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Some $g(1700)$ decay modes

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From a study of 8-GeV/c π^-p interactions, the various two-pion and four-pion decay channels available to the g^- meson have been investigated. Our results indicate that the dominant 4π decay modes involve intermediate ρ and ω production without significant A_2 formation.

I. INTRODUCTION

Although the even-G-parity mass region from $1.5-1.8$ GeV/c^2 has been exhaustively investigated, the precise physical interpretation of the experimental data has yet to be delineated. The current assessment of this mass region would appear to be that of the Particle Data Group[1] whereby all even-G-parity resonances in this region are assumed to be various manifestations of the $g(1700)$ unless proved otherwise. Because of the wide divergence of the various parameters reported for the g in different experiments, the experimental situation is far from resolved. The purpose of this paper is to present our data from a rather large 8-GeV/c π^-p experiment where we shall establish that the $\omega\pi^-$ decay mode of the g^- is one of its more substantial channels. This decay channel has, in the past, been controversial, even though the narrow width of the ω should permit an unambiguous determination of the magnitude of its presence. We shall also show that the $\omega\pi^-$ branching fraction is more significant than that of the $(A_2\pi)^-$ and shall present our data concerning the production of ρ mesons as decay products of the g^-

II. EXPERIMENTAL PROCEDURE

The data for this experiment come from a 780 000-picture exposure of the SLAC 82-inch hydrogen bubble chamber to an rf-separated 8-GeV/c π^- beam. This report is based on samples of $\sim 192\,000$ two-prong and $\sim 136\,000$ four-prong interactions. These events were measured on the UT-ORNL spiral reader, the MIT precision-encoding and pattern-recognition machine (PEPR) and the Hough-Powell device (HPD) at Tohoku. The events were then processed through the TVGP(GEOMAT)-SQUAW-ARROW chain of programs.

We present results concerning the following reactions:

(1) $\pi^-p\to\pi^-\pi^0p$ (12 055 events, $\sigma=0.733\pm0.20$ mb).

(2) $\pi^-p\to\pi^-\pi^-\pi^0\pi^+p$ (22 969 events, $\sigma=1.60\pm0.04$ mb).

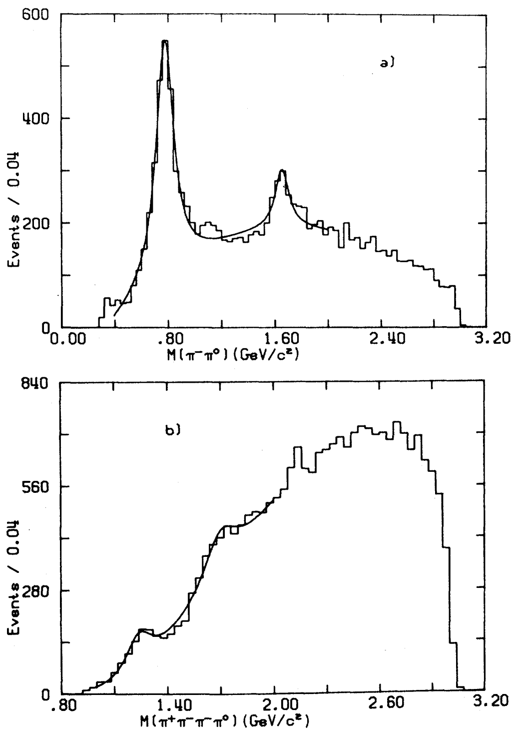

FIG. 1. (a) Full $\pi^-\pi^0$ mass spectrum from $\pi^-p\to\pi^-\pi^0p$. (b) Full $\pi^+\pi^-\pi^-\pi^0$ mass spectrum from $\pi^-p\to\pi^+\pi^-\pi^-\pi^0p$.

As these reactions are one-constraint (1C) fits, care must be taken in the hypothesis selection for each event. Therefore, the following procedure was used:

(a) If the event had a successful 4C fit, i.e., no variables missing and probability $>10^{-4}$, then the event was rejected.

(b) If the missing mass in the corresponding 0C fit was greater than two standard deviations from the π^0 mass, the event was rejected.

