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HADROPRODUCTION OF HEAVY FLAVOURS

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1. INTRODUCTION

Hidden charm in the form of the J/ψ was discovered in 1974¹, naked charm in the form of the D meson in 1976² (though the first example³ of Λ_c^+ was probably seen in 1975), hidden beauty in the form of the T in 1977⁴, and naked beauty through its decay kaons and electrons in 1980⁵. Even though the partner of the beauty, the top, is still to be discovered, and heavier flavours may exist, there is now a tendency, in these days when enterprising people are hunting for intermediate vector bosons, Higgs bosons, SUSY particles, proton decay, neutrino oscillations, etc., to take the world of heavy flavours for granted, or at best as a subject for e^+e^- colliders. However, there are several compelling reasons to pursue a vigorous effort in this field with proton machines:

- i) A heuristic reason is that, contrary to prevailing prejudice, most of the first evidence for new flavours was found, directly or indirectly, in hadronic interactions. This was the case for pions and strange particles (cosmic rays) and all their resonances (bubble chambers) -- for lack of competition, one may say -- but, more recently, this was true also for the J, the T, the Λ_c , the Σ_c , the F (as opposed to the Ψ , D, D^* , and B for the e^+e^- colliders) and there are still many charmed particles and all of the B particles to find! As for the naked top the competition is open between the SPS $p\bar{p}$ collider and the boosted-up PETRA. If the mass of the top is too high and/or if heavier flavours exist, only the $p\bar{p}$ colliders (at CERN or FNAL) remain in the game -- until the advent of TRISTAN, SLC, and LEP.

- ii) Another heuristic reason is that fixed-target experiments with high-energy beams (γ or hadrons) are the only way, thanks to the Lorentz dilation of time, to measure very small lifetimes, as are expected for beauty particles ($\tau \lesssim 10^{-14}$ cm $\rightarrow \lambda \lesssim 100$ μ m at $p \approx 150$ GeV/c). In the same line of thought, hyperon and kaon beams should be a good way to produce charmed-strange particles (Λ , F^+ , ...).
- iii) Finally, a more profound motivation to study hadroproduction of heavy flavours lies in the fact that it falls in a domain of relatively large Q^2 's where QCD should apply -- and hence, as for the Drell-Yan process or the high- p_T phenomena, QCD should have a predictive power which can be tested by experiment. As we shall see, this is not yet quite the case for charm production, though qualitatively our understanding has progressed a lot over the last two years; experimental data on beauty production, which involves higher Q^2 's, should be extremely valuable, as well as more complete results on charm production versus energy.

These lectures are essentially devoted to the third point and will present the latest results on charm hadroproduction and the evolution in theoretical ideas which they have brought about. In the light of this confrontation, the possibility of finding b and t particles in hadronic interactions [point (i)] will be discussed. But first, new results on properties of heavy-flavoured particles, originating either from proton [point (ii)] or e^+e^- machines, will be presented, since they have an important bearing on the interpretation of production data or on design of new experiments -- and also for their own interest.

2. PROPERTIES OF HEAVY-FLAVOURED PARTICLES

2.1 Charmed Particles

The experimental results available at the end of 1980 have been excellently summarized by Trilling⁶. The data were rather extensive for the D^+ , D^0 , and D^* mesons, meagre for the Λ_c and Σ_c , scanty and controversial for the F meson, and non-existing for other charmed particles. This 1980 information on mass, decay modes, and branching ratios is still valid; on these points nothing has been added to our knowledge of the D mesons, and rather little to that of the charmed baryons, but a few decay channels of the F meson seem to be identified now with more certainty. The main progress lies in the better determination of lifetimes, especially of the D^0 and D^+ mesons, owing to the increased use of new (or revived) techniques.

Since results of several of those experiments will be mentioned at various places -- and also because some of these techniques

should be more and more important in the near future -- let us describe them briefly. All use a vertex detector able to separate the interaction point from the decay apex of the charmed particle and to measure the distance of flight $\ell = c\tau p/m \approx 300 \mu\text{m}$ for $p = 20 \text{ GeV}/c$ and $\tau = 10^{-13} \text{ s}$ (however, up to now, this characteristic property of charm has not been used as a trigger). The various techniques used are:

i) Visual identification of decays, either with emulsions, high-resolution bubble chambers, or streamer chambers, usually followed by a spectrometer measuring and (ideally) identifying the secondary particles.

The emulsion experiments are E531 ⁷, in a neutrino-beam at FNAL, and WA58 ⁸ in a 40-70 GeV/c photon beam at CERN (the spectrometer is the Ω). An example of $\Lambda_c \bar{D}^0$ production in WA58 is shown in Fig. 1; the Λ_0 from the Λ_c is seen in the Ω .

Fig. 1. A $\Lambda_c \bar{D}^0$ event in emulsion (Ref. 8).

The bubble-chamber experiments are BC73 ⁹, using the SLAC 40 ft hydrogen chamber in a 19.5 GeV/c photon beam, NA16 ¹⁰, where LEBC, a small rapid-cycling hydrogen chamber in front of the (incomplete) EHS spectrometer, was exposed to 340 GeV/c π 's and 360 GeV/c protons, and NA18 ¹¹, which exposed BIBC, a very small heavy liquid bubble chamber followed by a streamer chamber, to a 340 GeV/c π^- beam. Figure 2 shows the photoproduction of a charmed pair, as seen in experiment BC73.

Fig. 2 A charmed pair in a bubble chamber (Ref. 9)

ii) Detection of the increase of charged multiplicity due to D-decay(s), downstream from the interaction. This was achieved by the photoproduction experiment NAL¹², using an active silicon target in front of the FRAMM spectrometer. Figure 3 clearly shows two steps $\Delta n_{ch} = 2$, as expected from two successive charm decays (however background from secondary interactions and photon conversion is not negligible). Quite a few groups plan to use a similar technique in the years to come -- and possibly to incorporate it in a "charm trigger".

iii) Reconstruction of vertices (interaction and decay) by extrapolation of tracks measured in precise vertex detectors. For the moment, this approach has been used only by the MARK II group¹³ with the help of a small high-precision ($\sim 50 \mu m$) cylindrical drift chamber surrounding the vacuum tube of PEP. Extrapolation gives a longitudinal error of about $700 \mu m$ on the decay vertex, good enough to measure the lifetime of the τ lepton¹⁴: $\tau(\tau) = 3.31 \pm 0.57 (\pm 0.6) \times 10^{-13} s$, in agreement with the theoretical value ($\sim 2.8 \times 10^{-13} s$). Several groups are working on vertex detectors built of silicon microstrips, with which a resolution of several microns can in principle be achieved; a more ambitious goal would be, with the help of fast processors, to use them in the trigger.

Fig. 3 Multiplicity steps in a silicon active target (Ref. 12).

2.1.1 The D mesons. Table 1 gives the properties of the D mesons most useful to the experimentalist.

Except for the lifetimes, all values are from Ref. 6, in which branching ratios for a few other exclusive decay channels can be found (all of the order of a few per cent, with rather large errors). The mean charged multiplicity is 2.16 ± 0.16 for the D^+ and 2.46 ± 0.14 for the D^0 . Finally, the measured inclusive branching ratios (BR) of the D mesons into $\bar{K}$ are, within errors, compatible with the expected value $\cos^2 \theta_c$ ($\sin \theta_c \approx 0.22$) -- i.e. Cabibbo-favoured decays do dominate.

