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DECAYS OF THE $\psi'(3684)$ TO OTHER CHARMONIUM STATES*

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* Ph.D. dissertation.

DECAYS OF THE $\psi'(3684)$ TO OTHER CHARMONIUM STATES

MASTER

We report on an experimental study of the decays of the $\psi'(3684)$ to other charmonium states. The decays of 10^6 $\psi'(3684)$'s were observed with the SLAC-LBL Mark II detector at the e^+e^- storage ring SPEAR. Branching ratios have been measured for $\psi'(3684)$ decays to $\gamma\chi$ where the χ decays to $\gamma\psi(3095)$ or to hadrons. An upper limit of 0.13% is set on the branching ratio for $\psi' \rightarrow \gamma\chi(3455) \rightarrow \gamma\gamma\psi(3095)$; this is a factor of 6 less than the branching ratio measured by a previous less sensitive experiment. We investigate the decay $\psi' \rightarrow \gamma\eta_c$, $\eta_c \rightarrow$ hadrons. The decay $\psi' \rightarrow \pi^0\psi$, which violates isospin conservation, is observed with a branching ratio of $(0.15 \pm 0.06)\%$.

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Chapter I

INTRODUCTION

Since the discovery of the ψ particle in 1974¹ several other related particles have been found. These particles are called charmonium states since the most successful theory explaining them is the charmonium model. This paper gives new experimental results on the existence and properties of these states. First we'll give a brief review of the charmonium system (theory and experiment) as it stood prior to this experiment.

The charmonium model was formed in analogy to the positronium system. A charmed quark and a charmed anti-quark are bound in a potential well. In contrast to the u, d, and s quarks, the charmed quark is so massive that nonrelativistic approximations can be successfully used. Figure 1 shows the states predicted by this model. The masses of the states are determined by the form used for the potential. The form of this potential as $r \rightarrow 0$ and as $r \rightarrow \infty$ is inspired by Quantum Chromodynamics, but the potential in the intermediate region is adjusted to give the masses measured by experiments. Each state in the diagram has 3 labels. The atomic physics label is in the form $n^{2S+1}L_J$; where n is the sum of the quark spins (0 or 1); L (S,P,D,F,...,1,2,3) gives the relative orbital

¹J. E. Augustin *et al.*, Phys. Rev. Lett. **33**, 1453 (1974); J. J. Aubert *et al.*, Phys. Rev. Lett. **33**, 1404 (1974).

angular momentum of the two quarks; J is the sum of $\vec{L}$ and $\vec{s}$, the total spin; and N gives the radial excitation of system. The second label, J^{PC} , gives the total spin, parity, and charge conjugation of the state. The third label gives the experimental mass and name of the particle associated with the level. There are several excellent review papers which give details on the form of the potential and which summarize the predictions of masses and branching ratios.²

The experimental status of the charmonium system in 1977 is also summarized in Figure 1. The most distinctive evidence for the $\psi(3095)$ and $\psi'(3684)$ comes from their production in e^+e^- annihilation where they show up as huge peaks in the hadronic cross section. The other charmonium states below 3.7 GeV/c² have the wrong quantum numbers to be produced directly in e^+e^- annihilation. They are seen in radiative decays of the ψ and ψ' . Several methods have been used to observe these radiative decays.

1. Peaks in the inclusive energy distribution of photons from ψ' decays give strong evidence for the decay $\psi' \rightarrow \gamma X$ with X masses of 3.415, 3.510, and 3.555 GeV/c².³
2. Strong evidence for states with these same 3 masses comes from observation of the decay $\psi' \rightarrow \gamma X$, $X \rightarrow$ hadrons. These hadronic decays also provide information on the quantum numbers of the states.

²E. Eichten *et al.*, Phys. Rev. **D17**, 3090 (1978); T. Appelquist *et al.*, preprint SLAC-PUB-2100; V. A. Novikov *et al.*, Phys. Reports **41C** (1978); M. Kramer and H. Krasemann, preprint DESY 79/20 (1979).

³C. J. Biddick *et al.*, Phys. Rev. Lett. **38**, 1324 (1977).

Figure 1: Charmonium level diagram: before. Solid lines indicate things confirmed by experiment. Dashed lines indicate things with a small amount of experimental evidence. Dotted lines indicate things predicted by the Charmonium model for which there is no experimental evidence.

3. The $\chi(3510)$ and $\chi(3555)$ have also been observed in the cascade decay $\psi' \rightarrow \gamma \chi$, $\chi \rightarrow \gamma \psi$.⁴ In addition there is evidence for a fourth state, the $\chi(3455)$.⁵ The evidence consists of 4 events where less than one event background was expected. This state has not been observed with any of the other methods. It is normally associated with the 2^1S_0 charmonium level, the η_c' . This association causes theoretical difficulties because calculations and measurements of its branching ratios differ by over an order of magnitude.
4. Evidence for the $\chi(2830)$ came from the decay $\psi \rightarrow \gamma \chi$, $\chi \rightarrow \gamma \psi$.⁶ It has not been observed with any of the other methods. It is normally associated with the 1^1S_0 charmonium level, the η_c . Like the $\chi(3455)$, this association causes theoretical difficulties because calculations and measurements of its branching ratios differ by over an order of magnitude.

There are several excellent review papers⁷ which summarize the experimental status of the charmonium system. Briefly, the $\psi(3095)$, $\psi'(3684)$, $\chi(3415)$, $\chi(3510)$, and $\chi(3555)$ states are well established. Enough of their quantum numbers have been measured so there is a unique

⁴W. Braunschweig *et al.*, Phys. Lett. **57B**, 407 (1975); W. Tanenbaum *et al.*, Phys. Rev. **D17**, 1731 (1978).

⁵W. Tanenbaum *et al.*, Phys. Rev. **D17**, 1731 (1978).

⁶W. Braunschweig *et al.*, Phys. Lett. **57B**, 243 (1977).

⁷B. H. Wiik and G. Wolf, DESY 78/23 (1978); H. Schopper, DESY 77/79 (1977).

correspondence to the predicted charmonium levels. Evidence for the $\chi(2830)$ and $\chi(3455)$ is much weaker and confirmation is needed.

To learn more about the charmonium system an experiment has been done with the SLAC-LBL Mark II magnetic detector at the e^+e^- storage ring, SPEAR. During 6 weeks of running, the decays of $10^6 \psi'(3684)$'s have been observed. The general purpose Mark II detector combined with the high statistics data sample provides an excellent opportunity to study the charmonium system.

Chapter II

THE DETECTOR

The Mark II consists of a series of cylindrical detectors coaxial with the SPEAR beam line. There are drift chambers in a magnetic field to measure directions and momenta of charged particles, scintillation counters to measure their velocity, and shower counters to detect photons and identify electrons. An end view of the detector is shown in Figure 2.

A particle leaving the interaction region travels through the following parts of the detector.

1. The beam pipe is a cylinder of 0.21 mm thick corrugated stainless steel.
2. The pipe counter consists of two cylindrical, 0.6 cm thick, plastic scintillation counters. They are 81 cm long at radii of 11 and 12.5 cm. Each cylinder is divided in half along the vertical plane through the beam line.
3. The 16 drift chamber layers are at radii 0.414 m through 1.448 m with lengths of 1.984 m through 2.642 m. Six layers have axial wires (parallel to the beam line) and 10 layers have stereo angles of $\pm 3^\circ$ to provide position measurements in the axial direction. The resolution is typically $\sigma = 0.22$ mm. More

Figure 2: Schematic view of the Mark II detector.
 (A) vacuum chamber, (B) pipe counter, (C) drift chamber, (D) time-of-flight counters, (E) solenoid coil, (F) liquid argon shower counters, (G) iron absorber, (H) muon proportional tubes.

information about the drift chamber is available in a previous publication.⁵

4. The 48 time-of-flight (TOF) counters are at radius 1.524 m with an active length of 3.442 m. They are viewed with XP2230 phototubes on both ends. The time-of-arrival and integrated charge of the phototube pulses are recorded.
5. The aluminum coil for the solenoid magnet contains most of the 1.6 radiation lengths of material which lies between the beam and the shower counter. The field was mapped with Hall and NMR probes before insertion of the drift chambers. A polynomial was fit to this field map with a maximum error of 0.03%. This fit is then used by the track reconstruction program. During data taking the magnetic field is monitored with an NMR probe. The systematic error in the field value is less than 0.2%.
6. The liquid argon shower counters form an octagon around the coil. Their active area subtends $0.64 \cdot 4\pi$ steradians. They contain 14 radiation lengths of lead and liquid argon. The lead is divided into strips with a width of 3.8 cm. These strips run parallel, perpendicular and at 45° to the beam direction to allow reconstruction of the shower position. More information about the shower counter is available in a previous publication.⁶

⁵W. Davies-White *et al.*, Nucl. Instrum. Methods **160**, 227 (1979).

⁶G. S. Abrams *et al.*, IEEE Transactions on Nuclear Science **NS-25**, 309

7. The muon system subtends $0.5 \cdot 4\pi$ steradians. It consists of steel hadron filters (which double as the magnetic flux return) followed by proportional chamber tubes.

The ends of the cylinder are instrumented with shower counters. Each counter subtends $0.07 \cdot 4\pi$ str.

The trigger is described in minute detail in Appendix A. A brief description is given here. Both layers of the pipe counter must fire within ± 5 ns of the time the beams cross. This provides cosmic ray rejection. Then a track finding processor must find at least 2 tracks in the drift chambers, one of which must fire a TCF counter. The other need only go through the inside 5 drift chamber layers. All events satisfying these criteria are logged on tape.

