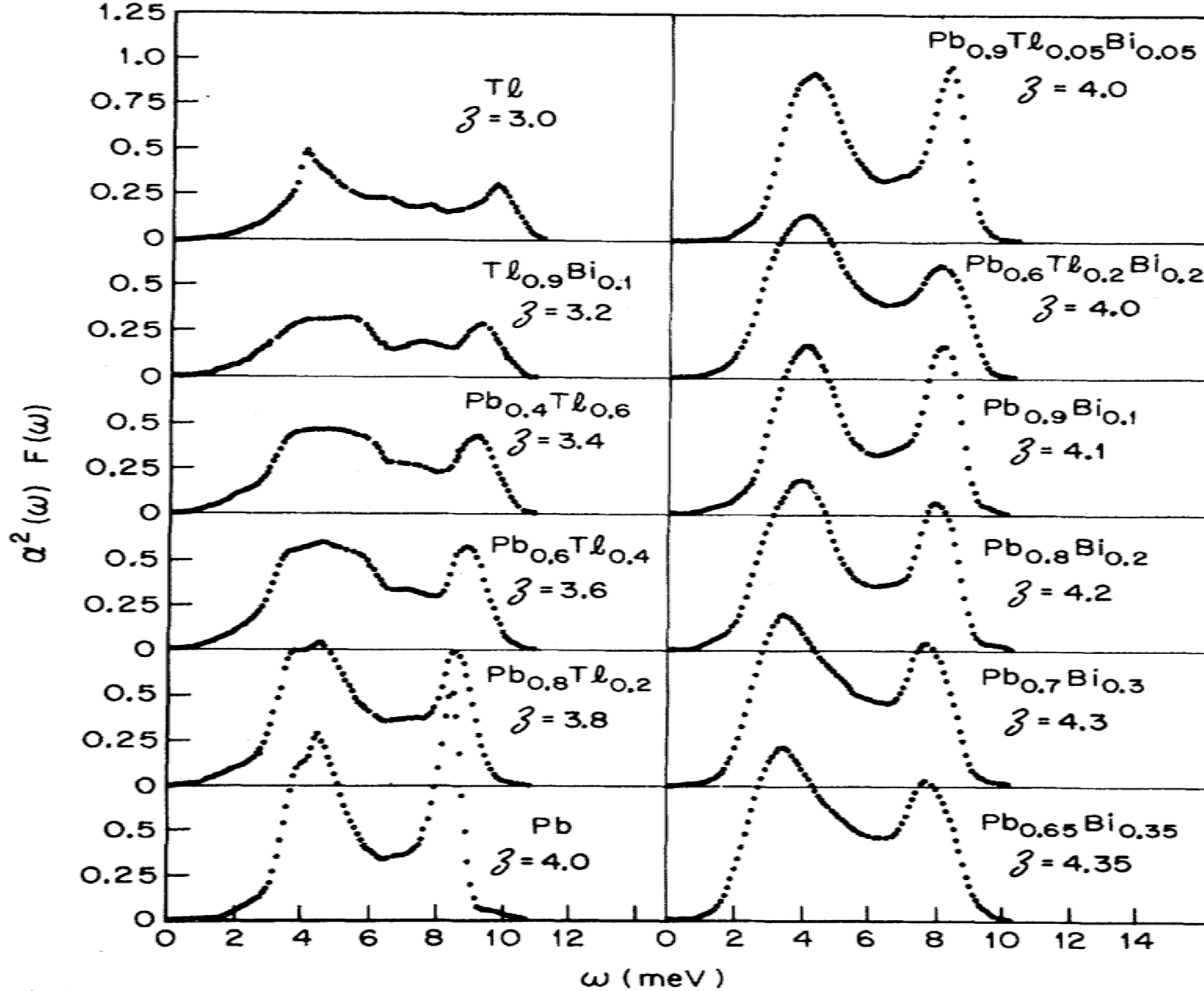
Schrieffer, Scalapino, Wilkins, University of Pennsylvania, 1963.
Rowell, Anderson, Thomas, Bell Labs, 1963.



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."

McMillan, London Prize lecture, 1978.

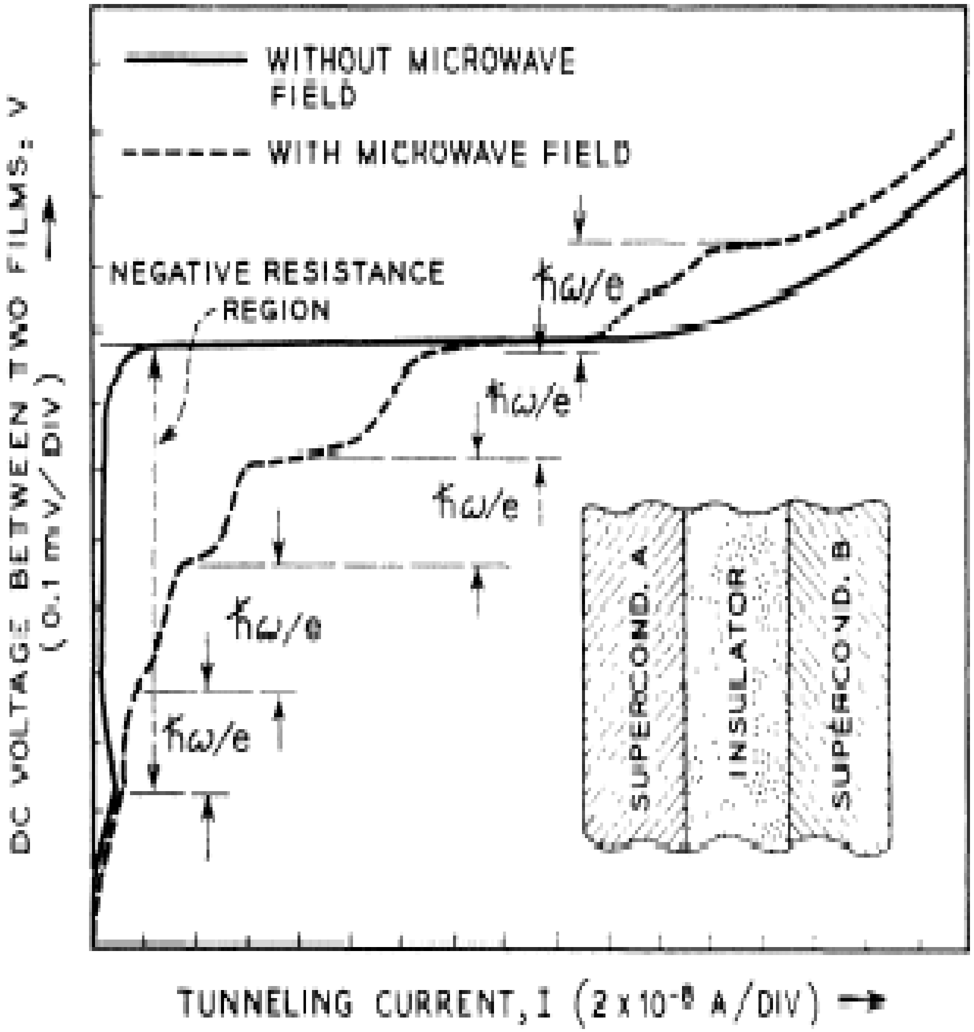
McMillan and Rowell, Bell Labs, 1964.



