# THE ABSORPTION OF COSMIC RAYS

ANOMALIES OF THE ABSORPTION CURVE

OF

COSMIC RAYS IN LEAD

By

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A Thesis

Submitted to the Faculty of Arts and Science

in Partial Fulfilment of the Requirements

for the Degree

Master of Science

McMaster University

October 1952

MASTER OF SCIENCE (1952)
(Physics)

McMASTER UNIVERSITY
Hamilton, Ontario

TITLE: Anomalies of the Absorption Curve of Cosmic Rays in Lead

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NUMBER OF PAGES: 24, (with 5 figures)

SCOPE AND CONTENTS:

This thesis contains a brief discription of the apparatus, the procedure, and the results of an investigation of the absorption of cosmic rays in thin absorbers. The existence of an anomalous maximum at a thickness of 10.5 cm. of lead is reported, which is tenatively interpreted as being caused by the production of a penetrating ionizing radiation by a neutral radiation through some seemingly unknown process.

## ACKNOWLEDGEMENTS

The author wishes to acknowledge his gratitude to Professor F. Gulbis for the indispensable advice and helpful suggestions so freely given. Thanks are also due to Professor A. B. McLay for the facilities to carry out the investigations reported herein.

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## I-INTRODUCTION

From the study of the absorption of cosmic rays in matter it is a well established fact that the intensity does not decrease regularly with the thickness of the absorbing material. This is due to the existence of two fundamentally different types of radiation. Considering lead as the absorber, the intensity of the cosmic rays diminishes rapidly for the first 10 cm. thickness, and then falls off much more slowly with increase in thickness. That part which is readily absorbed by 10 cm. of lead is termed the soft component, while that which is little affected by this much lead and is absorbed only with difficulty is termed the hard component (1, 2).

The hard component consists chiefly of highly energetic mesons, of which there are at least two main groups. First the pi-mesons (3, 4), which may have a positive or negative electronic charge, and have a very short mean lifetime of the order $10^{-8}$ seconds (5, 6), and a mass of 285 electron masses (7). The positive pi-meson decays spontaneously into a lighter positive meson, termed mu-meson, and a neutral particle or particles. The negative pi-meson may either decay into a negative mu-meson and one or more neutral particles or be captured by a nucleus, followed by disintegration of the nucleus (3, 4, 8). The latter process is the more probable.

The positive and negative mu-mesons so formed have a mass of 215 electron masses (9) and also a short mean life of 2.2 microseconds (10). The positive mu-meson decays into a positive electron and one or more neutral particles (11). The negative mu-meson may decay into a negative electron and one or more neutral particles, or be captured by a nucleus. The former process is the more likely for low Z absorbers (Z less than 6) and the latter more likely for high Z absorbers (12).

Besides the above mentioned particles, the hard component is also believed to consist of a small number of fast protons, a few neutrons, and some electrons as well as photons of extremely high energy. In addition to these, there has been reported the existence of mesons with masses quite distinct from those of either the pi or mu, both heavier (15, 16) and lighter (13, 14), which may contribute to the hard component.

The soft component, on the other hand, consists of chiefly positive and negative electrons, and about an equal number of photons (17). In addition there are possibly a small number of slow mesons, neutrons, protons, and heavier particles. The electrons of the soft component originate in two ways, first from the decay of mu-mesons (<u>decay electrons</u>) and secondly from the result of direct impact of the fast mesons with orbital electrons (<u>knock-on electrons</u>) (18). These electrons interact with the radiation and nuclear fields of the surrounding matter producing a photon which may in turn materialize, producing an electron pair, in the vicinity of a nucleus. This multiplication of electrons maintains the electron concentration and produces events known as showers (19).

The absorption curve has been thoroughly studied for thick absorbers (20, 21), and the shape of the curve well established at large thicknesses. Also studies have been made of the effects under thin absorbers separating the shower-producing particles from the non-shower producing particles; i.e., the electronic and mesonic components have been studied separately (22, 23, 24). The general shape of the curve is not in doubt but some observers have reported anomalies in the curve for thin absorber thicknesses (22, 23, 25, 26, 27). Others, on the other hand, looking explicitly for these anomalies, have failed to find them (28). Hence it was felt that a thorough investigation should be carried out on the absorption curve for low absorber thicknesses and to determine the cause of any anomalies found.

## II-THE TELESCOPE

A simple diagram of the telescope, used for the present absorption experiments, is shown in Figure 1. The geiger counters used were of the self-quenching type. They were constructed of 1 mm. thick brass tubing, 40 cm. long and 2.5 cm. in diameter, with a 0.1 mm. tungsten anode wire of an active length of 35 cm. The tubes were coupled mechanically by means of copper tubing to form trays with six tubes in each tray. Hence the gas characteristics of each tube in any one tray were the same. The filling consisted of one part by volume of alcohol vapour and nine parts of dry argon at a pressure of 10 cm. of Hg. The plateaus were about 75 volts wide with a slope well under 1%, thus the effects on the counting rate, caused by fluctuations in the stabilized high tension supply for the geiger tubes, would be negligible.

The telescope was defined by three trays as shown in Figure 2. The trays were spaced a distance of 20 cm. between each one. This gave an aperature of $44^{\circ}$ in the lateral direction and $81^{\circ}$ in the longitudinal.

