Charge-exchange photoproduction of the $a_2^-(1320)$ in association with Δ^{++} at 19.3 GeV/c

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We examine the negative 3π final state produced in association with $\Delta^{++}(1232)$ in the reaction $\gamma p \to \Delta^{++}\pi^+\pi^-\pi^-$ at an incident photon energy of 19.3 GeV. The most prominent enhancement in the 3π spectrum occurs at a mass and with a width consistent with the parameters of the $a_2(1320)$. This identification is confirmed by the various angular distributions. The a_2 production cross section, corrected for efficiencies and alternate a_2 decay modes, is 0.45 ± 0.05 μb.

INTRODUCTION

The reaction $\gamma p \to p\pi^+\pi^-\pi^-$ has been the subject of many investigations. As with most photoproduction reactions, there is a large diffractive component which, in this case, leads to $\rho(1700)$ production[1] as well as to inelastic production[2] of $\rho(770)$ in association with excited isospin-$\frac{1}{2}$ baryons (N^*). These processes account for about $(70\pm10)\%$ of the cross section in this channel. The purpose of this paper is to present evidence that a dominant feature of the remaining cross section for this channel is the associated production of a negatively charged (3π) resonance $a_2(1320)$ with Δ^{++} baryons. In the past, arguments based primarily on vector-meson photoproduction have been used to exclude all but a minor amount of particle exchange as a contributor to photoproduction processes[3–5] at energies in excess of 5 GeV. However, a study of inclusive Δ^{++} production in γd interactions[6] at 7.5 GeV/c reported that one-pion exchange (OPE) at the baryon vertex gave good agreement with the data. Similarly, higher-energy neutral-$b_1(1235)$ photoproduction[7] has been found to be inconsistent with s-channel helicity conservation. So far as s-channel helicity conservation typifies diffractive processes, it is reasonable to infer that the reason for this inconsistency lies in interference with a particle-exchange contribution to b_1 photoproduction. It should also be noted that the reaction $\gamma p \to \rho^-\Delta^{++}$ persists[8] to energies as high as 20 GeV/c. The presence of an observable signal from this reaction indicates the existence of charge-exchange photoproduction processes.

This reaction is particularly significant because the ρ^- has a small ($\sim$70 keV) radiative width to $\pi\gamma$. This is considerably smaller than either the predicted or measured $\pi\gamma$ widths[9–14] for the $a_1(1260)$, a_2, and b_1 mesons, which are about five times this value. Thus, if OPE is the production mechanism, readily observed a_1 and a_2 signals should appear in the reaction $\gamma p \rightarrow \Delta^{++}\pi^+\pi^-\pi^-$. The possibility of isolating a photoproduced a_1 is of more than routine interest. Because the a_1^0 has even charge conjugation, it cannot be photoproduced by either OPE or Pomeron exchange. This statement is obviously consistent with previous data. This lack of observation of a_1^0 also indicates that there is no operable "Deck" mechanism[15] which will simulate a_1^0 in photoproduction. This further implies that there is no Deck process which will simulate charged-a_1 photoproduction ($\gamma p \rightarrow a_1^- \Delta^{++}$). Thus, charge-exchange photoproduction presents an opportunity to observe a Deck-free a_1. The interest here lies in the fact that it is far from trivial to unify the a_1 parameters deduced from πp interactions and from the products of τ-lepton decay.[16,17]

Experimental details

Our data come from a large hydrogen-bubble-chamber experiment, performed at the Stanford Linear Accelerator Center, utilizing incident photons of average energy 19.3 GeV with a full width at half-maximum of 1.7 GeV. The photon beam was generated by backscattering laser photons from the SLAC 30-GeV electron beam. The experimental details have been given in prior publications.[18] The events, upon which this paper is based, are those which had a kinematic fit to the three-constraint reaction:

$$\gamma p \rightarrow p\pi^+\pi^+\pi^-\pi^-$$

with a calculated photon energy between 16.5 and 21.0 GeV, a χ^2 probability in excess of 0.01%, and no better fit to any other reaction or mass permutation. This procedure provided an event sample of 5441 events.