Chapter III

EVENT RECONSTRUCTION

The origin of the coordinate system used for the analysis is at the nominal beam collision point, the center of the detector. The x, y, and z axes point towards the center of SPEAR, up, and in the positron beam direction respectively. The polar angle, θ , is the angle between a vector and the +z axis. The azimuthal angle, ϕ , is the angle between the x axis and the projection of a vector on the x-y plane while r is the length of the projection of a vector on the x-y plane. The actual beam collision point, the interaction region, moves when the configuration of SPEAR is changed. This position is measured using Bhabha events ($e^+e^- \rightarrow e^+e^-$).

The event reconstruction starts with charged particle tracking. A pattern recognition program looks for hits in the drift chamber which lie on a helix. Since a helix has 5 free parameters, at least 5 measurements are needed to determine it. To provide redundancy and allow resolution of the right-left ambiguity the tracking program requires 7 hits on a track. This allows tracks with $|\cos \theta| < 0.85$ to be found. The parameters of the track are obtained with a least squares fit to the measured drift times. The resolution of these drift time measurements was previously determined¹⁰ and parameterized as a function of angle and

(1978): G. S. Abrams et al., to be published in IEEE Transactions on Nuclear Science (1979).

¹⁰H. Davies-White et al., Nucl. Inst. and Meth. 160, 227 (1979).

position in the drift cell. The fit uses these resolutions and the errors caused by multiple scattering to calculate an error matrix for the track.

Each track is projected to the time-of-flight counter radius. The z position where the track hit the counter and the times and pulseheights of the two phototube pulses are used to calculate a flight time. This time and the pathlength of the track determine the particle's speed. The speed and momentum can then be used for particle identification. Figure 3 shows the distribution of the expected time-of-flight minus the measured time-of-flight for muons in the decay $\psi' \rightarrow \pi^+ \pi^- \psi$, $\psi \rightarrow \mu^+ \mu^-$. The distribution is Gaussian with a standard deviation of 0.313 ns. This resolution provides π -e, π -K, K-p separation up to 0.3, 1.35, and 2.2 GeV, respectively.

To allow identification of electrons, the energy deposited in the liquid argon calorimeter by charged tracks is determined by summing the charge deposited on strips passing near the projection of the track.¹¹ The summed charge is converted to deposited energy using a calibration based on electro-magnetic shower Monte Carlo calculations,¹² and on measurements of Bhabhas and of photons from the decays $\psi \rightarrow \pi^+ \pi^- \pi^0$ and $2\pi^+ 2\pi^- \pi^0$. Photons are detected in the calorimeter by looking for spatial coincidences of strips with deposited charge. Since liquid argon shower counters have no gas multiplication, very sensitive amplifiers

Figure 3: Time-of-flight resolution. Expected TOF minus measured TOF for muons in the decay $\psi' \rightarrow \pi^+ \pi^- \psi$; $\psi \rightarrow \mu^+ \mu^-$. The Gaussian fit has mean = -0.02 ns and sigma = 0.313 ns.

¹¹G. S. Abrams *et al.*, to be published in Nucl. Inst. and Meth.

¹²EGS Code, R. L. Ford and W. R. Nelson, SLAC Report No. 210 (1978).

(capable of detecting 10 femtocoulombs) must be used. Thermal noise in the first stage of these amplifiers causes pulseheight to be recorded for strips which have no deposited charge. The pattern recognition program has pulseheight cuts to help prevent this noise from generating false photons. These cuts cause low efficiency for low energy photons. Figures 4 and 5 show the efficiency for photons and the energy spectrum of false photons. These properties are particularly important for this analysis. The angular resolution of the liquid argon system varies from 4 mrad for high energy tracks to 8 mrad for low energy tracks. The energy resolution is $\sigma = 0.13\sqrt{E}$ (GeV).

The next step in the event reconstruction is vertex reconstruction. Charged particles can usually be identified as π 's, K's or p's by TOF. The decays $K_S \rightarrow \pi^+ \pi^-$ and $\Lambda \rightarrow \pi^- p$ are detected by looking for pairs of tracks consistent with such decays. Figure 6 shows the mass distribution for the candidate K_S 's. After the mass cut indicated in the Figure, signal-to-noise is 0.81:1. for Λ 's signal-to-noise is 5.1:1. From the remaining tracks, a primary vertex is found. If this has $R < 4$ cm and $|z| < 15$ cm, a beam constrained fit is done. Using the parameters and error matrices from the single track fits and the previously measured position and size of the beam, a vertex position is determined. By constraining the tracks to go through this vertex, one obtains beam constrained momenta and error matrices. The beam constrained fits have better resolution than the single track fits because the pathlength over which the track is measured is increased by .40%. The resulting momentum resolution is $\sigma^2/p^2 = .015^2 + .005^2 p^2$. This formula is calculated from the size of the beam spot and the drift chamber resolution (which causes the sec-

Figure 4: Photon efficiency. The curve shows the efficiency found with the shower Monte Carlo. The points show the efficiency measured with $\psi \rightarrow \pi^+ \pi^- \pi^0$ and $\psi \rightarrow 2\pi^+ 2\pi^- \pi^0$.

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Figure 5: Liquid argon false photon spectrum.
Energy spectrum of photons found in $\psi' \rightarrow \pi^+ \pi^- \psi$ events. There is an average of 0.2 false photons per event.

ond term) and multiple scattering (which causes the first term). The widths of the K_S and ψ peaks (Figures 6 and 7) agree with the expected resolutions. These data provide checks on the resolution both when it is multiple scattering limited and when it is limited by measurement error. The position of these peaks provides a check on the absolute scale of the momentum measurements. Our K_S mass measurement of 498.16 ± 0.08 is $0.46 \text{ MeV}/c^2$ from the world average. The systematic error of .2% on the magnetic field can account for this difference. The ψ peak centers at $3096.2 \text{ MeV}/c^2$ which is $1.2 \text{ MeV}/c^2$ above the value determined by scanning SPEAR's energy over the peak. This difference is consistent with SPEAR's energy calibration error of 0.13%. In summary, both the resolution and the magnitude of the momentum are consistent with expected errors.

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Figure 6: $\pi^+\pi^-$ mass of K_s decay candidates.
A fit to a Gaussian plus flat background gives mass and sigma of 498.16 ± 0.08 and $5.0 \text{ MeV}/c^2$.

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Figure 7: $\mu^+\mu^-$ mass of ψ decay candidates.
A fit to a Gaussian plus flat background gives mass and sigma of 3096.2 ± 0.7 and $35 \text{ MeV}/c^2$.

Chapter IV

$\psi' \rightarrow \pi^+ \pi^- \psi$, $\psi \rightarrow \ell^+ \ell^-$

The decay $\psi' \rightarrow \pi^+ \pi^- \psi$, $\psi \rightarrow \ell^+ \ell^-$ ($\ell = \text{lepton}$) is interesting both for its physics implications and for its use as a tool in understanding the detector. The two high momentum leptons leave such a distinctive signature in the detector that one can get a nearly background free sample of events with very loose cuts. This allows comparison of the data with the Monte Carlo allowing checks that the resolution and acceptance of the detector are properly modeled by the Monte Carlo. The number of detected $\pi^+ \pi^- \psi$ events gives the number of produced ψ' (3684)/s. The $\pi^+ \pi^-$ mass distribution shows effects of the dynamics of this decay. Finally, the branching ratio for $\psi' \rightarrow \eta \psi$ can be measured from the decays $\eta \rightarrow \pi^+ \pi^- \pi^0$ or $\pi^+ \pi^- \gamma$.

4.1 THE MONTE CARLO

The Monte Carlo consists of two main parts: event generation and particle detection. The event generation is done with a simple phase space model. The decay sequence must be specified and the 3-momenta are distributed according to phase space. In some cases the phase space distribution has been modified to put in angular distributions caused by the dynamics of the interaction. This is explicitly mentioned wherever it is done.

To simulate particle detection, the generated particles are tracked through the detector and raw data (drift times, pulseheights...) are generated. These raw data are then analyzed by the same programs used for the real data. The following effects are included as part of the raw data generation.

1. The position of the primary vertex is distributed according to the known size of the beam.
2. The particles lose energy and undergo multiple coulomb scattering as they pass through material.
3. Photons can convert to e^+e^- pairs in the material through which they pass.
4. Electrons bremsstrahlung photons with the known energy spectrum.
5. Particles interact both elastically and inelastically with the nuclei in the material through which they pass. Measured cross sections are used.
6. Particles decay with their known lifetimes. This is especially important for charged K's, half of which decay before leaving the drift chamber.
7. The drift times in the drift chamber are generated with the measured resolution. This resolution varies with the position in the cell and the angle of the track.

8. The drift chamber cell efficiency is 95% to simulate the dead cells in the real drift chamber.
9. 1.5% of the drift times are generated with a random time between 0 and the expected drift time. This simulates an effect in the real data attributed to delta rays.
10. Two neighboring drift chamber cells sometimes fire, as observed in the real data.
11. Flight times to the TOF counters are generated with the measured resolution of 0.313 ns.
12. Raw data are not generated for the liquid argon system. The measured efficiency and resolution of the liquid argon system are used directly to generate the parameters of the photons which are found.

4.2 COMPARISON OF DATA AND MONTE CARLO

To compare data and Monte Carlo, we use $\psi' \rightarrow \pi^+ \pi^- \psi$ events where one of the π 's is allowed to be missing. From the 3 measured tracks and conservation of 4-momentum, the 4-momentum of the fourth track is calculated. Checking to see if the fourth track was detected gives the tracking efficiency as a function of 3-momentum. Repeating this for the data and the Monte Carlo with varying cuts on the fourth track provides a good check of the accuracy with which the Monte Carlo reproduces the data. It also allows one to estimate the systematic errors on branching ratios caused by uncertainties in the acceptance calculation. The Monte Carlo

events used for this comparison are generated with the $\pi^+ \pi^-$ mass distribution observed in the data (Section 4.5.0) and the positive lepton is given a $1 + \cos^2 \theta$ distribution.

