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Decay Properties of the $A_2(1310)$ Meson[*]

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ABSTRACT

The properties of the A_2 enhancement are determined from the $K\bar{K}$ and $\pi\rho$ decay modes independently. The characteristics of both systems are consistent with the decay of a particle having $I^G J^P = 1^- 2^+$.

Existence of a strong $\pi\rho$ enhancement between 1.0 and 1.4 BeV was discovered by Goldhaber et al. in a study of the reaction $\pi^+p \rightarrow \pi^+\pi^+\pi^-p$ at 3.65 BeV/c.[1] The ABBBHLM Collaboration[2] and Chung et al.[3] demonstrated that the enhancement consisted of two peaks: the A_1 at 1080 MeV and the A_2 at 1310 MeV. In addition, Chung et al. reported evidence for existence of a $K\bar{K}$ peak at 1310 MeV; the assignment $I^GJ^P = 1^-2^+$ was deduced on the assumption that the $\pi\rho$ and $K\bar{K}$ peaks represented alternative decay modes of the $A_2(1310)$. In several recent studies of the $\pi\rho$ system alone, the assignment $J^P = 2^+$ has been favored for the $A_2(1310)$.[4-6] In others, however, the assignments $J^P = 1^+$ or 2^- have appeared more likely;[7-9] in this case, the $K\bar{K}$ peak represents the decay of a new particle. In the present Letter we attempt to resolve this question by determining quantum numbers independently for the $K\bar{K}$ and $\pi\rho$ peaks; the analysis supports the original assumption of Chung et al.[3]

The film was obtained in the course of a systematic study of π^-p interactions near 3.2 and 4.2 BeV/c in the Lawrence Radiation Laboratory's 72-inch hydrogen bubble chamber. The experimental details are given by Hess[10] and Chung.[11] The observed numbers of events and corresponding cross sections are given in Table I.

The $K\bar{K}$ system has been studied in both $pK^-K_1^0$ and $nK_1^0K_1^0$ final states where the decays $K_1^0 \rightarrow \pi^+\pi^-$ were observed; all successfully fitted events in the fiducial volume were used. In contrast, the $A_2(1310)$ represents less than 10% of the $\pi^+\pi^-\pi^-p$ final state, so that useful comparisons are possible only after imposition of stringent selection criteria. For subsequent analysis, $\pi^-\rho^0p$ events are defined as those with at least one $M(\pi^+\pi^-)$ combination in the interval 0.66 to 0.84 BeV. Background due to the sequence $\pi^- p \rightarrow \pi^-\pi^- N^{*++}(1238) \rightarrow \pi^-\pi^-\pi^+ p$ has been minimized by rejecting events with 1.12 BeV $\leq M(\pi^+ p) \leq$ 1.32 BeV and $\Delta^2_{p\pi^+} \leq 1.5\ (\mathrm{BeV}/c)^2$. In addition, events were rejected if they fell into the region where the Deck mechanism[12] is strongest, $\Delta^2_{p\pi^-} \leq 0.55\ (\mathrm{BeV}/c)^2$ and $\hat{p}_p \cdot \hat{p}_0 \equiv \cos\theta_p \leq -0.8$. Here $\underset{\sim}{p}_p$ is the momentum of the outgoing proton and $\underset{\sim}{p}_0$ is the beam direction in the $p\pi^-$ rest frame.[13]

The effective-mass distributions, $M(K\bar{K})$, for the $K\bar{K}$ systems are shown in Fig. 1a; the $M(\pi^-\rho^0)$ distribution is shown in Fig. 1d for events with $\Delta^2_p \leq 0.65\ (\mathrm{BeV}/c)^2$. In both cases a good fit is provided by a Breit-Wigner resonance, with $M_0 = 1310 \pm 20$ MeV and $\Gamma = 65 \pm 20$ MeV, above a smooth background. The Δ^2_N distributions for events in the A_2 interval, 1.24 to 1.38 BeV, are shown separately for $K\bar{K}$ events (Fig. 1, b and c) and $\pi^-\rho^0$ events (Fig. 1, e and f). After comparison with control regions we conclude that, within statistics, contributions from the 1310-MeV peak are similar in all cases.

