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Λ_c PRODUCTION CHARACTERISTICS IN PROTON-PROTON INTERACTIONS AT 400 GeV/c

LEBC-EHS Collaboration

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ABSTRACT

We present the measurements of Λ_c production cross section in proton-proton interactions at $\sqrt{s} = 27.4$ GeV and give new limits on the exclusive branching ratio $\Lambda_c \to pK^+\pi^-$.

The experimental knowledge on the properties of the charm baryon Λ_c is still very scarce. There has been recent progresses on the lifetime measurement [1,2], but branching ratios and hadronic production features are still largely unknown.

In this paper we report on the Λ_c cross section(*), production properties and some information on branching ratios, obtained in the CERN NA27 experiment using the LEBC-EHS apparatus.

The LEBC-EHS experimental set-up [3] has proven to be a powerful tool to study charm decay and hadronic production, due to the excellent spatial resolution of the target and the track reconstruction capability of the spectrometer in the presence of complex final states. Its main features are:

(a) A high resolution hydrogen bubble chamber (LEBC) as a target, producing bubbles with diameter 20 µm and density 80/cm.

(b) A two lever-arm spectrometer, giving a momentum precision better than 0.8% over the full momentum range, and with almost full acceptance for charm particles produced forward in the c.m. system.

(c) A complex particle identification system, composed of four different detectors (SAD, ISIS, FC, TRD), covering the momentum range 0.5-400 GeV/c.

(d) Electromagnetic and hadronic calorimeters for the measurement of neutral particles.

LEBC was exposed to a CERN SPS proton beam of 400 GeV/c ($\sqrt{s} = 27.4$ GeV). One million interactions in the visible volume of LEBC were collected, corresponding to a sensitivity of (38.5 ± 1.1)ev/µb. The details of scanning, measuring, reconstruction and charm selection procedures can be found in ref. [3]. Here we give only the most relevant analysis details.

The trigger efficiency for charm decays is close to unity $(98^{+2}_{-3})\%$. The double scan efficiency depends on the topology and on the cuts used in the analysis. For topologies with at least two tracks in the decay, it is around 95%.

After a first measurement and geometry processing, events are kept if:

(a) The decay is inside a cylinder with radius R coaxial with the beam trajectory.

(b) The decay length is less than L.

(*) Unless otherwise stated, a specific state will imply its charge conjugate as well.

(c) The number of decay tracks outside a spectrometer acceptance of 180 mrad is not more than N.

(d) All impact parameters are less than T.

The value of these parameters for the different topologies are given in table 1. The topology notation gives the charge of the decay and the number of decay tracks detected (C is for a charge decay, V for a neutral one, X for a decay of unclear nature).

In addition to the geometrical cuts, C1 and V2 decays in events with one decay only were required to have a track with at least 250 MeV/c transverse momentum with respect to the line of flight of the decaying particle to eliminate the strange particle decays.

Our final charm sample consists of 324 events. They were all measured on an HPD, a high precision device that measures the impact parameter of each track with a precision of 2.5 µm. After this stage we find, with almost 100% efficiency, secondary tracks having impact parameter to the primary vertex as small as 7 µm.

The analysis of Λ_c properties in this paper is based on the full sample of 134 three-prong decays. We do not make use of the one-prong topology, since it has strong biases. To reduce the charm particle ambiguities and to eliminate the strange particle background, we restrict the sample used for this analysis to decays with three well reconstructed tracks. The EHS spectrometer acceptance is such that 67 three-prong decays are kept. The background coming from strange particle decays in this sample is negligible (less than 0.3 decay).

To give reliable measurements of the charm cross section it is important to know accurately the efficiency of the scanning and measuring chain. This is particularly important for Λ_c particles, because the low value of the lifetime puts the visibility of such decays near the limits of the apparatus.

In our experiment, there are two ways to detect decay vertices: directly in at least one of the two independent scans, or during the measurement of the event on a high precision measuring device (HPD). Consequently, to compute the visibility and acceptance weights, we have defined different decay selection criteria for the two possibilities.

