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*Birmingham-CERN-Imperial College-München(MPI)-Oxford-
University College London Collaboration (WA21)*

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ABSTRACT

Using data from a νp and $\bar{\nu} p$ experiment with BEBC at CERN, the rates for inclusive production of D^{*+} , Λ_c^+ and D^0 in νp scattering and of D^{*-} in $\bar{\nu} p$ scattering are measured. Some examples of the exclusive production of D^{*+} , Λ_c^+ and Σ_c^{++} are given. The cross section for the reaction $\nu p \rightarrow \mu^- \Sigma_c^{++}$ is estimated.

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1. Introduction

This paper summarizes the results on the production of charmed hadrons in neutrino and antineutrino proton interactions obtained in the bubble chamber experiment WA21. Although the experiment was not specially designed to study charmed particles, it is one of the first neutrino experiments in which examples of exclusive charm production have been found and in which inclusive charm production rates have been measured [1]. Due to the high accuracy of momentum measurement, charmed particle masses have been determined with high precision although the statistics were very low [2, 3]. While the results given in Refs. [1, 2, 3] are based on part of the data, this paper uses the complete statistics of the experiment.

The paper is organized as follows: after describing the main features of the experiment in Section 2, the inclusive production of charmed hadrons is discussed in Section 3. Section 4 deals with the exclusive production of charmed hadrons, and Section 5, in particular, with the reaction $\nu p \rightarrow \mu^- \Sigma_c^{++}$. The results are summarized in Section 6.

2. Experimental details

The data were obtained with the bubble chamber BEBC, filled with liquid hydrogen and exposed to the horn-focussed ν and $\bar{\nu}$ wide band beams at the CERN SPS. BEBC was equipped with an external muon identifier (EMI) [4] to allow the identification of muons with momenta greater than 3 GeV/c. In parts of the experiment, the bubble chamber was surrounded by a cylindrical array of single wire proportional tubes, the Internal Picket Fence (IPF) [5], which recorded position and time information for most of the particles entering or leaving BEBC. A total of 458 400 pictures with incident ν and 307 400 pictures with incident $\bar{\nu}$ have been taken in several runs during the years 1977 to 1983.

The film was double-scanned for events with at least three charged particles, with a scanning efficiency of 95% for 3-prong events and greater than 99% for higher multiplicities. Muons are identified by means of the EMI. About one quarter of all protons are recognized on the basis of range, bubble density, energy loss, or multiple scattering in hydrogen. K^0 mesons and Λ hyperons are detected if they decay within BEBC into $\pi^+\pi^-$ and $p\pi^-$ pairs, respectively. Also, a small fraction of charged pions and kaons can be identified using their decays or bubble density. The average track length used for momentum measurement amounts to 135 cm, yielding on average a relative momentum error of 2.2% and errors in the dip and azimuthal angles of 2.5 mrad.

Nearly all neutrons and π^0 mesons are not detected so that, in general, the energy (E) of the incident (anti-)neutrino cannot be directly inferred from the visible energy. E is, therefore, estimated from the momenta of the muon and the observed hadrons by a method based on transverse momentum balance [6]. For events with an acceptable kinematic fit to the reaction at the production vertex ($\sim 22\%$ and $\sim 15\%$ of all measured charged current (CC) events in νp and $\bar{\nu} p$ scattering respectively), the fitted value of E is used.

The analysis is restricted to CC events which satisfy the following criteria: The event vertex lies within a fiducial volume of 19 m^3 to ensure good measurement conditions. The CC event contains only one muon of the right charge (μ^- for νp and μ^+ for $\bar{\nu} p$). The muon momentum is required to be greater than $3\text{ GeV}/c$ to obtain good muon identification by the EMI. In cases where the muon misses the EMI it may be identified by a successful kinematic fit. The resulting sample consists of 19 029 νp and 11 704 $\bar{\nu} p$ CC events.

3. Inclusive production of charmed hadrons

a) Investigation of mass distributions

In this section, the inclusive production of the charmed hadrons D , D^* , Λ_c and Σ_c is investigated. Their hadronic, Cabibbo-favoured decays lead to final states with definite values for the charge, strangeness, and baryon number. Invariant mass distributions of particle combinations with these properties are studied in order to find indications for the production of charmed particles.

Since one cannot discriminate between the π , K and p interpretations for most of the observed particle tracks in this experiment, all possible interpretations are tried in turn if relevant for the decay modes considered. The D meson, for example, decays preferentially into a kaon and pions. Thus, to study the production of D mesons in neutrino interactions, every negative track in an event is in turn assumed to be a K^- while the other tracks are taken to be pions. If additional information about the identity of a track is available, only mass assignments compatible with this information are considered. No additional K^- mass assignment is tried for events with an identified K^- or K^0 meson. For each mass interpretation of an event, the invariant masses of all relevant combinations (like $K^-\pi^+$, $K^-\pi^+\pi^-$, etc.) are calculated, and are entered into the corresponding histograms.

The procedure of trying various combinations for each one of various mass assignments to the tracks of an event leads, in general, to more than one entry per event in a histogram.