Possible quantum numbers for the $K\bar{K}$ peak at 1310 MeV are readily deduced. Since the decay $K_1^0 K_1^0$ is observed, C is +1 and J^P is $(\mathrm{even})^+$. Histograms of decay cosine ($\cos\theta_K$ in the $K\bar{K}$ rest frame) and Treiman-Yang angle are plotted in Fig. 2. The decay cosine distributions for both the $K^- K_1^0$ and $K_1^0 K_1^0$ events contain strong $\cos^2\theta$ components, so that J is not equal to zero. Since I is 1 for $K^- K_1^0$, we conclude that $G = (-1)^{J+I} = -1$. Consequently, I^G is 1^- and J^P is 2^+, 4^+, etc. for the $K\bar{K}$ peak at 1310 MeV.

In deducing possible quantum numbers for the $\pi\rho$ system, we note first that the decay $A_2(1310) \rightarrow \pi\rho$ is allowed, consequently G is -1; in addition, Abolins et al. have shown that I = 1.[14] To determine the spin and parity, we consider the decay correlations in the A_2 rest frame; we define $\underset{\sim}{q}$ as the relative momentum of the $\pi^+\pi^-$ pair forming the ρ^0, $\underset{\sim}{p}$ as the momentum of the third pion, and $\cos\beta \equiv \hat{q} \cdot \hat{p}$. For collinear decays, corresponding to points on the boundary of the Dalitz plot $\cos\beta = \pm 1$. For these decays $\psi\,(3\pi)$ is proportional to $Y_J^M\,(\hat{q})$, so that P is $-(-1)^J$; consequently, for 3π systems with $P = (-1)^J$, collinear decays are <u>not allowed</u>.[15] Since the parity of the 3π system can be deduced <u>only</u> from the density on the Dalitz plot near the boundaries, a precise estimate of background is crucial; for systems with $P = (-1)^J$, a small residual background of collinear events can lead (erroneously) to the <u>opposite</u> parity assignment.

The $\cos\beta$ distributions are shown in Fig. 3, b, c, and d for events in the A_2 region and control regions; the strong contribution from the decay $A_2 \rightarrow \pi\rho$ produces the peak at $\cos\beta \simeq 0.2$ in Fig. 3b. Events in the interval 1.24 to 1.38 BeV may be identified as (1) $A_2 \rightarrow \pi\rho$, (2) $\pi\rho$ background, or (3) 3π background. We designate the fraction of events of each type by ϵ_i. The smooth curve in Fig. 1d suggests that $\epsilon_2 + \epsilon_3 = 0.6 \pm 0.1$; the $M(\pi^+\pi^-)$ distribution for the same events gives $\epsilon_3 = 0.4 \pm 0.1$.

For comparison with the experimental data, theoretical $\cos\beta$ distributions[16] for possible J^P assignments were modified by addition of noninterfering background. To examine the dependence of each J^P assignment on background, $\epsilon_2 + \epsilon_3$ was varied from 0 to 1. The $\pi\rho$ background was calculated using the matrix element for an s-wave $\pi\rho$ interaction (i.e., $J^P = 1^+$ appropriately symmetrized);[17] a uniform distribution in $\cos\beta$ was assumed for the 3π background. The behavior of χ^2 (for 19 degrees of freedom) is shown in Fig. 3a as a function of the assumed background level; the slopes are discontinuous, since we have arbitrarily set $\epsilon_2 = 0$ for $\epsilon_1 \geqslant 0.6$. We note that when background is ignored, the most likely assignments are $J^P = 1^+(\ell = 0)$ and $J^P = 2^-(\ell = 1)$. However, for a realistic background level of 40 to 70%, $J^P = 2^+$ represents the only assignment (of those considered) compatible with the data: the fitted distribution is shown in Fig. 3b for $\epsilon_1 = 0.4$. Consequently, for a model with noninterfering background, parsimony requires that we identify the $\pi\rho$ and $K\bar{K}$ peaks as alternative decay modes of an $I^G J^P = 1^- 2^+$ state at 1310 MeV; production cross sections are given in Table II. The combined data give $\Gamma(A_2^- \to K\bar{K})/\Gamma(A_2^- \to \pi\rho) = 0.05 \pm 0.02$; a factor of 1/2 has been included for the unobserved $\pi^0\rho^-$ decays. The decay $A_2 \to \pi\eta$ is allowed; some evidence for a peak near 1310 MeV has been reported. We have examined the $M(\pi^-\eta)$ distribution from the $\pi^-(\pi^+\pi^-\pi^0)p$ final state and (after correcting for unobserved decays) estimate $[\Gamma(A_2^- \to \pi\eta)]/[\Gamma(A_2^- \to \pi\rho)] = 0.12 \pm 0.08$.

