INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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H4.SMR 346/ 5

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

DOUBLE BETA DECAY

by

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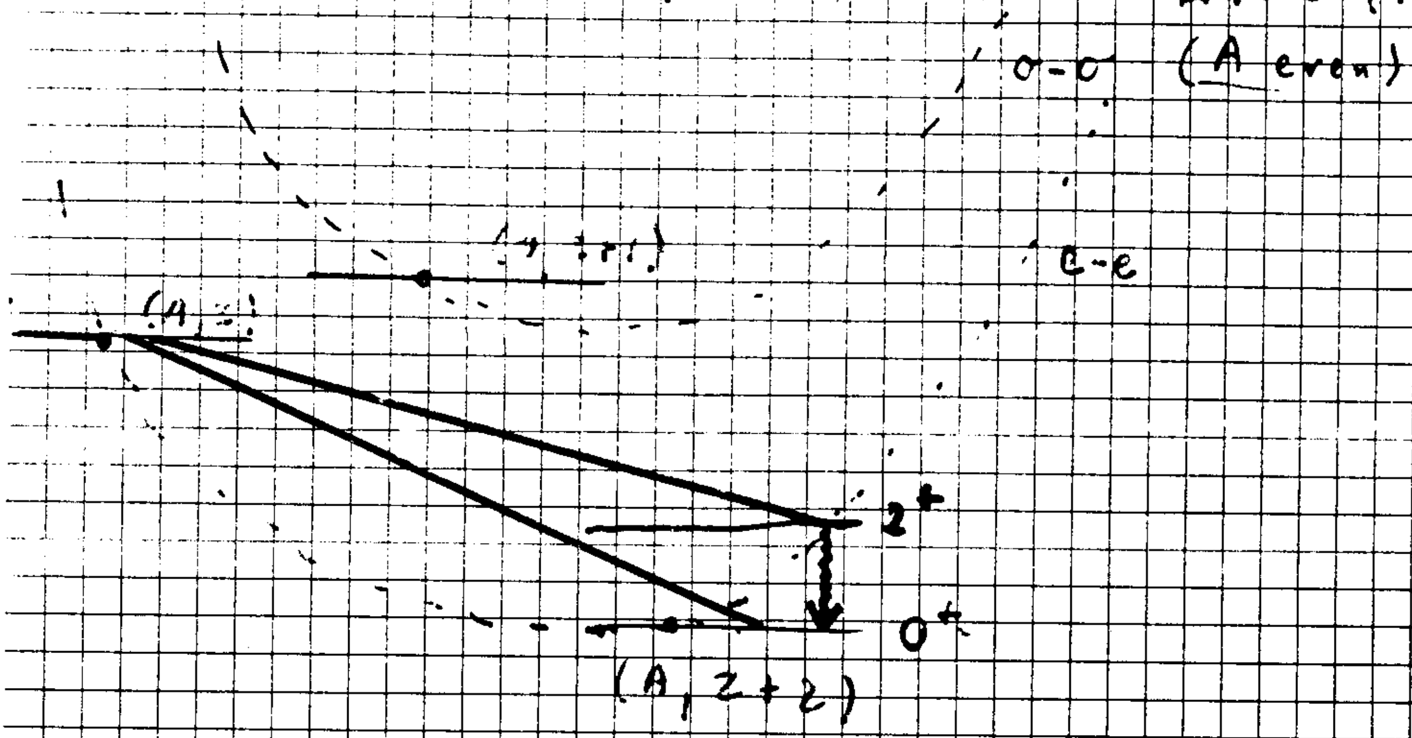
Universita degli Studio di Milano
Italy

DOUBLE BETA DECAY

FIRST STUDIED BY M. GÖPPERT MAYER (1935)



WHY $\beta\beta$ DECAY IS IMPORTANT?

$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$

$(A, Z) \rightarrow (A, Z+2) + 2e^- \qquad \Delta L = 2$

$(A, Z) \rightarrow (A, Z+2) + 2e^- + \chi$ (majoron)

(2) STRONGLY ENHANCED ($10^6 - 10^8$) WITH RESPECT TO (1) BY PHASE SPACE

CAPABLE OF DETECTING A VERY TINY VIOLATION OF LEPTON NUMBER.

THE NUCLEUS IS A MICROLABORATORY

Fig. 3b

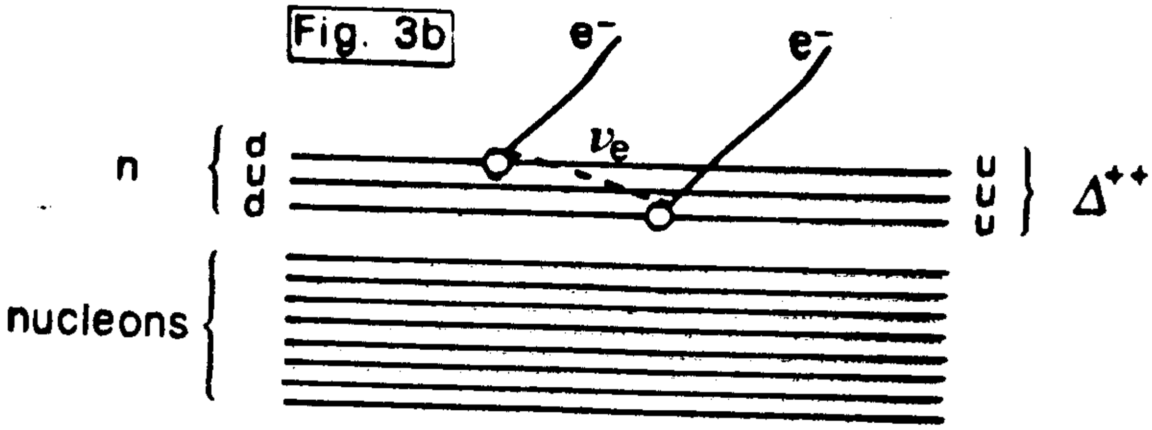


Fig. 4

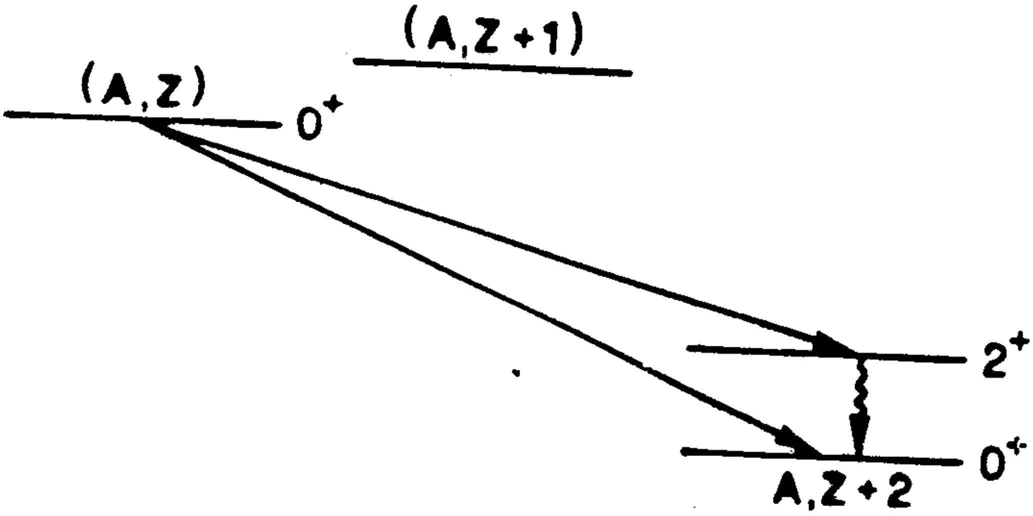


Fig. 5

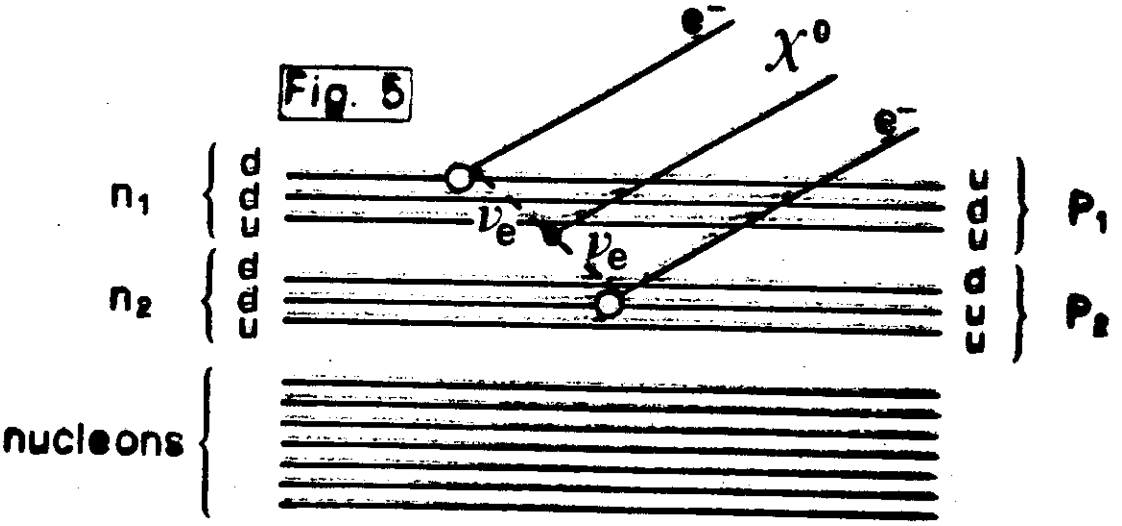
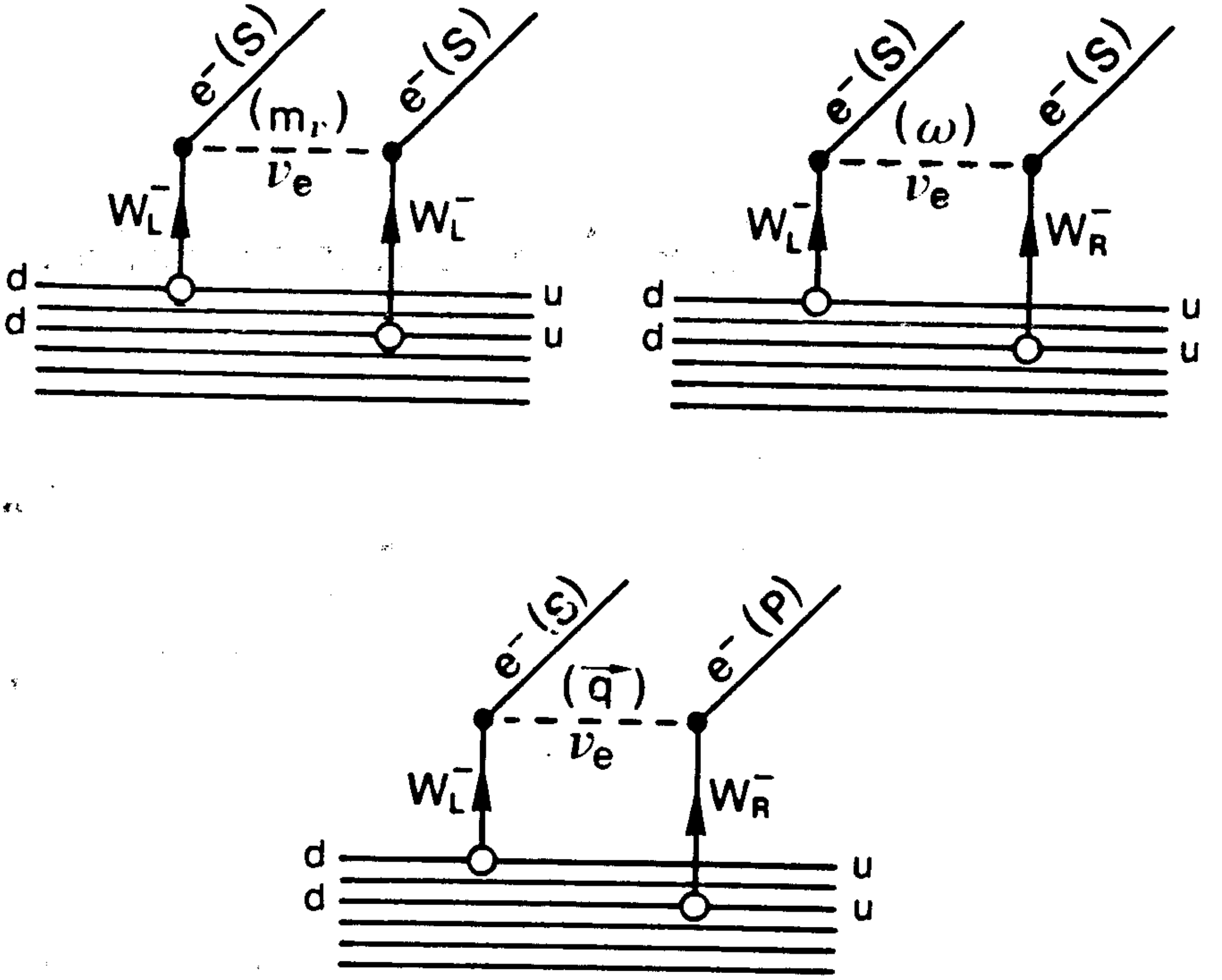
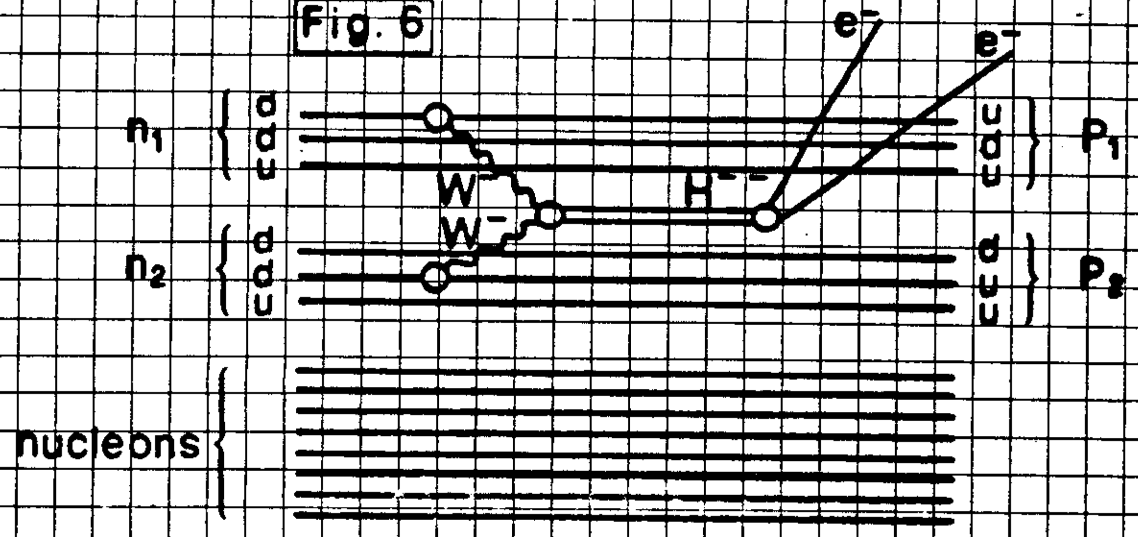


Fig. 8



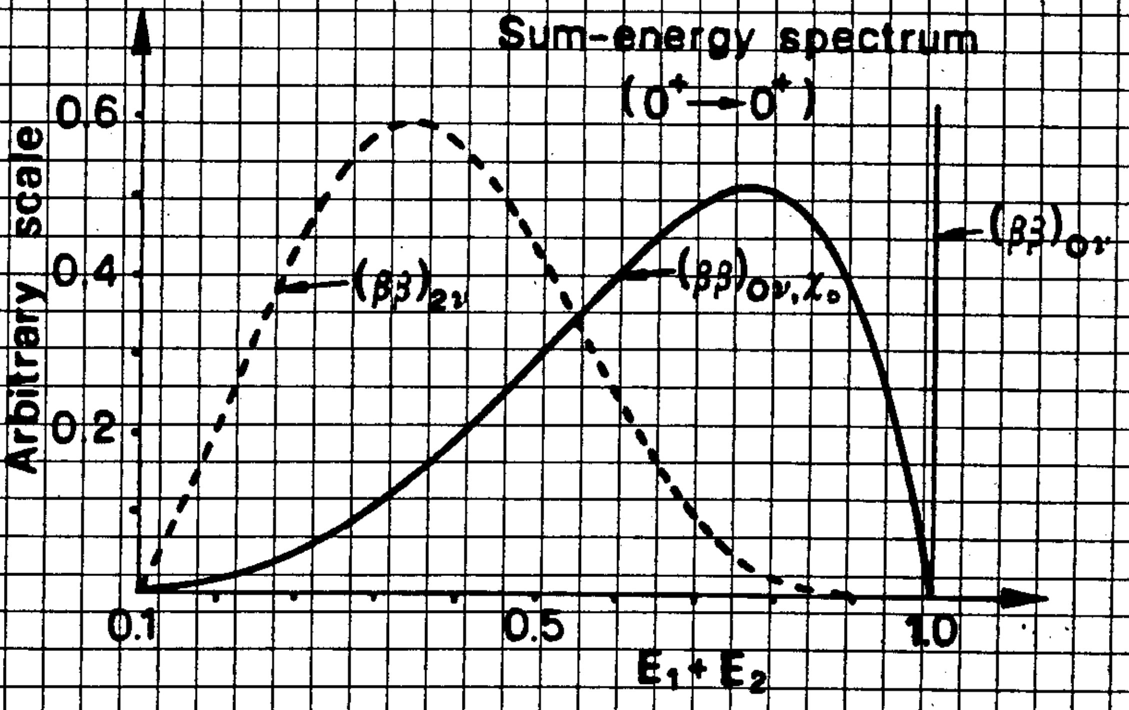
e⁻(S)
e⁻(S)
(m_ν)
ν_e
W_L^-
W_L^-
d
d
u
u
e⁻(S)
e⁻(S)
(ω)
ν_e
W_L^-
W_R^-
d
d
u
u
e⁻(S)
e⁻(P)
$(\vec{q})$
ν_e
W_L^-
W_R^-
d
d
u
u

Fig. 6



e⁻
e⁻
n1
d
d
u
u
d
u
P1
W⁻
W⁻
H⁻⁻
n2
d
d
u
d
u
u
P2
nucleons

Fig. 7



Sum-energy spectrum
$(0^+ \to 0^+)$
Arbitrary scale
0.6
0.4
0.2
$(\beta\beta)_{2\nu}$
$(\beta\beta)_{0\nu,\chi_0}$
$(\beta\beta)_{0\nu}$
0.1
0.5
1.0
$E_1 + E_2$

GUT ⇒ ALLOW [illegible] VIOLATE LEPTON NUMBER..

EXPERIMENTAL PROPERTIES OF $\beta\beta$ DECAY

HOW TO DETECT DOUBLE BETA DECAY ?

GEOLOGICAL METHODS.

TAKE A ROCK CONTAINING (A,Z) ^{82}Se, ^{128}Te, ^{130}Te (WHICH IS THERE SINCE BILLIONS YEARS)

EXTRACT Kr (possibly from $^{82}Se \to {}^{82}Kr$) or
Xe (" " $^{128,130}Te \to {}^{128,130}Xe$)

ANALYSE THE GAS WITH MASS SPECTROSCOPY TO DETECT ABNORMAL ABOUNDANCE OF ISOTOPES ^{82}Kr, ^{128}Xe, ^{130}Xe

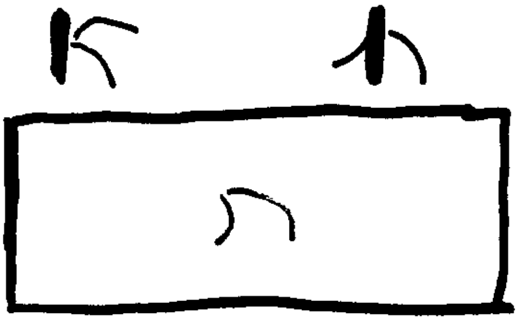
DIFFICULTIES: GAS COULD EXCAPE; $(A,Z+2)$ COULD BE PRODUCED BY PROCESSES OTHER THAN $\beta\beta$ DECAY IN THE LONG AND "NOT MONITORED" TIME OF THE EXPERIMENT

PRESENT SITUATION

	HEIDELBERG	MISSOURI
$Se-{}^{82}Kr$	$(1.3\pm.05)\times10^{20}\,y$	$(1.0\pm.3)\times10^{20}\,y$
$Te-{}^{128}Xe$	$>5\times10^{24}\,y$	$(1.4\pm.4)\times10^{24}\,y$
$Te-{}^{130}Xe$	$(1.63\pm.14)\times10^{21}$	$(7\pm2)\times10^{20}$

POSITIVE EVIDENCE FOR "SOME" TYPE OF ββ DECAY HAS BEEN OBTAINED INDIRECTLY, BUT TWO-NEUTRINO MODE (ALLOWED) AND NEUTRINO-LESS MODE (FORBIDDEN) CANNOT BE SEPARATED ③

DIRECT (INSTRUMENTAL) EXPERIMENTS



- SOURCE ≠ DETECTOR

  SOURCE = DETECTOR

  E. F. Dell'Antonio and E. F. (1960)
  (suggested gas detector, scintillators etc.)

SOURCE ≠ DETECTOR

VARIOUS EXPERIMENTS WITH SCINTILLATORS CARRIED OUT IN USSR, JAPAN AND USA

ALL NEGATIVE RESULTS (SINCE A FEW MONTH AGO)

KIEV: $\tau_{0\nu}({}^{96}Zr) > 6.[illegible] \times 10^{19}$ $\tau_{0\nu}({}^{100}Mo) > 2.1 \times 10^{21}$ $\tau_{0\nu}({}^{130}Te) > 1.2 \times$ [illegible]

MOSCOW $\tau_{0\nu}({}^{150}Nd) > 1.[illegible] \times 10^{21}$

OSAKA (${}^{100}Mo$) $\tau_{2\nu} > 2.[illegible] \times 10^{17}$ $\tau_{0\nu} > 1.9 \times 10^{20}$ $\tau_{0\nu\chi} > 1.9 \times 10^{1[illegible]}$

LBL + M.H + NEW MEXICO " $> 5 \times 10^{19}$

IRVINE " 6.8×10^{17} 1.3×10^{19} $> 7.5 \times 10^{18}$ y

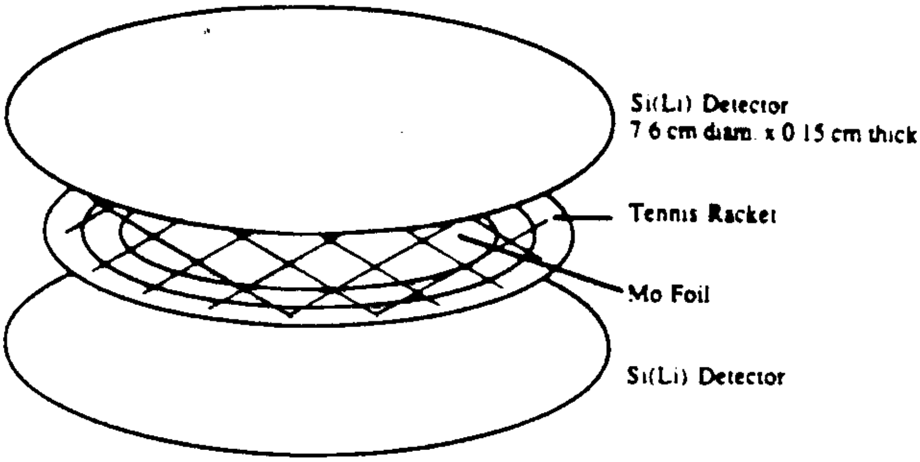


Fig. 1. Exploded view of part of the detector array. The gaps between detectors are 0.1 cm.

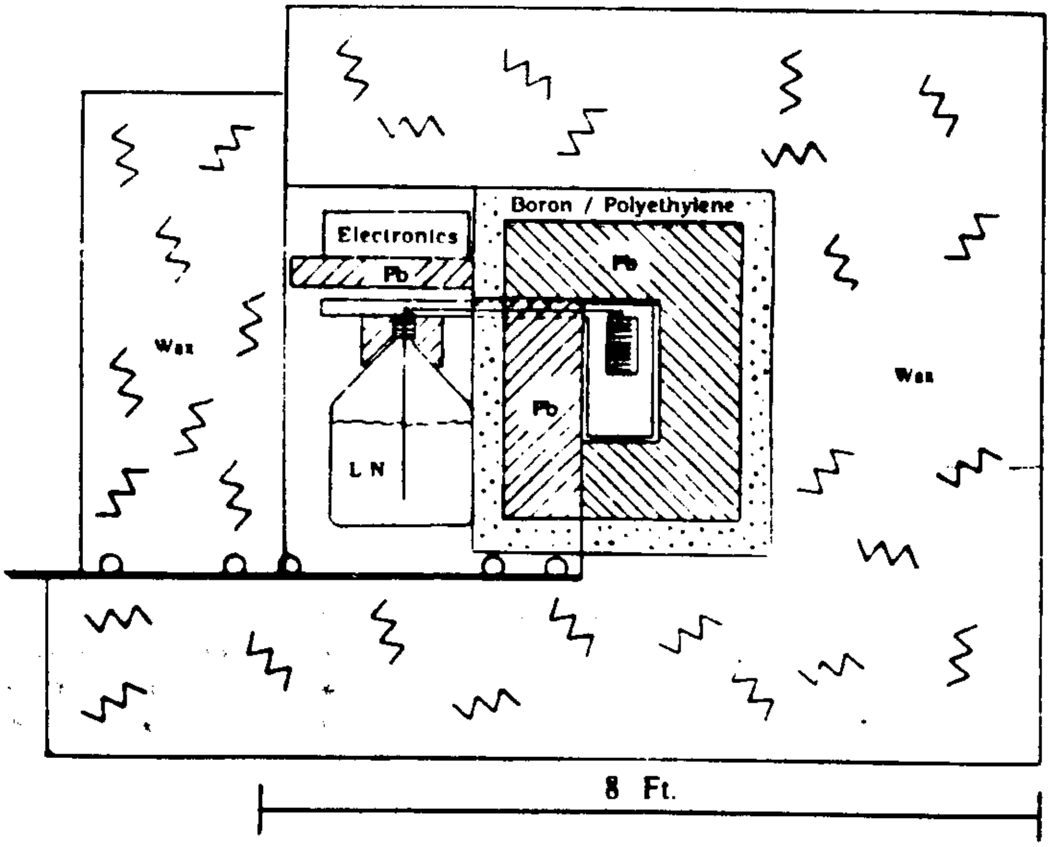


Fig. 2. Elevation of experiment.

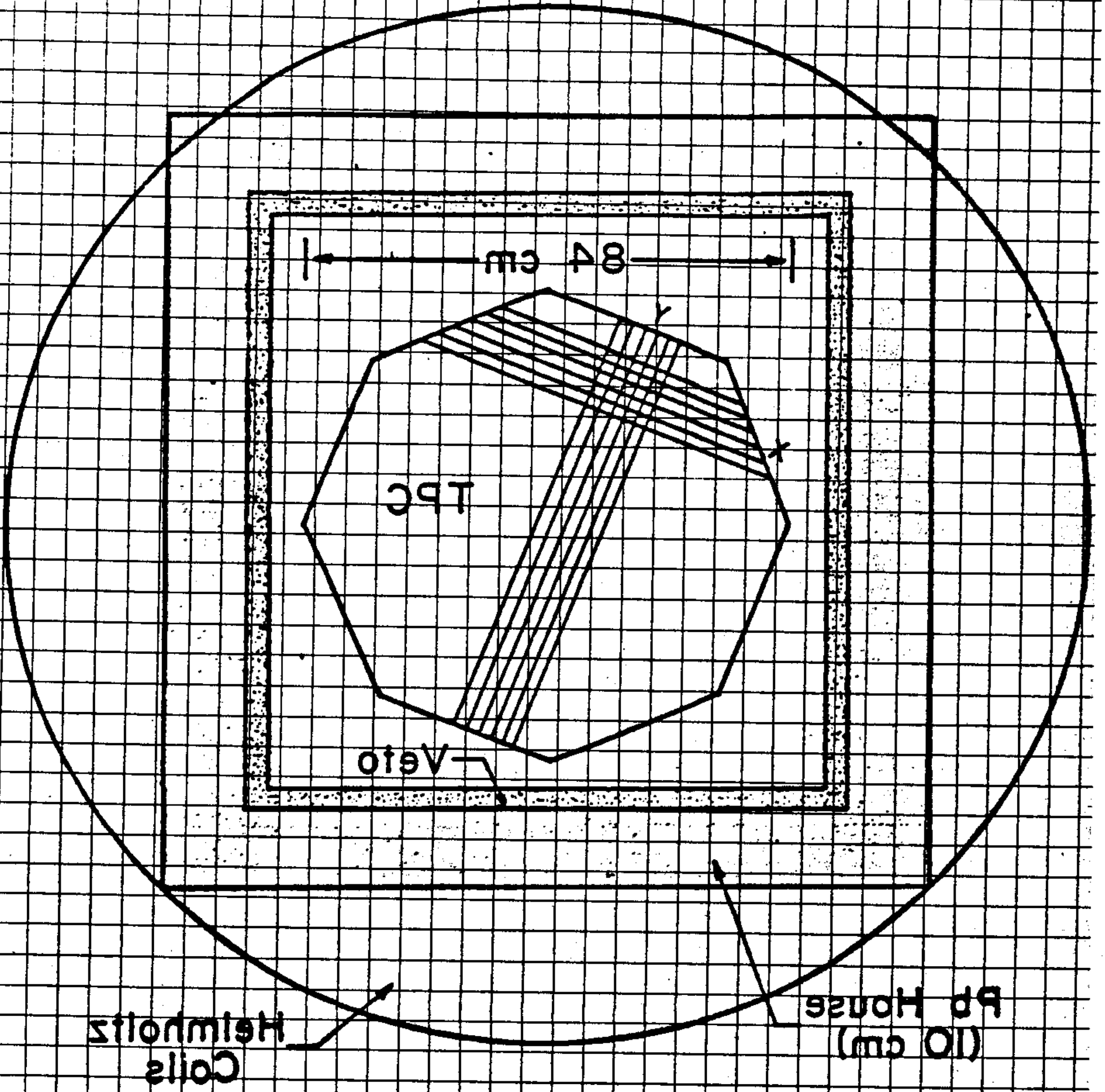


Fig. 2 Schematic axial view of TPC

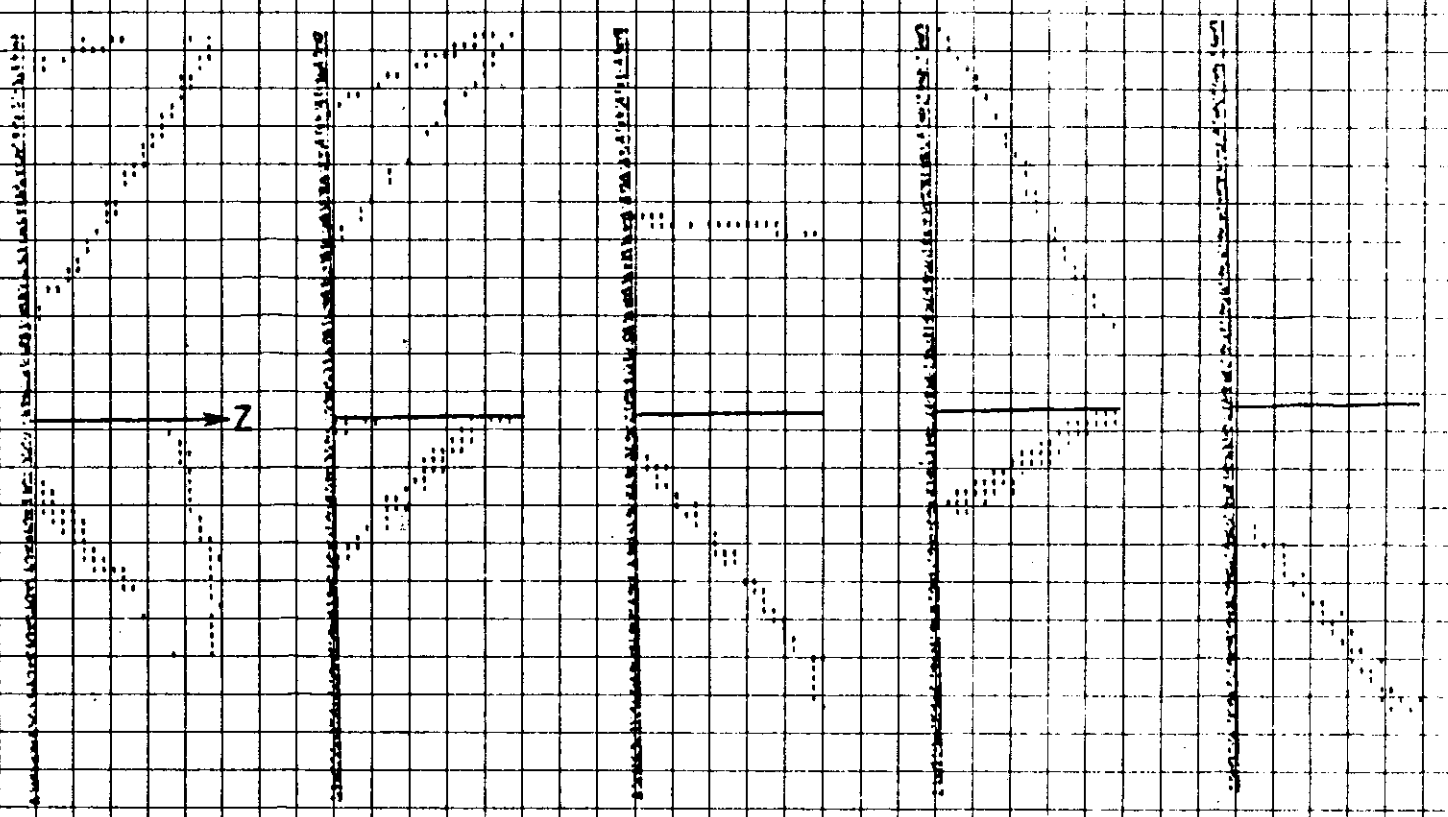


Fig. 5 Some cosmic ray muon and electron tracks in 80% He, 20% CH_4 with 32 anode (top half) and 32 cathode (bottom half) channels connected on only one side of the selenium source. The anode display is equivalent to the right side of Fig. 1. Two anode channels are dead. The magnet was off.

