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February 12, 1962

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Since the discovery of the two-pion and the three-pion resonances,[1-3] the search for a four-pion resonance has acquired much interest. The interest is threefold:

1. Chew and Frautschi,[4] using the "Regge poles" theory, predict a possible resonance (or unstable particle) with spin 2 and with the same other quantum numbers as the vacuum (T=0, parity even) at the region of 1 Bev. This particle could decay into two, four, or six pions. But the four-pion decay could be favored because a two-pion decay would require a d wave, whereas a four-pion decay would need only two pion sets in p wave.

The four-pion resonance could also come from a decay of χ^0, the pseudoscalar meson with T=0 formulated by many theoreticians.[5]

2. The ω meson has been attributed a spin and parity 1^{--} (the first superscript refers to the parity and the second to G parity) if the decay is through strong interactions. But because of the small width of this meson ($\Gamma/2 \leq 12$ Mev, and could be zero[2]), Duerr and Heisenberg suggest the possibility of electromagnetic decay with nonconservation of G parity.[7] Four more states must then be considered: 0^{++}, 1^{-+}, 1^{++}, and 0^{-+} (we consider only states with spin ≤ 1). Duerr and Heisenberg eliminate the states 0^{++} and 1^{-+} because their three-pion decay would either not occur or be extremely weak.[7] The assignments 1^{++} and 0^{-+} would lead to Dalitz plots with uniform density and cannot be eliminated by the present data. Therefore, the ω meson can still have one of three assignments

1^{--}, 0^{-+}, or 1^{++}. But Duerr and Heisenberg point out that these three states behave differently with respect to the four-pion decay.[7] For 1^{--} the four-pion decay is strongly forbidden and therefore is completely negligible compared with the three-pion decay. For the 0^{-+} the four-pion decay is an allowed transition, but reduced to small value by the fact that two d states and one p state are required for the outgoing waves. For 1^{++} the four-pion decay is allowed, and can be large. Therefore, the very existence of a neutral four-prong resonance at 780 Mev would rule out the 1^{--} spin-parity; its nonexistence would be an argument against the 1^{++} assignment, but not against the 0^{-+} assignment.

It would also be interesting to see the decay of a ρ meson into four pions. This decay is allowed by strong interactions, but is not as favorable as the two-pion decay. Of special interest is the decay mode $\rho \rightarrow \pi + \eta$,[8] with $\eta \rightarrow \pi^+ + \pi^- + \pi^0$ (η being the T=0 550-Mev three-pion resonance discovered by Pevsner et al.[3]). Because the G parity of ρ is +1 and that of π is -1, this decay is allowed if the G parity of η is -1 and forbidden if it is +1.

We have analyzed 595 six-prong events produced by antiprotons of 1.61 Bev/c in the 72-inch hydrogen bubble chamber.[9] As we have stated before, these events are a very pure sample involving annihilation of six charged pions,[2]

$$\bar{p} + p \rightarrow 3\pi^+ + 3\pi^- + n\pi^0.$$

After fitting these six-prong events by using the kinematic program KICK, we found

153 that fit the hypothesis $\bar{p} + p \rightarrow 3\pi^+ + 3\pi^-$;

let us call them "6π" events;

239 that fit the hypothesis $\bar{p} + p \rightarrow 3\pi^+ + 3\pi^- + \pi^0$;

let us call them "7π" events;

139 that do not fit the two preceding hypotheses and have a missing mass $\geq$ 280 Mev (within 1 standard deviation), and could have two or

more π^0 missing;

let us call them "8π" events.

Most of the remaining 64 have a negative missing energy or imaginary missing mass, and can be attributed to Dalitz pairs associated with four-prong events.

An event is considered fitted to the hypothesis $\bar{p} + p \rightarrow 3\pi^+ + 3\pi^-$ when it has $\chi^2 \leq 30.0$ for this hypothesis. It is considered fitted to the reaction $\bar{p} + p \rightarrow 3\pi^+ + 3\pi^- + \pi^0$ when it has $\chi^2 \geq 30.0$ for the first hypothesis and $\chi^2 \leq 5.1$ for the latter.