Dynes, Rowell, Bell Labs, 1974.

"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, Univ. Pennsylvania, 1961.

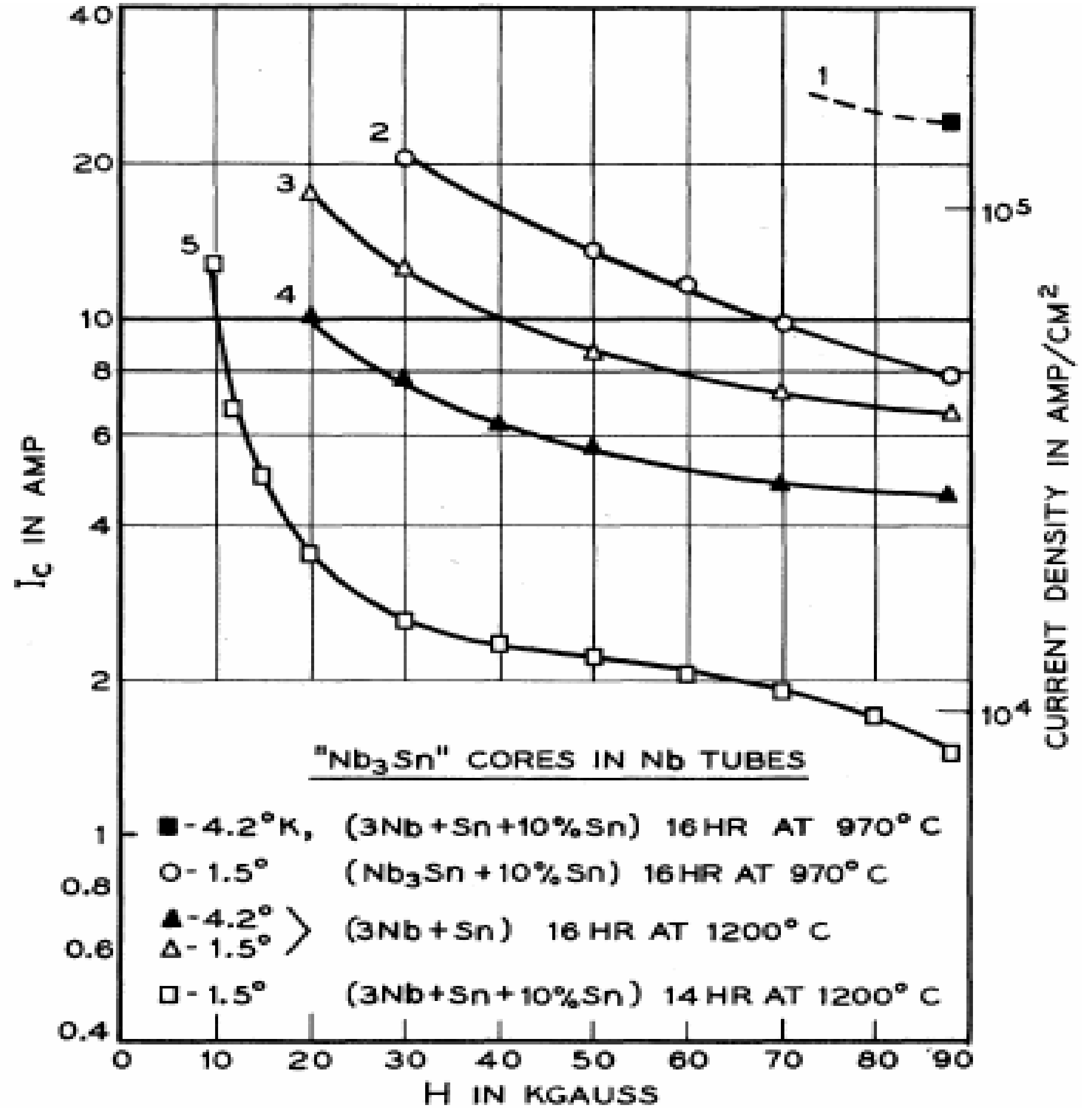


Dayem and Martin, Bell Labs, 1962.

Large Supercurrents @ High Magnetic Fields in Nb_3Sn

Nb_3Sn with T_c = 18 K

Matthias, Geballe, Geller, Corenwit, Bell Labs, 1954.



Kunzler, Buehler, Hsu and Wernick, Bell Labs, 1961.

“whether the absence of Joule heat makes feasible the production of strong magnetic fields using coils without iron, for a current of very great density can be sent through very fine, closely wound wire spirals.”

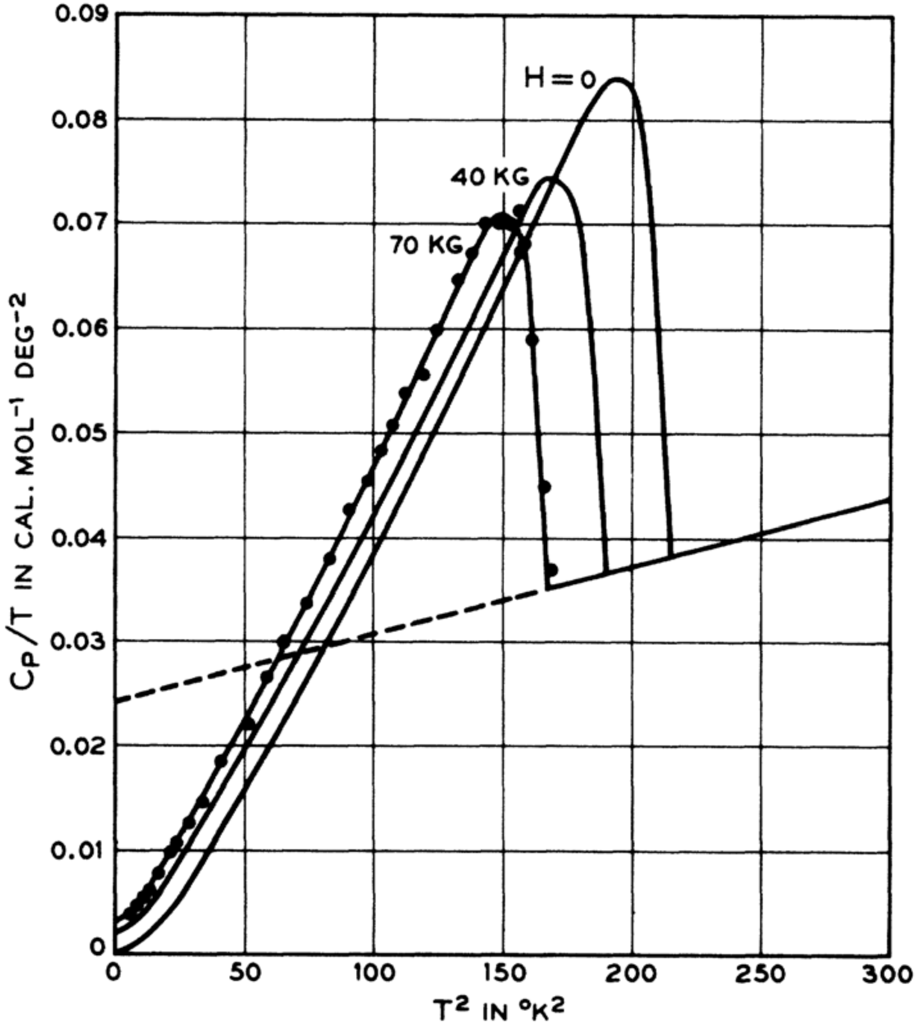
Onnes, Noble lecture,1913.

