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STUDY OF STRANGE BOSONS DECAYING INTO BARYON-ANTIBARYON PAIRS

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ABSTRACT

We have collected 6100 events in the reactions $K^+p \to (\bar{\Lambda}p)p$ and $K^-p \to (\Lambda\bar{p})p$ at an incident energy of 50 GeV, with the Geneva-Lausanne spectrometer at the SPS. We have investigated the production of strangeness $S = \pm 1$ baryon-antibaryon pairs with mass up to 3 GeV, by performing a moment analysis of the decay angular distribution. An amplitude analysis of the moments shows evidence for two broad states with spin-parity 2^- and 4^-, at 2.3 GeV and 2.5 GeV, respectively, coupling to $\bar{\Lambda}p$ and $\Lambda\bar{p}$.

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1. INTRODUCTION

The production of baryon-antibaryon pairs with strangeness S = ±1 gives an interesting possibility for studying strange mesons in an unexplored mass region above 2 GeV, and in a final state which can have both natural and unnatural spin-parity. The simple two-body decay mode, and the possibility of measuring the Λ polarization by its decay asymmetry, makes an amplitude analysis feasible.

We present here data on the reactions $K^+p \to (\bar{\Lambda}p)p$ and $K^-p \to (\Lambda\bar{p})p$, where the $\bar{\Lambda}p$ or $\Lambda\bar{p}$ pair is produced in the forward direction. The data sample obtained in this experiment is one to two orders of magnitude larger than other samples available at present.

2. EXPERIMENTAL SET-UP AND DATA ANALYSIS

The data have been obtained in the experiment WA10 (measurement of the energy dependence of resonance production), carried out by a Geneva-Lausanne Collaboration at the CERN SPS in an unseparated beam at an energy of 50 GeV.

The double-arm spectrometer consists of a proton detector to measure the direction and momentum of slow recoil protons at large laboratory angles, and a forward detector to measure the directions of the fast forward particles. The forward momenta are not measured. The set-up is similar to the one used in a previous experiment at 10 GeV/c at the CERN PS, which is described in detail elsewhere [1].

For the SPS experiment, the layout [2] has been complemented by the addition of a 16-cell threshold Čerenkov counter in the forward arm for π, K, and p identification, a liquid-argon detector for measuring electromagnetic showers (neither are used in the present analysis), and a set of gamma counters consisting of scintillator-lead-scintillator sandwiches filling the solid angle not covered by the liquid-argon detector.

The trigger requires a well-identified incident particle, a single track in the proton detector, between three and six tracks in the forward detector, and no hits in the gamma counters.

The procedure for event selection is essentially the same as that described in Ref. [1] (10 GeV/c experiment), with the following criteria:

i) The secondary decay vertex is required to be at least 100 mm downstream from the primary interaction vertex.

ii) The three unknown moduli of the forward track momenta are determined by a solution of the three equations of momentum conservation. Energy conservation for the hypothesis $K^+p \to \bar{\Lambda}pp$, $\bar{\Lambda} \to \bar{p}\pi^+$ is then required to be satisfied to within ±20 MeV, and the reconstructed $\bar{p}\pi^+$ mass is required to be consistent with the mass of the $\bar{\Lambda}$, $M(\bar{p}\pi^+) < 1165$ MeV.

iii) A two-constraint kinematic fit is then made using energy-momentum conservation at both the production and decay vertices. The χ^2 probability of this fit is required to be at least 10%.

Our final sample consists of 3368 events of the reaction $K^+p \to (\bar{\Lambda}p)p$ and 2709 events of the reaction $K^-p \to (\Lambda\bar{p})p$, in the momentum transfer range $0.05 < |t| < 1$ $(GeV/c)^2$, and in the effective mass range $2.05 < M_{\bar{\Lambda}p} < 4$ GeV.