THE IRVINE EXPERIMENT ON

$^{82}Se \rightarrow {}^{82}Kr$ (N.Y. TIMES JULY, 87)

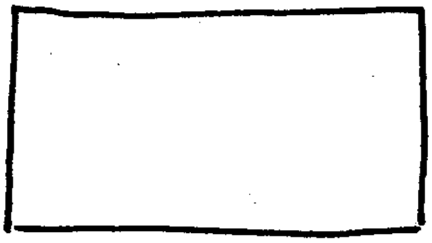
A TPC IN A MAGNETIC FIELD (900 GAUSS) WITH CENTRAL PLATE MADE OF ENRICHED Se (97 % ^{82}Se)

POSITIVE EVIDENCE IN FAVOUR OF TWO-NEUTRINO DECAY - • $\tau_{2\nu} = 1.1 \times 10^{20}$ y $(0.8 - 1.7) \times 10^{20}$ y at the 68 % c.l.

IT IS THE LONGEST HALF LIFE EVER MEASURED! IN AGREEMENT WITH THEORY -

LIMITS $\tau_{0\nu\chi} > 4.4 \times 10^{20}$ y (90 % c.l.) -

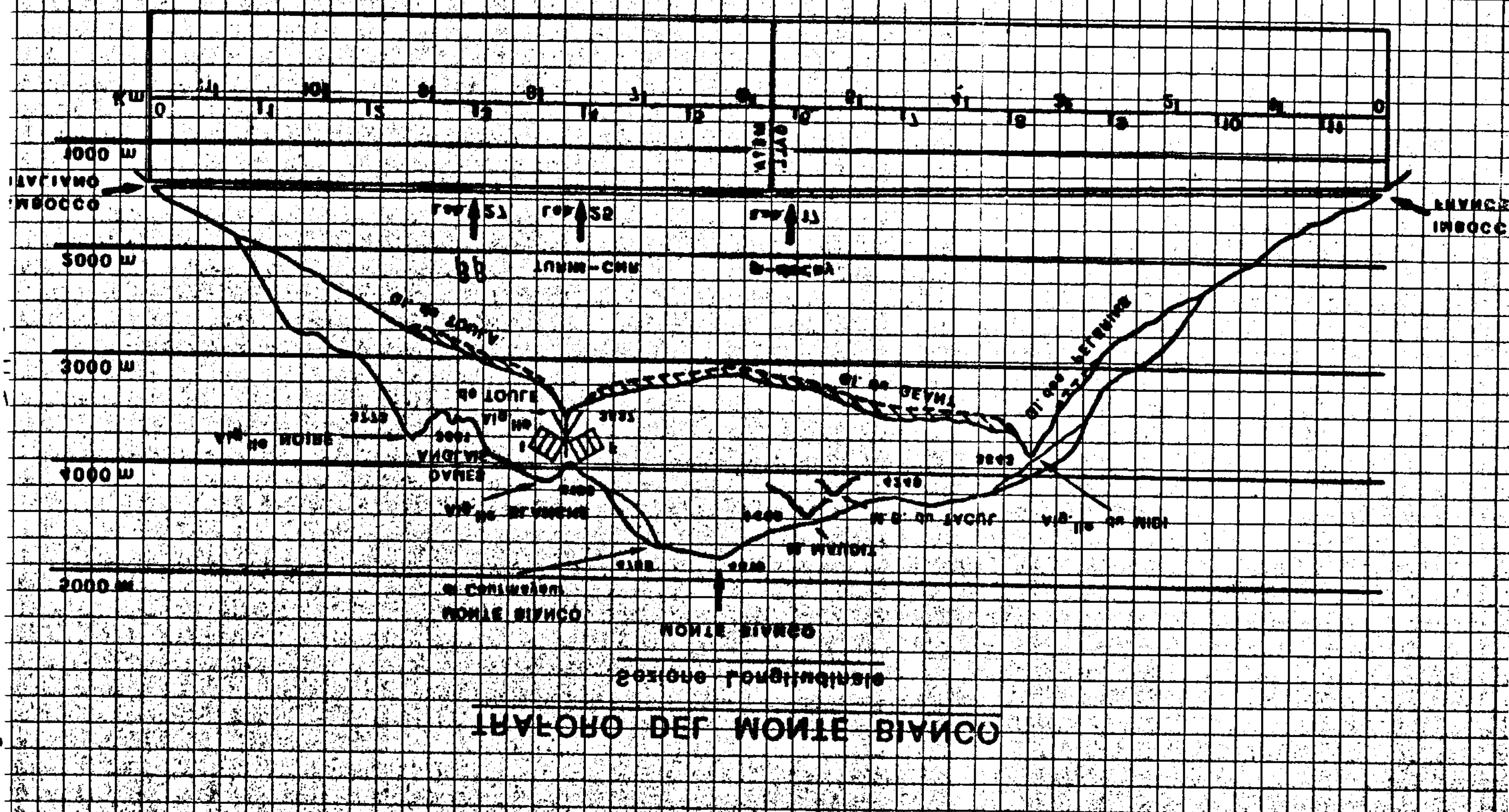
SOURCE $\doteq$ DETECTOR



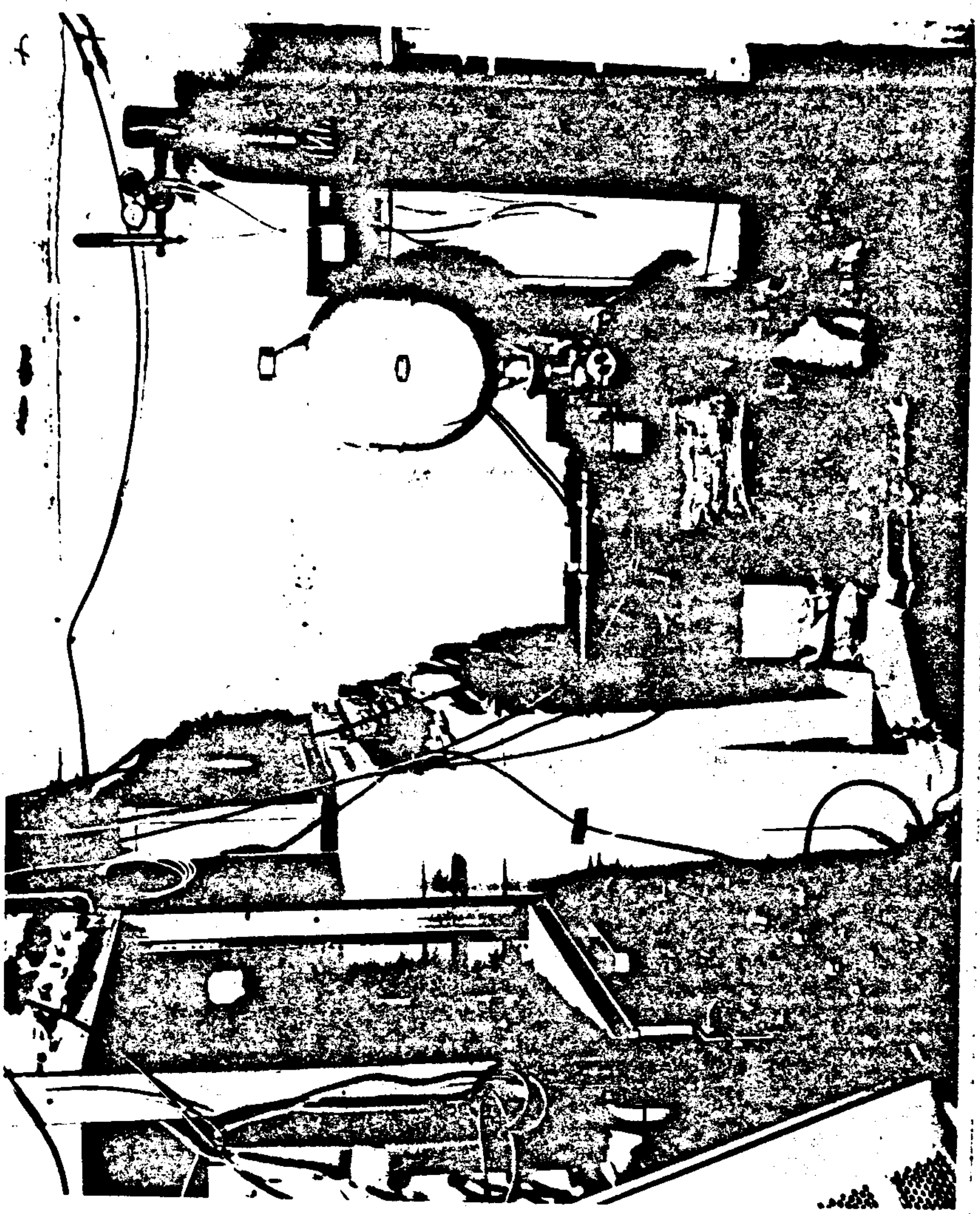
~~FINAL~~ PROBLEM : THE BACKGROUND

ω

Fig. 8



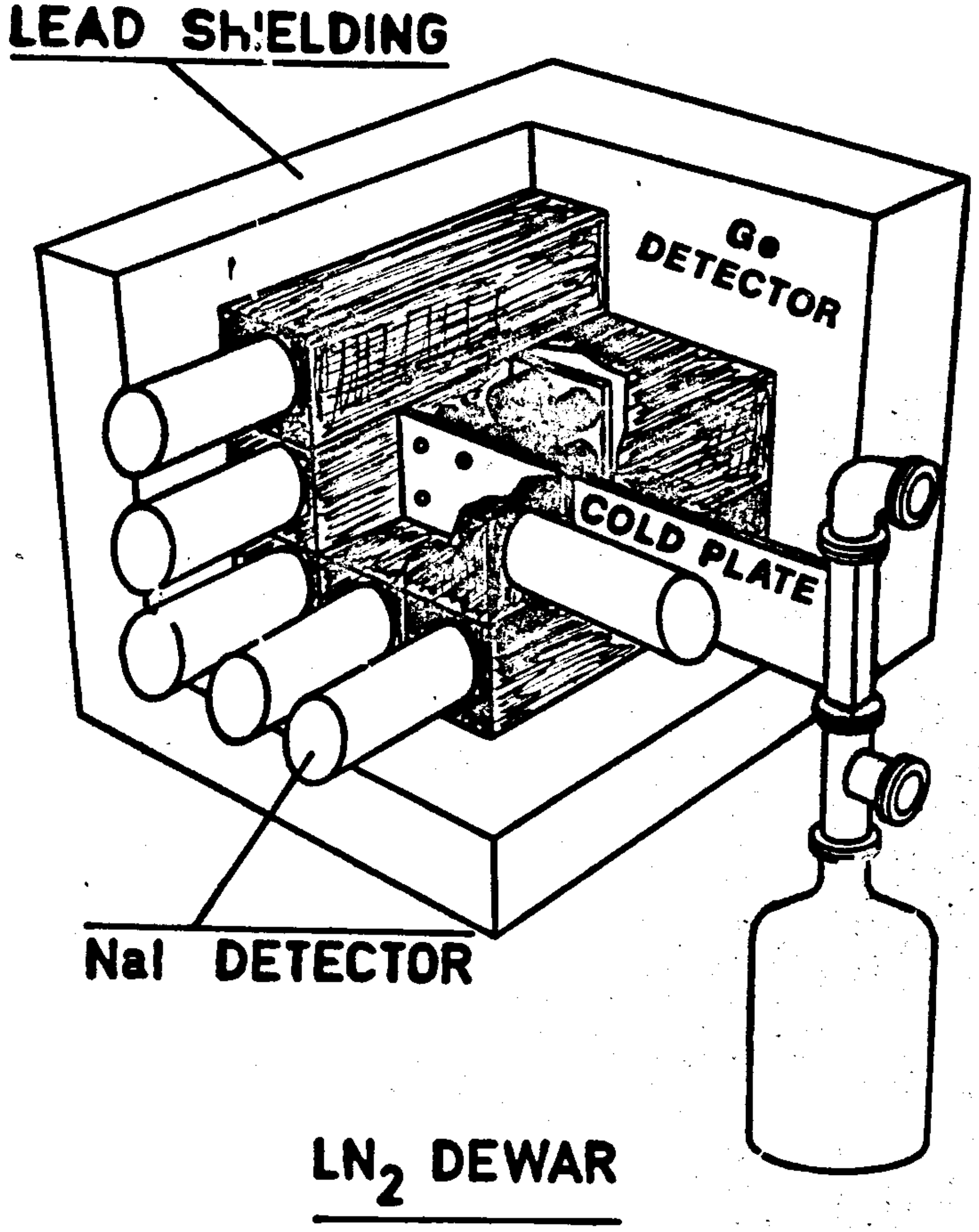
Km
0
1000 m
2000 m
3000 m
4000 m
5000 m
IMBOCCO ITALIANO
IMBOCCO FRANCESE
TURIN-CHR
MONTE BIANCO
Sezione Longitudinale
TRAFORO DEL MONTE BIANCO



— Ge crystals.
— NaI crystals-

U.C. Sta Barbara / L.B.L.

$\tau_{1/2} > 5 \times 10^{23}$ y



6

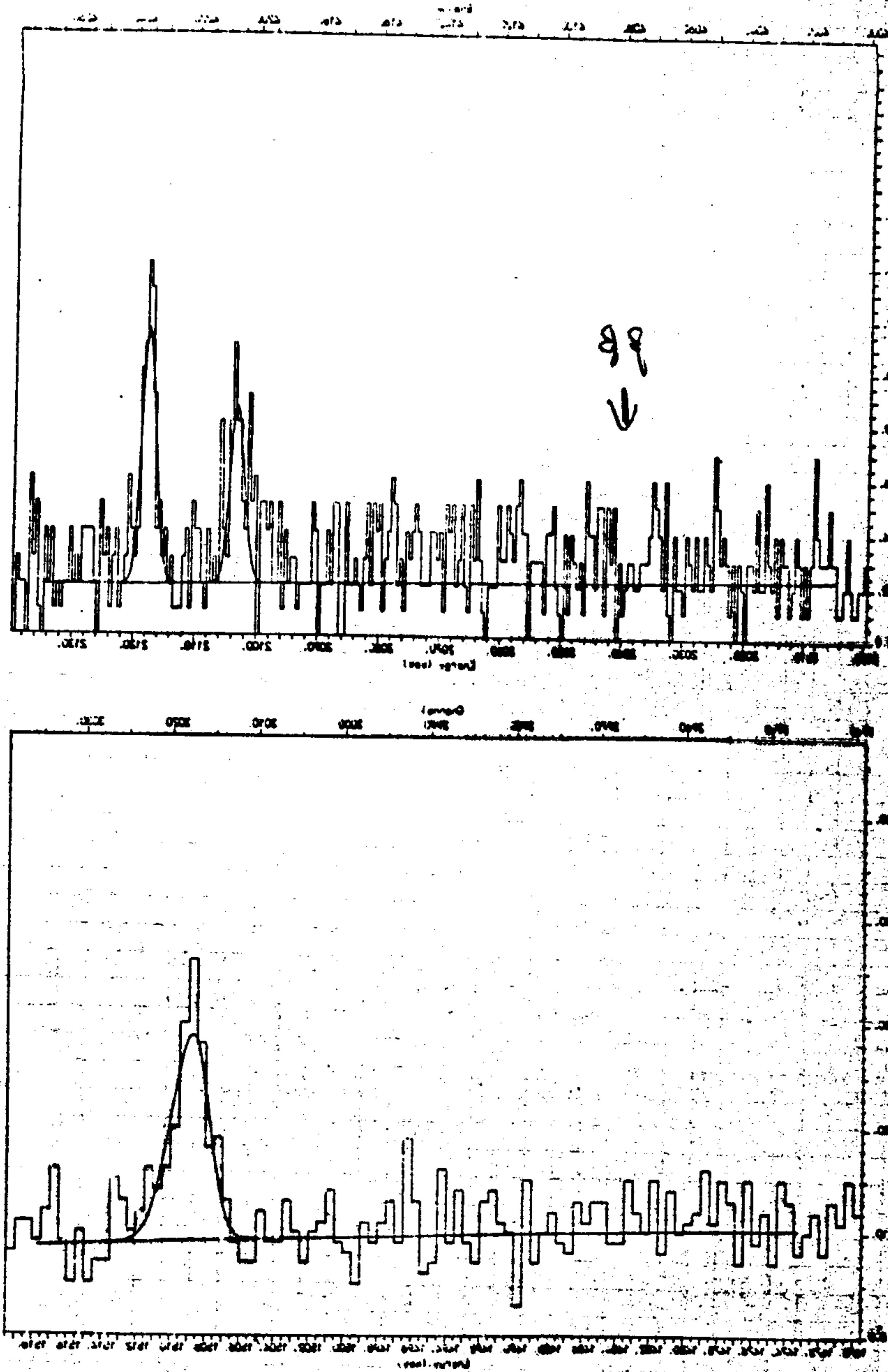


Fig.4.18 Ge(Li)2: Regione dello spettro relativa alle transizioni ββ senza emissione di neutrini sullo stato fondamentale (a) e sul primo stato eccitato 2^+ (b).

SOURCE = DETECTOR

BEST RESULTS SO FAR FROM

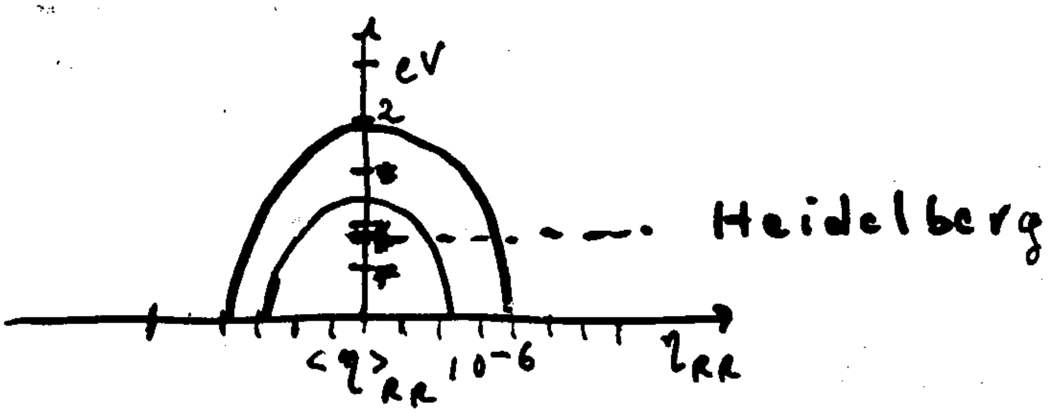
$^{76}Ge \rightarrow {}^{76}\underline{Se}$ $\Delta E = 2,040.71 \pm .52$ keV

i.a. $\underline{7.5}$ %, -

Experiment by Milano group in 1967 -

RECENT EXPERIMENTS

		$(0^+-0^+)0\nu$	$(0^+-2^+)0\nu$	2ν
Caltech-SIN-Neuchatel	deep (1)	1.2×10^{23}		
Bordeaux - Zaragoza	deep A.C	6×10^{22}	6×10^{22}	—
Guelph-Aptec-Kingston	moderate (2)	3.2×10^{22} (sensitivity 1.2×10^{23})		
SAVIA	deep	A.C. $.73\times10^{23}$	$.57\times10^{23}$	1×10^{20}
NW-USC	deep (3)	3.0×10^{23}		
Milano	deep	3.3×10^{23}	2.7×10^{22}	2×10^{19}
CSB-LBL	moderate A.C.	5×10^{23}		



(1) RUNNING ON SURFACE WITH 8×145 cm^3

(2) GOING TO RUN WITH 3×200 cm^3

(3) GOING TO RUN WITH 6×140 cm^3

RISE AND FALL OF THE MAJORON -

$(A,Z) \to (A,Z+2) + 2e^- + \chi$ (massless Goldstone boson)

(Chicashige, Mohapatra and Peccei, Gelmini and Roncadelli, Georgi, Glashow, and Nussinov) -

NY Times Jan. 19

EVIDENCE PRESENTED BY F. AVIGNONE

TWO RUNS : • 281 days with 7 cm thick Cu
12g (only low energy)
• 121 old Pb
402

PEAK EXPECTED AT ~ 1600 keV -

SUBTRACTION OF BACKGROUND : FROM THE KNOWN PEAKS -

$\underline{\tau = (6 \pm 1) \times 10^{20}\ y}$ $\quad (8 \pm 1) \times 10^{-4}$ $g_{\chi \nu e}$ Fluxton $(1.1 \times 10^{-3} \pm .2)$ Klapdor $(5 \pm 1) 10^{-4}$

HOWEVER :

a. two different spectra are overposed

b. other type of background :

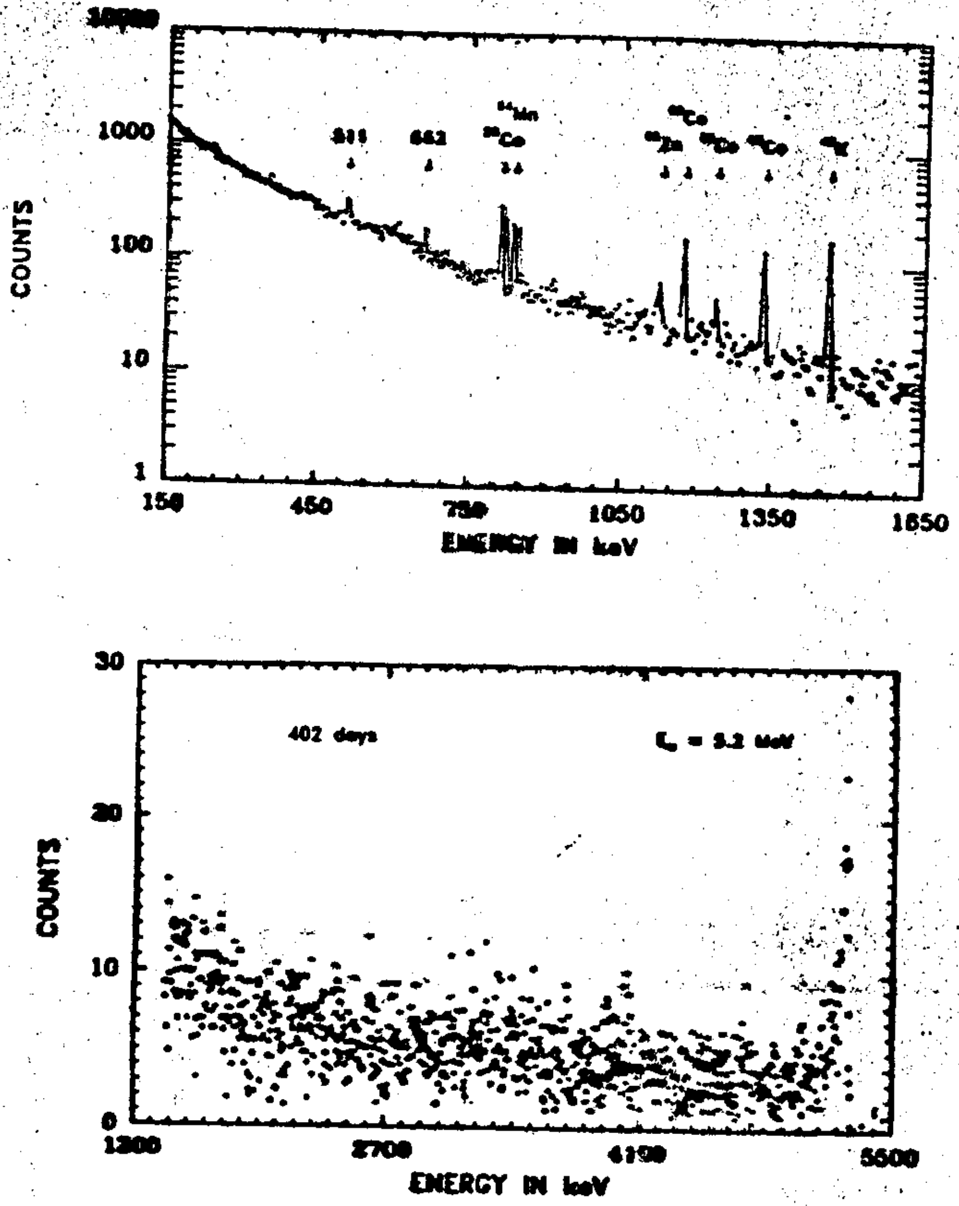
a. radioactivity in the non totally active distorted field region of detector (50%)

b. $^{70}Ge(n,3n)^{68}Ge \xrightarrow[280\,d]{} EC \to {}^{68}Ga \xrightarrow[X\ days]{} \beta^+ (1.89\ MeV)$ (20%)

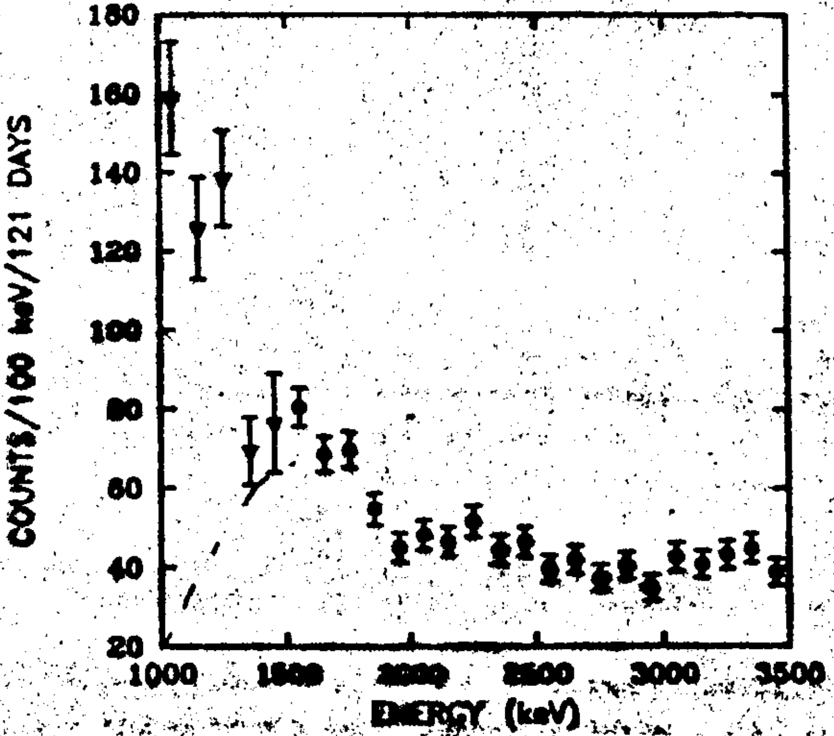
c. other β decaying contaminants

d. NEUTRON INTERACTIONS

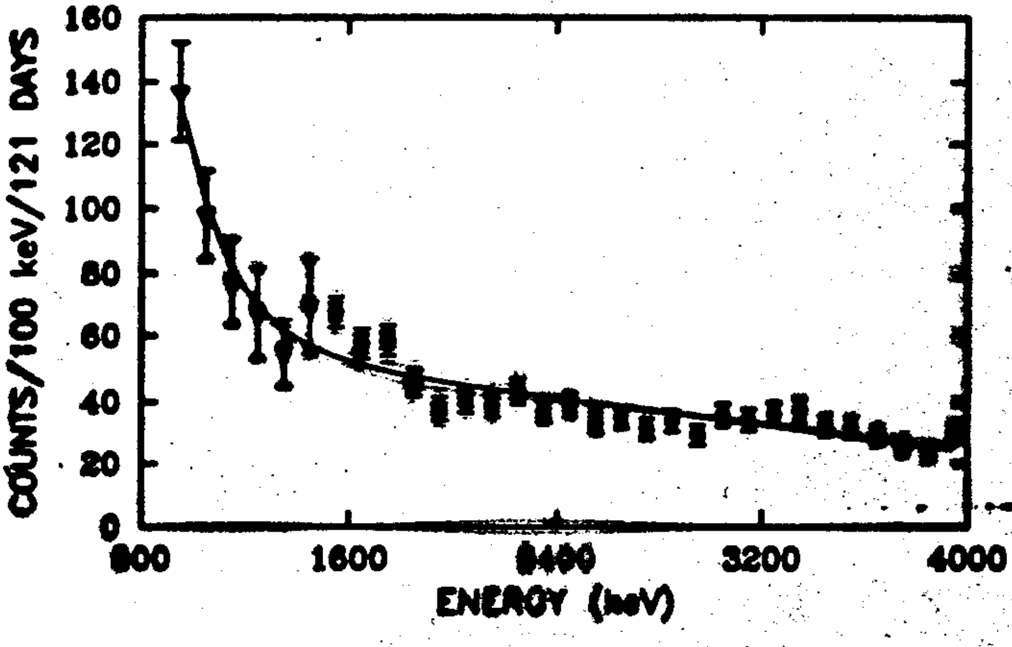
13


COUNTS
ENERGY IN keV
511
662
^{54}Mn
^{58}Co
^{65}Zn
^{60}Co
^{40}K
402 days
COUNTS
ENERGY IN keV

14


COUNTS/100 keV/121 DAYS
ENERGY (keV)

$T_{1/2}^{0\nu\beta\beta} \geq 2\times10^{21}$ yr.