There still remained the problem of ambiguities between the 1C π^0 fit and the 1C neutron fit. In the case of reaction (1) this problem was solved by assigning the event to the 1C neutron channel. This is justified on the following basis: For these events that were ambiguous in the fit selection, it was found that in the 1C π^0 fit, if the positive track were treated as a π^+ and the "π^+" π^--invariant mass was plotted, the histogram was dominated by the ρ^0. If the same was done to the unambiguous events, no ρ^0 peak was seen in the "π^+" π^- spectrum. For reaction (2), the ambiguities were resolved strictly on the basis of probability since what was true for reaction (1) ambiguities was not true for reaction (2).

The full, uncut bosonic mass spectra from these channels are presented in Fig. 1. Both spectra have been fitted with Breit-Wigner resonances superimposed upon fourth-order-polynomial backgrounds. The parameters derived from these fits together with their associated errors are given in Table I. The ratio of 2π to 4π decays of the g^- is 0.40 ± 0.07, which agrees well with the world average reported by the Particle Data Group.[1] This number ignores any contribution from the possible decay mode $\pi^-\pi^0\pi^0\pi^0$. It should be noted that the mass and width of the $4\pi g^-$ decays exceed the values determined in the dipion decays—a fact we attribute to the relatively larger background present in the 4π spectrum, as well as the somewhat diminished resolution in the 4π channel as opposed to the dipion channel. We estimate that the resolution in the 4π channel, when a neutral particle is involved in the mass to be 40 MeV in the g^- region whereas in the dipion channel it is 25 MeV. The g^- and $B^-(1235)$ are, however, both present in the 4π spectrum at approximately the 10σ level. The determination of the B^- cross section has been corrected for the presence of $\pi^+\pi^-\pi^-\pi^0$ events due to the $\eta\pi^-$ decay mode of the A_2^-. This correction amounts to 3.5 ± 0.8 μb in the full 4π spectrum and is reflected in the value reported for the B^- cross section in Table I.

III. RESULTS AND ANALYSIS

The neutral 3π mass spectrum from reaction (2) is displayed in Fig. 2 (each event appearing twice)

TABLE I. Meson production data from the reactions $\pi^-p\to\pi^-\pi^0p,\pi^+\pi^-\pi^-\pi^0p$.

Meson	Mass (MeV)	Width (MeV)	Cross section (μb)	χ^2 per degree of freedom/ No. of degrees of freedom
$p\rho^-(2\pi)$	777 ± 3	161 ± 6	176 ± 5	1.6/37
$pg^-(2\pi)$	1654 ± 9	126 ± 22	34 ± 4	
$pB^-(4\pi)$	1239 ± 8	185 ± 20	47 ± 4	1.1/31
$pg^-(4\pi)$	1699 ± 13	239 ± 34	85 ± 9	

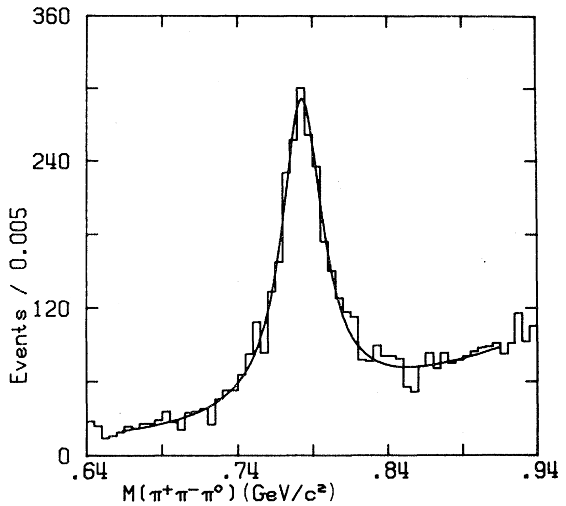

FIG. 2. $\pi^+\pi^-\pi^0$ spectrum from reaction (2).

