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**Charm Photoproduction : A Laboratory to Test Perturbative
and Non Perturbative Aspects of QCD**

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CHARM PHOTOPRODUCTION : A LABORATORY TO TEST PERTURBATIVE AND NON PERTURBATIVE ASPECTS OF QCD

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Abstract : Preliminary results from recent CERN charm photoproduction experiments are presented.

These measurements can provide accurate tests of perturbative QCD.

We would like to insist on the very clean and simple structure of the hadronic final states. The detailed study of these events will be also a good place to test models for hadronization.

Institutes involved in the NA14' experiment :

Technical University (Athens) - Universitat Autònoma (Barcelona) - CERN -
Imperial College (London) - LAL (Orsay) - Collège de France (Paris) -
Saclay - University of Southampton - Strasbourg - University of Warsaw

Institutes involved in the EMU 06 experiment :

In addition to the NA14' collaboration, institutes from :

Bologna - Firenze - Genova and Moscow are doing this experiment.

1. RECENT CHARM PHOTOPRODUCTION EXPERIMENTS AT CERN

At this seminar specific talks have been devoted to experiments which are at the completion level : NA1 and WA58. Thus I will speak only about those which have taken data last year and have just started their analysis : NA14' and EMU06.

1.1 The NA14' spectrometer

These two experiments use the same spectrometer which is shown on fig. 1.

Fig. 1 : NA14' spectrometer

The momenta of charged tracks are measured using two magnets and 70 MWPC planes. Photons are measured by 3 electromagnetic calorimeters which cover an angle of ± 250 mrad as seen from the target. Two gas Cerenkov counters are used to identify kaons and protons.

Incident photons of energy between 40 and 120 GeV (mean energy 90 GeV for charm events) interact in a silicon active target inside the magnetic field of the upstream magnet.

For charm physics, the most important and indispensable component of this spectrometer is the vertex detector. It consists of two parts (fig. 2).

Fig. 2

- a silicon active target :

It is segmented along the beam direction in 500 μ steps (312 μ of silicon - 200 μ of air) and consists of 2.1×40 mm² slabs in a plane transverse to the beam. (This is to reduce electromagnetic background interactions). The analog signal gives a measurement of the ionization deposited around the vertex position.

The target is used at the trigger level and provides a measurement of the vertex position along the beam direction. Apart from a special class of events, called "clean target events", this information is not yet used in the present analysis.

- a telescope of microstrips planes¹ :

Ten planes of 1000 channels each, with a 50μ pitch are read in a digital mode to allow us to reconstruct charged particles with a transverse accuracy of about 17μ at the vertex. There are 4 planes of vertical strips, 4 planes of horizontal ones and 2 planes are tilted at $+30^\circ$ and -60° respectively.

9937 of the 10^4 channels are working. A minimum ionizing particle (mip) gives a signal with a mean value at about 14 times the noise fluctuation. The readout threshold is set to .35 mip to register two adjacent hits for tracks which cross the frontier between two strips. The number of spurious hits generated by the detector and by its electronics is about 6 in a 50 ns gate. The cluster size is 1 for 90 % of the impacts. Because of financial constraints we have connected 2 strips on the same readout chain in such a way that aligned points issued from a charged track give dispersed hits for the paired channels.

1.2 Triggering conditions (fig. 3)

To select events we have used an hadronic interaction trigger which requires at least one charged track at the exit of the second magnet above and below the horizontal plane (the main component of the magnetic field is vertical and disperse electromagnetic pairs into the horizontal plane).

This trigger has an higher efficiency for charm events than for normal hadronic interactions and provides an enrichment factor of a least 2. Only 5 % of the registered events have an electromagnetic origin.

Fig. 3 : Triggering conditions

1.3 The EMU06 experiment

Approved at the beginning of June 1986 it was run between the 23 and 25 of October. The active target was replaced by an emulsion stack. Ten liters of emulsion have been exposed in 365 stacks of dimensions $5 \times 3 \times 2 \text{ cm}^3$. Two scintillation counters, placed at the exit of the stack, were used to require a minimal charged particle multiplicity (4.25 mip) (fig. 4). The other triggering conditions were left unchanged.

The stacks were transported by a chariot from a drum to their correct position in the beam. This system was driven by an Apple computer and a video camera allowed to survey its operation.

131 000 triggers -corresponding to about 100 charmed interactions- have been registered on tapes. The off line reconstruction program was just installed on the CRAY computer at CINECA (Bologna). The emulsion processing has been done in the Soviet Union and is completed.

The microstrip information was used to scan a very small volume inside the emulsion stack ; correlations between charged tracks measured in the spectrometer and in the emulsions have been observed.

