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Early Cascade Development of Energetic Electrons

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ABSTRACT

Electron pairs have been materialized in emulsion, and 294 individual pair tracks with energies >5 GeV and visible path length >20 mm were closely examined. Cascade multiplication along each track is evaluated in terms of the conversion distance y for the initial secondary pair, and the resultant y-distribution compared with theoretical prediction. Over the initial time interval 10^{-10} sec., cascade development appears to occur at a rate 30±10% less than expected. This result is considered critically.

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INTRODUCTION

Recent experiments have taken advantage of the high resolving power of emulsion to search for charmed-body decays, with lifetimes $\sim 10^{-12}$ sec, among the products of energetic nuclear collisions[1]. A corollary question arises with regard to uncharged objects which undergo neutral decays with ultimate products which include photons. A study of this kind would examine the electron pairs associated with nuclear collisions, and for this purpose an experimental sample should be collected regardless of pair energy, star-pair distance or recognition factors at a pair origin. A back-follow method is described by which such a sample is being accumulated among the products from 300 GeV proton-nucleus collisions.

In the course of following electromagnetic cascades backward to a primary-pair origin, it has been noted that two individual pair tracks frequently run close together, unaccompanied by secondary development, for long distances, $\sim$ radiation length. Alternatively, the energetic member of a pair often separates quickly from its low-energy partner and travels several cm before showing any degradation or secondary multiplication. An example has been described by Jain and Girard.[2] These observations have generally been ascribed to statistical fluctuations. With the assembly of a reasonably objective sample of primary pairs, it has become possible to examine this apparent "delayed cascading" effect more closely.

A record has been compiled of those individual pair tracks which satisfy simple path-length and energy criteria, and a search for the initial secondary pair has been made along each such track. The study has not been confined to those primary pairs associated with beam stars, but has been extended to the primary pairs of background cascades in the experiment. Primary pairs due to $\gamma \to 4e$ and to the 2e in $\pi^0 \to \gamma + 2e$, have not been included.

Previous studies of electromagnetic cascades in emulsion [3-6] have used the cosmic radiation, with an intense background of low-energy tracks distributed over a wide range of angles. Conversely, some cosmic-ray cascades are so energetic that the tracks of early development cannot be resolved from one another, and are often intermingled with accompanying hadron tracks. These problems do not arise in this experiment. The radiation length, L_0 = 30 mm for electrons in emulsion, has been verified [7] as has been the conversion length, λ = 38.5 mm.[8]

EXPERIMENTAL

The Back-Follow Method:

The experiment has been pursued in Ilford K5 emulsion, 600 microns thick, which was exposed to a 3.0×10^3 cm^{-2} 300-GeV proton beam parallel to the emulsion plane. The low beam intensity ensures that individual lightly-ionized tracks can be followed for several cm across a single plate, experiencing little confusion with other tracks. Thin tracks of small dip angle, $<|10|$ m radian, occur generally at inclinations <50 m radian to the beam direction. One such "flat" track is chosen at random and followed upstream. If the selected track is due to a beam proton, it will generally lead back to the input edge of the plate. If, however, the track is caused by a secondary particle, it may lead back to a nuclear collision or to the origin of an electron pair. A pair which is evidently secondary in an electromagnetic cascade will be nearly parallel to a parent track which may in turn be followed back to the primary pair of the cascade. For $\sim$20% of the primary pairs, a backward search for 5mm along the extrapolated photon path leads to a nuclear collision with which the pair is aligned and evidently associated.

The experimental conditions are remarkably clean. The collection of data on primary pairs is unhindered by any multi-directional background of low-energy tracks. The small grain size of K5 emulsion allows, for the range of pair energies found, resolution of the individual cascade tracks to within 1 mm of the primary origin.

The Primary Pairs:

When a primary pair was found by the back-follow search, a check was made to ensure that it had not been previously noted. Those primary member tracks which, over the first 15 mm, displayed evident rectilinearity against a focal-plane hairline of the ocular goniometer were recorded, together with the visible path length T and inclination to the beam direction. The distance T was measured, in one plate, from the primary origin to the point where the primary member either left the emulsion or underwent deflection $\gtrsim 10$ m radian. From among $\sim$700 primary pairs, 417 rectilinear member tracks with T>20 mm were subjected to multiple - scattering measurement and a close search for secondary multiplication.

