Investigation of higher-mass even-G states from 15-GeV/c π^+d collisions

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From a study of 15-GeV/c π^+-deuterium interactions obtained in an 890000-picture exposure in the SLAC 82-inch bubble chamber, evidence is presented for at least two broad dipion states beyond the $g(1680)$ region. These states appear in the spectrum representing highly peripheral interactions, and in the spectra obtained by eliminating those interactions for which the transverse momentum of each pion is less than a specified minimum value. Further, examination of the $\pi^+\pi^-$MM (missing mass) spectrum from the reaction $\pi^+n \to p\pi^+\pi^-$(MM) indicates that agreement with the previously obtained branching ratios is possible only if higher-mass dipion states are present. Evidence is also presented which suggests a finite decay probability of the g (or a state of similar mass) into $\pi^+\pi^-\eta$ and/or $\pi^+\pi^-\eta'$.

INTRODUCTION

Although considerable experimental effort has been devoted to the study of the mesonic resonances of mass less than 3 GeV/c^2, much fundamental information concerning the higher-mass states is yet to be delineated. One question which has remained unanswered is that of the number of broad dipion states beyond the $g(1680)$. The only well-established resonance in this region is the $h(2040)$ with a width of ≈200 MeV observed by Apel *et al.*[1] and Blum *et al.*[2] Evidence has also been presented by Antipov *et al.*[3] for a dipion state (H) with a mass of 1922 MeV and a width of 107 MeV. Previously, indications of structure beyond the g region have been present in the works of Boesebeck *et al.*,[4] Armenise *et al.*,[5] Caso *et al.*,[6] and Kemp *et al.*[7] Our experiment strongly suggests the existence of a meson with a mass of 1935 MeV and a width of ~130 MeV, as well as a higher-mass state in what has become known as the U region.

In another area the $\pi^+\pi^-\pi^0\pi^0$ decay rates of the f^0 and g^0 mesons have been determined in, at most, several experiments.[8–10] We will present our data pertaining to this multipion decay mode of the f^0 and g^0 as well as investigate the formation of intermediate states in this multipion decay channel for the g^0.

EXPERIMENTAL METHOD

The data derive from an 890 000-picture exposure of the deuterium-filled SLAC 82-inch bubble chamber, with an rf-separated π^+ beam at 15 GeV/c. All of the events were scanned and predigitized at the Florida State University. The initial 40% of the events were measured on the University of Pennsylvania Hough-Powell device while the remainder were digitized on the University of Tennesses spiral reader at the Oak Ridge National Laboratory. The pattern-recognition, geometry, and kinematic computer reductions were performed at Florida State University using the ATF, POOH, TVGP, and SQUAW programs.

The reactions for which data are to be presented include

(1) $\pi^+d \to pp\pi^+\pi^-$ (3622 three- and four-prong events),

(2) $\pi^+d \to pp\pi^+\pi^-$(MM) (MM $\geq 2\pi^0$; 8466 four-prong events).

Because of the overconstrained nature of reaction (1), both three- and four-prong events are included in our sample. The four-prong events were required to have one dark stopping track, i.e., a spectator proton, while the three-prong events were required to have one dark track which either stopped in the chamber or had a curvature corresponding to a momentum of less than 650 MeV/c. Since the automatic measuring devices produced ionization information for most of the tracks, the information was used in the event selection. For those events where the program could not make unique particle-identification selection, the data were sent to an experienced scanner to check the predicted bubble density with the ionization on film for particle identification. For the events which did not have a good four-constraint fit, if the track momentum was greater than 1.5 GeV/c, the particle was assumed to be a pion. This criterion for events of reaction (2) delimits the second proton in the four-prong events to momenta $\lesssim$1.5 GeV/c. For the study to be presented here of meson production at small momentum transfers, these cuts introduce no more than negligible bias. Events were further required to have a χ^2 fit probability of greater than 0.1%, be at least a three-constraint fit, and have a missing mass squared between -0.12 and 0.12 GeV^2. This resulted in a final sample of 3622 events, corresponding to an experimental size of 10.0 ± 0.7 events per microbarn. None of the results, to be presented within, is substantially altered by the inclusion of the three-prong events.