The support for the absorbers was constructed of 8 inch concrete blocks, with horizontal iron plates arranged so that lead could be placed in positions above the first, second and third trays as shown in Figures 1 and 2. The counter trays were held in position by a wooden rack (not shown in the diagram).

The electronics for the telescope were of conventional design and have been thoroughly discussed elsewhere (29). A simple block diagram is shown in Figure 1. The resolving time of the Rossi coincidence circuit is of the order of 130 microseconds while that of the scalar and pen-recorder is 0.05 seconds.

## III-THE EXPERIMENT

Before the experiment proper was performed a preliminary test was made of the electronics. The apparatus was allowed to operate for a period of time with the high tension to the geiger tubes off, to check for spurious pulses developed in the electronics. The results were negative and, therefore, the experiment proper was proceeded with. The experiment was performed in five parts which will be termed as runs.

For the first run the telescope was not as shown in Figure 2, but consisted simply of two trays, numbers 1 and 3, in coincidence. The thickness of lead in position A was varied in 2.5 cm. steps up to a total thickness of 27.5 cm. of lead, with no absorber between the counter trays.

This run, however, was subjected to a relatively high error due to a high spurious counting rate (174 counts per hour). The spurious counts arise from two sources; first from side showers, i.e., two particles from outside the telescope beam passing through the two trays simultaneously, causing a coincidence; and secondly from accidentals, i.e., pulses arising from independent events at the two trays arrive within the resolving time of the coincident circuit, causing a count to be registered. The error was reduced by placing a third tray in coincidence as shown in Figure 1. This reduced the spurious counts from 7% of the true rate to less than 1%. The other four runs were carried out with this geometry.

The second run was similar to the first in that the lead in position A was varied, with no absorber in position B or C. In this run the variation of the absorber was in smaller steps and the final thickness less, in order to investigate more completely the first part of the curve. Checks were made throughout the run of the starting potentials of the geiger trays to determine whether or not there was any leakage. There was no measurable change. Also to assure that there was no drift in the electronics, readings were taken from time to time throughout the run with a 5 cm. lead absorber. The values so obtained agreed within statistical fluctuation. As a further precaution against changes in the absorption curve being instrumental, the absorber thickness was varied randomly.

The third run was carried out in the same manner as the second except the absorber was placed in position C instead of A, with no lead in positions A and B.

The fourth run was performed by varying the absorber in position A with a fixed absorber of 5 cm. of lead in position C. In this run the triple coincidences were registered by the pen-recorder, as well as the scalar, and the results so obtained were analysed to check that the events were random.

The fifth run was much like the fourth with an additional fixed absorber of 5 cm. of lead in position B.

## IV-RESULTS

The results of the five runs are given in the tables on pages 9 - 13, and graphs following page 24. The uncertainty associated with the counting rates is simply the standard deviation.

The actual total absorber consisted of the lead and other incidental materials. In all cases there were the iron supports for the lead. Also runs one, four and five were carried out under a 40.7 gm./cm.$^2$ concrete ceiling, while runs two and three were performed under a $\frac{1}{2}$ inch wooden ceiling with standard tar and stone roofing.

For the iron and concrete ceiling the equivalent lead thickness was computed according to the difference in densities. This has been included in the thickness of absorber given in the tables and in the graphs, except in Figure 5 (a). This equivalence is true only for particles which lose their energy through collisions, hence considering the electronic component the result is in error. In the case of Figure 5 (a) where the absorber thickness is expressed in shower units (0.36 cm. for lead and 1.26 cm. for iron) the thickness of the iron has been converted to shower units and added to that of the lead.

The results of the first run (Table I, Figure 3) shows evidence for the existence of a maximum between 10 and 14 cm., followed by another maximum between 23 and 26 cm., with a drop or change in slope at 26 cm. Fenynes and Haiman (25) reported maxima at 18.2 and 26.6 cm. of lead. While George and Appapillai (26) found a plateau in the absorption curve between 10 and 17 cm. Also Aiya (24) has reported a drop in the curve between 21 and 24 cm. of lead, but no change in slope.

In the first run, as in the work of the above experimenters the points were too widely spaced. Also the correction for the concrete ceiling introduces an error in the estimated thickness of absorber. Hence the second run was performed to determine more precisely the shape of the curve up to 15 cm. of lead. The results of the second, third, fourth and fifth runs are given in Tables II, III, IV, V, and in curves I, II, III, IV, of Figure 4 in the order mentioned.

The second run (curve I of Figure 4) shows maxima at 0.8 and at 10.5 cm. of lead. The third run (curve II) shows no maximum at 0.8 cm. of lead. The fourth run again shows a maximum at 10.5 cm. of lead while the fifth run shows no maximum at this thickness.

TABLE I

Results of the first run; absorber in position A varied.

| Absorber Thickness cm. of Pb. | Hours of Observation | Total* Counts | Coincidences per Hour |
|---|---|---|---|
| 4.4 | 45.4 | 113650 | 2500 ± 7 |
| 6.9 | 17.0 | 39094 | 2300 ± 12 |
| 9.5 | 23.9 | 53921 | 2260 ± 10 |
| 12.0 | 23.25 | 53136 | 2285 ± 10 |
| 14.6 | 23.0 | 52026 | 2260 ± 10 |
| 17.1 | 20.8 | 45488 | 2190 ± 11 |
| 19.8 | 24.5 | 53179 | 2175 ± 10 |
| 22.2 | 19.0 | 41186 | 2170 ± 11 |
| 24.7 | 25.6 | 55936 | 2190 ± 9 |
| 27.3 | 16.0 | 33632 | 2100 ± 11 |
| 29.8 | 24.5 | 51003 | 2060 ± 9 |
| 32.3 | 27.6 | 55852 | 2025 ± 9 |

* Corrected for accidentals.

