A Dependence of Charm Production

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The prompt neutrino ($\nu_e + \bar{\nu}_e$) flux produced by the interaction of 400-GeV protons with targets of beryllium, copper, and tungsten has been measured in a beam-dump experiment at Fermilab. With the assumption that these neutrinos arise from charm decay, the cross section for charm production by protons on nuclei varies as A^α, where $\alpha = 0.75 \pm 0.05$. No significant variation of α with neutrino energy is observed.

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The quantitative successes of quantum chromodynamics (QCD) have been achieved in a kinematic region in which multiple interactions between the constituent quarks are greatly reduced and perturbative techniques can be employed. For example, the Drell-Yan production mechanism for lepton-pair and hadron production at large transverse momentum can be understood by use of perturbative QCD. Characteristically, in the impulse approximation, the cross section depends on the number of quarks; thus for nuclear targets $\sigma \propto A$, the atomic weight of the target. Practically, the picture is complicated by effects due to the nuclear environment such as Fermi motion, rescattering, coherent scattering, and the final-state interactions which occur as the quarks hadronize. These effects reduce the transparency of the nucleus and the result of this "shadowing" is that the cross section approaches its geometrical value, $\sigma \propto A^{2/3}$.

The production of heavy quarks, although similar in some respects to the processes noted above, can be described with use of both nonperturbative and perturbative processes, which are distinguished by the A dependence of the partial cross section. In general, nonperturbative or diffractive models favor an $A^{2/3}$ dependence while perturbative QCD models require A^1. Nuclear effects, of course, may alter this dependence. Halzen[1] has pointed out the issues concerning A-dependent effects in interpreting heavy-quark production. Skubic *et al.*[2] have measured the A^α dependence of the production of the strange quark (Λ, K^0) and found $\alpha < 0.7$ for Feynman $x > 0.2$.

We have measured the A dependence of the production of the charm quark in a beam-dump experiment[3] at Fermilab, using a 400-GeV proton beam which was directed into thick targets of tungsten, copper, and beryllium. The resultant hadronic cascade is absorbed in the target, and the muons produced are either absorbed or deflected in magnetized iron. The neutrinos escape and were detected 56 m downstream in a lead-scintillator calorimeter.

The primary source of these neutrinos is the semileptonic decay of charm quarks. Because of their short lifetime most charm particles decay before interacting, producing prompt neutrinos whose rate is independent of the target density. Of course, some pions and kaons also decay into neutrinos, producing a flux of nonprompt neutrinos, but their rate does depend on target density. In beam-dump experiments[4-8] the variation of the observed rate with target density is one method which can be used to separate the prompt neutrinos from the nonprompt background.

Behind the calorimeter is a muon spectrometer of iron toroids and drift chambers. Neutrino interactions in the calorimeter are categorized in the analysis as 1μ (muon identified in the spectrometer) or 0μ (no muon identified). Events occurring during beam spills[9] associated with beam halo were eliminated ($\sim 5\%$ of total incident protons) and the events arising from cosmic

TABLE I. A summary of the data from the different targets, both full density and partial density, showing the integrated number of protons, the number of observed events, and the corrected rates per 10^{16} protons.

Target	Protons	ν_μ CC events	$\bar{\nu}_\mu$ CC events	0μ events	ν_μ CC per 10^{16}	$\bar{\nu}_\mu$ CC per 10^{16}	0μ per 10^{16}
W	13.7×10^{16}	769	277	1026	90.5 ± 3.3	30.8 ± 1.9	89.0 ± 2.9
W/3	3.9×10^{16}	398	130	366	162.4 ± 7.7	47.9 ± 4.0	128.8 ± 6.7
Cu	2.7×10^{16}	201	65	193[a]	123.2 ± 8.7	32.3 ± 4.1	103.9 ± 7.6
Cu/2.4	0.8×10^{16}	126	29	122	227.3 ± 19.1	47.1 ± 8.4	
Be	7.7×10^{16}	777	191	958	229.5 ± 10.0	63.4 ± 5.5	155.3 ± 4.8

