CHERENKOV RADIATION DETECTOR

by

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ABSTRACT

Most of Radiation detectors based on the Cherenkov Effect are essentially very bulky and expensive for schools and colleges. An inexpensive yet very compact radiation detector is designed, built and tested. It is used to measure the Cherenkov angles for natural radioactivity from sources as Cs^{137} p32 with energies 0.51 MeV, 1.17 Mev and 1.71 MeV respectively. It has angular percentage resolution of 4, has detector efficiency of 60%. The Cherenkov angle expected from 0.51 MeV C_sl37 is 40^0 and the angle measured with the radiator is 41.6^0. It is known that 1.17 MeV C_sl37 emits a cone of Cherenkov angle of 45^0 while the radiator measured $43^0$24' angle. The determined angle for 1.71 MeV beta from p^{32} is $46^0$14' as against the theoretical value of 47^0. The simple inexpensive radiator compares favourably with the very expensive heavy counters.

NOTATIONS

= D' Alembertion = $\nabla^2 \quad \mu\varepsilon \dfrac{\partial^2}{\partial t^2}$

μ_0 = Pereability of free space

n = index of refracton

ε = permitivity

t' = retarded time (see appendix)

j = current density

$\hat{x}, \hat{y}, \hat{z}$ = unit vectors in x, y and z

x', y', z' = are components of source vector

v = $\frac{c}{n}$

θ = chrenkov angle, the half cone angle of the emitted radiation it is the angle between the charge particle velocity vector and the radiation unit vector.

β = particle velocity parameter (= $\frac{v}{c}$)

ε = the particle energy

S_o = the cathode efficiency expressed in practical units μA/lumen.

N_v = the number of quanta emitted per unit radiation length of radiator in frequency and + d

R_{AR} = The radiation length of beta particles for laboratory energies in aluminum (in g cm^{-2})

X_C = The critical distance in the radiator.

η_o = The absolute quantum efficiency of photo cathode at peak of the response curve.

E = electric field

B = magnetic field

S(λ) = the response of a photo multiplier to an equi-energy spectrum.

t(λ) = transmission characteristics

c(λ) = Cherenkov spectrum energy distribution

ζ = optical efficiency for codecting light at the cathode

INTRODUCTION

Experimental discovery by Cherenkov *(1934) [1]* of the coherent response of a medium to the passage of a reletivistic particle, gave birth to the Cherenkov Detectors. Original theory given by Frank and Tamm (1937) *[2]* have been modified by several authors, Ginsburg (1940) [3] and Botoviskii (1957) *[4]* for example.

The various designs of the Cherenkov Detectors are functions of the Cherenkov, angle, the index of refraction of the radiator, and the velocity parameter of the particles. Most of the existing designs
use very high energies. Marshall (1952) *[5]* described a focussing Cherenkov system using two photomultiplies, a cylindrical mirror, and two plane mirrors. In the measurement of pi-messons of 145 Mev, he reported a measured angle of 39.9^0 as compared with the theoretical angle of 40.4°. Mather and Martinelli (1953)*[6]* in their study of $¶^0$ meson devised a directional counter with three photo multiples and a lucite radiator among other parts. The counter was used at energies of about 340 Mev. Sutton et al (1955) [7] achieved 8% resolution at 435 Mev in their proton-proton experiments. Chamberlain and Wiegand (1956) *(8)* designed a Cheronkov velocity counter with which they reported ability to select the particle velocity in the designed a Cheronkov velocity counter with which they reported ability to select the particle velocity in the range $0.75<\beta<0.78$. Cherenkov radiation from the atmosphere was carried out by Galbraith and Jelley (1955) {9} using an f/0.5 60cm diameter parabolic mirror and a 5-inch diameter phototube incorporated in their Cherenkov detector. Cherenkov detectors are not exclusive to solid radiators. Hanson and Moore(1956) [10] described a CO_2 counter used to detect sea-level cosmic ray μ-meson with a counting efficiency of about 3% for μ-meson with velocities below threshold. A good number of these energy counters has been described by Jelley (1958) [11].

In this paper we describe the design, construction, and testing of a low cost, compact, light-weight yet efficient low energy detector which is capable of modification to cover various energy ranges. Section II gives a brief theory of Cherenkov radiation, the basic principles of which is contained in Section II.1 The duration of the emitted light is discussed in 11.2 while the energy resolution of the detector is described in 11.3. Section 11.4 sees the estimation of the number of photoelectrons per unit centimetre path. In section III we discuss the design criteria for the detector. Sections IV and V contain the experiments and discussions respectively.

II THEORY

II.1 The Basic Principles of Cherenkov Radiation.

The explanation of the Cherenkov radiation can be understood from classical electrodynamics, Jackson (1962) *[12].* The radiation is a part of the density effect in collisional energy losses treated by Fermi (1940) *{13}*.If a charged particle moves in a medium where $\mu = \mu_0$, the D'Alembertian operator applied to the vector potential $\underline{A}$ leads to an inhomogeneous equation:

$$\underline{A} = \nabla^2 \underline{A} - \frac{n^2}{c^2}\frac{\partial^2 A}{\partial t^2} = -\mu \underline{j} \quad (1)$$

where $\underline{j}$ is the current density defined in such a way to localize the charge and indicate its direction of motion, such as

$$\underline{j} = e\underline{v}(z^I - vt)\partial(y^{'})\partial(x^{'}) \quad (2)$$

which localizes the charge moving in the z-direction at the point (x',y',z') and makes $fjdy^{'}\,dx^{'} = e\hat{z}$. The solution of (1) is essentially that obtained for a vacuum solution with c replaced by c/n ($n = \sqrt{\varepsilon/\varepsilon_0}$) and the retarded time t =r *n/c.* It can be shown that if the incident particle velocity is very close to the speed of light, the particle could reach a speed greater than the speed of light, in that medium. This is a cause of the Cherenkov radiation. A quantitative estimate of such a radiation is arrived at via Fourier analysis. Such analysis show that if the radiated energy $\underline{S}$

and the electric field $\underline{E}$ are defined-by

$$\int_{-\infty}^{\infty} \underline{S}(t)dt = \int_{\infty}^{\infty} (\underline{E} \wedge \underline{H})dt \quad (3)$$

$$|\underline{E}| = \frac{1}{n}\left(\frac{\mu_0}{\varepsilon_0}\right)^{\frac{1}{2}} \underline{H} \quad (4)$$

then the energy loss in the frequency band dω is given by the relation:

$$\varepsilon(\omega)d\omega = 4\pi\int_{-1}^{1} Sin^2\theta \frac{Sin^2(1-\frac{nu}{c}Cos\theta)\frac{\omega z}{u}}{\frac{\omega^2}{u^2}(1-\frac{nu}{c}Cos\theta)^2} d(Cos\theta) \quad (5)$$

$$\phi = e^2 \quad \omega^2\ n/16\pi^2\varepsilon_0\ C^2$$

where θ is given by (9)
Equation (5) reduces to:

$$\varepsilon(\omega)d\omega = \frac{e^2 z}{2\pi\varepsilon_0 c^2}(1-\frac{1}{n^2\beta^2})\omega d\omega \quad (6)$$

From equation (6) it can be shown that the energy loss per unit path is given by relation

$$\frac{\Delta\varepsilon(\omega)\omega}{\Delta L} = \frac{e^2}{4\pi\varepsilon_0 C^2}(1-\frac{1}{n^2\beta^2})\omega d\omega \quad (7)$$

while the number of quanta off energy hω is represented by

$$\frac{\Delta N}{\Delta L}d\omega = \frac{e^2}{4\pi\varepsilon_0 hC}(1-\frac{1}{n^2\beta^2}) \quad (8)$$

Qualitatively if the velocity of the charged particle is less than the velocity of light in the medium i.e., if $u < C(\varepsilon/\varepsilon_0)^{\frac{1}{2}}$

The spherical waves do not interfere so as to produce radiation fig. 1(a).