The data for reaction (2) are restricted, because of their unconstrained nature, to four-prong events (as defined in the above paragraph). Our sample is culled from only those events which possessed neither a one-constraint nor a four-constraint fit. For reaction (2) we find that 4.9 ± 0.3 events correspond to 1 μb. The resolution of various mass calculations varies with the event type. For events of reaction (1) the $\pi\pi$ mass resolution (σ) is from 5 to 40 MeV with an average value of 20 MeV. For events of reaction (2) the $\pi\pi$ mass resolution (σ) is somewhat worse and varies from 25 to 150 MeV with an average of about 50 MeV. For mass calculations which include the neutral particles, the mass resolution increases by a factor of 1.5. Further details of the exposure, event selection, and procedure are available in previous analyses of the data.[11]

STATES BEYOND THE g(1680)

The histogram in Fig. 1 displays the full dipion mass spectrum from reaction (1). While the spectrum is dominated by ρ^0 and f^0 production, the population of the higher-mass region of the spectrum is not small. Indeed, from this spectrum alone, it can be argued that, unless the background at higher dipion masses has a bizarre shape, the presence of the g(1680) implies the existence of higher-mass states. This can be made more decisive by subjecting the dipion spectrum to t' cuts of 0.2 (GeV/c)^2 and 0.03 (GeV/c)^2 ($t' = t_{\pi,2\pi} - t_{\min}$), which are shown in Figs. 2(a) and 2(b), respectively. Fitting the mass distribution for the more restrictive t' cut [Fig. 2(b)] to a polynomial background, including terms quadratic in mass, together with Breit-Wigner resonances for the ρ, f, g, H(1900), and U(2350) yields enhancements of 4.0 and 6.0 standard deviations for the H and U, respectively. The curve on the histogram in Fig. 2(b) represents the result of our fit from threshold to 3 GeV. No detectable improvement in the quality or character of the fit derives from including cubic or quartic mass terms in the background. The resonance parameters and production cross sections derived from this fit are given in

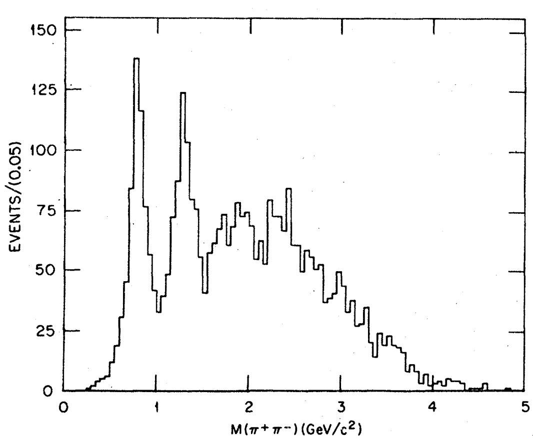

FIG. 1. Full dipion spectrum from the reaction $\pi^+ d \to pp\pi^+\pi^-$.

