A CLOUD-CHAMBER INVESTIGATION OF CHARGED V PARTICLES

Thesis by

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ABSTRACT

An analysis of 84 charged V events obtained during two years of operation of a vertical magnetic cloud-chamber array is presented. The particular features of interest which are studied in detail are the distribution of P*, the momentum of e charged secondary in the rest system of the primary, and the possible existence of a component of short lifetime (i. e., $\tau < 5 \times 10^{-10}$ sec.).

The P* distribution from 19 slow, accurately measurable positive events is shown to imply that the large majority of these events arise from one or more two-body decays from primaries of mass approximately equal to that of the τ meson. One case turns out to be inconsistent with this interpretation, and is presumed to represent a three-body decay.

The P* distribution from six slow, accurately measurable negative events is consistent with a single two-body decay having a P* value of about 200 Mev/c. This suggests the existence of a negative counterpart to the well-known θ^0 particle, though the statistics are much too poor to permit any strong conclusion.

The lifetime analysis provides strong evidence for the existence of a negative component of lifetime equal to or less than $(1.3 \pm 0.6) \times 10^{-10}$ second. The transverse momentum distribution for these short-lived events is shown to suggest a two-body decay with a P* value of 201 ± 12 Mev/c.

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I. INTRODUCTION

The properties of charged particles, heavier than the π meson, which decay into a single charged secondary have been studied in detail both in magnetic[(1),(2)] and multiple-plate[(3),(4)] cloud chambers, and in photographic emulsions[(5)]. The results from various studies have tended to indicate that there are apparently several different kinds of such particles, the observed relative number of each kind depending upon the experimental geometry used. Up to the present time, evidence has been obtained for the following decay schemes:

(a)	$\kappa^{\pm} \rightarrow \mu^{\pm} + ? + ?$ (5)	$m_{\kappa} \approx 1000\ m_e$
(b)	$\chi^{\pm} \rightarrow \pi^{\pm} + ?$ (5)	$m_{\chi} \approx 1000\ m_e$
(c)	$K_{\mu}^{+} \rightarrow \mu^{+} + \nu$ (3)	$m_{K_{\mu}^{+}} = 928 \pm 13\ m_e$
(d)	$\theta^{+} \rightarrow \pi^{+} + \pi^{\circ}$ (6)	$m_{\theta^{+}} = 965\,^{+30}_{-20}\ m_e$
(e)	$\tau^{+} \rightarrow \pi^{+} + 2\pi^{\circ}$ (7)	Alternate decay mode of τ meson
(f)	$\Sigma^{+} \rightarrow P + \pi^{\circ}$ (1),(8),(9)	$Q = 117 \pm 1$ Mev
(g)	$\Sigma^{\pm} \rightarrow n + \pi^{\pm}$ (9)	$Q \approx 130$ Mev
(h)	$\Xi^{-} \rightarrow \Lambda^{\circ} + \pi^{-}$ (10),(11)	$Q = 66 \pm 6$ Mev

Some of the particles listed under different headings above may be identical.

This thesis describes an analysis of 84 charged V events observed in a magnetic cloud chamber, and gives a possible interpretation of these events in terms of the above-listed particles. This discussion does not include those few events which are clearly examples of "cascade decays" (category [h] above).

II. DESCRIPTION OF APPARATUS

The data discussed in this thesis were obtained with the 48" magnet cloud chambers which have been in operation at the Cosmic Ray Laboratory since January, 1953. This equipment, designed by Professors C. D. Anderson, R. B. Leighton, and E. W. Cowan, and shown schematically in Fig. 1, consisted of a vertical array of four rectangular cloud chambers each 55 cm in length, 20 cm in height, and 20 cm in illuminated depth, operated in the field of a large electromagnet. In July, 1953, the two top chambers were replaced by a single chamber of the same length and depth, but 46 cm in height. The electromagnet was supplied with approximately 80 kilowatts by a motor generator set, and produced a field of approximately 8000 gauss over a volume 59 cm in length by 117 cm in height by 30 cm in depth.

The expansions of the chambers were triggered by a penetrating-shower selector which consisted of three trays of eight G. M. counters placed above, between, and below the chambers. Each pair of chambers was separated by about 50 gm/cm^2 of lead absorber (this was replaced by copper for a period of five months), and about 200 gm/cm^2 of lead were used above the top chamber. The availability of two pulse-height discrimination circuits permitted the use of two parallel coincidence requirements, usually 2-2-1 (two or more counts from the upper tray, two or more from the middle tray, one or more from the bottom tray) and 0-2-2. With these requirements, the expansion rate was approximately three per hour. After each expansion a dead time of about three minutes was allowed to permit the chambers to get back to equilibrium.

The photographs were taken by two cameras (one for each pair of chambers) on 70 mm Linagraph Pan film. Each camera used a pair of

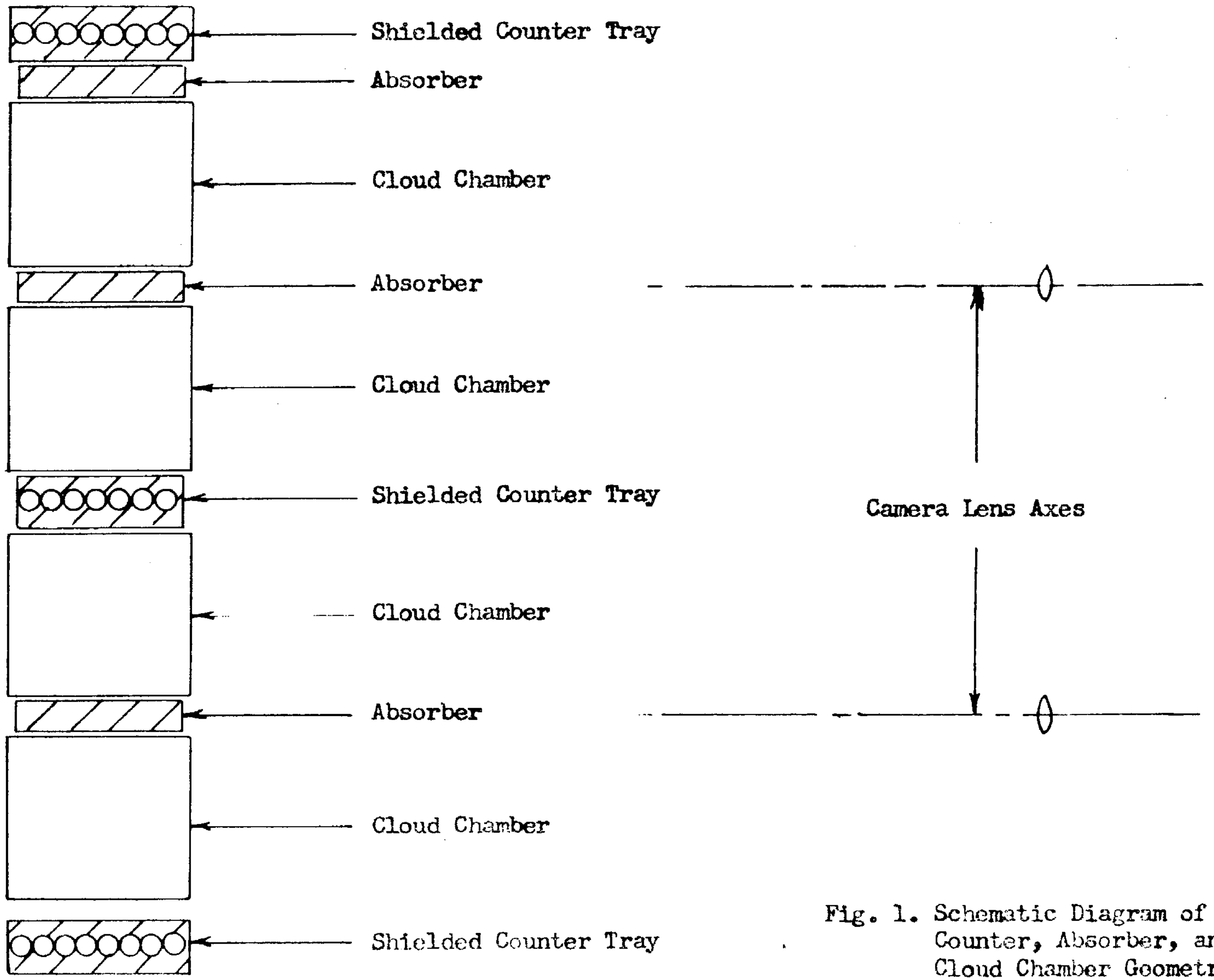

Fig. 1. Schematic Diagram of the Counter, Absorber, and Cloud Chamber Geometry.

Ross 12.7 cm focal length lenses with axes 17.8 cm apart to take stereoscopic views of each expansion. The distance from the lenses to the pistons of the chambers was about 125 cm, resulting in a demagnification of about 9 in the photography. The illumination was supplied by a G. E. F.T.500 tube powered by a 500 mf, 4000 volt capacitor bank, and came in through a glass window at the side of each chamber. The lenses were stopped down to f/22 for most of the work described here.

Inasmuch as it was desired to secure maximum quantitative information from individual decay events, great care was taken to minimize convective distortions resulting from unsatisfactory temperature conditions on the chambers. For this purpose an elaborate thermostating arrangement was used to produce as uniform temperature conditions over the chambers as possible, with the exception of slight vertical gradients used to insure stability. Even so, during the time over which the experiment was performed, the magnitude of thermal distortions varied considerably. The assignment of errors was made using 3 Bev/c (believed to be a conservative figure) as the maximum detectable momentum of tracks of 20 cm length, except when the presence of visible distortions required a corresponding increase in the estimated magnitude of the errors.

The measurement and reprojection procedures, which were essentially scaled-up versions of those used by Leighton et al.[12], have been described in great detail by Van Lint[13].

III. THEORETICAL CONSIDERATIONS RELEVANT TO THE MEASUREMENT AND INTERPRETATION OF DECAY ENERGIES

A. INTRODUCTION

The value of P*, the momentum of the charged secondary in the rest system of the primary particle, is one of the most fundamental properties of each decay event. Its absolute value can be used, if information concerning the identity of both the charged and neutral secondaries is available, to obtain a lower limit to the mass of the primary. If only two secondaries are emitted in the decay, and if the exact identity of both secondaries is known, the actual mass of the primary can be obtained from P* with usually better accuracy than any other method. On the other hand, if estimates of the primary mass are available from other sources, the value of P* can be used to provide upper limits to the masses of the secondaries. The distribution of values of P* for different decays can be used to provide information on the number of neutral particles emitted in each decay as well as evidence on the number of different kinds of charged V particles. It is clear then that estimates of P* are of great value in the interpretation of charged V data.

B. NOTATION

Before getting on to a detailed discussion of the calculation of P*, it is appropriate to define all the symbols which will be used. The following notation will apply throughout this thesis.

1. Laboratory System

P_1 -- Momentum of the primary

I_1 -- Ionization of the primary

M	--	Mass of the primary
β	--	Velocity of the primary in units of the velocity of light
γ	--	$(1 - \beta^2)^{-\frac{1}{2}}$
P_2	--	Momentum of the charged secondary
I_2	--	Ionization of the charged secondary
m	--	Mass of the charged secondary
θ	--	Angle between P_1 and P_2
P_L	--	$P_2 \cos\theta$
P_T	--	$P_2 \sin\theta$
E_2	--	$(P_2{}^2 + m^2)^{\frac{1}{2}}$

2. Center-of-Mass System

P^*	--	Momentum of the charged secondary
θ^*	--	Angle between P_1 and P^*
P_L^*	--	$P^* \cos\theta^*$
P_T^*	--	$P^* \sin\theta^*$
E^*	--	$(P^{*2} + m^2)^{\frac{1}{2}}$

It should be noted that in all applications of the above notation, it will be assumed that momenta, energies, and masses are expressed in energy units.

C. THE MEASUREMENT OR ESTIMATION OF P*

In order to calculate the value of P* for a particular decay event one must be able to measure the quantities P_1 or I_1 (provided $I_1 > I_{min}$), P_2, and θ. Inasmuch as in essentially every case where $I_2 > I_{min}$, P_2 is much more accurately measurable than I_2, the possibility of using I_2 instead of P_2 is not considered here. From I_1 or from P_1 (provided a suitable assumption concerning the primary mass is made) it is easy to calculate β , the velocity of the primary, and then to compute P* from the Lorentz transformations,

$$P_T^* = P_T = P_2 \sin\theta, \quad (1a)$$

$$P_L^* = \gamma P_2 \cos\theta - \gamma\beta E_2, \quad (1b)$$

$$P^* = [P_T^{*2} + P_L^{*2}]^{\frac{1}{2}}. \quad (1c)$$

In estimating the errors in such a calculation, one should consider two distinct sources. First, errors will exist in the measurements of I_1 or P_1, P_2, and θ, and will introduce errors into the values of P*. The effect of such errors upon P* can be computed from the following relations:

$$\frac{\partial P^*}{\partial(\gamma\beta)} = \frac{P_L^*}{P^*}\left[P_2 \cos\theta\beta - E_2\right], \quad (2a)$$

$$\frac{\partial P^*}{\partial P_2} = \frac{P_L^*}{P^*}\left[\gamma\cos\theta - \frac{\gamma\beta P_2}{E_2}\right] + \frac{P_T^*}{P^*}\sin\theta, \quad (2b)$$

$$\frac{\partial P^*}{\partial\theta} = \frac{P_2}{P^*}\left[P_T^* \cos\theta - \gamma P_L^* \sin\theta\right]. \quad (2c)$$

In using (2a), the error in $\gamma\beta$ is estimated from the anticipated uncertainty in I_1 or from the assumed error in P_1, depending upon which is used for the calculation of P*.

A second source of error in P* may arise from an incorrect estimate of the primary mass if the primary momentum P_1 is used to calculate the velocity β , and from an incorrect assumption as to the identity of the charged secondary. The latter effect is best taken care of by separate calculations of P* for all possible known secondary particles which are consistent with momentum and ionization measurements (usually only μ and π mesons). As to the former source of error, its effect upon P* is given, to first order, by

$$\Delta P^* = \cos\theta^* \beta E^* \frac{\Delta M}{M} \qquad (3)$$

where ΔP^* is the error in P^* arising from an error ΔM in the primary mass. If one assumes an isotropic angular distribution in the center-of-mass system, for which $\langle\cos\theta^*\rangle = 0$, the error is essentially a random effect. The probable error in $\langle\cos\theta^*\rangle$ per case is approximately 0.4. For the events of interest, $E^*/M \approx \frac{1}{2}$ and $\beta \lesssim 1$, so that one gets

$$\Delta P^* \leqslant 0.2 \, \Delta M \qquad (4)$$

as the probable error per case. As long as $\Delta M \leqslant 50$ Mev the effect of this error is generally negligible in comparison to the usual errors of measurement.

There are usually many events for which neither P_1 nor I_1 can be measured, but such that both P_2 and θ are obtainable. For such cases it is not possible to calculate actual values of P^*; however, a lower limit to P^* is often useful for the interpretation of such events and can be readily calculated. In particular the quantity $P_T = P_2 \sin\theta = P^* \sin\theta^*$ is such a lower limit. It is often a meaningful lower limit in the sense that its distribution if the decay takes place isotropically in the center-of-mass system,

$$F(P_T)\, dP_T = \frac{P_T \, dP_T}{P^* \, (P^{*2} - P_T^{\,2})^{\frac{1}{2}}} , \qquad (5)$$

is strongly peaked at $P_T = P^*$, and therefore assumes values much lower than P^* only infrequently.

Under special circumstances it is possible to obtain better lower limits to P^* than are afforded by transverse momenta. In particular if the laboratory decay angle θ is greater than 90°, the secondary momentum P_2 is always a lower limit to P*. This is not a very useful result since most cases which have backward emitted secondaries in the laboratory system have heavily ionizing primaries, and therefore permit a direct measurement of P*. A more useful method of obtaining a lower limit to P* consists of calculating the value of P* which corresponds to whatever lower limit can be set on the primary velocity, either from ionization or from momentum. If in this calculation, the secondary turns out to have a backward momentum in the center-of-mass system (i. e., $\theta^* > 90^\circ$), then the value of P* thus calculated is a lower limit to the true P*; if, on the other hand, the calculation results in a forward emitted secondary ($\theta^* < 90^\circ$), this method cannot be used to give a higher lower limit to P* than the value of P_T. These results follow from the easily verified fact that, given the secondary momentum and the angle of decay, the longitudinal momentum of the secondary in the center-of-mass system is a monotonically decreasing function of the primary velocity. Most frequently a lower limit can be set on the primary velocity from the ionization of the primary particle. If this ionization is, for example, less than twice the minimum value, lower limits to P* which are higher than P_T can be obtained by the above method for all decays whose angles in the laboratory are greater than 50°.