For $u < C(\varepsilon/\varepsilon_0)^{\frac{1}{2}}$ the wavelets emitted from successive instantaneous positions of the particle produce "shock waves" similar to bow waves in water. Thus this radiation gives information of the charged particle motion fig. 1(b).

The angle θ is given

$Cos\ \theta \frac{lc}{nu} = \frac{1}{\beta n}$ the measure of the Cherenkov angle θ. These equations indicate among other things that the energy per unit path per unit frequency interval is proportional to the frequency; the energy per unit path length per unit wavelength interval is inversely proportional to square of the wavelength and that the number of quanta
per unit path per unit frequency interval is constant. It is understood from [6], [7] and [8] that the energy losses are the radiated energies hence the above deductions.

II.2 DURATION OF EMITTED LIGHT

An aspect of the Cherenkov radiation that requires consideration is the duration of the flash of emitted radiation The duration t depends on the medium whether it is dispersive or not. For a none dispensive medium the wavefront is infinitely thin and hence the duration may be considered very very short. In a dispensive medium θ is now given by

$$\theta = \theta(W) \quad (10)$$

such a dependence leads to Δt fig. 2 (modified form of fig. 1) duraion given by

$$\nabla t = \frac{\varrho}{\beta C}\left[\beta^2 n^2(\omega_2 - 1)^{\frac{1}{2}} - \beta^2 n^2(\omega_1 - 1)^{\frac{1}{2}}\right] \quad (11)$$

$$= \frac{b}{\beta C}[tan\theta_2 - tan\theta_1]$$

II.3 Energy Resolution

In term of the rest mass as a unit of energy, the total particle energy is given by

$$\varepsilon = (1-\beta^2)^{-1/2}$$

$$\frac{\partial\varepsilon}{\partial\beta} = \beta\varepsilon^3 \quad (12)$$

On using the relation between θ-and β, and with a little rearrangement

$$\frac{\partial\varepsilon}{\partial\theta} = \beta^2\varepsilon^3 tan\theta \quad (13)$$

Or

$$\frac{\Delta\varepsilon}{\varepsilon} = \beta^2\varepsilon^3 tan\theta\partial\theta$$

for a hemispherical radiator radius a and x units away from the photocathode one has

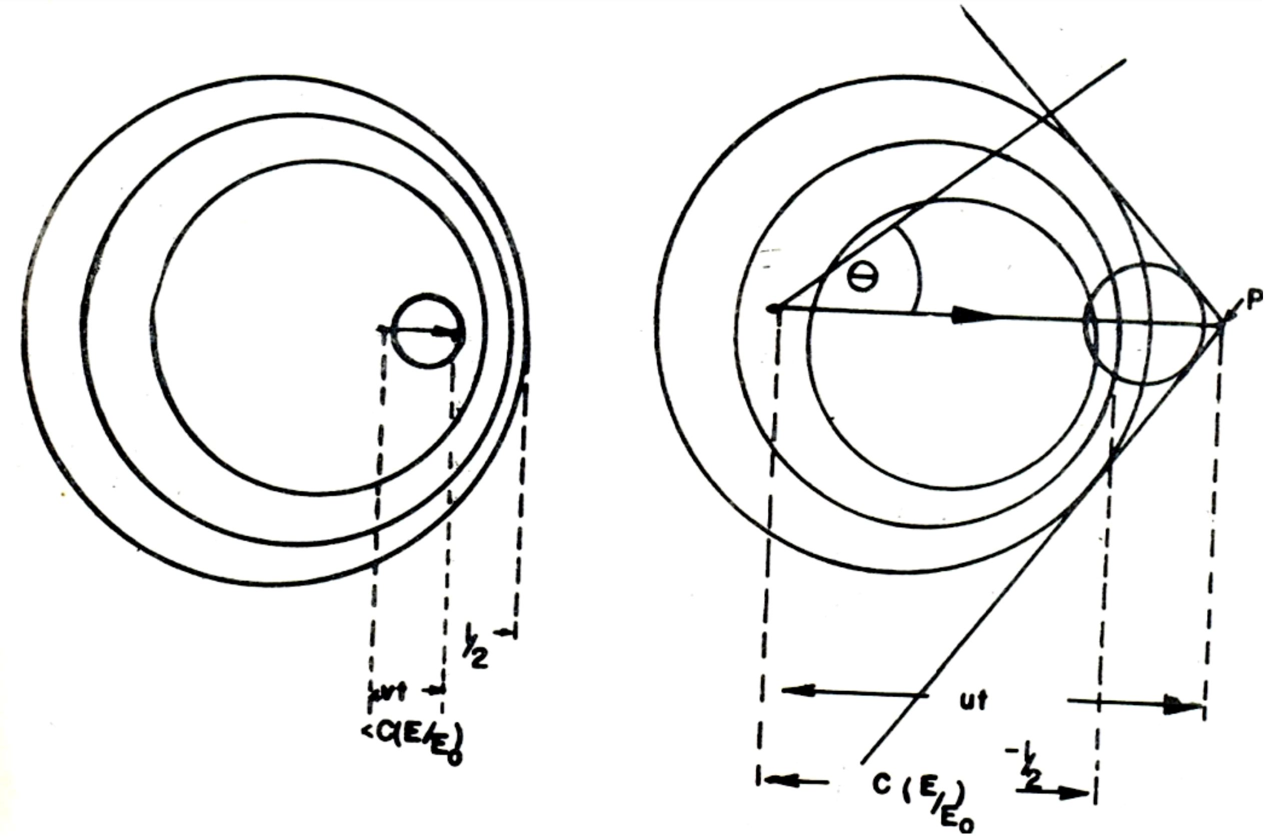

Fig. 1. Passage of a charged particle in a medium with different velocities. In (a) particle velocity is less than the velocity of light in the medium. In (b) particle velocity is greater than the velocity of light in the medium. P represents the instantaneous position of the charged particle

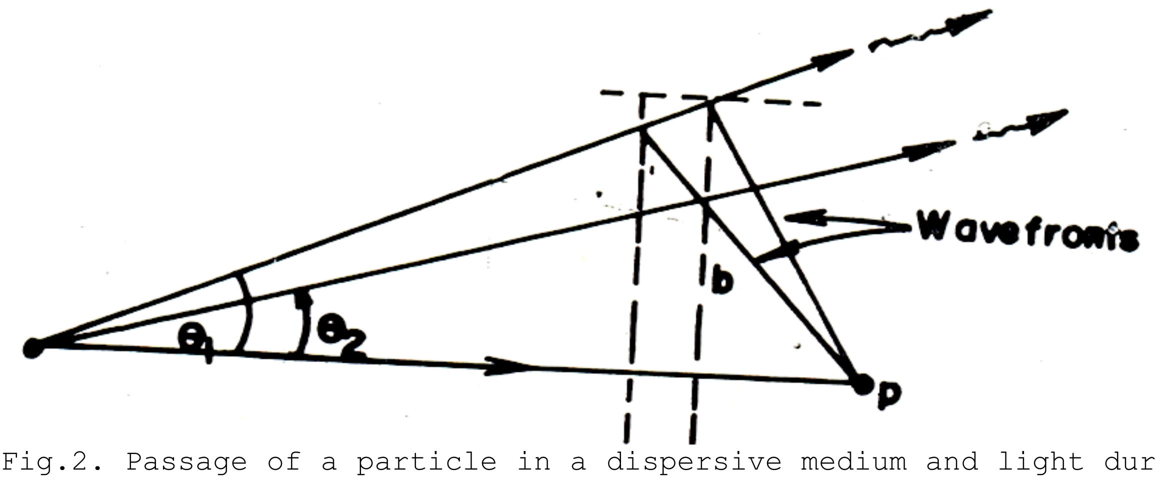

Fig.2. Passage of a particle in a dispersive medium and light duration. P represents the charged particle.

