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SOME NEW DEVELOPMENTS ON TRANSITION RADIATION DETECTORS FOR HIGH-ENERGY PARTICLES

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1. REVIEW OF SOME PRINCIPAL CHARACTERISTICS OF TRANSITION RADIATION AND IMPORTANT ACHIEVEMENTS IN RECENT INVESTIGATIONS

It would be helpful to review briefly some of the basic characteristics of transition radiation in order to appreciate fully the reasons for its importance in its application to the detection and identification of high-energy particles in the relativistic region. Now let us consider a relativistic charged particle, moving uniformly in vacuum and traversing into a medium of dielectric constant ε (assuming its magnetic permeability $\mu = 1$). Energy is lost by the particle at the interface between the two media (vacuum and the medium with dielectric constant ε) and this energy loss is emitted in the form of electromagnetic radiation known as the transition radiation$^{1)}$. The energy of the transition radiation emitted per unit solid angle and per unit of frequency interval from the interface, at an angle θ from the direction of the traversing particle, is given by

$$\frac{d^2W}{d\Omega d\omega} = \frac{e^2}{\pi^2 c} \frac{\beta^2 \sin^2\theta \cos^2\theta}{(1-\beta^2\cos^2\theta)^2} \left| \frac{(\varepsilon - 1)(1 - \beta^2 \mp \beta\sqrt{\varepsilon - \sin^2\theta})}{(\varepsilon\cos\theta + \sqrt{\varepsilon - \sin^2\theta})(1 + \beta\sqrt{\varepsilon - \sin^2\theta})} \right. , \quad (1)$$

where $\beta = v/c$ is the velocity of the particle and ε is generally a complex quantity given by

$$\varepsilon(\omega) = 1 - \left[\omega_p^2/\omega(\omega + i\delta)\right] ,$$

and where ω_p is the plasma frequency of the medium given by

$$\omega_p^2 = 4\pi N_e^2/m_e$$

and δ is related to the inverse of relaxation time which is quite small ($\hbar\delta \sim 0.2$ eV). For aluminum $(\hbar\omega_p)_{Al} \approx 34$ eV. The + sign refers to the backward emission and the − sign refers to the forward emission.

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The frequency of the transition radiation extends from below the radio frequency region upward through the optical region and to an upper limit given by $\gamma\omega_p$, where γ is the Lorentz factor ($\gamma = 1/\sqrt{1-\beta^2}$). For a particle with $\gamma = 1000$, this upper frequency limit is ∿ 34 keV for aluminum, which is well in the X-ray region.

By integrating Eq. (1) over all angles, assuming $\beta \approx 1$, Garibian obtained very simple expressions of the total energy of the transition radiation emitted from a single interface, a) for the optical region

$$W_{opt} = \frac{2e^2}{c}(\ln 2\gamma - 3/2)\Delta\omega \ , \tag{2}$$

where $\Delta\omega$ is the optical frequency range; and b) for the X-ray frequencies

$$W_{X\text{-ray}} = \frac{2e^2\omega_p}{3c}\gamma \ . \tag{3}$$

In both cases (a) and (b), the total energy of the transition radiation is a function of γ instead of functions of the particle velocity β, as in the case of ionization energy loss or of Čerenkov radiation. Of particular importance in the X-ray region, the total energy of the transition radiation is linearly proportional to γ of the charged particle involved. It is to be remembered, however, that the probability of emitting a single photon from an interface by a charged particle is ∿ 1%, so that a large number of interfaces are needed to obtain a sufficient number of photons for the detection of a single particle. In general practice, a stack of thin foils, spaced short distances apart, are used as radiators.

The angle θ_m at which the maximum intensity of the transition radiation is emitted with reference to the direction of the traversing particle is ∿ $1/\gamma$, and there exists a minimum thickness of the medium (material or vacuum) that the particle must traverse before the transition radiation can be created, all according to predictions from theory. This latter minimum thickness is known as the formation zone Z, and is given, for relativistic particles, by

$$Z = \frac{c}{\omega}\,\frac{1}{(1/\gamma)^2 + \frac{1}{2}(\omega_p/\omega)^2} \ . \tag{4}$$

This is essentially the distance in which the particle field and the photon field interact coherently.

In a recent visit to Erevan, I was happy to hear from Prof. Garibian that he and his colleagues have worked out the formula for the X-ray transition radiation produced in an irregular stack of plates, which has taken into account the self-absorption and is presented in a form convenient for numerical calculation[2).

Now I shall list some of the major experimental achievements accomplished during the past few years, which are of considerable significance in the understanding of the basic nature of transition radiation and in the application of such radiation to the detection and identification of charged particles in the relativistic region. These are as follows:

i) Establishment of feasibility of measuring transition radiation from a single charged particle both in the optical and in the X-ray region by using multilayered radiators with regular or irregular spacings.

ii) Verification of the logarithm dependence of the optical transition radiation intensity on γ of the charged particle.

iii) Verification of the linear dependence characteristic of the X-ray transition radiation intensity on γ.

iv) Verification of the $\theta_m \approx 1/\gamma$ relationship both in the X-ray and in the optical region of the transition radiation.

v) Measurement of the transition radiation energy spectra for different γ's in the X-ray region is in reasonably good agreement with theoretical predictions. This holds true for both regularly and irregularly spaced radiators.

vi) Verification of the formation zone effect in the transition radiation intensity both in the X-ray and in the optical region for air and for material media.

vii) Verification of the total transition radiation intensity emitted as predicted by theory in both the X-ray and optical region.

viii) Essential elimination of the Landau tail of the ionization loss spectrum by means of a simple computer device.

2. PRESENT OBJECTIVES IN THE APPLICATION OF TRANSITION RADIATION DETECTORS

As the investigations in particle physics and cosmic rays go into higher and higher energies, the identification and discrimination of the particles involved become more and more difficult with conventional detector systems, whose resolving power is a function of the velocity β of the particle and thus goes down with the particle energy, whereas the resolving power of a transition radiation detector increases with γ, i.e. with the energy of the particle. In many experiments now existing in high-energy accelerators and in cosmic rays, one often finds the need to separate high-energy electrons from pions, protons from pions and muons, etc. It is with applications such as these that we try 1) to devise a practical transition radiation detector system with present techniques, and 2) to further investigate new approaches to such methods.

2.1 Investigations with present techniques

2.1.1 To measure the total X-ray transition radiation without the presence of the charged particle

In this case a stack of 1000-2000 thin foils of light material are used as radiators, together with a magnet to deflect away the charged particle from entering the X-ray detector. A series of such detector systems (1-5) can be easily realized in the beam transport system of a high-energy accelerator. Good accuracy on γ of a charged particle can be expected from such measurements. The energy spectrum of 10 GeV electrons measured with a Ge(Li) detector in a single stack system is shown in Fig. 1.

2.1.2 To measure the X-ray transition radiation with the presence of the associated charged particle

When studying high-energy reactions or cosmic rays, particles under investigation can enter the detector system from any direction; thus the detector system employing a magnet as described in Section 2.1.1 above is no longer applicable. We are obliged to resort to a detector system which should be able to measure the ionization loss of the charged particle as well as the associated transition radiation in comparable magnitudes. A workable "sandwich" system transition radiation detector was devised in our laboratory some ten years ago as a compromise measure. Today, such a system still seems to be the generally accepted practical method. The system consists of a successive series of stacks of radiators interposed with thin X-ray detectors such as multiwire proportional chambers. The number of radiator foils in each sandwich stack should be such that a detectable low-energy photon emitted from the first foil should be able to traverse the rest of the foils in this stack without being absorbed, and reach the detector. The thickness of each detector (multiwire proportional chamber) should be thin enough to give an ionization loss signal comparable to that given by transition radiation photons. Optimization of such a system for specific applications has been extensively studied$^{3)}$ by varying the factors such as the radiator material and thickness, the foil spacing, the number of foils, the thickness and gas mixture in the wire chambers, and the number of sandwich stacks, etc.