For the histograms shown in this section, the following method of reducing these multiple entries is used: the mass abscissa of the histogram is divided into several intervals (whose width, in general, exceeds the bin width of the histogram) and not more than one entry per interval per event is allowed. Within one interval, we can then speak of “events” instead of “combinations” since different entries correspond to different events. The width of the intervals is chosen such that the observed charm signal is expected to lie within one interval.

In addition to the general cuts defined in Section 2, the following selections are applied to the data sample: the (anti-)neutrino energy is restricted to the range 5 to 200 GeV and, because of their relatively high contribution to the combinatorial background, events with more than 8 charged hadrons are not considered. This latter cut removes about 3% of the νp and about 1% of the $\bar{\nu} p$ events. A sample of 18 225 νp and 11 526 $\bar{\nu} p$ CC events fulfils all these criteria.

The distributions in Figs. 1 and 2 investigate the D^{*+} production in νp scattering. The decay mode considered is $D^{*+} \rightarrow D^0 \pi^+$, with the D^0 decaying into $K^- \pi^+$ or $K^- \pi^+ \pi^+ \pi^-$. This decay chain has the advantage that two charmed particles, D^{*+} and D^0 , are involved. Thus, the distributions of the masses $m_{D^{*+}} \equiv m_{K^- \pi^+ (\pi^+ \pi^-) \pi^+}$ and $m_{D^0} \equiv m_{K^- \pi^+ (\pi^+ \pi^-)}$ (compatible with a D^{*+} and D^0 decay) and of the difference $\Delta m = m_{D^{*+}} - m_{D^0}$ are investigated.^{†)} The mass difference Δm is well determined experimentally [1] and has a value around 145.5 MeV for real D^{*+} and D^0 decays, whereas $m_{D^{*+}}$ and m_{D^0} are independent for background combinations. More generally, two of the three quantities $m_{D^{*+}}$, m_{D^0} and Δm can be treated as independent. This feature is exploited by histogramming one quantity while restricting a second one to the physically expected range.

The fact that there are two independent quantities characterizing the decay chain is also used for the above mentioned method of reducing the multiple entries in a histogram: from the multiple entries in one interval that combination is chosen in which the second, independent quantity is closest to the value expected for charm decay. With this method, the real charm decays should be preferred over background combinations.

The results are shown in Figs. 1 and 2: Fig. 1a shows the distribution of the mass difference Δm for combinations $D^{*+} \rightarrow D^0 \pi^+$, where the D^0 combinations are of the type

^{†)} Analogous mass definitions are used below to indicate particle combinations compatible with D^0 , $\bar{D}^0$, D^{*-} , Λ_c^+ and Σ_c^{++} decays.

$K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-$, and are required to lie in the D^0 mass range (1864.6 ± 15) MeV. The mean measurement errors of $m_{D^{*+}}$, m_{D^0} , and Δm are estimated to be 14 MeV, 12 MeV and 1.1 MeV, respectively [7]. The interval width to reduce multiple entries in the histograms is chosen to be 8 MeV.

Fig. 1: Distribution of the mass difference $\Delta m = m_{D^{*+}} - m_{D^0}$ for particle combinations compatible with $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^-\pi^+(\pi^+\pi^-)\pi^+$ in νp interactions, with the selections (a) m_{D^0} in the interval (1864.6 ± 15) MeV, (b) $1780 \text{ MeV} < m_{D^0} < 1840 \text{ MeV}$ or $1890 \text{ MeV} < m_{D^0} < 1950 \text{ MeV}$. (See text for the definitions of $m_{D^{*+}}$ and m_{D^0} .)

A signal is observed near the expected D^{*+} - D^0 mass difference of 145.5 MeV. For comparison, Fig. 1b shows the D^{*+} - D^0 Δm distribution for D^0 combinations with a mass in the ‘wrong’ region 1780 to 1840 MeV or 1890 to 1950 MeV (below or above the D^0 mass). The signal above background in Fig. 1a amounts to $11.8^{+5.8}_{-4.8}$ events, using the distribution of Fig. 1b to estimate the background shape. The signal is counted in the Δm region 144 to 147 MeV; the remaining regions of the histogram are used to normalize the background distribution. The signal of $D^{*+} \rightarrow D^0 \pi^+$ decays is also seen in the distribution of the D^{*+} mass for combinations with Δm in the range (145.5 ± 1.0) MeV (Fig. 2).

Fig. 2: Distribution of the invariant mass $m_{D^{*+}}$ of particle combinations compatible with $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^-\pi^+(\pi^+\pi^-)\pi^+$ in νp interactions, with the selection $\Delta m = m_{D^{*+}} - m_{D^0}$ in the interval (145.5 ± 1.0) MeV.