TABLE II

Results of the second run; absorber in position A varied, with no absorber in positions B or C.

| Absorber Thickness cm. of Pb. | Hours of Observation | Total Counts | Coincidences per Hour |
|---|---|---|---|
| 0 | 18.0 | 53400 | 2960 ± 13 |
| 0.8 | 27.8 | 85676 | 3085 ± 10 |
| 1.5 | 21.8 | 65784 | 3020 ± 10 |
| 2.1 | 17.25 | 50108 | 2910 ± 13 |
| 3.3 | 17.0 | 45864 | 2700 ± 13 |
| 5.8 | 16.1 | 39264 | 2450 ± 12 |
| 6.8 | 12.0 | 27616 | 2300 ± 14 |
| 8.3 | 12.75 | 28652 | 2250 ± 13 |
| 9.8 | 12.0 | 28044 | 2340 ± 14 |
| 10.8 | 12.0 | 27980 | 2330 ± 14 |
| 11.8 | 11.5 | 26576 | 2310 ± 14 |
| 12.4 | 12.2 | 27484 | 2260 ± 14 |
| 13.3 | 12.0 | 26532 | 2210 ± 13 |
| 15.5 | 11.6 | 25404 | 2190 ± 14 |

TABLE III

Results of the third run; absorber in position C varied, with no absorber in positions A or B.

| Absorber Thickness cm. of Pb. | Hours of Observation | Total Counts | Coincidences per Hour |
|---|---|---|---|
| 0.5 | 11.2 | 31024 | 2770 ± 16 |
| 1.9 | 12.0 | 30084 | 2510 ± 14 |
| 3.3 | 12.75 | 31188 | 2450 ± 14 |
| 4.2 | 11.8 | 27636 | 2340 ± 14 |
| 5.5 | 12.1 | 27300 | 2260 ± 14 |
| 6.9 | 11.4 | 24748 | 2180 ± 14 |
| 8.3 | 11.6 | 23936 | 2060 ± 14 |

TABLE IV

Results of the fourth run; absorber in position A varied, with a fixed absorber of 5 cm. Pb. in position C and no absorber in position B.

| Absorber Thickness cm. of Pb. | Hours of Observation | Total Counts | Coincidences per Hour |
|---|---|---|---|
| 4.4 | 20.8 | 44452 | 2130 ± 10 |
| 6.9 | 19.1 | 39712 | 2080 ± 10 |
| 9.4 | 24.8 | 51324 | 2070 ± 9 |
| 10.7 | 18.4 | 38284 | 2080 ± 10 |
| 11.9 | 20.6 | 42074 | 2040 ± 10 |
| 12.9 | 18.7 | 37192 | 1990 ± 10 |
| 14.4 | 42.4 | 83074 | 1970 ± 7 |
| 17.9 | 18.1 | 35248 | 1950 ± 10 |

TABLE V

Results of the fifth run; absorber in position A varied, with fixed absorbers of 5 cm. Pb. in positions B and C.

| Absorber Thickness cm. of Pb. | Hours of Observation | Total Counts | Coincidences per Hour |
|---|---|---|---|
| 4.4 | 47.4 | 95080 | 2010 ± 7 |
| 6.9 | 22.0 | 43168 | 1965 ± 9 |
| 9.4 | 48.0 | 91488 | 1910 ± 6 |
| 11.9 | 18.7 | 36076 | 1930 ± 10 |
| 14.4 | 24.6 | 47104 | 1920 ± 9 |
| 16.9 | 24.0 | 44576 | 1900 ± 9 |

## V-INTERPRETATION

The shape of the curve of Figure 3 will not be discussed because of the uncertainties mentioned previously. However, the curves of Figure 4 yield some interesting facts.

With an increase in absorber thickness a decrease in intensity would be expected. However, curve I shows an initial increase before the intensity begins to fall off at thickness greater than 0.8 cm. of lead, followed by a further increase beginning at about 9 cm. of lead. It appears as if some event has taken place in the lead in position A to produce an increase in the number of cosmic ray particles, detectable by the telescope, over that of the number of normal particles, (i.e., those particles impinging on the absorber from above). These secondary particles would then traverse the instrument and be recorded. The first maximum does not appear in curve II for the reason that with the lead in position C, any detectable particle produced in the lead would pass only through tray #3. Hence since a triple coincidence is required between the three trays to produce a count, the particle would not be recorded. Following this line of thought, the difference between curve I and curve II would indicate the magnitude of the effect in the lead. This is given in Figure 5 (a). Unfortunately the construction of the telescope prevented using absorber thicknesses greater than 8.5 cm. in position C. However, and indication of the effect at 10.5 cm. is given by the increase of the curve over that shown dotted. This increase, both for curve I and III, is shown in Figure 5 (b).