Table 1. Masses, Lifetimes, and Branching Ratios (BR) of D Mesons

	M (MeV)	τ (10^{-13} s)	BR($D \rightarrow e^+$)	Main Hadronic Channels	BR (%)
D^0	1863.7 ± 0.4	$4.0^{+1.2}_{-0.9}$	$\begin{cases} < 5 \\ 5.5 \pm 3.7 \end{cases}$	$K^-\pi^+$ $K^0\pi^+\pi^-$	2.6 ± 0.4 3.9 ± 0.9
D^+	1868.4 ± 0.4	$9.3^{+2.7}_{-1.8}$	$\begin{cases} 24 \pm 3.7 \\ 16.8 \pm 6.4 \end{cases}$	$\bar{K}^0\pi^+$ $K^-\pi^+\pi^+$	1.8 ± 0.5 4.7 ± 0.8
D^{*0}	2007.0 ± 1.2			$D^{*0} \rightarrow \gamma D^0$ $D^{*0} \rightarrow \pi^0 D^0$	~ 40 ~ 60
D^{*+}	2010.1 ± 0.8			$D^{*+} \rightarrow \pi^+ D^0$ $D^{*+} \rightarrow \pi^0 D^+$ $D^{*+} \rightarrow \gamma D^+$	~ 63 ~ 30 ~ 7

Quoted lifetimes are the world averages of the recent experiments described above as reported at the 1982 Paris Conference¹⁵. The results of individual experiments are given in Fig. 4, and are seen to agree fairly well with each other (as a comparison, at the 1980 Madison Conference, the result of the statistically most significant experiment, E531, was $\tau_0 = 1.0 \pm 0.4^{+0.3}_{-0.2}$ s and $\tau^+ = 10.3 \pm 1.0^{+0.5}_{-0.8}$ s). This leads to a ratio

$$R = \tau(D^+)/\tau(D^0) = 2.2^{+0.9}_{-0.6} \quad (1)$$

(instead of 10 or 5, two years ago). As observed by Treiman and Pais¹⁶, for Cabibbo-favoured semi-leptonic decays, which are isospin 0 transitions between two isospin $1/2$ states, the relation $\Gamma(D^+ \rightarrow \ell^+ \dots) = \Gamma(D^0 \rightarrow \ell^+ \dots)$ should hold, and hence

Fig. 4. D^0 and $D^{\pm}$ lifetimes (compiled by S. Reucroft).

$$\frac{BR(D^+ \rightarrow e^+ \dots)}{BR(D^0 \rightarrow e^+ \dots)} = \frac{\tau(D^+)}{\tau(D^0)} = R. \quad (2)$$

Results on BR from two different experiments at SPEAR are given in Table 1; obviously more precise data are needed to check relation (2). On the other hand, the data on the inclusive electron energy spectrum from D decay, from both SPEAR and DORIS, are precise enough and allow it to be interpreted in terms of an ~ 50 -50 mixture of $K\pi$ and $K^*\pi$ final states⁶.

At this point, it is necessary to stress that the commonly used value $BR(D \rightarrow e^+) \approx 8\%$ applies to the mixture of various charmed particles, as produced in e^+e^- collisions with $3.77 < \sqrt{s} < 8$ GeV. If, as is the case at the Ψ'' mass ($M = 3.77$ GeV), only D^0 and D^+ are produced, in approximately equal numbers, one can then derive -- with all due caution! -- $BR(D^0 \rightarrow e^+) \approx 5\%$ and $BR(D^+ \rightarrow e^+) \approx 11\%$, as values which could be used in the analysis of experimental data on D^0 and D^+ production, when triggered by an electron (or a muon). These values of $BR^{\pm}$, together with the measured values of $\tau^{\pm}$ lead to $\Gamma(D \rightarrow e^+) \approx 1.2 \times 10^{11} \text{ s}^{-1}$, in good agreement with the theoretical¹⁷ value $\Gamma \approx (G_F^2/192\pi^3)M_C^5$, with $M_C \approx 1.5 \text{ GeV}/c^2$. This value is calculated using the so-called spectator model, illustrated in Fig. 5a for Cabibbo-favoured decays. That model predicts identical lifetimes for D^+ , D^0 (and also F and Λ_C). The observed value $R = \tau_{D^+}/\tau_{D^0} \approx 2$ is qualitatively explained by the presence for the D^0

Fig. 5. a) Spectator model diagram; b) Decay of D^0 by W exchange (Ref. 6).

of a W-exchange diagram (Fig. 5b), which does not exist (for Cabibbo-favoured transitions) for the D^+ , and which leads to extra hadronic final states. (Gluon radiation is necessary to avoid suppression by helicity arguments.)

2.1.2 The F meson. Evidence for the F^+ meson (c, s, u) lies mainly (apart from a few well-reconstructed events from the emulsion-neutrino experiment E531⁷ and some, not unambiguous, events in the bubble-chamber experiments at CERN^{10,11}) in mass peaks observed in photoproduction experiments. Figure 6 shows the $\eta(5\pi)$, $\eta(3\pi)$, and $\eta\pi$ peaks seen in experiment WA14¹⁸ with the 40-70 GeV γ -beam in the CERN Ω spectrometer, and Fig. 7 the $\eta(4\pi)$ and $KK(2\pi)$ peaks in experiment NAL¹², already described. Mass ($M \approx 2.05$ GeV/c) and branching ratios are still poorly known.

Lifetime measurements from four of the five experiments just quoted are given, together with those of the Λ_c , in Fig. 8. The average is $\tau(F) = (2.9 \pm 1.8) \times 10^{-13}$ s subject to an uncertainty due to a possible misidentification of F decays, especially in the bubble-chamber experiments; the same remark applies to Λ_c decays, for which $\tau(\Lambda_c^+) = (2.2 \pm 0.9) \times 10^{-13}$ s.

Fig. 6. Some evidence for F photoproduction (Ref. 18).

Fig. 7 Other evidence for F photo-production (Ref. 12)

Fig. 8 F and Λ_c lifetimes (compiled by S. Reucroft)

With this caveat in mind, one notes that the F and Λ_c lifetimes seem to be smaller than that of the D^+ ($\sim 9 \times 10^{-13}$ s). As in the case of the D^0 , this may be explained by annihilation or exchange diagrams, as shown in Figs. 9a and b for Cabibbo-favoured transitions. Hence one expects $\tau(F) \approx \tau(\Lambda_c) \approx \tau(D^0) < \tau(D^+)$, in agreement with present data [more detailed theoretical considerations lead to the expectation of $\tau(F) > \tau(D) > \tau(\Lambda_c)$]. It should be remarked that

Fig. 9. a) F^+ annihilation diagram, b) Λ_c exchange diagram (Ref. 6).

the dominant final states resulting from the annihilation diagram (Fig. 9a) will not be $s\bar{s}$ like those expected from the spectator model in Cabibbo-favoured transitions (Fig. 5a). Experimentally the proportion of $s\bar{s}$ final states ($K\bar{K}$, $\eta\pi\pi$, ...) in F decays is still an open question.

2.1.3 Charmed baryons. The best known is the singlet Λ_c (c, u, d), with the following characteristics⁶:

$$M(\Lambda_c) = 2285 \pm 5 \text{ MeV}$$

$$BR(\Lambda_c \rightarrow K^- p \pi^+) = (2.2 \pm 1.0)\%$$

Other observed decay modes ($K^0 p$, $\Lambda \pi^+$, $\Sigma^0 \pi^+$) seem to have branching ratios of roughly one-half the above value. Upper limits of suspected decay modes ($\Lambda^0 \pi^+ \pi^+ \pi^-$, $K^0 p \pi^+ \pi^-$) are of the same order. The bulk of the Λ_c decay modes are consequently unknown.

A new result¹⁹ has come from MARK II, using a procedure similar to that which gave the branching ratio into $K^- p \pi^+$:

$$BR(\Lambda_c \rightarrow e^+ \dots) = (4.5 \pm 1.7)\%$$

including

$$BR(\Lambda_c \rightarrow p e^+ \dots) = (1.8 \pm 0.9)\%$$

$$BR(\Lambda_c \rightarrow \Lambda^0 e^+ \dots) = (1.1 \pm 0.9)\%$$

The Σ_c ($I = 1$) has been seen via its (strong) decay modes: $\Sigma_c^{++} \rightarrow \Lambda_c^+ \pi^+$ and $\Sigma_c^+ \rightarrow \Lambda_c^+ \pi^0$. Its mass is such that $M(\Sigma_c) - M(\Lambda_c) = 168 \pm 3 \text{ MeV}$, as compared with an expected theoretical value of $\sim 160 \text{ MeV}$.

At the time of that write-up, preliminary evidence was presented for the charmed strange hyperon A^+ (c, s, u), in the form of an $\sim 5 \sigma$ peak in the $\Lambda K^- \pi^+ \pi^-$ mass spectrum (Fig. 10) obtained²⁰ with a spectrometer in a 135 GeV/c Σ^- beam [however, the corresponding production cross-section seems rather large and the A^0 (c, s, d) member of the doublet has not been seen].