For the reaction $\gamma p \rightarrow \Delta^{++}(1232)\pi^+\pi^-\pi^-$, the efficiency of our apparatus in the 3π mass range between 0.95 and 2.5 GeV/c^2 varies between 0.87 and 0.91. We therefore eschew any correction in the various mass plots. We do account for the efficiency in the cross-section quotations and the various angular distributions where its effects are not uniform.

PERIPHERAL Δ^{++} PRODUCTON

In Fig. 1 we show the $p\pi^+$ mass spectrum for those events for which the recoiling $\pi^+\pi^-\pi^-$ systems have $|t'_{\gamma,3\pi}| < 0.2$ GeV^2 (3219 events). If both $\pi^+\pi^-\pi^-$ combinations satisfy this condition, then the one with the lower t' is selected. This selection procedure for Δ^{++} will be followed throughout this paper. The prominence of the Δ^{++} signal is apparent and the remainder of this work is devoted to those events which have such a peripheral Δ^{++}. We define the Δ^{++} mass region as having $M(p\pi^+)$ less than 1.4 GeV/c^2.

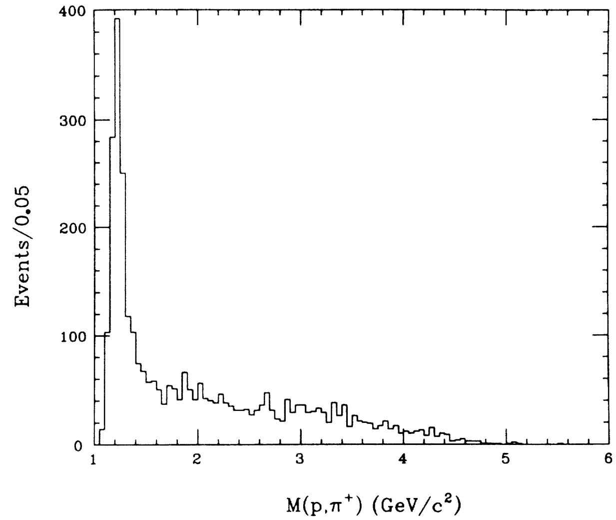

FIG. 1. $p\pi^+$ mass spectrum for events with $|t'_{\gamma,3\pi}| < 0.2$ GeV^2.

Before proceeding further we shall establish that the primary production mechanism for these Δ^{++} is one-pion exchange. If we fit the t' distribution for the peripheral Δ^{++} to an exponential of the form $e^{-b|t'|}$ we find $b = 10.1 \pm 0.7$ GeV^{-2}. This compares favorably with the value of 11.1 ± 0.7 GeV^{-2} which was reported for the reaction[19] $\pi^+ p \rightarrow \Delta^{++} f_2(1270) \rightarrow p\pi^+\pi^0\pi^0$ at 15.7 GeV. This reaction is a classic one-pion-exchange reaction and the example cited is kinematically similar to the photoproduction of interest here. One can contrast this with the t' distributions[20,21] observed in the reaction $\pi^+ p \rightarrow \Delta^{++}\pi^0$ at 8.0 and 13.1 GeV where the value of b is less than half this value. This pion-charge-exchange reaction has been long considered to be a typical ρ-exchange process (π exchange is forbidden by G-parity conservation at the meson vertex).

The spin-density-matrix elements for the Δ^{++}, in the Gottfried-Jackson frame, have been determined by the method of moments (without background subtraction). These are given in Table I along with the predictions for these quantities in the absorptive one-pion-exchange model.[22] We also show, in Table I, these quantities for the Δ^{++} produced in the ρ-exchange reaction[20] $\pi^+ p \rightarrow \pi^0 \Delta^{++}$ at 8 GeV. Whereas all of the determina-

TABLE I. Spin-density-matrix elements for the Δ^{++} in the Gottfried-Jackson frame.