OTHER EXPERIMENS ON ^{76}Ge

CALTECH-NEUCHATEL-SIN

90 cm^3 Ge in GOTTHARD – 3373 R

Background comparable with Avignone

Evidence of ^{68}Ga – (also ^{71}Ge –

SUBTRACT → TAILS OF γ-lines, ^{68}Ga, Compton from outside radioactivity, γ without photo-peak

$\tau_{0\nu\chi} > 1.2 \times 10^{21}$ y (90% c.l.) Haxton Klapdor $< 8.1 \times 10^{-4}$ $< 3.2 \times 10^{-4}$

UCSB-LBL- 4–8 detectors-

Background similar to Avignone-

SUBTRACT TAILS AND ^{68}Ga – 30% REMAINS BUT DO NOT HAVE THE SHAPE OF MAYORON – ONE OF THE DETECTOR HAS ACTIVITY, AND A PULSE DISTRIBUTION SIMILAR TO AVIGNONE

$\tau_{0\nu\chi} > 1.4 \times 10^{21}$ (90% c.l) $< 7 \times 10^{-4}$ $< 3 \times 10^{-4}$

IRVINE TPC

SE-82 – $\Delta E = 2{,}995$ keV

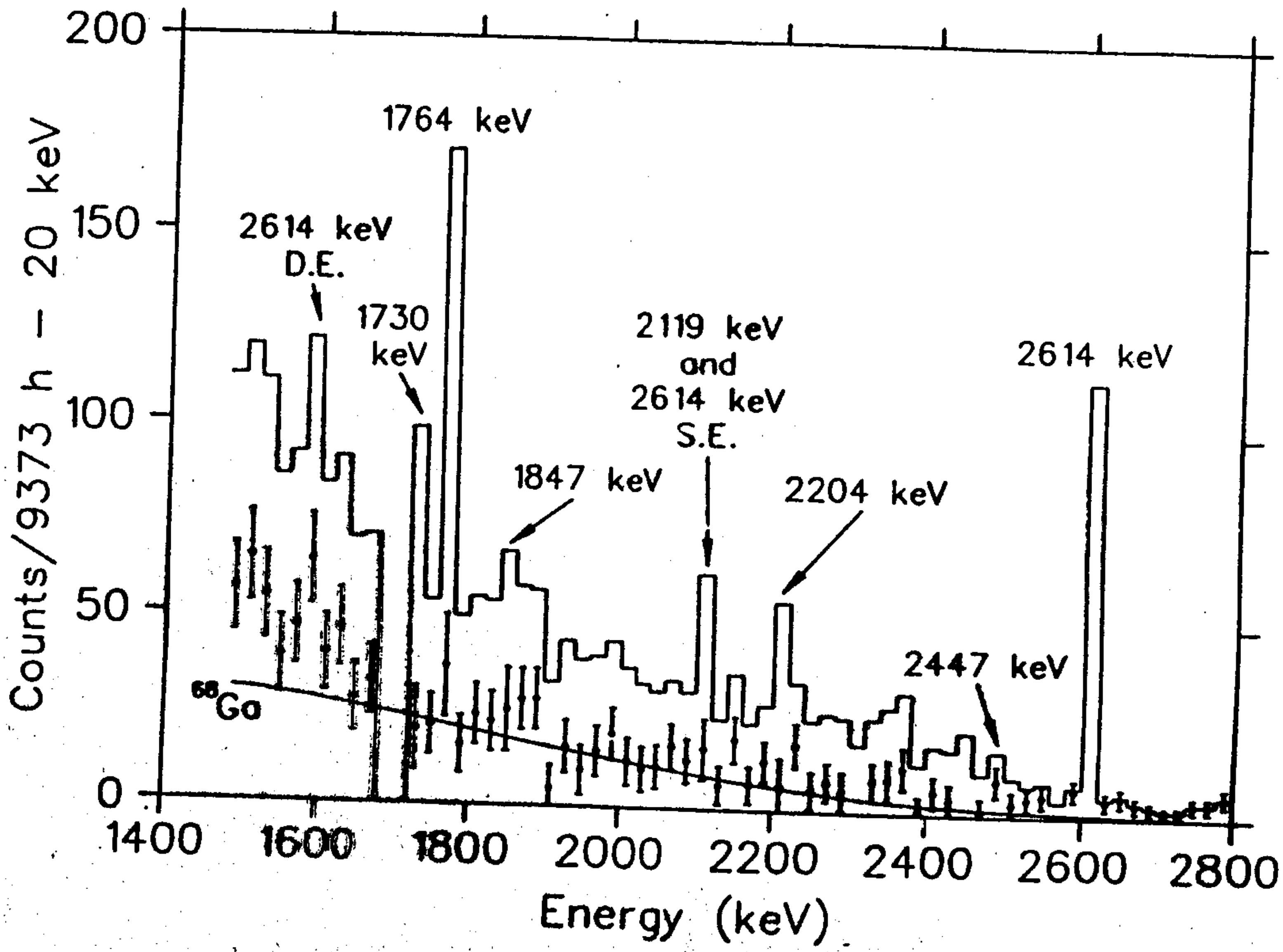
$\tau_{0\nu\chi} > 5 \times 10^{20}$ y $< .4 \times 10^{-4}$ $< 2 \times 10^{-4}$

LBL + Mt. Holyoke, New Mexico and Osaka

Mo-100 3,034 keV

$\tau_{0\nu\chi} > 5 \times 10^{19}$ (68% c.l.) $< 1.9 \times 10^{19}$ (68% c.l.)

$< 4 \times 10^{-4}$ $< 2 \times 10^{-4}$



1764 keV
2614 keV
D.E.
1730
keV
2119 keV
and
2614 keV
S.E.
2614 keV
1847 keV
2204 keV
2447 keV
68Ga
Counts/9373 h - 20 keV
200
150
100
50
0
1400
1600
1800
2000
2200
2400
2600
2800
Energy (keV)

Fig. 1

(7)
(13)

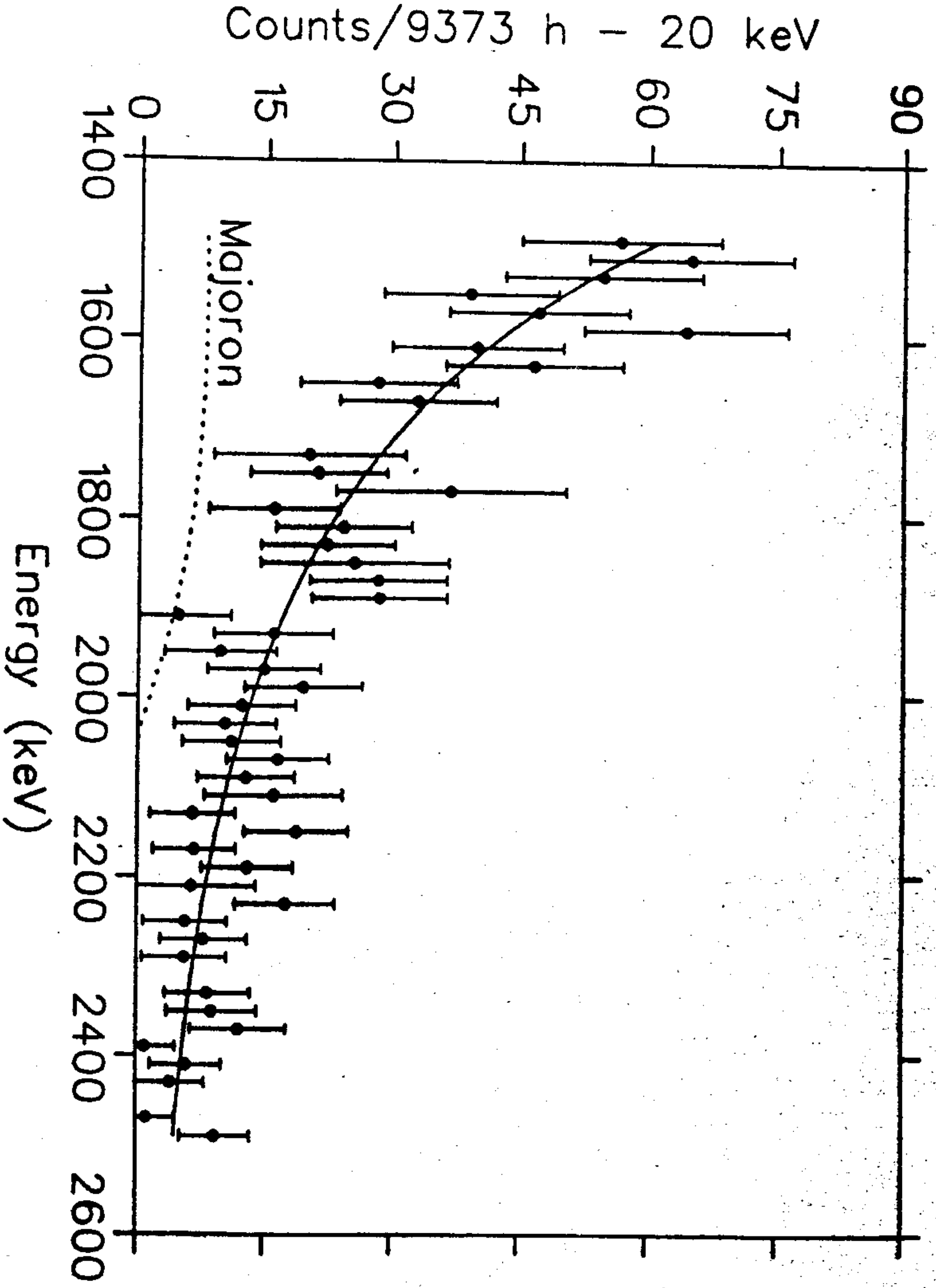
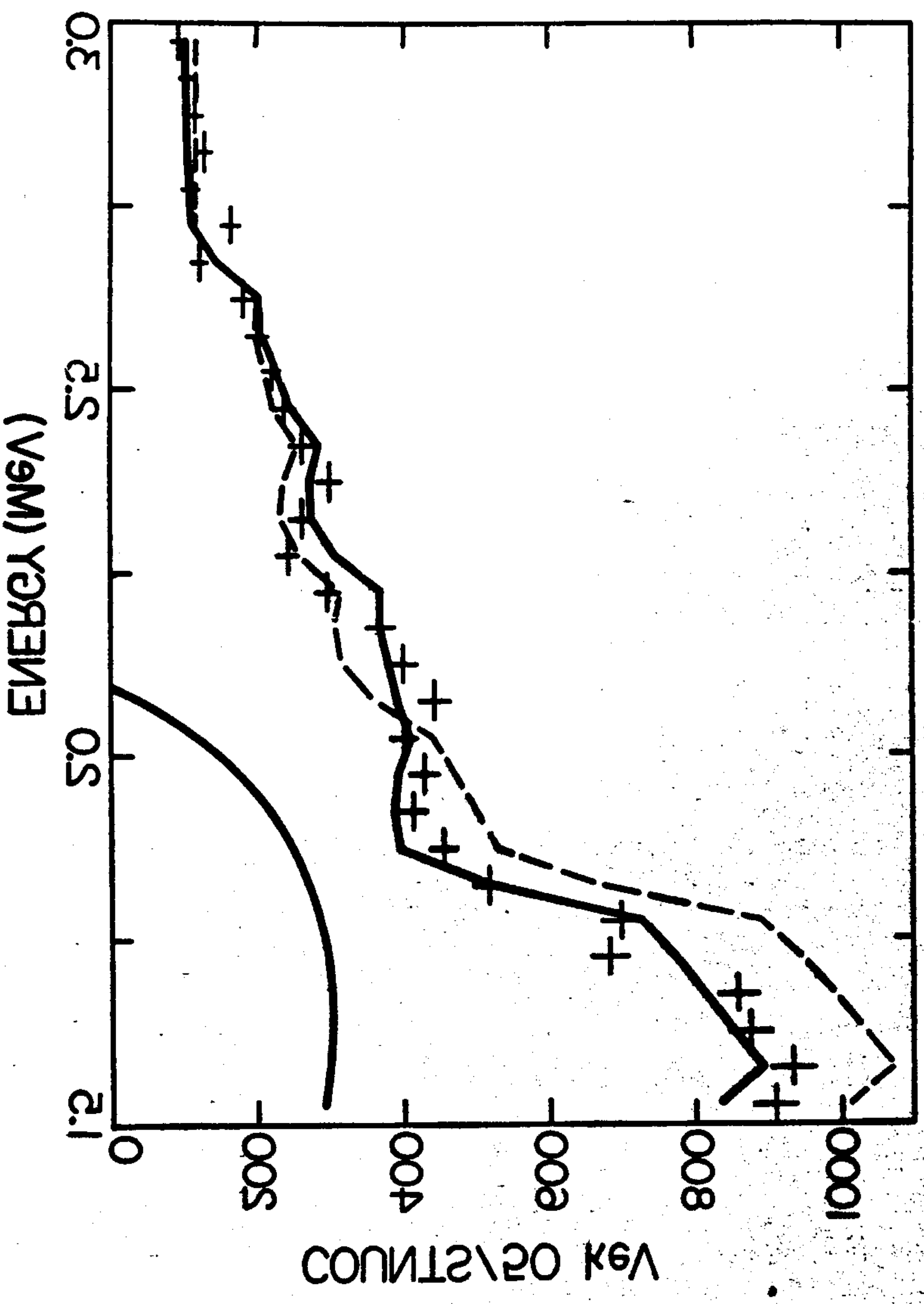

Counts/9373 h – 20 keV
0
15
30
45
60
75
90
1400
1600
1800
2000
2200
2400
2600
Energy (keV)
Majoron

Fig. 2


ENERGY (MeV)
COUNTS/50 KeV
1.5
2.0
2.5
3.0
0
200
400
600
800
1000

XENON EXPERIMENTS - 9

(14)

Xe - 136   2,479 keV   1.2, 8.9%

GAS (FUTURE POSSIBLY LIQUID OR SOLID) DETECTORS -

CALTECH - PROTOTYPE OF 1.1 ℓ operated
DETECTOR OF 300 ℓ operated up to
5 ATM.

MOSCOW - IONIZATION CHAMBER -
MEASUREMENTS WITH ^{136}Xe enriched (1.8×10^6 s)
and nat. Xe ($\sim 1.3 \times 10^6$ s) -

$\tau_{1/2}(2\nu) \geq 5.7 \times 10^{19}$ y $\tau_{0\nu}(0^+0^+) \geq 3 \times 10^{21}$ y

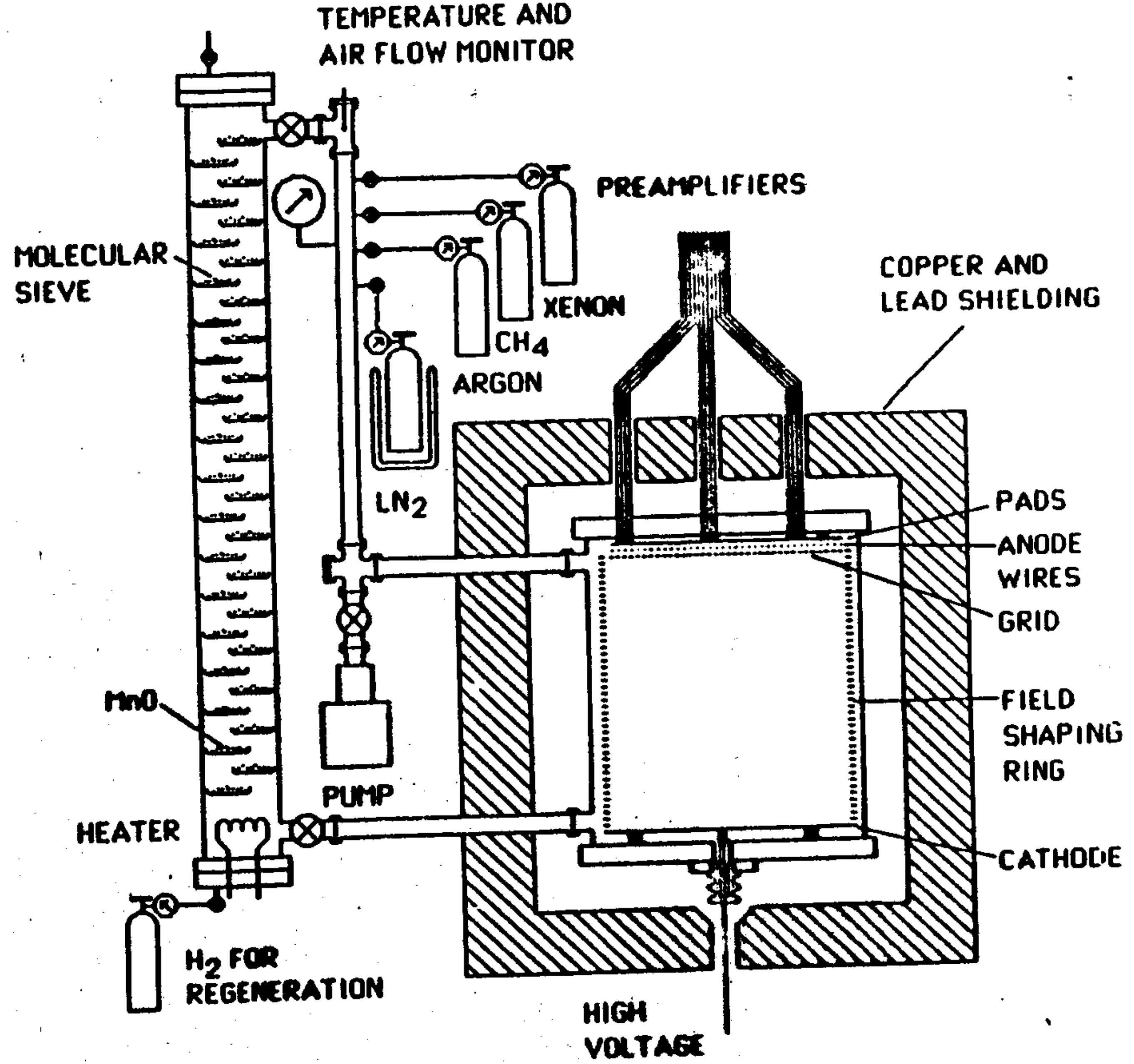
$\tau_{1/2}(0^+2^+) > 1.3 \times 10^{21}$

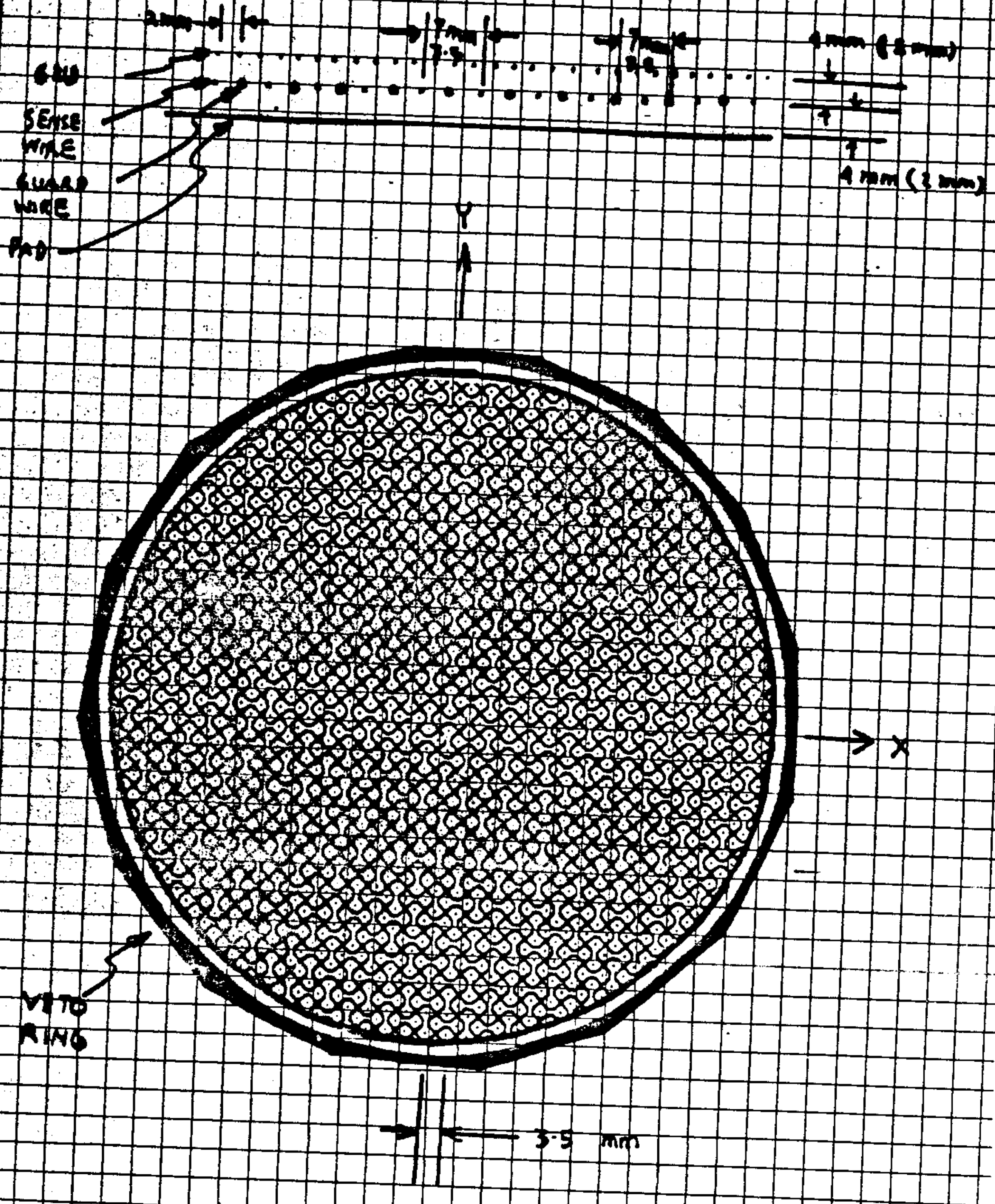
MOSCOW (Barabanov et al)
Liquid Xenon Scintillation spectrometer
0.321 y of 93% enriched in ^{136}Xe

$\tau_{0\nu} \geq 2.4 \times 10^{21}$ y

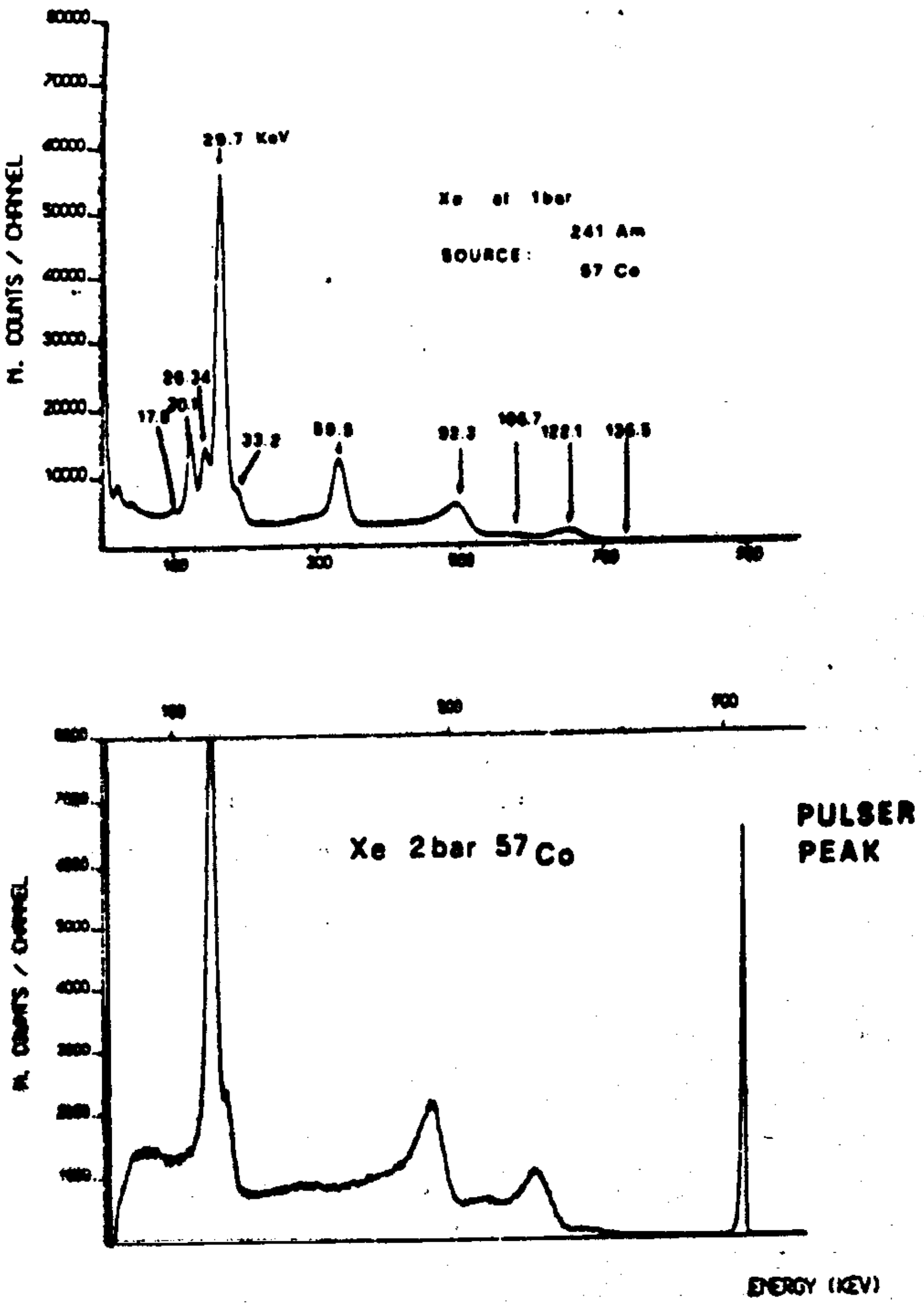
Milano - A MULTICELL PROP. CHAMBER
AT 10 ATM OPERATED IN GRAN SASSO
PEAKS HAVE BEEN SEEN!
PRELIMINARY (5×10^5 seconds)

$\tau_{0\nu} > 2 \times 10^{21}$ y $\tau_{0\nu\chi} > 6 \times 10^{19}$ y

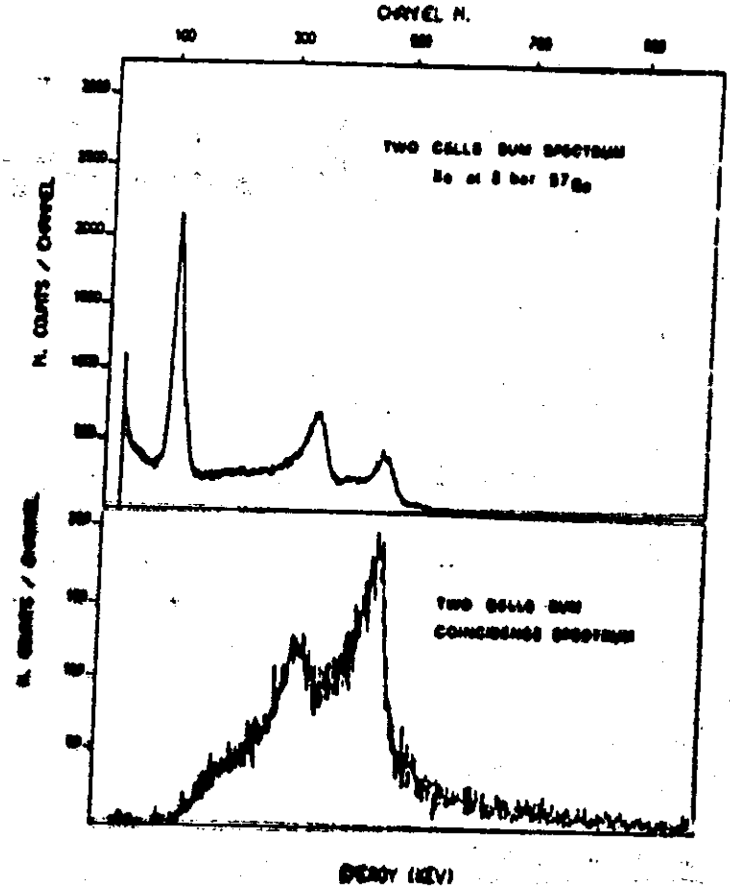

TEMPERATURE AND
AIR FLOW MONITOR
PREAMPLIFIERS
MOLECULAR
SIEVE
XENON
CH_4
ARGON
COPPER AND
LEAD SHIELDING
LN_2
PADS
ANODE
WIRES
GRID
MnO
FIELD
SHAPING
RING
PUMP
HEATER
CATHODE
H_2 FOR
REGENERATION
HIGH
VOLTAGE



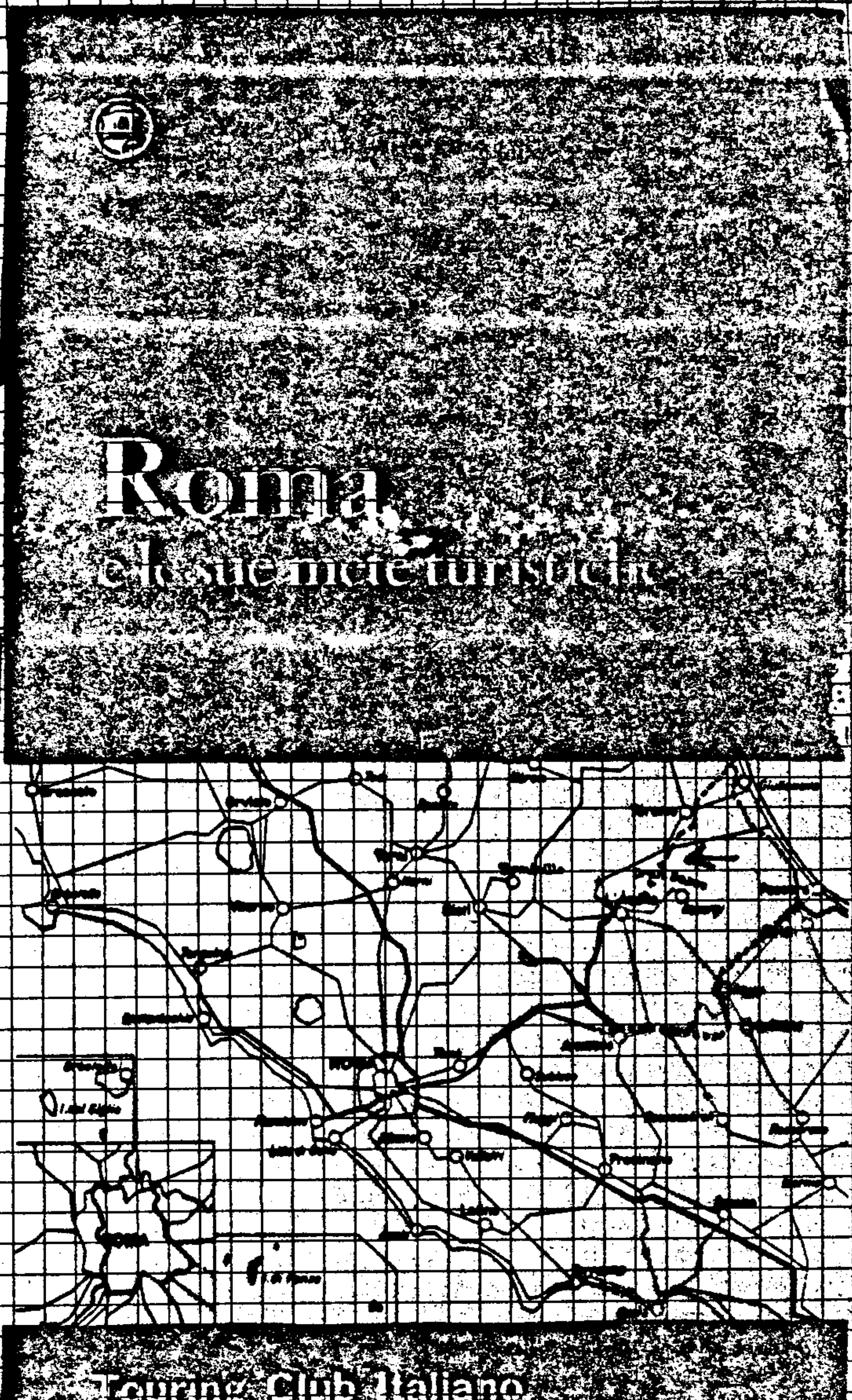
168 X CHANNELS
168 Y CHANNELS



Spectra of the single cell obtained with calibration sources.



Sum spectra of two wires with ^{57}Co.


