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ASSOCIATED PHOTOPRODUCTION OF CHARMED Λ_c^+ BARYONS AND $\bar{D}$ MESONS AND WEAK DECAYS OF THE Λ_c^+ BARYON

Photon Emulsion Collaboration

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ABSTRACT

Data on associated photoproduction of Λ_c^+ charmed baryons and $\bar{D}$ charmed mesons using incident photons of energies between 20 and 70 GeV are presented. Results on the production mechanism, decay modes and lifetime of Λ_c^+ baryon are obtained.

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1. INTRODUCTION

The present knowledge about the production and decay properties of charmed particles, especially charmed baryons, are still quite poor. Due to the small cross sections, short lifetimes, numerous unknown decay modes and many sources of background the experimental investigation in this field turns out to be quite difficult. For the time being only visual vertex detectors in large hybrid experiments were able to measure directly the decay path of Λ_c^+ baryons and give some indication about their mean lifetime. The world statistics of the visually observed and identified decays of charmed baryons do not exceed at present 33 events [1].

2. EXPERIMENTAL DATA

In this paper we describe and analyze the updated sample of reconstructed Λ_c^+ baryons observed in the WA58 CERN experiment [2]. This experiment used a tagged photon beam from 20 to 70 GeV and targets of nuclear emulsion(*) which simultaneously served as vertex detector with a spacial resolution of 0.5 micron.

The experimental set-up is sketched in fig. 1. The CERN OMEGA prime spectrometer was used for detection and momentum measurement of charged secondary particles from interactions in the targets. Charged particle identification was provided by a carbon-dioxide multicell Cherenkov counter. Forward photons and electrons were detected in the OLGA lead glass system. A detailed discussion of the experimental method has been made elsewhere [3]. However, we should like to remind here a few essential points.

(a) Very soft trigger conditions were used in data taking (i.e. at least four particles detected in OMEGA or at least three with on-line identification of a kaon) providing an unbiased sample of interactions in the emulsion targets.

(*) The nuclear emulsion used was of the BR -2 type (sensitivity 32 to 35 grains per hundred microns for relativistic tracks), produced by the Moscow Institute for Photochemical Projects.

(b) The events of electromagnetic nature were effectively rejected at the trigger level without loss of hadronic events, keeping thus the dead time of the data acquisition system short enough.

(c) Single pellicles of emulsion of 0.6 mm thickness were exposed one by one to the photon beam at an angle of 5 degrees with respect to the direction of the beam. In this way a double objective was reached. First, a large fraction of the charmed particles decayed in the emulsion (fig. 2). Second, the path of incident photons through the emulsion was about 0.25 radiation length so that the electromagnetic background was kept at a sufficiently low level for good scanning and measuring conditions.

(d) The OMEGA prime spectrometer allowed to determine the momentum of secondary particles and, through the geometry reconstruction program TRIDENT [3], to localize the interaction point in the emulsion with a high precision (about 0.5 mm transverse to the beam). Also the correspondence between the directions of tracks measured in the emulsion and in the spectrometer (average difference of 0.5 mrad in azimuth and 1 mrad in dip) provided a good matching of the events seen in emulsion with those recorded in the spectrometer. Moreover, this matching means that in such a hybrid experiment the emulsion gets an additional feature which is "time resolution" (the same as that of the OMEGA MWPC's). Using this experimental tool we were able to associate unambiguously decays of neutral charmed particles to the primary interactions in which they were produced.

Among some 17000 matched interactions, found in emulsion near the predicted positions with an efficiency of about 50%, we observed 45 events in which charmed particles were produced and decayed in the emulsion.

In the search for charged particle decays, we followed the forward relativistic and gray tracks from the interaction vertex up to their exit from the emulsion (if they did not interact or decay). For neutral particle decays, an area scanning in the forward direction was made. Special care was naturally taken in those cases where predicted tracks were missing at the interaction vertex. Among the 36 double events found in this way, eleven charmed Λ_c^+ baryons were unambiguously identified. One more event, which could also be taken as a D^+, was assigned to the sample of Λ_c^+ since this hypothesis was found to be the most probable according to a Monte-Carlo calculation.

The mean value for the mass of the Λ_c^+ baryon obtained from four 3C fit events is $M(\Lambda_c^+) = (2.301 \pm 0.017)$ GeV/c^2.

3. RESULTS

3.1 Photoproduction mechanism and cross section

In the quoted sample of twelve events there are five cases in which the Λ_c^+ baryon is associated to a D^- meson. In the other seven cases the charmed partner of the Λ_c^+ is a $\bar{D}^0$ meson. We did not find any case of charmed baryon-antibaryon pair.

In our experiment, the total cross section for the photoproduction of charmed pairs in the photon energy interval (20-70 GeV) was found to be (230 ± 57)nb/nucleon [4]. The partial cross section for associated photoproduction of $\Lambda_c^+\bar{D}$ was found to be (64 ± 31)nb/nucleon. Some indication of its possible dependence on the energy of the incident photon is shown in fig. 3.