The interpretation of these maxima as being due to a multiplication of the particles in the cosmic ray beam, through some event taking place in the lead by which a single particle gives rise to a number of particles, must be ruled out because of the relatively long resolving time of the coincidence circuit. In order for the telescope to count particles separately, they must traverse the telescope with a delay time between them greater than 130 microseconds. Such a long delay in associated particles from one event, is far beyond experimental experience (30, 31). Therefore, these maxima can hardly be caused by any detectable particles such as electrons, mesons, or protons.

To make this point clearer, consider the possibility of the first maximum being caused by an electron-initiated shower. Without the lead the normal electron would traverse the telescope and produce one count. With the lead in place the electron radiates a photon which produces an electron pair, thereby increasing the number of detectable particles. However, the two particles so formed pass through the telescope with a very short delay, well within the resolving time of the coincidence circuit. They will, therefore, produce only one count, instead of two and the number of counts would not be increased by this process. The same argument holds if the initial particle is a meson or any other ionizing particle, which gives rise to two or more detectable particles.

However, the reason for the first maximum can be explained by a well known phenomenon. The geiger counters have a low efficiency for the detection of photons. But placing lead in the path of the cosmic ray beam increases the probability of the photons to materialize and the electons so formed are readily detected by the telescope. Thus the curve of Figure 5 (a) is the Rossi transition curve showing the frequency of photon-initiated showers, containing at least one particle, as a function of the thickness of the shower producing medium, in this case lead. Hence the abscissa is expressed in shower units, which is that distance in which a very fast electron loses, on the average, 0.5 of its initial energy. This result compares favourably with that of Rossi and Janossy (32) who were studying the phenomenon directly. Also shown in Figure 5 (a) are the theoretical curves giving the average probability of a photon-initiated shower, containing at least one electron, as a function of the depth, assuming either a Polya or Poisson fluctuation formula. The agreement is no better for one than the other but is quite satisfactory, considering the error introduced by subtracting the two curves.

The second maximum on the other hand has not been observed previously, and an explanation is not as readily obtained. Again it is unreasonable to assume that the increase in counting rate is produced by some multiplication process of the normal particles, because of the relatively long resolving time. Thus mesons, electrons and protons must be ruled out as the causative agent. It, therefore, seems that the increase is due to some non-ionizing particles, normally undetectable, which produce one or more ionizing particles, detectable by the telescope, in a manner analogous to the reason for the first maximum. The results show that both the normal and secondary particles are very penetrating, since the maximum does not begin until a thickness of 9 cm. of lead is reached, and since it still exists, as shown in Figure 5 (b), when 5 cm. of lead is placed in position C. In this latter case the ionizing particles are produced in A and then must pass through the absorber in position C before causing a triple coincidence.

Accounts are found in the literature of the production of a penetrating radiation by non-ionizing particles. Tabin (33) as well as Schein and Wilson (34) carried out experiments, the results of which are interpreted as the production of mesons by photons. These authors have assumed that the meson is produced by a direct interaction of the photon with a nucleon. However, the results are not compatable with those reported here. Tabin found that saturation in the production of the mesons in lead was reached at a thickness of a few centimeters, while in the present work the maximum was reached at a thickness of 10.5 cm. This seems to rule out a direct interaction between photons and nucleons as being the event causing the maximum.

A seemingly different type of production of penetrating ionizing particles by neutral particles has been reported by Clay (35). He claims that the production is proportional to the number of nuclei and not to the number of nucleons. This indicates an event analogous to pair-production rather than a direct interaction with the nucleons. Also, he stated that the maximum of production was reached with 10 cm. of lead, and that the range of the secondary particles did not exceed about 10 cm. in heavy material. More recently Boehmer and Bridge (36) have reported the existence of a neutral particle with a mean free path of 12.7 $\pm$ 2.7 cm. in lead, which produces penetrating showers. The mean free path is defined here, as the mean thickness in which an event takes place, leading to the production of a secondary ionizing particle.

There are many photographs in the literature (37, 38, 39) as well as results of counter experiments (40) which are interpreted as a penetrating pair of ionizing particles (mesons) produced by a neutral particle (photon).

Christy and Kusaka (41) have calculated the probability of pair-production of mesons with a spin of 1 by photons and found that at energies greater than $10^{14}$ e.v. meson pair-production is more probable than pair-production of electrons. But for mesons of spin 0 or $\frac{1}{2}$ the predicted pair-production is practically negligible even at extremely high energies. Since the spin of the mu-meson is believed to be either 0 or ½ (42), production of a mu-meson pair is highly improbable. However, the spin of the pi-meson is though to be 1, hence the production of a pi-meson pair is probable on the basis of spin. On the other hand to account for the increase in intensity, observed underneath 10.5 cm. of lead, by this process would necessitate that about 7% of the total radiation be photons of energy greater than $10^{14}$ e.v. The existence of such a large per cent of high energy photons at sea level is unreasonable (43).

Also if the second, or high energy, maximum was produced by materialization of photons as was the first, it would be natural that the shape of the two curves of Figure 5 would be the same; they are decidedly not.

Curve 5 (a) shows the increase of the probability of materialization as the number of nuclei in the path of the beam is increased until the probability reaches a maximum, beyond this point the curve decreases. This decrease is caused by an exponential absorption of the secondary particles as the absorber thickness is increased. Curve 5 (b), on the other hand, is almost symmetrical about the maximum and does not show an exponential absorption. Thus we must reject photons as the particle responsible whether by direct interaction or by pair-production.

