Evidence for a Neutral Boson of Mass 953 MeV and Narrow Width*

B. Maglich, J. Oostens, and M. Silverman
Rutgers, The State University, New Brunswick, New Jersey 08903

and

H. Brody, G. Featherston, E. Groves,† R. Van Berg, and W. Wales
University of Pennsylvania, Philadelphia, Pennsylvania 19104

and

G. B. Cvijanovich and D. Hartman
Upsala College, East Orange, New Jersey 07019
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A 20-standard deviation peak is observed at a mass of $953.4^{+1}_{-2.5}$ MeV and with a physical width $\Gamma < 15$ MeV, produced with $(d\sigma/d\Omega)_{\mathrm{c.m.},60°} = 2\times10^{-35}$ cm^2/sr in the reaction $p + d \to \mathrm{He}^3 +$ missing mass. The incident proton energy was 3 BeV and the proton-to-meson and proton-to-He^3 transfers $t = -1.74$ and $u = -4$ (BeV/c)^2, respectively. The $\eta_0(958)$, $\delta^0(963)$, and $\varphi^0(1019)$ are not observed and the $\rho^0(765)$ not apparent in our data.

The high-precision, high-statistics missing-mass spectrometer[1,2] search for the minor peaks in the neutral-meson spectrum produced in the reaction $p + d \to \mathrm{He}^3 + X^0$ has yielded the following results.

(1) We have observed a narrow, neutral boson, which will be referred to as ξ^0 in order to distinguish it from $X^0(958) = \eta'$, with the following mass, physical width, and isospin values:

$$M_\xi = 953.4^{+1}_{-2.5}\ \mathrm{MeV}, \tag{1}$$

$$\Gamma_\xi \leq 15\ \mathrm{MeV}\ \text{(compatible with zero width)}, \tag{2}$$

$$I_\xi = 0 \text{ or } 1. \tag{3}$$

The data are shown in Figs. 1 and 2. In the region of the ξ peak, the statistics are ~20 000 events per a mass bin about 4 MeV wide and the mass-squared resolution is $\Delta M^2 = 0.018$ GeV^2.

The unusually small absolute mass errors are the result of the simultaneous observation of the π, η, and ω peaks whose known masses are used for calibration of the variable incident proton momentum. The only other quantity used in determination of the missing mass is the angle of He^3 in our method.[1,3] The uncertainties in the shape and slope of the mass distribution are unlikely to produce a significant mass shift. The ω and ξ peaks are observed within the acceptance band of one spectrometer setting.

The ξ bump cannot be $\delta(966)$ since the mass is significantly different. If the mass value of η', which is 957.7 ± 0.8, is fixed in the program, it is rejected by the data with a confidence level $P(\chi^2) < 10^{-4}$. The inability of our instrument to exclude a contribution from the η' to the ξ peak gives rise to the asymmetric error in Eq. (1).

However, ξ could be the recently reported resonance[4] of mass 953 ± 2 MeV, $\Gamma < 10$ MeV, called M, observed by the Brookhaven Bubble Chamber Group, which decays into $\pi^+\pi^-\gamma$. A meson at this mass decaying into $\pi^+\pi^-\gamma$, called D', was recently predicted[5] to be the ninth meson with $J^{PC} = 1^{++}$. The invariance of the peak is demonstrated in Fig. 2; it is observed at all three subsamples, each at a slightly different average incident momentum: A, 3.74, B, 3.79, and C,

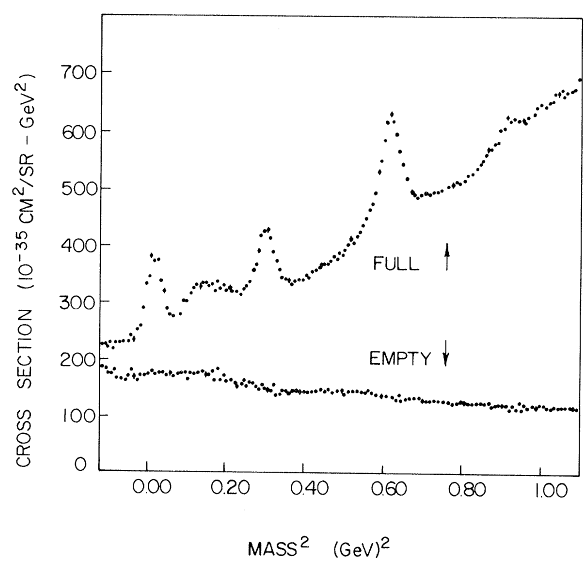

FIG. 1. All 3-GeV full-target and empty-target data. Mass bins are 0.0075 GeV^2 wide. Error bars (not shown) are about equal to ±1.5 times diam of each dot.

