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THE HOLOGRAPHIC BUBBLE CHAMBER EXPERIMENT AND
THE DETERMINATION OF THE EFFECTIVE CHARMED QUARK MASS AND
THE K-FACTOR FOR HADRONIC CHARM PRODUCTION

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ABSTRACT

In the first holographic bubble chamber experiment - the HOBC experiment - we have accumulated a total of 40000 holograms with particle interactions. We have determined the total charm pair cross section in pN collisions to be $23.3^{+10}_{-7.7} \mu\text{b}$ and $3.6^{+2.3}_{-1.7} \mu\text{b}$ for 360 and 200 GeV/c incident protons respectively. We have assumed a linear dependence of the cross section on the atomic number of the target. This experiment has demonstrated the feasibility of holographic recording in small bubble chambers. Assuming that the charm cross section can be described by the standard QCD factorized expression with gluon fusion and quark-antiquark annihilation, we have used our measured charm cross sections with other measurements to determine the effective charmed quark mass to be $1.8^{+0.25}_{-0.35} \text{ GeV}/c^2$. The K factor, which describes the importance of the higher order corrections, is calculated to be $9.8^{+12.5}_{-6.9}$.

1. INTRODUCTION

Several authors [1,2] have recently pointed out that the QCD parton model is able to describe charm particle production in hadron-hadron interactions, provided that one allows for substantial higher order corrections to the basic gluon fusion diagrams, and for final state interactions between the charm quark and other quarks in the initial hadron.

The arguments in favour of this point of view are the following. On the experimental side the contention that the QCD parton model is unable to describe charm production depends mainly on results obtained at the CERN ISR [3-12] which indicated a total charm production cross section in pp interactions at $\sqrt{s} = 60$ GeV of almost 1 mb, and on the observation, again mainly at the ISR, of charm production at very large x_F values. Both experimental observations have recently been questioned. The E743 Collaboration has published a cross section for charm pair production at 800 GeV/c: $\sigma(c\bar{c}) = 29^{+10}_{-7} \mu\text{b}$ [13]. This experiment uses a well-proven technique based on the high resolution hydrogen bubble chamber LEBC. The result is insensitive to uncertainties due to the x_F dependence, or the atomic number dependence, of the charm cross section. The error is mainly statistical. Comparing this value with the result obtained by the same technique at 400 GeV/c ($\sigma = 17 \pm 2 \mu\text{b}$), it seems unlikely that the charm cross section at ISR energies is anywhere near 1 mb. In this context it should also be pointed out that two measurements at the ISR give a cross section $\sim 70 \mu\text{b}$ [14-16]. One of these experiments [14] is particularly convincing since it is based on the observation of opposite sign $e\mu$ pairs in the central region. Concerning the x_F dependence the EHS Collaboration has observed a clear distinction between the x_F distribution for charmed particles which can contain a valence quark from one of the initial hadrons and those which cannot contain such a valence quark [17-19]. The latter are produced very centrally $(1 - x_F)^7$ as expected from a straightforward QCD calculation [20]. This result suggests that deviations from this simple prediction are due to final state interactions in the form of a quark recombination mechanism, and not to a different production mechanism, e.g. intrinsic charm.

On the theoretical side it had been argued that "charm excitation" diagrams are likely to be important [21-23]. In these diagrams a charmed quark perturbatively generated in the quark sea of one of the initial hadrons is "excited" and set free by the collision. These diagrams are difficult to calculate but it was argued that their contribution to the cross section was probably more important than the contribution

to the cross section from gluon fusion. In a recent paper [24] the lower order contribution (α_s^3) to the flavour excitation cross section was found to be either already part of the higher order corrections to charm creation or to be negligible. This sheds serious doubts on the validity of the original arguments which suggest that flavour excitation gives a large contribution. It follows from all this that charm production could well be a hard process in the sense of QCD and that the basic production mechanisms are gluon fusion and quark antiquark annihilation. Substantial higher order corrections are to be expected since they have been found to be important in the related Drell-Yan process. These higher order corrections can be expressed as a multiplicative factor (K-factor) to the lowest order cross section. The lowest order cross section is very dependent on the value used for the charmed quark mass. In principle this is not a problem since the value one should use is the current quark mass which is well known (~ 1.25 GeV). The charmed quarks produced however must somehow convert into charmed hadrons. The energy to do this must possibly be provided by the charmed quarks themselves. This results in an effective charmed quark mass which is now an empirical parameter to be determined by experiment. It is clear that this picture is meaningful only if this empirical factor turns out to be in the range 1.2–1.87 GeV.

The aim of this paper is to present experimental results on the total charm cross section in pN interactions at 200 and 360 GeV/c, and to use these data on the energy dependence of the cross section with other data to determine an effective charmed quark mass. This will allow a determination of the K factor. The experimental data were obtained with the holographic heavy liquid bubble chamber HOBC. Since this is the first holographic bubble chamber experiment and several more are planned we feel justified in going into details of the technical aspects of this experiment when they are different to the conventional bubble chamber techniques.

2. THE ADVANTAGES OF HOLOGRAPHY

Due to very short lifetime, visual detection of charmed particles requires very high spatial resolution. Particularly in hadronic interactions, where the charm cross section is of the order of 10^{-3} of the total cross section, a direct observation of the charm decay is important in order to obtain a clean sample of events. Holographic image recording has been used to improve the resolution of bubble chambers. The main advantage of holography is the possibility of obtaining a high

resolution and large depth of field simultaneously. With a conventional optical system the depth of field and the resolution are related; high resolution can only be obtained at the expense of the depth of field.

