Review of Recent Results on Heavy Flavor Production

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Abstract

Recent experimental results on photo- and hadroproduction of heavy flavor particles are reviewed. After a short introduction on the recent advances in the theoretical ideas describing the production of heavy flavors, current experimental techniques used in heavy flavor search in fixed target experiments are briefly discussed. New results on the production characteristics, production cross section and on the A-dependence of the open and hidden charm cross section are presented.

1. Introduction

After more than a decade of experimental studies on heavy flavor particles at various high energy laboratories, the subject of production of heavy flavor particles has entered into a new era as high statistics samples are now available. Production is interesting since it provides a meaningful test of perturbative QCD, provided that the mass of the heavy quark is sufficiently high. Understanding of heavy quark production is also necessary to predict the production rate for new particles and evaluate the background in many rare processes.

In QCD the lowest order processes are photon-gluon fusion for photoproduction [$O(\alpha_s \alpha_{em})$], and gluon-gluon fusion and quark-antiquark annihilation for hadroproduction [$O(\alpha_s^2)$]. In the last couple of years, there is a major breakthrough in the theoretical front in that the next-to-leading order calculations [$O(\alpha_s^2 \alpha_{em})$ and $O(\alpha_s{}^3)$] respectively for photo- and hadroproduction have been completed. [1] The results of these calculations indicate that the calculated cross sections are larger, by about 30% for photoproduction of charm and by about a factor of three for hadroproduction. Lowest-order calculations required a low value for the charm quark mass (around 1.2 GeV) to account for the magnitude of the cross section. Calculations including the higher order terms can accommodate the data with the more reasonable mass for the charm quark of 1.5 GeV. [2]

The distributions in x_f and p_t^2 are not significantly affected by the inclusion of higher order terms. There is no large enhancement of the cross section at large xf and the xf behavior is consistent with $(1 - x_f)^n$ for n between 6 and 7.5 for pp collisions at $\sqrt{s}$ from 27.4 to 62 GeV. [3] There is, however, a difference between heavy quark and antiquark production which is not present in the lowest order calculations. [3,4]

2. Experimental Techniques

Production studies are obviously an exclusive domain of hadron machines and both the CERN SPS and FNAL Tevatron have an extensive programme devoted to these studies. While hadron machines have superior luminosity compared to e^+e^- colliders and hence heavy flavor particles are produced abundantly, the production rate of heavy flavor particles is small. In fixed target experiments, the ratio of charm production cross section to the total inelastic cross section is 1/200 in photoproduction and 1/1000 in hadroproduction. Beauty cross sections are estimated to be more than two orders of magnitudes smaller. The lifetimes of heavy particles are short (from about 0.2ps for Λ_c to about 1 ps for D^+ and beauty particles) and hence the typical decay length is of the order of a few mm. Furthermore, any particular decay mode of these particles has only a very small branching fraction and this makes collection of high statistics very difficult.

Earlier experiments in the late 70 s to the early 80 s searched for the heavy flavor particles by looking for bumps in the combinatorial mass spectra. Over the years, more sophisticated methods have since been developed. The essential ingredients for fixed target heavy flavor experiments are high resolution vertex detectors to measure the finite decay paths of these particles, combined with a large acceptance spectrometer with good momentum resolution and particle identification and a selective and efficient trigger scheme and/or fast offline filters to speed up the data processing.

For vertex detection, one can use optical devices (emulsion and bubble chambers) or solid state detectors such as silicon microstrip detectors (SMD) or charge-coupled devices (CCD). The advantages of optical devices are their superb spatial resolution (about 1mm) and that they provide a strong topological evidence for a decay. Tracks are measured with high efficiency and can be accurately associated with the production or decay vertex. Their limitation lies mainly in their limited data rate capability and cumbersome scanning procedures. Solid state detectors, on the other hand, can be used in fully electronics experiments and thus high statistics is possible. SMD were first pioneered by the ACCMOR collaboration at CERN (experiment NA11) in 1982. They have good spatial resolution and are usable in online trigger (WA82) and/or offline filter. They can also be used as an active target in which evolution of the charged multiplicity in the target (e.g., due to charm decays) can be measured and the primary interaction point can be determined precisely. Using SMD, a photoproduction at FNAL, E691 has collected about 10K charm candidates, proving that fixed target experiments can be very competitive with e^+e^- colliders even in decay studies of charm particles. Hadroproduction experiments, however, are more difficult because of the smaller production ratio and the higher multiplicity in each event. Since single-sided SMDs are one-dimensional devices, they can lead to ambiguities in track reconstruction. To help with the pattern recognition, one can use a pixel device such as a CCD which has the striking advantage of providing two-dimensional information with good precision through one output channel. The disadvantage of the CCD is the rather long readout time and the impossibility of gating. Using solid-state devices, some of the present generation of experiments as listed in Table 1 have acquired more than 1K fully reconstructed charm candidates.