Since A_2 events are concentrated at low Δ_N^2 and the decay $A_2 \to \pi\rho$ is dominant, it is likely that production occurs through ρ exchange. Unmodified, this model predicts a $\cos^2\theta_K \sin^2\theta_K(1 + a\cos 2\phi)$ distribution for the $K\bar{K}$ decay mode, where ϕ is the Treiman-Yang angle; the $\cos\theta_K$ distributions in Fig. 2 are in strong disagreement with this prediction. Similarly, the model does not account for the observed correlation between the beam direction and the normal to the $\pi\rho$ decay plane.[11] Analogous discrepancies in other reactions involving ρ exchange have been explained by absorption effects.[18]

We wish to thank the scanning and measuring staff for their untiring efforts in bringing this experiment to a successful completion. It is a pleasure to acknowledge the encouragement and support of Professor Luis Alvarez throughout the course of this experiment.

FOOTNOTES AND REFERENCES

[*] Work done under the auspices of the U. S. Atomic Energy Commission.

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13. This cut reduces the number of events in the mass region below the A_2, but eliminates few events in the A_2 region itself. The analysis was also carried out without this cut, and the conclusions remained unchanged. See Ref. 11 for a detailed account.

14. M. A. Abolins, D. D. Carmony, R. L. Lander, O. Piccioni, Ng. H. Xuong, and P. M. Yager, Phys. Letters 21, 584 (1966).

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16. We have used a computer program written by R. Diebold, CERN/TC/PROG 64-25 modified for our purpose. As an alternative method for taking background into account, varying amounts of the $\cos\beta$ distribution in the control region were subtracted from the distribution in the A_2 interval. A comparison of the resulting distribution with theoretical curves for various J^P assignments yielded similar results; see Ref. 11 for details.

17. We thank Dr. Vanya Cocconi (private communication) for informing us that calculated distributions for events produced through the Deck mechanism resemble closely those for a $J^P = 1^+$ system.

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Table I. Final states analyzed.

Final state	Number of events		Cross section (μb)	
	3.2 BeV/c	4.2 BeV/c	3.2 BeV/c	4.2 BeV/c
$p\pi^+\pi^-\pi^-$	6318	2986	1910 ± 80	1920 ± 100
pK^0K^-	228[a]	95[a]	65.1±5.3	65.7±7.9
$nK_1^0K_2^0$	201[b]	68[b]	45.3±4.1	36.6±5.1

[a] $K_1^0 \to \pi^+\pi^-$ decay was observed for these events. The cross sections were corrected for this detection efficiency ($\epsilon \approx 1/3$).

[b] Decay of both $K_1^0 \to \pi^+\pi^-$ was observed for these events. The cross sections were corrected for this detection efficiency ($\epsilon \approx 4/9$).

Table II. Cross section for A_2 production.

Reaction	Cross section (μb)	
	3.2 BeV/c	4.2 BeV/c
$\pi^- p \rightarrow A_2^- p;\ A_2^- \rightarrow K^0 K^-$	18 ± 4	17 ± 5
$\pi^- p \rightarrow A_2^0 n;\ A_2^0 \rightarrow K\bar{K}$	36 ± 10	18 ± 9
$\pi^- p \rightarrow A_2^- p;\ A_2^- \rightarrow \rho^0 \pi^-$	150 ± 50	175 ± 45

FIGURE LEGENDS

Fig. 1. (a) Effective-mass histogram for the $K\bar{K}$ systems at 3.2 and 4.2 BeV/c. (b) and (c) Histograms of Δ_N^2 at 3.2 and 4.2 BeV/c for $K\bar{K}$ events in the A_2 region. (d) Effective-mass histogram for the $\pi^-\rho^0$ system at 3.2 and 4.2 BeV/c. Selections are discussed in the text. (e) and (f) Histograms of Δ_p^2 at 3.2 and 4.2 BeV/c for the $\pi\rho$ events in the A_2 region.

