Evidence for $I=1$ (A_1) and $I=0$ (H) Axial-Vector Resonances in Charge Exchange

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Results are presented from an isobar-model partial-wave analysis of a high-statistics sample of the neutral 3π system produced in forward charge exchange. Large forward phase motions relative to an exotic reference wave are seen for partial waves with the quantum numbers of the A_1 and of the previously unobserved isoscalar companion ("H") of the B(1235).

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We have performed an isobar-model partial-wave analysis (PWA) of the $\pi^+\pi^-\pi^0$ system produced in the reaction

$$\pi^- p \to \pi^+\pi^-\pi^0 n, \quad \pi^0 \to \gamma\gamma$$

at 8.45 GeV/c, and find resonant signals for both neutral $(I,J^{PC})=(1,1^{++})$ and $(0,1^{+-})$ mesons. This is the first observation[1] of a candidate for the isoscalar companion "H" of the B(1235), and the first detection of the A_1 in forward charge exchange.

The data were obtained at the Argonne National Laboratory zero-gradient synchrotron with the charged and neutral spectrometer which detected both γ's as well as the π^+ and π^-. Descriptions of this apparatus[2-4] and histograms[3,4] of $\pi^+\pi^-\pi^0$ and $\gamma\gamma$ effective masses and of nucleon missing mass have been published elsewhere. The event sample which passed the kinematic cuts on π^0 and neutron masses is five to ten times larger than has been previously available[5] in nondiffractive 3π production. Stringent limits[3,4,6] on $n\pi$ mass have greatly reduced the 3π background from ρN^* reflections. The events used in the PWA, shown in the histogram in Fig. 1(a), were also required to have momentum transfer $-t'$ below 0.45 (GeV/c)^2. There are typically 2000–4000 events per 40-MeV mass bin below 1.4 GeV in this final selection.

The partial-wave analysis was performed with a somewhat modified version of the University of California, Berkeley–Stanford Linear Accelerator Center amplitude-analysis program.[4,7] The isobars ρ, ϵ, S^*, and f were included, with the ρ and f parametrized as Breit-Wigner resonances with standard values[1] for the mass and width. The ϵ and S^* were described by a coupled-channels fit to $\pi\pi$ phase shifts which were constrained to pass through recent K_{e4} data[8] near threshold. Angular momenta up to $J=3$ were tried. The procedures[4] were generally similar to those used in

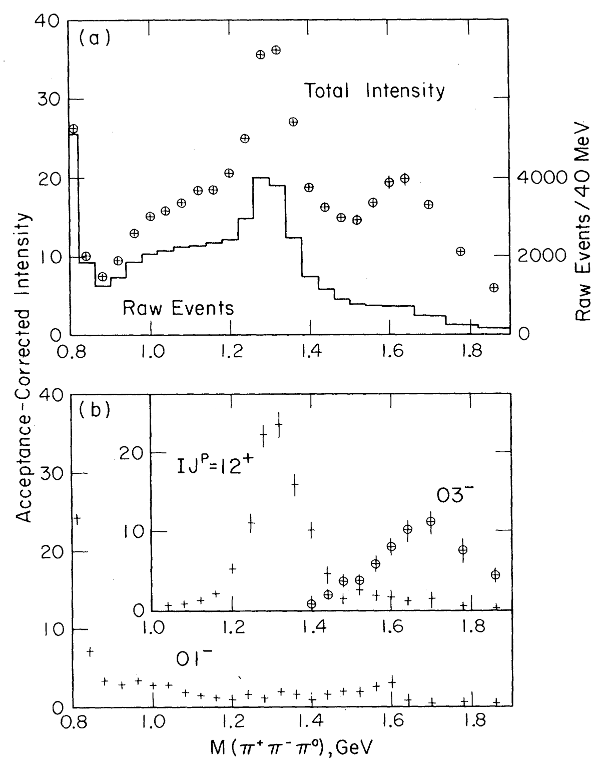

FIG. 1. (a) Uncorrected $\pi^+\pi^-\pi^0$ mass distribution for events used in the PWA (histogram), and total acceptance-corrected intensity from the PWA (circled points). (b) Acceptance-corrected total intensities for partial waves with IJP = 01−, 12+, and 03−.

previous analyses of spectrometer experiments.[9] We use the notation IJP(isobar)$LM\eta$ to describe a partial wave, where I is the isospin, J is the spin, P is the parity, L is the orbital angular momentum of the bachelor pion, M is the spin orientation (t-channel frame), and η is the reflection parity corresponding asymptotically to natural or unnatural parity exchange (NPE, UPE).

