Study of the Reactions $K^-p \to \bar{K}2\pi N$ from 1.2 to 1.7 BeV/c*

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This report summarizes the study of $\bar{K}2\pi N$ final states resulting from K^-p interactions over the energy region from 1.2 to 1.7 BeV/c, with the emphasis on $\bar{K}\pi$ and $\bar{K}2\pi$ systems. It is shown that except for the 1520-MeV Y_0^*, no other resonance contributes markedly to these channels in this energy range. More specifically, there is no evidence for any $J^P=1^+$ meson of negative strangeness. The branching ratio of the K^* into a κ and a π is shown to be less than 0.2% of its total rate. The cross section for the reaction $K^-p \to \kappa\pi N$ over this range of energies is shown to be less than or equal to a few microbarns.

I. INTRODUCTION

In recent years we have seen a rapid growth in understanding of strong interactions through the study of mass spectra of the two- and three-particle systems from the many-particle final states. We report here on the study of the reactions $K^-p \to \bar{K}2\pi N$ from 1.2 to 1.7 BeV/c, with special emphasis on the study of the $\bar{K}\pi$ and $\bar{K}\pi\pi$ systems.

No data exist at present at any momentum on the reactions under study here. The reaction $K^+p \to K^+\pi^-\pi^+p$ at 1.97 BeV/c has been studied recently by Chinowsky *et al.*,[1] and others, and has been shown to proceed dominantly through the $K^+p \to K^{*0}N^{*++}$ mode. The momentum interval we have studied ends just at the threshold for the $\bar{K}^*N^*$ production and thus affords a good way of investigating other processes without being overwhelmed by the K^*N^* production.

Some of the specific points that are of interest in these reactions are:

(a) The search for a $J^P=1^+$, $S=-1$ meson,
(b) The search for $K^*(890) \to \kappa(725)+\pi$ decay mode,
(c) Determination of the $K^*(890) \to K\pi\pi/K^*(890) \to K\pi$ branching ratio,
(d) Search for the reactions $K^-p \to \bar{K}^*(890)\pi N$ and $K^-p \to \bar{\kappa}(725)\pi N$.

II. EXPERIMENTAL PROCEDURE

A. Exposure

The exposure was made from September 1961 to June 1962 in the Berkeley 72-in. hydrogen bubble chamber placed in a two-stage separated K^- beam.[2] The magnets were set to accept a K^- beam with a momentum spread of about $\pm 3\%$. The data under discussion come from six different momentum settings ranging in central value from 1.22 to 1.7 BeV/c and spaced approximately 100 MeV/c apart. The whole exposure involved approximately 500 000 pictures.

B. Scanning, Measuring, and Computer Analysis

There are six possible charge states for the reactions $K^-p \to \bar{K}2\pi N$:

$$K^-+p \to \bar{K}^0\pi^-\pi^+n \quad (1)$$
$$\to \bar{K}^0\pi^-\pi^0p \quad (2)$$
$$\to K^-\pi^+\pi^-p \quad (3)$$
$$\to \bar{K}^0\pi^0\pi^0n \quad (4)$$
$$\to K^-\pi^+\pi^0n \quad (5)$$
$$\to K^-\pi^0\pi^0p. \quad (6)$$

Since the last three reactions involve more than two invisible neutrals, the events cannot be identified in the kinematic fitting and consequently do not enter into the discussion below.

Of the other three, the first two are topologically V^0 2-prong events; the third one is a 4-prong. Both of these topologies were scanned for twice in all of the film. Comparison of the two scans indicated that the scanning efficiency on each individual scan was better than 90% for both topologies. In addition, in part of the film the observed V^0 2-prong events were scrutinized again to reject the events in which the V was a certain Λ decay. The events were then measured on a digitized projection microscope ("Frankenstein") and processed through our PACKAGE and EXAMIN computer programs.