Some of the earlier results showing the separation of electrons and pions at 2 GeV/c with a 10-chamber sandwich (argon-methane MWPC) and the effect of transition radiation caused by 10 GeV electrons in comparison with the ionization loss in a 20-chamber sandwich system, are shown in Figs. 2 and 3. The latter result made use of the geometrical mean computing device to eliminate the Landau tail effect. A brief description of the computing device is shown in Fig. 4.

2.1.3 Transition radiation from lithium radiators[4)]

The yield of transition radiation is expected to be higher from radiators of material having a low Z, owing to the low self-absorption in the radiator material. Yields of transition radiation from lithium foils have been measured using MWPC as well as using a thin NaI 0.5 mm thick detector with electrons of a momentum from 0.5 to 3.5 GeV/c, i.e. a γ value of from 1000 to 7000. The radiators*) used consisted of 1000 foils of 50 μ thick lithium foils spaced at 0.5 mm. These measurements were carried out by our group at the Brookhaven AGS. Members of our group are: P. Alley, F. Dell, H. Uto, and L.C.L. Yuan.

The results obtained using the NaI detector are shown in Figs. 5a and 5b. Figure 5a shows the energy spectra of the transition radiation from lithium, mylar, and background radiators, respectively. In Fig. 5b, the average detected energy including background is plotted as a function of electron energy. The NaI detects 80 keV of transition radiation at 2 GeV/c. However, the ionization loss is ∿ 250 keV. A thinner NaI detector of ∿ 75 μ thick would yield a much better signal-to-background ratio.

In Fig. 6 the average detected energy of transition radiation as a function of electron energy is shown. Figure 6a gives the observed values of transition radiation detected by three different MWPC (1.3, 2.1, and 4.2 cm) filled with 90% argon and 10% methane. There is good energy dependence. In Fig. 6b, calculated values using a theory are shown. The experimental values are lower, probably because 1) experimental results are usually ∿ 70% of theoretical predictions, and 2) there is a deterioration of the lithium radiators (transmission of 6 keV X-rays decreased noticeably with time).

Figures 7a and 7b show the pion-electron separation effected by a lithium radiators/argon chamber and a lithium radiators/xenon (35% Xe, 55% He, 10% methane) chamber, respectively. A good pion to electron rejection ratio is clearly evident.

2.1.4 Experimental studies of the separation of protons and pions in the 100 GeV to 250 GeV region[5)]

These experiments were carried out by our group at Brookhaven at the Fermi National Accelerator Laboratory in Batavia, Illinois. One of our objectives was to study the separation of the hadrons and letpons with a varied number of radiator-MWPC elements (from one up to 30 elements), so as to obtain the optimum design of a practical transition radiation detector.

The experiments are still in progress and only some initial results are shown (Figs. 8-10). It can be seen that the separation of pions from protons increases

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*) The lithium radiators were loaned to us by Drs. W. Willis and V. Radica.

with energy, and that at 250 GeV/c, pions and protons can be completely separated even with argon MWPC. The MWPC filled with xenon or a xenon mixture would give far better separation than that indicated by the present results.

2.1.5 Cosmic-ray experiments in progress using transition radiation detectors

A 15-element radiator-MWPC sandwich detector system is being set up at Mt. Climax, in collaboration with the Louisiana State University group and using their energy spectrometer. A 3-element radiator-MWPC sandwich detector system has been set up at Mt. Aragats in Armenia by the Erevan Physics Institute group. A brief discussion of their preliminary results will be presented.

2.2 Investigation of novel methods of transition radiation detection

2.2.1 Utilization of superheated superconducting grains for the detection of transition radiation

In the present methods of transition radiation detection, there exist two major effects which limit detection efficiency. These are:

i) the self-absorption of the radiator foils, which absorb most of the low energy transition radiation photons;

ii) the thin chambers used to maximize transition radiation/(dE/dx) do not detect all X-rays.

The method of transition radiation detection$^{6)}$ described below is a very novel one in which the radiators serve also as detectors with 100% efficiency for detecting the more abundantly produced low-energy X-ray photons.

Certain Type I superconducting materials such as indium and mercury, when broken up into small granules of a few to 100 microns in size, can remain in a superconducting state even when brought above the critical temperature and field. This state is called the superheated superconducting state, and remains stable (but actually in a metastable state) until some external energy perturbation causes it to become normal. The Orsay group$^{6)}$ has succeeded in making a colloid containing such metallic granules embedded in a medium of polyethylene. Since the granules and the surrounding medium have different dielectric constants, a high-energy charged particle traversing through the interface between the polyethylene medium and the metal grain would emit transition radiation X-rays which are immediately absorbed by the high-density granules. The absorbed energy could be sufficient to change the superheated superconducting state of these granules to the normal state. Since the energy spectrum of the transition radiation X-rays as well as the probability of photon emission is a function of the γ of the charged particle in question, the number of granules in the path of the particle that would be converted from the superheated superconducting state to the normal state would also be a function*) of γ. Thus it would only be necessary to measure the number of granules Δn, changing state in order to determine the γ of the particle. The Δn can be determined a) by measuring the change in the resonance frequency of an LC circuit, L being the inductance of a pick-up coil surrounding the colloid; or b) by measuring the $d\phi/dt$ caused by the "Meissner" effect, i.e. the exclusion of the magnetic field from the superconducting granules. The frequency of the LC circuit is higher when the granules are in the superconducting state than in the normal state, also because of the "Meissner" effect.

A collaboration has been effected between our group at Brookhaven and a solid-state group at Orsay to investigate jointly the practical application of this novel method for the detection and the measurement of γ of high-energy particles.

Some preliminary tests have been made at Orsay and the results are very encouraging. Figure 11 shows the resonance frequency of an LC circuit of the pick-up coil surrounding an indium granule/polyethylene colloid as a function of a magnetic field (measured in terms of the current in amperes in the coil of a solenoid) which envelopes the colloid sample. One can see that the loop, similar to that of a hysteresis loop, signifies the superheated superconducting state on the upper portion and the supercooled normal state on the lower portion. In Fig. 12 the solid lines show the resonance frequencies of the LC circuit as a function of time for different states of superheated superconductivity and of supercooled normal conductivity. The resonance frequencies are in the region of 9.8 MHz, whereas the frequency measuring device is able to detect a frequency change of a few cycles/second (Hz). It is seen that both the superheated and the supercooled states remain extremely stable as a function of time. However, when an X-ray source (^{198}Ir) was brought near the colloid sample to simulate the transition radiation X-rays, the resonance frequency dropped very sharply in time, as shown by the dotted lines. These results serve to demonstrate the potential feasibility of such a method for the detection of transition radiation produced by a charged particle. Furthermore, a colloid sample containing a single granule of mercury has been tested recently at Orsay and at CERN with a special low-noise amplifier, and the flipping of a single granule from its superheated superconducting state gave a highly detectable signal.

Preparations are being made jointly with the Orsay group to make direct tests with high-energy electrons (γ values from 1000 to 10,000) at the electron synchrotron DESY, Germany.

