Evidence Concerning Pion-Pion Interactions below the 765-Mev Pion-Pion Resonance*

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A search has been made for pion-pion resonances in the reaction $\pi^-+p\rightarrow\pi^-+\pi^0+p$ at incident pion energies of 871 Mev and 775 Mev, using a sodium-iodide luminescent chamber as a detector. The spectra of m^*, the total energy of the two pions in their own barycentric system, are presented and compared with the spectra predicted by phase-space alone. The maximum m^* which can be obtained in this experiment is 695 Mev and the recoil proton momenta range from 400 to 700 Mev/c. The 871-Mev spectrum shows a deviation from the phase-space prediction in the form of an abrupt rise at an m^* of 590 Mev. This rise is most prominent for the spectrum with recoil proton momenta above 550 Mev/c. The 775-Mev spectrum does not show any strong deviations from phase space. It is concluded, on the basis of this experiment and other experiments at similar or somewhat higher-incident pion energies, that the peak above phase space in the m^* spectrum range of 575 to 700 Mev is due to at least one other process besides the 765-Mev two-pion resonance particular. The possible existence of a new two-pion, $T=1$ resonance with an m^* of about 600 Mev is discussed. An evaluation of the performance of the luminescent chamber in this experiment is made.

I. INTRODUCTION

In the experiment described below, the reaction

$$\pi^-+p\rightarrow\pi^-+\pi^0+p \tag{1}$$

was studied for incident pion energies of 775 and 871 Mev. The purpose was to search for evidence of pion-pion interactions, and in particular for the two-pion resonance first predicted by Frazer and Fulco[1] to be at an m^* of about 450-Mev total energy, where m^* is the total energy of the two final pions in their own barycentric system. The experiment was performed at the Bevatron of the Lawrence Radiation Laboratory. Subsequent to this experiment, several bubble chamber studies[2–4] have found such a resonance at an m^* of 765 Mev. Since the maximum observable m^* is 695 Mev in the experiment being reported here, the 765-Mev resonance is not seen directly. Nevertheless, the results presented in this paper, namely the m^* spectra at the two incident pion energies, are believed to be of interest.

This experiment was performed using a small liquid hydrogen target, in which the reaction occurred, and using a sodium iodide luminescent chamber to measure the angle and range of the recoil proton. An arrangement of scintillation counters was used to limit the photographs to only those events with recoil proton momenta between 400 and 700 Mev/c.

The apparatus is discussed in Sec. II; details of its operation and performance are presented in Sec. III, and results are presented and discussed in Sec. IV. Conclusions are given in Sec. V. This experiment and an elastic pion-proton experiment,[5] carried out immediately preceding it at the Bevatron, are the only published physics experiments to have been performed using the luminescent chamber technique. Therefore, also included in Sec. III is a discussion of the properties and performance of the luminescent chamber as exhibited by both of these experiments. This experiment was also carried out at 682 Mev but the results are not included in this paper.

The remainder of this introduction discusses the question of theoretical interpretation. In reaction (1), with an unpolarized hydrogen target, a convenient set of independent kinematic variables are: K, the relative momentum of the two pions in their own barycentric system; m^*, the total energy of the two pions in that system; and p, the momentum of the recoil proton in the laboratory system. Now, the goal of a complete theory of this reaction is to give a distribution function of these kinematic variables. The parameters in the distribution function would be functions of the total energy. However, this has not yet been done exactly, but only in a very approximate way by attributing most of the reaction to one or two dominant processes.

Two dominant processes have been proposed for reaction (1). One of these processes is the formation of excited states of the proton corresponding to the $J=\frac{3}{2}$, $I=\frac{3}{2}$ resonance and other resonances in pion-nucleon elastic scattering.[6] Here one visualizes the incoming pion exciting the proton and scattering off the excited proton; the excited proton then decaying to the recoil proton and another pion. A completely different process is based upon a strong two-pion resonance.[7,8] Here one

* Supported in part by the Office of Naval Research.
† Part of a thesis submitted by C. Clyde Peck in partial fulfillment of the requirements for the degree of Doctor of Philosophy at the University of Michigan.
[1] W. R. Frazer and J. R. Fulco, Phys. Rev. **117**, 1609 (1960).
[2] E. Pickup, D. K. Robinson, and E. O. Salant, Phys. Rev. Letters **7**, 192 (1961).
[3] D. Stonehill, C. Baltay, H. Courant, W. Fickinger, E. C. Fowler, H. Kraybill, J. Sandweiss, J. Sanford, and H. Taft, Phys. Rev. Letters **6**, 624 (1961).
[4] A. R. Erwin, R. March, W. D. Walker, and E. West, Phys. Rev. Letters **6**, 628 (1961).
[5] K. W. Lai, L. W. Jones, and M. L. Perl, Phys. Rev. Letters **7**, 125 (1961).
[6] R. M. Sternheimer and S. J. Lindenbaum, Phys. Rev. **123**, 333 (1961).
[7] G. F. Chew and F. E. Low, Phys. Rev. **113**, 1640 (1959).
[8] C. Goebel, Phys. Rev. Letters **1**, 337 (1958).

visualizes the incoming pion reacting with a virtual pion to produce two outgoing pions, the proton not taking part in the reaction except to emit or absorb the virtual pion.

One way to study these reactions is to compare the experimental distribution functions with those predicted by phase-space alone. The deviation of the experimental distribution functions from the phase-space prediction gives the behavior of the transition matrix element. A convenient comparison can be made by integrating over two of the variables and looking at the spectrum of the third variable. One hopes that a strong and striking deviation from the phase-space prediction will be evident which can in turn be related to a particular dominant process in the reaction.

