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The Lifetime of the Positive Pi Meson

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Abstract

The lifetime of the positive π meson has been measured using a method similar to that used by Richardson in his measurement of the negative π meson. The lifetime obtained is $\tau = 1.97 \pm \times 10^{-8}$ sec. or $\tau_{1/2} = 1.37 \pm \times 10^{-8}$ sec. These values are about 2.5 probable errors from Richardson's[1] value of $\tau = 7.7 \pm \times 10^{-9}$ sec. The method has been extended so that two points on a decay curve could be determined and the geometry of the system determined to better accuracy. The geometry of the apparatus was checked by measuring the effective "lifetime" of the α-particles in the same configuration; this was found to be greater than $.5 \times 10^{-6}$ sec.

(1) J. R. Richardson, Phys. Rev. 74, 1720 (1948)
See also U. Camerini, H. Muirhead, C. F. Powell, D. M. Ritson, Nature 162, 433, (1948) for a very approximate evaluation of the lifetime of the π meson in cosmic rays.

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Introduction

The measurement of the lifetime of the negative π meson was made by Richardson.[1] Richardson's work was done in the α-particle beam of the 184-in. cyclotron. Since the yield of mesons for 380 Mev α-particles is less by about a factor of 10 than the yield of mesons with the 350 Mev proton beam now available, it was decided to improve the data by taking several points on the decay curve and to improve the statistical reliability.

Experimental Method

The method used to determine the lifetime of the π^+ meson consists of measuring the attenuation, beyond geometrical losses, of a beam of mesons as a function of the number of cyclotron orbits it has traversed. In Richardson's experiment the number of turns over which the attenuation was measured was 1. This has been increased to 2 and therefore enables one to determine 2 points on the decay curve.

Fig. 1 shows schematically the experimental arrangement. The cyclotron beam strikes the carbon target, thus producing mesons which are emitted in all directions and with various energies. These then move along helical paths in the magnetic field of the cyclotron. Channels provided in the copper shielding select positive mesons within a small angular interval about 180° from the beam direction, and in an energy interval of from 8 Mev to 14 Mev. One channel accepts a bundle of helical paths which are rising from the target, while the other accepts the equivalent paths which descend from the target. Since the mesons are focused in one dimension, the geometrical loss from the channel is linear. The helical channels have been approximated with a plane, as can be seen in Fig. 2 and 3. Fig. 4 shows the developed channel, the solid lines representing the situation of the 14 Mev mesons while the dotted lines refer to the channel as seen by 8 Mev mesons. Appropriate wedges were placed at the 180° position to prevent cross talk between the various channels.

Photographic plates are placed at 180° from the target in the copper channel and at either 540° or 900° in the lower spiral. The ratio of π^+ mesons found at 180° to those at either one of the other angles determines two points on the decay curve for the meson.

In the earlier experiment of Richardson only the 380 Mev alpha particle beam of the 184-in. cyclotron was available for producing mesons. His choice of fairly low energies was dictated by the success of other exposures with the same energy interval. However, when the 350 Mev proton beam came into operation it was estimated that the number of mesons produced would greatly increase and that the peak of the energy distribution would be at quite a high energy. It therefore appeared desirable to measure the lifetime at higher meson energies than those used by Richardson.

Early experiments with the proton beam indicated that much better ratios of the number of meson tracks to the number of unwanted tracks were obtained by exposing the plates at larger distances from the target and therefore at higher energies. However, an upper limit to the meson energy which can be used for this experiment is imposed by the available space in the cyclotron air lock. The energy that was chosen is the maximum allowed by this restriction.

The type of plates used for this experiment were Ilford C-3 100μ plates. These are slightly more sensitive than the Ilford C-2 plates and therefore facilitate finding the μ meson in the π-μ decay. This aids considerably in identifying a meson as a π meson.

In Richardson's experiment the emulsion was sandwiched between glass and the edge of the plate was exposed to the mesons. This procedure is fairly good only if precise measurements are not wanted since there is a variation in the thickness of the emulsion of around ± 16 percent. To avoid this error, plate holders which held two plates as shown in Fig. 5 were made. The solid angle accepted by such a device is independent, to the first order, of its orientation.

Since it is necessary to have the mesons stop in the emulsion, so that they may be identified as π mesons, the method of using tilted plates requires an absorber in front of the plate holder which will slow down the mesons to an appropriate energy. In view of the fact that the energy varies from 8-14 Mev across the plate it is necessary to use a tapered absorber. This is allowed since the plates are exposed at odd multiples of 180° from the target where the magnetic field focuses each energy at a definite position. The thickness of the absorber was chosen by using the range-energy curves of Aron, et al.[2] and the range-energy curves for mesons in emulsion.[3] A residual range of approximately 300 microns was left near the center of the plates and this increased at both ends. Only the center regions of the plates were scanned for this measurement.

(2) W. Aron, B. Hoffman, F. Williams, AECU-103

(3) H. Bradner, F. M. Smith, W. H. Barkas, A. S. Bishop, (to be published in the Physical Review)

This absorber introduces some difficulties since mesons scatter in it and some mesons therefore leave the emulsion which otherwise would have stopped. However, since the geometries of the plates at the 180° and farther positions are identical it was felt that with a reasonably large number of mesons counted in each position, the fraction lost would be independent of position.

