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Initial bremsstrahlung conversion

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Electromagnetic cascades arising from a primary electron pair have been studied in emulsions exposed to 300-GeV protons, and also in emulsions exposed to 200-GeV negative pions. Cascade development is examined through the occurrence of initial bremsstrahlung conversion along some hundreds of primary-pair-member tracks of path length > 10 mm and energy > 3 GeV. Cascades associated with pion-nucleus collisions evidently develop in accord with theory, while those from proton-nucleus collisions show cascading delay $\sim 10^{-11}$ sec. A check on cascades generated by 400-GeV proton-nucleus collisions also shows this delayed cascading. After close consideration of error sources, an explanation is sought in assumptions about the electromagnetic field.

INTRODUCTION

An energetic electron is created at a point in a medium of radiation length L_0 and travels distance y through the medium emitting k bremsstrahlung photons, of energies > 25 MeV, per unit length. The probability $P_{<y}$ of initial bremsstrahlung conversion (> 25 MeV) within y is[1]

$$P_{<y} = 1 - \exp\{-k[y - \lambda + \lambda \exp(-y/\lambda)]\},$$

where $\lambda = \frac{9}{7} L_0$ is the conversion length in the medium. The curve of Fig. 1 shows $P_{<y}$, $0 < y < 9$ mm, for an 8-GeV electron in Ilford K5 emulsion, $L_0 = 30$ mm. The points $P^*_{<y}$ in Fig. 1 are the results of a corresponding Monte Carlo calculation derived from 1714 histories of 8-GeV electrons originating at $y = 0$ in emulsion, for $y = 3$, 6, and 9 mm. $P^*_{<y}$ includes an increased allowance for the longer conversion lengths of lower-energy bremsstrahlung photons, 25–400 MeV. For purposes of comparison with experiment, we take the best fit of $P_{<y}$ to the $P^*_{<y}$ points. At primary-pair electron energies of ~ few GeV, $P_{<y}$ and $P^*_{<y}$ are nearly independent of energy.

In a previous paper,[2] experimental results of initial bremsstrahlung conversion along primary-pair tracks of electromagnetic cascades have been compared with theoretical prediction. The cascades were generated in 300-GeV proton-nucleus collisions in Ilford K5 emulsions, and candidate primary-pair tracks were required to show visible path length > 20 mm and energy > 5 GeV. Initial cascade multiplication was found to occur at a rate $(30 \pm 10)\%$ lower than expected, corresponding to cascading delay 10^{-11} sec. This anomalous "delayed cascading" is consistent with observations of some "slow" cascades which possess little individual significance and can only be recognized statistically. This paper reports observations extended to a larger number of cascades in the 300-GeV proton exposure, and also on cascades in emulsions exposed to 200-GeV negative pions. The study has been made with greatly reduced instrumental uncertainties, in the first 3×10^{-11} sec of each cascade. The occurrence of delayed cascading in the proton exposure is confirmed, and an attempt is made to interpret this phenomenon.

EXPERIMENTAL

Nuclear emulsion provides an instrument of high resolving power in examining electromagnetic processes hitherto largely unexplored. The experimental conditions in our stacks are generally similar, with low incident-beam intensities and freedom from undesired background. Electromagnetic cascades have been systematically recorded,[2] and those with primary-pair vertex outside the emulsion, or too closely associated (< 100 μm) with a beam collision, excluded. Some 1500 primary pairs have been inspected in each of the stacks, which had been exposed to 300-GeV protons and 200-GeV negative pions, respectively.