Except for a possible contribution of Σ^0 production in the sample, background from other reactions is of the order of 7%. Monte Carlo calculations show that 20% of produced Σ^0 events are accepted by our geometrical and kinematical selection procedures. Assuming that the energy dependence of the production cross-section is the same for Λ and Σ^0, and using the Λ:Σ^0 ratio of 1:1 measured at 12.7 GeV/c [3], we expect a Σ^0 contamination of about 20% in our Λ sample. The effect of this Σ^0 contamination has also been studied using Monte Carlo calculations. We find that the Σ^0 angular distribution is closely approximated by that of its decay Λ, and therefore its moments will be properly calculated, though with somewhat reduced angular resolution.

3. MASS SPECTRA

Figure 1 shows the effective mass spectra of the forward baryon-antibaryon pair for the K^+ and K^- initiated reactions. No acceptance correction has been applied.

The main feature of the mass spectra is a broad low-mass enhancement centred at ∿ 2300 MeV and with a width of ∿ 400 MeV. We observe no significant narrow peaks, and in particular we do not see the structure in the 2800-3000 MeV region found in an earlier experiment [4]. Our apparatus is, however, not sensitive to reactions involving baryon exchange. The $\bar{\Lambda}p$ mass resolution is approximately $\sigma = 20$ MeV for this experiment.

4. MOMENT ANALYSIS

We have calculated the moments of the angular distribution of the $\bar{\Lambda}$ in the $\bar{\Lambda}p$ t-channel helicity frame as a function of $\bar{\Lambda}p$ mass. We have used the linear method described in Ref. 1 to determine the moments and correct for geometrical acceptance and inefficiencies of the spectrometer.

The acceptance has been calculated by a Monte Carlo technique. As a function of $\bar{\Lambda}p$ mass, it varies by less than 20% in the interval $2 < M_{\bar{\Lambda}p} < 3$ GeV. As a function of decay angles, the acceptance drops to a minimum of 50% for $\bar{\Lambda}$ emitted at small forward angles. The sensitivity of the data is 2.1 (1.7) events per nb in the corrected $\bar{\Lambda}p$ ($\Lambda\bar{p}$) mass spectrum.

As the moments of both K^+ and K^- induced data show the same structure within statistical errors, we have combined both sets of data. Figure 2 shows the unnormalized moments $N\langle Y_L^M \rangle$ with $L \leq 8$ and $M \leq 2$. This set of moments fits the angular distribution well, so that no higher moments are needed.

Apart from the broad low-mass enhancement in $\langle Y_0^0 \rangle$, we observe very significant signals in the $M = 0$ moments $\langle Y_4^0 \rangle$, $\langle Y_6^0 \rangle$, and $\langle Y_8^0 \rangle$, in the region of 2.3 and 2.5 GeV. Smaller signals appear in some $M = 1, 2$ moments, in particular $\langle Y_4^1 \rangle$ and $\langle Y_4^2 \rangle$.

5. AMPLITUDE ANALYSIS

We use the data to study the production of mesonic states R by the processes $K^{\pm}p \rightarrow R^{\pm}p$, and their subsequent decay $R^+ \rightarrow \bar{\Lambda}p$ and $R^- \rightarrow \Lambda\bar{p}$. If we allow R to be a mixture of different spin-parity states $A = J^{\eta}$, then the moments of the decay angular distribution can be written as

$$\sqrt{4\pi}\,\langle Y_L^M\rangle = \sum_{\substack{AA' \\ \Lambda\Lambda'}} \left[\frac{(2J+1)(2J'+1)}{2L+1}\right]^{1/2} H_\Lambda^A H_{\Lambda'}^{A'*} \langle J\ -\Lambda\ J'\ \Lambda'|L\ M\rangle \times$$

$$\times \sum_{\lambda_1\lambda_2} F_{\lambda_1\lambda_2}^{A} F_{\lambda_1\lambda_2}^{A'*} (-1)^{\lambda-\Lambda} \langle J\ -\lambda\ J'\ \lambda|L\ 0\rangle\ ,$$

where H_Λ^A is the helicity amplitude for production of a state R with spin-parity A and t-channel helicity Λ, and $F_{\lambda_1\lambda_2}^A$ is the amplitude describing the decay $R \to \bar{\Lambda}p$ from a state A, where λ_1, λ_2 are the helicities of $\bar{\Lambda}$, p, respectively, in the c.m. frame of R, and $\lambda = \lambda_1 - \lambda_2$.