A preliminary determination of combined stage and emulsion multiple-scattering noise was made through observations on proton beam tracks in different parts of each plate, with 500-micron, 1000-micron and 2000-micron cells. The resultant noise deflection, 0.24±0.03 micron/1000 microns, is due primarily to spurious scattering in the stack and implies a measurement upper limit $\sim$14 GeV, after a 40% correction for deflection effects of radiative collisions. A candidate track was accurately aligned on the stage and the complete track configuration of the pair, with secondaries, was mapped. Each multiple-scattering measurement was confined to the first 15 mm of a candidate track, since in that distance an initial electron energy is degraded an average 39%. The mean particle momentum so determined is based upon sixteen 1000-micron cell readings, a compromise between uncertainties due to noise correction (∿30% at 7 GeV) and statistics (∿25%). Among 417 determinations of energy E, there were 135 with 5 GeV<E<10 GeV and 159 with E>10 GeV. This study of cascade multiplication is derived from these 294 primary tracks with E>5 GeV and T>20 mm.

Initial Secondary Pairs:

In a cylindrical volume of diameter 60 microns centered on a candidate track, a search was made for the origins of secondary pairs evidently due to bremsstrahlung conversion. In the conditions of the experiment, the low density of tracks ensures that identification of an initial secondary pair relative to its parent may be made with a high degree of certainty. For the origin of each initial secondary pair, the distance y from the primary origin and the lateral displacement x from the parent track were recorded. Those secondary pairs determined to be of energy <20 MeV were excluded because (1) the theoretical comparison is based only on secondary pairs >25 MeV and (2) the search efficiency for secondary pairs declines sharply at lower energies. Among the 294 primary tracks with E>5 GeV and T>20 mm, 125 showed an initial secondary pair with y<20 mm and x<30 microns. The distribution $\frac{\Delta N}{\Delta x}$ for these 125 secondary pairs is shown in Fig. 1 together with the corresponding calculated distribution[9] for electrons of incident energy 10 GeV. From the evident agreement of these results, it may be assumed that the fraction of initial secondary pairs ($y<20$ mm) with $x>30$ microns would be small.

There are three sources of ambiguity in the assignment of secondary pairs. When both primary tracks are visible in the field of view, a secondary pair is assigned to the closer one. If an initial secondary pair is not readily assignable to either primary, and a subsequent secondary pair materializes along one of them, the two y-values are assigned to the different primary tracks. Further, if multiplication on one primary leads to a secondary pair ambiguously close to the other primary, two y-values are recorded. Since the subject of this study is an apparently insufficient number of secondary pairs, these principles conservatively assign the observed secondaries as far as possible among the candidate primary tracks.

THEORETICAL

The Calculated y-Distribution:

When an energetic electron generates k bremsstrahlung photons per unit path length, the probability that the first secondary pair has not been converted within distance y is[5]

$$P_{>y} = \exp\left\{ -k\left[y - \lambda + \lambda \exp\left(\frac{-y}{\lambda}\right)\right] \right\},$$

where λ is the conversion length, $\lambda = \frac{9}{7}$ Lo = 38.5 mm in emulsion. The quantity k is estimated by assuming a bremsstrahlung spectrum with low-energy cutoff 25 MeV,

$$k = \frac{1.45}{\lambda} \ln \frac{E}{25} ,$$

for electrons of energy E (MeV), with an included correction for increased conversion length for bremsstrahlung photons with energies between 25 MeV and $\sim$ 300 MeV. Setting the minimum secondary pair energy as high as 25 MeV is a conservative procedure when some secondaries of lower energy might be included in the experiment. In Fig. 2, the probability $P_{<y} = 1 - P_{>y}$ is plotted for electrons of initial energies E of 500 GeV and 10 GeV.

The Monte Carlo Calculation: As a check on the validity of the $P_{<y}$ curve for E = 10 GeV, a one-dimensional Monte Carlo calculation has been performed. The program was based on ten equal-likelihood intervals of electron traverse distance before a radiative collision, and twenty corresponding intervals of bremsstrahlung photon energy between 0.5 MeV and 10 GeV. When the electron energy fell below 5 GeV, modified traverse-distance and photon-energy intervals were employed. The usefulness of this model was checked by evaluating the average sequential rate of radiative loss for a 10-GeV electron over a radiation length, through 100 histories. The result, 210 ± 20 MeV/mm, was consistent with that expected. Bremsstrahlung photons in ten energy channels between 25 MeV and 10 GeV were then converted, with 100 equal-

likelihood intervals of conversion distance within each channel. This procedure gave values of the least y for a 10-GeV electron which traverses a distance exceeding 40 mm in emulsion, through 383 histories. Four Monte Carlo points, $P^*_{<y'}$, for y' = 10 mm, 20mm, 30mm and 40mm, are also shown in Fig. 2. The agreement with the 10-GeV $P_{<y}$ curve is reasonable, with an indication that $P_{<y}$ is undercorrected for increased conversion length at lower energies.