We looked for the possible manifestation of higher excited states of charmed baryons. In three events, the invariant mass combinations of the Λ_c^+ with a π^+ meson from the same interaction are the following: 2.532, 2.480 and 2.482 GeV/c^2. In four other events, the invariant mass combinations of the Λ_c^+ with a γ or a π^0 detected by the spectrometer are: 2.413, 2.453, 2.443 and 2.478 GeV/c^2. All the other combinations are well outside the interval (2.3-2.7 GeV/c^2). It suggests that a significant part of the associated production cross section goes through excited baryon states in the first place. If so, we can estimate the following two charmed baryon masses:

$$M(\Sigma_c^{++}) = (2.492 \mp 0.019)\ \mathrm{GeV/c^2} \quad \text{and} \quad M(\Sigma_c^{+}) = (2.447 \mp 0.027)\ \mathrm{GeV/c^2}.$$

In fig. 4 the fraction of the photon energy, $E(\bar{D})/E_\gamma$, taken by the $\bar{D}$ meson is plotted against the fraction of the photon energy, $E(\Lambda_c^+)/E_\gamma$, taken by the Λ_c^+ baryon. It shows that in most cases the $\bar{D}$ meson takes the largest fraction of the energy. This suggests that the charmed baryon is formed by a c quark and two light quarks picked up from the target nucleus. The $\bar{D}$ meson is formed by a $\bar{c}$ quark and only one light quark and thus is likely to take a larger fraction of the incident photon energy than the Λ_c^+ baryon.

Similarly, figs 5(a) and 5(b) show the distribution of the X_f variable for $\bar{D}$ mesons and Λ_c^+ baryons. $\bar{D}$ mesons are mainly produced with positive X_f while Λ_c^+ baryons are mainly produced with negative X_f. The solid curves on the plots are based on the photon-gluon fusion model [4]. The above observations support the assumptions of the photon-gluon fusion model according to which the production of c and $\bar{c}$ quarks is followed by the formation of strings between the $\bar{c}$ quark and one quark of the target nucleus as well as between the c quark and the remaining diquark of the target nucleus. That system undergoes then a fragmentation process.

3.2 <u>Weak decays of the Λ_c^+ baryon</u>

The Λ_c^+ decay modes observed in this experiment are displayed in table 1.

We observed nine one-prong decays and three three-prong decays, which indicates topological branching ratios of

$$\Lambda_c^+ \to \text{(one prong)/all } \Lambda_c^+ \to \text{hadrons} = 3/4 \qquad \text{and}$$

$$\Lambda_c^+ \to \text{(three prongs)/all } \Lambda_c^+ \to \text{hadrons} = 1/4$$

In 6 of the 9 one-prong events a Λ^o hyperon was observed among the final decay products. All Λ^o's were reconstructed from their $\Lambda^o \to p\pi^+$ decay seen in the OMEGA spectrometer and their average mass was found to be $(1.118 \pm 0.008)\mathrm{GeV}/c^2$.

In two of these events the reconstruction of the decay mode $\Lambda_c^+ \to \Lambda^o\pi^+\pi^o$ requested the assumption of the existence of at least one π^o among the decay products. These π^o's were not detected by the OLGA system for either acceptance or efficiency reasons. The nature of the charmed particle in these cases was inferred both from the kinematical reconstruction of the decay (0C fit) and from the unambiguous nature of its charmed partner. The existence of only one unseen π^o was assumed in calculations, although we cannot exclude that they were more.

In those events where, in addition to the Λ^o hyperon, a photon was detected in the OLGA calorimeter, we tested the $\Lambda^o\gamma$ invariant mass combinations. Fig. 6 shows the distribution of the mass differences $M(\Sigma^o) - M(\Lambda^o\gamma)$ for this subsample. Two cases (shaded) are compatible with the decay mode $\Lambda_c^+ \rightarrow \Sigma^o\pi^+\pi^o$ which would thus be observed for the first time. The average invariant mass of the Σ^o in these cases is

$$M(\Lambda^o\gamma) = (1.189 \pm 0.012)\ \mathrm{GeV/c^2}.$$

In the other cases, there is no kinematically constrained solution implying a Σ^o.

Let us turn to the three prong decays. In one case, one of the positively charged tracks makes a wide angle kink of 30° in the emulsion at a distance of 2680 microns from the Λ_c^+ decay vertex. This track, leaving the emulsion, hits the target support and therefore is not detected in the spectrometer. However, the evaluation of its momentum by a multiple scattering measurement was possible, giving a $p\beta = (1.3 \pm 0.3)\mathrm{GeV/c}$. Assuming the decay of a Σ^+ hyperon, we get for the original charmed baryon an invariant mass of $(2.333 \pm 0.195)\mathrm{GeV/c^2}$. This event is a possible evidence of the unknown decay mode $\Lambda_c^+ \rightarrow \Sigma^+\pi^+\pi^-$. Two other events show evidence of the already known decay mode $\Lambda_c^+ \rightarrow \Delta^{++}$ + hadrons, followed by the strong decay $\Delta^{++} \rightarrow p\pi^+$.