D. INTERPRETATION OF THE P* DISTRIBUTION

The shape of the experimentally obtained P* distribution can be very useful in determining whether or not more than one neutral particle may be emitted in each decay, and also whether there are several different decay schemes represented by the data. The expected features of the distribution can be discussed for various possible types of decay scheme.

For a single two-body decay, the theoretical distribution is a single line. In actual fact, the experimentally obtained distribution will have a finite width arising from the errors of measurement.

If there are several two-body decays present in the data, the theoretical distribution will consist of lines corresponding to each decay. As far as experiment is concerned, however, no two lines can be resolved from each other unless their separation is not small in comparison to the error width.

For a three-body decay, the theoretical distribution is not well known. In the absence of detailed knowledge concerning the energy dependence of matrix elements corresponding to the decay, the usual approximation is to use a distribution whose energy dependence arises solely from statistical factors proportional to the phase space volume which corresponds to a particular division of energy among the secondaries of the decay. Such a distribution has been discussed by York[14]; and, for the special case of the decay,

$$K^+ \rightarrow \mu^+ + 2\nu,$$

it is given by

$$G(P^*)\, dP^* = A\,[3(M^2 + m^2) - 6M\,(P^{*2} + m^2)^{\frac{1}{2}} + 2P^{*2}]\, P^{*2}\, dP^*, \quad (6)$$

where A is a constant. Again the errors of measurement will, to some extent, modify this distribution.

It is important to emphasize that the data can be considered to favor one particular decay scheme or combination of decay schemes over some other combination only if the widths of the two combinations being compared are not both small in comparison to the error width. One should also note that the relation between actually measured values of

P* and the mass of the primary particle is very much dependent upon the decay scheme assumed. If, therefore, outside information concerning the mass of the primary particle is available, it may be of great usefulness in determining the decay schemes represented in the data.

If the P* distribution can be shown to represent largely a single two-body decay, the best value of P* for that decay can be obtained by taking the mean of the measured values, each value being weighted according to its estimated accuracy. Such a weighted mean, however, has little meaning if the errors of measurement only account for part of the spread of the distribution. In such a situation, unless the errors are so small that it is easy to separate out the P* values corresponding to any two-body scheme represented, individual accurately measured values of P* must be used to characterize any such decay scheme.

E. INTERPRETATION OF THE P_T DISTRIBUTION

The P_T distribution can in general be used to distinguish between a narrow and a broad P* distribution and to calculate a characteristic value of P* (its mean value, for example). The statistics available are, in general, too limited to determine any further details of the P* distribution.

If the decay is assumed to take place isotropically in the center-of-mass system, the P_T distribution is related to the P* distribution by the formula,

$$F(P_T)\, dP_T = \int_{P_T}^{P^*_{max}} \frac{G(P^*)\, dP^*}{P^* \,(P^{*2} - P_T{}^2)^{\frac{1}{2}}}\, P_T\, dP_T. \qquad (7)$$

A very simple way of deriving information about the P* distribution from the P_T distribution which it generates is to note that the following very simple relations hold true independently of the distribution of P*:

$$\langle P^* \rangle = \frac{4}{\pi} \langle P_T \rangle \quad , \qquad P^*_{max} = P_{Tmax} \, . \tag{8}$$

The accuracy with which the above formulae can be used to calculate $\langle P^* \rangle$ from a given P_T distribution depends of course upon the number of cases represented, and the statistical error can easily be estimated. If the decay is a two-body one, then $\langle P^* \rangle$ is just equal to P* itself; and, therefore, within both errors of measurement and statistical errors there should be no value of P_T larger than $\frac{4}{\pi} \langle P_T \rangle$. On the other hand, if the P* distribution is a broad one, there should definitely be values of P_T which are appreciably larger than the quantity $\frac{4}{\pi} \langle P_T \rangle$. For example, if a three-body decay of the type,

$$K^{\pm} \rightarrow \mu^{\pm} + 2\nu,$$

is involved, then $\langle P^* \rangle$ is roughly only 2/3 of the maximum value. Thus with reasonable errors of measurement and reasonable statistics one can expect to separate such a three-body decay from a two-body decay without too much difficulty. As in the P* distribution, any available information concerning the mass of the primary particle can be combined with knowledge of $\langle P^* \rangle$ as obtained from the P_T distribution to arrive at conclusions concerning the decay schemes represented.

F. THE EFFECTS OF BIASES

The previous discussion of the interpretation of the P* and P_T distributions has completely neglected the possible effect of biases introduced by the cloud chambers. Because of these biases, events which occur in one part of the distribution may be favored over those which occur elsewhere so that the resulting distribution may depend not only on the decay properties but also upon the limitations of observation and measurement introduced by the cloud-chamber geometry. It should be noted that such biases will exist even if the width of the distribution arises wholly or in part from experimental errors, for in such cases events in which the errors are in one direction may be more easily measured than those for which the errors are of opposite sign.

This bias problem may be attacked in two ways:

1. The range of the variable in the distribution and the sample of events represented can be selected so that a member of this sample would have been included no matter where it had occurred within the allowed range of the variable.

2. The theoretical distributions can be altered to take account of the cloud-chamber biases.

As illustrations of these ideas, the P^* and P_T distributions will be considered in some detail. It will be assumed in this discussion that the three fundamental quantities P^*, θ^*, and β (all previously defined) are independently distributed. The main source of bias in the P^* distribution arises from the fact that for unfavorable locations in the cloud chamber a decay may be measurable only if its value of P^* is not too large. Even if the P^* distribution is actually only a single line, those cases in which the errors tend to decrease the measured value of P^* will appear to be more accurately measurable than those in which the errors increase P^*. On the other hand, very low values of P^* will also tend to be discriminated against because of the likelihood of confusion with $\pi - \mu$ decays and scatterings.

For each event one must therefore assign a range of possible values of P* such that for any of these values, the event could have been measured with sufficient accuracy, and not confused with $\pi - \mu$ decays and scatterings. The upper limit of this range is obtained by requiring that the secondary momentum be measurable to a certain pre-assigned accuracy. In considering the effect of increasing P* upon the secondary momentum, one must keep the other fundamental quantities θ* and β, as well as the location of the point of decay, fixed. Though, strictly speaking, the laboratory angle of decay and hence the length of secondary track visible in the chamber vary somewhat with P*, this effect is very small as can be seen from the formula for the laboratory angle θ,

$$\tan\theta = \frac{\sin\theta^*}{\gamma\cos\theta^* + \gamma\beta\frac{E^*}{P^*}} . \qquad (9)$$

The only dependence of θ on P* comes from the term E*/P*, which in situations of interest in the study of charged V decays is a slowly varying quantity nearly equal to one. Hence the maximum measurable momentum of the secondary can be calculated on the basis of the track length actually observed in the decay.

The lower limit of the range of measurable values of P* must be fixed so as to avoid confusion with scatterings and $\pi - \mu$ decays. For cases with heavily ionizing primaries this lower limit is essentially zero since such events are identifiable as charged V particles regardless of the value of P*. When the primaries have minimum ionization, one can take as the lower limit that value of P* which for the same θ* would give 50 Mev/c transverse momentum(1). Having thus assigned a useful range to each event, one should take for the distribution an overall range which is within the limits of most of the cases and over which the shape of the distribution has interest; and one should include in the distribution only those cases whose individual ranges of measurable P* include the overall range for the distribution. Carrying out such a procedure does not mean that events thereby excluded should be completely disregarded. Such events, however, would tend to be the least accurately measured ones; and, by themselves, could not be used to provide very strong evidence without being quite sure that their errors had been properly estimated.

The bias situation in the analysis of the transverse momentum distribution is considerably more complicated. Here the biases arise from the fact that the most easily detectable and measurable events are generally those which are emitted with large backward angles in the center-of-mass system. Such biases are most pronounced for decays which occur in unfavorable locations in the chambers such that the secondary track length is short, and for events in which the primary is very fast. The effects of these biases can be conveniently discussed by consideration of the quantity $\langle P_T \rangle / \langle P^* \rangle$ already mentioned in Section III-E. It was noted in that discussion that $\langle P_T \rangle / \langle P^* \rangle$ is equal to $\pi/4$ for an isotropic decay in the center-of-mass system, and that therefore $\langle P^* \rangle$ could be computed from $\langle P_T \rangle$ with great ease. One can expect that because of biases not all values of θ^* will yield secondaries of measurable momentum, in addition to which decays will be hard to see for values of θ^* which result in very small laboratory angles of decay. Thus, as a result of biases, those events whose transverse momentum can be measured will not, in fact, have isotropically distributed secondaries in the center-of-mass system. If one supposes that the effect of the biases is to make the θ^* distribution isotropic for all angles greater than a certain minimum value θ^*_{min}, then the quantity $\langle P_T \rangle / \langle P^* \rangle$ becomes

$$\frac{\langle P_T \rangle}{\langle P^* \rangle} = \frac{\int_{\theta^*_{MIN}}^{\pi} \sin^2\theta^* \, d\theta^*}{\int_{\theta^*_{MIN}}^{\pi} \sin\theta^* \, d\theta^*} = \frac{2(\pi - \theta^*_{min}) + \sin 2\theta^*_{min}}{4(1 + \cos\theta^*_{min})} . \quad (10)$$

This function of θ^*_{min} is plotted in Fig. 2. The usual theoretical distribution of P_T is obviously correct for $\theta^*_{min} = 0^o$ and $\theta^*_{min} = 90^o$. It is clear however that values of θ^*_{min} appreciably greater than 90^o may introduce large changes in $\langle P_T \rangle / \langle P^* \rangle$ which, if not taken into consideration, can invalidate any conclusions drawn from the P_T distribution. Fortunately, inspection of Fig. 2 shows that $\langle P_T \rangle / \langle P^* \rangle$ remains nearly constant for all values of θ^*_{min} less than 90^o (sufficiently so, for example, to distinguish between two- and three-body decays from the P_T distribution). It is clear, then, that a useful P_T distribution can be obtained provided that each event included in the distribution is sufficiently well located and sufficiently slow that if the secondary had been emitted with the maximum value of P^* at 90^o in the center-of-mass system, it would have been measurable; and the laboratory angle of decay would have been sufficiently large to permit easy detection of the event. In trying to apply such a criterion, it is obviously necessary to have some information concerning the speed of the primary, since this determines the secondary momentum at $\theta^* = 90^o$ and $P^* = P^*_{max}$. In general, precise information of this type will not be available (since if it were, one could compute P^* itself rather than try to work

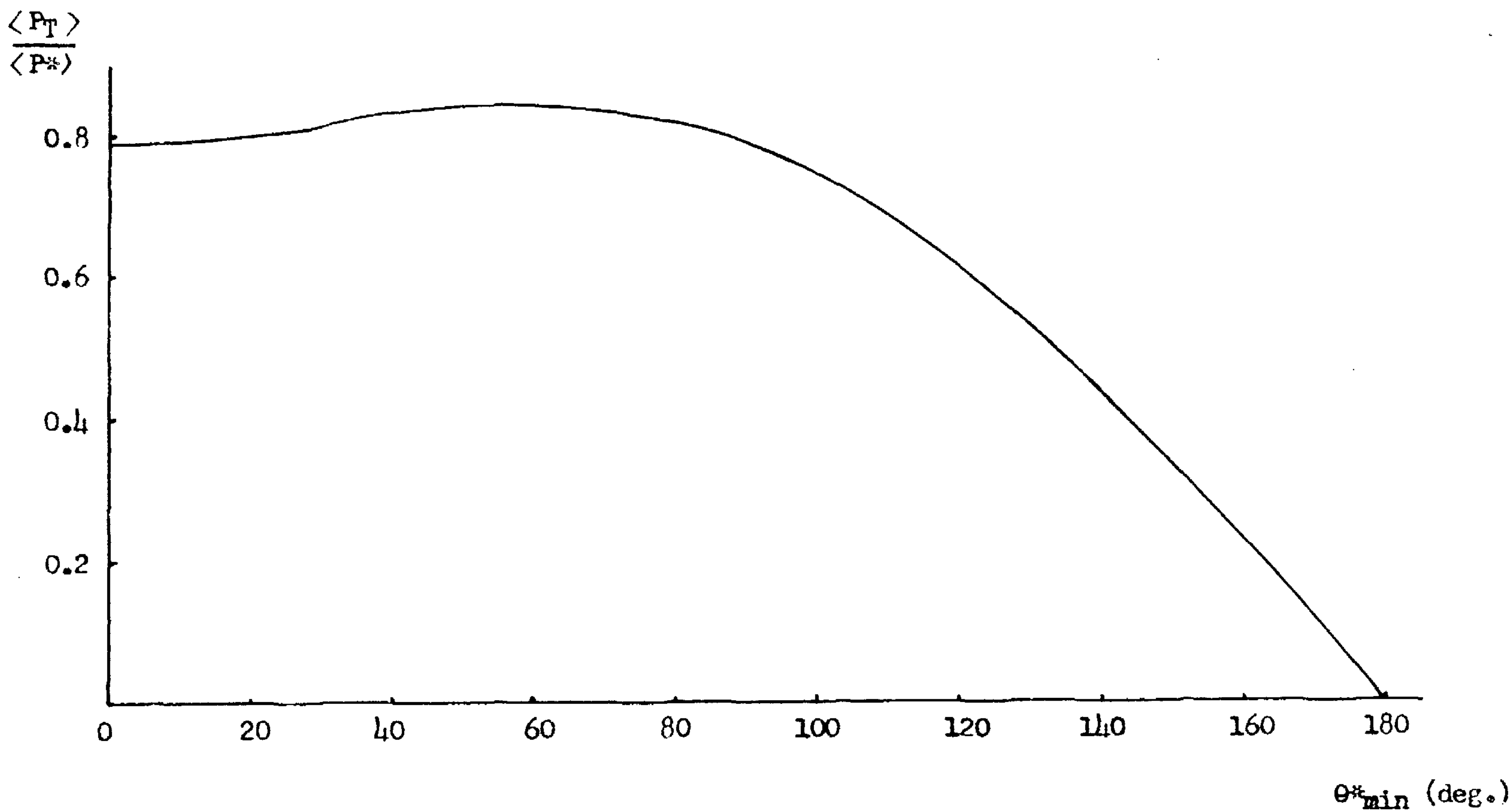

Fig. 2. Plot of $\frac{\langle P_T \rangle}{\langle P^* \rangle}$ versus θ^*_{min}.

with P_T), but rough estimates can be made from ionization, and from angles of decay and magnitudes of secondary momenta which will be adequate for the selection of suitable events. Examples of such estimates will be given in the discussion of the data. Another slight difficulty arises from the fact that at $\theta^* = 90^\circ$, the laboratory angle of decay and, hence, the length of visible secondary track in the chamber, will not be the same as the length observed for the actual decay, making it difficult to estimate the maximum measurable momentum of the secondary at 90° emission. Inasmuch, however, as no clear bias is introduced by just using the actually observed length of secondary to calculate the maximum measurable momentum, there appears to be no objection to introducing that simplifying approximation when making the selection of the sample.

IV. DISCUSSION OF THE DATA-- GENERAL CONSIDERATIONS

A. GENERAL PRESENTATION OF THE DATA

Out of approximately 30,000 pictures obtained over two years of operation, a total of 84 analyzable charged V events were obtained. In the identification of these events, the transverse momentum of either the primary or the secondary was required to be greater than 50 Mev/c without any visible recoil blob at the apex(1), to eliminate scatterings and $\pi - \mu$ decays. The data obtained from each case are shown in Table I. The momenta listed in the table were all obtained from the curvatures of the tracks involved, due account being taken of the effects of the conical projection and the non-axial components of the magnetic field.(13) The ionizations were estimated visually. The angles of decay were obtained from the reprojections of the events and are believed to be accurate to one degree except where one of the tracks was very short. The quantities x and d listed in Table I will be discussed in Section VI-B. The numbering of the chambers goes from top to bottom, and the number 12 refers to the double-size chamber which replaced Chambers 1 and 2.

