The theoretical wave functions we use here involve only *sd*-shell orbits. However, both examples we have studied so far do involve minor shell closures, $d_{5/2}$ at ^{28}S and $s_{1/2}$ at ^{32}S. Hence the excited 0^+ states do have a mild "particle-hole" type of structure relative to the ground state. Whether this is an essential element for the manifestation of the weak-coupling structure, or whether the phenomenon occurs for essentially all first excited 0^+ states, is one of the interesting points for further study.

Of course, the primary need now is to obtain experimental tests of our predictions for two-nucleon transfer. If these are validated, then it would appear that further experimental work is in order to delineate fully the extent of this pleasingly transparent sort of nuclear coupling, and that a more extensive study of the shell-model wave functions, with the aim of projecting out all their "weak-coupling" features, would be valuable.

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Direct Electron-Pair Production by 200-GeV Protons*

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Forty directly produced electron pairs have been found by following 713.4 m of 200-GeV–proton track length in nuclear emulsion. For these pairs we have analyzed (i) the total energy distribution, (ii) the energy partition between the two members, (iii) the angular divergence, (iv) the transverse momentum distribution, and (v) the invariant mass of the electron pairs. Present theories disagree with our experimental results.

Observations of the direct production of electron pairs arising from the interaction of fast charged particles with the Coulomb fields of nuclei have been studied extensively.[1] Some of the experimental data between 1 and 100 GeV have shown conflicting results with the theories, and beyond 100 GeV there do not exist any reliable experimental data. In most of these experiments the primary beams used were either high-energy electrons or photons from cosmic rays where the beam energy is neither monoenergetic nor accurately determined. The accuracy of the energy of the primary beam is very essential in making any analysis of the observed data. Several authors[2-4] have computed the cross section for direct pair production and have modified the theories to fit the experimental data.

The recent availability of a monoenergetic beam of 200-GeV protons at the National Accelerator Laboratory makes it very appropriate to look into this fundamental problem from the point of view of checking quantum electrodynamics at small distances, which has attracted considerable attention over the years. In the present experiment we have considered electron-pair production by a monoenergetic beam of 200-GeV protons in the Coulomb potential of an emulsion nucleus with an effective charge $Z \approx 21.4$. Electron-positron pairs used in the present analysis were obtained by scanning along 713.4 m of track length in Ilford G-5 emulsion, 600 μm thick, exposed[5] to a flux of 2×10^4 particles/cm^2 in a 200-GeV proton beam parallel to the emulsion plane. At a distance of 0.5 cm from the edge of the plate we pick up a track parallel to the primary beam at about halfway up from the bottom of the pellicle and follow it with others along the X motion of a Koristka microscope stage at an average speed of about 25 cm/h. Whenever an interaction is observed, the parent track is rechecked for its parallelism with the other beam tracks followed in the same field of view. Thus we find the inelastic-interaction mean free path of 200-GeV protons in nuclear emulsion to be $\lambda_{\rm int} = 32.1 \pm 0.6$ cm. The percentage of white stars[6] with $N_h = 0$ for all interactions is 17%, out of which 18% are tridents. Our scanning efficiency of low-multiplicity events is quite high (> 96%). Out of a total of 76 tridents, 40 were identified by scattering measurements as directly produced electron pairs. The vertex of each trident was carefully checked to eliminate spurious events such as (a) bremsstrahlung pairs; (b) conversion of γ rays from the decay of a neutral particle, like $\pi^0 \to \gamma + e^+ + e^-$ (Dalitz decay), which occurs only $\frac{1}{80}$ of the time; (c) tridents from strong incoherent (p-n) interactions; and (d) coherent production of particles through Coulomb or diffraction dissociation of pion pairs.[5,7] The calculated total background was <1%. The characteristics of pions and electrons are quite distinctive in nuclear emulsion. One can see this when following a track for the measurements of the ionization density and the energy by multiple scattering. A relativistic electron, unlike more massive particles, loses a considerably greater fraction of its energy through bremsstrahlung than is to be expected from ionization alone.