RESULTS

The numbers $N_{T>y'}$ of tracks of energy > 5 GeV and path length T > y' are shown in Table 1. The corresponding numbers $N_{y<y'}$ of tracks that show an initial secondary pair with y < y' then yield fractions $f_{<y'} = N_{y<y'}/N_{T>y'}$. Also set out in Table 1 is $\phi = f_{<y'}/P^*_{<y'}$, where the values of $P^*_{<y'}$ are taken from the Monte Carlo calculation. Agreement between experiment and theory would be indicated by ϕ-values $\sim$ unity. The probability is < 0.7% that ϕ derived from y < 20 mm, $\phi = 0.70 \pm 0.11$, arises from chance fluctuation. This suggests that on the time scale 10^{-10} sec, the rate of cascade multiplication might be 30% less than expected.

DISCUSSION

An obvious criticism of the experiment arises from the unconventional method of collecting track data, with possible systematic errors. It is demonstrable, however, that the accumulation of track information favors the recording of those pair members which undergo more rapid multiplication, in the opposite sense of the result. Serious consideration must be given to the possibility that some initial secondary pairs might escape detection, and for this reason the search for secondaries has been pursued along each candidate track at least three times. The fraction of initial secondaries found on re-scan, $\sim$ 5%, all at $y > 20$ mm, indicates that search efficiency exceeds 90%, at least for $y < 20$ mm. Failure to detect some initial secondaries is probably compensated by the occurrence of competitive direct pair production and the assignment of y-values in examples of cascade ambiguity.

The energy requirement, $E > 5$ GeV, causes the exclusion of some candidate pair members of initial energy > 10 GeV which undergo rapid degradation in $T < 15$ mm. An estimate of this effect has been made by inspection of the multiple-scattering records of the $E < 5$ GeV reject tracks. Twelve among the 123 rejects (i.e. 12/306) fall into this "rapid-cascader" category. Among the 383 Monte Carlo histories, there are sixteen examples of 10 GeV electrons which decline to < 2 GeV in distance < 7.5 mm, yielding a similar proportion ($\sim$4%) of fast radiators. The observed slow cascading cannot, therefore, be accounted for by the imposition of experimental criteria. Further consideration of statistical effects indicates that the fluctuation magnitudes found in cascades initiated by an electron are much smaller than in cascades initiated by a photon of corresponding energy.

The experimental points of Fig. 2 might be satisfied by a theoretical curve $P_{<y}$ derived from a pair-particle radiation length $\sim 2L_0$. Alternatively, a fraction $1 - \phi$ of the pair particles might have radiation length $\gg L_0$, corresponding to a weakly radiating phase. The plot of $1-\phi$ vs time shown in Fig. 3 suggests that this phase could be a short-lived phenomenon, becoming undetectable on the 10^{-9} sec time scale. Observations by P. Auger et al[10] on the extensive air showers of the cosmic radiation did, however, find delayed cascading in the traverse of the soft component through 10-cm Pb plates incorporated into a Wilson chamber. Subsequent speculations assuming associated hadron interactions have not satisfactorily accounted for Auger's result.

The high photon energy required and the short time scale are compelling aspects in the design of further experiments. We are grateful to L. Voyvodic and his colleagues at Fermilab for their cooperation in making the beam exposure, and to E. Hart for helpful comments.

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CAPTIONS TO FIGURES

Fig 1. The experimental $\Delta N/\Delta X$ in lateral displacement x for 125 initial secondary pairs (y<20 mm) found along 294 primary pair tracks of energy >5 GeV and path length T>20 mm. The curve P (x) is calculated for a 10-GeV electron which traverses 20 mm of emulsion.

Fig 2. The calculated probability, $P_{<y}$, that the initial secondary pair for a parent electron of energy E will materialize within distance y in emulsion. (a) E=500 GeV; (b) E=10 GeV. The results, $P^*_{<y'}$, of the corresponding Monte Carlo calculation are shown, together with experimental results, $f_{<y'}$, from Table 1.

