Indiana Condensed Matter Playhouse Presents:

Early History of High Field Superconductivity: 1930-1967 A Tragicomedy in Twelve Acts

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NOTES:

1. This play borrows heavily from Ted Berlincourt's "Type II Superconductivity: Quest for Understanding," *IEEE Trans MAG* **23**(2): 403-412, online at <http://mcaf.ee/tqc23>, thanks to Paul Grant - scroll down to the next-to-last listing under "Classic Superconductivity Papers."

2. The following pages are scanned copies of transparencies shown in the pre-PowerPoint era at seminars at Indiana University in February 1989 and UC-San Diego in July 1989. I thank Peter Lee of the National Magnetic Field Laboratory for his invaluable assistance in processing this pdf.

3. The adjective *nutty* is applied to: (a) George Ynetma on page 14 and thereafter; (b) Ted Berlincourt, Don Leslie, and Dick Hake on page 15 and thereafter; (c) Bruce Goodman on page 21 and thereafter. Here *nutty* is used because most observers *erroneously* thought that George, Ted, Don, Dick, and Bruce were *nutty* because of their unorthodox activities and viewpoints.

4. The reference is: Hake, R.R. 2011. "Early History of High Field Superconductivity: 1930-1967 - A Tragicomedy in Twelve Acts," scanned transparencies from seminars at Indiana University and UC-San Diego in 1989; online as ref. 65 at <http://bit.ly/a6M5y0>.

EARLY HISTORY OF HIGH FIELD SUPERCONDUCTIVITY 1930-1967 AD

A Tragicomedy in Twelve Acts

R.R. Hake (borrowing heavily from ref. 1)

I.U. Condensed Matter Playhouse 2/3/89 (slight revisions 7/89)

OUTLINE

REFERENCES

1. T.G. Berlincourt "Type II Superconductivity: Quest for Understanding" [H. Kamerlingh Onnes Symposium on the Origins of Applied Superconductivity] IEEE MAG 23, 903 (1987)

2. J.E. Kunzler "Recollection of Events Associated with the Discovery of High Field-High Current Superconductivity," Ibid., p. 396.

3. G.B. Yntema, "Niobium Superconducting Magnets," ibid., p. 390.

4. A.B. Pippard, "Early Superconducting Research (Except Leiden)," ibid, p. 371.

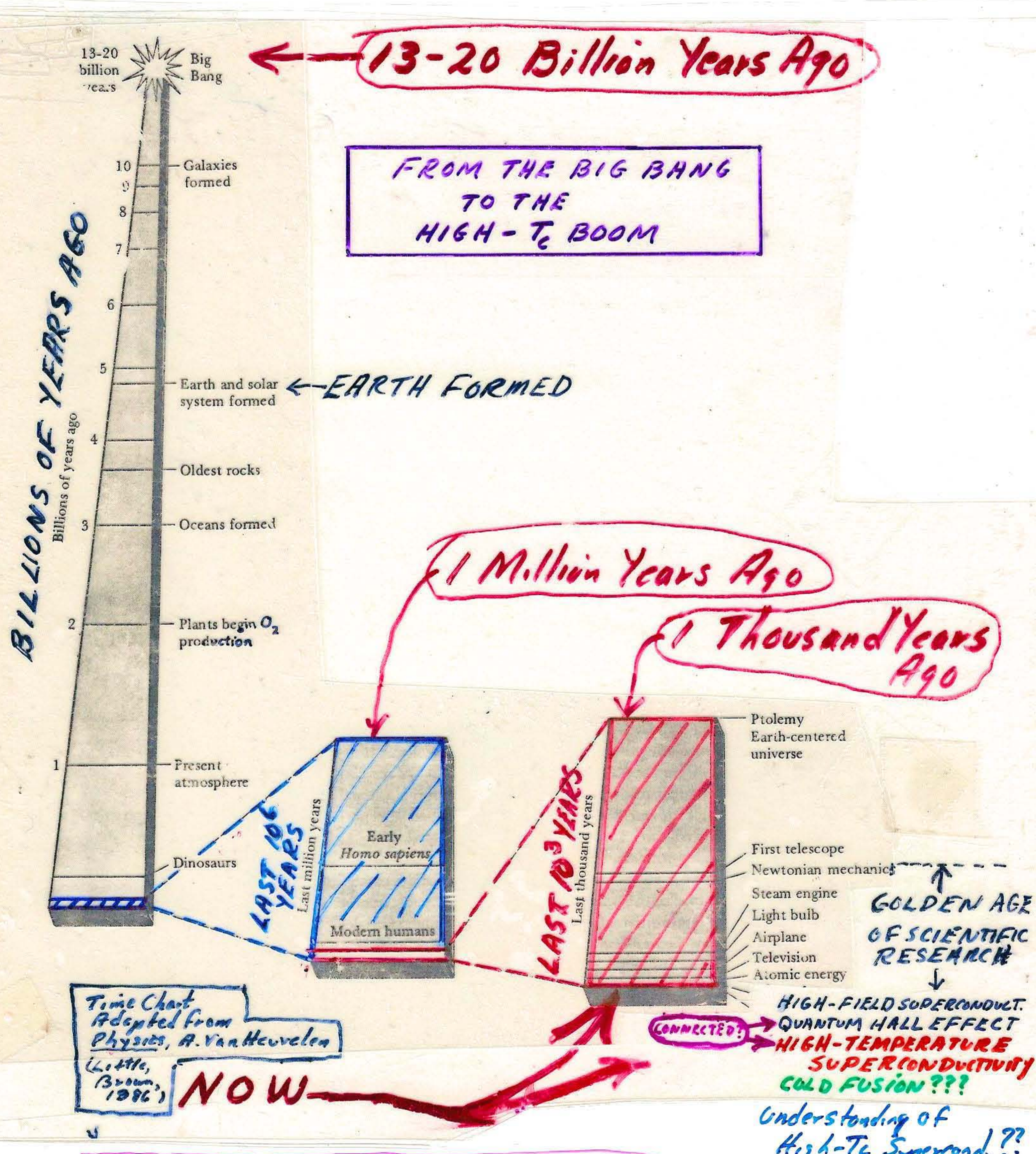
5. R.R. Hake, "High Field Superconductors" in Encyclopedia of Materials Science and Engineering, ed. by M.B. Bever (Pergamon, 1986) p. 2132.

6. T.G. Berlincourt, "Emergence of Nb-Ti as a Supermagnet Material," Cryogenics 27, 283 (1987).

7. E.W. Collings, A Sourcebook of Ti-Alloy Superconductivity (Plenum, 1983); Metallurgy and Physics of Ti Alloys (2 vol.) (Plenum, 1986).

PROLOGUE

"HE WHO KNOWS ONLY HIS OWN GENERATION REMAINS ALWAYS A CHILD"
Cicero (in "Orator")

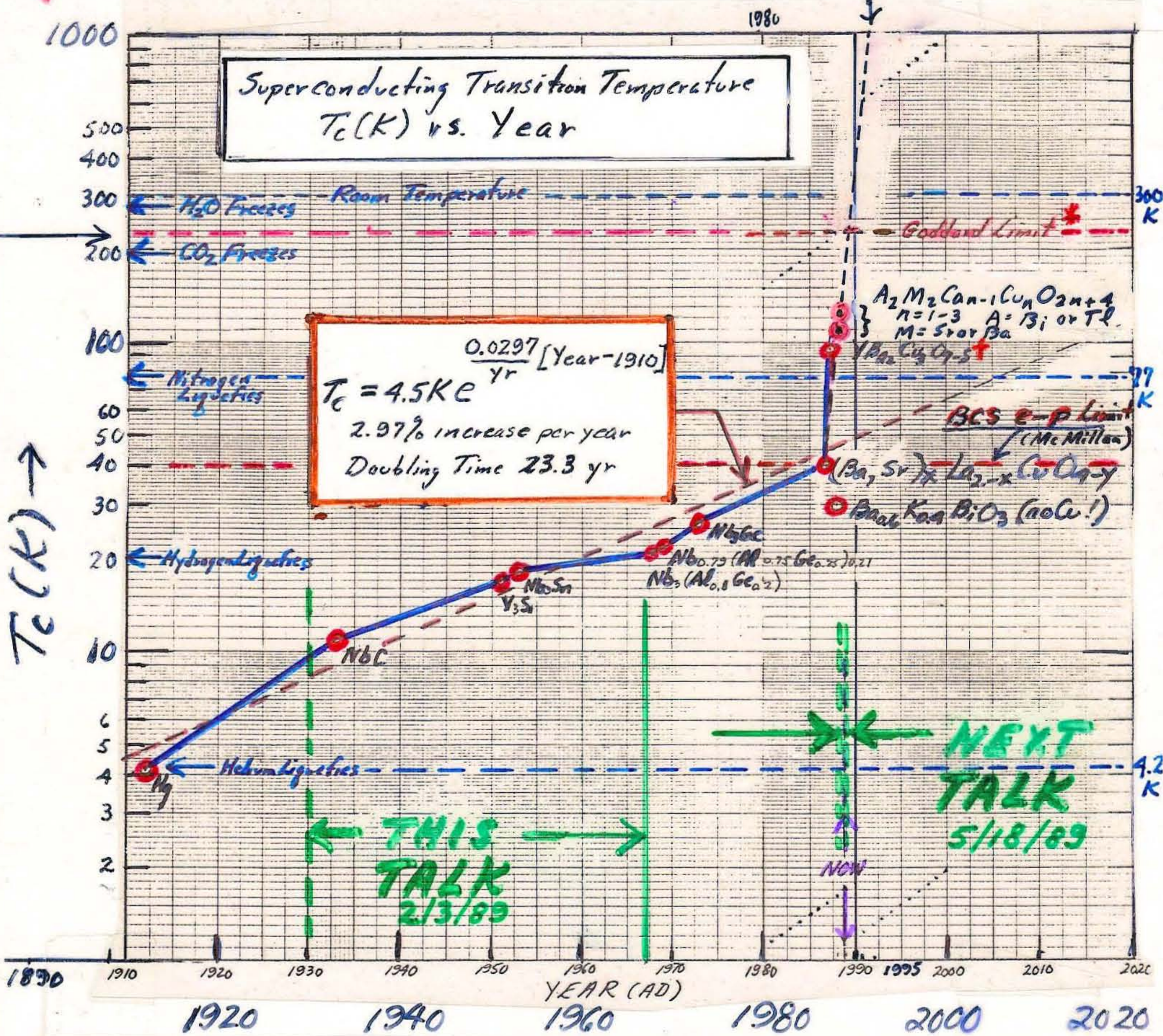


Understanding of High-Tc Supercond.??
$T_c \geq 300\ K$???

"It's a great time to be alive"
A. Einstein

1 Hundred Years Ago

June 25, 1991
$T_c = 1000\,°K$!



Electrons first did some new tricks
In nineteen eighty and six
And on that occasion
Bill's single equation
Showed magnets were giving holes kicks.

[Based on Caltech Alumni News report of Feb. 1989 stating that superconductivity was discovered in 1986 and then explained by Bill Goddard's single equation!]

Note: This graph indicates that the Wu-Chu-Mainland China discovery of $T_c \approx 90K$ represented a DISCONTINUITY in $\log T_c$ vs time. Should the Nobel award have gone only to Bednorz and Muller?

ACT I. PURE OR SPONGE?

