

## Evidence for a Second $F_{35}$ Pion-Nucleon Resonance near 2000 MeV

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A recent isobar-model, partial-wave analysis of  $\pi N \rightarrow \pi\pi N$  finds strong indications of the  $F_{35}$  pion-nucleon resonance belonging to the  $(\underline{70}, L=2^+)$  baryon multiplet. This conclusion is drawn from recent predictions of baryon decays obtained with baryon compositions determined by the Isgur-Karl quark model. The highly inelastic  $F_{35}$  resonance is observed through its dominant  $p$ -wave decay to  $\rho N$ .

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This Letter reports strong evidence for the observation of the  $F_{35}$  pion-nucleon resonance belonging to the  $(\underline{70}, 2^+)$  supermultiplet. Existence of this resonance is inferred from results of a recent isobar-model partial-wave analysis of 241 000  $\pi N \rightarrow \pi\pi N$  bubble-chamber events in the center-of-mass energy range 1320 to 1930 MeV.<sup>1</sup>

Quark models of baryon spectroscopy predict two low-energy  $F_{35}$  resonances as members of the  $(\underline{56}, 2^+)$  and  $(\underline{70}, 2^+)$   $SU(6) \otimes O(3)$  supermultiplets. The  $F_{35}$  resonance strongly excited in  $\pi N$  reactions has long been accepted as the  $(\underline{56}, 2^+)$  state but, before now, the  $(\underline{70}, 2^+)$  state has never been identified. The first experimental suggestion