Fig. 3 shows the mass distribution of the combinations $\Lambda \pi^+$ and $\Lambda \pi^+\pi^+\pi^-$ which are possible final states from the decay of the Λ_c^+ baryon, in the νp event sample. The Λ ’s are observed with about 60% efficiency through their decay into $p\pi^-$. In the distribution there is an enhancement near the Λ_c^+ mass of 2281 MeV, possibly indicating Λ_c^+ production. The expected measurement error of the Λ_c mass is 9 MeV [7]. If one counts the events in

the range 2265 to 2295 MeV and takes the mean of the remaining bins in the histogram as the background level, one obtains for the Λ_c^+ signal a number of $7.4^{+7.0}_{-5.9}$ events above background.

Fig. 3: Distribution of the invariant mass $m_{\Lambda_c^+}$ of particle combinations compatible with $\Lambda_c^+ \rightarrow \Lambda \pi^+ (\pi^+ \pi^-)$ in νp interactions. For the hatched distribution, a possible Σ_c^{++} or Σ_c^0 combination is required and $\Delta m = m_{\Sigma_c} - m_{\Lambda_c}$ is restricted to (167 ± 5) MeV.

The hatched regions of the histogram show the subsample of Λ_c^+ combinations which possibly come from decays $\Sigma_c^{++} \rightarrow \Lambda_c^+ \pi^+$ or $\Sigma_c^0 \rightarrow \Lambda_c^+ \pi^-$. For this purpose, the mass difference $\Delta m = m_{\Sigma_c} - m_{\Lambda_c}$ is restricted to the range (167 ± 5) MeV. A group of 4 events near the Λ_c^+ mass may indicate Σ_c production.

Without further cuts, no signals of inclusive D meson production are found in the data sample. However, indications for a D signal seem to appear if certain kinematic cuts are applied: Fig. 4 shows the mass distribution of the $K^- \pi^+$ combinations with a value for the Feynman scaling variable $x_F(K^- \pi^+) > 0.2$, and with $z(K^-) > 0.2$, where $z(K^-)$ is the fraction of the laboratory hadronic energy (E_H) carried by the K^- meson. These two cuts are suggested by the assumption that the D^0 comes from the fragmentation of a c -quark emitted in the forward (current) direction and by the hard fragmentation function of the c -quark. The cut on the charged hadron multiplicity is not applied in Fig. 4 since it does not lead to any further improvement of the signal. Otherwise, the data sample is defined as above. The D^0 signal observed in the mass region 1859 to 1871 MeV contains $13.6^{+6.7}_{-5.6}$ events above background, estimating the background level by the mean of the remaining histogram regions.

Fig. 4: Distribution of the invariant mass m_{D^0} of particle combinations compatible with $D^0 \rightarrow K^- \pi^+$ in νp interactions, with $x_F(K^- \pi^+) > 0.2$ and $z(K^-) = E_{K^-}/E_H > 0.2$. E_{K^-} and E_H are the energies of the K^- and the total hadronic system in the laboratory system.

Analogous to D^{*+} production in νp scattering is the production of D^{*-} mesons in $\bar{\nu} p$ scattering. Fig. 5 shows the distribution of the mass difference $\Delta m = m_{D^{*-}} - m_{\bar{D}^0}$ for the combinations with the properties of $D^{*-} \rightarrow \bar{D}^0 \pi^-$ in the $\bar{\nu} p$ data sample. The distribution is completely analogous to Fig. 1a. The $\bar{D}^0$ combinations ($K^+ \pi^-$ or $K^+ \pi^- \pi^+ \pi^-$) are required to lie in the mass range $(1864.6 \pm 15) \text{ MeV}$. A group of combinations with Δm near 145.5 MeV is observed, indicating D^{*-} production. Counting the signal in the region 143 to 148 MeV and using the same background shape as in the D^{*+} case, one obtains a D^{*-} signal of $7.3^{+4.3}_{-3.2}$ events above background.

Fig. 5: Distribution of the mass difference $\Delta m = m_{D^{*-}} - m_{\bar{D}^0}$ for particle combinations compatible with $D^{*-} \rightarrow \bar{D}^0 \pi^- \rightarrow K^+ \pi^- (\pi^+ \pi^-) \pi^-$ in $\bar{\nu} p$ interactions, with the selection $m_{\bar{D}^0}$ in the interval $(1864.6 \pm 15) \text{ MeV}$.

b) Inclusive production rates and cross sections

The distributions of Figs. 1a, 3, 4, and 5 are used to estimate the rates and cross sections for the inclusive production of the charmed hadrons D^{*+} , Λ_c^+ , D^0 , and D^{*-} , respectively. The rates are defined as the ratios of the cross sections for charmed particle production to that for all CC reactions.

Inclusive D^{*+} production:

$11.8^{+5.8}_{-4.8}$ events above background are observed in the D^{*+} region of Fig. 1a. With a 22% correction for the D^0 mass window of $(1864.6 \pm 15) \text{ MeV}$, estimated from the distribution of the mass errors of the D^0 combinations, one calculates a D^{*+} signal of $14.5^{+7.1}_{-5.8}$ events. The branching ratios for the decay modes considered are taken to be [8]:

$$B(D^{*+} \rightarrow D^0 \pi^+) = 0.49 \pm 0.08 \quad (1a)$$

$$B(D^0 \rightarrow K^- \pi^+) = 0.054 \pm 0.004 \quad (1b)$$

$$B(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-) = 0.109 \pm 0.010 \quad (1c)$$

With these ratios, one arrives at a total D^{*+} production of 181^{+95}_{-80} events in the data sample, corresponding to $(0.99^{+0.52}_{-0.44})\%$ of the νp CC events with up to 8 charged hadrons,

or to $(1.31^{+0.69}_{-0.58})\%$ of the νp CC events with up to 8 charged hadrons and a hadronic mass $W > 2.8$ GeV, i. e. above the threshold for charmed meson production.