No ionization information was used in the programs but all possible hypotheses were tried in the kinematic fit. The ambiguous events were then resolved by inspecting the ionization of the tracks. This procedure left only about 1% ambiguous events, which were apportioned to the reaction that gave the best χ^2. A large number of the 4-prongs were produced by π's because, although the pion contamination in the K beam was about 10%, the cross section for the production of

* Work done under the auspices of the U. S. Atomic Energy Commission.
† Present address: L'École Polytechnique, Paris, France.
[1] W. Chinowsky, G. Goldhaber, S. Goldhaber, W. A. Lee, and T. A. O'Halloran, Jr., Phys. Rev. Letters 9, 330 (1962); R. Kraemer, L. Madansky, I. Miller, A. Pevsner, C. Richardson, R. Sigh, and R. Zdanis, in *Proceedings of the Athens Topical Conference on Recently Discovered Resonant Particles, Athens, Ohio, 1963* (Ohio University, Athens, Ohio, 1963), p. 130; M. Ferro-Luzzi, R. George, Y. Goldschmidt-Clermont, V. P. Henri, B. Jongejans, D. Leith, G. Lynch, F. Muller, and J. M. Perreau, submitted to the International Conference on Elementary Particles, Siena, 1963.
[2] H. K. Ticho, G. R. Kalbfleisch, J. Kirz, D. H. Miller, J. B. Shafer, D. Stork, and C. G. Wohl, Lawrence Radiation Laboratory, Berkeley (unpublished data).

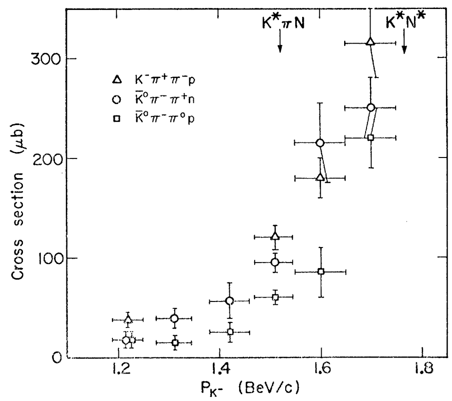

FIG. 1. Cross sections for the reactions $K^-+p\rightarrow K^-\pi^+\pi^-p$, $K^-+p\rightarrow \bar{K}^0\pi^-\pi^+n$, and $K^-+p\rightarrow \bar{K}^0\pi^-\pi^0p$ as a function of energy.

4-prongs by π's is approximately 10 times as large as for K^-. Consequently, a certain sample of events fitting reaction (3) was inspected for ionization of the negative tracks, to test for the possibility of spurious fits. We feel confident that the spurious fits (if any) represent considerably less than 10% of the events accepted.

The path length at each momentum was obtained in two independent ways: (a) by counting τ decays and (b) by counting interactions and then normalizing to the measured K^-p cross sections.[3] The pion background was obtained from the number of associated production events observed in the film and by counting δ rays on interacting tracks. The two methods of determining the path length gave agreement to better than 10% at all momenta.

III. RESULTS AND DISCUSSION

A. Cross Sections

Table I indicates the number of events fitting the hypotheses (1) through (3) as well as the K^- path length at each momentum setting. The cross sections for each process are illustrated in Fig. 1, together with

TABLE I. Data on path length and cross sections at each momentum.

Momentum (BeV/c)	Path length (events/mb)	Number of events[a]		
		$K^-\pi^+\pi^-p$	$\bar{K}^0\pi^-\pi^0p$	$\bar{K}^0\pi^-\pi^+n$
1.22	1.22	41(45)	7(22)	7(22)
1.32	1.42	Not measured	6(20)	17(55)
1.42	0.8	Not measured	6(20)	14(45)
1.51	5.14	459(620)	90(290)	153(490)
1.60	0.7	113(125)	15(60)	37(150)
1.70	1.08	303(340)	60(240)	71(275)

[a] The numbers in parentheses represent the corrected number of events, after allowing for invisible decay modes of K^0, failing events, scanning inefficiency, and incomplete film samples used for some topologies.

[3] V. Cook, B. Cork, T. F. Hoang, D. Keefe, L. Kerth, W. A. Wenzel, and P. F. Zipf, Phys. Rev. **123**, 320 (1961).

the thresholds for $K^*\pi N$ and K^*N^* reactions. The error flags reflect not only the statistical uncertainties, but also other possible effects. The predominance of processes (1) and (3) over the process (2) can be explained at least in part by the production of $Y^{*0}(1520)$ (see below).