The experiment, till now, has been discussed as though the magnetic field of the cyclotron were completely uniform; this, of course, is not the case. In order to provide magnetic focusing for the cyclotron beam the field is made to fall off slowly with increasing radius. This decreasing field has the effect of distorting the helical paths of the mesons. Since the mesons spiral in small circles at the edge of the cyclotron field, an investigation of the motion of charged particles in a non-uniform magnetic field was undertaken.

The motion was analyzed in two ways. In the horizontal plane the non-uniform field causes the small circular orbits to precess about the center of the cyclotron. The effect on the vertical motion is to introduce some vertical focusing, so that the particle instead of maintaining its vertical component of velocity will oscillate about the central plane of the magnetic field. The calculations indicated that these effects were small if one performed the experiment with the target at 65-in. radius in the cyclotron.

Since the motion of a particle in a magnetic field is characterized by its $H\rho$, it is possible to check the geometrical decay of the channel experimentally by replacing the target with a thick alpha-particle source. An alpha-particle source (Am^{241}) of approximately 10^7 alphas/sec. was constructed by Mr. William Crane for this purpose. It was necessary to have the activity concentrated in an area the size of the target (1/8"x1/8") since with larger sizes part of the source would be blocked from the far positions.

Only the 900° point was checked in this way. The data contained in Table I show that the ratio of the number of alpha-particles which arrive at the 180° position to the number which arrive at the 900° position is uniform across the plate and that the deviation from the expected ratio 5.00 is within the probable error.

For the computation of the lifetime the geometrical factors of 3.00 for the 540° and 5.00 for the 900° position were used.

In order to make exposures it was necessary to provide additional shielding. Fig. 6 shows the arrangement of the shielding in the cyclotron.

Since the target is very small compared to the beam height it was necessary to provide a stop for the beam on the other side of the cyclotron. After the

Table I

Distance along plate from the low-energy side (cm)	Ratio α's at 180 / α's at 900
2	5.07 ± .25
3	5.62 ± .28
4	5.04 ± .25
5	4.99 ± .25
6	5.23 ± .25
Weighted Average	5.16 ± .11

beam strikes this block some of the protons are scattered into the copper channel holder. It was found from other experiments that these protons were the cause of a great deal of the background tracks in the plates. To eliminate them, a large carbon block was placed in the dee approximately 90° away from the target inside the cyclotron dee. As an additional precaution about 8 in. of lead was mounted in the cyclotron on the beam side of the channel. With these measures it was possible to get readily readable plates.

In order to find out how many mesons were capable of getting to the plates without going through the prescribed channel, identical exposures to those determining the lifetime were made with the downward channel blocked at 180°. The ratios of the numbers of mesons at 180° to that at 540° and that at 900° in these runs give a measure of the background.

Evaluation of Data

Since the energies of the mesons are in the neighborhood of 10 Mev whereas the rest mass is 145 Mev relativistic effects will be small.

It is simple to show however that using a large energy interval will not affect the lifetime measurement.[4] This is a consequence of measuring the

(4) See e.g., W. F. G. Swann, Phys. Rev. 76, 157 (1949)

lifetime in terms of the decay per revolution in the field. Thus, although it is true that an observer would see the lifetime lengthened for the higher energy mesons by a factor $\frac{1}{\sqrt{1 - \beta^2}}$ it is equally true that the period per revolution as seen by the observer would also be lengthened by $\frac{1}{\sqrt{1 - \beta^2}}$. Thus, the fraction decaying per revolution would be independent of β.

It is interesting to note that if the experiment were carried out to higher accuracy for both fast and slow mesons, it constitutes the experimental equivalent of the clock paradox.(5) It would be observed that the fast meson returning to its starting point has actually lived longer in the laboratory frame as compared to a slow one. This experiment therefore in principle depends on the fact that the laboratory frame is a preferred one in relation to the masses in surrounding space. It is also of interest to note that the mean life measured in terms of number of turns is independent of relativistic considerations; this fact is a reasonable one since it is a pure counting operation and not an experiment involving physical measurement.

The plates were scanned using a Spencer microscope with a 1.8 mm oil immersion achromatic objective and 6 power eyepiece. This results in a field of view of approximately 250 micron in diameter.

Two methods of measuring the scanned area were used depending on the meson density in the plate. For the plates exposed at 180° a reticule with 2 parallel rulings which marked a region 73 microns wide in the field of view was used. The plate was scanned parallel to the direction of the mesons and only mesons stopping in the 73 micron swath were tabulated. In this way the area is found by measuring the total length of scan. For the plates at 540° and 900° it was desirable to utilize all of the mesons in a given area. This was especially true of the 900° plates where the total number of mesons available was not very great. In these cases the observation was done by taking overlapping scans. At

(5) R. C. Tolman, Relativity, Thermodynamics and Cosmology. Oxford, 1934, 194 ff.

the end of each swath the plate was moved 100 microns so that there was an overlap of about 150 microns. The area was then obtained from the vernier on the microscope stage. For the 180° plates this method would have lead to confusion as to which mesons had already been tabulated.

Table 2 shows the data which were obtained from the background plates.

Table 2

Position	Number of Decays	Area Scanned mm^2	Density of Mesons/No./mm^2
180°	21	20	.953
540°	3	160	.0187
180°	70	60	1.17
900°	3	800	0.00375

These data give the following ratios:

$$\frac{\text{Density at } 540^\circ}{\text{Density at } 180^\circ} = 0.0197 \pm 0.009$$

and

$$\frac{\text{Density at } 900^\circ}{\text{Density at } 180^\circ} = .00320 \pm .0012.$$

The shielding for the background runs was not as good as in the lifetime runs and hence this background is considered as an upper limit and will not be used for correction but will be incorporated in the probable error of the final result.

