Evidence for the Electromagnetic Production of the A_1

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(Received 3 January 1984)

Using data on the coherent production of $\pi^+\pi^+\pi^-$ systems in π^+ collisions with nuclei, we have extracted an estimate for the radiative partial width of the A_1. The rate for $A_1^+ \to \pi^+\gamma$ is 640 ± 246 keV, which is a factor of about 2–3 below the value expected on the basis of predictions from quark models and from vector dominance ideas.

PACS numbers: 14.40.Cs, 13.40.Hq, 13.75.Gx

From its initial discovery,[1] the A_1 was thought to be the isovector member of the $J^{PC} = 1^{++}$ antiquark-quark octet. The pioneering partial-wave analysis of Ascoli and co-workers[2] provided the first convincing evidence for a $J^P = 1^+$ assignment for the A_1. More recently, several experiments have provided strong support for a resonant interpretation of the A_1 as observed in diffractive,[3] charge exchange,[4] baryon exchange,[5] and τ-lepton decay[6] processes. Nevertheless, the estimates of the A_1 mass and width are still rather uncertain.[7] In this Letter we present evidence for the Coulombic production of the A_1, from which we extract the first estimate of the radiative decay width for $A_1 \to \pi\gamma$. Theoretical estimates for this partial width, based on the quark model and on vector dominance ideas, have been typically in the range of 1.0–1.6 MeV.[8]

The data were obtained by using a 202.5-GeV/c incident π^+ beam on copper and lead targets. The specific reaction involved coherent production of three pions:

$$\pi^+ A \to \pi^+\pi^+\pi^- A. \qquad (1)$$

This reaction is dominated by nuclear diffractive production, in which the presence of a large nonresonant Deck contribution[9] has always obscured the extraction of the A_1 resonance parameters. The diffractive mechanism favors production of helicity $M = 0$ states in the t channel, particularly at small values of momentum transfer. Coulombic production, on the other hand, involves $|M| = 1$ states, which carry the helicity of the mediating ($q^2 \simeq 0$) photon.

Despite the spin-flip nature of the electromagnetic process, and unlike the case in hadronic spin-flip reactions, the cross section for Coulomb production of the A_1 is expected to peak very close to the forward direction. This is because the presence of the photon propagator in the long-range Coulomb interaction provides a cross section that peaks at $t \approx 2t_0$, where t_0 is the minimum momentum transfer needed to produce any three-pion mass. The maximum for the strong spin-flip cross section occurs at the much larger values of t that characterize the nuclear form factor [$t \approx (12A^{2/3})^{-1}$ GeV^2].[10]

A discussion of the apparatus and the data-taking procedure can be found elsewhere.[11] Also, the general features of the data and the methods used in the analysis of Reaction (1) have already been published.[12] In the present analysis we restrict ourselves to 85 200 events on Cu and 30 100 events on Pb, selected to be within the coherent forward peaks ($t < t^* = 0.4A^{-2/3}$ GeV^2), with three-pion masses $m_{3\pi} < 1.5$ GeV. The $|M| = 1$ component of the data is isolated by means of a partial-wave analysis (PWA), with use of the density-matrix formulation in the Gottfried-Jackson frame.[13]

For the PWA, the phase-space–dependent part of the detection efficiency (geometric acceptance, triggering, and reconstruction efficiencies) was parametrized as a function of the momenta of the final-state pions. The average overall acceptance dropped from 37% at $m_{3\pi} = 0.9$ GeV to 20% at $m_{3\pi} = 1.5$ GeV. The sensitivity of the acceptance-corrected data is 31.3 events/μb and 6.7 events/μb for Cu and Pb targets, respectively.

The fits to the density-matrix elements were performed with use of a maximum-likelihood method. An isobar model was used for the 3π states, which permitted $\pi^+\epsilon$, $\pi^+\rho$, and π^+f^0 substates. (ϵ refers to an isoscalar $J^P = 0^+$ wave, with a mass at 0.77 GeV and a width of 0.4 GeV.) We follow the conventional J^PLM^η partial-wave notation,[13] where J is the total spin of the 3π system, P is its parity, L is the decay angular momentum between the isobar and the bachelor pion, M is the 3π helicity, and η is the reflection parity. The only waves needed for $m_{3\pi} < 1.5$ GeV were 0^-S, 0^-P, 1^+S, 1^+P, 1^+D, 2^-P, 2^-S, 3^+P, 3^+D, 1^+S1^+, 2^+D1^+, and 1^-P1^+, where $M^\eta = 0^+$ is assumed if not otherwise specified.