B. Dominating Mechanisms

The only processes that produce resonances that are accessible energetically at all of the momenta under study are the $Y^{*0}(1520)$ and $N^*(1238)$ production. The ρ production is energetically forbidden even at the highest momentum; $K^*(890)\,\pi N$ production can be expected to be strongly suppressed by phase space even at 1.7 BeV/c. Accordingly, to be able to understand the mass spectra of $\bar{K}\pi$ and $\bar{K}\pi\pi$ systems, it is important to see to what extent the Y^* and N^* isobars are produced and what sort of mechanism dominates their production.

The combined mass spectra of the K^-p and the $\bar{K}^0n$ systems over all incident K^- momenta are displayed in Fig. 2. It is clear that the Y^{*0} resonance is indeed produced in approximately 20% of all the events. Examination of these mass plots at various momenta indicates that at least within the statistics this fraction does not vary greatly as a function of energy. A study of the events involving Y^{*0} production indicates that at least

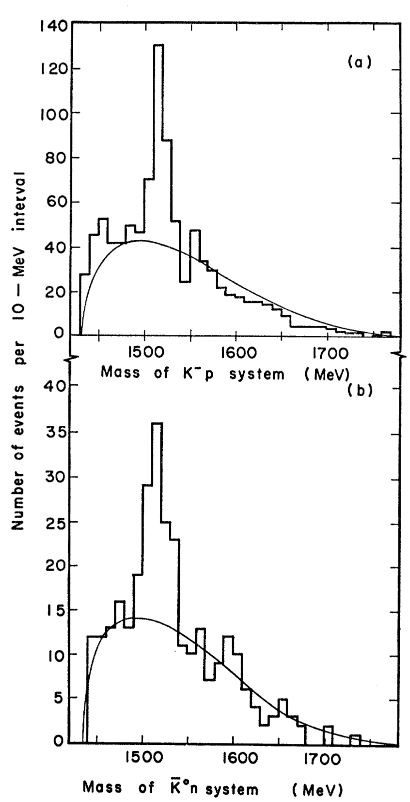

FIG. 2. Mass spectra of the K^-p and $\bar{K}^0n$ systems. The curve represents phase space normalized to 80% of the total data.

to a first order we can view the reaction

$$K^-+p\rightarrow Y^{*0}+\pi^-+\pi^+ \tag{7}$$

as proceeding via a matrix element that is reasonably constant as a function of the energy of any of the three final-state particles.

The mass spectra of the $N\pi$ systems (not shown) show no clear evidence for N^* production. However, we must point out that N^* would not stand out as clearly as the Y^{*0}, because of its greater width, as well as two $N\pi$ combinations in every event.

C. $\bar{K}\pi$ and $\bar{K}\pi\pi$ Systems

1. Study of the $\bar{K}\pi\pi$ System

Angular-momentum and parity considerations forbid the decay of a 1^+ $S=-1$ meson into a $\bar{K}$ and a π. Energetically, the most favorable decay state would be a $\bar{K}$ and two pions, and thus the existence of a 1^+ meson would manifest itself as an enhancement in the mass spectrum of the $\bar{K}\pi\pi$ system.

Until this experiment, the only large sample of events involving the $\bar{K}\pi\pi$ system came from the study of the reaction

$$K^++p\rightarrow K^++\pi^-+\pi^++p \tag{8}$$

(see Ref. 1). Reaction (8), however, was found to be strongly enhanced by the production mode

$$K^++p\rightarrow K^{*0}+N^{*++}, \tag{9}$$

and thus the search for other effects is made more difficult. In our experiment the only dominating channel appears to be $Y^{*0}(1520)$ production which, however, only occurs in about 20% of the events.

We have investigated the question as to what extent N^* or Y^* production could alter the shape of the $\bar{K}\pi\pi$ (or $\bar{K}\pi$) mass spectrum from the shape predicted by the statistical model. We have found that the mass of the $\bar{K}\pi\pi$ system is relatively insensitive to the amount

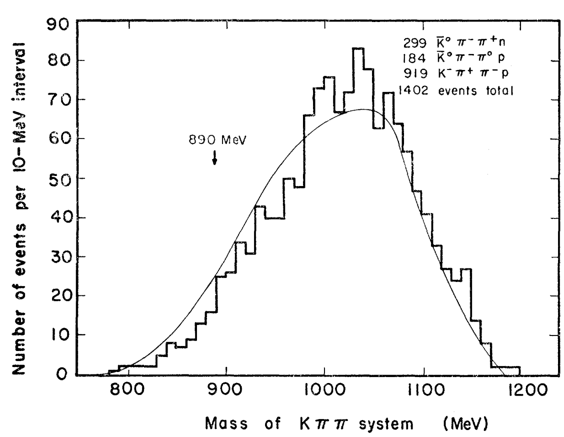

FIG. 3. Mass spectrum of the $K\pi\pi$ system. The curve represents phase space normalized to all of the data.