We define, in the usual way, amplitudes corresponding to natural-parity exchange (NPE) and unnatural-parity exchange (UPE), which we denote by N_Λ^A and U_Λ^A, respectively:

$$N_\Lambda^A = C_\Lambda\left[H_\Lambda^A - \sigma(-1)^\Lambda H_{-\Lambda}^A\right] \qquad C_\Lambda = \begin{cases} 1/2 \text{ for } \Lambda = 0 \\ 1/\sqrt{2} \text{ for } \Lambda \neq 0 \end{cases}$$

$$U_\Lambda^A = C_\Lambda\left[H_\Lambda^A + \sigma(-1)^\Lambda H_{-\Lambda}^A\right]$$

where $\sigma = \eta(-1)^J$ is the naturality of the produced state. It follows that states R with helicity $\Lambda = 0$ and natural (unnatural) parity can only be produced by UPE (NPE).

The observation of large signals in the M = 0 moments and the absence of comparable signals in the M = 2 moments implies the dominance of $\Lambda = 0$ amplitudes. At 50 GeV/c it is reasonable to assume that NPE dominates. This then implies that the observed structures have unnatural parity $J^\eta = 0^-, 1^+, 2^-, \ldots$.

There are two independent amplitudes describing the decay of a mesonic state into $\bar{\Lambda}p$, namely F_{++}^A and F_{+-}^A. For unnatural parity states we may label these amplitudes s and t, respectively, corresponding to the spin-singlet and spin-triplet configuration of the $\bar{\Lambda}p$ system in the ℓ-s formalism. For these states generalized C-parity conservation*) leads to the selection rule that the only non-zero over-all production and decay amplitudes are

*) Conservation of C-parity in the production of a $\bar{p}p$ pair from an incident π by C = +1 SU(3) singlet (e.g. Pomeron) exchange gives $C(\bar{p}p) = +1$. On the other hand, for unnatural parity $\bar{p}p$ states we have orbital angular momentum $\ell = J$ from parity conservation, and therefore $C(\bar{p}p) = (-1)^{\ell+s} = (-1)^{J+s}$, which leads to J + s = even. The rule can be generalized within SU(3) to apply to the production of a $\bar{\Lambda}p$ system from an incident K^+.

$$J_0^s \equiv N_0^A F_{++}^A \quad \text{for J even}$$

$$J_0^t \equiv N_0^A F_{+-}^A \quad \text{for J odd .}$$

Consider now the structure of the individual moments. The non-zero value of $\langle Y_8^0 \rangle$ implies the presence of the amplitude $N_0^{4^-}$. Moreover, the sign of $\langle Y_8^0 \rangle$ means that the decay amplitude F_{++} is more important than F_{+-}, in agreement with generalized C-parity conservation. As a minimum, we therefore need $G_0^s = N_0^{4^-} F_{++}^{4^-}$. Similarly, the magnitude and sign of $\langle Y_4^0 \rangle$ mean we must include the 2^- singlet amplitude D_0^s. The behaviour of $\langle Y_6^0 \rangle$ may be accounted for by either the interference of D_0^s and G_0^s, or by also including the 3^+ triplet amplitude F_0^t. The data are unable to determine F_0^t as reliably as D_0^s and G_0^s. We choose to neglect this smaller 3^+ production. Finally, the smallness of $\langle Y_2^0 \rangle$ requires the presence of lower partial waves, and is most naturally accounted for by S_0^s - D_0^s interference. Using only S_0^s, D_0^s, G_0^s and their interference contributions we are able to reproduce the behaviour of the observed $\langle Y_L^0 \rangle$ moments with L = 0, 2, 4, 6 and 8 as a function of the $\bar{\Lambda}p$ mass.