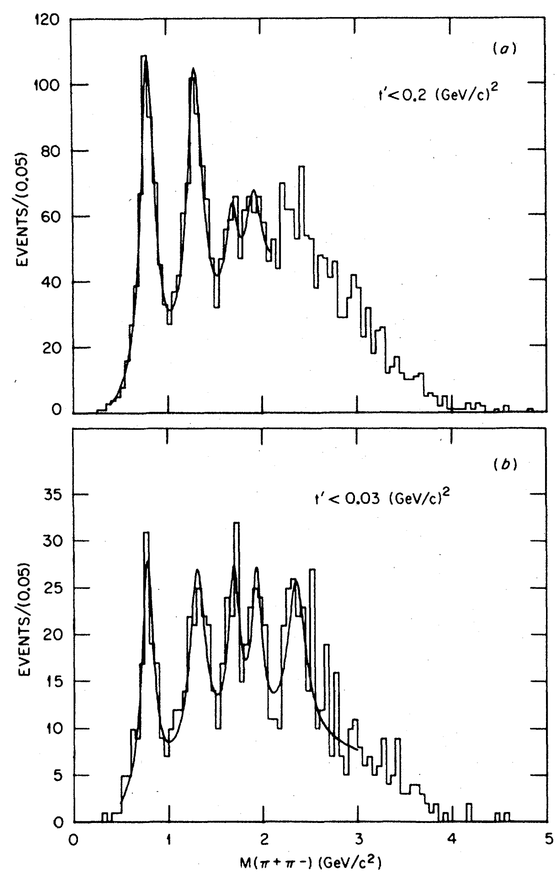

FIG. 2. For the reaction, $\pi^+ d \to pp\pi^+\pi^-$: (a) Dipion spectrum at $|t'| \leq 0.2$ (GeV/c)^2. (b) Dipion spectrum at $|t'| \leq 0.03$ (GeV/c)^2.

TABLE I. Mass, width, and production cross sections for dipion states at $t' < 0.03$ (GeV/c)^2 in the reaction $\pi^+ d \to pp\pi^+\pi^-$. If the fit is truncated at 2200- MeV, excluding perforce the U region, the width and cross section for the H both increase about 10%.

State	Mass (MeV)	Width (MeV)	Cross section (μb)
ρ^0	779 ± 11	149 ± 32	11.5 ± 1.6
f^0	1308 ± 21	200	12.7 ± 1.8
g^0	1695 ± 21	150 ± 58	8.2 ± 1.9
H	1935 ± 22	129 ± 45	6.7 ± 1.7
U	2356 ± 25	235^{+65}_{-50}	12.6 ± 2.3

Table I. The quoted cross-section errors follow from adding, in quadrature, the statistical errors of the fit to the errors in the μb equivalent of our cross section.

It should be clear that in order to fit this spectrum in the g region with reasonable parameters for the g, higher-mass states are required. If higher-mass states are excluded, only poor quality fits result with the mass and width of the g ballooning to unreasonably large values.

We have also attempted to fit this spectrum to a polynomial background (with terms up to M^3) using the masses and widths for the ρ, f, and g, as determined in Table I, without any higher-mass resonances. Our best fit, under those conditions, for the 14 mass bins between 1.85 and 2.55 GeV, had a χ^2 of 34.8 which is an increase of 20.6 in χ^2 over that resulting from including the higher-mass states. For the fit without the H, U states, if we assign a degree of freedom for each mass bin, our fit corresponds to a confidence level of ~10^{-3}. Furthermore, approximate agreement with the reported g branching ratios is impossible to obtain without the presence of higher-mass states, as will be discussed presently.

Kinematically, any peripherally produced dipion system as massive as the g, with a strong forward angular distribution, will have a pion-nucleon mass combination in the diffractive region ($M_{p\pi} < 2$ GeV). Recently, it has been shown by Hagopian *et al.*[12] and by Deutschmann *et al.*[13] that higher-mass states can be enhanced relative to both the lower-mass states and the reflected diffractive background, by restricting the spectrum to only those events for which each decay particle of the resonance has a large transverse momentum relative to the beam (p_T). Figure 3 shows our dipion spectrum subjected to the condition that both the π^+ and π^- have values of p_T greater than $(p_T)_{min}$ where $(p_T)_{min} = 0.3$, 0.35, 0.4, 0.45 GeV/c. These spectra, in general, illustrate the principal thesis espoused by these authors, namely, that as $(p_T)_{min}$ is increased, the higher-mass states become enhanced. In particular, at the larger $(p_T)_{min}$ values, aside from a small f^0 signal, the $g(1680)$ and the $H(1920)$ enhancement are the most significant features of the dipion spectrum. At the largest-p_T cut, the H appears with approximately the same statistical significance as the g—both being ~4.8σ above background.