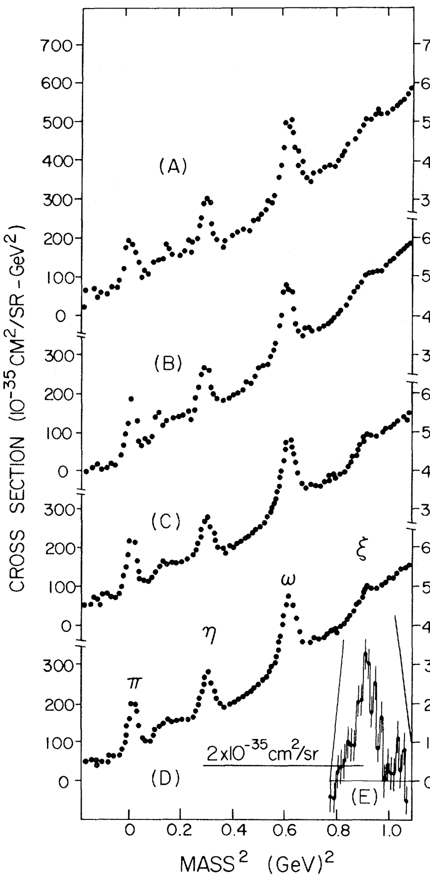

FIG. 2. Data at 3 GeV for full target minus empty target. Mass bins are 0.015 GeV^2 wide. Error bars (not shown) are $\pm$ diameter of each dot. The fit shown includes resonance terms plus phase-space background. A, band of the incident proton momenta is 3.71—3.77 GeV/c; B, 3.77—3.81 GeV/c; C, 3.81—3.85 GeV/c. D, all 3-GeV data, $A+B+C$. E, excess above the background line in the ξ region of diagram D; both the horizontal and vertical scales have been blown up, by factors of 1.7 and 8.5, respectively. The area under the histogram corresponds to $(2\pm0.1)\times10^{-35}$ cm^2/sr in the center of mass.

3.83 GeV/c.

The ξ excess above the phase space contains about 4000 events. The differential cross section for ξ production at a c.m. angle of 60° is

$$(d\sigma/d\Omega)_{\text{c.m.}} = (2.0\pm0.1)\times10^{-35}\ \text{cm}^2/\text{sr}. \tag{4}$$

The t and u values at which ξ is observed are

$$t(p\text{-to-}\xi) = -1.74;$$
$$u(d\text{-to-}\xi) = -4.11\ (\text{GeV}/c)^2 \tag{5}$$

at $T_p = 3$ GeV ($s = 18.5$ GeV^2).

(2) The $\eta'(958)$, $\delta(963)$, and $\varphi(1019)$ are not evident in our data.[6] The ρ meson, while not ap-

TABLE I. Cross sections and widths of resonances observed.

Meson observed	Mass (MeV)	Physical width (MeV)	$(d\sigma/d\Omega)_{\text{c.m.}}$ (10^{-36} cm^2/sr)
Incident proton momentum 3.71—3.85 GeV/c; $T_p = 3$ GeV			
π^0	135 ± 2 [a]	0.0 [b]	77 ± 2
η	549 ± 1 [a]	0.0 [b]	52 ± 2
ω	783 ± 0.3 [a]	11.5 ± 2.5	121 ± 4
ρ	768 [b]	160 [c]	271 ± 130
ξ(953)	$953.4^{+1}_{-2.5}$	$0\leq\Gamma\leq15$	20 ± 1
Incident proton momentum 2.8 GeV/c; $T_p = 2$ GeV			
π	135 ± 2 [a]	0.0 [b]	542 ± 26
η	549 ± 1 [a]	0.0 [b]	395 ± 14

[a] The masses of the π, η, and ω were fitted by a two-parameter fit for beam energy and angle calibration.

[b] Assumed by fitting program. The errors shown in the table above are statistical. The values of the cross sections for narrow resonances have an error of about 15% due to the uncertainty in the absolute proton intensity and the exact magnitude of the background. The uncertainty in the background shape can increase the errors in the mass and width by 50%.

[c] The widths of broad peaks cannot be measured with any degree of confidence by our spectrometer because of its relatively narrow mass bite per setting (~150 MeV).