We believe that about 85% of the 139 8π events actually do have two missing pions, because the missing-mass distribution of these events follows, within statistics, the effective-mass distribution of two charged pions coming from the same events.

For all categories of events we have evaluated the four-body effective mass,

$$M_4 = \left((E_1 + E_2 + E_3 + E_4)^2 - (\vec{p}_1 + \vec{p}_2 + \vec{p}_3 + \vec{p}_4)^2\right)^{1/2}.$$

for each pion quadruplet.

For the 6π and 8π events we can get only the combinations $Q = 0$ and $|Q| = 2$. For the 7π events we can also get the $|Q| = 1$ combination.

For the 8π events we can also calculate the effective mass of two charged pions and two neutral pions by calculating the missing mass of the system consisting of the incoming antiproton, the proton target, and the four remaining visible charged pions:

$$M'_4 = \left((E_{\bar{p}} + M_p - E_1 - E_2 - E_3 - E_4)^2 - (\vec{p}_{\bar{p}} - \vec{p}_1 - \vec{p}_2 - \vec{p}_3 - \vec{p}_4)^2\right)^{1/2}.$$

For M'_4, we can form only the $Q = 0$ and $|Q| = 2$ combinations. We calculated for each value of M_4 or M'_4 an uncertainty δM_4 or $\delta M'_4$ by using the error matrix propagated by KICK. For the 8π events the half-width $\Gamma/2$ of the resolution function of M_4 is 14.5 Mev, and that of M'_4 is 15 Mev (in the region of 1000 Mev). However, because of systematic errors known to exist in our track reconstruction, our estimate of $\Gamma/2$ probably should be multiplied by $\sqrt{2}$ to give $\Gamma/2 = 20.5$ Mev for M_4 and $\Gamma/2 = 21$ Mev for M'_4. For the 6π and the 7π events $\Gamma/2$ is a little smaller.

Figure 1a is a histogram of the M_4 distribution of the $Q = 0$ combination of 6π events. The solid curve represents the background distribution estimated from the $|Q| = 2$ distribution of the same events. (Smooth curve drawn through $|Q| = 2$ distribution.)

Figures 1b and 1c are the histograms of the M_4 distribution of the 7π events, respectively, with $Q = 0$ and $|Q| = 1$. We use the $|Q| = 1$ and $|Q| = 2$ distributions to estimate the phase-space distribution (solid curves). In Figure 1d we renormalize the $|Q| = 1$ distribution of the 7π events and plot it against the neutral distribution of the same events.

None of these histograms shows any strong disaccord with the background distribution.

In Fig. 2 we plot separately the histogram of the neutral distribution of $M_4(\pi^+\pi^-\pi^+\pi^-)$ (Fig. 2a) and the histogram of the neutral distribution of $M'_4(\pi^+\pi^-\pi^0\pi^0)$ (Fig. 2b). The solid curves represent the background distribution estimated from a smooth curve drawn through the sum of the distributions of $M_4(\pi^\pm\pi^\pm\pi^\pm\pi^\mp)$ and of $M'_4(\pi^\pm\pi^\pm\pi^0\pi^0)$ with $|Q| = 2$ of the same events (Fig. 3a). Figure 3b is the histogram of the sum of the neutral distributions of M_4 and M'_4.

The neutral distribution shows a suggestive but inconclusive peak in the region of 1040 Mev. If this peak really exists, it may be a resonance with T=0 or T=1. It could come from a possible decay of the χ^0 meson (spin = 0, T=0, parity odd) or the particle predicted by Chew and Frautschi (spin = 2, T=0, parity even). In the latter case, it could also decay into two pions or two kaons.

2. To estimate the ratio $R(\omega \to 4\pi/\omega \to \pi^+\pi^-\pi^0)$ we note that we have seen in the sample of $\bar{p}$-p interactions 79±18 interactions of the form

$$\bar{p} + p \to 2\pi^+ + 2\pi^- + \omega \text{ with } \omega \to \pi^+ + \pi^- + \pi^0.$$ [2]

If the ω produced by the preceding reaction were to decay by $\omega \to \pi^+ + \pi^- + \pi^0 + \pi^0$ we would see the results in our 8π events. But the distribution of $M'_4(\pi^+\pi^-\pi^0\pi^0)$ (Fig. 2b) does not show anything greater than the phase-space calculation in the region 780±20 Mev. At this energy the background is about 26 pion quadruplets; therefore we can estimate a maximum of 10 pion quadruplets that could come from the decay of the ω, and the upper limit of the ratio of $R(\omega \to \pi^+\pi^-\pi^0\pi^0/\omega \to \pi^+\pi^-\pi^0)$ is about 12%.