B. THE MASSES OF THE PRIMARIES AND SECONDARIES OF CHARGED V EVENTS

Table II lists all events in which the ionization of the primary or of the secondary is greater than minimum, and gives limits on the masses of these particles obtained from their ionizations plus whatever information is available concerning their momenta. It is clear from these limits that all heavily ionizing primaries have a mass consistent with a value around 1000 electron masses, though a few could, from the available information, have a considerably higher value. It is also evident that

Table I. Data on 84 Charged V Events

Case No.	Chamber and Sign	P_1 (Mev/c)	I_1/I_{min}	P_2 (Mev/c)	I_2/I_{min}	θ	P_T (Mev/c)	x (cm)	d (cm)
02297	3 -	---	< 2	85 ± 5	1.5 - 3	87°	85 ± 5	---	---
02671	4 +	---	< 1.5	---	< 1.5	23°	---	6.8	12.8
03236	1 +	---	< 1.5	---	< 1.5	41°	---	5.7	9.1
04456	2 -	---	< 1.5	420 ± 160	< 1.5	16°	120 ± 45	8.2	12.0
04612	4 -	---	< 1.5	204 ± 40	< 1.5	15°	54 ± 10	---	---
05830	4 -	---	< 1.5	---	< 1.5	25°	---	9.6	12.0
06622	4 -	---	< 1.5	---	< 1.5	37°	---	12.0	13.8
06823	1 +	225 ± 17	3 - 6	112 ± 10	< 2	100°	110 ± 10	18.3	22.7
06905	4 +	400 ± 100	1.5 - 3	300 ± 90	< 1.5	43°	204 ± 61	11.9	15.5
08506	2 +	500 ± 130	1.5 - 3	---	< 2	17°	---	---	---
08940	2 +	---	< 2	221 ± 60	< 1.5	44°	153 ± 41	9.9	15.5
09475	4 -	---	< 2	89 ± 6	< 2.5	51°	70 ± 5	1.1	5.4
09538	3 +	415 ± 80	1.5 - 3	200 ± 40	< 2	89°	200 ± 40	12.6	12.8
09644	2 -	---	< 2	179 ± 20	< 2	59°	154 ± 17	0.4	16.0

Case No.	Chamber and Sign	P_1 (Mev/c)	I_1/I_{min}	P_2 (Mev/c)	I_2/I_{min}	θ	P_T (Mev/c)	x (cm)	d (cm)
09965	4 -	---	< 1.5	180 ± 70	< 1.5	35°	104 ± 40	7.2	13.2
10041	2 +	630 ± 90	< 2	270 ± 38	< 2	53°	216 ± 30	18.1	35.1
10057	3 +	490 ± 160	2 - 4.5	131 ± 40	1.2 - 2.5	63°	116 ± 35	11.7	15.2
11023	2 -	---	< 2	425 ± 45	< 2	27°	194 ± 20	---	---
11365	1 -	---	< 1.5	137 ± 11	1.2 - 2.5	63°	122 ± 9	6.8	14.8
11654	1 +	---	> 1.5	140 ± 17	< 2	41°	92 ± 11	2.1	8.5
12010	4 +	~ 48	> 30	322 ± 40	< 1.5	37°	192 ± 25	---	---
12191	1 +	251 ± 75	2.5 - 4.5	126 ± 23	< 2	132°	93 ± 17	2.4	15.4
12322	3 +	360 ± 80	1.5 - 2.5	---	---	7°	---	---	---
12564	3 +	600 ± 130	< 1.7	117 ± 14	< 2	92°	117 ± 14	6.3	30.2
12973	2 +	270 ± 100	2.5 - 5	165 ± 45	< 1.5	34°	92 ± 25	8.7	9.6
13798	2 -	---	< 2	245 ± 24	< 2	38°	150 ± 19	1.1	8.3
13954	2 -	---	< 2	428 ± 52	< 2	33°	232 ± 42	2.6	17.1
14458	4 -	---	< 2	---	< 1.5	29°	---	1.3	4.0
16091	12 +	473 ± 55	1.2 - 2.5	107 ± 6	---	101°	106 ± 6	38.7	42.0
16990	4 -	---	< 2	227 ± 22	< 2	39°	145 ± 21	0.5	14.8
17261	4 -	---	< 3	160 ± 30	< 2	76°	155 ± 29	4.1	14.3

Case No.	Chamber and Sign	P_1 (Mev/c)	I_1/I_{min}	P_2 (Mev/c)	I_2/I_{min}	θ	P_T (Mev/c)	x (cm)	d (cm)
17429	4 -	---	< 2	100 ± 7	1.5 - 3	106°	96 ± 8	0.1	22.7
17461	12 +	---	< 2	824 ± 75	< 2	13°	187 ± 17	14.1	32.2
17496	12 +	545 ± 54	1.1 - 1.8	460 ± 70	< 1.8	11°	91 ± 14	20.4	36.8
17501	3 -	460 ± 160	1.5 - 3	225 ± 50	< 1.5	36°	132 ± 30	4.8	15.8
17700	12 -	---	---	427 ± 15	< 2	31°	217 ± 13	---	---
18375	12 -	---	< 2	303 ± 50	< 2	25°	126 ± 20	8.9	33.7
18393	3 +	590 ± 150	< 2	530 ± 95	< 2	7°	97 ± 15	---	---
18571	3 +	340 ± 95	2 - 4	150 ± 10	1.2 - 2	97.5°	148 ± 10	8.1	21.0
18670	12 +	218 ± 15	3 - 6	204 ± 19	1.1 - 2	97°	202 ± 19	17.5	18.5
18972	12 -	---	< 2	390 ± 90	< 2	33°	210 ± 50	0.8	36.8
19267	12 +	---	< 2	422 ± 35	< 1.7	33°	230 ± 19	8.1	46.5
19382	3 +	255 ± 75	3 - 6	180 ± 45	1.1 - 2	58°	152 ± 38	10.2	15.9
19604	4 -	---	< 2.5	280 ± 12	< 2.5	43.5°	193 ± 8	1.5	15.3
19648	4 -	500 ± 80	< 1.5	660 ± 190	< 2	23°	256 ± 74	0.6	12.9
20445	12 +	230 ± 11	2.5 - 5	210 ± 20	< 2	112.5°	197 ± 19	30.2	37.2
22641	4 -	---	< 2	---	< 2	19°	---	3.2	13.1
22644	4 +	590 ± 150	< 2	360 ± 55	< 2	38°	222 ± 31	4.5	12.6

Case No.	Chamber and Sign	P_1 (Mev/c)	I_1/I_{min}	P_2 (Mev/c)	I_2/I_{min}	θ	P_T (Mev/c)	x (cm)	d (cm)
23569	4 -	---	<2	550 ± 180	<2	16°	150 ± 50	2.8	14.9
24018	4 -	101 ± 15	10 - 20	220 ± 55	<2	102°	215 ± 54	9.5	10.6
24508	3 +	370 ± 76	1.5 - 3	198 ± 40	<1.5	77°	193 ± 40	11.4	23.0
24631	4 +	---	---	68 ± 5	2.5 - 6	86°	68 ± 5	5.8	15.9
25924	12 -	---	---	640 ± 190	<1.5	13°	147 ± 44	14.9	41.0
25926	12 +	---	1.1 - 2.5	264 ± 12	<1.7	63.5°	235 ± 11	10.0	25.9
26378	12 -	---	---	195 ± 15	<2	55°	160 ± 12	3.1	9.9
26717	3 -	204^{+125}_{-62}	2 - 4	280 ± 65	1.2 - 2.5	41.5°	185 ± 43	5.4	15.5
26971	12 -	1100 ± 280	<1.3	205 ± 16	<2	39°	129 ± 10	25.0	35.4
27161	12 -	---	<2	---	<2	51°	---	8.6	15.4
27192	3 -	---	<2	150 ± 25	1.1 - 2	41°	99 ± 17	1.6	7.1
27615	12 +	330 ± 90	<2.5	390 ± 80	---	33°	214 ± 44	10.1	26.4
28663	4 +	350 ± 120	<2	340 ± 100	<2	44°	235 ± 69	9.8	16.0
28697	12 -	---	<1.3	333 ± 52	<1.3	15.5°	89 ± 14	24.2	34.4
28883	12 -	---	<2	147 ± 20	<2	10°	26 ± 3	---	---
29312	12 +	164 ± 15	4 - 8	329 ± 25	<1.5	26°	144 ± 11	16.8	26.3
29613	12 -	---	---	620 ± 90	<2	13°	141 ± 20	---	---

Case No.	Chamber and Sign	P_1 (Mev/c)	I_1/I_{min}	P_2 (Mev/c)	I_2/I_{min}	θ	P_T (Mev/c)	x (cm)	d (cm)
29651	4 -	---	<2.5	316 ± 40	<1.5	10°	54 ± 7	---	---
29685	12 +	---	<2	195 ± 30	<2	39°	122 ± 19	12.9	20.9
30166	12 +	202 ± 11	3 - 5	330 ± 25	<1.5	45°	234 ± 18	25.0	37.1
31855	12 +	---	1.5 - 2.5	285 ± 29	<1.5	41°	188 ± 19	11.6	30.6
31945	12 +	---	<2	---	<2	6.5°	---	---	---
32121	12 +	---	<2	---	<2	12°	---	8.6	25.1
32269	4 -	---	<2	260 ± 50	<1.5	74°	250 ± 48	5.7	5.9
33178	4 -	---	<2	425 ± 65	<1.5	26°	184 ± 30	1.7	12.8
33596	3 +	---	<1.5	390 ± 80	<1.5	21°	140 ± 30	2.8	12.6
33615	12 +	---	1.1 - 2	175 ± 20	<1.5	61°	152 ± 17	13.5	35.0
33631	4 -	---	<1.5	360 ± 120	<1.5	10°	65 ± 22	5.7	5.8
33725	12 +	1000 ± 300	<1.5	300 ± 25	<1.5	38°	185 ± 15	14.7	22.9
34082	4 -	---	1.3 - 2.5	186 ± 18	<1.5	61.5°	163 ± 16	8.9	16.8
34393	12 -	---	<1.5	95 ± 6	2 - 4	60°	82 ± 5	6.5	34.8
34608	4 -	---	<2	285 ± 25	<1.5	37°	171 ± 20	0.2	1.3
35286	12 -	---	<1.5	175 ± 7	<1.5	60°	152 ± 8	1.1	37.3
35325	12 +	---	<1.5	296 ± 15	<1.5	9°	45 ± 2	---	---

Case No.	Chamber and Sign	P_1 (Mev/c)	I_1/I_{min}	P_2 (Mev/c)	I_2/I_{min}	θ	P_T (Mev/c)	x (cm)	d (cm)
35487	12 -	300 ± 125	2.5 - 5	213 ± 5	<1.5	66°	197 ± 5	2.7	25.4
37034	4 +	130 ± 30	3.5 - 7	206 ± 21	<1.5	90°	206 ± 21	1.1	2.8

Table IIa. Masses of Primaries

Case No.	Sign	Momentum (Mev/c)	I/I_{min}	Mass (m_e)
06823	+	225 ± 17	3 - 6	700 - 1300
06905	+	400 ± 100	1.5 - 3	550 - 1700
08506	+	500 ± 130	1.5 - 3	700 - 2200
09538	+	415 ± 80	1.5 - 3	600 - 1700
10057	+	490 ± 160	2 - 4.5	800 - 3000
12010	+	~50	>30	$\gtrsim$800
12191	+	251 ± 75	2.5 - 4.5	500 - 1500
12322	+	360 ± 80	1.5 - 2.5	500 - 1300
12973	+	270 ± 100	2.5 - 5	500 - 1800
16091	+	473 ± 55	1.2 - 2.5	550 - 1600
17501	-	460 ± 160	1.5 - 3	550 - 2150
18571	+	340 ± 95	2 - 4	600 - 1800
18670	+	218 ± 15	3 - 6	700 - 1300
19382	+	255 ± 75	3 - 6	600 - 1800
20445	+	230 ± 11	2.5 - 5	650 - 1200
24018	-	101 ± 15	10 - 20	600 - 1350
24508	+	370 ± 76	1.5 - 3	550 - 1550
26717	-	204^{+125}_{-62}	2 - 4	350 - 1400
29312	+	164 ± 15	4 - 8	600 - 1200
30166	+	202 ± 11	3 - 5	650 - 1050
31855	+	$\gtrsim$ 500	1.5 - 2.5	$\gtrsim$ 900
34082	-	$\gtrsim$500	1.3 - 2.5	$\gtrsim$800
35487	-	300 ± 125	2.5 - 5	500 - 2100
37034	+	130 ± 30	3.5 - 7	400 - 1000

Table IIb. Masses of Secondaries

Case No.	Sign	Momentum (Mev/c)	I/I_{min}	Mass (m_e)
02297	-	85 ± 5	1.5 - 3	150 - 310
10057	+	131 ± 40	1.2 - 2.5	120 - 500
11365	-	137 ± 11	1.2 - 2.5	160 - 450
17429	-	100 ± 7	1.5 - 3	170 - 350
24631	+	68 ± 5	2.5 - 6	180 - 400
26717	-	280 ± 65	1.2 - 2.5	280 - 1050

all heavily ionizing secondaries have a mass consistent with that of either a π or a μ meson. For many of the minimum ionizing secondaries listed in Table I, an upper limit of mass can be set from their momentum, which in all cases is consistent with a light meson and in most cases inconsistent with anything as massive as 1000 m_e. There is then no evidence at all for any proton secondaries, such as have been observed by York et al[1].

C. CHARGE ASYMMETRY OF THE DATA

Because the work of other groups has suggested the existence of certain positive-negative asymmetries, it appears worthwhile to see if any general asymmetries are indicated from a qualitative consideration of the data. The division of all events among positives and negatives (namely 41 positives, 43 negatives) is consistent with perfect symmetry. However, the probable existence of several different kinds of charged V particles makes it important to observe if this symmetry is preserved within various possible subdivisions of the entire group of events. One such subdivision is the consideration of only the decays with slow, heavily ionizing primaries which have been listed in Table II. Of these there are 19 positives and 5 negatives. If one supposes that this large asymmetry arises from a statistical fluctuation, the probability of obtaining from 24 slow events a distribution of equal or greater asymmetry is only .006.

Some information concerning the possible existence of very short-lived positive or negative charged V particles can be obtained from a consideration of the relative proportions of observed decays among the various chambers. In this connection, one should note that, on the average, one can see with ease about 2 cm closer to the production layer in Chambers 2 and 4 than in Chambers 12, 1, and 3 because of the locations of the cameras (see Fig. 1). Therefore any events whose mean decay distances are comparable to 2 cm will be predominantly found in Chambers 2 and 4.

Table III shows the numbers of positive and negative decays in each chamber. It is clear that there is no indication of any very short-lived positive component. In particular there are about as many decays in 1 as in 2, and in 3 as in 4; Chamber 12 shows the large number of decays expected for long-lived particles taking full advantage of the double size of the chamber. On the other hand, there are about five times as many negatives in Chambers 2 and 4 as there are in Chambers 1 and 3. This can be interpreted as a statistical fluctuation, but the probability that 30 events will split in the ratio 25 to 5 or worse if the a priori probabilities are equal is only .0004. Thus the distribution of decays among the chambers does suggest the presence of a very short-lived negative component.

From the above considerations, it is clear that although the total numbers of positives and negatives are nearly equal, there appear to be important differences between the two components. These will be treated in more detail further on when the quantitative aspects of the data are discussed.

