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L. Tau: TWO-BODY EFFECTIVE MASS SPECTRA IN THE PRODUCTS  
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sandro et al., if interpreted as a polarizability effect, imply a value of  $\alpha \approx 5 \times 10^{-40}$ .

In Fig. 1 the experimental values of  $\sigma(\theta)$ , after subtraction of the Schwinger contribution, are compared with theoretical curves obtained for various values of  $\alpha$ . The comparison should be made between the slopes of the experimental and theoretical curves rather than between absolute values as the absolute values are somewhat sensitive to the optical model parameters through  $|f_n|^2$ . From Fig. 1 it can be seen that the absence of an increase in  $\sigma(\theta)$  is consistent with  $\alpha \lesssim 2 \times 10^{-40}$  cm<sup>3</sup>; a value of  $\alpha$  as large as  $4 \times 10^{-40}$  is in severe disagreement with these data.

It is concluded that enhanced small-angle scattering of the magnitude observed at higher energies<sup>2-4</sup> does not occur at a neutron energy of 0.57 MeV and that the increase in  $\sigma(\theta)$  previously observed is not the result of an induced electric dipole moment in the neutron.

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## TWO-BODY EFFECTIVE MASS SPECTRA IN THE PRODUCTS OF THE REACTION $\gamma + p \rightarrow p + \pi^+ + \pi^-$

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We report here the preliminary results of an experiment on the reaction

$$\gamma + p \rightarrow p + \pi^+ + \pi^- \quad (1)$$

in which we have measured the  $(\pi^+, \pi^-)$  invariant mass spectrum, in the interval from 280 to 600 MeV, at a fixed proton laboratory angle of  $35^\circ$ .

The experimental apparatus is shown in Fig. 1. The photon beam of the Frascati electron synchrotron, operated at 1000 MeV, was collimated into a 1-cm diameter spot to strike a liquid hydrogen target 1 cm in length. Protons emitted at  $35 \pm 3^\circ$  in the momentum interval from 346 to 455 MeV/c are detected by a thin-plate spark chamber followed by a "range" spark chamber made up of 25 aluminum plates 1 mm in thickness.<sup>1</sup>

In addition to this we determine the direction of the two pions by letting each traverse a sys-

tem of two spark chambers. The positions of these were chosen so as to select, with reasonably flat geometrical efficiency, total center-of-mass energies of the  $\pi-\pi$  system within the interval from roughly 280 to 600 MeV. As a consequence of this, the accepted production angles of the  $\pi-\pi$  system in the c.m. of the reaction ranged from  $45^\circ$  to  $90^\circ$ . Figure 1 also shows eight scintillators (viewed by 56 AVP phototubes) which establish a fast time coincidence of the three particles and also reject some of the spurious events by means of a final anticoincidence on the proton side. A further experimental check to filter out the background was the measurement of the proton pulse height in counter 3P. Another was the measurement of the proton time of flight, obtained by displaying pulses from counters 1P and 3P on a fast oscilloscope. A marked separation in time and