The relevant results of the amplitude analysis are shown in Fig. 3. In the framework of the model, we see striking evidence for the existence of a 2^- mesonic state in the region of 2.3 GeV and for a 4^- state near 2.5 GeV, coupling to $\bar{\Lambda}p$ and $\Lambda\bar{p}$. Breit-Wigner fits to the amplitude results give masses of 2.32 and 2.51 GeV, respectively, both states having widths of about 250 MeV. Moreover, the behaviour of the relative 2^--4^- phase as a function of mass is consistent with the interference of two Breit-Wigner resonant forms. The relative 2^--0^- phase is harder to interpret, but we note that it is determined by $\langle Y_2^0 \rangle$, and is therefore more sensitive to the possible presence of other partial waves, in particular 1^+ and 3^+, which have been neglected in this analysis. We studied the stability of the analysis to the inclusion of Λ = 1 amplitude contributions and found the dominant amplitude structures essentially unchanged.

6. CONCLUSIONS

The data obtained in this experiment permit, for the first time, a detailed moment analysis of strange mesons decaying into baryon-antibaryon pairs. The moments of the Λ angular distribution in the t-channel helicity frame show large signals in $\langle Y_4^0\rangle$, $\langle Y_6^0\rangle$, and $\langle Y_8^0\rangle$. Under the assumption of NPE, the dominance of the M = 0 moments implies unnatural parity for the produced $\bar{\Lambda}p$ and $\Lambda\bar{p}$ states. The moments can be interpreted in terms of a simple model, consisting of production amplitudes for a $J^P = 2^-$ state at 2.3 GeV, a 4^- state at 2.5 GeV and a smooth 0^- background.

The $\bar{\Lambda}p$ and $\Lambda\bar{p}$ data are relevant in the search for baryonium. In particular, a model of Tsou [5] can accommodate broad 2^- and 4^- states at the observed masses. In view of such an interpretation, it will be interesting to compare $\bar{\Lambda}p$ with $K\pi\pi$ production data, in order to determine the branching ratio for baryonic relative to mesonic decays of the observed states.

Acknowledgements

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Figure captions

Fig. 1 : Effective mass spectra of forward produced $\bar{\Lambda}p$ and $\Lambda\bar{p}$ systems, in the range of momentum transfer from target to recoil proton $0.05 < |t| < 1\ (\mathrm{GeV}/c)^2$. No acceptance correction has been applied.

Fig. 2 : Spherical harmonics moments $N\langle Y_L^M \rangle$ of the $\bar{\Lambda}$ in the $\bar{\Lambda}p$ t-channel helicity frame. The moments are corrected for the acceptance of the spectrometer. $\bar{\Lambda}p$ and $\Lambda\bar{p}$ data have been combined.

Fig. 3 : Over-all amplitudes for production and decay of $J^{\eta} = 2^-$ and 4^- states, in addition to a 0^- background, obtained from a fit described in the text. The amplitudes correspond to production by NPE and decay into the spin-singlet configuration. There is a Barrelet-related solution with a larger $|S_0|$ and a smaller $|D_0|$.