Among the meson tracks observed, those were counted which showed a definite $\pi-\mu$ decay and were therefore certain to be due to π^+ mesons. Also counted were those tracks which could be identified as mesons but which did not stop in the emulsion, and those meson tracks which stopped in the emulsion but for which no decay track could be found. Table 3 gives a summary of the data.

Table 3

Plate No.	Position	No. of Decay	No. Scattered out of the Emulsion	No Showing No Decay	Area Scanned mm2
6603	180°	166	41	4	43.8
6602		130	37	3	43.8
6601	540°	114	45	6	140
6600		127	51	5	140
6571	180°	204	73	10	58.4
6570		148	50	7	58.4
6569	900°	116	42	7	400
6568		114	45	6	400

The reliability of the count for mesons which did not stop in the emulsion is not very high since the identification is not certain in many cases, and such tracks are easily overlooked if one is intent on observing mesons that stop. In view of the uncertainty of this number, the data appear to be quite consistent as to the fraction which stops in the emulsion. The mesons going through the emulsion were not included in the computation of the lifetime since some of them might very well be μ mesons. Those meson tracks which did not appear in conjunction with decay meson tracks are probably due to μ mesons, π^+ mesons which do not decay by π-μ decay or mesons which stopped in a region of the plate which would not record a μ meson of 4 Mev.

Considering only the π-μ decays recorded in Table 3, the density of mesons at the various positions may be computed. These are recorded in Table 4.

Table 4	
Position	Density of Mesons in Plates No/mm^2
180°	3.48 ± .14
540°	0.862 ± .036
180°	3.02 ± .10
900°	.288 ± 0.012

These values give the following ratios:

$$\frac{\text{Meson Density } 540^\circ}{\text{Meson Density } 180^\circ} = \frac{0.862}{3.48} = 0.248 \pm .014,$$

$$\frac{\text{Meson Density at } 900^\circ}{\text{Meson Density at } 180^\circ} = \frac{0.288}{3.02} = 0.0954 \pm .0052.$$

If the lifetime were infinite, the expected ratios would be 0.333 and 0.200 respectively. The decrease in density due to decay in flight if normalized to 1 at 180° is then given by Table 5.

Table 5	
Position	Relative Density R (Due to Decay in Flight)
180°	1.00
540°	0.743 ± .042
900°	0.476 ± .026

All of the errors recorded are purely statistical.

In order to average the 540° and 900° points in such a way that the errors could be computed, the 540° point was extrapolated to 900° by using the mean life computed from the 540° point. The probable error at the extrapolated point was doubled. Thus from Table 5 the ratio R at 540° is:

$$R_{540^\circ} = 0.743 \pm 5.6 \text{ percent.}$$

Extrapolated to 900° this gives:

$$R_{540^\circ} = 0.564 \pm 11.3 \text{ percent.}$$

The ratio obtained from the 900° data is:

$$R_{900^\circ} = 0.476 \pm 5.45 \text{ percent.}$$

Averaging these two 900° points by weighting inversely with the square of the probable errors gives:

$$R_{900^\circ_{av.}} = \frac{.476\ (4.32)\ +\ .564}{5.32} = 0.492 \pm .024,$$

the probable error being computed by weighting in the same way.

From this value the mean life in cyclotron revolutions at a magnetic field of 14,300 gauss is easily computed to be:

$$= 2.84 \pm 0.20 \text{ revolutions.}$$

Using the magnetic field data obtained recently by Bradner and Bishop(3) with the proton magnetic moment resonance method we obtain H = 14,295 gauss for the mean field over the orbit. Using adopted values of the atomic constants(6) we

(6) J. W. M. DuMond and E. R. Cohen, Rev. Mod. Phys. 20, 82-108 (1948)

thus obtain a period per revolution of

$$\tau = 0.6945 \times 10^{-8} \text{ sec.}$$

Using this number we obtain for the mean and half-lives

$$\tau = 1.97 \pm 0.139 \times 10^{-8} \text{ sec.}$$

$$\tau_{1/2} = 1.37 \pm 0.095 \times 10^{-8} \text{ sec.}$$

In addition to these statistical errors there is a probable error in the geometrical ratio of approximately 3 percent, and the effects of background to lengthen the lifetime. On combining the errors one arrives at the following limits.

1. In the upward direction,

$$\frac{\Delta\tau}{\tau} = \sqrt{(.07)^2 + (.03)^2} = 0.076.$$

2. In the downward direction,

$$\frac{\Delta\tau}{\tau} = \sqrt{(.07)^2 + (.03)^2 + (.05)^2} = 0.086.$$

Using these errors one has as the final result.

$$\tau = 1.97 \pm {}^{.14}_{.17} \times 10^{-8} \text{ sec.}$$

$$\tau_{1/2} = 1.37 \pm {}^{.10}_{.12} \times 10^{-8} \text{ sec.}$$

Although this result is somewhat outside of Richardson's published value,

$$\tau_{1/2} = 7.7 \pm {}^{.21}_{.16} \times 10^{-9} \text{ sec.,}$$

it can be seen from Fig. 7 that the disagreement is not as extreme as is implied. Certainly one could not say that the experiment shows a difference between the π^+ and π^- mesons. However, the discrepancy is enough so that it might warrant investigation.