Figure 8 shows a typical $\pi^+ \pi^- \psi$ event. Events with 3 or 4 detected charged tracks are used. Two of these must be of opposite charge with invariant mass within 0.1 GeV of the ψ mass. Both of these tracks must be identified as muons by the muon system or as electrons by the liquid argon system. To reduce background from events with a ψ and a converted photon, events are not used if there is a track of momentum < 1 GeV/c that is identified by TOF or liquid argon as an electron. To reduce problems caused by mismeasured tracks, each of the 3 tracks used in the following analysis must have $|z|$ at point of closest approach to the origin less than 0.1 m and radial distance of closest approach to the interaction region less than 0.005/p (m/GeV).

For these events, the sum of the 4-momenta of the two leptons is constrained to give the ψ mass. This improves the resolution. Figure 9 shows the distribution of the mass squared (M^2) recoiling against the $\pi\psi$. Events with 2 π 's satisfying the above cuts appear twice in this histogram. The peak comes from $\psi' \rightarrow \pi^+ \pi^- \psi$. It will be shown below that the shoulder at high recoil mass comes from $\psi' \rightarrow \eta\psi$, $\pi^+ \pi^- \pi^0 \psi$ or $\pi^+ \pi^- \gamma$. To select the $\pi^+ \pi^- \psi$ events we require $0.0 < M^2 < 0.035$. The following analysis has also been done with much looser cuts, giving consistent results. This, together with the results of scanning several hundred event pictures, indicates that less than 1% of the events are background.

Figure 8: Typical $\pi^+\pi^-\psi$ event. The numbers just outside the octagon are liquid argon pulseheights in GeV. The numbers by the small rectangles (representing the TOF counters) are the measured flight times in ns.

Figure 9: Mass squared recoiling against the ψ

For each set of 3 tracks which satisfy the above cuts, the 3-momentum of the fourth is calculated. The average errors on this prediction are $\pm 7^\circ$ in angle and ± 0.021 GeV/c in p_t (momentum transverse to the beam direction). Checking to see how often the fourth track is found and satisfies various quality cuts gives the efficiency as a function of these cuts. The variables used are $r_0 = r$ at point of closest approach of the track to the origin; $z_0 = |z|$ at point of closest approach to the origin; and $r_{90} =$ radial distance from the track to the interaction region. Table 1 compares the efficiencies obtained from the data and the Monte Carlo with various cuts. These efficiencies are for tracks with predicted $|\cos \theta| < 0.5$ and $p_t > 0.1$ GeV/c. The inefficiency is caused by particle decays, nuclear interactions in the pipe counter, and pattern recognition problems. Figure 10 compares the efficiencies as a function of p_t . Note that these curves actually show the true efficiency smeared out by the resolution of 0.021 GeV/c. Since the efficiency drops sharply for $p_t < 0.1$ GeV/c, such tracks will not be used in later analysis. Similarly, the efficiency drops sharply for $|\cos \theta| > 0.76$, (the Monte Carlo and data disagree by 0.02 on the location of this drop) so such tracks will not be used in later analysis. Figure 11 compares the r_0 distributions. The non-Gaussian tails are primarily due to particle decays and nuclear interactions. Since the tails differ slightly between data and Monte Carlo, the r_0 cut used in later analysis will be 0.06 m. This minimizes systematic errors due to the different tails. Similarly, the cut $z_0 < 0.15$ m will be used. Table 1 shows that for these cuts the Monte Carlo and data efficiencies differ by $(0.3 \pm 0.6)\%$. In acceptance calculations a systematic error of 1.0% times

the number of charged tracks is used to allow for this uncertainty in the efficiency.

TABLE 1
Comparison of tracking efficiencies

Quality cuts	Data Efficiency (%)	Monte Carlo Efficiency (%)
none	95.6 $\pm$ 0.3	94.2 $\pm$ 0.3
$r_0 < 0.06$	92.5 $\pm$ 0.4	92.3 $\pm$ 0.4
$r_0 < 0.06, z_0 < 0.15$	90.5 $\pm$ 0.4	90.2 $\pm$ 0.4
$r_{90} < 0.015, z_0 < 0.15$	81.9 $\pm$ 0.6	80.2 $\pm$ 0.5

The muons from $\pi^+\pi^- \rightarrow \mu^+\mu^-$ events are used to check the TOF system. The TOF residuals are shown in Figure 3. The measured resolution of 0.313 ns is used in the Monte Carlo. The measured efficiency of 98.8% is not in the Monte Carlo, but we correct for it in later acceptance calculations. Similarly, we correct for the effect of the small non-Gaussian tails (1.6% of the events are outside 2.6σ rather than the expected 1%). Uncertainties in these corrections contribute a systematic error of 1% times the number of tracks for which TOF is required. This error and that due to the charged track detection efficiency will be added in quadrature to give the systematic error in later acceptance calculations.

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Figure 10: Tracking efficiency vs. P_T .
The solid points are data and the open triangles are Monte Carlo.
Tracks must have $r_0 < 0.06$ m and $|z| < 0.16$ m to be counted as efficient.

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Figure 11: Comparison of r_0 distributions.
The solid points are data and the open triangles are Monte Carlo.

4.3 $\psi' \rightarrow \eta \psi$, $\eta \rightarrow \pi^+ \pi^- \pi^0$ OR $\pi^+ \pi^- \gamma$

Following the method used by the Mark I group,¹³ we now investigate $\psi' \rightarrow \eta \psi$. The cuts used in this analysis are the same as those in the previous section up to the cut on the mass squared recoiling against the $\pi \psi$. The events where this recoil mass is large (Figure 9) arise from the decay $\psi' \rightarrow \eta \psi$. This is seen in Figure 12 where the M^2 recoiling against the ψ is plotted separately for events with M^2 recoiling against the $\pi \psi$ greater than 0.08 and between 0.0 and 0.035 (GeV/c)². The first group of events has a peak of 251 events at the η mass with width consistent with our resolution. The second group has a much broader mass spectrum. The background under the η peak from $\psi' \rightarrow \pi^+ \pi^- \psi$ is calculated in two ways: by Monte Carlo and by assuming the peak in Figure 9 is symmetric about the π mass. They give 21 and 52 events, respectively; the average is used for the background subtraction. The Monte Carlo predicts no background from $\psi' \rightarrow \gamma \gamma \psi$ or $\psi' \rightarrow \pi^0 \pi^0 \psi$ where a γ converts. The acceptance for $\psi' \rightarrow \eta \psi$ is also obtained by Monte Carlo where the η is produced with a $1 + \cos^2 \theta$ distribution. Using the number of produced $\psi'(3684)$'s which will be calculated in the next section, the branching ratio for $\psi' \rightarrow \eta \psi$ is $(3.0 \pm 0.5)\%$. The error includes the statistical and systematic error on the number of produced η 's and the systematic error on the number of produced $\psi'(3684)$'s.

¹³M. Tanenbaum et al., Phys. Rev Lett. 36, 402 (1976).

Figure 12: M^2 recoiling against the ψ . for (a) M^2 recoiling against the $\pi \psi$ greater than 0.08; for (b) M^2 recoiling against the $\pi \psi$ between 0 and 0.035.

4.4 NUMBER OF PRODUCED $\psi'(3684)$'s

By counting the number of detected $\psi' \rightarrow \pi^+ \pi^- \psi$, $\psi \rightarrow \ell^+ \ell^-$ events and using previously measured branching ratios for $\psi' \rightarrow \pi^+ \pi^- \psi$ and $\psi \rightarrow \ell^+ \ell^-$, the number of $\psi'(3684)$'s produced in this experiment can be calculated. This number will then be used to calculate branching ratios for other reactions.

To do this we will count the total number of 4 prong events which contain a ψ decay to leptons and subtract the number of these which result from $\psi' \rightarrow \eta \psi$, $\eta \rightarrow \pi^+ \pi^- \pi^0$ or $\pi^+ \pi^- \gamma$. Events are selected by requiring exactly 4 charged tracks to pass within $r < 0.06$ m and $|z| < 0.15$ m from the origin. These four tracks must have $|\cos \theta| < 0.76$ and $p_t > 0.1$ GeV/c. The total charge must be zero. To eliminate events with converted photons, events with two tracks of opposite charge with cosine of the angle between them greater than 0.95 are removed. For the remaining events Figure 13 shows a histogram of the largest invariant mass of a neutral particle pair. For this purpose, the events were divided into 3 classes: both particles of the high mass pair are identified as electrons by the liquid argon system, both particles are identified as not being electrons by the liquid argon system, and other (e.g. a particle missed the active liquid argon volume). All 3 classes are used in counting the total number of events; the separation is only used to compare $\psi \rightarrow e^+ e^-$ and $\psi \rightarrow \mu^+ \mu^-$. The low mass tail in the " $e^+ e^-$ " spectrum is primarily caused by radiation of the electrons. A check of events in the low mass tail of the " $\mu^+ \mu^-$ " mass spectrum shows that half of them are really $\mu^+ \mu^-$ events (identified by the muon system) and the other half are not muons (they are probably π 's or K's). Since the ψ signal is so clean,

the last cut needed is to require this particle pair mass to be between 2.8 and 3.4 GeV/c². 10221 events satisfy this cut. From the low mass tail of the " $\mu^+ \mu^-$ " spectrum, 110 ± 50 of these events do not really contain a ψ decay. An additional subtraction of 70 ± 30 events is made to remove events of the form $\psi' \rightarrow \eta \pi$, $\eta \rightarrow \pi^+ \pi^- \pi^0$ or $\eta \rightarrow \pi^+ \pi^- \gamma$. This results in 10041 ± 117 detected $\psi' \rightarrow \pi^+ \pi^- \psi$, $\psi \rightarrow \ell^+ \ell^-$ events.