Roma
e le sue mete turistiche
Touring Club Italiano

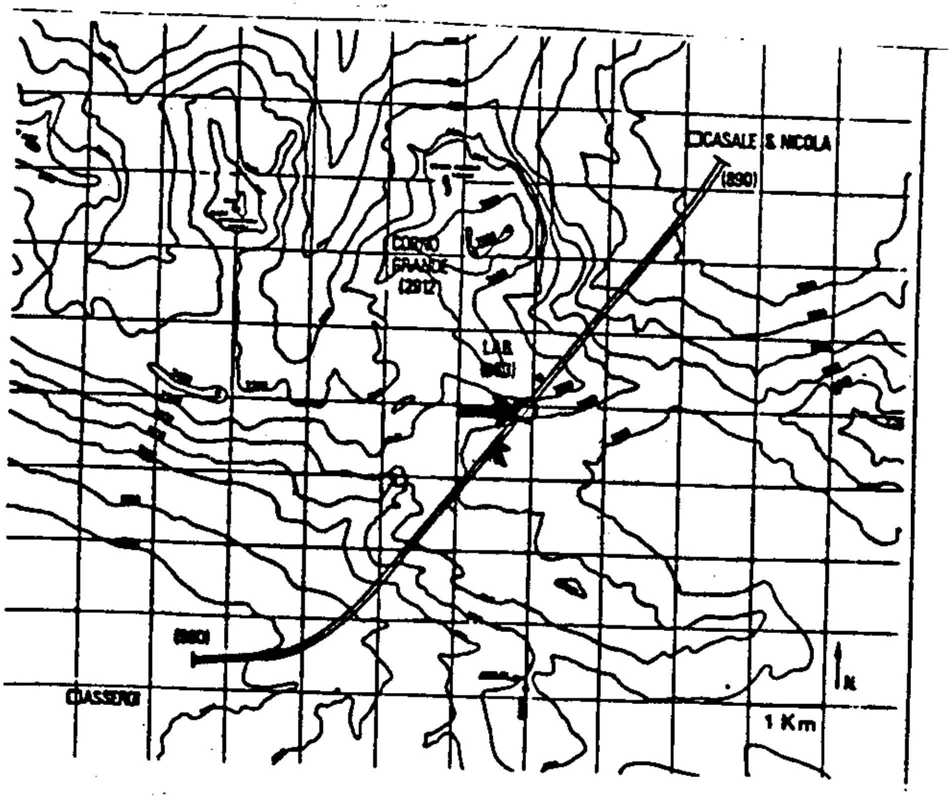
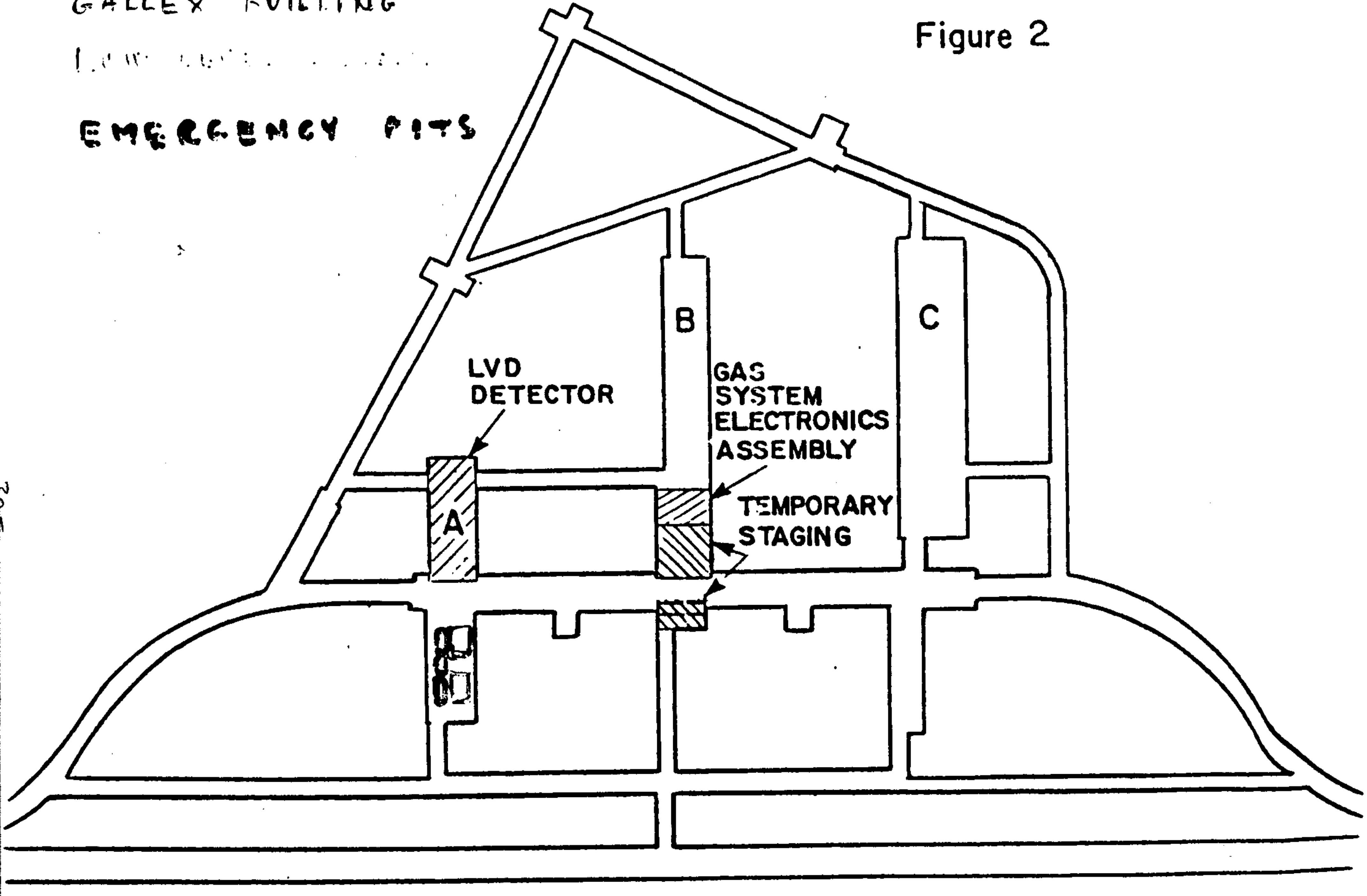


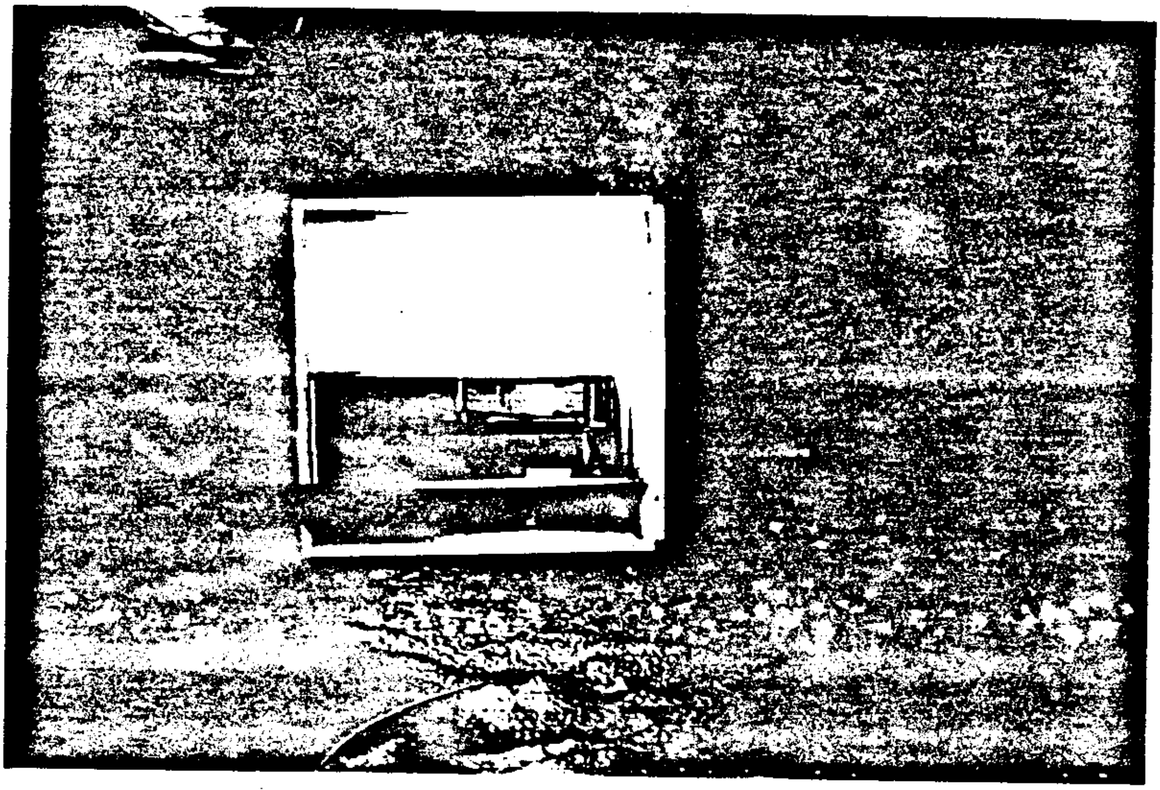
Fig. 1 - Map of the Gran Sasso tunnel.

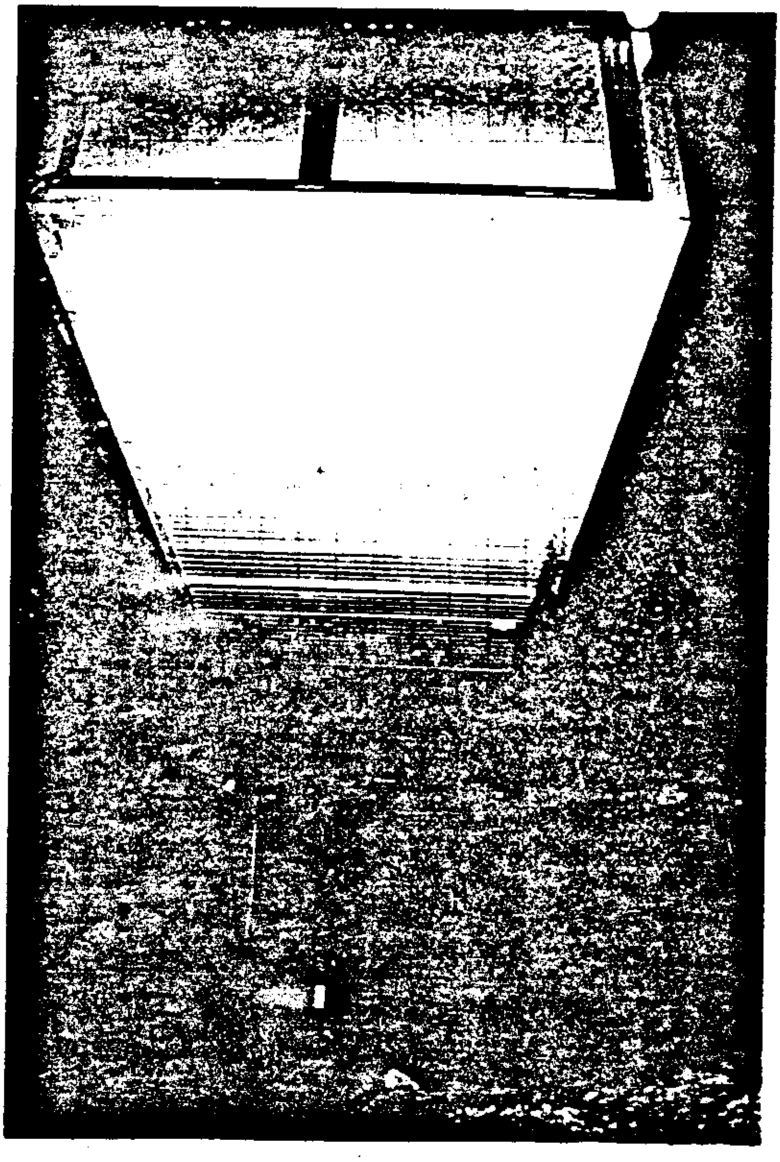
GALLEX BUILDING

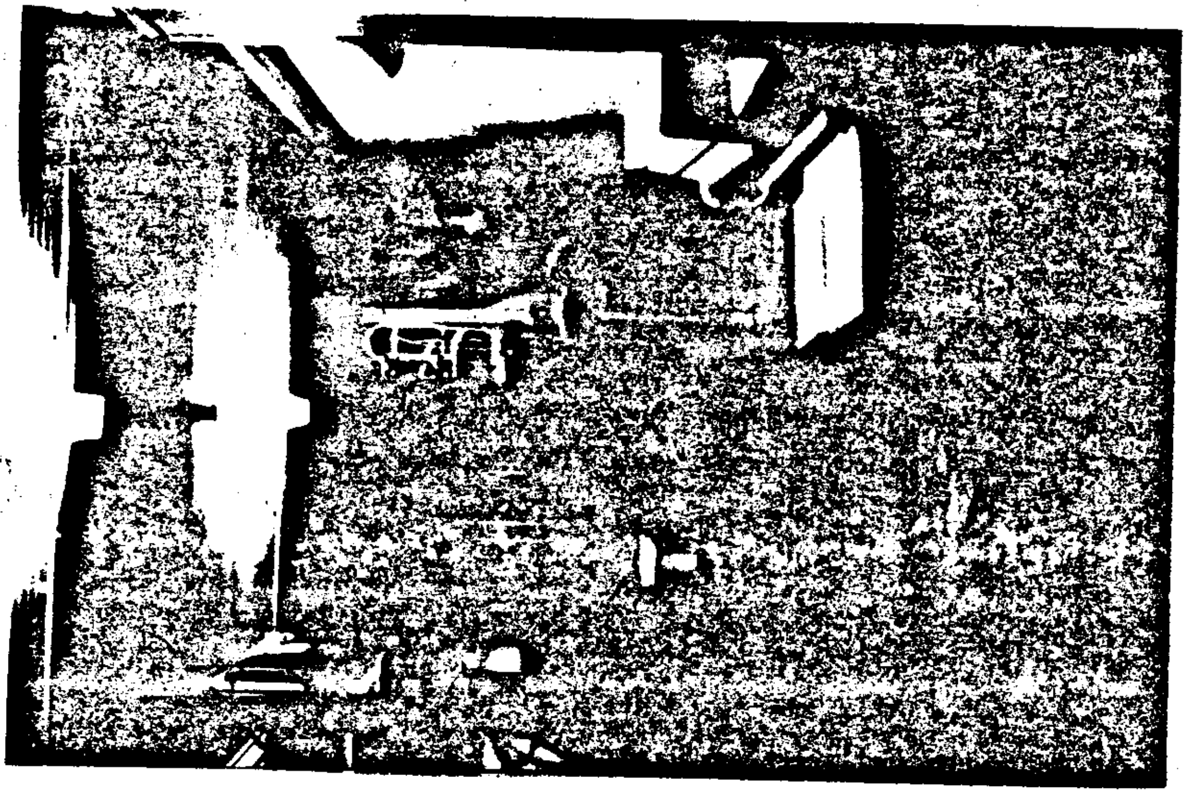
EMERGENCY PITS

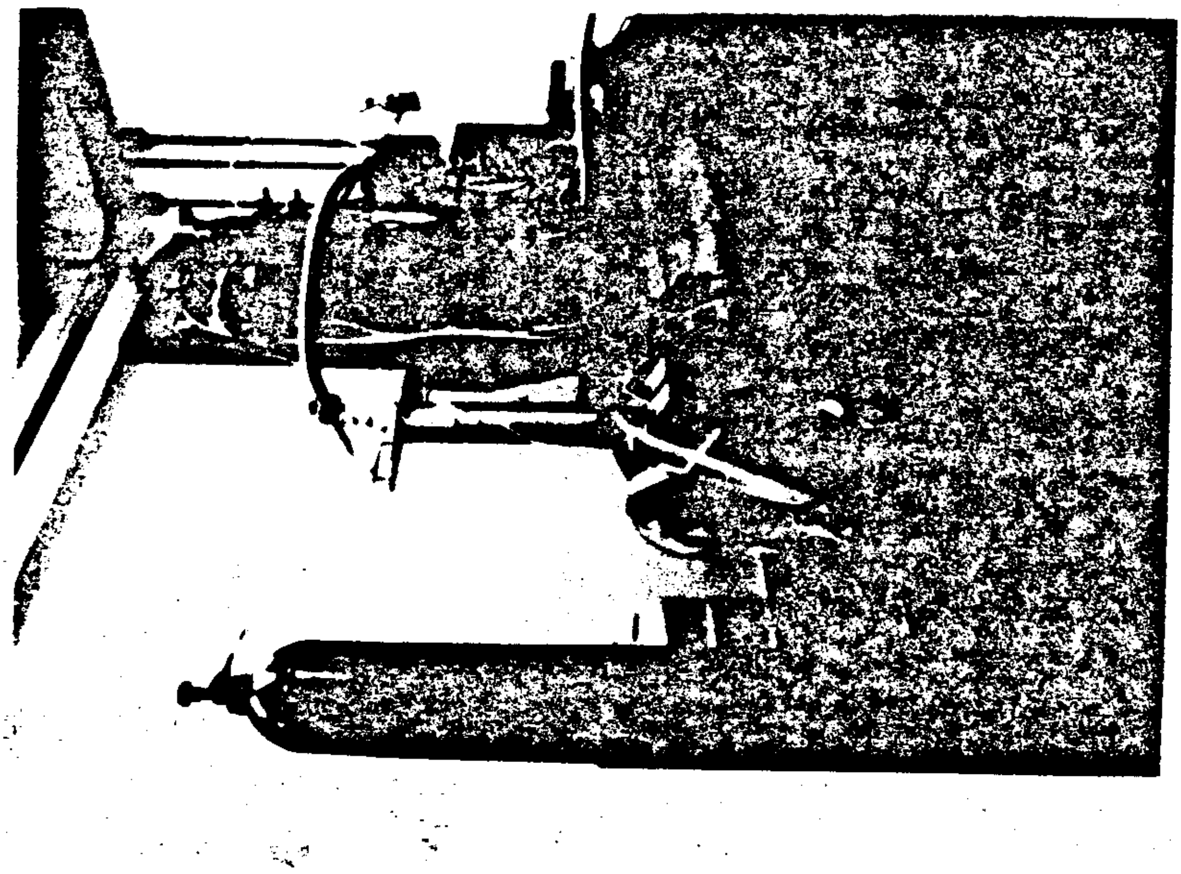
Figure 2

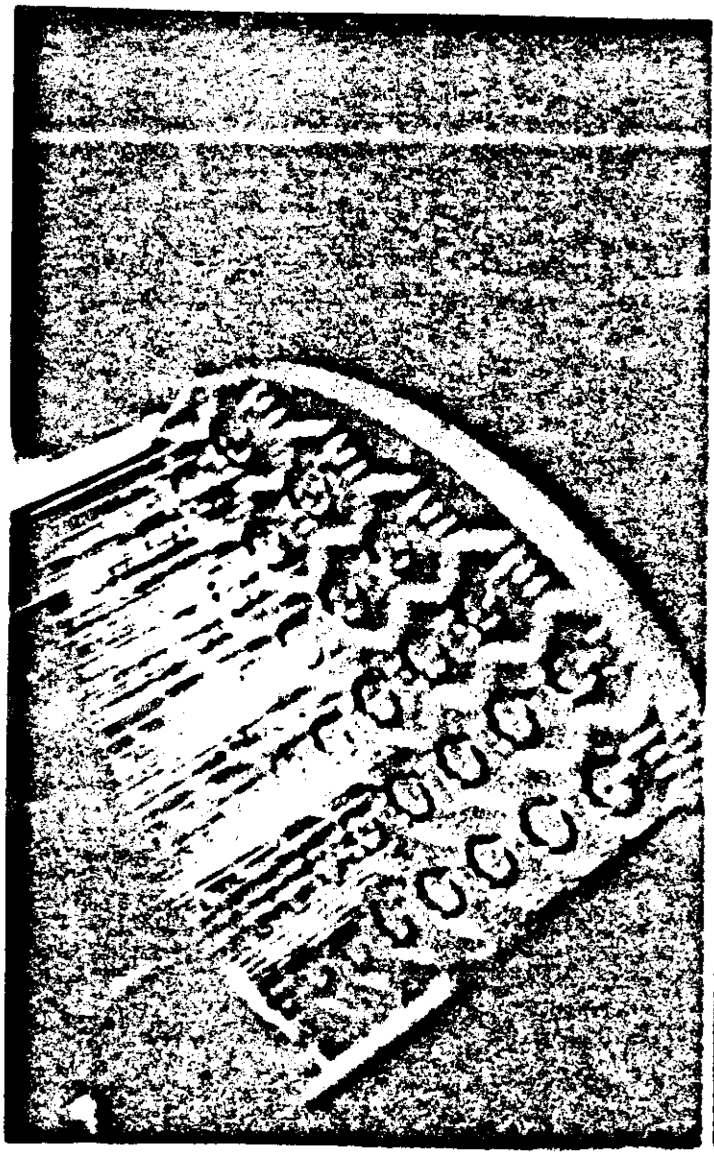


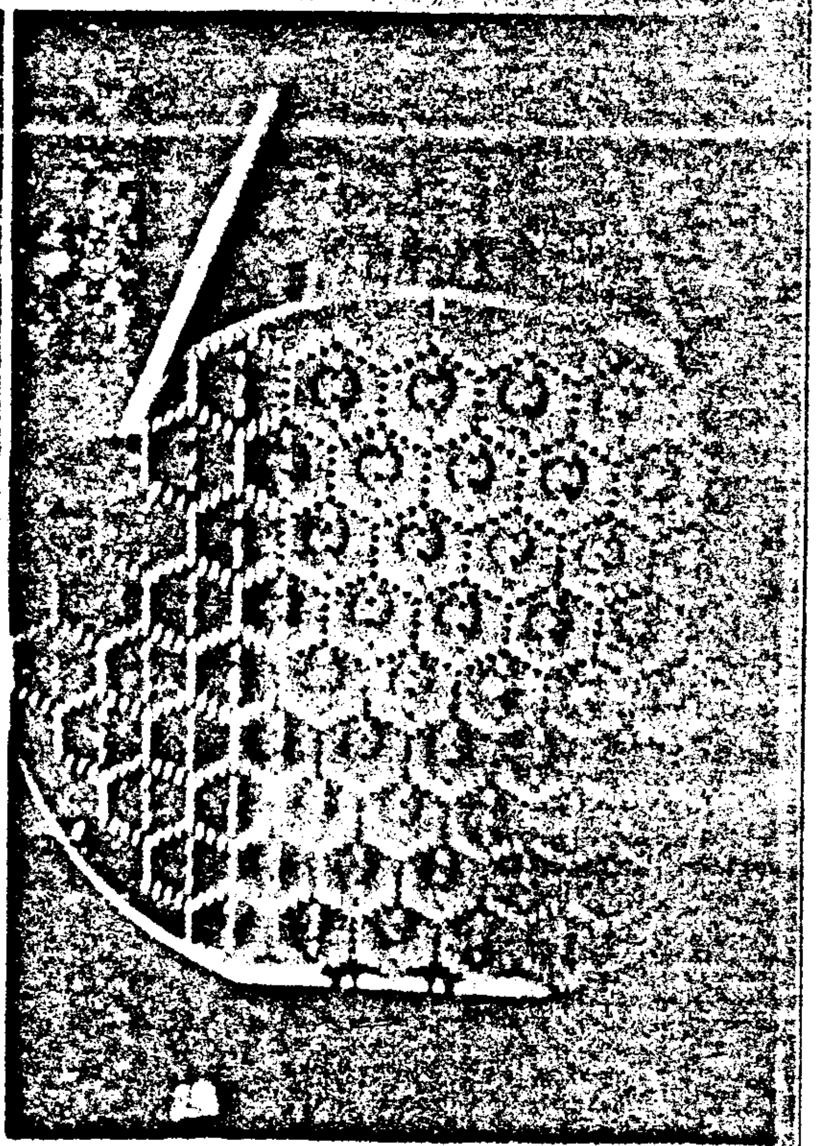


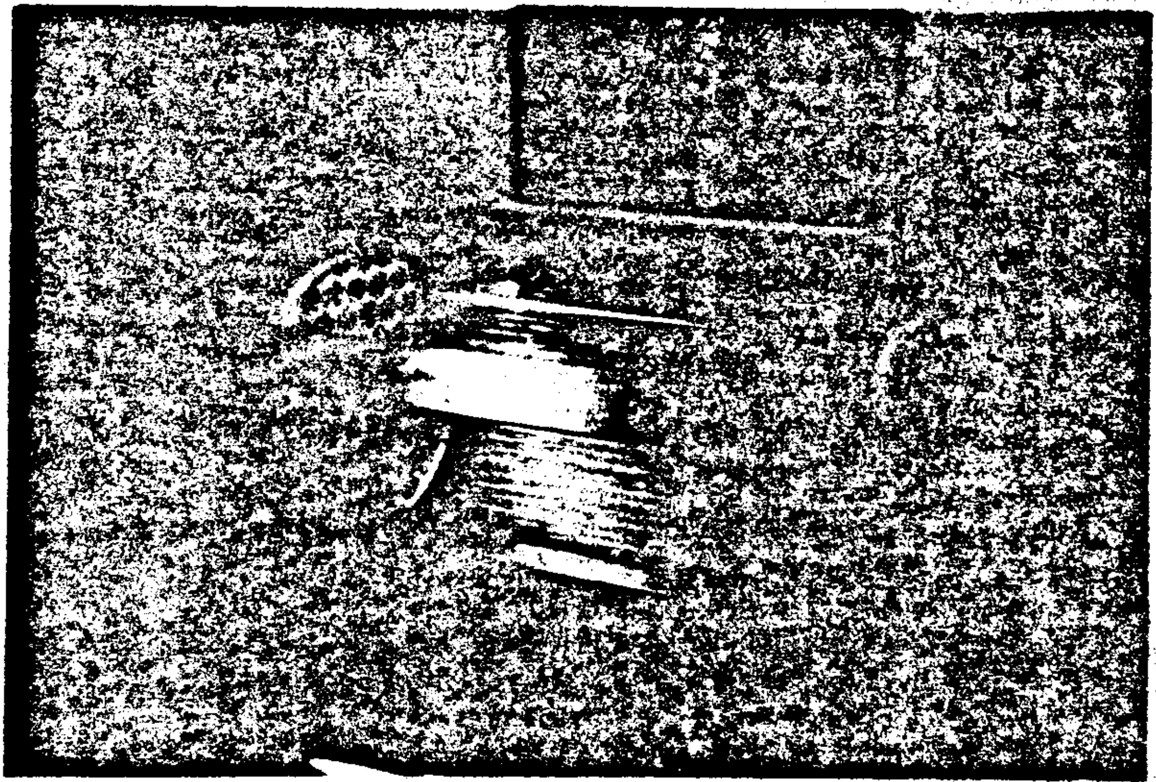




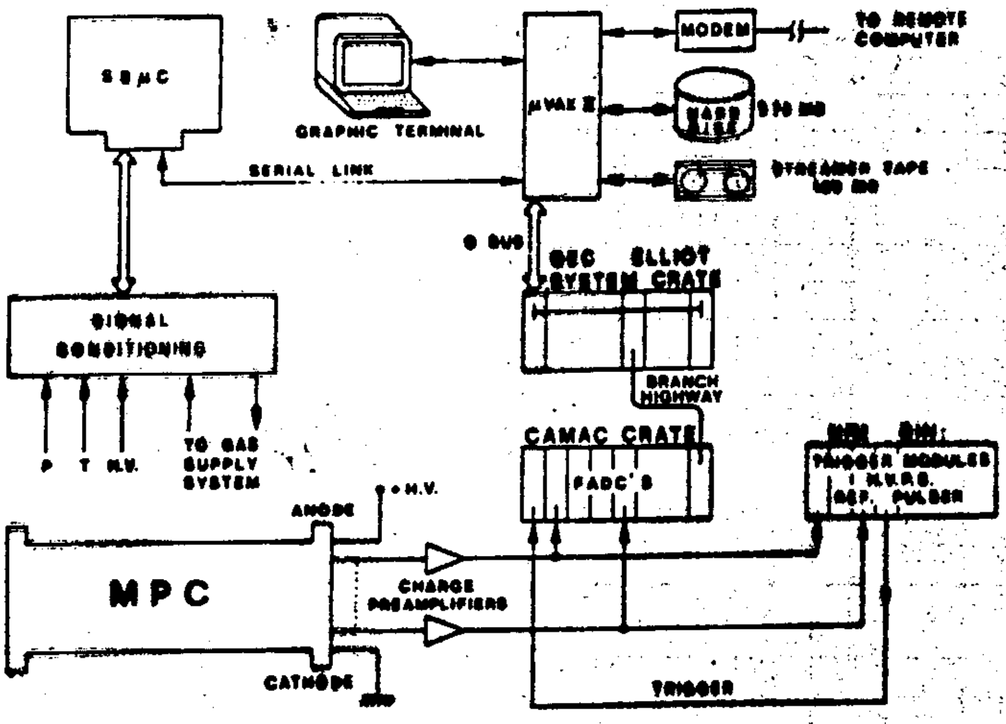








Electronic read-out system.



Electronic readout system.

- hybrid charge preamp. (Laben 5254)
- Flash ADC system with 1 μsec clock and 256 byte RAM / ch. (1 ev ⇒ 16 Kbyte)