$$tan\theta = \frac{r}{a+x} \; and \; d\theta = \frac{-rdx}{(a+x)^2 + r^2}$$

It is then straight – forward to show that

$$\frac{\Delta\varepsilon}{\varepsilon} = -\frac{\varepsilon^2}{n^2} * \frac{r^2\Delta x}{(a+x)^2} \qquad (16)$$

Equation (16) allows us to calculate $\Delta\varepsilon/_\varepsilon$ at the critical distance x_c of the radiation.

II.4 Quantum Conversion and Photocathode Response.

The detection efficiency is dependent on the Cherenkov spectrum, the quantum efficiency of the photomultiplier, the efficiency with which light is collected and transferred by the photocathode, and the response of the photomultiplier to a Cherenkov spectrum. It is shown Jelley (op cit) that

$$Rc \; \alpha \int C(\lambda)\, S(\lambda) d\lambda \; \ldots\ldots\ldots\ldots (17)$$

Where $C(\lambda)\alpha \, \frac{1}{\lambda^3} d$

hence the number of photons N_P emitted between λ_1 and λ_2 is given by

$$N_P = \frac{2\pi e^2}{hc}\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)\left(1 - \frac{1}{\beta^2 n^2}\right) \qquad (18)$$

The main aspect of this is the yield of the number of photons per unit path length is given by

$$\frac{dN_P}{d\lambda} = \frac{2\pi}{137}\left(1 - \frac{1}{\beta^2 n^2}\right)\int \frac{1}{\lambda^2} d\lambda \qquad (19)$$

A little reflection indicates that the number of photelectrons produced per unit cm path at the cathode is given by

$$\frac{dN_e}{d\lambda} = \frac{2\pi}{137}\zeta n_o[1 - \frac{1}{\beta^2 n^2}]\int s(\lambda)\frac{1}{\lambda^2} d\lambda \qquad (20)$$

The working formula results if we replace n_o by S_o the cathode efficiency expressed in μA/lumen, normally obtained with a standard curve or supplied by the manufactures. This relation is given by

$$\frac{dN_e}{d\lambda} = \frac{2\pi}{137}\zeta S_o F[1 - \frac{1}{\beta^2 n^2}]\int \frac{S(\lambda)d\lambda}{\lambda^2} \qquad (21)$$

F is calculated from the ratio of n_o to the photocathode sensitivity in μA/lumen where

$$\eta = K\frac{\int \varepsilon(\lambda)S(\lambda)d\lambda}{\int \varepsilon(\lambda)V(\lambda)d\lambda} \qquad (22)$$

In the evaluation of (22) two fundamental conversion factors are used (i) 1 Watt of luminous energy at the wavelength corresponding to that of maximum visibility (λ = 0.555 μm) is equivalent to 685 lumen (ii) Use is made of Table 5A Jelley (op.cit) which gives the equivalent photocurrent for the quantum efficiency at the peak of the response curve for the cathode.

Noting that for the EMI Cs-56 tube the quantum efficiency at peak is 17% and that it is equivalent to 70 μA/lumen F becomes $2.4xI0^{-3}$ and (21) reduces to

$$\frac{dN_e}{d\lambda} = 1.1 \times 10^{-4}\zeta S_o\left[1 - \frac{1}{\beta^2 n^2}\right]\int s(\lambda)\frac{1}{\lambda^2} d\lambda \qquad (23)$$

For the production of photoelectrons in Perspex with ζ = 0.9, β = 0.7, n = 1.5, S_o = 70, λ_{lower} = 0.3 μM λ_{high} = 0.6 μM

$$\left(1 - \frac{1}{\beta^2 n^2}\right) = 0.093 \qquad = 1.02 \times 10^4 cm^{-1} = \int \frac{s(\lambda)}{\lambda^2} d\lambda$$

and hence the number of photoelectrons per unit cm path is

$\frac{dN_e}{d\lambda}$= 7 photoelectrons.

The total photoelectrons produced through a path-length of 1.255 at the cathode of the phototube is 7 on the assumption that 10% of the available light is lost by reflection.

Equation (23) incorporates the angle through βn and if we consider a maximum angle of 48^0 then the maximum number of photoelectrons is 39 per cm of path at the cathode. This explains the maximum reading at the Cherenkov angle.

III. DESIGN PARAMETER CRITERIA

The selection of the radiator is based on various factors. These factors include the refractive index of the material, the coefficient of absorption for the material, its density and its atomic number. Ritson (1960) [4] has considered various radiators in terms of density and index of refraction, while Madey (1956)[15] discussed the degree of scintillation produced by various radiators.

The type source of radiation needed depends on the type of radiation detector envisaged, and the availability of the minimum energy - the threshold energy - needed to produce Cherenkov radiation. Since the radiation detector envisaged is to be used in places where high energy particles are not readily available, another added factor is the half-life of the radiation.

The material radiator used for this detector was perspex whose properties were kindly supplied by the plastic division of ICI. The ICI "Perspex", Polymethyl Methacrylate has the following properties:

Specific gravity s = 1.19 at 20^0C
Index of refraction n = 1.495 1.49 unplasticized
Relative dispension n_D = 53.7 58.0 "
Critical angle
Perspex to air 42^0 "

The transmission characteristics of the radiator is given b in fig.5.10 of Jelley (op.cit) and is reproduced, with the Cherenkov spectrum superimposed, in the appendix for ease of reference. The relation between S(λ) the response curve of the tube, C(λ) and t(λ) is given in the appendix. Jelley (op.cit) fig.5.9 gives the same but without the transmission characteristics of the radiator. The chemical composition is very close to the form $C_5H_B0_2$ or

CH_3
|
-C – CH_2H –
|
- CO – O - CH_3

The ICI claims that the amount of heavier atoms such as Fe, Zn, AI,Cu and Cr present is only to one part per million. The various Design Parameter Relations are given below. The basic equation for the Cherenkov angle has already been given

$$\theta = \cos^{-1}(1/\beta n)$$

The number of quanta emitted per unit radiation length of the radiator in the frequency range *V* & *V* + dv is

$$N_v = \frac{2\pi e}{hc}\left(1 - \frac{1}{\beta^2 n^2}\right)\frac{dv}{c}$$

The range of beta particles for the laboratory available energies in Al is given by the relations, Segre(1964)[16]

$$R_{A1} = 0.407\varepsilon^{1.38}\ for\ 0.8 < \varepsilon < 1.15 MeV$$
$$R_{A1} = 0.452\varepsilon^{-0.133}\ for\ 0.8 < \varepsilon < 3MeV \quad (24)$$

For other materials one needs only compare them with aluminum to their densities. For energy between *0.8* and 1.15 MeV the range in perspex is 0.024 cm and for the other energy range 0.8 MeV E 3.0 MeV range is 1.255 cm.

