Nuclear Physics B139 (1978) 61–71

CHARGED Σ HYPERON PRODUCTION BY K⁻ MESON INTERACTIONS AT REST

R.J. NOWAK *, J. ARMSTRONG, D.H. DAVIS, D.J. MILLER and D.N. TOVEE
Department of Physics and Astronomy, University College London, UK

D. BERTRAND **, M. GOOSSENS ***, G. VANHOMWEGEN *** and G. WILQUET **
Inter-University Institute for High Energies (ULB-VUB), Brussels, Belgium

M. ABDULLAH, N.H. BEDFORD, J. CIBOROWSKI *
J.V. MAJOR and J.A. ZAKRZEWSKI *
Department of Physics, University of Durham, UK

D. KIEŁCZEWSKA, T. TYMIENIECKA and E. RONDIO
Institute of Experimental Physics, University of Warsaw, Poland

Received 31 October 1977

Bubble chamber pictures have been scanned for the interactions of stopping K^- mesons in hydrogen. New determinations of the ratios

$$\gamma = \frac{K^-p \to \Sigma^-\pi^+}{K^-p \to \Sigma^+\pi^-}\,, \qquad R_c = \frac{K^-p \to \text{charged particles}}{K^-p \to \text{all final states}}\,,$$

for K^- meson interactions at rest, are presented, as well as the branching ratio

$$B = \frac{\Sigma^+ \to n\pi^+}{\Sigma^+ \to n\pi^+,\, p\pi^0}\,.$$

The values found for R_c, 0.664 ± 0.011, and for B, 0.488 ± 0.008, are in agreement with previous results. On the other hand, two values, resulting from different methods of analysis, have been found for γ, namely 2.38 ± 0.04 and 2.35 ± 0.07. They agree with one of the two previous precise measurements but are inconsistent with the other.

* On leave of absence from the University of Warsaw, Poland.
** Chercheur agréé IISN, Belgique. Now at CERN, Geneva, Switzerland.
*** Erkend Navorser IIKW, België.
** Chercheur agréé IISN, Belgique.

1. Introduction

Determinations of the coupling-constants for the ΛKN and ΣKN interactions have been made from analyses of $\bar{K}N$ interactions using dispersion relations [1]. A critical part of the determination arises from an integration over the unphysical region below the $\bar{K}N$ threshold (1432 MeV). This requires that fits to the data have to be extrapolated from the physical region to below the threshold, but the quality of the available data close to threshold (K^- momentum $\lesssim 300$ MeV/c) is so limited by lack of statistics that it is possible to find a number of different parametrisations as a basis for the extrapolation. While constant scattering-length fits [2] and various K-matrix fits, with or without an effective-range approximation [3,8], have all been able to reproduce the data above threshold, they differ considerably in their extrapolated predictions for the region below threshold, notably in the region of the Λ(1405) [4].

In addition, recent measurements of the forward real parts of $\bar{K}N$ and KN elastic scattering amplitudes above 1 GeV/c give an interpolated value for the "discrepancy function" [5] at the K^-p threshold which disagrees by more than four standard deviations with the values calculated from the successful K-matrix fits to the low-energy K^-p data. This suggests that there may be some unreliable measurements among these data, especially at the K^-p threshold where the statistics are comparatively good and the numbers should be more accurate. A review of the current situation, with a new fit to the data which includes the forward real parts, has been given by Martin [6].

Previous measurements of the ratio $\gamma = (K^-p \to \Sigma^-\pi^+)/(K^-p \to \Sigma^+\pi^-)$ for K^- mesons at rest have been summarised in ref. [7]. The two most precise measurements disagree. Kim [8], who used a hydrogen bubble chamber, obtained $\gamma = 2.06 \pm 0.06$, but Tovee et al. [7], using nuclear emulsion, found $\gamma = 2.34 \pm 0.08$. However, only Kim's value has been used in many of the K-matrix fits.