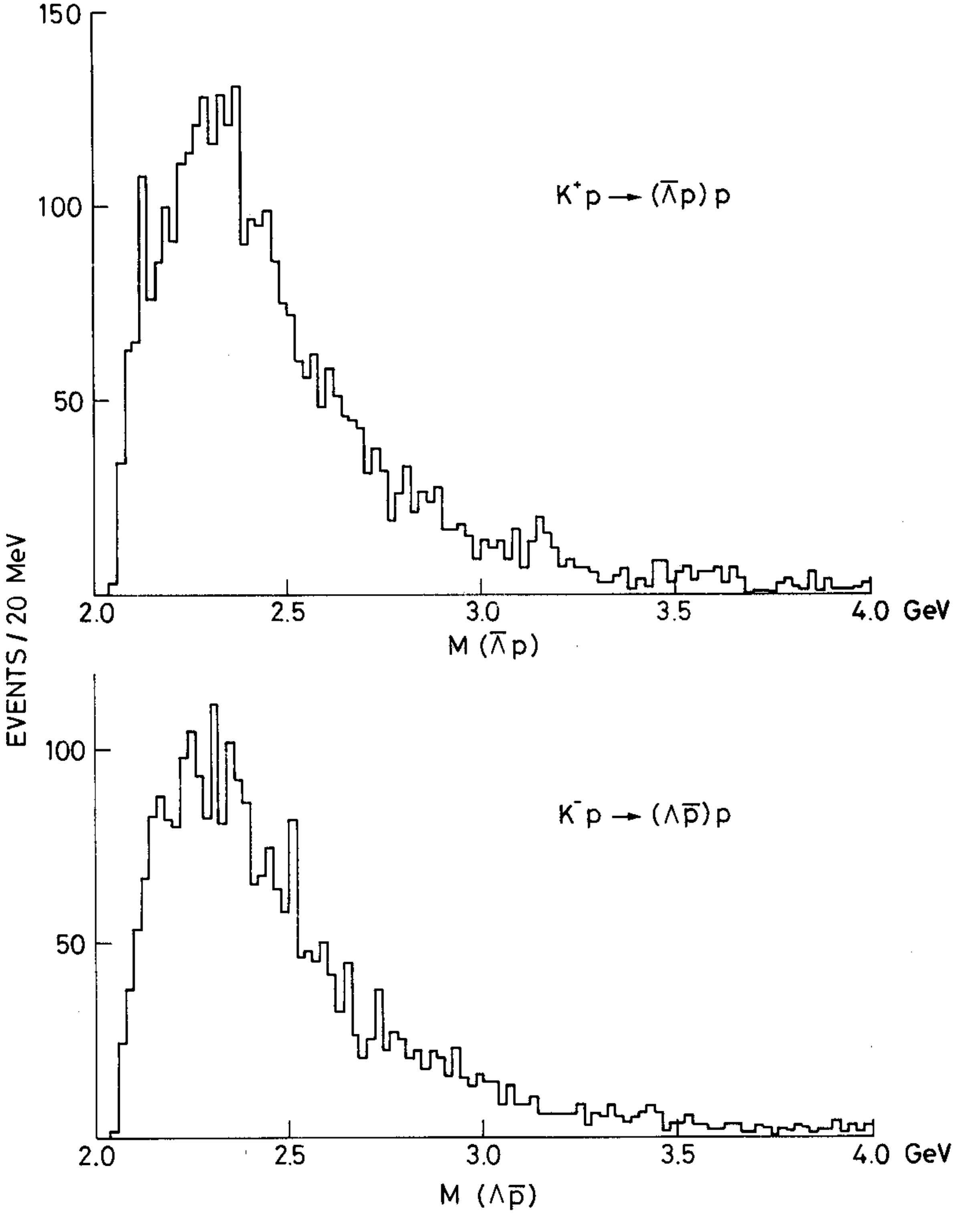

150
100
50
EVENTS / 20 MeV
$K^+p \rightarrow (\bar{\Lambda}p)\,p$
2.0
2.5
3.0
3.5
4.0 GeV
$M\,(\bar{\Lambda}p)$
100
50
$K^-p \rightarrow (\Lambda\bar{p})\,p$
2.0
2.5
3.0
3.5
4.0 GeV
$M\,(\Lambda\bar{p})$