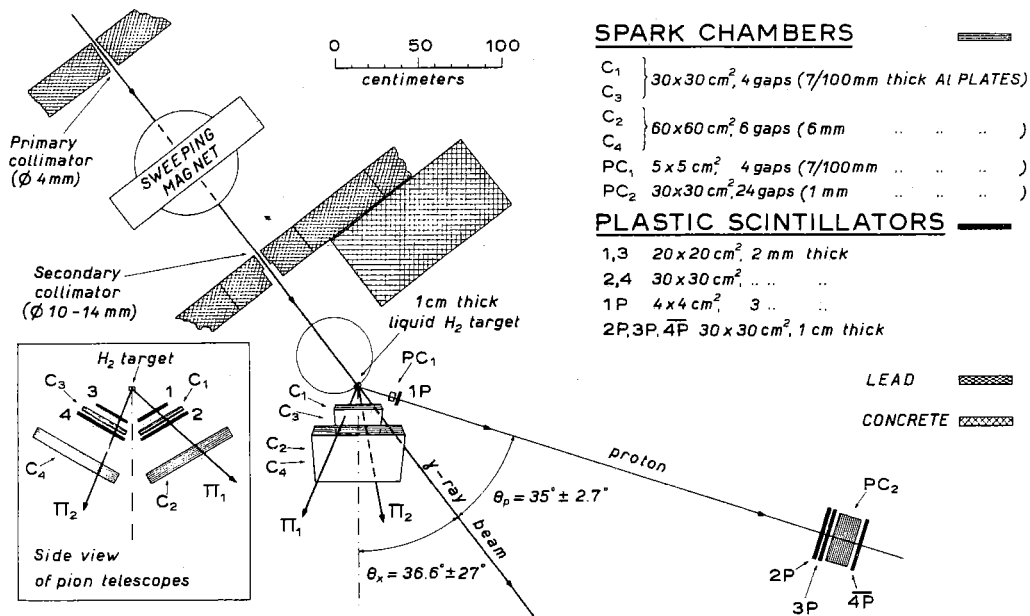


FIG. 1. A drawing of the experimental apparatus.

pulse height was found between protons and other particles.

Multiple scattering of the three final particles and  $\gamma$ -ray conversion were kept to a minimum (i) by making the outer jacket wall of the hydrogen target with aluminum 0.5 mm thick, (ii) by using 2-mm thick scintillator for counters 1, 2, 3, 4, and 1P, and (iii) by constructing the first spark chamber in each branch with five 0.07-mm aluminum foil plates. The spark chambers, filled with commercial He, were operated with a clearing field of 75 V/cm and triggered by pressurized nitrogen spark gaps. The total delay time was about 200 nsec. Under these conditions the measured efficiency per gap was more than 85% for tracks with angles up to 30° with respect to the electric field direction.

The coordinates of the three particles in the six spark chambers constitute the input data for an analysis made on an IBM 1620 computer. The first operation of the program is a least-squares fit to find the reaction point within our target. Most of the points cluster very well within the known target dimensions and a criterion for getting rid of background was introduced on this basis.

The spatial directions of the particles, together with the proton momentum, overdetermine by one the kinematical parameters of the reaction. We chose this additional parameter to be the  $\pi_1$  and  $\pi_2$  masses, assumed equal, i.e., the known value of the pion mass  $\mu$  is not used in the data analysis, but is left as a free parameter

to be calculated by the computer. Figure 2 shows the spectrum of values obtained for  $\mu$ . Another criterion for selecting events was decided on this basis, taking into account the calculated resolution function. The low amount of background outside the peak assures us that the contamination due to three-pion photoproduction is less than 2%. We find that most of the events with wrong masses have also erratic source

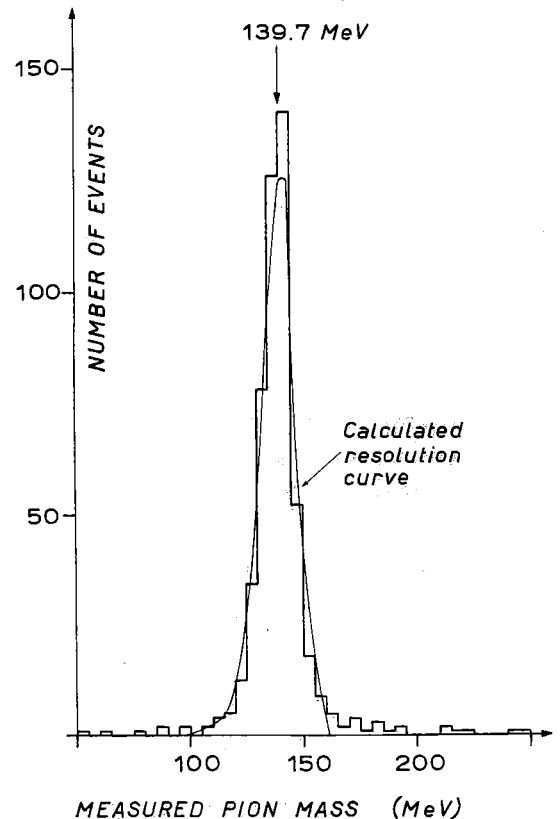


FIG. 2. The spectrum of the measured pion masses.

