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V. Efremenko, A. Fedotov, P. Gorichev, V. Kaftanov,
G. Kliger, V. Kolganov, S. Krutchinin, M. Kubantsev,
I. Makhlyueva, V. Shekeljan, and V. Shevchenko
Institute of Theoretical and Experimental Physics, Moscow, USSR

and

J. P. Berge, D. Bogert, R. Hanft, J. Malko, G. Harigel,
G. Moffatt, F. Nezrick, and J. Wolfson
Fermi National Accelerator Laboratory, Batavia, Illinois 60510 USA

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V. Ammosov, A. Denisov, P. Ermolov, G. Gapienko,
V. Gapienko, V. Klukhin, V. Koreshev, P. Pitukhin,
V. Sirotenko, E. Slovodjuk, and V. Zaetz
Institute of High Energy Physics, Serpukhov, USSR

and

J. Bell, C. T. Coffin, W. Louis, B. P. Roe, R. T. Ross,
A. A. Seidl, D. Sinclair, and E. Wang
University of Michigan, Ann Arbor, Michigan 48104 USA

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Abstract

A search for charmed particle production in antineutrino-nucleon neutral current interactions is reported. The recognition signature used was positron decay of the charmed particle; however all single positron events found can be attributed to known sources. Based upon a possible signal of one event, the 90% confidence level upper limit for the rate of neutral current charmed particle production with subsequent positron decay relative to charged current interactions is 0.87×10^{-3}. Assuming a branching ratio of 0.1, we find corresponding limit for the right handed $\bar{u}c$ coupling is 1.9×10^{-2}.

The production of charmed particles in charged current neutrino and antineutrino interactions is experimentally well established and is, at least qualitatively, well understood.[1] In the standard model of weak interactions developed by Weinberg and Salam[2] the weak neutral current is quark flavor conserving; according to this model charmed particle production in neutral current interactions should occur only in pairs from c- and $\bar{c}$-quarks in the sea. This production mechanism is expected to be strongly suppressed.[3,4] There exists a number of other gauge models which are consistent with available charged current data but which allow neutral current induced transitions between different quark flavors.[4,5] In particular in these models enhanced charmed particle production is expected via valence u-quark to c-quark transitions: $\bar{\nu}_\mu u \rightarrow \bar{\nu}_\mu c$. We report here a search for this charm changing neutral current (CCNC) process using as the charm signature the subsequent positron decay of the c-quark: $c \rightarrow e^+ \nu_e X$.

The data come from an 85,000 picture exposure of the Fermilab 15-ft bubble chamber to the two-horn broad-band antineutrino beam. Calculations indicate that the four kinds of neutrinos in this beam should produce events in the ratios $\bar{\nu}_\mu/\nu_\mu/\bar{\nu}_e/\nu_e$ = 100/12/0.6/0.6. The chamber was filled with a mixture of 64% neon and 36% hydrogen by atoms which has a radiation length of 39 cm.

The film was scanned for neutral induced events with visible momentum along the beam direction greater than 1 GeV/c. These events were closely examined for a single electron or single positron (not paired with a positron or electron, respectively) having momentum $p_e > 0.8$ GeV/c at the primary vertex. The sample obtained was purified by requiring the electron or positron to show two or more of the following signatures, at least one of which must be a bremsstrahlung conversion: spiralization to a point, sudden change of curvature, bremsstrahlung conversion, trident production, annihilation (for positrons only), and large delta rays. The efficiency of the purification process was determined to be 83% by applying our procedure to known electrons and positrons from gamma conversion. The External Muon Identifier supplemented with a kinematic selection method was used to identify events which also have muons; those events are reported in detail elsewhere.[6]

After removing events with identified muons, we obtained a sample consisting of 74 events with a single e^+, 67 events with a single e^-, and two events with high energy e^+/e^-, where the sign of the electric charge cannot be determined. We interpret the majority of these events as $\bar{\nu}_e$ and ν_e induced charged current events. These numbers of events are consistent with expectations based on calculations of beam performance. This interpretation for the e^+ events is further supported by the Y_{VIS} distribution in Fig. 1 which shows the characteristic $(1 - y)^2 \approx (1 - Y_{VIS})^2$ behavior expected for $\bar{\nu}_e$ (and $\bar{\nu}_\mu$) charged current events.[7] For comparison the dashed curve in Fig. 1 shows the Y_{VIS} distribution obtained from the same experiment's $\bar{\nu}_\mu N \to \mu^+ X$ events.

