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DIFFRACTIVE PHOTOPRODUCTION OF A $b_1\pi$ SYSTEM

Omega Photon Collaboration

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Abstract

It is shown that a likely interpretation of the $b_1^{\pm}\pi^{\mp}$ mass spectrum from diffractive photoproduction is that it is due to contributions from the $\omega_3(1670)$, in accord with corresponding production of the $\rho_3(1690)$, and from a further peak with a mass of 1.88 ± 0.04 GeV and a width $\leq$ 0.3 GeV. The possibility that this latter peak can be due to a group of $q\bar{q}g$ hybrid states, as proposed by Isgur and Paton, is explored.

1. Introduction

This paper reports the analysis of the reaction

$$\gamma p \rightarrow b_1^{\pm}(1235)\pi^{\mp}p \tag{1}$$

in the photon energy range 25-50 GeV. Some results of this work have been reported earlier [1]. The more detailed analysis presented here has been prompted by the suggestion of Isgur and Paton[2], and of Isgur, Kokoski and Paton[3] that this reaction should be a good place to look for particular examples of quark-antiquark-gluon hybrid states. The model of hybrid states, which was proposed in the first paper of Isgur et al.[2], starts with ordinary meson states of quark and antiquark joined by a string of glue, and then considers hybrid states as vibrational excitations of the string of glue. The second paper [3] suggests that:

(i) such hybrid states will have decay products including excited meson states, such as $b_1(1235)\pi, a_1(1270)\pi$ or $h_1(1190)\pi$; and

(ii) an important mechanism for production of these hybrid states could be diffractive excitation. For example, where a photon produces a quark-antiquark vector meson relatively strongly by diffraction, there should also be some probability of producing a vibrational excitation and so also producing the corresponding hybrid excited state.

Isgur et al.[3] present the view that diffractive photoproduction of vibrationally excited ω-mesons, decaying to $b_1(1235)\pi$, should be the most fruitful possibility to study. Other such excited states decay to produce systems such as $a_1(1270)\pi$ or $h_1(1190)\pi$, where the much wider $a_1(1270)$ or $h_1(1190)$ mesons will be harder to identify. For these vibrationally excited ω-mesons, masses are predicted [2] around 1.9 GeV, with an uncertainty of 0.1 GeV. For the exotic examples, which are the only ones for which decay calculations are reported [3], widths are predicted to be 0.25 and 0.5 GeV, with uncertainty of a factor of about 2.

In the previous study [1] of the reaction

$$\gamma p \to \omega\pi^+\pi^- p \tag{2}$$

a broad $\omega\pi\pi$ mass spectrum was observed, together with a contribution from $b_1(1235)\pi$ which was confined to the region $1.6 < M(\omega\pi\pi) < 2.0$ GeV. At that time this production of a broad peak in the $b_1(1235)\pi$ mass spectrum was not studied in detail, since a probable interpretation was that of a non-resonant threshold effect, as for example is seen in diffractive dissociation of π-mesons to $\pi\rho$ states (see typically Daum et al.[4], which gives references to earlier work).

As well as the incentive of seeking possible hybrid states, a further motivation for extending the study of reaction (1) comes from the observation [5] of diffractive photoproduction of the $\rho_3(1690)$. One can estimate the cross section for corresponding production of the latter's nonet partner, taken to be the $\omega_3(1670)$ which has been observed to decay into $b_1(1235)\pi$[6]. It will be shown that a likely interpretation of the broad peak is that the lower half results from production of the $\omega_3(1670)$, with the predicted intensity, leaving the upper half to be explained by another peak of width ≤ 0.3GeV. This latter peak is at a much higher energy than is typical for a threshold effect, and so is presented as a candidate for a resonance or group of close resonances, which could include the suggested hybrid states. The cross section for production of this latter peak therefore enables limits to be put on the probability of the vibrational excitation mechanism in diffractive dissociation suggested by Isgur et al.[3]. Such a limit should, at least, be useful in suggesting where and how to seek this excitation mechanism in other reactions.

Section (2) of this paper presents a summary of the theoretical background assumed in the present work. Section (3) reports the experimental data, its selection and analysis, Section (4) describes the likely interpretation and Section (5) discusses the results.