W. J. de Haas & J. Voogd, Commun. Phys. Lab U. Leiden #208b (1930); ibid. #214b (1931)

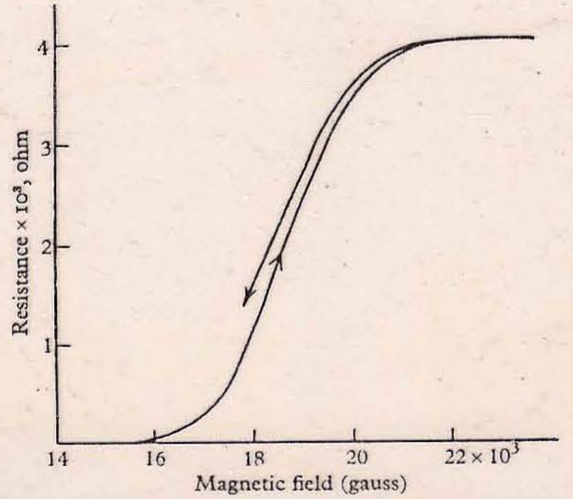


Fig. 14. Restoration of resistance of Pb-Bi eutectic by a magnetic field at 4·2° K. (de Haas and Voogd, 1930).

[Attempts at technological application for production of high H-fields in superconducting wire solenoids at Leiden (1935) and Kharkov (1935) failed. Why?]

Early Ideas on High-Field Superconductivity

I. Could be bulk property of HOMOGENEOUS (**PURE**) materials associated with negative interphase surface energy:

H. London, Proc. Roy. Soc. (London) A152, 650 (1935)
C. J. Gorter, Physica 2, 449 (1935)
(says $H_{max} \simeq \frac{\lambda}{\xi} H_c$) ← Thermodynamic Critical Field
Gorter's "minimum size of superconductor" is essentially same as GL coherence distance ξ

II. K. Mendellsohn Proc. Roy Soc. (London) A152, 34 (1935)

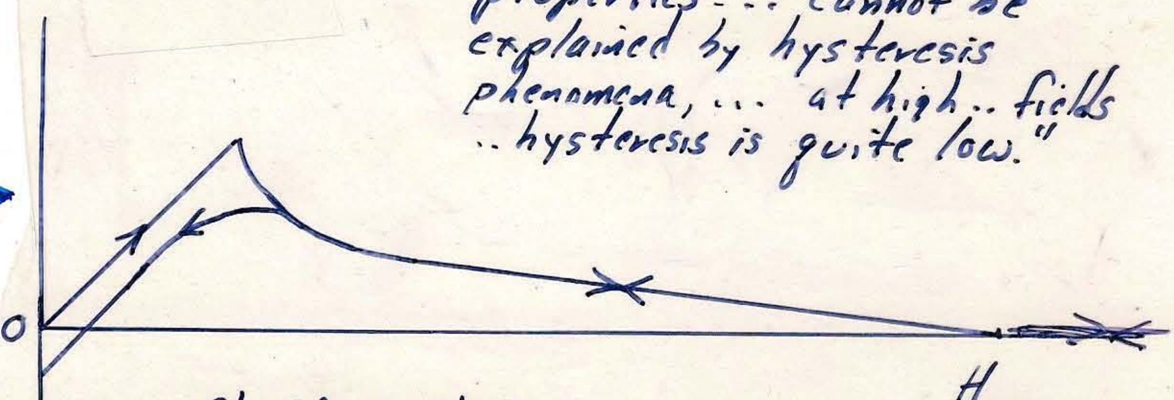
"We think that all experimental results so far obtained on IMPURE (our caps & underline) metals and on alloys can be explained by their INHOMOGENEITY (US) which causes the formation of a **SPONGE** of higher threshold value."

III. **THE CRUCIAL EXPERIMENT** (5)

L.V. Shubnikov, V.I. Khotkevich, J.D. Shepelev, J.N. Rjabinin, J. Exptl. Theoret. Phys. (USSR) 7, 221 (1937) [Portions were reported in English! : J.N. Rjabinin and L.V. Shubnikov, Nature 135, 581 (1935); Phys. Z. Sowjet 7, 122 (1935).]

"Such unusual magnetic properties ... cannot be explained by hysteresis phenomena, ... at high .. fields .. hysteresis is quite low."

This work ignored for 20 YEARS until Abrikosov compared this data with his theory in 1957!!



Pb-Tl & Pb-In
Single Phase Single Crystals

Shubnikov et al. said:

1. $\int M dH$ = Superconducting state condensation energy
2. Even though Hmax exceeds H_c of pure metals, the condensation energies are are comparable and depend on T in the same way
3. The zero-field specific heat jump in an alloy superconductor should be comparable to that of a pure superconductor, (and not have gigantic value, expected if complete flux expulsion existed up to Hmax)

BUT SHUBNIKOV et al. "FAILED TO EXPLOIT THEIR NEWFOUND UNDERSTADING"... (making) "no mention of the Gorter-H. London theory .... "nor of the Mendelssohn SPONGE..." T.G. Berlincourt

Compare:

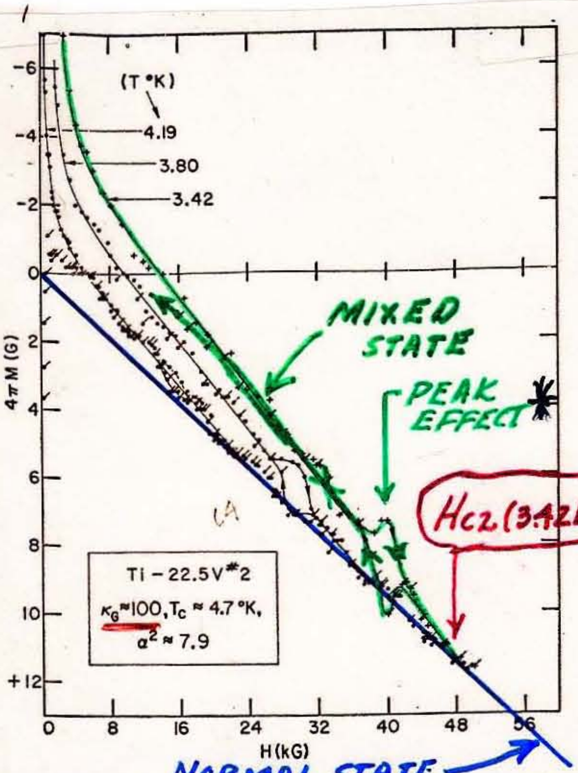


FIG. 9. Isothermal magnetization M versus applied magnetic field H for Ti(22.5 at.% V) No. 2 after the heavy etching indicated in Fig. 8. The points with ticks were obtained on the return decreasing-H cycle.

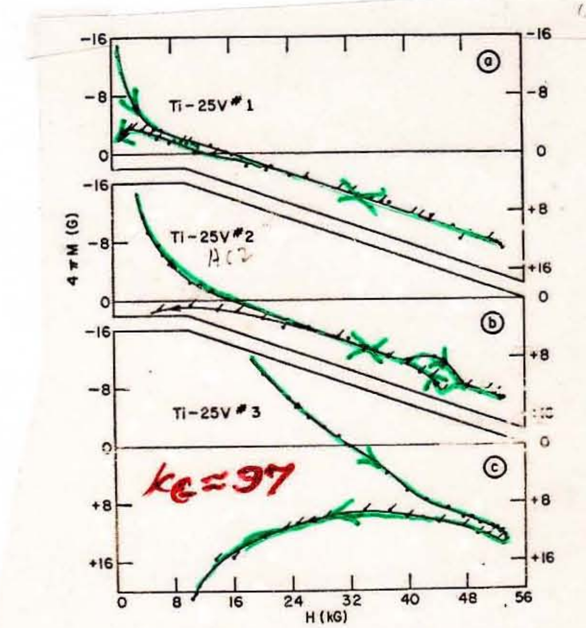


FIG. 10. Isothermal magnetization M versus applied magnetic field H at $T = 4.19$°K for Ti(25 at.% V) specimens; No. 1 [as arc cast with no precipitate as shown in Fig. 1(b)], No. 2 (cold rolled to a reduction of ≈2:1), and No. 3 [annealed and containing an annealing-induced precipitate as shown in Fig. 1(c)]. The κ_G, α^2, and T_c values are listed in Table I.

From R.R Hake "Paramagnetic Superconductivity in Extreme Type-II Superconductors" Phys. Rev. 158, 356 (1967)

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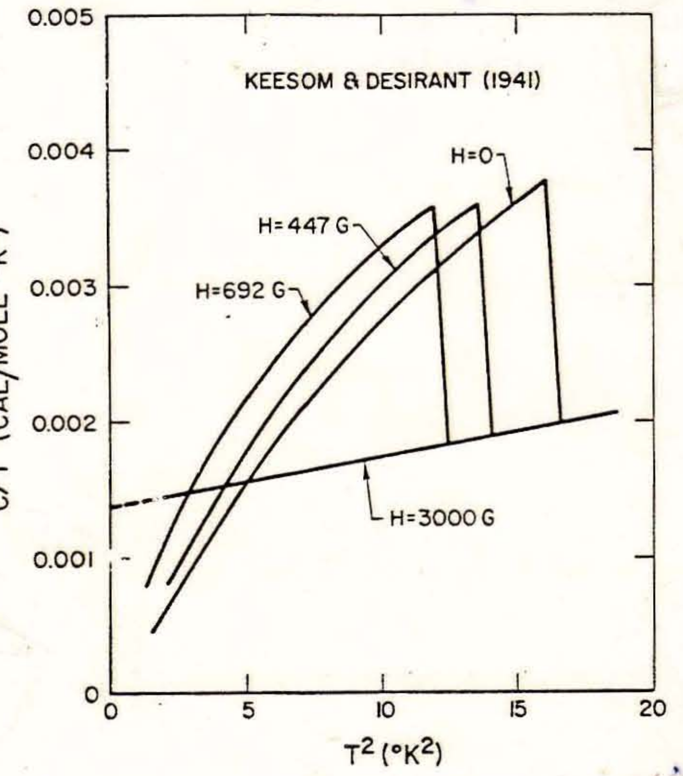
* PEAK EFFECT: see T.G. Berlincourt, R.R. Hake, and D.H. Leslie, Phys. Rev. Letters 6, 671 (1961). (p. 19 of this talk).

ACT II: LEIDEN IN THE DARK: DUTCH SLOPS IGNORE RUSSIAN SLOPS

W. H. Keesom and M. Desirant, Physica 8, 273 (1941)
[apparently ignorant of work of Schubnikov et al., even though Schubnikov had worked at Leiden with de Haas to discover the "Shubnikov-de Haas oscillations" in $\Delta\rho(H)$.