2.2 Beauty

Since the first hints⁵ of naked beauty in e^+e^- collisions, via formation of a broad resonance T''' with abundant K and electron yields (as expected from $T''' \rightarrow B\bar{B}$, $B \rightarrow C \dots$, $C \rightarrow K \dots$, and

Fig. 10. First evidence for the Λ^+ baryon (Ref. 20).

$B \rightarrow C + e + \dots$), some properties of the B meson have been more precisely measured (see Ref. 15 for more details).

From the non-observation of the ~ 50 MeV γ 's expected to arise from $B^* \rightarrow B\gamma$, leading to the inequality $2M_B > M(T''') - 50$ MeV, together with the obvious inequality $2M_B < M(T''')$, one estimates $M(B) = (5256 \pm 7)$ MeV.

The energy spectrum of the decay electrons has a shape in agreement with that predicted for a decay $B \rightarrow e^- \bar{\nu} X$, with $M(X) \approx 2$ GeV, as expected if the favoured decay mode is $b \rightarrow ce^- \bar{\nu}$ rather than $b \rightarrow ue^- \bar{\nu}$. More quantitatively, from the decay spectrum, $|b \rightarrow u|^2 / |b \rightarrow c|^2 < 0.042$. The branching ratio for electron decay (average of four experiments) is found to be $(13 \pm 2)\%$, and $BR(B \rightarrow \mu^- \dots)$ has a comparable value.

The dominance of $b \rightarrow c$ decays, followed by Cabibbo-favoured $c \rightarrow s$ decays implies the presence in the final state of almost 2K's ($1K, 1\bar{K}$) per $B\bar{B}$ event. The present experimental results on K^0 and $K^\pm$ yield $(b \rightarrow c)/\text{all} = 0.74 \pm 0.18$, a less precise number than that derived from the electron spectrum. The mean charged multiplicities per B decay are 4.1 ± 0.35 for semi-leptonic decays and 6.3 ± 0.3 for hadronic final states.

Finally, only an upper limit ($\tau_B < 1.4 \times 10^{-12}$ s) has been measured for the lifetime. Theoretical expectations²¹ based on the spectator model (annihilation diagrams should be less important than for charm, because of the higher mass) are around $\tau \approx 10^{-14} - 10^{-15}$ s (assuming $b \rightarrow c$ dominance), leading to a decay length visible in emulsions, but very difficult, if not impossible, for other techniques.

2.3 Top

The top quark should build with the beauty quark the 3^d quark doublet, corresponding to the 3^d lepton doublet ($\tau, \bar{\nu}_\tau$). The only

thing we know for sure about it, if it exists, is that its mass is higher than ≈ 20 GeV (from the non-observation of toponium at PETRA). Theoretical upper limits for the mass are reviewed elsewhere²¹; a firm one²² is ≈ 200 GeV, which leaves ample room (however, the higher the mass, the more difficult it will be to find it).

The lifetime ($\sim m^{-5}$) will be unmeasurable. Semi-leptonic decays, with BR $\approx 12\%$ each and $\langle p_T \rangle \gtrsim 10$ GeV, should be relatively easy to detect, if not to identify. Favoured hadronic decays should be into $b\bar{c}s$ and bud , the first one leading to three kaons in the final state. If the mass is high enough, decays such as $t \rightarrow bH^+$, $t \rightarrow bW^+$ should occur.

3. HADROPRODUCTION OF CHARMED PARTICLES

3.1 Experimental Methods

As will be seen below in more detail, the production of a pair of charmed particles, C and $\bar{C}$, via the reaction:

$$p(\text{or } \pi^-) + p \rightarrow C\bar{C}'X \quad (3)$$

has a total cross-section, summed up over the various possible $C\bar{C}'$ pairs, equal to about 10^{-3} the total inelastic pp cross-section at the maximum SPS energy ($\sqrt{s} \approx 27$ GeV), rising to somewhat more than 10^{-2} at the ISR ($\sqrt{s} = 52$ or 63 GeV).

To separate the charmed signal from the dominant background, various characteristic features of charmed decays are used at the analysis stage and in some cases the trigger level.

3.1.1 Lepton emission. This proceeds according to the $\Delta Q = \Delta C$ rule:

$$C \rightarrow \ell^+ \nu \dots, \quad \bar{C}' \rightarrow \ell^- \bar{\nu} \dots \quad (\ell = e \text{ or } \mu) \quad (4)$$

In the charmed particle c.m. the spectrum of E^* , the lepton-energy, ends at about 1 GeV for the D meson. Hence, in the laboratory system, if $p_T(D) < M(D)$, most leptons will have $p_T < 1$ GeV/c and their average energy will be $\langle E \rangle \approx x_F \sqrt{s}/2M \langle E^* \rangle$ at the ISR and $\langle E \rangle \approx x_F p/M \langle E^* \rangle$ in a beam of momentum p, x_F and M being the Feynman x and the mass of the charmed particle, respectively. For $M \approx 2$ GeV, and with $\langle E^* \rangle \approx M/4$, $\langle E \rangle \approx 4 x_F$ at the ISR and $\langle E \rangle \approx 100 x_F$ at the SPS (in GeV). The high values of $\langle E \rangle$ at the SPS, together with the small value of p_T , makes the detection of muons and neutrinos relatively easy and efficient in a small-angle forward cone but not that of electrons, which are accompanied in that cone by other particles which cannot be filtered out, as they are in beam-dump experiments designed to search for prompt μ 's or ν 's. On the other hand, μ or

ν detection is impractical or impossible at the ISR, where only inclusive yields of electrons at large angles have been measured.

Besides the experimental problem of subtraction of leptons of non-charm origin (electrons from γ conversion, μ 's and ν 's from π and K decays), the main drawback of this approach is that it gives only, so to say, second-hand information on charm production: the observed lepton spectrum results from the (unknown) charm-production spectrum through a convolution with the charm-decay spectrum.

Moreover the nature of the parent charmed particle (D^+ , D^0 , Λ_c , ...) is not directly known -- and, as seen above, the semi-leptonic branching ratio, and hence the inferred production cross-section, will depend on the assumption made about it.

The method has been extended to dilepton ($e^+\mu^+$, $\mu^+\mu^+$) detection, reducing the background problems, but "squaring" the uncertainties in interpretation.

3.1.2 Narrow mass peaks. These are looked for in exclusive hadronic decay channels, such as the Cabibbo-favoured $\Delta C = \Delta S$ decays (see Table 1):

$$D^0 \rightarrow K^-\pi^+ \quad \text{or} \quad \Lambda_c^+ \rightarrow K^-\pi^+\pi^+ . \quad (5)$$

Since the decay is a weak process, the width of the peak should be equal to the experimental resolution. Hence resolutions of a few megaelectronvolts allow charmed decays to be distinguished from strange resonances, which, in that mass range, have a width of the order of 100 MeV. Supplementary confirmation of the charm nature may be provided

i) by direct quantum number assignment, as in

$$D^+ \rightarrow K^-\pi^+\pi^+ \quad \text{or} \quad \Sigma_c^{++} \rightarrow \Lambda_0 \pi^-\pi^+\pi^+\pi^+ \quad (6)$$

which clearly cannot be $I = 1/2$ or $I = 1$ resonances of strangeness -1;

ii) by the presence in the interaction (through the trigger, for instance) of a lepton of the right sign, i.e. an e^- with a C particle, an e^+ with a $\bar{C}$;

iii) by the observation of a distribution of small, but non-zero, decay lengths associated with the mass peaks, as in Ref. 12 or 13.

Usually, the sought-after charmed mass peak, if any, will sit on a much bigger non-charmed background, owing to the many non-charmed combinations in the same mass range. This background is

reduced (but not completely suppressed) by particle identification -- a comprehensive charm production study thus calls for an ideal 4π spectrometer (which up to now does not exist). The signal can also be enhanced by selecting *a priori* a region of phase space (for instance, "diffractive" production or high p_T) where intuition or theory points to a better signal/background ratio -- of course this procedure introduces a strong bias.