The detection efficiency is calculated by Monte Carlo. Phase space is modified by throwing the $\pi^+ \pi^-$ mass according to the distribution in the next section. The positive lepton is forced to have a $(1 + \cos^2 \theta)$ angular distribution. Finally, the leptons from the ψ decay can radiate internally (immediately after leaving the vertex). Since 38% of the $\psi \rightarrow e^+ e^-$ events are lost due to radiation causing the $e^+ e^-$ mass to be less than 2.8 GeV/c², it is important to check that the Monte Carlo properly models this radiation. Assuming that the branching ratios for $\psi \rightarrow e^+ e^-$ and $\psi \rightarrow \mu^+ \mu^-$ are equal, the data and Monte Carlo agree on the following ratios: (number of detected $\mu^+ \mu^-$) / (number of detected $e^+ e^-$), fraction of the total $e^+ e^-$ events in the tail between 2.8 and 2.975 GeV/c², and fraction of the total $\mu^+ \mu^-$ events in the tail between 2.8 and 2.975 GeV/c². Since the radiative tails seem to be properly modeled, the systematic error on the acceptance is just 4% as calculated in section 4.2.0. Thus there are $47,150 \pm 1900$ $\psi' \rightarrow \pi^+ \pi^- \psi$, $\psi \rightarrow \ell^+ \ell^-$ events produced. Using previously measured branching ratios¹⁹ for $\psi' \rightarrow \pi^+ \pi^- \psi$ (0.33 ± 0.03) and $\psi \rightarrow \ell^+ \ell^-$ (0.14 ± 0.02) gives $(1.02 \pm 0.04 \pm 0.17) \cdot 10^6$ $\psi'(3684)$'s produced for this experiment. The first error is from the acceptance calculation.

¹⁹Particle Data Group, Phys. Lett. **75B** (1978).

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Figure 13: Mass of charge 0 pair in 4 prong events

The second error is from the errors on the previously measured branching ratios. This number of produced $\psi'(3684)$'s will be used below to calculate branching ratios.

4.5 DYNAMICS OF THE DECAY $\psi' \rightarrow \pi^+ \pi^- \psi$, $\psi \rightarrow e^+ e^-$

The decay $\psi' \rightarrow \pi^+ \pi^- \psi$ is a good place to study the $\pi^+ \pi^-$ interaction. Photoproduction experiments¹⁵ indicate that the ψ nucleon interaction is much weaker than the π nucleon interaction. So the dynamical structure of the $\psi' \rightarrow \pi^+ \pi^- \psi$ decay is primarily determined by the final-state interaction of the outgoing pions. Since both ψ and ψ' have isospin zero, the dipion system must also have $I=0$. Previous studies of angular distributions¹⁶ show that the $\pi^+ \pi^-$ usually have zero relative orbital angular momentum. Studies of our data (to be published) indicate that the D-wave amplitude is less than 10%.

To study this system we use those events from the previous section which have a mass recoiling against the $\pi^+ \pi^-$ system between 3.06 and 3.13 GeV/c^2 . This helps ensure that the π 's are well measured. The $\pi^+ \pi^-$ mass distribution of the 9248 remaining events is shown in Figure 14a. Figure 14b shows the mass distribution for the s-wave phase space Monte Carlo. The different forms of these two spectra show that final state interactions are important. The square root of the quotient of the two above distributions is shown in Figure 14c.

¹⁵U. Camerini et al., Phys. Rev. Lett. **38**, 263 (1977).

¹⁶G. S. Abrams, Proceedings of the 1975 Symposium on Lepton and Photon Interactions at High Energies, 25.

Figure 14: $\pi^+\pi^-$ mass distribution.
(a) the data; (b) the phase space Monte Carlo; (c) the square root of (a)/(b).

Since the $\pi^+\pi^-$ system is dominantly s-wave, Figure 14c gives the magnitude of the s-wave matrix element. The shape of this curve can be directly compared to theoretical predictions. Note that the normalization is arbitrary, and thus only the shape has any physical significance.

The 4 points at lowest mass should be ignored because there are so few signal events in these bins that the background events become important. The 4 points at highest mass should be ignored because the phase space factor changes very rapidly there and the Monte Carlo may not properly simulate the data in this respect.

Since the original measurement of the $\pi^+\pi^-$ mass spectrum, explanations have been published in several papers. Methods used include an intermediate ϵ resonance¹⁷ and partially conserved axial-vector currents.¹⁸ Both methods predict a straight line for the matrix element, but more work is needed to properly calculate the x-intercept of the line.

¹⁷R. Decker and M. Moreno, *Nuo. Cim. Lett.* **13**, 407 (1975); B. J. Harrington, S. Y. Park, and A. Yildiz, *Phys. Rev.* **D12**, 2765 (1975).

¹⁸L. S. Brown and R. N. Cahn, *Phys. Rev. Lett.* **35**, 1 (1975); D. Morgan and M. R. Pennington, *Phys. Rev.* **D12**, 1283 (1975).

Chapter V

$\psi' \rightarrow \gamma\gamma\psi$

The decay $\psi' \rightarrow \gamma\gamma\psi$ has been observed by several experiments.^{1*} This final state can result from the decays

1. $\psi' \rightarrow \pi^0\psi, \pi^0 \rightarrow \gamma\gamma$
2. $\psi' \rightarrow \gamma X, X \rightarrow \gamma\psi$
3. $\psi' \rightarrow \pi^0\psi, \pi^0 \rightarrow \gamma\gamma$.

The last decay mode violates isospin conservation and has only recently been observed.

5.1 EVENT SELECTION

A typical event of the topology we are looking for is shown in Figure 15. We require that at least two photons be detected in the barrel liquid argon calorimeter. Photons detected within 0.3 m. of a charged track are not used. This helps eliminate false photons caused by energy deposited by the charged track. It also helps eliminate photons radiated by the outgoing electrons. Events with more than two detected photons are included in the sample because noise in the liquid argon pream-

Figure 15: A $\psi' \rightarrow \pi^0\psi$ event.

^{1*}M. Tannenbaum et al., Phys. Rev. D **17**, 1731 (1978); W. Bartel et al., Phys. Lett. **79B**, 492 (1978); R. Brandelik et al., DESY 79/31 (1979).

plifiers sometimes causes the tracking programs to find a false photon. The losses, if such events were eliminated, would be difficult to calculate precisely.

In those events with at least two photons, the ψ is detected by its decay to two leptons: $\psi \rightarrow e^+e^-$ or $\psi \rightarrow \mu^+\mu^-$. We require that there be exactly one positive and one negative particle coming from the interaction region, that is, they must have $r < 0.06$ m. and $|z| < 0.15$ m. at their point of closest approach to the origin. Figure 16 shows the mass distribution of these particle pairs. The peak at $3.095 \text{ GeV}/c^2$ is from the decay $\psi \rightarrow 2 \text{ leptons}$. The shaded region shows only those events where both particles are identified by the liquid argon system as not being electrons. The low mass tail of the unshaded region comes from $\psi \rightarrow e^+e^-$ where an electron radiates a photon. The high mass tail comes from $e^+e^- \rightarrow e^+e^-$ where an electron radiates. The selection of $\psi(3095)$'s is made by requiring the dilepton mass to be between 2.8 and $3.4 \text{ GeV}/c^2$.

Events satisfying these cuts are fit to the hypothesis $\psi' \rightarrow \gamma\gamma\psi$, $\psi \rightarrow \lambda^0\lambda^0$ with the kinematic fitting program SQUAW. In events with more than two photons, fits are attempted with each photon pair. Generally only one such fit succeeds. This fit greatly improves the mass resolution which otherwise is limited by the energy resolution of the liquid argon calorimeter. Figure 17 shows the χ^2 probability distribution for this 5-constraint fit. The peak at low probability indicates a background contamination. To reduce background, the χ^2 probability is required to be more than 0.08. Most of this background comes from $\psi' \rightarrow \pi^0\pi^0\psi$. The smooth curve in the following mass plots is a Monte Carlo calculation of

Figure 16: Mass of plus-minus particle pair. Shaded region contains events where particles are not electrons.

Figure 17: χ^2 probability distribution for 50 fit $\psi' \rightarrow \gamma\gamma\psi$, $\psi \rightarrow \lambda^0 \lambda^-$.

this background. The Monte Carlo was run with the same parameters used for generating $\pi^+\pi^-$ events in section 4.5.0.

5.2 $\psi' \rightarrow \eta\psi$

Figure 18 shows the $\gamma\gamma$ mass spectrum of the remaining events. The sharp peak at 547.56 ± 0.17 MeV/c² comes from $\psi' \rightarrow \eta\psi$, $\eta \rightarrow \gamma\gamma$. The width of this peak is consistent with the expected mass resolution of ± 1.7 MeV/c². The error given for the central value of the peak is statistical only. There is an additional systematic error of 0.0008 GeV/c² due to the uncertainty of the $\psi' - \psi$ mass difference. The consistency of this mass with the accepted value provides a check on the systematic errors.