If the ω mesons produced by the reaction $\bar{p} + p \to 2\pi^+ + 2\pi^- + \omega$ were to decay into $2\pi^+ + 2\pi^-$, we would see them in the reaction $\bar{p} + p \to 4\pi^+ + 4\pi^-$. We have only 4±2 of the latter reactions.[10] This gives a maximum of 5% for $R(\omega \to \pi^+\pi^-\pi^+\pi^-/\omega \to \pi^+\pi^-\pi^0)$. We can then conclude that the ratio $R(\omega \to 4\pi/\omega \to \pi^+\pi^-\pi^0)$ is less than 17%, and can very possibly be zero.

If the ω produced by $\bar{p} + p \to 2\pi^+ + 2\pi^- + \omega$ were to decay in the neutral mode, it would show in the distribution of the missing mass of the reaction $\bar{p} + p \to 2\pi^+ + 2\pi^- + n\pi^0$. By ω → neutral, we mean the decays $\omega \to 3\pi^0$, $\omega \to 2\gamma$; and $\omega \to \pi^0 + \gamma$. Looking at the latter distribution, J. Button et al.[1] reported seeing no "peak" at the region of 780 Mev, and, using our value of 0.6±.15 mb for the cross section of the reaction $\bar{p} + p \to 2\pi^+ + 2\pi^- + \omega$ with $\omega \to \pi^+ + \pi^- + \pi^0$,[2] they estimate $R(\omega \to \text{neutral}/\omega \to \pi^+\pi^-\pi^0) \leq 0.5$.[1]

The small value of $R(\omega \to 4\pi/\omega \to \pi^+\pi^-\pi^0)$ agrees with a spin and parity assignment of 1^{--} and could rule out the 1^{++} assignment, but does not rule out the possiblity of 0^{-+} for the spin and parity of the ω meson.[7]

The ratio of $R(\omega \to \text{neutral}/\omega \to \pi^+\pi^-\pi^0)$ is estimated by Duerr and Heisenberg to be larger than 3/2 for the 0^{-+} assignment and very small (10^{-4}) for the 1^{--}

assignment.[7] Our values of the two ratios $R(\omega \to 4\pi/\omega \to \pi^+\pi^-\pi^0)$ and $R(\omega \to \text{neutral}/\omega \to \pi^+\pi^-\pi^0)$, which can be very small, agree with the 1^{--} assignment and disagree with the 0^{-+} assignment for the spin and parity of the ω meson. Since all other interpretations of spin and parity (with spin ≤ 1) can be ruled out by the present data,[6] we conclude that the spin and parity of the ω meson is most probably 1^{--}. This agrees with the conclusion reached by Stevenson et al.[6] Table I gives a summary of the experimental determination of spin, parity, and G parity for the ω meson.