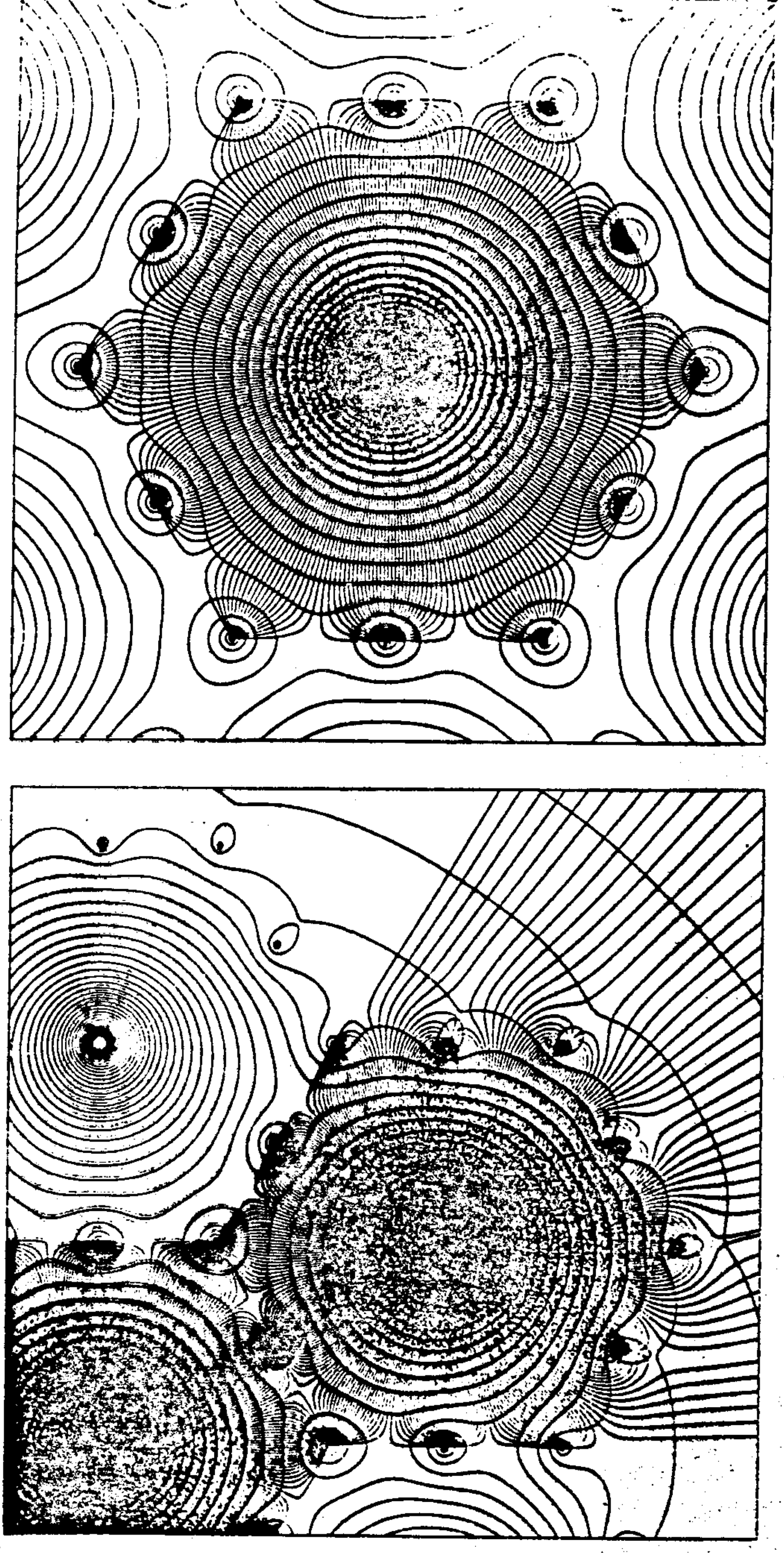
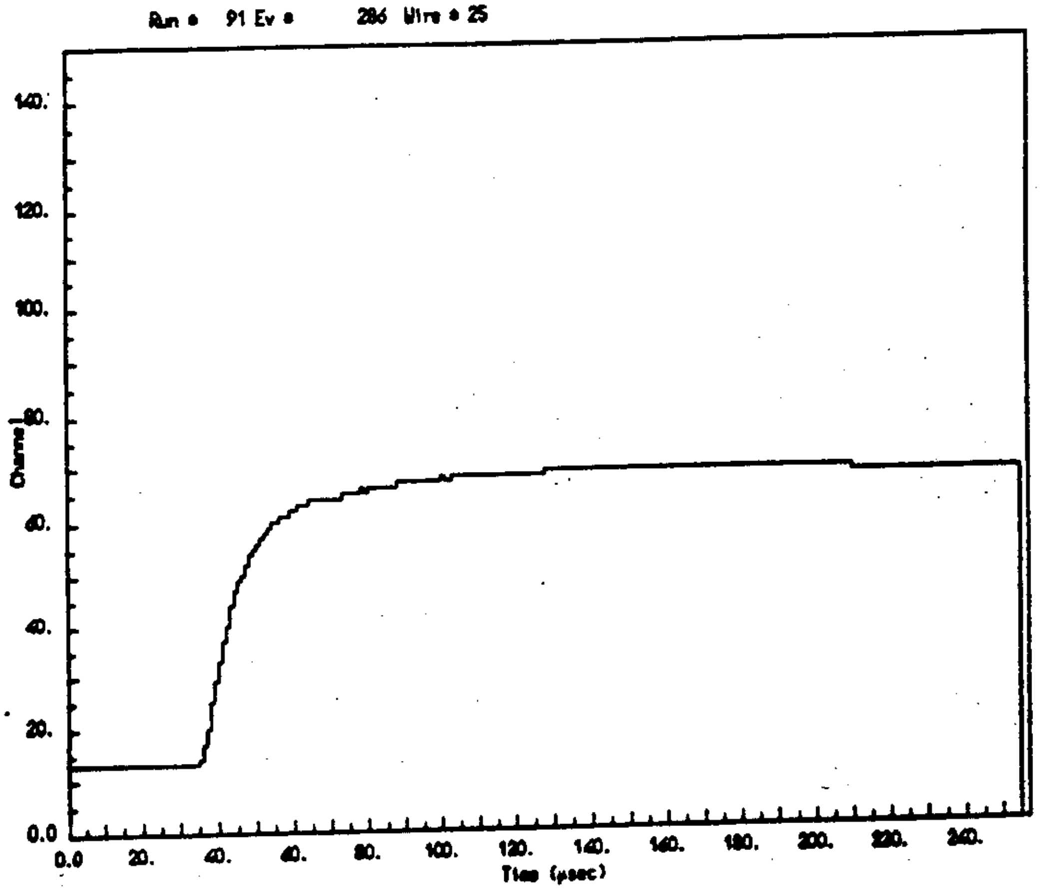
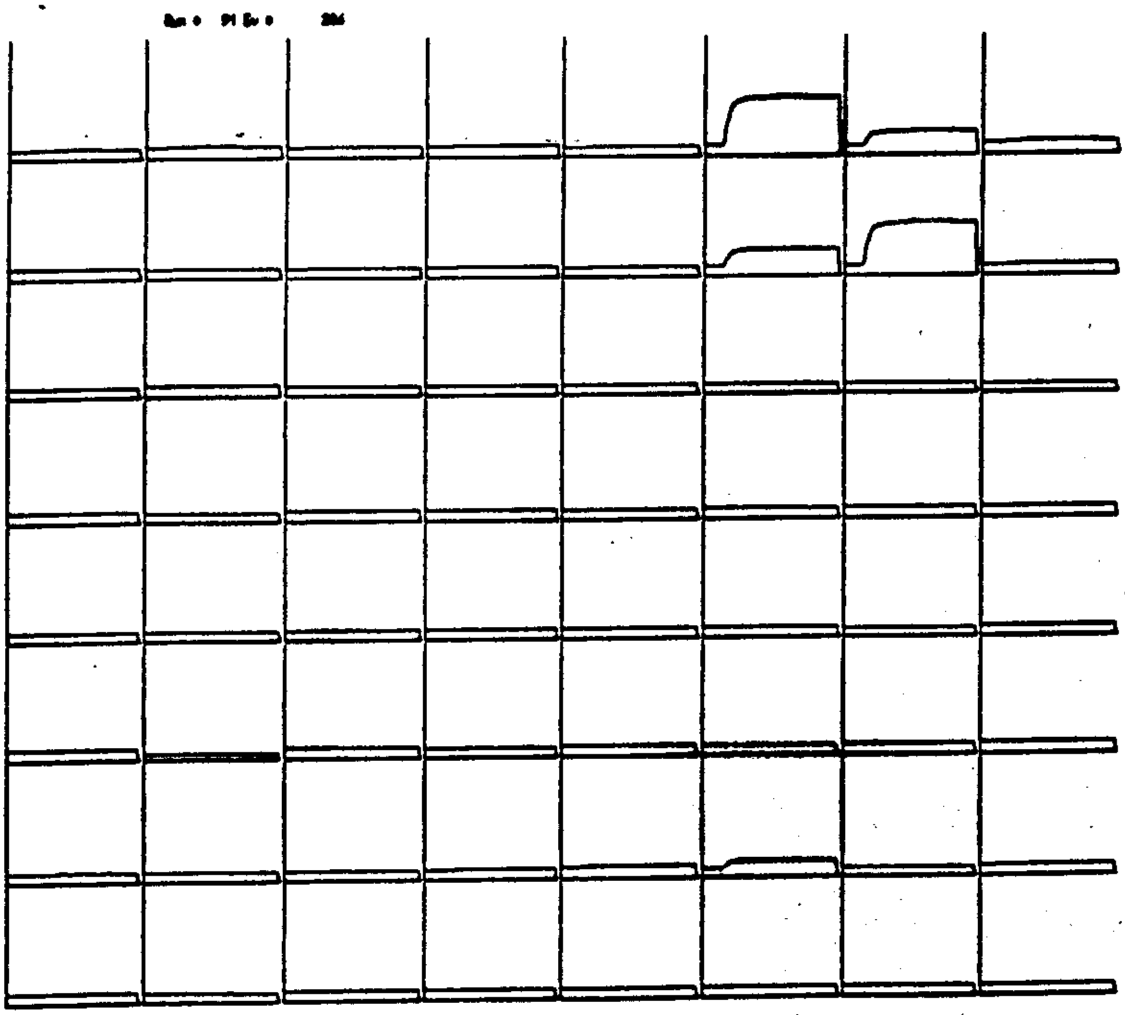


Fig.5.5 **Distribuzioni del potenziale e del campo elettrico nel contatore multiproporzionale per le configurazioni a 5 (a) e 3 (b) fili per ciascun lato della cella.**

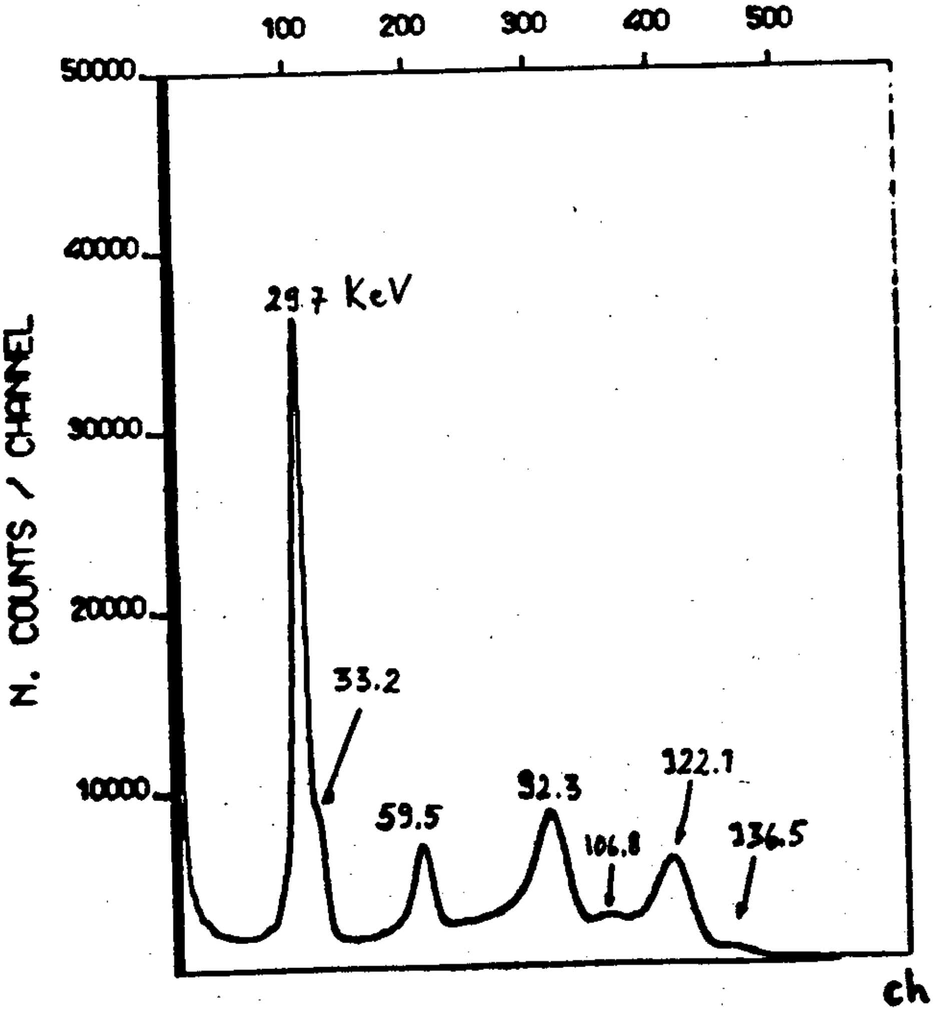

Run # 91 Ev # 286 Wire # 25
Channel
Time (μsec)



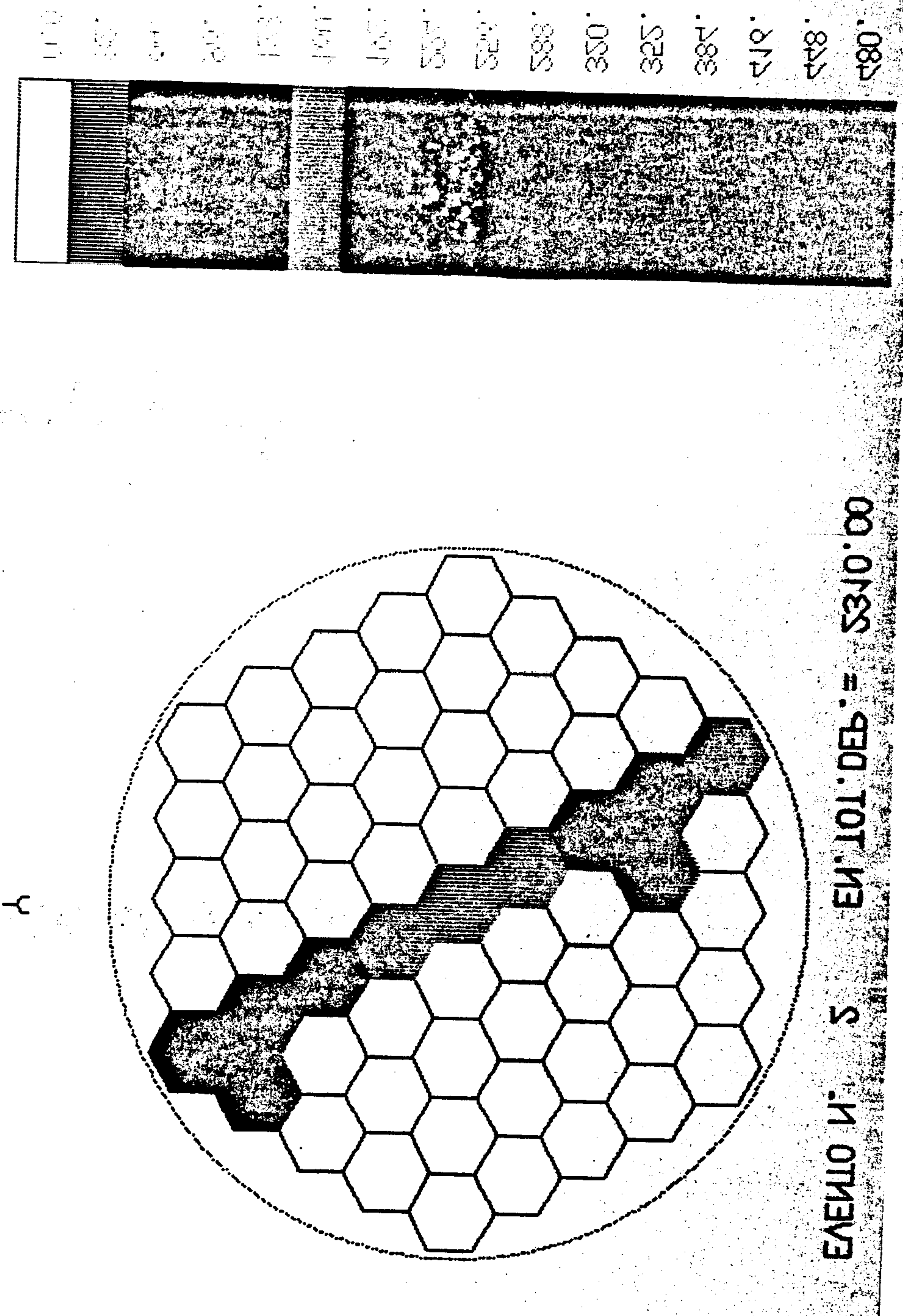
Single wire energy spectrum

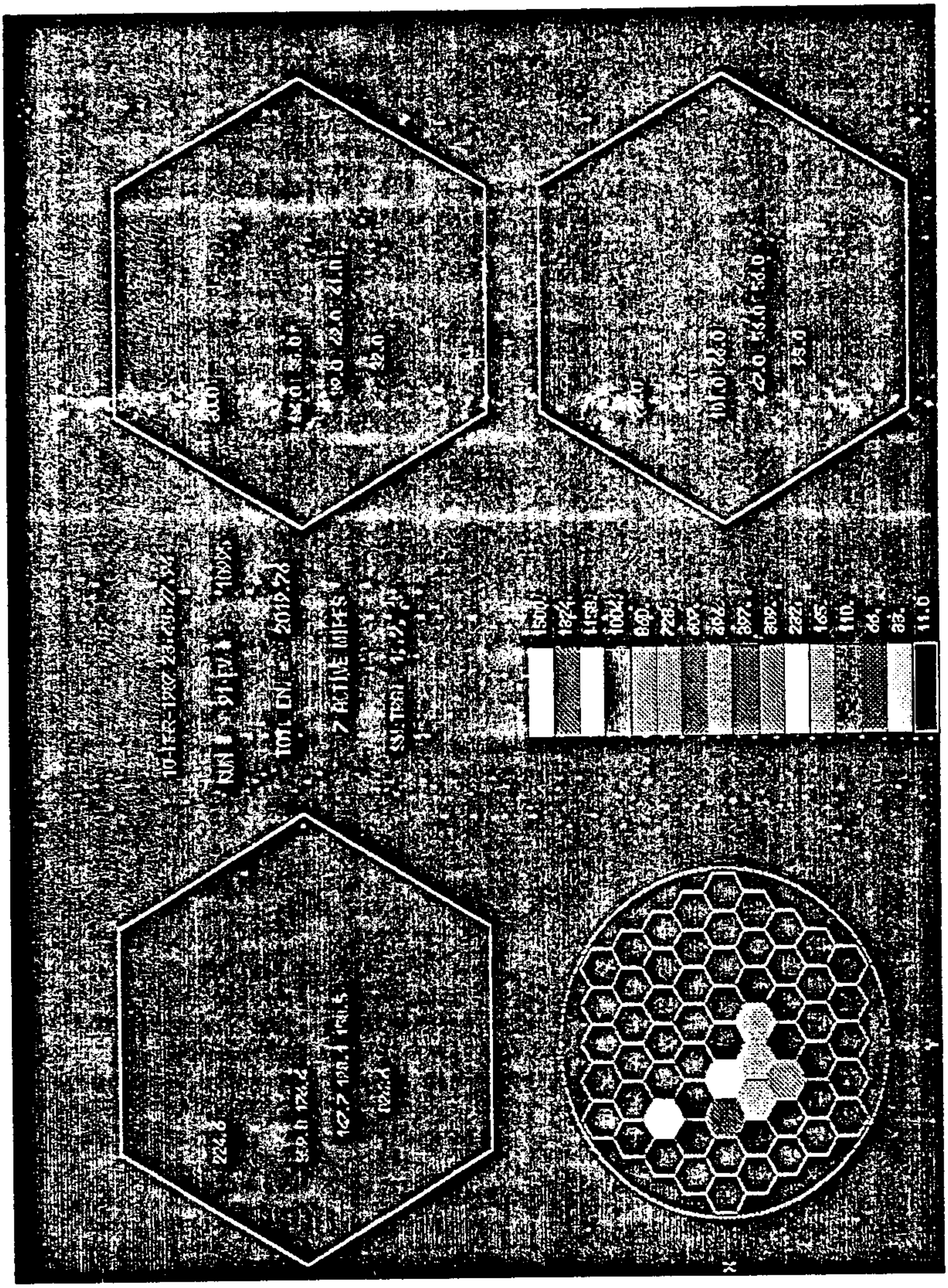
Pure Xe at 4.5 bar

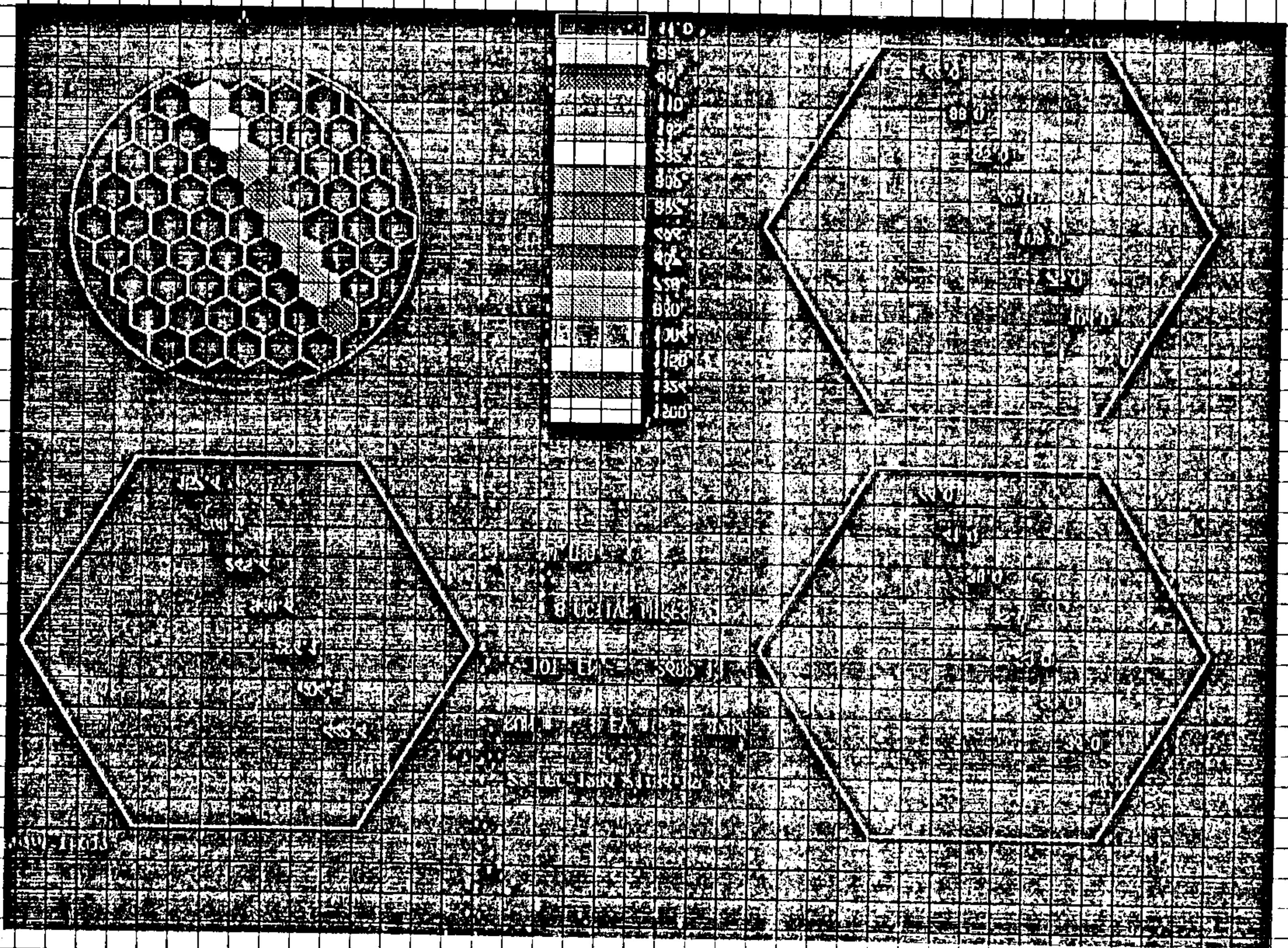
sources: ^{57}Co , ^{241}Am

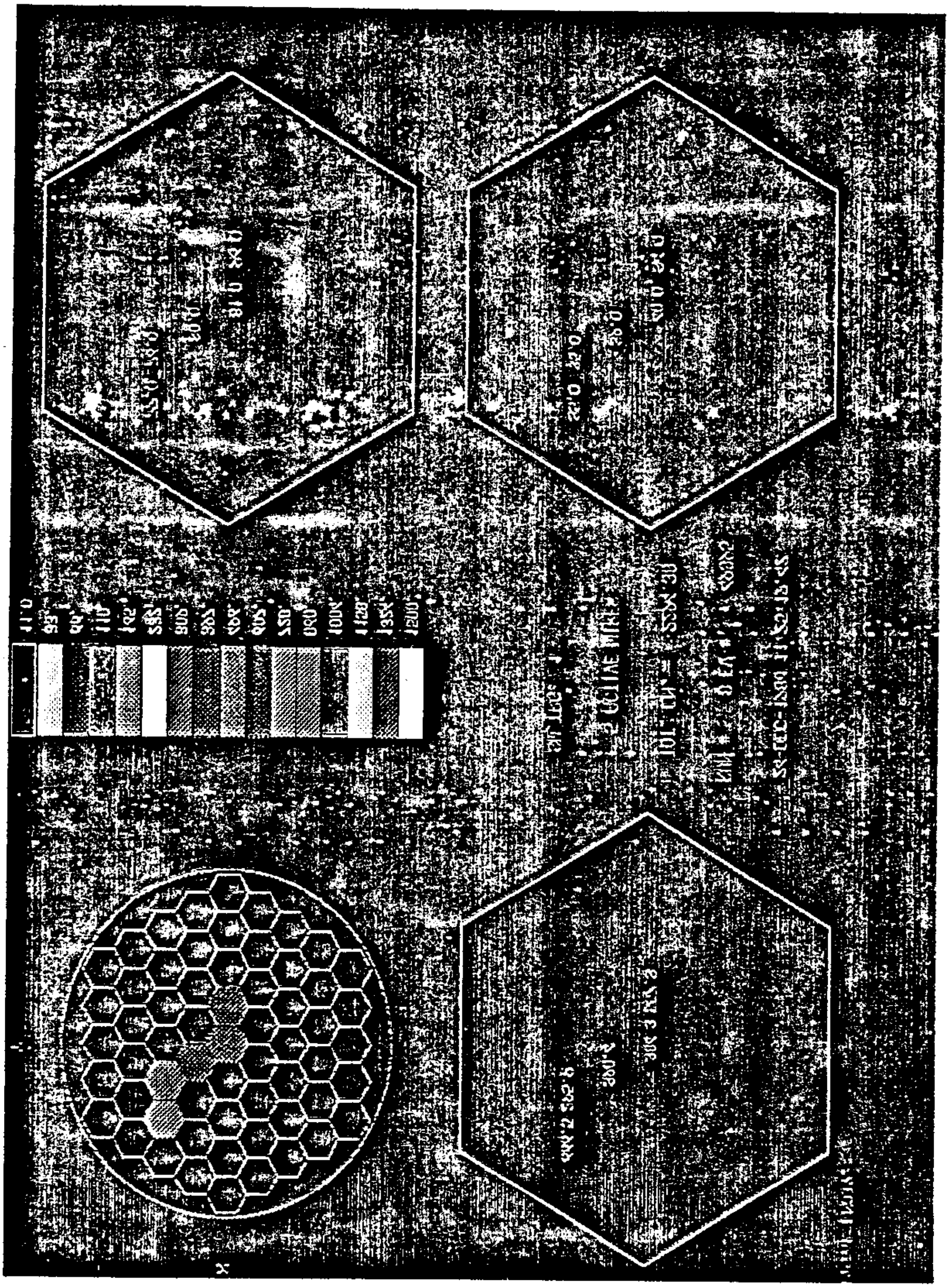


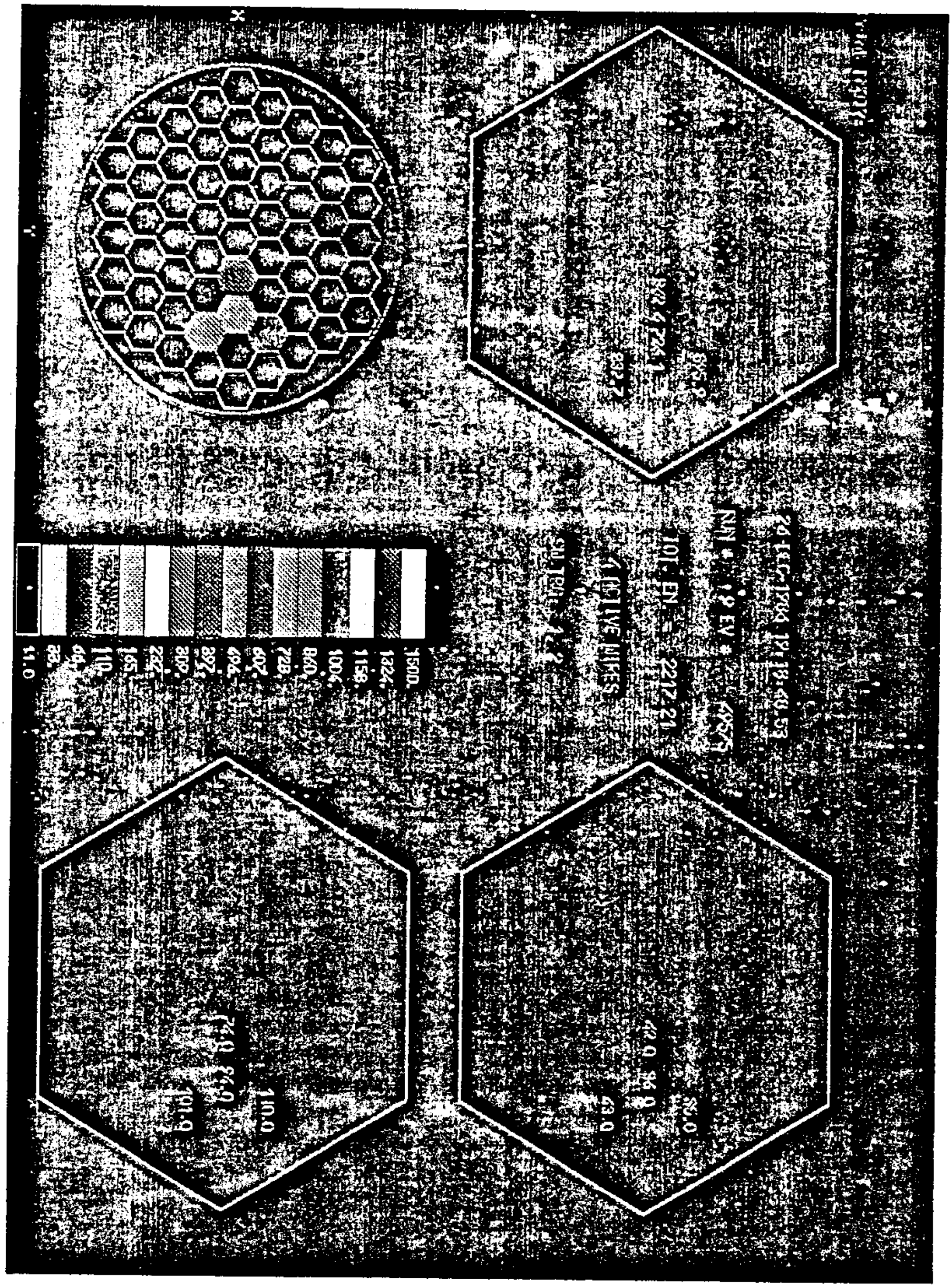
En. resolution: 7.5% FWHM @ 122 keV


Y
EVENTO N. 2 EN.TOT.DEP. = 2310.00
480.
448.
416.
384.
352.
320.
288.

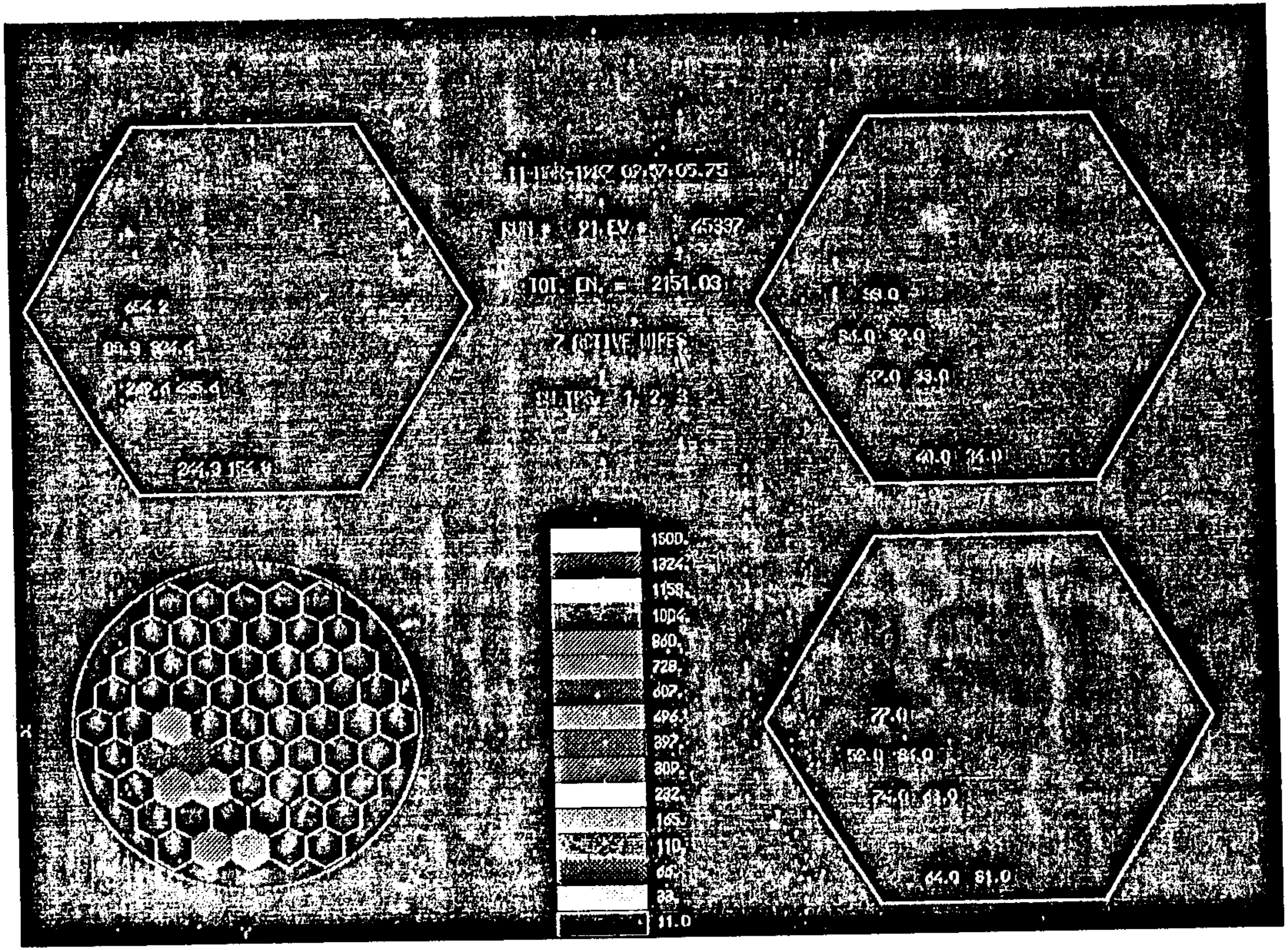




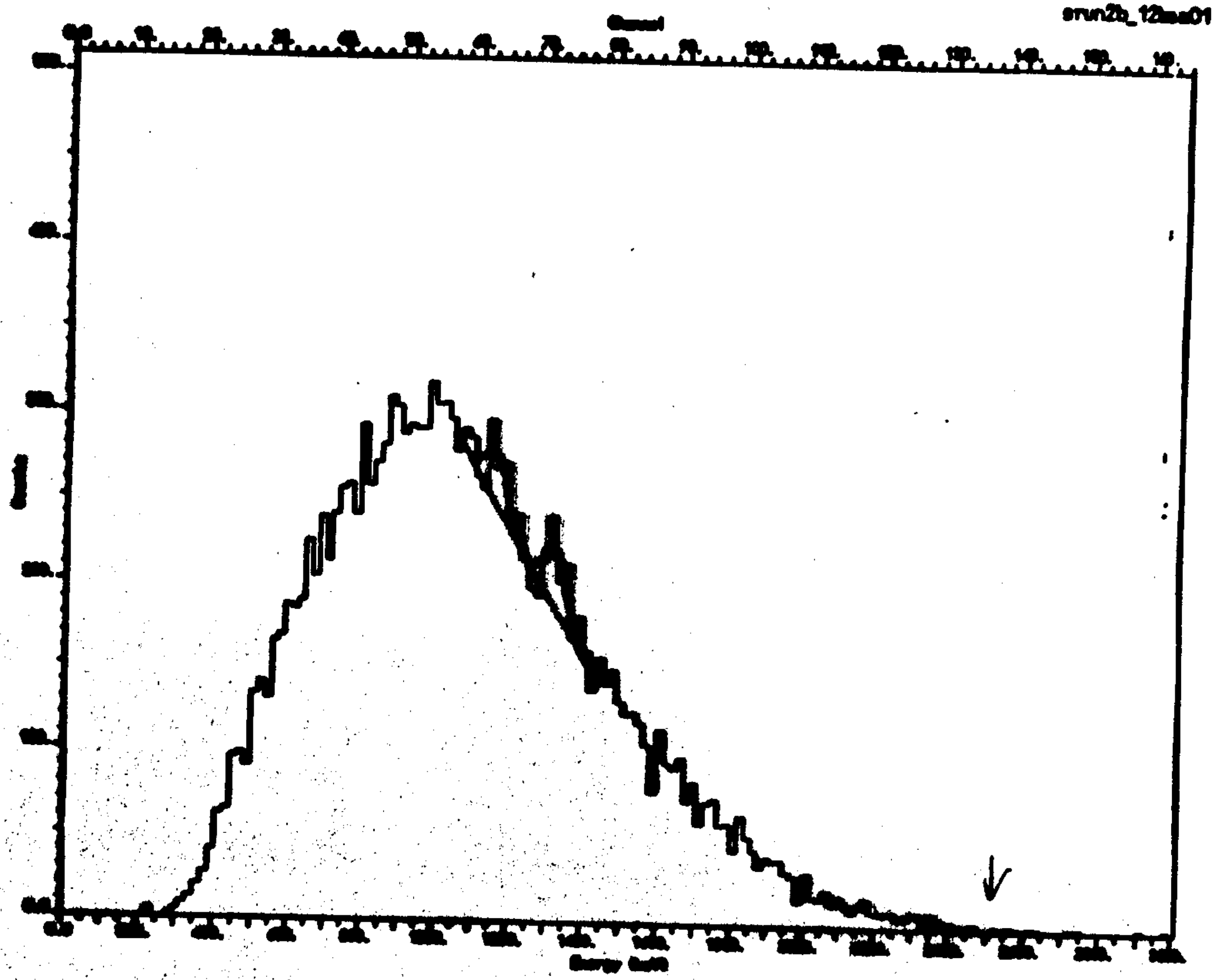




91


TOT. EN. = 2151.03
7 ACTIVE WIRES
1500.
1324.
1158.
1004.
860.
728.
607.
496.
397.
232.
110.
66.
33.
11.0
58.0
40.0 34.0
77.0
64.0 81.0

0.5 × 10^6 ... fit. 3-?