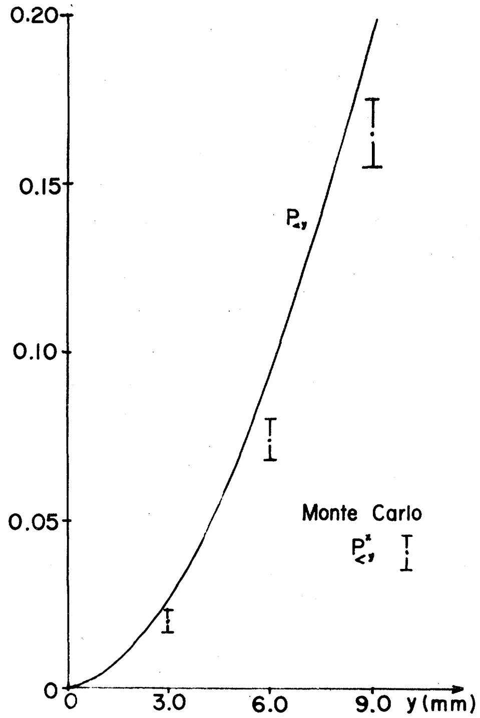

FIG. 1. The smooth curve shows the theoretical probability $P_{<y}$ for initial bremsstrahlung conversion within y by 8-GeV electrons in emulsion, L_0 = 30 mm. The points $P^*_{<y}$ are the corresponding results of a Monte Carlo calculation.

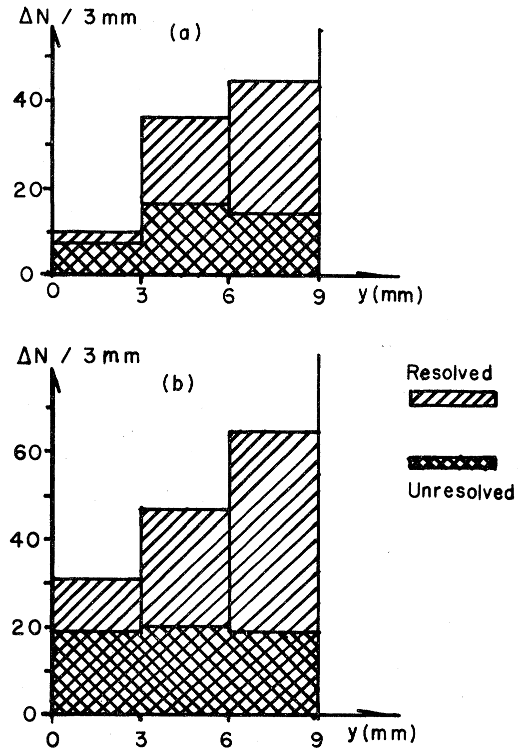

FIG. 2. Experimental y distributions for initial secondary pairs (> 25 MeV) (a) along 728 primary-pair candidate tracks in the 300-GeV proton exposure, and (b) along 833 corresponding tracks in the 200-GeV pion exposure. Unresolved secondary pairs include some direct pair production.

A compilation has been made of those primary-member tracks of visible path > 10 mm and energy > 3 GeV, based on a crude multiple-scattering measurement over ten 1-mm cells, with accuracy ~50% at 5 GeV. e^+ and e^- are here indistinguishable. Emulsion noise prevents energy determination ≳ 12 GeV, but taking those in the noise as 12 GeV yields an average primary-member energy ~8 GeV in both stacks. When both primary-member tracks maintain separation ≲35 μm over a 10-mm path, each one is generally found to be > 3 GeV. We find 728 candidate tracks from 539 primary pairs in the proton exposure, and 833 candidate tracks from 608 primary pairs in the pion exposure.

Secondary-pair vertices are readily detected along a candidate track, rarely showing lateral displacement > 5 μm from the parent. Associated primary pairs from a common source are, at these energies, generally too divergent and too distant to be misinterpreted as bremsstrahlung conversion. Some 42% of secondary pairs have the vertex superposed on the parent track, and represent both direct pair production (trident) and unresolved bremsstrahlung conversion. Secondary pairs of obvious low energy have been measured, so that those < 25 MeV can be excluded. The distance y from primary vertex to initial secondary vertex may be measured with accuracy ≲15 μm, and the y distributions (y < 9 mm) in three 3-mm intervals are shown for both exposures in Fig. 2. There are 142 initial secondary pairs, E > 25 MeV,

TABLE I. Deduction of corrected observed fraction $f_{<y}$ from the raw data of Fig. 2. In the pion-beam experiment, $f_{<y}=N^{\rm corr}_{<y}/833$, and in the proton experiment, $f_{<y}=N^{\rm corr}_{<y}/728$.