To estimate the ratio of $R(\rho \to 4\pi/\rho \to 2\pi)$ we use some results from J. Button et al.[1] They find about 386 ρ^0 with $\rho^0 \to \pi^+\pi^-$, and about 274 $\rho^\pm$ with $\rho^\pm \to \pi^\pm\pi^0$, by analyzing the reaction $\bar{p} + p \to 2\pi^+ + 2\pi^- + \pi^0$ from a smaller sample of the same $\bar{p}$ picture of our experiment. In our larger sample this would correspond to 482 $\rho^0 \to \pi^+\pi^-$ and 323 $\rho^\pm \to \pi^\pm\pi^0$. If the ρ mesons produced by the same mechanism decayed into $\rho^0 \to 2\pi^+ + 2\pi^-$ and $\rho^\pm \to \pi^+\pi^-\pi^\pm\pi^0$ we would see them in the M_4 distributions of the 7π events (Fig. 1b and 1c). In the region around 750 Mev in these distributions we see nothing exceeding phase-space calculation, and we estimate a maximum of 2% for $R(\rho^0 \to \pi^+\pi^-\pi^+\pi^-/\rho^0 \to \pi^+\pi^-)$ and a maximum of 5% for $R(\rho^\pm \to \pi^\pm\pi^0\pi^+\pi^-/\rho^\pm \to \pi^\pm\pi^0)$. To estimate the ratio $R(\rho^\pm \to \pi^\pm + \eta,\ \eta \to \pi^+\pi^-\pi^0/\rho^\pm \to \pi^\pm\pi^0)$ we analyze carefully all the $|Q| = 1$ quadruplets with effective mass M_4 in the region 750±50 Mev (41 quadruplets). In particular we compare the distribution of the effective mass of three pions coming from these quadruplets with $Q = 0$ $(\pi^+\pi^-\pi^0)$ with that for $|Q| \geq 1$ $(\pi^\pm\pi^\pm\pi^\mp$ and $\pi^\pm\pi^\pm\pi^0)$(the latter is used here as an estimated background). In the region of 548±10 Mev we have 19 neutral triplets and 15 charged triplets. This enables us to estimate the number of $\rho^\pm \to \pi^\pm + \eta$ with $\eta \to \pi^+\pi^-\pi^0$ to be 4±6, and the ratio $R(\rho^\pm \to \pi^\pm + \eta,\ \eta \to \pi^+\pi^-\pi^0/\rho^\pm \to \pi^\pm\pi^0)$ to be 1.2 ± 2.0%. This result agrees very well with the estimate by Rosenfeld et al., who find

Table I. Summary of experimental determination of spin parity and G parity of ω meson ($I = 0$, $M_{\pi^+\pi^-\pi^0} = 780$ Mev)

Possible assignment (Spin $\leqslant 1$, parity, G parity)	Eliminated by
0^{--}	Dalitz plot
0^{+-}	Parity conservation
$\boxed{1^{--}}$	
1^{+-}	Dalitz plot
0^{-+}	Dalitz plot and small ratio $R(\omega \to \text{neutral}/\omega \to \pi^+\pi^-\pi^0)$
0^{++}	Parity conservation
1^{-+}	Small ratio $R(\omega \to 4\pi/\omega \to \pi^+\pi^-\pi^0)$
1^{++}	Dalitz plot; small ratio $R(\omega \to 4\pi/\omega \to \pi^+\pi^-\pi^0)$ and small ratio $R(\omega \to \text{neutral}/\omega \to \pi^+\pi^-\pi^0)$

$R(\rho^+ \to \pi^+ + \eta,\ \eta \to \text{neutral}/\rho \to \pi^+ + \pi^0) \leq 0.6\%$.[11] The actual data on the η meson seem to rule out all spin parity assignments except 1^{--} and 0^{-+}.[3] The theoretical ratio $R(\rho \to \pi + \eta/\rho \to \pi\pi)$ is very small for 0^{-+}. In the case of 1^{--}, this ratio is not yet well determined (25% for a simple phase-space calculation,[11] 1% after Glashow and Sakurai.[11]). We conclude that the small value of the ratio $R(\rho \to \pi + \eta/\rho \to \pi + \pi)$ favors the 0^{-+} assignment for the spin, parity, and G parity of the η meson; whether this can rule out the 1^{--} assignment depends on a more precise calculation.

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FIGURE LEGENDS

Fig. 1. Histograms of the distribution of the effective masses (M_4) of pion quadruplets; (a) quadruplets of ($\overline{p} + p \rightarrow 3\pi^+ + 3\pi^-$) events with $Q = 0$; (b) and (c) quadruplets of ($\overline{p} + p \rightarrow 3\pi^+ + 3\pi^- + \pi^0$) events with $Q = 0$ and $|Q| = 1$, respectively. In (d) and (c) distribution (shaded area) is compared with the (b) distribution.

Fig. 2. Histograms of the distribution of effective masses of neutral pion quadruplets of $\overline{p} + p \rightarrow 3\pi^+ + 3\pi^- + 2\pi^0$ events; (a) distribution of M_4 ($\pi^+\pi^-\pi^+\pi^-$), (b) distribution of M'_4 ($\pi^+\pi^-\pi^0\pi^0$). The same smooth curve has been drawn on (a) and (b).