	This expt.	OPE (Ref. 22)	$\pi^+ p \rightarrow \Delta^{++}\pi^0$ (Ref. 20)
ρ_{33}	0.065 ± 0.019	0.08	0.30 ± 0.05
ρ_{3-1}	-0.007 ± 0.025	0.006	0.16 ± 0.06
ρ_{31}	-0.102 ± 0.033	-0.04	0.01 ± 0.05

tions of ρ_{31} are more or less consistent with zero, the values for ρ_{3-1} and ρ_{33} appear to differentiate rather reliably between π and ρ exchange. The 13.1-GeV data of Scharenguivel *et al.*,[21] for the $\pi^+p \to \pi^0\Delta^{++}$ reaction, are quite consistent with this assessment. However, it is difficult to be more precise because their data are presented only in graphic fashion. Still, it is clear that both the values of ρ_{33} and ρ_{3-1} and the slope of the t' distribution for the ρ-exchange reaction are quite distinct from the values of these quantities extracted in this photoproduction experiment. It is also apparent that the spin-density-matrix elements for the photoproduced Δ^{++} are in satisfactory agreement with the absorptive OPE predictions.[22]

Further confirmation that ρ exchange is an unlikely Δ^{++} production mechanism is available from the observation that neither $f_2(1270)$ nor a_2^0 mesons have been seen in the photon reactions[23–26] $\gamma p \to p\pi^+\pi^-$ and $\gamma p \to p\pi^+\pi^-\pi^0$, respectively. Theoretical calculations,[27] as well as implications from the measured $\gamma\gamma$ radiative widths[9] of both the f_2 and a_2^0, indicate a substantial $\rho^0\gamma$ radiative width for both so that if ρ exchange were to occur at an observable level, both of those states should be seen. Because of charge-conjugation invariance, the photoproduction of these states cannot occur by either pion or Pomeron exchange. For all of the above reasons we conclude that the charge-exchange reaction $\gamma p \to \Delta^{++}\pi^+\pi^-\pi^-$ is dominated by one-pion exchange at $|t'_{\gamma,3\pi}| < 0.2$ GeV.[2]

THE BOSONIC SYSTEM RECOILING FROM THE PERIPHERAL Δ^{++}

In Fig. 2(a) we show the full 3π spectrum recoiling from the Δ^{++} at $|t'_{\gamma,3\pi}| < 0.2$ GeV^2 (1358 events). That this 3π spectrum is dominated by ρ^0 production is confirmed in Fig. 2(b) which is the dipion spectrum (both combinations) for these recoiling 3π events. One also notes the presence of a signal in the mass region of the $f_2(1270)$. Close inspection of the ρ^0 peak shows considerably less skewing than is present in diffractive ρ^0 photoproduction ($\gamma p \to \rho^0 p$). In fact, fitting this dipion spectrum to Breit-Wigner distributions for the ρ^0 and f_2 over a background of the form

$$(a+bM+cM^2)(1-de^{-(M-M_0)/f}) ,$$

where a, b, c, d, f, and M_0 are parameters, yields a good fit in the ρ mass region with a resulting ρ mass of 753 ± 5 MeV/c^2 and a ρ width of 151 ± 10 MeV/c^2. This is in contradistinction to ρ^0 production via Pomeron exchange[2,24] where the fit to a simple Breit-Wigner is of poor quality and where the dipion mass spectrum peaks at $\sim$725 MeV/c^2.

A sharpening of the bosonic spectrum can be obtained by requiring either (or both) of the neutral dipion mass combinations to be in the ρ region ($0.6 \le M(\pi^+\pi^-) \le 0.9$ GeV/c^2). This $\rho^0\pi^-$ spectrum (954 events) is shaded in Fig. 2(a). Previous data[9] indicate that the a_1^- and a_2^- are consistent with their $\pi^+\pi^-\pi^-$ decay modes occurring entirely through the $\rho^0\pi^-$ intermediate state. We note that this spectrum, which contains directly produced 3π states, as well as background events from the reaction $\gamma p \to \rho^0 N^* \to \rho^0\pi^+\pi^- p$, shows the presence of enhancements in the a_2^- and $\pi_2(1670)$ (A_3) mass regions. The imposition of the requirement of the presence of a peripheral Δ^{++} effectively eliminates $\rho(1700)$ production as a background in this spectrum. This is verified by a plot (Fig. 4 below) of the 4π mass for the peripheral Δ^{++} events (as discussed further below).