FUTURE:

a. DIFFERENT NUCLEI

(e.g. GeH_4 proportional counters or TPC)

b. ISOTOPE – NATURAL ELEMENT. DIFF.

c. NEW TECHNIQUES.

a. RIS – FOR COUNTING SINGLE ATOMS ($^{82}Se \rightarrow {}^{82}Kr$)

down to 1000 ± 100 atoms, but

PROBLEMS WITH BACKGROUND –

b. "MILKING" EXPERIMENTS –

(Haxton, Cowan and Goldhaber)

1000 kg of $^{238}U \rightarrow {}^{238}Pu$ 1,148 keV (99.3%)

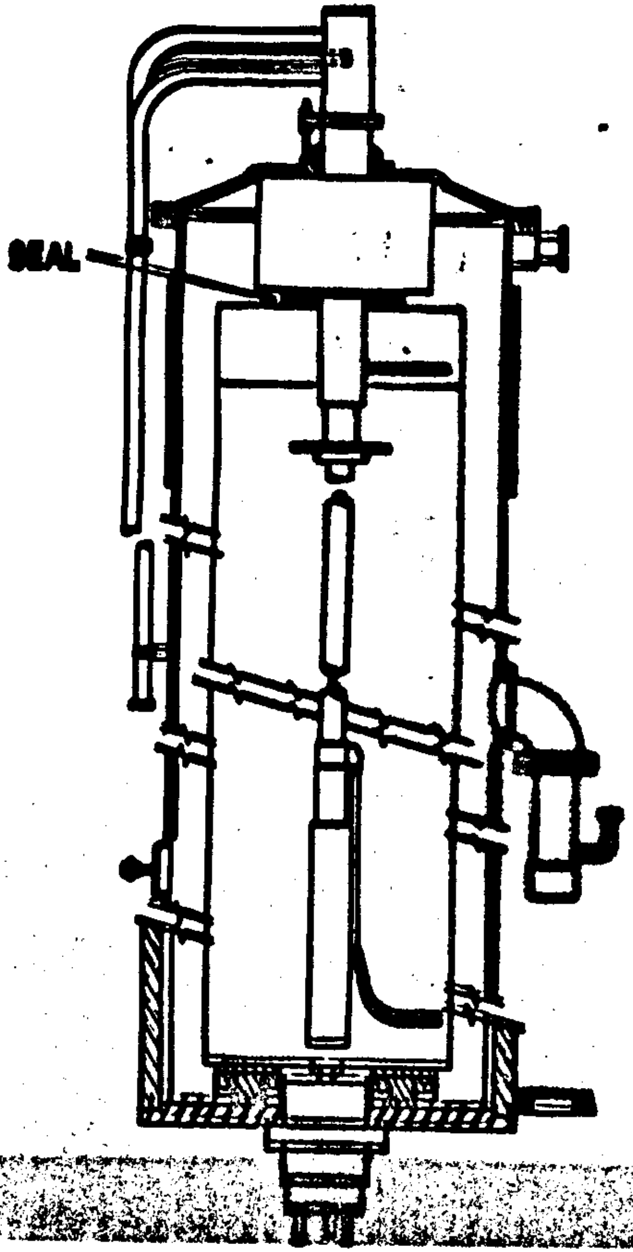
MILKED EVERY ~4 MONTHS.

c. LOW TEMPERATURE BOLOMETRY

(proposed in 1984 by E.F. and T.Niinikoski

(later – 1986 – Cabrera, Caldwell, Sadoulet)

GAS CENTRIFUGE IS VERSATILE



PERFORMANCE CHARACTERISTICS

- $\Delta U \propto \Delta M^2 \cdot L \cdot V^4$
- LARGE QUANTITIES CAN BE HANDLED ECONOMICALLY

PROCESS GAS REQUIREMENTS

- GAS STABLE TO 300°C
- MOLECULAR WEIGHT >80
- VAPOR PRESSURE ~5 torr AT 40°C

MARTIN MARIETTA

15

MASS AND RARE DECAYS.

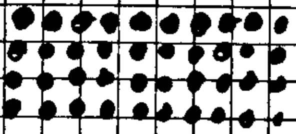
1903 P. Curie and A. Laborde - Compt. Rend.

1927 Ellis and Wooster - ^{210}Bi

Dec. 4, 1930 - W. Pauli - letter "Radioactive ladies and gentlemen,

1932-34 Fermi theory of weak interactions.

a. Superconductive granules



b. Josephson junctions

c. Bolometric crystals

Proposed by E.F. and T. Niinikoski (CERN - MILANO) and Mather et al (NASA - WISCONSIN)

Results by Aarus, Berkeley, Cern, Genova, Goteborg, Milano, Munchen, Oregon, Saclay, Stanford, Wisconsin.

THE PRINCIPLE.

$$C_{cond} = \gamma T \quad (\gamma \approx \text{millijoule}/K)$$

$$C_{s.cond} = k\, e^{-\frac{T_c}{T}}$$

$$C_{Lattice} = 1944 \frac{V}{V_m} \left(\frac{T}{\Theta_D}\right)^3 J/K$$

Example $1\ cm^3$ of Si ($\Theta_D = 645\ K$) at 50 mK

$$C_V = 8 \times 10^{-11}\ J/K$$

$$\Delta T = \frac{Q}{C_V} = \frac{P \cdot \Delta E}{C_V}$$

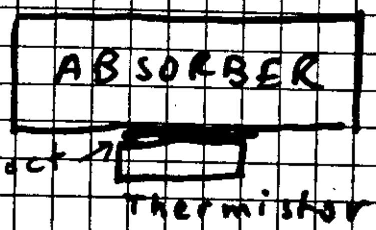
P = percentage of thermalization = could be theor. 100%
FOUND TO REACH 70-80 %

ΔT can be measured by change of resistance of a thermistor in therm. contact with the crystal

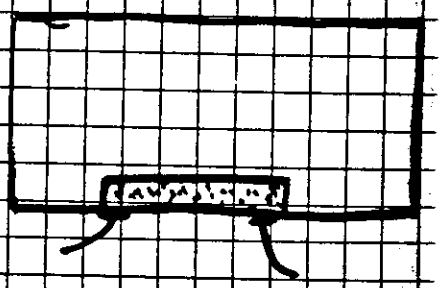
THREE POSSIBILITIES

A thermistor acting as calorimeter (considerable heat capacity)

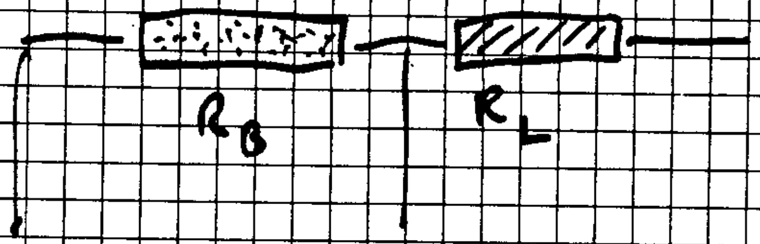
A COMPOSITE BOLOMETER



AN INTEGRATED CALORIMETER WITH AN IMPLANTED THERMISTOR



ELECTRIC CONNECTION



RISETIME → v_s

DECAY TIME → KAPITZA RESISTENCE

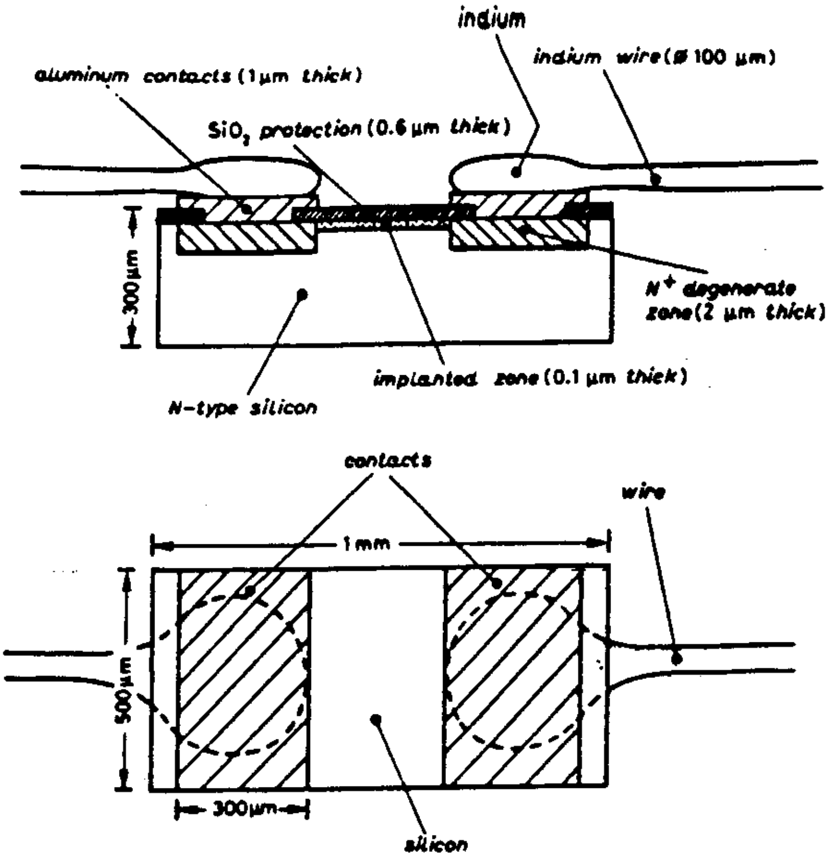


Fig. 1. – The implanted Silicon calorimeter.

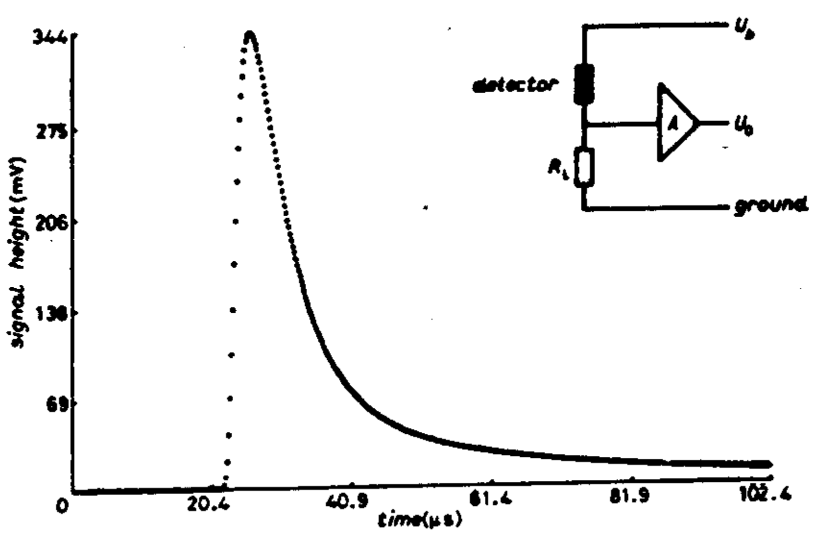


Fig. 2. – A typical pulse (at 500 mK). In the inset, the input circuit.

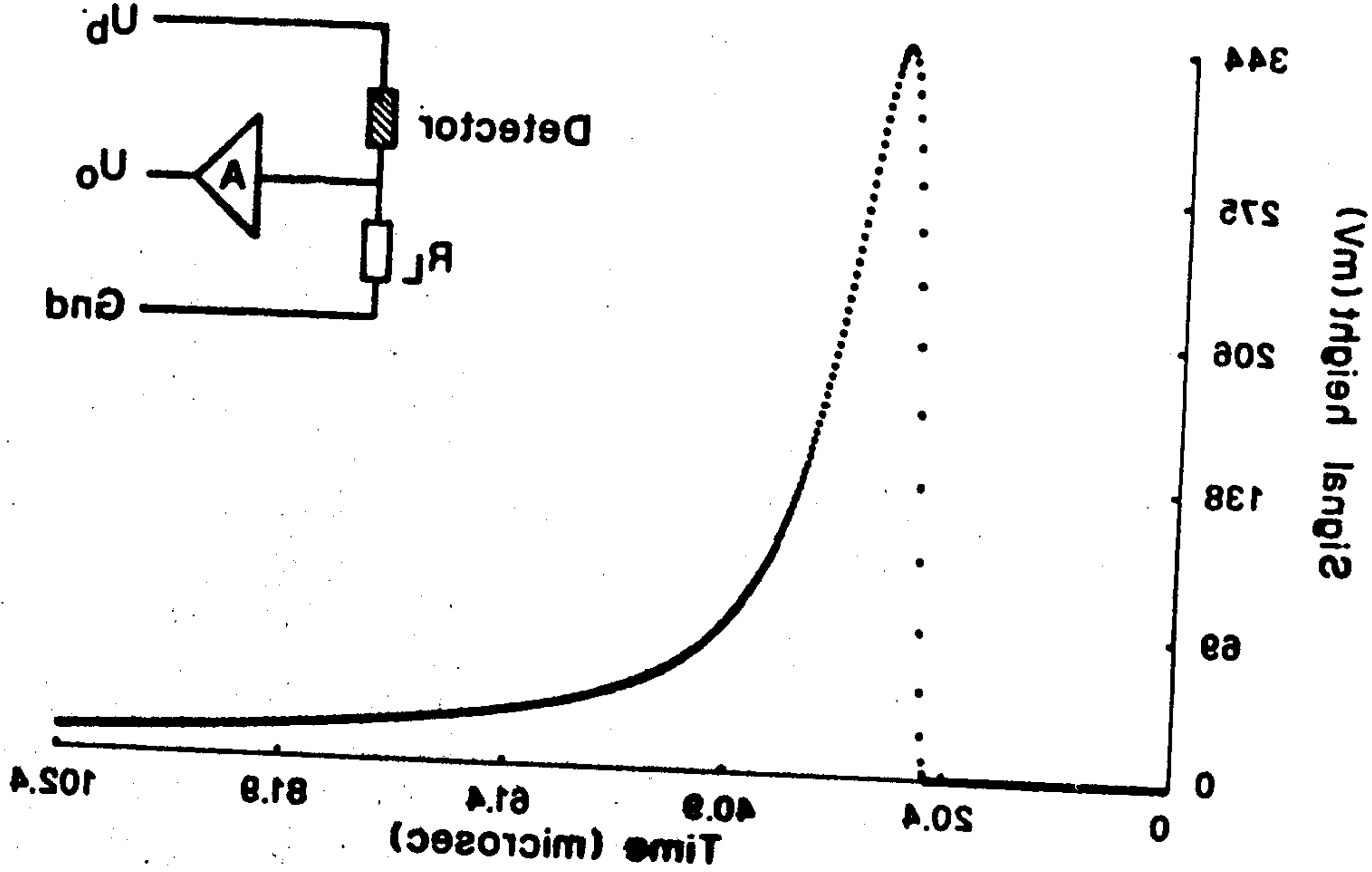

Ub
Uo
Gnd
A
Detector
R_L
Signal height (mV)
344
275
206
138
69
0
0
20.4
40.9
61.4
81.9
102.4
Time (microsec)

Fig. 2

13 B.S

RESOLUTION:

. Johnson noise of R_B

. " " " R_L

. Noise of the PRE

1. Thermal fluctuations

$$E_{phonon} = kT \approx 10^{-3} - 10^{-4}\ eV$$

(versus ~ 30 for ionization detectors and ~ 3 for sol. state detectors)

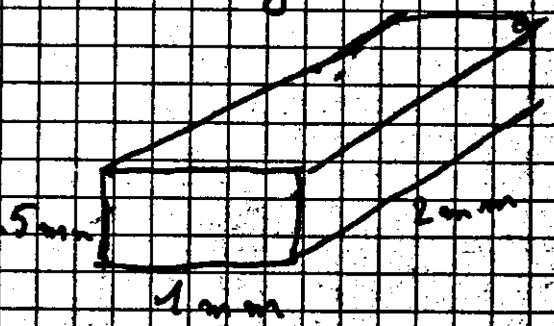
$$\Delta E = \xi \sqrt{k \cdot C_V T^2}$$

$k = 1.38 \times 10^{-23}$ J/K

ξ depend on sensitivity $= \dfrac{d \log R}{d \log T}$

(could be 1-2)

Example Silicon crystal



$V = 1\ mm^3$ $V_m = 12\ cm^3$

$T = 50\ mK$ $\Theta = 645\ K$

$C_V = 9 \times 10^{-13}$ J/K $\Delta E = 1\ eV$

ADVANTAGES: EXCELLENT RESOL. (Theor)

70 - 100% of therm. energy

DISADVANTAGES: THERMAL INSTABILITIES

LONG RISE- AND DECAY TIMES

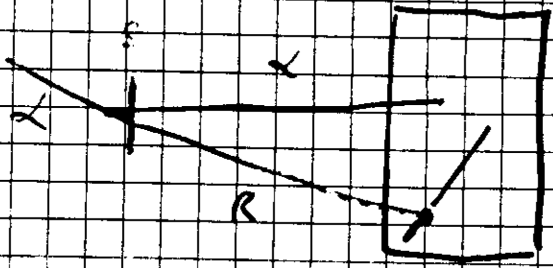
RESULTS:

COLLABORATION AARHUS - CERN - GOTEBORG - SACLAY

Diamond ($\sim 10^{-3}$ cm^3)
Ge Thermistor 0.3 - 1. K

ALPHA SPECTRA MEASURED TO 1‰

FIRST EVIDENCE OF NUCLEAR RECOIL



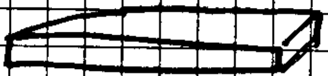
NASA - WISCONSIN

Various detectors (10^{-3} - 10^{-6} g)

SINGLE (Ge + As), doped (Ge, Si, ...)

MAIN AIM: X-RAYS IN ASTROPHYSICS, NEUTRINO MASS

RECENT EXPERIMENT:



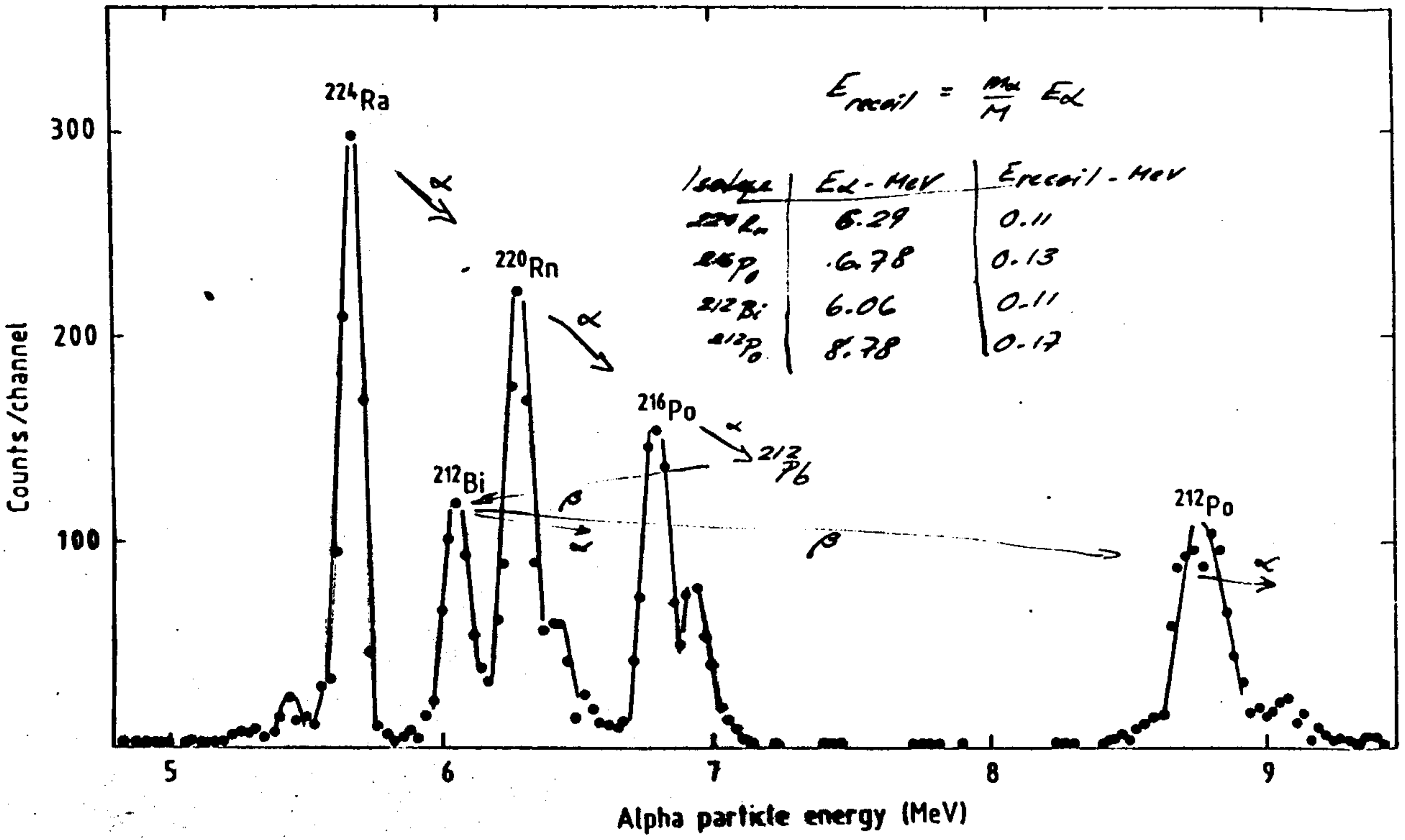
HgCdTe 500 μm × 500 μm × 10 μm
$= 2.5 \times 10^{-6}$ cm^3

T = 80 mK

^{55}Fe X-rays (5.9, 6.5 keV)

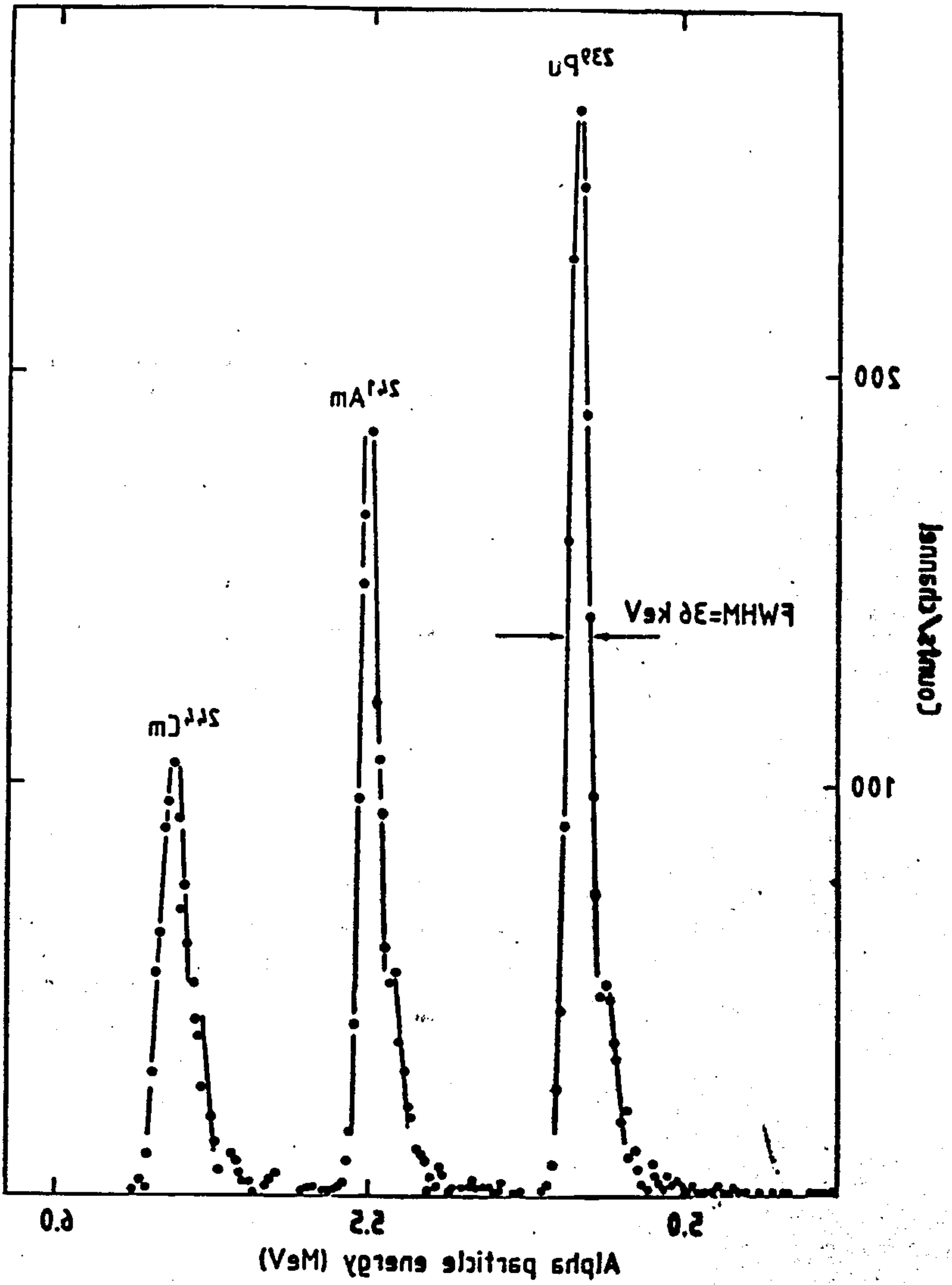
$\Delta E = 17.4$ eV BASELINE 13.1 eV

RESIDUAL 11 eV could be due to non uniform response across the detector or residual thermalization noise



Stroke, Artzner, Coron, Daubier, Hansen, Jugandez, Jonson, Leblanc, Lepeltier, Nyman, Ravn, Testard, IEEE Transactions Nuclear Science NS-33, 759 (1986)

(5)



^{239}Pu
^{241}Am
^{244}Cm
FWHM=36 keV
Counts/channel
200
100
6.0
5.5
5.0
Alpha particle energy (MeV)

Fig.1

MILANO

A. Alessandrello, D. Camin, E.F, A. Giuliani
(+ M. Buraschi and G. Pignatel - SGS)

AIMS:

a. Fast pulses to study thermal behaviour

b. Large detectors

FAST PULSES:

RISETIME DOMINATED BY THE INPUT RC

SPECIAL SGS DETECTORS WITH LOW R

STRUCTURE AND R(T).