To recapitulate our arguments favoring the existence of broad states beyond the g in our data, we note that the only way our dipion spectrum can accommodate the presence of the g, with parameters that are consistent with its established properties, is to require the presence of higher-mass states. The very restrictive t' cut, imposed in Fig. 2(b), strongly supports this conclusion, as do the spectra derived from placing restrictions on the transverse momenta. A possible identification for the H would be to assume it is the charged decay mode of the $h(2040)$. However, because of

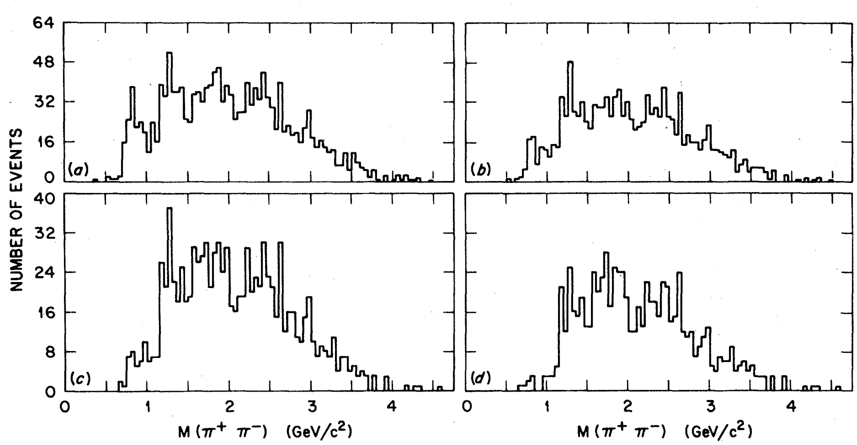

FIG. 3. Dipion spectrum when both pions have a minimum transverse momentum in excess of (a) 0.3 GeV/c, (b) 0.35 GeV/c, (c) 0.4 GeV/c, (d) 0.45 GeV/c.

the ≈100-MeV mass difference, this must remain a speculative connection. A more natural correlation would appear to be with the state observed by Antipov *et al.*[3] at an almost identical mass, even though the fitted width, derived in our experiment, is somewhat in excess of their value.

DECAY OF f^0 AND g^0 INTO $\pi^+\pi^-$MM

Recently Baltay *et al.*,[10] using 15-GeV/c π^+p interactions determined the relative probabilities for the decay of the neutral g into $\pi^+\pi^-$, $\pi^+\pi^-\pi^0\pi^0$, and $2\pi^+2\pi^-$. Since the most frequent g^0 decay mode is to $\pi^+\pi^-$MM, which involves the unconstrained events of reaction (2), we deem it appropriate to present our results here, even though they lack the statistical authority of those of Ref. 10. This follows from the fact that this prior determination of the g^0 decay into ($\pi^+\pi^-$MM) utilized the π^+p initial state where the study of neutral bosons was effected by counting each event twice (once for each π^+ in the final state). There is the further consideration that Δ^{++} production is a much more prominent feature of π^+p interactions than is either Δ^+ or Δ^0 production in π^+n collisions. Both of these effects indicate the possibility of substantial background differences between the two experiments, indicating the desirability of the second determination.

In Fig. 4, the full bosonic mass spectrum $M(\pi^+\pi^-\text{MM})$, where MM indicates missing mass (MM$\neq 0$, m_π), is shown with the restriction $|t'_{d,pp}| < 0.2$ (GeV/c)^2. This spectrum is to be compared with the $\pi^+\pi^-$ spectrum, from the four-constraint events, at a similar t' cut [Fig. 2(a)]. This t' cut approximately maximizes the signal-to-background ratios in the g region for both spectra. Because the nature of any resonance formation at

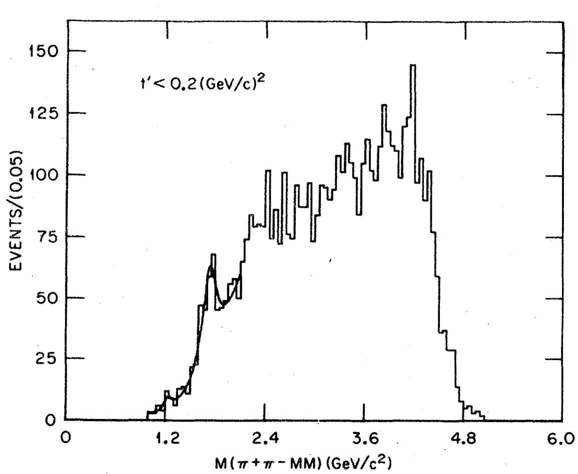

FIG. 4. ($\pi^+\pi^-$MM) spectrum at $|t'| < 0.2$ (GeV/c)^2.