SLOP:
SOLid state Physicist

SLOTH:
SOLid state THeorist

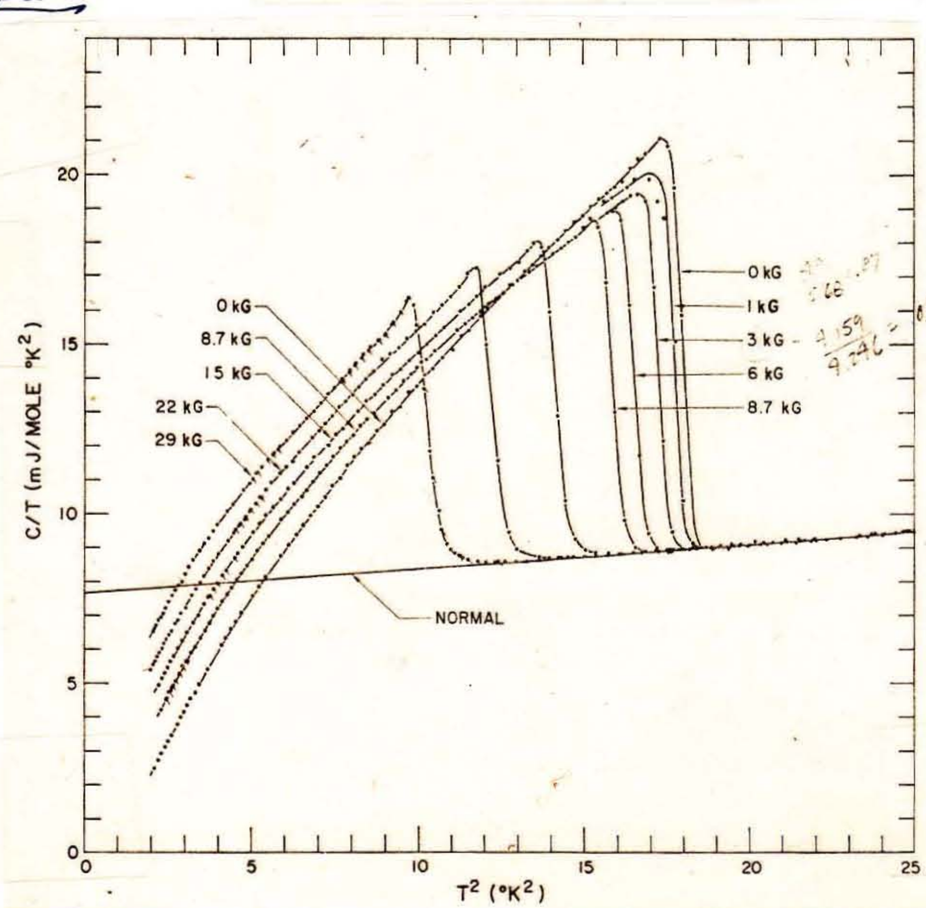


Impure Ta ($R \approx 2.5$)

Ordinary $\Delta C(T_c)$

2nd-order transitions in H-field!

Compare:



Ti-16 at% Mo
$R \approx 67$
Barnes & Hake
Phys. Rev. 153, 435 (1967)

ACT III. RUSSIAN SLOTHS IGNORE RUSSIAN SLOPS

V.L. Ginzburg and L.D. Landau, Zh. Eksperim. i Teor. Fiz. 20, 1064 (1950).

"It has not been necessary to investigate the nature of the state which occurs when $\kappa > 1/\sqrt{2}$, since from the experimental data .... it follows that $\kappa \ll 1$." [Apparently oblivious of Schubnikov *et al*.!!]

K. Mendelssohn to T.G. Berlincourt 1963

"It was extremely nice of you to send me a copy of your own paper, as well as a translation of Shubnikov's paper published in 1937. This is indeed of considerable help in assessing the earlier developments. At that time the Stalin Purge was only beginning, and I was very puzzled at the blanks I drew in trying to get in touch with Shubnikov. In 1957 Landau introduced me in Moscow to Shubnikov's widow, Olga Trapeznikova, who also is a physicist. She told me that her husband had just been exonerated posthumously from all charges. This made it possible for Abrikosov to refer to Shubnikov's papers, since up to then Soviet etiquette required that anyone who had disappeared in the purges had never lived."

(According to Balabekyan,(1966) Shubnikov was unjustly arrested in 1937, sentenced to 10 years imprisonment, and died in 1945.)

ACT IV. PIPPARD PIDDLES WHILE GINZBURG SQUIRMS

In 1951-53 Pippard used intuitive ideas to explain that a short electron mean free path would lead to negative surface energy. He was aware of GL-theory and the Gorter - H. London ideas.

PIPPARD IS VERY SMART!

WHY DIDN'T PIPPARD PUT IT ALL TOGETHER?

"So in the early 1950's there was a certain amount of conflict which wasn't helped, incidentally, by the fact that Ginzburg kept on writing small papers in which he said it would be much better if we interpreted the electronic charge as not being exactly e, but e times a small numerical factor which might be as large as 2! He didn't say it was exactly 2; instead he wanted to introduce a fudge factor of (say) 1.6, and Landau kept on telling him he couldn't just put in arbitrary numbers, and muttered darkly about gauge invariance going wrong if you did."

A.B. Pippard in "Historical Context of Josephson's Discovery" in SQUIDS & Machines (Plenum, 1977) p.1.

ACT V. THE KID PROTAGONISTS

SLOP: N.V. Zavaritski, Doklady Akad. Nauk. USSR
Dokl. Akad. Nauk. SSSR **86**, 501 (1952)

SOLid state Physicist

"Discussing with Zavaritski the possible origin of this discrepancy, we came to the idea that the approximation K << 1 based on the surface tension data (where K is the Ginzburg-Landau parameter) could be incorrect for objects such as low-temperature films. Particularly one could suppose that K > 1/ √2. According to Ginzburg and Landau, the surface energy should be negative under these conditions. Intuitively it was felt that in this case the phase transition in a magnetic field would always be of second order, and this was in fact what Zavaritski observed."

A SLOP FINALLY GETS THROUGH TO A SLOTH!!

"When I calculated the dependence of the critical field on the effective thickness with K > 1/ √2, it appeared that the theory corresponded to the experimental data. This gave me the courage to state in my article of 1952 containing this calculation that apart from ordinary superconductors whose properties were familiar, there exist in nature superconducting substances of another type, which I proposed to call superconductors of the second group (now called type II superconductors). The division between the first and the second group was defined by the relation between the quantity K and its critical value 1/ √2."

PROTAGONISTS

SOLid state THeorist

A.A. Abrikosov, 1974

SLOTH: A.A. Abrikosov, Doklady Akad. Nauk. USSR **86**, 489 (1952)

$H_{c2} = \sqrt{2}\, K H_c$

"At this time I became ill and had to stay in bed for almost three months. One day Landau visited me. The conversation, as in most cases, concerned everything but physics, and Landau sipped with great pleasure from a glass of glühwein, which was not at all like him. And then suddenly I destroyed all this paradise by telling him what I had invented for the mixed state, namely, the elementary vortices. As Landau's eyes fell on the London equation with a δ function on the right-hand side, he became furious. But then, remembering that an ill person should not be bothered, he took possession of himself and said, 'When you recover we shall discuss it more thoroughly.' Then he hastily bade farewell and disappeared."

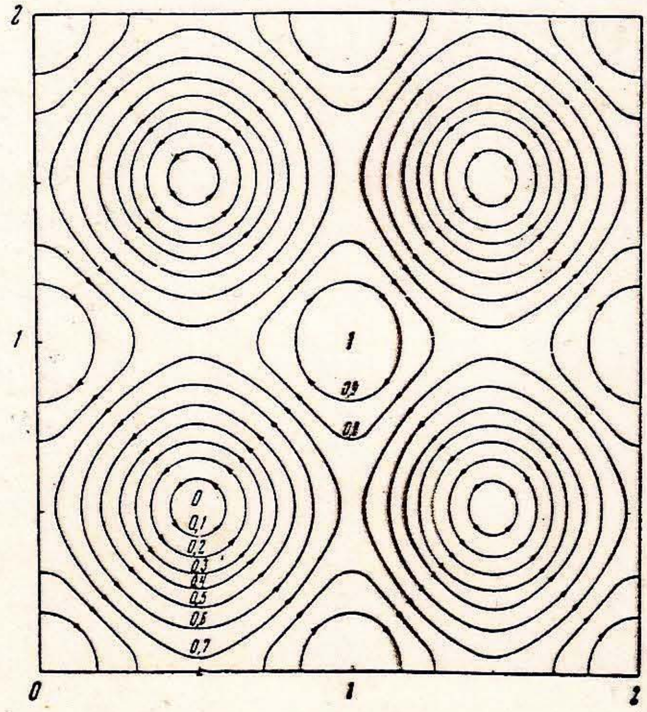
"He did not come to me any more. When I felt better and appeared at the Institute and tried to tell him again about the vortices, he swore rather ingeniously. At that time I was still very young and did not know the temper of my teacher well enough. He had seen in his life many kinds of pseudoscience, and this made him suspicious toward unusual statements. However, by making some effort and disregarding the noise which he made, one could always 'drag' him through any reasonable idea. But at that time I sadly put my calculations in my table drawer 'until better times.'"

R.P. Feynman in *Progress in Low Temperature Physics I* (North Holland, 1957) ed. by C.J. Gorter, p.17.

"When Landau began to praise Feynman's work I asked him, 'Dau, why are you ready to accept the vortices from Feynman while you flatly rejected the same idea from me?' Landau answered, 'You had something different.' 'Well then, look, please,' I said, and produced my calculations from the drawer. This time no objections followed. We discussed the subject very thoroughly and Landau's remarks were very useful."

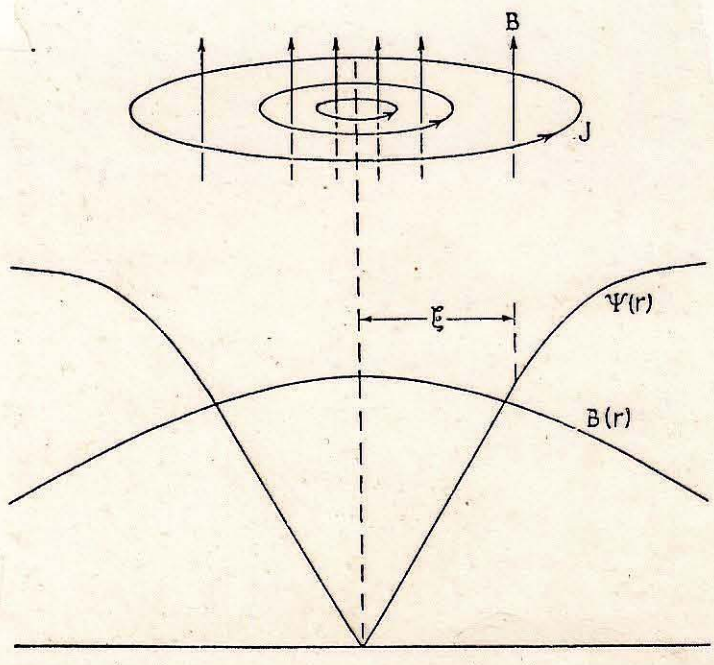
(11)

A.A. Abrikosov, Zh. Eksperim. i Teor. Fiz. 32, 1444 (1957)
[Sov. Phys. JETP 5, 1174 (1957).



(Square lattice)

- Figure 3. The Abrikosov **vortex lattice.**



ACT V. THE KID AND GEEZER SLOTHS TEAM UP FOR SOME BREAKTHROUGHS: BCS AND GLAG

NOBEL PRIZE WINNING MICROSCOPIC THEORY OF SUPERCONDUCTIVITY

J. Bardeen, L.N. Cooper, J.R. Schrieffer

Phys. Rev. 108, 1175 (1957)

L.P. Gor'kov, Zh. Eksperim. i Teor. Fiz. 36, 1918 (1959); Sov. Phys. JETP 9, 1364 (1959)

[In "dirty limit" $H_{c2}(T=0) = (\text{const.})\, \rho_n \gamma T_c$]

GLAG: Ginzburg, Landau, Abrikosov, Gor'kov

The basic theory of high-field superconductivity (except for the paramagnetic limitation) is in place in 1959 but virtually ignored until 1962!