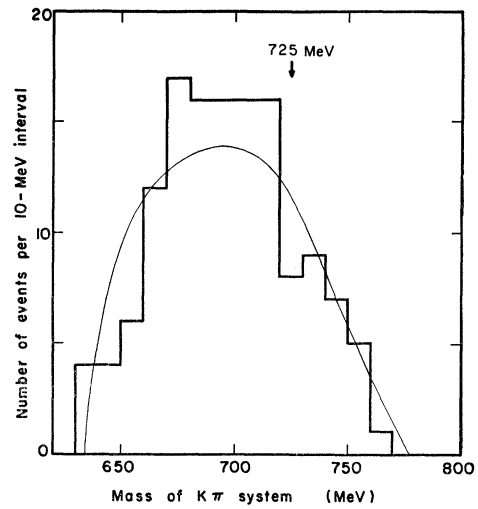

FIG. 4. Mass spectrum of the $K\pi$ systems (excluding $K^-\pi^-$ and $\bar{K}^0\pi^+$) arising from those events with $860<M(K\pi\pi)<920$ MeV. The curve represents the phase-space prediction.

of N^* or Y^* production, and thus the phase-space prediction should be quite reliable for the estimate of the background. The same conclusion holds for the mass spectrum of the $\bar{K}\pi$ system.

The combined $\bar{K}\pi\pi$ mass spectrum over all charge states and all momenta is shown in Fig. 3. The curve represents the prediction due to phase space and appears to give a reasonable fit. We see no evidence for any statistically significant enhancement. Since for a reasonable width ($\Gamma\lesssim 30$ MeV) we should be able to detect an excess of about 40 events, we conclude that no reasonably narrow, $S=-1$, 1^+ meson with a mass less than 1150 MeV is produced in K^-p interactions with a cross section greater than about 40 μb. For a mass less than 1 BeV we can set an upper limit of about 10 μb. These upper limits allow for the fact that some of the decay modes would be inaccessible to us—i.e., reactions (4) through (6).

We further observe that there is no evidence for any decay mode

$$\bar{K}^*(890)\rightarrow\bar{K}\pi\pi,$$

which should be allowed for a 1^- meson, although it would be strongly suppressed by phase space and the P-wave centrifugal barrier. Since in the corresponding film sample we observe about 10 000 K^* productions,[4] we conclude that the 3-body decay mode must be suppressed with respect to the 2-body mode by at least a factor of 500—i.e., 0.2% (assuming that we could detect an excess of more than 20 events). This upper limit (0.2%) is greater than the recent estimate of Sweig[5]

[4] S. G. Wojcicki, G. R. Kalbfleisch, and M. H. Alston, Phys. Letters **5**, 283 (1963); also, S. G. Wojcicki, Phys. Rev. **135**, B484 (1964), preceding paper.

[5] Mitchel J. Sweig, Phys. Rev. **131**, 860 (1963).

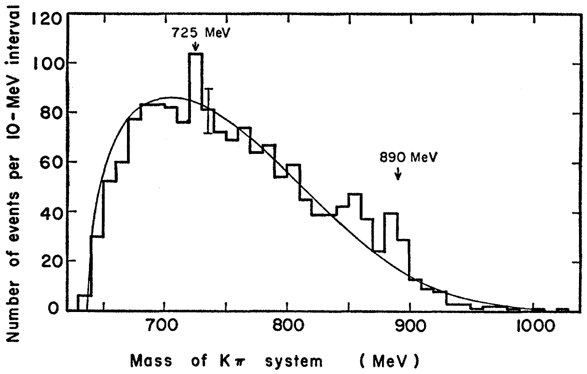

FIG. 5. Mass spectrum of the $K\pi$ systems (excluding $K^-\pi^-$ and $\bar{K}^0\pi^+$). The curve represents phase space normalized to all the data.

who obtained

$$\frac{\Gamma(K^* \to K\pi\pi)}{\Gamma(K^* \to K\pi)} \approx 0.002\%$$

by using unitary symmetry. But it is smaller than the estimate ($\approx 3.9\%$) of Fujii[6] who, however, did not take into account the angular-momentum barrier due to the K^* spin.