For a semi-spherical radiator of radius a, critical length x and an index of refraction n, the energy resolution reduces to

$$\frac{\Delta\varepsilon}{\varepsilon} = -\frac{\varepsilon^2}{\pi^2}\frac{r^2}{(a+x_c)^2}\Delta x_c \quad (25)$$

The physical properties of possible radiator materials, the nature of these materials, as well as the threshold energies of the available particles and the half lifes of these particles are shown in the appendix.

Table la indicates the various substances that could be used. Liquid radiators were unsuitable because of the fact that good sealants for both light and liquids must be found. The liquid if used must be movable. Gases are ruled out unless one considers ancillary equipments like vacuum pump, pressure gauge and thermostat. It is then clear why non of the substances were considered.

While table l(b) suggests that only β beta are available in the laboratory where high energies are not available- 1(c) indicates that any radioactive element with the right threshold energy and life time is a candidate.

The final design is shown in fig.8. The radiator is a hemispherical bowl mounted on a collimator of copper material with an aperture of 1 mm collinear with the superplaced radiator chamber. The system (dismountable) is moved via a long threaded brass, rod with a pitch of 0.0049 cm.

The ancillary equipments included an amplifier and a scalar both manufactured by Echo Electronics Ltd., Southend-on-Sea, Essex, England. The Echo N640A type - amplifier has a gain ranging from x25 to x 1000 with minimum output voltage +55 volts or -5 volts. The scalar is the N529D dekatron.

IV. EXPERIMENT

The Cherenkov light is radiated in a cone. When the radiator is in contact with the phototube all the light is received. As the radiator is moved away the amount of light detected should remain constant until a critical position for the radiation is reached. Beyond this value ie. for $x > x_c$ the detected light falls. This is illustrated in fig.3.

In fig.3(a),the radiator and the cathode are very close and all the light is received by the cathode and hence detected. This happens until X_c is reached (fig. 3c). Beyond which the recorded count/time decreases. This suggests that one can detect the presence of more than one energetic particle by the number of plateaux in the count/time vs distance curve provided the lengths are not very close, fig. 4b. The location of the critical distance is enhanced by the use of "angular selector". The use of the angular selector - a thin piece of aluminium designed to cut, off the internal section of the light cone- gives a well-defined peak at the critical length, as shown in fig.3.

The suitable radiator shape finally chosen was a hemispherical bowl since any radiation emitted at the centre will always be perpendicular to the radiator air surface and thus avoid the possibility of total internal reflection at the air-radiator surface.

The graph from the readings are shown in figures 5 and 6. Figure 7 compares the measured angles with the theoretical angles as functions of the critical distance x_c, while Plate I shows the radiation detector with one of its ancillary' equipment, Plate II shows the two types of radiator shapes with the advancing holder. Plate III illustrates the internal assembly in the detectors housing, and Fig.8 illustrates the radiator dimension of 0.66mxO.084m of cylindrical copper housing thickness 0.51 cm. The overall weight is 8kg.

CONCLUSION

An inexpensive and light weight radiation detector has been designed, built and tested. For laboratory energies from radioactive substance it has an angle resolution of less or equal to 4. Knowledge of the angle allows the measurement of the particle energy. A hemispherical shaped radiator is preferred to a cylindrical shaped one to avoid the need to use a medium of intermediate index of refraction, essential for the removal of total internal reflection. The critical distance for C_sl37 fig.6A, using angular selector does not fit into the callibration curve because it was measured with a cylindrical radiation.

The radiator is capable of modification if need for monitoring cosmic rays. The essential modifications is in the radiator size and cathode surface area. This type of modification would imply that both the radiator and the system of photomultipliers remain fixed. Jelley (op cit.) has discussed different high energy Cherenkov detectors and their applications. These are on the expensive side compared to the present detector. The detector could detect higher energetic particles than used in the above.

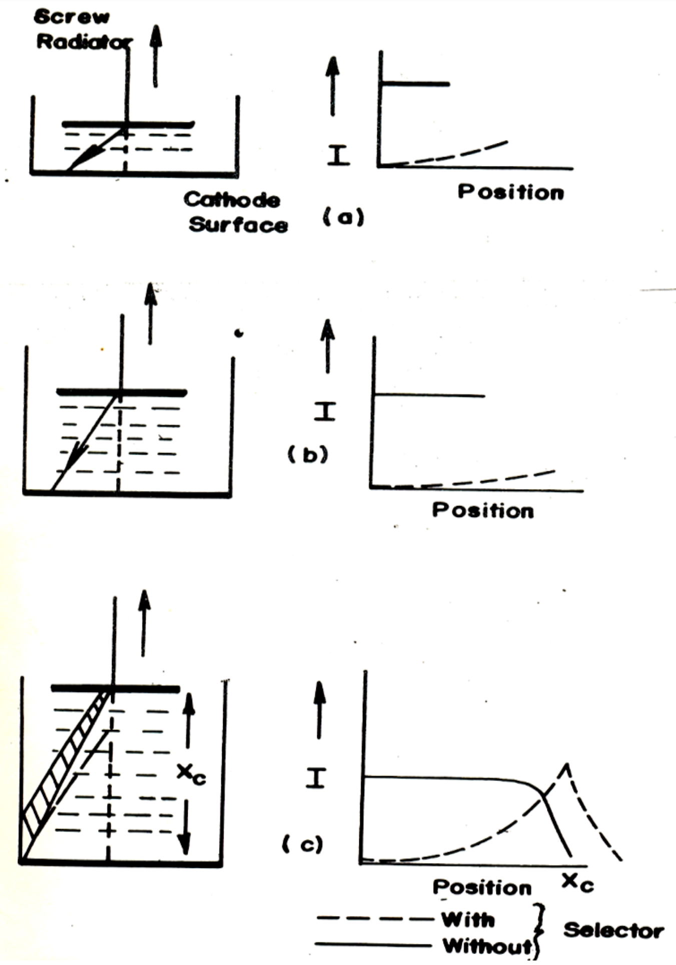

Fig.3. The relation between the radiator position with respect to the phtocathode and the recorded intensity. ………… indicates the use selector and - intensity without selector

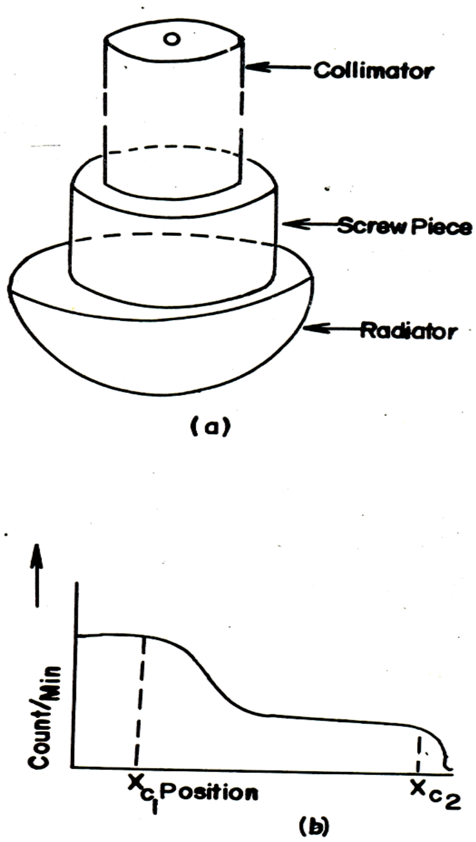

Fig.4. The radiator with the mount and the collimator;
(b) two plateaux for radiations with different energies.