We remark that a possible source of single positron events is heavy lepton M^+ production via $\overline{\nu}_\mu N \rightarrow M^+X$ followed by the decay $M^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$. Using calculations based on the work of Albright et al.,[8] we analyzed the Y_{VIS} distribution in Fig. 1 to obtain a 98% confidence level lower limit of 6 GeV for the mass of the M^+, assuming the branching ratio of the decay $M^+ \rightarrow e^+\nu_e\overline{\nu}_\mu$ to be 20%.

In order to enhance any possible CCNC signal we employed two selections: (1) Charmed particles produced in $\overline{\nu}_\mu$ and ν_μ charged current interactions in Fermilab wide-band beams have laboratory momenta of the e^- and e^+ decay products, respectively, of a few GeV/c.[6,9] We expect CCNC charm production in $\overline{\nu}_\mu$ interactions to give e^+ also of a few GeV/c; such events when (incorrectly) interpreted as $\overline{\nu}_e$ charged current events would have large values of Y_{VIS} or, equivalently, small values of $z = p_e/\Sigma p^{\parallel}_{VIS}$. Therefore we searched for the CCNC signal in the region $z < 0.5$. (2) In addition we considered the quantity $U_{VIS} \equiv X_{VIS}\,(1 - Y_{VIS})$ which is useful for characterizing neutral current events. It can be estimated as $(\Sigma p^{\perp}_{VIS})^2/2\,M_p\,\Sigma p^{\parallel}_{VIS}$, where $p^{\perp}_{VIS}$ and $p^{\parallel}_{VIS}$ are visible hadron momenta components perpendicular and parallel, respectively, to the beam direction. Since the final state antineutrino, which is expected to have substantial transverse momentum component, is not included in the summations, U_{VIS} is expected to be large for neutral current events. If the expression for U_{VIS} is evaluated for $\overline{\nu}_e$ charged current events by including the observed e^+ (incorrectly) in the sums over hadrons, the resulting value of U_{VIS} will be small, usually less than 0.02. The effectiveness of the cut

$U_{VIS} > 0.02$ in further removing $\bar{\nu}_e$ charged current events was tested by assuming μe universality and studying the U_{VIS} distribution obtained from known $\bar{\nu}_\mu$ produced charged current events analyzed by including the final state μ^+ in the sums.

After applying the restrictions $z < 0.5$ and $U_{VIS} > 0.02$ to the sample of e^+ events we obtained one candidate event. The background indicated by the study of $\bar{\nu}_\mu$ charged current events is 2.9 ± 0.8 $\bar{\nu}_e$ charged current events. Other sources of background considered are neutral current events with asymmetric Dalitz pairs or close gamma conversions, K_{e3} decays, and $\mu^- e^+$ pairs with unidentified muons. The total expected number of background events from all sources is estimated as 3.8 ± 0.9 events.

To estimate the selection efficiency of the z and U_{VIS} cuts we used 12 $\mu^+ e^-$ and 6 $\mu^- e^+$ events found in same film[6] that have been interpreted as charmed particle production in $\bar{\nu}_\mu$ charged current interactions. The scatter plot in Fig. 2 shows the distribution of z and U_{VIS} for these μe events and, for comparison, this distribution for the single e^+ events. Thirteen of the 18 μe events fall in the region selected to enhance any CCNC signal. This suggests our z, U_{VIS} selection would lose only ~30% of any CCNC signal.

The effects of the z, U_{VIS} cuts were also investigated using a Monte Carlo model calculation for CCNC charm production. The salient features incorporated into this calculation are (1) the known $\bar{\nu}_\mu$ beam energy spectrum, (2) only D^0 production with a step function excitation curve, (3) three-body decay to $K^0 e^+ \nu_e$.

(4) fragmentation functions found to be consistent with counter experiment dimuon data[10] and (5) experimental resolution functions obtained from our $\bar{\nu}_\mu$ data. This calculation indicates that the z and U_{VIS} selections lose ~35% of CCNC events and the p_e > 0.8 GeV/c cut loses an additional ~20% of these events.