In an attempt to resolve these discrepancies, γ and the fraction R_c of K^-p interactions at rest giving charged final state particles, have been determined and the results are presented in this paper. The determination of the third independent ratio, that of Λ to Σ^0 hyperon production, is in progress and will be presented elsewhere. These three ratios for K^- meson interactions at rest, together with their values and the cross sections for K^- mesons in flight which are also being measured in this film, will provide a new basis for determining the $\bar{K}N$ K-matrix. Well-constrained $I = 0$ K-matrix parameters, consistent with the forward dispersion relations, would make it possible to tell whether the Λ(1405) resonance is a virtual bound state of the $\bar{K}N$ potential or a CDD pole coming from some higher symmetry group such as SU(6) [6,9].

A new value is also presented for the branching ratio

$$B = \frac{\Sigma^+ \to n\pi^+}{\Sigma^+ \to \text{all final states}} .$$

2. Beam and exposure

The pictures used for this analysis were taken in the British 1.5 m bubble chamber, equipped with a track-sensitive target (TST). The liquid outside the target was a molar mixture of 78% neon and 22% hydrogen. The short radiation length (~45 cm) of the mixture was chosen to convert γ-rays from events in the $\Lambda\pi^0$ and $\Sigma^0\pi^0$ channels, but the results reported in this paper come almost entirely from interactions and tracks observed in the pure hydrogen inside the TST. The target covered the whole visible width (45 cm) and length (1.4 m) of the bubble-chamber. Perspex walls 1 cm thick contained the hydrogen layer, which was 7.8 cm deep.

The tracks in the hydrogen had closely spaced small bubbles (~0.17 mm diameter) due to the high operating temperature (29.5 K) which was required for compatibility with the neon-hydrogen mixture. This was very useful in studying short Σ hyperon tracks, where the sign of the Σ hyperon could be resolved down to a range of ~0.5 mm (see subsect. 3.3). It was possible in both liquids to identify most of the tracks uniquely as those of pions, kaons or protons by using bubble-density information and the event topologies.

The K^- beam was produced at 0° from a copper target in an extracted proton beam from NIMROD. It was transported at 600 MeV/c with two stages of DC separation. After passing across the fringe field of the bubble chamber the beam was degraded to ~250 MeV/c by a block of aluminium 30 cm thick, mounted inside the TST close to the beam-entry window. In total, 225 000 pictures were taken with these conditions, with a large fraction of the K^- mesons stopping in the hydrogen within a clearly visible central fiducial region.

3. γ ratio analysis

3.1. Scanning and measurements

About 40 000 frames were carefully scanned and rescanned for K^-p events which could involve $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$ final states. Due to the short lifetime of the Σ hyperons and to background processes it is impossible to assign all events unambiguously into Σ^+ or Σ^- channels at the scanning stage. Events were therefore recorded in a number of "scanning categories" as follows:

Σ^-_π	:	observed $\Sigma^- \to \pi^- n$, with collinear π^+ recoil;
Σ^-_σ	:	observed Σ^- which appears to interact, with collinear π^+ recoil;
$\pi^+\pi^-$	:	unresolved $\Sigma^\pm\pi^\mp$ events due to short Σ tracks;
Σ^+_π	:	observed $\Sigma^+ \to \pi^+ n$, with collinear π^- recoil;
Σ^+_p	:	observed $\Sigma^+ \to p\pi^0$, with collinear π^- recoil;

π^-p : unresolved events arising almost exclusively either when a Σ^+ hyperon decays quickly to a proton, together with a recoiling π^- meson, or when a Λ hyperon decays in apparent spatial coincidence to the K^- interaction vertex.

The scanning efficiencies for all of these categories were better than 99.5%.

Where a clear Σ track could be seen, events with the K^- meson at rest were selected by the collinearity of the Σ track with that of the recoiling pion.