VI. ACKNOWLEDGMENT

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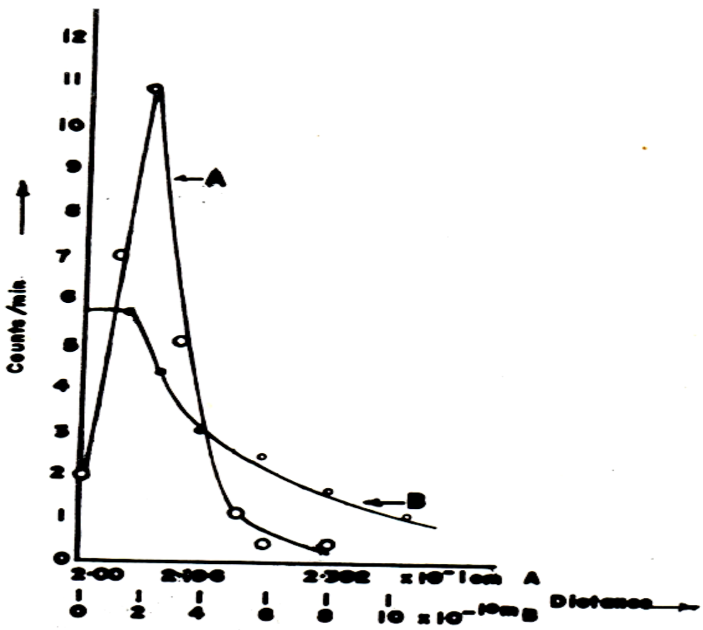

Fig.5. Count rate for Cs^{137} 0.-51 MeV.Beta. A with angle selector.

B without. The critical distance corresponding to an angle of 41.6^0 is indicated with the arrow.

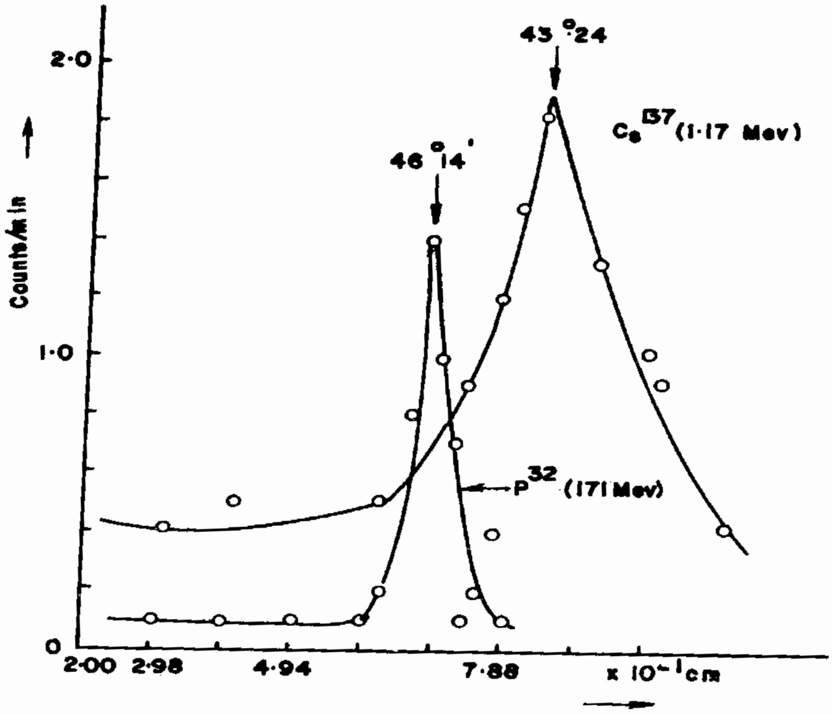

Fig.6. Count rate for P^{32} 1.71 MeV Beta and Cs^{137} 1.17 MeV using angle selector. The arrows indicate the critical distances which correspond to measured angles of 46.23° and $43^{\circ}24'$.

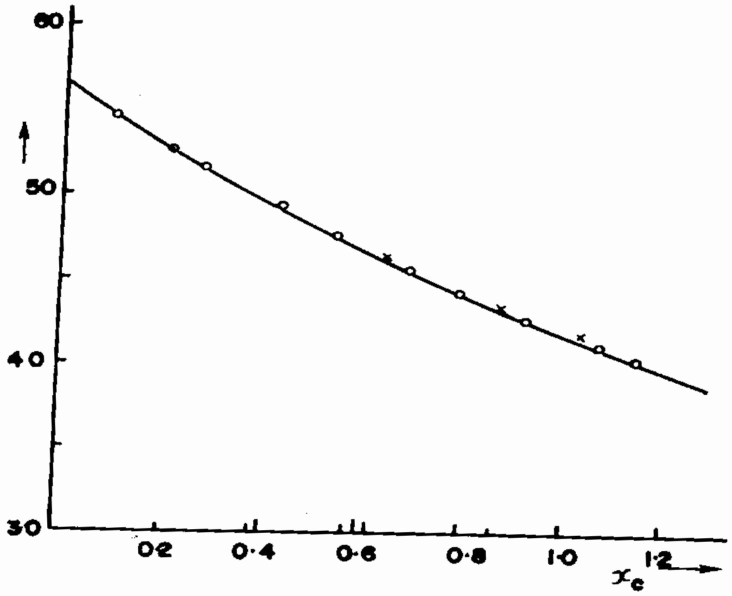

Fig.7. The relation between the Cherenkov angle and the measurable critical distance; o for theoretical points and x for experiment with laboratory available energies.