(a) Selection A (decays visible at scanning). To assure high scanning efficiency $(94^{+2}_{-3})\%$ and no topological ambiguities with D^0 decays into 2 charged tracks (V2) with the decay vertex superimposed on a primary track, the following cuts are applied in addition to those previously defined. Calling L the decay length and y_1, y_2, y_3 the impact parameters of the three-decay tracks in decreasing order of magnitude, we require $L > 500\ \mu m$, $y_1 > 50\ \mu m$, $y_2 > 10\ \mu m$ and also $y_3 > 7\ \mu m$ unless the two other tracks have the same sign. These criteria select 59 decays. Assuming a lifetime of $1.2 * 10^{-13}$ s, the cuts accept about 10% of all the Λ_c produced forward in the c.m. system.

(b) Selection B (decays coupled to another charm activity seen at scanning). In this selection we include decays detected at the measuring stage. These events were sent to measurement only if another decay was found at scanning. To compute the efficiency of this selection, we must be sure that the partner decay is a D meson, for which we have a good and well-known scanning efficiency [4]. For this reason we require that the largest impact parameter of the partner is $y_{max} > 50\ \mu m$ if the partner is neutral or $y_{max} > 100\ \mu m$ if it is charged. The larger limit imposed on the charged partner removes most of the Λ_c decays and reduces, if present, the contamination from D_s. Because of these cuts, the sample obtained with selection B can give information only on $\sigma(\Lambda_c D)$, and not on $\sigma(\Lambda_c)$ inclusive. The visibility weight of the partner, averaged over all the different topologies, taking into account the selection criteria applied to our scanning sample (including the losses due to the D^0 decay in all neutrals), is 2.7 ± 0.1 for D^0 and 2.7 ± 0.2 for $D^\pm$. The errors come mainly from the uncertainty on the lifetime and the x_F distribution. The fact that the two weights are the same, due to the high cut on y_{max} for $D^\pm$, will simplify the analysis of this sample. For the C3 to be used in the Λ_c analysis, the cuts are the following: $L > 200\ \mu m$, $y_1 > 10\ \mu m$, $y_2 > 10\ \mu m$ and also $y_3 > 7\ \mu m$ unless the two other tracks have the same sign. After this selection 27 decays survive, 21 of them belong also to the sample of selection A. The fraction of Λ_c accepted by these criteria, not including the partner visibility, is about 28% of all the Λ_c produced forward in the c.m. system.

Among the C3 decays of selection A and B, 17 have a kinematic fit to a Λ_c decay hypothesis. Six of these, taking also into account the particle identification information, have only a Λ_c interpretation, and are listed in table 2. We will define these in the following as sample C. We cannot estimate reliably the loss which this uniqueness requirement causes. However, the sample is unbiased as far as the production properties are concerned, once corrected by the proper visibility and acceptance weights, which are smooth functions of x_F and p_T and do not vary more than ± 15% in the forward x_F hemisphere.

In the following analysis, unless explicitly stated, we will use Λ_c's with $x_F \geq 0$, because of the low acceptance of the spectrometer at negative x_F. The cross section for all x_F will be obtained making use of the symmetry of the initial state.

In all the results of this paper, the visibility weights will be computed using the value of $\tau = (1.2^{+0.5}_{-0.3}) * 10^{-13}$ s measured by our experiment [2]. A change of the lifetime by one standard deviation would change the weights used to compute the Λ_c cross sections by roughly 40% for selection A and roughly 25% for selection B.

To identify a Λ_c signal, we use three different but complementary methods, based on the impact parameter distribution, the proton identification among the decay tracks and the kinematic fits to exclusive channels.

(a) Impact parameter

The Λ_c should appear as an excess of events at low impact parameter values. With this method, a clean separation between forward and backward production is not possible, because in final states with a Λ^o or a neutron, a large fraction of the momentum can be carried out by the neutral baryon. Therefore we do not apply any cut on the longitudinal momentum, and include the acceptance uncertainty in the error of the result.

Varying the exponent n of the x_F production distribution $(1 - x)^n$ between $n = 1$ and $n = 5$, and averaging over the final states, the mean weight differs by less than 25% with respect to the value at $n = 3$ (used in the calculations), taking also into account the uncertainties on the relative frequency of the final states.

