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SCHOOL ON
NON-ACCELERATOR PHYSICS
25 April - 6 May 1988

SUPERCONDUCTING DETECTORS OF WEAKLY INTERACTING PARTICLES

by
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Spring 1987

ANDRZEJ K. DRUKIER

"SUPERCONDUCTING DETECTORS OF

WEAKLY INTERACTING PARTICLES"

based on work done in collaboration with

L. Stodolsky
K. Freese, D. Spergel
F. Avignone, S. Ahlen, R. Brodzinski, G. Gelmini
A. Kotlicki, M. LeGros, B. Turrell

MENU

1) WHY SCATTERING ON NUCLEI?

2) WHY VERY LOW TEMPERATURE DETECTORS?

3) COMPARISON OF CRYOGENIC DETECTORS.

4) SUPERHEATED SUPERCONDUCTING COLLOID DETECTOR (SSCD)

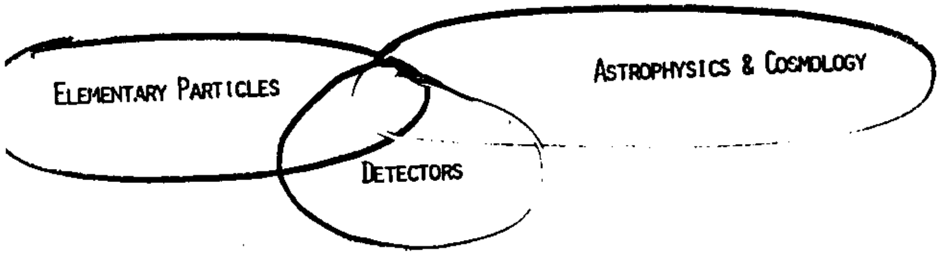
   a) PHYSICS OF SSCD;

   b) GRAINS: PRODUCTION/SELECTION/QUALITY;

   c) IRRADIATION TESTS;

   d) ELECTRONIC READ OUT USING SQUID'S.

WHY IS IT IMPORTANT ? ? ?



TWO IMPORTANT PROBLEMS...........

1) SOLAR NEUTRINO DEFICIENCY

IS OUR SUN WELL UNDERSTOOD?

ARE NEUTRINO OSCILLATING ?

IF YES, WHAT KIND OF OSCILLATIONS ?

IF YES, WHAT IS NEUTRINO MASS ?

2) DARK MATTER PROBLEM

IS IT BARYONIC ?

IF IT IS WEAKLY INTERACTING ARE THIS MASSIVE NEUTRINOS ?

IF NOT MASSIVE NEUTRINOS THEN :

S-NEUTRINOS, MAJORANA NEUTRINOS, PHOTINOS, SHADOW-MATTER

AXIONS, FAMILIONS, MAJORONS

MAGNETIC MONOPOLES

??????????????????

1940 – 1975 image of astrophysics:
Science about internal structure and evolution of stars.

However, 3 great scientific revolutions were started by astronomers :

1) Kinematics of solar system:

Tycho Brahe ⇒ Copernicus ⇒ NEWTON

2) Kinematics of Galaxies escape

Hubble ⇒ BIG BANG COSMOLOGY

3) Kinematics of stars in Galaxy

Galaxies in clusters

DARK MATTER ⇒ ? ? ? ?

V.C.RUBIN ET AL., AP.J. 238(1980)471
A.BOSMA, ASTRON.J.86(1981) 1825
FABRICANT&GORENSTEIN, AP.J.267(1983)535
S.KENT, PREPRINT 2231, CFA, 1986

FABER&GALLAGHER, ANN.REV.ASTRON.ASTROPHYSICS 17(1979)135
HUCHRA&GELLER, AP.J.257(1982)423
PRESS & DAVIS, AP.J.259(1982)449
DAVIS & PEEBLES, AP.J.267(1983)465
BAHCALL & SONEIRA, R.S.AP.J. SUPP. 55(1984)67
BAHCALL & CASERTANO, "SOME REGULARITIES IN MISSING MASS PROBLEM", IAS PREPRINT 1985
BUBLES, BUBLES. ...V.LAPPARENT ET AL., PREPRINT 2231, CFA, 1986

DETECTING WEAKLY INTERACTING MASSIVE PARTICLES/WIMP'S

M. Goodman, E. Witten, Phys. Rev. D31, 3059, (1985)
I. Wasserman, Cornell preprint DE 3065 (1985)
A. K. Drukier, K. Freese, D. N. Spergel, Phys. Rev. D33, 3495 (1986)

$$T_{max} = \frac{2Mm^2}{(M+m)^2}\beta^2$$

! excludes scattering on electrons !

$$\sigma \approx \frac{M^2m^2}{(M+m)^2}\ |A|^2$$

Where M = mass of WIMP, and m = mass of target nuclei,
|A| is reduced amplitude and depends on type of WIMP.

For solar cosmions (L. Hall et al.)

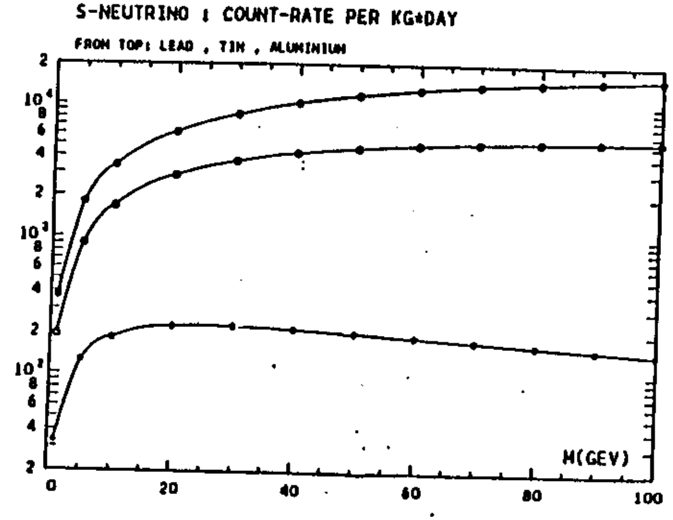
$|A|^2 \approx (Z+N)^2$!very large!

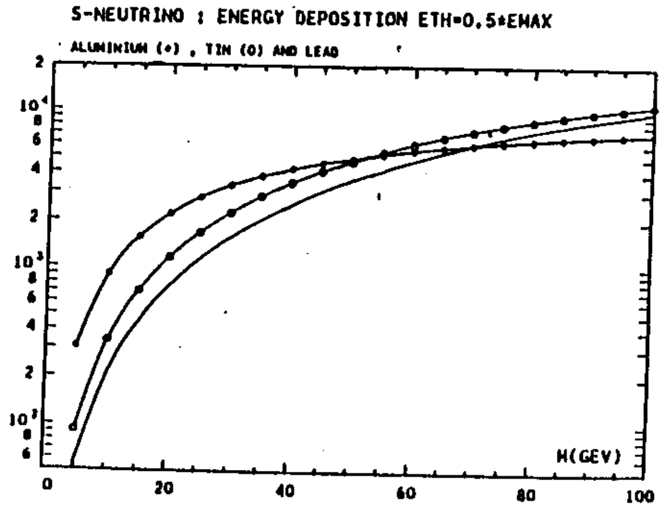
For s-neutrinos, massive Dirac neutrinos

$|A|^2 \approx N^2$!large!

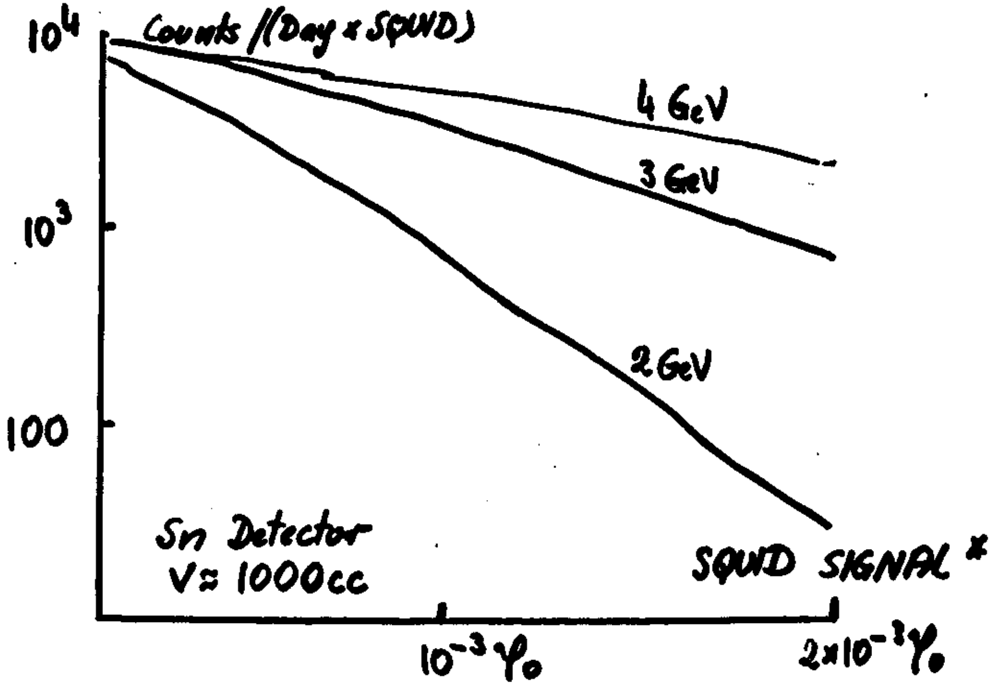
For photinos, majorana neutrinos

$|A|^2 \approx J(J+1)$!small, only odd isotopes!



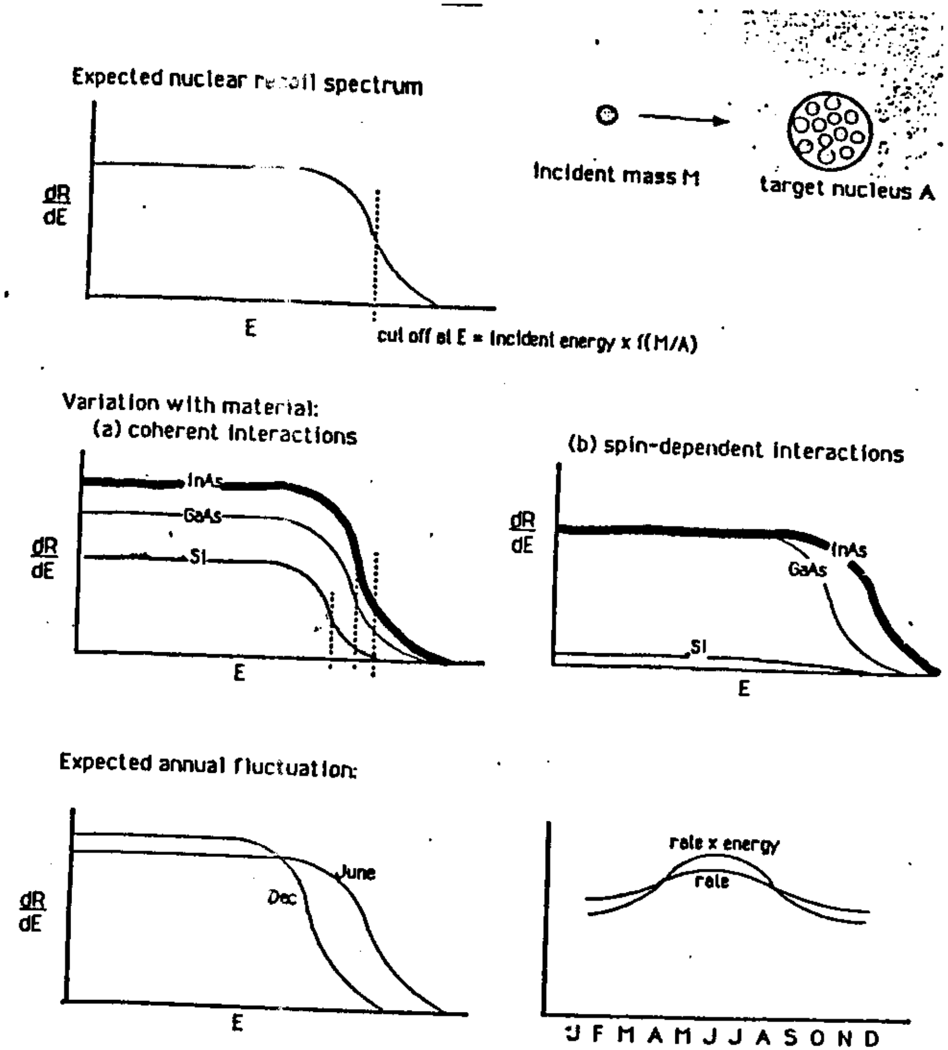


A.K. DRUKIER, K. FREESE, D. SPERGEL
March 1986



* S/N ≈ 10

SIGNATURES OF EVENT DUE TO WIMP's



Illustrative form of nuclear recoil spectra, showing mass-dependent cut-off, expected variation with target material for coherent or spin-dependent interactions, and expected annual modulation due to earth's orbital motion.

