Photoproduction of Narrow Resonances

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(Received 3 February 1975)

A very narrow resonance with a mass of 3.105 GeV/c^2 is observed in the reaction $\gamma + \text{Be} \to \mu^+ + \mu^- + X$. The total cross section for this process, as well as its t distribution, is given.

Recently, a very narrow resonance with a mass of 3.105 GeV/c^2 was observed in nucleon-nucleon collisions[1] and e^+e^- collisions.[2,3] Soon thereafter, a second narrow resonance with a mass of 3.695 GeV/c^2,[4] and an enhancement at 4.15 GeV/c^2,[5] were observed in e^+e^- collisions. We report in this Letter the preliminary results of a search for these states in the reaction $\gamma + \text{Be} \to \mu^+ + \mu^- + X$. The experiment is being carried out in the broad-band photon beam at the Fermi National Accelerator Laboratory.

The photons are obtained from a 0-mrad neutral beam which is produced by the interactions of 300-GeV protons in a 30.5-cm Be target. The γ-to-n ratio is improved by a factor of roughly 200 above the γ-to-n ratio at production by passing the beam through 34 m of liquid D_2. The photon spectrum at the experimental target is shown in Fig. 1.

The detector, which is shown in Fig. 2, consists of a multiwire-proportional-chamber magnetic spectrometer and a particle identifier. The spectrometer magnet $M2$, which has a field integral of 20 kG m, bends the trajectories of charged particles vertically. The magnet aperture, which is 61 cm high and 40.6 cm wide, determined the acceptance of the spectrometer.

The particle identifier consists of an electron

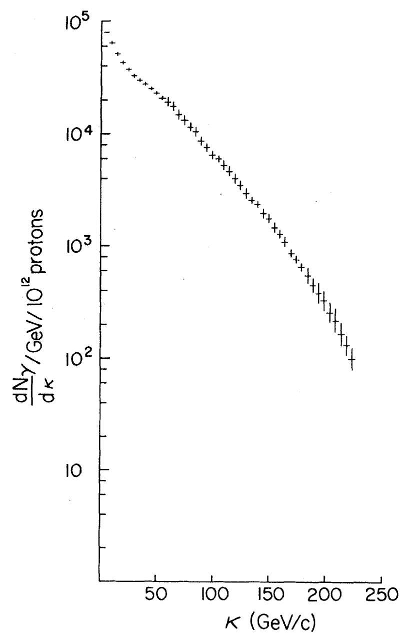

FIG. 1. Photon energy spectrum observed at photon target with the cryostat filled with liquid D_2.

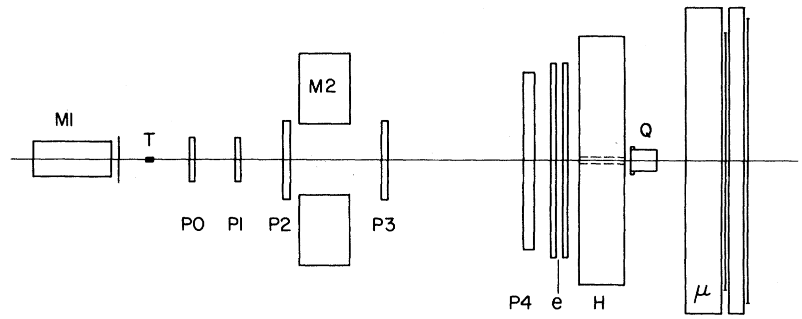

FIG. 2. Layout of detectors in experimental enclosure.

(and photon) calorimeter, a hadron calorimeter, and a muon identifier. The electron calorimeter is made up of an upstream and a downstream shower-counter hodoscope. Each hodoscope is split into two identical halves which are separated horizontally from each other by 10 cm, in order to allow the beam and the copiously produced e^+e^- pairs to pass through. Each upstream hodoscope counter contains six layers of lead and plastic, and each counter of the downstream hodoscope contains sixteen layers of lead and plastic. A layer is composed of a 4.8-mm-thick plastic scintillator and a 6.3-mm-thick Pb sheet.

The hadron calorimeter consists of 24 4.45-cm steel plates interleaved with 6.3-mm sheets of plastic scintillator. A 15-cm square hole allows the beam to pass through the calorimeter. The muon identifier consists of a steel shield which is 120 cm thick, a 22-element horizontal scintillation-counter hodoscope, a second steel shield which is 60 cm thick, and an eighteen-element vertical scintillation-counter hodoscope.

The photon beam intensity is monitored continuously by a 26-radiation-length Wilson quantameter.[6] At regular intervals, the photon spectrum is determined by measuring the total momentum of e^+e^- pairs produced in a 0.04-radiation-length lead target. The target is inserted in the photon beam during the calibration runs, in front of a horizontally bending dipole magnet $M1$ which opens the e^+e^- pairs so that their momentum can be measured in the multiwire-proportional-chamber spectrometer. The electrons are identified by their pulse heights in the electron calorimeter.