from which it can be seen that it is dominated by the presence of the ω. From this spectrum we find that ω production is present at the 185 ± 7 μb level and that the mass and width of the ω, determined without regard to our resolution, are $M=783\pm1$ meV, $\Gamma=33\pm1$ MeV, respectively. Probably the most arcane aspect of $g^{\pm}$ decay is the wide divergence reported in the $\omega\pi^{\pm}$ decay fractions. Since the ω is a narrow resonance, produced in moderate-energy pion-induced reactions with minimal background, the determination of the $\omega\pi^{\pm}$ decay fraction would appear to be straightforward. However, the reported $\omega\pi^{\pm}$ to all $\pi^+\pi^-\pi^+\pi^0$ decay fractions often stand in stark contrast with one another. These range from 0.33 ± 0.07 (Ref. 2) to an upper limit (Ref. 3) of only 0.09. The most recent, high-statistics determination was in the form of an upper limit[4] whereby the $\omega\pi$ fraction was found to be less than 0.11 at a 95% confidence level. In Figs. 3(a) and 3(b), we plot the $\omega\pi^-$ and $\pi^+\pi^-\pi^-\pi^0$ spectra at low momentum transfers to the 4π system ($t'_{\pi,4\pi}<0.2$ GeV^2). Also shown in Fig. 3 are the results of our fits to these data. The 4π spectrum was fit with Breit-Wigner resonances for the B and g superimposed on a fourth-order polynomial in the mass. Because of the shape of the $\omega\pi$ spectrum, the best fits we could obtain utilized a background of the form $A+B/M^n$ where n was a positive integer greater than one. (No fractional exponents were tried.) All values of n between 2 and 9 gave acceptable fits, the worst having a χ^2 of 1.01 per degree of freedom. The fit selected for Fig. 3(b) is of the form $A+B/M^6$. This form was chosen since it gave a small χ^2 per degree of freedom (0.86), it closely approximated our "eyeball" estimates, and also because it most nearly yielded the same number of B^- in the $\omega\pi^-$ spectrum as are found in the equivalent unselected 4π spectrum. No decay mode for the B other than $\omega\pi$ has been identified.[1] If a different background ($A+B/M^n$, $n\neq6$) were selected, the B signal would change by less than 15% for $2\leq n\leq9$. This would still be consistent, to within a standard deviation, of no B decays other than to $\omega\pi$. The only relevance of this, insofar as the g is concerned, is that the g^- signal is a minimum for $n=6$. The parameters for the B and g found by the above fitting procedures as well as the quality of the fits are given in Table II. As in Table I, an A_2 contribution to the B^- signal (1.4 ± 0.3 μb) is reflected in the entry for the B^- production cross section. The relevant branching ratio is thus found to be

$$(g^-\to\omega\pi^-)/(g^-\to\pi^+\pi^-\pi^-\pi^0)=0.37\pm0.07\ .$$

This includes a small ($\sim12\%$) correction for the wings of the ω distribution not included by our ω cut (0.72−0.84 GeV). The above ratio would change by less than a standard deviation if the full uncut spectra were employed in its determination. There would, similarly, be an insignificant effect if

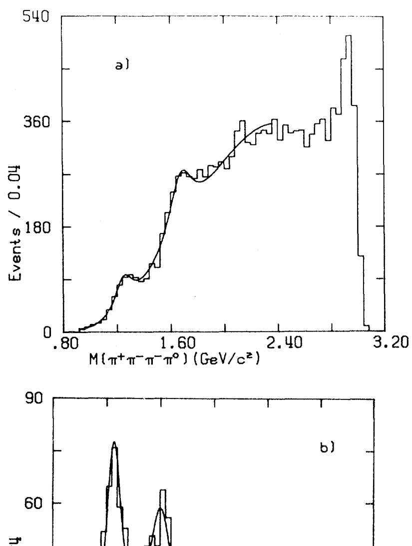

FIG. 3. (a) 4π mass spectrum from reaction (2) with $|t'_{p,p}|<0.2$ GeV^2. (b) $\omega\pi$ mass spectrum from reaction (2) with $|t'_{p,p}|<0.2$ GeV^2.

TABLE II. B^- and g^- production parameters from the $\pi^+\pi^-\pi^-\pi^0$ and $\omega\pi^-$ final states ($t'<0.2$ GeV^2).

Meson	Mass (MeV)	Width (MeV)	Cross section (μb)	χ^2 per degree of freedom/ No. of degrees of freedom
$B^-(4\pi)$	1250 ± 10	162 ± 21	23.2 ± 3.2	0.77/36
$g^-(4\pi)$	1675 ± 10	215 ± 30	64.0 ± 4.5	
$B^-(\omega\pi)$	$1254\pm\ 8$	135 ± 20	23.0 ± 3.3	0.85/30
$g^-(\omega\pi)$	1602 ± 16	207 ± 43	23.5 ± 3.5	