It can be shown [25] that (1) describes the maximum depth of field obtainable in an in-line hologram

$$z = 4R^2 \Delta l / 18\lambda^2 \quad (1)$$

where R is the resolution required, Δl is the coherence length of the laser, λ is the laser wavelength, and z is measured from the surface of the hologram.

Thus the depth of field depends on the coherence length of the laser. Taking typical values of $5 \mu\text{m}$ resolution, a wavelength of 514 nm , and a coherence length of 100 mm the full depth of field is just over 2 m . Contrasting this with the classical incoherent depth of field [26] in an optical system operating at unit magnification shows the great advantage of holography. The half-depth of field obtainable in an aberration free system, operating at unit conjugate ratio is

$$\Delta z = 2R^2 / \pi\lambda. \quad (2)$$

For a resolution R of $5 \mu\text{m}$ and $\lambda = 514 \text{ nm}$ this gives a half-depth of field of $31 \mu\text{m}$.

The pioneering work on the holographic photography of bubble chamber tracks was performed with the heavy liquid bubble chamber BIBC [27]. The NA25 experiment was a full scale pilot study of the capabilities and limitations of holographic techniques [28].

3. THE NA25 EXPERIMENT

In this experiment the charm cross section is measured for the first time at different beam energies with the same apparatus. Particularly at lower energies there is considerable confusion about the value of the charm cross section. Some experiments [29-33] have reported results which imply a large ($> 10 \mu\text{b}$) cross section at incident momenta as low as $50 \text{ GeV}/c$, while other experiments [34-36] provide measurements or upper limits which suggest a cross section well below $10 \mu\text{b}$.

The data were taken with a positive, unseparated beam at the CERN SPS accelerator. At 360 GeV/c the beam contained only protons, while at 200 GeV/c it contained 76.4% protons, 21% pions, and 2.6% kaons. The protons and the pions were tagged with two beam Cherenkov counters (CEDAR counters). Our results use data from incoming protons only. It was required that particles were incident on the experiment only during a 200 μ s window in the middle of the bubble chamber expansion cycle; however, only a slowly extracted primary beam is available in the SPS North Area so a kicker-magnet/shutter system was employed [37]. A fast kicker-magnet in the beamline upstream of the primary target was used to deflect the primary beam off the target for a period of 2.5 ms before and after the required window. The shutter was used to suppress the beam during periods when the kicker-magnet was quiescent; it could not be used to suppress the beam during periods near the beam window without interfering with the beam during this window. The shutter consisted of a rotating collimator in the form of a copper cylinder 800 mm long and 160 mm in diameter. Two radial slots, each 50 mm high by 12 mm wide, were positioned opposite each other. The system was not satisfactory as protons at the edge of the primary beam could still intercept the production target when the kicker was energised. This system allowed a small number of particles to arrive during the bubble chambers sensitive period, but prior to the beam window. At low operating temperatures (<50°C) bubbles grow rapidly (fig. 1), thus bubbles from such early particles could obscure much of the image. Under such conditions these problems limited the incident particle flux, but they were not a limiting factor at the relatively high temperatures used for the majority of the data taking.

The experimental arrangement consisted of the HOlographic Bubble Chamber (HOBC), its associated beam defining and interaction counters, and a muon detector. HOBC was a small, heavy liquid, rapid cycling bubble chamber designed for in-line holography [38-40]. A schematic of the bubble chamber is shown in fig. 2. It was a see-through chamber, fitted with high quality optical glass (BK7) windows. On the top of the chamber was a heat exchanger, the filling valve, a safety valve, and a pressure gauge. The visible volume (a cuboid 110 mm by 50 mm by 60 mm) was separated from the expansion system by a 1.5 mm thick VULKOLAN rubber membrane; thus reducing the number of joints causing spurious boiling. Thermal stability was very important. Control was achieved by two water loops in the chamber body and one in the piston. The water came from a single water reservoir with a temperature which was stable to within a few hundredths of a °C.

It was necessary to ensure that the chamber liquid was maintained at a uniform temperature otherwise the resulting variations in refractive index of the freon would seriously compromise the quality of the holograms. To help achieve such uniformity the aluminium tank surrounding the chamber was filled with air and heated, with electrical heating strips, to the same temperature as the chamber body. However, local temperature differences generated by the growth and recompression of bubble gave rise to severe problems; causing distortions of the illuminating, object and reference beams. As a result it was necessary to limit the cycling rate of the chamber to allow sufficient time for the heat to dissipate. Fig. 3 shows the dissipation time as a function of temperature. It is obvious that running at higher temperatures enables the chamber to be cycled at a faster rate. This is because the slower bubble growth rates result in smaller bubbles at recompression, and hence less heat to be dissipated. Unfortunately the bubble density decreased at high temperatures. This was thought to be due to boiling on the surfaces of the bubble chamber. This meant that the final operating conditions used (table 1) were the result of a compromise between the desire for high bubble densities and fast cycling rates [40].

4. HOLOGRAPHIC RECORDING

The three dimensional properties of a hologram make it possible to measure all three space coordinates in one image, and thus only one holograph was recorded per event.

Two different schemes of holographic recording were considered, and both were tested using HOBC under real operating conditions.