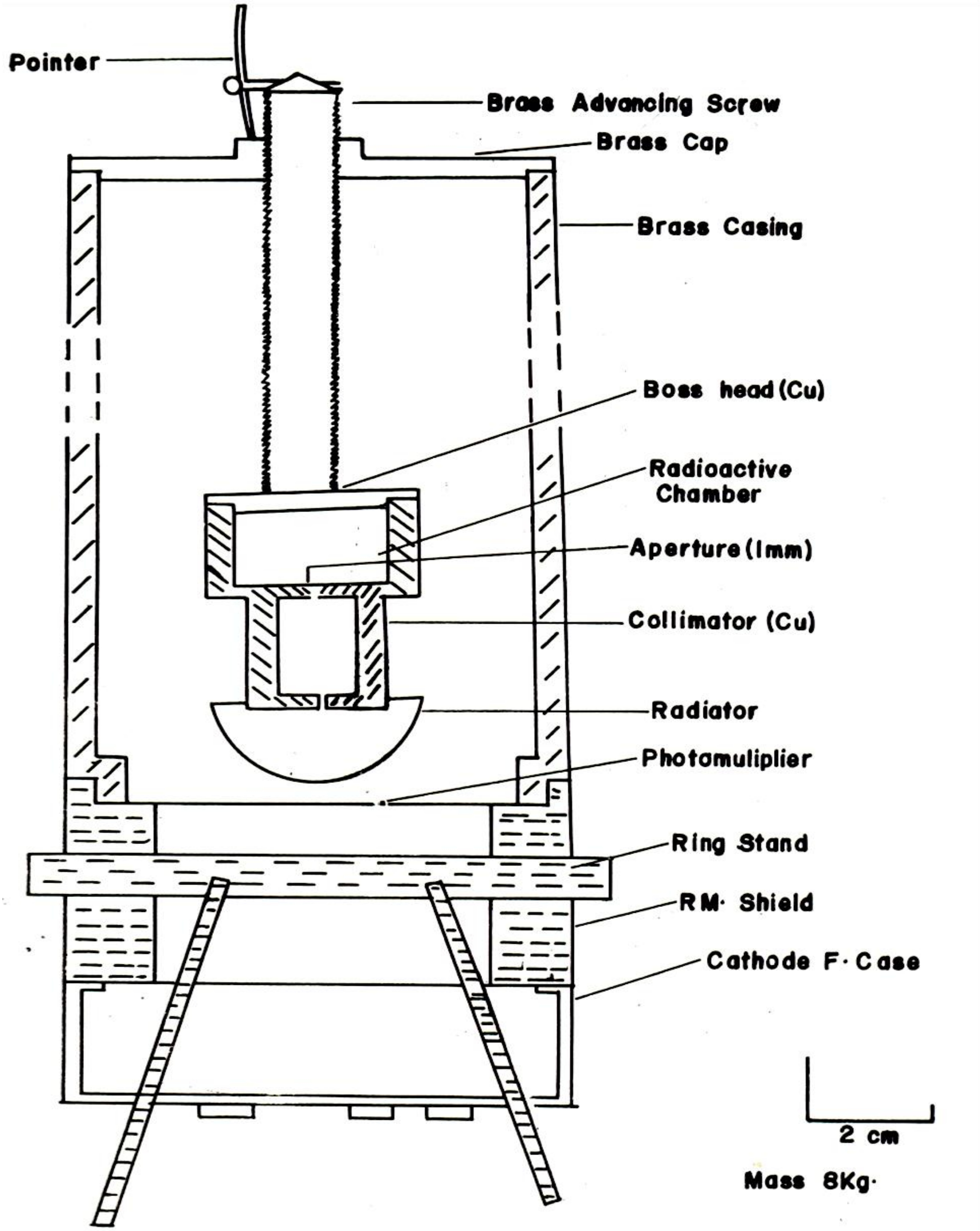

Fig. 8. The Cherenkov Radiation Detector

APPENDIX

TABLE I

Photoelectric Energy Relations (Hughes & Du Bridge 1932) [17]

Wavelength, (u m)	Frequency, CT Hz)	Photon Energy (J2,336) (eV)	Max Photo-electric yield uA/uW
0.10	3000	12.34	0.081
0.20	1500	6.17	0.162
0.25	1199	4.93	0.203
0.30	999	4.11	0.243
0.35	857	3.53	0.284
0.40	749	3.08	0.324
0.45	666	2.74	0.365
0.50	600	2.47	0.405
0.55	545	2.24	0.446
0.60	500	2.06	0.486
0.65	461	1. 90	0.527
0.70	428	1. 76	0.567
0.80	375	1. 54	0.649
0.90	343	1. 37	0.710
1. 00	300	1. 23	0.811

This paper thus aims at giving the account of the design of very simple but yet efficient Cherenkov radiation detector and how it may be modified to measure cosmic rays.

TABLE 1a

Possible radiator materials. Radiator Survey and Characteristics (Ritson, op cit.)

Material	Density (g cm $^{-3}$)	Index or refraction
Fluorochemcal FC75	1.77	1.276
Ethyl Alcohol	0.78	1.36
Water	1.00	1.33
Water and Sugar	1.40	1.33-1.50
Glycerine	1.26	1.47
CS_2	1.26	1.63

GASES

Name	Critical Temp. ^oC	Critical Pressure (Psi)
FC 75	228	230
CO_2	31	1000
Freon 13	29	550
Freon 13 B 1	66	550
Freon C 318	115	395

SOLIDS

Name	Density	Refractive index
FusedLucite(uv absorbing)	1.18	1.5
Quartz	2.65	1.46

Heavy Cherenkov Radiators

Name	Radiation Length (cm)	Density g cm^{-3}
Lead Glass	2.6	3.9
Carbon Tetraachloride	12	1.6
Tetra – bromoethane	3.6	2.96
79% Zinc-bromide Solution	5.0	2.50
Thallium Chloride	0.83	7.0

The theoretical threshold energy for various possible particles, their charge and rest mass in units of electron rest mass is shown in the table 1 (b) while the half life and the emitted particles, their energy in MeV for chosen radioactive sources is shown in table (c).

Table 1 (b)
Threshold Energies.

Name	Charge	Rest mass	$E_{threshold}$ (MeV)
Proton	e^+	1836	322
Neutron	0	1839	325
Alpha	e^{2+}	7344	1600
Beta	e^-	1	0.1538
Meson	$e\pm$	207	36
	$e\pm$	273	47
	$e\pm$	966	750

Table 1(c)
Half Life and emitted particles for three radiatctive materials

Source	Half Life	Particles and Energies (MeV)	
CS^{137}	2.3y	B 92%	0.51 MeV
		B 8%	1.17 Mev
		0.66 MeV	
CO^{60}	5.3y	1.37 MeV,	1.17 Mev;
		B 0.31MeV	
P^{32}	14.5 days	1.71MeV pure beta.	

It is clear from tables 1a, b and c that for a radiation detector in a non nuclear zone only radioactive sources are applicable.

TABLE VIII

Source Energy	Critical distance	FWhm (cm)	Measured angle (degrees)	Theoretical angle (degrees)	% resolution
Cs^{137}					
0.51MeV	0.2098(a)	0.1176	41.6	40	4
	0.2000(a)	0.1176	41.6	40	4
	0.2000(a)	0.1176	41.6	40	4
1.17MeV	0.8272	0.2849	$43^0 34'$	45	4
P^{32}					
1.71MeV	0.6802	0.0804	$46^0 14'$	47	2

(a) These were measured with the cylindrical radiator. The percentage resolution in angle is 4.

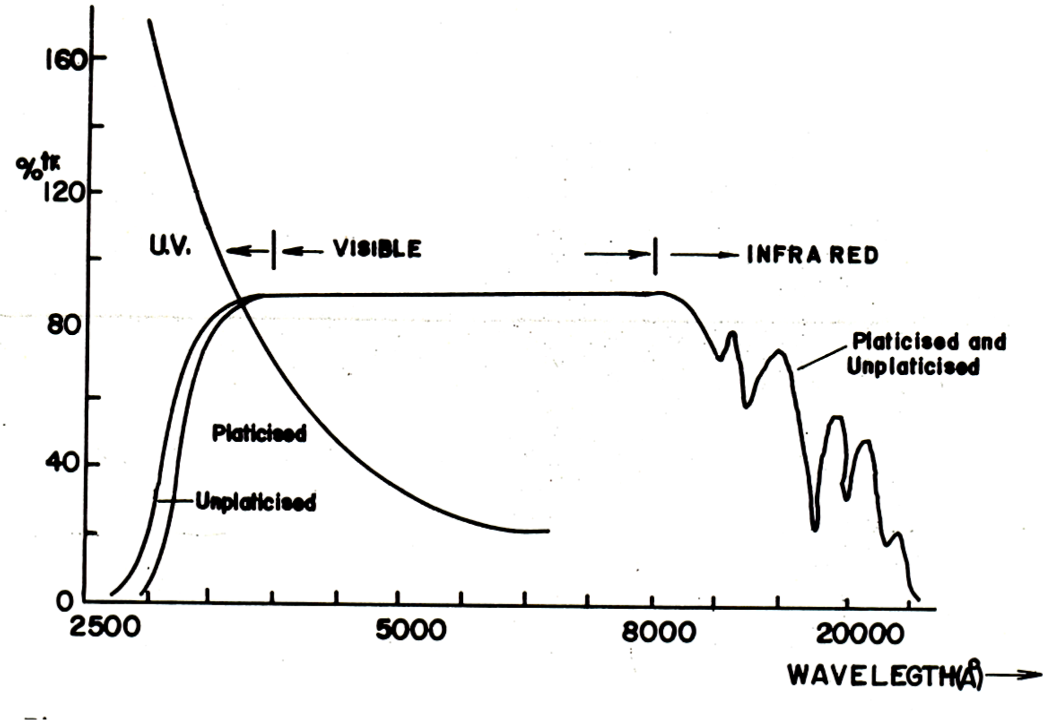

Fig. 9. Transmission characteristic Perspex and Lucite kindly supplied by the plastics division of I.C.I. Ltd., Herts. England. The Cherenkov spectrum is superimposed.