2. Theoretical background

This section states the assumptions made in the analysis, which are based on the model of Isgur et al.[2,3]. Firstly it is assumed that the states to be looked for are produced by diffractive dissociation. This is taken to involve exchange of the quantum numbers of the vacuum, which, in photoproduction, restricts attention to production of C = −1 states. From the list in Table 1 of Ref. [2], the candidates to be sought have the following values of J^π(S) (where S denotes the resultant spin of the quarks): 0+(1), 1+(1), 2+(1), 1−(0). It is widely assumed that diffractive processes should not change the state of the spins of the quarks, particularly as a consequence of the s-channel helicity conservation observed in elastic scattering at small momentum transfer (see Donnachie and Landshoff [7] as a recent reference). If this holds in general, then excitation of only S = 1 states would be expected in diffractive photoproduction. Such a selection rule for inelastic diffraction was discussed in detail some years ago [8,9,10]. There it was shown that several inelastic processes, which should be forbidden by this selection rule, are observed and are not strongly inhibited. A present-day list of examples includes production of the $D_{13}(1520)$ and $S_{11}(1535)$ baryon states in diffractive dissociation of the proton [8,9,10], production of the $a_1(1270)$ in diffractive dissociation of the π-meson [4], and diffractive photoproduction of the $b_1(1235)$ [11] and probably of the $h_1(1190)$ [12]. Therefore no such selection rule has been assumed to apply to the inelastic diffraction considered here.

Isgur et al.[3] assume that the major decay modes of the quark-antiquark-gluon hybrid states will be by pion emission, which then leaves the angular momentum of the glue excitation to be carried through into similar excitation of the other decay product. Detailed calculations of this model are reported only for the exotic states [3], where the dominance of a decay mode to $b_1(1235)\pi$ is indicated for the I = 0 exotic states with J^π = 2+ or 0+. The general nature of this argument suggests a similar dominance of this decay mode for the 1+ state with I = 0, and perhaps for the 1− state with I = 0.

One must also consider the possibility of $q\bar{q}$ mesons, which could have a broad range of spins and either parity. States which could be diffractively photoproduced and which are reported in this mass range include the $\phi(1680)$, reported in electron-positron annihilation [13] but not seen at a corresponding rate in photoproduction [1,14], a peak in photoproduced $\pi^+\pi^-\pi^o$, a peak in photoproduced $K\bar{K}$ [15,16], and the $\omega_3(1670)$, which decays, with a branching ratio of approximately one-half, into $b_1(1235)\pi$.

A non-resonant threshold effect, due to some mechanism such as was initially proposed by Drell and Hiida[17] and by Deck[18], has also to be borne in mind. Such threshold effects are well-known, for example, in diffractive dissociation of π to $\pi\rho$ states (see Daum et al.[4] for references), and would be expected to produce two particles with relative s-wave motion (see Stodolsky[19] for a discussion), so a $b_1\pi$ threshold effect would have mainly $J^\pi = 1-$.

All these states have $C = -1$, so that, when finally observed as $\omega\pi^+\pi^-$, the $\pi^+\pi^-$ combination must have $C = +1$, and will therefore be symmetric under interchange. Therefore $b_1^+\pi^-$ and $b_1^-\pi^+$ states should be produced with equal amplitude, and there should be constructive interference between the two resonance bands on the $\omega\pi^+\pi^-$ Dalitz plot.

In the data analysis described in the next section, estimates of production of $b_1(1235)\pi$ systems are made by fitting the observed $\omega\pi\pi$ mass distributions with contributions from $\omega\pi\pi$ phase space and from a $b_1\pi$ model. $b_1\pi$ models depend not only on the interference between contributions from the two b_1-meson bands on the Dalitz plot but also on the distribution along the b_1-meson bands. This latter distribution is determined by the $b_1 \rightarrow \omega\pi$ angular distribution in the helicity frame, and in the present analysis this distribution has been taken to be isotropic. The reported small d-wave contribution to the $b_1 \rightarrow \omega\pi$ decay [20] would result in a weak peaking of the intensity along the resonance band on the Dalitz plot.

A further possible problem, which has not been taken into account in the present analysis, should also be noted. It has been shown [1] that the main production of $\omega\pi\pi$ by reaction (2) is production with $J^\pi = 1-$. Therefore any production of $b_1\pi$ with $J^\pi = 1-$, either from a resonance or from a threshold effect, could interfere with the $\omega\pi\pi$ background to produce observable effects both in the $\omega\pi\pi$ mass spectrum, and in the projections of the $\omega\pi\pi$ Dalitz plot. Any analysis taking such effects into account would need considerably improved data or more theoretical input.

3. Data and analysis

The same data-set, from the WA57 experiment at the CERN Omega Spectrometer, is used as in the previously reported work [1], so only a brief summary of the experiment and data selection will be given here.