A full account of our partial-wave analysis is in preparation and will be published elsewhere.[14] Here we concentrate on the only two significant $|M| = 1$ waves: 2^+D1^+, which is dominated by the A_2 meson, and 1^+S1^+, which is a candidate wave for Coulombically produced A_1. Both waves contribute to the total intensity at a level of several percent. Because these waves do not have a large effect on the total fit likelihood, to ascertain that their fitted intensities did not simply follow the behavior of the dominant waves, subsequent to the overall fit we studied and maximized the fit likelihood as a function of just the intensities of the 2^+D1^+ and 1^+S1^+ waves.

The A_2^+ was observed previously in the same experiment (with little background) in its $\eta\pi^+$ and $K^+K_S^0$ decay modes.[15] Consequently, its properties can be compared to those recovered through the PWA of Reaction (1). The published measurement[15] indicates rather convincingly that the production is dominated by the Coulomb mechanism. Although the strong-interaction background is certainly different in Reaction (1) than in the other A_2-decay channels, the presence of the A_2 provides us with a crucial test of the sensitivity of our analysis to the rather small signals involved.

In Fig. 1 we present the intensity of the 2^+D1^+ wave, extracted by PWA from the data of Reaction (1). For comparison, we show the absolute yield of A_2 expected from the measured radiative width $A_2^+ \to \pi^+\gamma$, ignoring interference between strong and electromagnetic production (dashed curves). We also show (continuous curves) the yield that would be expected if the interference between the two production mechanisms were identical to that in the cleaner A_2 channels.[15] Considering the difference in the background, the agreement for both Cu and Pb targets is surprisingly good.

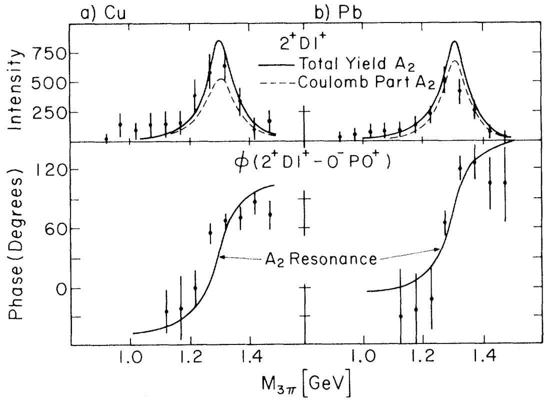

FIG. 1. Intensities and relative phases of the 2^+D1^+ waves for Cu and Pb targets as a function of 3π mass in Reaction (1). Smooth curves are expectations for A_2 production.

The relative phases of the 2^+D1^+ and 0^-P0^+ waves are also shown in Fig. 1. Fast forward motion is seen at the A_2 position. The curves represent the phase behavior expected from a pure relativistic Breit-Wigner D wave. Although any intrinsic phase motion of the 0^-P0^+ reference wave has not been taken into account, the agreement is quite reasonable. The 0^-P0^+ phase was chosen as reference because it shows little intrinsic motion over the mass range of interest,[3] while phases of other potential reference waves (0^-S0^+ and 1^+S0^+) move rather significantly. The interference between the 0^-P0^+ and 2^+D1^+ waves is substantial ($\sim 70\%$ of maximum), and the phase difference is therefore well determined.

The t dependence of the 2^+D1^+ intensity for $1.2 < m_{3\pi} < 1.4$ GeV is shown in Fig. 2. It is compared with the absolutely normalized A_2 differential cross section expected from Ref. 15. The agreement is again quite good. In particular, the 2^+D1^+ wave does not exhibit the forward dip, characteristic of hadronic spin-flip amplitudes observed at lower energies.[16] We interpret this result as evidence for Coulombic production of this wave.