From studies of dimuon events [9], it is known that the rates of charm production in neutrino and antineutrino interactions depend strongly on the (anti-)neutrino energy E in the energy range of the present experiment. The dimuon rates increase with increasing energy and approach their asymptotic value at about 80 GeV. Taking this behaviour into account, a linear rise of the production rate $R_{D^{*+}}(E)$ for neutrino energies between 5 and 80 GeV and a constant value above 80 GeV is assumed to determine the D^{*+} production cross section at higher energies.

The measured ratio R is the number of events with D^{*+} production ($N_{D^{*+}}$) to the total number of CC events (N_{tot}). This ratio is related to the D^{*+} cross section $\sigma_{D^{*+}}(E) = R_{D^{*+}}(E) \cdot \sigma_{\text{tot}}(E)$, to the total CC cross section $\sigma_{\text{tot}}(E)$, and to the neutrino flux $\phi(E)$ via

$$R = \frac{N_{D^{*+}}}{N_{\text{tot}}} = \frac{\int \sigma_{D^{*+}}(E) \phi(E) dE}{\int \sigma_{\text{tot}}(E) \phi(E) dE}. \quad (2)$$

The flux $\phi(E)$ can be calculated from the energy spectrum of the total CC event sample and the known function $\sigma_{\text{tot}}(E)$. Using $\sigma_{\text{tot}}^{\nu p}(E)/E = (0.474 \pm 0.029) \cdot 10^{-38} \text{ cm}^2/\text{GeV}$ [10] and the measured value of R , one obtains for the asymptotic inclusive D^{*+} production rate

$$R_{D^{*+}}(E \gtrsim 80 \text{ GeV}) = (2.1^{+1.1}_{-0.9}) \cdot 10^{-2}$$

and for the asymptotic inclusive D^{*+} cross section

$$\sigma_{D^{*+}}(E)/E|_{E \gtrsim 80 \text{ GeV}} = (0.99^{+0.52}_{-0.44}) \cdot 10^{-40} \text{ cm}^2/\text{GeV}.$$

These results apply to D^{*+} production in νp CC events with up to 8 charged hadrons. This might be a substantial limitation since about 5% of the CC event sample with $W > 2.8$ GeV have higher charged multiplicities, and since charm production is expected to lead to rather high multiplicity events. Event losses due to the other cuts on the data and due to experimental inefficiencies are assumed to be cancelled approximately in the ratio of eq.(2).

Inclusive Λ_c^+ production:

A possible Λ_c^+ signal of $7.4_{-5.9}^{+7.0}$ events is observed in Fig. 3. With a correction factor of 1.7 [11] to account for the probability of detecting a Λ hyperon by its decay in the bubble chamber, one obtains an inclusive Λ_c^+ production rate, multiplied by the (unknown) branching ratio $B_1(\Lambda_c^+) = B(\Lambda_c^+ \rightarrow \Lambda\pi^+) + B(\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^+\pi^-)$, of $(0.69_{-0.55}^{+0.65}) \cdot 10^{-3}$ in the νp CC event sample. The corresponding rate in the sample of events above $W = 2.4$ GeV, the Λ_c^+ production threshold, is $(0.84_{-0.67}^{+0.79}) \cdot 10^{-3}$. Under the above assumptions for the threshold behaviour of charm production, one can calculate the asymptotic values for the rate and cross section of inclusive Λ_c^+ production, multiplied by the branching ratio $B_1(\Lambda_c^+)$. The numbers are given in Table 1 which summarizes the major results derived in this section.

Inclusive D^0 production:

The D^0 signal in the $K^-\pi^+$ histogram (Fig. 4) is estimated to contain $(13.6_{-5.6}^{+6.7})$ events above background. Using the Lund Monte Carlo program [12], a factor of $2.01 \pm 0.15(\text{stat.})$ is calculated to correct for the effects of the applied kinematic cuts. Together with the branching ratio of eq. (1b), one obtains a total number of 506_{-216}^{+255} events with D^0 production. This corresponds to $(2.6_{-1.1}^{+1.3})\%$ of the νp CC events or to $(3.4_{-1.4}^{+1.7})\%$ of the νp CC events with $W > 2.8$ GeV. The resulting values for the asymptotic rate and cross section of inclusive D^0 production are listed in Table 1.