The background in Figure 18 comes from two sources: $\psi' \rightarrow \pi^0 \pi^0 \psi$ and $\psi' \rightarrow \gamma\gamma$, $\pi^0 \rightarrow \gamma\gamma$. The smooth curve in the Figure is the Monte Carlo calculation of the first source. Note that it peaks at high mass as the $\pi^+\pi^-$ mass in $\psi' \rightarrow \pi^+\pi^-\psi$ does (section 4.5.0). Estimating the background from the 6 bins on each side of the η peak, there are 166 ± 14 signal events. The acceptance (including branching ratios for $\eta \rightarrow \gamma\gamma$ and $\psi \rightarrow \lambda^0 \lambda^-$) is $(0.66 \pm 0.13)\%$. The systematic error is primarily due to uncertainty in the photon detection efficiency. The number of produced ψ' 's (3684) from section 4.4.0 then gives the branching ratio $\psi' \rightarrow \eta\psi = (2.5 \pm 0.6)\%$.

Figure 18: $\gamma\gamma$ mass distribution. The smooth curve shows the expected background from $\psi' \rightarrow \pi^0 \pi^0 \psi$.

5.3 $\psi' \rightarrow \gamma \chi$, $\chi \rightarrow \gamma \psi$

To see $\psi' \rightarrow \gamma \chi$, $\chi \rightarrow \gamma \psi$ we remove the $\psi' \rightarrow \eta \psi$ events by cutting out events with $0.540 < \gamma\gamma \text{ mass} < 0.556 \text{ GeV}/c^2$. Since each event has two photons, two $\gamma\psi$ masses can be formed. Figure 19 is a scatter plot of the high mass combination versus the low mass combination. The known χ states are expected to appear in the high mass projection. Two peaks are seen, along with their kinematic reflections in the low mass projection. The solid line is a fit to the spectrum using two peaks whose masses and magnitudes are allowed to vary but whose shapes are fixed to the known resolution function. The shape of the background is fixed to that expected from $\pi^0 \pi^0 \psi$, but its magnitude is allowed to vary (the number of background events found in this way is 9% less than the Monte Carlo prediction). The dashed line in the high mass projection is the background determined in this way. The masses and branching ratios are given in Table 2. Again, the acceptance is determined with the Monte Carlo and the main source of systematic error is the photon detection efficiency. Two errors are given for the masses. The first is the statistical error. The second results from the $0.004 \text{ GeV}/c^2$ uncertainty in the ψ and ψ' masses. The kinematic fit actually determines $A = (M_{\chi} - M_{\psi}) / (M_{\psi} - M_{\chi})$. We use 3.09500 and $3.68400 \text{ GeV}/c^2$ for the ψ and ψ' masses. Different values of the ψ and ψ' masses make our χ mass measurements change to keep A constant. The statistical errors dominate other systematic errors.

There is no evidence in Figure 19 for other intermediate states. We are insensitive to the state at $3.60 \text{ GeV}/c^2$ reported by the OESY-Heidel-

TABLE 2

Branching ratios for the decay $\psi' \rightarrow \chi + \gamma\gamma$.

The branching ratio for $\chi \rightarrow \gamma\gamma$ is obtained using previous measurements (7 $\pm$ 2)% for the branching ratio $\psi' \rightarrow \gamma\chi$.

mass (GeV/c ²)	events	(B.R. $\psi' \rightarrow \gamma\chi$) (B.R. $\chi \rightarrow \gamma\gamma$) (%)	(B.R. $\chi \rightarrow \gamma\gamma$) (%)
3.410	<40	<0.56 (90% C.L.)	<8.
3.455	<11	<0.13 (90% C.L.)	
3.508 $\pm$ 0.0006 $\pm$ 0.0040	254 $\pm$ 31	2.4 $\pm$ 0.6	34 $\pm$ 13
3.555 $\pm$ 0.001 $\pm$ 0.004	69 $\pm$ 11	1.1 $\pm$ 0.3	16 $\pm$ 6

Figure 19: Scatterplot of the higher $\gamma\gamma$ mass vs. the lower $\gamma\gamma$ mass.

berg group²⁰ because our efficiency for a 0.090 GeV photon is very low. Table 2 gives branching ratio limits for states at 3.410 and 3.455 GeV/c². The former is well established by its hadronic decay modes and by its presence in the inclusive photon spectrum.

Only one experiment has published a branching ratio for a $\chi(3455)$.²¹ Others have had a few candidate events there²² but have not published branching ratios. In the work of Ref. 21, the $\chi(3455)$ was observed in the decay $\psi' \rightarrow \gamma\gamma\gamma$ where one of the two photons was observed by its pair conversion while detection of the second photon was not required. There were 4 events in the signal where one background event was expected in

²⁰W. Bartel *et al.*, Phys. Lett. **79B**, 492 (1978).

²¹M. Tanenbaum *et al.*, Phys. Rev. **D17**, 1731 (1978).

²²B. H. Wiik and G. Wolf, DESY 78/23, 79 (1978).

the whole scatterplot. The published branching ratio is a factor of 6 higher than our limit. Since the present experiment has higher statistics and a good understanding of the backgrounds, it seems probable that the old signal was an unfortunate statistical fluctuation. Note that in contrast to the other χ states, the $\chi(3455)$ has not been observed in hadron decays or inclusively.

The $\chi(3455)$ had been associated with the expected 2^1S_0 state, the π_c' . With this assignment, measured branching ratios differed from theoretical predictions by an order of magnitude.²³ This new limit means the $\chi(3455)$ is no longer a candidate for the π_c' , removing these difficulties.

5.4 $\psi' \rightarrow \pi^0 \psi$

The decay $\psi' \rightarrow \pi^0 \psi$ violates isospin conservation and hence is expected to have a very small branching ratio. To detect it, one needs good resolution and low background. With the 5-constraint fit, the π^0 mass resolution is $\pm 0.004 \text{ GeV}/c^2$. Most of the non-eta events in Figure 18 come from $\psi' \rightarrow \gamma \chi$, $\chi \rightarrow \gamma \psi$ (the $\gamma\gamma$ mass distribution from χ events is roughly proportional to the $\gamma\gamma$ mass). These χ events are removed by cutting out all events with high $\gamma\gamma$ mass greater than $3.488 \text{ GeV}/c^2$. The resulting $\gamma\gamma$ mass spectrum is shown in Figure 20a. There is a small peak at the π^0 mass. To reduce the background still further, 4 other cuts are applied. First we require the measured energy of both photons to be

Figure 20: $\gamma\gamma$ mass distribution with χ 's removed. The different cuts used for a, b, and c are explained in the text. Note that the π peak is scaled down by a factor of 10. The arrow points to the π^0 mass. The inner tick marks show the signal region. The region between the inner and outer tick marks indicates the region used to estimate the background.

²³Herwig Schopper, DESY 77/79 (1977).

more than 0.14 GeV. This reduces background from false photons while having little effect on the π^0 detection efficiency. This cut was not used before because it would cut out the decay $\psi' \rightarrow \gamma X(3.550)$ which gives a 0.13 GeV photon. Second, events where the difference in azimuthal angle of the two leptons is greater than 178.5° are cut out. This reduces background from $e^+e^- \rightarrow e^+e^-$ where the initial or final state electrons radiate a photon. This cut was not used before because in the decay, $\psi' \rightarrow \eta \psi$, the ψ is nearly at rest. Therefore the leptons from its decay are nearly back-to-back and often fail this cut. Third, photons which use a strip in the calorimeter that is also used by a charged track are cut out. This is done because the pattern recognition program is more likely to find a false photon when one strip has real pulse-height on it. Fourth, events which have a photon with energy > 0.175 GeV in addition to the 2 photons used in the fit are cut out. This helps reduce background from $\psi' \rightarrow \pi^0 \pi^0 \psi$. The 0.175 GeV requirement helps keep false photons (see Figure 5) from causing real $\psi' \rightarrow \gamma \gamma \psi$ events from being lost. The third and fourth cuts were not used before because of the difficulty of estimating the fraction of signal events lost. These cuts introduce systematic errors in the branching ratio measurements. For the case $\psi' \rightarrow \pi^0 \psi$, the statistical errors are large enough so that this systematic error is not important. Also, we measure the fraction of signal events lost by these cuts by noting their effect on the signal $\psi' \rightarrow \eta \psi$.

Figure 20b shows the resulting $\gamma\gamma$ mass spectrum. Taking the ± 6 MeV/c² region around the π^0 mass as the signal (the expected resolution is 4 MeV/c²), and the 48 MeV/c² region on each side as background, 7

events are observed where the expected background is 1.1. The probability that this background could fluctuate upwards to 7 events is $1.5 \cdot 10^{-8}$. Further evidence that these 7 events are not background comes from their flat χ^2 probability distribution (Figure 21). A signal should have a flat χ^2 probability distribution while, as shown in the figure, background tends to peak at low probability.

The narrow width of the signal helps exclude the possibility of a missing particle, for example, $\psi' \rightarrow \gamma \pi^0 \psi$. A Monte Carlo study of this process shows that if a 0.025 GeV/c photon is missing, the peak shifts to 0.140 GeV/c² which is inconsistent with the data. A Monte Carlo study of the $\psi' \rightarrow \pi^0 \pi^0 \psi$ background gives no events with mass less than 0.330 GeV/c². Hence any missing particle must be a photon or neutrino of less than 0.025 GeV.

In Figure 20b the remaining events at low $\gamma\gamma$ mass come from $X(3510)$'s in the non-Gaussian tail of the peak. Removing all events with high $\gamma\gamma$ mass > 3.448 GeV/c² results in Figure 20c. Three signal events remain with essentially no background.

Attributing the signal to the reaction $\psi' \rightarrow \pi^0 \psi$, we calculate the branching ratio. There are 5.9 ± 2.6 signal events. The acceptance (including $B(\psi \rightarrow L^+ L^-)$) calculated with the Monte Carlo is $(0.43 \pm 0.09)\%$. An additional factor of 0.90 coming from cuts 3 and 4 above is obtained from noting the decrease in the η signal caused by these cuts. The resulting branching ratio for $\psi' \rightarrow \pi^0 \psi$ is $(0.15 \pm 0.06)\%$. The ratio $\Gamma(\psi' \rightarrow \pi^0 \psi) / \Gamma(\psi' \rightarrow \eta \psi)$ is 0.06 ± 0.02 .