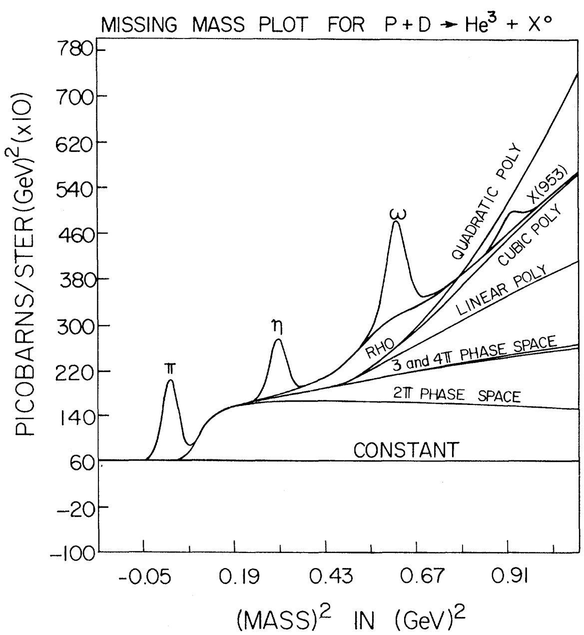

FIG. 3. Summed terms in fit to 3-GeV mass distribution of Fig. 2, D. Note that the cubic term in the polynomial is negative.

parent, is compatible with our data on account of its width (see Table I). This is demonstrated in Fig. 3 which shows the contributions of each term to the best fit to our data. The higher-mass region is fitted with a general polynomial in mass squared; only the linear and cubic terms were needed.

(3) The combination of the good resolution of the apparatus and the high statistics of the data makes it possible to place limits on the cross sections of bumps which were not seen. From an examination of the mass plot of our data, it is clear that we have no evidence for any narrow resonances (except those listed in Table I) produced with cross sections comparable to 25% that of the $\xi(953)$ [i.e., with $(d\sigma/d\Omega)_{\mathrm{c.m.}}$ greater than 5×10^{-36} cm^2/sr] in the mass region to 1.1 GeV^2.

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†Now at Rutherford High Energy Laboratory, Chilton, Didcot, Berkshire, England.

[1]H. Brody *et al.*, Phys. Rev. Lett. 24, 984 (1970). The ordinate of Fig. 1 was mislabeled; it should read 1 through 5 (rather than 0.1 through 0.5). The $d\sigma$ values in Table I are correct.

[2]E. Groves, Ph.D. thesis, University of Pennsylvania, 1970 (unpublished).

[3]See Eq. (4) in B. Maglić and G. Costa, Phys. Lett. 18, 185 (1965).

[4]M. Aguilar-Benitez *et al.*, Phys. Rev. Lett. 25, 1635 (1970).

[5]J. Rosner and E. Colglazier, Phys. Rev. Lett. 26, 933 (1971).

[6]S. Barshay, Princeton-Pennsylvania Accelerator Report No. 23, 1969 (unpublished) (also reproduced in Ref. 2, above), predicts on the basis of our observed π^0-to-η^0 production ratio and the η-η' mixing angle 4 times more η' production than π production in our experiment. Our data give a maximum η' production only one quarter as large as π production.

Prism Plot: A New Analysis of Multibody Final States*

J. E. Brau,† F. T. Dao, M. F. Hodous, I. A. Pless, and R. A. Singer
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 9 July 1971)

We present a new technique for analyzing multibody states. This analysis makes possible the selection of samples of events that contain only resonances, particle correlations, or phase space. A unique feature of this analysis is that every event in the data is assigned to a particular sample. The three-body final state $\pi^+ + p \to p + \pi^+ + \pi^0$ is analyzed as an example.

In this Letter we present a technique for analyzing multibody final states. The bases of this analsis are the Van Hove[1] angular variables and an N-dimensional energy simplex. The underlying concept is an attempt to utilize a complete set of parameters to analyze the final states. Given an unpolarized beam and target and an N-body final state, there are $3N-5$ free parameters required to specify that final state completely. We define $2N-2$ parameters that form a generalized equilateral rectangular prism. In addition, we define the remaining $N-3$ required parameters in a manner useful for specific problems.

We will use the previously published $\pi^+ + p$ data[2] at 3.9 GeV/c as an example. For $N=3$ we need four parameters. The first parameter which we choose is the well-known Van Hove angle.[1] Figure 1(a) gives our representation of this angle in a manner useful for generalizing to higher dimensions; namely, the N unit longitudinal momentum vectors lie in $(N-1)$-dimensional space in such a way that any two of them form an angle with each other such that the cosine of this angle is equal to $-1/(N-1)$. Therefore, we have defined the Van Hove angle (θ) so that baryons produced with positive center-of-mass longitudinal momenta are in the angular region $0° \leq \theta \leq 180°$.

Our second parameter is $R/R_{\max}$, which is the ratio of the length of the radius vector in the Van Hove plot to the maximum length that vector could have at the given Van Hove angle [Fig. 1(b)]. If $R/R_{\max}=0$, the event lies in a plane perpendicular to the incident direction, and if $R/R_{\max}=1$, the event is collinear with the incident direction.