Another difficulty associated with the high energy maximum is that the width of the maximum appears to be of the order of 5 cm. in lead, but placing 5 cm. of lead in the path of the secondary particles reduces their intensity only by about 60%, as shown in Figure 5 (b), and that the penetrating power of this secondary radiation is between 5 and 10 cm. of lead, shown by curves III and IV of Figure 4.

However, the curve of Figure 5 (b) may not be the true shape for the curve representing the phenomenon discussed here. For although the other experimenters, (25, 26, 28), because of the procedure employed (placing the absorbers between the coincident counters), failed to detect the maximum reported here, they did detect other anomalies within or close to this region which may have some bearing on the shape of this maximum.

Also the results of curves III and IV must not be over emphasized since they were carried out under a concrete roof, the exact effect of which is not known.

One further conclusion may be drawn from the results. Namely that the phenomenon is not a direct collision with, or disintegration of a nucleus by a neutral particle. This is seen by the fact that the maximum number of events occur at a thickness of 10.5 cm., while the collision length, or mean free path of a particle, corresponding to the geometrical cross-section of lead nuclei is about 14 cm. This seems to rule out the possibility of the particles being produced by the collision of a neutron with a nucleus.

The indications are that a penetrating non-ionizing radiation produces one or more penetrating ionizing particles by some seemingly unknown process.

This result is particularly interesting in the light of recent reports of the existence of a second maximum in the Rossi transition curve (44, 45). There may be some connection between that maximum and the one reported here.

However, before more definite conclusions may be drawn, further experimentation is required.