The partial waves occur in four incoherent groups having either NPE or UPE and either helicity nonflip or flip at the nucleon vertex. Although the nucleon helicities were not measured, angular momentum conservation requires characteristic t' dependence of the form $(-t')^n$ near $t'=0$ for each value of M. To help distinguish nucleon helicities, we have included factors $(-t')^n e^{bt'}$ in the parametrization of the partial waves. An iterative procedure[4] was used to determine the exponential slopes b. In addition to the four physical incoherent groups, we included a fifth group which was designed to pick up feedthrough from $\eta' \to \rho\gamma$ decays, a very small effect. A sixth group with only the bland 10-ϵS0+ wave (included to absorb any remaining incoherent background) attracted a structureless intensity distribution containing 7% of the events, consistent with our estimate[3,4] of inelastic contamination. The search for solutions[4] employed both random starts in each mass bin and sweeps in which the solution in one mass bin was used as a starting point for searches in neighboring bins. Although some discrete ambiguities were encountered, the major features of all solutions with satisfactory likelihoods were very similar.

The total acceptance-corrected intensity from the PWA is given by the circled points in Fig. 1(a). Total intensities from the partial waves with IJP = 01-, 12+, and 03- [Fig. 1(b)] have peaks at the known ω, A_2, and ω_g resonances. The observed absence of feedthrough of large peaks in one partial wave into small tails in another is good evidence that the analysis is behaving correctly and that the experimental acceptance has been properly accounted for.

Figure 2 presents PWA results from the incoherent group having NPE and nucleon helicity nonflip. The partial wave with quantum numbers of the H, 01+ρS0+, has a large intensity peak [Fig. 2(a)] which is described quite well by a Breit-Wigner form [dashed curve, Fig. 2(a)] with M = 1.13, Γ = 0.28 GeV. The 11+ wave in this group [Fig. 2(b)] is much smaller and peaks at lower mass, while the 21+ wave [Fig. 2(c)] is consistent with zero. The 12+ρD1+ intensity [Fig. 2(d)]

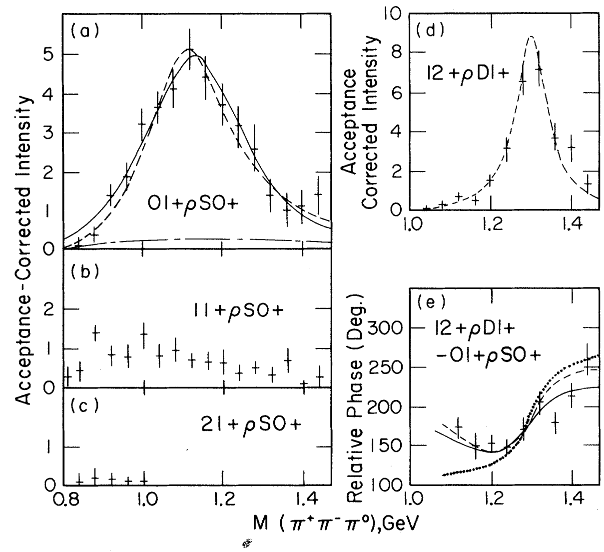

FIG. 2. PWA results from the incoherent group with nucleon helicity nonflip and NPE. Acceptance-corrected intensities for the partial waves (a) 01+ρS0+, (b) 11+ρS0+, (c) 21+ρS0+, and (d) 12+ρD1+. (e) Phase of 12+ρD1+ relative to 01+ρS0+. The curves through the PWA points represent pure Breit-Wigner forms (dashed) and results of a rescattering model with free background (solid and dot-dashed).

shows a large A_2 signal. The phase of this 12+ wave relative to 01+ρS0+ [Fig. 2(e)] does not have the full excursion expected from the A_2 resonance (dotted curve), but rather the more limited relative motion expected if the 01+ wave were also resonant (dashed curve). However, it should be noted that most of this effect occurs in the tail of the A_2, where the 12+ phase can easily be distorted by coherent background, as discussed below.