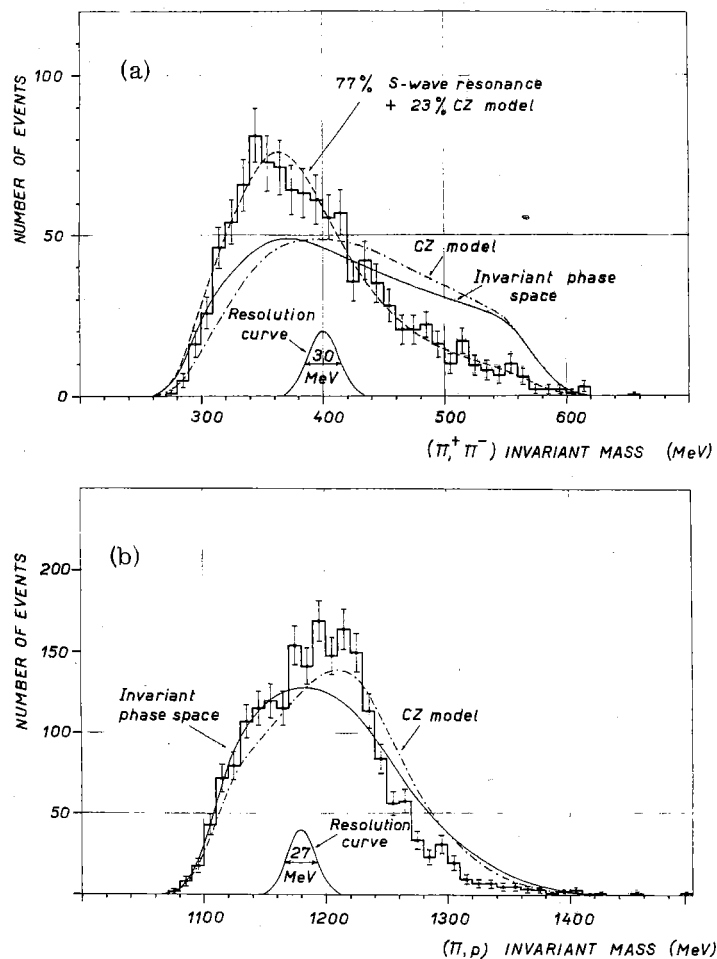


FIG. 3. (a) The  $(\pi^+, \pi^-)$  effective mass spectrum; (b) the sum of the  $(\pi^+, p)$  and  $(\pi^-, p)$  effective-mass spectra. The Gaussian curves are the calculated resolution functions; their widths are constant over the full mass intervals.

points. Of a total of 1315 events in which there was at least one trace in each spark chamber, 1037 passed our selection criteria.

The  $(\pi^+, \pi^-)$  effective mass spectrum is shown in Fig. 3(a); in Fig. 3(b) we show the  $(\pi, p)$  effective mass spectrum, which is actually the sum of the  $(\pi^+, p)$  and  $(\pi^-, p)$  spectra, as we are unable to distinguish the charge of the pions. As a starting point for a discussion of our data, we compared these spectra with the invariant phase-space factor normalized to the same number of events. To obtain this factor we made a Monte Carlo calculation which takes into account the bremsstrahlung spectrum and the geometrical limitations of the detection apparatus. Folded into the calculation was the resolution curve of our detection system, which we had obtained by another Monte Carlo calculation.<sup>2</sup> The data are not in agreement with the curves.