In both cases (lepton or mass-peak detection) the experimental result is a $dN/dp_T dx$ distribution (background subtracted) over a limited region of phase space, with acceptance varying over that region. To extract from it a production cross-section, one has to assume a charm production law, calculate from it the expected $d\sigma/dp_T dx$ (of the lepton or the mass peak), and compare it with the observed one (for most experiments, statistics do not allow one to distinguish between various possible production distributions and one can then only quote the values of the total production cross-section under the various hypotheses). The most commonly used production law is of the form:

$$E \frac{d^3\sigma}{dp^3} \sim (1-x)^n e^{-bp_T} \quad (\text{or } e^{-b'p_T^2}), \quad (7a)$$

which describes a central production process if $n \approx 5$ and a forward process if $n \approx 1$ (see later). Other phenomenological distributions have been used, especially for the early ISR data:

$$\text{a flat-}y \text{ distribution: } \frac{d\sigma}{p_T dp_T dy} \sim e^{-bp_T} \quad (7b)$$

$$\text{a flat-}x \text{ distribution: } \frac{d\sigma}{p_T dp_T dx} \sim e^{-bp_T}. \quad (7c)$$

When two leptons or a mass peak associated with leptons are observed, the same procedure is applied, starting from an assumed double distribution law at production, which may be a product of two distributions of type (7) (uncorrelated production), or the distribution resulting from the decay of a $C\bar{C}$ system produced according to some law of type (7) (correlated production).

3.1.3 Small decay length. Up to now, as seen in Section 2.1, this method was used mainly for lifetime determinations. In the case of emulsions or bubble chambers, the primary flux is limited, yielding a rather small sample of charmed events, but these events are essentially background free and usually well identified, and moreover, the acceptance is almost constant* (for $x_F > 0$). Hence,

* The charm decay is detected during scanning by the presence of a secondary track missing the interaction vertex by a distance d , whose most probable value is $d \approx c\tau$, for $x_F > 0$.

they are perfectly suited for production studies and, indeed, as will be seen below, recent results from bubble-chamber experiments at CERN have brought novel information on D-production. One may hope that, in the near future, charm triggered microstrip detectors (or high-precision drift or streamer chambers) will provide decent samples of rather pure charmed events. Of course, as outlined above, a good spectrometer behind is a must.

Finally, one word of caution should be said about results extracted from experiments with a heavy target; it is now customary, for the naked charm production cross-section σ_c , to assume that $\sigma_c(pA) = A^\alpha \sigma_c(pp)$, with $\alpha \approx 1$ as found experimentally for μ -pair or J/ψ production²³. An $A^{2/3}$ law, as used for total cross-section or diffraction, would lead to charm cross-sections about 4 times higher with a Cu target (this was partly responsible for some high cross-sections reported from the first beam-dump experiments²⁴). Recent experimental data²⁵ on inclusive particle production as a function of Feynman x , shown in Fig. 11, indicate that the exponent α decreases when x increases, roughly in the same way for all non-charmed particles. Knowledge of the corresponding curve for charm would be most useful and should be a goal of future experiments; for lack of it, one can only make an educated guess: $\alpha \approx 1$ for small x , dropping perhaps to about $2/3$ for high x . In what follows, cross-sections will be calculated with $\alpha = 1$, except otherwise mentioned, but this word of caution should be kept in mind. Note also that a dependence of α on x , such as in Fig. 11, will make the inclusive x -distribution obtained from a heavy target softer than the one seen in pp collisions, since small values of x will be more favoured (a similar remark²⁶ applies to the p_T distribution, which becomes wider when A increases).

Fig. 11. The exponent α in $\sigma(A) = A^\alpha \sigma(p)$ (Ref. 27).

3.2 First Results and Theoretical Background

Let us briefly summarize the evolution of data and theoretical ideas up to 1981 (for more complete experimental surveys, see Ref. 27, and for a lucid theoretical appraisal see Ref. 28).

First QCD calculations for charm production (see for instance, Ref. 29) were based on the diagrams of Fig. 12a ($q\bar{q}$ annihilation) and 12b (gluon-gluon fusion), the last one being dominant in pp collisions. They predicted (Fig. 13) total charm production cross-sections of a few microbarns at the SPS. The first (1978) convincing evidence for charm hadroproduction came from beam-dump experiments²⁴ and pointed to a much higher cross-section ($\sim 30 \mu\text{b}$ in the CDSH experiment). Figure 14 shows an attempt³⁰, by varying parameters, to accommodate that value within the framework of the gluon-gluon fusion model; in particular the mass of the c quark had to be chosen equal to 1.15 GeV, whereas $m_c = 1.5 \text{ GeV}$ is required²⁸ for a good fit of the data on charm photoproduction to the gluon-photon fusion model³¹, which is very similar to the gluon-gluon fusion model. Except for the proviso about absolute cross-sections, most data, old and recent, from proton beam-dump experiments seem to fit well a $D\bar{D}$ central production model [Eq. (7a)] with $n \approx 4-6$, $b \approx 2 \text{ GeV}$, and $\sigma(D\bar{D}) \approx 20 \mu\text{b}$ and leave little room for production of charmed particles at large x values (see later for more details).

Soon after (1979) three different ISR experiments³² detected large mass peaks in the (until then unknown) $\Lambda_c \rightarrow K^- p \pi^+$ decay

Fig. 12 $c\bar{c}$ creation diagrams (Ref. 29)

Fig. 13 Charm production (upper curves: $p\bar{p}$, lower: pp) via $c\bar{c}$ creation (Ref. 29)

Fig. 14 Gluon fusion: a) at $\sqrt{s} = 27 \text{ GeV}$, b) with $m_c = 1.1 \text{ GeV}$, $\Lambda = 0.5 \text{ GeV}$ (Ref. 30).

channel and one of them³³ also reported D^+ production. These results had two important common features: the total inclusive cross-section was large (200–400 μb for either the Λ_c^+ or the D^+), and an abundant production of the Λ_c^+ and the D^+ was observed at large Feynman x values. These two characteristics have since then been confirmed by other ISR experiments; Fig. 15, from Ref. 34, shows that the x behaviour of Λ_c^+ production is in close analogy with that of the Λ^0 , which is well known. Clearly some other process must exist, besides gluon-gluon fusion which predicts much smaller cross-sections (Fig. 14) and central production (reflecting the soft distribution of the gluons).

Fig. 15 Λ_c^+ production at the ISR, compared to Λ^0 and $\bar{\Lambda}^0$ (Ref. 34)

Actually, as first pointed out by Combridge³⁵, another possibility for charm production is charm excitation, as illustrated in Figs. 16a and b, whereby a parton from one nucleon excites a charmed quark from the sea of the other one. The charm cross-section versus energy, as calculated in Ref. 35 using the then standard parton distributions and evolution laws³⁶ and $m_c = 1.87$ GeV, is shown in Fig. 17, together with the experimental results available in 1981 (black dots) and some new results (open dots), which will be discussed below. The cross-section is smaller than that of the former gluon-fusion model³⁰ (with $m_c = 1.15$ GeV), but it has the interesting feature of growing much faster (using the same *ad hoc* trick as in Ref. 30, i.e. putting $m_c = 1.3$ GeV, one even obtains a rather good fit of the data). This indicates that the diagram of Fig. 16b (which dominates over that of 16a) should have not been forgotten, even though in its original formulation³⁵, it did not explain the large x_F values (the knocked-out c quark should give a charmed particle in the central region, the other charm will be in the spectator jet, with an x_F resulting from the usually low x of the $\bar{c}$ quark via recombination with appropriate normal quarks).

Fig. 16. Charm excitation diagrams (Ref. 35).