THE GLAG PICTURE

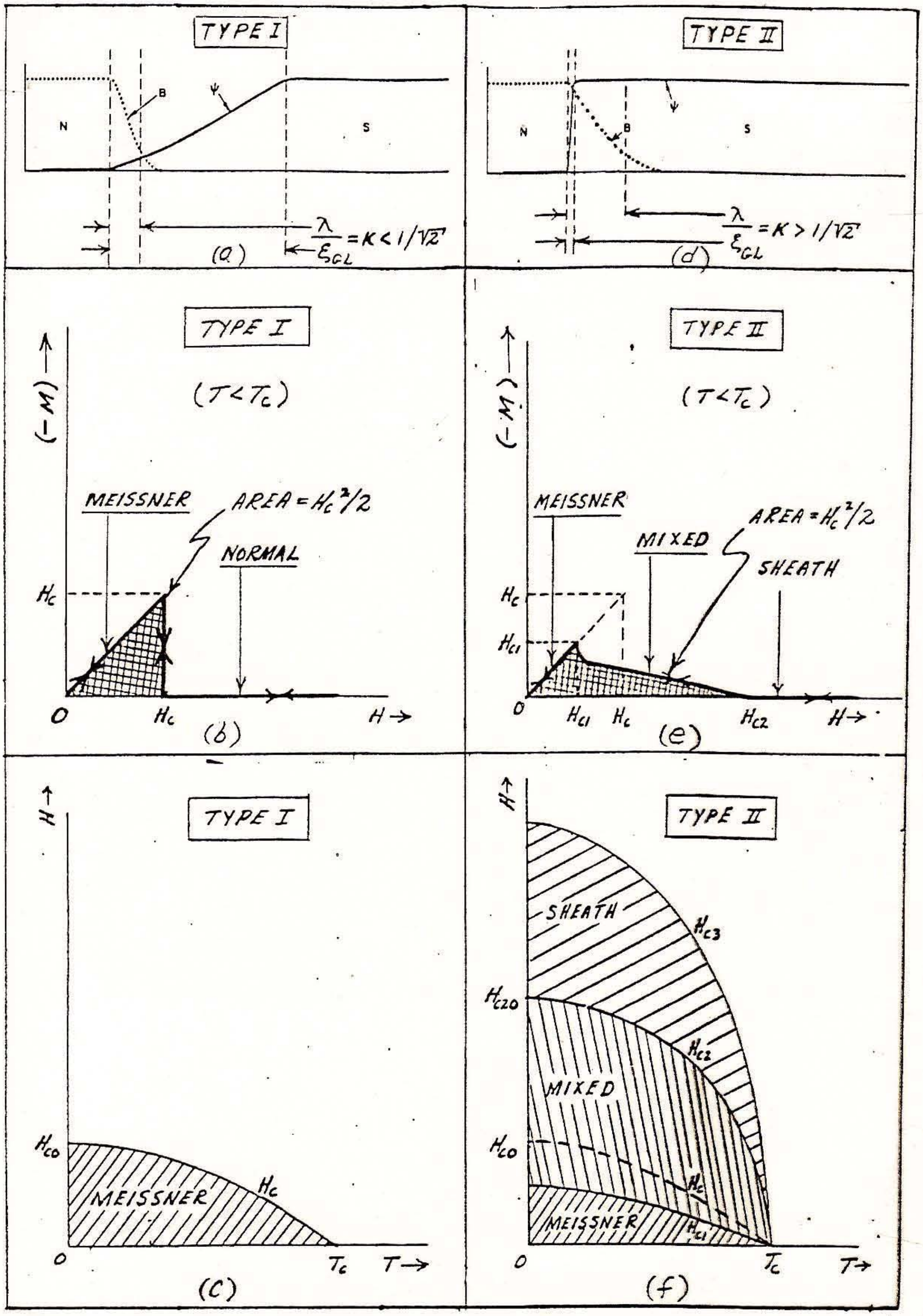


Figure 1
Characteristics of type-I and type-II superconductors

ACT VII. NUTTY GEORGE*

G. B. Ynetma, Phys. Rev. 98, 1197 (1955)
Also (unaware of Ynetma): S. H. Autler, Bull. Am. Phys. Soc. 4, 413 (1959)

FIRST SUPERCONDUCTING-WIRE MAGNET

0.71 Tesla

Cold-drawn Nb wire

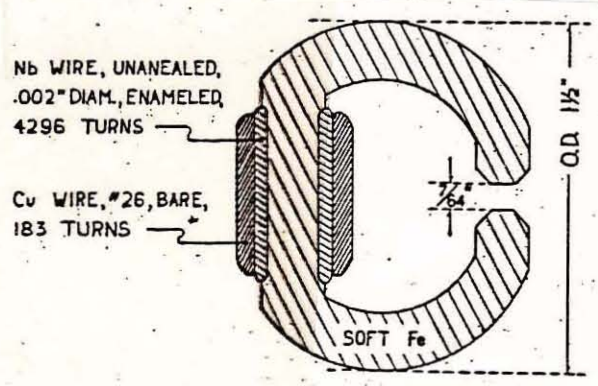


Figure 2. Electromagnet with superconducting niobium windings, horizontal cross-section. Magnet constructed at University of Illinois in 1954.

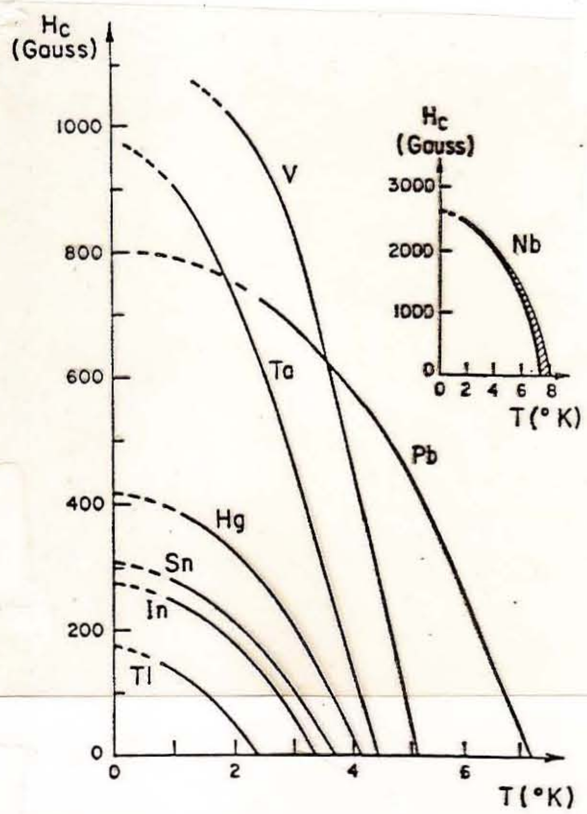


Figure 1. Critical fields as functions of temperature. Traced from figure compiled by D. Shoenberg, 1952 (Ref. 1).

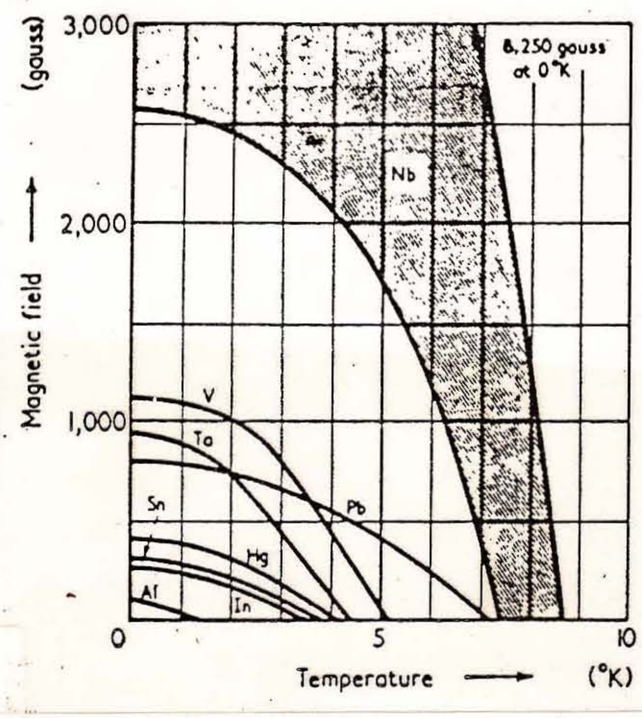


Figure 8. Critical fields as functions of temperature. The shaded area shown for niobium illustrates the variation in reported values. Compiled by V. D. Arp and R. H. Kropschot, 1960 (Ref. 18).

*Note Added - 6 Oct 2011: I was recently asked to explain the heading "Nutty George." George Ynetma and I overlapped in the superconductivity group at the University of Illinois in the 1950's, George as a postdoc and I as graduate student. Most people in that group thought ***George was nutty*** - ever since the work at Leiden and Kharkov in the 1930's (see page 4) it had been well know by the cognoscenti that superconductors could ***not*** be used to make useful superconducting magnets!

ACT VIII. NUTTY TED, DON, AND DICK

T. G. Berlincourt, J. Phys. Chem. Solids 11, 12 (1959)

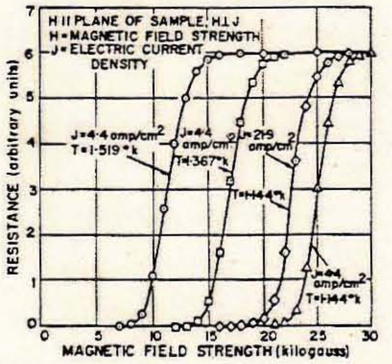


FIG. 6. Magnetic-field-induced superconducting transitions for a metastable γ-phase uranium alloy containing 11·6 a/o Mo.

bcc
U – 11.6 at.% Mo
$T_c \approx 2K$

R. R. Hake, D. H. Leslie, and T. G. Berlincourt, Bull. Am. Phys. Soc. 4, 362 (1959); J. Phys. Chem. Solids 20, 177 (1961).

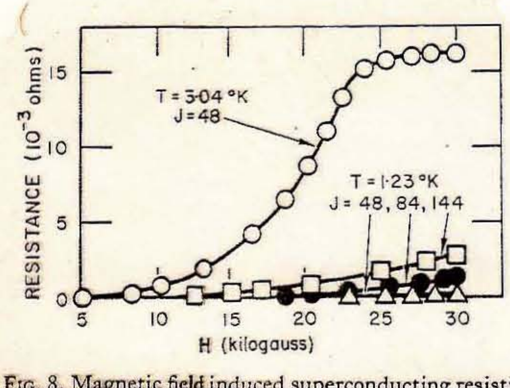


FIG. 8. Magnetic field induced superconducting resistive transitions for specimen K (b.c.c. Ti–16·3 a/o Mo), at two different temperatures and for different measuring current densities J in A/cm². All the transitions were taken in decreasing magnetic fields which were perpendicular to the plane of the specimen. These transitions are typical of all those measured for the different samples.

bcc
Ti – 16.3 at.% Mo
$T_c \approx 4K$

ACT IX. BELL BOYS' BRITTLE BONANZA

Nb_3Sn Compound

R.M. Bozorth, H.J. Williams, D.D. Davis, Phys. Rev. Letters 5, 148 (1960)

Not realized by Bozorth et al.: $\Delta M \Rightarrow J_c$ (77, 4.2K) ~ 6×10^3 $\frac{A}{cm^2}$ as pointed out by Berlincourt.

CRITICAL FIELD FOR SUPERCONDUCTIVITY IN NIOBIUM-TIN

R. M. Bozorth, A. J. Williams, and D. D. Davis
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received July 20, 1960)

It is well known[1] that Nb_3Sn is a superconductor with a high critical temperature, 18°K. The measurements here reported show that it has also an exceptionally high critical field, about 70 000 oersteds at 4.2°K, necessary for the suppression of all superconductivity.