Fig. 1

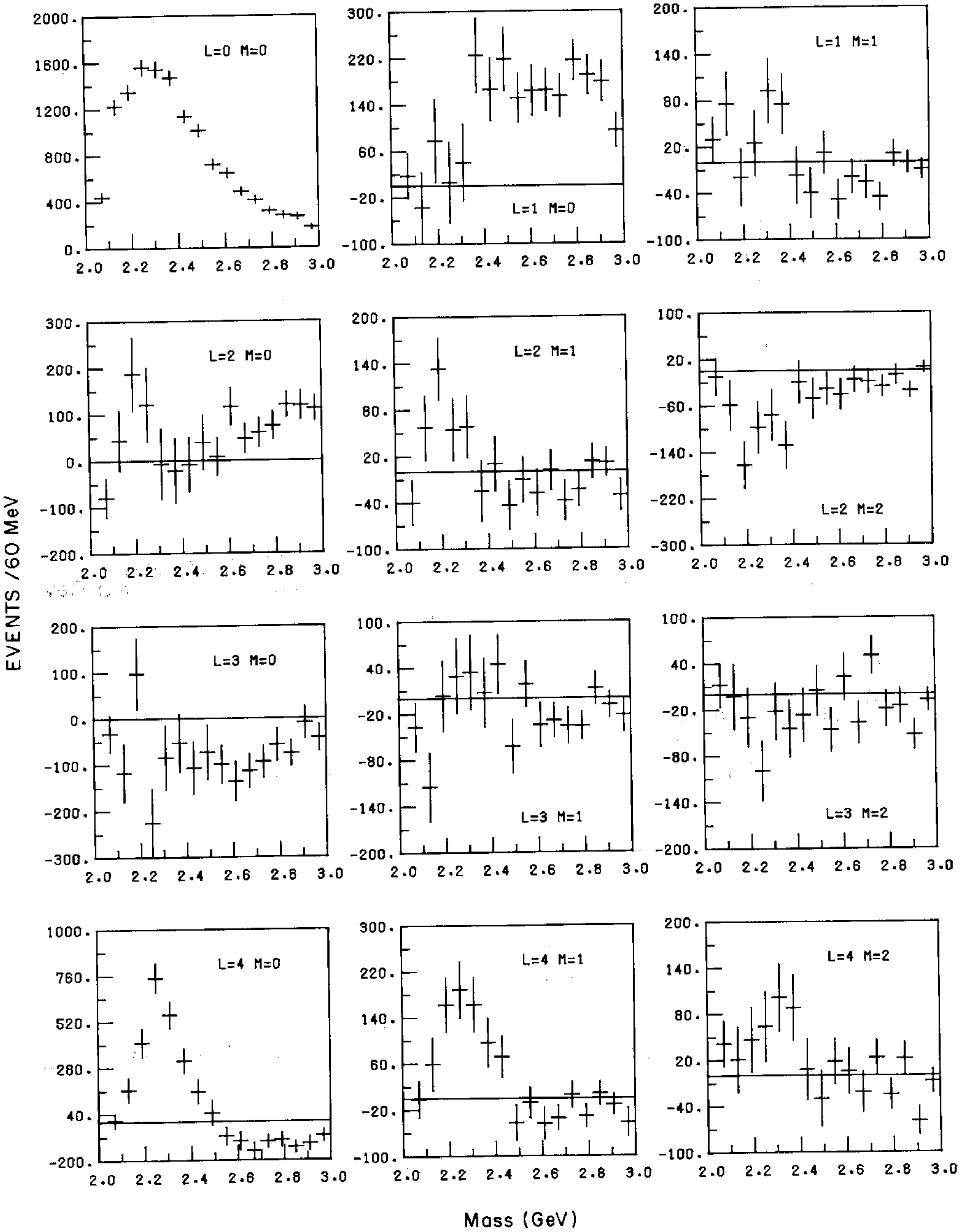