A first attempt at explaining charm production at large x (besides earlier models, such as those for diffractive production³⁷ or gluoproduction³⁸) was the intrinsic charm model³⁹. The hypothesis -- which is based on debated theoretical grounds -- is that the ground state of the proton is a superposition of several states: $|\psi\rangle = (1-\epsilon)|uud\rangle + \epsilon_1|uudc\bar{c}\rangle + \dots$, i.e. that a $c\bar{c}$ pair has a probability $|\epsilon_1|^2$ of being present in the proton -- hence the name "intrinsic". This is in contrast with $c\bar{c}$ pairs from the QCD sea, which start to be generated only when $Q^2 > Q_0^2$ (they are sometimes called "extrinsic"). An immediate consequence of the hypothesis is that the c -quarks, in order to remain bound with the other ones, must have the same velocity: hence, since they are heavier, the c and $\bar{c}$ quarks share between them most of the momentum of the proton. Figure 18a illustrates this fact, and Figs. 18b and c give the x_F distributions for Λ_c and D production which result from the c -quark x distribution. Qualitatively at least, a 1-2% intrinsic charm component could thus explain the main features of charm production at the ISR, as well as a D^+ (D^-) signal observed⁴⁰ in 217 GeV/c π^-p

Fig. 17 Charm pp production cross-sections compared to various models (see text)

Fig. 18 Intrinsic charm model predictions (Ref. 39)

diffractive interactions* at FNAL, and reproduced in Fig. 19. However, in this model, the cross-section is proportional to $\log s$ (as a diffractive cross-section), not enough to account for the big ratio (> 10) between SPS and ISR. A more stringent argument against intrinsic charm may be the fact that it does not seem to manifest itself in the charm structure function derived from charm muoproduction experiments. Figure 20 shows this structure function as obtained by the EMC experiment⁴¹ from dimuon events produced in the (virtual) photoproduction process $\mu\text{Fe} \rightarrow \mu\text{C} \dots$, $\text{C} \rightarrow \mu \dots$. It fits rather well the gluon fusion model (GFM) used by the authors (plain curves) in the acceptance region, giving an upper limit of 0.28% at 90% c.l. for intrinsic charm. However, the deviation from GFM at high Q^2 may indicate the onset of an intrinsic charm component (IC) with a strong threshold suppression⁴².

* Detection of a recoil proton signalled the diffractive interaction; one of the D decays was tagged by the presence of a muon, the other one was seen as a mass peak in the $D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$ mass distributions. In the natural hypothesis of $X^- = D^+ D^- \pi^-$ diffractive production, one finds $\sigma(p\pi^- \rightarrow pX^-) = (7-10) \pm 4 \mu\text{b}$, using $\text{BR}(D^+ \rightarrow \mu^+) = 23\%$ (Table 1).

Fig. 19 Diffraction production of $D^\pm$ (Ref. 40)

Fig. 20 Measured charm structure function (Ref. 41) versus two models (see text)

Fig. 21. Calculated x -distributions of charm a) at ISR, b) at SPS (Ref. 43).

A more recent model⁴³ tries to avoid the theoretical and experimental objections raised by the intrinsic charm model. While retaining the idea of charm excitation from an evolutive sea as in Ref. 35, it gives the charm quarks a hard distribution $x_C(x) \sim x(1-x)$ similar to that resulting from the intrinsic charm model³⁹. In the diagram of Fig. 16b, then, the knocked-out or "active" quark carries away its fractional momentum, while the spectator quark may recombine with its original proton. The resulting x_L distributions at ISR and SPS energies are shown in Figs. 21a and b. The agreement

with ISR results looks good, but the total experimental ISR cross-section ($\Lambda_c + D^+ + D^0$) is several times higher than the calculated one (see Fig. 17) (this is because the excitation cross-section is roughly proportional to $\log^2 s$ only).

3.3 Recent Results and Developments

They can be summarized in one sentence: several SPS or FNAL experiments, using very different techniques, have now observed the large x component of charm production, which was one of the surprises brought about by the ISR, with the following caveat: this effect is seen mainly in π^- interactions, only two experiments have indirect evidence for it in proton interactions (contrary to the ISR, Λ_c production remains elusive at SPS energies). Results are now reported, starting with those most easy to interpret.

3.3.1 Results from visual detectors. In 360 GeV π^-p interactions, the LEBC experiment NA16 has reported results⁴⁴ of a new kind on D and $\bar{D}$ production: for the first time, the production of the various charged states could be observed in the same experiment, and, despite the small statistics (18 D decays) new information has emerged. Figures 22a and b show the x distribution of D^- and D^0 events on the one hand, and D^+ and $\bar{D}^0$ on the other. It is clear that the first one extends to high x , whereas the second does not; qualitatively, this may be explained by the fact that a spectator c or $\bar{c}$ can recombine with the $\bar{u}$ or d quark of the π^- to give a D^0 or

Fig. 22 x -distributions of various D mesons in LEBC (Ref. 44)

Fig. 23 Integral x -distribution of all D mesons in LEBC (Ref. 44)

D^- , but cannot give in the same way a D^+ or $\bar{D}^0$ -- lending support to the diagram in Fig. 16b, as treated in Refs. 39 or 43 (see Ref. 45 for a more complete discussion). Figure 23 shows the integral x distribution of all observed D and $\bar{D}$ particles, where two components may be seen, one (central) with slope $n \approx 6$, the other one with $n \approx 1$ containing about 30% of the D 's. The p_T distribution (not shown) is $\sim \exp(b' p_T^2)$ with $b' = (1.1 \pm 0.3) \text{ GeV}^{-2}$, and the total cross-section for inclusive $(D + \bar{D})$ production is $40 \pm 15 \mu\text{b}$ for $x > 0$ ($\approx 31 \mu\text{b}$ for $D + D^0$, ≈ 9 for $D^+ + \bar{D}^0$). Another interesting result is that $D\bar{D}$ observed in pairs seem to be strongly correlated: $\langle \Delta y \rangle \approx 0.5$ (which should be considered as a lower limit, since the pair is not always seen).

The same experimental set-up was used with a 360 GeV/c proton beam⁴⁶. Here no difference in the x distribution was seen between the various D particles; the inclusive D distribution fitted a $(1-x)^{1.8 \pm 0.8} e^{-(1.1 \pm 0.3) p_T^2}$ law*, with $\sigma(D + \bar{D}) = 56 \pm 25 \mu\text{b}$ (for all x). If the excess of $\bar{D}$ is interpreted as due to $\bar{\Lambda}_c \bar{D}$ production, then $\sigma(D\bar{D}) = 19 \pm 13 \mu\text{b}$, and $\sigma(\Lambda_c \bar{D}) = 18 \pm 10 \mu\text{b}$ (only 3 ambiguous Λ_c decays have been detected, one of which is $\Lambda_c \rightarrow K^- p \pi^+$, corresponding to $\sigma \sim 40 \mu\text{b}$). Finally no strong correlation between D and $\bar{D}$ is observed ($\langle \Delta y \rangle > 1.2$), unlike what happens in $\pi^- p$ interactions.

In another experiment¹¹, NA18 (340 GeV/c π^- in BIBC, a small C_3F_8 bubble chamber), 14 well-identified D candidates were found and reconstructed (in a streamer chamber downstream). Their x distribution is given in Fig. 24, together with the acceptance; the average value of p_T is 0.95 GeV/c. Using a central production

Fig. 24 x -distribution of D mesons in BIBC (Ref. 11) compared to acceptance

* One would not expect an $n = 1$ value similar to that observed for D^- in $\pi^- p$ interactions (or expected for Λ_c in pp , as at the ISR): $\bar{D}$'s can be formed by using one quark of the proton, and, according to quark counting rules⁴⁷, an $n \approx 3$ value would be expected in that case, versus $n \approx 5$ (truly central production) for D 's.

model, which from Fig. 24 seems to be favoured*, the authors obtain, from ~ 35 (background subtracted, but non-identified) double decays, $\sigma(\pi^- p \rightarrow D\bar{D}) = 28 \pm 11 \mu\text{b}$ (73 ± 27 if $\sigma \sim A^{2/3}$).

Finally an experiment in which a stack of 600 μm thick emulsions was exposed to 400 GeV/c protons reported⁴⁸ a background-subtracted signal of eight 3-prong but otherwise unidentified charm decays. Assuming these are $\Lambda_c \rightarrow K^- p \pi^+$ decays ($D^\pm$ decays would give a much higher cross-section, because of the large escape probability due to the bigger $D^\pm$ lifetime), a cross-section $\sigma(pp \rightarrow \Lambda_c \dots) \sim 100 \mu\text{b}$ is obtained.