Table 2 gives the branching ratios of some specific decay channels with respect to all known hadronic decay modes, taking into account the evaluated fraction of undetected events because there is among their decay products either a $\Lambda^o \rightarrow n\pi^o$ or a $K_L^o \rightarrow \pi\pi$.

In connection with our experimental observations it seems appropriate to add a few words about the weak decay mechanism of Λ_c^+. Both the spectator and the W exchange diagrams are Cabibbo-allowed for the Λ_c^+ decay (fig. 7(a,b)). The observed decay mode $\Lambda_c^+ \to \Lambda\pi^+$ (table 1) is due to the spectator diagram only, while the decay mode $\Lambda_c^+ \to \Delta^{++}K^{*-}$ is an evidence for the W exchange diagram.

The corresponding Cabibbo-allowed spectator diagrams for D^o and D^+ as well as the W exchange diagram for D^o are shown in fig. 7(c,d). In fact, D^+ decays may be explained by two versions of the spectator diagram leading to identical final states (fig. 7(e)). This creates a destructive interference of amplitudes. An experimental evidence for such an interference has been obtained in [4] from branching ratios of decay modes.

3.3 Lifetime of Λ_c^+ baryon

For the estimate of the lifetime τ of the Λ_c^+ baryon we used the following likelihood function

$$L = -\ell n \prod_{i=1}^{n} \exp(-t_i/\tau)\{\tau[\exp(-t_i^{min}/\tau) - \exp(-t_i^{max}/\tau)]\}^{-1}$$

where t_i is the time of flight of the i^{th} particle and where t_i^{min} and t_i^{max} are the times corresponding respectively to the minimum path length and the potential path length of the i^{th} decaying particle in the emulsion. The minimum path length is the minimum distance at which at least one of the secondary particles from the given decay would have had an impact parameter ≥ 1 μm with respect to the primary interaction vertex. The potential path length is the maximum distance the given particle would have covered if it had not decayed before leaving the emulsion.

The value, which maximizes the function L is: $\tau(\Lambda_c^+) = (2.3^{+0.9}_{-0.6} \pm 0.4) \cdot 10^{-13}$ s, where the statistical and systematic errors are given, the latter resulting from the uncertainty in the choice of the solution for 0C fit events (i.e. those with unseen neutral decay components).

In our experiment we obtained also the following estimates for the lifetimes of the D^o, $\bar{D}^o$ and $D^\pm$ charmed mesons [6]: $\tau(D^o, \bar{D}^o) = (3.6^{+1.2}_{-0.8} \pm 0.7) \cdot 10^{-13}$ s and $\tau(D^\pm) = (5.0^{+1.5}_{-1.0} \pm 1.9) \cdot 10^{-3}$ s.

The observed hierarchy in the charmed particle lifetimes, $\tau(\Lambda_c^+) < \tau(D^o, \bar{D}^o) < \tau(D^{\pm})$, can be understood if preasymptotic effects of various types are considered [7]. Each of these effects gives a factor of ~ 1.5. Moreover interference phenomena between diagrams (fig. 7(e)) play an important role. The decay probability of the Λ_c^+ is also increased by the quark scattering mechanism cd → us. It would be interesting to know the contribution of the existing W exchange diagram to this hierarchy of lifetimes.

4. CONCLUSIONS

The following results have been obtained about the photoproduction and decay of charmed Λ_c^+ baryons.

(a) The contribution of the associated production to the total photoproduction cross section for charmed particles is of (28 ± 13)%.

(b) The associated production cross section possibly rises with the photon energy.

(c) The charmed baryons are produced mainly with negative X_f while the associated charmed mesons are produced mainly with positive X_f. This is in agreement with the predictions of the photon-gluon fusion model.

(d) There is some evidence for the following decay modes:

$$\Lambda_c^+ \rightarrow \Sigma^o \pi^+ \pi^o$$

$$\Lambda_c^+ \rightarrow \Sigma^+ \pi^+ \pi^-$$

$$\Lambda_c^+ \rightarrow \Delta^{++} K^- \pi^o$$

The last one indicates the existence of a W exchange diagram in the decay process.

(e) The estimated lifetime of the charmed Λ_c^+ baryon is

$$\tau(\Lambda_c^+) = (2.3^{+0.9}_{-0.6} \pm 0.4) \; . \; 10^{-13} \text{ s}$$

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TABLE 1

Topology	Nr. of events	Decay modes(*)	Nr. of decays	
One-prong decays	9	$\Lambda_c^+ \to \Lambda^o \pi^+$	1	
		$\Lambda_c^+ \to \Lambda^o \pi^+ \ (\pi^o)$	3	
		$\Lambda_c^+ \to \Sigma^o \pi^+ \pi^o$ ↳ $\Lambda^o \gamma$	1	} 2
		$\Lambda_c^+ \to \Sigma^o \pi^+ (\pi^o)$ ↳ $\Lambda^o \gamma$	1	}
		$\Lambda_c^+ \to p\bar{K}^o$	1	
		$\Lambda_c^+ \to p\bar{K}^{*o}$ ↳ $\bar{K}^o (\pi^o)$	1	
		$\Lambda_c^+ \to p(\bar{K}^o)$ $\pi^+(\Lambda^o)$	1	
Three-prong decays	3	$\Lambda_c^+ \to \Sigma^+ \pi^+ \pi^-$	1	
		$\Lambda_c^+ \to \Delta^{++} K^{*-}$ ↳ $K^- \pi^o$ ↳ $p\pi^+$	1	
		$\Lambda_c^+ \to \Delta^{++} K^- (\pi^o)$ ↳ $p\pi^+$	1	