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# VIII-FIGURES

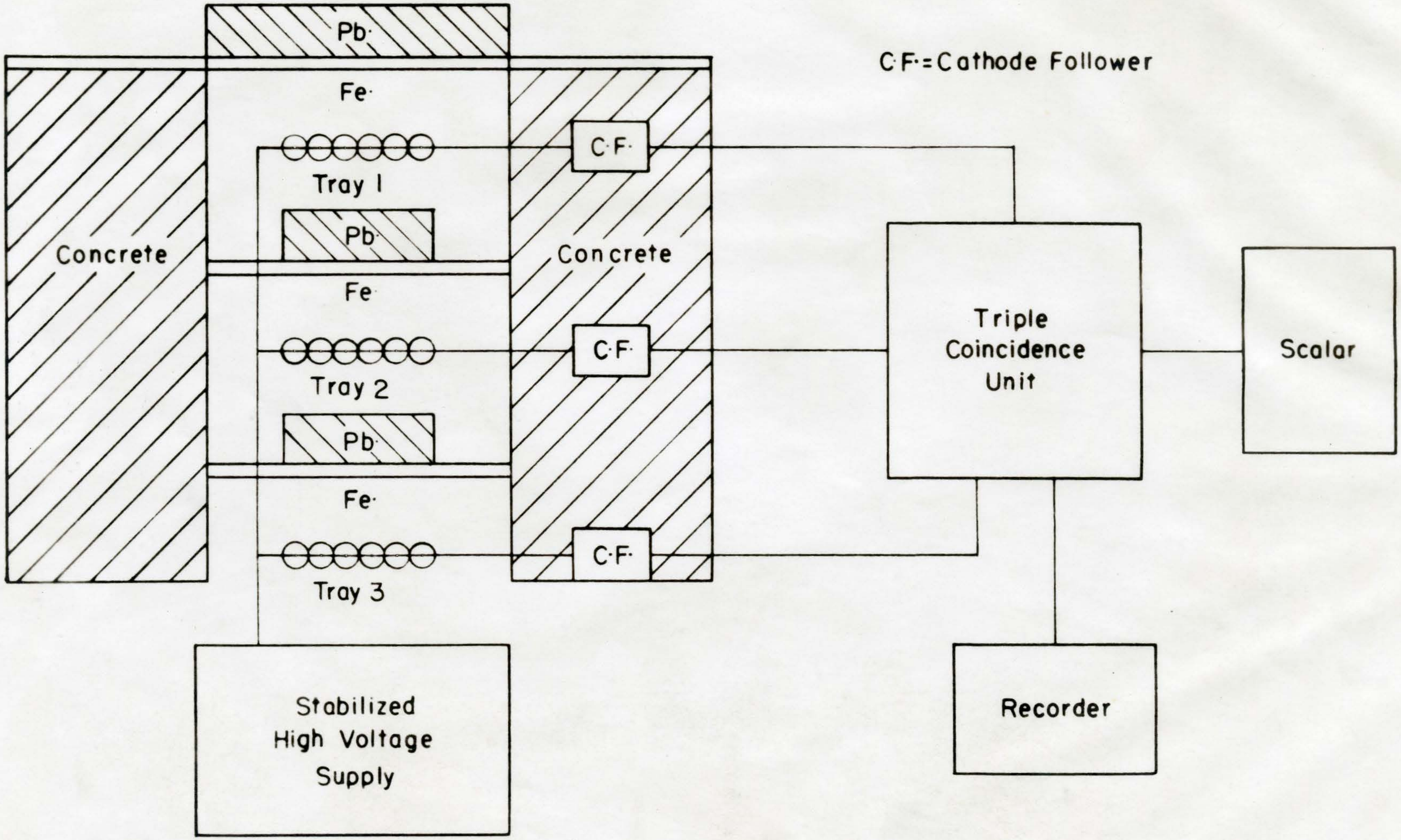


FIGURE I· A simple diagram of the telescope & associated parts

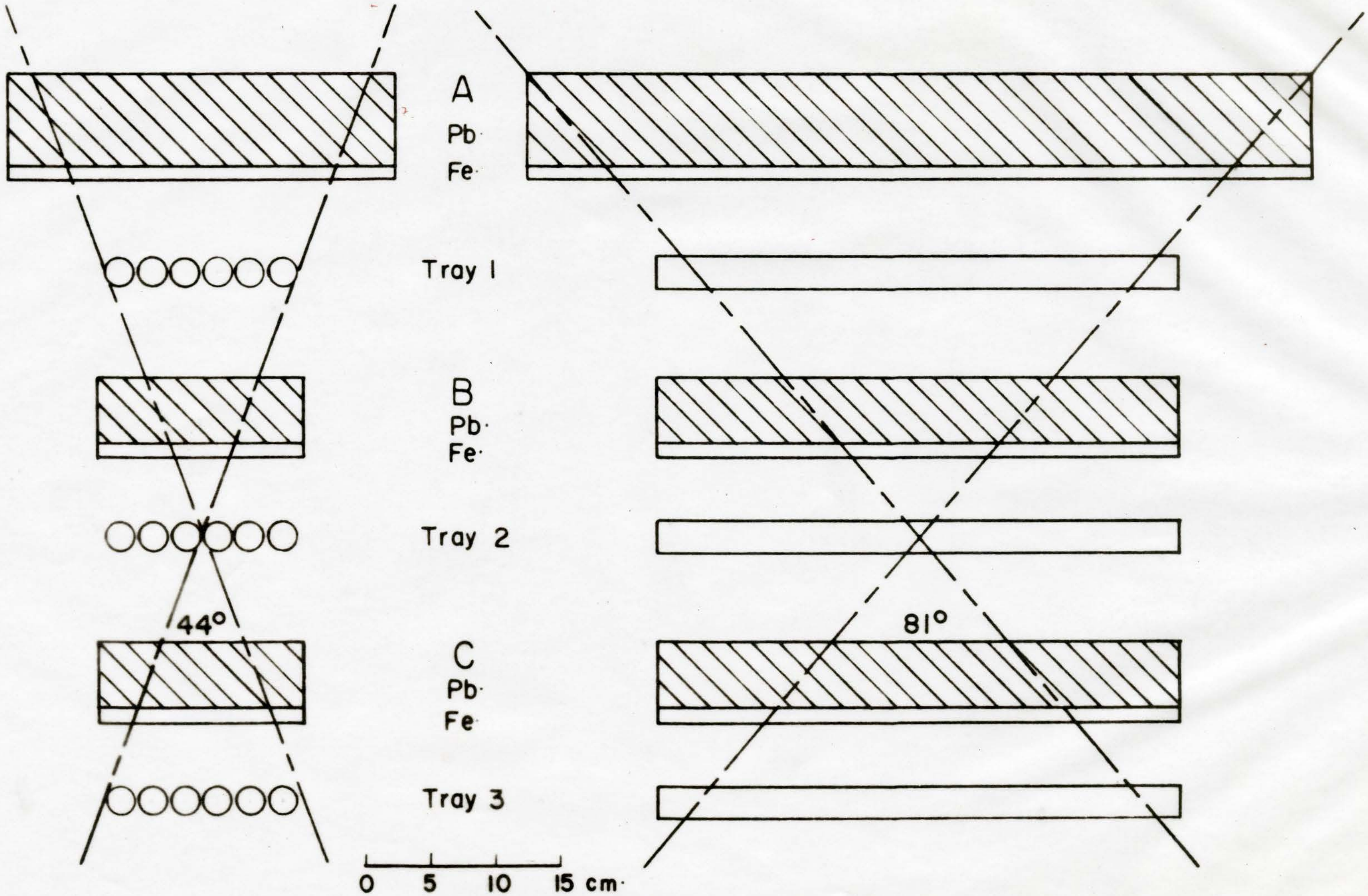


FIGURE 2 The telescope geometry