As seen in Fig. 3(b), we are investigating a kinematical region of our process where the contribution of the  $\frac{3}{2}, \frac{3}{2}$  pion-nucleon isobar is

not negligible. This contribution is taken into account by the Cutkowsky and Zachariasen model<sup>3</sup> (abbreviated CZ). This model predicts<sup>4</sup> correctly the total cross sections for the reaction (1) as measured by Chasan *et al.*<sup>5</sup> The next step of our analysis was therefore the comparison of our data with this model.<sup>6</sup> While it is in reasonable agreement in the case of the  $(\pi, p)$  spectrum, it fails in the case of the  $(\pi^+, \pi^-)$  spectrum. Figure 4(a) shows the Dalitz-Fabry plot of all the events. The distribution of the points is another confirmation of the fact that the anomaly cannot be ascribed to the effect of the  $\frac{3}{2}, \frac{3}{2}$  nucleon isobar.

The invariant matrix element squared, as a function of the  $(\pi^+, \pi^-)$  mass, shows a broad but clear peak around  $m_{\pi\pi} = 380$  MeV. To our knowledge there is no obvious interpretation of this fact, even from a qualitative standpoint. There seem to be two possible simple explanations: The first, which we cannot exclude with the present set of data, is connected with the fact, shown in Fig. 4(b), that there exists in our experiment a narrow correlation between the  $m_{\pi\pi}$  value and the energy,  $k$ , of the photon initiating the reaction.<sup>7</sup> The explanation would then be that photons with energies around 610 MeV excite the nucleon to an isobar which then decays emitting two pions. The isobar mass would be 1420 MeV; some indication for this has probably been found by Cocconi *et al.*<sup>8</sup> and by Bareyre *et al.*<sup>9</sup> The second possible interpretation is that of assuming a strong  $\pi$ - $\pi$  final-state interaction. Following this line, we conclude that the  $\pi$ - $\pi$  invariant scattering amplitude shows a maximum, probably connected with a resonance to which however this experiment does not allow a spin and isospin assignment. On the other hand, as the dipion energy is fairly low, it is not unreasonable to assume that the resonant state has  $J=0$ . Assuming this to be the case, we tried to fit the data by introducing, as an enhancement factor, an invariant pion-pion scattering amplitude squared given by the following S-wave resonance formula:

$$|I|^2 = \beta^2 / [(W^2 - W_0^2)^2 + \beta^2 q^2 / W^2].$$

This corresponds to the effective-range equation

$$(q/W) \cot \delta = (1/\beta)(W_0^2 - W^2),$$

where  $W = m_{\pi\pi}$ ,  $q = (W^2/4 - \mu^2)^{1/2}$ , and  $\beta$  and  $W_0$  are two adjustable parameters. The fitting procedure takes into account the finite resolution of our detection system and determines also the unknown fraction  $\alpha$  due to the contribution of