Fig. 4 : EMU06 apparatus for emulsions exposure

2. A FEW PRELIMINARY RESULTS FROM THE NA14' EXPERIMENT

2.1 Data processing

Data were recorded during Summer 85 (~ 5M events) and Summer-Autumn 86 (~ 12M events). The complete analysis of one event requires about 2 s (IBM 3090) and we are not able to process all the events in this way. We have thus developed an off line filtering program (.2 s/event) which has a higher efficiency for charm events than for other hadronic interactions. This program selects ~ 20 % of the total event sample and keeps ~ 70 % of the charmed ones (this

number is based mainly on a Monte-Carlo simulation). We have verified that the filtering efficiency is independent of the decay length of the $D^0 \rightarrow K\pi$ channel and of its transverse momentum.

For some classes of events we do not want to lose in statistics and we have created special filters, e.g. multi K (or p) final states and events in which a very clean interaction is registered in the active target. For this last class of events no highly ionizing particle is produced in the forward direction and multiplicity steps can be detected.

2.2 Some results from the "clean active target" data sample

These are events for which we can measure the initial and final charged tracks multiplicities in the silicon active target ; they represent 7 to 8 % of all events.

The position of the main vertex along the beam direction is given by the active target and the secondary vertex position is reconstructed using the microstrips telescope. For $K\pi\pi$ events, in about 50 % of the events, a multiplicity step is visible in the active target.

In figure 5 a-b, we have displayed the $K\pi\pi$ mass distributions after a cut on the distance between the primary and secondary vertices of 0.5 mm and 1 mm respectively.

Similar distribution for the $D^0 \rightarrow K\pi$ channels are shown on figure 6 a-b.

Fig. 5 : $K\pi\pi$ mass distribution for "clean active target" events (12M raw data events)

Fig. 6 : $K\pi$ mass distribution for "clean active target" events (5M raw data events)

2.3 A few results from the microstrips filtered events

At present the main and secondary vertices positions are measured using the microstrips telescope.

- D^0 lifetime measurement

12M events have been processed through the analysis chain described before. To isolate the $K\pi$ channel we have imposed a mass cut between 1.7 and 2 GeV and candidates are selected by a cut on the ratio between the flight distance divided by the corresponding error.

The $K\pi$ channel has been used until now as a laboratory to optimize the off line reconstruction program of charged tracks in the microstrips telescope. This is why, for other channels, we have analysed a smaller statistics.

We obtained two data samples depending on whether or not the D^0 comes from a charged D^* decay (fig. 7 a-b). These two independant samples have to satisfy very different cuts and the final ratio signal/background is also quite different (table 1).

Fig. 7a : $K\pi$ mass distribution for D^* events

Fig. 7b : $K\pi$ mass distribution K identified

channel	flight/ σ	minimal decay time	N_{signal}	N_{BKG}	$\tau(10^{-13}\text{s})$
$D^0 \rightarrow K\pi$ (no D^*)	4	$4 \times 10^{-13}\text{s}$	85	40	$4.42 \pm .52$
$D^0 \rightarrow K\pi$ (from D^*)	1	$2 \times 10^{-13}\text{s}$	88	20	$4.44 \pm .53$

TABLE 1

The two obtained lifetime measurements for the D^0 (fig. 8) are in agreement and their combination gives :

$$\tau_D^0 = 4.43 \pm .37 \cdot 10^{-13} \text{ s}$$

Fig. 8a : Lifetime distribution for $D^0 \rightarrow K\pi$ from D^* decays (background subtracted)

Fig. 8b : Lifetime for $D^0 \rightarrow K\pi$ (not coming from an identified D^*) background subtracted

- $D^\pm \rightarrow K\pi\pi$ signal and expectations

The mass distribution shown on fig. 9 corresponds to about 1/4 of the statistics used for the $K\pi$ channel.

In the near future the complete data sample will be available and a better treatment of the vertex detector information will improve the ratio signal/background in mass distributions. For instance, in the $K\pi$ channel a factor 2 increase in statistics is expected and 700 signal events situated above the same number of background can be obtained. For the charged D , decaying into $K\pi\pi$, a factor 7 increase is expected in comparison to what we have presented, other D decay modes will be also considered.

The spectroscopy and lifetime measurements of the D_s and Λ_c particles will be also studied.

We plan to use the active target information to fix the main vertex position; this can help to reduce, in the case of charm events, the biases generated by the determination of this position using the microstrips alone.

3. CHARM PHOTOPRODUCTION AND QCD

We would like to show that charm photoproduction is a good place to test QCD in its perturbative and non perturbative behaviour.