The simplest scheme, that of in-line holography, is illustrated in fig. 4. An expanded laser beam provides colinear object and reference beams which record onto a plane film surface normal to the beam. There are two main requirements for this to work satisfactorily. First, in order to adequately separate the real and virtual images, the recording must occur in the Fraunhofer diffraction region of the bubbles, while remaining in the near field of the reference beam. Secondly the bubbles must not obscure the reference beam by more than 1% of the region being recorded. There is no angle between the object and reference beams and this minimizes the resolution requirements of the film. The in-line scheme requires very simple recording and replay arrangements and minimises the laser power and coherence length requirements.

The other scheme, that of two-beam holography is shown in fig. 5. Compared with in-line holography it requires a more complex recording and replay system, but it does offer some advantages.

- (a) The virtual and real images are separated both laterally and in depth; this reduces the interference from the virtual image compared with the in-line scheme. This is the major advantage of double beam holography.
- (b) The ratio of the object beam intensity to the reference beam intensity can be accurately controlled for optimum recording.
- (c) Dark field illumination is used, and potentially this offers a better signal to noise ratio upon reconstruction.

One serious disadvantage of the side-band Fresnel hologram (which is what the double beam hologram would be in the HOBC recording arrangement) is that it requires a higher film resolution to record a given maximum object frequency than does the in-line Fraunhofer hologram [41].

Tests carried out in HOBC [40] showed that under actual operating conditions the difference between the two schemes was minimal in terms of the quality of the replayed image. The in-line arrangement was chosen for the data taking runs because of its simplicity.

The pulsed laser used was a Lambda Physik EMG101 excimer laser. It was filled with XeCl and produced 10 ns pulses at a wavelength of 308 nm. The ultraviolet beam from the excimer laser was used to pump a dye laser so that a visible beam could be produced. The dye laser was a Lambda Physik FL2000E, tuned to 514 nm to match the strong green laser line of the argon-ion laser, and was used with an intercavity etalon to narrow the single mode bandwidth. Tests carried out at CERN [42] using the similar FL2002 dye laser, showed that a coherence length of around 140 mm could be obtained with a 4 mm Fabry-Perot etalon in the oscillator cavity. The dye laser was obscured so that its output was 3 mJ, this was enough to expose the film to a density of 1.3 which was very close to the maximum contrast exposure [43].

Considerations of resolution made it desirable to locate the recording plane as close to the bubbles as possible, once the far-field condition had been satisfied. The problems of locating a camera system close to HOBC and its aluminium heat shield led to an image of the chamber being holographically recorder rather than the chamber itself. The optical problems of turbulence in the bubble chamber could also be reduced by minimising the distance between the object and the hologram plane. The useful information in the diffracted wave lies in the modulating envelope due to the finite extent of the object. If the extent of this envelope can be made small with respect to the mean turbulence size then both the diffracted wave and the reference wave suffer similar distortions. A high quality relay lens ($f = 300$ mm, f -number = 2.8) was used with a three element field lens ($f = 330$ mm) at the rear image point of the first lens. With this lens system the centre of HOBC was effectively situated at a distance of 40 mm from the hologram.

The camera and film transport were capable of working at speeds of up to six frames per second. The film used was Agfa Holotest 10E56 on a $170\text{ }\mu\text{m}$ polyester base with an anti-halo coating. The cut-off frequency for this emulsion is around 3000 lines/mm.

5. THE TRIGGER

HOBC was surrounded by an array of scintillation counters (fig. 6). S1 consisted of two circular scintillators, of radius 25 mm. A coincidence between S1A and S1B was used to determine when there was a single particle incident on the bubble chamber. S2 consisted of a rectangular scintillator 400 by 420 mm^2 , with a circular hole of diameter 45 mm. It was used to veto incident particles which were accompanied by a particle in the beam halo. S3 consisted of four scintillators each 100 by 100 mm^2 by 5 mm thick. An interaction in HOBC was indicated by a pulse height exceeding 2.3 times that produced by a minimum ionising particle in each of the four scintillators.

The muon detector (fig. 6) was composed of a 2 m iron dump with a tungsten core, followed by a sandwich of iron plates, Multi-Wire Proportional Chambers (MWPC), and scintillation counter hodoscopes [44]. Charmed particles have typical semileptonic branching ratios in the region of 10%. Detection of a fast forward muon can thus be used to select interactions which have a relatively high probability of containing charmed particles. An improvement in the signal to background ratio of about 20 can be obtained. There was no magnetic field, muons were identified

merely by their ability to penetrate. The dump was positioned as close as possible to HOBC, in order to reduce the possibility of pions decaying into muons. Muons emitted at less than 54 mrad from the beam direction had to penetrate 65 mm of copper, 2000 mm of tungsten, and 400 mm of iron to reach the first hodoscope, which had an active area of $1200 \times 1200 \text{ mm}^2$. Muons emitted at large angles had to penetrate 2400 mm of iron. This corresponds to a momentum cut off for the muons of 5.8 and 3.1 GeV/c respectively.

The event trigger demanded one incident particle, an interaction in HOBC and at least one muon candidate penetrating as far as the first hodoscope. With this trigger a total of 23000 and 17000 holograms were recorded at 360 and 200 GeV/c respectively.

6. DATA ANALYSIS

During the subsequent off line analysis of the MWPC data the events were required to have a reconstructed muon track in the wire chambers W1 downstream of the dump [45]. Muons emitted at angles greater than about 100 mrad would miss W1 and so were rejected at this stage; 55% of the triggers had a reconstructed track in wire chamber W1.