This paper is concerned only with the effects of the two-pion resonance as a dominant process. Now most of the recent interest in the effects of a two-pion resonance in the distribution functions of reaction (1) has been directed not so much at understanding this reaction as at extracting information about the two-pion resonance, for example such information as its position (m^* value), width, and strength.

This is precisely what is attempted in this experiment in which the spectrum of m^* is studied. If this spectrum, when compared with the phase-space prediction, shows a strong peak at some m^* value then one may suspect a two-pion resonance at that m^*. Furthermore, if a peak occurs at the same m^* for different incident pion energies then the evidence for a two-pion resonance at that m^* is very good. This is the reason for studying the m^* spectrum at many incident pion energies.

More generally Chew and Low,[7] and Goebel[8] have shown how data of this sort can be used to find the entire pion-pion cross section by considering only small values of p, and extrapolating to negative p values. The range of the recoil proton and the scintillation counters limit p to values 400 to 700 Mev/c in this experiment. No attempt at extrapolation or at extraction of a pion-pion cross section was made because these values of p are still too high for this purpose. However, they are still sufficiently low so that a two-pion resonance could be more prominent in the m^* spectrum than in an m^* spectrum with all values of p used. Thus, the attention in the analysis was concentrated on the more qualitative search for deviations from phase space of the m^* spectrum under fairly favorable limits on p.

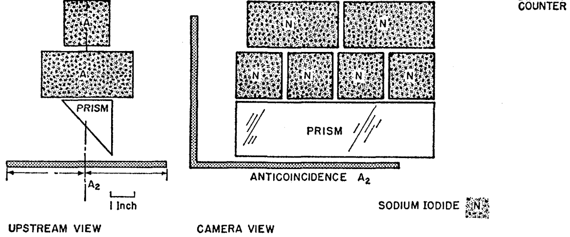

FIG. 1. Experimental arrangement of the sodium-iodide luminescent chamber and the event-defining counters.

Because of this emphasis on qualitative analysis, the data were divided into high- and low-momentum parts, above and below 550-Mev/c recoil proton momentum. This would then show whether any deviations from phase space tended to be the result of a "peripheral" type of interaction, where the recoil proton momentum is low. On the other hand, if the deviation occurred with high momentum transfer, then the Chew-Low theory would not be applicable, and the dominant reaction would be "nonperipheral."

II. APPARATUS

The apparatus, Fig. 1, included a 1.5-in.-diam and 3-in.-long liquid hydrogen target in which the reaction occurred. Immediately below the target was a 4.5-in.-high by 9-in.-long by 2.25- to 4.5-in.-wide sodium-iodide luminescent chamber in which the recoil protons stop. The angle of the proton is thus directly seen, and the momentum is easily determined from its range. Equally important is the ionization density information provided by the luminescent chamber track which enables one to separate stopping protons from stopping pions.

The 10-μsec time resolution and $\frac{1}{2}$-μsec image storage time of the luminescent chamber system makes it possible to photograph only events of probable interest. The selection of those events was done by placing a 0.125-in.-thick by 0.5-in.-wide by 9.25-in.-long scintillation counter, Fig. 1, between the hydrogen target and the sodium iodide chamber, and placing an "L"-shaped, 0.25-in.-thick scintillation counter below the chamber. The "L"-shaped counter had a cross section such that any particle coming from the hydrogen target and going through the upper counter must also go through the "L"-shaped counter, unless the particle was stopped or deflected in the luminescent chamber. A signal from the upper counter in coincidence with an incoming beam particle signal and no signal from the "L"-shaped counter indicated a stopping proton, stopping pion, or a scattered particle. Upon this signal combination a picture was taken. The beam particles were defined by three scintillation counters in coincidence, and two anticoincidence counters. One of the latter, A_2, was placed between the last beam-defining counter B_3 and the hydrogen target. A_2 was 3 in. by 3 in. with a $\frac{1}{2}$-in. by $\frac{1}{2}$-in. hole. This hole was the same size as the outer dimensions of B_3, and thus A_2 reduced the number of events produced by reactions in B_3. The other anticoincidence counter, A_3, was a 3 in. by 3 in. counter placed 3 ft downstream from the hydrogen target to eliminate events from pions so slightly scattered that the recoil proton was too slow to enter the luminescent chamber.

A block diagram of the electronics is displayed in

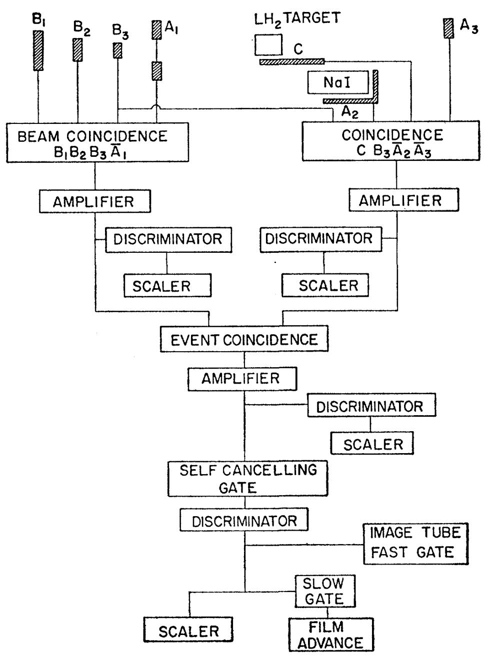

FIG. 2. Block diagram of the counting circuitry.