The events were produced by interaction of 25-50 GeV tagged photons in a 60 cm liquid hydrogen target. The experimental trigger required between 2 and 5 charged particles to be detected in a forward MWPC, together with at least one gamma-ray, with energy > 2 GeV, detected in a large photon detector. Events corresponding to the reaction

$$\gamma p \to \pi^+\pi^-\pi^+\pi^-\pi^0 p \tag{3}$$

were selected off-line by requiring any missing energy, carried by unobserved particles, to lie within the range -1.5 GeV to 1.0 GeV. Reaction (2) was then selected by cuts on the $\pi^+\pi^-\pi^0$ mass spectrum, which had 4 combinations/event. For every combination with the $\pi^+\pi^-\pi^0$ mass in the range 0.75-0.82 GeV, the corresponding event was given weight $= +1$. The background under the ω-meson peak was then subtracted by giving weights of -1 to $\pi^+\pi^-\pi^0$ combinations in the mass ranges 0.715-0.75 or 0.82-0.855 GeV. After these selections, the background due to events in which more particles are produced than in reaction (2) is estimated to be 25%.

The acceptance, for which a major contribution was due to the aperture of the photon detector, was deduced from a full simulation of both apparatus and software. The results of this simulation are shown in the previous paper [1], indicating an acceptance which scarcely varies with $\omega\pi\pi$ mass. There is some fall of acceptance for $\cos\theta_\omega < -0.5$, where θ_ω is the angle between the direction of the ω-meson and the s-channel helicity axis in the $\omega\pi\pi$ rest system. No correction for acceptance is made to the histograms presented in the present analysis, since the conclusions do not change within the accuracies quoted.

The indication of a peaking in the $b_1(1235)\pi$ mass spectrum is demonstrated in Fig.1, which shows $\omega\pi$ mass spectra for three different $\omega\pi\pi$ mass ranges. On each $\omega\pi$ mass spectrum the solid curve shows a fit, assuming the shape arising from $\omega\pi\pi$ phase space. These fits have the following values of χ^2/d.o.f.:

$$1(a) 1.3 < M(\omega\pi\pi) < 1.6 GeV : 9.1/10$$

$$1(b) 1.6 < M(\omega\pi\pi) < 2.0 GeV : 38.0/15$$

$$1(c) 2.0 < M(\omega\pi\pi) < 2.5 GeV : 25.0/27$$

These results show a significant departure from phase space for the middle $\omega\pi\pi$ mass range, and good consistency with phase space for the other two $\omega\pi\pi$ mass ranges. The departure from phase space in Fig.1(b) is due to a definite peaking in the $\omega\pi$ mass spectrum. This peaking was explored by fitting the $\omega\pi\pi$ mass-spectrum of Fig.1(b) with $\omega\pi\pi$ phase space plus a Breit-Wigner peak. To check on the stability of fits, a number were made with the width of the Breit-Wigner peak fixed at values over the range 0.05-0.18 GeV. Approximately parabolic variation of χ^2 as a function of width was observed, with a minimum of χ^2 =6.5 for 13 d.o.f. From the behaviour of these fits it was estimated for the best fitting Breit-Wigner peak that:

$$M = 1.214^{+0.017}_{-0.009} GeV$$

$$\Gamma = 0.090^{+0.055}_{-0.038} GeV$$

The errors quoted are purely statistical, and do not include any systematic uncertainty due to the assumptions made in these fits, namely that there is no interference between the crossing $b_1^{\pm}$ bands in the $\omega\pi\pi$ Dalitz plot and that the effect of the $b_1^{\pm} \rightarrow \omega\pi^{\mp}$ projection on to the $\omega\pi^{\pm}$ mass spectrum can be approximated with phase space. Notwithstanding these uncertainties, these results are consistent with the known values [20] for the $b_1(1235)$ and indicate that the peaking in Fig.1(b) is due to reaction (1).

More detailed fits were therefore made to $\omega\pi\pi$ mass spectra compiled for 0.1 GeV bins of $\omega\pi\pi$ mass, assuming contributions from $\omega\pi\pi$ phase space and from $b_1\pi$. It was assumed that $b_1^+\pi^-$ and $b_1^-\pi^+$ had equal intensity and that the $b_1 \rightarrow \omega\pi$ angular distribution was isotropic in the helicity system. Further, the interference between the two b_1 resonance bands was calculated assuming the standard phase variation across a resonance, with complete and constructive interference at the peaks of the two resonances. Monte Carlo simulations generated events with distributions according to these assumptions, including also the effect of the peak selection and side-band subtraction on the resulting $\pi^+\pi^-\pi^0$ mass spectrum which was applied to the experimental data. It was checked that the acceptance made no significant distortion of the resulting $\omega\pi$ mass spectra. It was found , for $M(\omega\pi\pi) < 1.5$ GeV, that the $\omega\pi$ mass spectra for the phase space and $b_1\pi$ contributions were not sufficiently different for the fits to give useful answers. So, as the data showed no significant departure from phase space at these low masses, it is assumed that no $b_1\pi$ contribution was needed there. For $1.5 < M(\omega\pi\pi) < 2.5 GeV$, good fits were obtained with values of χ^2/d.o.f. ranging from 0.60 to 1.30. (The result of combining the four fits for $1.6 < M(\omega\pi\pi) < 2.0$ GeV is compared with the data in Fig.1b, where it is plotted as the dashed curve. This fits the data well having χ^2/d.o.f $= 13.1/14$.) As functions of $\omega\pi\pi$ mass the resulting intensity of $\omega\pi\pi$ phase space is shown in Fig.2(a), and the intensity of the $b_1\pi$ contribution is shown in Fig.2(b). Figure 2(b) shows an indication of a broad peak, of mass ~ 1.8 GeV and width ~ 0.4 GeV, in the $b_1\pi$ mass spectrum from reaction (1).