The holograms corresponding to events which satisfied the above selection criteria were scanned. Each hologram contained typically 70 incoming beam tracks and 5 interactions. With conventional photography such pictures would be too complex to analyze. The proportional chambers B1 and B2 (fig. 6) consisted of two orthogonal planes of 1 mm pitch and were used to locate the beam track corresponding to the trigger. About 47% of these holograms had an interaction inside the fiducial volume of the bubble chamber. An interaction was retained for further analysis only if it was situated at least 15 mm upstream of the visible end of the chamber, and if the incoming beam track had a visible length in the bubble chamber of at least 2 mm. Interactions with a charged secondary multiplicity of greater than 30 were also not scanned. A total of 12% of the events were rejected because of poor picture quality or ambiguous beam track: 4117 and 2208 primary interactions were retained for final analysis at 360 and 200 GeV/c respectively.

6.1 Options for holographic scanning machines

Once the real (or virtual) image has been reconstructed there are three basic layouts that an analysis machine can take:

- (a) Direct projection onto a conventional table.
- (b) Direct ocular microscopy.
- (c) Indirect TV camera microscopy.

The first method is very simple, and existing tables with Mangiaspago (or similar) digitisers can be easily modified. It enables quite a large region of the hologram to be seen in great detail, and allows sensitive kink and multiple scattering detection. It has a high resolution, with few optical elements to degrade the image. However this method has some disadvantages. To project onto an area of 1 m^2 requires a laser providing around 0.25 W at 514 nm, this is expensive and potentially highly hazardous. The speckle in the image may be unpleasant for some scanners, and cannot easily be removed.

The second method has the advantage of low laser power and high resolution, but is more complex, cannot easily detect kinks, and is too hazardous.

The third method, used in all but one of the production machines in the collaboration, has the advantages of layout (b) without being hazardous. The problems of kink detection were solved in various ways in the different machines and are briefly discussed below.

6.2 Kink detection

The most difficult decay topology to detect systematically was the K1, that is a charged track which kinks. Large kink angles ($> 100 \text{ mrad}$) can be easily seen by visual inspection during a general scan of the frame, but small angle kinks must be searched for systematically. The various production scanning machines in the collaboration illustrate the differing approaches taken to kink detection.

- (a) Visual: Brussels.
- (b) Electronic: CERN, Mons, Paris.
- (c) Measurement: Vienna and UCL.
- (d) Mechanical: Bari and CERN.

6.2.1 Visual detection

The direct projection machine at Brussels [46] used the well tried and tested method of sighting along a track to detect kinks and multiple scatters. When a suspected kink was found, the track segments before and after the kink were checked with a metal rule to confirm the kink vertex. This method of detection is only applicable to a direct projection table.

6.2.2 Electronic detection

The HOLMES machine at CERN [47] used two electronically generated cursor crosses mixed with the low magnification image. These moved with the image when the stages were moved by the operator such that any line going through both cursors also passed through a fixed origin, usually chosen to be the primary vertex. Any deviation in the track being followed showed up as a misalignment when the track is compared with the cursors (fig. 12 of [47]). A similar technique was adopted in Mons and Paris.

A further technique used for scanning a part of the events on HOLMES consisted of a geometrical image transformation leading to a picture as seen in fig. 8 [48].

6.2.3 On-line track measurement

This is the most obvious improvement on visual scanning on a camera machine, but is time consuming. Every track has two or more points measured on it and a line is fitted through their projections onto the X-Y plane. If the track does not kink then the fitted line will pass close to the primary vertex. In the case of a track that has kinked a line fitted through points measured following the kink will have an impact parameter different from zero at the vertex. The impact parameter must be divided by the error on the impact parameter to allow for inaccuracies in the measurements. From measurements on undeviating tracks, using CHIMAERA [49,50], it was calculated that impact parameters at the primary vertex down to 25 μm at 3σ could be detected.

6.2.4 Mechanical detection

The Bari table used an interesting method of kink detection that relied upon the integrating effect of the camera tube and human eye. The entire X-Y state assembly could be pivoted about its centre and translated along the original X-axis direction by hand. Thus a track at an angle to the beam track could be followed rapidly back and

forth along its length. The integration effect of the viewing system allowed this track and any others parallel to it to be easily seen on the video monitor, but tracks at other angles became faint or invisible during the motion. This effect was the basis for a rapid and sensitive method of kink location. At the point where the track kinked the track would disappear, or become much fainter.

6.3 Scanning

Two independent scans were made and the differences were checked by a physicist. Any activity in a 2.8 mm wide band forward from the primary vertex to the end of the frame was recorded. At the scanning level a decay candidate was defined as being any secondary activity which did not have a heavily ionising or backward track. In addition no decay track should show evidence for multiple scattering. These requirements remove less than 3% of the genuine charm decays but most of the interactions, gamma conversions, and delta electrons.

For every scanned interaction the charged secondary multiplicity was recorded, and the position of the primary vertex measured. For every secondary activity found, the number of forward, minimum ionising tracks and the number of backward, or heavily ionising tracks was separately recorded; the position of the secondary vertex was measured; and where possible the incoming particle was identified as neutral or charged [45]. For each decay candidate a point on each secondary decay track was also measured. The measurement accuracy in the plane perpendicular to the optical axis was 6 μm in space (r.m.s.). Position measurements along the optical axis were performed by focussing on a bubble and have an accuracy of 120 μm on isolated tracks. The presence of other tracks in the vicinity of the one being measured can however degrade this resolution by a factor of at least two.