Fig. 2. Histograms of decay cosine ($= \hat{p}_K \cdot \hat{p}_0$ in the A_2 rest frame) and the Treiman-Yang angle for $K\bar{K}$ events in the A_2 region. The A_2^- histogram is shown in (a) and (b) and the A_2^0 in (c) and (d). In (c) and (d) two points have been plotted per event.

Fig. 3. (a) Variations of χ^2(19 degrees of freedom) for various J^P assignments for the A_2 as a function of the background level. (b) The $\cos\beta$ distribution in the A_2 region. See text for explanation of the curves. (c) The $\cos\beta$ distribution for the region below the A_2(1.0 to 1.14 BeV). (d) The same distribution for the region above the A_2(1.48 to 1.62 BeV).

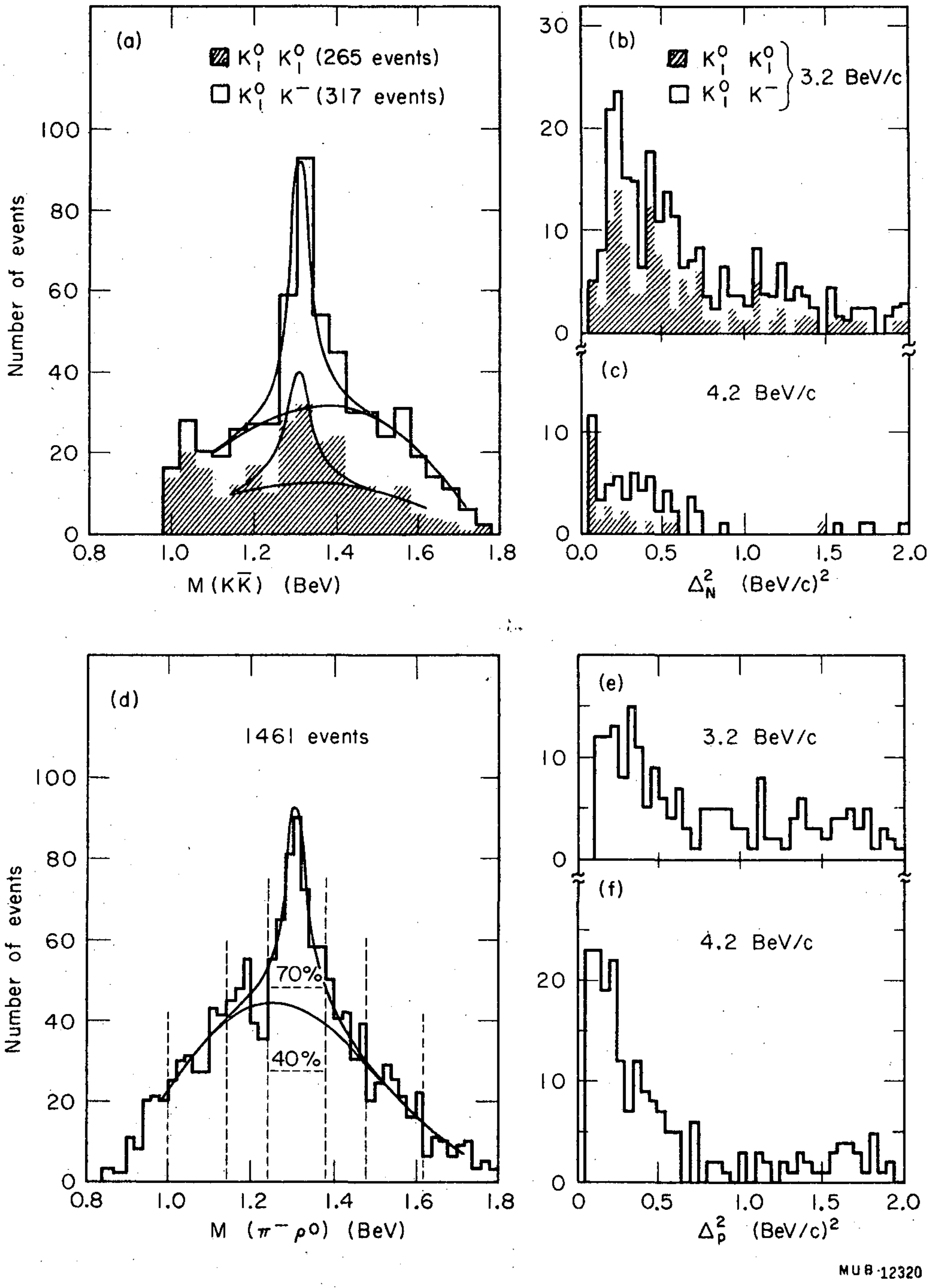
(a)
▨ $K_1^0 K_1^0$ (265 events)
☐ $K_1^0 K^-$ (317 events)
Number of events
0
20
40
60
80
100
0.8
1.0
1.2
1.4
1.6
1.8
M (K$\bar{K}$) (BeV)
(b)
▨ K_1^0 K_1^0
☐ K_1^0 K^-
3.2 BeV/c
0
10
20
30
(c)
4.2 BeV/c
0
10
0.0
0.5
1.0
1.5
2.0
Δ_N^2 (BeV/c)^2
(d)
1461 events
70%
40%
Number of events
0
20
40
60
80
100
0.8
1.0
1.2
1.4
1.6
1.8
M ($\pi^- \rho^0$) (BeV)
(e)
3.2 BeV/c
0
10
(f)
4.2 BeV/c
0
10
20
0
0.5
1.0
1.5
2.0
Δ_p^2 (BeV/c)^2
MUB-12320