Since the heavy flavor production cross section is relatively small compared to the total cross section, the experiment trigger is important to enrich the heavy quark content of a data set. For cross section studies, the trigger should be as bias free as possible which unfortunately, is in conflict with the desire to collect a large statistics sample. Table 2 summarizes different trigger approaches that have been used by experiments.

A final issue is on particle identification. While particle identification is not necessary in extracting charm signal in decay modes like $D^+ \to K^-\pi^+\pi^+$, using particle identification information, the signal to noise ratio improved by about a factor of three. For rare decay modes and for decays like $\Lambda_c \to pK^-\pi^+$, particle identification is important to resolve ambiguities.

Since there is hardly any new data on beauty production, only the results on photo- and hadroproduction of charm are reviewed in the following sections.

3. Photoproduction

With photoproduction of charm, there are four experimentally measurable quantities that can be made: the total production cross section, the energy dependence of the cross section, and the x_f and p_t dependence of the cross section. These quantities are dependent upon m_c and n_g, two physics parameters of general

Table 1:
Recent Heavy Flavor Production Experiments

Photoproduction of Open Charm		
	E691	Fermilab - Tagged Photon Laboratory (TPL)
	E687	Fermilab - Broad Band Beam
	NA14'	CERN
Hadroproduction of Open Charm		
	E653	Fermilab - Hybrid Emulsion with π and p
	E769	Fermilab - Hadrons at TPL
	NA32	CERN - ACCMOR
	WA82	CERN - Omega
γ, Hadro- and Muo- Production of J/ψ and Y		
	E537	Fermilab - High Intensity Lab
	E772	Fermilab - Mass Focusing Spectrometer
	NMC	CERN - New Muon Collaboration
	E687	Fermilab - Broad Band Beam
Open Beauty		
	WA78	CERN - π^- Uranium interactions

Table 2: Triggering schemes used by present experiments

Experiment	Trigger	Charm Enrichment	Comments
E691/E769	Transverse energy $E_t >$ a few GeV	modest x2-3	rejection factor about 3, less biased
NA32	A pair of K/p of opposite charge	x7 for Λ_c and D_s	biased for D decays systematic error ~ 10%
WA82	Impact Parameter of at least 1 track between 0.1 to 1mm at primary vertex	x15 for D^+	biased against short lifetimes and charmed baryons

interests. Here m_c is the charm quark mass and n_g is the exponent in the parametrization of the gluon structure function.

Results on photoproduction of charm from E691 have been published.[5] The new broad band photoproduction experiment at FNAL, E687 , will extend the energy range of charm photoproduction. The average photon energy has moved from 100 GeV from NA14' at CERN to 145 GeV for E691 and now, to 250 GeV in E687.

E691 has recently deduced from their production cross section measurements a value for m_c and n_g. [6] The input to this is the four quantities mentioned above and the ratio $\sigma(cx)/\sigma(cx)$ which is found to be bigger than one. This is consistent with a string fragmentation type hadronization (string connection of the c quark to a target diquark). Given this and using next-to-leading order calculations of the total cross section and leading order differential cross section shapes, they then performed a maximum likelihood fit to obtain a value of 1.74±0.15 for m_c and 7.1±2.2 for n_g.

4. Hadroproduction

Hadroproduction is more difficult both theoretically and experimentally compared with photoproduction. Because of the large contribution from higher order terms, the magnitude of the cross section goes up by factor of 3 compared to the lowest order calculations. Moreover, the charm quark mass may be too light for the reliable application of perturbative QCD and the theoretical errors are large and hard to estimate. Experimentally, besides the smaller production ratio and the higher multiplicity, there are a few open issues making comparison of different results very confusing. In the past, experiments had only limited statistics, typically in a limited number of decay modes. The problem is further compounded by the fact that different incoming beam particles and different target materials have been used. Thus, to get a clear picture, one needs to understand the following:

1) dependence on the atomic number of the target,
2) dependence on the incident particle type,
3) leading particle effects ,
4) strong forward component.