The final step in the isolation of directly produced $\rho^0\pi^-$ systems, is to eliminate the effects of direct, inelastic ρ^0 photoproduction in association with N^* baryons. We do this in two stages. First, we remove all events for which the appropriate masses satisfy the reaction $\gamma p \to \rho^0 N^*$, with $|t'_{\gamma,\rho^0}| < 0.2$ GeV^2. In this removal, any event with a $p\pi^+\pi^-$ mass less than 2.1 GeV/c^2 is considered to be an N^*. Because of the skewed nature of the

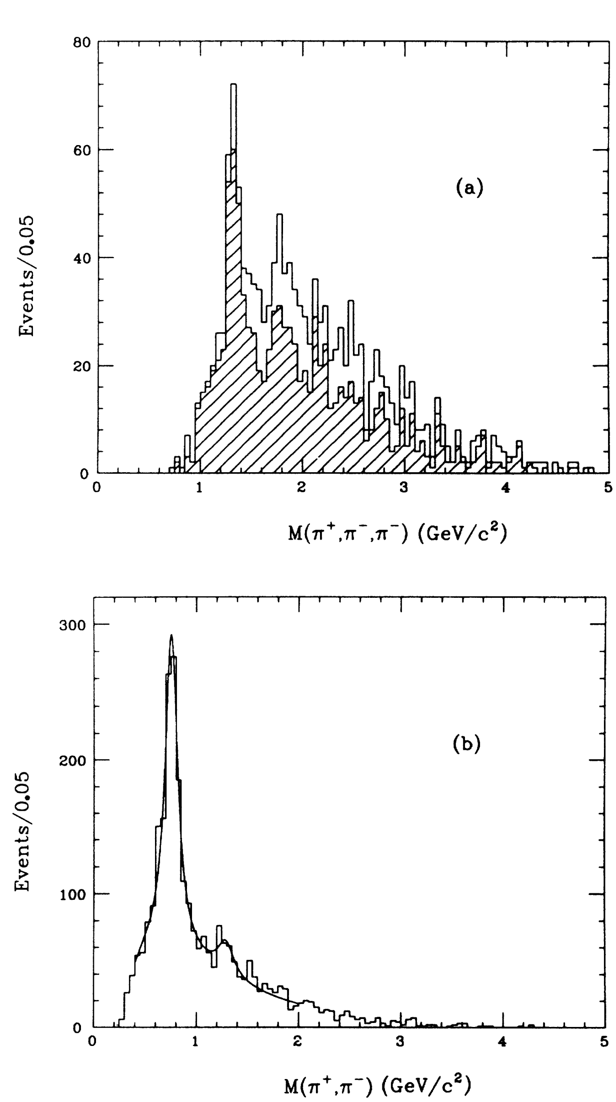

FIG. 2. (a) $\pi^+\pi^-\pi^-$ mass spectrum opposite Δ^{++} with $|t'_{\gamma,3\pi}| < 0.2$ GeV^2. The shaded region is the $\rho^0\pi^-$ spectrum. (b) The dipion spectrum (both neutral combinations) for the events in (a).

direct ρ^0 photoproduction,[2,24] for this removal, the ρ^0 mass was taken to be between 0.55 and 0.90 GeV/c^2. This left a sample of 565 $\rho^0\pi^-$ events, which form the unshaded portion of Fig. 3, i.e., the full histogram less the shaded portion. That most of these 389 excluded $\rho^0 N^*$ candidate events do in fact represent inelastic ρ^0 production ($\gamma p \rightarrow \rho^0 N^*$) is affirmed by the determination of the beam polarization P_γ using the $\rho^0 N^*$ sample at $|t'_{\gamma,\rho^0}| < 0.2$ GeV^2. We find, assuming s-channel helicity conservation, without background subtraction, that $P_\gamma = 0.47 \pm 0.05$. This is consistent with the value of 0.52 expected for our experimental arrangement. It is also consistent with the value found from elastic ρ^0 photoproduction in this experiment[24] ($P_\gamma = 0.49 \pm 0.02$). The second stage in the $\rho^0 N^*$ removal process involves reinsertion of some of the excluded events into our sample. The reason for this is that peripheral $\rho^0 N^*$ production has a common region of phase space with peripheral $\Delta^{++} a_2^-$ production. This commonality, so far as the a_2^- is concerned, consists mainly of those forward-going ρ^0 (in the Gottfried-Jackson system for the a_2^-). Failure to repopulate the $\rho^0\pi^-$ spectrum with these events results in a serious distortion of the angular distributions (the forward and backward "spikes" in Fig. 6(d) below are due to these $\rho^0 N^*$ events). In order to determine this repopulation, the $\rho^0\pi^-$ spectrum for the $\rho^0 N^*$ events was fitted to an a_2 and $\pi_2(1670)$ together with a quadratic background. In this way ~38 events are returned to the spectrum. These events are shaded in Fig. 3 and in all subsequent figures.

