# Observation of the production of charmed $\Sigma_c^{*++}$ baryons in neutrino interactions at the SKAT bubble chamber

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Quasielastic production of charmed baryons at protons has been studied with the SKAT bubble chamber, exposed to a neutrino beam at the Serpukhov U-70 accelerator. The results are reported. The first observation of a $\Sigma_c^{*++}$ baryon, with a mass $M(\Sigma_c^{*++})=2.530\pm0.005\pm0.005$ GeV, is reported. Estimates are found for some reaction cross sections: $\sigma(\nu p\rightarrow\mu^-\Sigma_c^{++})=(2.3\pm2.0)\times10^{-40}$ cm$^2$ and $\sigma(\nu p\rightarrow\mu^-\Sigma_c^{*++})=(4.5\pm4.0)\times10^{-40}$ cm$^2$.

**1. Introduction.** The first experimental data on the production of charmed baryons were obtained more than 15 years ago in a neutrino experiment at the Gargamelle bubble chamber.[1] However, the experimental information which has been acquired on charmed baryons since then is considerably scantier than that on charmed mesons.

In this letter we are reporting a study of quasielastic production of charmed baryons at protons in the reactions

$$\nu p\rightarrow\mu^-\Sigma_c^{++},\quad \Sigma_c^{++}\rightarrow\Lambda_c^+\pi^+, \tag{1}$$

$$\nu p\rightarrow\mu^-\Sigma_c^{++*},\quad \Sigma_c^{++*}\rightarrow\Lambda_c^+\pi^+. \tag{2}$$

Other possible reactions are the quasielastic production of charmed baryons at a neutron:

$$\nu n\rightarrow\mu^-\Lambda_c^+, \tag{3}$$

$$\nu n\rightarrow\mu^-\Sigma_c^+,\quad \Sigma_c^+\rightarrow\Lambda_c^+\pi^0, \tag{4}$$

$$\nu n\rightarrow\mu^-\Sigma_c^{*+},\quad \Sigma_c^{*+}\rightarrow\Lambda_c^+\pi^0. \tag{5}$$

Reactions (1) and (2) are considerably more convenient to study than reaction (3), since the difference between the $\Sigma_c^{(*)++}$ and $\Lambda_c^+$ masses can be determined much more accurately than the masses themselves. Analysis of reactions (4) and (5) is complicated by the presence of the $\pi^0$ meson, which cannot be detected very efficiently.

A search for charmed baryons in quasielastic reactions makes it possible to substantially reduce the combinatorial background and to make effective use of a kinematic analysis of events. The neutrino beam of the Institute of High Energy Physics is ideal for searching for the quasielastic production of charmed baryons, since the

TABLE I. Theoretical predictions of the $\Sigma_c^{*++}$ mass.

| Model | $\Lambda_c^+$ | $\Sigma_c^{++}$ | $\Sigma_c^{*++}$ |
|---|---|---|---|
| J. Basdevant *et al.*[9] | 2.251 | 2.372 | 2.496 |
| S. Samuel *et al.*[10] | 2.282 | 2.431 | 2.594 |
| C. Kalman *et al.*[11] | inp | 2.424 | 2.499 |
| Chiaki Iton *et al.*[12] | 2.282 | 2.455 | 2.532 |
| Kalinovsky *et al.*[13] | 2.282 | 2.449 | 2.555 |
| S. Fleck *et al.*[14] | inp | 2.443 | 2.542 |

maximum in the ratio of the cross section for such reactions to the total neutrino interaction cross section corresponds to the maximum intensity of the neutrino beam.

**2. Model-based predictions.** The experimental situation regarding the production of the $\Sigma_c^{++}$ and $\Sigma_c{}^{*++}$ baryons is completely different. While the $\Sigma_c^{++}$ baryon has been observed in several experiments on $\nu N$ scattering,[1-5] in $e^+e^-$ collisions,[6,7] and in $nA$ collisions,[8] no data are available at this point on $\Sigma_c{}^{*++}$. There are several model-based predictions of the $\Sigma_c{}^{*++}$ mass, shown in Table I. We see that all the predictions of the mass $M(\Sigma_c{}^{*++})$ fall in the interval 2.5–2.6 GeV. The most recent studies predict values of $M(\Sigma_c{}^{*++})$ in the interval 2.530–2.550 GeV. Very important to an experimental search for the $\Sigma_c{}^{*++}$ baryon is the question of its width. Figure 1 shows the width of $\Sigma_c{}^{*++}$ versus the mass $M(\Sigma_c{}^{*++})$ calculated from the formula derived in Ref. 15. We see that for the $\Sigma_c{}^{*++}$ mass interval of interest this width is about 10 MeV; this figure is comparable to our experimental resolution.