Acknowledgments

We should like to acknowledge our indebtedness to Dr. J. Reginald Richardson from whose experiment this work has grown. We should also like to express our gratitude to Prof. E. O. Lawrence for interest, encouragement and advice concerning the performance of the experiment. We also have benefited greatly from the previous experiment of the photographic film group at the Radiation Laboratory, particularly H. Bradner, E. Gardner and C. M. G. Lattes. The bombardments were carried out by the cyclotron crew under direction of J. Vale.

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Figure Captions

Figure 1. Schematic diagram of meson trajectories in lifetime apparatus. Note that the "upper trajectory" is a 180° orbit while the "lower trajectory" mesons can be observed either at 540° or 900°.

Figure 2. Photograph of lifetime apparatus with 180° channels exposed.

Figure 3. Photograph of lifetime apparatus assembled.

Figure 4. Developed view of lifetime apparatus; i.e., a plot of the meson trajectory and channel walls in vertical coordinates vs. angular position. Solid parallelograms show the channel walls as "seen" by a 14 Mev π^+ meson while dotted parallelograms show the walls as "seen" by an 8 Mev meson. Note the "cross-talk stops" which prevent mesons from reaching the 180° position after 540° travel and from reaching the 900° position after 540° travel.

Figure 5. Geometry of plate-holder showing meson incident on inclined surfaces of photographic plates. The sum of tracks on the two plates is virtually independent of the inclination of the plate holder assembly toward the beam direction.

Figure 6. Disposition of shielding in the tank of the 184-inch cyclotron. The copper block shown is slotted to limit the vertical oscillation amplitude of the beam. The carbon block inside the Dee serves to stop protons scattered by the target from striking the shielding (lead blocks) behind the lifetime apparatus.

Figure 7. Decay curve of the π^+ meson. The point of Richardson[(1)] is shown also. Ordinates plotted represent the fall-off in intensity other than due to geometry, plotted relative to the 180° position.