Fig. 1 gives the distribution of the average impact parameter, y_{av}, of the three tracks of each decay for selection A + B. The full curve is the distribution expected from $D^{\pm}$ decays, normalized at $y_{av} > 100$ µm. For the sample A, in the region $y_{av} < 60$ µm 16 events are present whereas $9.1^{+1.9}_{-1.6}$ $D^{\pm}$ are expected. This gives an excess of $6.9^{+5.3}_{-4.4}$ events. For the sample B, we are left with 13 events with

$y_{av} < 60\ \mu m$, the $D^{\pm}$ contribution being $4.2^{+1.9}_{-1.4}$ events. This gives an excess of $8.8^{+4.9}_{-4.1}$ events. The excess of events at low impact parameters thus gives the following Λ_c cross sections, neglecting a possible contamination from D_s production:

$$\sigma_{\mathrm{all}\ xF}\ (\Lambda_c/\bar{\Lambda}_c) \times \mathrm{BR}\ (3\ \mathrm{prongs}) = 3.1\ ^{+2.4}_{-1.8}\ \mu b \qquad (1)$$

$$\sigma_{\mathrm{all}\ xF}\ (\Lambda_c\bar{D}/\bar{\Lambda}_c D) \times \mathrm{BR}\ (3\ \mathrm{prongs}) = 3.4\ ^{+2.0}_{-1.6}\ \mu b \qquad (2)$$

The upper limits at 90% confidence level are 6.1 μb and 5.8 μb respectively, independently of the D_s contamination. Comparing these two relations and using the relation $\sigma(\Lambda_c/\bar{\Lambda}_c) = 2\ \sigma(\Lambda_c\bar{\Lambda}_c) + \sigma(\Lambda_c\bar{D}/\bar{\Lambda}_c D)$ we can obtain the following upper limit on $\sigma(\Lambda_c\bar{\Lambda}_c)/\sigma(\Lambda_c\bar{D}/\bar{\Lambda}_c D)$:

$$\sigma(\Lambda_c\,\bar{\Lambda}_c)/\sigma(\Lambda_c\bar{D}/\bar{\Lambda}_c\,D) < 0.7\ . \qquad (3)$$

We recall once more that this result is valid if the D_s cross section is small compared to the Λ_c one.

(b) Identification of protons among the decay particles

The (anti)protons produced in Λ_c decays must have the same sign as the decaying particle. We have therefore searched for particles heavier than the pion among the "like-sign" decay products.

With this method, the restriction at positive x_F can be obtained statistically with a cut at 30 GeV/c on the total seen longitudinal momentum of the decay. The results depend little on the exact value of this cut. A maximum likelihood fit to the particle identification data has been performed, taking into account both the ionisation data of ISIS and the signals from the forward Cerenkov. The percentage of tracks with good ionisation information is 70%. The search has been done on the decays with $y_{av} < 60\ \mu m$. Among the like-sign tracks of sample A, $3.8^{+3.8}_{-2.3}$ must have a mass bigger than the pion one, and among the like-sign tracks of sample B, $2.9^{+3.5}_{-2.7}$. No signal is observed among decays with $y_{av} > 60\ \mu m$. Apart from Λ_c decays, possible sources of this signal can be Cabibbo-unfavoured decays of D mesons, and D_s decays. The former contribution is expected to be a fraction (0.5) of an event. For the latter, we cannot make estimates since the D_s cross section and branching ratios are unknown. However, given the bigger lifetime of the D_s meson, $\tau = (3.8^{+0.7}_{-0.5}) * 10^{-13}$ s [5], we would expect its signal in the region $y_{av} > 60\ \mu m$ to be 1.5 times the signal in the complementary region.

If we neglect the D_s production the signals correspond to the following cross sections:

$$\sigma_{\text{all } xF}\ (\Lambda_c/\bar{\Lambda}_c)\ \times\ \text{BR}\ (p + 2\ \text{prongs}) = 3.5\,^{+3.5}_{-2.2}\ \mu\text{b} \tag{4}$$

$$\sigma_{\text{all } xF}\ (\Lambda_c\bar{D}/\bar{\Lambda}_c D)\ \times\ \text{BR}\ (p + 2\ \text{prongs}) = 3.4\,^{+2.7}_{-1.4}\ \mu\text{b} \tag{5}$$

where the errors include the uncertainty of the different branching ratios. The corresponding upper limits are 12.1 μb and 9.8 μb respectively (at 90% CL).