Fig. 2. The coincidence and amplifying circuits and the scalers were standard equipment of the Lawrence Radiation Laboratory.[9] The pulsing circuits have been described before.[10]

The luminescent chamber itself consisted of six 2-in. by 2-in. by 4-in. blocks of sodium iodide. Each block was clad in glass which was 0.125 in. thick. They were arranged as in Fig. 1. A prism immediately below the chamber provided a 90-deg stereo image for determining whether a particle left the chamber. The particle track and its stereo image were focussed by the same lens onto the photocathode of the first image tube in the intensifying system. The lens consisted of a 12-in. focal length $f/2.5$ Areoektar immediately preceded by a 24-in. focal length $f/5$ achromatic telescope objective. The magnification of the chamber was 0.4 through this lens system.

The image intensifying system consisted of three image tubes, Fig. 3. The first one was a Westinghouse WX4171 with a 5-in. diameter S20 photocathode and a 1-in. P15 anode and was coupled by two $f/0.85$, 76-mm focal length Super Farron lenses to the cathode of a three-stage RCA C73491 image tube. This image tube had a 1-in. diameter S20 photocathode and a 1-in. diameter P20 anode. This was in turn coupled through a pair of $f/1.5$, 85-mm Nikkor lenses to a second C73491. The output phosphor of this tube was coupled by a second pair of Super Farron lenses to a camera magazine using

[9] University of California Radiation Laboratory Counting Handbook, UCRL 3307, 1959 (unpublished).

[10] M. L. Perl, L. W. Jones, and K. W. Lai, *Proceedings of an International Conference on Instrumentation for High-Energy Physics*, Berkeley, 1960 (Interscience Publishers, Inc., New York, 1961), p. 186.

TABLE I. Percentage of electron and muon contamination in beam.

	871 Mev	775 Mev
Muon	8.0	15.0
Electron	23.0	19.0

Royal X-pan film. The WX4171 was normally "on" while the first three-stage tube, which was normally "off," was turned on for 5 to 7 μsec by the gate signal from the counters. There was a 0.4-μsec delay between the passage of the particle through the scintillator and the application of the gate pulse. The second three-stage tube, also normally "off" to reduce background fog on the film, was turned on for a 10-msec period. The decay character of the P15 phosphor limited the over-all time resolution of the system to about 10 μsec, and the camera film advance limited data collection to one event per Bevatron pulse.

III. OPERATION AND PERFORMANCE OF THE SYSTEM

The pion beam from an internal target at the Bevatron was focused and momentum analyzed using two bending magnets and two quadrupole doublets. The momentum of the beam was determined by the method of a current-carrying wire under tension. These measurements were confirmed by the use of the same beam at higher energies for an elastic scattering experiment[5] where the momentum can be independently determined. The momentum spread of the beam was $\pm 3\%$ and the central momentum was known to 2%. The muon and electron contamination in the beam were measured with a threshold Čerenkov counter. Precentage contaminations are given in Table I. Not all data at any energy were taken at a single stretch. Rather, energies were alternated several times during the run so that changes in the Bevatron operation and recording apparatus would not bias the results of one energy with respect to another.

A stopping proton can come from single-pion production, from elastic scattering, and from multiple-pion production. Elastically scattered protons will appear at 140 Mev in the m^* spectrum and can therefore be separated from inelastic protons. Since there is no way

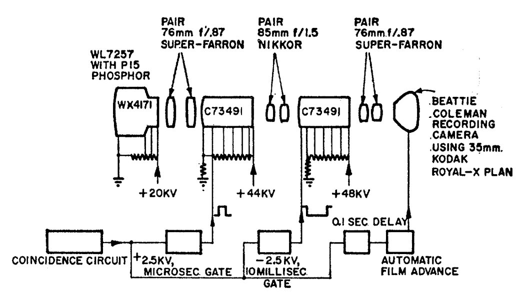

FIG. 3. Image intensifying system.

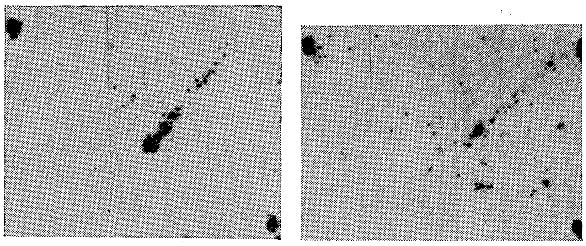

FIG. 4. Typical particle tracks in the luminescent chamber. The picture on the left is a proton stopping in sodium iodide. The large gap in the middle of the track is caused by the proton crossing the $\frac{1}{8}$-in. of glass separating the sodium-iodide crystals. On the right is a pion stopping. These tracks are not the best tracks obtained, nor the worst, but are reasonably representative of the quality obtained.

in this experiment to separate events with a proton and three or more final pions from events corresponding to reaction (1), the incoming pion energy was purposely kept low so that the multiple pion production is a negligible contamination. For 0.95-Bev pion-proton collisions, phase-space calculations[11] say that the ratio of all events with three pions in the final state to all events with two pions in the final state is 0.099. Experiments with 0.96-Bev negative pions on protons[12,13] give the ratio of events with a proton and three pions in the final state to events corresponding to reaction (1) to be 16%. Assuming that the ratio between this last experimental ratio and the phase-space ratio persists, calculations show that the contaminations are 12% for 871 Mev and 5% for 775 Mev.