6.3.1 The identification of secondary activities

The charm decay sample contains misidentified decays arising from different sources. Individual decay topologies can also be contaminated by overlaps of real charm decays upon minimum ionizing tracks from the primary vertex. Thus neutral 2-prong decays can appear in the charged 3-prong category. For neutral charm decays with their short decay length this is a problem as the narrow cone of tracks from the primary vertex results in a significant probability of overlap. Some of the decay topologies are more susceptible to contamination than others, and for this reason the backgrounds in each topology will be discussed separately.

6.3.2 Topological background

(a) 2-prong neutral decays V2

A large number of the two-prong decays are due to misidentified gamma conversions, arising from pion decay and the short (280 mm) radiation length of the freon, and the decays of K and Λ particles. These backgrounds are expected to be uniformly distributed in distance from the primary vertex. The gamma conversions can be removed to a large extent by applying an opening angle cut, however this also removes a significant fraction of the charm decays in this topology. Another source of background is due to a secondary interaction of a neutral particle (n, K, Λ) emitted from the primary vertex, where no nuclear recoil or nuclear fragments were seen.

(b) 4-prong neutral decays V4

Very few strange decays can generate a background in this topology. Misidentified interactions could provide some background. This topology is expected to be fairly clean.

(c) 1-prong charged decays K1

The backgrounds in this topology come mainly from electrons, gamma conversions in the confusion zone close to the primary vertex, and delta rays where a slight amount of multiple scattering simulates a small angle kink. In addition there is a background from other charged tracks with multiple scattering and from strange particle decays. The strange decay background can be reduced by a cut in transverse decay length (L_t). Large angle single scatters are very rare, we estimate that only 1 primary interaction per 1000 will produce a pion which will single scatter with an angle greater than 10 mrad in the region $L_t < 500 \mu\text{m}$.

(d) 3-prong charged decays K3

The decays of strange particles into 3 charged particles are a small fraction of all strange decays, and are thus a smaller background in the K3 topology than in the K1. A background that is expected to be significant is that of V2 decays from Λ or K particles overlapping a charged track from the primary vertex. The probability of this occurring is inversely proportional to the distance from the primary vertex. Overlapping gamma conversions can also contribute, although these should be removed by a minimum opening angle cut. There will be some background from

interactions in which the short prong was missed. Considered topologically there is a contamination from charmed decays coincident with a loss in the V2 category, arising from the decay of the D^* to $D\pi$. The D^* production cross section is of the same order as the D production cross section.

(e) 5-prong charged decays K5

The only non-charmed background in this topology is due to interactions that have been misidentified. Charmed decays to V4 have a significant probability of overlapping a track from the primary vertex and becoming K5 topologies.

In this experiment the charm signal is extracted using only the topological and geometrical information on the charm decay candidates. A decay candidate was required to have correct multiplicity (neutral decays must have even multiplicity and charged decays odd multiplicity). To reduce the background we required the transverse decay distance, the impact parameter and the decay angles to satisfy the cuts listed in table 2. When there was any ambiguity in the topology the cuts applied were always the least severe.

The transverse decay distance and the impact parameter are defined in fig. 7. The parameters are of the order of the proper decay length of the decaying particle ($\approx c\tau$) and thus of the order of a few hundred microns for charm particles. Because of the limited accuracy of the depth measurement the cuts are always imposed on quantities projected onto the film plane. The cuts on the transverse decay distance and the impact parameter remove only a few per cent of the genuine charm decays. However a minimum kink angle for charged one-prong decays and a minimum opening angle for other decays is necessary to reduce the contamination by electrons as discussed above. These cuts remove a significant fraction of the charm decays as can be seen in table 2. Table 3 gives the total number of charm candidates satisfying these cuts.

Even with these cuts most of the charm decay candidates are background. To reduce the background further, we restrict our attention to the sample with two charm decay candidate in the same event. In this sample the background can be evaluated using the assumption that the probability of a secondary activity simulating a charm decay candidate is independent of the fact that there is already such an activity present in the event. In this case the number of events with two (or more) charm decay candidates is given by:

$$N_{b,d} = N_T [1 - (1 + N_s/N_T) \exp(-N_s/N_T)] \quad (3)$$

where N_T and N_s are the total number of primary interactions analysed and the total number of charm decay candidates respectively. If this formula is applied to samples with little or no charm content, it correctly predicts the number of events with two or more secondary activities (table 4). Eq. (3) predicts 4.2 doubles at 360 GeV/c (15 observed) and 2.6 doubles at 200 GeV/c (8 observed). We conclude that there is a clear signal for charm decay both at 360 and 200 GeV/c. Fig. 8 shows an example of such a double event. This procedure overestimates the background since there is of course a contribution of charm to the singles sample. The excess in the doubles is used to estimate the amount of charm in the singles, which is then subtracted from the singles to evaluate the background in the doubles using (3). After a few iterations the procedure converges and the final result is:

	Doubles observed	Background
360 GeV/c	15	1.9
200 GeV/c	8	2

7. CHARM PRODUCTION CROSS SECTIONS

To calculate the cross sections we need to evaluate the trigger acceptance, the corrections due to the charm decay candidate cuts and the detection efficiency for charm decays during the scanning of the holograms. This was done with a detailed Monte-Carlo simulation.

7.1 The Monte-Carlo simulation

We have used an uncorrelated production model where both the charmed particles are generated according to the following differential cross section:

$$\frac{d^3\sigma}{dx dp_T^2} = (1 - |x_F|)^a \exp(-bp_T^2) \quad (5)$$

with $a = 3.0$, $b = 1.1 \text{ (GeV/c)}^{-2}$.