(*) The symbol (π^o) stands for undetected π^o's

TABLE 2

Decay channel	Branching ratio(*)
$\Lambda_c^+ \to p$ + hadrons	37^{+20}_{-18}
$\Lambda_c^+ \to \Lambda^o$ + hadrons (not including Σ^o)	39^{+23}_{-19}
$\Lambda_c^+ \to \Sigma^o\pi^+\pi^o$	16^{+15}_{-13}
$\Lambda_c^+ \to \Sigma^+\pi^+\pi^-$	10^{+8}_{-5}
$\Lambda_c^+ \to \Lambda^o\pi^+\pi^o$	24^{+17}_{-17}
$\Lambda_c^+ \to \Delta^{++}K^-$ + hadrons	10^{+9}_{-8}
$\Lambda_c^+ \to pK^o$ + hadrons	30^{+19}_{-16}

(*) The statistical errors given correspond to confidence intervals of 0.683 probability [5].

FIGURE CAPTIONS

Fig. 1 General layout of the OMEGA prime spectrometer, in which the position of the emulsion target is shown.

Fig. 2 Probability for charmed particles to decay inside the emulsion target vs their lifetime. Curves (1) and (2) represent the probability to see either one or both decays. The full lines correspond to central production, the dotted lines to diffractive production.

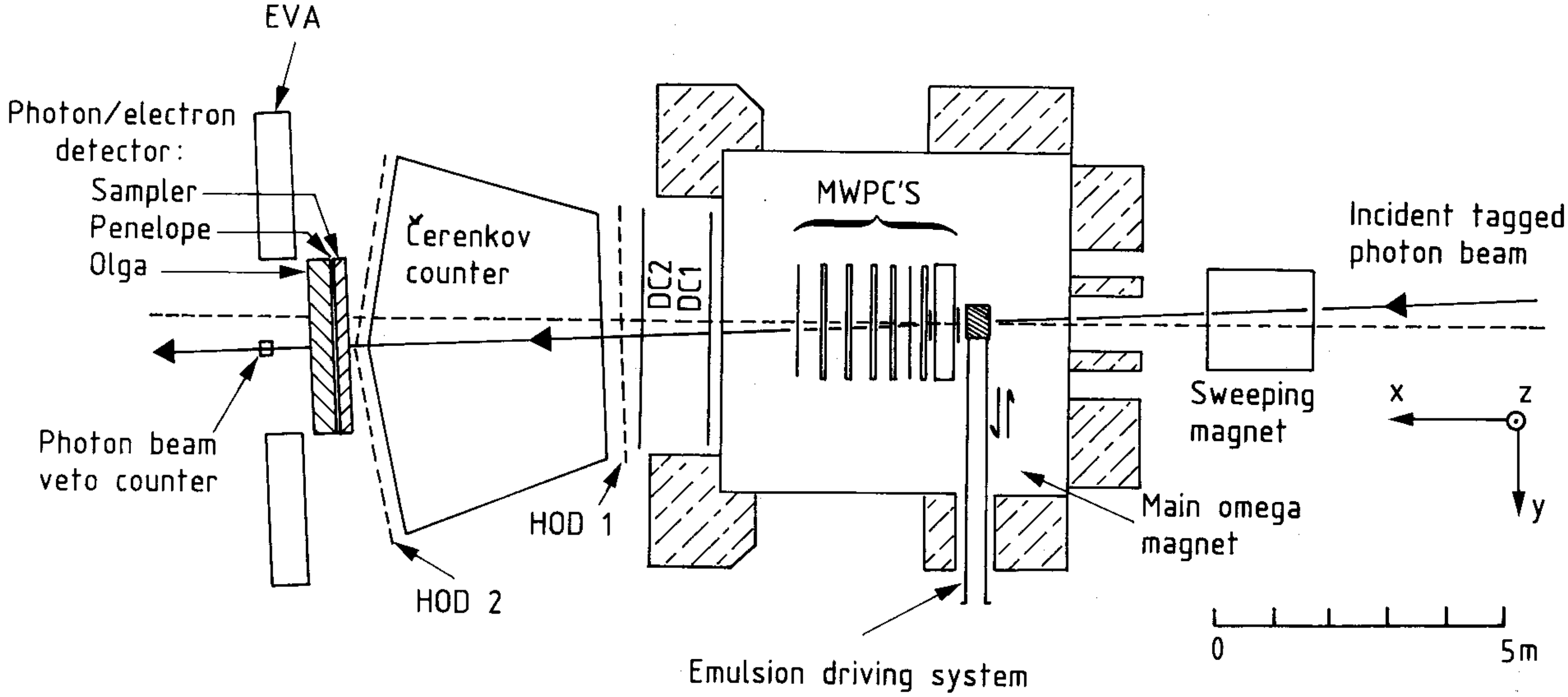
Fig. 3 Cross section for the associated photoproduction vs photon energy.