TABLE II. Production data for dipion states at $t' < 0.2$ (GeV/c)^2 in the reaction $\pi^+d \to pp\pi^+\pi^-$.

State	Mass (MeV)	Width (MeV)	Cross section (μb)
ρ^0	793 ± 6	179 ± 14	57.2 ± 4.6
f^0	1294 ± 8	200	54.7 ± 5.0
g^0	1685 ± 19	153^{+57}_{-42}	13.6 ± 3.1
H	1916 ± 25	200^{+65}_{-44}	18.8 ± 3.2

masses >2 (GeV/c^2) in the ($\pi^+\pi^-$MM) spectrum cannot be resolved at this time, we fit both spectra from threshold to 2.1 GeV/c^2. The branching ratios for the f^0 and g^0 are, to within our errors, independent of this upper limit. Again the quality of the fits was not enhanced by either cubic or quartic mass terms in the background. The smooth curves in Fig. 2(a) and Fig. 4 represent the fits obtained with a quadratic background. The parameters obtained from these fits are given in Tables II and III. Some difficulty was experienced in effecting both fits in the f^0 region. Our fitting program produced a width of 209 MeV for the dipion decay of the f^0, and, if unconstrained, fit the f^0 in the ($\pi^+\pi^-$MM) spectrum with a width of less than 50 MeV. Apropos of this, the f^0 width, in either spectrum was constrained to lie between 130 and 200 MeV. The number of g^0 events in either spectrum is independent of the f^0 parameters. From Tables II and III, we determine the following branching ratios:

$$R_{f^0} = \frac{f^0 \to \pi^+\pi^-\text{MM}}{f^0 \to \pi^+\pi^-} = 0.08 \pm 0.03\,,$$

$$R_{g^0} = \frac{g^0 \to \pi^+\pi^-}{g^0 \to \pi^+\pi^-\text{MM}} = 0.27 \pm 0.07\,.$$

In these determinations, we assume no significant amounts of either D or A_2 in the ($\pi^+\pi^-$MM) spectrum. The observed A_2 production cross section in the $\pi^+\pi^-\pi^0$ channel of this experiment (10.4 ± 3 μb) does suggest that in the f^0 mass region, about 1.5 μb of all-neutral A_2^0 decays may be present.

The f^0 decay rate into ($\pi^+\pi^-$MM) has been reported by Eisenberg *et al.*[8] to be $R_{f^0} = 0.23 \pm 0.09$

TABLE III. Production parameters for particles in the $\pi^+\pi^-$MM spectrum [$t' < 0.2$ (GeV/c)^2] in the reaction $\pi^+d \to pp\pi^+\pi^-$(MM).

Particle	Mass (MeV)	Width (MeV)	Cross section (μb)
f^0	1237 ± 24	130	4.6 ± 1.7
g^0	1730 ± 15	200	50.0 ± 6.0

while Emms *et al.*[9] found R_{f^0} to be 0.10. Our data are certainly in consonance with the latter result and within a standard deviation or so of that of Ref. 8. However, as mentioned above, our fitting program, unless otherwise constrained, would drive the f^0 width to less than 50 MeV, with a concomitant reduction in $f^0 \to (\pi^+\pi^-\text{MM})$ branching fraction. In this sense, we regard our value of the decay ratio R_{f^0} to be more of an upper than a lower limit. The possible presence of the A_2 in the $(\pi^+\pi^-\text{MM})$ spectrum is supportive of this conclusion.

The only previous determination of the g^0 branching ratio into $(\pi^+\pi^-\text{MM})$ has been that of Baltay *et al.*,[10] who found $R_{g^0} = 0.35 \pm 0.11$. It is apparent that the two experiments are in good agreement. The presence of g^0 decays in our $(\pi^+\pi^-\text{MM})$ spectrum argues implicitly in favor of the existence of the higher-mass states discussed in the previous section. Without the presence of higher-mass dipion states, our dipion g^0 signal when combined with the decay $g^0 \to \pi^+\pi^-\text{MM}$ would yield a branching ratio R_{g^0} quite inconsistent with its previous determination.