Events which have two or more tracks and which satisfy any of the following requirements are recorded on magnetic tape: two or more muons in the muon identifier, two or more electrons in the electron calorimeter, one electron and one muon, and, finally, any event which deposits more than a preset amount of energy in the hadron calorimeter. While the track reconstruction of all types of events has been performed, only the analysis of the dimuon data will be presented. For each event, all possible tracks are reconstructed from the multiwire-proportional-chamber hits. Events which have between two and five tracks are retained for further analysis. Each track is extrapolated back to each plane of muon counters, and a circle with a radius 2.5 times the expected deviation due to multiple scattering is computed. Any muon counter with a hit which overlaps this circle is considered to be correlated with the track. A "muon" track is required to have correlated hits in both muon-counter planes. From the previous sample, the subsample of all events with two muon tracks is extracted.

The paths of the two muons are extrapolated back to the target to determine if the pair came from a single point within the target. The distance of closest approach, the shortest line segment connecting the two tracks in front of the magnet, is required to be less than 2.5 mm. The vertex of the event is defined to be the midpoint of this line segment. It must be located within 20 cm of the target along the beam direction.

The momentum of each track is computed assuming that the magnetic field is uniform. The momentum resolution in the limit of a uniform field is calculated to be $\delta p/p = \pm 0.02$ [p in (GeV/c)/100]. The following kinematic variables are calculated from the momenta of the tracks: $M_{\mu\mu}$, the invariant mass of the dimuon pair; P, the total momentum of the dimuon; and t, the square of the four-momentum transfer to the dimuon pair.

The raw mass spectrum for all events with momenta greater than 80 GeV/c is shown in Fig.

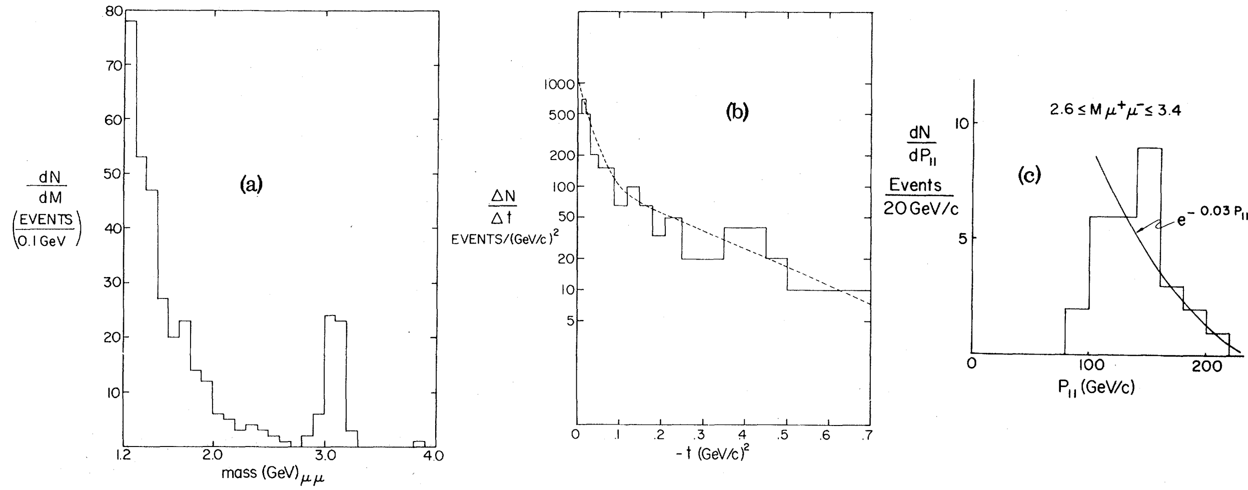

FIG. 3. (a) Dimuon invariant mass distribution observed above 1.2 GeV. (b) Observed t distribution for events in 3.1-GeV peak of (1). (c) Observed laboratory momentum spectrum of the events in (b), shown with the photon energy spectrum superimposed.

3(a). The two principal features of these data, which can be seen readily, are a preponderance of events at low mass, characteristic of muon-pair production by the Bethe-Heitler mechanism, and a peak at 3.1 GeV/c^2. It should be pointed out that this sample was not restricted to two-track events. The peak at 3.1 GeV/c^2 contains sixty events[7]; the width is consistent with our experimental resolution. We associate the 3.1-GeV/c^2 peak with the narrow resonance which was seen in e^+e^- annihilations and nucleon-nucleon collisions. Hereafter, only the events in the mass interval $2.8 < M_{\mu\mu} < 3.4$ GeV/c^2 will be discussed.