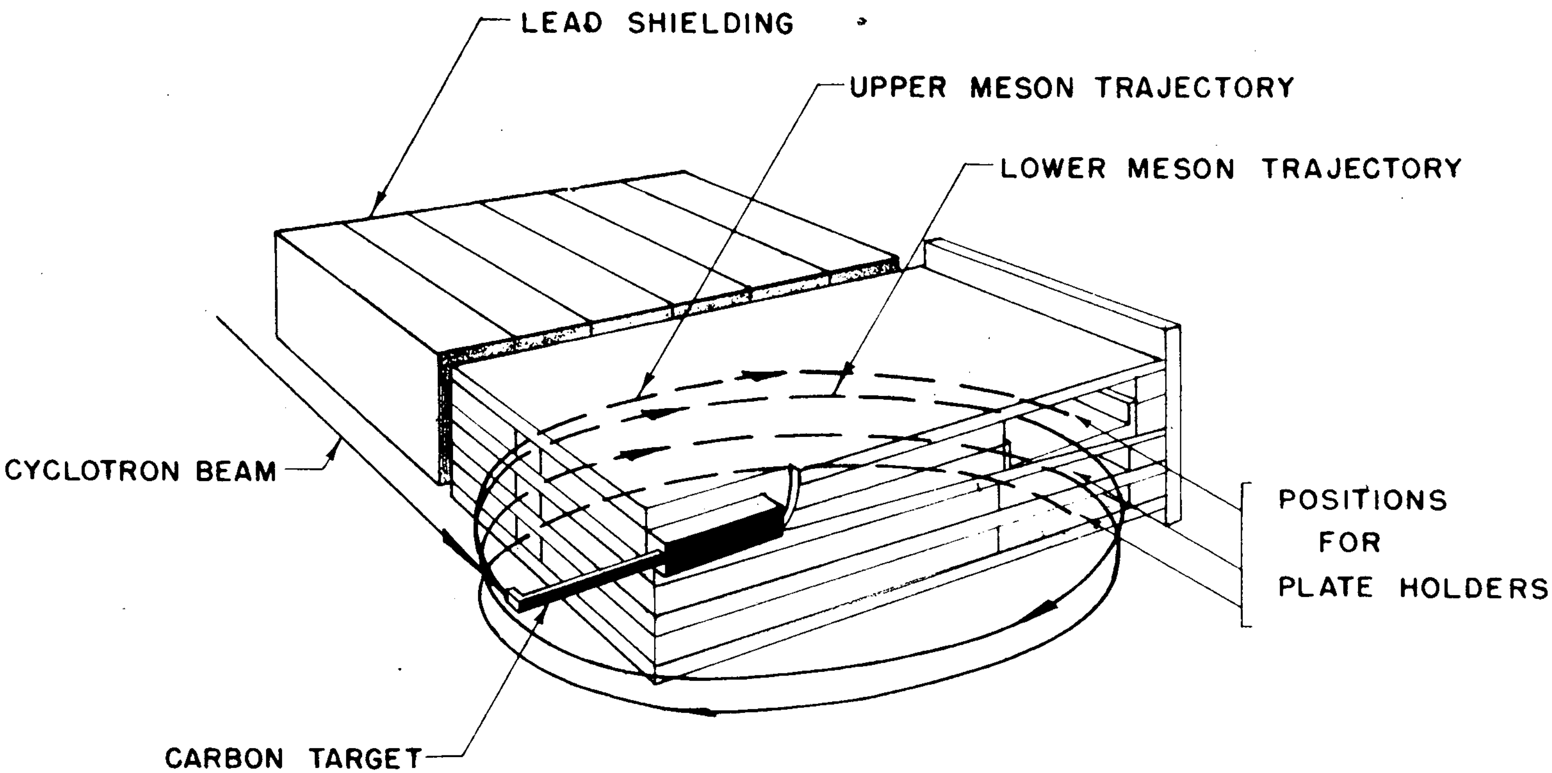


FIG. 1
SCHEMATIC VIEW OF APPARATUS

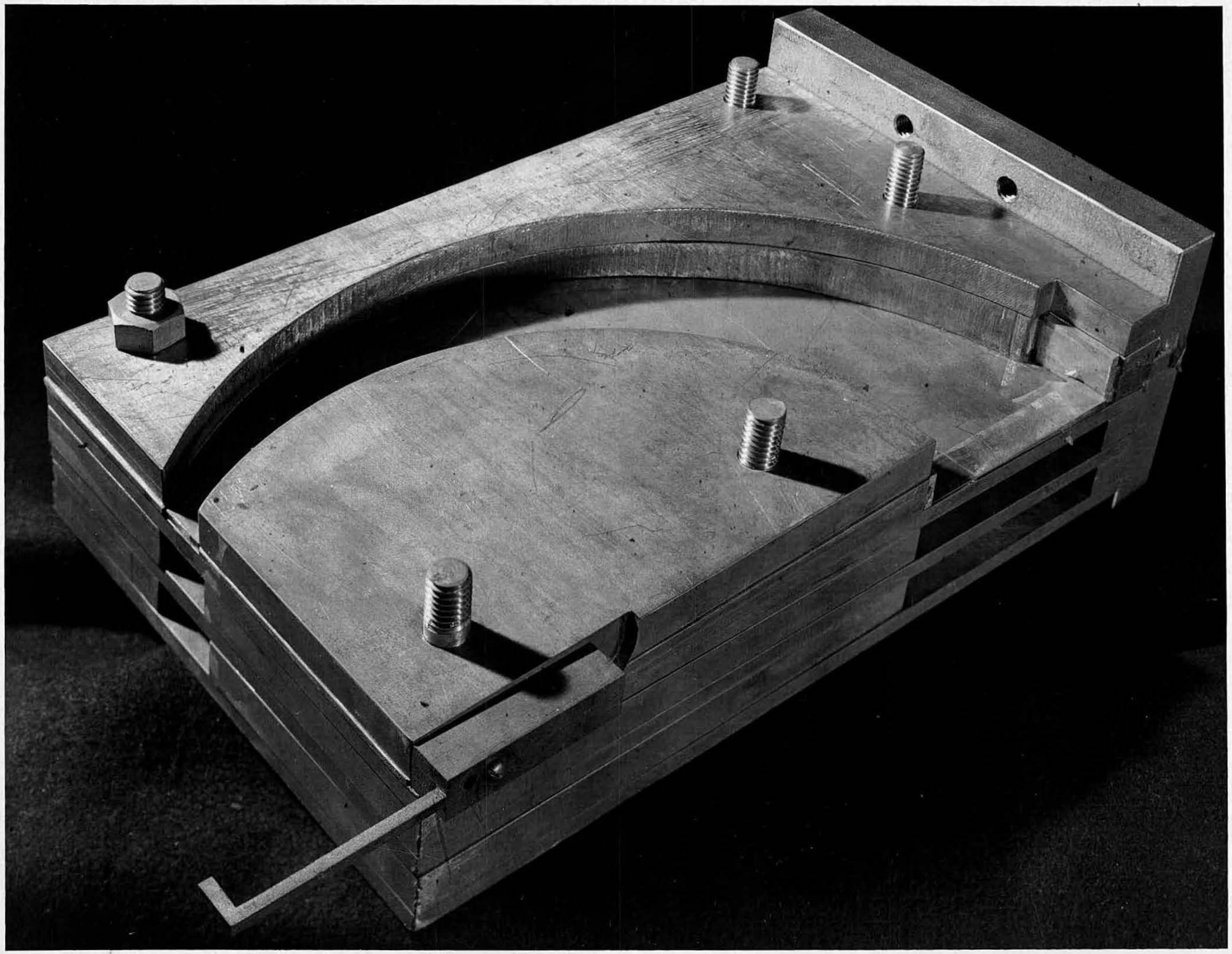