Inclusive D^{*-} production:

For antineutrinos, a signal of $7.3_{-3.2}^{+4.3}$ events above background is observed in the D^{*-} histogram (Fig. 5). Corrected for the cut on the $\bar{D}^0$ mass this corresponds to $9.0_{-3.9}^{+5.3}$ events. Using the branching ratios of eqs. (1), one obtains a total number of 112_{-53}^{+69} D^{*-} mesons, corresponding to $(0.88_{-0.41}^{+0.54})\%$ of the $\bar{\nu} p$ CC events with up to 8 charged hadrons or to $(1.5_{-0.7}^{+0.9})\%$ of the $\bar{\nu} p$ CC events with up to 8 charged hadrons and $W > 2.8$ GeV. (The applied number of CC events includes a correction for the 1-prong events occurring in $\bar{\nu} p$ scattering [10].) Assuming again the above threshold behaviour of charm production, the asymptotic rate and cross section of inclusive D^{*-} production in $\bar{\nu} p$ CC reactions is obtained as given in Table 1. This cross section is calculated using a total $\bar{\nu} p$ CC cross section of $\sigma_{\text{tot}}^{\bar{\nu} p}(E)/E = (0.500 \pm 0.032) \cdot 10^{-38} \text{ cm}^2/\text{GeV}$ [10].

TABLE 1: Inclusive production rates and cross sections for the charmed particles D^{*+} , Λ_c^+ , D^0 , and D^{*-} in νp and $\bar{\nu} p$ interactions, respectively. Except for the D^0 , all results refer to charm production in events with up to 8 charged hadrons. The values for the Λ_c^+ baryon refer only to the fraction decaying into $\Lambda\pi^+$ or $\Lambda\pi^+\pi^+\pi^-$. A W threshold of 2.8 GeV, or 2.4 GeV for Λ_c^+ , respectively, is used.

reaction	charmed particle	observed events above background	production rate (above W threshold)	asymptotic production rate	asymptotic cross section divided by E
νp	D^{*+}	$11.8^{+5.8}_{-4.8}$	$1.31^{+0.69}_{-0.58}$	$2.1^{+1.1}_{-0.9}$	99^{+52}_{-44}
νp	$\Lambda_c^+ \rightarrow \Lambda\pi^+(\pi^+\pi^-)$	$7.4^{+7.0}_{-5.9}$	$0.084^{+0.079}_{-0.067}$	$0.15^{+0.14}_{-0.12}$	$6.9^{+6.5}_{-5.5}$
νp	D^0	$13.6^{+6.7}_{-5.6}$	$3.4^{+1.7}_{-1.4}$ *)	$5.3^{+2.7}_{-2.3}$ *)	250^{+130}_{-110} *)
$\bar{\nu} p$	D^{*-}	$7.3^{+4.3}_{-3.2}$	$1.5^{+0.9}_{-0.7}$	$2.1^{+1.3}_{-1.0}$	107^{+67}_{-51}

*) Corrected values using the Lund model.

4. Events with exclusive production of charmed hadrons

A unique signature for charm production in (anti-)neutrino nucleon reactions is the relation $\Delta S = -\Delta Q$, where ΔS is the change of strangeness and ΔQ the change of charge of the hadronic system. This relation is only expected in the case that from a non-strange quark a single charmed particle is produced, which then decays via its Cabibbo-favoured mode. In contrast, in all other (anti-)neutrino reactions ΔS is either zero or equal to ΔQ ($= \pm 1$). In particular, those events in which charmed particles are produced from strange (anti-)quarks in the nucleon have $\Delta S = 0$ if the decay is Cabibbo-favoured, or $\Delta S = \Delta Q$ otherwise. Using standard sets of proton structure functions and the value of the Cabibbo angle, one estimates that in νp ($\bar{\nu} p$) scattering $\sim 40\%$ ($\sim 15\%$) of all charmed hadrons are produced from non-strange quarks [7, 11, 13].

The relation $\Delta S = -\Delta Q$ can be established for single events if the nature of all secondary particles is uniquely determined. In the present experiment, this is possible for a few events, using the particle identification provided by the EMI, by the bubble chamber (bubble density, range in hydrogen, multiple scattering, $\pi^\pm$ -, $K^\pm$ -, K^0 - and Λ -decays, secondary interactions), and by kinematic fits for the reaction at the production vertex.

The events which *unambiguously* obey $\Delta S = -\Delta Q$ are listed in Tables 2 to 4. The events in Tables 2 and 3 have been discussed in detail in Refs. [1, 2, 3]; the two events in Table 4 are new events which will be described in the following.

The new candidates were measured several times independently in order to rule out wrong conclusions based on bad measurements. In the tables, the average fitted momenta of the secondary particles are listed, and in brackets it is indicated whether a particle is identified by the EMI, by a secondary interaction (SEC), by ionization (ION), or by a decay (DEC). The tables also contain relevant kinematic quantities determined from the fits. For each event in Table 4, all measurements yield only one kinematic fit which is consistent with these (direct) particle identifications. The kinematic fit gives a further confirmation for the mass assignments.

In order to prove the $\Delta S = -\Delta Q$ interpretation one has to check whether other mass hypotheses are kinematically possible that violate the $\Delta S = -\Delta Q$ relation but are still consistent with the direct particle identifications.