Fig. 1

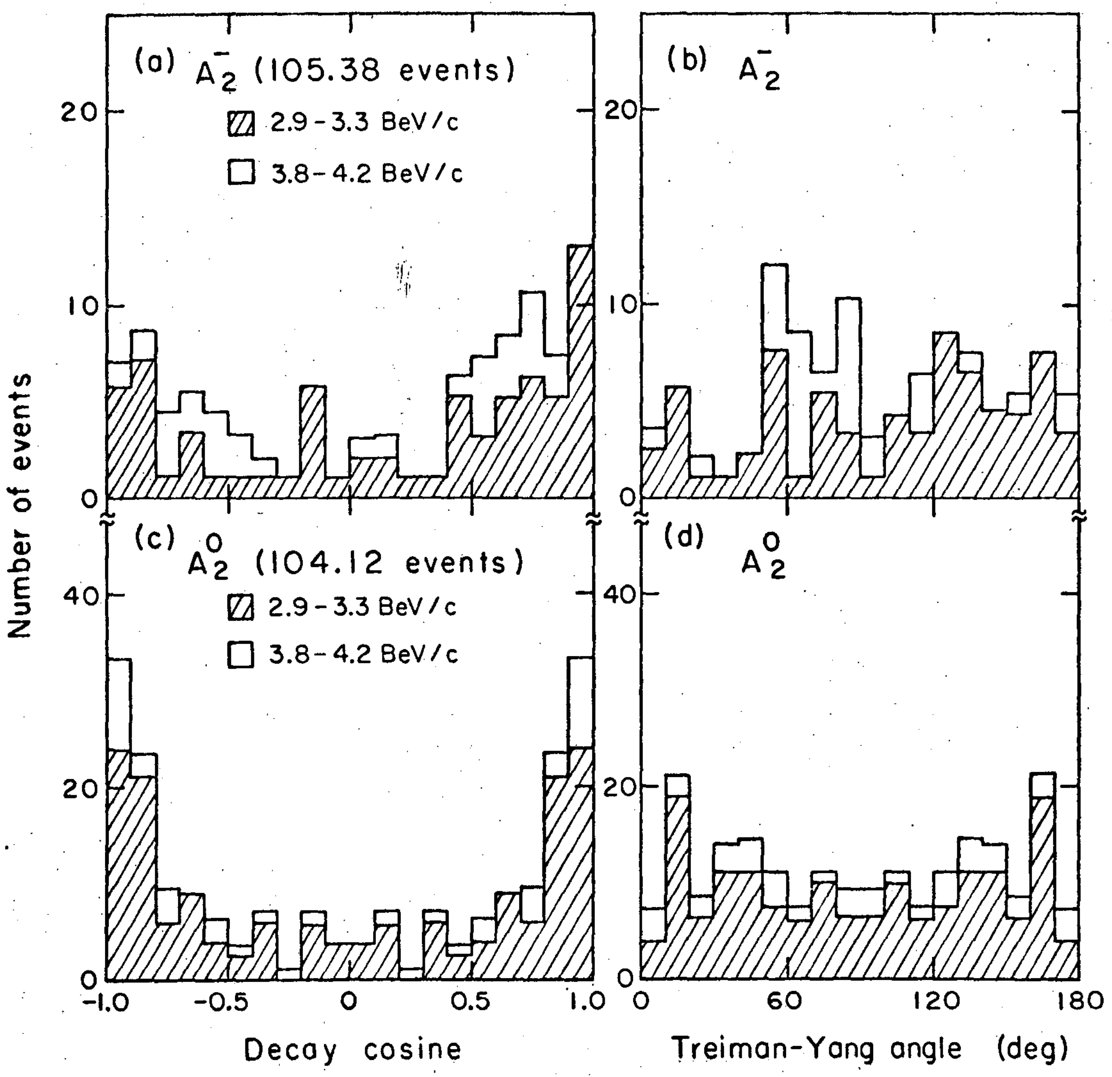
(a) A_2^- (105.38 events)
▨ 2.9-3.3 BeV/c
☐ 3.8-4.2 BeV/c
(b) A_2^-
(c) A_2^0 (104.12 events)
▨ 2.9-3.3 BeV/c
☐ 3.8-4.2 BeV/c
(d) A_2^0
Number of events
0
10
20
40
-1.0
-0.5
0
0.5
1.0
60
120
180
Decay cosine
Treiman-Yang angle (deg)