For events in this broad peak the production angular distribution of the $b_1\pi$ system has been studied as a function of $\cos\theta_B$ where θ_B is the angle between the direction of the b_1 system and the s-channel helicity axis in the $\omega\pi\pi$ system. For 100 MeV bins of $\omega\pi\pi$ mass in the range $1.6 < M(\omega\pi\pi) < 2.0$ GeV, $\omega\pi$ mass spectra were plotted for $\cos\theta_B > 0.0$ and for $\cos\theta_B < 0.0$. Each of these mass spectra was then fitted with contributions from $\omega\pi\pi$ phase space and the $b_1\pi$ model, as before. The contributions from these fits were combined to give N_F, the number of $b_1\pi$ events with $\cos\theta_B > 0.0$, and N_B, the number of $b_1\pi$ events with $\cos\theta_B < 0.0$, in the total mass range, giving

$$(N_F - N_B)/(N_F + N_B) = 0.27 \pm 0.16.$$

Hence there is no significant asymmetry in the $b_1(1235)$ angular distribution.

The cross section for production of this broad peak in the $b_1\pi$ mass spectrum in reaction (1) is of the order of 20 nb. Systematic uncertainties which are known to be in the experiment, particularly in the normalisation of the intensity of the incident beam, are larger than the statistical errors and are $\sim 25\%$. There is a further contribution to the systematic uncertainty from the possible variations in the model of the $b_1\pi$ system which have been discussed, or from its possible interference with the $\omega\pi\pi$ background. These latter contributions are difficult to quantify.

4. An interpretation of the peak

Diffractive photoproduction of the $\rho_3(1690)$ has been reported recently [5], so one expects corresponding production of its isoscalar partner, $\omega_3(1670)$, which is known to decay to $b_1(1235)\pi$[6]. Estimating the cross section for this photoproduction of $\omega_3(1670)$ as 1/9 of that for the $\rho_3(1670)$, one deduces a contribution of 16R nb, where R denotes the branching ratio of $\omega_3(1670) \rightarrow b_1(1235)\pi$ and a further factor of 2/3 has been included because of the particular charge states in reaction (1). It should be noted that the $\rho_3(1670)$ photoproduction cross section and the present measurements came from the same experiment, so that their overall systematic uncertainties due to beam normalisation should not be combined in making comparisons between them. A large contribution to the uncertainty is from the uncertainty in branching ratios of the $\rho_3(1690)$, which were taken to be

$$(\rho_3 \rightarrow a_2\pi)/(\rho_3 \rightarrow 4\pi) = 0.495$$

$$(\rho_3 \rightarrow 4\pi)/(\rho_3 \rightarrow \text{ all }) = 0.71$$

To explore this contribution of the $\omega_3(1670)$ to the mass spectrum in Fig.2(b), fits were made (over the mass range 1.5-2.1 GeV) with the sum of two Breit-Wigner intensities, where the mass and width of the lower peak was fixed at the values reported [20] for the $\omega_3(1670)$. In detail the intensities of the two peaks were fitted, with the mass and width of the upper peak successively fixed at a net of values, and the variation of χ^2 over this net was studied.

A typical fit is compared with the data in Fig.2(b). The mass of the upper peak was well determined by these fits, but acceptable fits were obtained for a very large range of widths. The cross section for production of the $\omega_3(1670)$ peak varied, with width of the upper peak, over the range 10-14 nbarn, which is close to the expected value of 8nb (corresponding to a branching ratio, R, of 0.5). A further set of fits was then made with the $\omega_3(1670)$ production cross section constrained to 8 nb. Acceptable fits were obtained over a similar range of masses and widths for the upper peak, with the intensity of the upper peak being ~ 4 standard deviations from zero. It therefore seems that a likely interpretation of the observed $b_1(1235)\pi$ mass spectrum is that there is a contribution from the $\omega_3(1670)$, with an intensity corresponding to that found for the $\rho_3(1690)$ [5], and from a further peak at higher mass, produced with a cross-section of ~ 10 nb. The mass of the upper peak is found to be 1.88 ± 0.04 GeV, but its width is only determined as ≤ 0.3 GeV.