The apparatus was operated both with the hydrogen target full and empty. One roll of target-empty pictures was taken for each 2.5 rolls of target-full pictures.

The photographs were scanned three times. The first scan was used to establish criteria for the selection of protons. The difference between a typical stopping proton and a typical stopping pion is demonstrated in Fig. 4. Once these criteria were established, an experienced scanner could scan and measure a photograph of a proton in about 2 min. Scanning an event which was not a proton took about 10 sec; pictures with no events required about 2 sec to scan.

A fiducial light was placed at each of the four corners of the box in which the crystals were held to provide a reference for the track orientation. Because of pincushion distortion in the final image caused by the intensifying system, a photograph of a grid system was taken through the same system. After aligning the grid with the image of fiducial lights which appeared on the photograph, tracks were measured by recording the coordinates of two points on the track.

The remainder of this section is devoted to a discussion of the properties of the sodium iodide luminescent chamber as exhibited by this experiment and the elastic scattering experiment.[5] In the case of counter-controlled, short-time-resolution track visualization devices, such as the scintillation chamber and the spark chamber, there are two kinds of properties of interest. One group of properties has to do with the quality of the picture itself; for example, resolution, contrast, ease of scanning, and information content. The other group is concerned with the counter-triggering system, ratio of useful events to all events which trigger the chamber, and the bias introduced by the triggering system.

In this experiment, stopping protons were distinguished from stopping pions, Fig. 4. In the elastic experiment,[5] protons of greater than 2 to 3 times minimum ionization were distinguished from minimum ionizing particles with a 2-in. track length. The angles of minimum ionizing particles with tracks at least 2 in. long in the sodium iodide can be measured with a root mean square error of 2°. This error decreases to about 1° for tracks longer than 4 in. For stopping particles with ranges less than this, multiple scattering increases the measurement error giving an over-all uncertainty of 3° to 4° depending on the range. Angles of stopping particles with less than $\frac{1}{2}$-in. range cannot be usefully measured. The range of a stopping particle can be measured to about 0.1 in.

As indicated by the scanning times given above, the pictures were simple to scan and to measure. Scanning of both experiments showed about 90% scanning efficiency for a single scan and negligible errors. The intensifying system worked reliably, requiring no maintenance, and very little adjustment during both experiments.

The triggering system in this experiment was insufficiently selective in determining events of probable interest. The effect was to decrease the number of events rather severely. It was expected that for every good event one or two false triggers would occur, mostly from pion stopping or interacting in the chamber. This did, indeed, happen; however, several times this number of false triggers occurred in which there was no track at all. A major cause for these false triggers was particles going through the Lucite lightpipe of the scintillation counter although not going through the counter itself. Gamma-ray and neutron conversion in the crystals and accidentals were also faults. With the beam intensity per pulse, which was available, a properly working trigger system would record a good event every five or ten beam pulses. The false triggers reduced this rate by a factor of 2 while causing a picture to be recorded almost every pulse. However, the simplicity of the trigger system which led to the inefficiency also kept the counter-induced bias very small and this bias was easily corrected. It is important to note that the problem of triggering efficiency is severe in many experiments with scintillation chambers or spark chambers since most

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[11] R. Serber, *Proceedings of the Seventh Annual Rochester Conference on High-Energy Nuclear Physics, 1957* (Interscience Publishers, Inc., New York, 1957), Session V, p. 1.

[12] V. Alles-Borelli, S. Bergia, E. Perez Ferreira, and P. Waloschek, Nuovo cimento **14**, 211 (1959).

[13] W. D. Walker, *Proceedings of the Sixth Annual Rochester Conference on High-Energy Nuclear Physics* (Interscience Publishers, Inc., New York, 1956), Session IV, p. 16.

TABLE II. Number of recorded and corrected events.

	871 Mev	775 Mev
Uncorrected elastic	228	312
Corrected elastic	292	408
Uncorrected inelastic	329	281
Corrected inelastic	420	406
Corrected target empty	35	33
Final inelastic with background subtracted	317	313

ways of increasing the efficiency introduce bias or decrease the rate of data acquisition.

In summary, the sodium iodide luminescent chamber performed in this experiment and in the elastic scattering experiment[5] about as expected. However, the triggering system was inefficient and many useless pictures were taken, particularly in this experiment.

IV. ANALYSIS AND RESULTS

Table II gives the number of uncorrected events found at each energy. These data were corrected by weighting each event by a correction factor determined from the following considerations.

First, a correction was made for the finite size of the hydrogen target and of the chamber. This was done by computing the available target volume for each event, this volume depending upon the proton angles and range. This factor was usually about 1.3 and was computed to within 5% accuracy of the correction itself.

Second, a correction was made for protons scattered in the chamber or target. This correction depended upon the proton momentum, was usually about 1.15, and was computed to within 10% accuracy of the correction itself.

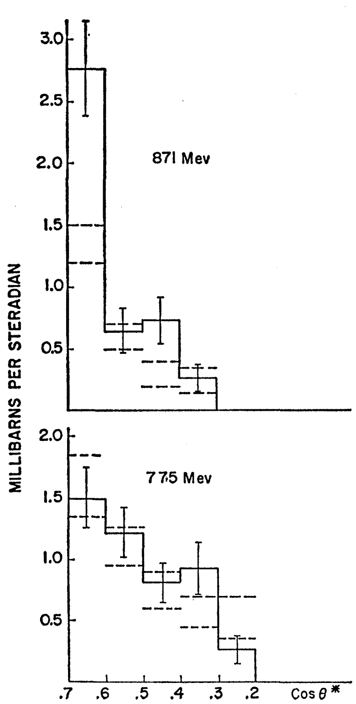

FIG. 5. Elastic differential cross sections at the incident pion energies used in this experiment. The dashed lines give rough limits to the cross sections interpolated from data taken at different energies. Because the cross section on the diffraction peak changes so rapidly, the large deviation from the interpolated data in the $\cos\theta^*$ region from 0.6 to 0.7 in the 871-Mev data can be caused by a small systematic error, to which the inelastic spectrum will be insensitive.