3.1 Perturbative QCD

The mass of the charm quark is high in comparison to the hadronization scale given by Λ_{QCD} and this allows one to compute the charm photo (or hadro) production cross section in a perturbative QCD approach. Several measurements of this quantity exist between 20 and 200 GeV incident photon energy in muo- or photo-production experiments. These measurements are generally in good agreement.

In contrast to most of the processes of non-perturbative origin for which perturbative QCD is generally present as a correction (usually small), for charm production, the whole cross section can be computed.

The first order diagram, the photon-gluon fusion process, gives a good account of the existing data. We must note however that the predictions are very sensitive to the choice of the value of the charm quark mass.

An advantage of photo-production in comparison to charm hadro production is that higher orders QCD diagrams are expected to give a relatively small contribution. For instance the process depicted next page is negligible in photo-production.

Fig. 9 : $D^{\pm} \rightarrow K\pi\pi$ mass distribution

Fig. 10 : Inclusive D mass spectrum used for P_T distribution analysis

Unfortunately, only the contribution of the first order QCD diagram has been actually computed.

In NA14' we have measured the transverse distribution of charm particles ; 500 charm particles (fig. 10) are used. Because of its mass, the D meson is expected to have an higher mean transverse momentum than a π , a K or a proton produced in an inclusive way. It is observed experimentally that inclusive particle production follows the parametrization : $d\sigma/dP_T^2 \sim e^{-6m_T}$ (m_T is the transverse mass). We observe that the background events are effectively distributed in this way (fig. 11a). These events have been selected from the wings on each side of the signal and also from candidates which appear in exactly the D mass region but only after relaxing the cuts imposed by the vertex detector.

D mesons up to $P_T^2 \sim 2 \text{ GeV}^2$ also obey this "universal" law but we measure a clear excess of events at higher P_T (fig. 11a).

Fig. 11a : Comparison between the P_T distribution of D mesons and of background events

Fig. 11b : Comparison of the D meson P_T distribution to the expectations from a photon-gluon fusion QCD Monte-Carlo

The D meson production has been simulated using the photon-gluon fusion QCD diagram. We have taken a "naïve" gluon structure function $x G(x) \sim (1-x)^5$, no Q^2 evolution has been introduced and a fixed mass has been used for the charm quark.

The data are well reproduced by this simulation and, in figure 11b we have shown the predictions for two values of the charm quark mass.

3.2 Non perturbative QCD behaviour : hadronization models

At the parton level, the structure of a charm photoproduction event is particularly simple because a single diagram is expected to contribute. The study of these events will thus provide information on the way this diagram gets hadronized. We can obtain diffractive or non diffractive events as shown below:

The amount of the diffractive component has not yet been measured but we can find theoretical arguments² to consider that it is smaller than for non charmed events -a few %-.

We are thus in a situation where essentially all events have their origin in a single QCD diagram and we can study if D particles and the accompanying hadrons are produced in a way which agrees with current hadronization schemes.

As an example of such a model we have used the dual parton model³ in which hadrons are generated along two strings. One "baryonic string" stretched between the charm quark and the target spectator diquark and one "mesonic string" stretched between the anticharm quark and the remaining target spectator quark. The structure functions of the spectator partons are obtained from low P_T physics⁴. For quarks, at small x , a $1/\sqrt{x}$ behaviour is expected whereas for diquarks we get $x^{1.5}$. This implies that most of the target energy is taken by the diquark. Hadrons are produced along two independant chains of very different masses (fig. 12) and we expect that the hadronization of non diffractive events produces an asymmetry between charm and anti-charm particles. Before detailing the predictions of the model we would like to recall a few measurements obtained by several photoproduction experiments.

Fig. 12a : "Baryonic string" mass distribution ($E_\gamma = 90$ GeV)

Fig. 12b : Mesonic string mass distribution ($E_\gamma = 90$ GeV)

3.4 A few experimental results on charm photoproduction mechanisms

The pioneering work in this field has been done by the WA4 experiment⁵ which observed an asymmetry between the production rates of D^0 and $\bar{D}^0$ mesons at 50 GeV incident energy. It also determined the X_F region in which D mesons are

produced : $[-.2, .6]$. At that time, no electronic vertex detector was available and signals included large combinatorial backgrounds which prevented a detailed study of the hadronization mechanism.

The previous results were confirmed and measured with more accuracy by two experiments : WA58⁶ and SHF⁷ (Slac Hybrid Facility).

The SHF experiment operated at 20 GeV beam energy and measured an amount of $\Lambda_c \bar{D}$ production equal to $71 \pm 11 \pm 6 \%$, the ratio D^-/D^+ is 33/15.