the ratio were calculated after removing the effects of Δ^{++} production from our data. Finally, we should emphasize that the g is present in the $\omega\pi$ spectrum at $t'<0.2$ GeV^2 to a significance of 6.5 standard deviations and that any more conventional background parametrization, i.e., using positive powers of the mass, would increase both the magnitude of the g signal as well as its statistical significance in the $\omega\pi$ spectrum. Close inspection of Table II shows that while the widths of the g in the $\omega\pi$ and 4π channels are comparable, the mass of the $\omega\pi$ signal in the g region is significantly lower than in the full 4π spectrum. To further investigate whether the observed $\omega\pi$ state is appropriately identified with the g, we plot in Fig. 4 the $\pi\pi$ scattering angular distributions, obtained in the Gottfried-Jackson frame, for the B,g, and a higher-mass background region ($1.8-0.2$ GeV/c^2). The $\cos\theta$ distribution for the B is substantially flat, thereby being consistent with a predominantly S-wave $\omega\pi$ decay. In the g and the 1.9 ± 0.1 GeV/c^2 regions, the bump near $\cos\theta=0$ suggests the involvement of higher partial waves. These distributions are quite similar to those obtained by Thompson *et al.*[2] who found the mass of their second $\omega\pi$ enhancement to be 1686 ± 9 MeV/c^2, a value wholly compatible with that of the g. A similar peak in the $\omega\pi^-$ mass at 1690 ± 15 MeV/c^2 has recently reported by Evangelista *et al.*[5] from a ~ 200 event/μb experiment using the CERN Omega Spectrometer. Because of the rather large differences in the g^- mass as determined by our 2π and $\omega\pi$ fits, we have also fitted the $\omega\pi$ spectrum, at $t'<0.2$ GeV^2, in the manner described above, to a Breit-Wigner resonance of fixed mass (1675 MeV) and width (160 MeV). Under these conditions, the quality of the fit deteriorates substantially. Nevertheless, when the B^- ($\rightarrow\omega\pi^-$) signal is equal to that in the full $\pi^+\pi^-\pi^-\pi^0$ spectrum, the g^- ($\rightarrow\omega\pi^-$) signal survives at the nine-standard-deviation level ($\sigma=16.6\pm1.8$ μb).

Our data also yield information on the other purported decay channels of the g involving A_2 and ρ mesons. Because of the strong, high-quality $\omega\pi^-$ signal in the g^- region and because the exclusion of ω events can scarcely affect the amounts of ρ production (or A_2 production if restricted to the $\rho\pi$ decay mode), the remainder of our discussion of the $\pi^+\pi^-\pi^-\pi^0$ channel will evolve from data from which ω events have been purged. (Branching ratios quoted for the various channels will, however, be reported relative to our full $\pi^+\pi^-\pi^-\pi^0$ signal in the g region.) A plot of the $\pi^+\pi^-\pi^0$ spectrum when the other neutral three-

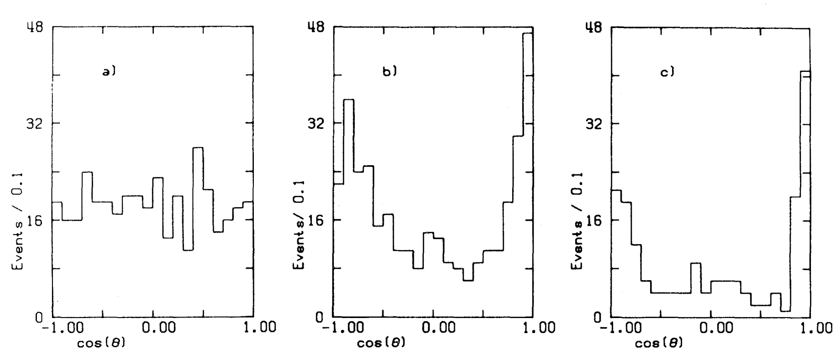

FIG. 4. Cosine of polar $\pi\pi$ scattering angle (Gottfried-Jackson frame) as a function of $\omega\pi^-$ mass.

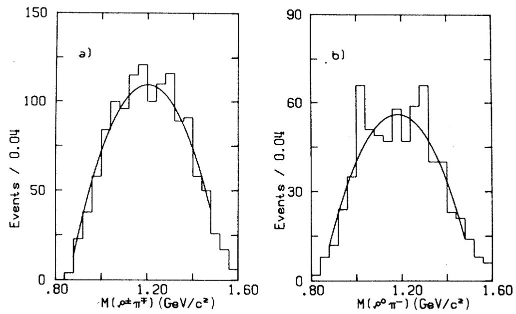

FIG. 5. For events with a 4π mass in the g^- region, $|t'_{p,p}| < 0.2$ GeV^2 with neither $\pi^+\pi^-\pi^0$ mass combination in the ω region. (a) $\rho^\pm\pi^\mp$ mass. (b) $\rho^0\pi^-$ mass.