After subtracting the background and correcting for the discussed efficiencies, we obtained the following 90% confidence level upper limit for the production of CCNC events with subsequent positron decay relative to $\bar{\nu}_\mu$ charged current events with $E_{\bar{\nu}}$ > 10 GeV:

$$R = \frac{\text{Events } (\bar{\nu}_\mu N \to \bar{\nu}_\mu \text{ CX; } C \to e^+\nu_e X)}{\text{Events } (\bar{\nu}_\mu N \to \mu^+ X)} < 0.87 \times 10^{-3}.$$

In some $SU_2 \otimes U_1$ gauge models off diagonal CCNC currents of the form $J = h_L(\bar{u}c)_L + h_R(\bar{u}c)_R$ are allowed where the left-handed coupling $h_L{}^2$ is assumed to be much smaller than the right-handed coupling $h_R{}^2$. Following Ref. 4 we assume $h_L{}^2 = 0$ and write the CCNC cross section as

$$\frac{d^2\sigma}{dxdy} = \frac{G^2 m_p E_{\bar{\nu}}}{4\pi} \left[u(x) + d(x)\right] h_R{}^2\, \theta(W - W_c)$$

where u(x) and d(x) are the u- and d-quark densities, W is the hadronic mass, and the step function θ accounts for the charm production threshold at $W_c \doteq 2.8$ GeV. Using our limit $R \leq 0.87 \times 10^{-3}$ and the branching ratio B_e $(C \to e^+\nu_e X) = 0.1$ we obtain

$h_R^2 \leq 1.9 \times 10^{-2}$ at the 90% confidence level. This limit is a factor of five to seven lower than the limit that can be obtained from high energy wrong sign single muon production[11] and single e^+ production[12] in a neutrino beam.

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$/2M_p\ (E_{\bar{\nu}} - E_\mu)$, where $-Q^2$ and θ_ℓ are the square of the four momentum transfer and the angle, respectively, between the incident antineutrino and final state lepton, and M_p is the proton mass. We use Y_{VIS} which is y evaluated with $E_{\bar{\nu}} \simeq E_{VIS}$, which is sum of the visible momenta along the antineutrino direction.

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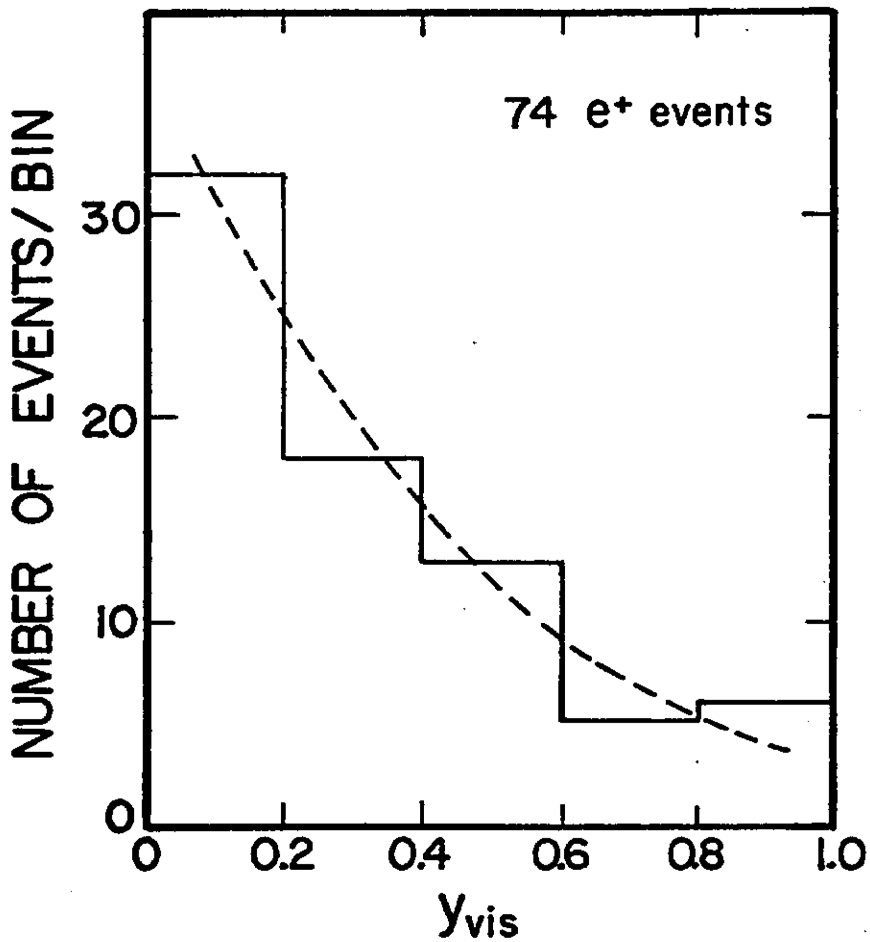

Fig. 1 The distribution of Y_{VIS} for single e^+ events. The dashed curve shows the distribution function obtained from $\bar{\nu}_\mu$ charged current events.