“these observations suggest the feasibility of constructing superconducting solenoid magnets capable of fields approaching 100 kgauss, such as are desired as laboratory facilities and for containing plasmas for nuclear fusion reactions”

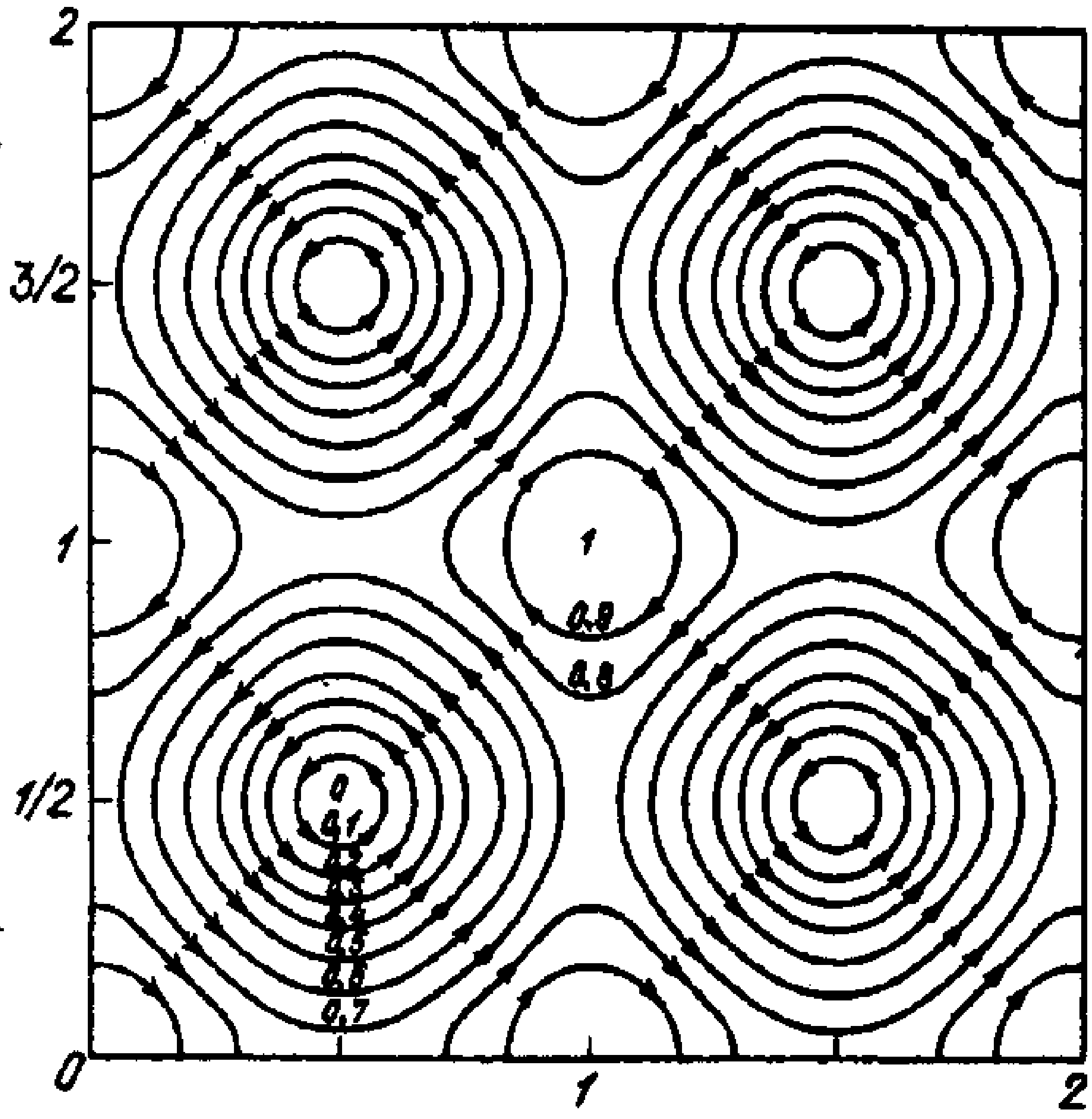
“Although the pertinent physics of the situation is not yet clear, it is tentatively concluded that the conditions of preparation of the clad samples are such as to lead to a structure containing large numbers of “filaments.”

Kunzler, Buehler, Hsu, and Wernick, Bell Labs, 1961.

“data suggest that most of the material remains superconducting even at fields many times the thermodynamic critical field, in spite of the fact that magnetic susceptibility data show that the magnetic field has penetrated most of the sample.”



Morin, Maita, Williams, Sherwood, Wernick and Kunzler, Bell Labs, 1962.



"I published my derivation… in 1952. This was the earliest introduction of type-II superconductors."

A. Abrikosov, Moscow State University, Nobel lecture, 2003.

NbTi Coil
(14 Tesla products in mid 1960s)