For event 1210-5572 there is no kinematic (0-constraint) solution for an additional K^0 in the final state. Taking the measurement errors into account, there could be an additional K^0 whose momentum would have to be greater than 40 GeV/c at 90% confidence

TABLE 2: Particle momenta, charm masses, and leptonic quantities for completely identified events with D^{*+} production. [1]

	event 294-995 [1]	event 297-1633 [1]
interpretation	$\nu p \rightarrow \mu^- D^{*+} p$ $\hookrightarrow D^0 \pi_1^+$ $\hookrightarrow K^- \pi_2^+$	$\nu p \rightarrow \mu^- D^{*+} \pi_4^+ \pi_2^- p$ $\hookrightarrow D^0 \pi_3^+$ $\hookrightarrow K^- \pi_1^+ \pi_2^+ \pi_1^-$
tracks and their fitted momenta [GeV/c]	π_1^+ : 3.590 p : 1.736 π_2^+ (ION, DEC) : 0.229 μ^- (EMI) : 42.360 K^- (ION, SEC) : 0.318	p (ION) : 0.991 π_1^+ : 0.925 π_2^+ (ION, SEC) : 0.437 π_3^+ (ION, SEC) : 0.357 π_4^+ (ION, SEC) : 0.299 μ^- (EMI) : 13.772 π_1^- : 2.408 K^- (SEC) : 1.409 π_2^- : 1.102
fit probability $P(\chi^2)$	30%	70%
$M_{D^{*+}}$ [GeV]	2.011 ± 0.006	2.013 ± 0.004
M_{D^0} [GeV]	1.865 ± 0.004	1.868 ± 0.004
$\Delta m = M_{D^{*+}} - M_{D^0}$ [GeV]	0.1452 ± 0.0005	0.1452 ± 0.0006
W [GeV]	3.156	3.811
E [GeV]	47.8	21.3
$\nu = E - E_\mu$ [GeV]	5.49	7.56
Q^2 [(GeV) 2]	1.21	0.53
$x = Q^2/2m_p\nu$	0.12	0.04
$y = \nu/E$	0.11	0.35

TABLE 3: Particle momenta, charm masses, and leptonic quantities for completely identified events with Λ_c^+ or Σ_c^{++} production. [2, 3]

	event 311-5074 [2]	event 327-3880 [2]	event 832-4611 [3]
interpretation	$\nu p \rightarrow \mu^- \Lambda_c^+ \pi_1^+ \rightarrow p K^- \pi_2^+$	$\nu p \rightarrow \mu^- \Lambda_c^+ \pi_1^+ \rightarrow p K^- \pi_2^+$	$\nu p \rightarrow \mu^- \Sigma_c^{++} \rightarrow \Lambda_c^+ \pi_2^+ \rightarrow p K^- \pi_1^+$
tracks and their fitted momenta [GeV/c]	μ^- (EMI) : 48.654 p (SEC) : 1.973 K^- : 2.574 π_1^+ : 1.255 π_2^+ (DEC) : 0.225	μ^- (EMI) : 10.384 p (ION) : 0.935 K^- : 2.514 π_1^+ : 1.081 π_2^+ : 1.483	μ^- (EMI) : 18.363 p : 2.965 K^- : 1.137 π_1^+ : 0.377 π_2^+ (ION) : 0.214
fit probability $P(\chi^2)$	62%	40%	26%
$M_{\Lambda_c^+}$ [GeV]	2.285 ± 0.005	2.280 ± 0.003	2.288 ± 0.005
W [GeV]	2.808 ± 0.005	2.796 ± 0.005	2.454 ± 0.005
$W - M_{\Lambda_c^+}$ [GeV]	0.523 ± 0.003	0.516 ± 0.003	0.166 ± 0.001
E [GeV]	54.1	15.9	22.4
$\nu = E - E_\mu$ [GeV]	5.41	5.56	4.07
Q^2 [(GeV) 2]	3.13	3.49	2.50
$x = Q^2/2m_p\nu$	0.31	0.33	0.33
$y = \nu/E$	0.10	0.35	0.18

TABLE 4: Particle momenta, charm masses, and leptonic quantities for completely identified events with Λ_c^+ or Σ_c^{++} production.

	event 918-3696	event 1210-5572
interpretation	$\nu p \rightarrow \mu^- \Lambda_c^+ \pi_2^+$ $\hookrightarrow p K^- \pi_1^+$	$\nu p \rightarrow \mu^- \Sigma_c^{++}$ $\hookrightarrow \Lambda_c^+ \pi_2^+$ $\hookrightarrow p K^- \pi_1^+$
tracks and their fitted momenta [GeV/c]	μ^- (EMI) : 4.824 p : 1.590 K^- (DEC) : 1.069 π_1^+ : 1.435 π_2^+ : 1.366	μ^- (EMI) : 12.030 p (INT) : 1.736 K^- (ION) : 0.605 π_1^+ : 0.739 π_2^+ (DEC) : 0.106
fit probability $P(\chi^2)$	62%	18%
$M_{\Lambda_c^+}$ [GeV]	2.285 ± 0.003	2.277 ± 0.003
W [GeV]	2.790 ± 0.004	2.445 ± 0.003
$W - M_{\Lambda_c^+}$ [GeV]	0.505 ± 0.002	0.168 ± 0.001
E [GeV]	9.73	14.8
$\nu = E - E_\mu$ [GeV]	4.90	2.75
Q^2 [(GeV) 2]	2.29	0.0546
$x = Q^2/2m_p\nu$	0.25	0.011
$y = \nu/E$	0.50	0.19