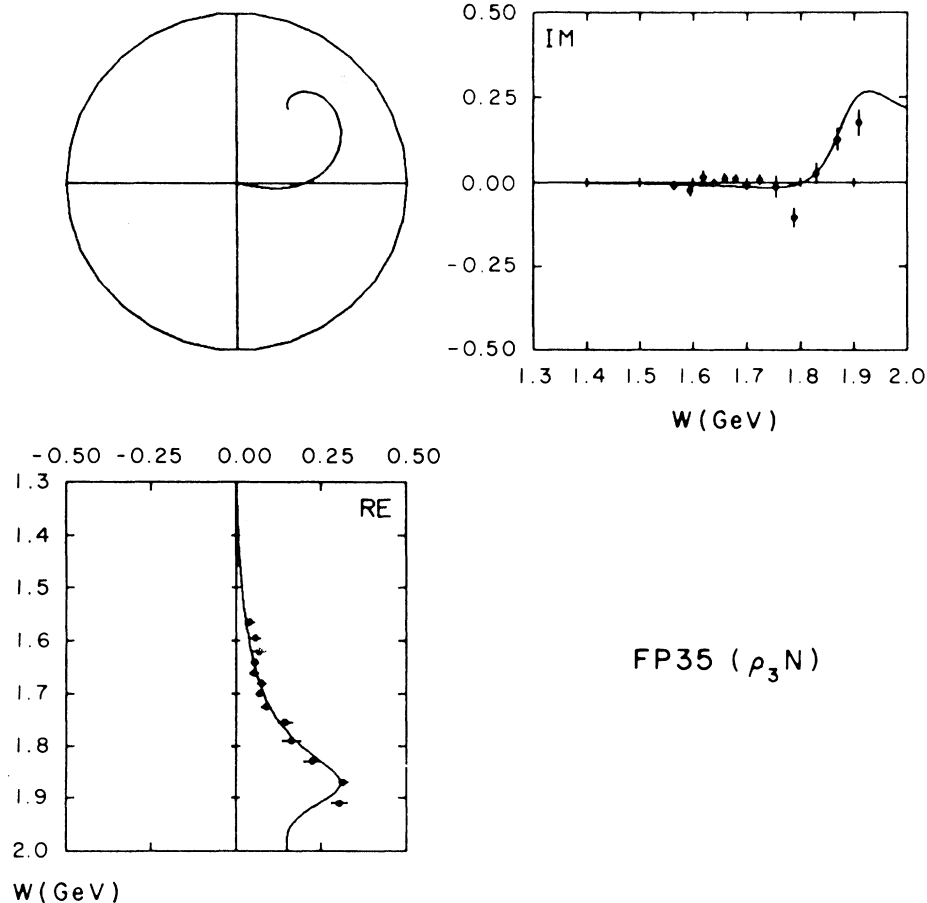


FIG. 1. Argand diagram for  $FP_{35}(\rho_3 N)$ . The real and imaginary parts were determined from the energy-independent analysis. Displayed errors have been scaled by a factor of 2. The curves were obtained from energy-dependent fits of the amplitudes.

of the  $(70, 2^+)$  state was found in a partial-wave analysis of  $\pi^+p \rightarrow \pi^0\Delta^{++}$  by Mehtani *et al.*<sup>2</sup> In that analysis, the  $\pi\Delta$  decay of the  $F_{35}(1905)$  resonance, identified with the mostly  $(56, 2^+)$  state, was discovered to proceed dominantly through an  $f$  wave rather than the  $p$  wave expected from centrifugal-barrier considerations. This  $f$ -wave dominance has been interpreted as requiring large configuration mixing between the  $(56, 2^+)$  and  $(70, 2^+)$  states.<sup>3</sup> Indeed, fairly recent calculations by Isgur and Karl<sup>4</sup> indicate that hyperfine interactions mix the two states with a mixing angle of about  $25^\circ$ . With this mixing angle, the mostly  $(70, 2^+)$  state is expected to be almost decoupled from the  $\pi N$  channel, which explains why it has not been seen in partial-wave analyses of elastic  $\pi N$  scattering.

In the most extensive previous partial-wave analysis of  $\pi N \rightarrow \pi\pi N$ , Herndon *et al.* discovered that inelasticity in the  $F_{35}$  partial wave was mainly associated with the  $\rho N$  channel.<sup>5</sup> Within their analysis, it was implicitly assumed that the large  $\rho N$

decay mode was associated with the  $F_{35}$  resonance strongly excited in  $\pi N$  reactions. This assumption, as discussed below, resulted in their inelastic  $F_{37}$  waves having an anomalously large background.

Inelastic scattering analyses such as the present one<sup>1</sup> and that of Herndon *et al.*<sup>5</sup> determine partial-wave amplitudes with an arbitrary overall phase at each energy. If background effects are small, this overall phase can be determined by requiring resonant elastic and inelastic amplitudes to share a common phase (modulo  $\pi$ ) in the vicinity of a single strong resonance. Herndon *et al.* determined the overall phase of their amplitudes between 1730 and 1810 MeV by using resonances in the  $D_{15}$ ,  $F_{15}$ ,  $F_{35}$ , and  $F_{37}$  waves.<sup>6</sup> They determined the overall phase above 1810 MeV using only the  $F_{35}$  and  $F_{37}$  waves. This group was unsuccessful in matching phases of the elastic and inelastic amplitudes for both the  $F_{35}$  and  $F_{37}$  waves. While the phase of their  $FP35(\rho_3N)$  amplitude<sup>7</sup> was adjusted to agree approximately with the phase of the elastic  $F_{35}$  wave, their large  $FF37(\pi\Delta)$  amplitude required a