The relative strength of the 2^+D1^+ wave, integrated over the 1.2–1.4 GeV mass range, is $\sim 2\%$ for the Cu target and $\sim 4\%$ for Pb. From our results on the A_2, we conclude that our analysis is reasonably sensitive to the waves at the several percent level. By comparing two independent sets of

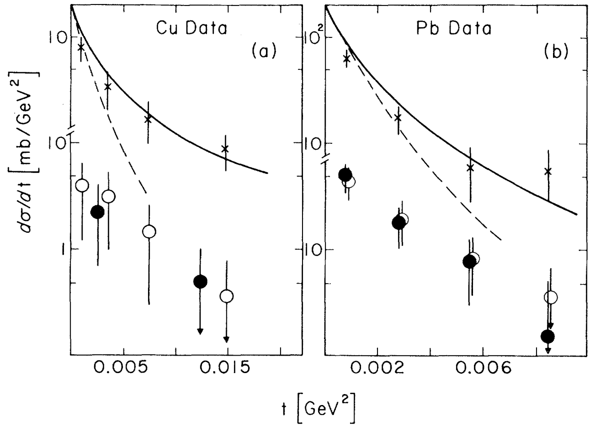

FIG. 2. The t dependence of the 2^+D1^+ wave for $1.2 < m_{3\pi} < 1.4$ GeV (crosses), and of the 1^+S1^+ wave for $1.0 < m_{3\pi} < 1.2$ GeV (open circles) and for $1.2 < m_{3\pi} < 1.4$ GeV (solid circles). Smooth curves are based on results in Ref. 15 for Cu and Pb targets: the solid curves correspond to the total yield of A_2 (including interference with strong production) and the broken curves represent just the Coulomb part of the A_2 yield.

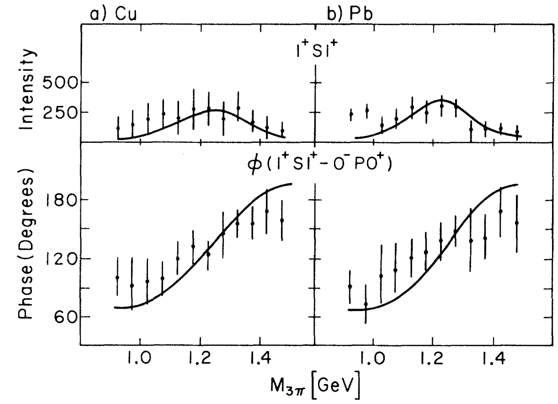

FIG. 3. Intensities and relative phases of the 1^+S1^+ waves for Cu and Pb targets as a function of 3π mass in Reaction (1). Smooth curves are predictions based on the standard A_1 parameters of Refs. 3 and 7.

PWA fits (mass- and t-dependent variations), and from the results of our other A_2 measurement for each target, we estimate that the overall uncertainty for the 2^+D1^+ intensity is about ± 30%.

Now we turn to the evidence for the Coulombic production of the A_1. The intensities and phases of the 1^+S1^+ waves (again with respect to the 0^-P0^+ wave) are shown in Fig. 3. The curves in the figure correspond to Primakoff-distorted[17] resonant behavior with the A_1 parameters of Ref. 3, namely $m_{A_1} = 1.28$ GeV, $\Gamma_{A_1} = 0.3$ GeV. The phase variation is somewhat weaker than expected for these A_1 parameters, which may reflect the presence of nonresonant contributions in the data. Nevertheless, the results are consistent with a broad resonance. Although, because of the large statistical errors, we cannot extract the resonant parameters from our measurement, an A_1 with a mass much below 1.2 GeV provides a significantly worse description of the data. (In fits to the 1^+S1^+ intensity, the χ^2 per degree of freedom for a resonant mass of 1.1 GeV was typically twice that for a resonant mass in the 1.2–1.3 GeV range.) Good fits are obtained for $1.2 < m_{A_1} < 1.4$ GeV and $\Gamma_{A_1} \geq 0.3$ GeV. The t dependence of the 1^+S1^+ intensity was already shown in Fig. 2; again, although the statistics are poor, the data are consistent with a t distribution expected for Coulomb production.