The nice results obtained by the WA58 collaboration will be detailed by Professor Diambri at this seminar. The incident photon energy spectrum is the same as for the WA4 experiment and the interactions occur in emulsions. The amount of $\Lambda_c \bar{D}$ production is $28 \pm 13 \%$ and no $\bar{\Lambda}_c$ is observed. (11 Λ_c are measured).

At higher energies the Fermilab E691 experiment⁸ ($E_\gamma \sim 170$ GeV for charm events) has measured a very symmetric charm-anticharm production :

$$D^0/\bar{D}^0 = 1.02 \pm .05$$

3.5 Interpretation of these results in the framework of the hadronization model

- Asymmetry $\Lambda_c/\bar{\Lambda}_c$:

It can come from an enhancement of the Λ_c or from a decrease of $\bar{\Lambda}_c$ "normal" production rates. To hadronize the strings we have used the Lund Monte-Carlo program which generates diquark-antidiquark pairs with a constant probability. But, if the string mass is too small we cannot produce such a pair. A priori we expect that the rate of $\bar{\Lambda}_c$ production will be affected by the small mass of the mesonic string whereas no such penalty is expected for the baryonic string. This is not in fact correct because all the mass of the baryonic string cannot be used for baryon production as shown below :

only the submass $M_1 < M_0$ is available, and in practice, the forward production of charmed baryons or antibaryons is very similar⁹.

Thus a single mechanism remains which can produce the asymmetry : this is the possibility for the charm quark and the spectator diquark to form a low mass system which decays into a Λ_c plus additional hadrons. From what we have said before we expect that such a possibility has a very steep energy dependence. We have used a very simple recipe which requires that the cQ system decays into $\Lambda_c + X$ if $M_{cQ} < M_s$. The value $M_s = 4$ GeV was chosen so that at $E_\gamma = 20$ GeV we reproduce the SHF result. More refined schemes can be found in ¹⁰.

At the energy of the WA58 experiment we predict a contribution of 21 % for the $\Lambda_c \bar{D}X$ final state which agrees with the data.

We must remark that this mechanism produces Λ_c baryons of relatively low energy as shown on figure 13. For instance, in the case of the E691 experiment we expect the same numbers of Λ_c and $\bar{\Lambda}_c$ with energy higher than 20 GeV whereas the total rate of Λ_c is two times bigger. For the NA14' experiment an excess of Λ_c is expected if their energy is below 40 GeV.

Fig. 13 : Expected $\bar{\Lambda}_c$ and Λ_c energy distributions

- Asymmetry $D/\bar{D}$:

The $D/\bar{D}$ asymmetry reflects the charm baryon asymmetry with the addition that in case of $\Lambda_c \bar{D}$ production, the $\bar{D}$ are very forward and thus usually well detected in the apparatus. But, at high incident photon energies this is a very small effect (mainly because Λ_c production is $\sim 10\%$ of D production).

- Asymmetry $F/\bar{F}$:

Even at low energies, we do not expect more $\bar{F}$ than F mesons because of phase space limitation in the mesonic string which prevents $\bar{F}KX$ production. There may be even a small excess of F mesons.

- D^+/D^0 :

The ratio of the production rates of charged over neutral D mesons depends mainly on the amount of D^* production. In our simulation we have used the default Lund parameters and obtain $D^+/D^0 = .36$ whereas the E691 experiment measures $.48 \pm .07$. This last number corresponds to a ratio of prompt D^* over D equal to 3. ⁸

In the LUND Monte-Carlo (version 6.1) we produce also 3 times more prompt D^* than D mesons but the branching fraction : $D^* \rightarrow D^0 \pi^+$ is assumed to be 64 %. If we take the value published in PDG 1986 for this last quantity (49 %) we reproduce the result of E691.

As D and $\bar{D}$ mesons are expected to be produced independantly from each other it can be interesting to measure the ratios D^+/D^0 and $D^-/\bar{D}^0$. They may be different because the $\bar{c}q$ string mass distribution is maximum at low mass values and this may produce an excess of D^* mesons ?.

The expected production rates for the various charm particles are shown on figure 14.

Fig. 14 : Expected rates of various charm particles versus the incident photon energy

5. CONCLUSIONS

The analysis of the NA14' experiment will be completed by the end of this year. It seems a priori difficult to compete with the E691 experiment for lifetime measurements but we hope to get an accuracy of the order of 5 % on the D^0 lifetime and with different systematic uncertainties.

High statistics P_T , X_F , Y distributions for D mesons are or will be available and it will be interesting to compare these distributions to a "complete" QCD computation.

NA14' covers an energy range which complements the one in which E691 operates. This is important to study hadronization mechanisms because the amount of various charm particle species is energy dependent, especially at low energies.

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