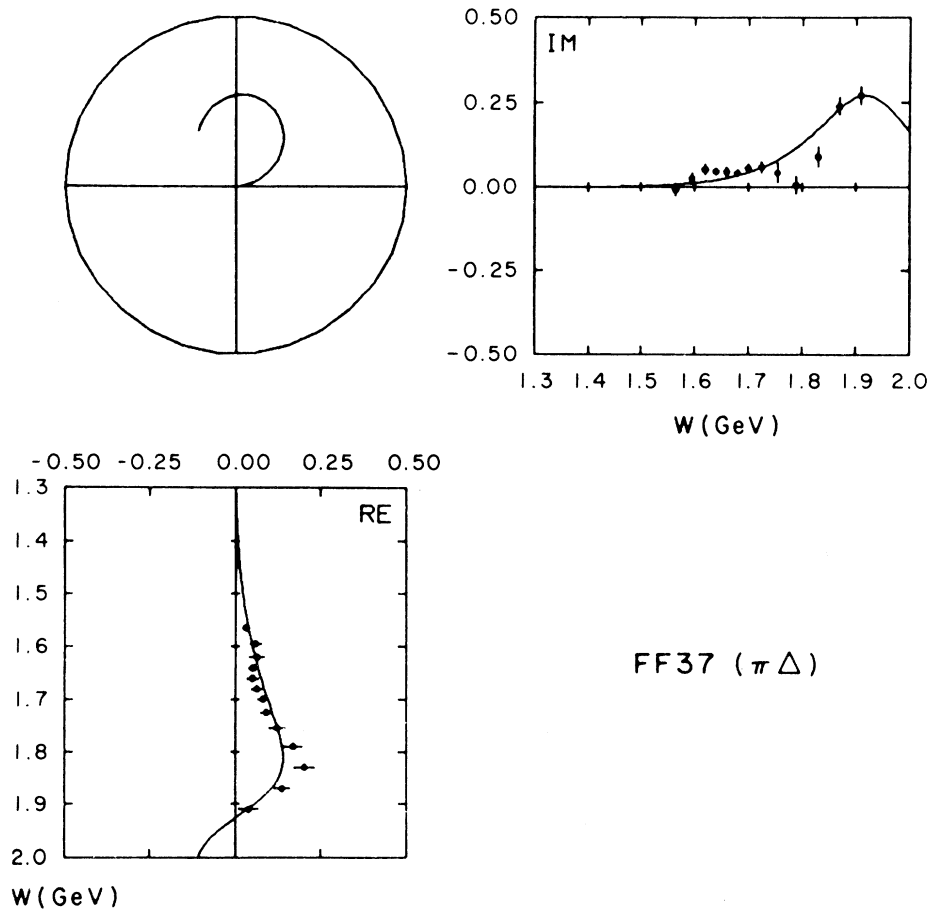


FIG. 2. Same as for Fig. 1, but for  $FF37(\pi\Delta)$ .

“background phase” of about  $70^\circ$ . Such a large background in the  $F_{37}$  wave, if real, would be difficult to understand, particularly since quark models predict only one  $F_{37}$  resonance in this energy range. Forewarned by predictions of two low-energy  $F_{35}$  resonances, the present analysis used only  $F_{37}$  waves to determine the overall phase above 1740 MeV. Above 1700 MeV, I found not only large resonant  $FP35(\rho_3N)$  and  $FF37(\pi\Delta)$  amplitudes, but also a large  $GD17(\rho_3N)$  amplitude, which presumably is associated with decay of the  $G_{17}(2190)$  resonance. If the procedure of Herndon *et al.* determining overall phase had been used, both  $FF37(\pi\Delta)$  and  $GD17(\rho_3N)$  amplitudes would have required large background phases.

Figures 1–3 present Argand diagrams for the  $FP35(\rho_3N)$ ,  $FF37(\pi\Delta)$ , and  $GD17(\rho_3N)$  amplitudes determined by the present analysis. The phases of these amplitudes have been adjusted to comply with the standard “baryon-first” phase convention. Further details and results for other amplitudes can be found in Ref. 1. It is clear from