Since the beam is not a pure photon beam, it is important to determine what fraction of these events are produced by hadrons. In a companion experiment,[8] we have eliminated the photons in the beam with a lead absorber and searched for the production of the 3.1-GeV/c resonance induced by neutrons. In that experiment, we not only observed the production of the 3.1-GeV/c resonance by neutrons but also measured the production cross section using the same apparatus. Our measured cross section in the neutron experiment and the known ratio of photons to neutrons in the beam allow us to determine the number of events in this experiment induced by neutrons. We expect that fewer than three events in this experiment originated from neutrons in the beam.

The t distribution of the resonance events is shown in Fig. 3(b). Five events with extra tracks which come from the same interaction are in this sample of 48 events. There are twelve events with $-t > 0.7$. The average value of $-t$ for these events is 1.6 (GeV/c)^2, while the largest value of $-t$ is 5.9 (GeV/c)^2. The t distribution for a sample of 1000 events in the $\pi^+\pi^-$ final state with a mass of the ρ meson has also been studied. The ρ data can be fitted very well with the sum of two exponentials, one with a slope of ~40 (GeV/c)$^{-2}$, which is characteristic of the coherent scattering from the Be nucleus, and the other with a slope of ~10 (GeV/c)$^{-2}$, which is characteristic of scattering from single nucleons in Be. One can also see these same features in the t distribution of the 3.1-GeV/c^2 resonance. The curve shown in Fig. 3(b) is the calculated t distribution, corrected for acceptance and resolution, assuming $d\sigma(\gamma + \text{Be} \rightarrow 3.1)/dt$ is proportional to $A^2e^{40t} + Ae^{bt}$, where A is the atomic number of the Be nucleus. We have made no attempt to fit for b, but we find that the value of 4 (GeV/c)$^{-2}$ is quite consistent with our data. We conclude, therefore, that the 3.1-GeV/c^2 resonance is photoproduced diffractively on the Be nucleus. The simplest explanation for this behavior is that the 3.1-GeV/c^2 resonance couples directly to the photon in the same way as do the ρ, ω, and φ. In Fig. 3(c), we show the total momentum distribution of the dimuon.

We have not attempted at this time to exclude the events which do not come from either coherent scattering from Be or quasielastic scattering from a single nucleon. The cross section is calculated as follows: The total flux of photons above 80 GeV/c was determined from the total energy measured by the quantameter and the photon energy spectrum shown in Fig. 1. A correction of 1.2 was made for electronics dead time. After correcting for the geometric acceptance, we obtain

$$\sigma(\gamma + \mathrm{Be} \to 3.1 + X) = 16 \pm 5 \text{ nb/nucleus}.$$
$$\quad\quad\quad\quad\quad \llcorner\!\to \mu^+\mu^-$$

The quoted error includes both the statistical error and the uncertainties in the absolute flux and the acceptance calculation.

In order to determine the total cross section for the 3.1-GeV/c^2 resonance on nucleons, we first extract from our data the differential cross section

$$d\sigma(\gamma + p \to 3.1 + p)/dt|_{t=0},$$

using the relation

$$\int_0^{-0.5} \frac{d\sigma}{dt}(\gamma + \mathrm{Be} \to 3.1 + X)\, dt$$

$$= \frac{d\sigma}{dt}(\gamma + p \to 3.1 + p)\bigg|_{t=0} \int_0^{-0.5} (A^2 e^{40t} + A e^{bt})\, dt.$$

By assuming vector dominance and the optical theorem, by letting the forward scattering amplitude be purely imaginary, and by taking the width of the 3.1-GeV/c^2 resonance to be 6 keV and the branching ratio of the decay to two muons overall to be 0.07, we obtain[9,10]

$$\sigma_T(3.1 + \text{nucleon}) \simeq 1 \text{ mb}.$$

Since the magnitude of this cross section is too large for a weak interaction or an electromagnetic process, we conclude that the 3.1-GeV/c^2 resonance is a hadron.

We summarize our conclusions concerning the 3.1-GeV/c^2 resonance as follows: (1) It is photoproduced diffractively on Be. (2) It is a hadron. (3) The fraction of events produced with large momentum transfer is surprisingly large.

*Research supported by the National Science Foundation.

†Research supported by the U. S. Atomic Energy Commission.

‡Sloan Foundation Fellow.

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[5]J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 764 (1975).

[6]F. Harris and D. Yount, Nucl. Instrum. Methods 114, 357 (1974).

[7]Events with more than two tracks are candidates for the 3.7-GeV resonance. However, over 80% of our events have only two tracks and are identified with the 3.1-GeV resonance.

[8]B. Knapp *et al.*, following Letter [Phys. Rev. Lett. 34, 1044 (1975)].

[9]Professor B. Richter has kindly provided us with revised values of the branching ratio.

[10]While these assumptions are reasonable for other processes, we have no evidence for their validity in this reaction.