All events in the categories π^-p and $\pi^+\pi^-$ were measured. The prime purpose of these measurements was to separate those π^-p events arising from Σ^+ hyperon production from those attributable to Λ hyperon decays. In addition, since collinearity obviously cannot be a criterion for these events to be ascribed to K^- interactions at rest, it was necessary to measure the momentum of the incoming K^- mesons. A simple scanning template was sufficient to reduce to negligible proportions (~0.2%) the contamination of K^- meson interactions in flight among the above classes of events. This was verified by sample measurements.

3.2. Corrections to the scanning categories

A plot of the invariant mass of the π^-p system *versus* the momentum of the π^- mesons, for events in the π^-p category, is displayed in fig. 1. Although the bulk of the events are seen to be clearly separated into Σ^+ and Λ hyperon categories. there are a few events in the overlap region which arise predominantly from poor measurements of steep pion tracks. These events have been subjected to further scrutiny at the scan table and the ambiguity between the Σ^+ and Λ origins is usually well resolved by consideration of the pion range.

For $\pi^+\pi^-$ events the momentum of the pion from Σ hyperon decay is often similar to that of the recoil pion so only a small fraction of these events may be resolved by measurement [10]. No attempts at such a resolution have been made.

One small category of events may have been lost completely at the scanning stage. These are $\Sigma^+ \to p\pi^0$ decays where the Σ^+ hyperon and proton tracks are so short that neither are visible. Such events resemble the very common K^- meson decays. The baryon tracks may be very short for one of two reasons: the Σ^+ hyperon went straight into the perspex target wall from a K^-p interaction near the edge of the hydrogen volume, or the proton from a quickly decaying Σ^+ hyperon was emitted backwards in the Σ^+ hyperon centre of mass. To help correct for this loss, a record was kept of all Σ^+_p and π^-p events where the observed baryon tracks did not travel beyond a circle of radius 3 mm centred on the K^-p vertex in any view. The distribution of the furthest extend d of these baryon tracks from the K^-p vertex was compared with a Monte Carlo computation (table 1). The number of events above 2 mm is used to normalise the Monte Carlo distribution to the experimental data, and it can be seen that there is a significant loss of events only for baryon distances of less than 1 mm. The data in table 1 include all

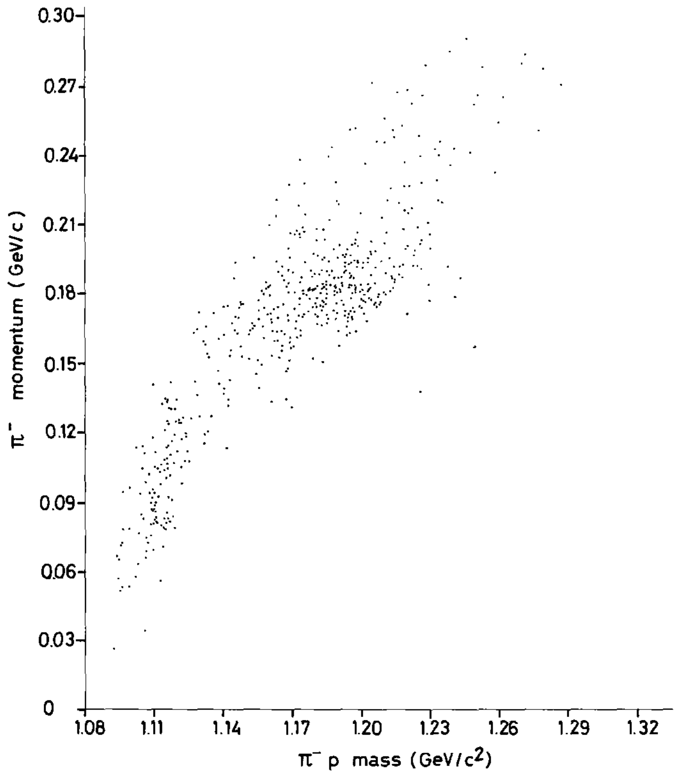

Fig. 1. π^-p invariant-mass *versus* π^- momentum for the ambiguous events in the π^-p category.