J. FRIEMAN et al.

"Signal Modulation in Cold Dark Matter Detection"

SLAC-PUB-1111 Sept. 1987

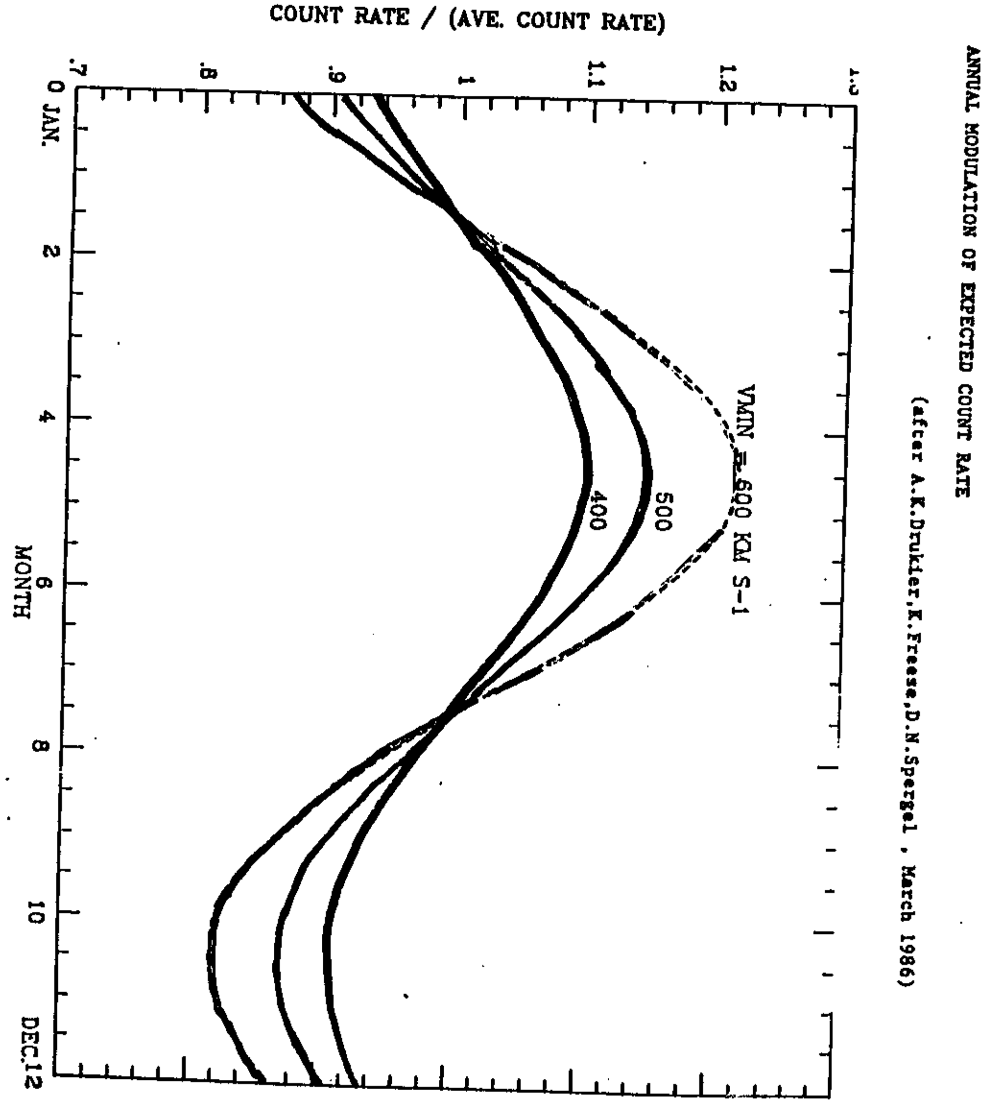
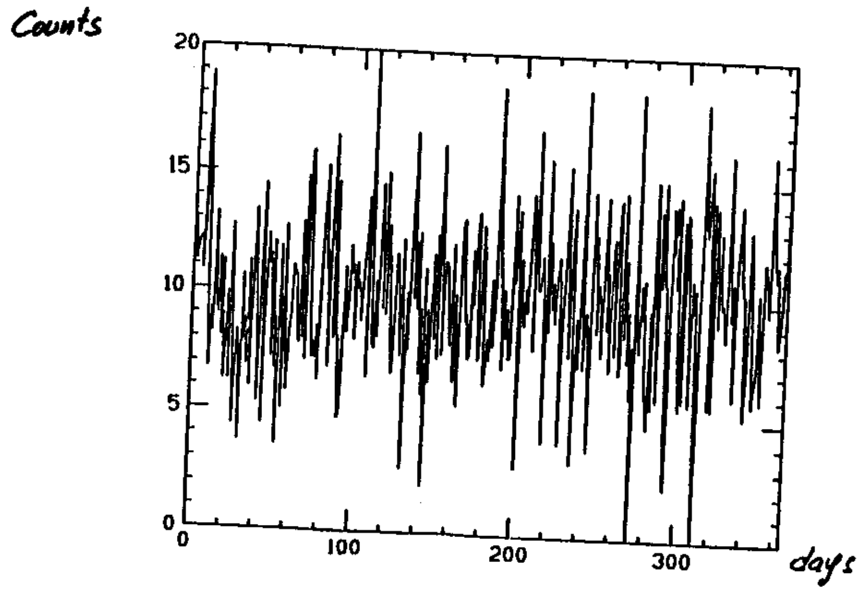
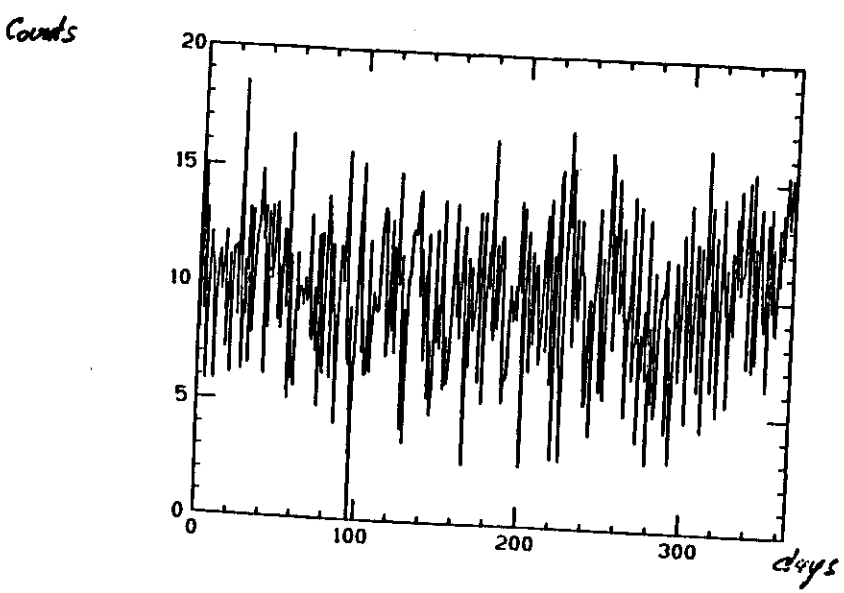


Figure 6.

To remedy this situation, one would like a clear signature which distinguishes the WIMP signal from other sources of background. Drukier, Freese, and Spergel[5] showed that, due to the earth's motion around the sun, the WIMP signal would have an annual sinusoidal modulation which peaks in late spring. Thus, they showed it would be possible, in principle, to demonstrate that the data was not pure background.[6]

In this paper, we analyze in detail the conditions under which one can measure the modulation of the WIMP signal. We also emphasize a different attitude toward the usefulness of modulation. In ref.5, modulation was viewed as a method of confirming a suspected WIMP signal; given this point of view, WIMP detection requires a large signal to noise ratio, and thus a reliable understanding of background levels. We argue that modulation can itself be used as the *primary* means of detecting WIMPs (rather than as a confirmation), even in the presence of large backgrounds (i.e., backgrounds comparable to or even larger than the WIMP signal). As a result, the prospects for detection of particles such as Majorana fermions, which generally have only spin-dependent interactions with nuclei and thus relatively small cross-sections, appear more promising than previously thought. Thus, a clear understanding of modulation is important not only in the analysis of data, but also in the design of experiments.





TYPES OF DETECTORS

1) SEMICONDUCTING: Silicon Germanium

S. Ahlen, F. Avignone, R. Brodzinski, A. K. Drukier, G. Gelmini, D. Spergel. Preprint CfA: 2292 (March 1986)

Sensitive only for M ≥ 15 Gev!
Unsensitive to photinos/majorana neutrinos!

2) HYBRID BOLOMETERS

A. K. Drukier, L. Stodolsky, preprint MPI 1982
E. Fiorini, T. O. Niinikoski, Nim 224, 83 (1984)
S. H. Moseley, J. C. Mather, JAP 56, 1257 (1984)
B. Cabrera et al., Phys. Rev. Lett 55, 25 (1985)

High Debye Temperature Material Absorber + Thermometer

ad: choice of absorber
crystal [high Θ_d, low atomic number] e.g. B, Si, Al_2O_3
refractory metal superconductors (Ir, Os, Rh, Ru, Mo, W) [high Θ_d, high atomic number]

3) SUPERCONDUCTING BOLOMETERS!!!

Absorber is Also Thermometer

superheated superconducting colloid detector
superconducting tunnel junctions

WHY BOLOMETRIC DETECTORS?

The recoiling heavy nuclei are too slow to ionize.