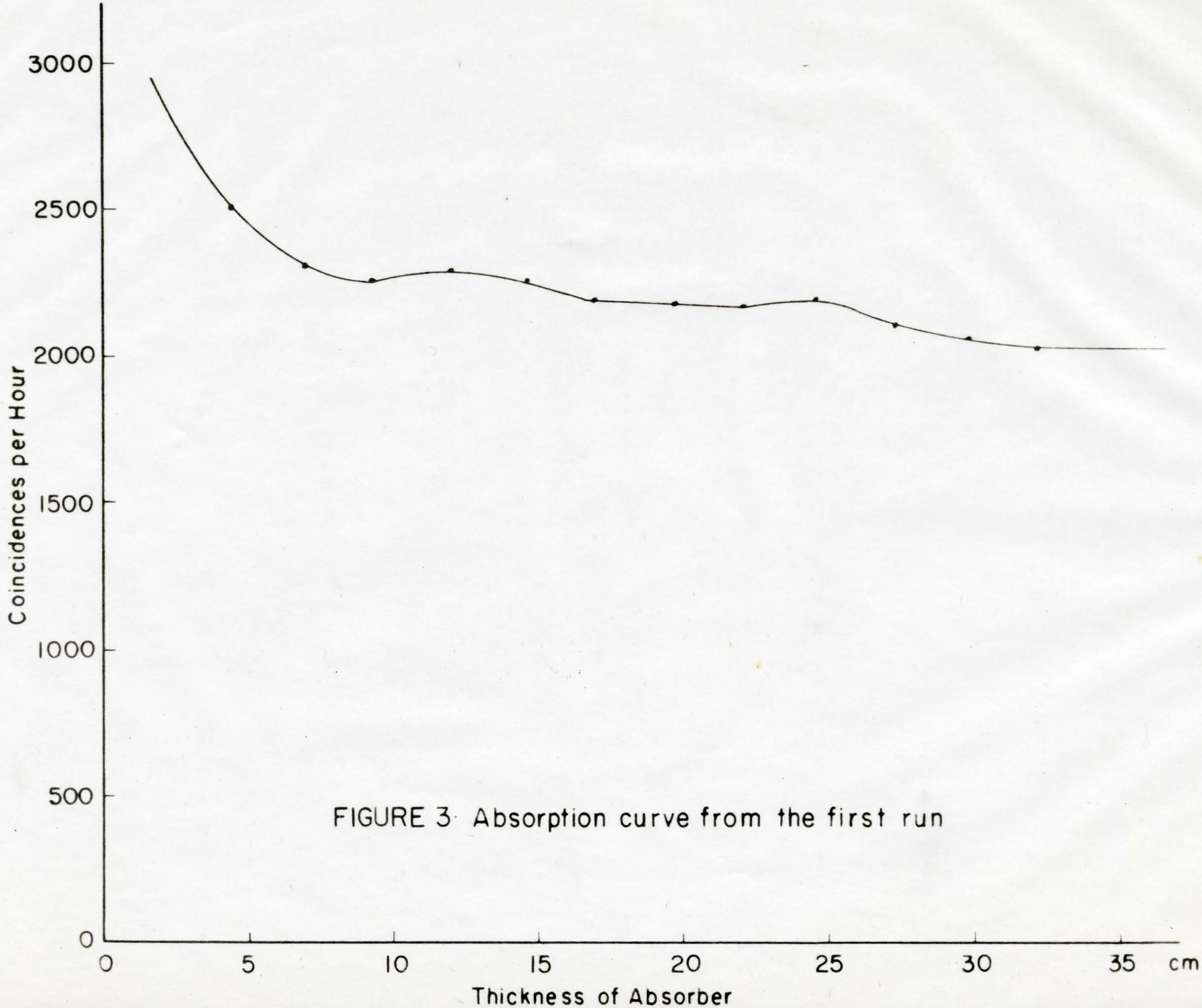


FIGURE 3· Absorption curve from the first run

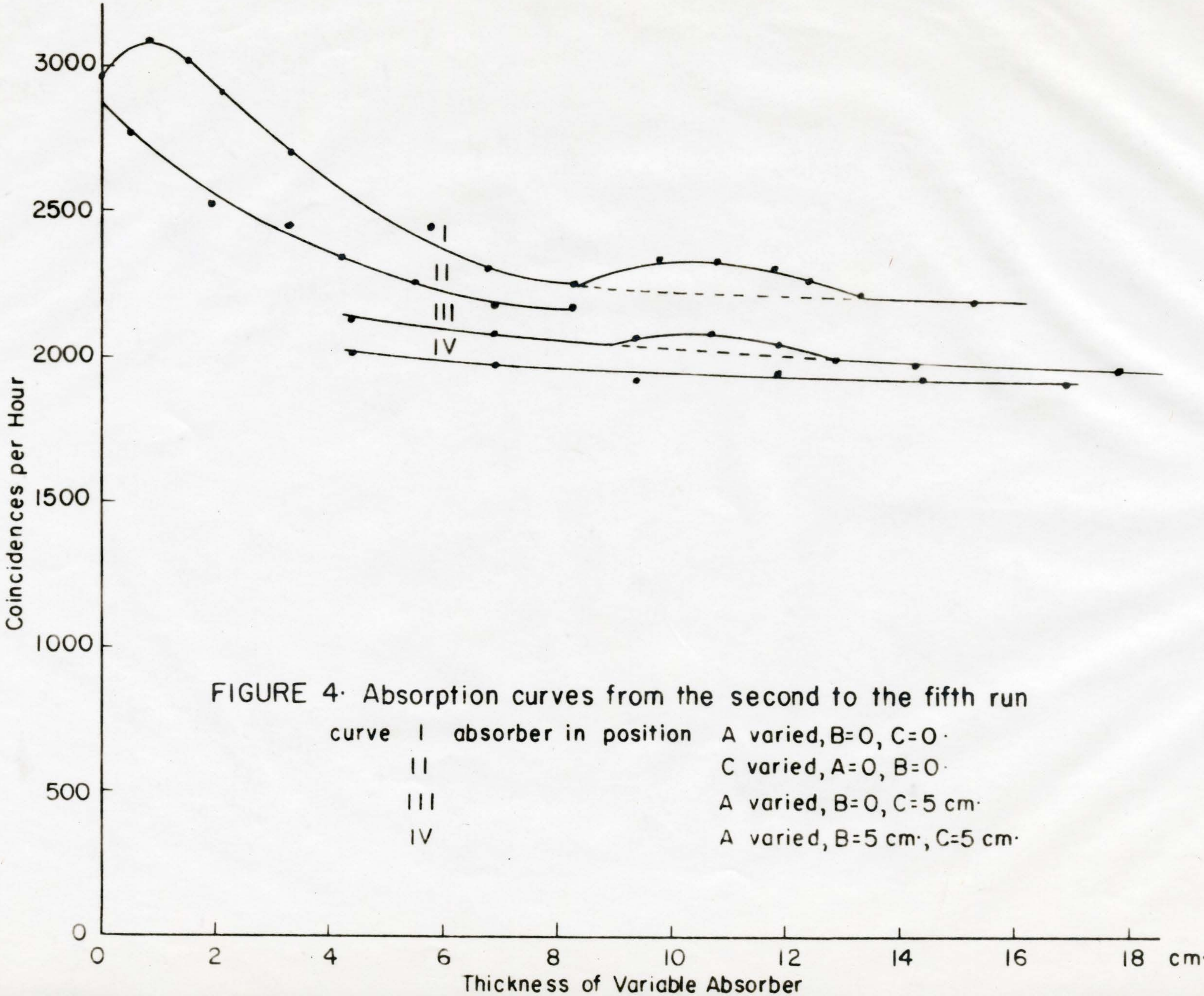


FIGURE 4· Absorption curves from the second to the fifth run

| | | |
|---|---|---|