Table III. Distribution of Decays among Chambers

		Positives	Negatives
Chamber	12	17	13
	1	4	1
	2	4	5
	3	9	4
	4	7	20
	Total	41	43

V. DISCUSSION OF THE DATA--THE P* DISTRIBUTIONS

A. P* DISTRIBUTION--POSITIVES

A total of 25 positive decay events had measurable secondary momenta and were heavily ionizing and/or had measurable primary momenta. Two values of P* were calculated for each of these events on the assumption of a μ - or a π -meson secondary. In making this calculation, the primary speed was obtained either from the ionization of the primary or from its measured momentum, a mass of 500 Mev being assumed. For events in which both primary momentum and ionization were available, whichever one gave the lowest estimated error in the speed of the primary was used. The results of these calculations are shown in Table IV. The errors in P* stated in Table IV were compounded from the errors in the primary velocity and secondary momentum on the assumption that these are independent. Prints of several of the cases represented in Table IV are shown in Figs. 3, 4, and 5. Ranges of values of P* for which each event was measurable were calculated as indicated in Section III-F, the upper limit of each range being set by requiring a 33 percent accuracy in the momentum of the secondary. The first 19 events listed in Table IV were measurable for 100 Mev/c $<$ P* $<$ 300 Mev/c, and their P* distribution calculated on the basis of a μ -meson secondary is shown plotted in the histogram of Fig. 6. The intervals on the histogram were chosen to include roughly equal numbers of cases, and each event was given the same rectangular area with a half-width equal to the assigned error. It is clear from Table IV and from the histogram that most of these events have values of P* consistent with a single two-body decay.

Table IV. P* Distribution -- Positives

Case No.	$\gamma\beta$	P_2 (Mev/c)	θ	$P^*(\mu)$ (Mev/c)	$P^*(\pi)$ (Mev/c)	ΔP^* (Mev/c)
06823	.45 ± .03	112 ± 10	100°	142	150	± 11
09538	.83 ± .16	200 ± 40	89°	272	282	± 55
10041	1.26 ± .18	270 ± 38	53°	242	251	± 34
12010	.10 ± .04	322 ± 40	37°	295	295	± 40
12191	.50 ± .15	126 ± 23	132°	200	211	± 41
12564	1.20 ± .26	117 ± 14	92°	232	262	± 39
16091	.95 ± .11	107 ± 6	101°	201	222	± 17
17496	1.09 ± .11	460 ± 70	11°	184	175	± 33
18571	.65 ± .15	150 ± 10	97.5°	206	214	± 23
18670	.44 ± .03	204 ± 19	97°	240	244	± 21
20445	.46 ± .02	210 ± 20	112.5°	274	280	± 25
22644	1.20 ± .30	360 ± 55	38°	222	222	± 31
24508	.74 ± .15	198 ± 40	77°	222	229	± 44
27615	.70 ± .18	390 ± 80	33°	247	240	± 55
29312	.33 ± .03	329 ± 25	26°	245	242	± 20
30166	.40 ± .02	330 ± 25	45°	259	257	± 20
31855	.80 ± .20	285 ± 29	41°	191	189	± 21
33725	2.00 ± .60	300 ± 25	38°	215	228	± 34
37034	.26 ± .06	206 ± 21	90°	215	216	± 22

Case No.	$\gamma\beta$	P_2 (Mev/c)	θ	$P^*(\mu)$ (Mev/c)	$P^*(\pi)$ (Mev/c)	ΔP^* (Mev/c)
06905	.80 ± .20	300 ± 90	43°	207	204	± 63
10057	.98 ± .32	131 ± 40	63°	143	158	± 38
12973	.54 ± .20	165 ± 45	34°	105	100	± 35
18393	1.20 ± .30	530 ± 95	7°	223	212	± 58
19382	.51 ± .15	180 ± 45	58°	152	152	± 38
28663	.70 ± .24	340 ± 100	44°	240	238	± 69

Fig. 3. Event No. 29312 -- V^+ Decay

$P^* = 245 \pm 20$ Mev/c

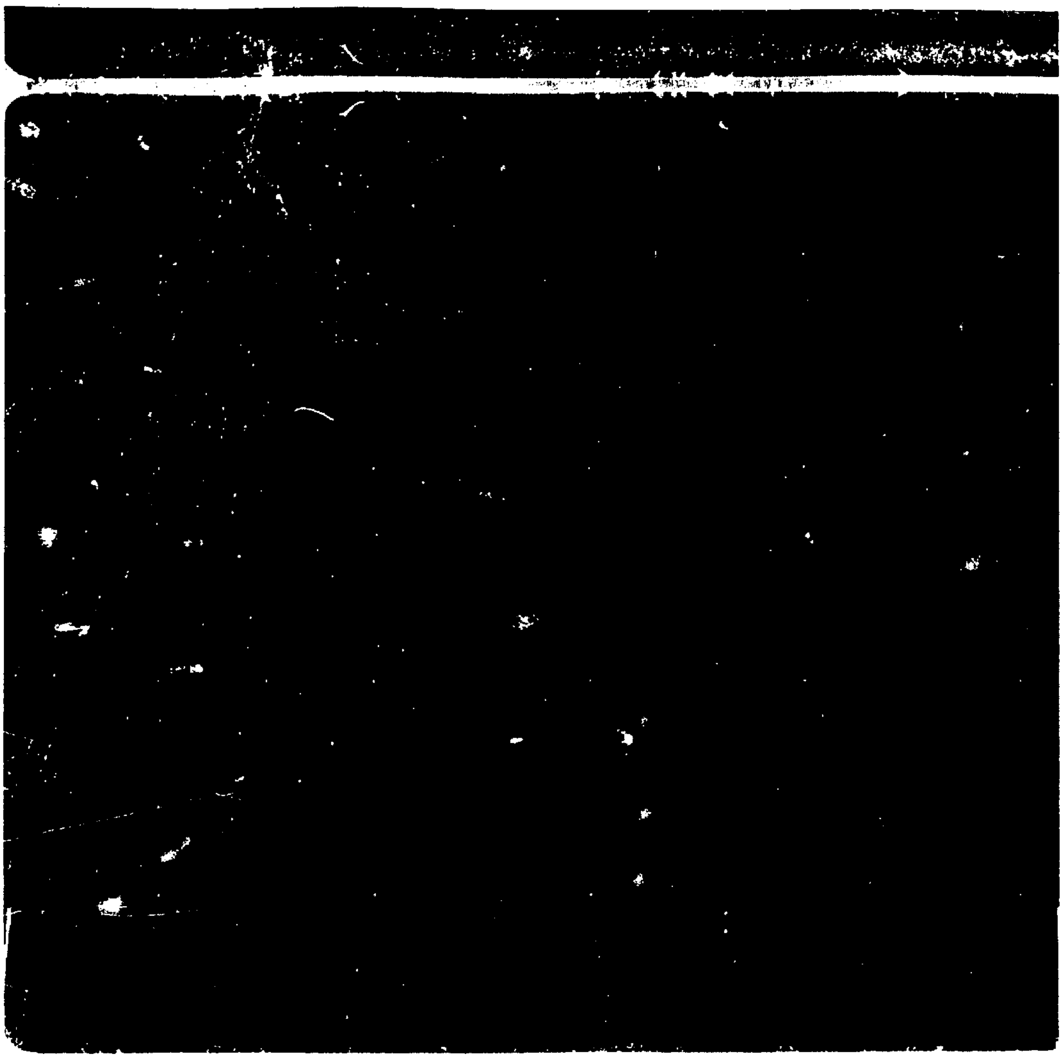

Fig. 4. Event No. 31855 -- V^+ Decay

$P^* = 191 \pm 21$ Mev/c

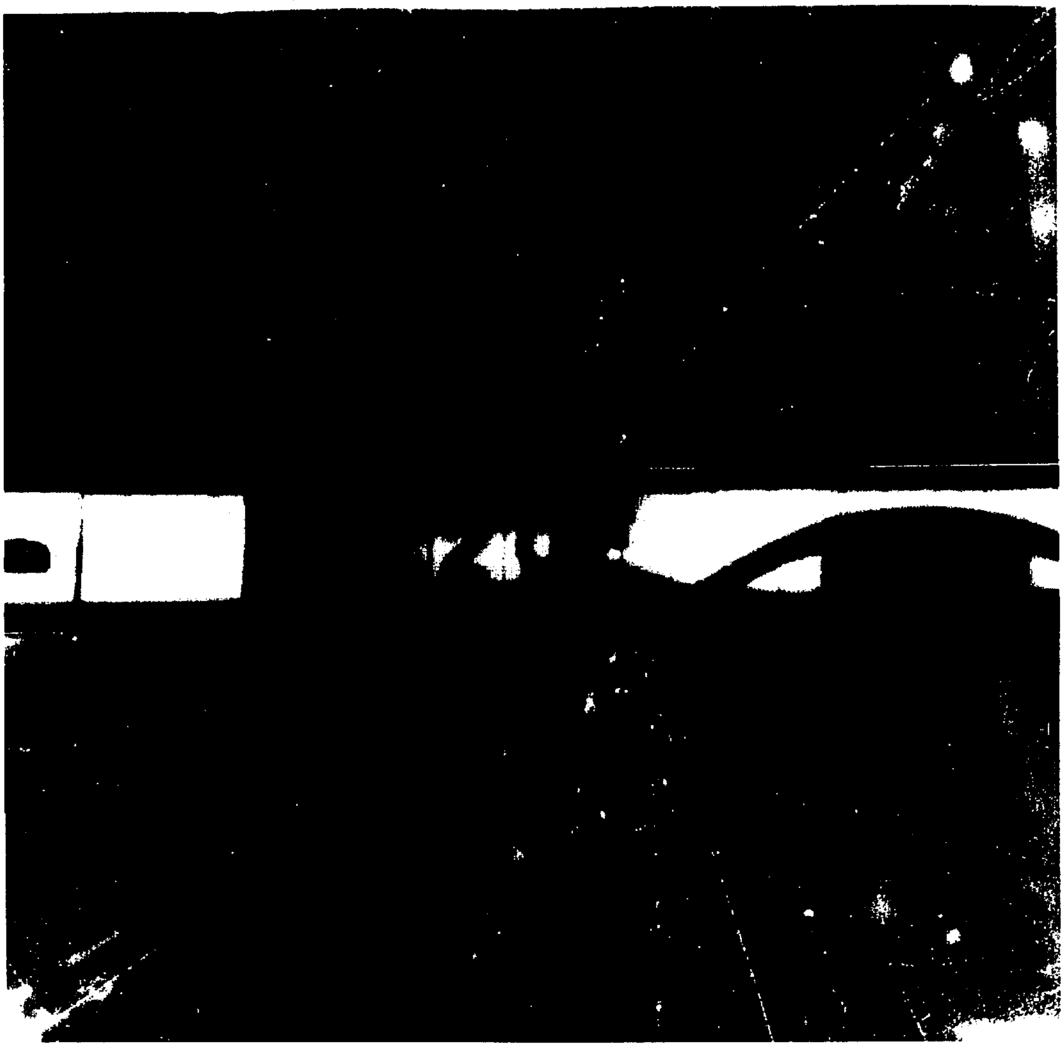

Fig. 5. Event No. 6823 -- V^+ Decay (Upper Chamber)

$P^* = 142 \pm 11$ Mev/c

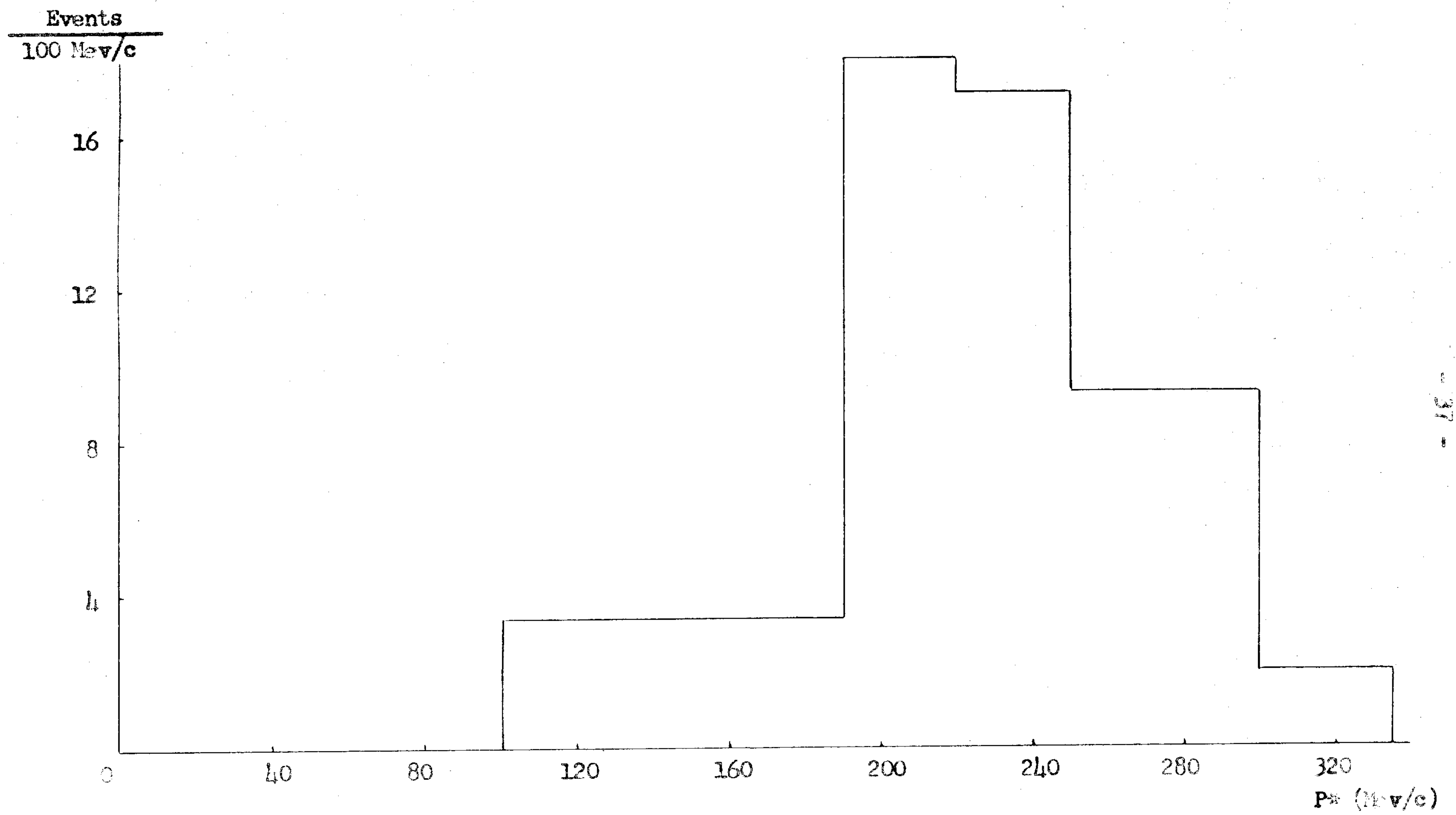

Fig. 6. P* Distribution
19 Positive Events

However, since the value of P* necessary for consistency with most of the data is obviously well over 200 Mev/c, it appears that there is at least one exceptional case inconsistent with this interpretation, namely No. 6823, for which $P^* = 142$ or 150 ± 11 Mev/c, depending upon whether the secondary is assumed to be a μ or a π meson. If one tries to interpret the whole data in terms of a single decay scheme which is assumed to give rise to the observed P* distribution, the mean value and R. M. S. deviation from the mean for this distribution obtained from the 19 cases plotted in the histogram are, again assuming a μ-meson secondary,

$$\langle P^* \rangle = 226 \text{ Mev/c}$$

$$[\langle P^{*2} \rangle - \langle P^* \rangle^2]^{\frac{1}{2}} = 36 \text{ Mev/c.}$$

It is of interest to compare these values with those which would be expected from a reasonable three-body distribution. One can consider, for example, the scheme,

$$K^+ \rightarrow \mu^+ + 2\nu ,$$

and assume that the P* distribution is given by Equation (6), Section III-D. Two situations can be considered:

(1) If the mass of the primary is equal to the τ mass, the expected value of $\langle P^* \rangle$ for 19 cases is 161 ± 11 Mev/c, a figure quite incompatible with the experimental value previously quoted.

(2) If the mass of the primary is chosen so as to give a mean P* in agreement with the observed value, namely equal to about 1330 m_e, the expected R. M. S. deviation from the mean is 68 Mev/c. If the estimated errors of measurement are also considered, the probability of getting as small a value of this deviation as was obtained is only .003.