A small amount of correlation does exist between the C and $\bar{C}$ due to energy and momentum conservation.

The purely leptonic decay modes were neglected, and the muonic and electronic branching ratios were assumed to be equal. The other particles produced in the interaction, which have an effect on the detectability of the charmed decays, were assumed to be pions. Their average multiplicity was reproduced using a KNO scaling function, and the total energy was conserved.

For the simulation the set-up consisted of the beam dump, the W1 wire chambers, and H1 and H2. A muon was assumed to go through the tungsten if its production angle (α) was less than 54 mrad. A signal in the W1 chambers was defined as a muon if 8 out of the 9 planes were hit combined with a hit in H1 or H2 depending on the muon definition used. We assumed only hits in H1 in his simulation. The threshold muon energies were:

$$\begin{array}{ll} 5.8 \text{ GeV} & (\alpha < 54 \text{ mrad}) \\ 3.1 \text{ GeV} & (\alpha \geq 54 \text{ mrad}) \end{array}$$

The experiment triggered on muons, thus at least one of the produced charmed particles must decay into a muon.

An investigation was made of the effect of Λ_c production on the calculated acceptance. At 360 GeV incident proton energy the acceptance was 0.095 with no Λ_c , 0.065 and with 1 $\bar{C} \Lambda_c$ pair. These values were calculated using the uncorrelated model.

Varying the parameters "a" by a factor of 2 and "b" by a factor of 2 or allowing D mesons to decay via the $K^*(892)$ channel changed the acceptance by a maximum of 3%.

7.2 Trigger and visibility

The trigger acceptance was 0.095 and 0.079 at 360 and 200 GeV/c respectively. This contains the geometrical acceptance of the muon detector (0.47 and 0.40 at 360 and 200 GeV/c respectively) and the semileptonic branching ratios: D^+ 17.2%, D^0 6%, D_s^+ 6%, Λ_c 4.5%. We further assumed that all charm is produced either as a meson-antimeson pair, or as a Λ_c -antimeson pair. The charm meson mixture was 39% D^+ 53% D^0 and 8% D_s^+ . The weight factor used to correct for the charm decay candidate selection cuts was 1.28 and 1.19 per decay at 360 and 200 GeV/c respectively. The visual detection efficiency for short decay lengths is determined from a comparison of the decay length distribution for all charm decays occurring in pairs with the Monte-Carlo simulation. This was done by

parametrising the visual detection efficiency as $V(Lx) = 1 - \exp(-\beta Lx)$, in a maximum likelihood fit to the two aforementioned distributions. From this fit the average detection efficiency for charm decays was estimated at 0.52 ± 0.14 at 360 GeV/c and at $0.94^{+0.06}_{-0.29}$ at 200 GeV/c. The larger detection efficiency at 200 GeV/c is due both to the improved picture quality at the end of the run when the 200 GeV/c data were taken, and to the reduction in event complexity at lower energy. The scanning efficiency at large decay lengths (> 10 mm) is determined to be $(94 \pm 3)\%$ from a comparison of two independent scans.

The resulting total charm pair production cross sections per nucleon are $(20 \pm 10)\mu\text{b}$ and $(3.6^{+2.3}_{-1.7})\mu\text{b}$ in 360 and 200 GeV/c proton nucleon interactions respectively. We have assumed a linear dependence of the charm cross section on the atomic number A , and a negligible contribution of Λ_c production to the total cross section. With a 20% $\Lambda_c \bar{\Lambda}_c$ production the cross section estimate will increase by 17% at 360 GeV/c and by 8% at 200 GeV/c,

An independent determination of the charm cross section at 360 GeV/c was obtained from a study of the decay length distribution for the events with only one charm decay candidate [50]. Using the charm candidate selection cuts described above, but excluding the impact parameter cut, we obtain a sample of 341 charm decay candidates. An impact parameter cut introduces a bias in the length distribution which would be difficult to correct for. The transverse decay length cut and the effect of the finite chamber length can be allowed for by appropriately weighting the events. After a correction for the loss at small decay lengths (using the visibility as a function of length as determined in the charm pair analysis above) the background events have a flat decay length distribution. The validity of the procedure was checked with secondary interactions (fig. 9).

Fig. 10 shows the length distribution of the charm particles after applying the procedure described. The flat background at large distances is clearly visible. This background is extrapolated to zero decay length and the excess in the region between 0 and 18 mm is interpreted as due to charm. A correction factor of 1.06 was used to account for charmed decays with $Lx > 18$ mm. The resulting charm pair production cross section is $(28^{+23}_{-12})\mu\text{b}$. Combining this with the result from the previous analysis gives $(23.3^{+10}_{-7.7})\mu\text{b}$.

8. DETERMINATION OF THE EFFECTIVE CHARMED QUARK MASS, AND THE HIGHER ORDER CORRECTION FACTOR

In the following analysis we assume that the charm production cross section in pp interactions can be written in the factorised form:

$$\sigma_{cc}^{-}(s) = \sum_{ij} \int dx_i dx_j G_{i/p}(x_i) G_{j/p}(x_j) \hat{\sigma}_{ij}(\hat{s}) \quad (6)$$

where s is the centre of mass energy squared of the two protons, $\hat{\sigma}_{ij}(s)$ is the cross section for the two subprocesses: $g \rightarrow c\bar{c}$ or $qq \rightarrow c\bar{c}$, $\hat{s} = x_i x_j s$ is the center of mass energy squared for the subprocess, and $G_{i/p}(x_i)$ is the probability of finding the quark or gluon i with a fraction of the momentum x_i of the proton. At the energies considered gluon fusion is the dominant subprocess, but quark antiquark annihilation was included in the calculation. There is no reason to assume that the lowest order (α_s^2) term is a good approximation to the total cross section. We define the K-factor as:

$$K(\hat{s}) = \sigma(gg \rightarrow c\bar{c}, \text{ all orders } \alpha_s) / \sigma(gg \rightarrow c\bar{c}, \text{ order } \alpha_s^2)$$