	Pion-beam experiment		
y	3 mm	6 mm	9 mm
$N_{<y}$	31	78	142
$N^{\rm corr}_{<y}$	26	68	127
$f_{<y}$	0.031 ± 0.006	0.082 ± 0.010	0.150 ± 0.014
	Proton-beam experiment		
y	3 mm	6 mm	9 mm
$N_{<y}$	10	46	91
$N^{\rm corr}_{<y}$	5.7	37.3	78
$f_{<y}$	0.008 ± 0.003	0.051 ± 0.008	0.107 ± 0.012

along 833 candidate tracks in the pion stack and 91 corresponding secondary pairs along 728 candidate tracks in the proton stack. A correction for direct pair production is made by finding the emulsion mean free path (MFP), 32 cm, for an 8-GeV electron trident.[3,4] Since directly produced pairs > 25 MeV represent 65% of the cross section, the effective MFP is 49 cm. We accordingly subtracted 15 directly produced pairs, $y < 9$ mm, $E > 25$ MeV, from the pion-experiment data of Fig. 2, and 13 corresponding pairs (4.3/3-mm interval) in the proton experiment.

The raw data of Fig. 2 are trident-corrected and summarized in Table I as $N_{<y}^{\text{corr}}$ for $y = 3$, 6, and 9 mm. Thus $f_{<y} = N_{<y}^{\text{corr}}/833$ is tabulated for the pion experiment, and $f_{<y} = N_{<y}^{\text{corr}}/728$ is likewise tabulated for the proton experiment. These figures enable a comparison of experimental results on initial bremsstrahlung conversion with theoretical $P_{<y}$. The validity of such a comparison employing data from various exposures is dependent on the uniformity of the radiation length in individual emulsions, and on consistency in recording primary pairs and iniital secondary pairs radiated and observed in different stacks over a period of time. Radiation length is insensitive to variation of emulsion composition, while gel/AgBr ratio is confined between narrow limits for registration of singly charged relativistic particles. Employment of the back-follow method[2] in recording electromagnetic cascades entails a considerable refind rate of those more rapidly developed, with opportunities for checking search efficiency on initial secondary pairs. There is a lesser, but still satisfactory, overview of "slow" cascades. A pattern of primary-pair occurrence emerges from the experiment and allows comparison of data extraction from different parts of each stack, in order to ensure a reasonably objective sampling of the cascade population. It is also noted that, for primary-pair energies of ~ few GeV, neither suppression of low-energy bremsstrahlung[5] nor charge cancellation at the origin is a significant factor.

DELAYED CASCADING

Comparison of experimental $f_{<y}$, from Table I, is made with theoretical $P_{<y}$ in Fig. 3, from which it is evident that while cascades from pion-nucleus collisions seem to develop in accord with theory, those from proton-nucleus collisions show cascading delay $\sim 10^{-11}$ sec. An early reaction to this surprise result has been to assume systematic error in cascade observations of the 300-GeV proton exposure, and to seek an explanation in cascades from 400-GeV proton-nucleus collisions. It is fortunate that our 400-GeV proton exposure was made in emulsions from the same batch as, and at nearly the same time as, those employed for the pion exposure.