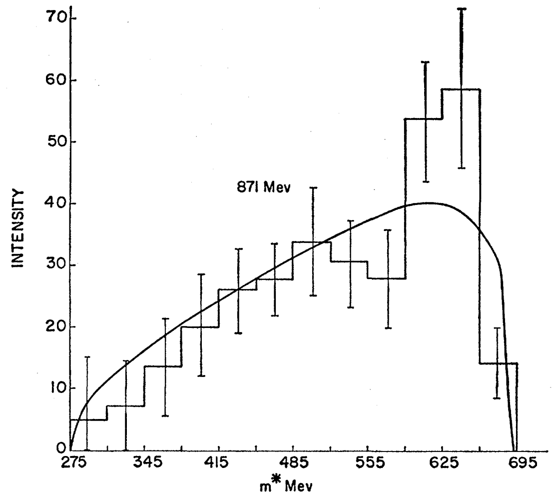

FIG. 6. The spectrum of all inelastic events at 871 Mev. The smooth line is phase-space normalized to the data.

Third, a search was made for bias caused by scanning errors or nonuniformities in the chamber detection efficiency. This was done by investigating the distribution of stopping protons in the chamber for a range of angles and momentum without geometric bias. About one eighth of the volume of the chamber in one corner of the chamber showed such a bias, which required a correction factor of about 1.2 for that region. This correction affected mostly the elastic events.

Fourth, a correction was made for the contamination of the beam by electrons and muons and for an error in the beam scaler. This error had been found in the elastic experiment[5] with the same beam, and the correction factor was taken from that experiment.

Finally, the target-empty data, also with these first four corrections, was subtracted from the target-full data to correct for events from the walls of the target and from the last beam defining counter.

Next an m^* spectrum was obtained from the corrected data using the equation

$$m^{*2}=(E_0-E)^2-(p^2-2p_0p\cos\theta+p_0^2), \qquad (2)$$

where p_0 is the incident pion momentum, E_0 is the total initial energy of the pion-proton system in the laboratory, and E is the recoil proton's total energy. For elastic events, m^* equals 139.6 Mev, and for inelastic events m^* is greater than 274.6 Mev. However, there is an error in the determination of m^* caused by errors in determining the range and angle. As stated in Sec. II the uncertainty in the range of protons in sodium iodide is equivalent to a momentum error of 10 to 15 Mev/c, depending on the range, while the angular uncertainty was 3 to 4 degrees. However, for elastic events, a 3- to 4-degree error in angle is equivalent to an uncertainty

of 50 Mev/c in momentum. Consequently it was the angular error which was principally responsible for the uncertainty in the determination of m^* value.

This uncertainty in m^* leads to a spreading of the elastic peak about 140 Mev so that a tail of the elastic peak extends into the inelastic region. The subtraction of this elastic contamination in the inelastic region was made statistically by using the elastic events on the low-m^* side of the elastic peak in combination with a study of the angle and range error distributions. The correction for inelastic events which lie below 275 Mev is negligible because of the slope of the inelastic spectrum. Table II shows the number of corrected events, both elastic and inelastic, as well as the total effect of the subtraction on the inelastic spectrum.

Figure 5 shows the elastic differential cross sections obtained in this experiment for each energy by plotting the distribution of the events falling in the elastic region against $\cos\theta^*$, where θ^* is the angle of the scattered pion in the barycentric system. Each graph also contains for comparison the differential cross section found in other experiments.[14–16] There are no measurements at exactly the energies used in this experiment so that it was necessary to interpolate from data at other energies which in turn leads to an uncertainty in the comparison differential cross section. Therefore these comparison differential cross sections are indicated by rough upper and lower limits rather than by a definite

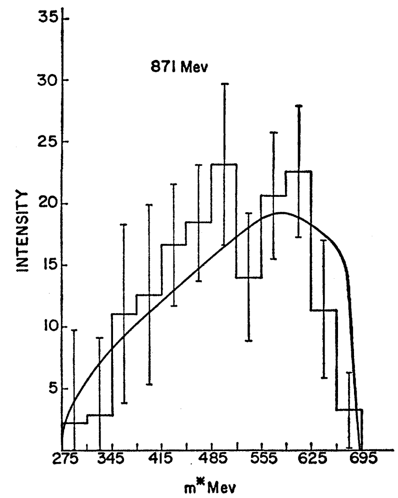

FIG. 8. Spectrum of inelastic events at 871 Mev where the recoil proton momenta are less than 550 Mev/c.

value. The agreement between the elastic differential cross sections from this experiment and from the interpolation from published data is good both in shape and in absolute value.