[a]The 0μ Cu events come from 2.1×10^{16} protons.

rays were subtracted by use of a beam-off gate to record the background ($\sim 2\%$ effect for 0μ events). The 0μ events are required to occur in a smaller fiducial volume ($\sim 76\%$) than the 1μ events to reduce the systematic uncertainty in their energy. The data are summarized in Table I, showing for each target the number of identified events and the corrected rate per 10^{16} protons of neutrinos with energy $\geqslant 20$ GeV and laboratory production angle $\theta \leqslant 30$ mrad. The rates are corrected for muon acceptance, analysis efficiency, and trigger threshold effects. Details of the analysis procedures and results obtained with use of the tungsten target have been published.[10]

In order to measure the A dependence we must use, in addition, a target of copper (beryllium) whose length is $6.1\lambda_{abs}$ ($2.6\lambda_{abs}$). We measure the $\nu_e+\bar{\nu}_e$ charged-current (CC) interactions, for which the signal-to-noise ratio is most favorable. Located immediately downstream of the targets is a solid-iron magnet used to deflect muons and in which the remaining hadronic cascade is absorbed. The change in nonprompt rates due to finite target length has been calculated to be $+7\%$ for W, 0% for Cu, and -35% for Be. Direct measurements of the nonprompt muon flux corroborate the calculations.

The $\nu_e+\bar{\nu}_e$ CC events are included in the 0μ category. In the analysis of the tungsten data we have extracted the $\nu_e+\bar{\nu}_e$ CC events by two independent methods: (1) subtraction of known backgrounds, and (2) use of the longitudinal shower length to estimate the $\nu_e+\bar{\nu}_e$ directly. Both methods agree.[10] In the first method we compute and subtract the rates for ν_μ CC events for which the muon is not accepted in the spectrometer, ν_μ neutral-current (NC) events and ν_e NC events, and, finally, the nonprompt $\nu_e+\bar{\nu}_e$ CC events, which are primarily (85%) from K_{e3} decays.

All subtractions are made bin by bin in energy. We calculated the energy distribution of the largest background rates including effects of muon acceptance and the known NC/CC ratio for ν_μ interactions (~ 0.3). The calculated distributions are normalized to the total number of observed 1μ events, both prompt and nonprompt. The muon acceptance calculated for ν_μ ($\bar{\nu}_\mu$) CC events was 0.63 (0.63) during early running and was 0.78 (0.86) for the later data. Those ν_μ and $\bar{\nu}_\mu$ CC events with unaccepted muons are included in the 0μ events and must be subtracted. The NC events from ν_e (both prompt and nonprompt) are removed, under the assumption that the NC/CC ratio for ν_e is the same as for ν_μ. The specific values used in this subtraction procedure are tabulated in Table II for the various targets.

The prompt $\nu_e+\bar{\nu}_e$ rates are shown in Fig. 1 for each target. Since they are roughly comparable for the three targets, the charm cross section, if parameterized as A^α, has a value of α similar to that which describes proton absorption cross sections[11] ($\sigma_{pp}\propto\sigma_0 A^{0.72}$). Assuming that the charm production cross section varies as $s^{1.3}$, where s is the square of the energy in the proton-nucleon center-of-mass system, we calculate

TABLE II. The corrected 0μ event rate per 10^{16} protons and the background (BG) rates which were subtracted to get the prompt $\nu_e+\bar{\nu}_e$ rate.