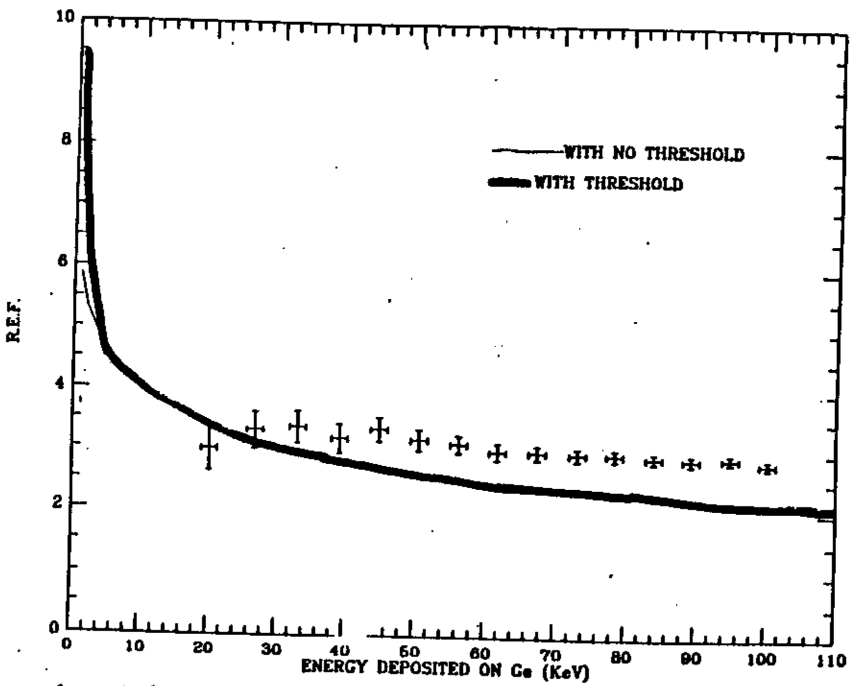
$P_{ionization} \approx \exp -(3 * E_{gap}/E_{excitation})$

In Germanium for WIMP'S with M = 10 GeV

$E_{gap} \approx 0.7$ eV

$E_{excitation} \leq 0.1$ eV

Most of energy goes into lattice vibration.



+ Experimental data of Chesman et al.

Low temperature particle detectors

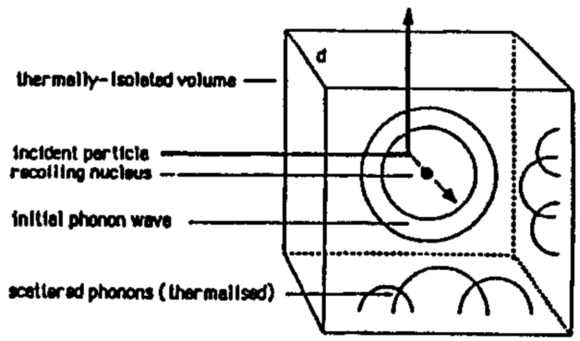


Fig 1.a Conversion of nuclear recoil energy to phonon wave, and subsequently to a rise in temperature after scattering and thermalisation of phonon distribution.

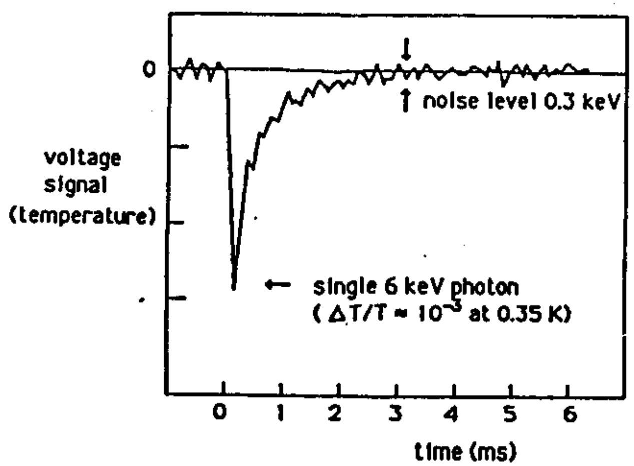


Fig 1.b Temperature pulse produced by 6 keV X-ray in silicon * (from MacCammon et al [39]).

* m ≈ 5 mg

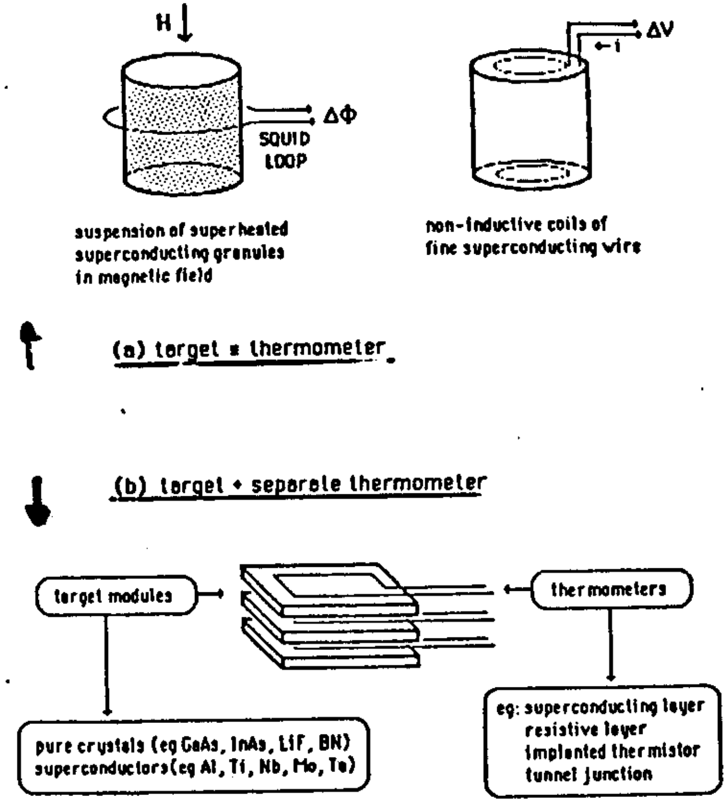


Fig 2 Some alternative possibilities for scale-up of calorimetric detection principle.

Development of cryogenic WIMP detectors

$$\Delta T \propto (d \times T_{operation} / \Theta_D)^3 \times f(Z, M, spin)$$

I) Small is beautifulll....

CfA/UBC ; MPI/TU ; Annency/Orsay ; Rutherford

- d as small as possible
- Θ_D reasonable (radioactivity pure materials)
- high Z materials
- $\Rightarrow$ $T_{operation} \approx 50$ mK

For case of SSCD we need to

- improve electronics ×10
- grain quality ×10
- $\Rightarrow$ improved $E_{th} \approx E_{th}(1986)/100$

II) Simple is beautifull ....

Stanford

- d as big as possible (say 1kg crystals)
- Θ_D good
- $\Rightarrow$ $T_{operation} \approx 5$ mK

For case of silicon one need to

- improve $E_{th} \approx E_{th}(1986)/10^6$
- improve radioactive background by 10^4

TABLE 1: CRYOGENIC WIMP'S DETECTORS

Detector	Mass	T	Material	Challenges	When
1st generation detectors ("solar cosmions")					
SSCD	0.01g	0.3°K	High Z	Better SQUID's colloid quality	1988
MC	0.01g	0.1°K	Si	Better thermistors 100 channels	1988
MC	0.01g	0.1°K	High Z	Specific heat data absorber/thermometer coupling	1989
2nd generation detectors (S-neutrino, massive Dirac neutrino)					
SSCD	100g	0.05°K	High Z	Background 10 channels SQUID's	1991
3rd generation detectors (photinos)					
SSCD	10kg	0.02°K	Al, V, Ga	Background 100 channels SQUID's	1992
BPC	10kg	0.01°K	B, Li, F	Background read-out $T \leq 10$ mK	1992

MC = microcalorimeters, BPC = ballistic phonon calorimeters

A. K. DRUKIER

Fall 1986

SUPERHEATED SUPERCONDUCTING COLLOID DETECTOR: STATE OF ART

ALSO:

L. Stodolsky et al., MPI f.Physik, MUNICH

F.V. Feilitzsch et al., TU, MUNICH

G. Waysand et al., ORSAY/SACLAY/PARIS/ANNENCY

A. Kotlicki et al., UBC, VANCOUVER

Superheated superconducting colloid detector vel. SSC vel. Super-CD

- looks like nuclear emulsion;
- works as bubble chamber;
- is read-out like MWPC or Magnetic tape.

MENU

1. What is it? How does it work?
   (Mechanism of change of state of irradiated grain)
2. Grains production and selection.
3. Collective effects.
4. Electronic read-out.
5. Irrad'ation experiments.
   Paris VI, Orsay, 1970-86/ZTTF, Munich, 1982-3/TU, Munich, 1984
6. How to detect single grains flios,
   Paris VI, Orsay, 1980-86/TU, Munich, 1984/UBC, Vancouver, 1985
7. What next?

SUMMARY

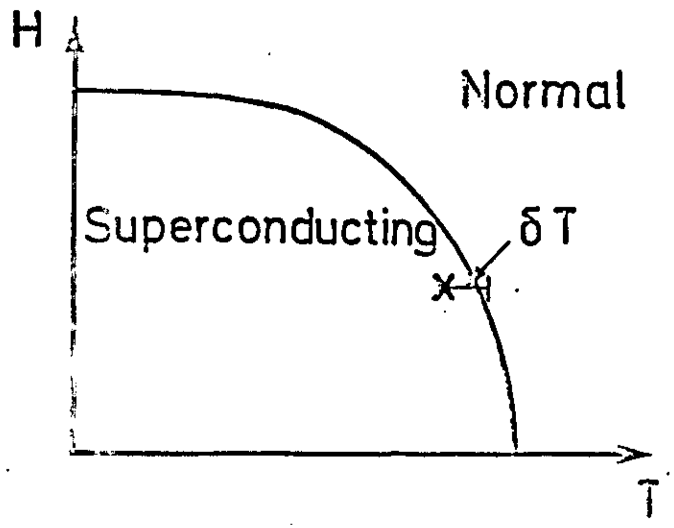
A) THE SUPERHEATED SUPERCONDUCTING COLLOID DETECTOR CAN BECAME A VERY IMPORTANT TOOL OF ASTRONOMY/PHYSICS IN THE NEXT FEW YEARS.

B) THE SSC DETECTOR EXISTS ! ,WAS TESTED EXPERIMENTALLY AND PHYSICS OF INVOLVED EFFECTS IS RELATIVELY WELL UNDERSTOOD.

C) THE SSC SHOULD BE EXPERIMENTALLY TESTED AT VERY LOW TEMPERATURES, SAY 50 MILLIKELVINS.

D) TO REACH THE ULTIMATE SENSITIVITY AND 100% QDE WE NEED EXPERIMENTS/IMPROVEMENTS IN :

- ELECTRONIC READ-OUT USING SQUID's.
- GRAINS PRODUCTION/SELECTION,
- COLLECTIVE EFFECTS ,E.G. THERMAL AVALANCHE.



$t = T/T_c$

$H_c(T) = H_c(0)*(1-t^2)$

$\lambda(T) = \lambda(0)*(1-t^4)^{1/2}$

$\Delta(T) = \Delta(0)*(1-t^2)$

For spherical grains $H_{grains} = \frac{2}{3} H_c$

SUPERHEATED SUPERCONDUCTING COLLOID DETECTOR (SSCD).

SSCD CONSISTS OF COLLECTION OF SMALL R = 1-10 μm
SUPERCONDUCTOR GRAINS IMMERSED IN DI-ELECTRIC

TYPICAL TYPE I SUPERCONDUCTORS: Cd, In, Sn, Hg
MOST OF OUR EXPERIENCE IS WITH In and Sn
FOR Sn: H_C = 330G, T_C = 3.3°K

WHY SSCD IS SO SENSITIVE BOLOMETER?

SIZE OF GRAINS IS VERY SMALL $V_g \approx 10^{-11} - 10^{-9}$ CC.