The final corrected inelastic spectrum is presented in Figs. 6–11. The data are plotted both for all recoil proton momenta and for the data divided into those events with recoil momenta above and below 550 Mev/c. In all figures, the experimental distributions are compared to the spectra predicted by phase-space alone, whose areas are normalized to the experimental areas. These phase-space spectra take account of the fact that not all possible proton momenta and angles are detected in this experiment. Phase-space density D, per m^* was calculated from the equation

$$\partial D/\partial m^* = (\mathrm{const}/p_0 M)(m^{*2}-4\mu^2)^{\frac{1}{2}} \times[\Delta_{\max}{}^2(m^*)-\Delta_{\min}{}^2(m^*)], \quad (3)$$

where M is the proton mass, μ is the pion mass, and Δ^2 is the square of the four-momentum transfer to the proton. The errors shown in the figures are root mean square statistical errors and include the statistical errors from the subtraction of the elastic and the target-empty contamination. The authors believe that the systematic errors in the data are of the same size or smaller than the statistical errors.

The spectra of all events at an incident pion energy of 871 Mev, Fig. 6, shows a rise above phase space at high m^* values, between 590 and 660 Mev. In Fig. 7, where the proton recoil momenta are above 550 Mev/c, this rise appears quite sharply. Furthermore, no such deviation occurs in events where the recoil momenta are less than 550 Mev/c, Fig. 8. Since phase-space factors cut off so rapidly, it is not possible to make a statement about the width of this deviation. Since the statistical errors are about 20% and systematic errors may be as large and there is no absolute normalization for the phase-space volume, the magnitude of the deviation from phase-space is uncertain.

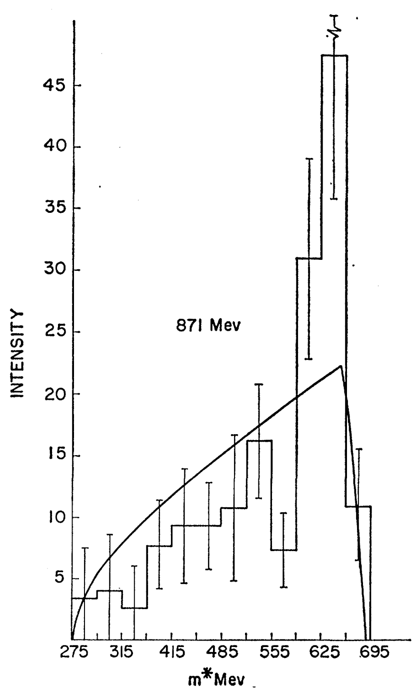

FIG. 7. Spectrum of inelastic events at 871 Mev where the recoil proton momenta are greater than 550 Mev/c.

[14] J. I. Shonle, Phys. Rev. Letters **5**, 156 (1960).
[15] R. R. Crittenden, J. H. Scandrett, W. D. Shepard, W. D. Walker, and J. H. Ballam, Phys. Rev. Letters **2**, 121 (1959).
[16] C. D. Wood, T. J. Devlin, J. A. Helland, M. J. Longo, B. J. Moyer, and V. Perez-Mendez, Phys. Rev. Letters **6**, 481 (1961).

In Fig. 9, the data taken at 775-Mev incident pion energy show no striking deviations from a phase-space distribution. For recoil proton momenta above 550 Mev/c, Fig. 10, despite phase space diminishing rapidly, there appears to be a rise above phase space between 590- and 625-Mev m^* value, which is consistent with the results at the higher energy. This feature does not appear where recoil momenta are below 550 Mev/c, (Fig. 11). Although none of the spectra are smooth, no deviations occur which are significant in themselves. The comments made above regarding the magnitude of the deviations apply here as well.

The cross section at incident pion energy of 871 Mev for the portion of phase space that can be seen in this experiment is 3.84 ± 0.96 mb. Using data from other experiments,[17–19] the total cross section for reaction (1) was interpolated to be 7 mb. The ratio of these two numbers is 0.55 ± 0.14 as compared to the ratio of phase-space volume, 0.30.

For incident pion energy of 775 Mev, a cross section of 2.66 ± 0.67 mb was found compared to the interpolated value of 4.2 mb. The ratio of these numbers is 0.63 ± 0.16 as compared to the phase-space prediction of 0.35.

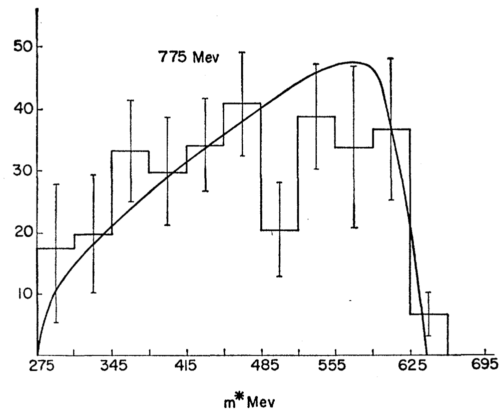

FIG. 9. The spectrum of all inelastic events at 775 Mev. The smooth line is phase-space normalized to the data.

V. CONCLUSIONS

The rise above phase space above 590 Mev in the m^* spectra, with recoil proton momenta above 550 Mev/c, constitutes the most interesting feature of the data presented here.

The existence of the 765-Mev resonance is based upon the findings of various experimental groups studying the m^* spectra from the reactions

$$\pi^- + p \to \pi^- + \pi^0 + p, \quad (1)$$

$$\pi^- + p \to \pi^+ + \pi^- + n, \quad (4)$$

$$\pi^+ + p \to \pi^+ + \pi^0 + p, \quad (5)$$

$$\pi^+ + p \to \pi^+ + \pi^+ + n. \quad (6)$$

This resonance has been seen in reactions (1) and (4) by Erwin *et al.*[4] with incident pions of 1.89 Bev and by Pickup *et al.*[2] with pions of 1.25 Bev incident energy. Stonehill *et al.*,[3] using 1.26-Bev incident pions, detected the 765-Mev resonance in (5) but not in (6). Only Erwin *et al.*[4] present the m^* spectra separately for low recoil proton momenta. In their data the 765-Mev resonance is most prominent for events with recoil proton momenta less than 400 Mev/c. The other groups present m^* spectra which include all the observed recoil proton momenta.