Fig. 4 Sharing of the incident photon energy between the associated Λ_c^+ and $\bar{D}$.

Fig. 5 X_f distributions of associated Λ_c^+ and $\bar{D}$. The curves show predictions from the photon-gluon fusion model. Both curves are normalized to the number of weighted events.

Fig. 6 Distribution of the mass differences between Σ^o and $(\Lambda^o\gamma)$ for all Λ_c^+ events with associated Λ^o and γ.

Fig. 7 Cabibbo-allowed decay diagrams for Λ_c^+, D^o and D^+ decays.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Photon/electron
detector:
Sampler
Penelope
Olga
Photon beam
veto counter
Čerenkov
counter
HOD 2
HOD 1
DC2
DC1
MWPC'S
Emulsion driving system
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magnet
Sweeping
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Incident tagged
photon beam
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Fig. 1

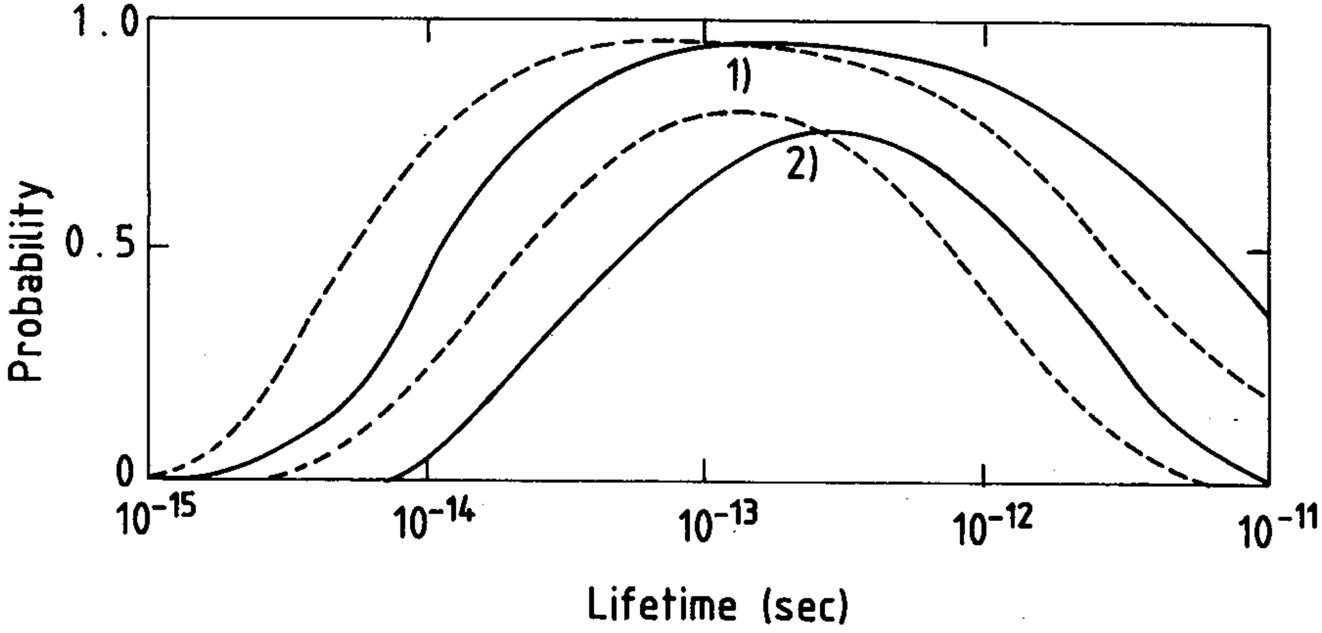


Fig. 2

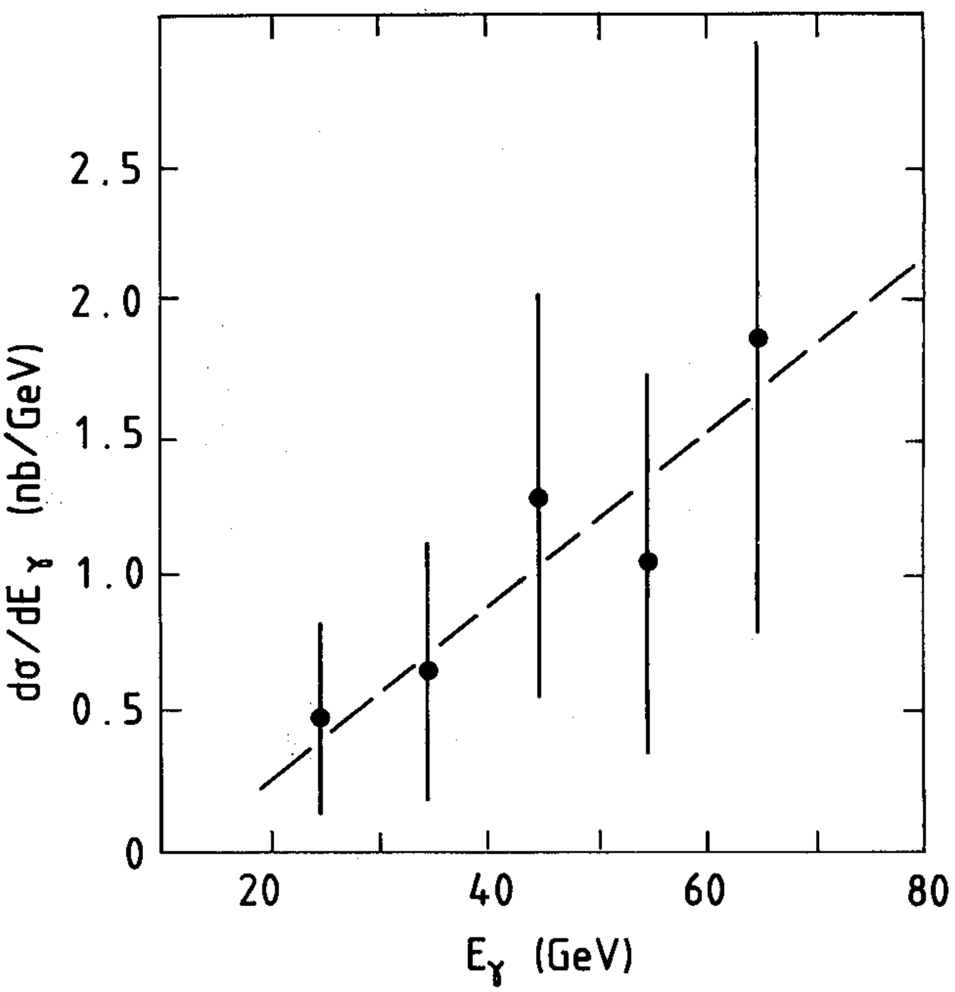


Fig. 3

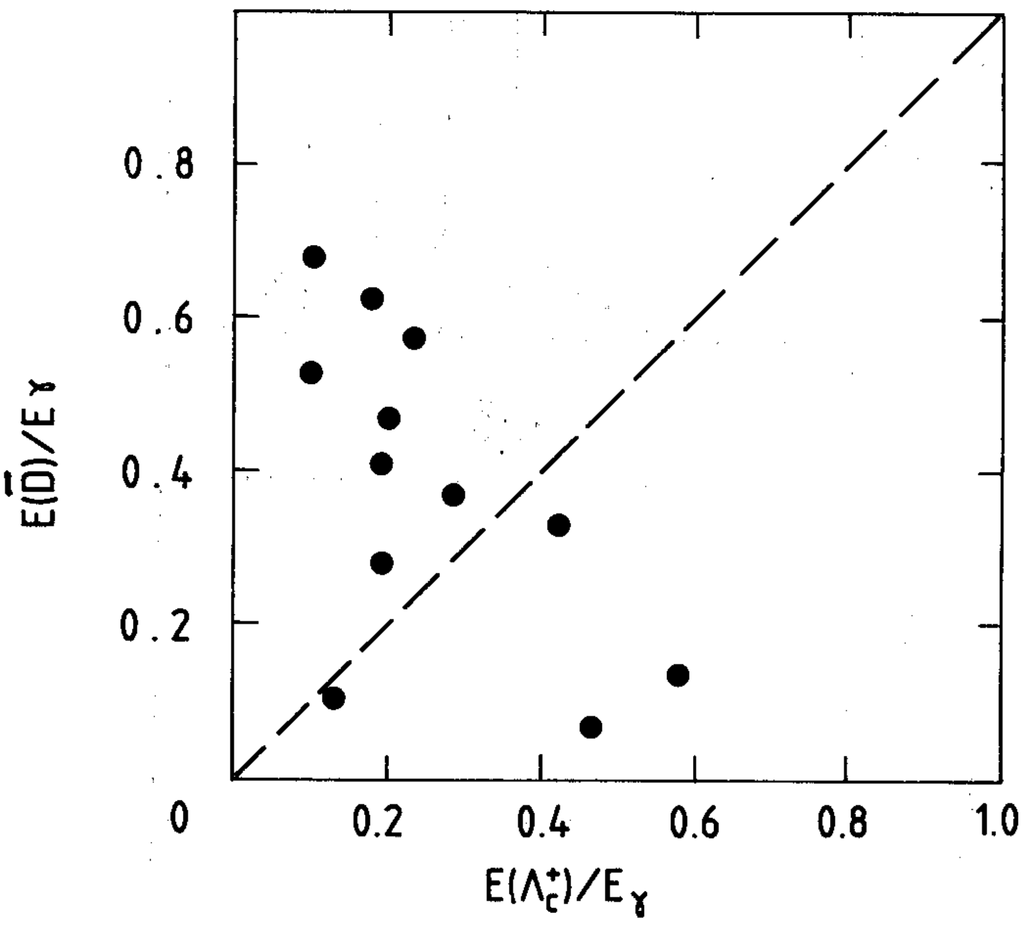
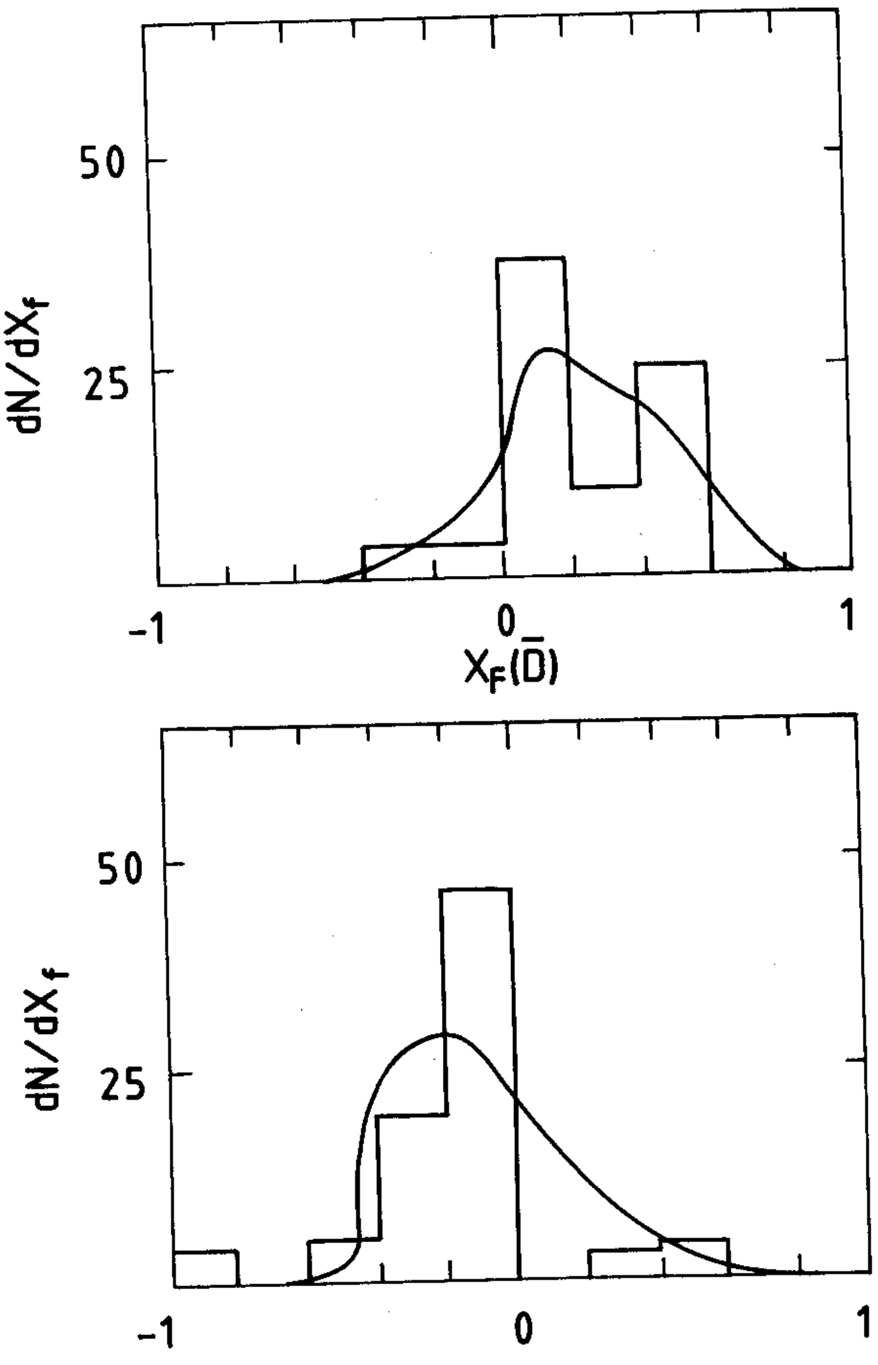