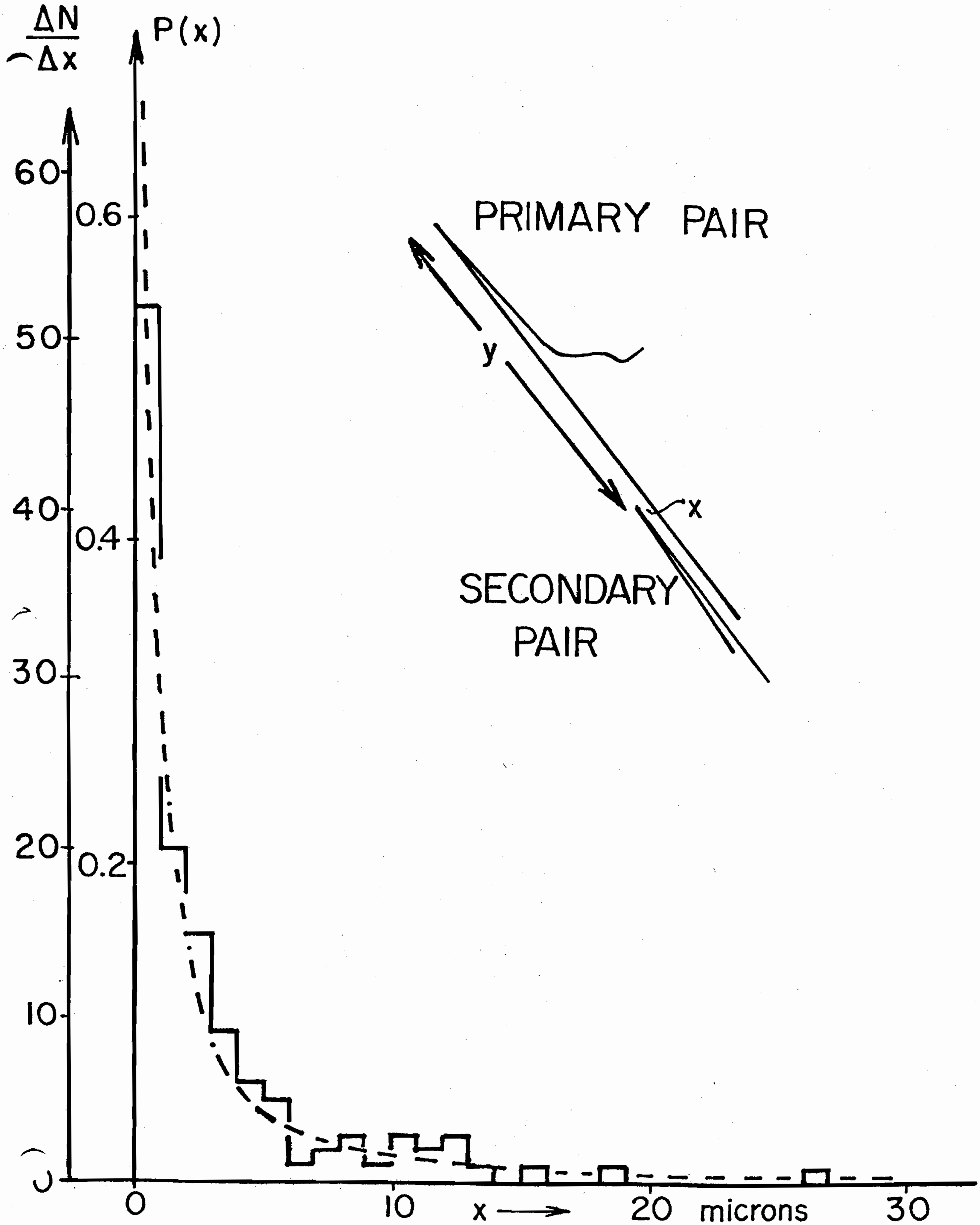
Fig 3. The deficit fraction, $1-\phi$, expresses how much the observed rate of cascade multiplication is slower than expected.