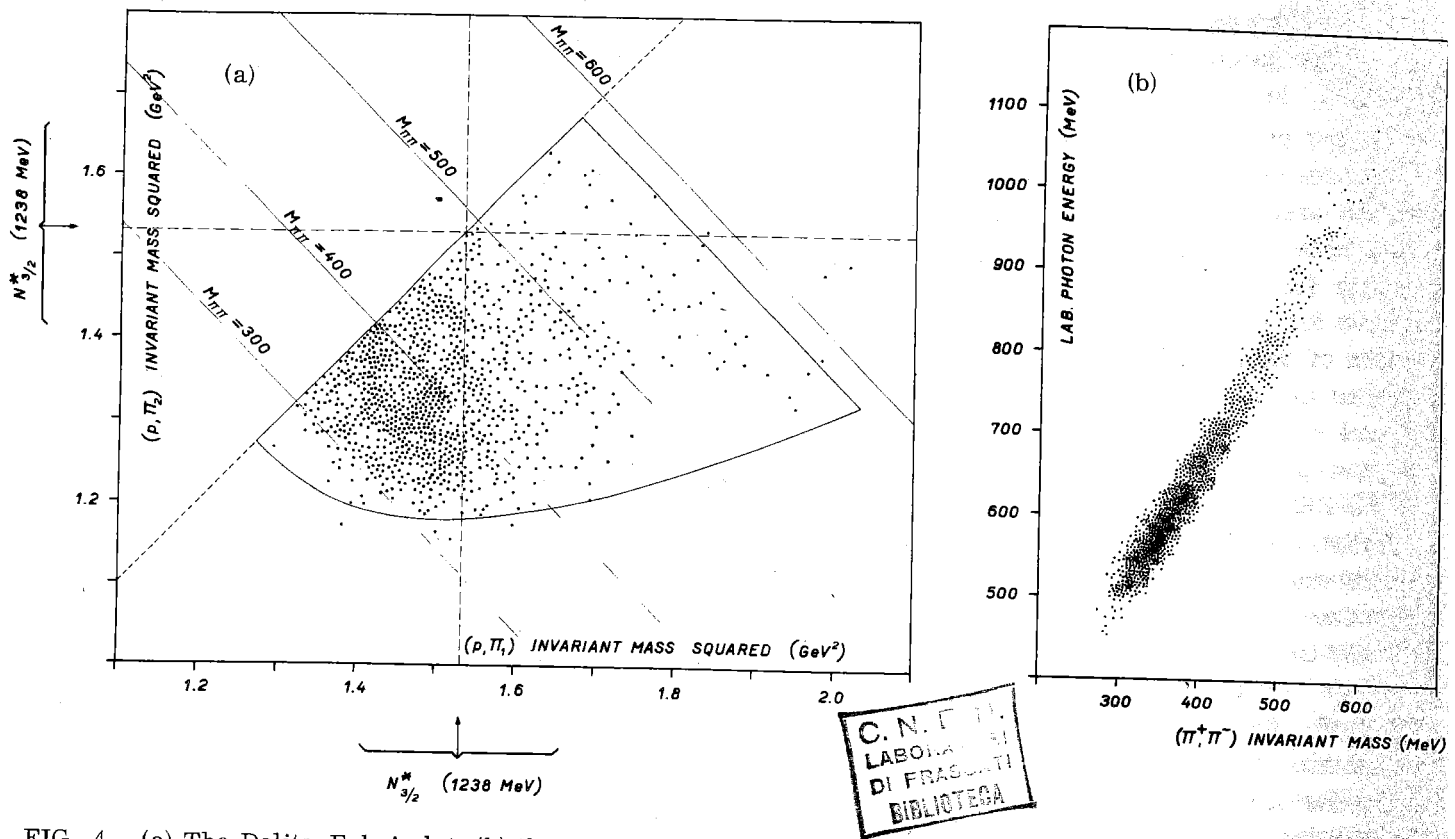


FIG. 4. (a) The Dalitz-Fabri plot; (b) the correlation between the laboratory photon energy and the dipion effective mass.

other processes, as described by the CZ model. We find that in 23% of the cases the reaction goes through these processes and in 77% of the cases through the resonant state. We find  $\chi_{\min}^2 = 20$  where 23 is expected. The fit, shown in Fig. 3(a), gives

$$\left. \begin{aligned} W_0 &= 379 \pm 4 \text{ MeV} \\ \Gamma &= \frac{\beta}{2W_0} \left[ 1 - \left( \frac{2\mu}{W_0} \right)^2 \right]^{1/2} = 139 \pm 13 \text{ MeV} \\ \alpha &= 0.23 \pm 0.04, \end{aligned} \right\} \quad (2)$$

where  $\Gamma$  is the full width at half maximum.

In the above procedure we have assumed that when the  $J=0$  state is produced the amplitude for process (1) differs from a constant only because of the final-state interaction between the two pions. A more rigorous procedure necessitates the proper symmetrization of the two-pion final-state wave function.<sup>10</sup> This symmetrization effect can be approximately taken into account by introducing in the phase space the factor  $1 + \exp[-4q^2(R/2.15)^2]$ , where  $R$  is the radius of the interaction volume. We have repeated the above calculations for  $R/(\hbar/\mu c) = 0.5, 0.75, \text{ and } 1.0$  but the values (2) do not change appreciably.