(c) Kinematical fits

The events of selection C are unambiguous Λ_c decays. They can be used to find a lower limit on Λ_c production. We have 4 decays satisfying both selections A and C and 2 events of selections B and C and positive x_F. This gives the following lower limits (at 90% CL):

$$\sigma_{\text{all } xF}\ (\Lambda_c/\bar{\Lambda}_c)\ \times\ \text{BR}\ (p + 2\ \text{prongs}) > 1.4\ \mu\text{b} \tag{6}$$

$$\sigma_{\text{all } xF}\ (\Lambda\,\bar{D}/\bar{\Lambda}\ D)\ \times\ \text{BR}\ (p + 2\ \text{prongs}) > 0.2\ \mu\text{b} \tag{7}$$

We have also performed a search for exclusive final states. In the mode $pK^-\pi^+$, there are only 2 decays of selection A having the correct mass value. They are also "unique" Λ_c, as can be seen in table 2. This provides the following value:

$$\sigma_{\text{all } xF}\,(\Lambda_c/\bar{\Lambda}_c) \times \text{BR}(p\,K^-\,\pi^+) = 1.2\,^{+1.6}_{-0.8}\ \mu\text{b} \tag{8}$$

Using selection B, we have 1 decay compatible with this hypothesis, but it is ambiguous with a D or D_s hypothesis.

We have also searched for decays into the $pK^-\pi^+$ final state with impact parameters so small to be invisible, even with the high resolution of the HPD. The cross section upper limit obtained in this way has the good property of becoming stronger if we assume a Λ_c lifetime smaller than the one used. The method is the following:

(a) Consider all the events of our charm sample containing only one decay with clear charm signature. We have 173 such events.

(b) Look for tracks from the primary vertex with the π mass assignment excluded from particle identification. There are 207 such tracks.

(c) Compute the $pK\pi$ effective mass for all the three particle combinations obtained adding to the track of point (b) two primary tracks of opposite sign, taking into account particle identification.

No significant peak is observed. A 20 MeV bin centred at the Λ_c mass contains 12 combinations, the average value in this mass region being 6.7.

The resulting upper limit on the cross section is, at 90% confidence level:

$$\sigma_{\mathrm{all}\ xF}\,(\Lambda_c\bar{D}/\bar{\Lambda}_c D) \times \mathrm{BR}\,(p\,K^-\pi^+) < 1.4\ \mu\mathrm{b} \qquad (9)$$

An upper bound to the Λ_c production cross section can be found independently of the analysis of our Λ_c candidates, on the basis of our measurements of $\bar{D}D$ and inclusive D cross sections, published in ref. [4]. Using the relation $\sigma(\Lambda_c\bar{D}/\bar{\Lambda}_c D) < \sigma(D/\bar{D}) - 2\sigma(D\bar{D})$ we obtain at 90% confidence level:

$$\sigma(\Lambda_c D^-/\bar{\Lambda}_c D^+) < 3.0\ \mu\mathrm{b} \qquad (10)$$

$$\sigma(\Lambda_c\bar{D}^o/\bar{\Lambda}_c D^o) < 4.7\ \mu\mathrm{b} \qquad (11)$$

$$\sigma(\Lambda_c\bar{D}/\bar{\Lambda}_c D) < 6.1\ \mu\mathrm{b} \qquad (12)$$

We can compare the cross section results obtained above to obtain information on the Λ_c branching ratios.