Fig. 3. Histograms of the distribution of effective masses of pion quadruplets of $\overline{p} + p \rightarrow 3\pi^+ + 3\pi^- + 2\pi^0$ events; (a) quadruplets with $|Q| = 2$, (b) quadruplets with $Q = 0$. The same smooth curve has been drawn on (a) and (b).

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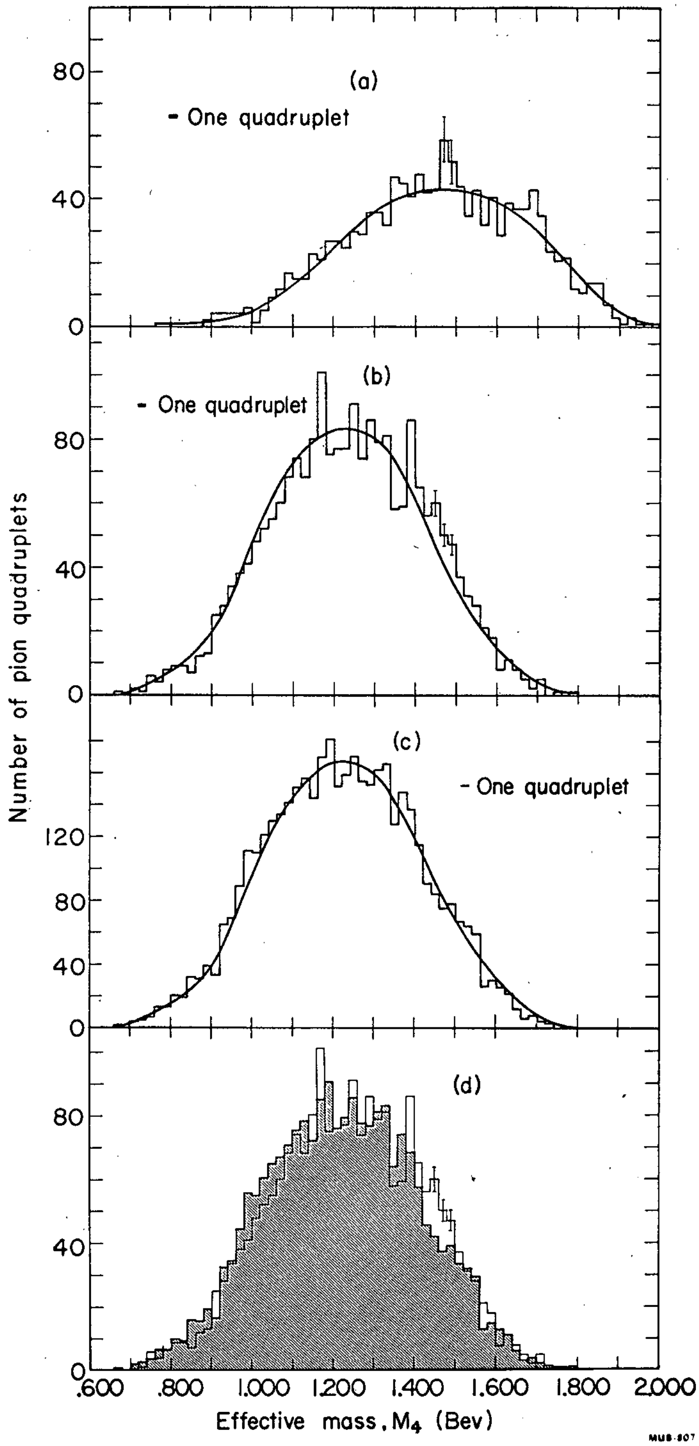
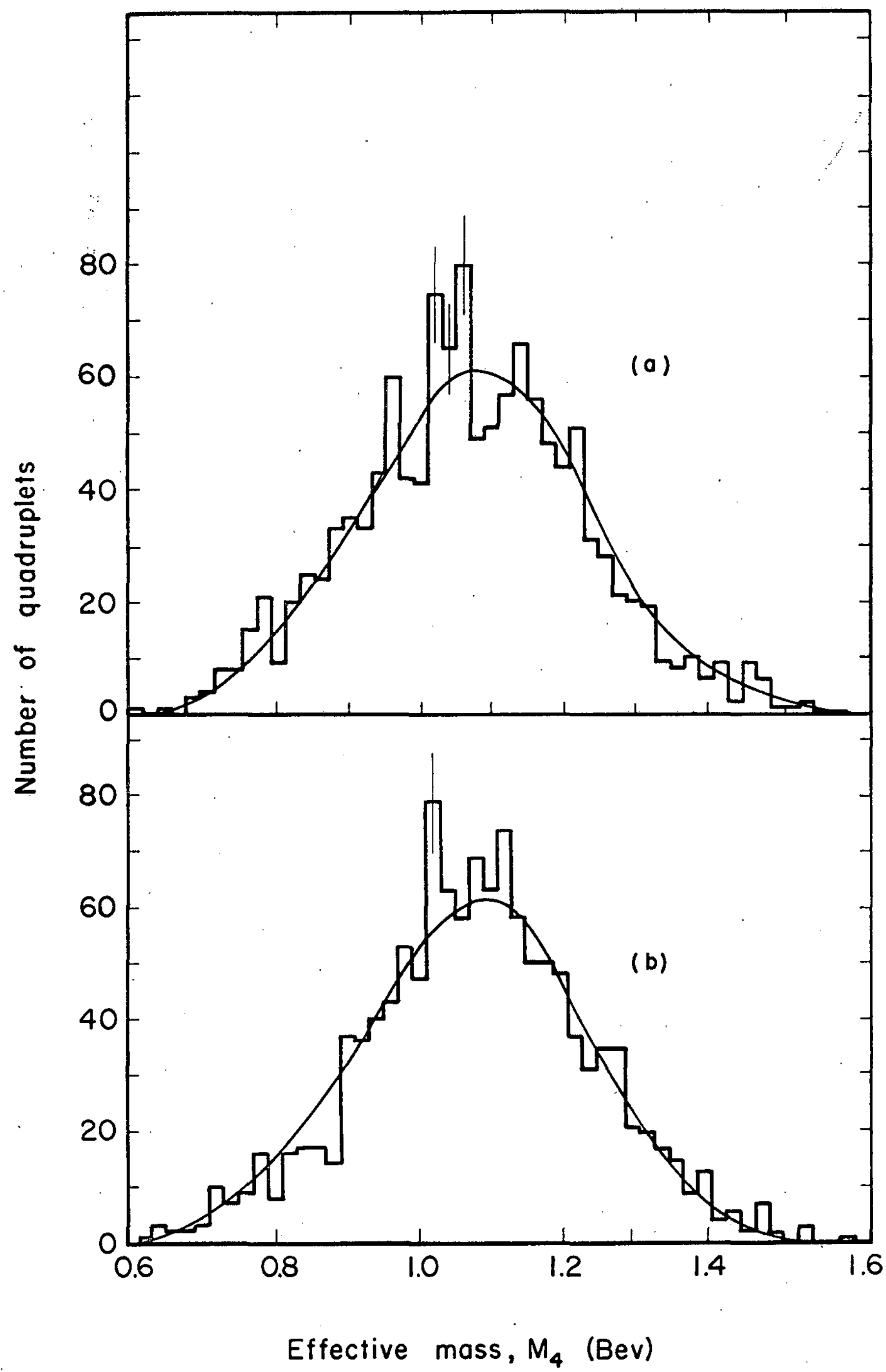