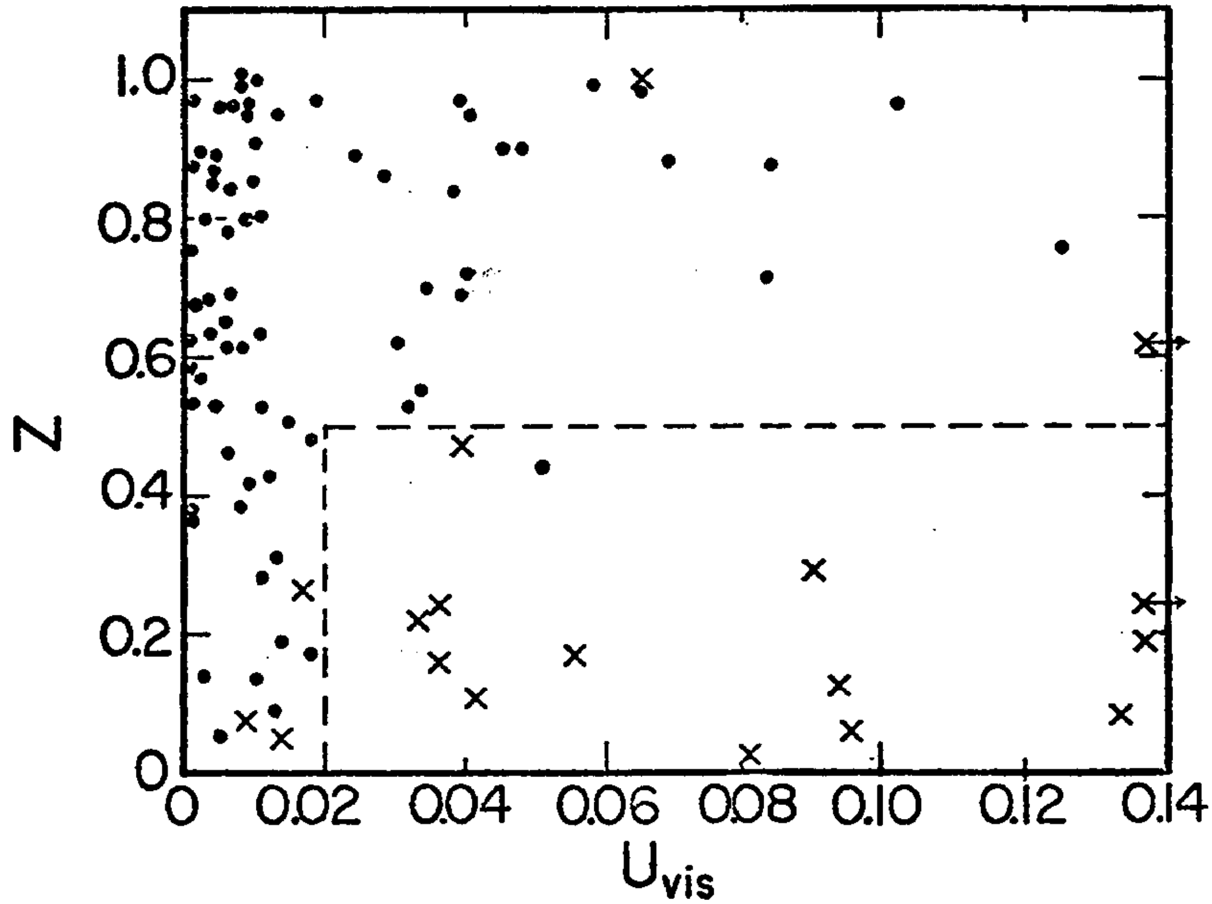

Fig. 2 The U_{VIS} - z plot for single e^{+} events (•) and μe events (+). The dashed lines show the experimental cuts $U_{VIS} > 0.02$ and $z < 0.5$.