**3. Experimental procedure.** The experiment was carried out at the SKAT bubble chamber in a wide-band neutrino beam at a proton energy of 70 GeV. To a large extent, the statistical data were obtained through the use of a propane-freon mixture (13% freon by volume) as the working liquid; a third of the statistical base was obtained with an ethane-propane-freon mixture. The properties of these two working liquids are very nearly the same ($\lambda_{\text{rad}}=52$ cm, with an interaction mean free path

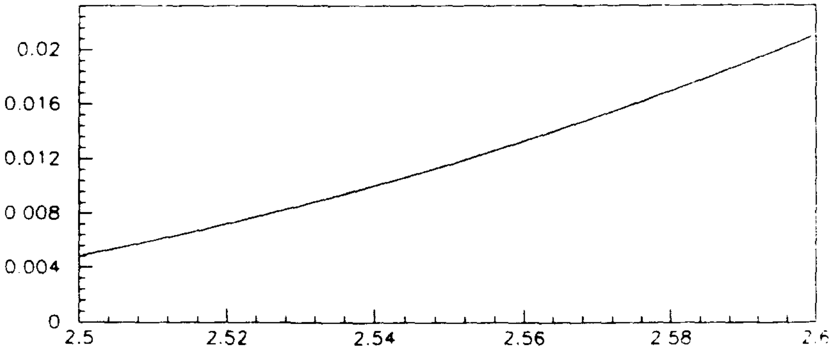

FIG. 1. Width versus the $\Sigma_c^{*++}$ mass (GeV).

$\simeq 120$ cm for hadrons). These properties lead to a good reconstruction of the momenta of the particles ($\Delta p/p = 0.02$, 0.08, and 0.20 for muons, hadrons, and $\gamma$ rays, respectively) and a good efficiency in the detection of the $\gamma$ rays ($\epsilon_\gamma = 0.5$). Our analysis is based on the statistical base built up over runs in 1987–1992, with a total of $4 \times 10^{18}$ protons incident on the target.

To suppress background processes, we selected events which satisfy the following criteria:

- The apparent neutrino energy is above 3 GeV.
- The muon momentum is above 0.5 GeV/c.
- The invariant mass of the hadron system is above 1 GeV/c$^2$.

In the experiment we detected 12 800 $\nu_\mu N$ interaction events in the charged current which satisfied these criteria. Of them, 8% were due to interactions of neutrinos with hydrogen, and 30% were due to interactions of neutrinos with protons inside nuclei. To distinguish reactions of the quasielastic production of $\Sigma_c^{*++}$ baryons, we selected events with a total charge of $+1$. The multiplicity of charged particles had to be at least 3 if a $V^0$ was detected in the event, and at least 5 otherwise. An event could not contain more than one identified baryon, i.e., proton or $\Lambda$ hyperon. The number of $\gamma$ rays in an event had to be even. Protons and $\pi^+$ mesons were identified in the stage of the physical scan on the basis of ionization and secondary interactions of these particles; the $\Lambda$ hyperons and $K_s^0$ mesons were identified from the results of a kinematic analysis.

To distinguish events which did not have undetected neutrons or $\gamma$ rays, and also to suppress the combinatorial background, the events were subjected to a kinematic fit. It was assumed that the direction in which the neutrons were moving was known. We also took account of the scatter in neutrino angles, which we found through a simulation of the neutrino beam for our experimental conditions. To distinguish events involving hydrogen we used a 3C fit of the event. Since a significant fraction of the events stemmed from interactions of neutrinos with protons within nuclei, a special procedure was developed for this case. It was assumed that the proton momentum had a normal distribution with a mean value of 180 MeV/c and a standard deviation $\sigma = 46$ MeV/c. These parameter values were selected in accordance with a Fermi distribution for the momenta of the nucleon inside the nucleus. A hypothesis was accepted if its probability was more than 0.5% and if the momentum of the target proton found by the fitting procedure was less than 230 MeV. In the case of 3C and 1C fits, preference was given to the 3C hypothesis.

In the fit of $\pi^+/p$ events, uncertain tracks were examined on the basis of two mass hypotheses: $\pi^+$ and $p$. In events which did not contain a $V^0$ particle, negatively charged particles which were not muons were also examined on the basis of two mass hypotheses: $\pi$ and $K$. In each event, among hypotheses having one strange particle and one baryon in the final state, we selected the hypothesis which had the highest probability. The use of fitted events made it possible to reduce the background from events containing undetected neutral particles by a factor of 4.