Figs. 1–3 that the experimental signs of the resonant amplitudes are positive for  $FP35(\rho_3N)$  and  $FF37(\pi\Delta)$  and negative for  $GD17(\rho_3N)$ . An experimental sign is positive (negative) if the resonance circle in the Argand diagram tends to point up (down). The present analysis also determines positive signs for the smaller amplitudes  $FP35(\pi\Delta)$  and  $FF35(\pi\Delta)$ . Table I presents recent theoretical predictions by Koniuk and Isgur<sup>8,9</sup> for the signs of resonant  $F_{35}$  amplitudes. The theoretical signs were calculated from decay models which used baryon compositions (mixing angles) obtained from the Isgur-Karl quark model.<sup>4</sup> Unlike the mostly  $(56, 2^+)$  state, Koniuk and Isgur predict that the mostly  $(70, 2^+)$  state should be almost decoupled from the  $\pi N$  channel. They further predict that its  $p$ -wave  $\pi\Delta$  decay width should be comparable with the  $f$ -wave  $\pi\Delta$  decay width of the mostly  $(56, 2^+)$  state. Thus, only the  $(56, 2^+)$  state is expected to be easily detectable in  $\pi N \rightarrow \pi N$  and  $\pi N \rightarrow \pi\Delta$  amplitudes. From Table I, we see that the experimental signs of  $FP35(\pi\Delta)$  and  $FF35(\pi\Delta)$  are, in

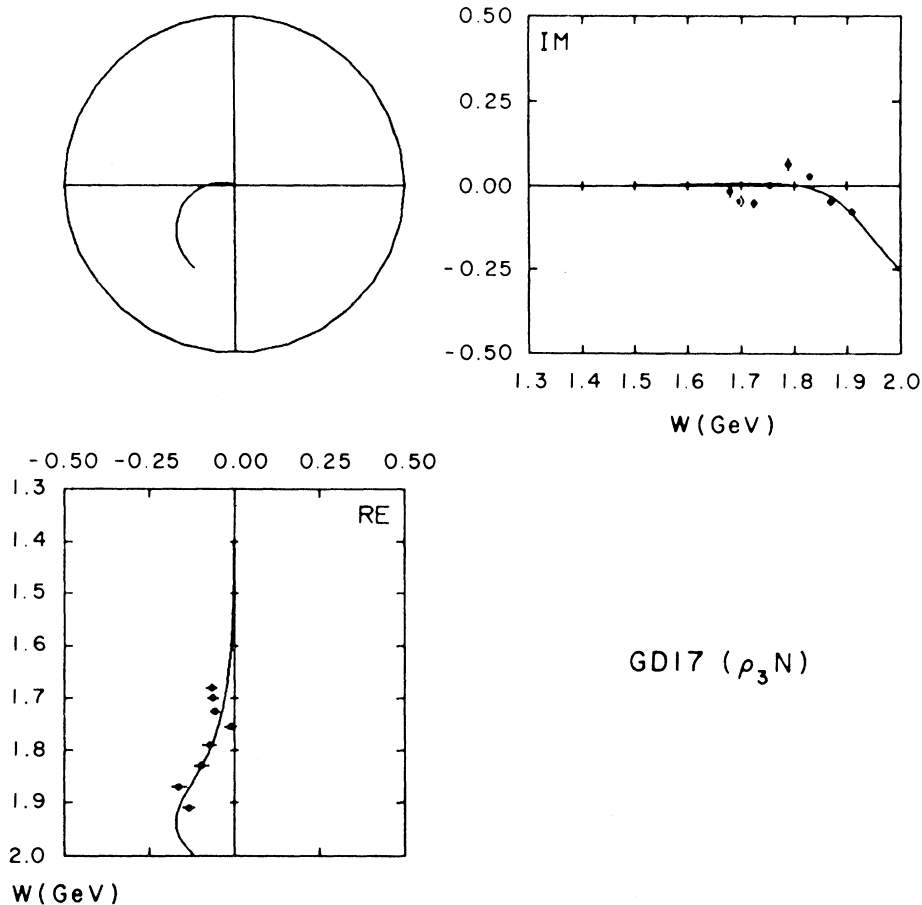


FIG. 3. Same as for Fig. 1, but for  $GD17(\rho_3N)$ .

TABLE I. Comparison of theoretical and experimental signs of resonant  $F_{35}$  amplitudes.