SPECIFIC HEAT $C_V(T) = \alpha T^3 + \gamma T$

e.g., $C_V(Sn)$ = 34 eV/ μ^{-3} K^{-1} AT 50 mK⁰ ⟸
= 280 eV/ μ^{-3} K^{-1} AT 0.4°K
= 790 eV/ μ^{-3} K^{-1} AT 1.0°K

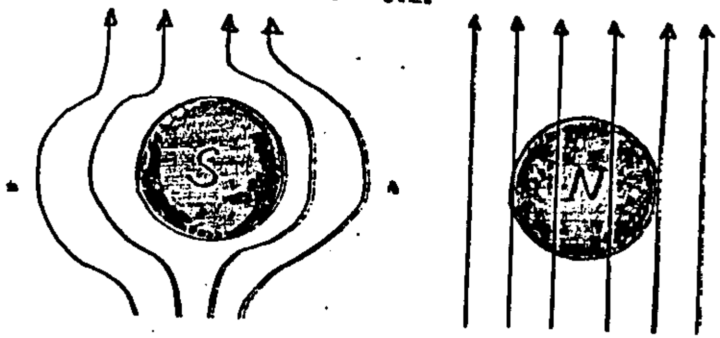
ENERGY THRESHOLD

$$E_{th} \approx A \times V_g \times C_V(T) \times \Delta T(H)$$

A - DEPENDS ON GRAIN
V_g - IS GRAIN VOLUME (SEE FIGURE 5)
$\Delta T(H)$ - INFLUENCED BY DIAMAGNETIC INTERACTIONS OF GRAINS

ELECTRONIC READ-OUT OF SSC

USES MEISSNER EFFECT. I.E.



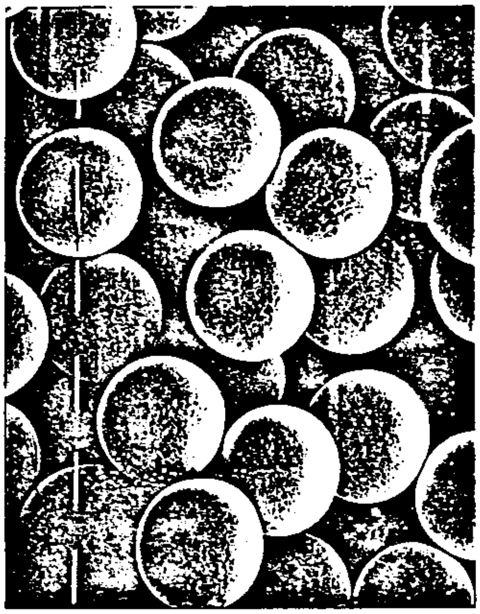
EXISTING ELECTRONICS

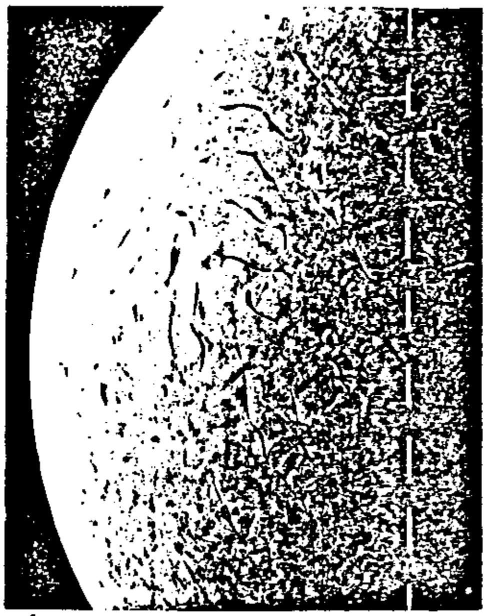
⟹ SI-FET BASED CHARGE SENSITIVE AMPLIFIERS (300⁰K) *
$\Delta\gamma \approx 50\%$; R= 5 MICRONS, L=0.5 MM ⟹ S/N =5

GA-AS BASED CHARGE SENSITIVE AMPLIFIERS (4.2 °K)
$\Delta\gamma \approx 5\%$; R= 2 MICRONS ,L=0.3 MM ⟹ S/N =5

JOSEPHSON-JUNCTION FLIP FLOPS (4.2°K)
$\Delta\gamma \approx 0.1\%$; R= 1 MICRON ,L=1.0 MM ⟹ S/N=5

⟹ SQUID's (4.2°K) *
$\Delta\gamma \approx 10^{-4}\,\gamma_0/\sqrt{Hz}$; R= 1 MICRON ,R_{LOOP}= 5.0 CM S/N=5





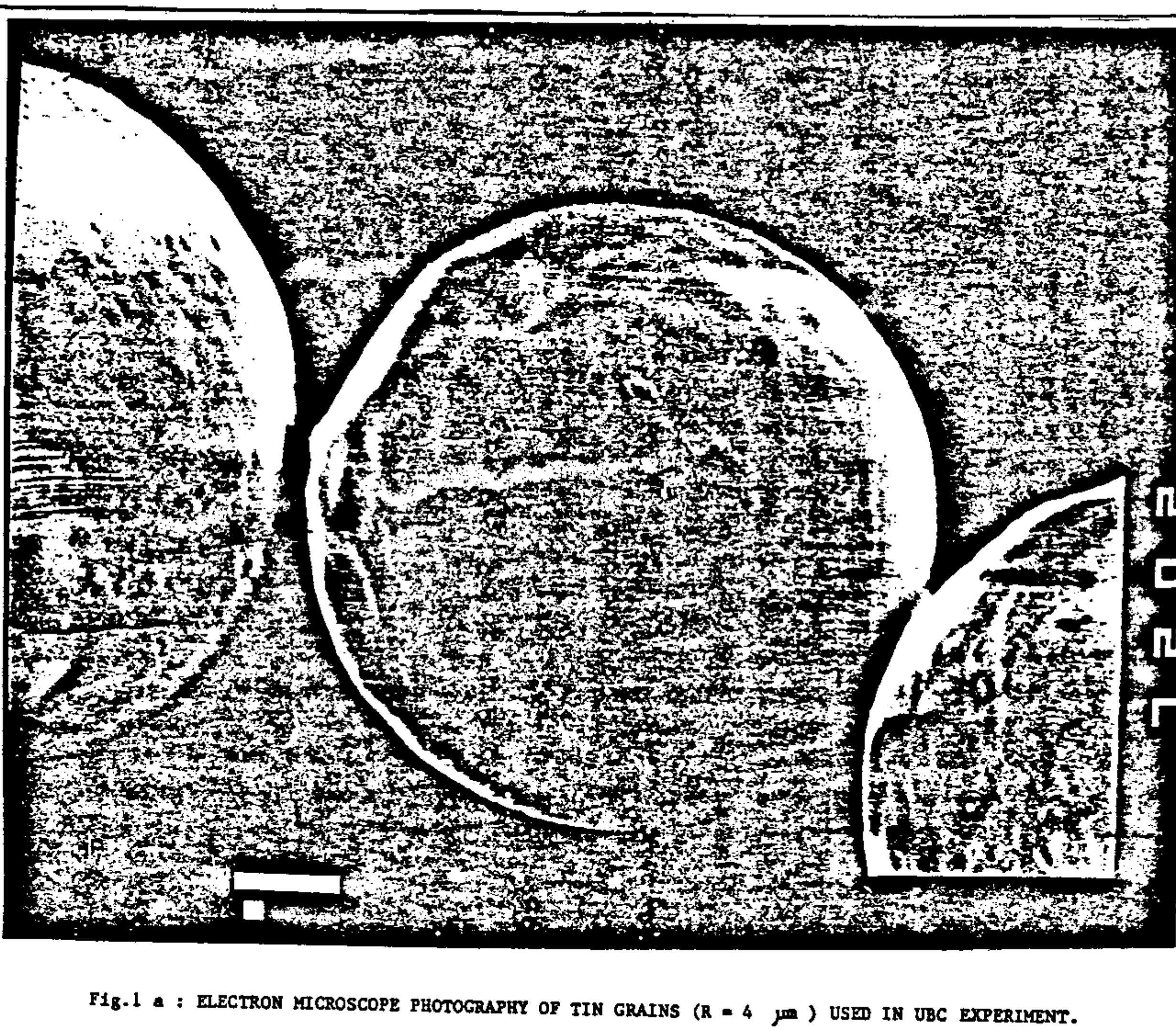
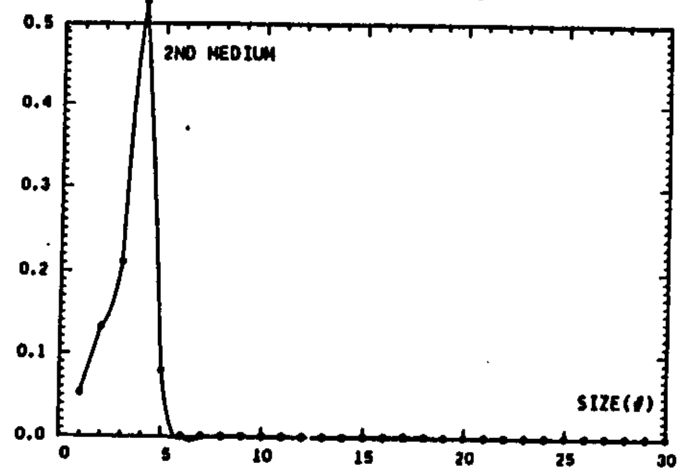


Fig.1 a : ELECTRON MICROSCOPE PHOTOGRAPHY OF TIN GRAINS (R = 4 μm) USED IN UBC EXPERIMENT.

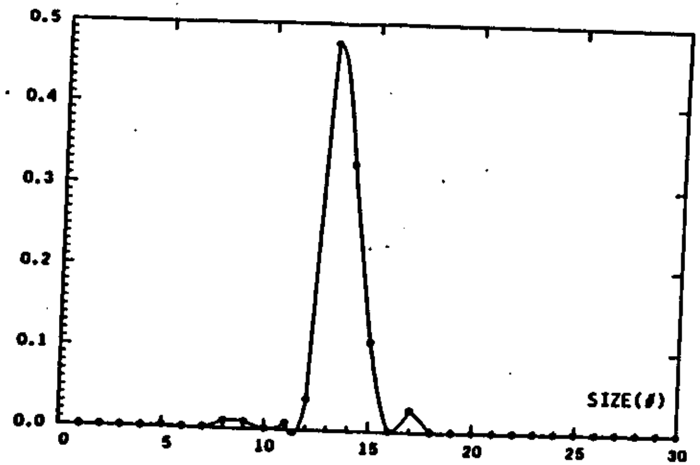
TABLE 1: Diameter of grains

Filter	Microscope [μm]	Diffraction [μm]
50 ≥ ø ≥ 45		51.7 ± 5.2 %
45 ≥ ø ≥ 40	44.8 ± 5.6 %	46. ± 5.2 %
40 ≥ ø ≥ 36	40.8 ± 6.8 %	38.9 ± 4.3 %
36 ≥ ø ≥ 32	38.0 ± 5.5 %	36.5 ± 6.8 %
32 ≥ ø ≥ 28	34.0 ± 9.8 %	33.7 ± 5.8 %
28 ≥ ø ≥ 25	32.2 ± 5.5 %	
25 ≥ ø ≥ 20	22.2 ± 6.1 %	18.0 ± 8.3 %
20 ≥ ø ≥ 15	17.2 ± 8.6 %	17.4 ± 8.6 %
15 ≥ ø ≥ 10	12.6 ± 7.5 %	
10 ≥ ø ≥ 5	6.8 ± 12.5 %	
5 ≥ ø (big)	4.0 ± 15.0 %	4.2 ± 6.3 %
5 ≥ ø (medium)	3.2 ± 30.0 %	
5 ≥ ø (small)	2.0 ± 50.0 %	