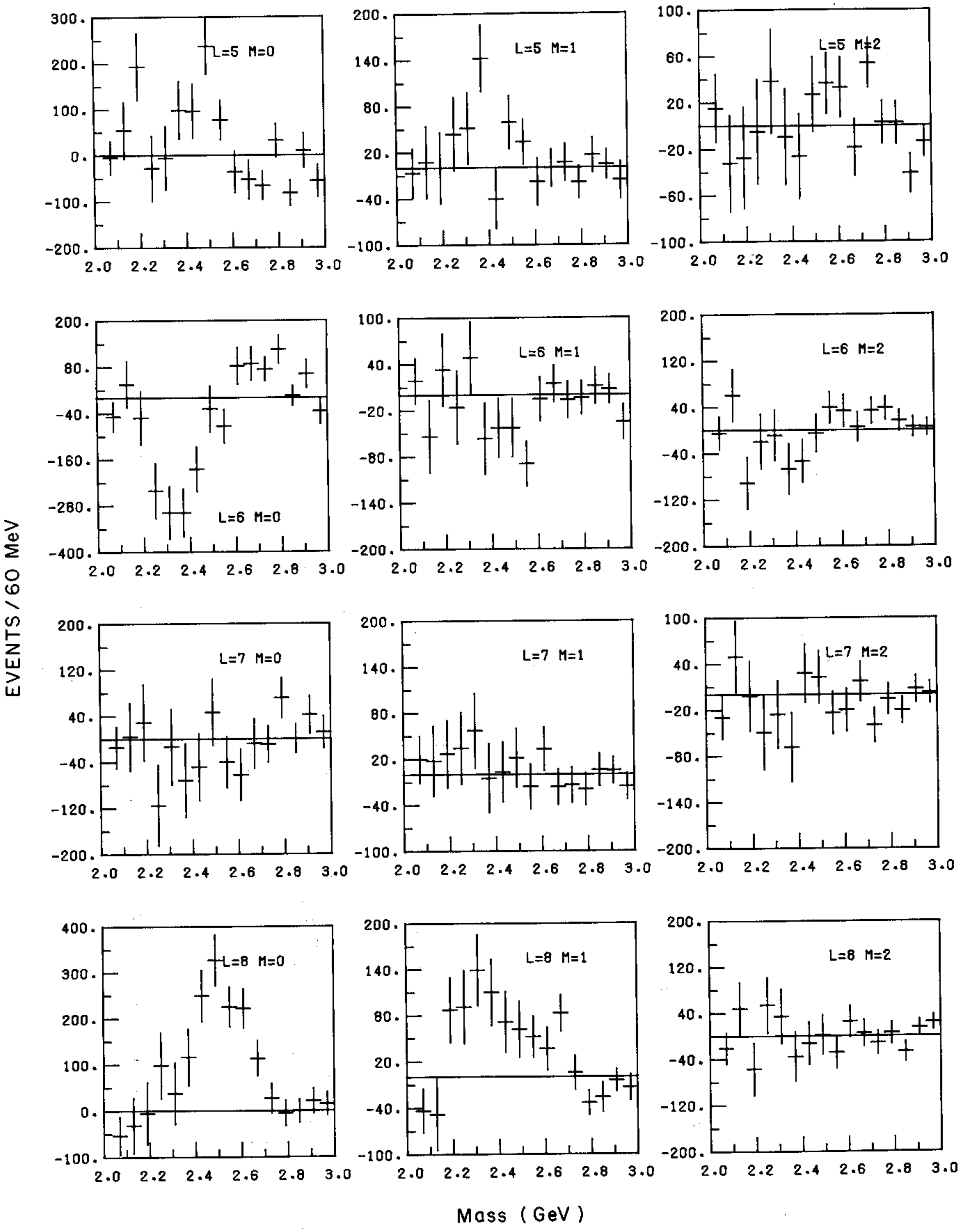