The above discussion makes it clear that it is very improbable that a three-body decay of the type suggested can be used to account for all the data, provided that the assumptions made are correct. The choice of different secondaries is not likely to change this conclusion appreciably. The possibility that the assumed three-body decay distribution is grossly incorrect, and that the existence of strong angular correlations between the decay products gives rise to the observed distribution, cannot be excluded, however.

In view of the above considerations it appears reasonable to assume that the major part of the distribution comes from one or more two-body decays, and that Case No. 6823 possibly represents a three-body decay which does not occur sufficiently frequently to mask the two-body character of most of the decays. If this event is temporarily deleted from the sample, and if the remaining 18 accurately measured events are assumed to arise from a single two-body decay, the P* of that decay can be obtained by taking a suitably weighted average of the individual values obtained for these events. In carrying out this weighting, it should be noted that events which give low values of P* tend to be assigned smaller errors than those yielding high values, an effect which if not taken into account will tend to give too low a value for the mean P*. To avoid this difficulty, an approximate P* of 230 Mev/c was assumed for each event, and the measured quantity (either the primary velocity or the secondary momentum) which caused the main error in each individual value of P* was recalculated assuming the other measured quantities as correct. A revised error in each value of P* was then estimated by using the recalculated quantities rather than the actually measured ones. The mean value of P* was calculated by taking a weighted average of the individual P* values, each event being weighted inversely as the square of its revised error. The result of this calculation for the 18 accurately measured events remaining after Case No. 6823 was deleted is

$$\langle P^* \rangle = 239 \pm 5 \text{ Mev/c} \qquad \mu \text{ secondary}$$

$$\langle P^* \rangle = 243 \pm 5 \text{ Mev/c} \qquad \pi \text{ secondary.}$$

The probable errors given above were computed from the spread of the P* distribution; and, hence, do not include any systematic effects. Before considering such effects, it is of interest to note in a quantitative way that the spread of the P* distribution obtained from the 18-case sample being considered is completely consistent with what can be expected from a two-body decay. In fact, if one considers the revised errors discussed above in connection with the calculation of $\langle P^* \rangle$ as probable errors, then the quantity,

$$\chi^2 = (.6745)^2 \sum_{i=1}^{18} \frac{[P_i^* - \langle P^* \rangle]^2}{(\Delta P_i^*)^2}, \qquad (11)$$

where ΔP_i^* is the revised error in P_i^*, has the well known χ^2 distribution. In particular, there is only a ten percent probability that 18 events with probable errors ΔP_i^*, and a single P* value will give a χ^2 any lower than the actually obtained value of 10. In other words, the spread is, if anything, even less than might be expected from a two-body decay with the estimated errors implying that at least insofar as random errors are concerned, these were assigned conservatively.

Systematic errors present in the above values of $\langle P^* \rangle$ can be expected to arise from two main sources:

1. The calibration of the magnetic field may be in error. Considering the care which was used in carrying out this calibration, it appears extremely unlikely that the error arising from this source is more than one-half percent. Even this figure seems, if anything, rather conservative.

2. Systematic distortions may have been present, and may have tended to affect the P* values for positive decays in always the same direction. In trying to investigate the possibility of such an effect, one should note two important points. Firstly, the decays being considered occurred in a large variety of locations and orientations in the chambers, and, for that reason, it is hard to see how any appreciable systematic effect could arise. Furthermore, no correlation between the P* value and orientation of the event in the chambers has been observed. Secondly, the existence of a systematic distortion would be expected to affect Q-value results for Λ^o events, since it is almost always the negative momentum which determines the error in the Q value. The 48" data on Λ^o's gives a Q value of 36 ± 0.5 Mev[15]. The agreement between this figure and the generally accepted 37 Mev[16] suggests that systematic distortion effects are very likely less than 1 1/2 percent. Thus the total systematic error is almost surely less than 2 percent. This implies a slight revision of the previously given errors in $\langle P^* \rangle$ with the results:

$$\langle P^* \rangle = 239 \pm 7 \text{ Mev/c} \qquad \mu \text{ secondary,}$$

$$\langle P^* \rangle = 243 \pm 7 \text{ Mev/c} \qquad \pi \text{ secondary.}$$

If one assumes that the two-body decay represented is

$$K^+ \rightarrow \mu^+ + \nu ,$$

the above value of $\langle P^* \rangle$ corresponds to a primary mass of 980 ± 30 m_e.

This figure is quite consistent with the mass of the τ meson, and is a little higher than, though not inconsistent with, the present best value of the K^+_μ, namely 928 ± 13 m_e[17]. (See discussion in Section IV-D.)

The above analysis was made on the assumption that the sample considered represented a single two-body decay. However, there is good evidence from other laboratories indicating the existence of the decay,[6],[18]

$$\theta^+ \rightarrow \pi^+ + \pi^0 \qquad\qquad P^* = 206 \text{ Mev/c} .$$

It is clear from Table IV that the errors on individual cases are fairly large, and that some of the events listed could well be θ^+ decays. In fact, several of the P* values agree much better with 206 than with 239 Mev/c. In view of the latter figure, however, it is certain that not all the events in the sample under consideration can be θ^+'s. If any appreciable fraction of the events are θ^+ decays, and if the presently accepted P* value for the K^+_μ of 225 Mev/c[17] is correct, then it seems very likely that there are events in the sample with P* values appreciably higher than that of the K^+_μ. Thus the 18 cases being discussed may well consist of a mixture of θ^+ events, K^+_μ events, and other decays giving higher values of P*. The natural spread of P* values for such a mixture (i. e., the spread expected if there were no errors of measurement) could easily be small in comparison to the fairly sizable measurement errors, so that there would be no inconsistency with the previously shown fact that the data are explainable in terms of a single two-body decay.

In all this discussion, Event No. 6823, whose P* is clearly inconsistent with the values obtained for the other good cases has been ignored. This event, shown in Fig. 5, has a primary mass roughly equal to 1000 m_e as determined by ionization and momentum; and, hence, if its decay products are among the known particles, the measured value of P* requires that there be at least three secondaries. One possible decay scheme is

$$\tau^+ \rightarrow \pi^+ + 2\pi^0 ,$$

but since the maximum allowed value of P* for this decay, namely 133 Mev/c, is nearly two probable errors below the measured value, this interpretation does not seem likely. Another more probable interpretation is in terms of the decay,

$$K^+ \rightarrow \mu^+ + ? + ? ,^{(5)}$$

which has been suggested by photographic plate results. It is, of course, quite possible that some of the higher values of P* which are consistent with the previously mentioned two-body decays really arise from the three-body decay suggested above. As has been shown before, however, the lack of events with low values of P* makes it very unlikely that this three-body decay could, by itself, account for the observed distribution.

B. P* DISTRIBUTION--NEGATIVES

Seven negative events were sufficiently measurable to permit calculation of P* values. The data for these cases are listed in Table V, the P* values having been computed in exactly the same way as for the positives. The first six of these cases are measurable for the full range 100 Mev/c $< P^* <$ 300 Mev/c and will be the only events considered in the discussion which follows. Unfortunately, the primary momenta for most of the events with heavily ionizing primaries were only crudely measured, so that, while a mass of about 1000 m_e seems to fit satisfactorily all the cases for which any estimate of momentum is available, the possibility that one or two of the cases listed in Table V are considerably more massive cannot be excluded. Consideration of the values of P* obtained for the best cases

Table V. P* Distribution -- Negatives

Case No.	$\gamma\beta$	P_2 (Mev/c)	θ	$P^*(\mu)$ (Mev/c)	$P^*(\pi)$ (Mev/c)	ΔP^* (Mev/c)
19648	1.00 ± .16	660 ± 190	23°	310	305	± 100
24018	.20 ± .03	220 ± 53	102°	236	238	± 58
26717	.65 ± .20	280 ± 65	41.5°	198	196	± 45
26971	2.20 ± .56	205 ± 16	39°	180	203	± 33
34082	1.00 ± .30	186 ± 18	61.5°	188	196	± 27
35487	.50 ± .20	213 ± 5	66°	198	198	$^{+12}_{-5}$
17501	.92 ± .32	225 ± 50	36°	132	132	± 31

seems to indicate that they are all consistent with a single value equal to 200 ± 10 Mev/c. In particular, the most accurately measured individual event (No. 35487 shown in Fig. 7) yields a value $198\,^{+12}_{-5}$ Mev/c, which seems considerably lower than the average given previously for the positives, but is highly consistent with the value, 206 Mev/c, expected for $\theta^{\pm}$ decay. The small number of cases of course prevents any strong conclusion regarding the existence of the decay,

$$\theta^- \rightarrow \pi^- + \pi^0 \qquad P^* = 206 \text{ Mev/c} \quad ,$$

but this scheme must be regarded as a possible interpretation of the data.

It has been suggested by the M. I. T. multiple-plate chamber data that the positive S particles consist predominantly of a mixture of particles undergoing the decays,

$$K^+_\mu \rightarrow \mu^+ + \nu$$
$$\theta^+ \rightarrow \pi^+ + \pi^0 \quad .$$

One possible interpretation of the positive negative asymmetry for slow events which is consistent with the present data is that only the θ^+ has a negatively charged counterpart. This is completely in agreement with the observations of the Paris group that essentially all particles which stop in their chambers are positive(3). If this interpretation were correct, it would imply that the K^+_μ and the θ^+ mesons are definitely not alternate decay schemes of the same particle. More data on negative decays are necessary, however, to establish the correctness of this interpretation.

C. COMPARISON WITH OTHER C. I. T. DATA

It is of interest to consider the information on P* values which has been obtained in other cloud chambers of the C. I. T. campus. Table VI lists the data for 14 events sufficiently measurable to yield a value of P*,

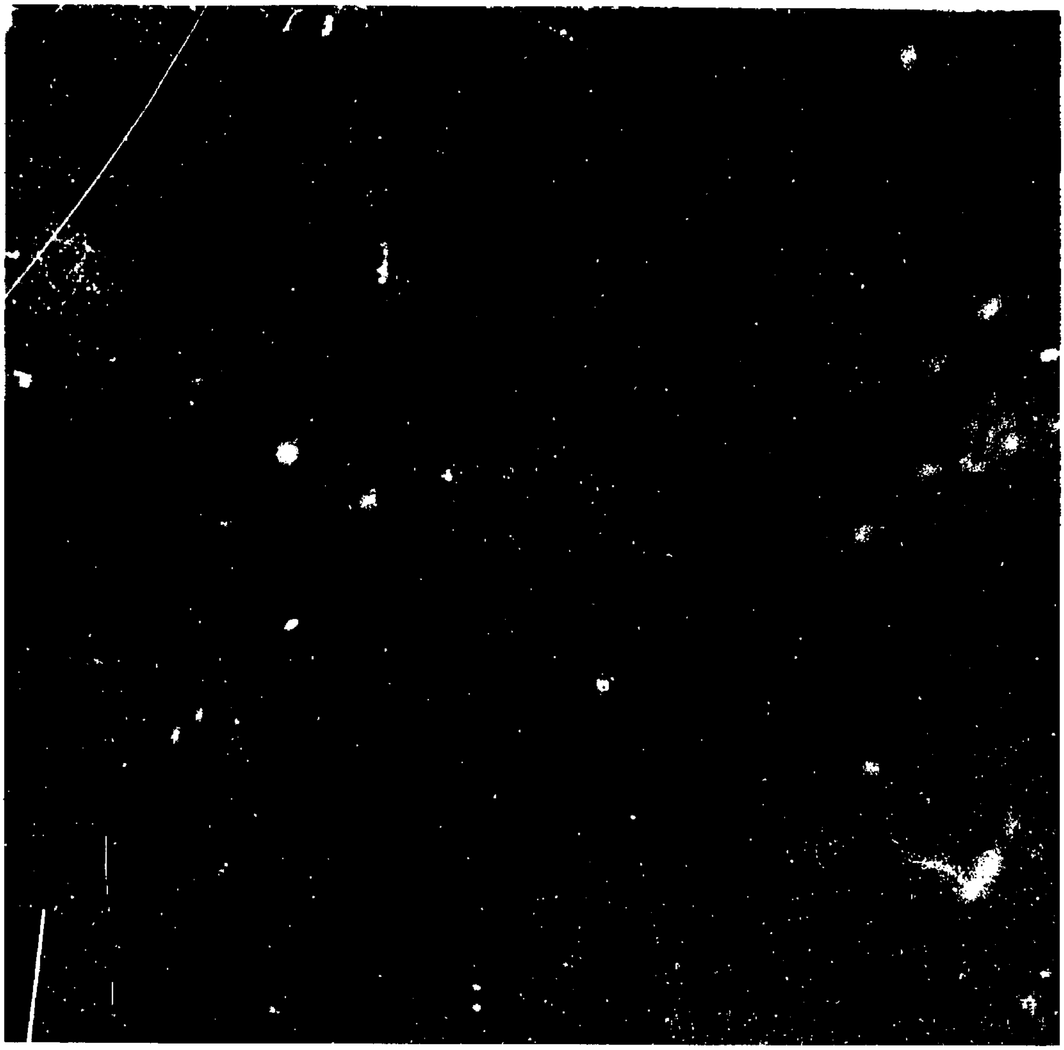

Fig. 7. Event No. 35487 -- V^- Decay

$P^* = 198 {}^{+12}_{-5}$ Mev/c

Table VI. P* Distribution -- 18" Cloud Chamber

Positives

Case No.	$\gamma\beta$	P_2 (Mev/c)	θ	P*(μ) (Mev/c)	P*(π) (Mev/c)	Δ P* (Mev/c)
25343	.37 ± .09	215 ± 43	51°	174	176	± 36
36726	.80 ± .25	140 ± 30	108°	236	250	± 57
40840	.19 ± .06	184 ± 20	87.5°	187	187	± 20
52999	.33 ± .17	215 ± 60	121°	267	271	± 80
60452	.50 ± .10	212 ± 10	99°	261	266	± 19
78113	.21 ± .03	251 ± 20	133°	290	294	± 25

Negatives

Case No.	$\gamma\beta$	P_2 (Mev/c)	θ	P*(μ) (Mev/c)	P*(π) (Mev/c)	Δ P* (Mev/c)
07029	.37 ± .05	150 ± 20	85°	159	162	± 20
17620	2.00 ± 1.00	750 ± 200	8°	183	171	± 89
26622	.80 ± .20	295 ± 65	33°	175	170	± 43
31589	.80 ± .25	265 ± 40	40°	173	172	± 26
32530	1.00 ± .30	590 ± 250	29°	316	314	± 138
54056	.80 ± .25	325 ± 75	13°	147	136	± 51
55482	.80 ± .20	182 ± 30	53.5°	149	152	± 24
65550	3.00 ± 1.60	120 ± 50	41.5°	210	277	± 100

which were obtained by York et al.(1) on the 18" cloud chambers. Table VII gives the same information for five such events obtained by Professor E. W. Cowan* with the 21" cloud chamber. For both of these sets of data, the values of P* were computed in exactly the same way as with the 48" results. Study of Tables VI and VII leads one to the following observations.

1. The positive excess for events with slow primaries noted in the 48" data is also quite apparent in the 21" results, though the term slow does not have quite the same meaning for these two sets of data; apparently, the 48" triggering system is sensitive to much slower events than the 21". Such an asymmetry is also found in the 18" data if only the very slowest events are considered. In all three groups of results, then, the slowest events detected always seem to be predominantly positive.

2. The errors on most of the 18" cases are sufficiently large to make any conclusion concerning the existence of two- or three-body decays difficult. On the other hand, the P* values for the 21" cases, being all above 200 Mev/c, tend to suggest the presence of one or more two-body decays rather than a three-body decay. Again this is in agreement with the 48" results.

3. The 18" negatives appear to have, for the most part, lower P* values than the positives. Many of them are consistent, within their errors of measurement, with the single P* value of 200 Mev/c suggested by the 48" results. On the other hand, two of the events (No. 7029 and No. 55482) have P*'s which are rather low. These may be negative

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* The author is indebted to Professor Cowan for supplying him these results.