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*) In a discussion with Prof. Garibian of the Erevan Institute of Physics, he pointed out that for $\gamma > \omega r/c$, where r is the radius of the granule, this condition may no longer hold true.

2.2.2 Investigation on the use of thin scintillation foils as both radiators and detectors

As stated above, an ideal transition radiation detector would consist of a system in which each radiator serves both as radiator and detector. The radiator-detector foils must be efficient in detecting X-rays and yet must be thin enough to yield comparatively low ionization signals from the primary particle. We had used earlier a thin (500 micron) NaI crystal detector, the thinnest available at the time, but it is too thick for this purpose. Recently, the Space Physics group, headed by Mme Lily Koch, at the Centre d'Etudes Nucléaires de Saclay, has succeeded in fabricating extremely thin plastic scintillator foils of 1 μ thick. In a collaborative effort, they made for us a sample stack of 10 such foils, each 1 μ thick, and spaced at 0.9 mm. We made a preliminary test in the 50 GeV pion beam at the Fermi National Accelerator Laboratory at Batavia and found that good detectable signals were obtainable from the ionization loss of the primary particles. Investigation is still continuing.

REFERENCES

1) For detailed references, refer to Luke C.L. Yuan, Recent progress in transition radiation detector techniques, Invited talk presented at the Int. Conf. on Instrumentation for High-Energy Physics, Frascati, 1973 (Lab. Naz. CNEN, Frascati, 1973), p. 334.

2) G.M. Garibian, L.A. Gevorgian and C. Yang, The calculation of X-ray transition radiation generated in regular and irregular layered media, submitted to Nuclear Physics.

3) Some of the earlier studies were contained in Ref. 1. Some more recent investigations by our group are in the process of being published, and those by Lorikian et al. are published in the internal reports of the Erevan Institute of Physics.

4) Luke C.L. Yuan, P.W. Alley, A. Bamberger, G.F. Dell and H. Uto, Transition radiation from lithium foils, being prepared for publication.

5) P.W. Alley, G.F. Dell, H. Uto and Luke C.L. Yuan, Observation of transition radiation from pions at 100-250 GeV, being prepared for publication.

6) First suggested to us by A.K. Drukier, C. Vallette and G. Waysand of the Dép. Physique des Solides, Faculté des Sciences d'Orsay, who are now collaborating with us in these investigations.
Refer also to the same authors' contributed paper: Development of particle detectors using superheated superconducting colloids, Proc. Int. Conf. on Instrumentation for High-Energy Physics, Frascati, 1973 (Lab. Naz. CNEN, Frascati, 1973), p. 441.