L=0 M=0
L=1 M=0
L=1 M=1
L=2 M=0
L=2 M=1
L=2 M=2
L=3 M=0
L=3 M=1
L=3 M=2
L=4 M=0
L=4 M=1
L=4 M=2
EVENTS /60 MeV
Mass (GeV)

Fig. 2a



EVENTS / 60 MeV
L=5 M=0
L=5 M=1
L=5 M=2
L=6 M=0
L=6 M=1
L=6 M=2
L=7 M=0
L=7 M=1
L=7 M=2
L=8 M=0
L=8 M=1
L=8 M=2
Mass (GeV)

Fig. 2b

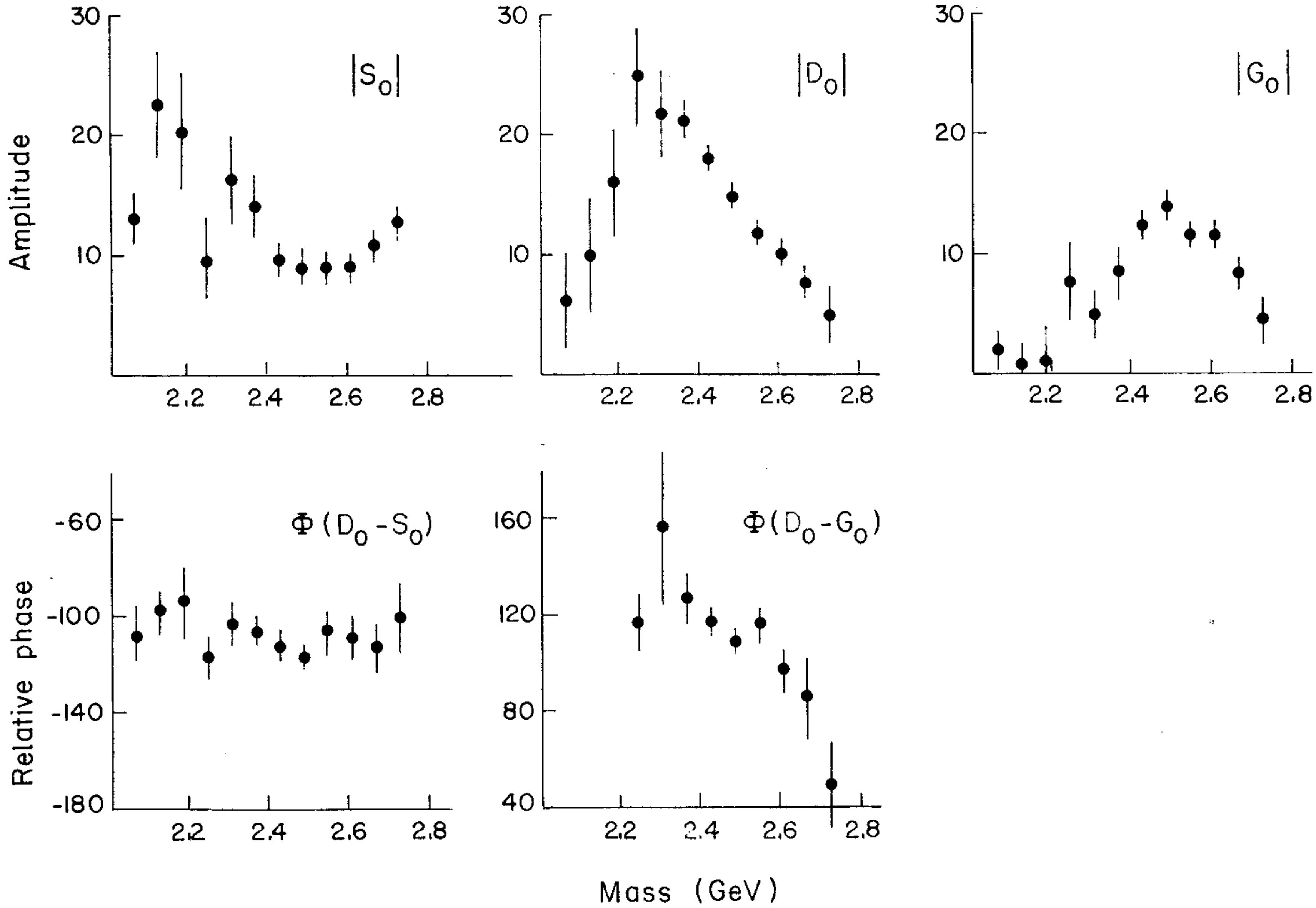

Amplitude
|S0|
|D0|
|G0|
30
20
10
2.2
2.4
2.6
2.8
Relative phase
Φ(D0-S0)
Φ(D0-G0)
-60
-100
-140
-180
160
120
80
40
Mass (GeV)

Fig. 3