The material was prepared by melting together niobium and tin in the argon arc, and the button so obtained was formed by grinding into a rod about 2 cm long and 4 mm in diameter, with rounded ends. The magnetic moment per gram, σ_g, was measured by pulling the specimen from one search coil to another in a constant field, the two search coils being connected in series opposition to a ballistic galvanometer. Calibration was with nickel of high purity.

Measurements were made in increasing fields, after cooling in zero field to liquid helium temperature. Results are shown in Fig. 1. The initial points (circles) follow accurately the line for $B=0$ ($H = -4\pi\sigma_g d$, where d is the density, 8.9), and then begin to deviate at about 4000 to 5000 oersteds. The variations in the readings in fields from 5000 to 20 000 oersteds reflect the well-known irregular changes in magnetization resulting from changes in domain structure in the intermediate state, as observed by Schawlow et al.[2] and others. The general shape of the magnetization curve is that observed in a hard superconductor. Polishing, or annealing the specimen at 1100°C for several hours, made no essential change in the character of the curve.

When the field was decreased from its maximum value (points marked with squares) some of the flux was frozen in, and irregularities were again observed.

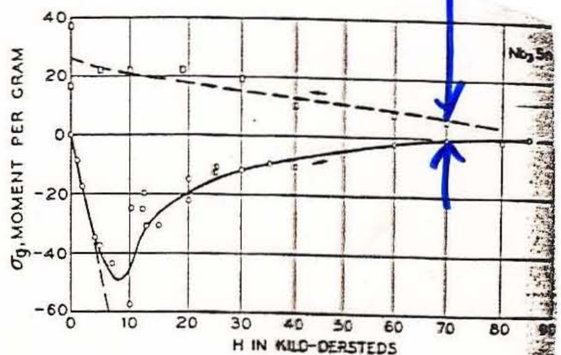


FIG. 1. Magnetization of Nb_3Sn as dependent on field strength, showing superconduction in entire specimen to about 5000 oersteds and superconduction in some parts of specimen to about 70 000 oersteds.

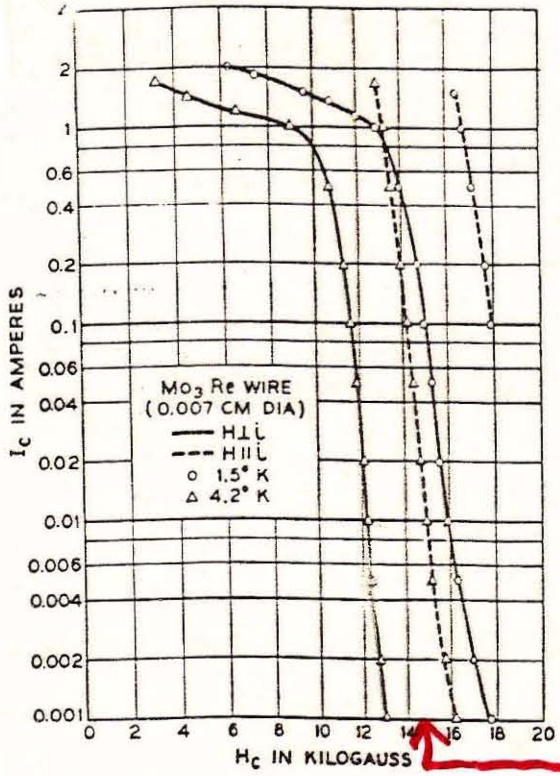
The authors are indebted to E. Corenzwit for preparation of the material, to W. E. Henry of the Naval Research Laboratory for details of the method of measurement, and to H. W. Dail for assistance with the experiment. The field was produced in a Bitter coil excited with a motor generator with a nominal power rating of one megawatt.

[1]B. T. Matthias and T. H. Geballe, Phys. Rev. 95, 1435 (1954).

[2]A. L. Schawlow, G. E. Devlin, and J. K. Hulm, Phys. Rev. 116, 626 (1959).

J.E. Kunzler, E. Buehler, F.S.L. Hsu, B.T. Matthias, C. Wahl, J. Appl. Phys. 32, 325 (1961)

(17)



Experimentally observed curves (critical magnetic field vs critical current) of the 0.007-cm diam Mo_3Re wire used for the solenoid. The magnetic field was externally applied to a straight piece of the wire and the points correspond to the initial detection of resistance. The knees in the curves with H ⊥ i at both 1.5°K and 4.2°K are typical of behavior observed in several materials. Data for each curve were taken by starting with the smallest value of current and repeating the initial point after the pertinent series was complete. This was done to ascertain that no annealing had occurred when the sample was driven into the normal state at high current density.

15kG

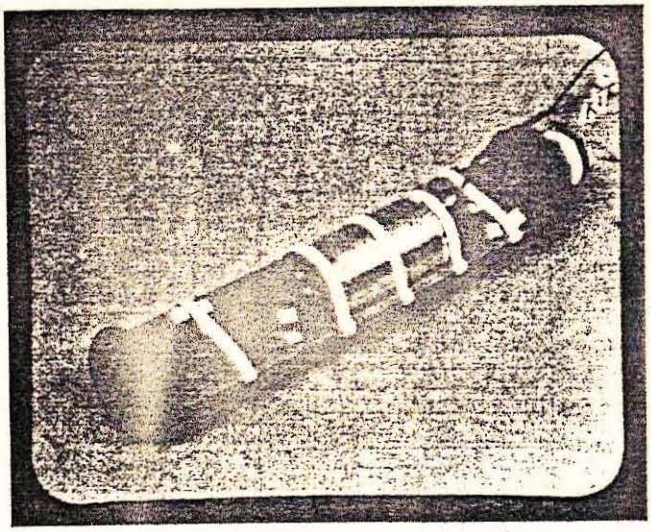


Figure 3. Photograph of 15 kgauss superconducting solenoid made in 1960. The solenoid diameter is slightly over 3/4 inch and is wound with 0.003 inch dia. Mo-Re wire using gold plating for insulation between turns within each layer.

Mo-25at%Re Alloy Superconducting Wire Magnet [3 mil diameter Au-plated wire]. The Bell Boys call it Mo_3Re (sic).]

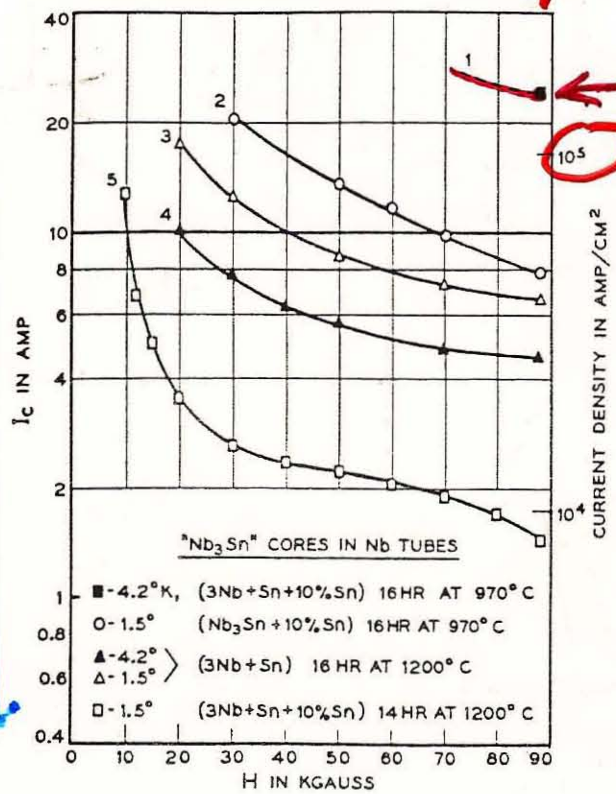
The Major Experimental Breakthrough

J.E. Kunzler, E. Buehler, F.S.L. Hsu, J.H. Wernick, Phys. Rev. Letters 6, 89 (1961) "Superconductivity in Nb_3Sn at High Current Density in a Magnetic Field of 88 kgauss."

High-Field Counterpart of "Superconductivity at 93K in a New Mixed-phase YBaCuO Compound System at Ambient Pressure"
M.K. Wu, ...
. . . .
. . . .
. . . .
. . . . C.W. Chu

Phys. Rev. Lett. 58, 908 (1987).

8.8T



Amp/cm²

Nb_3Sn (brittle compound)

FIG. 2. Critical current vs applied magnetic field for Nb-clad cores of "Nb_3Sn." The o.d. of the cores was about 0.015 cm and the o.d. of the Nb jackets was about 0.038 cm. "+ 10% Sn" in the table legend means 10 wt. % more Sn than is required to form Nb_3Sn assuming no reaction with the Nb tube. The magnetic field was perpendicular to the current direction. Each experimental point represents the maximum current, at the value of magnetic field indicated, for which no voltage drop along the sample was observed, the smallest detectable voltage being a few hundreths of one microvolt.

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."

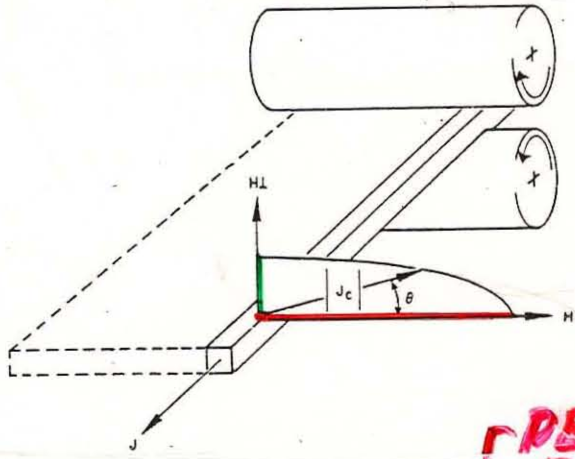
"Whenever such a profound change in perspective occurs, the human species feels a compulsion to account for it, and in the attempt often rushes headlong in the wrong direction."
Ted Berlincourt

TO THE SPONGE!

ACT X. RACE FOR THE SUPERMAGNET

T.G. Berlincourt, R.R. Hake, D.H. Leslie, Phys. Rev. Letters 6, 671 (1961).

THE TENACIOUS TRIO'S DUCTILE DELIGHT Nb-Zr Alloy Wire



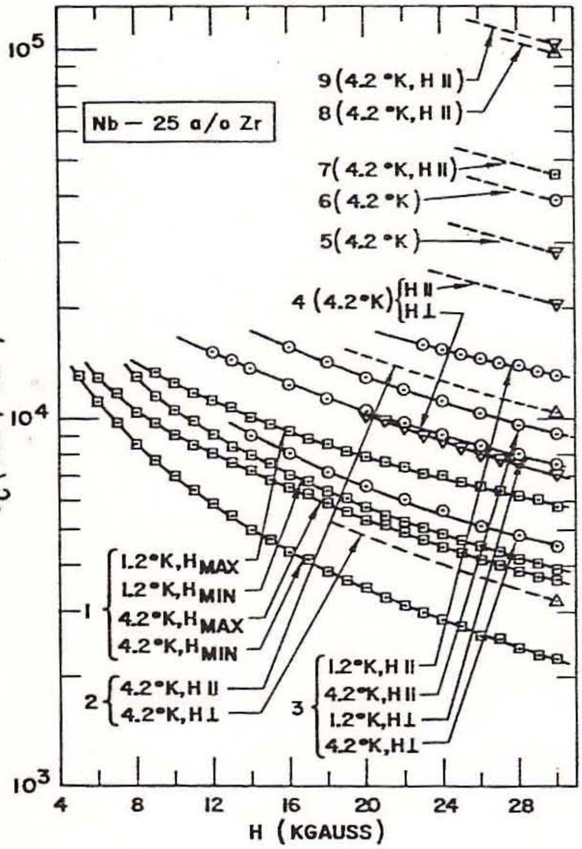


FIG. 1. Critical current density, J_c, for restoration of the first observable resistance vs applied transverse magnetic field, H, for Nb−25 at.% Zr alloy specimens 1 to 9 at different temperatures and field orientations parallel ($H \parallel$) and perpendicular ($H \perp$) to the rolled faces of the specimens. For specimen 1, which was ground to thickness, H_{max} and H_{min} designate field directions such that J_c is, respectively, a maximum and a minmum at 30 kgauss and 4.2°K. For source material, fabrication method, and cross-sectional dimensions of the specimens see Table I.