Fig. 1

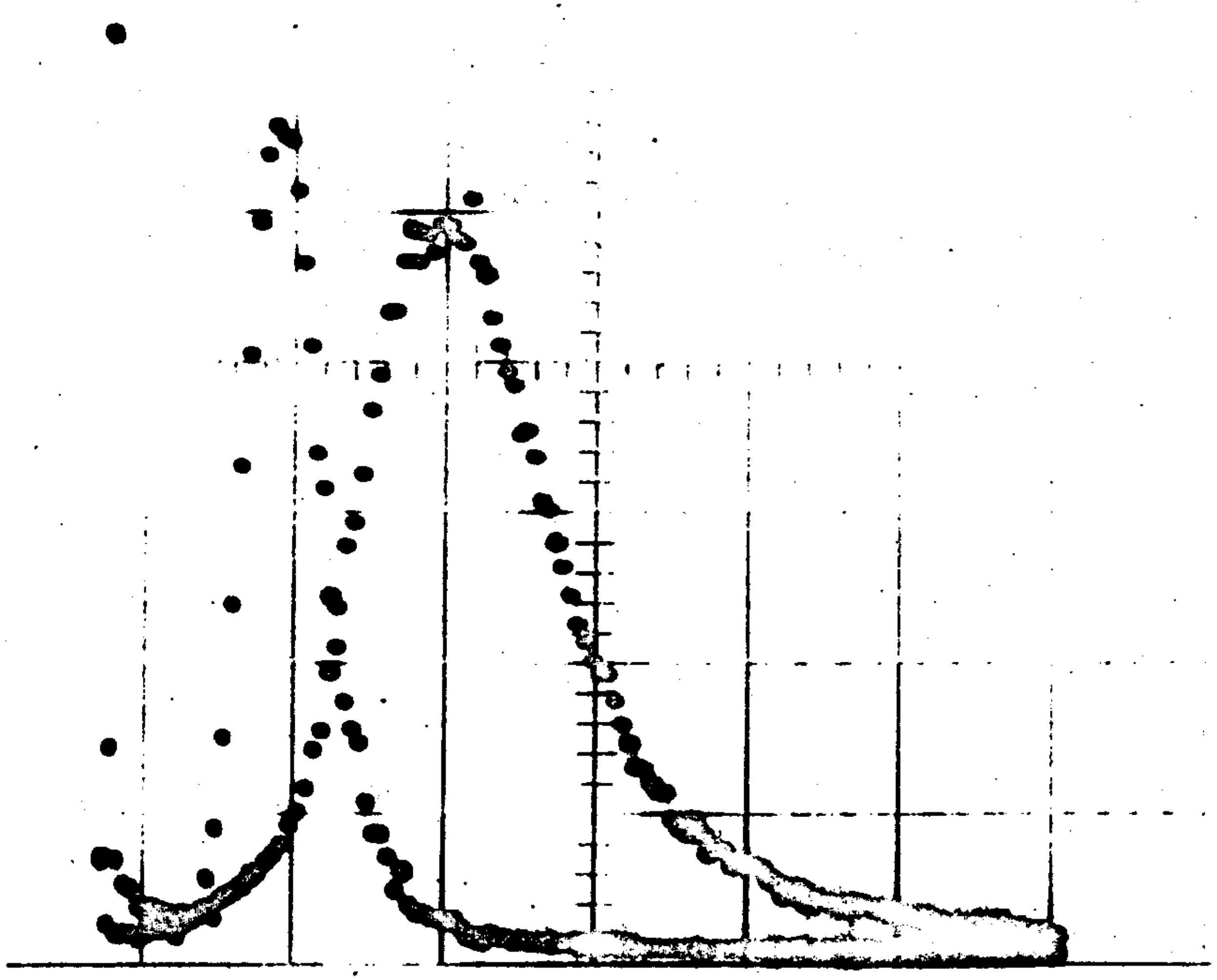


Fig. 2

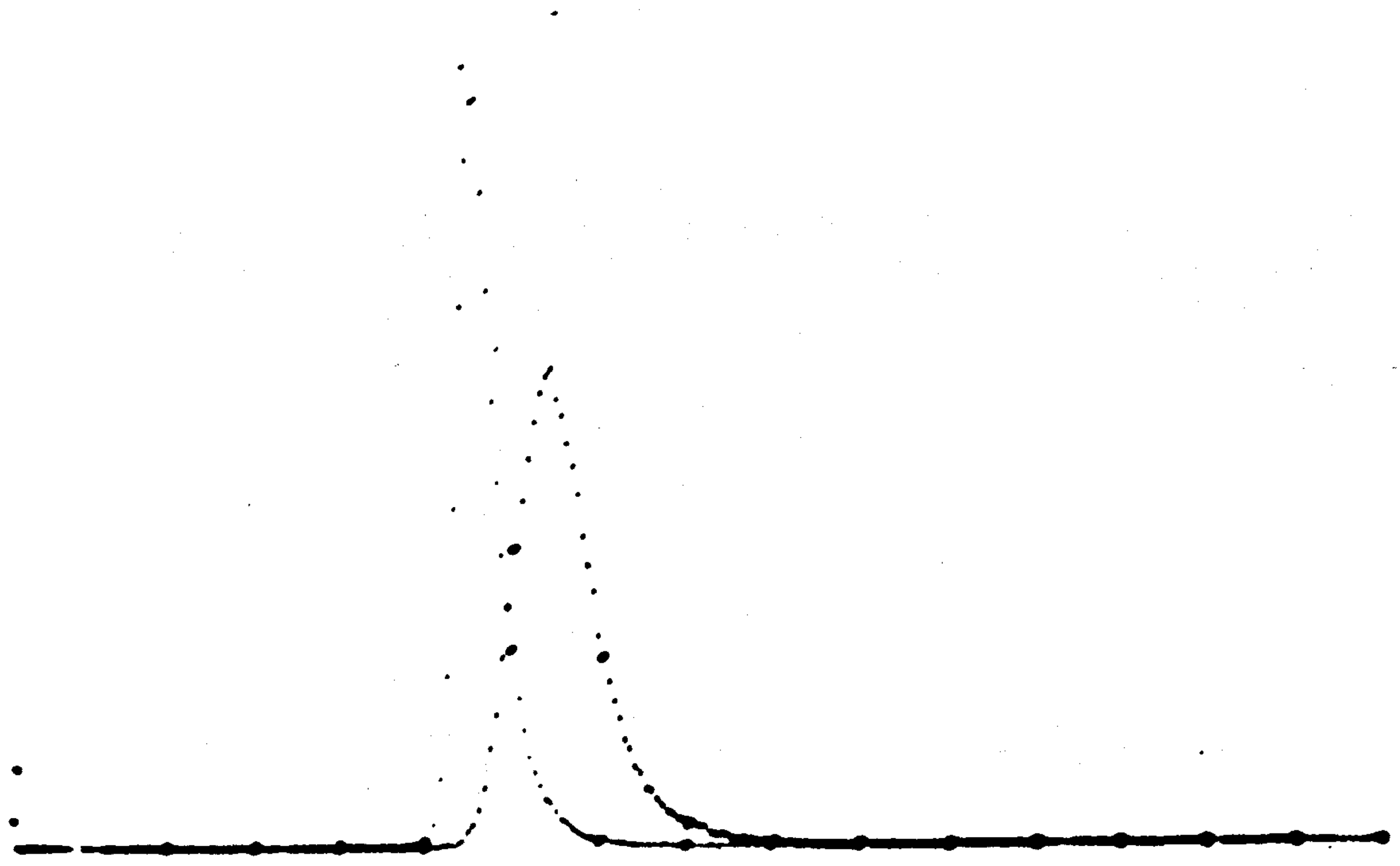


Fig. 3

GEOMETRIC MEAN DEVICE

$$Y = \left(\prod_{i=1}^{n} W_i \right)^{\frac{1}{n}}$$

$$\mathrm{LOG}\ Y = \left(\sum_{i=1}^{n} \mathrm{LOG}\ W_i \right) \frac{1}{n}$$

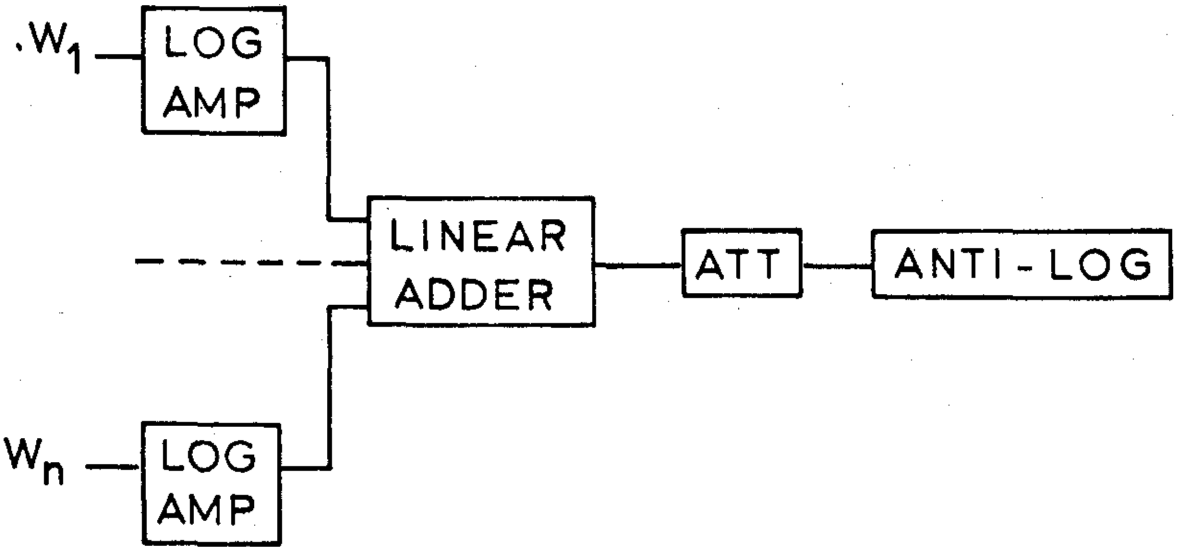


Fig. 4

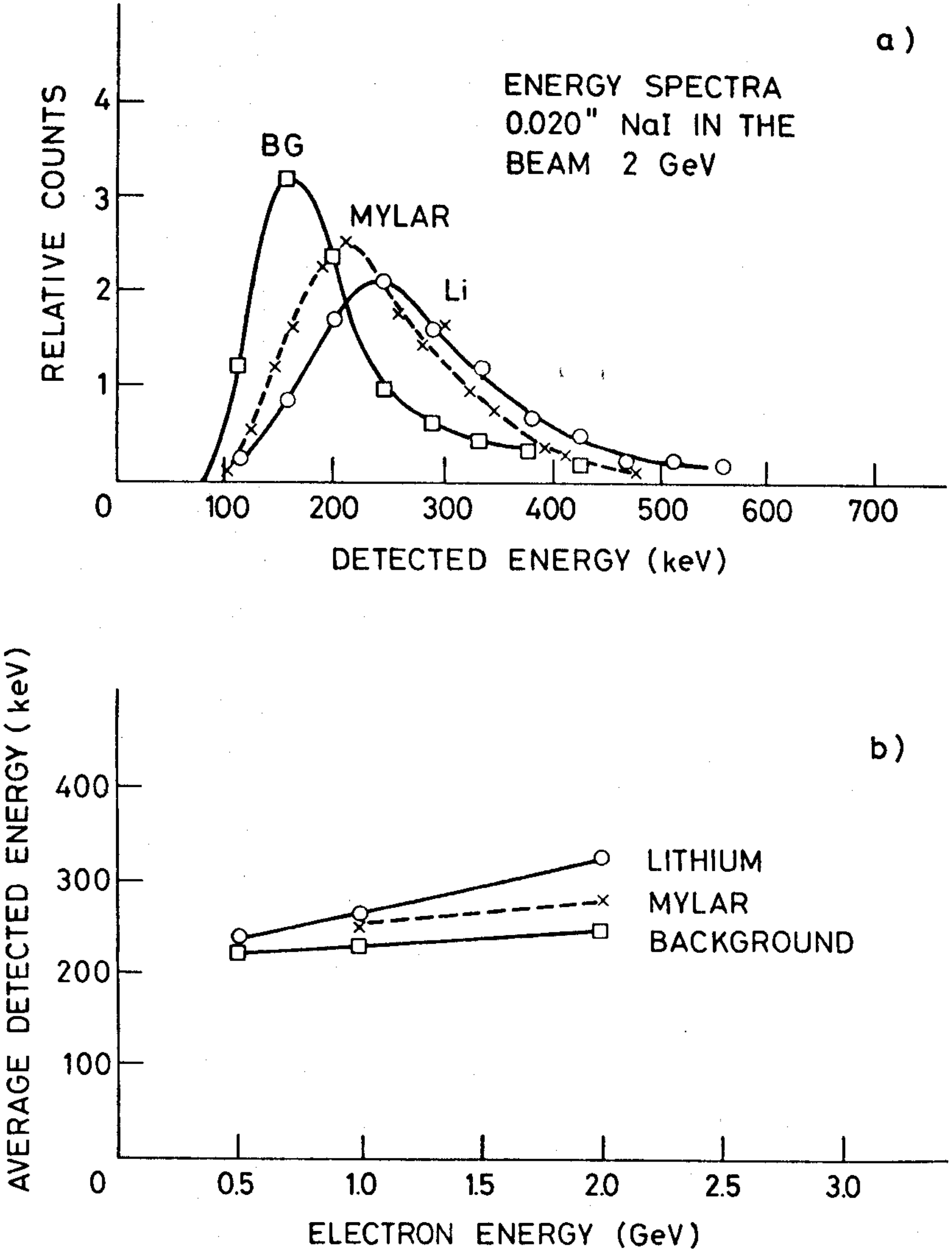

a)
ENERGY SPECTRA
0.020" NaI IN THE
BEAM 2 GeV
BG
MYLAR
Li
RELATIVE COUNTS
0
1
2
3
4
100
200
300