Intensities from the incoherent group with NPE and nucleon helicity flip are displayed in Fig. 3. As shown in Fig. 3(a), the wave that has $M=1$ and quantum numbers of the A_1, 11+ρS1+, is quite large in this group and has a shape approximately described (dashed curve) by the same Breit-Wigner from as the 01+ peak in Fig. 2(a). The corresponding 21+ρS1+ [Fig. 3(b)] and 11+ρS0+ and 01+ρS1+ (not shown) intensities are consistent with zero. The 01+ρS0+ intensity [Fig. 3(c)] is qualitatively similar to that in Fig. 2(a) but is smaller and peaks at lower mass. The $I=2$ wave 21+ρS0+ [Fig. 3(d)] is strong enough to serve as a phase reference. Omission of this wave caused a very significant decrease in likelihood; it was essential in the reproduction of the relative amounts of ρ^- and ρ^+ in the data.[4] The availability of a reference wave with exotic quantum numbers, and

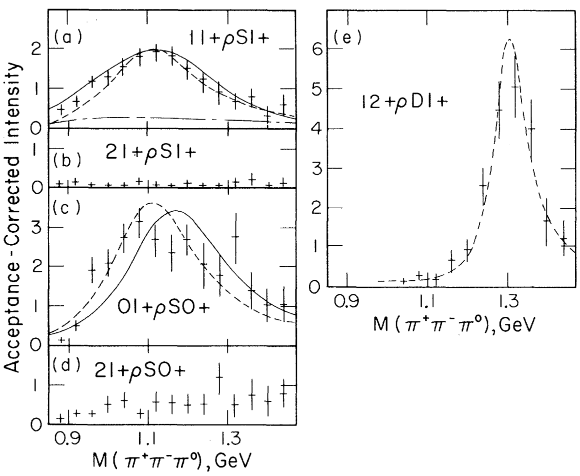

FIG. 3. PWA intensities from the incoherent group with nucleon helicity flip and NPE: (a) $11+\rho S1+$, (b) $21+\rho S1+$, (c) $01+\rho S0+$, (d) $21+\rho S0+$, and (e) $12+\rho D1+$. The curves in (a) and (c) represent Breit-Wigner forms (dashed) and results of a rescattering model (solid and dot-dashed). The curve in (e) is discussed in the text.

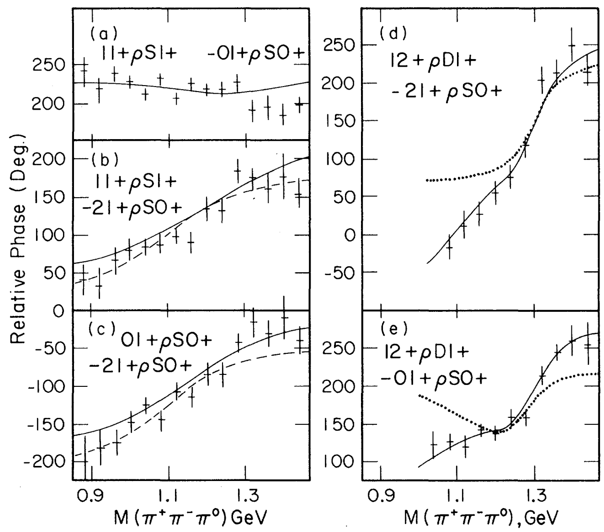

FIG. 4. Relative phases from the incoherent group in Fig. 3. (a) $11+\rho S1+$ relative to $01+\rho S0+$; (b) $11+\rho S1+$ relative to $21+\rho S0+$; (c) $01+\rho S0+$ relative to $21+\rho S0+$; (d) $12+\rho D1+$ relative to $21+\rho S0+$; (e) $12+\rho D1+$ relative to $01+\rho S0+$. The curves are discussed in the text.

hence presumably containing no resonant phase motion of its own, is a great asset in looking for resonances in other partial waves.

Relative phases from this group are shown in Fig. 4. The phase of $11+\rho S1+$ relative to $01+\rho S0+$ [Fig. 4(a)] is nearly flat, implying either that both partial waves resonate similarly, or that neither resonates. When the exotic $21+\rho S0+$ wave is used as the reference, however, both 11+ and 01+ phases [Figs. 4(b) and 4(c)] show striking forward phase motion of ~150°, establishing resonant behavior for both the A_1 and H. As seen from the dashed curves in Figs. 4(b) and 4(c), these phase motions are quite consistent with the Breit-Wigner parameters which described the intensities.