The comparison of (8) and (1) provides, at 90% confidence level,

$$\frac{\mathrm{BR}\ (pK^-\pi^+)}{\mathrm{BR}\ (3\ \mathrm{prongs})} > 9.2\% \qquad (13)$$

To compute this ratio with better statistical significance, we have also used the full sample A + B, including the data from a previous run using a π beam, and computed the ratio (13) dividing the total number of $\Lambda_c \to pK^-\pi^+$ found in this sample by the number of particle exceeding the D expectation in the y_{av} distribution. In fact, since the inefficiencies in detecting Λ_c decays depend only weakly on the decay final state, their effect almost cancels out in the ratio (13). The number of $\Lambda_c \to pK\pi$ can be evaluated from the mass plot in fig. 2, where a clear signal (6 events) is present at the nominal Λ_c mass value; the background can be evaluated to be ≤ 1 event, both from the neighbouring bins and from the ambiguity information of the kinematic fits. In the y_{av} distribution we find an excess of $18. \pm 6.2$ particles. Taking into account the difference in the acceptance for the various channels, this gives

$$BR(pK\pi)/BR(3\text{ prongs}) = (26^{+18}_{-15})\%.$$

The corresponding lower limit is

$$\frac{BR\ (pK^-\pi^+)}{BR\ (3\text{ prongs})} > 10.2\%\ . \qquad (14)$$

If the D_s cross section is small we can use results (4), (5), (1) and (2) and obtain (at 90% CL):

$$\frac{BR(p + 2\text{ prongs})}{BR(3\text{ prongs})} > 26\%\ . \qquad (15)$$

Combining results (2) and (12) with (14), we obtain:

$$BR(pK^-\pi^+) > 4.4\% \quad (\text{at } 90\%\text{ CL}) \qquad (16)$$

We stress that the limits (14) and (15) are insensitive to the value of the Λ_c lifetime used in the visibility calculation, while the limit (16) decreases by 20% assuming a lifetime of $1.7 * 10^{-13}$ s instead of $1.2 * 10^{-13}$ s.

As already mentionned, events of selection C in table 2, once corrected for visibility and acceptance, represent an unbiased sample as far as production is concerned. The visibility weights themselves do not depend on x_F by more than 15% in the forward hemisphere.

The weighted x_F average value for the 5 uniquely identified Λ_c having positive x_F (events 1 to 5 in table 2) is:

$$\langle x_F \rangle = 0.13 \pm 0.05.$$

Among these 5 $\Lambda_c/\bar{\Lambda}_c$, the 3 Λ_c give an average value

$$\langle x_F(\Lambda_c)\rangle = 0.17 \pm 0.06$$

and the two $\bar{\Lambda}_c$

$$\langle x_F(\bar{\Lambda}_c)\rangle = 0.08 \pm 0.07.$$

It turns out that only one uniquely identified Λ_c was rejected by the impact parameter cuts described above. If we include this Λ_c in the calculation of $\langle x_F\rangle$, we would get

$$\langle x_F(\Lambda_c)\rangle = 0.22 \pm 0.10.$$

We should also note that event 6 in table 2 is a uniquely $\bar{\Lambda}_c$ with $x_F = -0.12$.

These results imply that, at our energy, Λ_c are not dominantly produced at large x_F. We also note that we observe comparable numbers of Λ_c and $\bar{\Lambda}_c$. We stress here that careful studies have been made on our scanning and reconstruction efficiency at large x_F values, both on the experimental data and with Monte-Carlo simulations. We do not find evidence for special losses at large x_F.

For the 5 uniquely identified Λ_c with $x_F > 0$, the weighted average p_t^2 is 1.90 $(\mathrm{GeV}/c)^2$.

All the results reported, although based on limited statistics, give a quite coherent picture of Λ_c production in proton-proton interactions at $\sqrt{s} = 27.4$ GeV.

The associated production, i.e. $\sigma(\Lambda_c\bar{D})\bar{\Lambda}_cD)$, which can be estimated independently of the Λ_c lifetime, turns out to be significantly smaller than the $D/\bar{D}$ meson cross section ($\sigma(D/\bar{D}) = 30.2 \pm 2.2$ μb [4]):

$$\sigma(\Lambda_c\bar{D}/\bar{\Lambda}_c D) < 6.1\ \mu\mathrm{b} \quad (90\%\ \mathrm{CL}).$$

In addition, we find no evidence for a dominant Λ_c production at large x_F. However, within the present statistics, one cannot exclude a production distribution of the form $(1 - x)^n$ with $n \sim 2$ as reported by recent ISR measurements [6].