(a)
- One quadruplet
(b)
- One quadruplet
(c)
- One quadruplet
(d)
Number of pion quadruplets
80
40
0
80
40
0
120
80
40
0
80
40
0
.600
.800
1.000
1.200
1.400
1.600
1.800
2.000
Effective mass, M_4 (Bev)
MUB-807

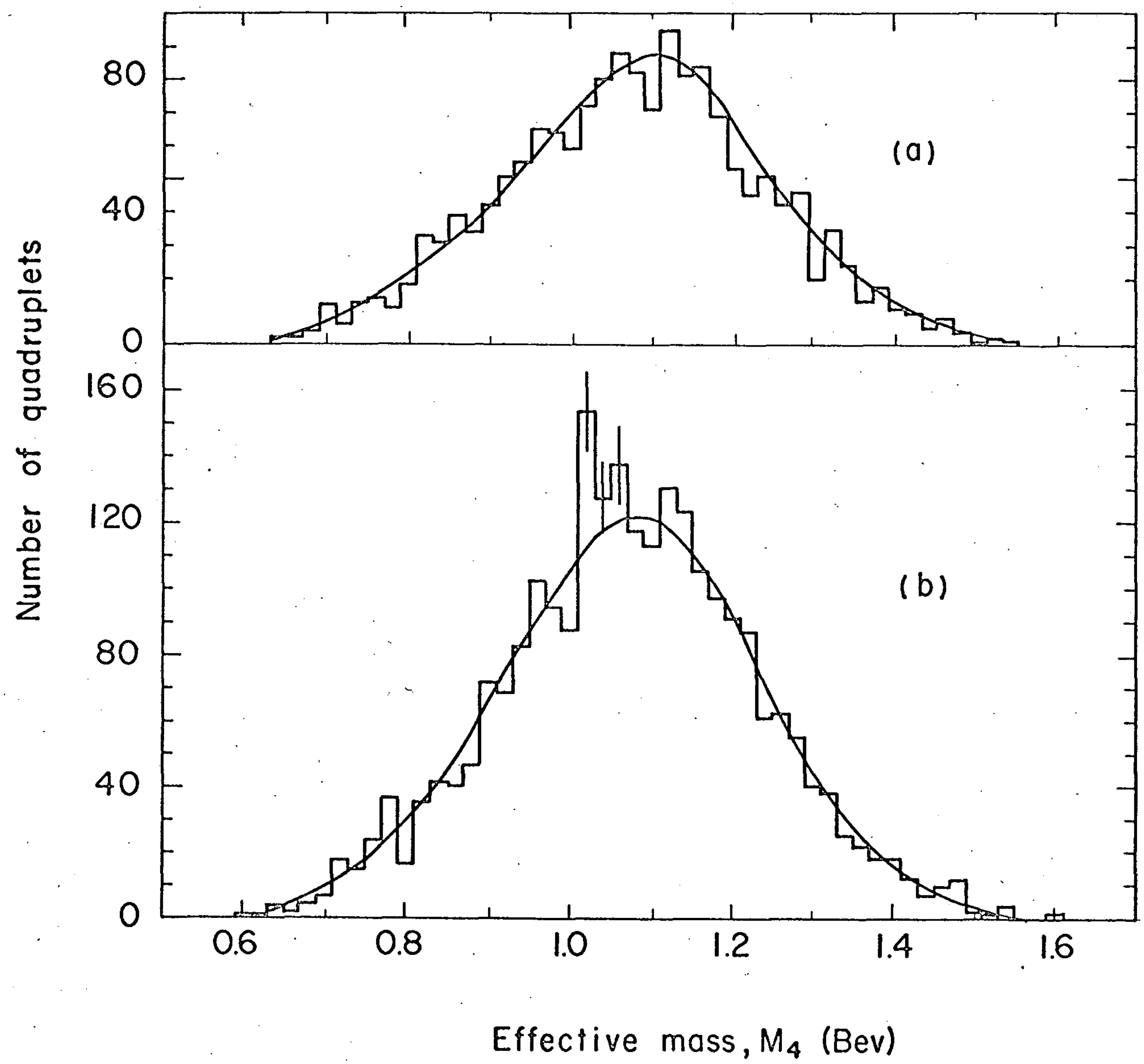
Fig 1



Number of quadruplets
80
60
40
20
0
(a)
80
60
40
20
0
(b)
0.6
0.8
1.0
1.2
1.4
1.6
Effective mass, M_4 (Bev)

MUB-946

Fig 2



Number of quadruplets
0
40
80
0
40
80
120
160
(a)
(b)
0.6
0.8
1.0
1.2
1.4
1.6
Effective mass, M_4 (Bev)

MUB-947

Fig 3.