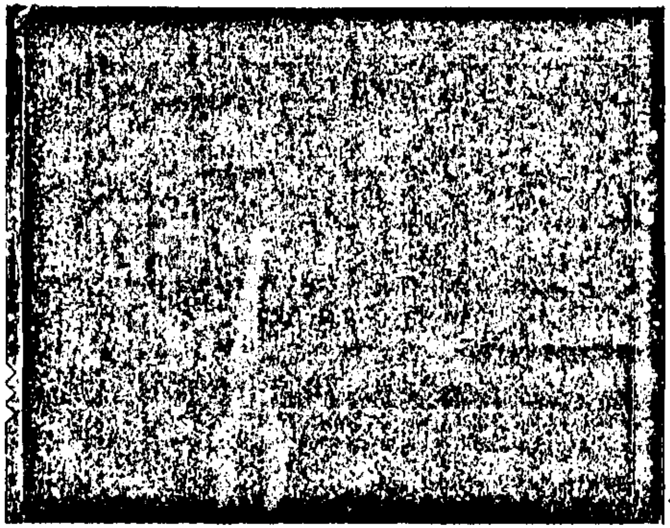
SIZE DISTRIBUTION N(%): D<5. MICRONS

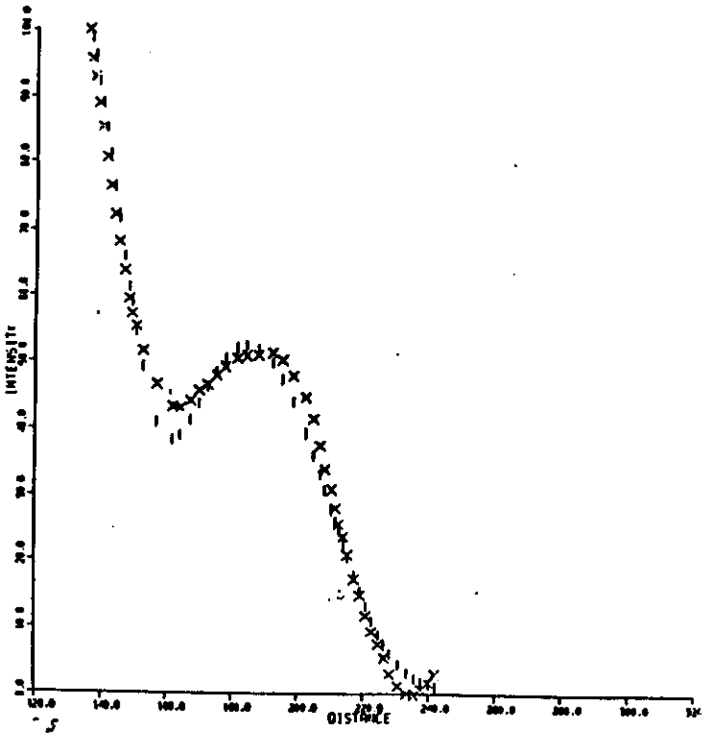


SCALE : 1 # = 1.2 MICRONS



SIZE DISTRIBUTION :25<D<28 MICRONS
SCALE : 1 # = 2.5 MICRONS





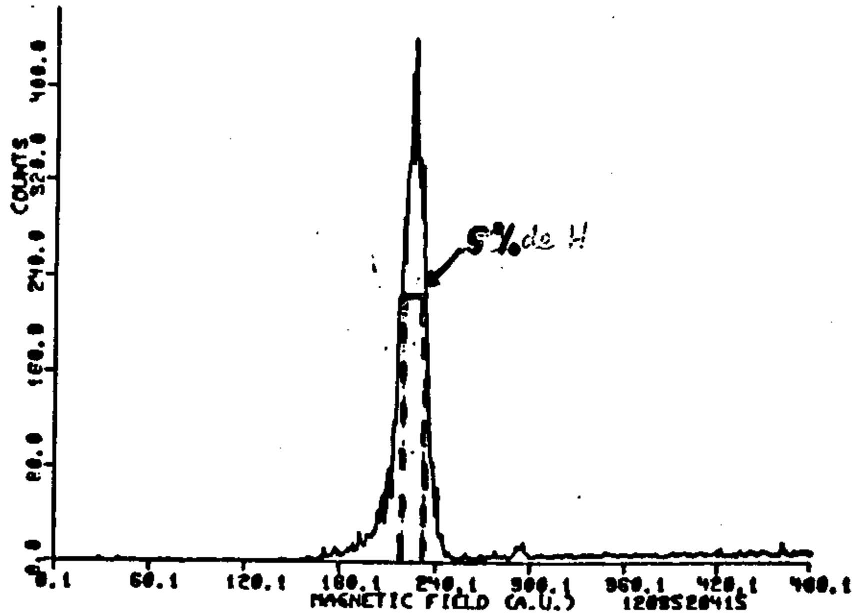
GRAINS QUALITY

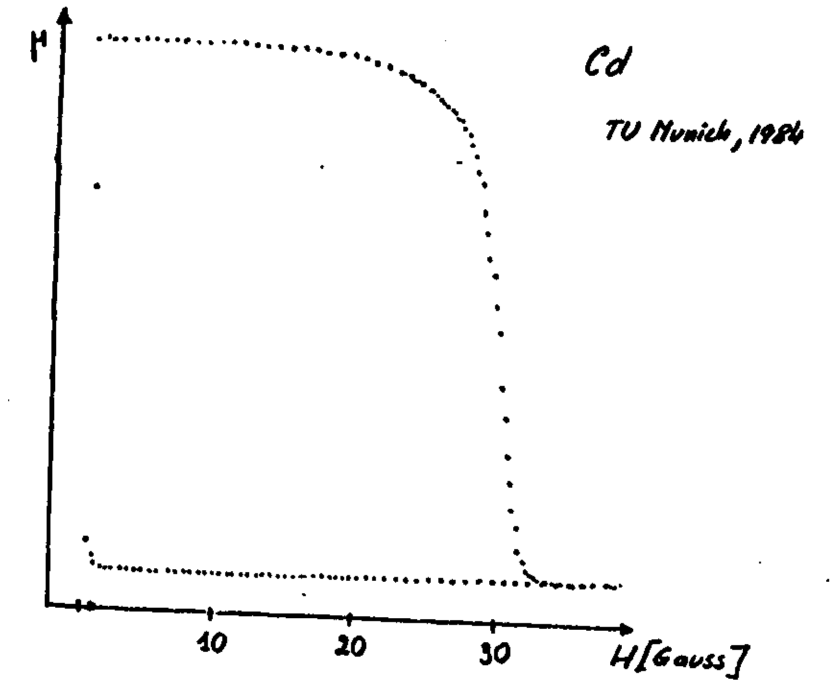
FOR SINGLE GRAINS, ONE OBSERVES THE PERFECT HYSTERESIS CURVE.I.E. CHANGE OF STATE IS VERY NARROW.

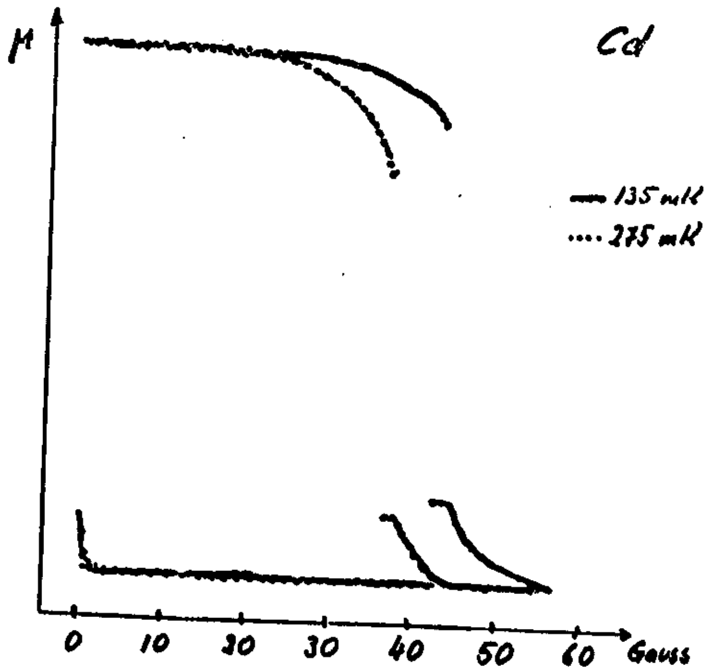
FOR SELECTED ,WELL SPACED GRAINS $\Delta H/H_{SH} \leq 0.5\%$ (UBC RESULTS).

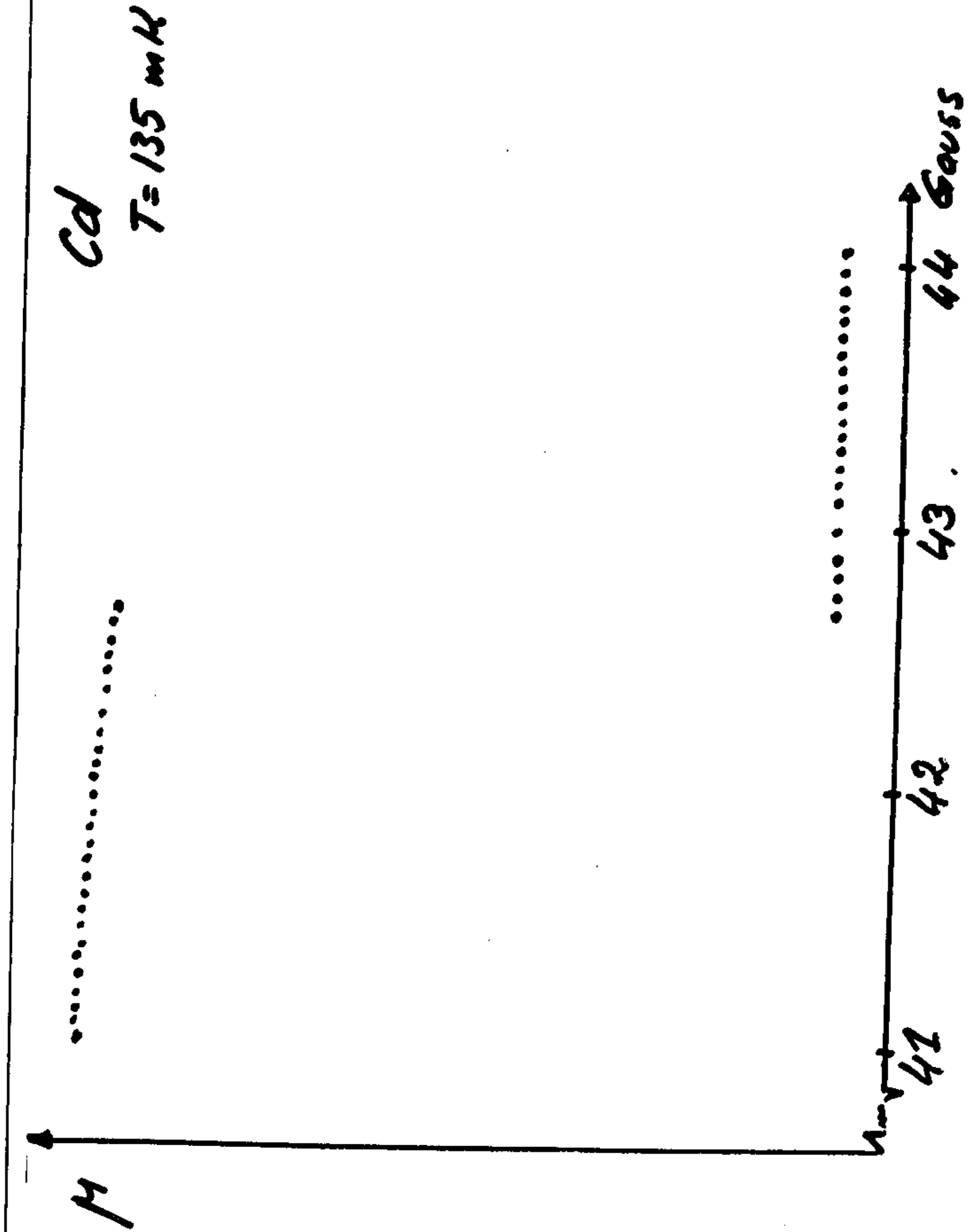
FOR LARGE CORRECTION OF GRAINS THE HYSTERESIS CURVE IS FAR FROM PERFECT, I.E. CHANGE OF STATE IS BROAD $\Delta H/H_{SH} \approx 5\%$ .THE REASONS ARE:

1) SOME GRAINS ARE NOT SPHERICAL CA.5%
2) SOME GRAINS HAVE DEFECTS CA.5%
3) THERE IS DIAMAGNETIC INTERACTION BETWEEN THE GRAINS WHICH ARE RANDOMLY DISTRIBUTED INSIDE OF DIAELECTRIC.