The dominant feature of Fig. 3 is the large enhancement in the mass region normally associated with the a_2. Figure 4 shows the 4π mass spectrum for the shaded events in Fig. 2(a). It should be clear that the bosonic enhancements in the $\rho^0\pi^-$ mass spectrum do not have their origins in this spectrum. If we proceed on the basis that the only resonances present in the $\rho^0\pi^-$ spectrum of Fig. 3 are an a_2 and π_2, we find an a_2 mass of 1325±10 MeV/c^2 and a width of 152±20 MeV/c^2. Although the width is somewhat larger than that given by the Particle Data Group[9] these parameters are quite consistent with the hypothesis that this is the a_2. We tentatively make this identification whence the a_2 photoproduction cross section represented by this ($\rho^0\pi^-$) enhancement is 0.099±0.011 μb. With an $e^{-10|t'|}$ production dependence, after accounting for the ρ^0 not included by our ρ^0 mass cut and for a_2^- decays into other than $\rho^0\pi^-$, the full a_2^- photoproduction cross section is 0.45±0.05 μb.

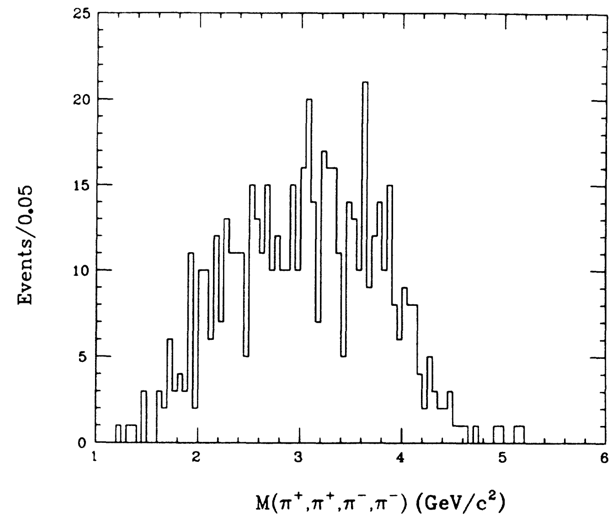

FIG. 4. $\pi^+\pi^+\pi^-\pi^-$ mass spectrum for the $\Delta^{++}\rho^0\pi^-$ events of Fig. 3.

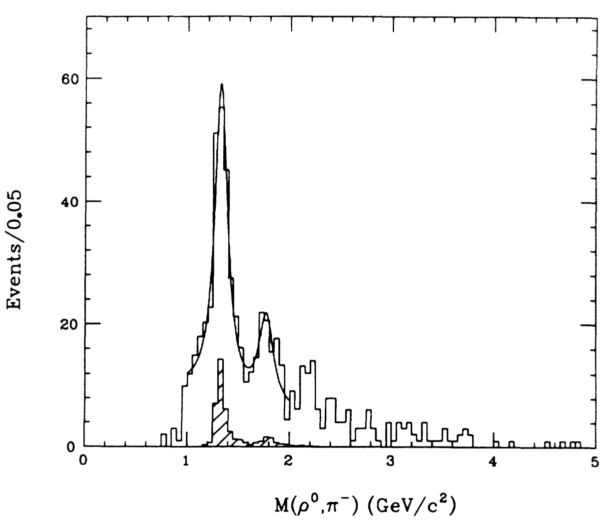

FIG. 3. The corrected $\rho^0\pi^-$ mass spectrum. The shaded area represents our correction for antiselection of peripheral $\rho^0 N^{*+}$ events.