Σ^+_p events, but only those π^-p events attributed to $\Sigma^+ \to p\pi^0$ decays.

There was an ambiguity in the determination of the decay channel for a small fraction (~1%) of the Σ^+ events. These are collinear events, classified in the π^-p category, where the observed baryon track is actually that of a Σ^+ hyperon enter-

Table 1
Correction of the Σ^+_p category for short baryon tracks

Distance d (mm)	Observed number	Monte Carlo prediction
<1	28	86
1–2	95	112
2–3	103	119
>3	3148	3132

These numbers refer to the sample of events used subsequently in method 2 for determining γ. The sample for method 1 was treated in a similar way.

ing a perspex wall. To resolve this problem, care was taken in recording those events, then being classified in the Σ^+_π category, if there existed a gap between the end of the visible Σ^+ track and the beginning of a clearly associated decay π^+ track in the hydrogen or in the mixture. These events are examples of $\Sigma^+ \to n\pi^+$ decays inside the perspex walls; their number was found to be in agreement with the prediction of a Monte Carlo calculation, indicating a negligible loss of such π^+ decays. Events without an associated π^+ were therefore classified as $\Sigma^+ \to p\pi^0$.

The problem associated with the perspex walls does not arise for Σ^- hyperons because the ensuing analysis only requires a knowledge of the sum of the Σ^-_π and Σ^-_σ scanning categories. Σ^- events with no decay π^- track have all been included in the Σ^-_σ category.

3.3. Analysis, method 1: the "effective resolvable length" method

Table 2 shows the numbers of events in the scanning categories used in this determination of γ. The numbers on the right of the table show the results of the corrections discussed above. Note that the entire sample of scanned events is included in the table; no events have been discarded. Although the confused π^-p events have been resolved there is still the ambiguous $\pi^+\pi^-$ sample to be split into Σ^+ and Σ^- events before γ can be determined.

The ability to distinguish the sign of the charge of a Σ hyperon should depend only upon whether the Σ track can be resolved, so that the charge of the recoil and the decay pions can be identified. If some length r is the minimum effective decay length needed to identify the charge of a Σ hyperon then the number $N_{\pi\pi}$ of $\pi^+\pi^-$ events, and the ratios γ and B, will depend upon the corrected numbers and on r as follows:

$$N_{\pi\pi}(r) = (N^-_\sigma + N^-_\pi)(e^{t^-(r)/\tau^-} - 1) + N^+_\pi(e^{t^+(r)/\tau^+} - 1)\,, \tag{1}$$

$$\gamma(r) = \frac{(N^-_\sigma + N^-_\pi)\, e^{t^-(r)/\tau^-}}{N^+_\pi\, e^{t^+(r)/\tau^+} + N^+_p}\,, \tag{2}$$

Table 2
Numbers of events for method 1

Scanning categories	Corrected numbers
Σ^-_π : 8499	N^-_π : 8506
Σ^-_σ : 1067	N^-_σ : 1070
$\pi^+\pi^-$: 1190	$N_{\pi\pi}$: 949
Σ^+_π : 1861	N^+_π : 1863
Σ^+_p : 1885	N^+_p : 2217
π^-p : 490	

$$B(r) = \frac{N_\pi^+ \, e^{t^+(r)/\tau^+}}{N_\pi^+ \, e^{t^+(r)/\tau^+} + N_p^+} \, . \tag{3}$$

Here $t^-(r)$ and $t^+(r)$ are the proper times for Σ^- and Σ^+ hyperons, respectively, to travel a distance r. These are well known, since the emission velocities are unique. τ^- and τ^+ are the Σ^- and Σ^+ lifetimes [11].