At 90% CL, the inclusive $\Lambda_c/\bar{\Lambda}_c$ production cross section times the topological branching ratio BR($\Lambda_c \rightarrow 3$ prong) is in the range:

$$1.4\ \mu\mathrm{b} < \sigma(\Lambda_c/\bar{\Lambda}_c) \times \mathrm{BR}(\Lambda_c \rightarrow 3\ \mathrm{prong}) < 6.1\ \mu\mathrm{b}.$$

Our data also suggest that the currently available value [7] of $\mathrm{BR}(\Lambda_c \rightarrow pK^-\pi^+) = (2.2 \pm 1.0)\%$ is underestimated since we find, at 90% CL:

$$\mathrm{BR}(\Lambda_c \rightarrow pK^-\pi^+) > 4.4\%.$$

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TABLE CAPTIONS

TABLE 1 Parameters used in the selection of charm decays.

TABLE 2 List of three-prong decays uniquely identified as Λ_c.

TABLE 1

Topology	R (mm)	L (mm)	N	T (mm)
X1-X6	2.0	-	1	1.5
C1	0.6	-	0	1.5
V2	0.2	30	1	0.5
C3, V4, C5	2.0	-	-	-

TABLE 2

Event identif.	Number of degrees of freedom	Decay mode	x_F	p_T GeV/c	y_{av} μm	Partner	Selection
1	3	$p\pi^+K^-\pi^0$	0.08	0.493	47	D^-	AC
2	0	$\bar{p}K^+\pi^-(\pi^0)$	0.01	0.327	26	$C3^+$	BC
3	3	$pK^-\pi^+$	0.27	1.940	23	$C1^-$	AC
4	3	$\bar{p}K^+\pi^-$	0.16	1.750	34	D^0	AC
5	3	$pK^-\pi^+\pi^0$	0.17	1.497	52	V2	ABC
6	3	$\bar{p}K^+\pi^-$	-0.12	0.832	14	D^0	BC

FIGURE CAPTIONS

Fig. 1 Distribution of y_{av}, the average impact parameter of the three decay tracks, for selection A + B (see text for the definition).

Fig. 2 $pK^-\pi^+$ effective mass for all the three-prong decays in proton and π^- beam data.