JUSTIFICATION FOR THE a_2 INTERPRETATION

Although the mass and width of the large enhancement in Fig. 3 approximate the Particle Data Group[9] listings for the a_2, the rather fluid situation regarding these parameters for the a_1 indicates that it would be desirable to seek confirmation for its identity. We begin, by plotting in Fig. 5 the Φ distribution for the a_2 mass region (1.25–1.40 GeV/c^2) where Φ is the angle of the photon

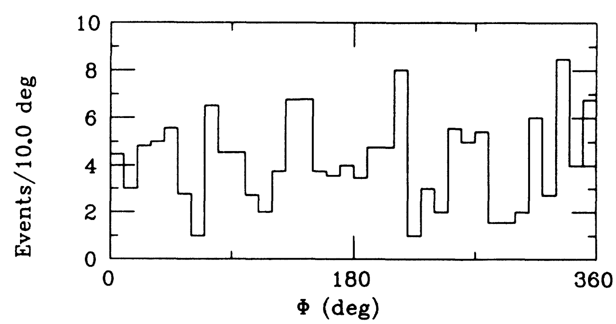

FIG. 5. Φ distribution for a_2^- region. Φ is the angle of the photon electric vector relative to the production plane in the c.m. system.

electric vector relative to the production plane in the c.m. system. If the production is mediated by one-pion exchange, t-channel helicity will be conserved and the Φ distribution will be isotropic.[28] Our data are consistent with this conclusion. We next consider the following polar-angular distributions:

θ_1, the angle that the positive pion makes with respect to a Z axis defined by the difference of negative pion momenta in the 3π rest frame.[29]

θ_2, the helicity angle for ρ^0 decay. The Z axis is taken as the direction of the ρ^0 in the 3π rest frame, with θ_2 specifying the direction of the π^+ in the ρ^0 rest frame.

θ_3, the so-called canonical angle adapted to t-channel processes. θ_3 is the polar angle between the incident photon direction, in the 3π rest frame, and the outgoing π^+ direction in the ρ rest frame.

θ_4, the (γ,ρ) scattering angle in the 3π rest frame.

The expected distributions for these angles are given in Table II for the cases where the $(\rho\pi)$ resonance has $J^P=2^+$ or $J^P=1^+$ (S-wave decay). The distributions for θ_1 and θ_2 are independent of the polarization of the 3π state while for θ_3 and θ_4, t-channel helicity conservation ($J_Z=\pm 1$) is assumed. In Figs. 6(a)–6(d) we present the experimental distributions for the a_2 mass region. The smooth curves represent fits to an incoherent sum of an isotropic background and the expected a_2 distribution. The fractions of the a_2 distributions represented by these curves are also given in Table II. In this region of 3π mass, the a_2 accounts for 0.72 ± 0.07 of the events in the mass spectrum. As can be seen, the general trend of the data is in accord with the a_2 expectations. The possibility that the large enhancement in Fig. 3 could be due to a_1 production[30,31] is not supported by the θ_1 and θ_2 distributions. We conclude that this enhancement is due primarily to a_2 photoproduction. In the vector-dominance model the picture that emerges is one where the incident photon, regarded as a polarized ρ^0, makes a glancing collision with an $L=2$ pion, resulting in the t-channel production of a polarized a_2. However, from 20 to 40% of