PULSE RISETIMES AS LOW AS 600 ns

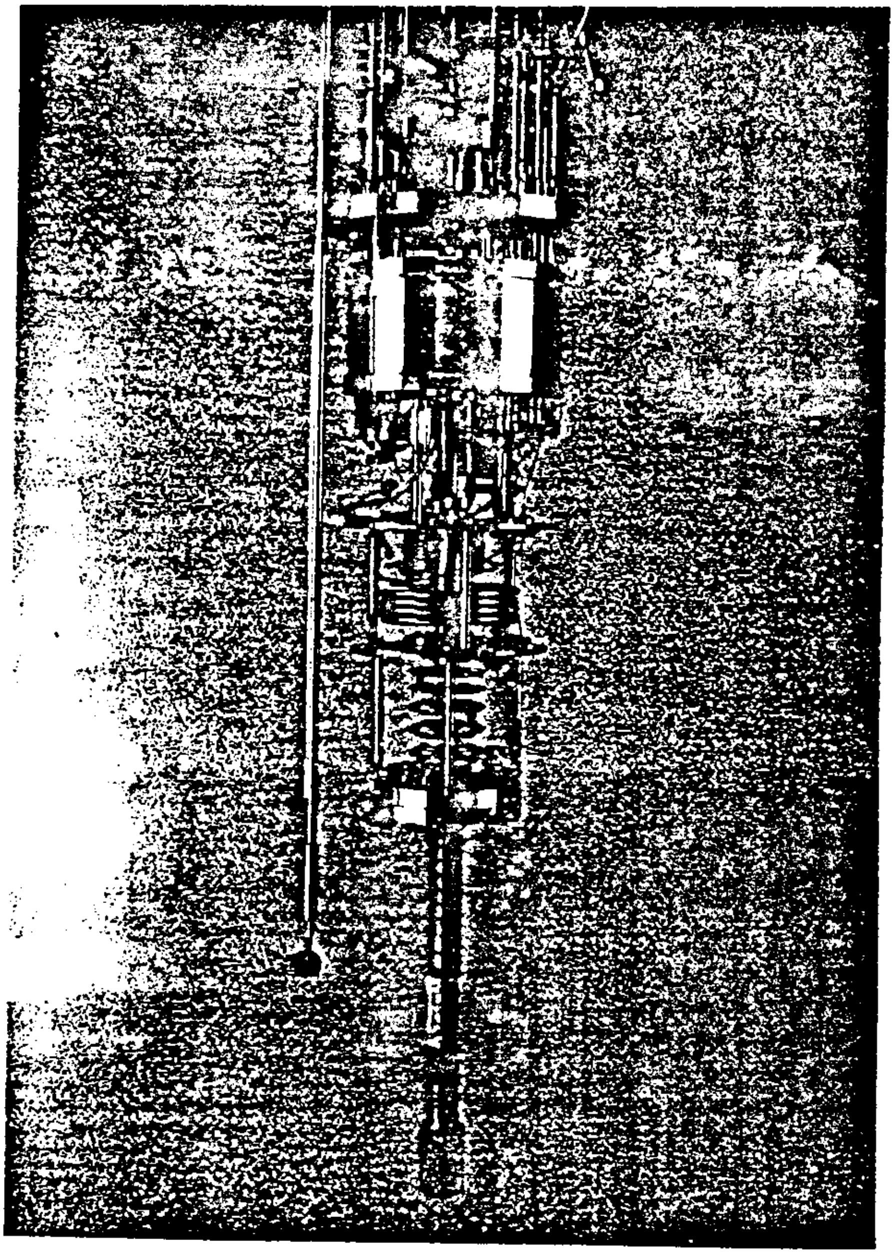
ALPHA SPECTRA WITH 1% RESOLUTION

DETERMINATION OF C_V vs. T

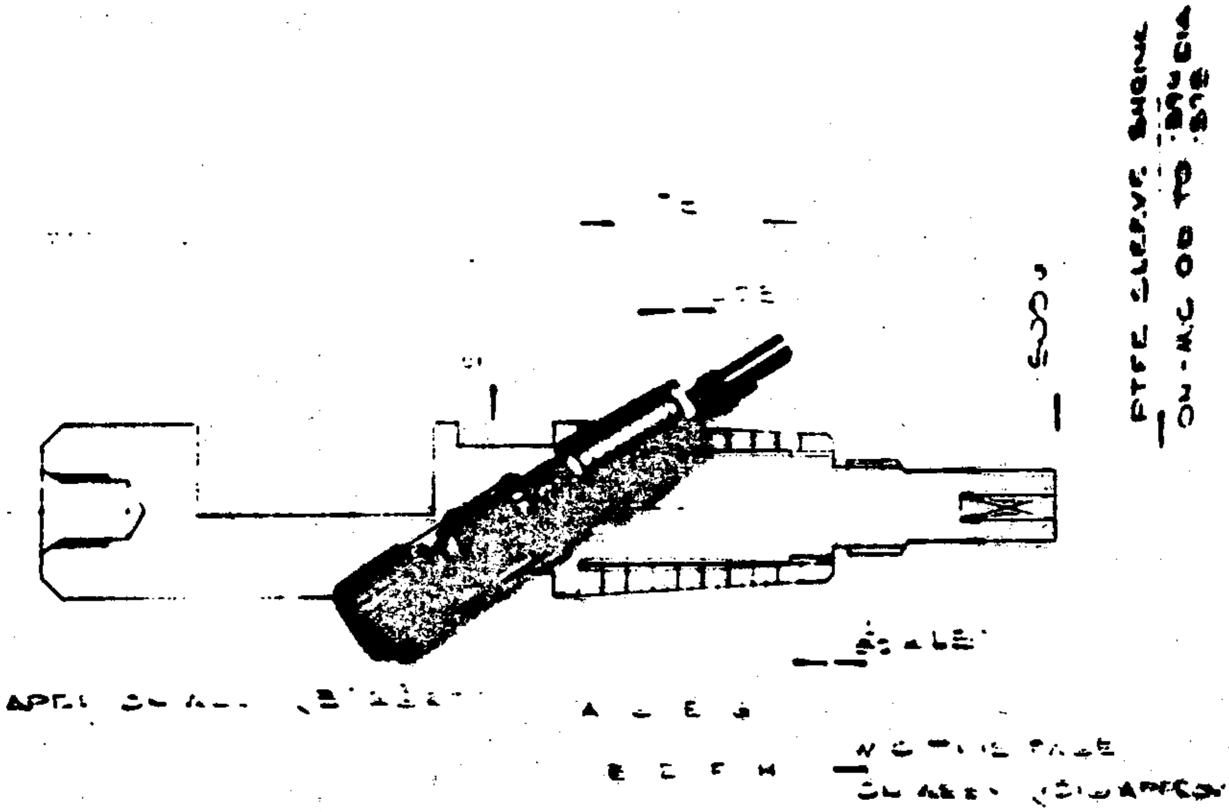
(FOR THE FIRST TIME BELOW 40 mK)

PERCENTAGE OF THERMALIZED ENERGY

~ 70 %



The dilution unit of the model 200 TLE refrigerator showing the components described in the section on top loading with electrical contacts.



The top loading with electrical contacts sample holder showing the space available for the sample and the 8 contactor rings.

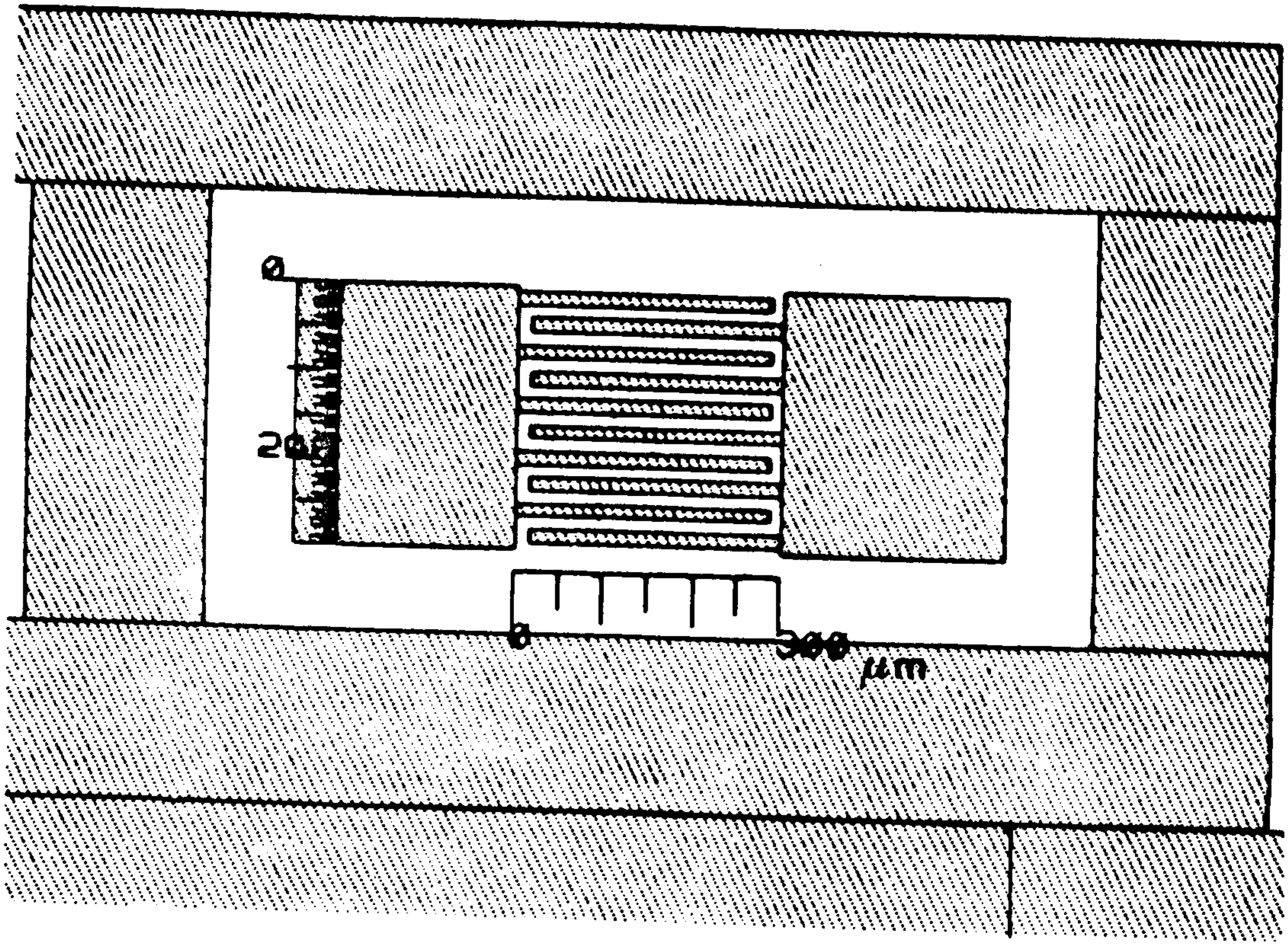
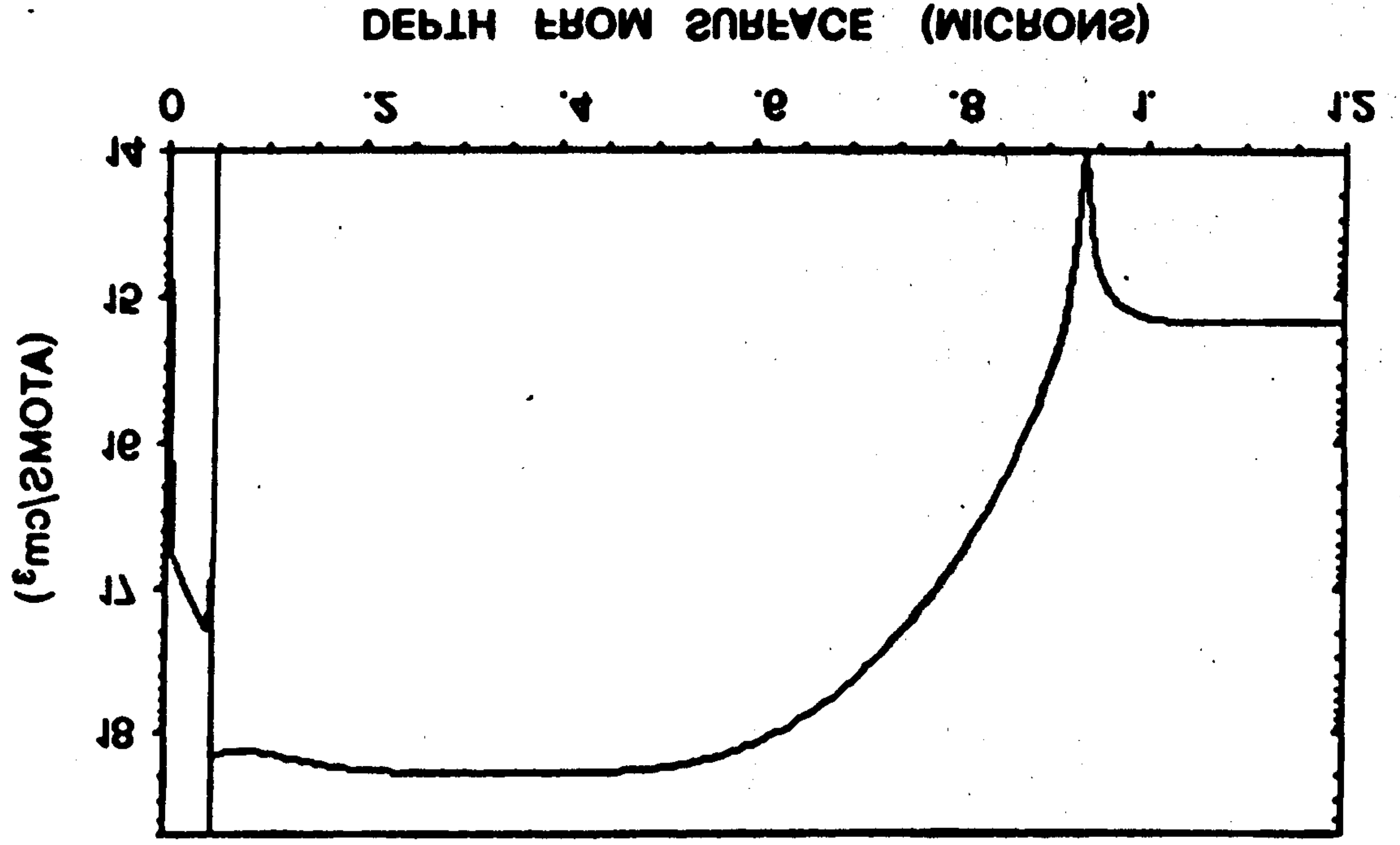