2. *The Branching Ratio* $K^*(890) \to \kappa\pi / K^*(890) \to K\pi$

The spin and parity of the recently observed κ meson[7] are still unknown at the present time, 0^+ and 1^- being the possibilities if one limits oneself to values of spin less than 2. The parity and angular-momentum considerations do not allow a decay $K^*(890) \to \kappa\pi$ for a 0^+ meson. On the other hand, this mode is allowed for a $1^-\kappa$ and should constitute a few percent of the total K^* decays if the $K^*K\pi$ and $K^*\kappa\pi$ coupling constants are equal.

We have examined the effective mass of the possible $T=1/2\bar{K}\pi$ systems for those events whose $\bar{K}\pi\pi$ mass lies between 860 and 920 MeV, i.e., in the K^* region. We find no evidence for any enhancement in the region of 725 MeV (see Fig. 4) and conclude that the data are consistent with a zero branching ratio into the $\kappa\pi$ mode. To set an upper limit for this decay mode we can assume that all events from 715 to 735 MeV come from $K^* \to \kappa\pi$ decays. Assuming that κ is a $T=1/2$ meson, as is suggested by the presently available data, we obtain a limit on the branching ratio

$$\frac{K^*(890) \to \kappa\pi}{K^*(890) \to K\pi} \leq \frac{1}{500}\,.$$

This value would seem to suggest 0^+ assignment for the κ meson. On the other hand since κ appears to be produced much more weakly than K^*, it is quite likely that K^* is coupled much more weakly to the $\kappa\pi$ than to the $K\pi$ system. As a matter of fact, a scheme which would require a vector κ and a relatively weak coupling of all known particles to the κ meson has been recently proposed by Tarjanne and Teplitz.[8] Thus it appears that it would be dangerous to draw any conclusions as to the spin of the κ from this low value of the branching ratio.

3. K^* *and* κ *Production*

All the previous experiments to date have indicated very small cross sections for the κ production, the κ being suppressed on the average by about one order of magnitude with respect to the $K^*(890)$ production. The energy region under study here is unfavorable for the K^* production because of phase-space limitation. Accordingly it is of interest to see if these reactions might exhibit abundant κ production.

The mass spectrum of all $\bar{K}\pi$ systems (excluding pure $T=3/2$ states) is shown in Fig. 5; Fig. 6 shows the pure $T=3/2$ states. There is no clear-cut evidence for κ production, although it must be noted that the biggest departure (about $2\frac{1}{2}$ standard deviations) from phase-space prediction in Fig. 5 occurs at 725 MeV.[9] It seems most natural to associate this effect with the κ production, which would set an upper limit on its average cross section of the order of few microbarns over this energy region. The structure of this $\bar{K}\pi$ mass histogram does not show any radical change over this range of energies.

We should note that very little $K^*(890)$ production

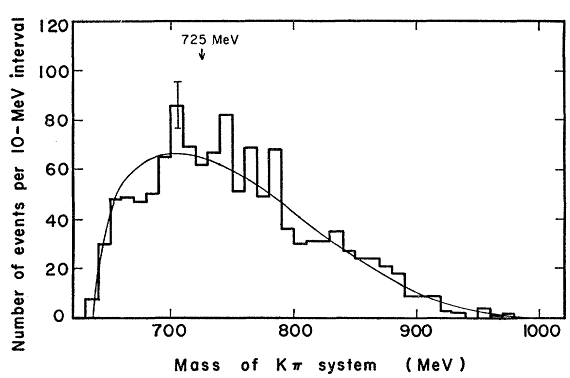

FIG. 6. Mass spectrum of the $K^-\pi^-$ and $\bar{K}^0\pi^+$ systems. The curve represents phase space normalized to all the data.

[6] A. Fujii, Phys. Rev. **124**, 1240 (1961).