In table 3 the values of $N_{\pi\pi}(r)$, $\gamma(r)$ and $B(r)$ are given as a function of r. The number of $\pi^+\pi^-$ events is determined in this experiment to be 949, see table 2, and thus $r = 0.045$ cm. Hence, from eqs. (2) and (3), γ and B are found to be $\gamma = 2.38 \pm 0.04$ and $B = 0.488 \pm 0.008$.

3.4. *Analysis, method 2: the "Σ^+ branching-ratio" method*

An alternative method of dealing with the ambiguous $\pi^+\pi^-$ scanning category has been applied to an enlarged sample of data. This method has the advantage that detailed separation of events in the Σ_π^-, $\pi^+\pi^-$ and Σ_π^+ scanning categories is not necessary; it is only necessary to recognize the events for which the Σ^+ hyperon decays into a proton. As in method 1, no events need to be discarded.

The total number T^- of $K^-p \to \Sigma^-\pi^+$ events and T^+ of $K^-p \to \Sigma^+\pi^-$ events are given by

$$T^- = N_\pi^- + N_\sigma^- + N_{\pi\pi} + N_\pi^+ - \left(\frac{B}{1-B}\right) N_p^+ \, , \tag{4}$$

$$T^+ = \frac{N_p^+}{1-B} \, . \tag{5}$$

Here $N_\pi^- + N_\sigma^- + N_{\pi\pi} + N_\pi^+$ and N_p^+ are values taken from table 4, incorporating the corrections described in subsect. 3.2, and the value of B is taken from the Particle

Table 3
The dependence of $N_{\pi\pi}$, γ and B upon r

r (cm)	$N_{\pi\pi}$	γ	B
0.02	409	2.361	0.470
0.04	835	2.373	0.484
0.06	1281	2.384	0.498
0.08	1745	2.393	0.512
0.10	2230	2.400	0.526
0.12	2737	2.406	0.539
0.14	3266	2.410	0.553
0.16	3819	2.412	0.567
0.18	4398	2.413	0.581

Table 4
Numbers of events for method 2

Scanning categories	Corrected numbers
$\Sigma^-_\pi + \Sigma^-_\sigma + \pi^+\pi^- + \Sigma^+_\pi$: 19 181	$N^-_\pi + N^-_\sigma + N_{\pi\pi} + N^+_\pi$: 18 905
Σ^+_p : 2895	N^+_p : 3449
π^-p : 767	

Data Group's tables [11]: $B = 0.4835 \pm 0.0073$. The γ-ratio is just T^-/T^+, giving $\gamma = 2.35 \pm 0.07$, in agreement with the value obtained from method 1.

Despite the larger statistics employed in method 2, and the introduction of a "world value" for B, the assigned error is larger than in method 1. This is dominated, in method 2, by the statistical error in T^+ which depends directly upon N^+_p in eq. (5). For method 1 the $\Sigma^+ \to p\pi^0$ and $\Sigma^+ \to n\pi^+$ samples are added in eqs. (2) and (3), so the effect of statistical fluctuations is reduced.

3.5. *Critique of the methods for determining γ*

Three different experiments have now been performed which determine γ with a comparable precision. The emulsion method of Tovee et al. [7] uses only those Σ^+ and Σ^- hyperons which decay after coming to rest in emulsion. The collinearity of the Σ and π tracks at the K^-p vertex establishes that the K^- meson was at rest, and the charge of the Σ hyperon is determined by its range in emulsion. Σ^+ and Σ^- hyperons have clearly separated range distributions and corrections for in-flight Σ decays can be made very reliably. The precision on the value of γ from the emulsion is limited primarily by statistics which are in turn limited by the laborious nature of emulsion scanning.

Bubble chambers have poorer optical resolution than emulsion and so must contend with large categories which may not be resolved into Σ^+ and Σ^- events. It has not been possible to tell from Kim's publications [8] exactly how these ambiguous categories were dealt with. In particular, doubts have been expressed [12] about the reliability of making corrections for cuts on the lengths and angles of the Σ tracks. The present method does not suffer from such difficulties because no such cuts have been made. Two alternative methods have been used on overlapping samples of data to overcome the difficulties caused by the presence of ambiguous $\pi^+\pi^-$ events, and consistent values for γ have been obtained. In addition, the more precise method for the determination of γ has given a new value for the Σ^+ decay branching ratio B which is in agreement with the previously quoted value.