Studies of reactions (1), (4), (5), (6) at lower pion energies allow a more direct comparison with the results of this experiment. Stonehill *et al.*[3] also studied (5) and (6) at 1.09-Bev and 0.91-Bev incident pion energies, where, again, a peak in the m^* spectra is seen only in (5). At 1.09 Bev the peak in m^* occurs at about 700 Mev. A peak which is less sharp occurs between m^* values 600 and 720 Mev in the data taken at 0.91 Bev. Again, the data presented include all recoil momenta. Reaction (1) has been studied by Rushbrooke and Radojicic[20] at an incident pion energy of 0.96 Bev. They find a peak at an m^* of about 660 Mev in events with proton recoil momenta greater than 550 Mev/c. Pickup *et al.*, in an earlier paper,[21] studied reactions (1) and (4) at 0.96 Bev. Here a peak at an m^* of about 600 Mev occurs in reaction (1) for protons scattered backward in the barycentric system of all three particles. No peak is seen for reaction (4). These backward events correspond to laboratory recoil proton momenta up to about 730 Mev/c, so that there is no conflict with the results of Rushbrooke and Radojicic. Anderson *et al.*[22] studied reactions (1) and (5) at 0.90 Bev for recoil proton momenta all below 400 Mev/c. Although the Chew and Low extrapolation method[7] does show a two-pion resonance at 625 to 660 Mev, there is no evidence for the resonance in the m^* spectrum in the physical region. It is particularly important that this sample of events, all with very low recoil proton momenta, do not show a peak in the m^* spectrum.

The most recent result is that of Barloutaud *et al.*[23] who studied reactions (5) and (6) at incident pion energies of 0.82, 0.90, and 1.05 Bev. They find a peak in the m^* spectrum of (5) but not in (6). This peak lies

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at 575 Mev in the 0.82-Bev, but seems to be shifted upward in the 0.90- and 1.05-Bev data. They state that the peak is not particularly prominent in events with low recoil proton momenta compared to those with high recoil proton momenta.

The data discussed in the last paragraph are consistent with the results of this experiment. Summarizing, in reaction (1) for incident pion energies from roughly 0.8 to 1.0 Bev, there is a peak in the m^* spectrum at about 600 to 700 Mev, compared to phase space. This peak is most prominent for events with relatively high recoil proton momenta, roughly above 550 Mev/*c*. According to this experiment, this peak in the m^* spectrum of reaction (1) is almost gone at incident energies somewhat below 0.8 Bev. Reactions (4) and (5) also show such a peak extending as low as 575 Mev although there are fewer published data showing which recoil proton momentum range is important.

The immediate question is whether this peak in reaction (1) is simply the tail of the two-pion 765-Mev resonance, with an apparent shift of the peak caused only by lack of available phase space, as has been speculated.[3] The authors are inclined to argue against this very simple explanation. First, at high incident pion energies, the 765-Mev resonance occurs most distinctly where momenta transfers to the protons are below 400 Mev/*c*.[4] The resonance can be seen at high recoil proton momenta, but is wider and less sharp. Second, at these higher incident energies, the half-width is 75 to 100 Mev. But the peak observed in this experiment can be seen as far away as 160 Mev below the 765-Mev peak and that of Barloutaud *et al.*[23] is 190 Mev below the 765-Mev peak. In order to obtain a shift of such magnitude and to explain the changing relative importance of the high and low recoil proton momentum ranges, one must consider a more complicated explanation than lack of available phase space. Such effects as changes in the nonresonant background, interference with the nonresonant background, and final-state interaction with the recoil proton would be required.

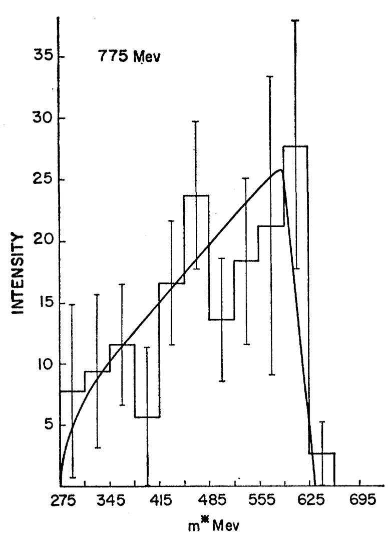

FIG. 10. Spectrum of inelastic events at 775 Mev where the recoil proton momenta are greater than 550 Mev/*c*.

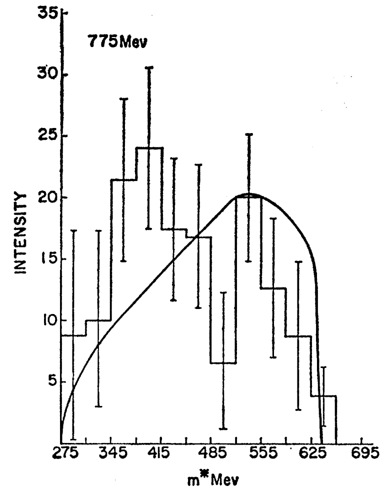

FIG. 11. Spectrum of inelastic events at 775 Mev where the recoil proton momenta are less than 550 Mev/*c*.