400
500
600
700
DETECTED ENERGY (keV)
b)
LITHIUM
MYLAR
BACKGROUND
AVERAGE DETECTED ENERGY (keV)
100
200
300
400
0.5
1.0
1.5
2.0
2.5
3.0
ELECTRON ENERGY (GeV)

Fig. 5

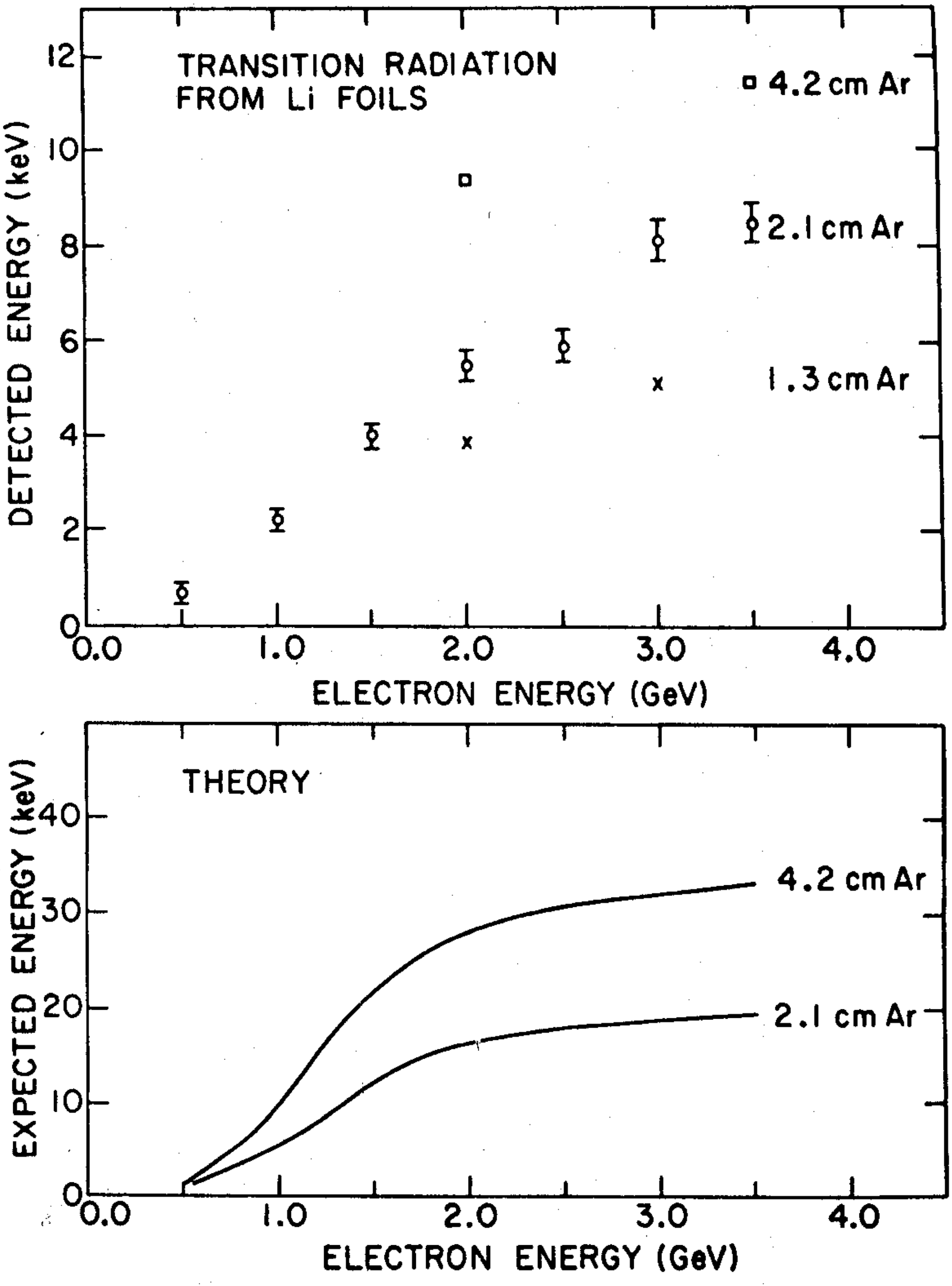

TRANSITION RADIATION
FROM Li FOILS
4.2 cm Ar
2.1 cm Ar
1.3 cm Ar
DETECTED ENERGY (keV)
0
2
4
6
8
10
12
0.0
1.0
2.0
3.0
4.0
ELECTRON ENERGY (GeV)
THEORY
4.2 cm Ar
2.1 cm Ar
EXPECTED ENERGY (keV)
0
10
20
30
40
0.0
1.0
2.0
3.0
4.0
ELECTRON ENERGY (GeV)