TABLE 1

$y' \rightarrow$	10 mm	20 mm	30 mm	40 mm
$N_{T>y'}$	294	294	224	167
$N_{y<y'}$	48	125	129	124
$f_{<y'}$	0.16±0.02	0.43±0.04	0.58±0.05	0.74±0.07
$P^*_{<y'}$	0.26±0.03	0.56±0.04	0.80±0.05	0.93±0.05
ϕ	0.63±0.07	0.76±0.09	0.73±0.10	0.80±0.11

CAPTION TO TABLE

Table 1. $N_{y<y'}$ is the number of primary tracks of $E>5$ GeV and $T>y'$ which show an initial secondary pair, $y<y'$. $f_{<y'}$ gives the observed rate of cascade multiplication, $N_{y<y'}/N_{T>y'}$. Quantity ϕ is the fraction ($f_{<y'}$ observed)/$P^*_{<y'}$ expected).



ΔN
Δx
P(x)
60
50
40
30
20
10
0
0.6
0.4
0.2
PRIMARY PAIR
y
x
SECONDARY PAIR
0
10
x →
20 microns
30

FIG 1

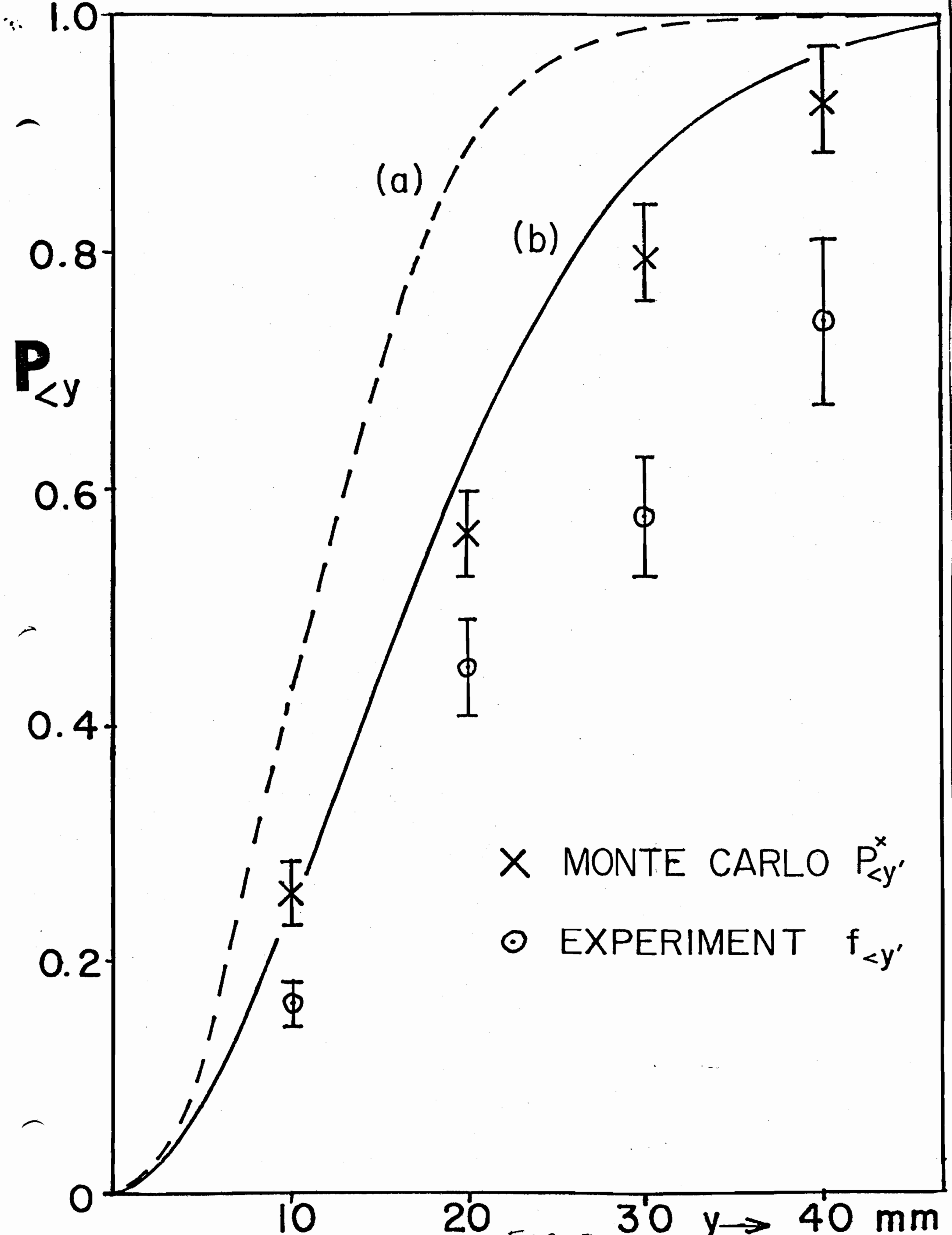

1.0
0.8
0.6
0.4
0.2
0
$P_{<y}$
(a)
(b)
10
20
30
y→
40
mm
MONTE CARLO $P^{*}_{<y'}$
EXPERIMENT $f_{<y'}$
FIG 2