Fig. 2

Fig. 1



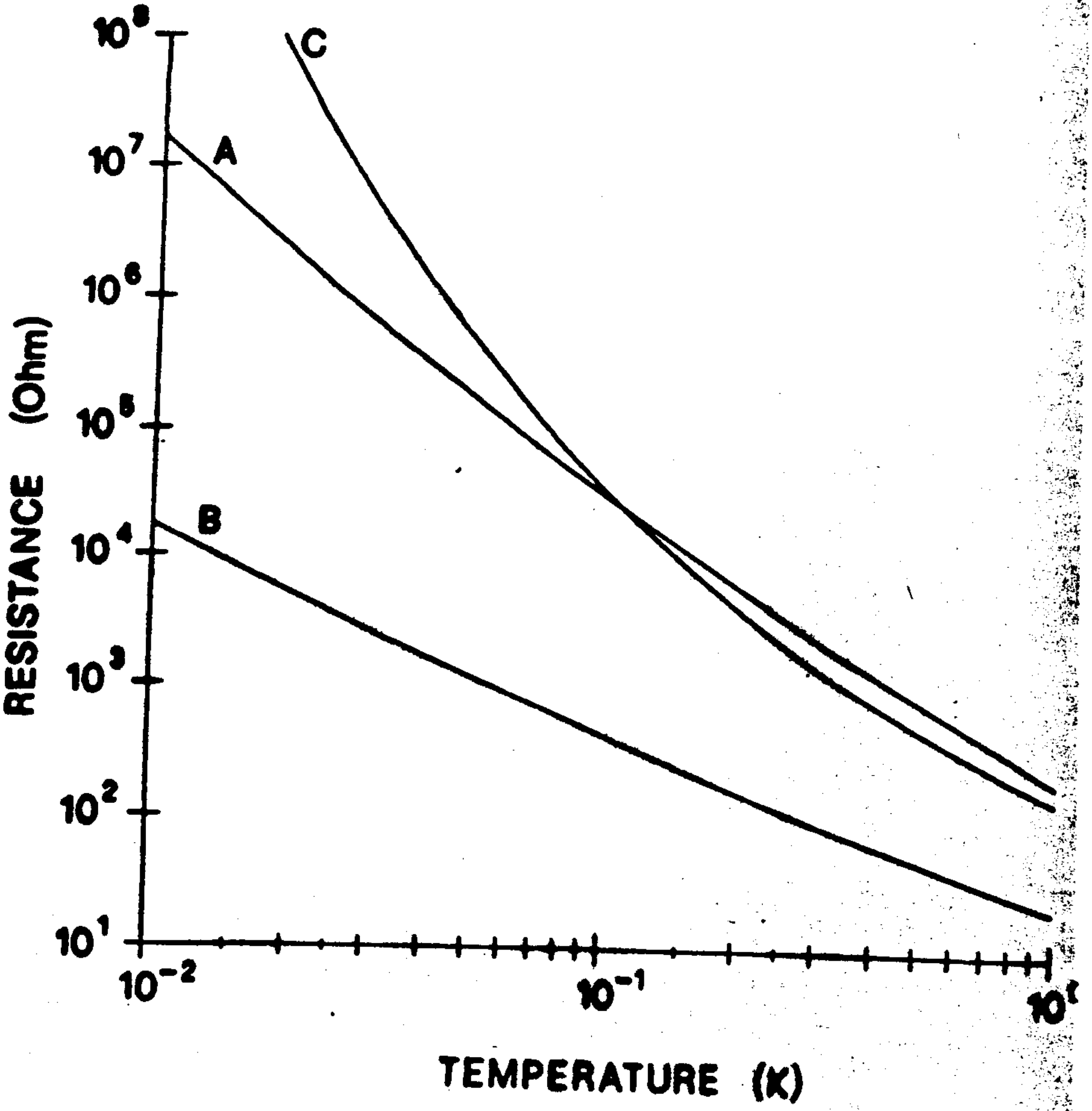


Fig. 3

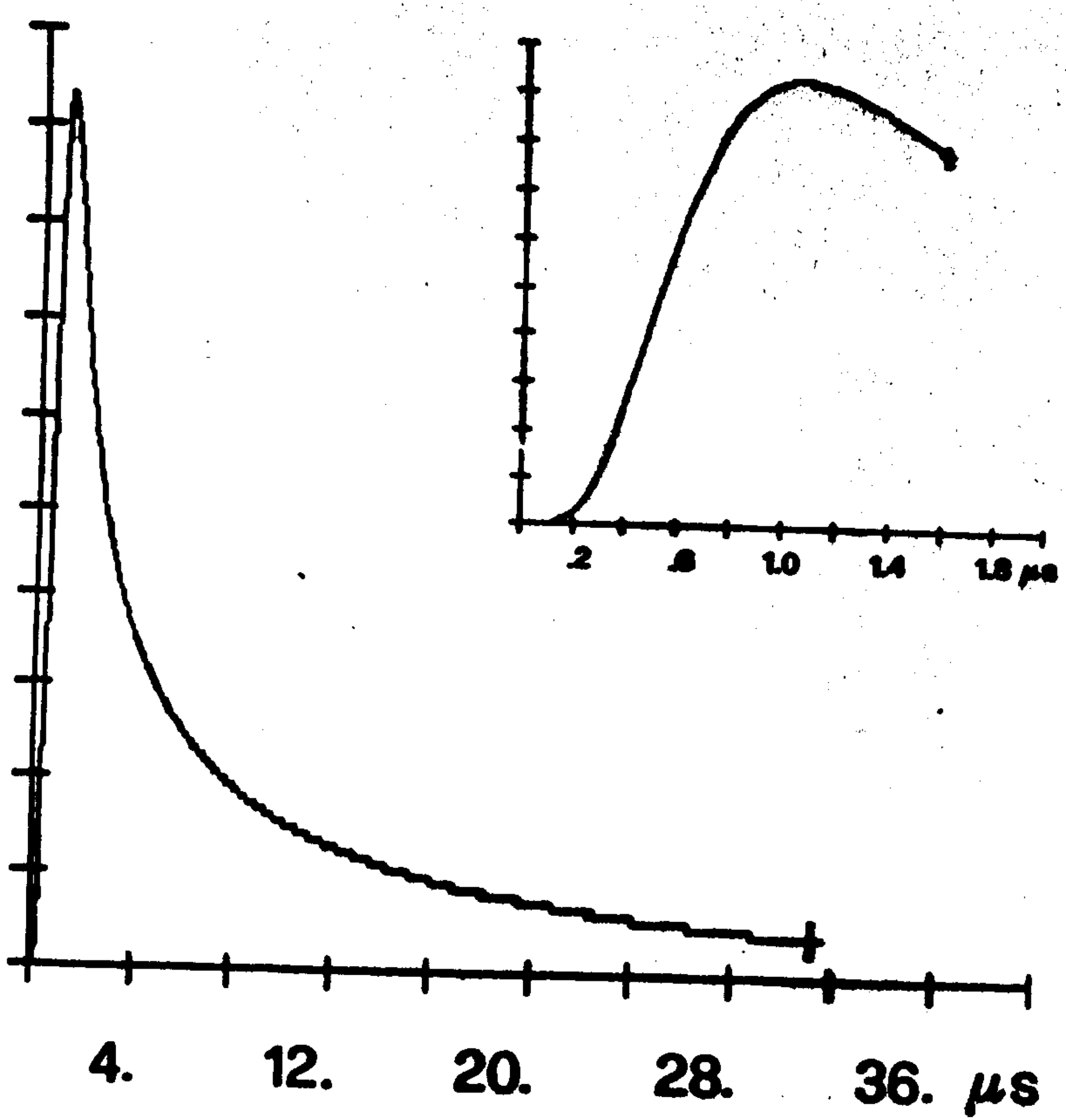


Fig. 1a

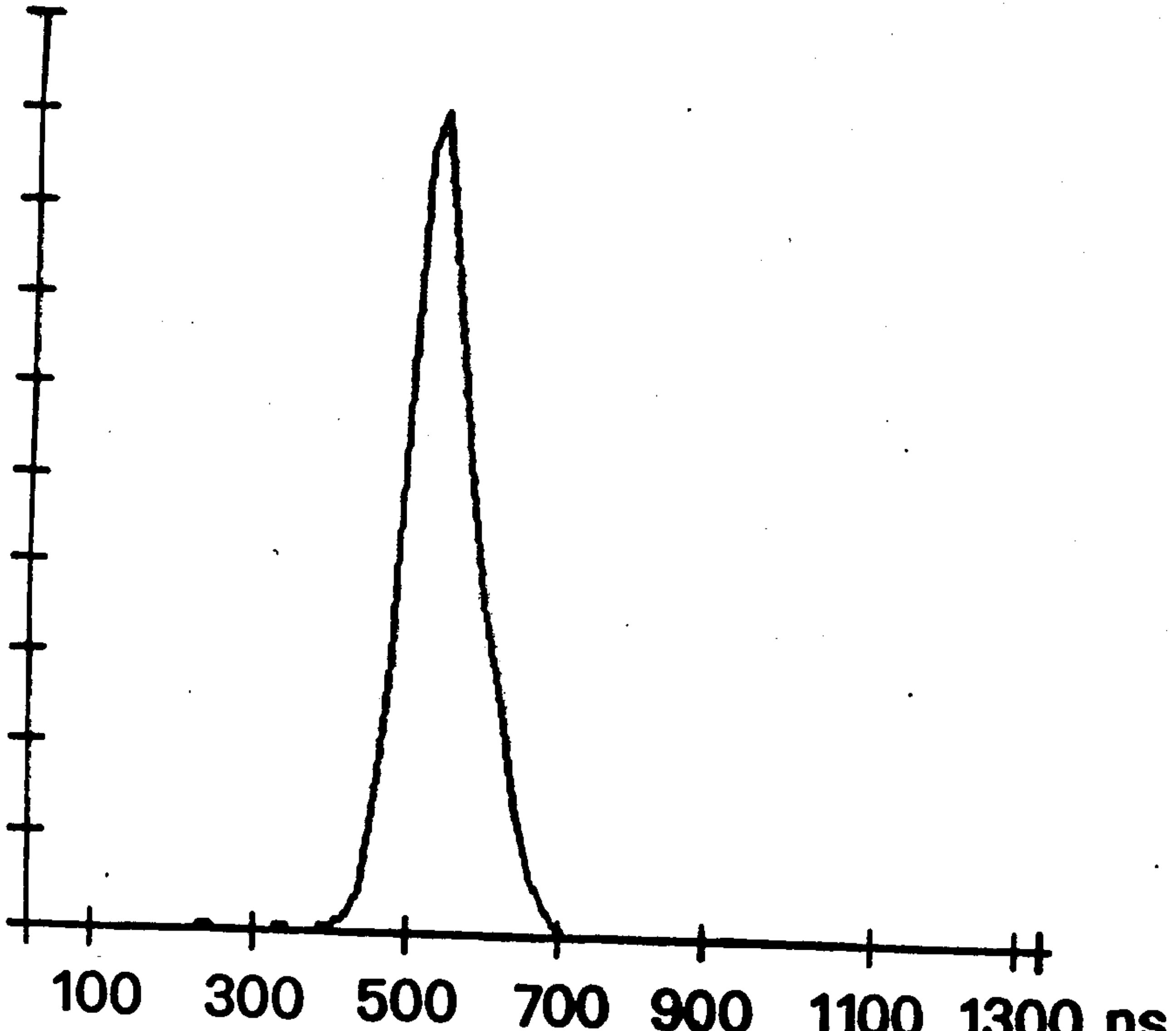


Fig. 1b

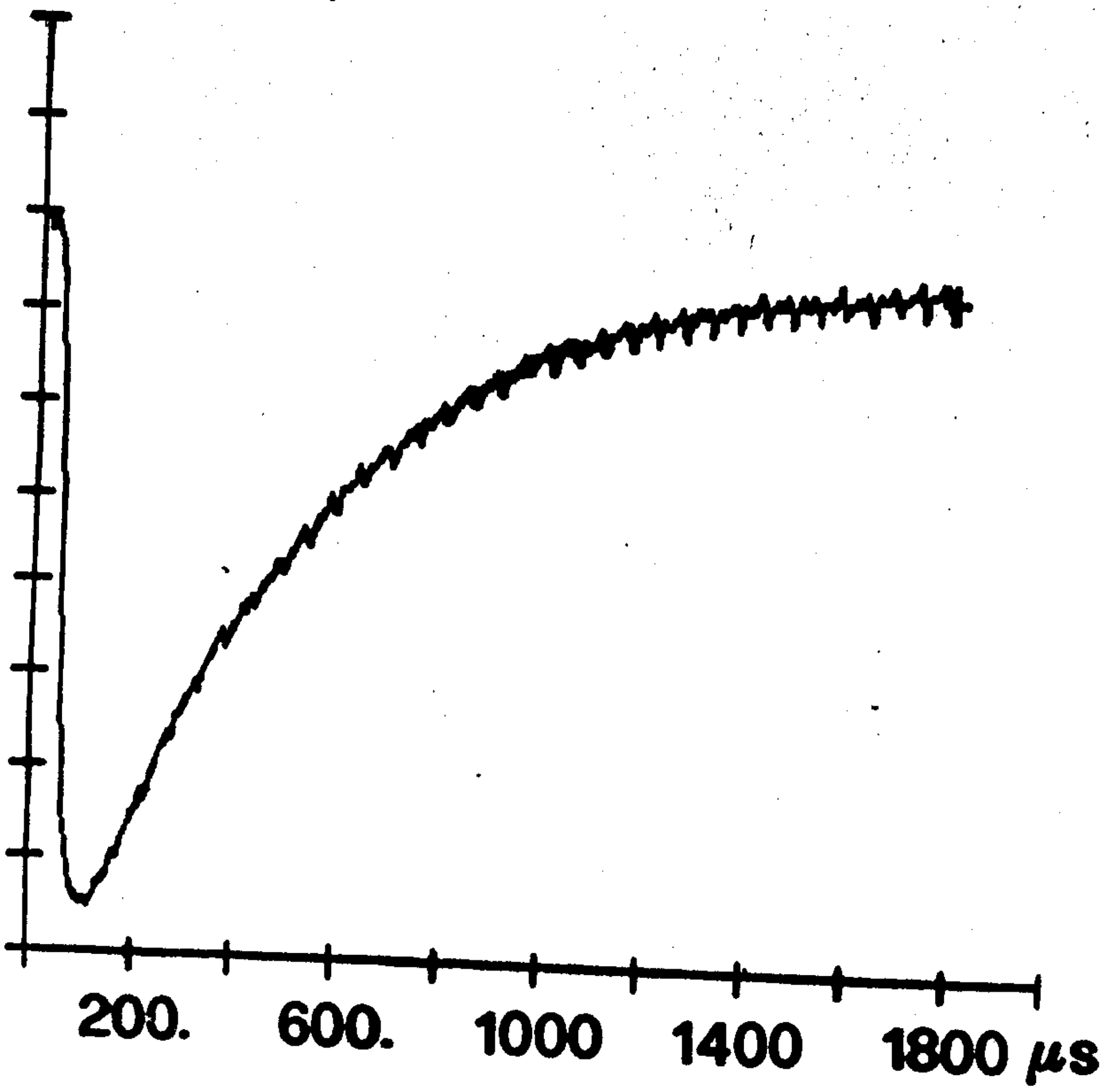


Fig. 3

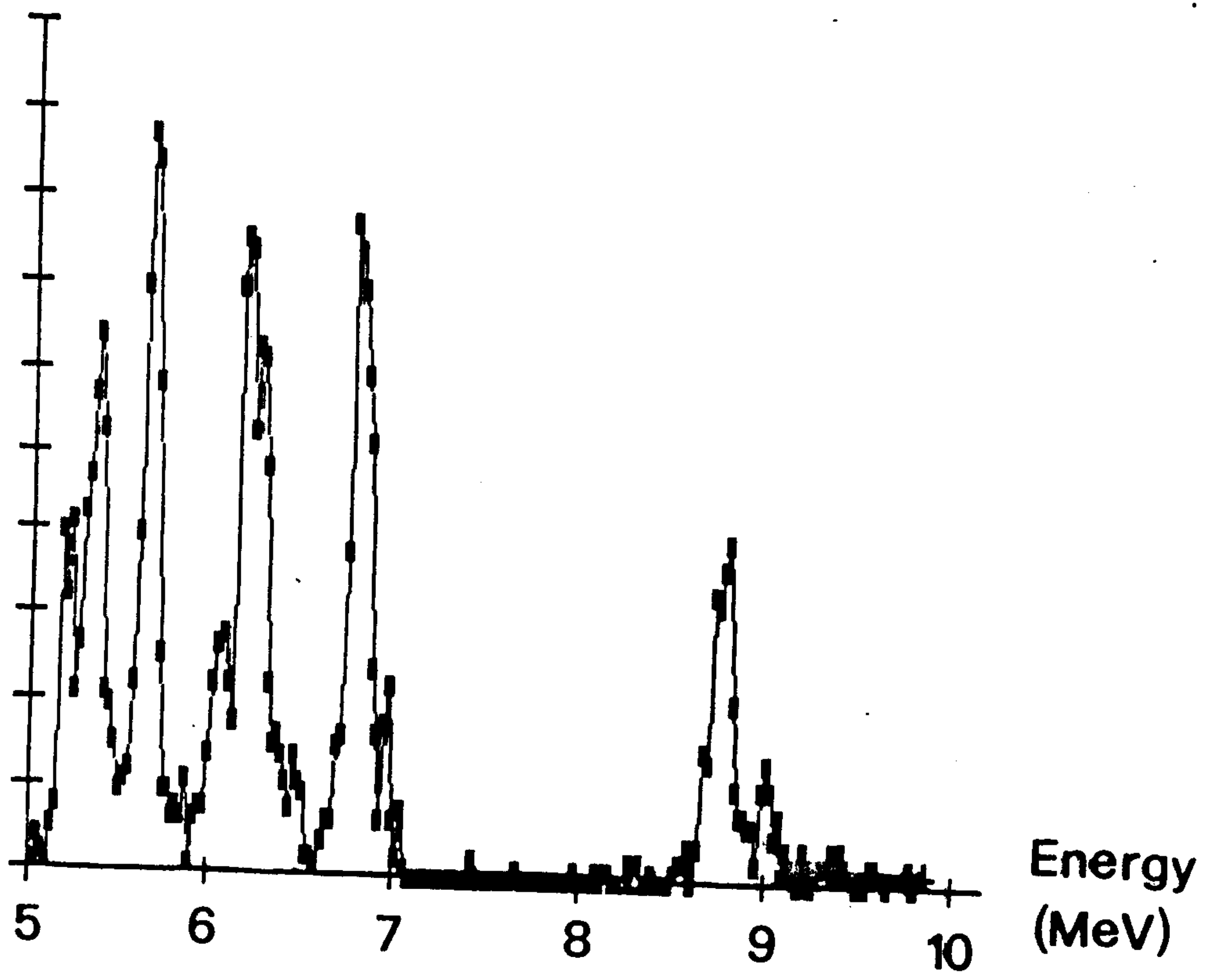


Fig. 2

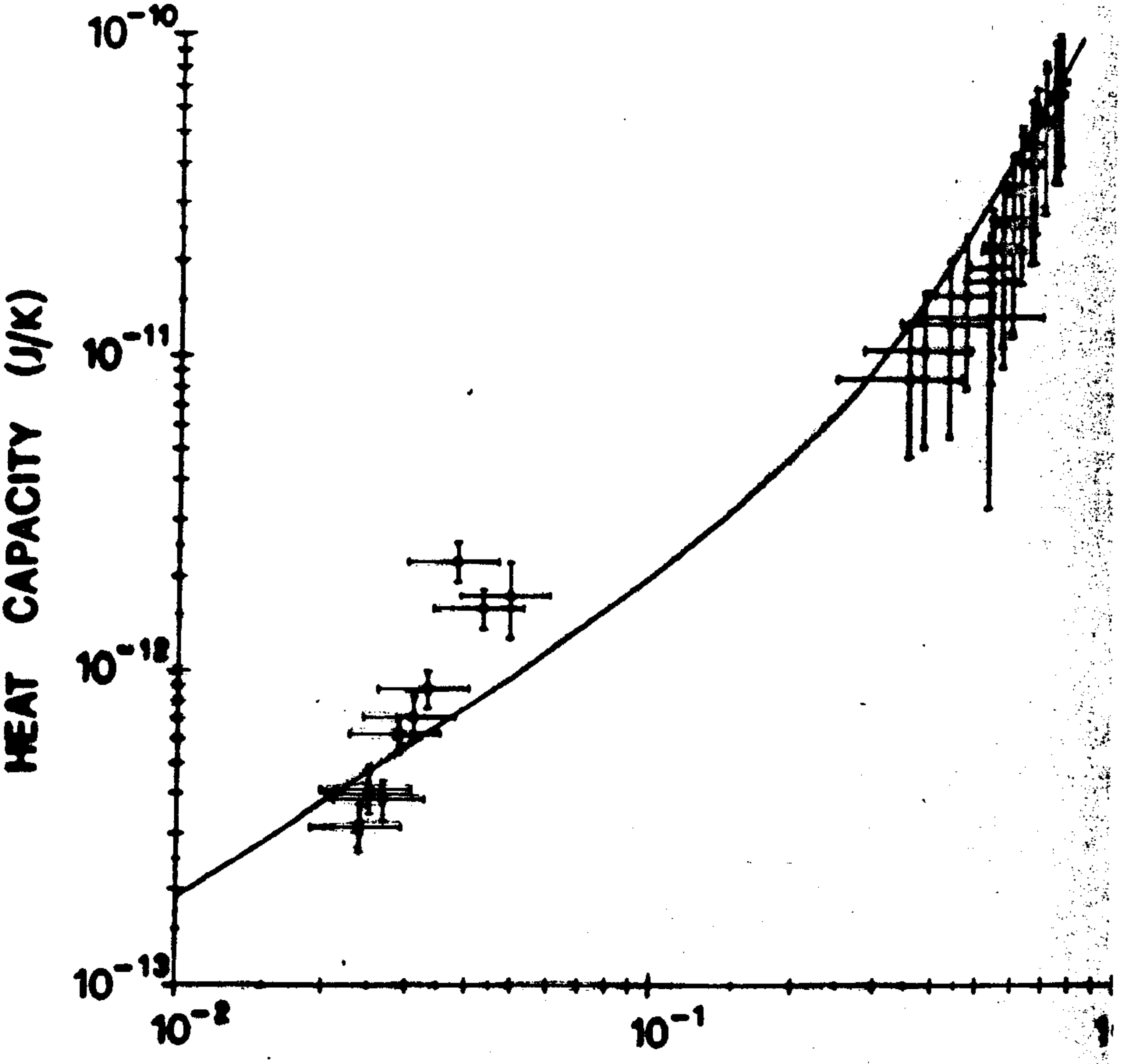


Fig. 4a

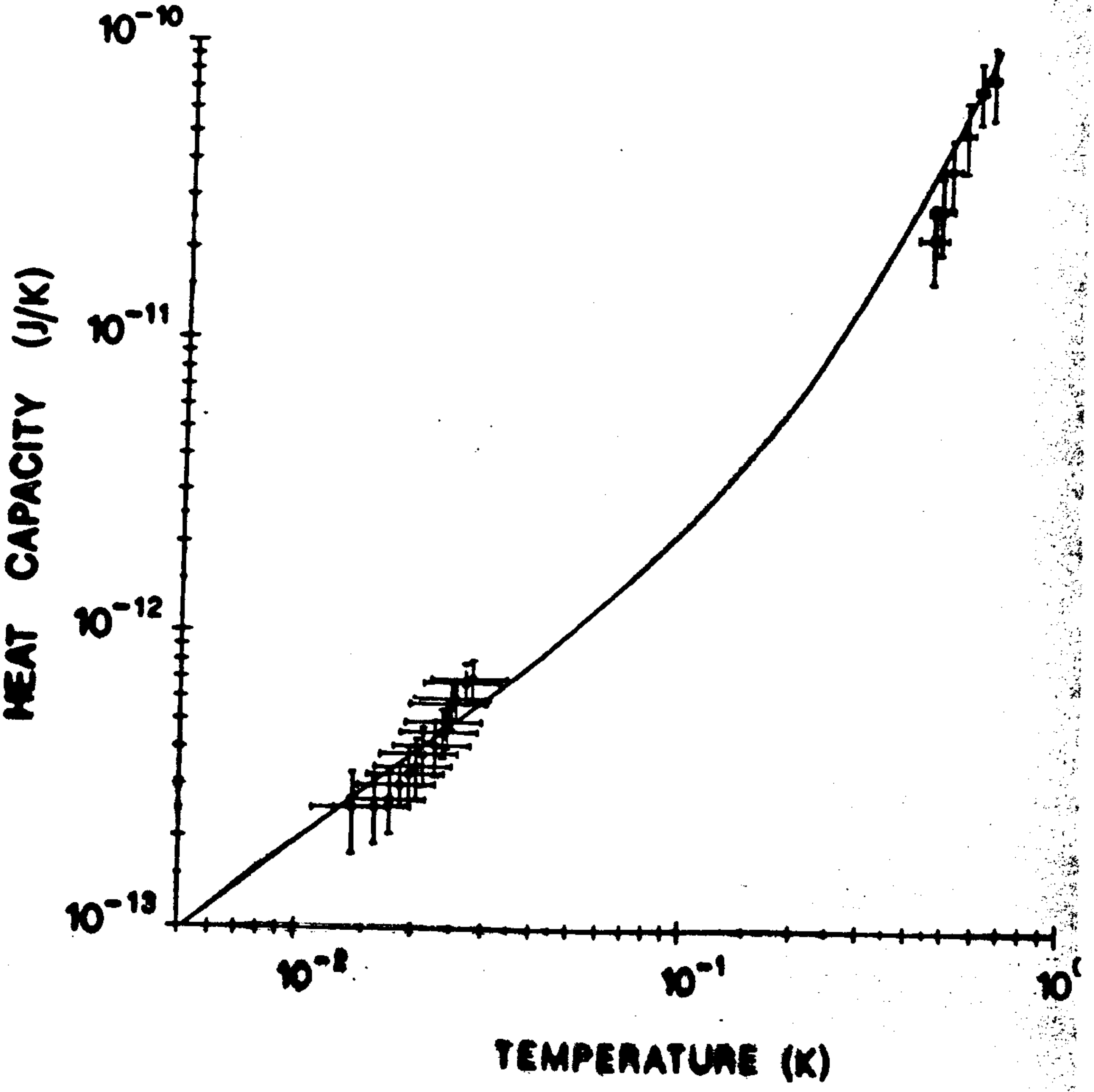

HEAT CAPACITY (J/K)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-2}
10^{-1}
10^{0}
TEMPERATURE (K)

Fig. 4b

(cr)

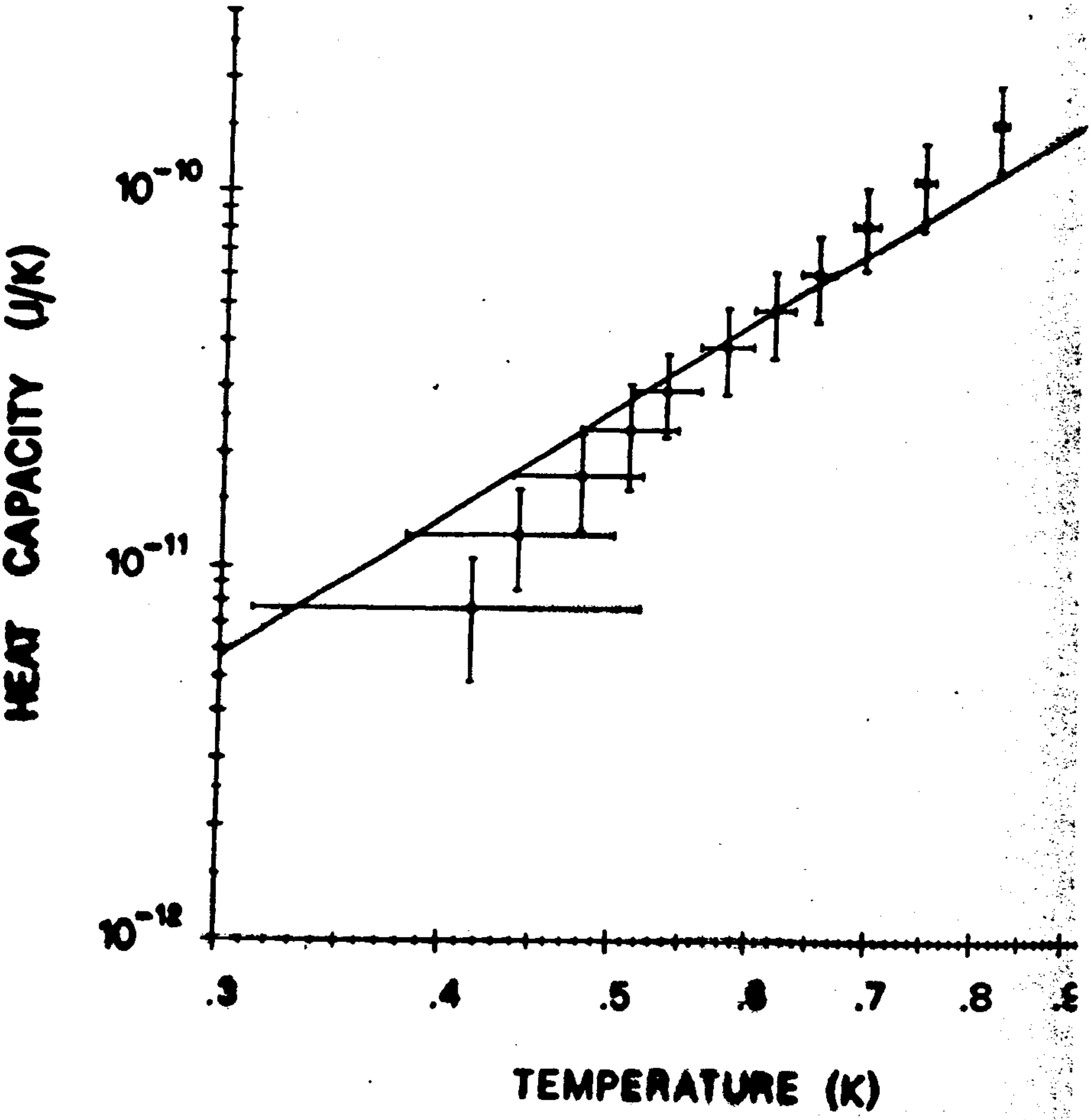


Fig. 4c

LARGE DETECTORS

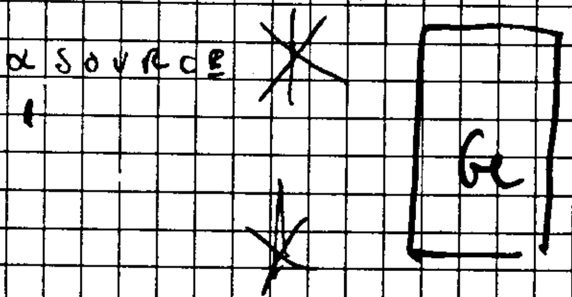
FIRST DETECTORS WERE VERY SMALL ($10^{-3} - 10^{-6}$ g) –

DETECTOR OF Ge OF $11 \times 5 \times 3$ mm^3 = .7 g
WITH A COMMERCIAL (S.I.) Ge thermistor

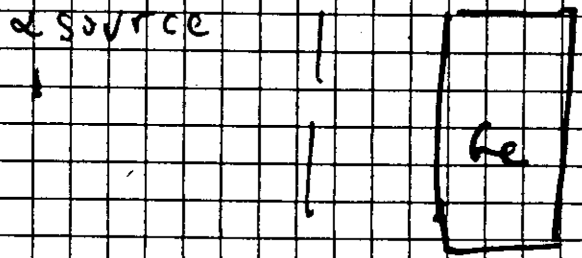
BASE TEMP. 42 mK
BOLOMETER " 71 mK
$R = 1.2\ M\Omega$ $\quad \gamma_1 = \dfrac{d \log R}{d \log T} = 6$

DETECTION OF α-PARTICLES

ON DEC. 22-23, 87 – PRE-IMPLANTED



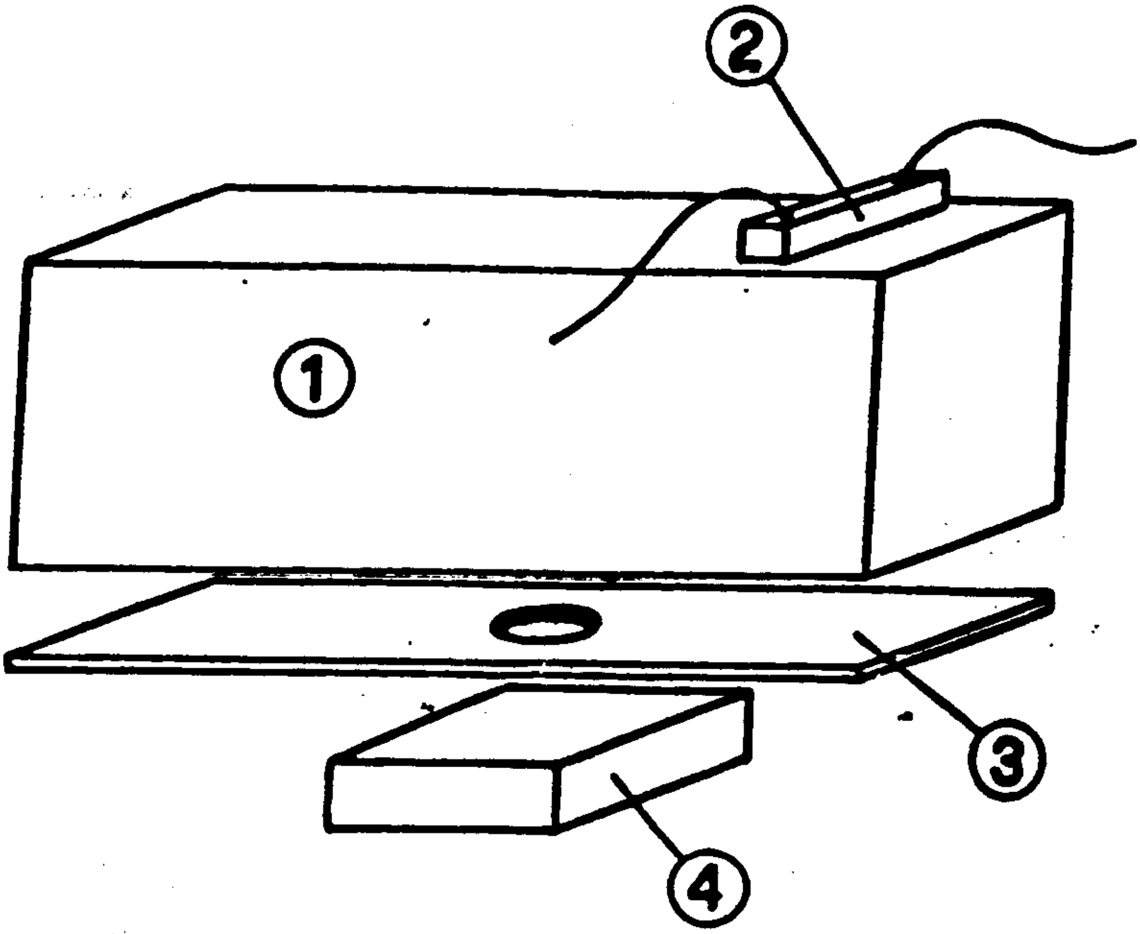
Then exposed



$\alpha \quad + \quad (\alpha + \text{Recoil})$

$T_\alpha \qquad T_\alpha + T_R$

EXPECT DOUBLETS ON EACH PEAK
WITH EXCEPTION OF THE FIRST



1 BOLOMETER
2 THERMISTOR
3 COLLIMATOR
4 α — SOURCE

Fig. 1

RISETIME ~ RC ≈ 300 μs - 6

MEASUREMENT BEFORE AND AFTER

X-mass.

$C_V = 2 \times 10^{-10}$ J/K ($C_{v,l} = .3 \times 10^{-10}$ J/K)

THEORY 1.5×10^{-10} ⇒ THERM. (.80 ± .15)

$$\frac{E_{SATELLITE} - E_{\alpha}}{E_{SATELLITE}} = 2.2 \pm .2\ \%$$

THEORY ~ 1.9 %.

THERM. OF α VS. SATELLITE (.80 ± .15)

A CRYSTAL OF 11 g of ^{76}Ge is presently

COUNTING γ-RAYS

$\boxed{\text{APPLICATIONS}}$

NEUTRINO MASS (ΔE ~ 1 eV)

RARE EVENTS (DETECTORS OF KGRAMS)

DETECTION OF NEUTRINOS

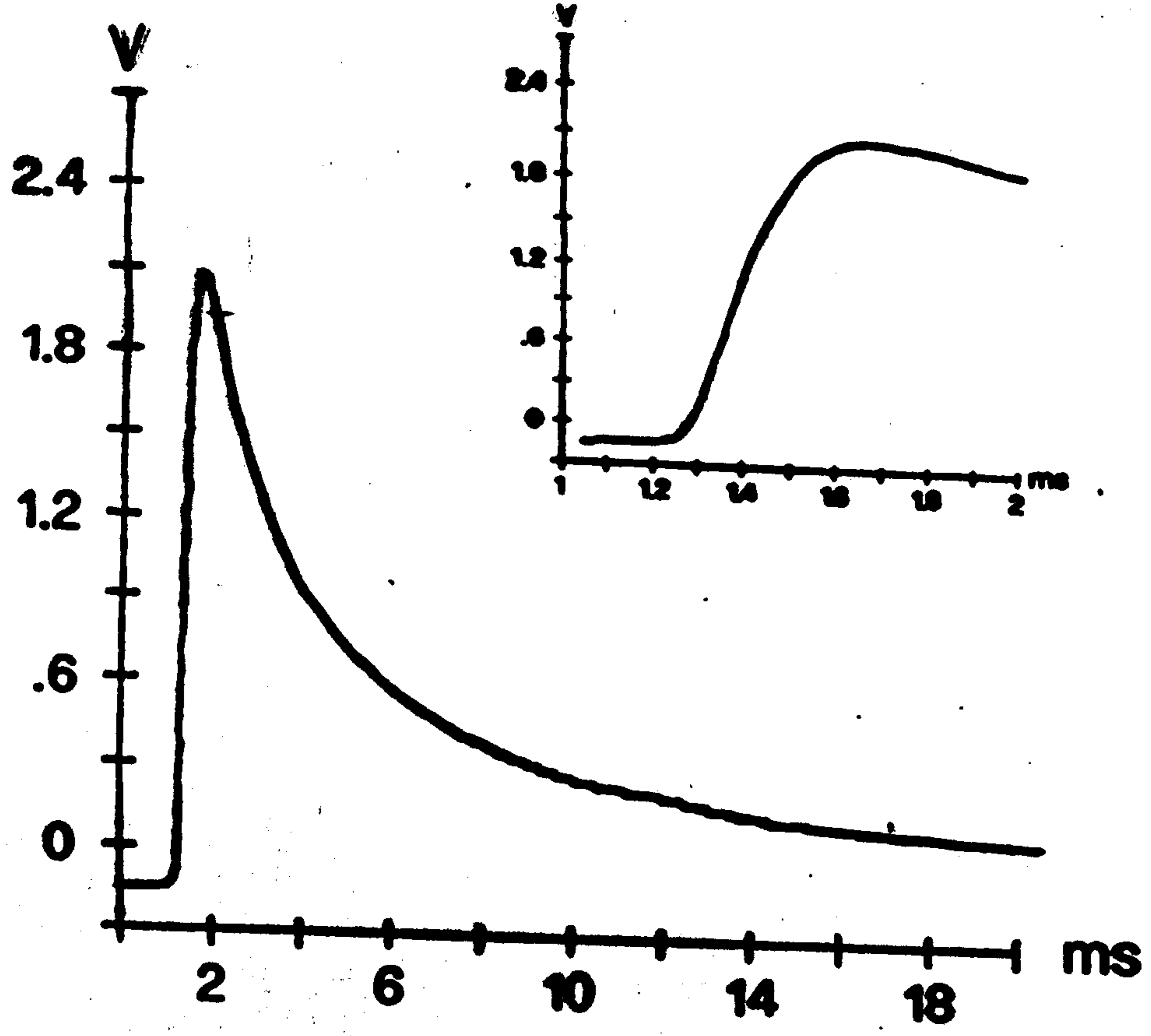


Fig. 2

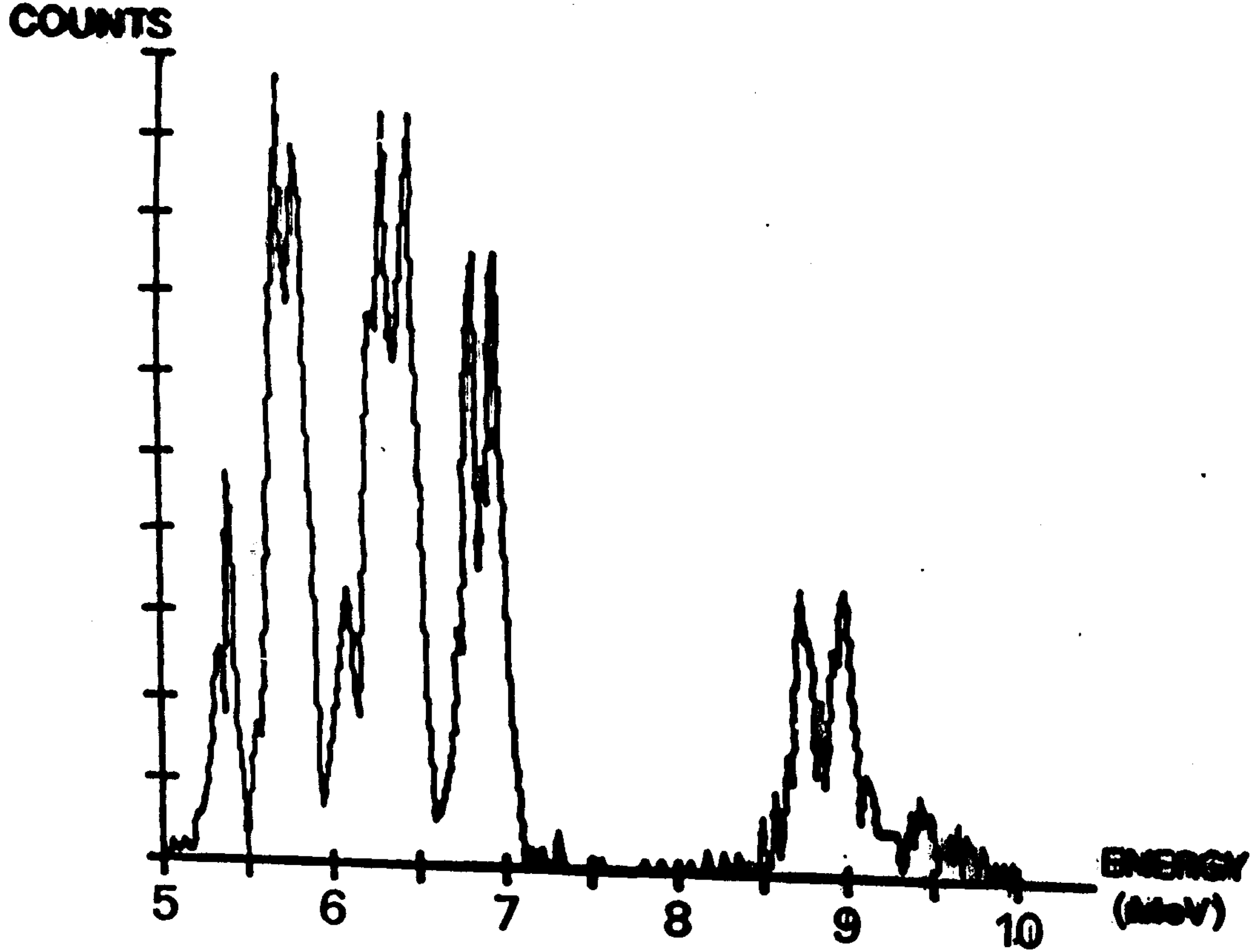
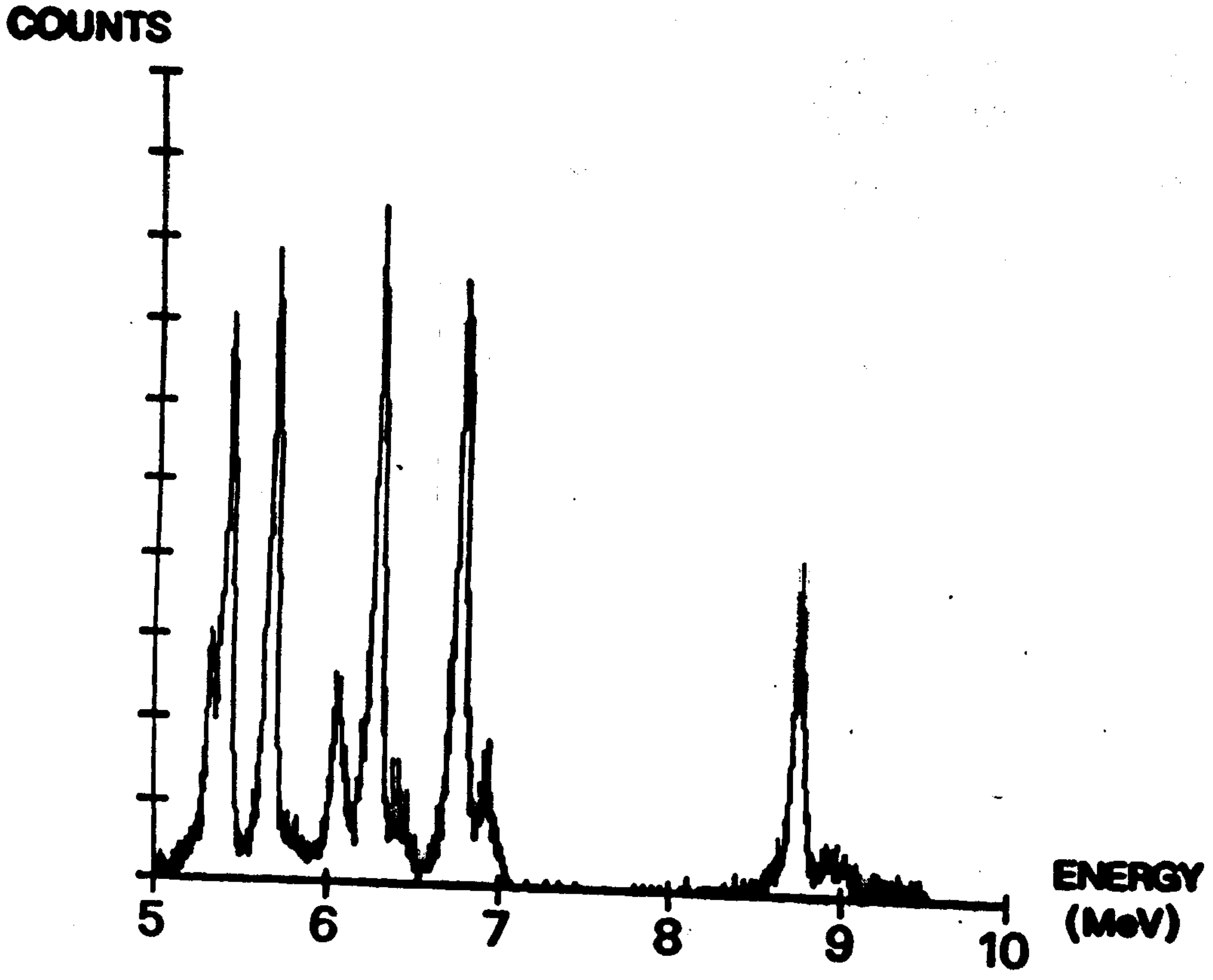
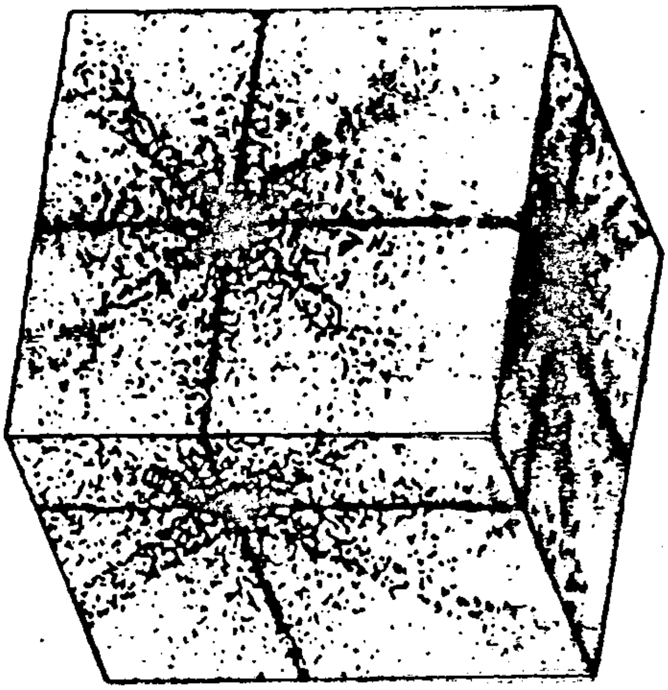
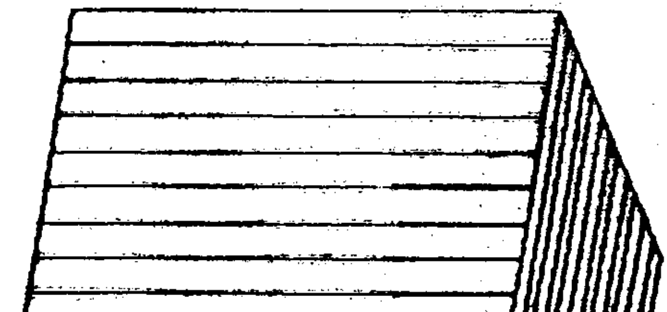


Fig. 3a


COUNTS
5
6
7
8
9
10
ENERGY
(MeV)





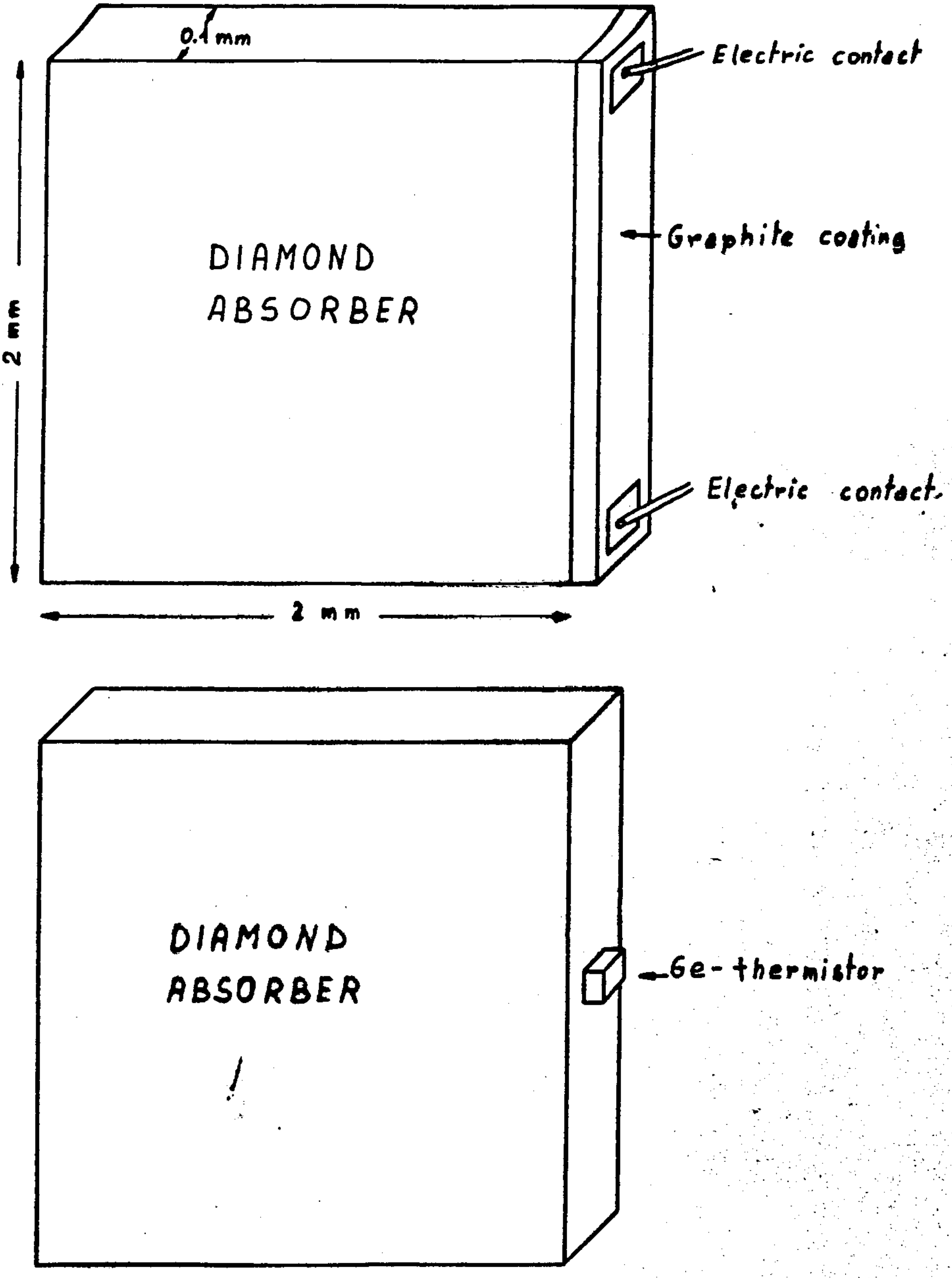

0.1 mm
Electric contact
Graphite coating
DIAMOND
ABSORBER
2 mm
Electric contact.
2 mm
DIAMOND
ABSORBER
Ge-thermistor

Fig.3