By leading particle effect, we mean forward production of charm particles which have one or more valence quarks in common with those of the incoming projectile. This in πN collisions, the leading mesons, the leading mesons are D^- and D^0. Experimentally, based on small statistics, one experiment claimed that there are two components in charm meson production: a central one and a forward one with the forward component associated with the leading particles.[7] Table 3 is a summary of earlier result on charm hadroproduction. Quite a few experiments have claimed the existence of a strong forward component ($x_f > 0.5$) and Table 4 summarizes the results. It is worth noting that none of these experiments possessed a precision vertex detector. Theoretically, both the leading particle effect and the strong forward component are not predicted by QCD calculations including the higher order corrections.

During the last year, results from a few high statistics charm hadroproduction experiments have become available. The differential cross section is usually parametrized as $(d^2\sigma / dx_f\, dp_t^2) = (1-x_f)^n e(-bp_t^2)$ and the value of n and b are measured to determine the differential cross section. Tables5 and 6 summarize the results on x_f and p_t^2 dependence of recent experiments. One can see that with high statistics, no large leading particle effect has been observed. In fact both NA32[8] and WA82[9] found that the leading particles are slightly more forward than the non-leading one but the difference is small. The three experiments using an incoming p beam at similar energies got a value of n of about 3.5. However, E653 which used an incoming proton beam of 800 GeV measured a value of 11±2 for n.[10] Comparing with earlier measurements at lower energy, one can see that the proton production seems increasingly central as the beam energy is increased. This suggests that the gluon structure function evolution will be important in interpreting the proton production data. New proton data is anticipated from E769 at 250 GeV. Higher energy π^- data will be available from the 650 GeV run of E653 and from the new FNAL experiment E791 which is the follow on to E769. The proton data from E653 also shows that the x_f distribution is symmetrical around $x_f = 0$.

The p_t dependence seems fairly uniform across the range of incoming beam energies and incident particle type. However, NA32 observed a difference in

Table 3: Earlier Measurements of Total Charm Cross Section

Expt	Interaction	$\sigma(\mu b)$	Comments
NA27	360 GeV $\pi^- p$	31.6±5.4	$D,\bar{D}$, all x_f
	400 Gev pp	30.2±3.3	$D,\bar{D}$, all x_f
E743	800 Gev pp	51±15	$D,\bar{D}$, all x_f
NA32	200 GeV π-Si	$5.1\pm^{0.6}_{0.5}\pm0.3$	$D,\bar{D}$, $x_f>0.$
	K^-Si	$8.0\pm^{1.9}_{1.3}\pm0.5$	$D,\bar{D}$, $x_f>0.$
	p Si	1.5±0.7±0.1	$D,\bar{D}$, $x_f>0.$

BEAUTY Cross section

WA78	320GeV π^-U	$\sigma_{B\bar{B}} = 3.1\pm0.4\pm1.0$ nb/nucleon
NA10	286 Gev π^-W	$\sigma_{B\bar{B}} = 14\pm^{7}_{6}$ nb/nucleon

Table 4: Summary of Results on Forward Charm Production

Experiment	Energy(GeV)	Signal	Cross section	Comment
BIS-2	<E>=58	$nN \to \Lambda_c^+(\Lambda^0 3\pi)$	$\sigma.B$ 2.3±1.1 μb	$x_f>0.5$
		$nN \to D^0$	28±14μb	per carbon
		$nN \to D^-$	26±13μb	nucleus
				n=1±0.5
E400	<E>=600	$nN \to \Xi_c^+$	$7.5\pm^{4.5}_{2.6}\pm1.9$	n=1.5±1.3
				$0<x_f<0.6$
R608	√s=62	$pp \to \Lambda_c$	150±27±37μb	n=1.7±0.3
				$x_f>0.5$
R422	√s=62	$pp \to \Lambda_c$	85±50μb	n=2.3±0.3
				$x_f>0.5$
WA62	<E>=135	$\Sigma^- N \to \Xi_c^+$	0.63±0.3μb	$x_f>0.6$