Through the Primakoff relation, the Coulomb production cross section of a resonance is proportional to its radiative width. To obtain an estimate of the radiative width of the A_1, we must use the total intensity for the 1^+1^+ state, summed over different isobar decay modes. Although the A_1 is primarily a $\pi\rho$ 1^+S state, the branching ratios into other modes are not negligible. Because the data in the helicity-one channel are statistics limited, the total 1^+1^+ intensity was calculated with the assumption of the same substructure for the $J^P = 1^+$ state in the $M^\eta = 0^+$ as in the $M^\eta = 1^+$ partial waves. (The $M^\eta = 0^+$ waves, which contribute to diffractive production, were far better determined in the data.[14]) The correction for other decays of the A_1 (i.e., for 1^+P and 1^+D waves) corresponds to about a 20% increase relative to the observed intensity of the 1^+S1^+ partial wave alone. Integrating over $0.9 < m_{3\pi} < 1.5$ GeV and $t < t^*$, the result is $\sigma(1^+1^+) = 0.10 \pm 0.02$ mb for Cu and 0.42 ± 0.06 mb for Pb.

The ratio of the Pb to the Cu cross section, 4.2 ± 1.0, is very similar to that measured previously for the A_2,[15] which is produced dominantly by the Coulomb mechanism. For pure electromagnetic production, a ratio of 6.4 would be expected. The fact that the scaling is not consistent with such behavior (i.e., essentially Z^2, but modified somewhat by the form factor) can be ascribed to the interference between Coulomb and hadronic mechanisms in the production of the 1^+S1^+ wave. The quality of the data for the 1^+S1^+ wave in Fig. 2 does not warrant an attempt to separate these two contributions. In the case of the A_2, ignoring this interference would have increased the radiative width by a factor of ~ 1.3.

The values of $\sigma(1^+1^+)$ can be used to estimate the radiative width of the A_1. We obtain $\Gamma_\gamma \approx 640 \pm 120$ keV, if we use the A_1 parameters of Ref. 3. The result for the radiative width is clearly sensitive to the assumed resonance mass and total width. For $M_{A_1} = 1.2$ GeV, $\Gamma_{A_1} = 0.3$ GeV, for example, we obtain $\Gamma_\gamma = 510 \pm 100$ keV. When a fit of the Primakoff mass distribution is performed simultaneously to Cu and Pb data (with Γ_γ being the only free parameter), the results for Γ_γ are typically ~ 25% smaller than those given above. This is because the fit does not attribute the entire integrated 1^+1^+ cross section to the A_1 resonance. We should also note that backgrounds to 1^+1^+ production (such as Regge contributions, or a possible Coulombic Deck effect) have not been considered in this paper, and could further reduce the estimated values of the radiative width.

The errors given above reflect the uncertainties of the maximum-likelihood fits of the PWA, assuming the presence of uncorrelated errors. Consequently, these errors are probably optimistic. Our estimate of the additional uncertainty due to the overall normalization in the experiment is ± 15%.[12] Finally, from the comparison with the A_2 data, we estimate an additional systematic uncertainty of ± 30% in our measurements of radiative widths in Reaction (1). Consequently, for the standard A_1 parameters,[3,7] we quote a radiative width of 640 ± 246 keV, with all errors added in quadrature.

The theoretical predictions for the radiative width of the A_1 are typically in the range of 1.0–1.6 MeV, for $M_{A_1} = 1.2$ GeV, $\Gamma_{A_1} = 0.3$ GeV. We conclude, therefore, that our data provide evidence for Coulombic production of a $J^P = 1^+$ state, consistent with a resonant mass of 1.2–1.4 GeV and total width of 300–400 MeV. However, the overall strength of the observed coupling is lowered by a factor of 2 to 3 than expected for the A_1.

We thank A. Kotanski for initial guidance and for providing us an early version of the PWA programs, and T. Roberts and K. Sliwa for helpful discussions. This work was supported by the U. S. Department of Energy and the National Science Foundation.

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