The f^0 and g^0 also have finite decay probabilities to $\pi^+\pi^+\pi^-\pi^-$. However, because of the smaller sample of film which was measured, any signal in this channel will not be significant. There is the further consideration that as the number of prongs increases in the event topology, the probability of missing low-momentum protons, in the scanning process, increases because of track obscuration.

The subchannels of the $(\pi^+\pi^-\text{MM})$ decay of the g^0 have not been previously reported. In Fig. 5, we present the various mass spectra for the g region (1.6–1.82 GeV/c^2). The appearance of any dipion state, in particular the ρ^0, is at most minimal. The $(\pi^\pm\text{MM})$ spectra both tend to peak in the A_2 mass region. However, because of our limited statistics and the expected phase-space distribution for these spectra, we are unable to determine whether this represents the $A_2\pi$ decay of the g or is a purely kinematic enhancement. Of more interest is Fig. 5(d) which shows the missing-mass (MM) spectrum for the g^0 region. This spectrum displays two features—a narrow low-mass enhancement in the η region as well as a wider enhancement at a mass of ~1 (GeV/c^2). The smooth curve [Fig. 5(d)] shows the results of fitting this histogram to a quadratic background together with a Gaussian resolution function from 650 to 1150 MeV. With the mass and width as free parameters, this Gaussian appears as a 3.9σ enhancement at a mass of 992 ± 23 MeV and width of 69^{+19}_{-15} MeV. These parameters would appear, when account is taken of the unconstrained nature of these missing-mass events, to be consistent with the η' (958). Our data, therefore, are at least suggestive of the existence of the decay channel, $\eta'(958)\pi^+\pi^-$, for the g^0 meson. The other interesting feature of Fig. 5(d) is the accumulation of events at small values of the missing mass. While the narrowness of the peak in the low-mass region must be regarded as anomalous, such an enhancement does suggest the existence of an $\eta\pi^+\pi^-$ component to g^0 decay. Because of the difficulty in quantifying the η fraction in this spectrum, we plot, in Fig. 6, the $\eta\pi\pi$ mass spectrum with the requirement that the missing mass lies in the η region ($0.48 \le M_\eta \le 0.62$ GeV/c^2). Again, the data are restricted to bosonic momentum transfers of ≤ 0.2 $(\text{GeV}/c)^2$. The smooth

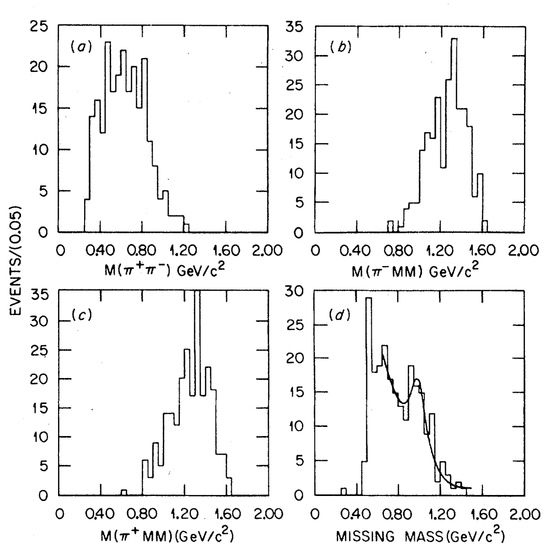

FIG. 5. For the g^0 region (1.6–1.82 GeV/c^2) (a) $M(\pi^+\pi^-)$, (b) $M(\pi^-\text{MM})$, (c) $M(\pi^+\text{MM})$, (d) missing-mass spectrum.