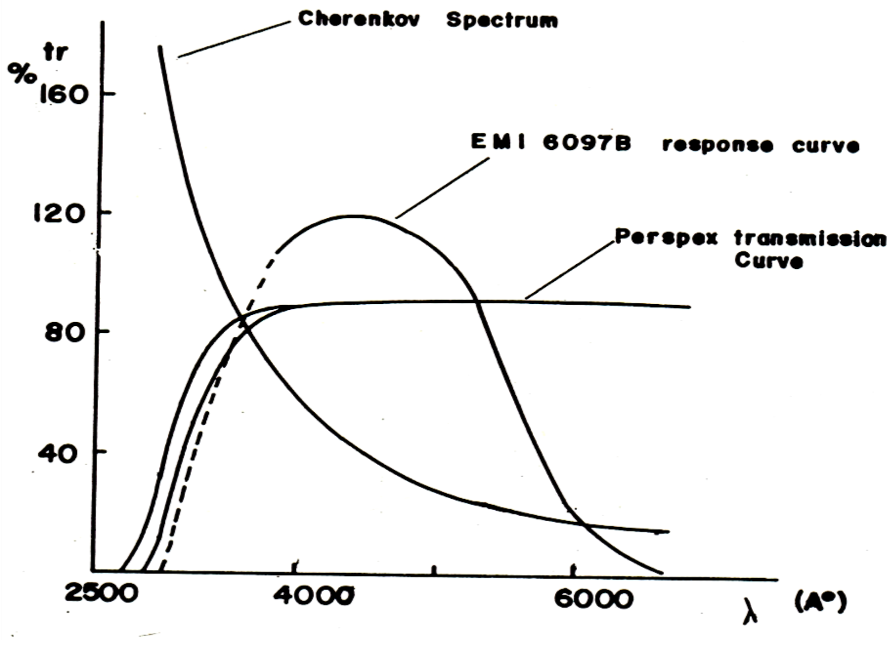

Fig. 10. Response curve for EMI tube 6097B provided by the Valve division of EMI electronics Ltd., Middlesex, England. The Cherekov spectrum and the transmission characteristics (Part) of Perspex are superimposed

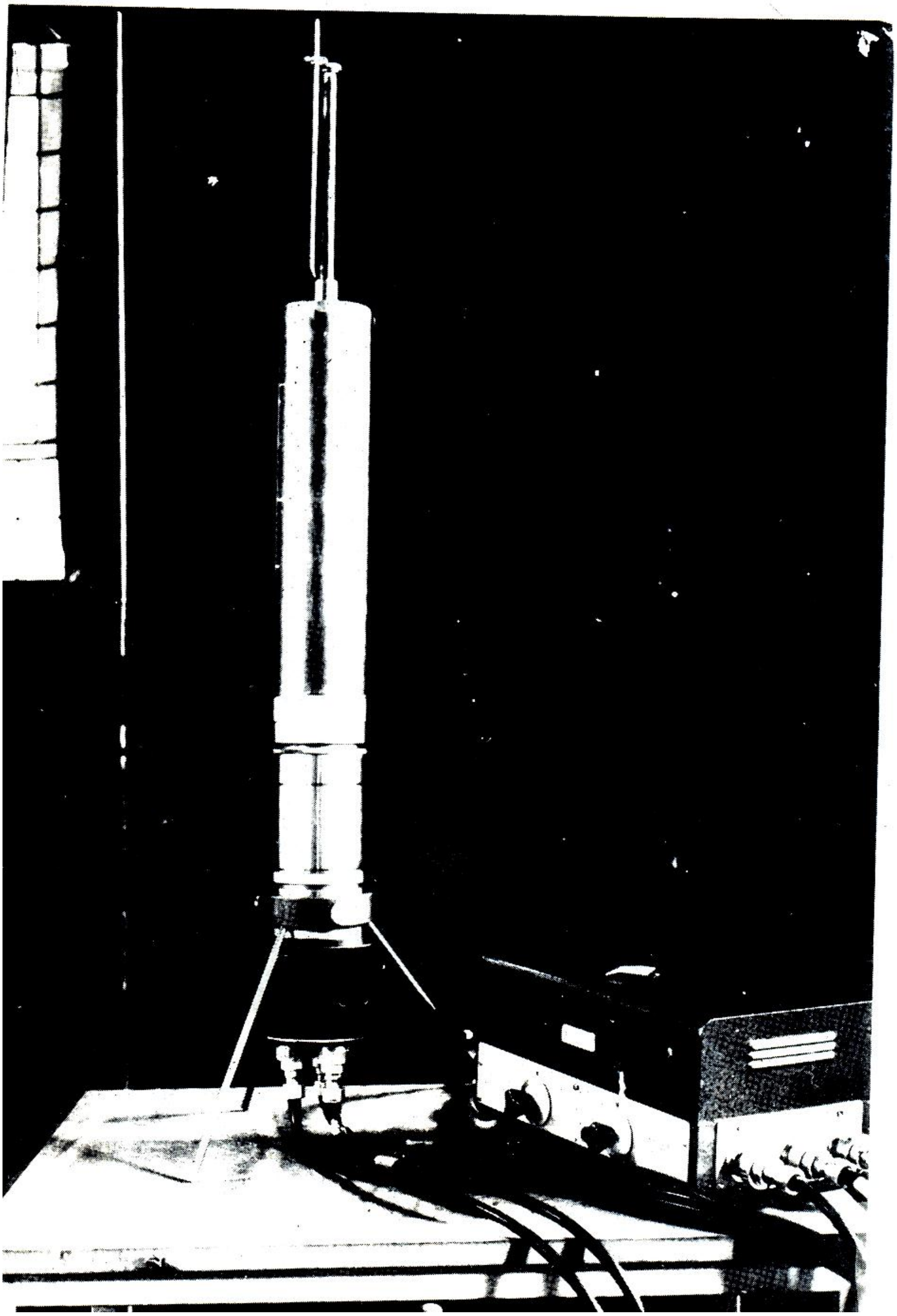

Plate I. Radiation detector with one of its ancillary equipments.