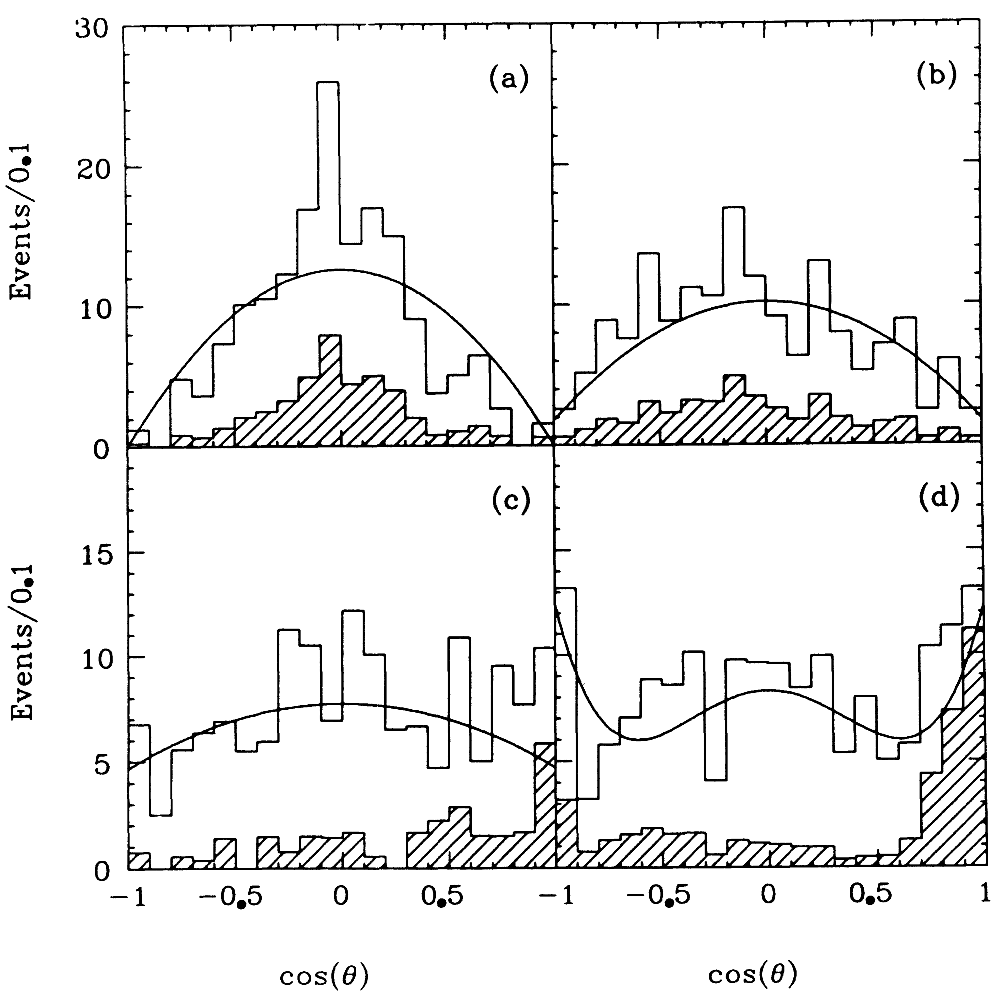

FIG. 6. Polar-angular distributions for the angles $\theta_{1,2,3,4}$ (a), (b), (c), (d), respectively, for the a_2 mass region. The smooth curves represent fits to an incoherent sum of the distribution expected for the a_2 and a constant distribution. The full histograms represent the corrected experimental distributions, while the shaded histograms represent the corrections for the removal of all $\rho^0 N^{*++}$ events and for our experimental acceptance.

TABLE II. Expected angular distributions.

Angle	$J^P=2^+$	$J^P=1^+$	Assumptions	Fraction of a_2 distributions in Fig. 6
θ_1	$\frac{3}{4}\sin^2\theta_1$	Constant	None	1.00
θ_2	$\frac{3}{4}\sin^2\theta_2$	Constant	None	0.81±0.16
θ_3	$\frac{1}{8}(5-3\cos^2\theta_3)$	$\frac{3}{4}\sin^2\theta_3$	$J_Z=\pm1$	0.60±0.40
θ_4	$\frac{5}{8}(4\cos^4\theta_4-3\cos^2\theta_4+1)$	Constant	$J_Z=\pm1$	0.45±0.23

the events in the region are due, apparently, to some process other than a_2 production. This background exhibits angular distributions not incompatible with those expected for a_1 production and decay. We conclude that this enhancement is due mainly to a_2 production, but we cannot exclude the possibility of significant a_1 production as well.

Thus far, there is no convincing evidence for the appearance of any a_1^- in our data. An a_1 is not required to fit the $\rho\pi$ mass spectrum. Indeed, unless artificially constrained, our fits always require the intensity of any resonance with mass less than 1280 MeV/c^2 to be negligible. Furthermore, the angular distributions of Fig. 6 all yield contributions indicating the presence of an a_2. The most recent a_1 parameters deduced by Isgur et al.[17] and by Bowler[16] can be bracketed by $M(a_1)=1240\pm50$ MeV/c^2, $\Gamma(a_1)=410\pm60$ MeV/c^2. Because of the large a_1 width, if the a_1 is present in our data, it should manifest itself in the mass regions on either side of the a_2 mass region. We thus present the angular distributions for $\theta_{1,2,3,4}$ for events with a $\rho\pi$ mass between 0.95 and 1.55 GeV/c^2 having excluded any event with a $\rho\pi$ mass in the a_2 mass region [Figs. 7(a)–7(d)]. These distributions are essentially isotropic. As shown in Table II, all of these angular