[7] G. Alexander, G. R. Kalbfleisch, D. H. Miller, and G. A. Smith, Phys. Rev. Letters **8**, 447 (1962); G. Alexander, L. Jacobs, G. R. Kalbfleisch, D. H. Miller, G. A. Smith, and J. Schwartz, in *Proceedings of the International Conference on High Energy Physics, Geneva, 1962* (CERN, Geneva, 1962), p. 320; D. H. Miller, G. Alexander, O. I. Dahl, L. Jacobs, G. R. Kalbfleisch, and G. A. Smith, Phys. Letters **5**, 279 (1963); also see Ref. 4.

[8] P. Tarjanne and V. L. Teplitz, Phys. Rev. Letters **11**, 447 (1963).

[9] D. H. Miller *et al.* (Ref. 7) have indicated that the mass of the neutral member of the κ multiplet might be some 20 MeV heavier than its charged counterpart. Our limited statistics do not allow us to test this hypothesis but we must note that most of the effect at 725 MeV does come from the $\bar{K}^0\pi^-$ combinations.

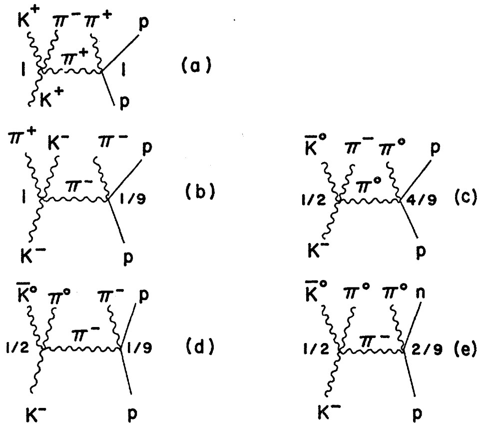

FIG. 7. One-pion-exchange diagrams leading to the three charge states under study.

appears in marked contrast to the high-energy K^+ data.[1] This can be easily understood because (a) the threshold for the K^*N^* final state is approximately at 1.7 BeV/c and (b) the charge states available here are not as favorable to K^*N^* production as in the K^+p interactions, if we think of the K^*N^* final state being produced through the OPE diagram, which appears to be the case for K^+p interactions.[1] The relative suppression of various charge states is illustrated in Fig. 7 where we show the lowest-order Feynman diagrams for the reactions in question. The number next to each vertex represents the relative strength of that vertex as compared with the corresponding vertex for the $K^+p \to K^+\pi^-\pi^+p$ reaction. We assume dominance of $T=1/2$ state for the $K\pi$ interaction and of $T=3/2$ for πN interaction.

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Vertex Functions and the Unitarity Relation*

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It is shown that a unitarity relation holds for vertex functions in a form analogous to the one for form factors and that the one-particle irreducible parts of scattering amplitudes satisfy unitarity by themselves. The second half of the present work considers the case of nonrelativistic S-wave scattering with one bound state. Interrelations among the S matrix, the denominator function, and functions for the bound state, such as the form factor, the propagator, and the vertex function are discussed under certain general restrictions.

1. INTRODUCTION

THE S-matrix theory of strong interactions considers physical quantities on the mass shell. By contrast, most fundamental in the Green's function approach are such functions as propagators and vertex functions which require knowledge of quantities off the mass shell. The connection between the two approaches has not been well understood, although it would be very desirable to see if an S-matrix theory could incorporate any new principle which is absent in Green's function theory. In some processes, such as electron-nucleon scattering and weak decay of strongly interacting particles, it becomes necessary to know about form factors. In S-matrix theory a link between scattering amplitudes and form factors is provided by the unitarity relation for the latter, although its solutions are known to have the ambiguity of Omnès.

S-matrix theory does not directly deal with propagators and vertex functions, but the single-dispersion parts in Mandelstam's representation for scattering amplitudes are closely related to them. Because of their importance it seems worthwhile to ask to what extent an S matrix can determine these functions. The main purpose of the present work is to study the problem for the case of nonrelativistic scattering under certain general restrictions. Properties of the form factor, the propagator, and the vertex function for a bound state are also discussed. It will be seen that there exists some kind of correspondence between the scattering amplitude and its one-particle irreducible part and between the form factor and the vertex function.

We shall begin with a relativistic case. After a brief summary in Sec. 2 of the main properties of a propagator and a vertex function, it is shown in Sec. 3 that a unitarity relation holds for the pion vertex functions

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