The partial wave $12+\rho D1+$ also shows very large forward phase motion relative to the 21+ reference [Fig. 4(d)], more than expected from a pure A_2 resonance (dotted curve). This phase motion can, however, be fitted very well [solid curve, Fig. 4(d)] by including a tiny coherent background[10] under the A_2, having only 3% of the maximum A_2 intensity. The 12+ intensity in this group is completely consistent with the presence of this background, as demonstrated by the dashed curve through Fig. 3(e). Finally, the phase of $12+\rho D1+$ relative to $01+\rho S0+$ [Fig. 4(e)] is fitted very well by using this prescription for the 12+ wave and a resonant H for 01+ [solid curve, Fig. 4(e)], while omitting the small 12+ background produces the much less-successful dotted curve in Fig. 4(e).

If the A_1 and H signals we see have no coherent (Deck-like) background, the neutral A_1 and H masses are both ~1.13 GeV/c^2, lower than those of the $B(1235)$ and of the charged A_1 (1.28±0.04 GeV/c^2) recently seen[11] in diffractive production. We have investigated[4] the effects of such a coherent background on the resonance parameters by fitting our PWA results to a Bowler model[12,13] similar to that used in Ref. 11 for the charged A_1. In these model-dependent fits, the H or A_1 resonance mass is varied and the level and shape parameters of the coherent background, and the resonance width, are adjusted to minimize χ^2 at each such trial mass. Generally, the larger the trial mass, the larger the required coherent background, and the best fits require nonzero background and hence masses higher than 1.13 GeV/c^2. From these Bowler-model fits we obtain the resonance parameters $M(A_1)=1.24\pm0.08$ GeV/c^2, $\Gamma(A_1)=0.38\pm0.10$ GeV/c^2; $M(H)=1.19\pm0.06$ GeV/c^2, $\Gamma(H)=0.32\pm0.05$ GeV/c^2, where the error estimates indicate the ranges that have acceptable χ^2's. The best fits to this model are shown by the solid curves in Figs. 2–4, while the corresponding background levels are shown as dot-dashed curves in Figs. 2 and 3. This background is significantly larger for the A_1 than for the H, and moves the observed peak farther from the resonance mass. We emphasize that our use of the Bowler model is illustrative, and that other treatments[14] of coherent background may give somewhat different values for the best resonance parameters.

We see no evidence for D-wave decay of the A_1; the observed suppression of $M=0$, NPE production of A_1 was predicted[15] to occur under these conditions. We also see no D-wave decay of H, nor $\epsilon\pi$ decay of A_1. The integrated cross section under the H intensity peak is comparable to that for the A_2, while that for the A_1 (including coherent background) is roughly half as large.

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[6]The $n\pi^+$ and $n\pi^0$ effective masses, whose spectra exhibited structure, were required to be above 1.75 GeV/c^2. No structure is seen or expected in $n\pi^-$ because this channel requires double charge exchange, and no cut was made.

[7]See, e.g., D. J. Herndon *et al.*, Phys. Rev. D 11, 3183 (1975).

[8]L. Rosselet *et al.*, Phys. Rev. D 15, 574 (1977).

[9]R. J. Cashmore, in *Proceedings of the Daresbury Study Weekend, 1975*, edited by J. B. Dainton and A. J. G. Hey (Science Research Council, Daresbury, United Kingdom, 1975).

[10]The coherent 12+ background used in this parametrization has a constant intensity 3% of the maximum A_2 intensity and a constant phase of 130° relative to the low-mass tail of the A_2. Very similar results have been obtained with use of the Bowler model [I. Aitchison and M. Bowler, J. Phys. G 3, 1503 (1977); M. Bowler *et al.*, Nucl. Phys. B97, 227 (1975); M. Bowler, J. Phys. G 5, 203 (1979)] to parametrize this background. There is evidence for a larger coherent background under the A_2 produced via UPE; see Ref. 4.

[11]C. Daum *et al.*, Phys. Lett. 89B, 281 (1980).

[12]Bowler and co-workers, Ref. 10.

[13]In this model, the T matrix is written $T=B[e^{i\delta}\cos\delta + (\alpha/k)e^{i\delta}\sin\delta]+(A/k)e^{i\delta}\sin\delta$, where B is the mass-dependent background amplitude, A is the amplitude for direct resonance production, δ is the mass-dependent resonant phase shift determined by the resonance mass and width, k is the $\rho\pi$ phase space factor, and α is a real constant. We have performed fits both with α free and with $\alpha=0$, and the quoted results span both cases.

[14]See, e.g., J. L. Basdevant and E. L. Berger, Phys. Rev. D 16, 657 (1977); R. Aaron *et al.*, Ann. Phys. 117, 56 (1979).

[15]H. E. Haber and G. L. Kane, Nucl. Phys. B129, 429 (1977).