4. Determination of ratio R_c

A small part of the film which had been scanned for $\Sigma^{\pm}\pi^{\mp}$ events was also double-scanned for stopping K^- meson interactions in the same fiducial volume, which gave no tracks of final state particles (zero-prong interactions). There is a complication due to the perspex wall of the TST since some K^- mesons, which appear from a template test to be at or near to rest, have actually entered the perspex and interacted. In order the eliminate this background all the K^- meson tracks in the zero-prong sample were measured, and the depth (the z coordinate) of the apparent interaction vertex was calculated. Fig. 2a shows an excess of events in the regions 19.0 cm $< z <$ 19.5 cm and 27.0 cm $< z <$ 27.5 cm, corres-

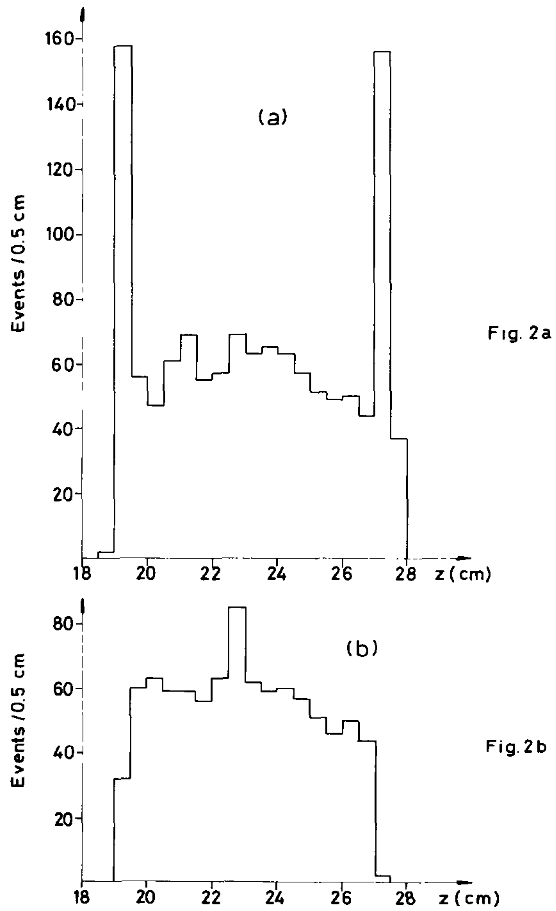

Fig. 2. z coordinate distribution of (a) zero-prong events, and (b) two-prong events.

ponding to the K^- meson entering the perspex walls. A total of 724 events originating from neutral channels was recorded in a central region, $20.0 \text{ cm} < z < 26.0$ cm, of the chamber. This number includes those events in the $\pi^- p$ scanning category which were recognized as $K^- p \to \Lambda\pi^0$ or $\Sigma^0\pi^0$, that is as zero-prong events, after measurement.

The number of two-prong events in the same sample of film was 1780. These events are not restricted to the range of depths $20.0 < z < 26.0$ cm. A separate unbiased sample of two-prong events has been measured in order to determine their depth distribution (fig. 2b). A fraction $f = 0.802 \pm 0.013$ of them was found to be within the restricted range of depth from 20.0 to 26.0 cm. It is assumed that the distribution of fig. 2b is the true depth distribution for all K^- interactions in hydrogen, so the corrected number of two-prong events is 1428, to be compared with the 724 zero-prong events in the same volume.

The ratio of charged to all final states from $K^- p$ interactions at rest is therefore $R_c = 0.664 \pm 0.011$.