For the direct production of electron pairs, we used the criteria that (i) the two outgoing secondary tracks should appear on opposite sides of the primary and be nearly coplanar; (ii) the middle track, which is the proton, should be practically undeviated from its original direction; (iii) the ionization density for electron tracks should be less than or equal to the plateau value; (iv) for the separation of fast electrons from low-energy pions, $p\beta c$ should be <0.21 GeV; and (v) at least one track, if not both, must show sufficient multiple scattering which is characteristic of an electron. Events produced through the coherent process were separated as mentioned earlier,[7] giving a mean free path $\lambda_{3,\rm coh} = 19.1 \pm 4.2$ m and $\sigma_{3,\rm coh} = 11.2 \pm 2.5$ mb in nuclear emulsion. By observing tridents with the above criteria, we obtained forty events which were produced through direct pair production, with $\lambda_{\rm pair} = 17.8 \pm 2.9$ m and thus $\sigma_{\rm pair} = 7.1 \pm 1.1$ mb. In order to see the dependence of $\sigma_{\rm pair}$ on the nature of the primary particle interacting at the same γ factor ($\gamma_p \sim 200$), we used 15.8-GeV/c negative muons[8] ($\gamma_\mu \sim 150$), giving $\lambda_{\rm pair} = 15.6 \pm 3.9$ m and $\sigma_{\rm pair} = 6.2 \pm 1.5$ mb, which shows the independence of the nature of the incoming particle at these energies. The errors shown are statistical. Recently, on the basis of very low statistics[9] of only eight electron pairs found in 130 m of track length in nuclear emulsion exposed to 200-GeV protons, the values of $\lambda_{\rm pair} = 19.1 \pm 6.8$ m and $\sigma_{\rm pair} = 6.7 \pm 2.4$ mb were presented. For the eighth event of Butt and King's Table I, we calculated the values of several parameters (i.e., $E_1 = 900$ MeV, $E_2 = 4100$ MeV, $R = 0.18$, $Q = 181$ MeV, and $\omega/\omega_0 = 140$) as defined in our Figs. 1(a) to 1(e). We find that the values of these parameters for this event are quite different from the rest of their[9] electron pairs as well as from our present data and hence this event does not belong to electron-pair production. The theoretical total cross sections with the screening effect, which were calculated by different authors,[2,3] lie in the range of 26–100 mb. The detection efficiency of low-energy electron (~1 MeV) pairs in emulsion is quite good. We may also mention that the contamination of the trident production from an electron beam in this experiment is practically negligible, as the energy transferred from the parent electron to the created pair is generally very large[3] (5 to 50%) with the result that the opening angle of the pair may be very small, $\sim mc^2/E$ rad. On the other hand, for direct pair production with a proton beam, a very small fractional energy (<0.05%) is transferred to the created pair, with a relatively large opening angle.

In Fig. 1(a) is shown the experimental histogram of the total energy transferred to the 36 electron pairs, with scattering-measurement errors up to ~15%. Because of unsuitable physical conditions of the emulsion in the vicinity of the electron pairs, the energy determination of either one or both of the tracks from four of the electron pairs was not dependable and hence these events are

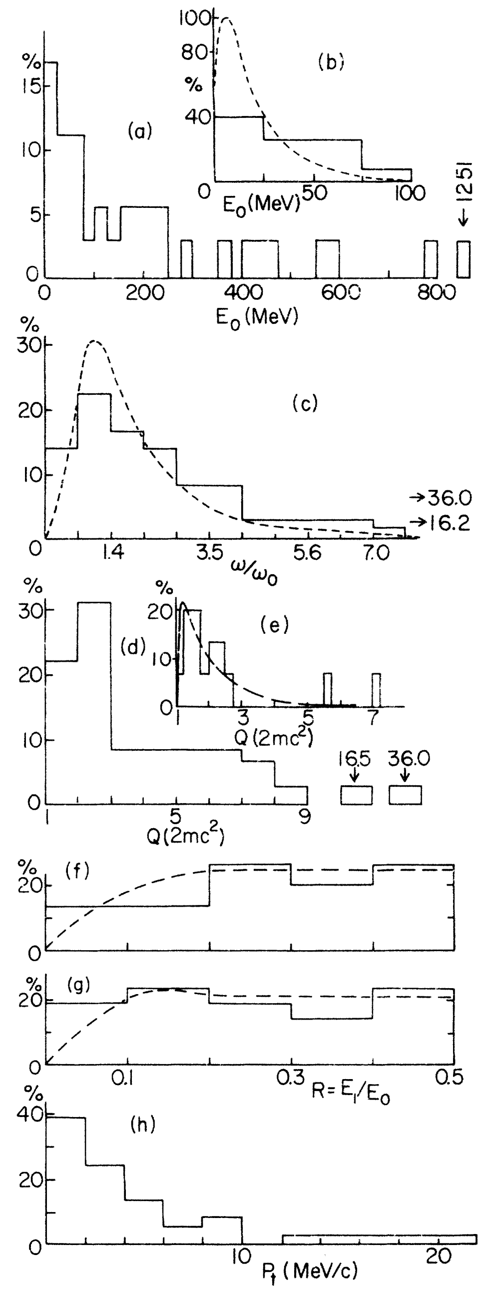

FIG. 1. (a) Energy distribution of the electron pairs. (b) Energy distribution of the electron pairs with E_0 <100 MeV, and theoretical curve given by Refs. 1 and 4. All theoretical curves in the figures are normalized to the experimental data. (c) Angular divergence ω for electron pairs in terms of Borsellino angle ω_0. The theoretical curve is given by Ref. 9. (d) Invariant-mass (Q) distribution for all events, in units of $2mc^2$. (e) Experimental and theoretical invariant-mass (Q) distribution for electron pairs with $E_0 \leq 100$ MeV, in units of $2mc^2$. (f), (g) Experimental and theoretical distributions for $R = E_1/E_0$ for $E_0 \leq 100$ MeV and $E_0 > 100$ MeV, respectively, where $E_1 < E_2$. (h) p_t distribution for all electron pairs.