A back-follow search for cascades has yielded 522 candidate tracks, > 10 mm, from 261 primary pairs in the 400-GeV proton exposure. No multiple-scattering measurements were made since these primary pairs all maintained separation $\lesssim 35$ μm over the 10-mm path. The 64 initial secondary pairs, $y < 9$ mm, $E > 25$ MeV, found along these 522 candidate tracks yield $f_{<9\,\text{mm}} = 0.104 \pm 0.014$, after trident correction. This is in close agreement with the 300-GeV result, $f_{<9\,\text{mm}} = 0.107 \pm 0.012$, and in contrast to theoretical $P_{<9\,\text{mm}} = 0.158$. A conclusion from Fig. 3 of 10^{-11} sec delay in development of cascades from proton-nucleus collisions appears to be a reasonable basis for discussion. We consider an electromagnetic field more complicated than presently conceived.

The weakly radiative phase of some cascades suggests that a fraction of the primary-pair particles might be singly charged leptons e^* of mass $m(e^*) > m(e)$. There can be little muonic

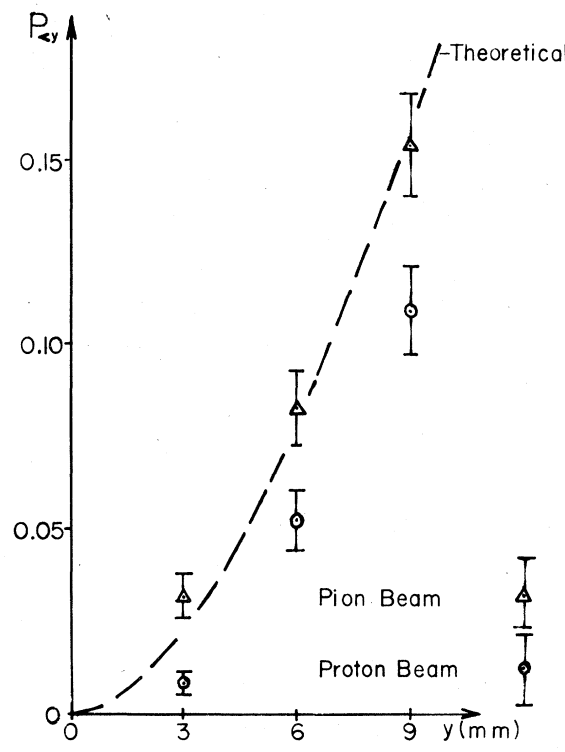

FIG. 3. The corrected experimental fraction $f_{<y}$, from Table I, of initial bremsstrahlung conversion (>25 MeV) within y. Comparison is made with theory, the best fit of $P_{<y}$ to the Monte Carlo points. Development of electromagnetic cascades in the pion exposure appears to be in reasonable agreement with theory.

contribution to e^* since, among primary-pair tracks which travel > 30 mm, some 90% ultimately show multiplication or visible degradation.[2] The value assumed for fraction $N(e^*)/N(e)$ affects the radiation length L_0^* deduced for e^*, and hence the mass ratio $m(e^*)/m(e)$, since $L_0^* = [m(e^*)/m(e)]^2 L_0$. However, if we take $N(e^*)/N(e) = 1.0$, a series of $P_{<y}$ curves may be drawn on Fig. 3, corresponding to $L_0^* = L_0$, $L_0^* = 2L_0$, $\ldots$, $L_0^* \to \infty$. The cascade observations for 300-GeV proton-nucleus collisions suggest that, for $N(e^*)/N(e) = 1.0$, $L_0^* \approx 1.7 L_0$, leading to the conclusion $m(e^*) \approx 1.3 m(e)$. It might further be supposed that $(e^*)^{\pm} \to (e)^{\pm}$ with lifetime $\sim 10^{-14}$ sec, and that the peculiar quantum properties of e^* would require photon conversion to e^* pairs.

The other disturbing feature of Fig. 3, the magnitude of cascading delay apparently dependent on the nature of the incident particle, must also be considered. If further observations provide support for this result, we might suspect the emission of two photon varieties, γ_n and γ_1 from π^0 (and $\bar{\pi}^0$) decay, with few γ_1 from pion-nucleus collisions. It may be noted that, if the conversion length of γ_1 were appreciably longer than that for γ_n, the distinction between γ_1 and γ_n might be acessible to further experiment.

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