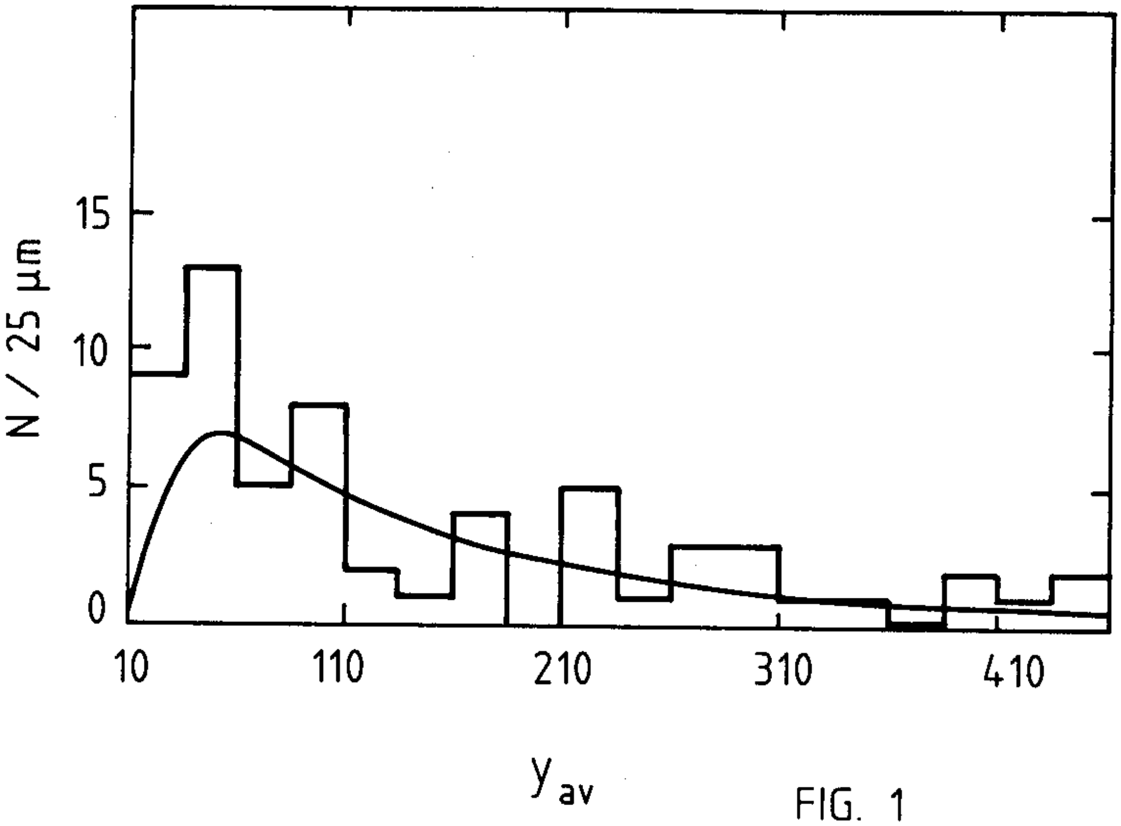

FIG. 1

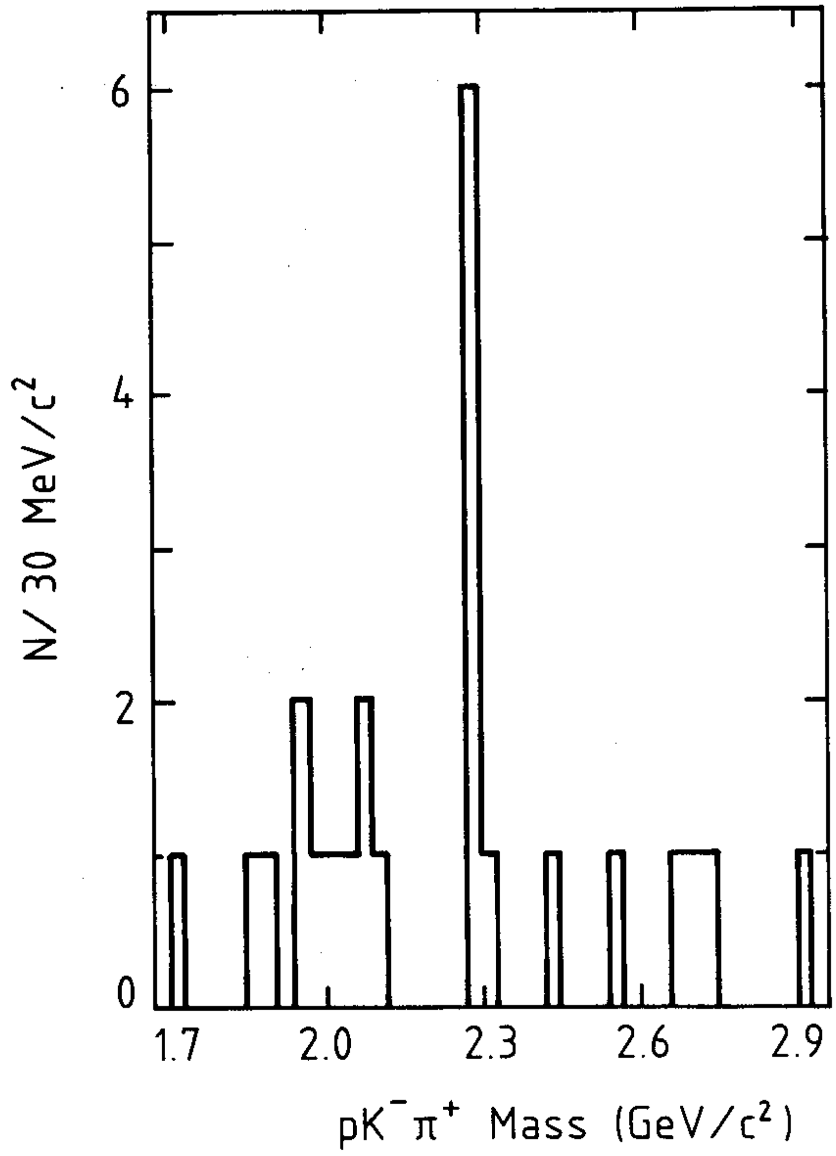

FIG. 2