Figure 21: χ^2 probability distribution for $\psi' \rightarrow \pi^0 \psi$ events. (b) for events which have no η 's or χ 's or π^0 's.

Another possible source of the signal is the nonresonant decay of the virtual photon directly to $\pi^0 \psi$. About 7% of the hadronic events at the ψ' energy come from virtual photon decays. It would have to have a branching ratio of $0.15/0.07=2.1\%$ to cause the signal. Typical branching ratios of e^+e^- to an exclusive final state are small (e.g. $B(e^+e^- \rightarrow \rho^+ \rho^-) < B(e^+e^- \rightarrow 2\pi^+ 2\pi^-) = 2\%^{24}$) and the decay $e^+e^- \rightarrow \pi^0 \psi$ is Zweig suppressed, which typically suppresses decays by a factor of 1000. So a reasonable estimate for $B(e^+e^- \rightarrow \pi^0 \psi)$ is less than 0.002%, a factor of 1000 below the observed signal strength.

Several papers have been published predicting the $\psi' \rightarrow \pi^0 \psi$ branching ratio.²⁵ The calculation involves mixing of the SU(3) symmetric π^0 , η , and η' states to form the physical π^0 , η , and η' states. These calculations show that the QED contribution to this mixing is small, making the decay $\psi' \rightarrow \pi^0 \psi$ a good place to study strong interaction violations of SU(2) (isospin) and SU(3) symmetries. Basically, these violations occur because the masses of the u, d, and s quarks in the strong interaction Hamiltonian are not equal. More recent work²⁶ where effects of symmetry breaking in the decay amplitude are included in the calculation gives $\Gamma(\psi' \rightarrow \pi^0 \psi)/\Gamma(\psi' \rightarrow \eta \psi) = 0.04 \pm 0.010$ consistent with this experiment.

²⁴B. Jean-Marie et al., preprint SLAC-PUB-1711.

²⁵G. Segre and J. Meyers, Phys. Lett. **62B**, 91 (1976); N. Deshpande and E. Ma, Phys. Lett. **69B**, 343 (1977); H. Genz, Nuovo Cim. Lett. **21**, 270 (1978); R. Bhandari and L. Wolfenstein, Phys. Rev. **D17**, 1852 (1978).

²⁶P. Langacker, preprint SLAC-PUB-2434.

Chapter VI
HADRONIC χ DECAYS

It is interesting to observe decays of the form $\psi' \rightarrow \gamma \chi$, $\chi \rightarrow$ hadrons for several reasons. The three established χ states can be observed in this decay, allowing studies of their decay modes and providing information on their quantum numbers. It may also be possible to observe the η_c or η_c' in this way. To enhance this possibility we have attempted to measure all final states for which the Mark II detector has a reasonable acceptance. Information on the quantum numbers of the χ 's can be obtained by measuring the angular distribution of the photon and by observing decays which are forbidden for particles with certain quantum numbers.

6.1 EVENT SELECTION

Figure 22 shows a typical completely detected hadronic χ decay. The event selection criteria are similar for all the decay modes, so the general technique will be described without reference to the specific decay modes. There must be the proper number of charged tracks passing within $r < 0.05$ m and $|z| < 0.15$ m of the origin. Detection of the photon is not required. Events where any of these tracks have $p_t < 0.1$ GeV/c or $|\cos \theta| > 0.76$ are not used. If there is no good TOF information for a track, it is assumed to be a pion. For tracks with good TOF information π , K or proton hypotheses are tried if the measured flight time is

Figure 22: Picture of $\psi' \rightarrow \gamma \eta_c(2970)$, $\eta_c \rightarrow \pi^+ K^0 K_s^-$. The K_s travels several centimeters before decaying to $\pi^+ \pi^-$.

within 0.78 ns of the expected flight time (this is a 2.6 σ , 1% confidence level cut). Multiple mass hypotheses are allowed for particles. For each set of particle identities that satisfies conservation of charge, baryon number, and strangeness, a recoil mass squared is calculated. If its magnitude is less than 0.1 (GeV/c²)² (a very loose cut) a 1 constraint kinematic (SQUAW) fit is done which constrains the recoil mass to zero (the photon mass). If an event has more than one successful fit, the one with the smallest total χ^2 (sum of SQUAW χ^2 and TOF χ^2) is used. In this way, the particle identification ambiguities are resolved. Events with SQUAW χ^2 probability less than 0.1 are rejected.

The remaining cuts are designed to remove specific backgrounds. The most serious backgrounds for 2 particle decays of the χ 's are $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$. These backgrounds are reduced by requiring both particles to be identified by the muon system as not being muons and by the liquid argon system as not being electrons. Candidates for $\chi \rightarrow \bar{p}p$ are not removed with these cuts if one of the particles is unambiguously labeled as a proton by TOF (TOF > (expected TOF for a kaon) + 0.78 ns). A background to $\chi \rightarrow \pi^+\pi^-\pi^+\pi^-$ or $\pi^+\pi^-K^+K^-$ is $\psi \rightarrow \pi^+\pi^-\psi$ or $\psi \rightarrow \eta\psi$ where $\psi \rightarrow \ell^+\ell^-$. This background is reduced by removing events with a mass recoiling against any $\pi^+\pi^-$ pair that is greater than 3.07 GeV/c². Finally, a background to other hadronic decay modes from $\psi \rightarrow \pi^+\pi^-\psi$, $\psi \rightarrow \text{hadrons}$ is reduced by removing events that have a mass recoiling against any $\pi^+\pi^-$ pair between 3.07 and 3.11 GeV/c². The unshaded histograms in Figure 23 show the resulting spectra for the decay modes in which signals are observed.

Figure 23: Mass spectra from fits to $\psi \rightarrow \gamma + \text{hadrons}$. The unshaded and shaded spectra come from 1-C and 4-C fits, respectively.

The shaded histograms in the figure are the result of an identical analysis where detection of the photon is required and a 4 constraint kinematic fit (conservation of energy and momentum) is done. These 4-C fits have less background and better resolution, but smaller acceptance than the 1-C fits.

6.2 BRANCHING RATIOS

Peaks are observed at 4 masses in the above spectra. The peaks at 3.67 GeV/c² come from direct ψ' decays to hadrons. The SQUAW fit shifts the mass down slightly from the ψ' mass of 3.684 GeV/c². In most of the spectra there are clear peaks coming from decays of the $\chi(3415)$, $\chi(3510)$, and $\chi(3555)$.

To obtain branching ratios from these spectra, the Monte Carlo is used to determine the acceptance. A phase space distribution is used to model the $\chi(3510)$, $\chi(3555)$, and $\eta_c(2970)$ decays. For the $\chi(3415)$ the photon is produced with a $1+\cos^2\theta$ angular distribution. To check for model dependence, the acceptance for $\chi(3415) \rightarrow \pi^+\pi^-\rho$, $\rho \rightarrow \pi^+\pi^-$ was also calculated. It differs from the acceptance for $\chi(3415) \rightarrow \pi^+\pi^-\pi^+\pi^-$ by a factor of 0.96 ± 0.02 . This 4% difference is added in quadrature to the systematic error calculated from section 4.2.0 to obtain the total systematic error of the acceptance calculation. This total systematic error is always less than 0.7 of the statistical error. The Monte Carlo is also used to determine the probability that events are misclassified (e.g. a $\chi \rightarrow 4\pi$ event is put into the $\chi \rightarrow 2\pi 2K$ histogram). The decays $\chi \rightarrow \pi^+\pi^-$ and $\chi \rightarrow K^+K^-$ are confused 10% of the time. Misidentification probabili-

ties are negligible for all other decay modes. The branching ratios are corrected for this misidentification.

The number of detected events is determined by fitting the spectra between 3.2 and 3.62 GeV/c² to a linear background plus three peaks. The masses of the $\chi(3510)$ and $\chi(3555)$ are fixed to 3 and 5 MeV/c² below those determined from the decay $\psi' \rightarrow \gamma\gamma\psi$ (Table 2). They are fixed lower than the actual masses because the 1-C SQUAW fits shift the peaks downwards. The mass of the $\chi(3415)$ is allowed to vary in each fit. The shapes of the peaks are fixed to the known resolution function and the x -intercept of the linear background is fixed to that determined by a Monte Carlo of the principle background: $\psi' \rightarrow \pi^0 \rightarrow \text{charged hadrons}$. The resulting fits for two of the decay modes are shown in Figure 24. The fitted masses for the $\chi(3415)$ are shown in Table 3. The errors on the separate mass measurements are statistical. The first error on the average mass is statistical and the second error results from the 4 MeV/c² uncertainty in the ψ' mass. Our $\chi(3415)$ mass measurement is directly proportional to the ψ' mass we use (3.68400 GeV/c²).

Figure 24: Fits of the 1-C χ mass spectra

TABLE 3
Mass of the $\chi(3415)$

mode	mass (MeV/c ²)
$\pi^+\pi^-$	3415 ± 2
K^+K^-	3414 ± 2
$2\pi^+2\pi^-$	3413 ± 1
$\pi^+\pi^-K^+K^-$	3412 ± 1
$\pi^+\pi^-pp$	3414 ± 2
$2K^+2K^-$	3416 ± 3
$3\pi^+3\pi^-$	3411 ± 2
average	$3412.9 \pm 0.6 \pm 4.0$

Since the spectra from the 1-C fits have higher statistics and smaller systematic errors than the 4-C spectra, they are used to determine all the χ branching ratios except $\chi \rightarrow \bar{p}p$ (where the 1-C fit shows no significant signal above the background). The η_c branching ratios and limits are obtained from the 4-C spectra since they have a smaller background and the efficiency for a 0.7 GeV photon is near 1. The η_c limits are calculated at a mass of 2.970 GeV/c², the value recently measured by the Crystal Ball experiment.²⁷ The limits are similar for all masses within 0.2 GeV/c² of this mass. The resulting branching ratios and limits are shown in Table 4. We have looked for many other decay modes,

²⁷E. Bloom, to be published in the proceedings of the Photon-Lepton Symposium at Fermilab (1979).

including decays with a π^0 or an η , but the branching ratio limits are too high to be of use.