The experimental distribution of the angle in the di-pion rest system between one pion and the di-pion flight direction is in agreement with the 23%-77% mixture of CZ model and S-wave resonance.

As stated above, the recoil proton is emitted at a laboratory angle of  $35^\circ$  in the momentum interval from 346 to 455 MeV/c. An average over this interval gives a photoproduction cross section for the resonant state which, in the c.m. of reaction (1), has the value  $\sim 1.3 \times 10^{-30} \text{ cm}^2/\text{s}$ .

Analyzing the products of  $\pi^- - p$  collisions at 4.7 GeV/c, Samios et al.<sup>11</sup> found some evidence for  $(\pi^+, \pi^-)$  resonances with  $I=0$  or 1 and with masses 395 and 520 MeV. Further anomalies near  $m_{\pi\pi} = 400$  MeV have been found in the  $I=0$  or 2 states by Richardson et al.<sup>12</sup> in  $\pi^+ - d$  collisions at 1.23 GeV/c. On the contrary no resonances in this mass region were observed by Alff et al.<sup>13</sup> in the products of  $\pi^+ - p$  collisions for incident pion momenta of 2.34, 2.62, and 2.90 GeV/c.

Kirz, Schwartz, and Tripp<sup>14</sup> have measured spectra of  $(\pi^+, \pi^-)$  masses by using secondary pions of the process  $\pi^- + p \rightarrow \pi^+ + \pi^- + n$ . They were able to prove that a peak exists in the case of the  $I=0$  pion-pion state. Unfortunately, the

position of the peak changes with the kinetic energy of the incident pions in the interval 360-780 MeV. In this energy interval the effect of the lowest pion-nucleon isobar is predominant, but an analysis due to Olsson and Yodh<sup>15</sup> shows that the observed anomaly is not completely ascribable to the isobar effect. It may be worth noticing that, while Kirz, Schwartz, and Tripp observe for each ( $\pi^+$ ,  $\pi^-$ ) mass the total cross section of the production process, the detected di-pions in our experiment are emitted between  $45^\circ$  and  $90^\circ$  in the c. m. of the reaction.

A pion-pion resonance with  $I=J=0$  and mass around 400 MeV ( $\sigma$  resonance) has been assumed by Brown and Singer<sup>16</sup> to explain the energy spectra and decay branching ratios of the  $\eta$  and  $K$  mesons. Following this line, Crawford *et al.*<sup>17</sup> are able to fit the  $\pi^0$  energy spectrum from the  $\eta \rightarrow \pi^+ + \pi^- + \pi^0$  decay with  $m_\sigma = 381$  MeV and  $\Gamma_\sigma = 48$  MeV. More recently Nishijima<sup>18</sup> was able to evaluate the  $K_1 - K_2$  mass difference by introducing the same resonance.

In conclusion, the anomaly shown by our set of data may be interpreted in terms of a  $\pi - \pi$  resonance with  $I=J=0$ . This is consistent with theoretical calculations and other experimental evidence, but more experimental work has to be done to exclude the effect of a nucleon isobar.

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<sup>1</sup>The momentum error due to the finite thickness of the plates is less than 5 MeV/c. The nuclear absorption alters the range-momentum correlation in only

4% of the events.

<sup>2</sup>The Monte Carlo calculation for the resolution includes the effects of scattering of the particles in the target, counters, and spark chambers, and also the error in the position of the sparks. The results of the Monte Carlo calculation for the phase-space factor have been checked by comparing them with the results of a direct integration.

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<sup>6</sup>In the calculation we have used the experimental values of  $\delta_{33}$ . Moreover, some kinematical corrections have been introduced in the formula to account for the finite nucleon mass.

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