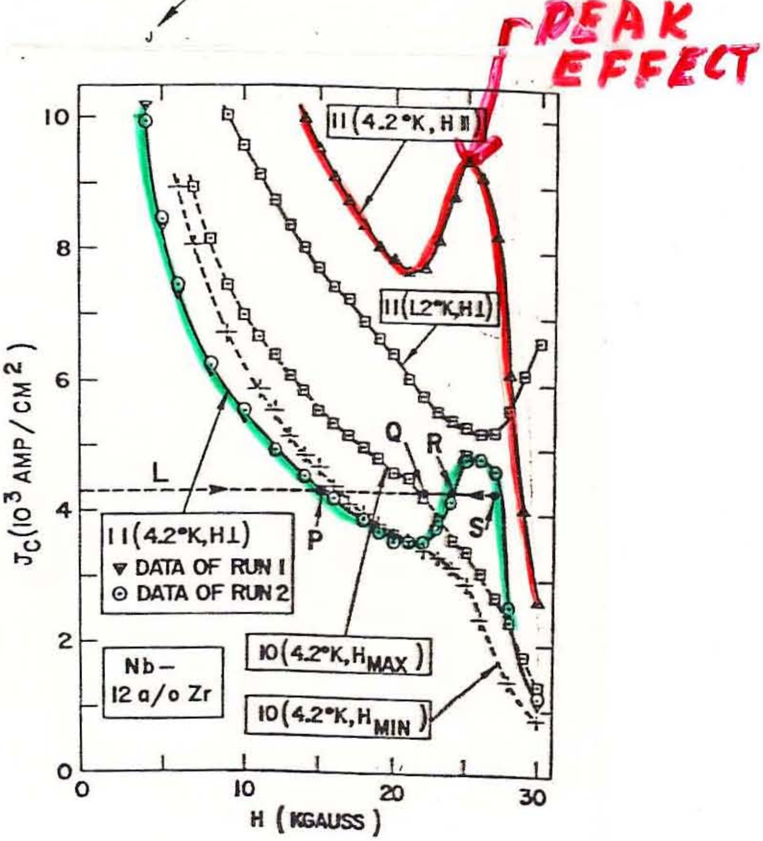


FIG. 2. Critical current density, J_c, for restoration of the first observable resistance vs applied transverse magnetic field, H, for Nb−12 at.% Zr alloy specimens 10 and 11 at different temperatures and field orientations parallel ($H \parallel$) and perpendicular ($H \perp$) to the rolled face of the specimen. For specimen 10, which was ground to thickness, H_{max} and H_{min} designate field directions such that J_c is, respectively, a maximum and a minimum at 30 kgauss and 4.2°K. For source material, fabrication method, and cross-sectional dimensions of the specimens see Table I. The line L and points P, Q, R, S are explained in the text.

A group of young men so frenetic
Struggle with matters magnetic.
Each day they conspire
To wind superwire
A pastime which some deem pathetic. W.J. Tomasch 1961

In ref. 6 Berlincourt quotes Tomasch's limerick but fails to observe poetic convention.

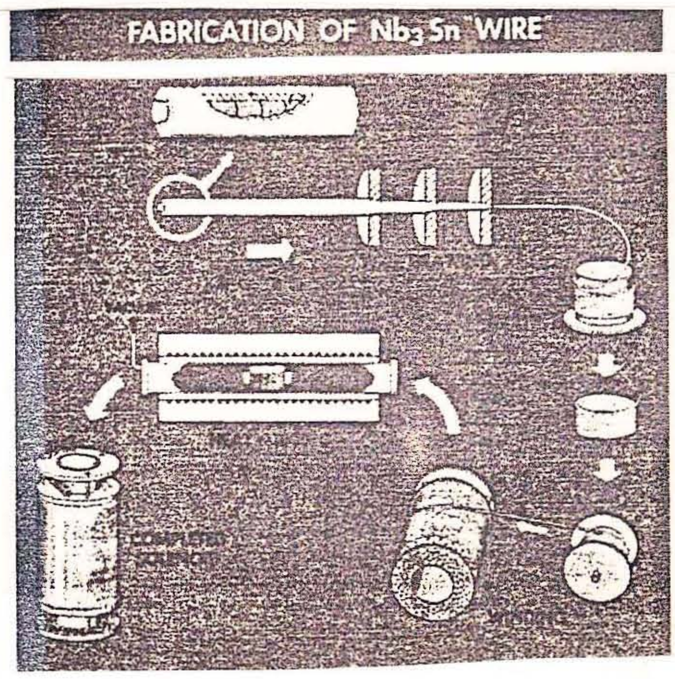
Walt Tomasch that famous Effect
Wrote limericks with lines so correct.
Three long and two short
Are the rules of the sport
Which the Navy should not redirect. R.R. Hake 1986

At the Finish Line: Proceedings of the International Conference of High Magnetic Fields, Kolm, Lax, Bitter, Mills, ed., (John Wiley, 1962):

FIRST PLACE: "Near 70 kG," J.E. Kunzler "Superconductivity in High Magnetic Fields At High Current Densities," p. 574
(A very awkward procedure was required)

SECOND PLACE: H = 59 kG (Nb-Zr), R.R. Hake, T.G. Berlincourt, D.H. Leslie, "A 59-Kilogauss Niobium-Zirconium Superconducting Solenoid," p. 341

THIRD PLACE: H = 58 kG (Nb-Zr), J.K. Hulm, M.J. Fraser, H. Riemersma, A.J. Venturino, and R.E. Wien, p. 332



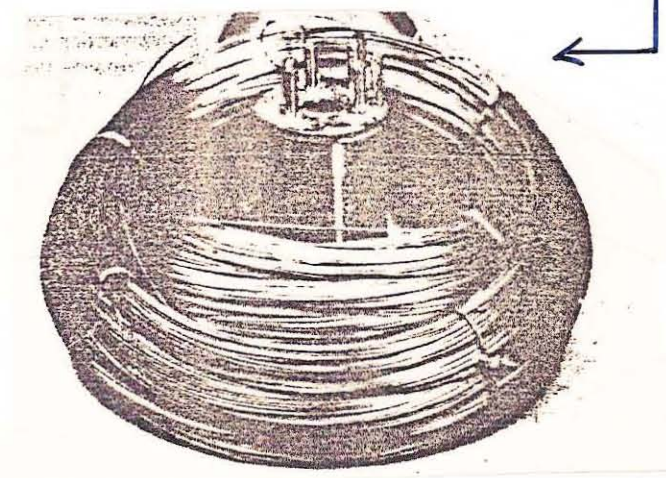


Figure 6. Photograph showing coils of composite wire fabricated by the process described in Figure 5. Also shown is a 4 in. diameter, 70 kgauss superconducting solenoid. The Nb_3Sn is formed within the core of the "wire" by heating to about 1000°C after the solenoid is wound.

ACT XI. SPONGERS EXPUNGE THE PURISTS

NUTTY BRUCE (UNAWARE OF GLAG!) PULLS OUT THE OLD GORTER–H. LONDON CHESTNUT AS POLISHED WITH A LITTLE OF PIPPARD'S NEGATIVE-SURFACE-ENERGY-SHORT ELECTRON-MEAN-FREE-PATH PALAVER AND PUTS FORTH A PREPOSTOROUS PLEA FOR **PURITY**: B.B. Goodman, Phys. Rev. Letters 6, 597 (1961):

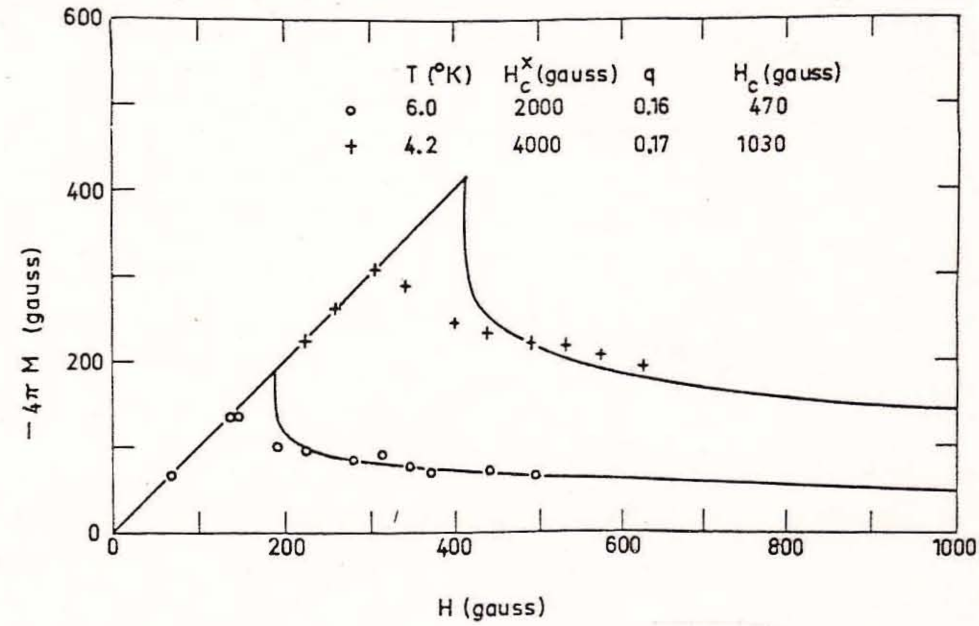


FIG. 2. Fit of the present model to the magnetization curves of Calverley and Rose-Innes' specimen of $Ta_{36}Nb_{64}$.

NUTTY BRUCE THEN DISCOVERS GLAG. AT THE IBM YORKTOWN CONFERENCE IN JUNE 1961 (Partially Organized By J.C. Swihart who lets in all the **SPONGERS** and **FLUX QUANTIZERS**) BRUCE YAKS ABOUT H_{c2} = Const. $\rho_n \gamma T_c$ YIELDING FAIR AGREEMENT FOR RESISTIVELY MEASURED "UPPER CRITICAL FIELDS" IN HIS OWN Pb-Tl and BERLINCOURT'S U-Mo.

BUT **99%** OF ATTENDEES ARE **SPONGERS**! THEY KNOW THAT "UPPER CRITICAL FIELDS" ARE ILLUSORY CURRENT-AND-DEFECT-DENSITY CONTROLLED PRODUCTS OF **PURISTS** FANTASIES.

PARAMAGNETIC LIMITATION APPLIED TO FILAMENTS BY SPONGERS

22

UPPER LIMIT FOR THE CRITICAL FIELD IN HARD SUPERCONDUCTORS

A. M. Clogston
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received August 9, 1962)

Recently a number of reports have been made of extremely high critical fields observed in certain hard superconductors.[1-7] It is generally believed that these high critical fields arise from some sort of filamentary structure of the hard superconductors, possibly associated with dislocations.[1-10] . . . .