5. Discussion and conclusions

It has been shown that a likely interpretation of the broad peak in the $b_1(1235)\pi$ mass spectrum is a contribution from the $\omega_3(1670)$, and a further peak at a mass of 1.88 ± 0.04 GeV and with a width ≤ 0.3 GeV. The contribution from the $\omega_3(1670)$ fits well the initial rise of the $b_1(1235)\pi$ mass distribution and has an intensity consistent with that expected from the observed photoproduction of the $\rho_3(1690)$. The upper peak is appreciably higher in mass than the $b_1\pi$ threshold, at 1.38 GeV, that it would seem it cannot be a non-resonant threshold effect, and so has to be taken as a candidate for a resonance or possibly a group of close resonances.

As the measured and predicted masses are close we discuss consequences of the hypothesis that the upper peak indicated by the analysis is entirely due to the hybrid states of Isgur et al.[2,3]. These states have I=0, so that there would be an unobserved contribution from $b_1^0\pi^0$,and therefore the total cross section for the states decaying into $b_1\pi$ would be ~ 15 nb. As the cross section for ω-meson photoproduction is 1μb [21], this implies the relative probability of excitation of the lowest states of excitation of the glue string, in the model of Isgur et al.[3], is ~ 0.015. Taking ratios to other related elastic diffraction cross sections, this then implies a cross section for producing the group of excited ρ hybrid states in photoproduction of $\sim$ 150 nb, and for producing the group of excited π hybrid states in π-meson scattering of $\sim$ 25-75 μb, depending on the relative probabilities of quark spin-flip and no-flip in elastic diffraction. From the decays predicted by Isgur et al.[3], the excited ρ states should contribute to diffractively produced 4π states, but they seem to be so broad that they would be difficult to identify. Four excited π states are predicted: three (J^π=2,1,0−) have S=1 and so would require spin-flip excitation of the π-mesons, while the fourth (J^π=1+) has S=0. Isgur et al. [3] only make a prediction for the decay of the 1− state. This prediction however is encouraging as the decay modes are to higher meson states ($b_1(1235)\pi, f_1(1285)\pi$) whose production has not yet been studied, and the width predicted is only $\sim$ 0.15 GeV. It would therefore seem that predictions of decay of the other excited π-meson states would be valuable, and a search for them could be a useful test of this model.

It is frequently suggested that the observation of an exotic state would be a valuable indicator of other than $q\bar{q}$ states. However any production by diffractive dissociation, as discussed in the present paper, can only lead to groups of overlapping states from which the exotic states are hard to separate. It is therefore useful to explore other modes of verification such as are discussed here.

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Figure Captions

1. $\omega\pi$ mass spectra for ranges of mass:

$(a) 1.3 < M(\omega\pi\pi) < 1.6 GeV$

$(b) 1.6 < M(\omega\pi\pi) < 2.0 GeV$

$(c) 2.0 < M(\omega\pi\pi) < 2.5 GeV$

The solid curves are results of a fit assuming $\omega\pi\pi$ phase space only, while the dashed curve, in Fig.1(b) only, shows the result of a fit assuming contributions from $\omega\pi\pi$ phase space and a $b_1(1235)\pi$ model, which is described in the text.

2. Yields of reactions as a function of $\omega\pi\pi$ mass:

(a) the estimated contribution of $\omega\pi\pi$ phase space

(b) the estimated contribution of $b_1(1235)\pi$

In Fig.2(b) the curves are

- - - - Fit with $\omega_3(1670)$ + a second resonance with M = 1.89 GeV,

$\Gamma = 0.20$ GeV.

oooooo contribution of $\omega_3(1670)$

.... contribution of other resonance.