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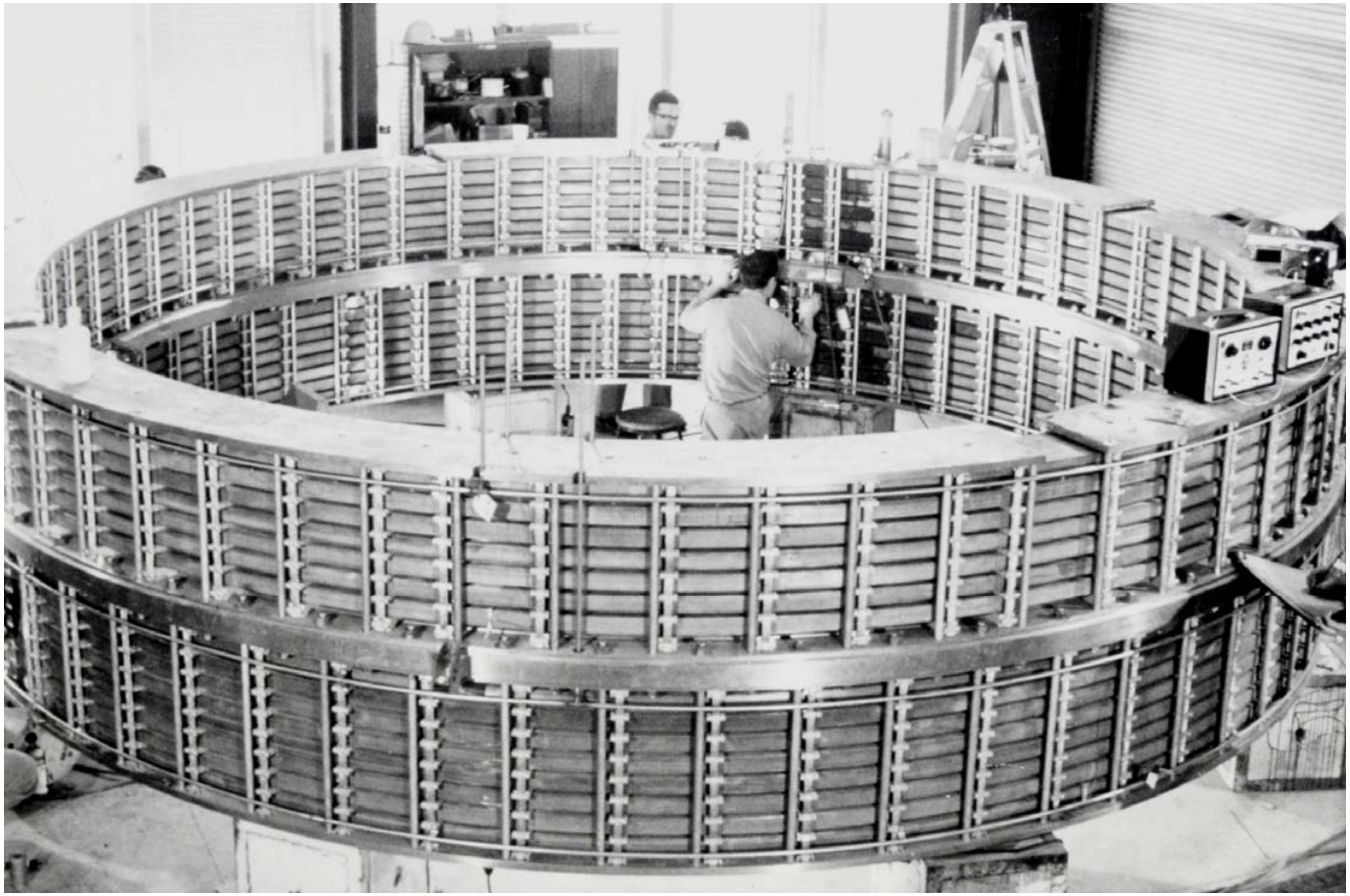


Bubble Chamber Magnet, 1968

Courtesy of Argonne National Lab

Accelerator Magnets in the LHC Tunnel

Superconducting MRI system in operation

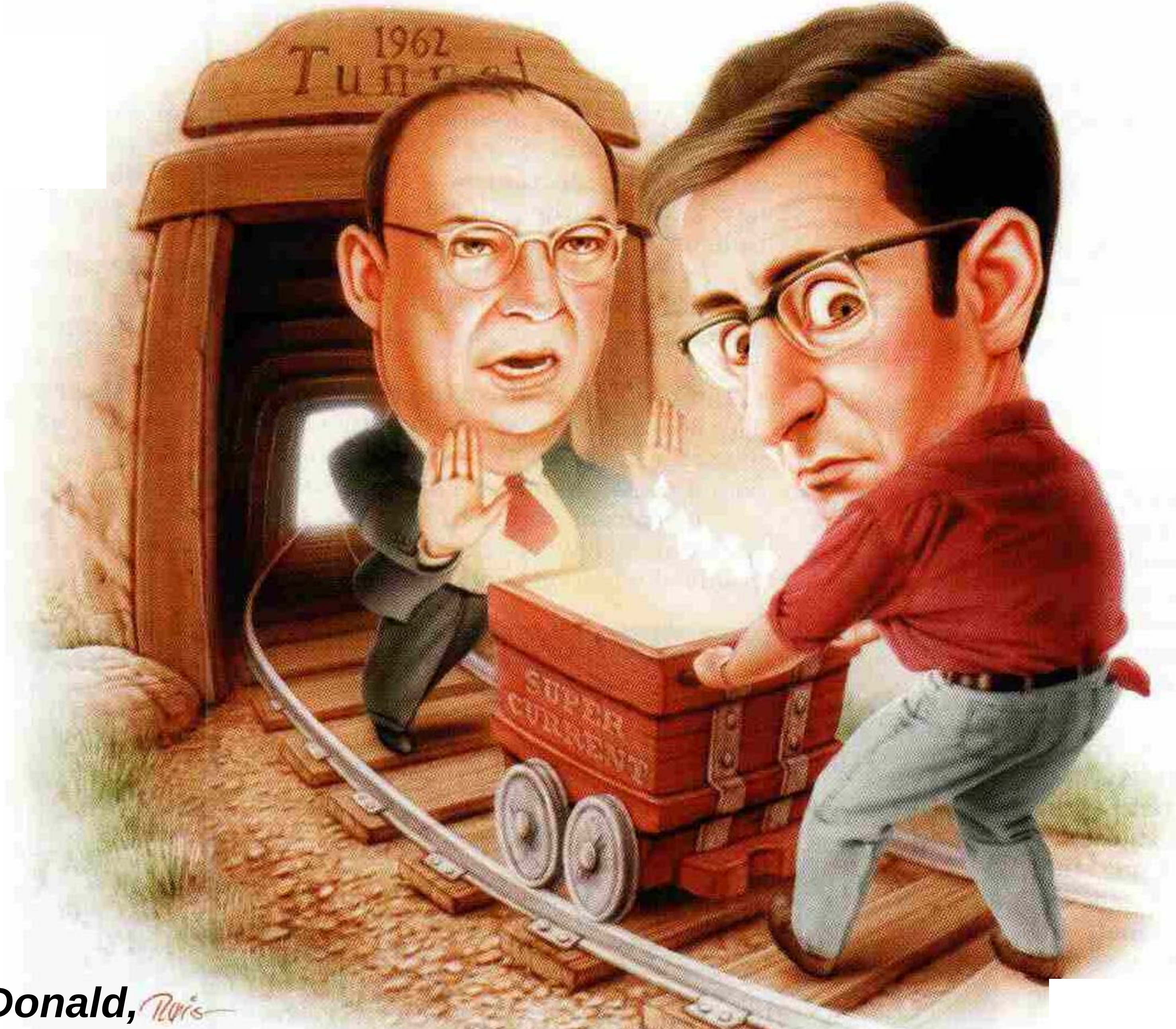
“New effects are predicted, due to the possibility that electron pairs may tunnel through the barrier.

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 $^{2eV}/_{\hbar}$.

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

B.D. Josephson, Cambridge, 1962.



McDonald, Physics Today, 2001.

"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."

Pippard, Cambridge, 1966.

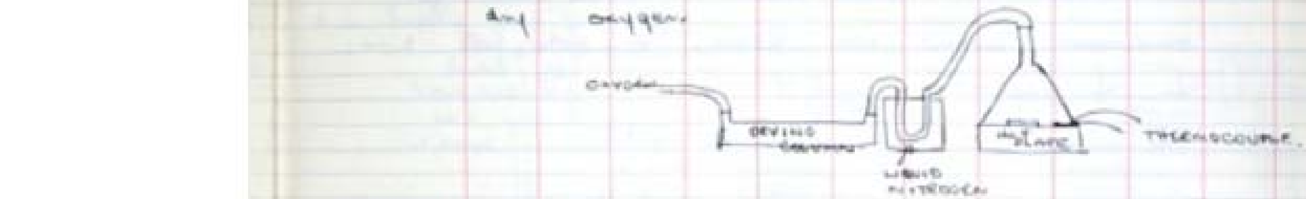
DATE

CASE No. 32722

Jan 24 '58

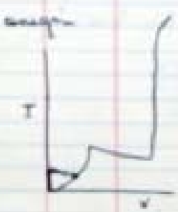
Due to wide variations (shorts to capacitors) of tin - tin oxide - lead sandwiches made by exposure to air for a few days we will try heating.