Also shown in the table are the results of a calculation using the statistical model.²⁸ This model assumes all available isospin states are populated with their statistical weights to relate the rates for decays to different charge states of a general decay mode. For example it relates $B(x \rightarrow \pi^0 \pi^0)$ to $B(x \rightarrow \pi^+ \pi^-)$ but does not relate these to $B(x \rightarrow K^+ K^-)$. The last column in the table gives the ratio of the rate for the observed decay mode to the rate for the general decay mode. It also gives the branching ratios for the general decay mode. The bottom lines of the table give the sums of the branching ratios to the observed general decay modes. Only 1/2 of the x decays have been observed. The reliability of this estimate is not very good since the statistical model is very simple and is certainly not completely correct.

Some of the above x hadronic decays have been previously observed.²⁹ This is the first report of decays to $K_s K_s$, $\bar{p}p$, $2K^+ 2K^-$, $4\pi^+ 4\pi^-$, and $\pi^+ K_s^+ K_s^-$. This last decay is important because a particle with $J = 0^+$ is not allowed to decay to $\pi^+ K_s^+ K_s^-$. The absence of a peak for the $x(3415)$ is further support for its quantum number assignment of 0^+ , while the observation of the $x(3510)$ decaying in this way shows that it is not 0^+ . This last fact was already known from observations of the angular dis-

²⁸A. Pais, Ann. Phys. **2**, 548 (1960).

²⁹M. Tanenbaum et al., Phys. Rev. **D17**, 1731 (1978).

³⁰ibid.

TABLE 4

x hadronic branching ratios.

The errors for $B(\psi' \rightarrow \gamma x) \cdot B(x \rightarrow f)$ do not include the overall scale uncertainty of 17% due to normalization (see Section 4.4.0). The values of $B(x \rightarrow f)$ are obtained using $B(\psi' \rightarrow \gamma x) = (7 \pm 2)\%$ from the Particle Data Group's Review of Particle Properties (1978) and $B(\psi' \rightarrow \gamma \eta_c(2970)) = (0.35 \pm 0.15)\%$ from the Crystal Ball experiment. The errors given in the table do not include these errors. The C.L. is the probability that the expected background could fluctuate upwards to give the signal. A "*" means there is too little background to calculate the C.L. All limits are 90% confidence level. The last column is explained in the text.

mode/ mass	events	$B(\psi' \rightarrow \gamma x) \cdot B(x \rightarrow f)$	C.L.	$B(x \rightarrow f)$	Statistical factor
$\pi^+ \pi^-$					
2970	<2.3	$<3 \cdot 10^{-5}$		$<8.6 \cdot 10^{-3}$	2/3
3415	105 ± 25	$(5.2 \pm 1.2) \cdot 10^{-4}$	10^{-103}	$(7.4 \pm 1.7) \cdot 10^{-3}$	$(1.1 \pm 0.2) \cdot 10^{-2}$
3510	<3.5	$<4 \cdot 10^{-5}$		$<5.7 \cdot 10^{-3}$	
3555	52 ± 13	$(3.0 \pm 0.8) \cdot 10^{-4}$	10^{-43}	$(4.3 \pm 1.1) \cdot 10^{-3}$	$(6.5 \pm 1.7) \cdot 10^{-3}$
$K^+ K^-$					
2970	<2.3	$<3 \cdot 10^{-5}$		$<8.9 \cdot 10^{-3}$	2/3
3415	75 ± 18	$(4.6 \pm 1.1) \cdot 10^{-4}$	10^{-60}	$(6.6 \pm 1.6) \cdot 10^{-3}$	$(9.9 \pm 2.4) \cdot 10^{-3}$
3510	<3.5	$<4.3 \cdot 10^{-5}$		$<6.1 \cdot 10^{-3}$	
3555	25 ± 8	$(1.5 \pm 0.5) \cdot 10^{-4}$	$7 \cdot 10^{-16}$	$(2.1 \pm 0.7) \cdot 10^{-3}$	$(3.2 \pm 1.1) \cdot 10^{-3}$
$K_s K_s$					
2970	<2.3	$<7.3 \cdot 10^{-5}$		$<2.1 \cdot 10^{-2}$	
3415	14 ± 4	$(2.0 \pm 0.5) \cdot 10^{-4}$	*	$(2.9 \pm 0.7) \cdot 10^{-3}$	
3510	<2.3	$<6.3 \cdot 10^{-5}$		$<1.0 \cdot 10^{-3}$	
3555	4 ± 2	$(6. \pm 3.) \cdot 10^{-5}$	*	$(8. \pm 4.) \cdot 10^{-4}$	
$\bar{p}p$					
2970	$3.5 \pm 2.$	$(1.4 \pm 0.8) \cdot 10^{-5}$	$2 \cdot 10^{-3}$	$(4.0 \pm 2.3) \cdot 10^{-3}$	$(6. \pm 4.) \cdot 10^{-3}$
3415	5 ± 2	$(2.7 \pm 1.2) \cdot 10^{-5}$	$2 \cdot 10^{-4}$	$(3.9 \pm 1.7) \cdot 10^{-3}$	$(6. \pm 3.) \cdot 10^{-3}$
3510	<2.3	$<3.0 \cdot 10^{-5}$		$<4.3 \cdot 10^{-4}$	
3555	1 ± 1	$(1.7 \pm 1.7) \cdot 10^{-5}$	*	$(2.4 \pm 2.4) \cdot 10^{-4}$	$(4. \pm 4.) \cdot 10^{-4}$
$\Lambda \bar{\Lambda}$					
2970	<2.3	$<2.0 \cdot 10^{-4}$		$<5.7 \cdot 10^{-2}$	
3415	<5.3	$<4.6 \cdot 10^{-4}$		$<6.6 \cdot 10^{-3}$	
3510	<2.3	$<2.0 \cdot 10^{-4}$		$<2.9 \cdot 10^{-3}$	
3555	<4.3	$<3.7 \cdot 10^{-4}$		$<5.3 \cdot 10^{-3}$	
$\pi^+ K^+ K_s^- + \pi^- K^+ K_s^-$					
2970	8 ± 3	$(3.2 \pm 1.2) \cdot 10^{-4}$	*	$(9. \pm 3.) \cdot 10^{-2}$	$(2.7 \pm 1.0) \cdot 10^{-1}$
3415	<4.	$<8.3 \cdot 10^{-5}$		$<1.2 \cdot 10^{-3}$	
3510	12 ± 4	$(2.1 \pm 0.7) \cdot 10^{-4}$	$6 \cdot 10^{-5}$	$(3.0 \pm 1.0) \cdot 10^{-3}$	$(9. \pm 3.) \cdot 10^{-3}$
3555	<7.	$<1.5 \cdot 10^{-4}$		$<2.1 \cdot 10^{-3}$	

$K^0 \bar{K}^0 + K^+ \bar{K}^-$

2970	$\langle 2.3$	$\langle 6.2 \cdot 10^{-4}$	$\langle 1.7 \cdot 10^{-1}$
3415	$\langle 9$	$\langle 1.2 \cdot 10^{-3}$	$\langle 1.7 \cdot 10^{-2}$
3510	$\langle 3.9$	$\langle 5.3 \cdot 10^{-4}$	$\langle 7.6 \cdot 10^{-3}$
3555	$\langle 6.5$	$\langle 8.9 \cdot 10^{-4}$	$\langle 1.3 \cdot 10^{-2}$

$2\pi^+ 2\pi^-$

2970	$\langle 5$	$\langle 4.8 \cdot 10^{-5}$	$\langle 1.4 \cdot 10^{-2}$	2/5
3415	504 ± 44	$\langle 1.1 \pm 0.2 \rangle \cdot 10^{-3}$	$\langle 3.0 \pm 0.3 \rangle \cdot 10^{-2}$	$\langle 7.5 \pm 0.8 \rangle \cdot 10^{-2}$
3510	193 ± 22	$\langle 8.2 \pm 1.0 \rangle \cdot 10^{-4}$	$\langle 1.2 \pm 0.1 \rangle \cdot 10^{-2}$	$\langle 3.0 \pm 0.4 \rangle \cdot 10^{-2}$
3555	313 ± 29	$\langle 1.3 \pm 0.1 \rangle \cdot 10^{-3}$	$\langle 1.9 \pm 0.2 \rangle \cdot 10^{-2}$	$\langle 4.8 \pm 0.5 \rangle \cdot 10^{-2}$

$\pi^+ \pi^- K^+ K^-$

2970	$\langle 3.3$	$\langle 5.4 \cdot 10^{-5}$	$\langle 1.5 \cdot 10^{-2}$	1/4
3415	262 ± 28	$\langle 1.9 \pm 0.2 \rangle \cdot 10^{-3}$	$\langle 2.7 \pm 0.3 \rangle \cdot 10^{-2}$	$\langle 6.8 \pm 0.8 \rangle \cdot 10^{-2}$
3510	60 ± 12	$\langle 4.0 \pm 0.8 \rangle \cdot 10^{-4}$	$\langle 5.7 \pm 1.1 \rangle \cdot 10^{-3}$	$\langle 1.4 \pm 0.3 \rangle \cdot 10^{-2}$
3555	126 ± 16	$\langle 8.2 \pm 1.1 \rangle \cdot 10^{-4}$	$\langle 1.2 \pm 0.2 \rangle \cdot 10^{-2}$	$\langle 3.0 \pm 0.4 \rangle \cdot 10^{-2}$