Target	0μ event rate	$\nu_\mu+\bar{\nu}_\mu$ CC BG rate	$\nu_\mu+\bar{\nu}_\mu$ NC BG rate	$\nu_e+\bar{\nu}_e$ NC BG rate	$\nu_e+\bar{\nu}_e$ nonprompt BG rate	$\nu_e+\bar{\nu}_e$ prompt rate
Be	155.3 ± 4.8	46.5 ± 2.1	41.4 ± 0.7	7.4 ± 0.7	18.1 ± 1.3	41.9 ± 5.4
Cu	103.9 ± 7.6	21.0 ± 1.3	18.4 ± 0.5	7.8 ± 0.9	6.6 ± 0.9	50.2 ± 7.8
W	89.0 ± 2.9	16.8 ± 0.7	14.6 ± 0.2	7.3 ± 0.3	3.9 ± 0.3	46.2 ± 3.0

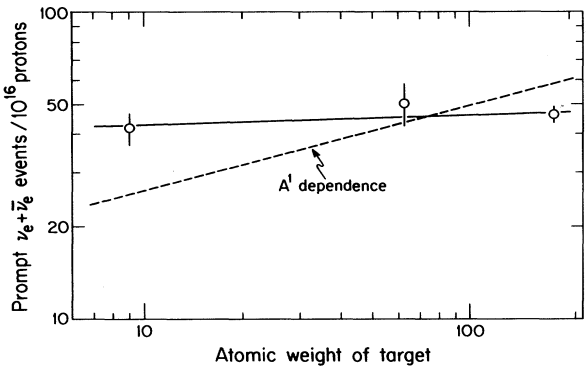

FIG. 1. The $\nu_e+\bar{\nu}_e$ prompt rate per 10^{16} protons as a function of the atomic weight of the targets: Be, Cu, and W. The solid line is a least-squares fit with $\sigma_c=\sigma_0 A^\alpha$ with $\chi^2=0.5$ for one degree of freedom. The fitted slope is 0.03 ± 0.05 which, combined with the A dependence of the absorption length for protons, gives $\alpha=0.75\pm0.05$. The dashed line is the fit with an A^1 dependence.

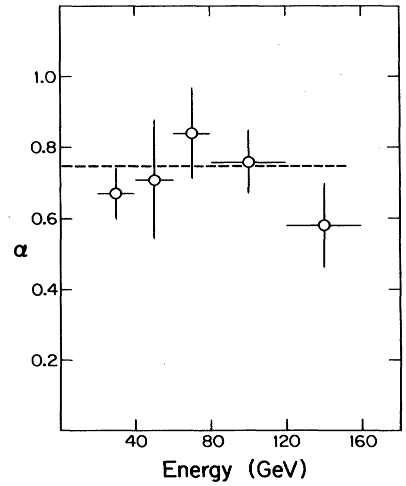

FIG. 2. The variation of α, the atomic number dependence, with neutrino energy under the assumption that the charm production cross section is parametrized as A^α.

the change in the prompt rate due to finite target length. The correction to the rate due to the secondary production in the cascade varies depending on α, from no effect for $\alpha=0.72$ to -1% for W and $+6\%$ in Be for $\alpha=1.0$.

From the prompt rates in Table II we find

$$\alpha=0.75\pm0.05,$$

with a $\chi^2=0.5$ for one degree of freedom, the solid line in Fig. 1. The dashed line in Fig. 1 is a fit assuming an A^1 dependence corrected for finite target length; it has $\chi^2=24.6$ for two degrees of freedom.

Although limited by the statistical accuracy of the data, we have investigated the possible variation of α with neutrino energy. The analysis was done independently in five energy regions with the results shown in Fig. 2. No significant variation with neutrino energy can be inferred, although the lower values at large energy are suggestive that the small values of α seen in the strange-quark production at large x_F may prove more universal.

The measurement of the A dependence from the ν_μ CC rates is much less precise because of the substantial nonprompt rates. The ν_μ and $\bar{\nu}_\mu$ CC data are plotted in Fig. 3 for the full- and partial-density Cu and W targets. An extrapolation in seven energy bins, constraining the shape of the nonprompt background to be smooth, results in the following prompt rates:

Target	ν_μ CC rate	$\bar{\nu}_\mu$ CC rate
Cu	49 ± 20	22 ± 9
W	43 ± 3	19 ± 4

which are consistent with equal rates for Cu and W targets.