level. There is no solution within 50 standard deviations for an additional π^0 if the K mass is assigned to the π_1^+ track, the only track not directly identified. The fact that no IPF activity is observed, apart from that uniquely attributed to a charged secondary particle, also indicates that no additional neutral particle is produced.

As to event 918-3696, the μ^- and K^- tracks are uniquely identified. The identity of the proton cannot be uniquely proven; however, the particle undergoes a secondary interaction, for which a good (4-constraint) kinematic fit for an elastic pp scattering is obtained. Again no IPF activity is seen which could suggest the production of a neutron or other neutral particles in the event. Otherwise, similar statements can be made as for the previous event: there is no kinematic (0-constraint) solution for an additional K^0 in the final state. The minimum momentum of an additional K^0 is 25 GeV at 90% confidence level, and there is no solution within 20 standard deviations if one of the π^+ tracks is reinterpreted as a K^+ .

5. Quasielastic production of charmed baryons

The quasielastic production of charmed baryons is a particularly interesting class of neutrino nucleon reactions. In several theoretical studies, properties and cross sections of these reactions have been predicted [14, 15]. However, there is still a lack of experimental results.

In this experiment, one expects the quasielastic reactions

$$\nu p \rightarrow \mu^- \Sigma_c^{++} \quad (3)$$

$$\nu p \rightarrow \mu^- \Sigma_c^{*++} \quad (4)$$

where Σ_c^* is an excited state of the Σ_c baryon. In the quark picture, these reactions are analogous to the reaction

$$\nu p \rightarrow \mu^- \Delta^{++}. \quad (5)$$

While in reaction (5) the Δ^{++} is obtained by turning the d -quark of the initial proton into a u -quark, the Σ_c in reactions (3) and (4) is produced by the corresponding Cabibbo-suppressed transition $d \rightarrow c$. Regarding the baryon spin, there is complete analogy with the Δ^{++} if the Σ_c^{*++} has spin 3/2. The spin of the Σ_c^{++} is 1/2.

A search has been made for reactions (3) and (4) in which the Σ_c baryon decays exclusively into observable particles, and the decay happens via a Λ_c^+ baryon. Only

Cabibbo-favoured decays of the Λ_c^+ are considered, so that the $\Delta S = -\Delta Q$ selection rule is applicable. The candidates have to satisfy the following criteria:

- An acceptable 3-constraint kinematic fit (with a probability $P(\chi^2) > 0.1\%$) exists for a $\Delta S = -\Delta Q$ reaction, possibly besides other fits.
- Given the mass assignments of the kinematic fit, a particle combination within the event has the quantum numbers of the Λ_c^+ decay and a mass compatible with the Λ_c^+ mass of 2281 MeV within 2 standard deviations.

These events are shown in Fig. 6. In the mass range of the Σ_c baryon (~ 2450 MeV) there are two events. Both are described in Section 4. For both events, the charm production is proven via the $\Delta S = -\Delta Q$ signature. The two values of the hadronic mass W are (2454 ± 5) MeV and (2445 ± 3) MeV, respectively, compatible with each other and in agreement with other measurements of the Σ_c mass [8]. The two events can, therefore, be regarded as two examples of reaction (3). The Σ_c^{++} mass determined from both events is (2449 ± 3) MeV. In both events the decay chain $\Sigma_c^{++} \rightarrow \Lambda_c^+ \pi^+$, $\Lambda_c^+ \rightarrow p K^- \pi^+$ is observed.

Fig. 6: Distribution of the total hadronic mass W for νp events with a kinematic fit to a $\Delta S = -\Delta Q$ reaction and containing a particle combination, the mass of which is compatible with the Λ_c^+ mass of 2281 MeV within 2 standard deviations. The Λ_c^+ particle combinations include a K^- , K^0 or Λ particle. The error bars in the upper histogram represent the measurement error of W .

From Fig. 6 it is seen that there are no other candidates for reaction (3) among the sample of CC events with a kinematic fit. The reaction is expected to have an energy dependence similar to that of reaction (5), which has been studied in this experiment in Refs. [16,17]. Comparing the event numbers for reactions (3) (2 events) and (5) (1186 events) for $E > 10$ GeV, the following upper and lower limits, at 90% confidence level, are derived for the ratio of the cross sections:

$$0.45 \cdot 10^{-3} < \frac{\sigma(\nu p \rightarrow \mu^- \Sigma_c^{++})}{\sigma(\nu p \rightarrow \mu^- \Delta^{++})} \cdot B_2(\Lambda_c^+) < 4.5 \cdot 10^{-3} \quad (90\% \text{ CL});$$

$B_2(\Lambda_c^+) = B(\Lambda_c^+ \rightarrow p K^- \pi^+)$ is the branching ratio of the observed Λ_c^+ decay channel, $B(\Sigma_c^{++} \rightarrow \Lambda_c^+ \pi^+)$ is assumed to be 1.