The cross section in (6) is dominated by the contribution of gluon fusion in a small $\hat{s}$ interval just above threshold. If $K(\hat{s})$ is a slowly varying function of $\hat{s}$ it can be taken as constant. This corresponds to the value of K for $\hat{s}$ just above threshold. Eq. (6) with the lowest order QCD result for gluon fusion with a K-factor should describe the energy dependence of the total charm production cross section. There are two free parameters: the charmed quark mass m_c and the K factor. In this case the K factor is essentially an overall scale factor. The value of m_c determined from the data must satisfy $1.2 \leq m_c \leq 1.87$ GeV otherwise the underlying physical picture becomes questionable. The K-factor can a priori have any value. It is in principle possible to calculate it.

The lowest order contribution (α_s^2) for charm production in gluon fusion and quark antiquark annihilation have been calculated by many authors [19-20,24,51-56]. The structure functions used are the two sets proposed by Duke and Owens (DO1 and DO2) [57]. These are sufficient to give us a feeling of how sensitive the result is to the choice of structure functions. The threshold in the integral in (6) is taken to be $\hat{s} = 4m_c^2$ and the Q^2 of the reaction is $\hat{s}$ and $\hat{s}/2$ for quark antiquark annihilation and gluon fusion respectively.

The data points used in the fit are listed in table 5. The only important omission from this table is some of the ISR measurements. These measurements have a large systematic uncertainty because the charm signal is observed in a small fraction of phase space only, and very large correction factors are needed to get a total cross section. The results from the fit are:

$$\begin{aligned}
 & m_C = 1.8^{+0.25}_{-0.35} \text{ GeV} \\
 \text{DO1} \quad & K = 9.8^{+1.2}_{-0.9} \\
 & \chi^2/\text{ND} = 4.3/5 \\
 & m_C = 2.0^{+0.35}_{-0.30} \text{ GeV} \\
 \text{DO2} \quad & K = 10.8^{+1.9}_{-0.7} \\
 & \chi^2/\text{ND} = 4.3/5
 \end{aligned}$$

The errors on m_C and K are highly correlated. This is because there is an accurate measurement of the cross section around 400 GeV/c, which, for each value of m_C essentially fixes K . Fig. 11 shows the data points with the result of the fit. Fig. 12 shows the variation of the K factor with m_C . The errors on m_C are more or less Gaussian, this is not true for the errors on the K factor.

9. DISCUSSION AND CONCLUSIONS

We have measured the total charmed pair production cross section in pN interactions at 200 and 360 GeV/c using the heavy-liquid holographic bubble chamber HOBC. The aim of the experiment was to measure the energy dependence of the charm cross section and to demonstrate the feasibility of holographic image recording in bubble chambers.

Our work shows that it is possible and practical to use holographic image recording in small bubble chambers. Two large holographic experiments are planned at FNAL. These experiments use large bubble chambers where the technical problems are certainly different. NA25 was intended as a pilot experiment and only a 10-day data-taking run was taken. Once the scanning systems were set up the total scanning and measuring time was two-man years. The errors on the cross section are essentially statistical.

From an analysis of the events with two charm decay candidates from the same primary vertex we derive a cross section per nucleon of $22 \pm 11 \mu\text{b}$ (360 GeV/c) and $3.9^{+2.5}_{-1.9} \mu\text{b}$ (200 GeV/c). An independent determination of the charm cross section at 360 GeV/c was obtained from the study of the decay length distribution of the candidates. Combining the two results the best value for the cross section at 360 GeV/c is $24.6^{+12.0}_{-8.3} \mu\text{b}$.

Several experiments have reported charm cross sections in proton-nucleon interactions for incident momenta in the range 350–400 GeV/c. All recent results are compatible with a total cross section of about $20 \mu\text{b}$ if an A^α with $\alpha = 1.0$ dependence of the cross section on the atomic number is assumed. Comparing our result with the result from NA27 [64] which used a hydrogen target ($\sigma = 17 \pm 2 \mu\text{b}$) gives $\alpha = 1.14^{+0.13}_{-0.16}$. There are two direct measurements which indicate a smaller value of α [66,67,69]. These values are for charm produced at large x_F [1]. Both this experiment and EHS have a good acceptance down to $x_F = 0$, so that we are giving α for the total cross section.

We have interpreted our data assuming that the charm production can be described by the standard QCD factorization (6) with only gluon fusion and quark antiquark annihilation. With these assumptions our measurements, together with other total cross section measurements, allow a determination of an effective charmed quark mass. In order to reproduce the measured cross section at 400 GeV/c, where several reliable measurements exist, one needs to assume $m \sim 1.15 \text{ GeV}$ if higher order corrections are not allowed. This possibility is excluded at the 2σ level. It is hence clear that substantial higher order corrections will be needed.