Table VII. P* Distribution -- 21" Cloud Chamber

All Events Positive

Case No.	$\gamma\beta$	P_2 (Mev/c)	θ	$P^*(\mu)$ (Mev/c)	$P^*(\pi)$ (Mev/c)	ΔP^* (Mev/c)
1099	4.20 ± .80	78 ± 3	36°	278	403	± 65
5999	.92 ± .03	369 ± 20	34°	217	213	± 12
6749	1.63 ± .09	108 ± 3	89°	266	306	± 13
9240	.88 ± .08	336 ± 35	37.5°	210	208	± 22
11403	.66 ± .06	391 ± 140	27°	234	229	± 87

counterparts of the decay,

$$K^+ \rightarrow \mu^+ + ? + ? ,$$

for whose existence some evidence was found in the 48" data, and much better evidence has been provided by photographic plate work(5). It is of course possible that the interpretation of the 48" events as representing a single two-body decay is incorrect, and that they are also examples of this same three-body decay whose P* values, by some statistical fluctuation, happened to be closely grouped together. The various alternative possibilities, namely that the two 18" events just mentioned have larger errors than have been estimated, or that the 48" events have been incorrectly interpreted, or that a mixture of a two- and a three-body decay is involved, cannot be eliminated until a much larger number of accurately measured negative decays has been obtained.

4. Both the 18" and the 21" data contain cases whose P* is too high to reconcile easily with the presently accepted value for the K^+_μ, namely 225 Mev/c. Cases Nos. 60452 and 78113 (Table VI) and Case No. 6749 (Table VII) all differ from the K^+_μ value by two or more times the assigned error. This evidence is in agreement with the 48" results which also suggest that there are some events whose P* is higher than 225 Mev/c. Thus, if the errors of measurement have not been underestimated, these results imply either that the P* value for the K^+_μ is higher than 225 Mev/c or that there is another particle which may decay with a P* appreciably higher than that value.

These observations, on the whole, tend to confirm the conclusions drawn from the 48" data. It is clear, however, that more events and greater precision of measurement will be necessary before many of the questions which have been discussed receive their final answer.

D. MORE DETAILED COMPARISON WITH RESULTS OF OTHER LABORATORIES

Evidence concerning the P* distribution for slow K particles has been obtained in several other laboratories. The magnetic cloud chamber results obtained by the Princeton, Paris, Berkeley, and Indiana groups up to the time of the 1955 Rochester Conference are listed in Table VIII*. Inspection of these results shows that, to a greater or lesser extent, every laboratory has an excess of positive slow events, a fact which has also been noted to be true of the C. I. T. results. It is clear from study of Table VIII that the majority of positive decay events are consistent with a unique P* value between 200 and 240 Mev/c. The most accurately measured events seem to have a somewhat lower P* value than the 239 ± 7 Mev/c figure from the present data; and, if they are all to be interpreted as arising from the same decay scheme (with the obvious exception of the very low P*'s), a P* value between 220 and 230 Mev/c seems to be favored. On the other hand, the data listed on Table VIII probably contain a mixture of K^+_μ decays, θ^+ decays, and possibly other types, so that exact P* values for individual decay schemes represented cannot be calculated by any averaging over events. Consequently, while it is clear that most of the events do arise from one or more two-body decays, the P* values for these decays cannot be obtained with any great certainty. There are too few negative events represented to draw any definite conclusions, though the Princeton data do suggest a single P* value somewhat higher than the figure of 200 Mev/c obtained in the present experiment. Most laboratories have obtained a few cases, both negative and positive, with very low values of P*. These events are

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* These results were reported to Professor C. D. Anderson during an informal discussion with Professors G. T. Reynolds (Princeton), L. Leprince-Ringuet (Paris), W. B. Fretter (Berkeley), and R. W. Thompson (Indiana).

Table VIII. P* Distribution from Other Laboratories

μ-Meson Secondary Assumed

Princeton		Ecole Polytechnique		Berkeley		Indiana
Positives (Mev/c)	Negatives (Mev/c)	Positives (Mev/c)	Negatives (Mev/c)	Positives (Mev/c)	Negatives (Mev/c)	Positives (Mev/c)
191±21	312^{+110}_{-60}	145±27	114±30	201±9	157±16	231±15
215^{+85}_{-30}	243±20	174±32	270±33	241±7	180±10	222±6
293±55	208^{+45}_{-40}	97±15	208±30	223±9		219±8
216^{+35}_{-30}	245±25	71±10	132^{+46}_{-22}	220±18		
221±5	213^{+40}_{-30}	230±10	259±14			
200^{+50}_{-45}	69±10	218±39				
68^{+66}_{-10}	244±18	118±9				
127±13	278^{+100}_{-75}	77^{+15}_{-11}				
245±48	192±18	205^{+49}_{-30}				
213±25	267^{+86}_{-68}	108±6				
219±11		202±11				
265±20		213±20				
219±14		228±12				
337^{+100}_{-85}		198^{+13}_{-24}				
205±18		197^{+153}_{-59}				
		215^{+35}_{-25}				
		223±13				

probably three-body decays of the type also observed in very small numbers in the present work.

Groups working at the French Ecole Polytechnique and at M. I. T. have studied the decay of K particles stopping in one of the plates of a multiple-plate cloud chamber (the so-called S events). In some cases they have been able to measure the ranges of the secondaries of such decays, from which they have obtained information concerning P* values. It should be noted that the ranges of the secondaries of decay events are very sensitive to both the P* value and the mass of the secondary. For this reason, these kinds of measurements allow much better separation of various decay schemes with not very different P* values than do magnetic cloud chamber measurements, and it is, therefore, possible to obtain information relevant to a pure sample of events. In particular, both laboratories are in agreement concerning the existence of the K_{μ}^{+} particle which undergoes two-body decay into a positive μ meson and a light neutral secondary, the range of the μ meson being 102 ± 2 gm/cm^2 of lead. The P* value corresponding to that range is 230 ± 3 Mev/c. The E. P. group has also been able to obtain both range and momentum for a number of K_{μ}^{+} primaries and has reported a mean mass of 928 ± 13 m_e (17) corresponding to a P* value of 225 ± 3 Mev/c. Both of these apparently very accurate values of P* are somewhat lower than the result of 239 ± 7 Mev/c obtained in the present work. It has already been pointed out in Section IV-A that the Λ° Q value of 36 ± 0.5 Mev obtained with the 48" cloud chambers places an upper limit of about two percent on systematic distortion errors. If the fact that this Q value is lower than the generally accepted value of

37 Mev is taken as a significant indication of the direction of such distortions, then a similar effect on the positive charged V data would cause an overestimate of P* of about 5 Mev/c, meaning that the correct value would be more like 234 Mev/c. This figure, though still a little high, is in fairly good agreement with the multiple-plate measurements. It is still true, however, that if any significant fraction of the 48" events are θ^{+} decays with a P* of 206 Mev/c, so that the average P* for the remaining cases is higher than the value obtained for the overall sample, then some events with P* appreciably greater than 225 Mev/c are almost surely represented.

VI. DISCUSSION OF THE DATA -- LIFETIME ANALYSIS

A. INTRODUCTION

The work of Mezzetti and Keuffel[19], Leprince-Ringuet[17], and others on the lifetime of charged V particles and S particles has indicated that at least part of these events have lifetimes of the order of $5 \times 10^{-9} - 10^{-8}$ second. The distribution of decay points in cloud chambers of the size used in the present experiment for such long-lived events would be essentially uniform. Appreciable departures from such uniformity can be expected only for events with mean lives less than 5×10^{-10} second, so that the existence of such non-uniformities can be used as evidence for the existence of a short-lived component (where the term short-lived will be used to refer to events of mean lifetime less than 5×10^{-10} second). The existence of such a short-lived component has already been suggested by the work of York _et al._[1] and Kim _et al._[20], and some evidence for it arising from the present data has already been discussed in Section IV-C. A more complete analysis of this question will now be presented.

B. THE MEASUREMENT OF x AND d

In order to verify the existence of a short-lived component and to measure its lifetime, it is necessary to measure the quantities x and d for each event, where x is the so-called decay length and d is the gate length. The specific procedure which was used for these measurements is as follows.

1. The boundaries of the well-illuminated regions of the chambers were determined. Any decay which did not occur within these boundaries was not included in the lifetime analysis.

2. Both x and d were measured from a point on the primary track 1 cm from where this track enters the well-illuminated region of the chamber, this 1 cm being measured along the projection of the track upon the plane of the chamber piston. Any cases for which the decay point was closer to the edge of the illuminated region were not used.

3. The end point for the measurement of d was determined for each event by requiring that enough secondary track be visible to establish that the transverse momentum was at least one probable error above 50 Mev/c. Specifically, if L is the minimum required secondary track length, ρ the secondary curvature, ρ' the curvature which the secondary would have if the transverse momentum were 50 Mev/c, and δ the distortion sagitta, then one gets the following:

$$\frac{L^2}{8\rho} + \delta \leq \frac{L^2}{8\rho'} ,$$

from which

$$L^2 \geqslant \frac{[8\delta\rho\rho']}{\rho - \rho'} . \qquad (12)$$

For these data $\delta = 0.3$ mm was used, and for events for which ρ was unmeasurable, a lower limit was used. In all cases a minimum of 3 cm secondary track was required to insure uniform detectability of each event considered.

4. All events with decay angles of less than 10° were excluded. Such events are generally difficult to detect when the primary track lengths are short; and, furthermore, tend to include the higher-energy charged V particles which are not very useful for lifetime analysis.

C. THE EXPERIMENTAL x/d DISTRIBUTIONS

Values of x and d were obtained for 71 events which satisfied the requirements discussed in Section VI-B. Histograms of the x/d distribution for all cases for which d was greater than or equal to 8 cm are shown in Fig. 8 (positives) and Fig. 9 (negatives). The corresponding mean values are as below.

Positives: $\langle x/d \rangle = 0.54 \pm .05$ (34 cases)

Negatives: $\langle x/d \rangle = 0.33 \pm .05$ (30 cases)

The errors given above are standard deviations calculated on the assumption that the measured values of x/d are a random sample drawn from a uniformly distributed population. The number of such standard deviations required to make up the difference between the measured $\langle x/d \rangle$ and the expected value of 0.5 is a measure of the probability that the experimental x/d distribution really represents a sample from a uniform population.

It appears clear from the histograms and from the above values of $\langle x/d \rangle$ that whereas the positives exhibit the uniform distribution expected from long-lived decay events, the negatives seem to contain a short-lived component. It should be noted that the evidence on this point provided by the x/d distribution is completely independent of that afforded by the numbers of events detected in the various chambers. If each of the observed distributions is interpreted as a statistical fluctuation rather than as due to the existence of a short-lived component, the probability of getting a combination of fluctuations of this sort is extremely small.

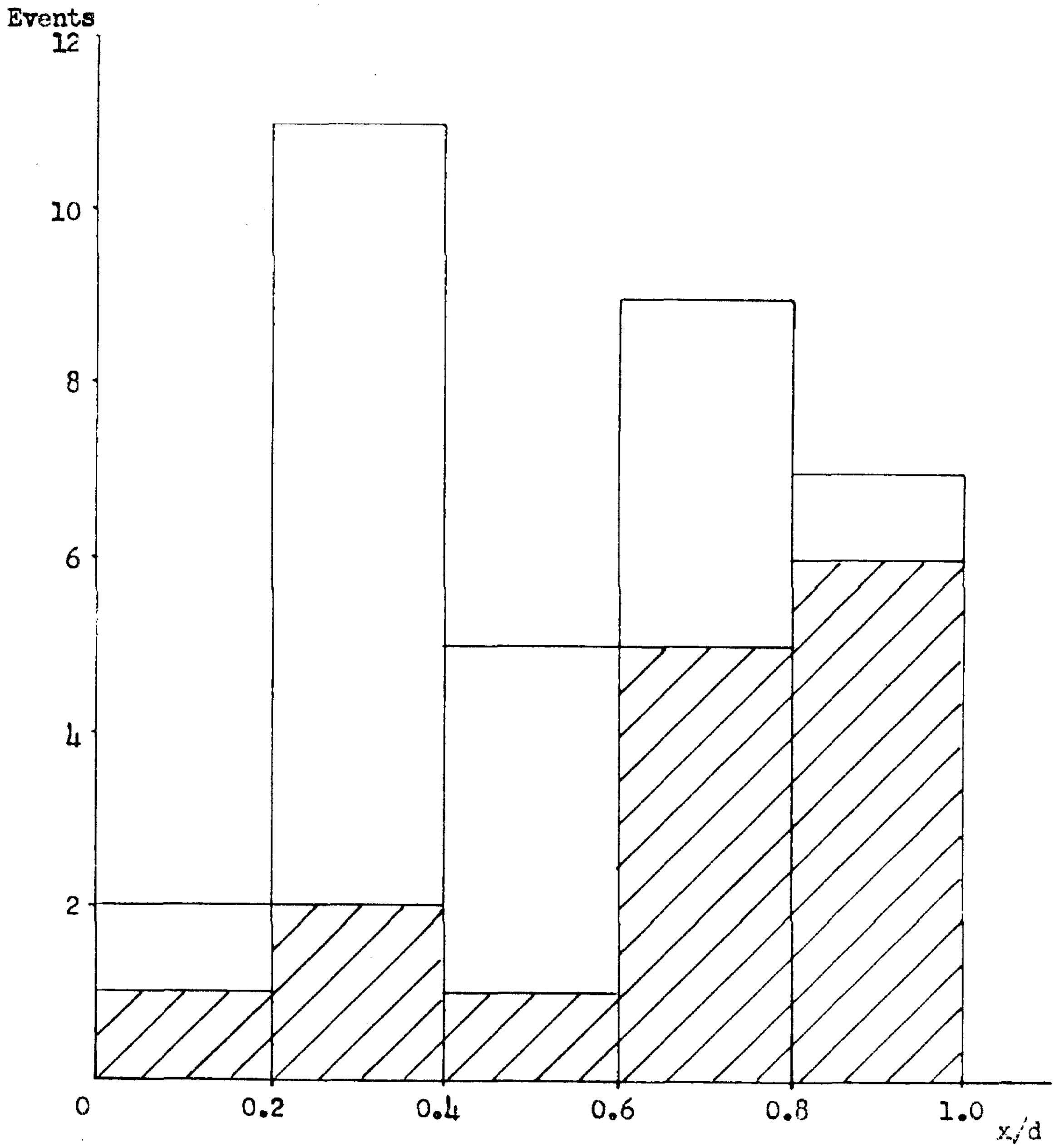

Fig. 8. x/d Distribution
34 Positive Events

Shaded area represents events with
heavily ionizing primaries.