Another explanation has been put forth by Barloutaud *et al.*[23] They interpret their results as demonstrating the existence of a 575-Mev two-pion resonance with $T=1$ and probably $J=1$. The apparent upward shifting of this peak at higher incident pion energies in all the quoted experiments would then be explained as the addition or interference of events from the 765-Mev, two-pion, $T=1$, $J=1$, resonance.

The explanation is in good agreement with the results of this paper. The 871-Mev data show a peak which can be directly attributed to the postulated 575-Mev resonance and this would add confirmation to the $T=1$ designation. Also the importance of nonperipheral events in the resonance is indicated in both experiments. The 775-Mev data have a maximum m^* so close to this possible new resonance that little indication of the peak is to be expected. In fact, in the events with recoil proton momenta above 550 Mev/*c* there is a rise above phase space for large m^*. But it is not statistically significant by itself. It should be noted that in the experiment reported here the restricted range of recoil proton momenta causes a sharper and lower m^* cutoff than in an experiment in which all recoil proton momenta are observed.

At this time the evidence for the new two-pion resonance is not as strong as that for the 765-Mev two-pion resonance. One difficulty is the confusion caused by this possible new resonance apparently not appearing in very peripheral events. Thus, Anderson *et al.*,[22] studying reaction (1) and (4) at 0.90 Bev, find no evidence of this new peak in the m^* spectrum on very low recoil proton momenta. Another difficulty is the apparent shifting of the peak upward as higher incident pion energies are used. Some explanation of the interaction of this new resonance with the 765-Mev resonance is required.

In conclusion, the results of this experiment and the other quoted experiments indicate that either a new

lower energy two-pion resonance exists, or that some other process besides the 765-Mev two-pion resonance is important in producing a peak in the m^* spectrum at incident pion energies of roughly 0.8 to 1.0 Bev in reactions (1), (4), and (5).

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Parity of the Neutral Pion and the Decay $\pi^0 \rightarrow 2e^+ + 2e^-$†

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Two hundred and six electronic decays of the π^0, $\pi^0 \rightarrow e^+ + e^- + e^+ + e^-$, have been observed in a hydrogen bubble chamber. The decay distributions of the electron pairs and the total rate for this process are shown to be in good agreement with theory. An examination of correlations of the e^+e^- pair decay planes on the basis of electrodynamic predictions is in agreement with the hypothesis that the π^0 is pseudoscalar, but disagrees for scalar pions by 3.6 standard deviations.

I. INTRODUCTION

The parity of the pion is, of course, important in all manifestations of the strong interaction. Perhaps the only previous direct experimental evidence on this incisive quantity is from the s-wave capture of π^- mesons in deuterium.[1] It is essential in the interpretation of these experimental results to demonstrate that the capture proceeds indeed from the s state, and this has been done in a convincing way.[2]

It was first pointed out by Yang[3] that the decay of the neutral pion offers, at least in principle, a means for an unambiguous measurement of the parity: The plane polarizations of the two photons must be parallel for scalar pions, and perpendicular in the pseudoscalar case. Unfortunately there are no known techniques for the measurement of this polarization correlation. The chief reason for this difficulty is that although the plane of the pair produced by the photon is well correlated with the polarization, the angle between positron and electron is so small that the scattering in converters of practicable thickness destroys this correlation.

It is remarkable and fortunate that this angle is much larger [$\approx (mc^2/E)^{\frac{1}{2}}$ in place of mc^2/E] in the internal conversion of the γ rays, so that the plane may be measured. The decay $\pi^0 \rightarrow 2e^+ + 2e^-$ offers then a means of determining the parity of the π^0. However, the decay is rare; the rate is expected to be of the order of $(1/160)^2$, already on the basis of Dalitz's original work on these internally converted pairs.[4]

We report here an experimental study of this process, based on an observation of 8×10^6 π^0 decays in some 836 000 bubble chamber pictures. Two hundred and six completely electronic decays were observed. A preliminary report based on one-half of the events has previously been published.[5]

II. EXPERIMENTAL DETAILS

π^- mesons from the Nevis Cyclotron are slowed down by polyethylene absorber and stopped in a hydrogen bubble chamber 12 in. in diameter, 6 in. in depth, placed in a 5.5-kgauss magnetic field. π^0's were produced in the reaction $\pi^- + p \rightarrow n + \pi^0$ which proceeds for 62% of the stopped pions. The pictures were obtained in a series of three separate exposures, the last of which consisted of 380 000 pictures accumulated at a chamber cycle rate of 90 pictures per min. On the average there are 15 stopping pions per picture (Fig. 1). The events were measured on a digitized scanning machine, on three views, with a measurement accuracy

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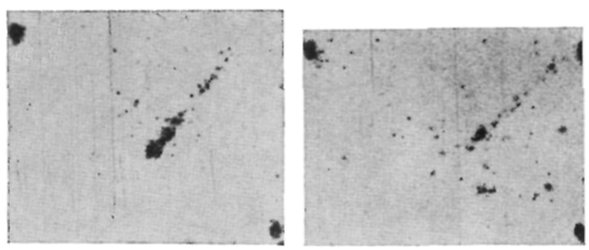

FIG. 4. Typical particle tracks in the luminescent chamber. The picture on the left is a proton stopping in sodium iodide. The large gap in the middle of the track is caused by the proton crossing the $\frac{1}{8}$-in. of glass separating the sodium-iodide crystals. On the right is a pion stopping. These tracks are not the best tracks obtained, nor the worst, but are reasonably representative of the quality obtained.