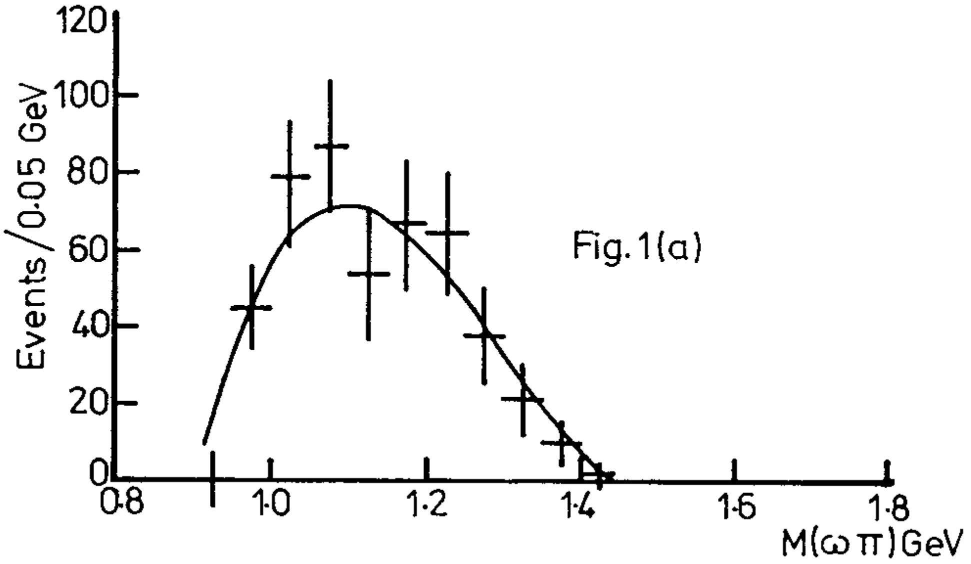
Fig. 1(a)

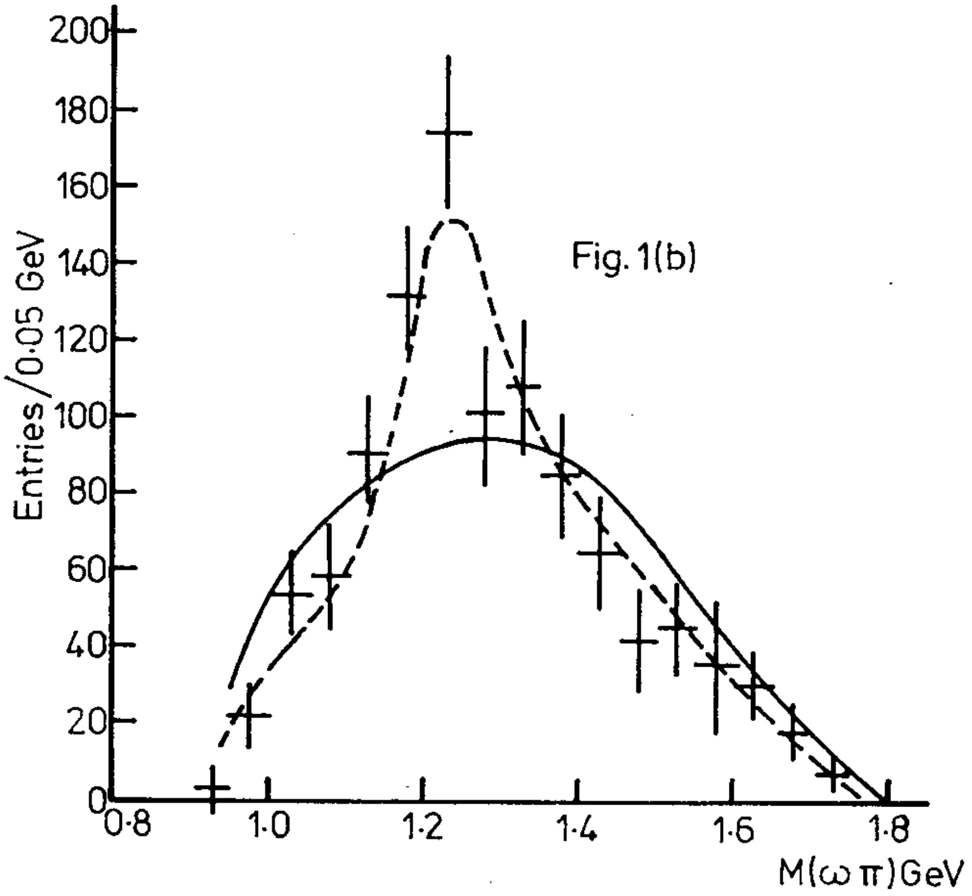
Fig. 1(b)