M
Cd
TU Munich, 1984
10
20
30
H[Gauss]


M
Cd
135 mK
275 mK
0
10
20
30
40
50
60
Gauss


Cd
T= 135 mK
M
41
42
43
44
Gauss

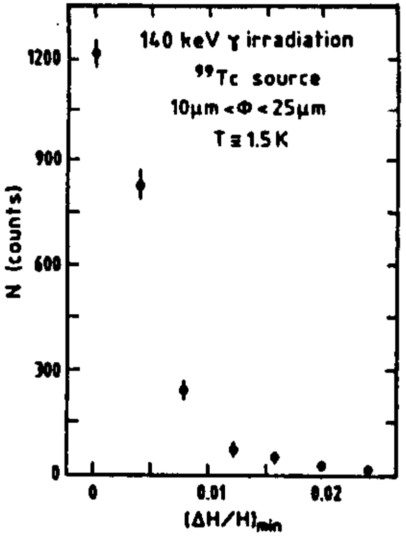


Fig. 7: Counts after 20 min. for sample d) irradiated with 140 keV γ's versus $(\Delta H/H)_{min}$.

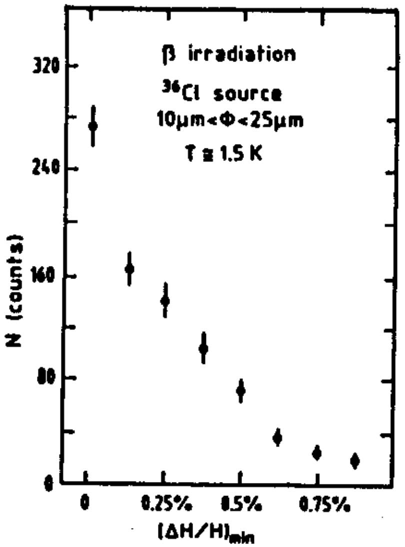


Fig. 8: Counts after 1 hour for sample d) irradiated with E < 714 keV β^- versus $(\Delta H/H)_{min}$.

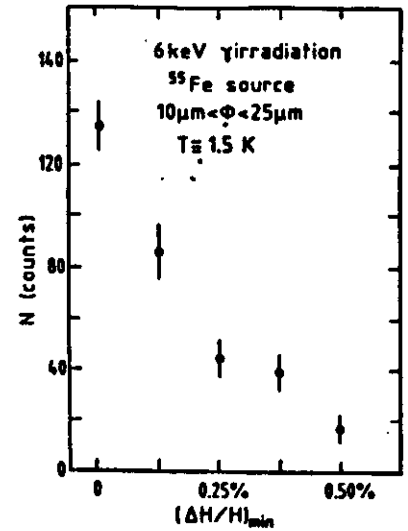
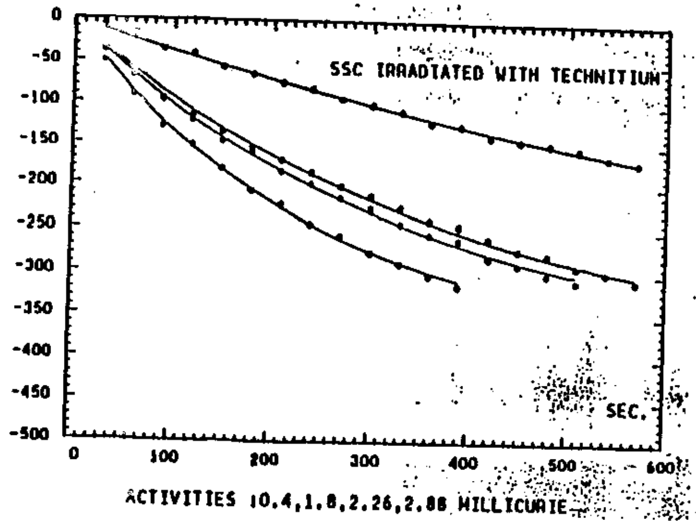


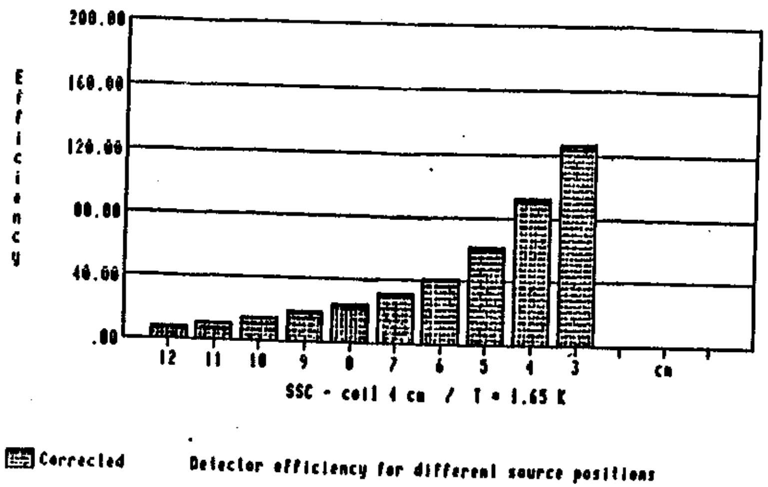
Fig. 10: Number of counts after 1 hour for sample d) irradiated with ^{55}Fe γ's.

D. Perret-Gallix / L. Gonzales-Mestres, LAPP/CERN

IRRADIATION EFFECT IS PROPORTIONAL TO GAMMA-FLUX



* = MEASURED EFFECT , CONTINOUSE LINES = EXPONENTIAL DECAY OF ACTIVITY



WHEN THE SOURCE IS MOVED OFF DETECTOR EFFECT DECREASES AS R^{-2}

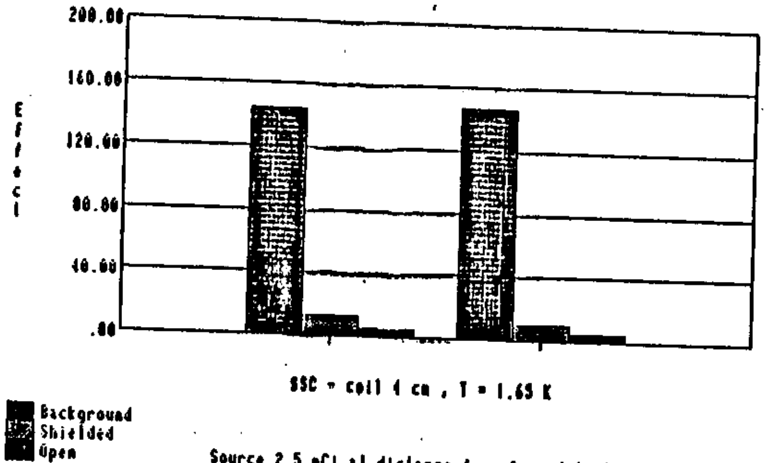
IRRADIATION TESTS - MUNICH 1980-82 (A.K.DRUKIER)

TESTED : TIN AND INDIUM SSCD (FILLING FACTORS 1-10%)
(GRAINS RADIUS =5 MICRONS ,$\Delta R/R$ =30%)

RADIOACTIVE SOURCES : GA-67(80 KEV) ,TC-99M (140 KEV)

$E_{DEPOSITED} = \sqrt{2} * R * 1.5$ KEV/MICRON = 10 KEV
SECONDARY PHOTONS (20 KEV)

MEASURMENT METHOD : INTEGRATING EFFECT DUE TO SOURCE OVER CA. 1 MIN
MEASURING THE MAGNETIC PERMEABILITY VIA.
RESONANCE FREQUENCY CHANGE IN LC OSCILLATOR



Source 2.5 mCi at distance 4 cm from detector

TESTS OF SSC AS PARTICLE DETECTOR

CD,IN,SN,HG LOW MELTING POINT TYPE-1 SUPRACONDUCTORS

R= 1 - 20 MICRONS

MINIMUM IONIZATION PARTICLES (DE/DX =1.5 KEV/MICRON)

$E_{DEPOSED} \geq 3$ KEV

PHOTONS (15 KEV - 150 KEV)

1970 C.VALETTE ,ORSAY (HG , BETA RADIOACTIVITY)

1971 C.VALETTE,A.K.DRUKIER (SN, ALPHA/BETA RADIOACTIVITY)

1972 L.ROSENBLUT ET AL.,RENNES (SN, A FEW MEV ELECTRONS)

1973-5 L.YUAN,C.VALETTE,G.WAYSAND,A.K.DRUKIER ,DESY ,HAMBURG
(SN, 1-5 GEV ELECTRONS & TR)

1977 J.IGALSON,L.SNIADOWER,A.K.DRUKIER ,WARSAW
(SN/LI ,THERMAL NEUTRONS)

1977-83 G.WAYSAND,C.VALETTE,D.HUEBER,PARIS
⇒ A.K.DRUKIER ,ZTTF,MUNICH
(SN/IN ,PHOTONS 30-300 KEV)

1984 W.SEIDEL ,TU MUNICH
(CD ,PHOTONS 90-140 KEV)

⇒ 1986 A. Kotlicki et al., UBC, Vancouver
(Sn, Photons 90 keV)

1987 K. Poetzel et al., MPI f. Physik, Munich
(Sn+ 1% Sb, big single grain)

⇒ 1987 D. Perret-Gallix et al., CERN
(Sn+1% Sb, 6 keV photons)

DEVELOPMENT OF SQUID READ-OUT FOR SSCD - UBC SUMMER 1986

A.K.DRUKIER, A.KOTLICKI, M.LEGROS, B.TURRELL

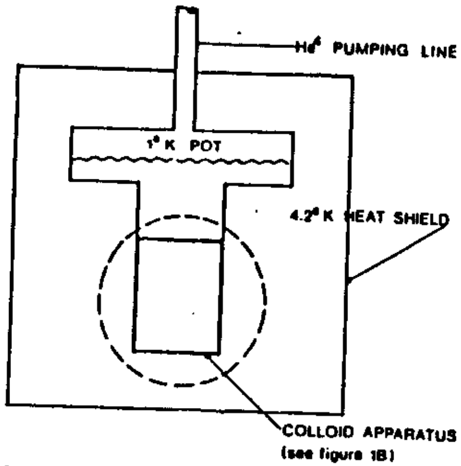
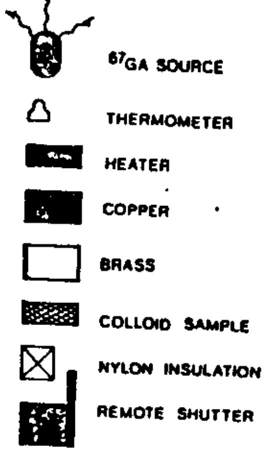