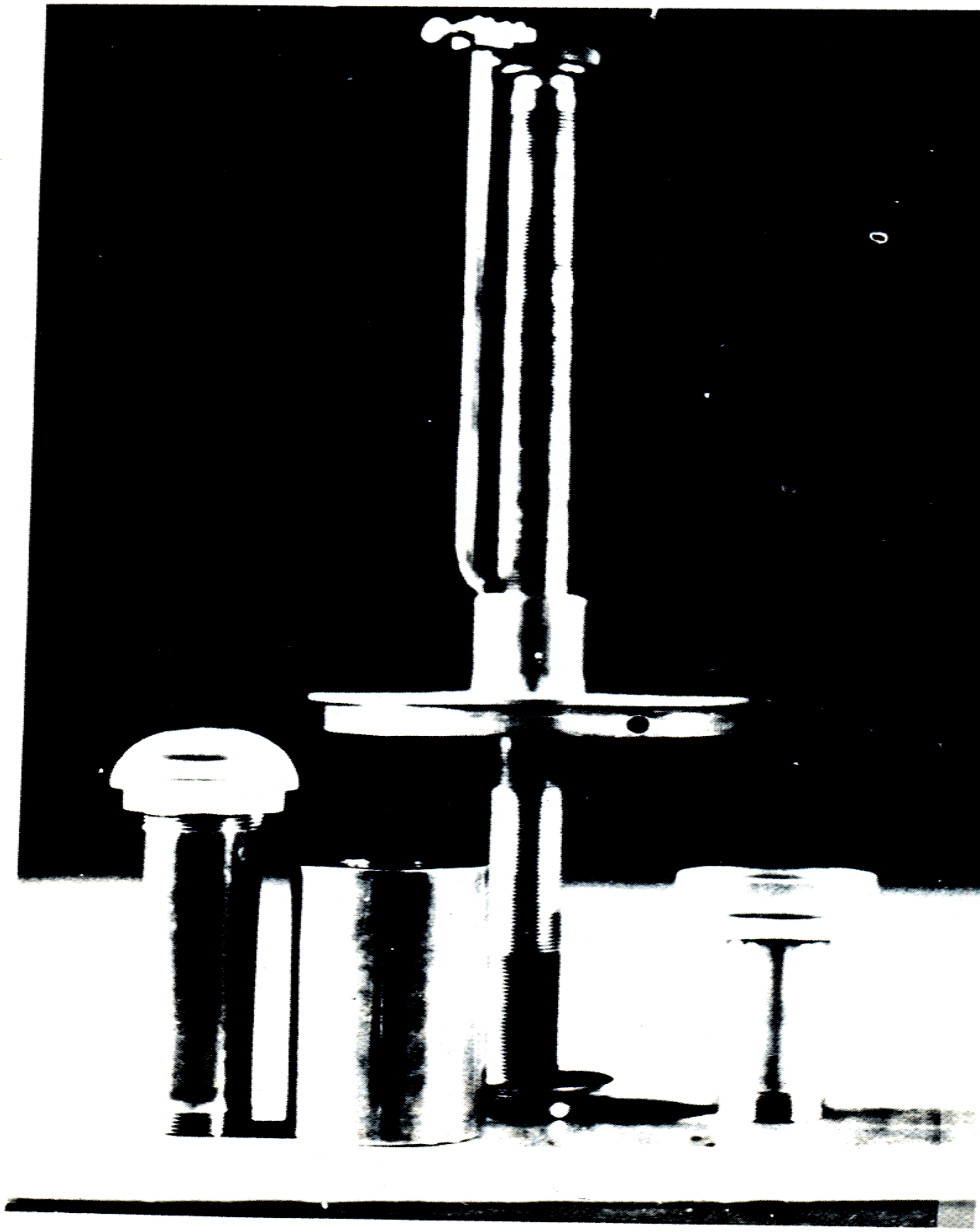

PLATE II: Two types of radiator shapes with advancing holder

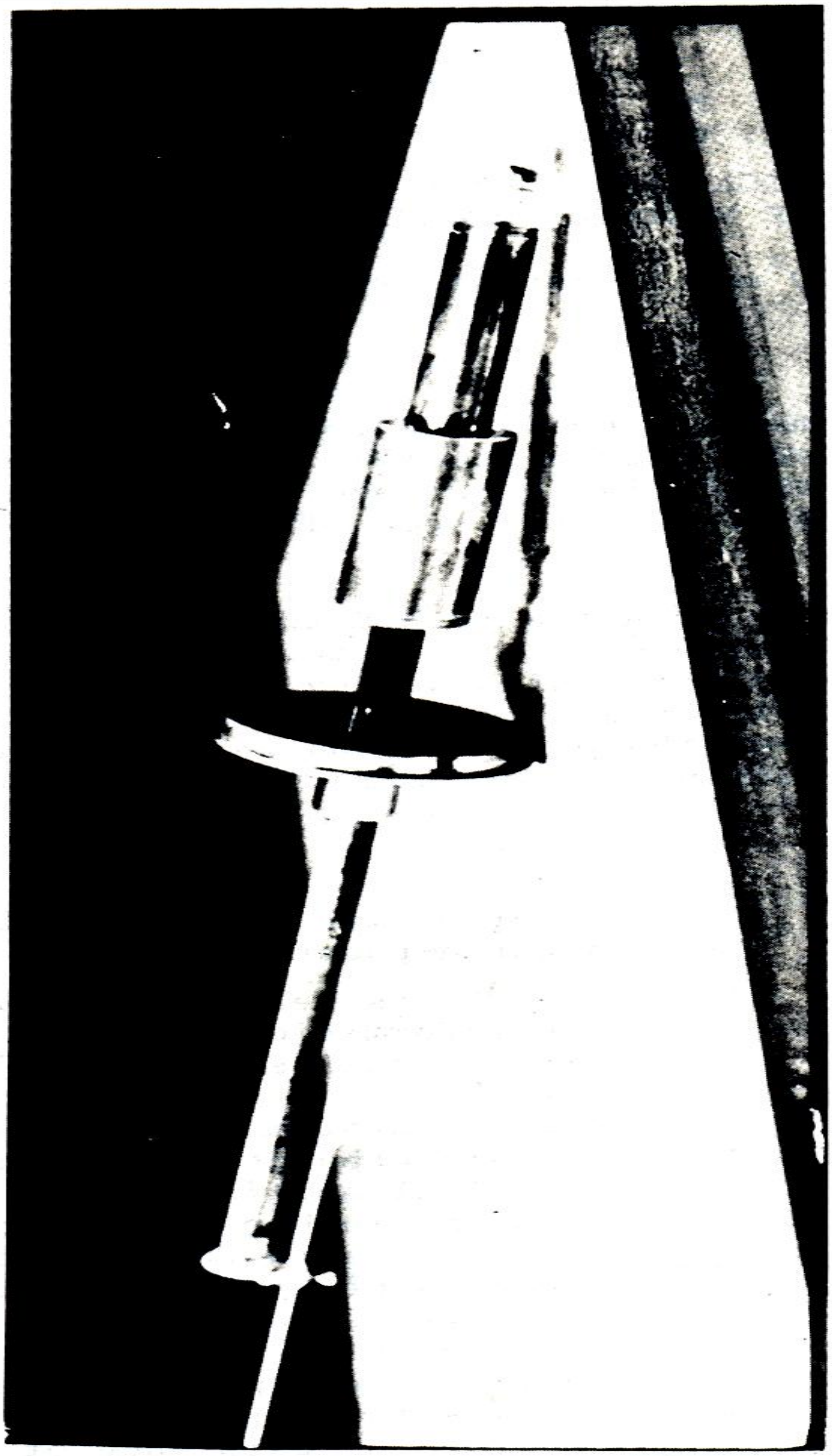

Plate III. Internal assembly in the detector housing