excluded from our discussion. In the energy distribution of these electron pairs about 50% of the events are produced with energy $E_0 \leq 100$ MeV, where $E_0 = E_1 + E_2$ is the total energy of the electron pair. In Fig. 1(b) the histogram shows the total electron-pair energy up to 100 MeV and this is compared with the theoretical curve given by the modified Bhabha theory[1,4] for $2mc^2 < E_0 < \gamma mc^2$, where γ in our experiment is ~200 and mc^2 is the rest mass of an electron. All theoretical curves are here normalized to our experimental data and the theory does not fit well with the observed data. The total cross section calculated by this theory for the range $E_0 \leq 100$ MeV is 26 mb, which is 10 times larger than the experimental value observed for the same range of E_0. In Fig. 1(c) we evaluated the angular divergence ω of the electron pair in terms of Borsellino's characteristic angle[10] $\omega_0 = E_0 mc^2/E_1E_2$. The calculated error[11] in the space angle is less than 5%. The theoretical curve is calculated from Eq. (14) of Ref. 10 in which we used from our experiment the overall average value $\langle E_0 \rangle = 250$ MeV and the imbalance ratio $R = 0.25$. The theoretical curve gives approximately the shape of the experimental histogram. In Fig. 1(d) is shown in histogram form the invariant-mass $Q = (E_0^2 - p^2)^{1/2}$ distribution for the electron pairs in units of $2mc^2$, where p is the total momentum of the pair; $\langle Q \rangle_{\text{pair}} = 4.8 \pm 0.8$ MeV for the present experiment, and for the 15.8-GeV/c muon beam[8] $\langle Q \rangle_{\text{pair}} = 4.3 \pm 1.0$ MeV. More than 50% of the events have $Q \leq 3$ MeV. For events with $E_0 \leq 100$ MeV, the values of Q are plotted in Fig. 1(e). For these events, the average value of the energy observed for the electron pairs is $\langle E_0 \rangle = 38$ MeV. Hence, the theoretical curve was fitted to this distribution for this average value of E_0. We see the sharp peak in the theoretical curve, but it is shifted to the left of the experimental data. Figures 1(f) and 1(g) show the experimental histograms of the imbalance ratio $R = E_1/E_0$ for $E_0 \leq 100$ MeV and >100 MeV, respectively. The theoretical curves in Figs. 1(f) and 1(g) were calculated from Eq. (31) of Bethe and Heitler[12] for $E_0 = 35$ and 350 MeV, respectively. Figure 1(b) shows the net p_t distribution of each electron pair; $\langle p_t \rangle_{\text{pair}} = 4.9 \pm 0.8$ MeV/c, and for the 15.8-GeV/c muon beam[8] $\langle p_t \rangle_{\text{pair}} = 3.6 \pm 0.8$ MeV/c. More than 50% of the events fall in the region of $p_t < 4$ MeV/c, with an upper limit of $p_t \simeq 20$ MeV/c.

In conclusion, the theoretical predictions on the cross section, the energy spectrum, the angular divergence, and the invariant-mass distribution of the electron pairs do not explain the observed experimental results. The discrepancies are rather large, e.g.,

$$\sigma_{\rm pair}(\text{theory}) \gg 5\sigma_{\rm pair}(\text{experiment})$$

in particular, for small E_0 and Q regions. Nuclear emulsion has a large detection efficiency for even extremely low-energy particles and here we have been able to detect electrons with kinetic energy <1 MeV. We feel that the present systematic experimental observations will be useful to the theorists who wish to look into these discrepancies very seriously.

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Observation of Muonless Neutrino-Induced Inelastic Interactions

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We report the observation of inelastic interactions induced by high-energy neutrinos and antineutrinos in which no muon is observed in the final state. A possible, but by no means unique, interpretation of this effect is the existence of a neutral weak current.

We report here additional results of our study[1] of high-energy neutrino interactions produced by the broad-band unfocused neutrino beam of the National Accelerator Laboratory. In this note we concentrate on reactions which are distinguished from the "ordinary" processes, $\nu_\mu(\bar{\nu}_\mu)$ + nucleon $\rightarrow \mu^-(\mu^+)$ + hadrons, by the absence of a muon in the final state. Data obtained with proton energies $E_p = 300$ and 400 GeV are presented here.

The experimental setup is shown in Fig. 1(a). The light from each of the sixteen segments of the target-detector was collected to generate a pulse proportional to the energy deposited in each segment.[2] The sixteen signals were combined to generate an event trigger whenever the total energy[3] exceeded a specific threshold (6 GeV at $E_p = 300$ GeV, 12 GeV at $E_p = 400$ GeV). The detector was gated on during two equal periods, one coincident with the machine burst, the other delayed to detect cosmic-ray events exclusively. At $E_p = 300$ GeV (400 GeV) the effective beam-spill duration was 100 μsec (15 μsec). For each