Tin films (2,000 Å) thick were evaporated on a sapphire substrate at a temperature of 3 mV on chromel alumel thermocouple attached to the cooled block supporting the sapphire. The slides were taken from the evaporator & placed on a hot plate at 50 °C in a stream of dry oxygen.



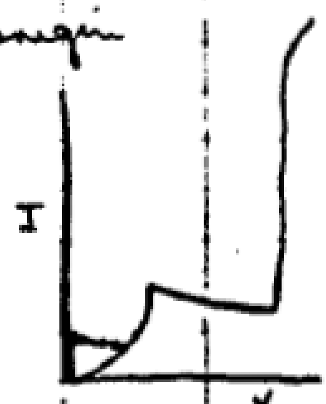
As shown in the notebook of Ian Kopf (notebook 37566) the slides were exposed for 7 & 15 minutes, replaced in the evaporator and crossing lead films (2,000 Å) evaporated. The usual masks were used with junction areas 8.5 10^{-4}, 1.35 10^{-3}, 2.1 10^{-3}, 1.35 10^{-3}, 8.5 10^{-4} sq mm.

Tested at [illegible] 1.7° in helium, all good but low resistance ($<1\,\Omega$) [illegible] show peculiar low resistance at the origin



[illegible] to bar magnet or horseshoe brought up outside the dewar destroys the effect. Tried to burn out by going up to 300 mV but characteristic not altered.

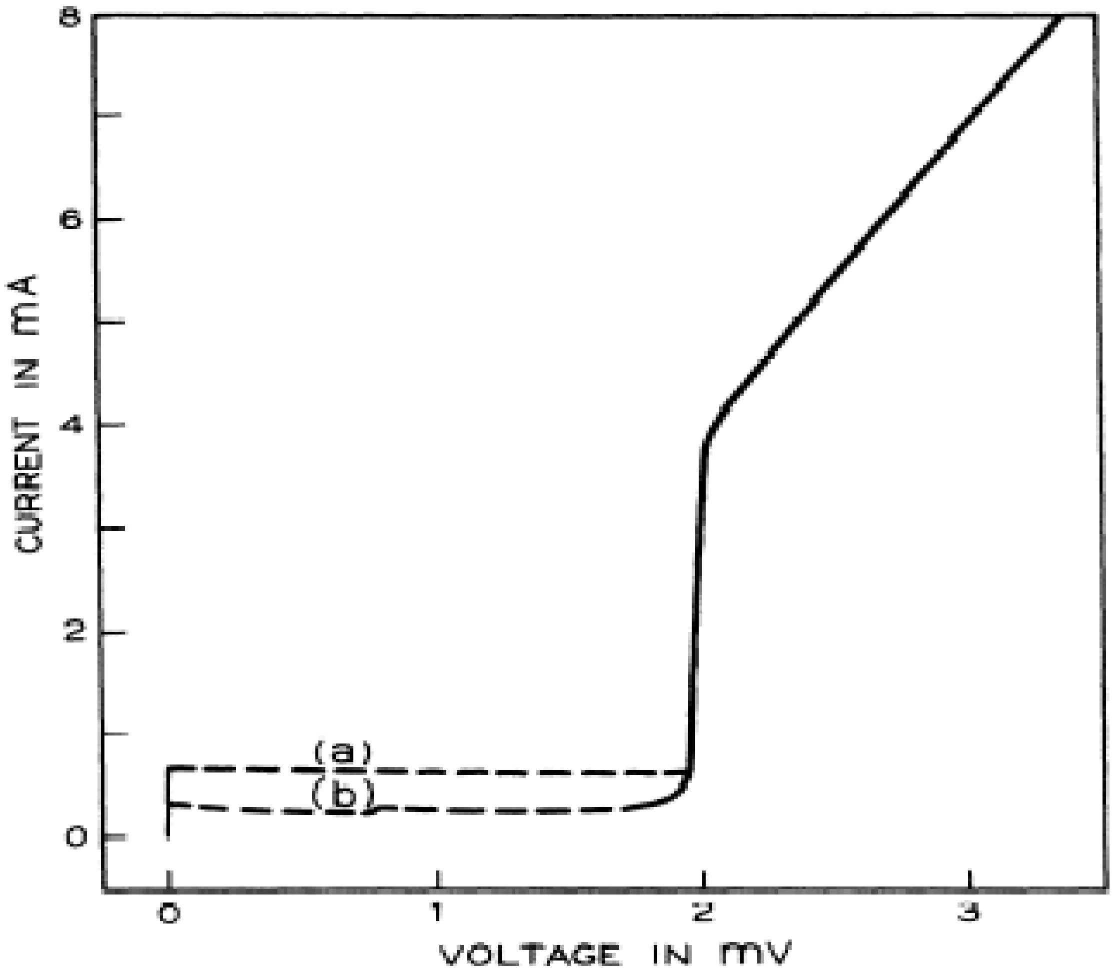
Tested at unit 17 in helium. All good but low resistance (<1Ω) All show peculiar low resistance at the origin