FIG. 2

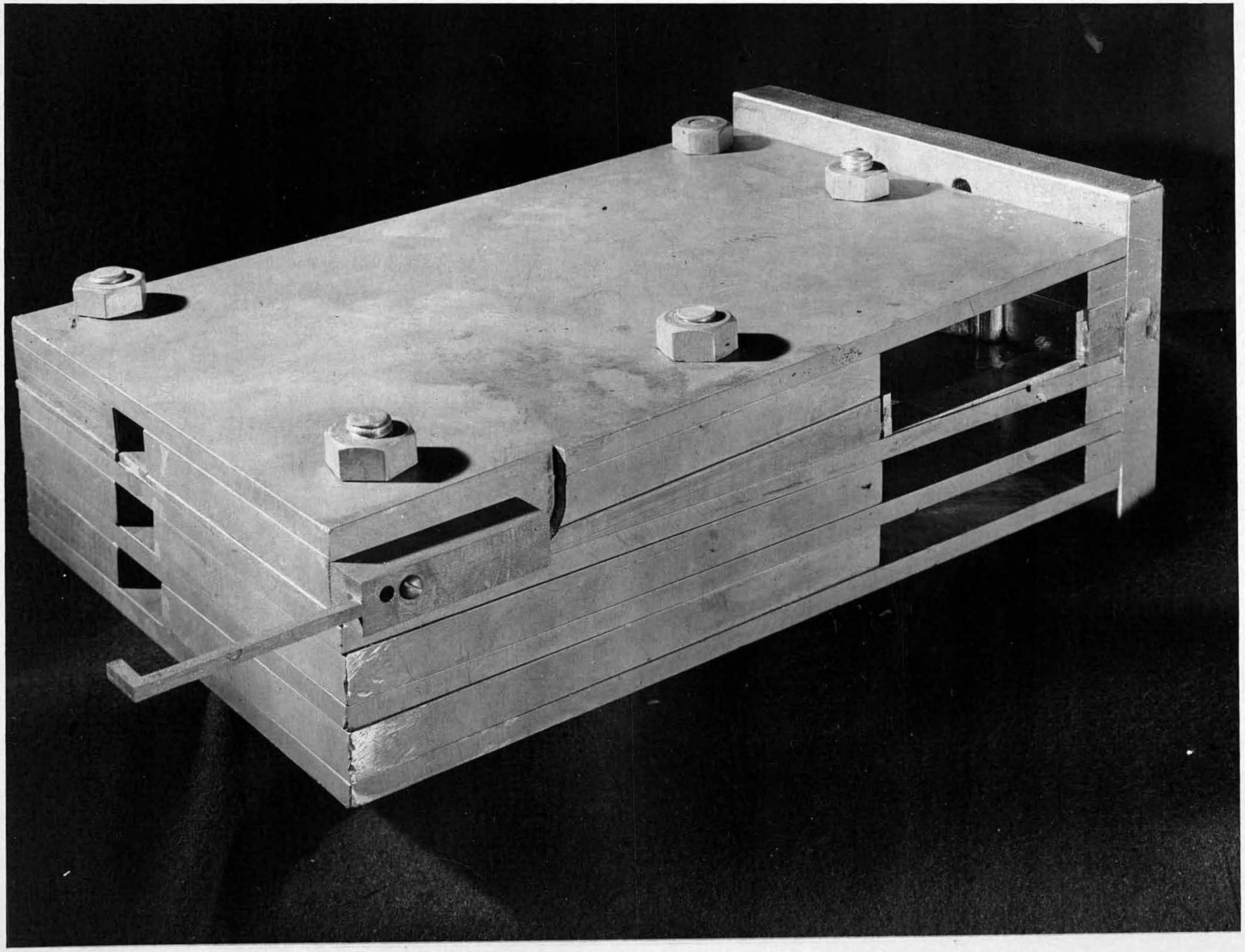
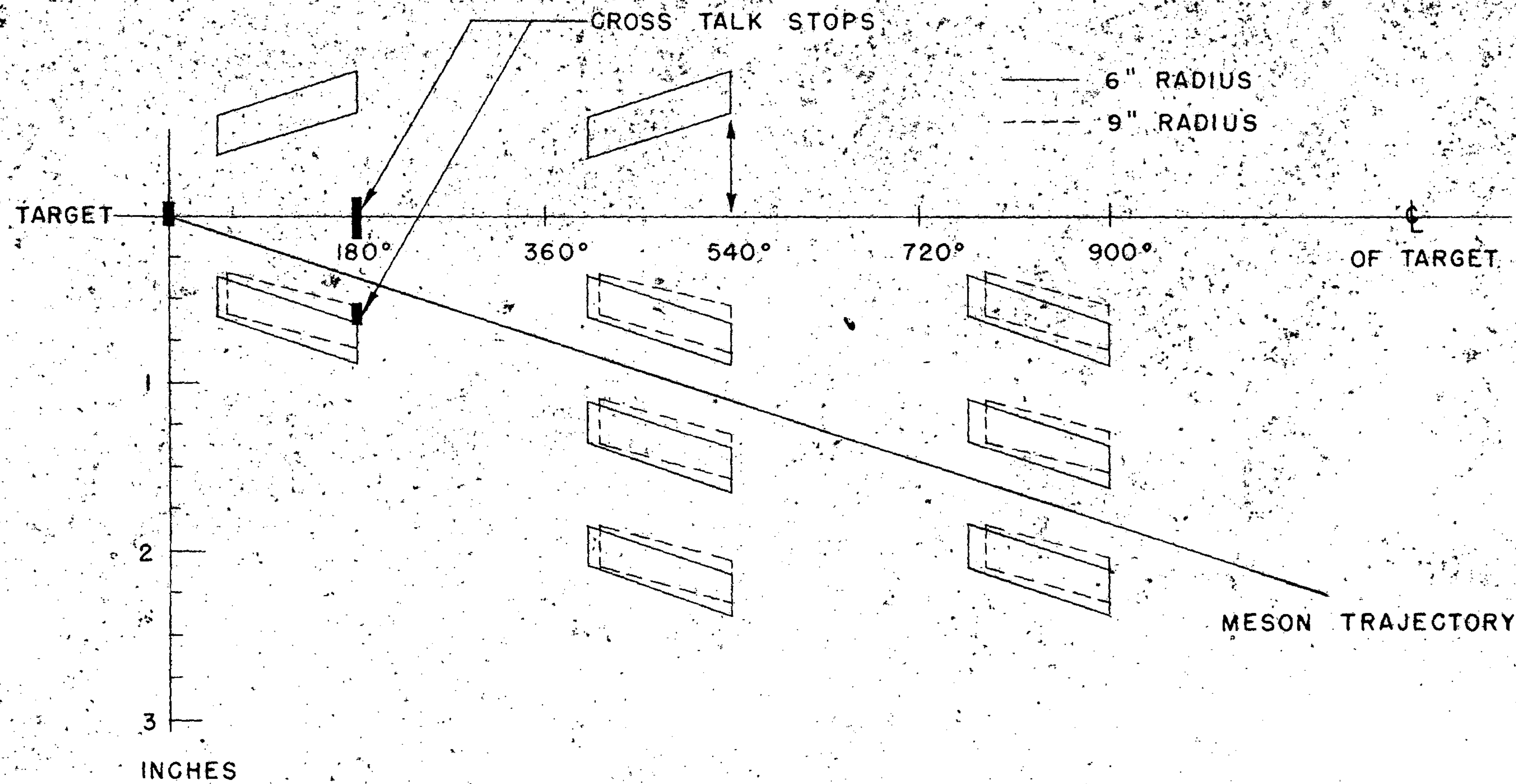