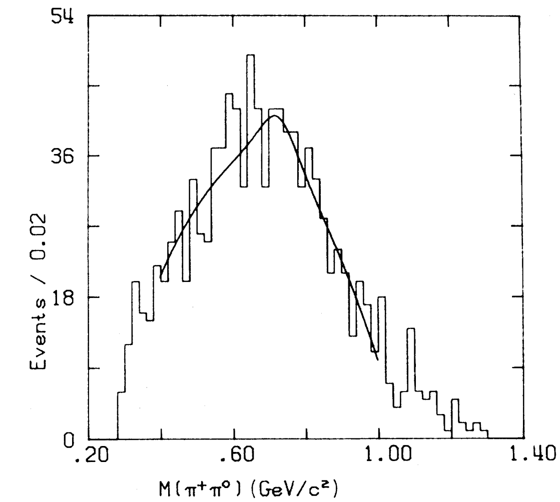

FIG. 6. $\pi^+\pi^0$ mass when 4π mass is in g^- region and $|t'_{p,p}| < 0.2$ GeV^2.

pion combination is in the ω region displays a small enhancement in the neighborhood of 1 GeV/c^2 as well as a smallish ω signal over a rather flat background extending beyond 1.6 GeV/c^2. The elimination of ω events has the additional benefit of reducing the large low-mass backgrounds, atypical of phase space, in the dipion spectra which will be presented later to investigate ρ production from g^- decay. We will continue to restrict our data to peripheral events ($t'_{\pi,4\pi} \leq 0.2$ GeV^2).

Reported values for the branching ratio of the $g^\pm$ into $(A_2\pi)^\pm$ are also in rather broad disagreement. Although some authors[6,7] have found the $A_2\pi$ decay channel to represent a rather insignificant fraction of charged g decays, others[4,8] have reported it to account for fractions as large as 0.60 ± 0.15 and 0.66 ± 0.08. Our data support the former results. In Fig. 5 we present the 3π spectra ($\pi^+\pi^-\pi^0$ and $\pi^+\pi^-\pi^-$) for those events whose 4π mass is in the g region ($1.56 \leq M \leq 1.78$ GeV/c^2). Since the 3π decay of the A_2 has not been observed except through the intermediate $\rho\pi$ state,[1,9] these spectra are restricted to those events for which the appropriate dipion combinations contain a ρ of the proper charge, i.e., ρ^+ or ρ^- in the $\pi^+\pi^-\pi^0$ spectrum and ρ^0 in the $\pi^+\pi^-\pi^-$ spectrum. The mass cut used to define the ρ meson is 0.66–0.86 GeV/c^2. The curves on these histograms represent fits to a quadratic background in either case and clearly indicate that the fraction of A_2 events, in the g region, which subsequently decay into $\rho\pi$ is not large. To quantify the $A_2\pi$ branching fraction, we have added these histograms together with the effect that the resulting fit to an A_2 Breit-Wigner resonance superimposed on a quadratic background yields an A_2 intensity of 33 ± 22 events. Correcting for the fraction of ρ meson excluded by our mass cuts (36%), our $A_2\pi$ branching fraction becomes

$$[g^-\to(A_2\pi)^-\to(\rho\pi\pi)^-\to\pi^+\pi^-\pi^-\pi^0]/(g^-\to\pi^+\pi^-\pi^-\pi^0)=0.08\pm0.13\ .$$

It is felt that this number is truly an upper limit since, as can be seen in Fig. 6, the existence of any ρ^+ signal from g^- decay is quite tenuous. The ρ^+ appears as a somewhat less than 3σ enhancement and then, at that level, only when the mass and width of the ρ are permitted rather wide latitude in their definition. Nevertheless, in order to set an upper limit to the $A_2\pi$ branching fraction, the ρ^+ "signal" was treated on an identical basis as those for ρ^0 and ρ^-. Because of the tiny A_2 signal, a background subtraction was deemed superfluous.