We wish to point out that the critical fields observed and predicted for various superconductors are so high that they are approaching a limit that will exist even in the limit of no Meissner effect. . . . .

If this condition is realized in practice, in the absence of any Meissner effect, we should write in place of Eq. (1) at absolute zero,

$$F_N - \tfrac{1}{2}\chi_p H_0^2 = F_S. \qquad (2)$$

In this equation we ignore the presence of any orbital paramagnetism that will be essentially the same in the normal and superconducting state. In terms of the density of states $N(0)$, $\chi_p = 2\mu_B^2 N(0)$, assuming a g factor equal to 2. According to the BCS theory[12] the free-energy difference $F_N - F_S = \frac{1}{2}N(0)\epsilon_0^2(0)$, where $\epsilon_0(0)$ is the energy gap at $T=0$. Equation (2) therefore becomes

$$(\mu_B H_0)^2 N(0) = \tfrac{1}{2}N(0)\epsilon_0^2(0)$$

or

$$\mu_B H_0 = (1/\sqrt{2})\epsilon_0(0) \qquad (3)$$

with the density of states cancelling out. If we assume $2\epsilon_0(0) = 3.5kT_c$, Eq. (3) yields

$$H_0 = 18\,400\, T_c \text{ gauss.} \qquad (4)$$

. . . .

For $V_{1.95}Ga$ the limit set by Eq. (4) may have already been reached. An interesting application of Eq. (4) has been made by Berlincourt and Hake[14] to the low current density critical fields of various transition metal alloys.

We conclude that the critical fields that obtain for the β-wolfram compounds are so high that they may be effectively limited at low temperatures by the normal-state paramagnetism. If this is the case, critical fields higher than about 300 kilogauss will not be realized unless materials can be discovered with higher transition temperatures.

[1]J. E. Kunzler, Revs. Modern Phys. 33, 1 (1961).
[2]J. E. Kunzler, J. Appl. Phys. 33, 1042 (1962).
[3]T. G. Berlincourt, R. R. Hake, and D. H. Leslie, Phys. Rev. Letters 6, 671 (1961).
[4]J. E. Kunzler, in Proceedings of the International Conference on High Magnetic Fields, Massachusetts Institute of Technology, November, 1961 (Massachusetts Institute of Technology Press, Cambridge, Massachusetts and John Wiley & Sons, Inc., New York, 1962), p. 574.
[5]H. F. Hart, I. S. Jacobs, C. L. Kolbe, and P. E. Lawrence, in Proceedings of the International Conference on High Magnetic Fields, November, 1961 (Massachusetts Institute of Technology Press, Cambridge, Massachusetts, and John Wiley & Sons, Inc., New York, 1962), p. 584.
[6]R. G. Treuting, J. H. Wernick, and F. S. L. Hsu, in Proceedings of the International Conference on High Magnetic Fields, Massachusetts Institute of Technology, November, 1961 (Massachusetts Institute of Technology Press, Cambridge, Massachusetts, and John Wiley & Sons, Inc., New York, 1962), p. 597.
[7]J. H. Wernick, F. J. Morin, F. S. L. Hsu, D. Dorsi, J. P. Maita, and J. E. Kunzler, in Proceedings of the International Conference on High Magnetic Fields, Massachusetts Institute of Technology, November, 1961 (Massachusetts Institute of Technology Press, Cambridge, Massachusetts, and John Wiley & Sons, Inc., New York, 1962), p. 609.
[8]R. Shaw and D. E. Mapother, Phys. Rev. 118, 1474 (1960).
[9]J. J. Hauser and E. Helfand, Phys. Rev. 127, 386 (1962).
[10]J. J. Hauser and E. Buehler, Phys. Rev. 125, 142 (1962).
[14]T. G. Berlincourt and R. R. Hake (private communication).

A NOTE ON THE MAXIMUM CRITICAL FIELD OF HIGH-FIELD SUPERCONDUCTORS

B. S. Chandrasekhar
Westinghouse Research Laboratories, Pittsburgh, Pennsylvania
(Received July 23, 1962)

A fair number of superconductors, mostly alloys of the transition metals, are now known to exhibit zero resistance in applied magnetic fields up to 100 kG or more.[1] It has become increasingly evident, mainly as a result of the work of Berlincourt and Hake,[1] that the maximum field H_m at which a given alloy still exhibits superconductivity (as indicated by zero resistance for current densities less than 10 A/cm^2) is a true parameter of the alloy, independent of its degree of cold work. They have also shown that H_m peaks sharply between 4 and 5 electrons/atom, reaching for example a value of ~145 kG for Ti-Nb.

The existence of superconductivity at very high fields is probably due, as has been suggested by several authors,[2,3] to a "filamentary" structure, with at least one characteristic dimension small compared to the penetration depth. . . . One would therefore expect that when the magnetic energy $2\mu H$ (where μ = the Bohr magneton) becomes comparable to the energy gap Δ (~3.5 kT_c at low temperatures) superconductivity will be destroyed. This leads to the relation $H_m \cong 2.6 \times 10^4\ T_c$.

PURISTS: NUTTY TED AND DICK DELIVER A POSTDEADLINE PAPER AT THE WASHINGTON APS MEETING IN APRIL 1962: Nb-Ti LOOKS GOOD FOR SUPERMAGNETS, GLAG ACCOUNTS FOR LOW-CURRENT DENSITY RESISTIVE CRITICAL FIELDS.

Only NUTTY GEORGE, in Washington to deliver a postdeadline paper on his hair-brained helium-hyped hallucinations of supercurrent vortices in alloy superconductors, was able to stay awake during Berlincourt's presentation!! (Nutty George had been off in operations research and was unaware of Abrikosov's supercurrent vortices!!)

In June 1962 NUTTY TED + DICK try again with a contributed paper to the APS Evanston Meeting:

Bull Am. Phys. Soc. 7, 408 (1962)
(Evanston meeting, June, 1962)

Q5 Pulsed-Magnetic-Field Studies of Superconducting Transition Metal Alloys at High and Low Current Densities.* T. G. BERLINCOURT AND R. R. HAKE, *Atomics International*.—At 1.2°K, supercurrent densities J of 20 000 and 10 000 A/cm² have been observed respectively at 100 and 120 kG in severely cold-worked Ti-50 at.% Nb, indicating its suitability for ~100 kG superconducting magnets. Low-current-density ($J=10$) resistive critical fields H_r of cold-rolled alloys in the systems Ti-V, Nb-Zr, Ta-Hf, Ti-Nb, Ti-Mo, Ti-Ta, and Nb-Hf have been measured between 1.2 and 4.2°K. $H_r(J=10, T=1.2°K)$ values >100 kG are common and reach ~145 kG in Ti-Nb. $H_r(J\leq 10)$ may be simply related to fundamental electronic parameters since it peaks up sharply between 4 and 5 electrons/atom, is roughly parabolic in temperature, and [unlike $H_r(J\gg 10)$] is almost (1) identical for longitudinal and transverse fields and for the transverse field parallel and perpendicular to the rolling plane and (2) independent of the degree of cold-working. For Ti-Mo and Ti-V alloys, for which thermodynamic critical fields H can be deduced from published calorimetric data, $61\leq[H_r(J=10)/H_c]\leq 115$ in reasonable accord with the Ginzburg–Landau–Gor'kov–Abrikosov theory.[1]

* Work supported by the U. S. Atomic Energy Commission.
[1] See L. P. Gor'kov, Soviet Phys.—JETP 10, 998 (1960).

NUTTY GEORGE WAS BACK IN HARTFORD VOTICIZING! EVERYONE (ALL SPONGERS) FELL ASLEEP!!

TO SPONGERS IT WAS ALL A MATTER OF STICKING THE RIGHT JUNK (DISLOCATIONS, INTERFACE BOUNDARIES, CROWDIONS, INTERSTITIALS, SECONDARY PHASES, URINE, etc., etc., etc., INTO ALMOST ANY "HIGH-T_c" "CARRIER." ONLY A FEW PURISTS [NUTTY TED, DICK, AND BRUCE] KNEW THAT THE GLAG $H_{c2} \propto \rho_n$ & T_c WAS THE KEY. THE KEY SINGLED OUT **Ti-Nb**, NOW THE WORKHORSE OF TECHNOLOGICAL SUPERCONDUCTIVITY!

Emergence of Nb–Ti as supermagnet material

T.G. Berlincourt

Office of Naval Research, Arlington, VA 22217-5000, USA

CYROGENICS 27, 283 (1987)

Received 13 March 1987

The discovery and emergence of Nb–Ti as a high field superconductor is reviewed. The prehistory and setting for its discovery are described, and an anecdotal history follows its development up to the first successful large scale applications.

Today, more than 20 years since the discovery of the superior superconducting magnet potential of Nb–Ti, this alloy is widely utilized in medical, technical and scientific applications. It comprises the windings of supermagnets in some 800 magnetic resonance imaging sytems which make possible medical diagnoses of unprecedented accuracy, safety and convenience. Prototype electric motors and generators with Nb–Ti field windings have achieved efficiencies and energy densities undreamed of with conventional technology. A Japanese experimental levitated train, which attained a record speed of more than 500 km h^{-1}, utilized Nb–Ti supermagnets for both levitation and propulsion. Enormous (hundreds of tons) Nb–Ti supermagnets are providing means for magnetic confinement of plasmas in controlled thermonuclear fusion experiments. In high energy physics experiments at the Fermi National Accelerator Laboratory more than one thousand 6 m long Nb–Ti supermagnets guide an energetic particle beam around the 6 km circumference of the world's most energetic accelerator, the Tevatron. Design studies for a three billion dollar 100 km circumference Superconducting Super Collider accelerator have selected Nb–Ti as the supermagnet material.

Despite the obvious importance of Nb–Ti the story of how it emerged from among the thousands of known superconductors to become the most widely utilized has not been written in any systematic fashion. Indeed, some modern accounts of high magnetic field superconductivity simply dismiss early Nb–Ti activity with a reference or two to an early Nb–Ti supermagnet patent by Matthias[1], or to a paper by Hulm and Blaugher[2] which first reported the superconducting transition temperatures of Nb–Ti alloys, or to early papers by Hake and myself[3–5] on the upper critical fields and critical current densities of Nb–Ti alloys, or to the early commercial suppliers of Nb–Ti wires. This leaves unsaid much that is of interest concerning the motivating circumstances during those times and the preconceptions which acted as barriers to the acquisition of the basic understanding which was required for progress to be made. In what follows, I attempt to fill in some of the missing background, to convey some of the excitement, urgency, suspense and frustration of those times, and to describe some of the missed clues, the serendipity and the behind-the-scenes activity.

IN JULY 1962 NUTTY TED AND DICK SUBMIT THEIR PURIST POPPYCOCK TO PHYS. REV. LETTERS:

T.G. Berlincourt & R.R. Hake "Upper Critical Fields of Transition metal Alloy Superconductors," finally published in October as Phys. Rev. Lett. 9, 293 (1962)

SPONGE REFEREES REJECTION REPORT: See also Phys. Rev. 131, 190 (1963).