Fig. 6

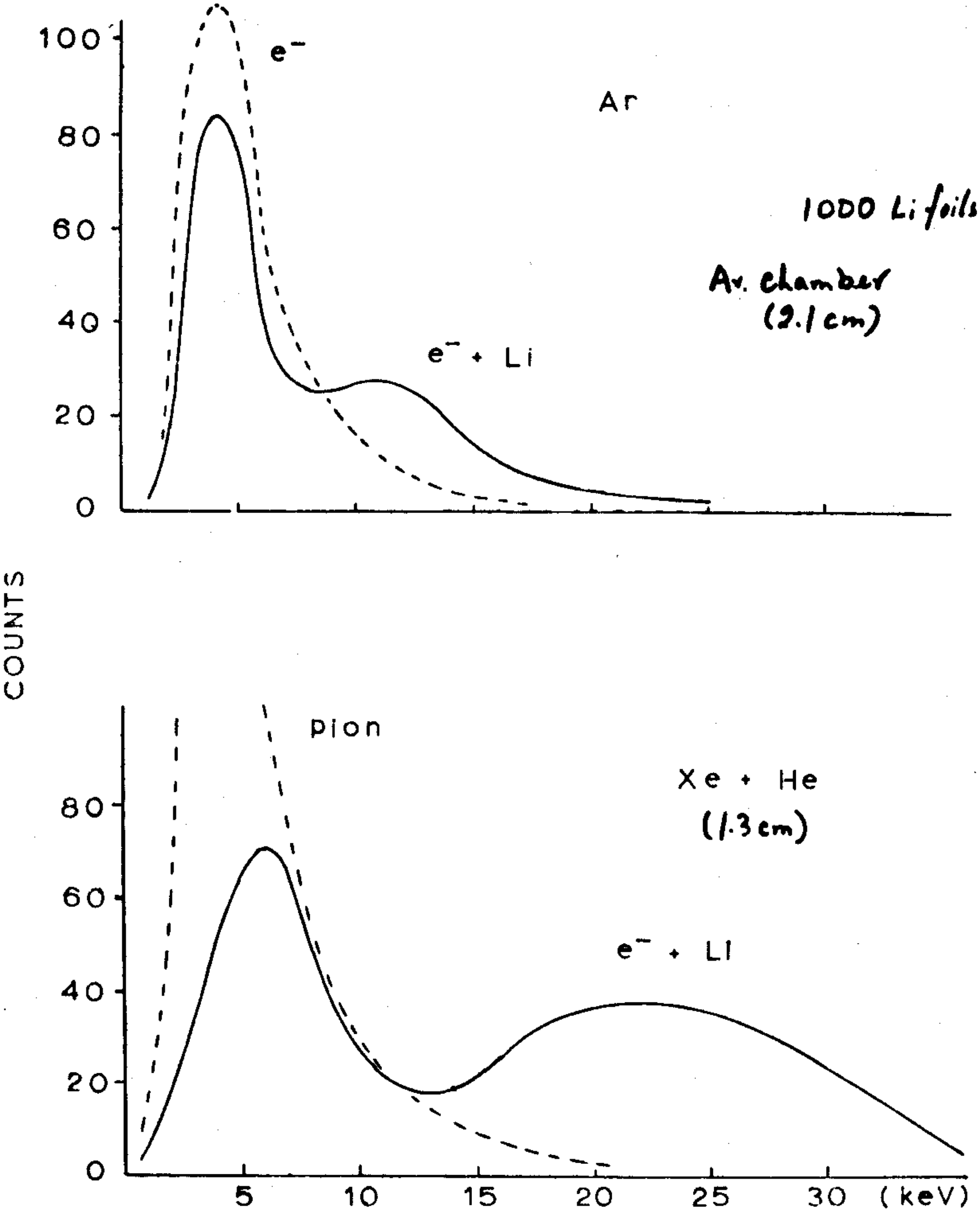

100
80
60
40
20
0
e⁻
Ar
1000 Li foils
Ar. chamber
(2.1 cm)
e⁻ + Li
COUNTS
pion
Xe + He
(1.3 cm)
80
60
40
20
0
e⁻ + Li
5
10
15
20
25
30
(keV)

Fig. 7

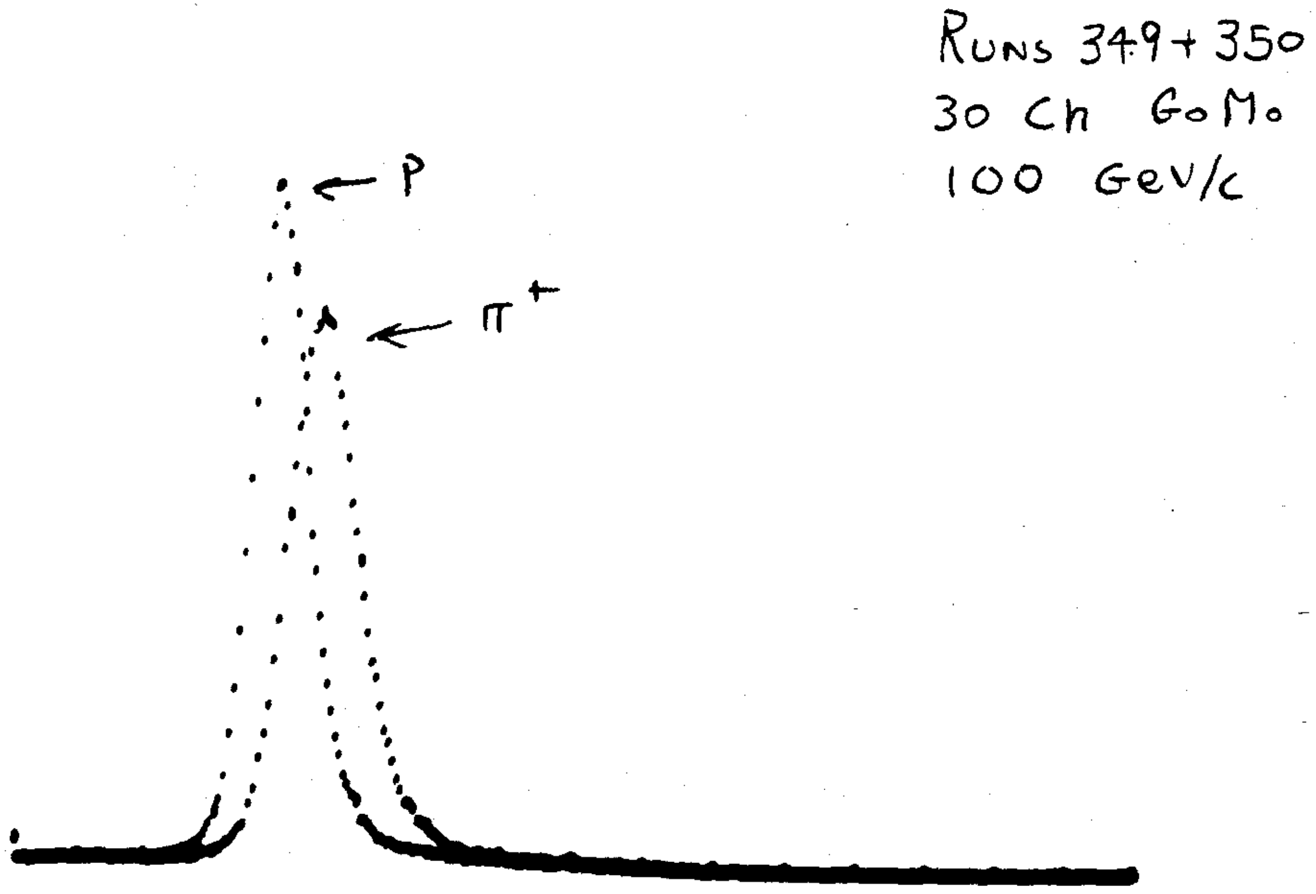
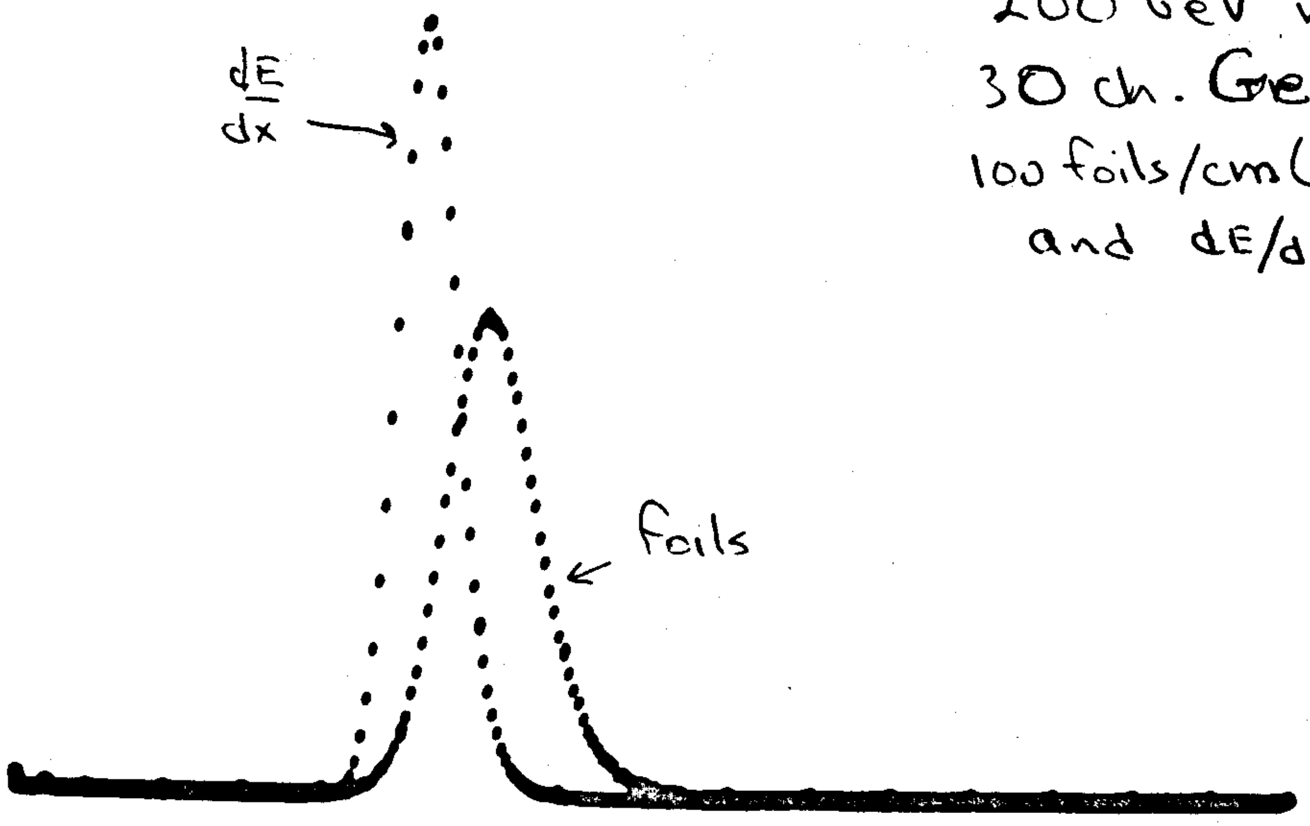