Table 5: Recent x_f Dependence Results

Expt	Beam	Particle	n
NA27	360 GeV π^-	All D	3.8±0.6
		LEADING D	$1.8\pm^{0.6}_{0.5}$
		NONLEAD.	$7.9\pm^{1.6}_{1.4}$
NA32	230 GeV π-	All D	3.74±0.23
		LEADING D	$3.23\pm^{0.30}_{0.28}$
		NONLEAD.	$4.34\pm^{0.38}_{0.35}$
		Λ_c	$3.52\pm^{0.51}_{0.49}$
		D_s	$3.94\pm^{0.93}_{0.86}$
WA82	340 GeV π-	All D	3.40±0.45
E769	250 GeV π-	D^+	3.8±0.4
		D^0	4.1±0.6
NA32	230 Gev K-	All D	$3.56\pm^{1.08}_{0.99}$
NA27	400 GeV p	$c,\bar{c}$	4.9±0.5
E743	800 GeV p	$c,\bar{c}$	8.6±2.0
E653	800 GeV p	$c,\bar{c}$	11.0±2.0
		$D,\bar{D}$	$7.5\pm^{2.0}_{1.7}$

Table 6: Recent p_t Dependence Results

Expt	Beam	Particle	b (GeV^{-2})
NA27	360 GeV π^-	All D	1.18±0.17
NA32	230 GeV π-	All D	0.83±0.03
		Λ_c	0.84±0.09
		D_s	0.59±0.10
WA82	340 GeV π^-	All D	1.27±0.18
E769	250 GeV π^-	D^+	0.98±0.07
		D^0	0.95±0.09
NA32	230 Gev K^-	All D	$1.36^{+0.32}_{-0.26}$
NA27	400 GeV p	$c,\bar{c}$	1.0±0.1
E743	800 GeV p	$c,\bar{c}$	0.8±0.2
E653	800 GeV p	$c,\bar{c}$	1.1±0.2
		$D,\bar{D}$	0.80±0.15

the value of b between leading and non-leading D mesons. Leading D mesons seem to be produced with a larger mean transverse momentum than the non-leading ones. Also, the D_s mesons are produced with larger mean transverse momentum than the D mesons. In fact, a few experiments (WA82, E653 and also NA32) noticed that there is a steep dependence for $p_t^2 < 5$ GeV^2 and a flatter one for larger values.

The only new data on charmed baryon production comes from NA32.[11,12,13] The production characteristics of Λ_c are : n=3.52± 0.50 and b = 0.84±0.09 GeV^{-2} similar to the ones of D mesons. No significant difference is observed between the production of particle and the antiparticle.

New results on correlation are available from E653 and NA32.[14] E653 has observed 44 charm pairs. The pairs are produced with x_f and p_t dependences similar to those of the single particles. The correlation is seen more clearly in the azimuthal angle between the two charm particles in a plane transverse to the beam. A clear peak is seen at 180° which is what one would expect from the gluon-gluon fusion model. In fact, correlation is enhanced for particles where the pair has a large p_t or high effective mass. The same correlation is enhanced for larger differences in x_f of the two charmed particles.

NA32 has all together a total of 642 double charm events, 584 of which are consistent with charm-anticharm production. Azimuthal angle correlations have been studied for the D and D_s mesons and Λ_c. There is a clear peaking at 180° for $D\bar{D}$ pairs, less pronounced for $\Lambda_c\bar{D}$ combinations and even weaker for $D_s\bar{D}$ events. This peaking is only marginally stronger for leading D-mesons. Compared with the fusion model, the data from NA32 showed that the peaking at 180° is not as strong as predicted. However, the higher order processes are expected to reduce this peak. [15]

Table 7 summarizes the recent results on the production cross section. For some final states, since the branching fraction is not known accurately, only the cross section times branching fraction is quoted. A few noteworthy features of these results are the near equality of Λ_c and anti-Λ_c production in a π^- beam and the K^- and π^-D production cross section. Another feature is that the total charm cross section for 800 GeV protons is similar to what one might expect from lower energy π^- data when

Table 7: Recent Open Charm Cross Section Results

(linear A dependence assumed)