FIG. 3

OZ 698



DEVELOPED VIEW OF CHANNEL
FIG. 4

14224-1

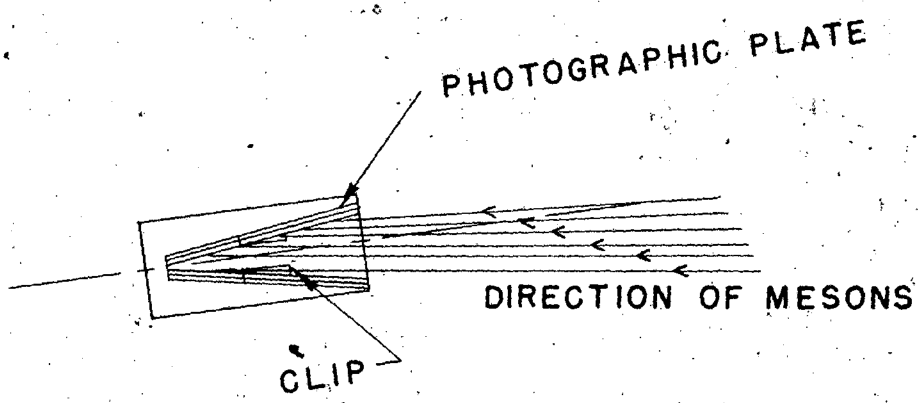
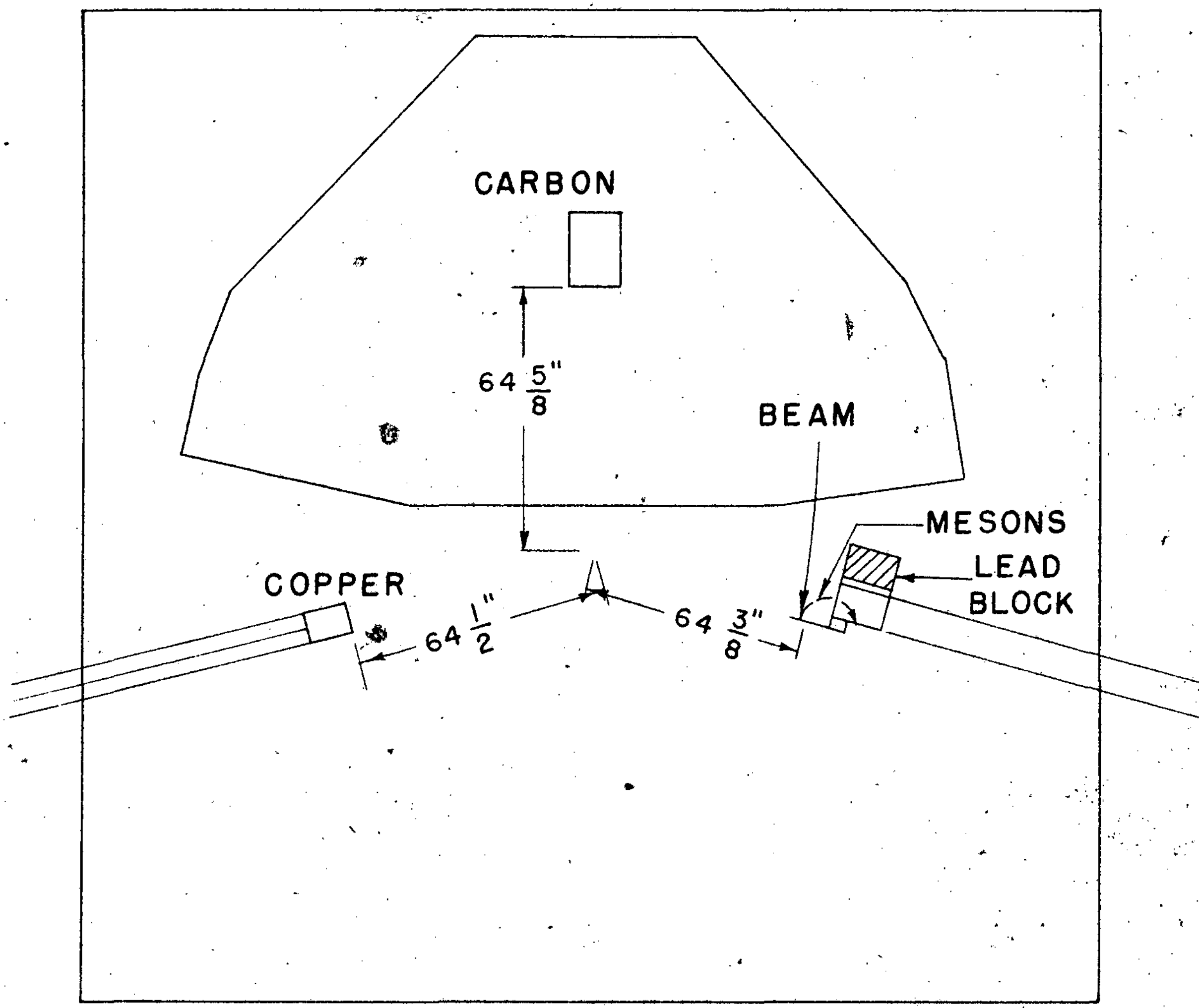