| curve I | absorber in position | A varied, B=0, C=0· |
| II | | C varied, A=0, B=0· |
| III | | A varied, B=0, C=5 cm· |
| IV | | A varied, B=5 cm·, C=5 cm· |

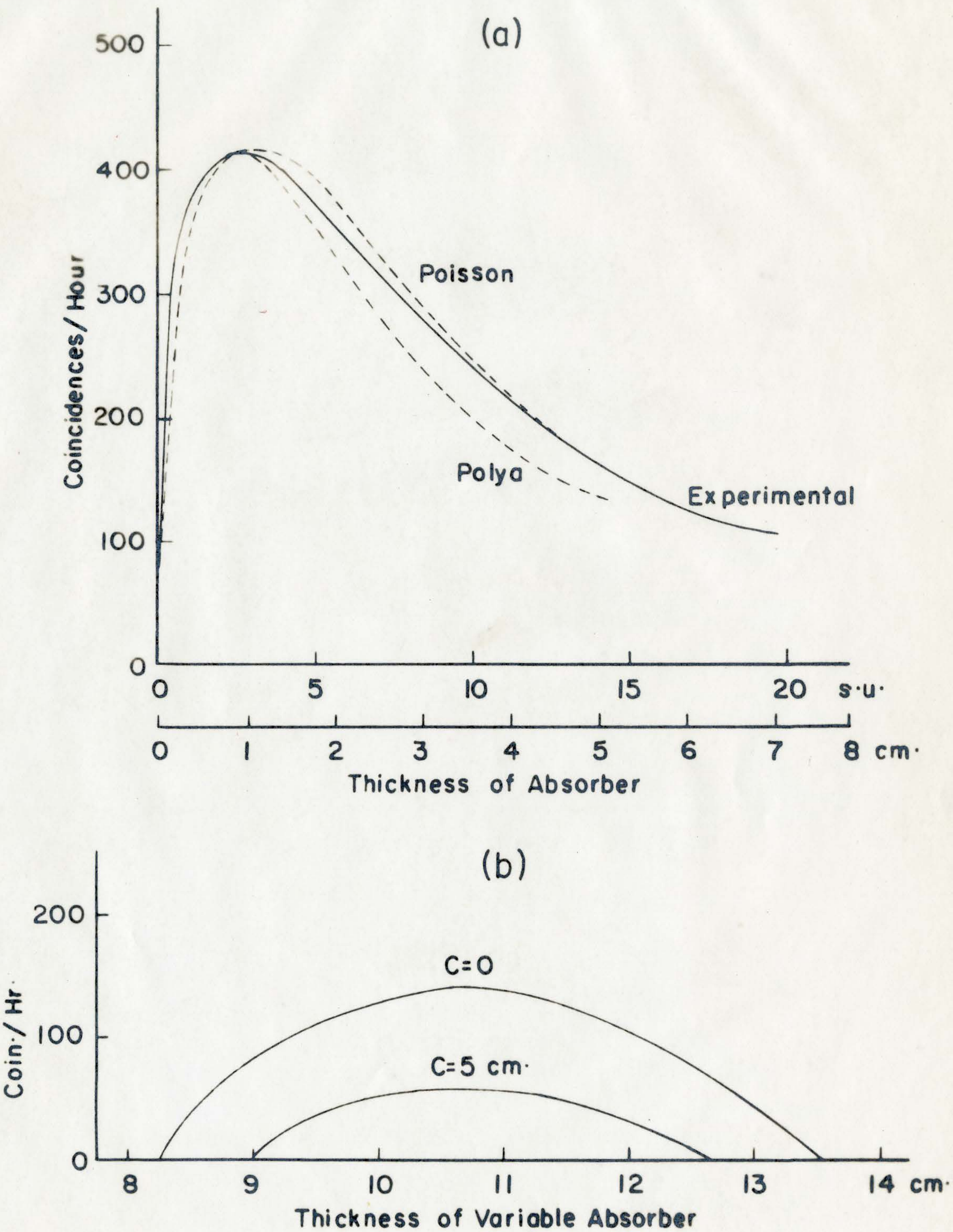


FIGURE 5· (a) The first maximum (b) The second maximum