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Direct Production of Electron Pairs by Energetic Protons

J. E. Butt and D. T. King
The University of Tennessee, Knoxville, Tennessee 37916
(Received 13 March 1973)

In a study of nuclear collisions produced by 200-GeV protons in emulsion, we have found eight events attributable to the direct production of electron pairs by protons. A crude measure of the cross section, 6.7 ±2.4 mb, is obtained. This result is viewed in relation to foregoing work on direct pair production by energetic leptons.

In the literature describing direct pair production by fast electrons, a number of experimental and theoretical difficulties appear. Cross-section measurements[1] are subject to large corrections due to competing electromagnetic effects. Calculation of the cross section has been carried out with increasing accuracy,[2,3] the result of Murota, Ueda, and Tanaka[4] being considered the most valid.[5] The theory has been extended to the production of muon pairs.[6,7] Experimental results have been in reasonable agreement with theory, including the $\ln^3 U$ dependence, for primary energies U up to ~100 GeV.[1,8-11] Typically, electron tridents exhibit a created pair, which carries away 5–50% of the primary energy,[8] and a small opening angle similar to ordinary photon conversion pairs of the same energy.

We report here observations of 200-GeV proton-nucleus collisions in emulsion for which the sole visible product is a directly created pair of small (~0.05%) fractional energy transfer and large opening angle. These pairs originate on, and are closely aligned with, the beam proton tracks, under conditions where the competing electromagnetic effects are satisfactorily low.

Ilford K5 emulsions 600 μm thick were exposed to 3×10^4/cm^2 200-GeV protons[12] with the beam direction parallel to the emulsion plane. The fine grain size of K5 emulsion is valuable for resolving lightly ionized tracks of small separation. Starting at the input edge of the stack, beam tracks were followed in doublets. A criterion of parallelism was applied to each doublet since multiple Coulomb scattering causes no perceptible change in the separation signature of two 200-GeV proton tracks over a path length of 1 cm. Tracks which failed to satisfy the parallelism criterion were identified as contamination, and the level of this was evaluated at $(7\pm2)\%$, of which we estimate no more than $\frac{1}{4}$ was leptonic.

As in similar experiments,[13,14] data on nuclear collisions of beam particles were collected by following beam tracks at scan speeds between 10 and 20 cm/h, but preserving the parallelism requirement for track doublets in order to exclude contamination. The separation signature of a doublet served as a useful mutual reference in the presence of background tracks. Beam doublets were followed for distances up to a maximum 5 cm from the input edge because at greater distances into the stack the background, including electromagnetic cascades with tridents,[1] was found to retard the scan.

In a total beam path of 132 m, 390 nuclear collisions of beam particles were found and, of these, 85 showed no visible nuclear evaporation although the tracks of β particles were often visible. For such "white" stars, all emergent tracks had ionization at or less than the plateau level, corresponding to velocities $>0.85c$. Ten of these white stars showed just three emergent tracks, and eight of these ten were remarkable in the following respects: (a) There was no detectable deflection (>0.1 mrad) of the middle secondary relative to the primary; (b) the outlying secondary (pair) tracks emerged on opposite

TABLE I. Observations on directly produced pairs.

E (MeV)	R	θ (mrad)	P_T (MeV/c)	cP_T/E (mrad)
44	0.36	27	0.2	4.8
66	0.14	43	1.9	20
72	0.43	67	0.7	9.8
72	0.15	99	0.6	8.4
130	0.27	31	1.3	10
190	0.16	73	0.6	3.2
440	0.14	38	1.2	2.7
5000	0.18	94	42	8.4

sides of the primary, nearly coplanar; (c) for seven of these eight events, one or both of the pair tracks had sufficient multiple scattering to be attributable to an electron. Evidently, electron pairs of low energy and large opening angle were materialized on or close to the tracks of beam particles.

Measurements of momentum (accuracy ~20%) and emission angle (~5%) for the pair tracks are summarized as pair energies $E=E^+ + E^-$, imbalance ratios $R=E^{+,-}/E$, and opening angles θ, in Table I. The quantity P_T expresses the net transverse momentum of the pair, while the momentum ratio cP_T/E is a measure of the inclination of the pair vector to the beam. The opening angle has little apparent relation to the pair energy, but is generally larger than that for ordinary conversion pairs of similar energy.

Events of this kind might occur either through direct production of electron pairs by beam particles or from competing electromagnetic effects such as unresolved bremsstrahlung conversion (pseudotrident[8]) or chance juxtaposition of a background pair origin with a beam track. The pseudotrident contribution here depends primarily on the emission angle of the bremsstrahlung photon, and from our determinations of cP_T/E above, we estimate this effect to be <1%. Background pairs occur in the first 5 cm of our plates with an average density ~300/cm^2, so that 6500 background pairs have materialized in the scan volume. Of these, 24% are inclined at angles <32 mrad to the beam direction, and we find that fewer than 10% of the forward pairs have large opening angle or energy ≲ 500 MeV. Under the conditions of the experiment, the probability that a given photon will convert so that the pair origin is unresolvable from a beam track is 0.25%. The chance juxtaposition effect among our tabulated observations is therefore ~5%. An alternative interpretation for these events might be sought through coherent production of a neutral pion followed by the $\gamma+2e$ decay mode, but the lack of momentum imbalance displayed by our data again reduces this uncertainty to <1%.

We have considered the possibility that some tridents, or white stars of low multiplicity, escape observation in the scan. One aspect of our comparison with theory is the proportion of tridents with very low pair energies, <100 MeV, although we believe that pairs with energies as low as 5 MeV can be detected. We have retraced some 20% of the beam doublets in an effort to find missed events, without result. It is noted that Antonova *et al.*, with 67-GeV protons and high scan efficiency, find 15% of the white stars to have three prongs[14] where we find 12%. On this basis, our scan efficiency is comparable. The production of tridents by muons or electrons present as beam contamination is also taken into account since cross sections for 100-GeV muons or electrons are, respectively, ~2 and ~12 times larger than that expected for 200-GeV protons.[4] The tabulated observations indicate a marked dissimilarity from electron tridents, both in opening angle and fractional energy transfer, an indication that the doublet scan method has effectively excluded contamination effects.

The mean path length in emulsion for 200-GeV proton tridents is found to be 19.1 ± 6.8 m when corrected for maximum likelihood.[15] The corresponding cross section is 6.7 ± 2.4 mb with error governed by the statistics. We note that the calculated cross sections reported by different authors[2-4] fall in the range 45–110 mb, with the preferred result of Murota, Ueda, and Tanaka being ~100 mb. We conclude that direct pair production by protons does occur, but that it is not yet possible to infer a significant difference between theory and experiment. In collecting futher data we are giving attention to improved search efficiency, as failure to detect tridents is the main factor in giving too small an experimental result. Experience so far suggests that trident visibility depends more on inclination of the pair plane rather than the pair energy or opening angle.

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Two informative footnotes should be added to this paper: with the title, "*Work supported by Deutsche Forschungsgemeinschaft"; with the author, "†Present address: Department of Physics, State University of New York at Stony Brook, Stony Brook, N. Y. 11790."