3.3.2 Results from mass peaks. They come essentially from experiment NAl1 at CERN. This experiment⁴⁹ uses an electron trigger ($p_T > 0.3$ GeV) to enhance the charm signal in π^- (or p) Be interactions detected in a spectrometer with Čerenkov identification and photon calorimetry (Fig. 25). With incoming 180 GeV/c π^- 's, a clear $D^0 \rightarrow K^- \pi^+$ (and c.c.) peak is observed (Fig. 26a), when applying the requirement $143 < m(K^- \pi^+ \pi^+) - m(K^- \pi^+) < 148$ MeV, i.e. requiring that the D^0 stems from a D^* . The acceptance-corrected x_F distribution of the D^* events, shown in Fig. 26b, agrees well with a $(1-x)^n$ law, with $n = 1 \pm 0.6$; an $e^- p_T$ dependence accounts

Fig. 25. The ACCMOR spectrometer (Ref. 49).

* This seems in contradiction with the result of NAl6, reported above. However a possible high- x tail may well be suppressed by statistical fluctuations or the reverse may have taken place (fitting the distribution of Fig. 23 to a single $(1-x)^n$ law yields $n = 2.8 \pm 1.2$).

Fig. 26. a) D^0 peak from $D^{*\pm}$ production, b) $X(D^*)$ distribution versus $(1-x)$ law (Ref. 49).

Fig. 27. Inclusive D production in experiment NALL (Ref. 49).

for the $d\sigma/dp_T^2$ distribution. Using these laws for D^{*+} and D^{*-} production, values approximately as in Table 1 for the various branching ratios, and $\sigma(\pi^-A) = A\sigma(\pi^-p)$, the authors obtain

$$\sigma(D^{*+} \dots) + \sigma(D^{*-} \dots) = (17 \pm 3) \mu\text{b} \pm 10 \mu\text{b} .$$

Inclusive D production is also directly observed, as shown in Fig. 27, where it is seen to extend also to rather high x-values. Assuming a D/D^* ratio of 1 at production, one gets $\sigma(D\bar{D}) = (34 \pm 8) \mu\text{b} \pm 24 \mu\text{b}$.

D^{*+} and D^{*-} production occurs in a similar way with 120 GeV/c π^- 's, from which one gets $\sigma(120 \text{ GeV})/\sigma(180 \text{ GeV}) = 0.41 \pm 0.15$ (the first measurement of energy dependence in the same experiment, hence without systematic errors).

Finally, with 150 GeV/c protons, no charm signal was observed, yielding an upper limit at 90% c.l. of $(24 \pm 17) \mu\text{b}$ for $\sigma(pp \rightarrow \Lambda_c \dots)$, when one uses production laws of type (7a) for $\Lambda_c D$ production, with $n = 2.5$ (4.5) and $b' = 2.5$ (2.5) for the $\Lambda_c(\bar{D})$.

The results of NALL on $D^{*\pm}$ production recall to mind those of an older 200 GeV π^- Be experiment at FNAL⁵⁰, which first used the trick of recognizing charm production by the small Q value of the decay $D^{*+} \rightarrow \pi^+ D^0$. The $x_F(D^*)$ distribution, shown in Fig. 28, fits best a $(1-x)^3$ law, without excluding $(1-x)$. With $(1-x)^3$, a cross-section $\sigma(\pi^- p \rightarrow D^*) \sim 4.4 \mu\text{b}$ was calculated.

No charge asymmetry between D^{*+} and D^{*-} production was mentioned in Refs. 49 and 50, as was found between D^+ and D^- in Ref. 44 (but not in the diffractive production of Ref. 40). The common feature of these experiments is the indication of a rather broad $x(D)$ distribution [$n = 1-3$ in Eq. (7a)], in qualitative agreement with the models of Refs. 39 and 43, and with the latest ISR results³⁴, rather than with a purely central production ($n \approx 5$).

Fig. 28. $x(D^*)$ distribution (Ref. 50).

Finally a spectrometer experiment in a 58 GeV/c neutron beam at Serpukhov⁵¹ has observed mass peaks in the $K^0 p \pi^+ \pi^-$ and $\Lambda^0 \pi^+ \pi^+ \pi^-$ final states, corresponding to $\sigma(np \rightarrow \Lambda_c \dots) \approx 44 \mu\text{b}$, a value which needs confirmation.

3.3.3 Results from single lepton experiments

i) Neutrino beam-dump experiments

A recent experiment, E613⁵² at FNAL, used a tungsten target (instead of copper as employed at CERN) and a detector much nearer to the target (allowing the recording of ν interactions up to 40 mrad, instead of ~ 2 mrad at CERN). The energy and angle distributions derived from ν_e ($\bar{\nu}_e$) charged-current events, shown in Fig. 29, agree with a $D\bar{D}$ production model $\sim (1-x)^n e^{-b p_T}$. With $n = 3$, $b = 2 \text{ GeV}^{-1}$, a cross-section $\sigma(pp \rightarrow D\bar{D}) = 18 \pm 4 \mu\text{b}$ is obtained*, using $\sigma(pA) \sim A\sigma(pp)$ and $\text{BR}(D \rightarrow \nu) = 16.4\%$ (twice the average value for $D \rightarrow e$). This can be compared with the result from the CHARM experiment at CERN⁵³, illustrated in Fig. 30, which can be translated into $\sigma(pp \rightarrow D\bar{D}) \approx 19 \pm 6 \mu\text{b}$ (with $n = 4$). For "central" $D\bar{D}$ production, one expects the yields of $\bar{\nu}$ and ν to be equal (in Ref. 52, $\bar{\nu}_\mu/\nu_\mu = 0.65 \pm 0.3$ for $E_\nu > 25 \text{ GeV}$).

Fig. 29. Distributions of ν events from FNAL experiment E513 (Ref. 52).

* Also, by considering the number of events in Fig. 29 with $E > 120 \text{ GeV}$, an upper limit at 90% c.l. for diffractive production $pp \rightarrow \Lambda_c D$ is obtained: $\sigma < 7.3 \mu\text{b}$ [using $\sigma(pA) \sim A^{2/3}$ and $\text{BR}(\Lambda_c \rightarrow e) = 4.5\%$].

Fig. 30 Distribution of shower energy from the CHARM experiment (Ref. 53)

Fig. 31 Distribution of shower energy from the CDHS experiment (Ref. 54)

On the other hand, the CDHS experiment at CERN⁵⁴ published recently a new interpretation of their data on prompt neutrino production. They explain their experimental result $\bar{\nu}_\mu/\nu_\mu = 0.46 \pm {}^{0.21}_{0.16}$ by $\Lambda_c \bar{D}$ production: the Λ_c being produced more forward than the $\bar{D}$, the higher acceptance at large x values allows the detection of more ν_μ 's (from Λ_c) than $\bar{\nu}_\mu$'s (from $\bar{D}$), whereas the reverse would be expected for DD production, if, according to quark-counting rules⁴⁷, D^- 's are produced more forward than D^+ 's. Figure 31 shows the shower energy distribution for ν_e 's, compared with predictions from $\Lambda_c \bar{D}$ production (unbroken line $n = 3$ for Λ_c^+ , $n = 5$ for $\bar{D}$; broken line $n = 1$ and 3), assuming the same semi-leptonic branching ratio for Λ_c and D [actually, as seen in Section 2.1.3, $BR(\Lambda_c \rightarrow e^+) \approx 0.6$ $BR(\bar{D} \rightarrow e^-)$, which should depress the high-energy tail of the calculated distribution, improving the agreement of the broken line]. Using for the Λ_c^+ a $(1-x)^3 e^{-2PT}$ distribution, and assuming a linear A dependence, the authors obtain from the rate of $\nu_\mu \rightarrow \mu^-$ events a value $\sigma(p + N \rightarrow \Lambda_c^+ \dots) \cdot BR(\Lambda_c \rightarrow \nu_\mu \dots) = (3.9 \pm 1.0) \mu\text{b/nucleon}$, from which, with $BR(\Lambda_c^+ \rightarrow \nu_\mu \dots) \approx BR(\Lambda_c^+ \rightarrow e^+ \dots) \approx 4.7\%$, one can derive

$$\sigma(pp \rightarrow \Lambda_c^+ \dots) \approx 40 \mu\text{b} .$$

As outlined in Section 3.1.1, the interpretation of beam-dump experiments in terms of charm production, is not unambiguous! A

potentially bigger question mark arises from the fact that the measured ratio of ν_e to ν_μ yields -- which should be equal to 1 if lepton universality holds, as we believe it does in charm decay -- seem to be less than 1. The experimental numbers are: 0.56 ± 0.21^{35} (BEBC), 0.64 ± 0.15^{22} (CDHS), 0.48 ± 0.10^{12} (CHARM), 0.78 ± 0.19 (E613). Except for one of them they are all individually consistent with 1 (and E613 outlines that $\nu_e/\nu_\mu = 1 \pm 0.3$ for $E_\nu > 30$ GeV), but the general trend clearly favours $\nu_e/\nu_\mu < 1$. The best way to check this surprising result would be to measure prompt electron and muon production in the same experiment.