Fig. 8



Overlap
Runs 401+402
200 GeV negative
30 ch. Geom Mean
100 foils/cm($\frac{1}{2}$ and $\frac{1}{4}$ mil)
and dE/dx

Fig. 9

Run 406
250 GeV/c π^-
30 CH G.M.
dE/dx

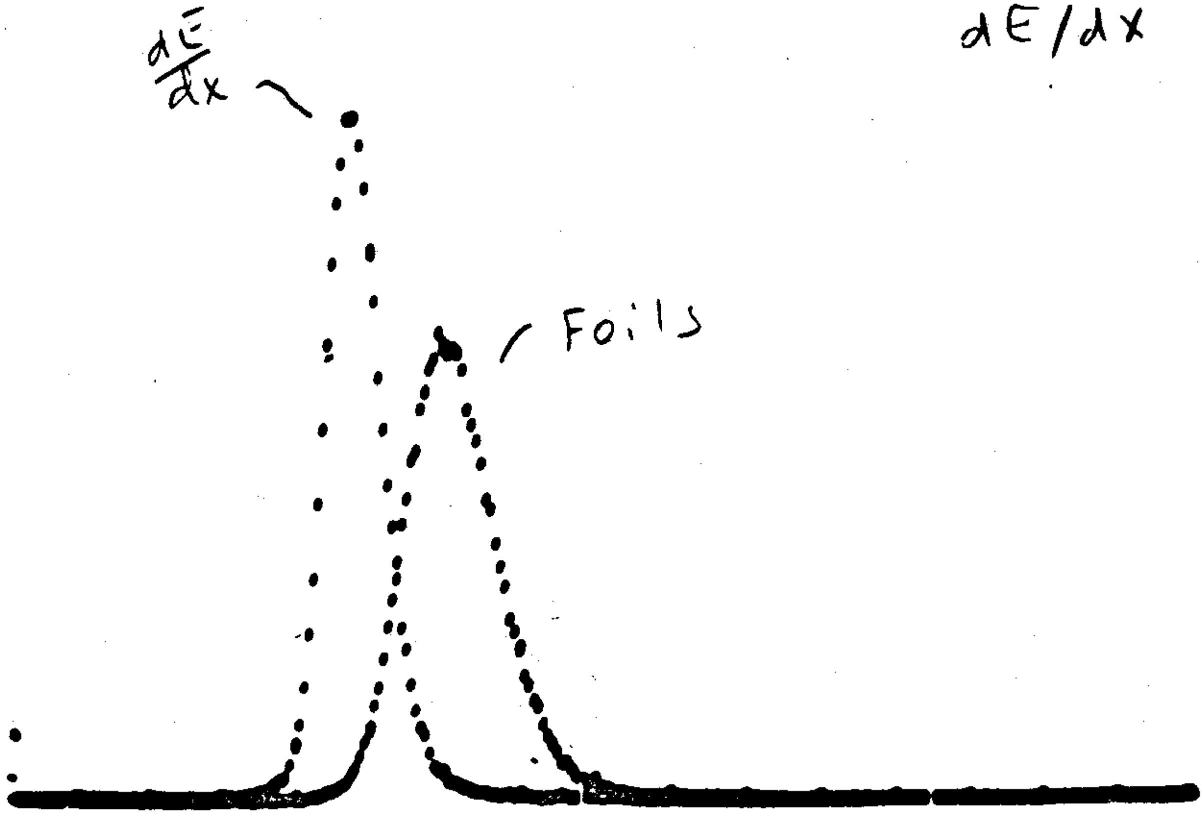


Fig. 10

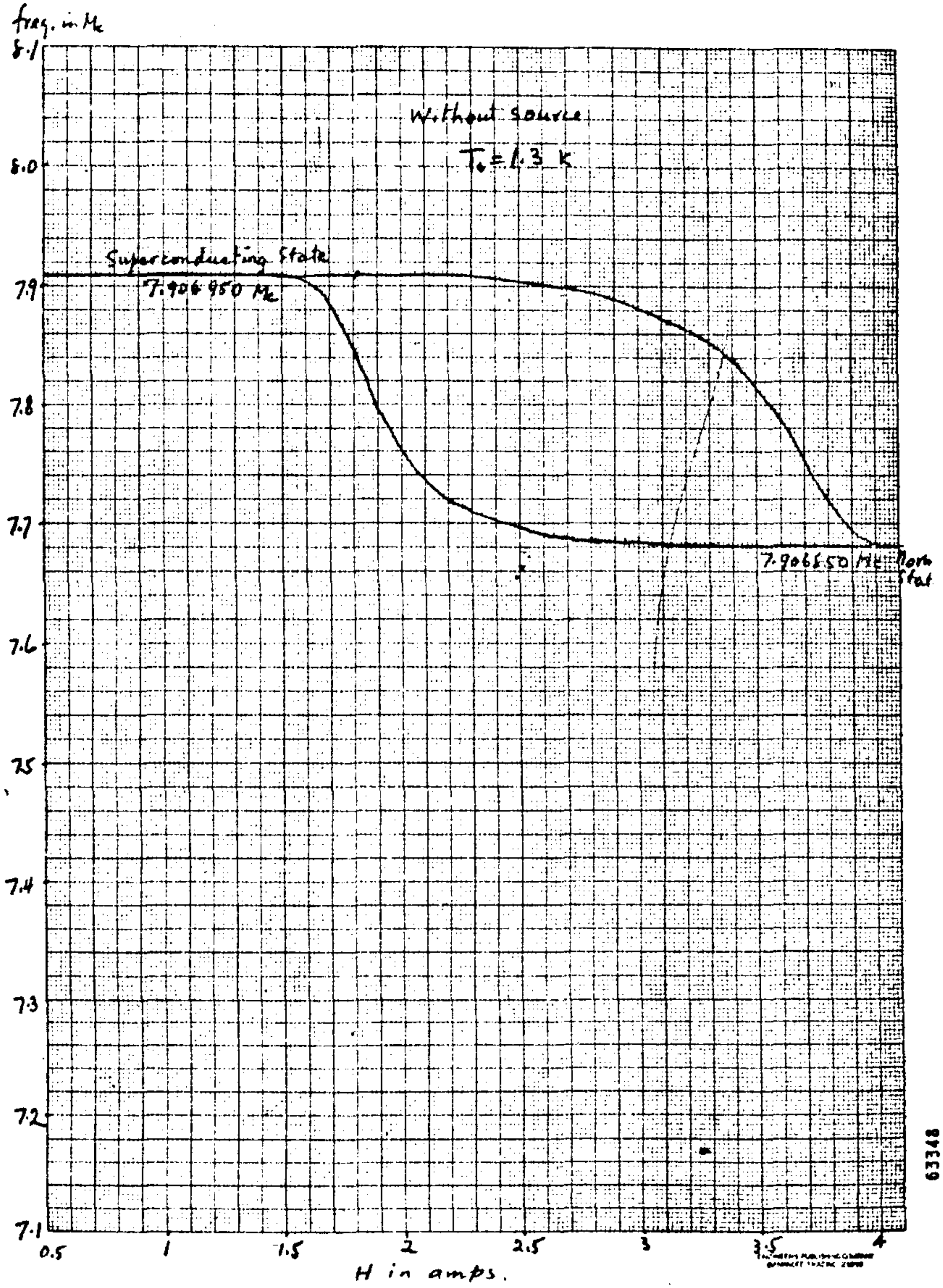

freq. in Mc
8.1
8.0
7.9
7.8
7.7
7.6
7.5
7.4
7.3
7.2
7.1
Without source
T₀ = 1.3 K
Superconducting State
7.906950 Mc
7.906650 Mc Norm Stat
0.5
1
1.5
2
2.5
3
3.5
4