The data favour a very large K factor of about 10, but a K factor of about 3 corresponding to $m_c = 1.45$ is only 1σ from the best supported value. It nevertheless seems difficult to avoid the conclusion that lowest order perturbation theory is not a reliable guide to calculate the cross section for the subprocesses in the standard QCD factorised expression (6). It should be mentioned that the picture considered here cannot be maintained if the total charm cross section at ISR energies ($\sqrt{s} = 60 \text{ GeV}$) exceeds $100 \mu\text{b}$. This would imply a charmed quark mass exceeding the D meson mass. Precise measurements of the charm cross section will probably soon be available at 800 GeV/c. If the increase between 400 GeV/c and 800 GeV/c exceeds a factor ~ 2.5 we would be forced to abandon the simple QCD model where charm is being produced by gluon fusion and quark antiquark annihilation.

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TABLE CAPTIONS

TABLE 1 Typical operating conditions for HOBC.

TABLE 2 Geometrical cuts which define a charm decay candidate. The corresponding selection efficiencies for genuine charm decays at 360 GeV/c are also given. The cuts refer to quantities projected on the plane perpendicular to the optical axis. At 200 GeV/c the numbers are very similar, the average selection efficiency is 78% and 84% at 360 and 200 GeV/c respectively.

TABLE 3 Total number of events in different topological categories.

TABLE 4 Number of events with two or more secondary activities as predicted under the assumption of uncorrelated production and detection efficiencies, compared with the observed number for decay categories containing little or no charm (360 GeV/c data).

TABLE 5 Data points used in the QCD cross section evolution fit. A linear dependence of cross section on atomic number has been assumed.

TABLE 1

Liquid	C_3F_8
Temperature	53°C
Cycling rate	10 Hz
Expansion length	9 ms
Laser delay	100 μ s
Bubble size	12 μ m
Bubble density	100 cm ⁻¹
Flux	70 tracks/expansion

TABLE 2

Decay topology	Max. L (μ m)	Max. L (μ m)	Min. opening or kink angle (mrad)	Selection efficiency %
1-prong	500	1000	10	63
3-prong	500	2000	5	97
2-prong	300	1000	10	81
4-prong	300	1000	5	99

TABLE 3

	200 GeV/c	360 GeV/c
Total number of primary vertices analyzed	2208	4117
Number of charm decay candidates with charged 1-prong topology	58	88
Number of charm decay candidates with charged 3-prong topology	12	19
Number of charm decay candidates with neutral 2-prong topology	21	40
Number of charm decay candidates with neutral 4-prong topology	0	3
Number of decay candidates with unknown charge	18	39
Number of events with two or more charm decay candidates	8	15

TABLE 4

Category	Number of doubles observed	Number of doubles predicted
Secondary interactions	148	162
Decay topologies without the cuts of table 2	317	279

TABLE 5

Beam momentum (GeV/c)	σ charm (μb)	Experiment	Reference
70	5 ± 4	Serpukhov - ν dump	[58]
200	$3.6^{+2.3}_{-1.7}$	NA25	This experiment
350	$11.3 \pm 1.1 \pm 1.8$	CCFRS - μ	[59]
360	$15.5^{+8.2}_{-4.6}$	EHS-NA16	[60-63]
360	$23.3^{+10}_{-7.7}$	NA25	This experiment
400	17.2 ± 2	EHS-NA27	[64]
400	$15.5 \pm 0.8 \pm 2.3$	FNAL - ν dump	[65-67]
400	31^{+29}_{-7}	CIT - μ	[68]
800	29^{+11}_{-18}	LEBC - E743	[13]
$\sqrt{s} \approx 57$	70 ± 36	ISR	[14]

FIGURE CAPTIONS

- Fig. 1 Bubble diameter versus growth time in C_3F_8 measured in HOBC. Measurements were performed in C_3F_8 using expansions of either 5 ms or 7 ms.
- Fig. 2 Cut view of HOBC showing the arrangement.
- Fig. 3 Heat dissipation time versus temperature. The dissipation time is defined as the time after which the turbulences produced by a track become undetectable. These data were taken in C_2F_5 C1 using a symmetric chamber expansion of length 3 ms. The results should be similar for C_3F_8 except the data points would be moved approximately 3° to the left.
- Fig. 4 In-line holographic recording arrangement.
- Fig. 5 Dual beam holographic recording arrangement.
- Fig. 6 General layout of the experiment B1 and B2 are beam defining proportional wire chambers, S1-S3 are scintillation counters, H1-H3 are scintillation hodoscopes and W1-W7 are proportional wire chambers.
- Fig. 7 Definition of the geometrical quantities used to select charm decays.
- Fig. 8 Example of a double charm decay. The picture is a computer generated perspective view. Angles and distances are non-linearly distorted. The event contains a one-prong and a three-prong decay at 8.9 and 12.1 mm from the primary vertex. The one-prong kink angle is 2.7° , and the three-prong opening angle is 1.1° .
- Fig. 9 Uncorrected and corrected length distributions for charged interactions.
- Fig. 10 Weighted length distribution for charged and neutral charm candidates.
- Fig. 11 A compilation of total charmed air production cross section data in pp interactions. The curve is the result of the fit described in the text. The two curves corresponding to the two structure functions DO1 and DO2 are virtually indistinguishable.
- Fig. 12 Variation of $\chi^2/\text{degrees of freedom}$ of K factor for fixed m.

Fig. 1

Fig. 2

Fig. 3

Recording Arrangement for In-line Holography

Fig. 4

Recording Arrangement for Two-Beam Holography

Fig. 5

Fig. 6

Fig. 7

P1L010A0.031

44000

1400

5600

HOLMES

Fig. 9

Fig. 10

Fig. 11

Fig. 12