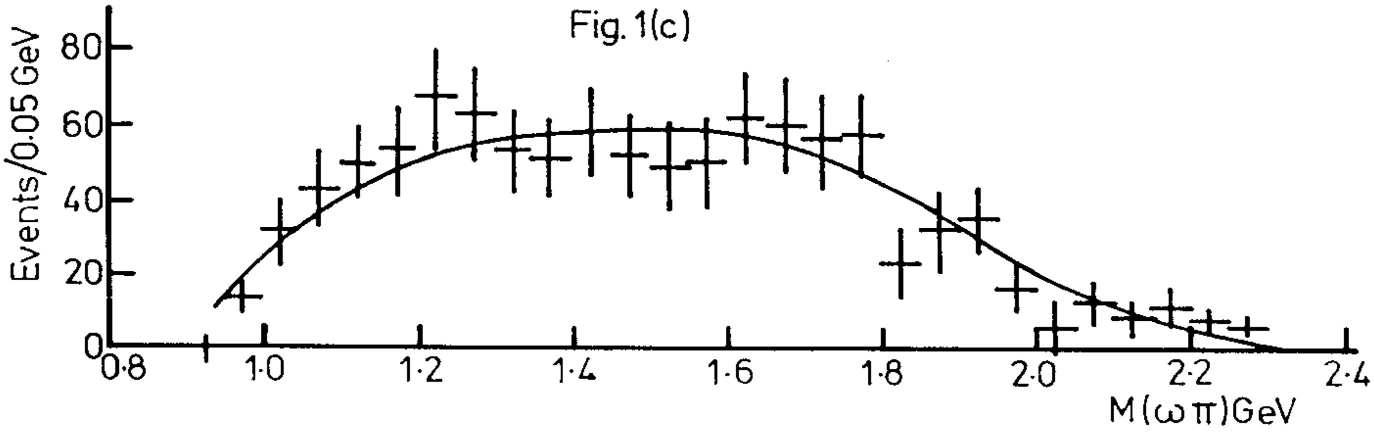
Fig. 1(c)

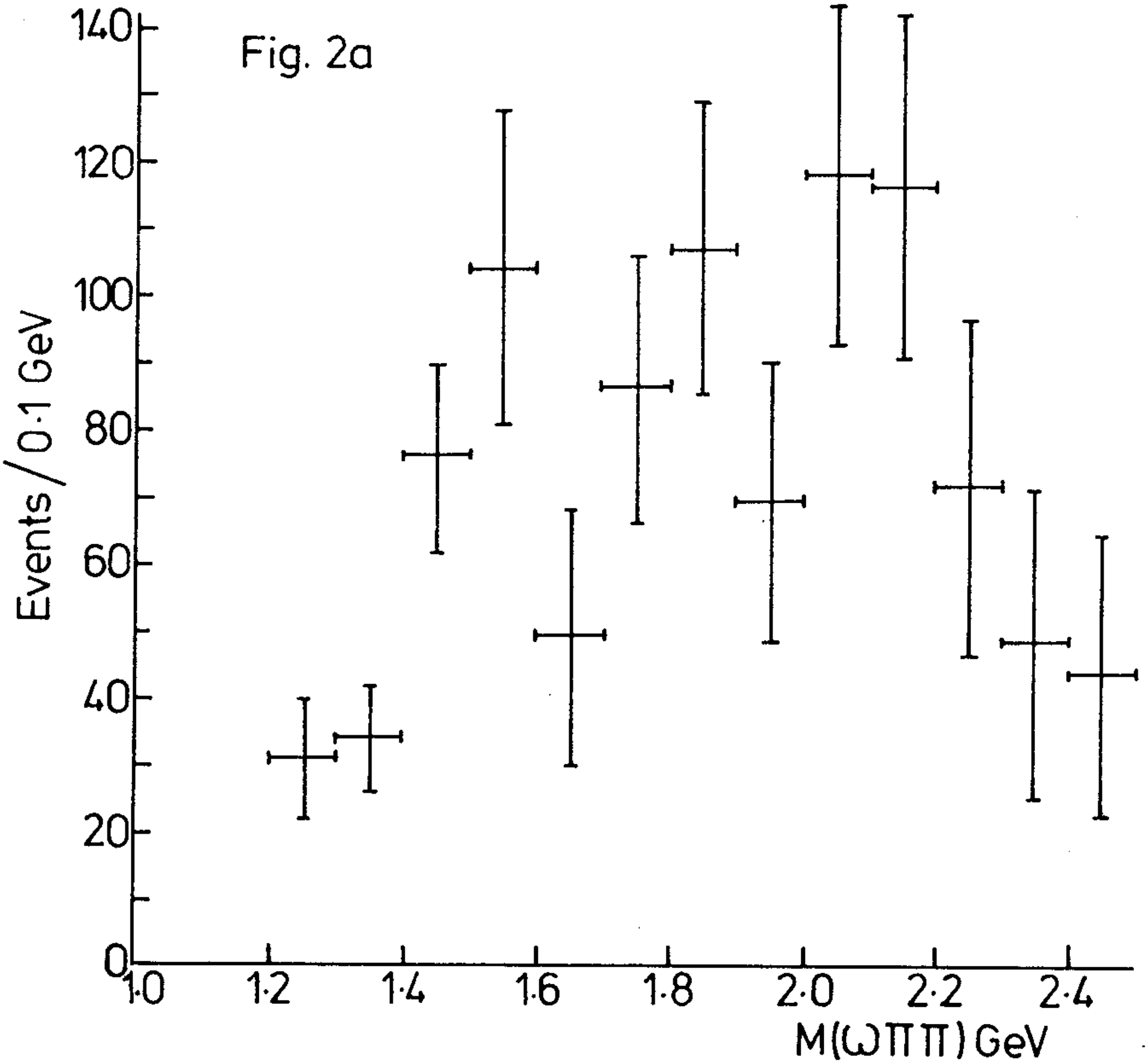

Fig. 2a

Events / 0·1 GeV
140
120
100
80
60
40
20
0
1·0
1·2
1·4
1·6
1·8
2·0
2·2
2·4
M(ωππ) GeV