FIG 3. D.T. KING PHYS REV D

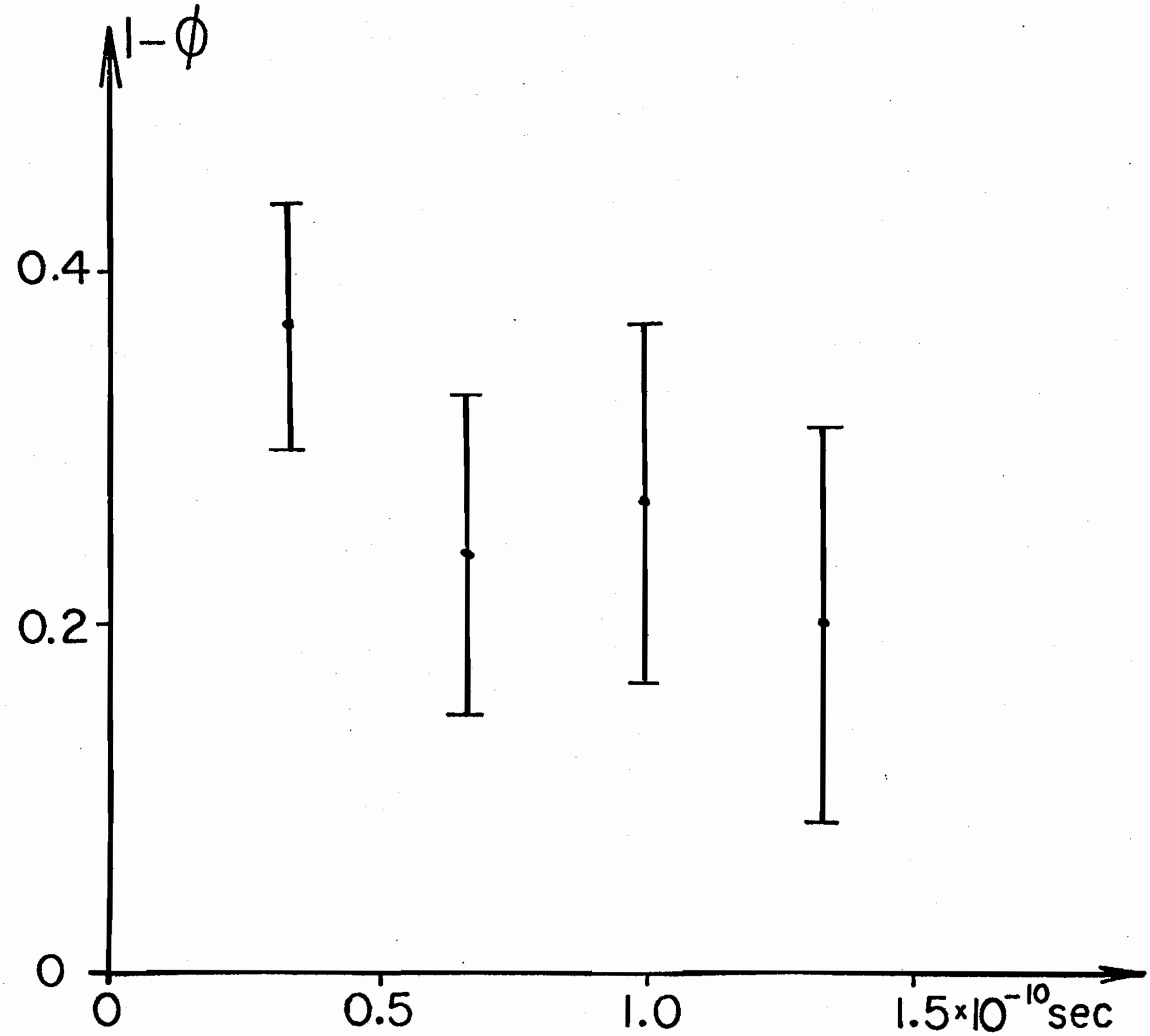


FIG 3