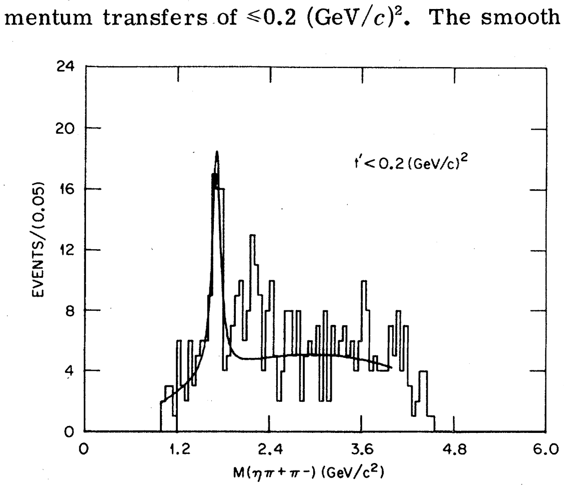

FIG. 6. $(\pi^+\pi^-\text{MM})$ spectrum at $|t'| \le 0.2$ $(\text{GeV}/c)^2$ with the missing mass in the η region (0.48–0.62 GeV/c^2).

curve on this histogram results from fitting it with a quadratic mass formula together with a g^0 Breit-Wigner form. The g^0 signal is a 5.0σ enhancement over background with fitted parameters: $M_g = 1703 \pm 15$ MeV, $\Gamma_g = 129 \pm 40$ MeV. (The g^0 signal is slightly intensified by including a second resonance at a mass of ≈ 2200 MeV ($\Gamma \approx 200$ MeV) which appears as an approximately 3σ effect.) From the fits to Fig. 5 and Fig. 6, we deduce the following branching ratios for g^0 decay relative to the decay $g^0 \to \pi^+\pi^-$MM:

$$\frac{g^0 \to \eta'\pi^+\pi^- \to \pi^+\pi^-\text{MM}}{g^0 \to \pi^+\pi^-\text{MM}} = 0.14 \pm 0.04\,,$$

$$\frac{g^0 \to \eta\pi^+\pi^- \to \pi^+\pi^-\text{MM}}{g^0 \to \pi^+\pi^-\text{MM}} = 0.26 \pm 0.07\,.$$

The branching ratio determination for the g^0 decay into $\eta'\pi'\pi^-$ was unaffected by background subtraction. No η' signal could be detected either by eye or by our fitting programs in the missing-mass spectrum corresponding to total bosonic masses in the range 1.2–1.6 GeV and 1.88–2.08 GeV. While we are aware of no data pertaining to g^0 decay via the η', several previous experiments,[14–16] at higher energies, whose aim was to study the D and E mesons, have investigated the $\eta\pi^+\pi^-$ final state. In only one of these is there an indication, not discussed by the authors, that such a decay may be present.[16]

Throughout this discussion, it has been assumed that the η and η' signals in the MM spectrum were the products of g^0 decay. This should be taken as a convenience rather than a necessity as our data neither confirm nor deny the conjecture that more than a single even-G-parity state exists in the g^0 mass region.

CONCLUSIONS

We have shown that the existence of higher-mass even-G-parity states at masses of 1935 ± 22 and 2356 ± 25 MeV is strongly suggested in the dipion spectrum, at low t', from the reaction $\pi^+ d \to pp\pi^+\pi^-$. This suggestion is reinforced by the fact that only by including higher-mass states can one achieve reasonable values for the mass and width of the g. Furthermore, the presence of g decays into the ($\pi^+\pi^-$MM) channel demands dipionic decays of the g^0. Agreement with the previously determined g^0 branching fraction into ($\pi^+\pi^-$MM) can be achieved only by the presence of the higher-mass states in the dipion spectrum. The f^0 and g^0 branching fractions into ($\pi^+\pi^-$MM) have been found to be in good agreement with prior determinations of these quantities, although our data favor a somewhat smaller percentage of f^0 decays to ($\pi^+\pi^-$MM) than previous data indicate. Examination of the missing-mass spectrum for the decay $g^0 \to \pi^+\pi^-$MM suggests that the g^0, or a heretofore unreported state, may have a finite decay probability into $\eta\pi^+\pi^-$ and/or $\eta'\pi^+\pi^-$.

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