FIGURE 1A

LEGEND



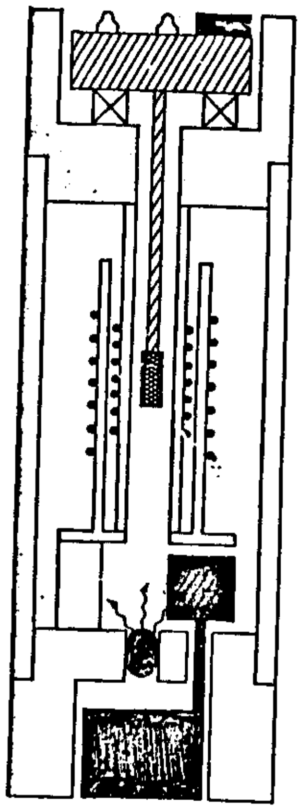
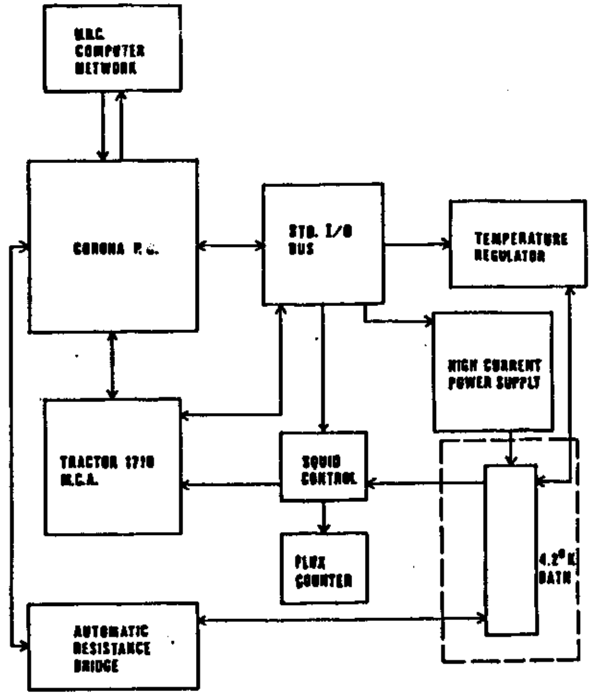


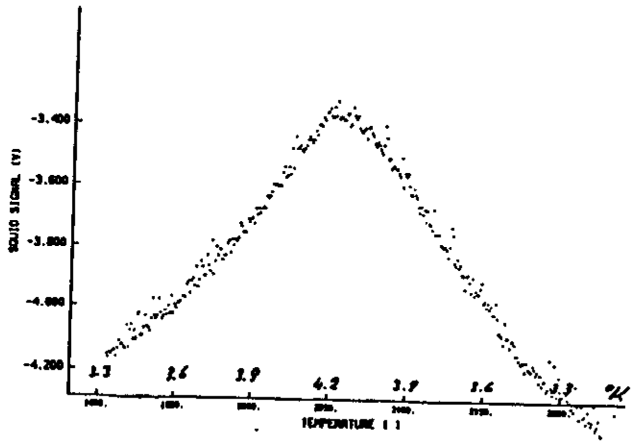
FIGURE 1B

FIG. 1 A SHOWS THE BASIC DESIGN OF EXPERIMENT

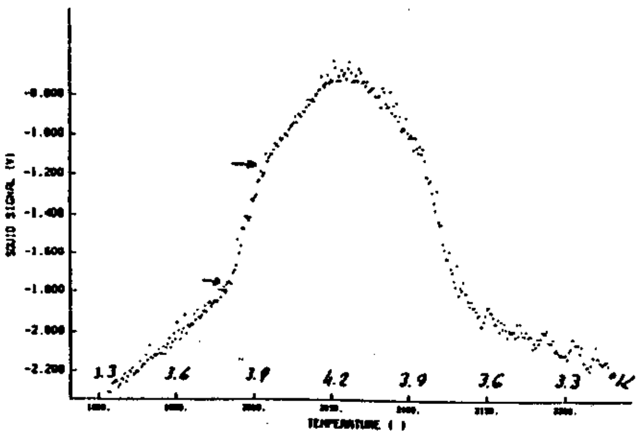
FIG.1 B SHOWS HOW THE APPARATUS IS MOUNTED IN THE 1^{O}K REFRIGERATOR.