In Fig. 3 the lines show the nonprompt backgrounds calculated by use of a parametrization of the hadronic production processes and the detector geometry and normalized to the full-density Cu and W targets. The agreement suggests that the nonprompt flux calculation is a good representation of the effects of both targets.

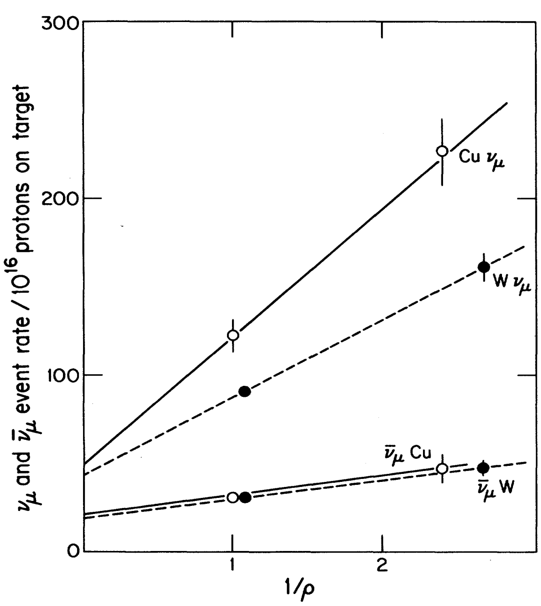

FIG. 3. The rate of ν_μ and $\bar{\nu}_\mu$ CC interactions per 10^{16} protons for the tungsten and copper targets in the larger fiducial volume. The solid and dashed lines are the predictions of the hadronic-cascade calculation for the nonprompt rate in the partial-density target; each is normalized to the observed rate in the full-density target.

get density and atomic number.

In summary, we have measured the variation of the charm production cross section with atomic number.[12] The result is nearly identical to that of the proton-nucleus absorption cross section, and different from the dependence of Drell-Yan lepton-pair production.[13,14] Thus we conclude that it is inappropriate to describe charm production by protons on nuclei solely in terms of the "hard scattering" processes which are analyzed by use of perturbative QCD.

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[1]F. Halzen, J. Phys. (Paris), Colloq. **43**, C3-381 (1982).

[2]P. Skubic *et al.*, Phys. Rev. D **18**, 3115 (1978).

[3]The apparatus has been described by R. C. Ball *et al.*, Phys. Rev. Lett. **51**, 743 (1983).

[4]P. Fritze *et al.*, Phys. Lett. **96B**, 427 (1980).

[5]M. Jonker *et al.*, Phys. Lett. **96B**, 435 (1980).

[6]H. Abramowicz *et al.*, Z. Phys. C **13**, 179 (1982).

[7]K. Winter, in *Proceedings of the 1983 International Symposium on Lepton and Photon Interactions at High Energies, Ithaca, N.Y.*, edited by D. Cassel and D. Kreinick (Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, N.Y., 1983), p. 177.

[8]A. Bodek *et al.*, Phys. Lett. **113B**, 77 (1982).

[9]A beam pulse is rejected if more than two of the thirty counters which monitor the halo of protons are outside permissible ranges.

[10]M. E. Duffy *et al.*, Phys. Rev. Lett. **52**, 1865 (1983).

[11]A. Barton *et al.*, Phys. Rev. D **26**, 1497 (1982).

[12]As noted by Barton *et al.* (Ref. 11), a general result of many experiments in which nuclear targets are used is that the extrapolation of A^α to $A=1$ does not yield the result measured with a hydrogen target. Thus conclusions concerning A dependence which use data on hydrogen should be drawn with great care.

[13]S. D. Drell and D. M. Yan, Phys. Rev. Lett. **25**, 316 (1970).

[14]M. Binkley *et al.*, Phys. Rev. Lett. **37**, 571 (1976).