The degree of involvement of ρ mesons in charged g decays has been another controversial feature of this resonance. The branching fractions which have been reported for the $\rho\pi\pi$ state relative to all 4π decays have mostly been near unity,[4,10,11]

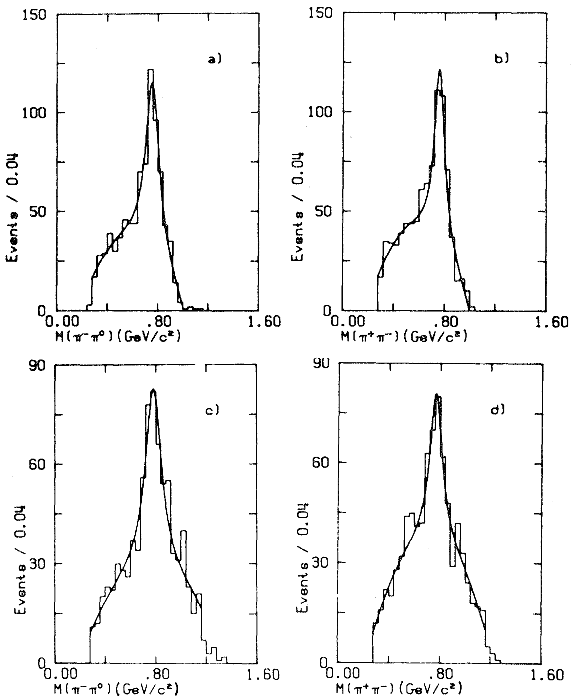

FIG. 7. (a) $\pi^+\pi^-$ mass for $\pi^-\pi^0$ mass in ρ^- region with 4π mass in g region, $|t'_{p,p}| \leq 0.2$ GeV^2. (b) As in (a) except $1.8 \leq M \leq 2.0$ GeV/c^2. (c) $\pi^-\pi^0$ mass for $\pi^+\pi^-$ mass in ρ^0 region and with 4π mass in g region, $|t'_{p,p}| \leq 0.2$ GeV^2. (d) As in (c) except $1.8 \leq M \leq 2.0$ GeV/c^2.

although Thompson *et al.*[2] suggest that this ratio is "probably <0.40." Because of our exclusion of $\omega\pi$ events, the $\rho\pi\pi/4\pi$ branching ratio cannot, perforce, exceed ~ 0.63. As has been emphasized by several groups,[2,4] the determination of the appropriate ρ content of g decay products requires a careful consideration of the nonresonant background contributions to the ρ signals. Our procedure is to determine the intensity of ρ^+,ρ^0, and ρ^- events in the g region of 4π mass (1.56–1.78 GeV/c^2) and in a background region (1.35–1.55 GeV/c^2 and 1.8–2.0 GeV/c^2). The lower-mass part of the background region has too few events to allow a meaningful assessment of the various ρ signals in it by itself. From a fit to the 4π mass spectrum, antiselected on ω events, the numbers of g events and background events in the g and background regions is known. If we now assume that the ρ signals have only two sources, viz., from g decay and from background production, the numbers of ρ events associated with g^- decays can be determined:

$$(g^- \to \rho^-\pi^+\pi^-)/(g^- \to \pi^+\pi^-\pi^-\pi^0) = 0.36 \pm 0.12 ,$$

$$(g^- \to \rho^0\pi^-\pi^0)/(g^- \to \pi^+\pi^-\pi^-\pi^0) = 0.47 \pm 0.11 ,$$

$$(g^- \to \rho^+\pi^-\pi^-)/(g^- \to \pi^+\pi^-\pi^-\pi^0) = 0.13 \pm 0.10 .$$

As mentioned in connection with the $A_2\pi$ branching-ratio determination, the ρ^+ fraction, while finite, is of inferior statistical quality (Fig. 6). The weak ρ^+ signal from g^- decay is entirely consonant with a negligible $(A_2\pi)^-$ decay fraction.