ii) Muon beam dump

The CFRS experiment detecting prompt muons produced in an iron target has recently published results⁵⁵ from 350 GeV/c protons and 278 GeV/c π 's. The proton data are in general agreement with neutrino beam-dump results (except Ref. 54), in that the ratio μ^-/μ^+ is found to be compatible with 1 (1.1 ± 0.2) and the μ^+ or μ^- energy distributions (Fig. 32a) fit well a central D or $\bar{D}$ production model ($n = 6 \pm 0.8$ for D or $\bar{D}$ inclusive production at $x > 0.3$), yielding $\sigma(pp \rightarrow D) = 24.6 \pm 2.1 (\pm 3.3) \mu\text{b}$, with the usual assumptions [$\text{BR}(D \rightarrow \mu) = 8\%$, $\sigma \sim A$].

On the other hand, the recent π^- exposure has produced significantly different results for μ^- and μ^+ : $\mu^-/\mu^+ = 2.23 \pm 0.29$ and different energy spectra (Fig. 32b). More precisely, the exponent n of the $(1-x)^n$ D distribution is found to be $n = 3.4 \pm 1.0$ for $D \rightarrow \mu^+$ and $n = 1.3 \pm 0.8$ for $\bar{D} \rightarrow \mu^-$ (for $x > 0.3$), yielding similar values for the inclusive D and $\bar{D}$ production cross-sections, $\sim 10 \pm 1 (\pm 3) \mu\text{b/nucleon}$. As for the NA16 results⁴⁴, the difference in the n values may be attributed to preferred D^- (and D^0) forward production, because of quark-counting rules⁴⁷.

Fig. 32. Distribution of μ momenta: a) with protons, b) with pions (Ref. 55).

Finally, the maximum intrinsic charm contribution is shown (dotted line) in Fig. 32, as it results from fitting the high-energy tail of the spectrum; the authors conclude that the intrinsic charm component in the proton and the pion is $\lesssim 2 \times 10^{-4}$.

iii) Single electrons

As mentioned in Section 3.1.1, prompt electrons have been the object of searches at the ISR -- ever since an e/π ratio of $\sim 10^{-4}$ for $p_T > 1$ GeV/c was found at FNAL (1974). The first ISR experiments confirmed this result, but also indicated⁵⁶ a rise of the e/π ratio (at $\theta = 30^\circ$ and $\sqrt{s} = 53$ GeV) with decreasing p_T (up to $\sim 5 \times 10^{-4}$ for $p_T \sim 0.4$ GeV/c). This controversial finding, which implied⁵⁷ a large (several hundred microbarns) charm cross-section has now been confirmed⁵⁸ in another ISR experiment (at $\theta = 90^\circ$ and $\sqrt{s} = 62$ GeV). A summary of ISR measured values of the e/π ratio in the central region versus p_T is given in Fig. 33; the curves indicate the contribution of various processes, in particular charm production, calculated for a 200 μb D production according to a $(1-x)^3$ law, and beauty production (1 μb). It is clear that the e/π ratio in the region $0.4 < p_T < 1$ GeV/c, where charm electrons dominate, can be accounted for by an ~ 500 μb charm-production cross-section, as directly measured from D^+ and D^0 mass peaks³⁴ -- there is no electron crisis. On the other hand, a further increase below $p_T \approx 0.4$ GeV/c, as observed⁵⁹ in 20 GeV/c π beams, would need another explanation⁶⁰.

Fig. 33. e/π ratios measured at the ISR (compiled by T. Ekelöf).

3.3.4 Summary. The variation of prompt lepton emission versus incoming proton energy is displayed in Fig. 34, which gives the measured values of ℓ/π ($\ell = \mu, \nu, e$) in the central region ($x \approx 0$) and for $\langle p_T \rangle \approx 0.5$ GeV/c. The factor of 10 increase between top SPS and ISR energies reflects the increase in charm production cross-section* displayed in Fig. 17 (linear A-dependence was used in both figures to extract pp results from beam-dump data).

The large increase of cross-section from SPS to ISR seems thus to be definitively established. Also, despite many discrepancies in details, the leading-particle effect suggested by quark-counting rules, has now been observed not only in Λ_c^+ production at the ISR, but also in D production with π^- beams (and possibly Λ_c^+ production with p beams). Theoretical models emphasizing the importance of flavour excitation (Fig. 16b) manage to predict x distributions (see for instance Fig. 21a) which seem in reasonable agreement with the available data (actually, no complete set of data from a single experiment allows a really meaningful comparison). The big rise in cross-section from SPS to ISR energies seems harder to account for; Fig. 17 displays a recent, apparently more successful, attempt⁶¹

Fig. 34. Measured ℓ/π ratios versus energy (Ref. 58).

* Note that, within the SPS and ISR energy ranges, the ℓ/π ratio--measured inside each region with similar techniques--exhibits a clear trend to increase with energy (this is not a surprise, but a check of the relative quality of the measurements).

(for a more optimistic appraisal, see Ref. 45). In the exoneration of theory it should be stressed again that experimental results on cross-sections are marred by systematic uncertainties, resulting from model dependence and/or A dependence (beam-dump experiments and most mass peak searches with spectrometers), and/or statistical errors (bubble chambers).

In conclusion, we now have a qualitative understanding of charm production, at least for D and Λ_c production. More reliable and precise results are needed for a truly quantitative description with predictive power, which would be most helpful for heavier flavour searches (and for searches for other charmed particles, such as F^+ , A^+ , etc.). Reliability implies good acceptance over most of phase space and small background (as in bubble chambers), precision requires good statistics. 4π spectrometers combined with an accurate vertex detector and provided with a high data-taking rate capability (and/or with an efficient and unbiased trigger) are being developed for that purpose both at CERN and FNAL (where they will operate at $\sqrt{s} \approx 40$ GeV, bridging the gap between SPS and ISR). In a few years, good samples of 10^3 - 10^4 charmed events, instead of 10^1 - 10^2 now, should bring some answers to the pending problems.

4. HADROPRODUCTION OF HEAVIER FLAVOURS

Data are scarce, and mostly negative, on beauty production and non-existing for top; theoretical predictions are rather uncertain, as seen in the case of charm production. So this section should be considered not as a review, but rather as an overview of present knowledge, theoretical prejudice and prospects for the future.

4.1 Beauty

The most stringent limits on beauty production come from multi-muon final states, often as a by-product of spectrometer studies of the production of J/ψ , T , and Drell-Yan pairs. If a $B\bar{B}$ pair is produced, it may lead via the decays $B \rightarrow C + \mu^- + \dots$ and $\bar{B} \rightarrow \bar{C} + \dots$, $\bar{C} \rightarrow \mu^+$ to a pair of same-sign muons, or even to 3 (or 4) muons if the C or (and) the $\bar{B}$ have a μ^+ decay. To go back from the observed numbers of 2, 3, or 4 muon events to the $B\bar{B}$ production cross-section per nucleon, one has to conjecture a production model (usually a central one is used), use the B and C semileptonic branching ratios and decay spectra, and assume an A -dependence: $\sigma(A) \sim A^\alpha \sigma(\text{nucleon})$. The uncertainties introduced by such a procedure have been amply outlined before, in the case of single-lepton emission as a signature of charm production; here they are even greater (pair production and cascade decay, instead of inclusive production and single decay).