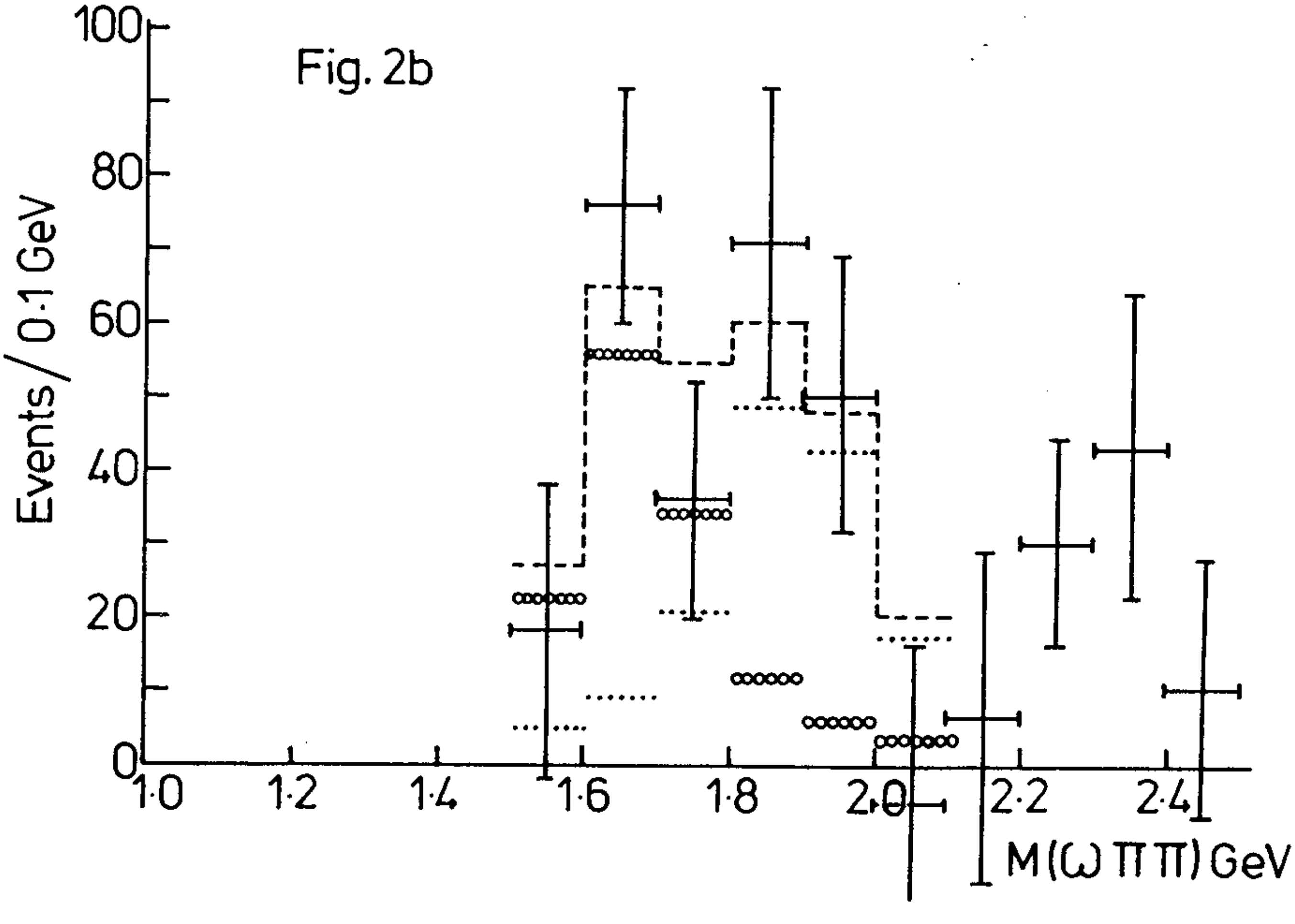

Fig. 2b

Events / 0·1 GeV
100
80
60
40
20
0
1·0
1·2
1·4
1·6
1·8
2·0
2·2
2·4
M(ωππ) GeV