"Although it is alleged that the independence of H_r on H, J and rolling plane at low current supports the GLAG theory, this fact can just as well be explained by the filamentary theory. At the very low current densities, where all filaments can be active and where the important fact is the best existing filaments and not their number, there will always be some filaments properly oriented (parallel to the applied field) that will yield the same critical field H_r regardless of orientation. As a matter of fact, this also explains why the number 10 amp./cm^2 cannot be taken for all alloys as this number will depend on the degree of anisotropy, number of filaments, etc. Figure 2 can be explained by the filamentary theory as well $H_f = k H_c$ where H_f is the filamentary critical field. H_c the bulk critical field and k a constant depending on the size of the filaments, the coherence length and the penetration depth. As H_c peaks between 4 and 5 e/a so will H_f. Finally, phenomena such as flux trapping, anisotropy, peak effect can be explained by the filamentary theory and not by the GLAG theory. Actually, ... the GLAG theories and filamentary models may both be correct but the GLAG model fits the more homogeneous and soft hard superconductors. There is no sharp line and negative surface energy may be needed to realize the filamentary structure."

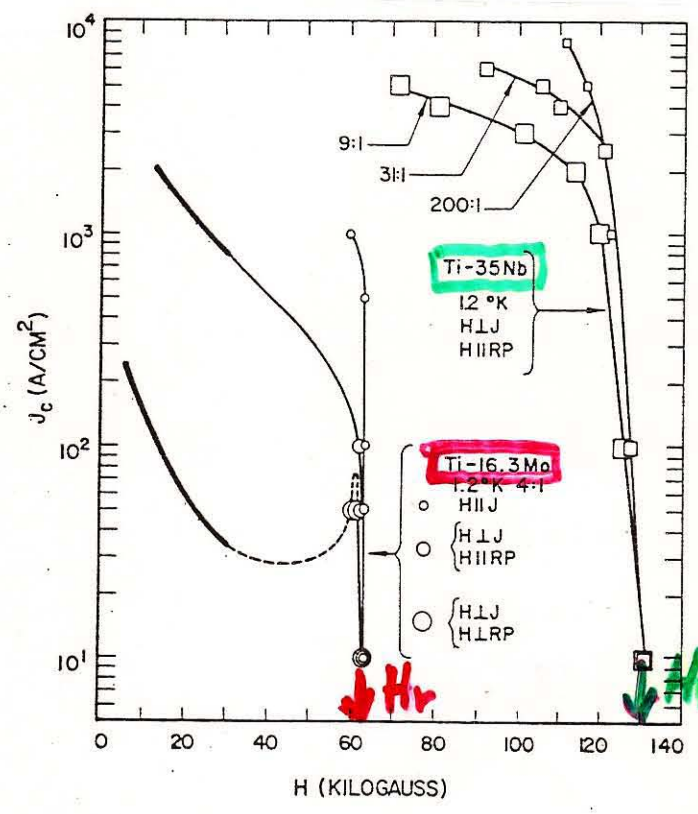


Figure 4. Illustrations of independence of low-current-density resistive critical fields upon cold working and relative orientations of magnetic field (H), current (J), and rolling plane (RP) defect structure. Ratios indicate cold-rolling thickness reductions. (After Berlincourt and Hake, 1962).

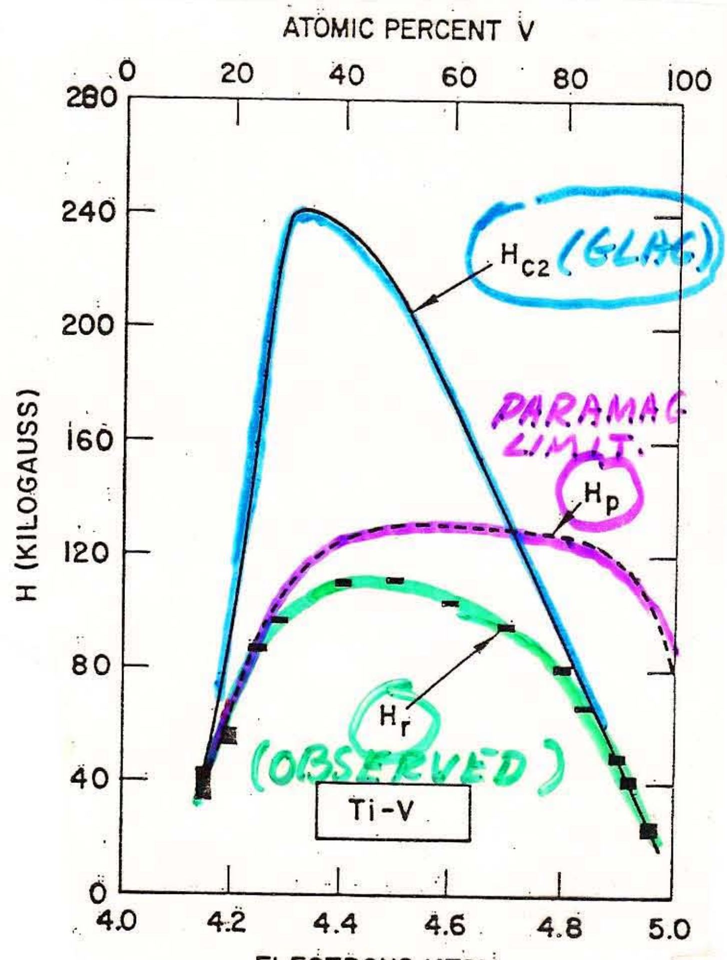
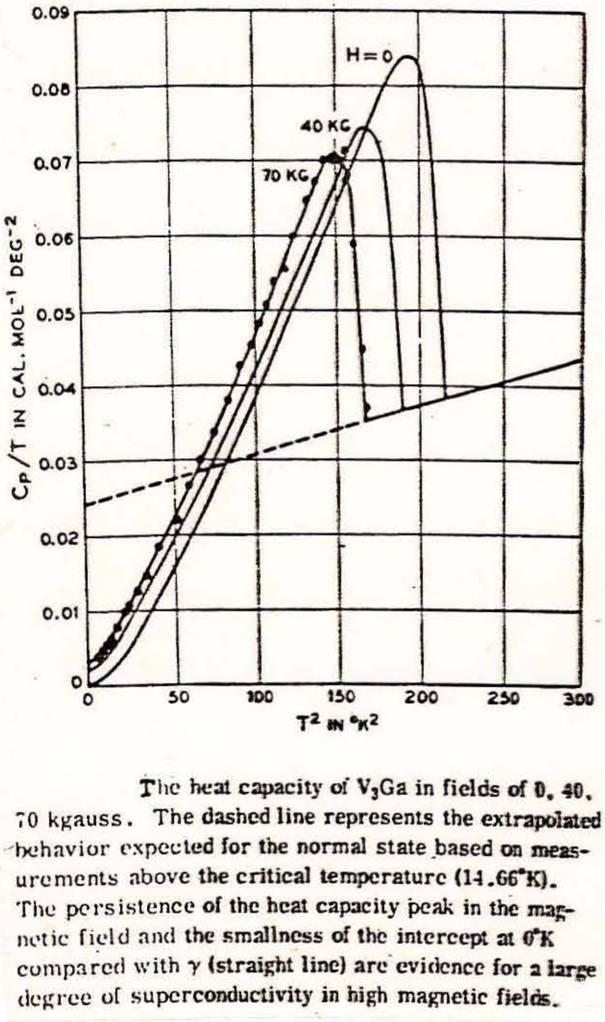


Figure 5. Experimentally determined transition field, H_r versus composition for Ti-V alloys, compared with theoretical values for H_{c2} (from GLAG theory) and for H_p (the paramagnetic limiting field). (After Berlincourt and Hake, 1962).

BUT THE BELL BOYS STILL REFUSE TO THROW IN THE SPONGE:

F. J. Morin, J. P. Maita, H. J. Williams, R. C. Sherwood, J. H. Wernick, J. E. Kunzler, Phys. Rev. Letters 8, 275 (1962):



cf. the data of Keesom & Desirant, 1941, on impure Ta !!

The heat capacity of V_3Ga in fields of 0, 40, 70 kgauss. The dashed line represents the extrapolated behavior expected for the normal state based on measurements above the critical temperature (14.66°K). The persistence of the heat capacity peak in the magnetic field and the smallness of the intercept at 0°K compared with γ (straight line) are evidence for a large degree of superconductivity in high magnetic fields.

"All of the results reported here can be interpreted by assuming that the sample contains a large number of filaments (probably dislocations) whose effective diameters are sufficiently large (but less than the penetration depth) that most of the sample appears superconducting. Because of the structure and low compressibility of V_3Ga, this assumption has been shown to be reasonable by Hauser and Helfand. However, it is expected that a perfect single crystal of V_3Ga (free of dislocations) would behave more like a 'soft' or nearly ideal superconductor and have a critical field of the order of 6 kgauss at 0°K." !

!

ACT XII. PURITY PREVAILS! VIRTUE IS RESTORED!!

INCONTROVERTIBLE VISUAL EVIDENCE FOR THE ABRIKOSOV VORTEX LATTICE.
THE FINAL DEATH KNELL OF THE SPONGE

U. Essmann & H. Träuble, Phys. Letters 24A, 526 (1967)

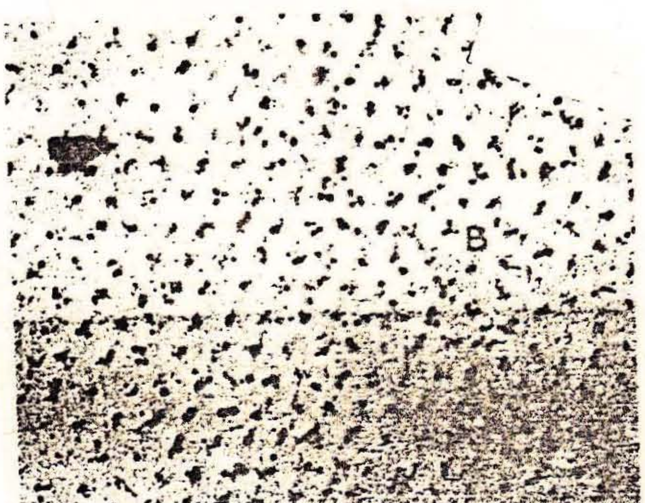


Figure 7. Triangular vortex lattice for type II superconductor as revealed by magnetic decoration technique. (After Essmann and Träuble, 1967.)

"If we wish to boast of our Achievements
Let us not point to the unerring pursuit of truth
By a logically faultless thinking machine,
But to the more astonishing way in which truth
Can be caused to emerge from the toils of error and stupidity"
[A.B. Pippard in SQUIDS and Machines (Plenum, 1977)]

"The pace of fundamental advance in physics
Is set by human stupidity.
The pace is, and always has been, very slow."
[Freeman Dyson, Sci. Amer. 199, 74 (1958)(Sept.)].

"I will examine arguments that young and impressionable students
At the start of a scientific career should be shielded from the writings
Of contemporary science historians" (because such writings) "do violence
To the professional ideal and public image of scientists as
Rational, open-minded investigators, proceeding methodically,
Grounded incontrovertibly in the outcome of controlled experiments,
And seeking objectively for the TRUTH, let the chips fall where they may."
Stephen G. Brush, "Should the History of Science be Rated X?,"
Science 183, 1164 (1974)]

"Many scientists owe their greatness not to their skill in solving problems
But to their wisdom in choosing them." ....
"From time to time the proposal is put forward that pure science
Should be planned 'by some master board of strategists'
Which would direct workers to those fields where gaps
were thought to exist.
The utter folly of this idea is apparent to anyone with the
Slightest knowledge of the history of science."
[E. Bright Wilson, An Introduction to Scientific Research
(McGraw-Hill, 1952).

"Looking back" (at the history of superconductivity), "perhaps through rose-tinted spectacles,
I have a warm memory of the encouragement that the colts received from the older horses...
Such kicks as were occasionally exchanged were harmless... we all enjoyed those times more
than can easily be described." A.B. Pippard, loc. cit. p. 1, ref. 4.