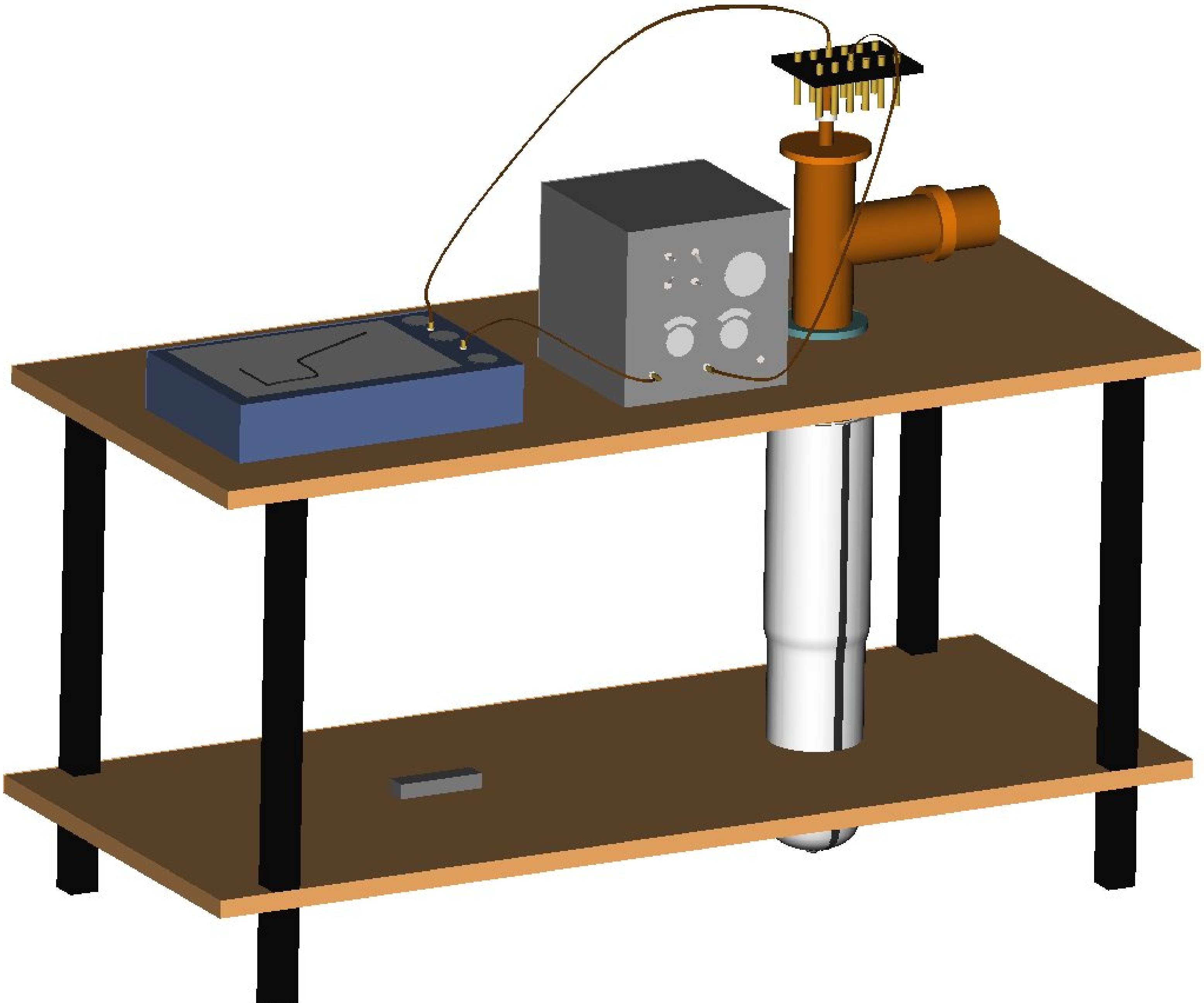


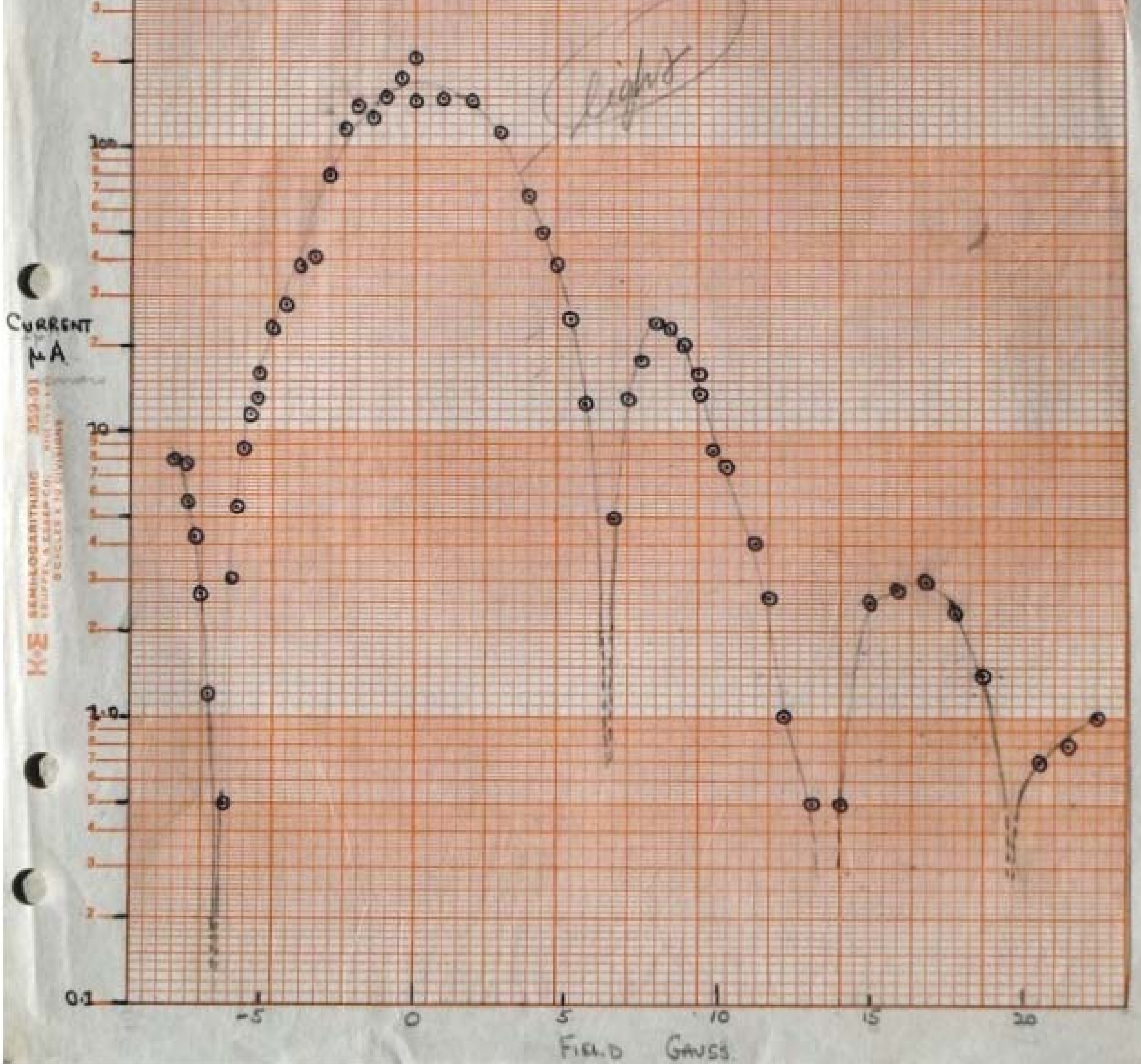
. A bar magnet or horseshoe brought up outside the dewar destroys the effect. Tried to burn out by going up to 300 mV but characteristic unaltered.

"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 - - -"

Anderson and Rowell, Bell Labs, 1963.