Expt	Beam	Particle	#Events	σ (μb/nucleon) ($x_f > 0.0$)
NA32	230 GeV	D^0	543	6.3±0.3±1.2
	π^-	D^+	249	3.2±0.2±0.7
		All D	792	9.5±0.4±1.9
		D^{*+}	147	3.4±0.3±0.8
	Particle & mode			σB (μb/nucleon)
	D_s--> KKπ		60	.067±.011±.010
	Λ_c--> pKπ		147	0.18±.02±.03
	Ξ_c^0--> pKK^{*0}		3	$.019\pm.011\pm^{.066}_{.009}$
	Ξ_c^+--> $\Xi^-\pi^+\pi^+$		3	$0.13\pm0.08\pm^{.05}_{.08}$
	Ξ_c^+--> $\Sigma^+K^-\pi^+$		2	0.012
	Beam	Particle	# Events	σ or σB
	230 GeV	All D	31	8.5±1.6±1.2
	K^-	D_s	4	0.11±0.06±0.02
E653	800 GeV	c,$\bar{c}$	288±44	32±4±12 (all x_f)
	p			

it is extended to all charm final states and all x_f. This is consistent with a harder gluon distribution in the π and K.

Although all the hadroproduction experiments have assumed linear A dependence in presenting their cross section measurements, previous experiments have indirectly measured that the charm cross section to vary as A^{α}, with a value of α equal to 0.76 for x_f>0.2. On the other hand, QCD favors a value of one for α and linear A dependence seems to provide reasonable agreement among experiments with different target materials. Recently, two experiments, E769 [16] and WA82 provide the first direct measurement of A dependence of open charm. These results, together with the high statistics J/ψ, ψ' and Y results from E772 [17] are presented in Table 8. The results indicate that for x_f>0, an A^{α} parametrization is quite adequate in describing the data with α in the range of 0.9 to 1.0. However, the data is now sufficiently big such that the A dependence as a function of x_f and p_t can be studied. This information is useful since earliermeasurements were done at high x_f values and also they can be used to check if higher twist effect is important in charm production. [18]

The very precise new data from E772 on the A dependence of J/ψ production indicate that indeed, α is strongly dependent on x_f and p_t. They also found that ψ' has the same A dependence as the ground state and the value of α for Y is larger and the suppression of Y production in heavy nuclear target is significantly less than for the lighter charm bound states. This cannot be explained within the framework of perturbative QCD and one theoretical explanation which can accommodate these observations is the intrinsic charm model. [19]

5. Outlook

The current situation for charm is that there is a great deal of new data being fully reconstructed and made available for analysis. In photoproduction, there will be new results from NA14' and E687 which extend the range of photon energies. This will help to tie down the QCD parameters. In hadroproduction, the final data sample from WA82 will be about five times larger than what they have presented so far. These will provide a sample of few thousand fully reconstructed D mesons. The

Table 8: Recent A-Dependence Results

Photoproduction			
E691	γA --> J/ψ	$\alpha = 0.93$	
Hadroproduction			
WA82	pA --> D's	0.89±.05±.05	$0.<x_f<0.7$
E769	pA --> D^+	0.97±.07	$0.<x_f<0.5$
	pA --> D^0	0.92±.08	
E772	pA --> J/ψ, ψ'	0.92	$0.<x_f<0.6$
	pA --> Υ(1s)	0.97	

full data set from E769 will provide measurements of the charm production characteristics of different beam particles and different target material. This will provide detailed information on the A dependence and beam particle dependence. Results from E653 will provide the first results on π of high beam energy. They will also provide a result for the beauty cross section which up till now has been limited to a few indirect measurements (hence model dependent) at CERN with lower energies.

There are quite a number of heavy flavor experiments which are at the stage of data-taking both at CERN and FNAL. Two experiments at FNAL (E687 and E791) will aim for very high statistics (>10K fully reconstructed charm decays). These very high statistics samples will finally allow a detailed study of the charm production and one can envisage to extract from the details of the measurement the more fundamental physics interpretation of the results. At CERN, WA89 aims to study, among many other things, charmed baryon production using a hyperon beam.

There are two experiments (E771 and E789) which specifically aim to do b-physics at FNAL. Both E791 and E687 will also study b-physics via the cascade decays of B to D's. There is a follow-on experiment to WA82 at CERN and they will upgrade the trigger with a fast vertex trigger processor to do b-physics. Since the situation is like the search for charm in the early 80 s, it is premature to speculate precisely on how well these experiments will be able to do and what their limitations are. Suffice to say that each has the potential to find a couple hundred fully reconstructed beauty decays in a reasonable run. Besides providing a measurement for b production, lifetimes and branching ratios, they will also be useful as a R&D effort to determine the most appropriate approach to do b-physics in a hadronic machine.

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