PLATE HOLDER GEOMETRY

FIG. 5

1422



LOCATION OF SHIELDING IN THE CYCLOTRON

FIG. 6

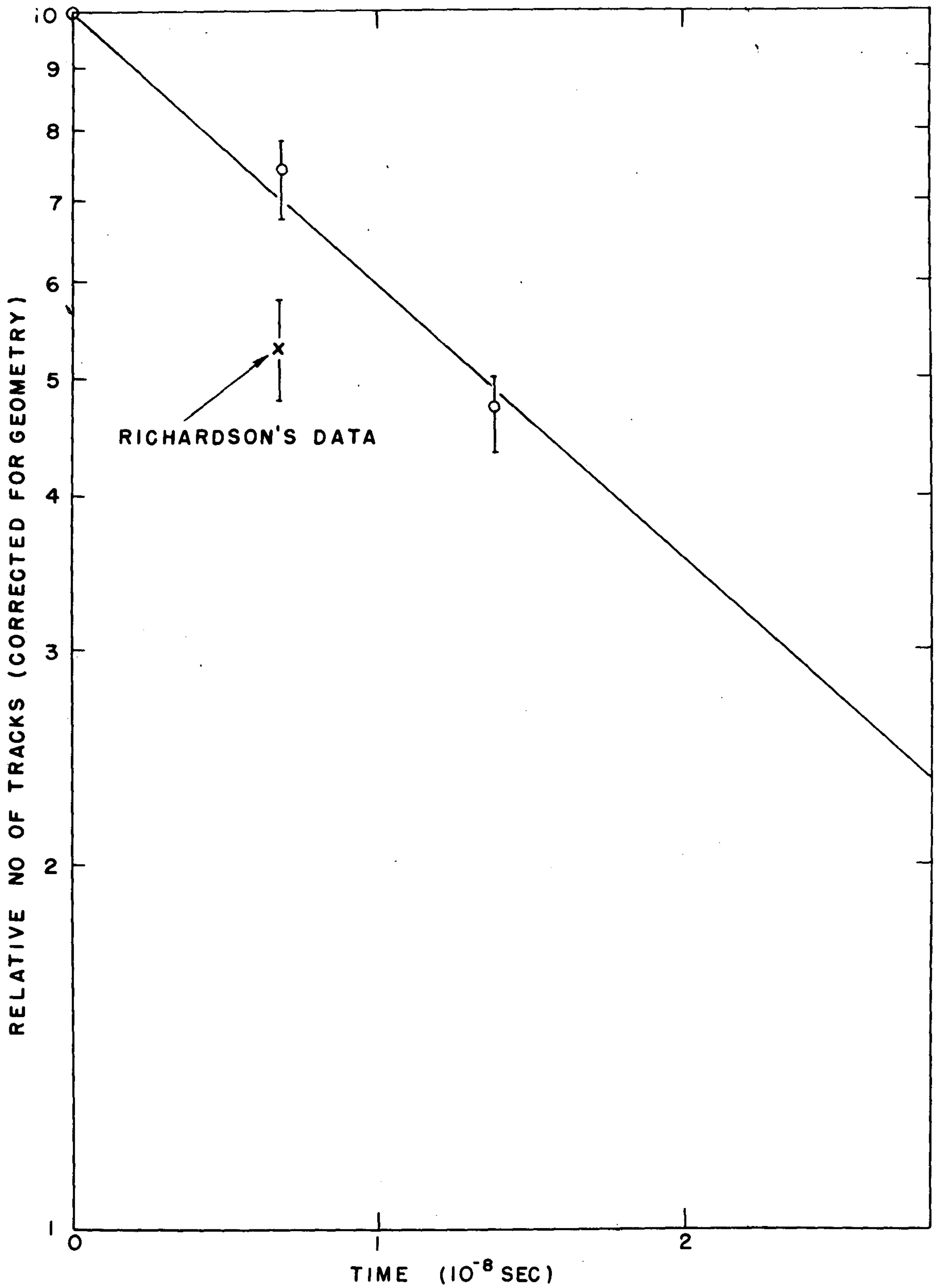

RELATIVE NO OF TRACKS (CORRECTED FOR GEOMETRY)
TIME (10^{-8} SEC)
RICHARDSON'S DATA
10
9
8
7
6
5
4
3
2
1
0
1
2

FIG. 7

07 696