CURRENT
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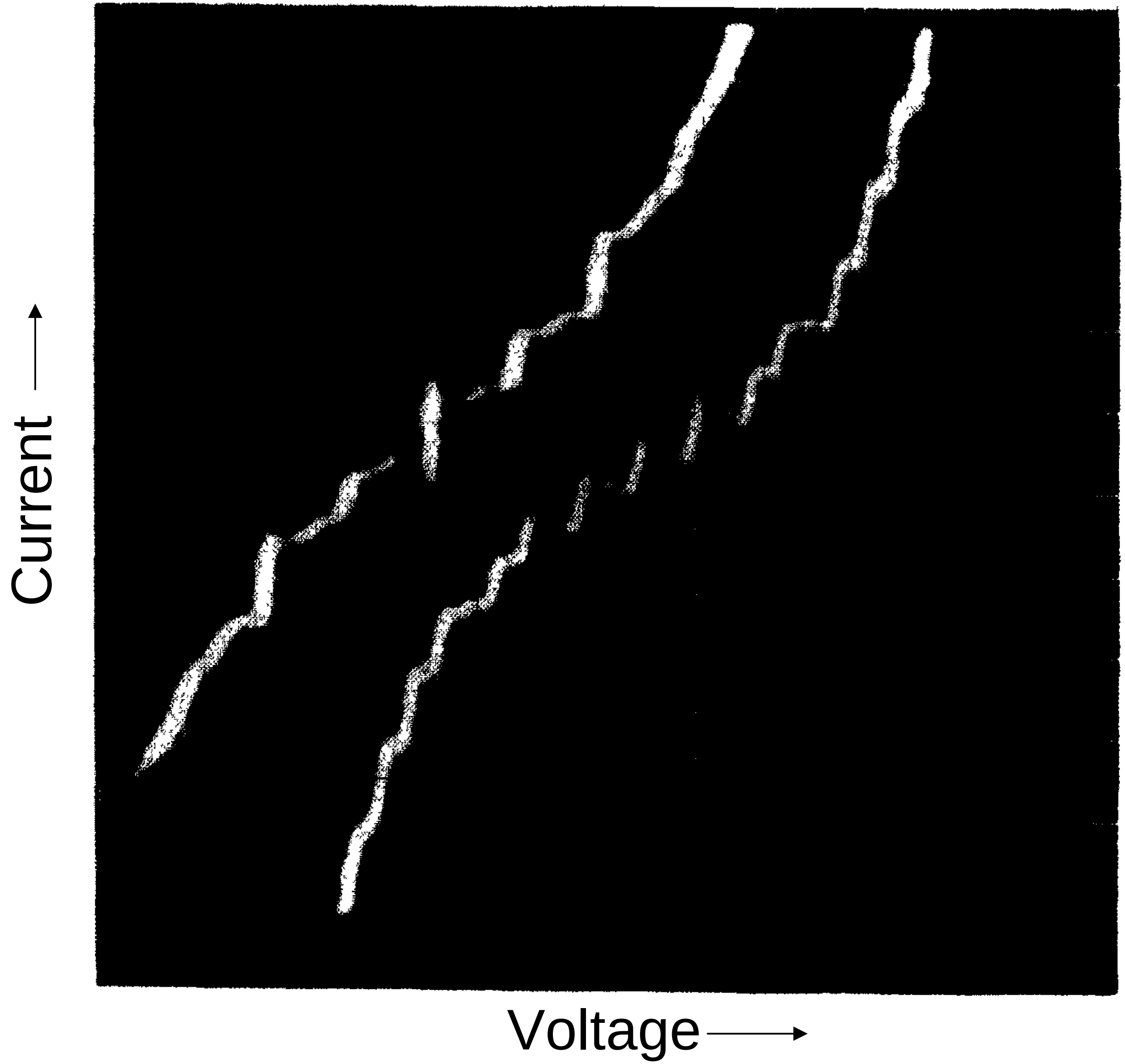
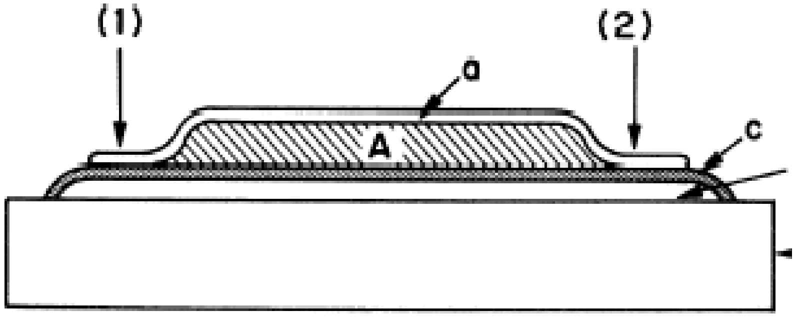


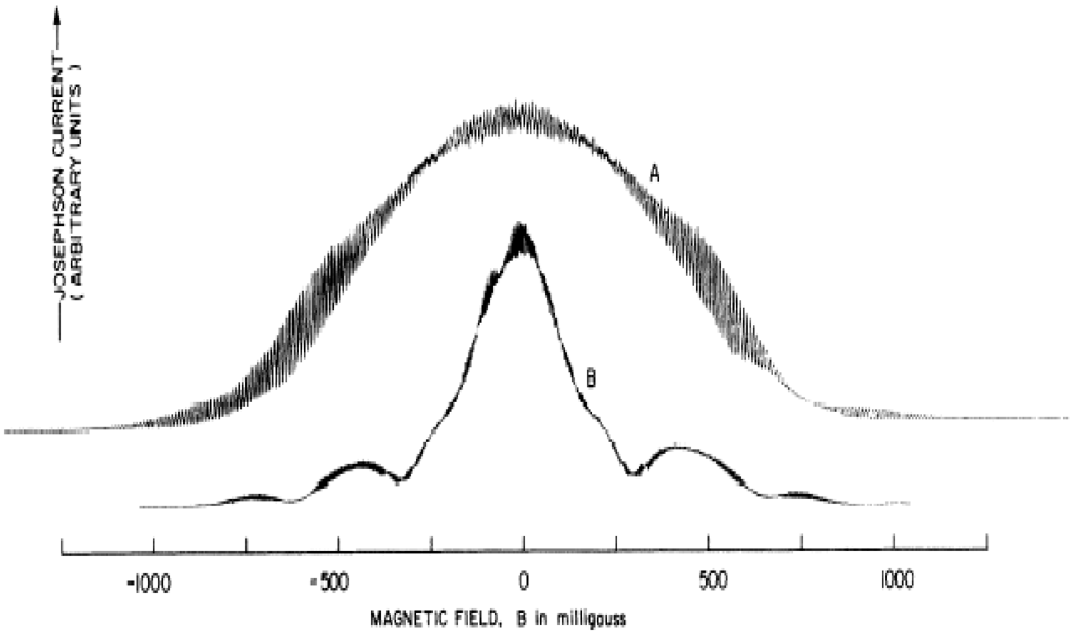
“Microwave steps” in I-V of Josephson junction