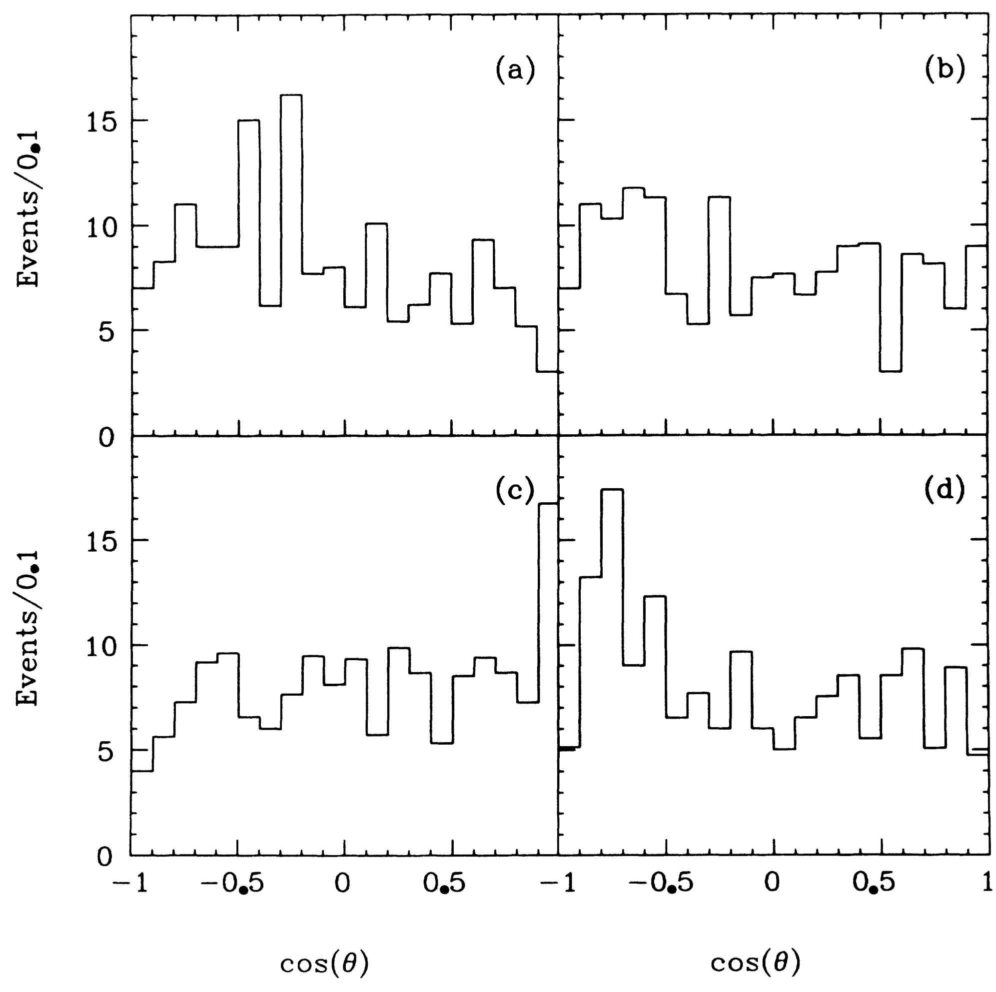

FIG. 7. Polar distributions for angles $\theta_{1,2,3,4}$ (a), (b), (c), (d), respectively, for the mass region ($0.95<M<1.55$ GeV/c^2) with the a_2 region excluded.

distributions are expected to be isotropic for a_1 production except for θ_3 where a polarized a_1 ($J_Z = \pm 1$), decaying via S wave, would yield a $\sin^2\theta_3$ distribution. Thus, Figs. 3, 6, and 7 indicate that there could well be a broad a_1 under the a_2 peak, extending below and above it. However, we cannot exclude the possibility that this broad background of $\rho\pi$, mainly in S wave, is nonresonant.

CONCLUSIONS

The principal result of this work is the observation of the reaction, $\gamma p \rightarrow a_2^- \Delta^{++}$ with a production cross section of 0.45 ± 0.05 μb at $p_\gamma = 19.3$ GeV/c. There is a broad, mainly S-wave $\rho\pi$ background for which we can exclude neither the possibility that is is nonresonant nor that it is due to a_1 production.

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