Limits for the cross section of quasielastic Σ_c^{++} production, again multiplied by the branching ratio $B_2(\Lambda_c^+)$, are obtained by comparing the 2 events for reaction (3) to the number of events for the reaction $\nu p \rightarrow \mu^- p \pi^+$ with $W < 2$ GeV. In the energy region $10 \text{ GeV} < E < 80 \text{ GeV}$, a cross section of $(68 \pm 7) \cdot 10^{-40} \text{ cm}^2$ has been measured for the latter channel [17], yielding

$$2.8 \cdot 10^{-42} \text{ cm}^2 < \sigma(\nu p \rightarrow \mu^- \Sigma_c^{++}) \cdot B_2(\Lambda_c^+) < 36 \cdot 10^{-42} \text{ cm}^2 \quad (90\% \text{ CL}).$$

Using the value $B_2(\Lambda_c^+) = (2.2 \pm 1.0)\%$ [8], one obtains the results

$$1.3 \cdot 10^{-2} < \frac{\sigma(\nu p \rightarrow \mu^- \Sigma_c^{++})}{\sigma(\nu p \rightarrow \mu^- \Delta^{++})} < 49 \cdot 10^{-2} \quad (90\% \text{ CL}),$$

$$0.80 \cdot 10^{-40} \text{ cm}^2 < \sigma(\nu p \rightarrow \mu^- \Sigma_c^{++}) < 39 \cdot 10^{-40} \text{ cm}^2 \quad (90\% \text{ CL}).$$

Theoretical predictions [14] for the cross section $\sigma(\nu p \rightarrow \mu^- \Sigma_c^{++})$ cover the range from 0.1 to $10 \cdot 10^{-40} \text{ cm}^2$.

The next event in the histogram of Fig. 6 occurs at $W = (2598 \pm 15) \text{ MeV}$. This event is a possible candidate for reaction (4) since it falls in the region where the mass of an excited state Σ_c^* can be expected [15]. However, several kinematic fits for different mass assignments are possible for this event, and the $\Delta S = -\Delta Q$ signature cannot be unambiguously proven. Another interesting feature of Fig. 6 is the accumulation of well identified events near 2.8 GeV (see events 311-5074, 327-3880, 918-3696 in Tables 3 and 4), which might be an indication of a charmed baryon state in this mass region.

6. Summary

Using data from a wideband beam experiment with BEBC at CERN, the production of charmed particles in νp and $\bar{\nu} p$ charged current interactions is investigated. The main results can be summarized as follows.

In νp scattering, the inclusive production rates for D^{*+} and D^0 mesons above $W = 2.8$ GeV are measured to be $(1.31_{-0.58}^{+0.69}) \cdot 10^{-2}$ and $(3.4_{-1.4}^{+1.7}) \cdot 10^{-2}$, respectively. This implies that $(19 \pm 13)\%$ of all D^0 mesons come from the decay of a D^{*+} . The production rate for Λ_c^+ baryons above $W = 2.4$ GeV, multiplied by the branching ratio for the decay modes $\Lambda_c^+ \rightarrow \Lambda \pi^+(\pi^+\pi^-)$, is $(0.84_{-0.67}^{+0.79}) \cdot 10^{-3}$. The D^{*-} production rate in $\bar{\nu} p$ scattering above $W = 2.8$ GeV is $(1.5_{-0.7}^{+0.9}) \cdot 10^{-2}$, of the same order as the D^{*+} production rate in νp scattering. Except for the D^0 rate, all these results refer to CC events with up to 8 charged hadrons.

Several examples of events are presented in which the production of charmed particles (D^{*+} , Λ_c^+ and Σ_c^{++}) is uniquely proven by the $\Delta S = -\Delta Q$ signature.

For the channel $\nu p \rightarrow \mu^- \Sigma_c^{++}$, two events are found, corresponding to a cross section of $2.8 \cdot 10^{-42} \text{ cm}^2 < \sigma(\nu p \rightarrow \mu^- \Sigma_c^{++}) \cdot B_2(\Lambda_c^+) < 36 \cdot 10^{-42} \text{ cm}^2$ at 90% confidence level, where $B_2(\Lambda_c^+) = B(\Lambda_c^+ \rightarrow p K^- \pi^+)$. The Σ_c^{++} mass determined from both events is $(2449 \pm 3) \text{ MeV}$.

In a search for an excited state of the Σ_c baryon, produced in the reaction $\nu p \rightarrow \mu^- \Sigma_c^{*++}$, no conclusive results are obtained. An accumulation of candidates at $W \sim 2.8 \text{ GeV}$ might be an indication for an excited Σ_c state.

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