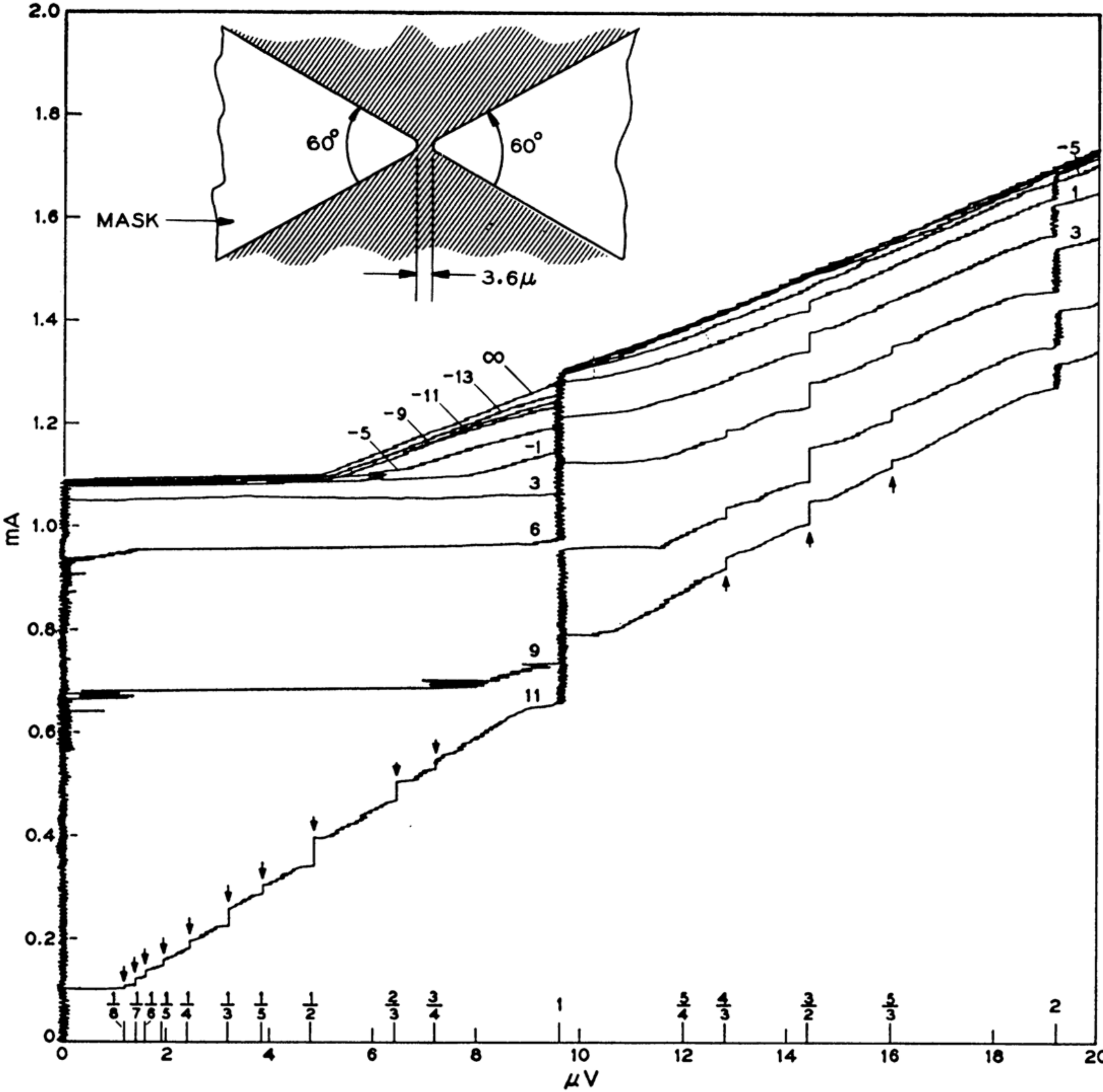
Shapiro, Arthur D. Little, 1963.

“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 ”

Jaklevic, Lambe, Silver, and Mercereau, Ford Lab,1964.

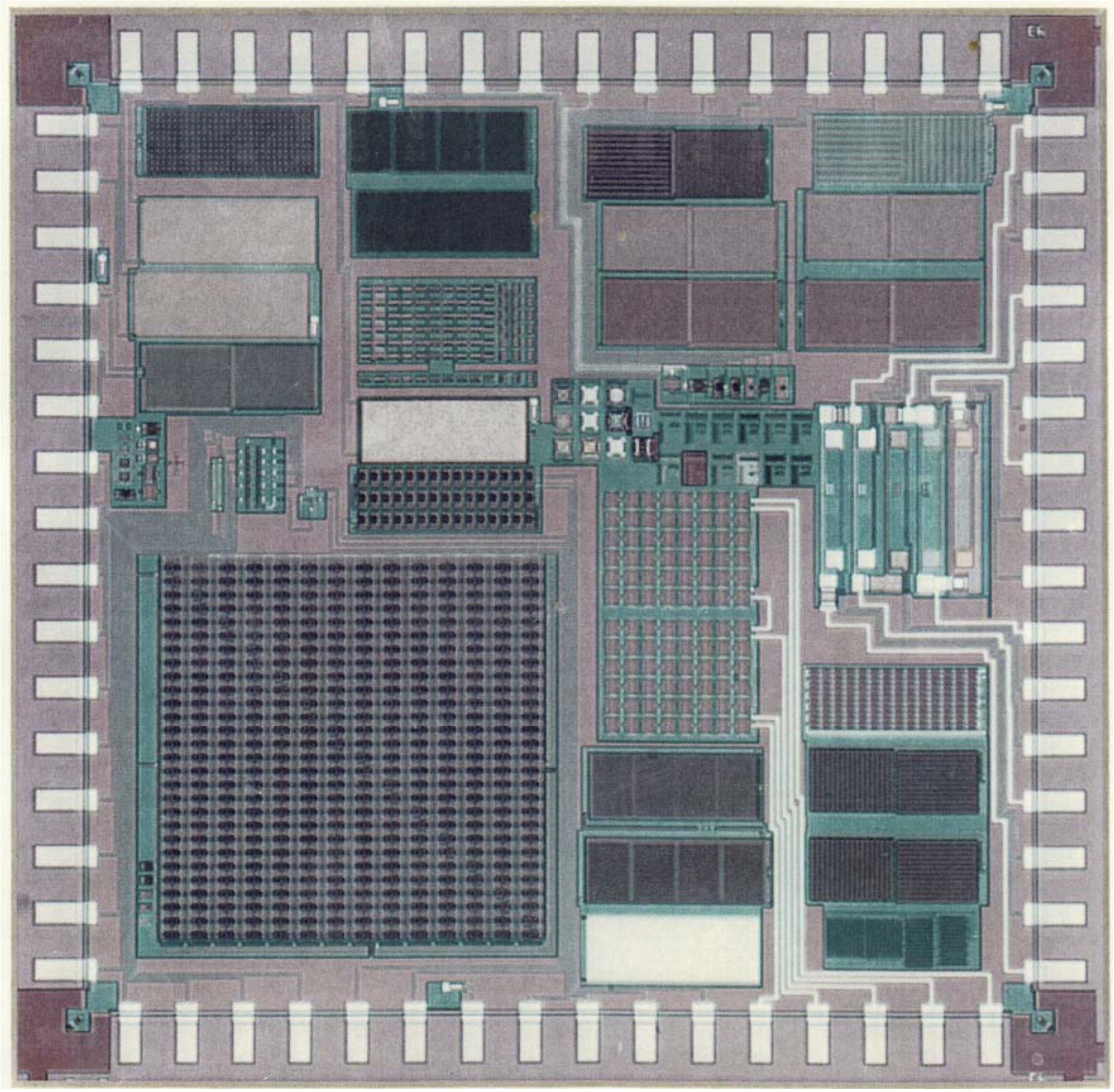






Anderson & Dayem, Bell Labs, 1964.

Superconducting Digital Chip, IBM, 1970s.



Conclusions

The decade after BCS, from 1957 to 67, saw remarkable progress in the understanding of superconductivity, both the science and the early applications

High critical currents at high fields

High Field magnets

Type II superconductors

Tunneling into superconductors

Tunneling spectroscopy of the electron-phonon interaction

The Josephson Effect

Conclusions (cont.)

And – it was a great time to work in industrial research laboratories

A. D. Little, Atomics International, Bell, GE, Ford, IBM, Westinghouse

Many thanks to all the friends I made over 50 years.