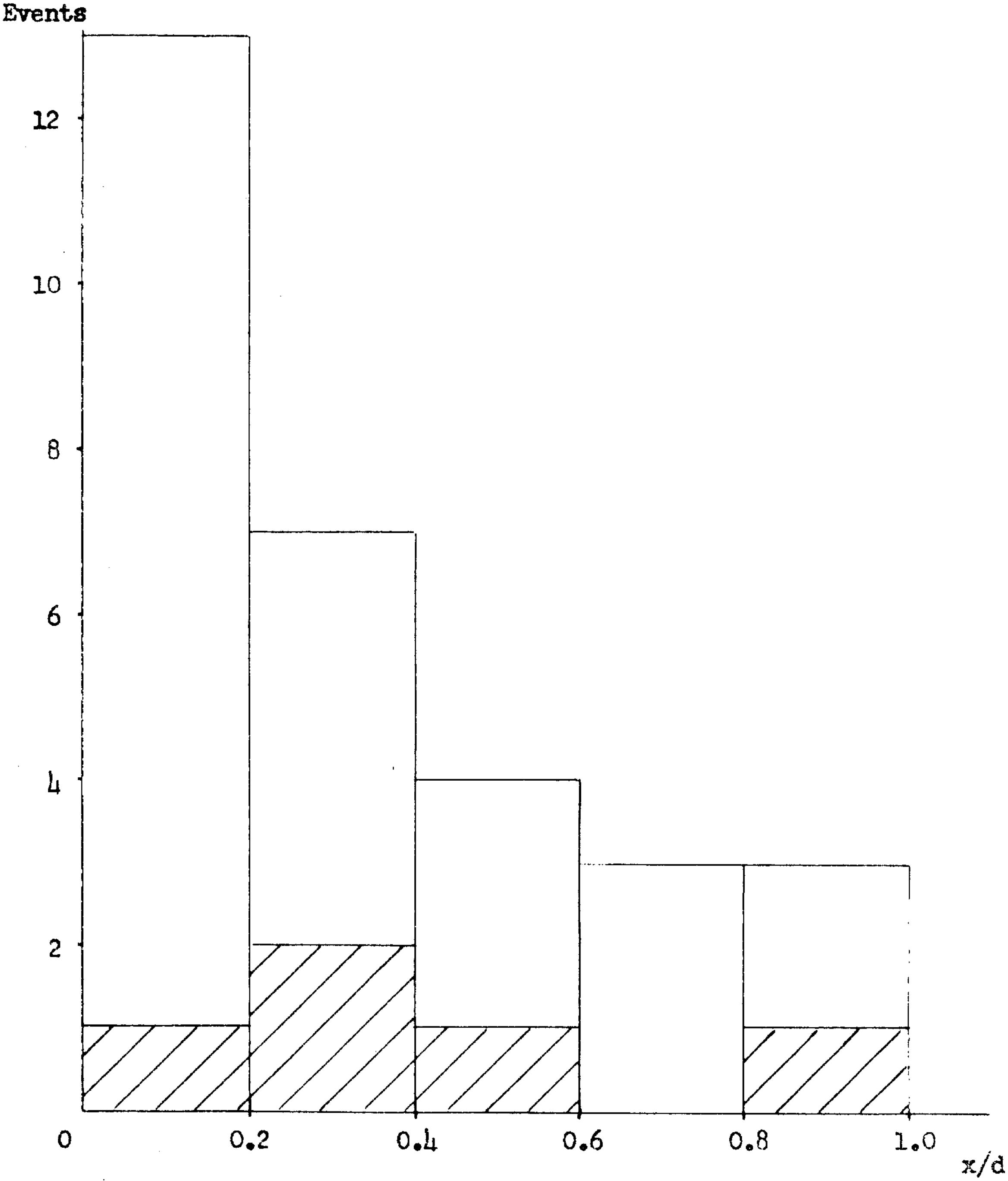

Fig. 9. x/d Distribution
30 Negative Events

Shaded area represents events with
heavily ionizing primaries.

Further support for the above conclusions is obtained by a study of the spatial distribution of the origins of the charged V particles. Fig. 10 shows a plot of the values of x/d versus Δ for all events which have origins less than 10 cm from the illuminated region of the chambers, where Δ is the distance between each origin and the illuminated region measured along the line of flight of the primary. The two vertical dashed lines on the plot are the limits determined by the cloud-chamber geometry within which most of the events are likely to have their origins. The following features should be noted:

1. The positives are distributed in approximately uniform fashion both with respect to x/d and with respect to Δ. There is no apparent correlation between low x/d and low Δ.

2. The negatives, on the other hand, seem definitely concentrated near the lower limit of Δ. Furthermore, the low values of x/d appear to be associated with close origins.

These observations provide additional evidence in favor of the interpretation of the low value of $\langle x/d \rangle$ obtained for the negatives as due to a short-lived component (i. e., $\tau < 5 \times 10^{-10}$ sec.).

If, then, one accepts the evidence which has been given as proof of the existence of a short-lived negative component, one must ask whether all the negative events can be interpreted in this way. This appears very unlikely for the following reasons:

1. Event No. 24018 (see Table I) has a decay time within the illuminated region of the chambers of about 2×10^{-9} second. Event No. 19648 traverses two chambers (one of these being the double size one) prior to decay and thus lives about 3×10^{-9} second. Such events are

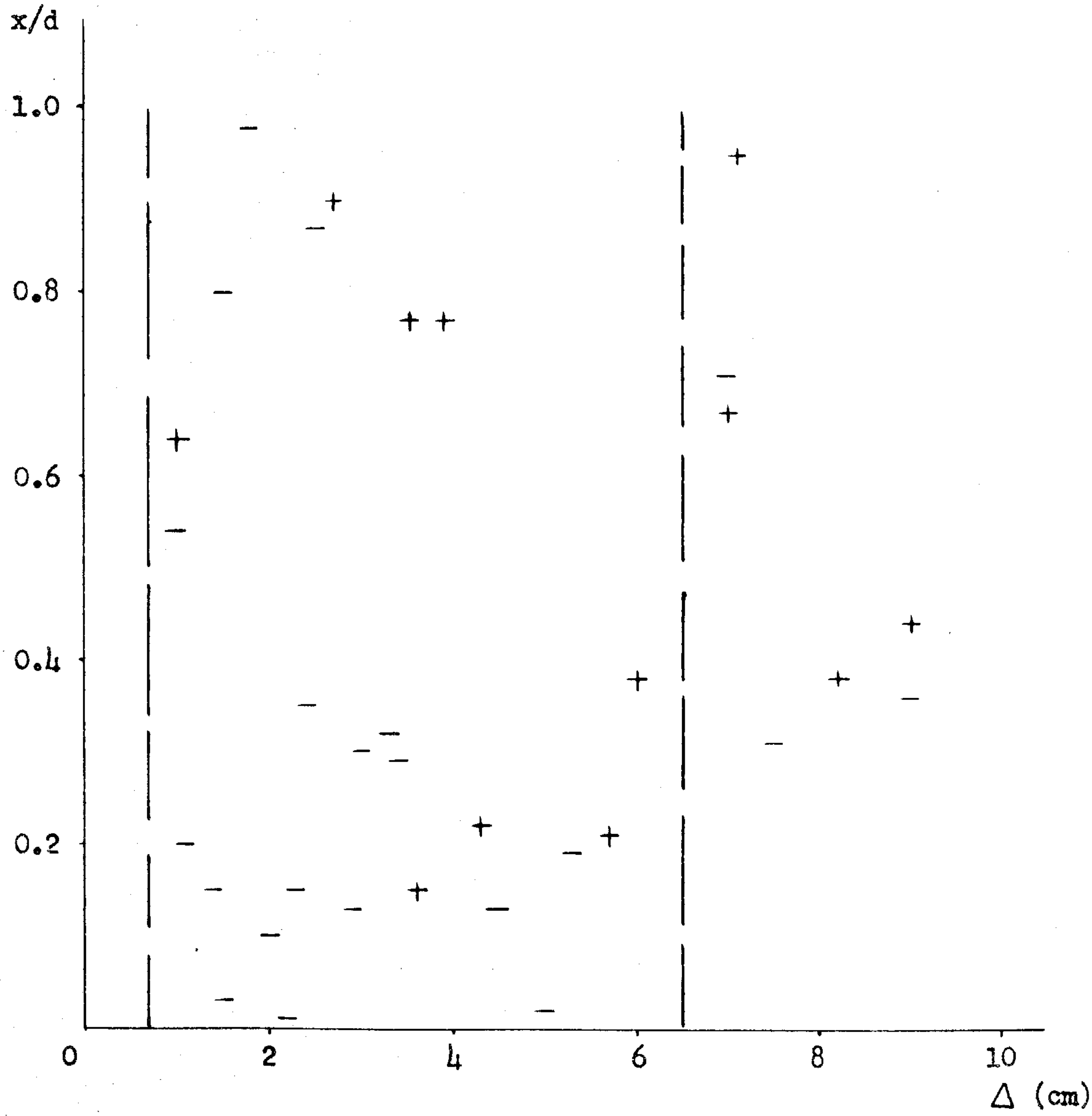

Fig. 10. Plot of x/d versus Δ
12 Positive Events
21 Negative Events

almost certainly not the same type of decay as the short-lived events discussed above.

2. There appears to be no correlation between slow primaries and very short decay distances. This is shown clearly in Fig. 9, where the cross-hatched region represents the five slow cases. It is apparent that these events have much longer mean lives than do those which are responsible for the peaking of the x/d distribution at the low end.

In view of these considerations, it is clear that the result of any detailed calculation of mean life for the negatives will tend to be, if anything, an upper limit to the true lifetime of the short-lived component. Such a calculation will be deferred until Section VI-E to permit first some discussion of the dynamics of the decays, from which estimates of primary velocities can be made.

No lifetime can be obtained for the positive events since their x/d distribution is uniform, and only a lower limit can be given. In particular the lifetime is probably much longer than the mean gate time of about 1×10^{-9} second. This result is of course consistent with the lifetime determinations for K particles made elsewhere which yield a value of about 8×10^{-9} second[19].

D. DYNAMICS OF THE SHORT-LIVED EVENTS

It is clear that for short-lived events, long secondary track lengths are, in general, available; hence one can hope to obtain a reasonably unbiased transverse momentum distribution for them. In order to obtain such a distribution a sample consisting only of negative events which satisfied the following requirements was selected.

1. Either the x values were less than or equal to 4 cm, or the primary track length was too short to permit a measurement of x.

2. The primaries were not heavily ionizing, nor were any of the primaries observed in any chamber above the one where the decay took place.

3. The transverse momentum was measurable at least to an accuracy of 25 percent.

Fifteen cases satisfied the above requirements (which, incidentally, would have been satisfied by only one positive event). If the previous interpretation of the lifetime data in terms of a short-lived negative component is correct, then one can reasonably expect that the above mode of selection will give a sample consisting chiefly of the short-lived events, and conclusions drawn from this sample should be applicable to the short-lived component. On the other hand, if all negative charged V particles are alike, and the previous interpretation of the lifetime data was incorrect, the selection procedure described above will in no way bias the transverse momentum distribution; and conclusions drawn from it will apply to all negative charged V particles.

In order to examine the effect of biases (discussed in Section III-F) on the transverse momentum distribution, the primary velocities must be estimated. For this purpose, a plot of the laboratory angle of decay versus the transverse momentum for the 15 cases under consideration is shown in Fig. 11. The line representing each case on the plot extends an amount equal to the estimated error on either side of the measured value of transverse momentum. An examination of this plot immediately shows that with perhaps one or two exceptions, the highest transverse

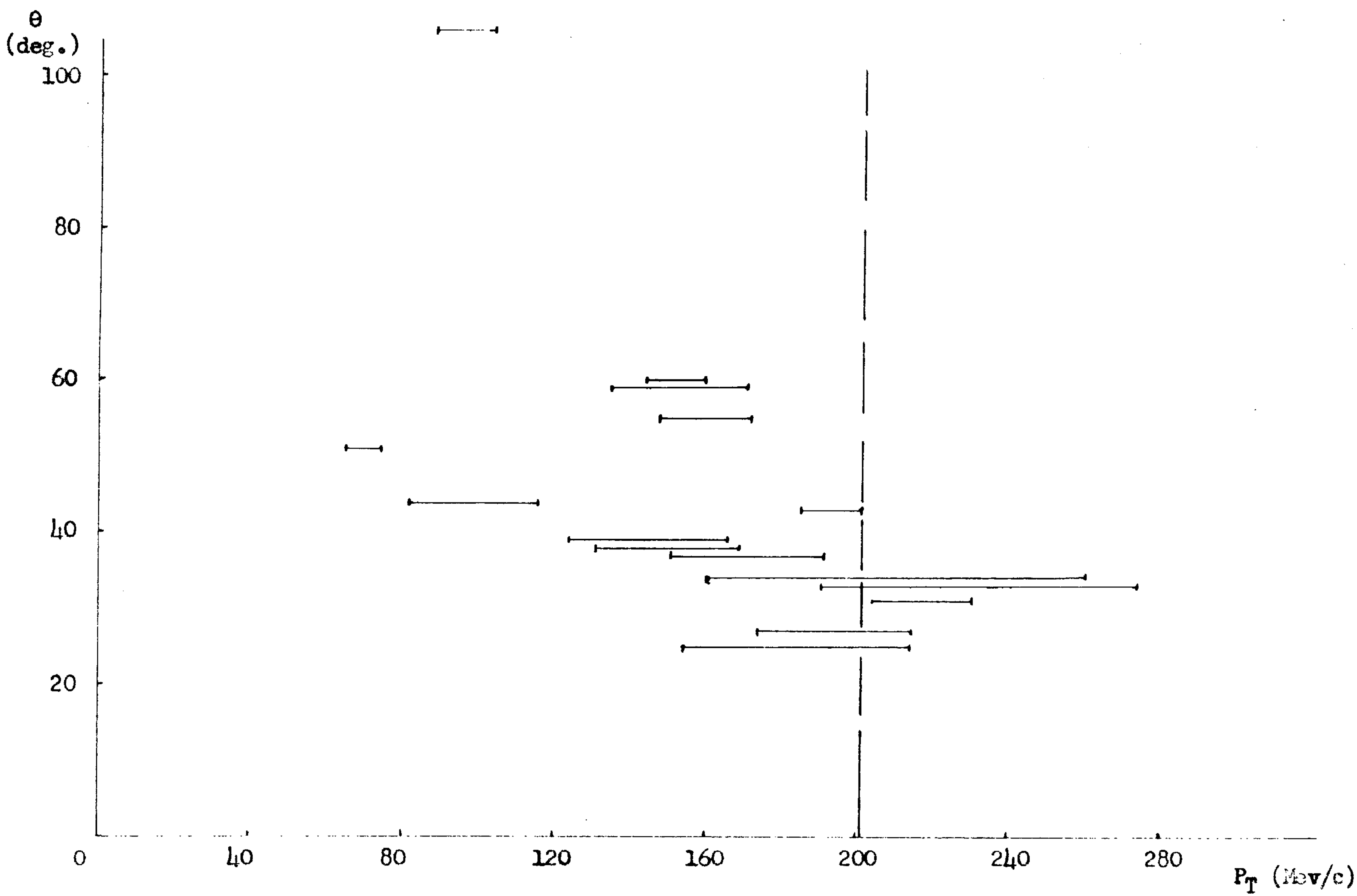

Fig. 11. Plot of Lab Angle versus Transverse Momentum
15 Short-Lived Negative Events

momenta are associated with the lowest angles of decay. This observation is clear evidence that, for most of the events, the secondaries are emitted backward in the center-of-mass system. A rough estimate of the mean speed of the primaries in these events can be obtained by making use of the fact that the maximum transverse momenta of about 200 Mev/c are associated with laboratory angles of about 30°. These numbers correspond to a $\gamma\beta$ of about 1.4, if it is assumed that they represent cases where the secondary is emitted at 90° in the center-of-mass system with a value of P* equal to 200 Mev/c. An alternate estimate can be made from the equation,

$$\langle P_L \rangle = \langle \gamma \rangle \langle P_L^* \rangle + \langle \gamma\beta \rangle \langle E^* \rangle \; . \qquad (13)$$

If one assumes the decays to be isotropically distributed in the center-of-mass system from $\theta^* = 90^{\circ}$ to $\theta^* = 180^{\circ}$, none occurring for $\theta^* < 90^{\circ}$, and if the events have a mean P* value of 200 Mev/c, then $\gamma\beta$ can be calculated from the mean longitudinal momentum of all 15 events and comes out equal to 1.5, in good agreement with the previous estimate. One may therefore expect that if only those events which satisfy the bias requirements of Section III-F, $\gamma\beta$ being assumed equal to 1.5 for each event, are considered, the resulting transverse momentum distribution will be reasonably unbiased. When this was done, only one case was eliminated, largely because the secondary track lengths of most of the short-lived events were very long. The distribution for the remaining 14 events is shown in Fig. 12. The histogram of Fig. 12 appears quite consistent with a two-body decay. If such a decay is assumed, with a value of P* equal to 200 Mev/c, one can compute a more accurate value of P* in the following way:

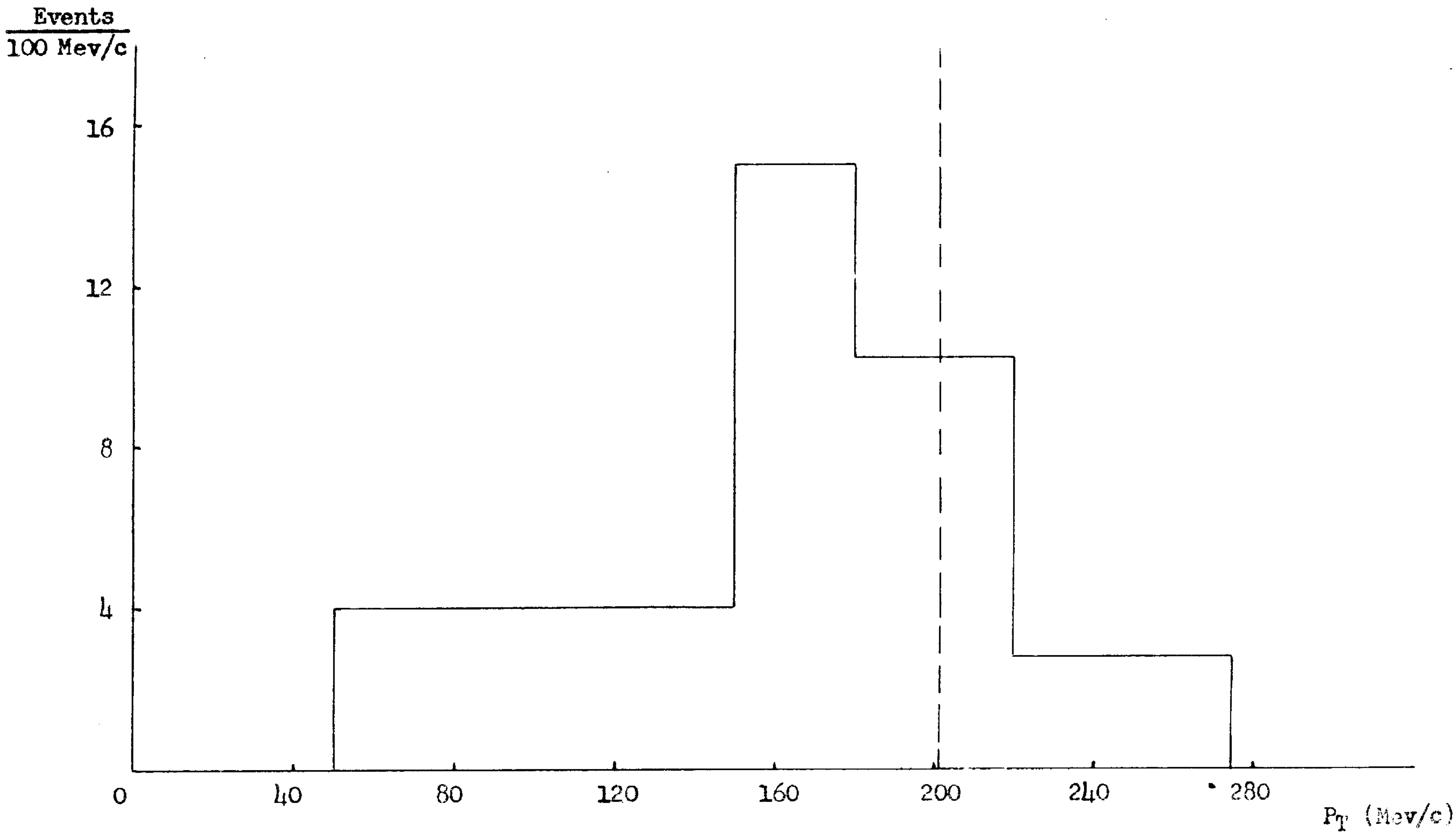

Fig. 12. Transverse Momentum Distribution
14 Short-Lived Negative Events

1. Using the plot of Fig. 11 to guess whether the emission of the secondary took place forward or backward in the center-of-mass system, and assuming $P^* = 200$ Mev/c, one can calculate a value of $\gamma\beta$ for each event.

2. By requiring a minimum laboratory angle of 10° and a minimum accuracy in the secondary momentum of 25 percent, one can determine the value of θ^*_{min} (defined in Section III-F) for each event. One can then use Fig. 2 to assign to each case an appropriate value of $\frac{\langle P_T \rangle}{\langle P^* \rangle}$.

3. These values averaged over all the events will give the correct $\frac{\langle P_T \rangle}{\langle P^* \rangle}$ for the whole sample, from which $\langle P^* \rangle$ can be calculated since $\langle P_T \rangle$ is known. If the decay is a two-body one, then $\langle P^* \rangle$ will just be the actual P^* of the decay.

This procedure was carried out, and the relevant numbers are shown in Table IX. The value of $\langle P^* \rangle$ thus obtained was

$$\langle P^* \rangle = 201 \pm 12 \text{ Mev/c},$$

where the quoted error combines the probable errors due to statistics and to measurement inaccuracies. The above value has been corrected for the fact that transverse momenta below 50 Mev/c are not included.

The value of $\langle P^* \rangle$ stated above is in good agreement with the maximum values of P_T from individual cases, as is clear from Fig. 11. This is good evidence that the interpretation of these events as two-body decays with $P^* = 201 \pm 12$ Mev/c is probably correct.

Comparison of this number with the P^* values obtained from longer-lived events for which a direct estimate of the primary velocity could be obtained shows that no distinction can be made between the two components on the basis of decay energies. One is therefore led to the following alternatives:

Table IX. Dynamics of Short-Lived Negative Events

Case No.	P_2 (Mev/c)	θ	P_T (Mev/c)	$\gamma\beta$	θ^*_{min}	$\frac{\langle P_T \rangle}{\langle P^* \rangle}$
09475	89 ± 6	51°	70 ± 5	1.8	103°	0.73
09644	179 ± 20	59°	154 ± 17	1.2	84°	0.80
11023	425 ± 45	27°	194 ± 20	1.3	32°	0.82
13798	245 ± 24	38°	150 ± 19	2.0	78°	0.82
13954	428 ± 52	33°	232 ± 42	1.8	40°	0.83
16990	227 ± 22	39°	145 ± 21	2.0	84°	0.80
17429	100 ± 6	106°	96 ± 8	0.7	25°	0.81
17700	427 ± 14	31°	217 ± 13	1.4	34°	0.82
18972	390 ± 90	33°	210 ± 50	1.3	81°	0.81
19604	280 ± 10	43.5°	193 ± 8	1.2	30°	0.82
26378	195 ± 15	55°	160 ± 12	1.2	30°	0.82
33178	425 ± 65	26°	184 ± 30	1.1	28°	0.81
34608	285 ± 25	37°	171 ± 20	1.9	44°	0.83
35286	175 ± 7	60°	152 ± 8	1.2	30°	0.82

1. The considerations which led to the separation of the negative events into at least two groups of different lifetime are invalid, and essentially all negative decays observed arise from the same primary particle and follow the same scheme. If this alternative is correct, then the P* value obtained for the "short-lived" events strengthens considerably the very tentative conclusion drawn in Section V-B that all the negative decays involve only two secondaries and have a P* of 200 Mev/c.

2. The lifetime separation is meaningful, and there are at least two different kinds of negative charged V particles, each of which, insofar as one can tell from very limited statistics, decays into two secondaries with a P* value of 200 Mev/c.

If, as seems more probable, the second alternative is the correct one, either the short-or the long-lived events can, insofar as decay dynamics are concerned, be interpreted as θ^- particles undergoing the decay,

$$\theta^- \rightarrow \pi^- + \pi^0 \qquad P^* = 206 \text{ Mev/c} .$$

However, whereas the direct mass measurements on the long-lived negatives, crude as they are, support their interpretation as θ^- particles, the primary track lengths obtained from the short-lived events are not sufficient to permit any direct mass estimates. Hence another interpretation of the short-lived decays, consistent with what little information has been obtained on them, is that the primaries are hyperons decaying according to the scheme,

$$\Sigma^- \rightarrow N + \pi^- .$$

The Q-value for this decay, derived from the measured P* value, would be 125 ± 12 Mev. This number is in good agreement with photographic plate results on the decays,

$$\Sigma^{+} \rightarrow P + \pi^{0} \qquad Q = 117 \pm 1 \text{ Mev}^{(8)}$$
$$\Sigma^{\pm} \rightarrow n + \pi^{\pm} \qquad Q \approx 130 \text{ Mev}^{(9)} .$$

If this interpretation is correct, one may reasonably ask why the positively charged counterparts of these events were not observed. One possible explanation might be that the Σ^{+} particle decays predominantly into a proton (rather than a neutron), in which case, with the velocities observed for the negative events, the maximum angle of decay expected would be about 9°. Such decays would be difficult to detect, particularly in view of the short life of the primary.

The fact that all "cascade" decays of the type,

$$\Xi \rightarrow \Lambda^{0} + \pi \qquad Q = 66 \pm 6 \text{ Mev},$$

which have been observed till now are negative might suggest that the negative short-lived events are decays of this type. The P* value corresponding to the above decay is only 140 Mev/c, however, so that in view of the fact that most of the short-lived events have transverse momenta much higher than this number, very few of them can be interpreted in terms of this decay scheme.

E. LIFETIME CALCULATION

The low value of $\langle x/d \rangle$ obtained for the negatives makes a lifetime calculation for these events possible. In view of the strong probability that the negatives do not represent a pure sample, any actual lifetime obtained should be considered as an upper limit to the true lifetime of the short-lived events. In order to make this upper limit as close as possible to the actual value, the following ways of eliminating long-lived events, without introducing biases into the sample, were used.

1. Only negative decays occurring in Chambers 2 and 4 were included in the sample.

2. No event with a heavily ionizing primary was included.

3. No event whose primary could be seen in a chamber above the one where the decay took place was included.

Seventeen events fulfilled all the necessary requirements for inclusion in the sample. The speeds of the primaries of these events, necessary for the calculation of the decay times and gate times, were estimated by assuming a unique P* value of 200 Mev/c for each decay and a π-meson charged secondary. It has previously been shown that this P* of 200 Mev/c is consistent with both long-lived and short-lived negative events; and, hence, can be expected to lead to reasonable estimates of the primary speeds even if the sample contains a mixture of both kinds of events.

For events with measurable secondary momenta, $\gamma\beta$ was calculated from the relation,

$$\gamma\beta = \frac{P_L E^* \pm E_2(P^{*2} - P_T^2)^{\frac{1}{2}}}{P_T^2 + m^2} \quad . \qquad (14)$$

The sign in front of the second term of the numerator is plus if $\theta^* > 90^o$ and minus if $\theta^* < 90^o$. If the second term is less than the first, as is usually the case, and if P_L is positive, the sign to be used is ambiguous. In the events under consideration the sign was determined both by use of Fig. 11 and by requiring that the observed ionization of the primary be consistent with the calculated speed.

For events for which the secondary track length was too short to permit a momentum measurement, it was assumed that the emission took place at θ^* equal to 90° with P^* equal to 200 Mev/c, giving for $\gamma\beta$,

$$\gamma\beta = \frac{P^*}{E^*} \cot\theta = 0.8 \cot\theta \quad . \qquad (15)$$

Table X lists the pertinent data for the 17 events under consideration. A lifetime was calculated for these events by means of the well known formula[21],

$$\tau = \frac{1}{N} \sum_{i=1}^{N} \left[t_i + \frac{T_i}{e^{\frac{T_i}{\tau}} - 1} \right] , \qquad (16)$$

where $t_i = x_i(\gamma_i\beta_i c)^{-1}$ and $T_i = d_i(\gamma_i\beta_i c)^{-1}$, with the result,

$$\tau = 1.3 \times 10^{-10} \text{second.}$$

This figure, even if the sample is assumed to be pure, is subject to errors arising both from uncertainties in the measurements of t_i and T_i, and from the statistical fluctuations expected for a finite sample. The errors in t_i and T_i arise wholly from the impossibility of obtaining the primary speeds accurately, and are estimated to amount to about 50 percent on each case. The statistical uncertainty can be calculated from the formula[21],

$$\Delta\tau = \tau \left\{ \sum_{i=1}^{N} \left[1 - \frac{T_i^2}{\tau^2} \frac{e^{\frac{T_i}{\tau}}}{(e^{T_i/\tau} - 1)^2} \right] \right\}^{-\frac{1}{2}} , \qquad (17)$$

where $\Delta\tau$ is an estimate of the standard deviation in τ. If these errors are combined, the final result obtained is

$$\tau = (1.3 \pm 0.6) \times 10^{-10} \text{second.}$$

As mentioned earlier, this number is, if anything, an upper limit to the true lifetime.

Table X. Lifetime Data -- Negative Events

Case No.	x (cm)	d (cm)	$\gamma\beta$	t (10^{-10} sec.)	T (10^{-10} sec.)
04456	8.2	12.0	0.9	3.0	4.5
05830	9.6	12.0	1.7	1.9	2.4
06622	12.0	13.8	1.1	3.6	4.2
09475	1.1	5.4	1.8	0.2	1.0
09644	0.4	16.0	1.2	0.1	4.4
09965	7.2	13.2	2.6	1.1	1.7
13798	1.1	8.3	2.0	0.2	1.4
13954	2.6	17.1	1.8	0.5	3.2
14458	1.3	4.0	1.4	0.3	1.0
16990	0.5	14.8	2.0	0.1	2.5
17261	4.1	14.3	1.0	1.4	4.8
17429	0.1	22.7	0.7	0.1	10.8
19604	1.5	15.3	1.2	0.4	4.2
23569	2.8	14.9	1.3	0.7	3.6
33178	1.7	12.8	1.1	0.5	3.9
33631	5.7	5.8	7.0	0.3	0.3
34608	0.2	1.3	1.9	0.0	0.2

F. COMPARISON WITH OTHER LIFETIME WORK

York et al.[1] have published the results of a detailed lifetime analysis of charged V events observed in the C. I. T. 18" cloud chambers. The main conclusions from this analysis, revised slightly by a recent reexamination of their data, are the following:

1. There is very clear evidence for the existence of a component of lifetime less than $(2.8 {}^{+2.0}_{-0.6}) \times 10^{-10}$ second.

2. This short-lived group shows no clear-cut charge asymmetry. If anything, the positives tend to predominate slightly.

The second of these conclusions is in disagreement with the present data, a fact for which no satisfactory explanation has been found. The probability that either set of observations was the result of a large statistical fluctuation is very small, and the experimental geometries were so similar that it is difficult to believe that very different types of particles were being observed. The difference between the two sets of data must be considered, for the time being, as an unelucidated mystery.

Kim et al.[20] have reported some evidence obtained from cloud chamber observations suggesting a long lifetime for positive charged V events and a short lifetime for negatives. These results are in complete agreement with the 48" data. These authors also suggested on the basis of the transverse momentum distribution for the negatives that these decays were likely to involve at least three secondaries. This particular conclusion, however, cannot be regarded as established; and, in fact, the interpretation of their P_T distribution is by no means unambiguous. Therefore there is no important disagreement on this point between the data of Kim et al. and the 48" results.

VII. CONCLUSIONS

The following conclusions can now be drawn from the data of the present experiment.

1. Among the slow long-lived primaries, there appears to be a considerable positive excess, implying either the existence of a positive V particle without negative counterpart, or a strong charge dependence of the production cross-section at the energies of interest.

2. The slow long-lived particles of both signs are all consistent with a mass of about 1000 m_e, although a few could be much heavier insofar as any determination from ionization and momentum is concerned.

3. The P* distribution of the positive K particles indicates the presence of at least one two-body decay. If it is assumed that, in fact, only one such decay is represented, its most likely interpretation in terms of known particles is the scheme,

$$K^+ \rightarrow \mu^+ + \nu \quad ,$$

where the mass of the primary, while most consistent with the τ mass, could be as low as the presently accepted K_{μ}^+ mass of 928 ± 13 m_e. If, however, some of the events actually arise from the scheme,

$$\theta^+ \rightarrow \pi^+ + \pi^0 \quad ,$$

known from the results of other laboratories to exist, then it is highly probable that some K particles significantly heavier than 928 ± 13 m_e are represented.

4. The P* distribution of the slow negative V events (which are very probably K particles), though very much lacking in statistics, suggests that most of these events undergo a two-body decay with

P* = 200 ± 10 Mev/c. A possible interpretation of this result is the existence of the decay scheme,

$$\theta^- \rightarrow \pi^- + \pi^0$$

5. There is good evidence for the existence of a very short-lived ($\tau = [1.3 \pm 0.6] \times 10^{-10}$ sec.) negative component. Its transverse momentum distribution suggests a two-body decay with P* value of 201 ± 12 Mev/c. The primaries of these decays can be either K particles or hyperons.

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