The most significant result obtained in this way is due to experiment NA3 at CERN; using a 280 GeV/c π^- beam on a platinum target and assuming $\alpha = 1$, NA3 obtains⁶² $\sigma(\pi^- p \rightarrow B\bar{B} \dots) < 2$ nb for central production, 10 nb for diffractive production, at 90% c.l. With 400 GeV protons, the lowest published⁶³ upper limit is 33 nb for central production; a limit of 40 nb has been reported⁶⁴ for diffractive production by 350 GeV/c protons (on iron, using $\alpha = 2/3$). The only possibly positive evidence for like-sign muon pairs originating from beauty comes from the EMC experiment⁶⁵ using a 250 GeV/c muon beam on iron, i.e. production by virtual photons; they observe three events, from which a photoproduction cross-section of about 1 nb can be derived, i.e. $\sim 10^{-3}$ of the charm photoproduction cross-section. On the other hand, it has been proved (see, for instance, Ref. 45) that the relatively abundant same-sign muon pairs observed in neutrino interactions cannot originate from beauty. One should also be aware of the fact that same-sign muon pairs may originate from D^0 - $\bar{D}^0$ mixing; a limit of 10^{12} h s^{-1} has been found⁶⁴ in this way, for the possible mass difference, Δm . If Δm is indeed not zero, then only a part of the same-sign muon-pairs come from beauty decays and the upper limits quoted above should be even lower.

Another means used to search for beauty was to look for decays of the type $B \rightarrow J/\psi + C$, $C \rightarrow K$ or μ , as suggested by Fritzsche⁶⁶. Here also results have been negative; using $\text{BR}(B \rightarrow J/\psi) = 1\%$ (the measured⁶⁷ upper limit is 1.4%), upper values for $\sigma(pp \rightarrow B\bar{B} \dots)$ ranging from ~ 10 nb to ~ 30 nb have been found^{62,68,69} with 200-300 GeV/c π -beams on complex targets. Events with two J/ψ 's have been observed by NA3, but their rate is too high to assign them to $B\bar{B}$ production⁶².

Experiment NA19 at CERN tried to detect beauty decays in emulsion, the production of beauty being tagged by the presence of three muons in the final state. No event was found, leading to an upper limit⁷⁰ at 90% c.l. of 90 nb for $\sigma(\pi^- p \rightarrow B\bar{B})$ at 350 GeV/c.

At the ISR, an estimate of central $B\bar{B}$ production can be obtained from the measured e/π ratio at 90° (Fig. 34) in the region $1 < p_T < 2$ GeV/c, which is compatible with a cross-section of a few (< 5) microbarns. Two SFM experiments have looked for forward Λ_B production, via the decay mode $\Lambda_B \rightarrow D^0 p \pi^-$: a signal at $m(\Lambda_B) \approx 5.42$ GeV was reported by one of them³⁴, corresponding, with a flat- $x(\Lambda_B)$ distribution, to $\sigma(pp \rightarrow \Lambda_B \dots) \text{BR}(\Lambda_B \rightarrow D^0 p \pi^-) = 27 \pm 17$ μb ; no signal was found by the other one⁵⁸ ($\sigma \cdot \text{BR} \lesssim 5$ μb). Experiments to obtain more conclusive results are in progress at the ISR.

In summary, experimental upper limits on beauty production cross-sections are of the order of a few nanobarns at SPS energies and a few microbarns at the ISR. The original calculations of Combridge³⁵ gave ~ 0.1 nb and ~ 0.1 μb , respectively at the SPS

and the ISR, whereas the more recent model of Barger et al.⁴³ yields ~ 100 nb at the SPS, $1 \mu\text{b}$ at the ISR, and $20 \mu\text{b}$ at the CERN $p\bar{p}$ collider ($\sqrt{s} = 540$ GeV). The energy dependence of the various processes involved in charm, bottom, and top production in that model is displayed in Fig. 35, for $p\bar{p}$ collisions (essentially not different from pp collisions, since the $q\bar{q}$ contribution is very small). As outlined for charm production, the energy dependence might well not be strong enough -- at least for the dominating flavour excitation diagram -- so that a value of 1-10 nb, compatible with experimental data, seems more realistic at SPS energy.

Fig. 35 Predictions for a) charm, b) beauty, c) top production (Ref. 43).

Several experiments are being prepared, both at CERN and FNAL, to detect beauty production by observing decays in emulsions. All associate with the emulsion a vertex detector accurate enough to select charm-decay candidates, a spectrometer for event reconstruction, and a trigger (multiplicity step, multimuon, or multikaon). Figure 36 shows sketches of two of those experiments, WA71 and WA75, both in $350 \text{ GeV}/c \pi^-$ beams, which will be running at CERN in 1983 and aim at sensitivities of the order of a few events per nanobarn.

Fig. 36. Two 1983 CERN experiments looking for beauty (see text).

4.2 Top

As mentioned before, the only reasonable hope for hadroproduction of top lies in the $p\bar{p}$ colliders ($\sqrt{s} = 540$ GeV at CERN, working; $\sqrt{s} \sim 1000$ GeV at FNAL, in 1986) or possibly later in the pp collider planned at BNL ($\sqrt{s} = 800$ GeV, much higher luminosity) or eventually in a very high energy fixed-target machine (20 TeV $\rightarrow \sqrt{s} \approx 200$ GeV).

According to Fig. 35, the production cross-section at the CERN collider would be ~ 0.1 μb . This value, for $m(t) = 20$ GeV, is comparable to that formerly calculated at $\sqrt{s} = 800$ GeV in Ref. 35; it drops when the mass increases, roughly by a factor of 10 when $m = 40$ GeV*.

Even with such small cross-sections and the limited luminosity of the SPS collider ($L \rightarrow 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ in 1983), top production is rather abundant (~ 1000 tt/day). The challenge is to fish it out of the sea of other flavours. As was the case for charm and beauty, the main problem is the trigger: i.e. reduce the counting rate by a factor $\geq 10^{-3}$ while keeping most of the top particles. The fact that this problem has not yet been solved satisfactorily for charm and beauty shows its difficulty. Among the various methods envisaged for beauty, i.e. multiplicity steps, multikaon, and multi-lepton triggers, only the last one is technically feasible with the present detectors at the collider. A single lepton (e or μ) trig-

* Above a value of m of the order of 50 GeV, one can then predict that production of top via the weak process $p\bar{p} \rightarrow W^{\pm} \dots, W^{\pm} \rightarrow t\bar{b}$ will be more important than hadroproduction (such events will look like jet-jet events⁷¹ and the presence of the heavy quarks may be shown by an abundance of strange particles.)

ger, with $E_T \gtrsim m(t)/4$, to eliminate most of the background*, would keep about 5% of the centrally produced $t\bar{t}$ events. The leptonic decay of one of the top particles, $t \rightarrow b\ell\nu$, would give rise to a jet from the beauty decay (in which a charmed combination should be found), and to a measurable missing energy corresponding to the neutrino, in which case the top decay could be reconstructed (the other top particle would probably be difficult to find).

Another possibility is to look for forward production, as was done with success for the Λ_c (and possibly the Λ_B) at the ISR. In that case one could trigger on a high- p_T lepton at angles around $20-30^\circ$ (as suggested by Horgan and Jacob⁷⁴), accompanied by a forward jet from beauty decay; the other top particle would most of the time give rise to a hadronic jet: $t \rightarrow b\bar{u}d$ or $t \rightarrow bcs$ which may, especially in the last case, be identifiable.

To conclude on the subject of heavier flavours, there is hope to have rather soon some evidence for beauty and top hadronic production (possibly in 1983, with some optimism), but further progress will be rather slow -- until the advent of a new generation of detectors (for beauty) and machines (for top and still heavier flavours). This was the case for charm production, a domain where the first rather contradictory results of 1978 (beam dump) and 1979 (ISR) are just beginning to be qualitatively understood -- and where improved detectors should lead to more confidence in results and trust in their interpretation.

Fig. 37 Single lepton yields at 90° at $\sqrt{s} = 540$ GeV, from b, c, and t ($m_t = 20, 45, 100$ GeV) production (Ref. 72).

* It is interesting to note⁷² that, besides the trivial backgrounds which mar lepton triggers, at collider energy the yield of single leptons from beauty decay is higher than that due to top decay, whatever the p_T value (Fig. 37). Various methods have been proposed⁷³, using some characteristics of lepton-pair production as a signature of $t\bar{t}$ production, but they need higher luminosities than available at the $p\bar{p}$ collider.

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* ICHEP = International Conference on High Energy Physics.

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