Amplitude	Theoretical sign <sup>a</sup>		Experimental sign <sup>b</sup>
	( $\underline{56}, 2^+$ )	( $\underline{70}, 2^+$ )	
$FP35(\pi\Delta)$	+	-	+
$FF35(\pi\Delta)$	+	+	+
$FP35(\rho_3N)$	-	+	+

<sup>a</sup>Refs. 8 and 9.

<sup>b</sup>Ref. 1.

fact, consistent with the ( $\underline{56}, 2^+$ ) assignment. Turning to the  $\rho N$  channel, we find that Koniuk predicts the ( $\underline{56}, 2^+$ ) state to have a small  $p$ -wave  $\rho N$  decay width.<sup>9</sup> Furthermore, the experimental sign of  $FP35(\rho_3N)$  is inconsistent with this assignment. The experimental sign is consistent, however, with the ( $\underline{70}, 2^+$ ) assignment. Moreover, since Koniuk predicts a very large  $p$ -wave  $\rho N$  decay for the ( $\underline{70}, 2^+$ ) state, its  $\pi N \rightarrow \rho N$  amplitude should be observable even though its coupling to  $\pi N$  is small.

The above observations strongly suggest that the elusive second  $F_{35}$  resonance has finally been detected. Further support for this conclusion comes from the masses of the two  $F_{35}$  states. By fitting the positive-parity excited baryons within a QCD-inspired quark model, Isgur and Karl found a mostly ( $\underline{56}, 2^+$ ) state at 1940 MeV and predicted a mostly ( $\underline{70}, 2^+$ ) state at 1975 MeV.<sup>4</sup> Analyses of  $\pi N$  elastic scattering determine the mass of the ( $\underline{56}, 2^+$ ) state to be between 1890 and 1920 MeV.<sup>10</sup> The Argand diagrams for  $FP35(\pi\Delta)$  and  $FF35(\pi\Delta)$  (see Ref. 1) in the present analysis are consistent with a mass near 1900 MeV. Although the present analysis does not extend sufficiently

high in energy to determine the mass of the ( $\underline{70}, 2^+$ ) state reliably, the Argand diagram of  $FP35(\rho_3N)$  in Fig. 1 suggests that its mass is probably near 2000 MeV.

In summary, results of a recent isobar-model partial-wave analysis of  $\pi N \rightarrow \pi\pi N$  are interpreted as strong evidence for an  $F_{35}$  resonance near 2000 MeV belonging to the ( $\underline{70}, 2^+$ ) supermultiplet. This interpretation is based upon recent theoretical predictions of baryon decays which used baryon compositions calculated from the Isgur-Karl quark model.

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<sup>1</sup>D. Mark Manley, Richard A. Arndt, Yogesh Goradia, and Vigdor L. Teplitz, to be published.

<sup>2</sup>U. Mehtani *et al.*, Phys. Rev. Lett. **29**, 1634 (1972).

<sup>3</sup>D. Faiman, J. L. Rosner, and J. Weyers, Nucl. Phys. **B57**, 45 (1973).

<sup>4</sup>Nathan Isgur and Gabriel Karl, Phys. Rev. D **19**, 2653 (1979).

<sup>5</sup>D. J. Herndon *et al.*, Phys. Rev. D **11**, 3183 (1975).

<sup>6</sup>R. S. Longacre *et al.*, Phys. Lett. **55B**, 415 (1975), and Phys. Rev. D **17**, 1795 (1978).

<sup>7</sup>Inelastic partial-wave amplitudes are denoted in the standard manner [ $l$ (initial),  $l$ (final), twice total  $l$ , twice total  $J$ ]. The total spin ( $\frac{1}{2}$  or  $\frac{3}{2}$ ) of the  $\rho$  and final-state nucleon is indicated by a subscript 1 or 3 on the  $\rho$ .

<sup>8</sup>Roman Koniuk and Nathan Isgur, Phys. Rev. D **21**, 1868 (1980).

<sup>9</sup>Roman Koniuk, Nucl. Phys. **B195**, 452 (1982).

<sup>10</sup>M. Roos *et al.* (Particle Data Group), Phys. Lett. **111B**, 1 (1982).