H in amps.
63348

Fig. 11

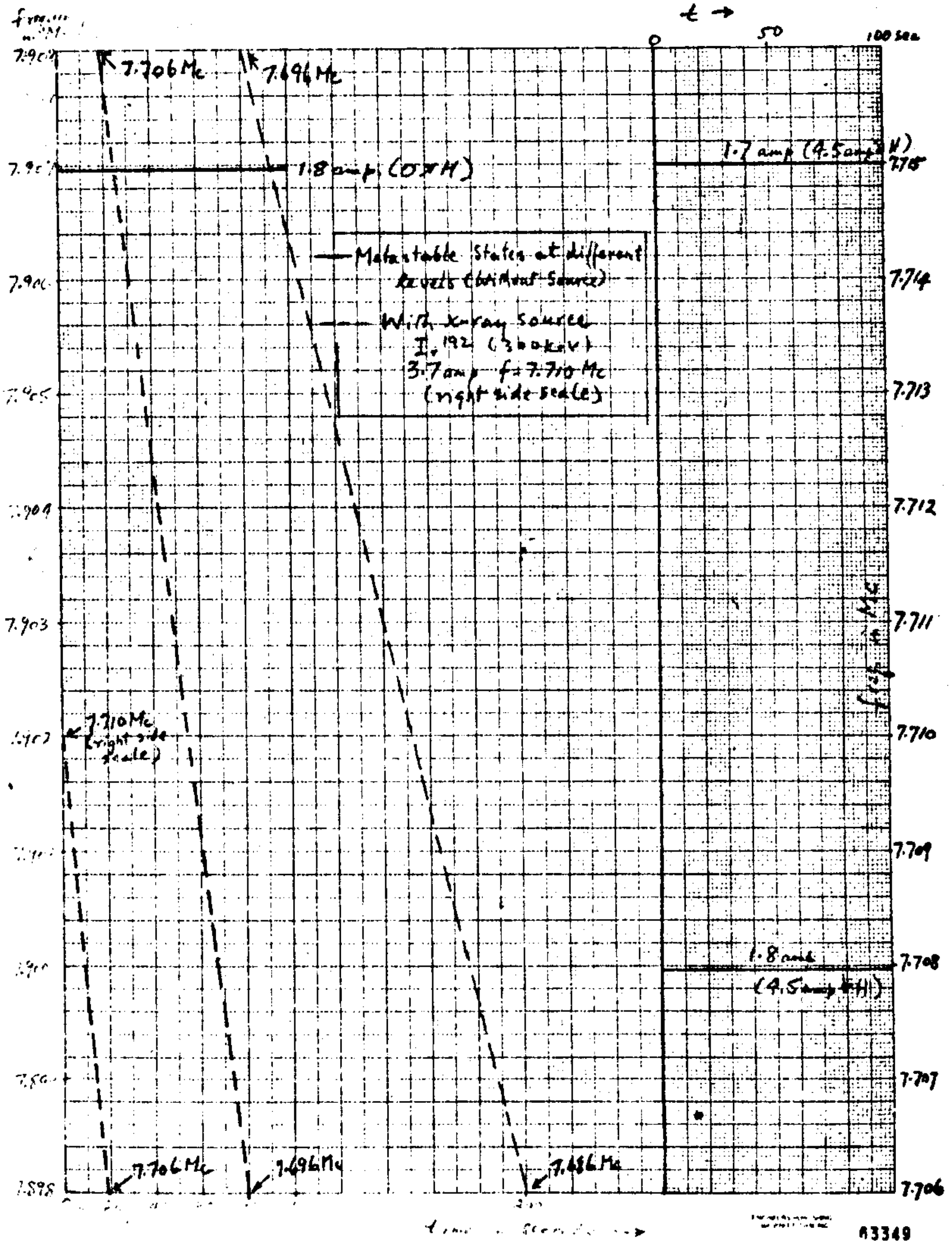

t →
0
50
100 sec
7.706 Mc
7.696 Mc
1.8 amp (OFH)
1.7 amp (4.5 amp H)
Metastable States at different levels (without Source)
With x-ray source
I_r^{192} (300 keV)
3.7 amp f = 7.710 Mc
(right side scale)
7.710 Mc (right side scale)
7.903
7.898
7.706 Mc
7.696 Mc
7.686 Mc
1.8 amp
(4.5 amp H)
f in Mc
7.715
7.714
7.713
7.712
7.711
7.710
7.709
7.708
7.707
7.706
83349

Fig. 12