Fig. 2

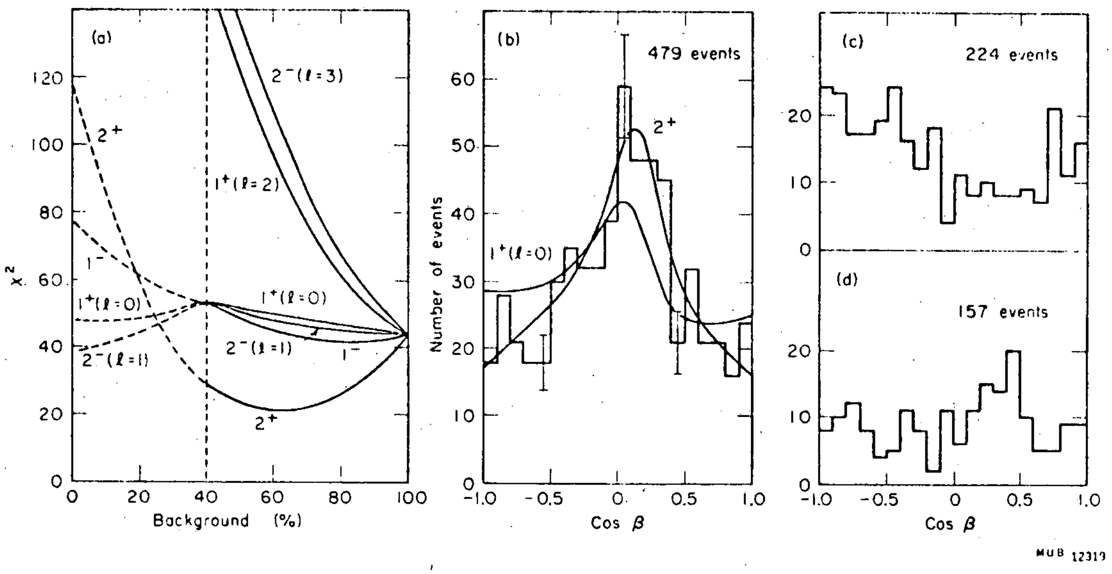
(a)
120
100
80
60
40
20
0
χ^2
2⁺
1⁻
1⁺(ℓ=0)
2⁻(ℓ=1)
2⁻(ℓ=3)
1⁺(ℓ=2)
1⁺(ℓ=0)
2⁻(ℓ=1)
1⁻
2⁺
0 20 40 60 80 100
Background (%)
(b)
479 events
Number of events
60 50 40 30 20 10 0
2⁺
1⁺(ℓ=0)
-1.0 -0.5 0 0.5 1.0
Cos β
(c)
224 events
20 10 0
(d)
157 events
20 10 0
-1.0 -0.5 0 0.5 1.0
Cos β
MUB 12319

Fig. 3