This compares well with the value obtained by Humphrey and Ross [13] of $R_c = 0.655$ ($\pm$ 0.011), where a statistical error has been estimated in the absence of their own.

5. Conclusions

The ratio $\gamma = (K^- p \to \Sigma^-\pi^+)/(K^- p \to \Sigma^+\pi^-)$ for K^- mesons at rest has been determined using two alternative methods of analysis. The results, which are not independent since the sample of events used for the first method is included in that used for the second method, are

$$\gamma = 2.38 \pm 0.04 \qquad \text{(method 1)}\,,$$

$$\gamma = 2.35 \pm 0.07 \qquad \text{(method 2)}\,.$$

Their near identity indicates that both methods of analysis are valid. They are seen to be in agreement with the value obtained by Tovee et al., namely 2.34 ± 0.08, but they disagree with Kim's value [8] of 2.06 ± 0.06.

The fraction $R_c = (K^- p \to \text{charged particles})/(K^- p \to \text{all final states})$ for K^- mesons at rest has been measured. The value $R_c = 0.664 \pm 0.011$ is close to that 0.655 ± 0.011 previously reported by Humphrey et al. [13].

Finally, the branching ratio for Σ^+ hyperon decays $B = (\Sigma^+ \to n\pi^+)/(\Sigma^+ \to \text{all})$ has been found to be 0.488 ± 0.008. This is in close agreement with the previously quoted value of 0.4835 ± 0.0073 [11] so it will leave essentially unchanged the status of the two triangle relationships involving $\Sigma \to N\pi$ decays, the $\Delta T = \frac{1}{2}$ rule and the Lee-Sugawara relation [14].

We wish to thank the beam-line and bubble chamber teams and the design personnel at the Rutherford Laboratory, especially W.A. Smith, F. Atchison and E.

Fitzharris. The measurers and data aides at all of our laboratories, and Mrs. G. Stuart's group at the Rutherford Laboratory also deserve our thanks. J.H. Bartley has given useful help and advice in the analysis of the data.

J.A.Z., J.A., N.H.B. and R.J.N. wish to thank the Science Research Council for their support and J.C. wishes to thank the Royal Society.

References

[1] B.R. Martin, Springer Tracts in Modern Physics 55 (1970) 73.
[2] J.K. Kim, Phys. Rev. Lett. 14 (1965) 29.
[3] B.R. Martin and M. Sakitt, Phys. Rev. 183 (1969) 1345;
A.D. Martin and G.G. Ross, Nucl. Phys. B16 (1970) 479;
D. Berley et al., Phys. Rev. D1 (1970) 1996.
[4] Y.A. Chao et al., Nucl. Phys. B56 (1973) 46.
[5] P. Baillon et al., Nucl. Phys. B105 (1976) 365;
P. Baillon et al., Phys. Lett. 50B (1974) 377;
P. Baillon et al., Nucl. Phys. B107 (1976) 189;
P. Baillon et al., Phys. Lett. 61B (1976) 171;
P. Jenni et al., Nucl. Phys. B105 (1976) 1.
[6] A.D. Martin, Phys. Lett. 65B (1976) 346.
[7] D.N. Tovee et al., Nucl. Phys. B33 (1971) 493.
[8] J.K. Kim, Thesis, Columbia University report NEVIS 149 (1966); Phys. Rev. Lett. 19 (1967) 1074.
[9] A.D. Martin et al., Phys. Rev. Lett. 35B (1971) 62;
P.N. Robson and R. McElhaney, Phys. Rev. D6 (1972) 3256.
[10] C.Y. Chang, Phys. Rev. 151 (1966) 1081.
[11] Particle Data Group, Rev. Mod. Phys. 48 (1976) S1.
[12] D.H. Davis et al., Nukleonika 22 (1977) 845.
[13] W.E. Humphrey and R.R. Ross, Phys. Rev. 127 (1962) 1305.
[14] N.H. Lipman et al., Phys. Lett. 43B (1973) 89.