FIELD=0.5 GAUSS I=15 MA R=15 MICRONS NOV.85

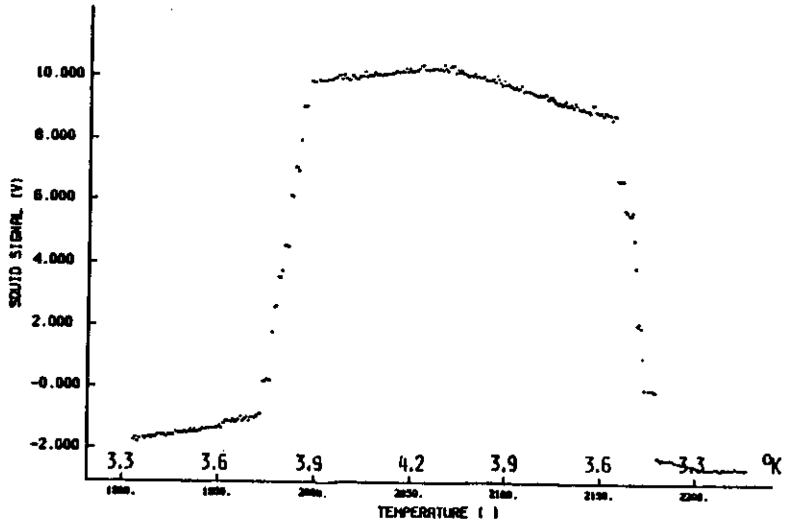


FIELD= 1.0 GAUSS I=30 MA R=15 MICRONS NOV.85

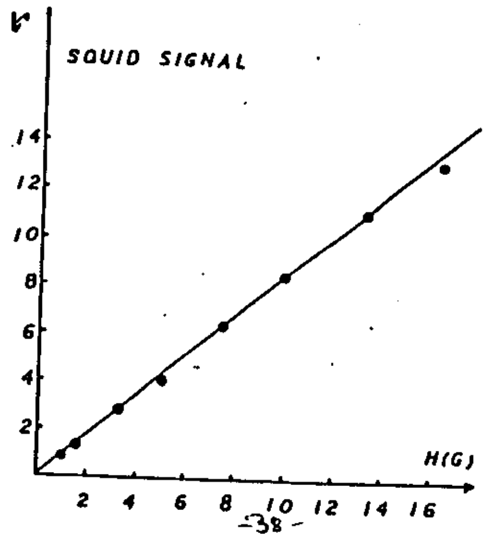


SIGNAL FOR COLLECTION OF TEN GRAINS ⇒ TEN STEPS IN SQUID OUTPUT

FIELD= 13.3 GAUSS I=400 MA R=15 MICRONS NOV.85



SIGNAL IS PROPORTIONAL TO THE APPLIED MAGNETIC FIELD AND S/N ≥ 20



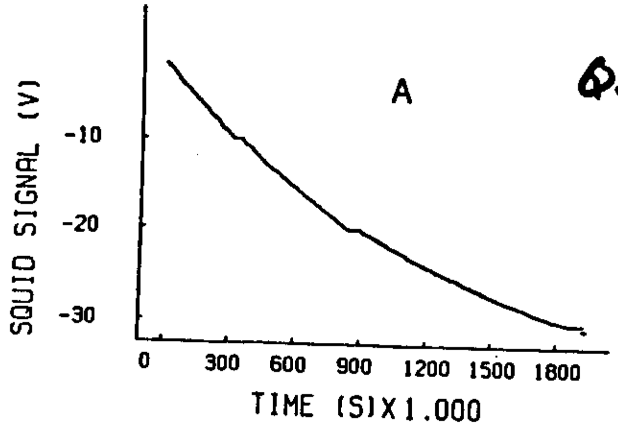
COLLECTION OF 10,000 GRAINS IRRADIATED WITH X- RAY PHOTONS

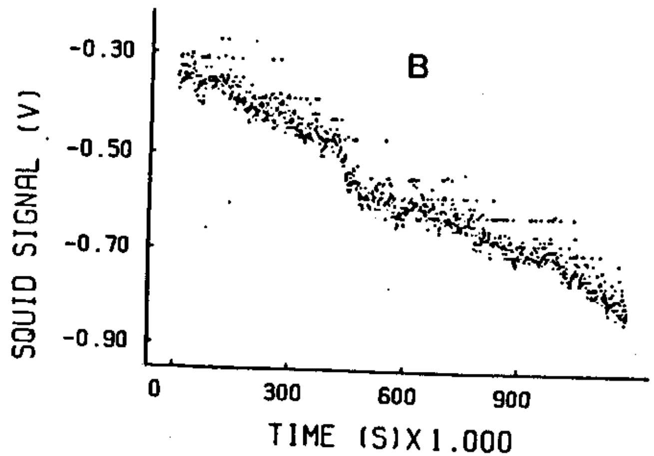
TYPICAL ENERGY DEPOSITION CA. 10 KEV

TEMPERATURE = 2^{0} K ; R_{GRAIN} = 2 MICRON ; H = 200 GAUSS

S/N ≥ 10 FOR R_{LOOP} = 0.5 CM

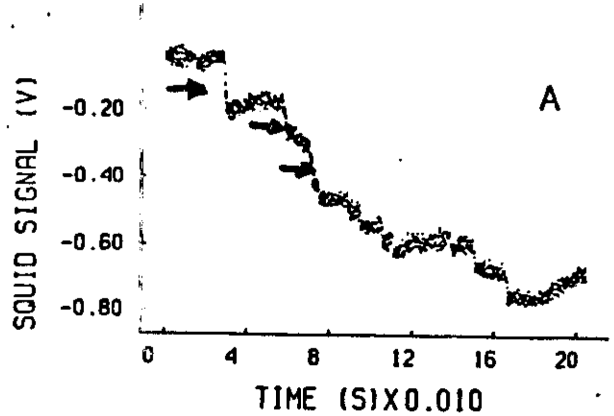
QDE≈90%

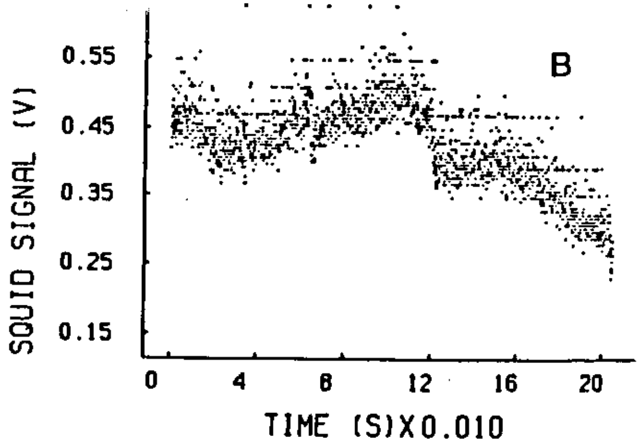




A - COLLIMATOR OPEN TO ALL PHOTONS

B - ONLY PHOTONS WITH E>200 KEV (RARE) CROSS COLLIMATOR



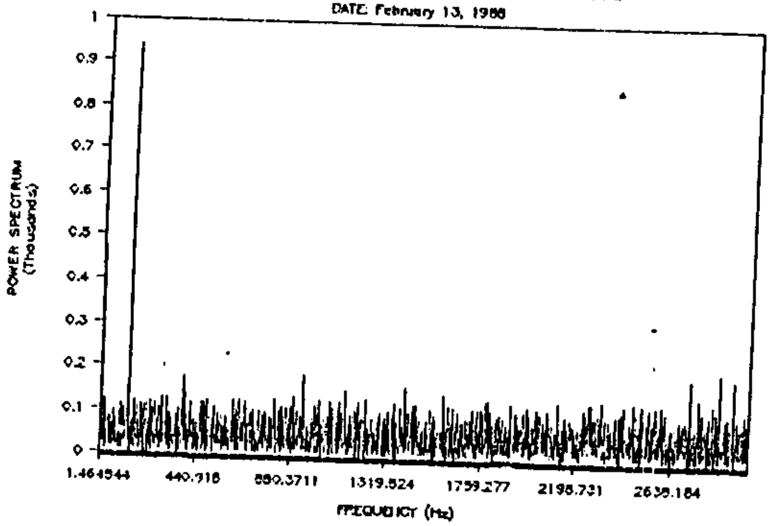


A) COLLIMATOR OPEN - NOTE SIGNALS DUE TO CHANGE OF STATE OF SINGLE GRAINS ➡

B) COLLIMATOR CLOSED - NO SIGNAL

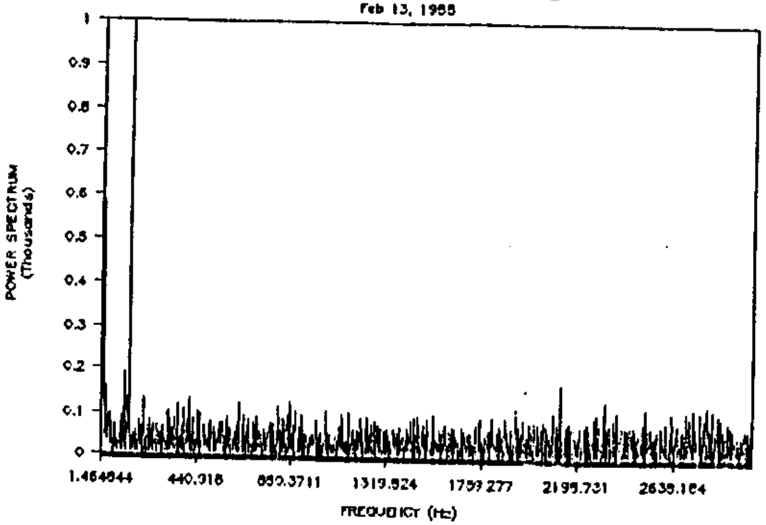
NOISE SPECTRUM – zero field

DATE: February 13, 1988



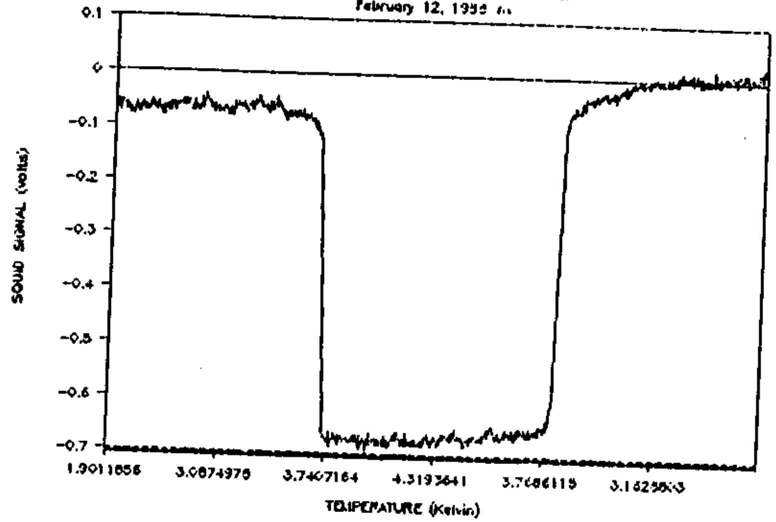
NOISE SPECTRUM – 300 gauss

Feb 13, 1988



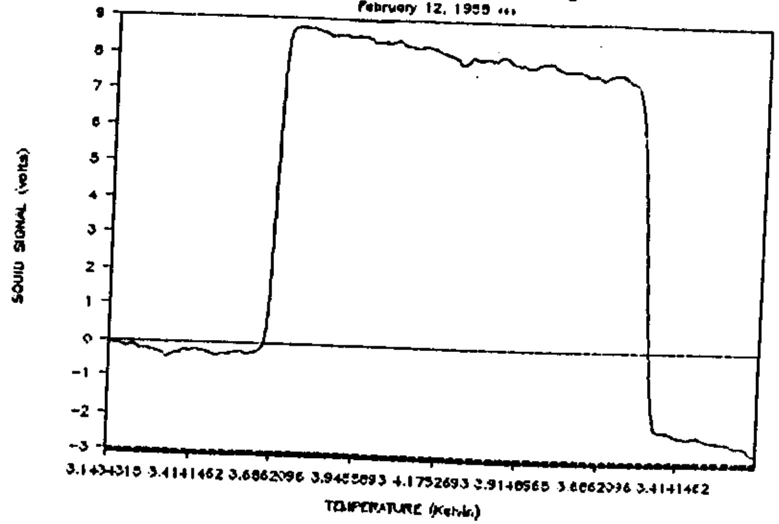
HYSTERESIS CURVE: earth's magnetic field

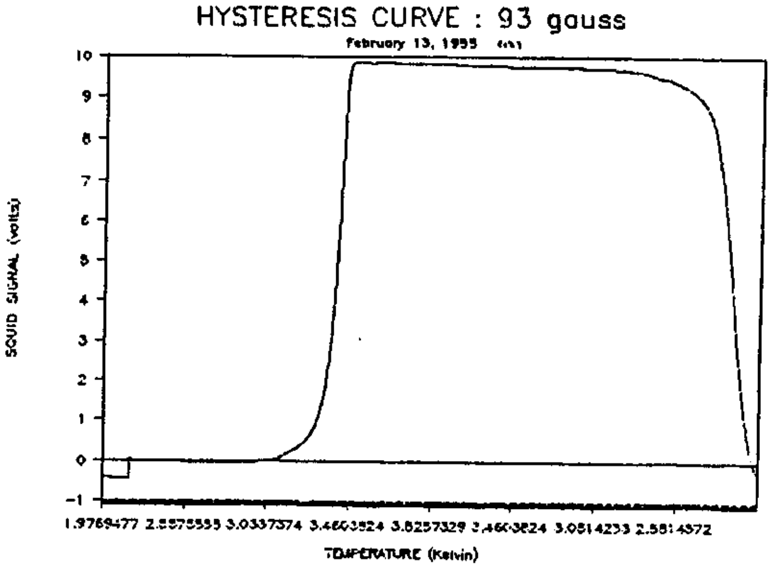
February 12, 1988

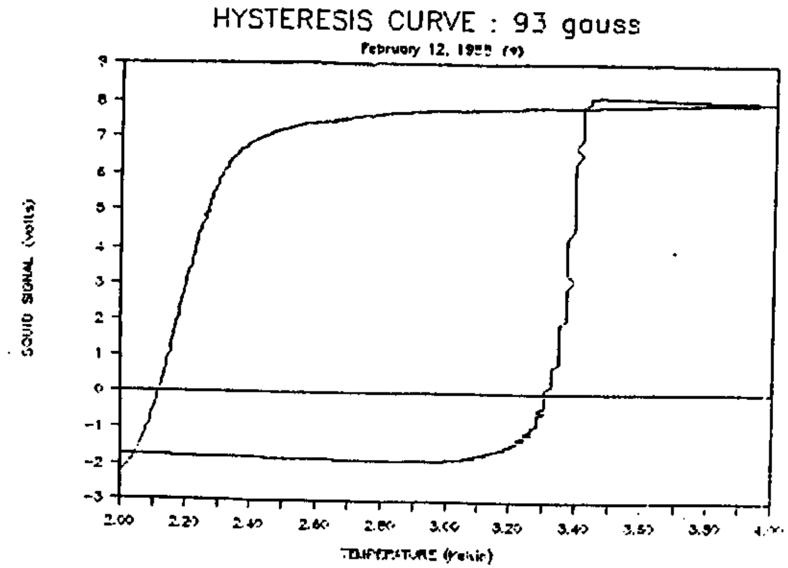


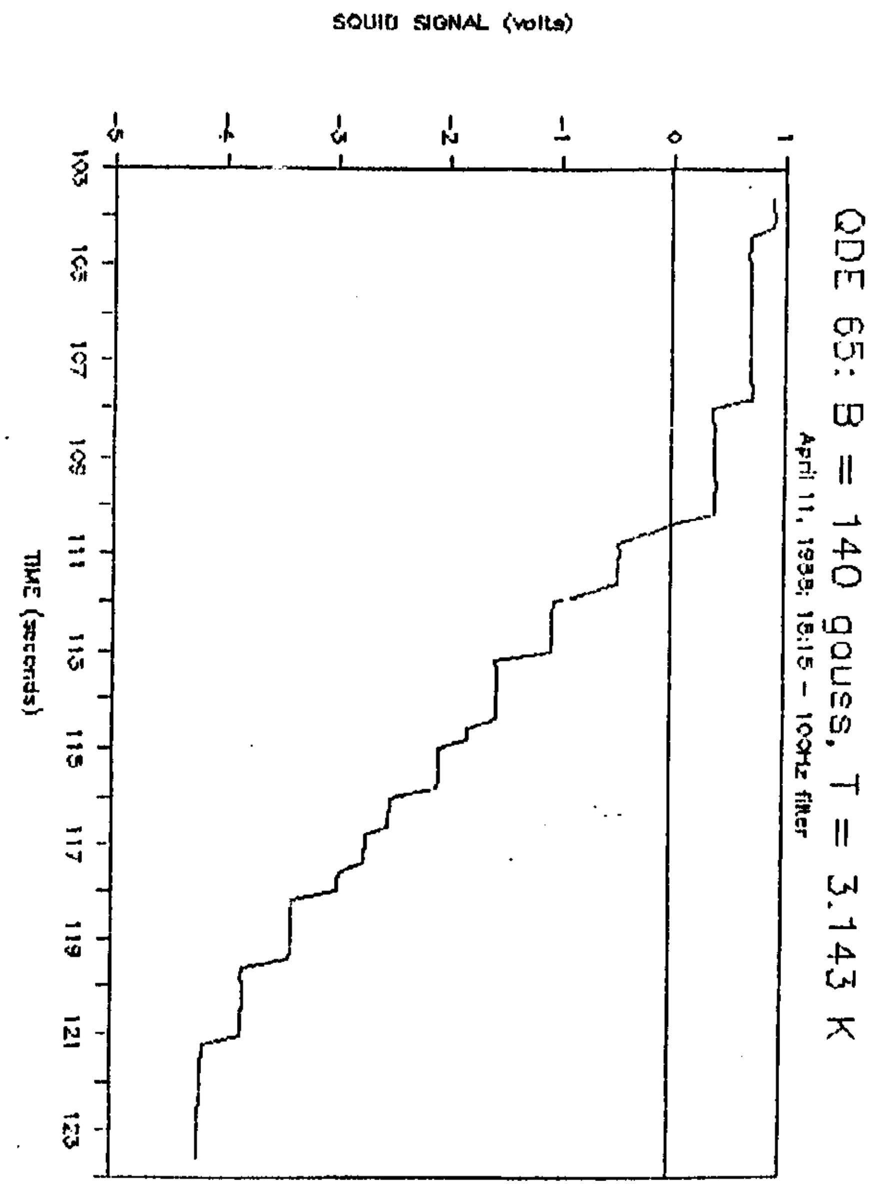
HYSTERESIS CURVE : 9.3 gauss

February 12, 1988




HYSTERESIS CURVE : 93 gauss
February 13, 1995
SQUID SIGNAL (volts)
TEMPERATURE (Kelvin)


HYSTERESIS CURVE : 93 gauss
February 12, 1995
SQUID SIGNAL (volts)
TEMPERATURE (Kelvin)


SQUID SIGNAL (volts)
TIME (seconds)
QDE 65: B = 140 gauss, T = 3.143 K
April 11, 1995, 15:15 - 100Hz filter