Fig. 4



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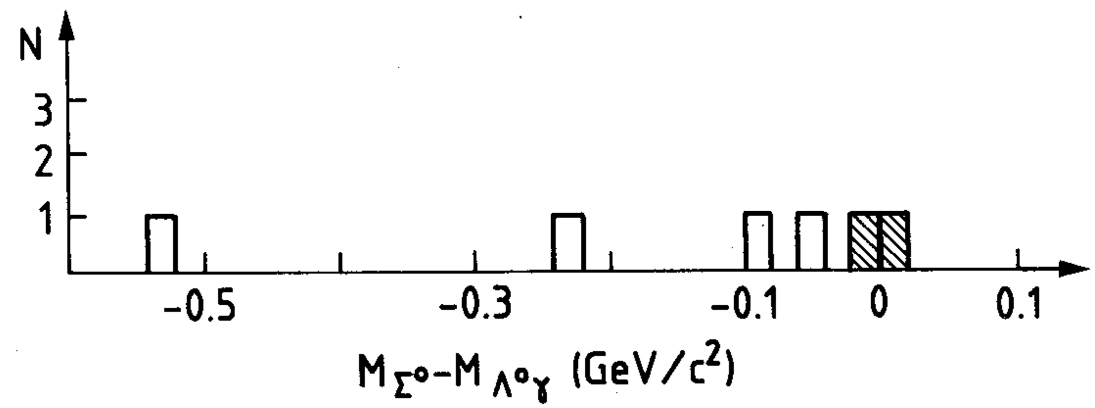

Fig. 6

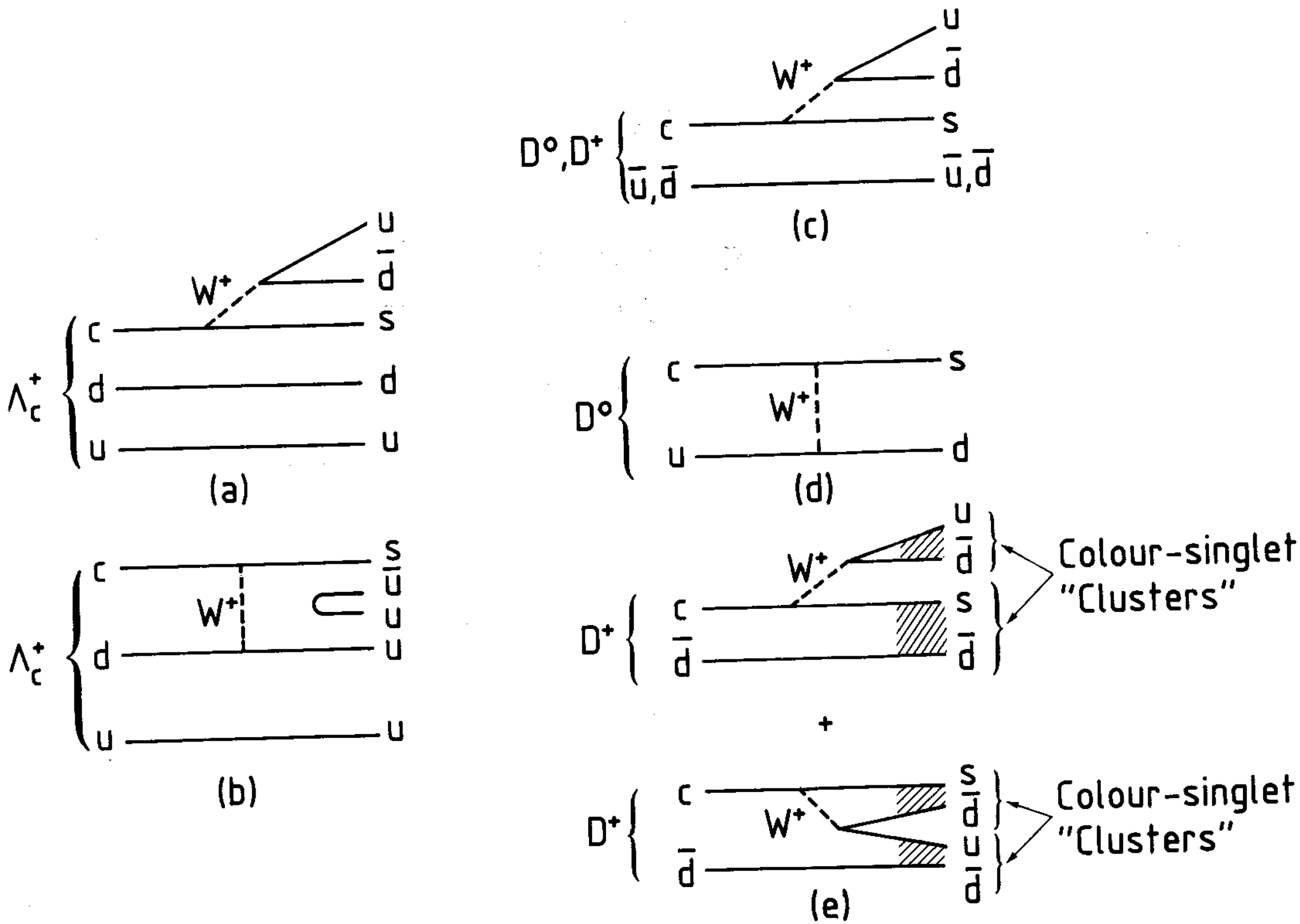

Fig. 7