For the selected hypotheses we determined the invariant mass of the entire had-

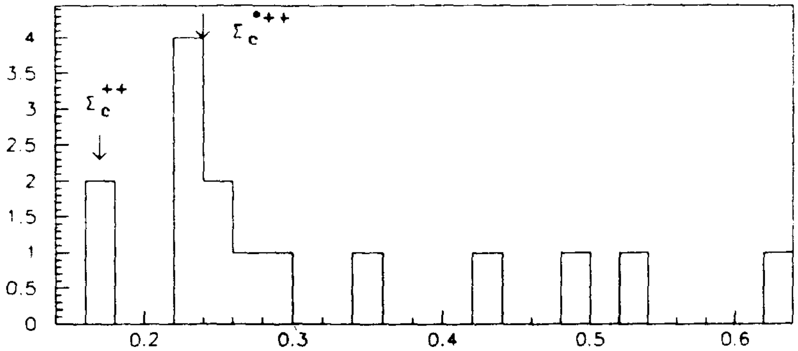

FIG. 2. Distribution with respect to mass difference (GeV).

ron system, $M^{++}$; the invariant mass of the hadron system without one $\pi$ meson, $M^{+}$; and the difference $\Delta M = M^{++} - M^{+}$. The errors in these quantities should not have exceeded 100 MeV. The mean values of the errors in these parameter values in our experiment were $\langle\sigma(M^{++})\rangle \simeq \langle\sigma(M^{+})\rangle = 60$ MeV and $\langle\sigma(\Delta M)\rangle = 15$ MeV.

We then selected events in which the $M^{+}$ deviated from the tabulated value of the $\Lambda_c^{+}(2285)$ mass by less than two standard deviations in $M^{+}$. After all these cuts we were left with 14 events.

To check the fitting procedure and the selection criteria we simulated the quasielastic production of charmed $\Sigma_c^{*++}$ baryons and also ordinary neutrino interactions. In this simulation we took account of the dimensions of the chamber and the experimental resolution. The simulated events were subjected to the kinematic-fit procedure. Analysis of the results of the fit showed that in 90% of the cases the topology of the event selected in accordance with the criteria listed above was the actual topology of the event.

**4. Experimental results.** Figure 2 shows the distribution with respect to mass difference for the events described above. We interpret the two events with $\Delta M = 174 \pm 2$ MeV and $160 \pm 5$ MeV as quasielastic production of $\Sigma_c^{++}$, for which the tabulated value of the mass difference is 168 MeV. The background for these events is ~0.1–0.2 event. The probability for a simulation by the background for these events is 0.1%. We then have a cluster of six events in the interval $\Delta M = 220$–$260$ MeV, which corresponds to mass values $M^{++} = 2.520$–$2.560$ GeV. To evaluate the background in this mass region we carried out a similar analysis with two shifted values of the $\Lambda_c^{+}$ mass: $M(\text{“}\Lambda_c^{+}\text{”}) = 2.085$ and 2.485 GeV. From this analysis we found the estimate that the background in the region $M^{++} = 2.520$–$2.560$ GeV was one event.

We are thus seeing an excess of events in the mass interval 2.520–2.560 GeV, which we interpret as the first observation of the production of the $\Sigma_c^{*++}$ baryon. The probability for a simulation by the background is 0.01% in this case. Two of these events contain a neutral strange particle in the final state (one event with a $\Lambda$ hyperon and one with a $K_s$ meson). The background for events with a neutral strange particle in the final state is ~0.1 event. The probability for a simulation by the background for these events is again 0.01%. The mass of the $\Sigma_c^{*++}$ baryon estimated from these events is $M(\Sigma_c^{*++}) = 2.530 \pm 0.005 \pm 0.005$ GeV. The distributions of events involving the production of $\Sigma_c^{++}$ and $\Sigma_c^{*++}$ with respect to the kinematic variables $Q^2$, $X$, and $Y$ agree satisfactorily with the distributions expected.

We also evaluated the cross sections for the production of the $\Sigma_c^{++}$ and $\Sigma_c^{*++}$ baryons. The primary causes of a loss of events from the analysis are the conversion of $\gamma$ rays outside the effective volume of the chamber and the presence of poorly measured tracks ($\Delta p/p \geqslant 0.6$) in the event. For events with neutral strange particles, some additional losses resulted from the decay of these particles outside the effective chamber volume and from decays by neutral modes. The efficiency of the passage of events through the analysis system was determined from an analysis of simulated events for reactions (1) and (2). The decays of the $\Lambda_c^+$ baryon were simulated by the JETSET 6.3 program. The overall efficiency for events containing a $K^-$ meson was estimated to be 0.5, and that for events containing a neutral strange particle was estimated to be 0.2. Using these efficiencies, we find estimates of the cross sections for reactions (1) and (2):

$$\sigma(\nu p \to \mu^- \Sigma_c^{++}) = (2.3 \pm 2.0) \times 10^{-40}\ \text{cm}^2,$$

$$\sigma(\nu p \to \mu^- \Sigma_c^{*++}) = (4.5 \pm 4.0) \times 10^{-40}\ \text{cm}^2.$$

These results agree with an estimate of the cross section for the quasielastic production of $\Sigma_c^{++}$ found at the BEPK bubble chamber:

$$10^{-40}\ \text{cm}^2 < \sigma(\nu p \to \mu^- \Sigma_c^{++}) < 1.3 \times 10^{-39}\ \text{cm}^2.$$

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