The final g^- decay fraction in the $\pi^+\pi^-\pi^-\pi^0$ channel, to which we address ourselves, is that fraction which decays simultaneously to ρ^- and ρ^0 mesons. Over the years the fraction of 4π decays which proceed through the channel $g^- \to \rho^-\rho^0$ has plummeted from more than 70% [Refs. 7, 8, and 12) to the more recent determinations[2,4] of 0.13 ± 0.09 and 0.12 ± 0.11. At least part of the cause of these rather divergent values would appear to derive from the $\rho\rho$ decay appearing as a threshold enhancement in the g region of the 4π spectrum and from the necessity of executing a background subtraction. In Fig. 7, we display the $\pi^+\pi^-$ and $\pi^-\pi^0$ spectra for those events which have a 4π mass in the g^- region and for which the "other" dipion combinations ($\pi^-\pi^0$ or $\pi^+\pi^-$, respectively) lie in the ρ region (0.66–0.86 GeV/c^2). Similar spectra for the background region (1.8–2.0 GeV/c^2) are also shown in Fig. 7. All of these spectra have been fitted to a Breit-Wigner resonance in the ρ region together with a quadratic background in the dipion mass. The fit quality varied from a χ^2 per degree of freedom of 0.81 to 1.38. For the g^- region, the fraction of events with a $\pi^+\pi^-$ forming a ρ^0, which also exhibit a ρ^- is 0.54 ± 0.04. For the background region, this fraction is 0.41 ± 0.04. Similarly when a $\pi^-\pi^0$ is in a ρ^- band, the fraction of events which show ρ^0 production is 0.40 ± 0.035 for the g^- region and 0.26 ± 0.036 for the background region. Because our 4π g signal extends to 1.56 GeV/c^2, no meaningful background-region subtraction is possible from the mass region beneath the g region. Correcting for the number of g events lying outside the g mass limits and the numbers of ρ events not included by our ρ mass cuts (37% of ρ^- and 29% of ρ^0), we find the branching ratio

$$(g \to \rho^-\rho^0)/(g \to \pi^+\pi^-\pi^-\pi^0) = 0.31 \pm 0.15 .$$

The large error derives principally from the indicated background subtractions and the $\sim 10\%$ errors in the determinations of the ρ signals. It should be noted that the determination of the $\rho^-\pi^+\pi^-$ and $\rho^0\pi^-\pi^0$ given above was relevant to

TABLE III. Decay branching ratios for the g^- meson. The fraction of g^- decays to the 4π final state through the intermediate states $(\omega\pi, \rho\pi, A_2\pi)$ exceeds unity since, for example, the sequence $g^- \to (A_2\pi)^- \to \rho^-\pi^+\pi^-$ is included both as an A_2 decay and a ρ^- decay. Similarly, all of the $\rho^-\rho^0$ decays are counted as both a ρ^- and a ρ^0 decay.

$(g^- \to \pi^-\pi^0)/(g^- \to \pi^+\pi^-\pi^-\pi^0)$	$=0.40\pm0.07$
$(g^- \to \omega\pi^-)/(g^- \to \pi^+\pi^-\pi^-\pi^0)$	$=0.38\pm0.07$
$[g^- \to (A_2\pi)^- \to (\rho\pi\pi)^- \to \pi^+\pi^-\pi^-\pi^0]/(g^- \to \pi^+\pi^-\pi^-\pi^0)$	$=0.08\pm0.13$
$(g^- \to \rho^-\pi^+\pi^0)/(g^- \to \pi^+\pi^-\pi^-\pi^0)$	$=0.36\pm0.12$
$(g^- \to \rho^+\pi^-\pi^-)/(g^- \to \pi^+\pi^-\pi^-\pi^0)$	$=0.13\pm0.10$
$(g^- \to \rho^0\pi^0\pi^-)/(g^- \to \pi^+\pi^-\pi^-\pi^0)$	$=0.47\pm0.11$
$(g^- \to \rho^-\rho^0/g^- \to \pi^+\pi^-\pi^-\pi^0)$	$=0.31\pm0.15$

the entire g signal including the $\omega\pi$ fraction. With the $\omega\pi$ events excluded, the fractions of the remaining g's which decay to ρ^- and ρ^0 are 0.68 ± 0.22 and 0.81 ± 0.19, respectively. Although the errors are not insubstantial, these data are clearly consistent with a significant fraction of simultaneous $\rho^-\rho^0$ decays.

For ease of reference, the principal results of this paper are collected in Table III, where, it should be emphasized, all fractions are relative to the entire g signal in the $\pi^+\pi^-\pi^-\pi^0$ spectrum.

IV. CONCLUSION

In conclusion, our study of the $g^-(1700)$ pionic decay modes indicates, in the 4π decay channel, a dominance of ω and ρ products without significant intermediate A_2 formation. In our data, the $\omega\pi^-$ channel is a principal g^- decay product accounting for $(38\pm7)\%$ of all 4π g^- decays. This is a considerably larger $\omega\pi^-$ branching ratio than has been found in several recent experiments where only an upper limit was quoted. The ratio of 2π to 4π decay of the g^- was consistent with the average reported by the Particle Data Group.

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