$\pi^+ \pi^- \bar{p} p$

2970	$\langle 4.3$	$\langle 5.2 \cdot 10^{-5}$	$\langle 1.5 \cdot 10^{-2}$	1/4
3415	46 ± 10	$\langle 2.6 \pm 0.6 \rangle \cdot 10^{-4}$	$\langle 3.7 \pm 0.8 \rangle \cdot 10^{-3}$	$\langle 1.5 \pm 0.3 \rangle \cdot 10^{-2}$
3510	19 ± 6	$\langle 1.1 \pm 0.3 \rangle \cdot 10^{-4}$	$\langle 1.6 \pm 0.4 \rangle \cdot 10^{-3}$	$\langle 6.4 \pm 0.2 \rangle \cdot 10^{-2}$
3555	36 ± 8	$\langle 2.3 \pm 0.5 \rangle \cdot 10^{-4}$	$\langle 3.3 \pm 0.7 \rangle \cdot 10^{-3}$	$\langle 1.3 \pm 0.3 \rangle \cdot 10^{-2}$

$2K^+ 2K^-$

2970	$\langle 2.3$	$\langle 8.7 \cdot 10^{-5}$	$\langle 2.5 \cdot 10^{-2}$	1/6
3415	28 ± 10	$\langle 4.4 \pm 1.6 \rangle \cdot 10^{-4}$	$\langle 6. \pm 2. \rangle \cdot 10^{-3}$	$\langle 3.8 \pm 1.4 \rangle \cdot 10^{-2}$
3510	6 ± 4	$\langle 8.5 \pm 5.7 \rangle \cdot 10^{-5}$	$\langle 1.2 \pm 0.8 \rangle \cdot 10^{-3}$	$\langle 7. \pm 5. \rangle \cdot 10^{-3}$
3555	14 ± 6	$\langle 2.0 \pm 0.9 \rangle \cdot 10^{-4}$	$\langle 2.9 \pm 1.2 \rangle \cdot 10^{-3}$	$\langle 1.7 \pm 0.7 \rangle \cdot 10^{-2}$

$3\pi^+ 3\pi^-$

2970	$\langle 2.9$	$\langle 8.7 \cdot 10^{-5}$	$\langle 2.5 \cdot 10^{-2}$	4/21
3415	136 ± 19	$\langle 1.8 \pm 0.3 \rangle \cdot 10^{-3}$	$\langle 2.5 \pm 0.4 \rangle \cdot 10^{-2}$	$\langle 1.3 \pm 0.1 \rangle \cdot 10^{-1}$
3510	78 ± 13	$\langle 9.0 \pm 1.5 \rangle \cdot 10^{-4}$	$\langle 1.3 \pm 0.2 \rangle \cdot 10^{-2}$	$\langle 6.8 \pm 1.1 \rangle \cdot 10^{-2}$
3555	132 ± 17	$\langle 1.7 \pm 0.3 \rangle \cdot 10^{-3}$	$\langle 2.4 \pm 0.4 \rangle \cdot 10^{-2}$	$\langle 1.3 \pm 0.2 \rangle \cdot 10^{-1}$

$2\pi^+ 2\pi^- K^+ K^-$

2970	$\langle 2.3$	$\langle 2.2 \cdot 10^{-4}$	$\langle 6.3 \cdot 10^{-2}$	1/9
3415	$\langle 45$	$\langle 2.0 \cdot 10^{-3}$	$\langle 2.9 \cdot 10^{-2}$	
3510	$\langle 9$	$\langle 4.1 \cdot 10^{-4}$	$\langle 5.9 \cdot 10^{-3}$	
3555	$\langle 10$	$\langle 4.5 \cdot 10^{-4}$	$\langle 6.4 \cdot 10^{-3}$	

$\pi^+ \pi^- 2K^+ 2K^-$

2970	$\langle 2.3$	$\langle 2.5 \cdot 10^{-3}$	$\langle 7.0 \cdot 10^{-1}$
3415	$\langle 5.5$	$\langle 3.1 \cdot 10^{-3}$	$\langle 4.4 \cdot 10^{-2}$
3510	$\langle 2.9$	$\langle 1.6 \cdot 10^{-3}$	$\langle 2.3 \cdot 10^{-2}$
3555	$\langle 3.3$	$\langle 1.8 \cdot 10^{-3}$	$\langle 2.6 \cdot 10^{-2}$

$4\pi^+ 4\pi^-$

2970	$\langle 2.3$	$\langle 4.0 \cdot 10^{-4}$	$\langle 1.1 \cdot 10^{-1}$	10/117
3415	7 ± 4	$\langle 5. \pm 3. \rangle \cdot 10^{-4}$	$\langle 8. \pm 4. \rangle \cdot 10^{-3}$	$\langle 9. \pm 5. \rangle \cdot 10^{-2}$
3510	4 ± 3	$\langle 3. \pm 2. \rangle \cdot 10^{-4}$	$\langle 4. \pm 3. \rangle \cdot 10^{-3}$	$\langle 5. \pm 4. \rangle \cdot 10^{-2}$
3555	9 ± 5	$\langle 7. \pm 4. \rangle \cdot 10^{-4}$	$\langle 1.0 \pm 0.6 \rangle \cdot 10^{-2}$	$\langle 12. \pm 7. \rangle \cdot 10^{-2}$

Sum of Hadronic Branching Ratios (Statistical Model)

2970	$\langle 2.8 \pm 1.0 \rangle \cdot 10^{-1}$
3415	$\langle 4.4 \pm 0.6 \rangle \cdot 10^{-1}$
3510	$\langle 1.9 \pm 0.4 \rangle \cdot 10^{-1}$
3555	$\langle 3.6 \pm 0.7 \rangle \cdot 10^{-1}$

Sum of Hadronic and $\pi^+ \pi^- \gamma \gamma$ branching ratios

2970	$\langle 2.8 \pm 1.0 \rangle \cdot 10^{-1}$
3415	$\langle 4.7 \pm 0.6 \rangle \cdot 10^{-1}$
3510	$\langle 4.2 \pm 0.9 \rangle \cdot 10^{-1}$
3555	$\langle 4.3 \pm 0.8 \rangle \cdot 10^{-1}$

tributions in $\psi' \rightarrow \gamma \gamma$, $\psi' \rightarrow \pi^+ \pi^-$.²⁰ While the decays $\psi' \rightarrow \pi^+ \pi^-$ and $\psi' \rightarrow K^+ K^-$ have been previously observed, the present statistics are much better and conclusively show that the $\psi(3415)$ and $\psi(3555)$ decay in this way while there is no evidence for decays of the $\psi(3510)$ to these final states. Since the possible J^{PC} states for two pseudoscalars are 0^{++} , 1^{--} , 2^{++} etc., the $\psi(3415)$ and $\psi(3555)$ must have these quantum numbers. Of course, all the ψ 's must have positive charge conjugation since they are reached by radiative transitions from the ψ' which is 1^{--} . So this leaves only 0^{++} , 2^{++} , 4^{++} etc. as possible quantum numbers for the $\psi(3415)$ and $\psi(3555)$. Note that the ψ 's quantum numbers prohibit their decay to $K_L^0 K_S^0$, so the $K_L^0 K_S^0$ branching ratio is twice the $K_S^0 K_S^0$ branching ratio given in the table.

Only the $\psi(3415)$ and $\psi(3555)$ have clear decays to $2K^+ 2K^-$. Figure 25 shows the distribution of the lowest $K^+ K^-$ mass in these events. The smooth curves show the phase space distribution. There are clear peaks at the $\phi(1020)$ mass. For the $\psi(3415)$ 13 of 28 events are in the ϕ peak while for the $\psi(3555)$ 10 of 15 events are in the ϕ peak. Of the 13 and 10 events with ϕ 's, in 4 and 2 of the events the other $K^+ K^-$ pair also have a ϕ mass.

Figure 25: Distribution of lowest K^+K^- mass in x decays to $2K^+2K^-$: (a) $x(3415)$, (b) $x(3555)$.

Saving the most interesting result for last, the peak in the 4-C spectrum for $\Psi' \rightarrow \gamma x$, $x \rightarrow \pi^+ K^- K_s$ will now be discussed. There are 9 events centered at a mass of $2.97 \pm 0.01 \text{ GeV}/c^2$. The width is consistent with the expected resolution of $\sigma = 0.013 \text{ GeV}/c^2$. There is very little background in the plot. This peak provides strong confirmation for the state observed at $2.98 \pm 0.02 \text{ GeV}/c^2$ by the Crystal Ball group.³¹ Even though very few of its properties have been measured, we'll refer to this state as the η_c because it is near the mass expected for the η_c . Since $\Psi' \rightarrow \gamma \eta_c$ the η_c has positive charge conjugation and since $\eta_c \rightarrow \pi^+ K^- K_s$ it cannot be $J^{PC} = 0^{++}$. Using the Crystal Ball group's measurement of $B(\Psi' \rightarrow \gamma \eta_c) = (0.35 \pm 0.15)\%$ we obtain $B(\eta_c \rightarrow \pi^+ K^- K_s) + B(\eta_c \rightarrow \pi^- K^+ K_s) = 9.1\%$. Assuming it decays to K_L 's as often as K_s 's and using isospin (assuming the η_c has isospin=0) to get $B(\eta_c \rightarrow \pi^+ K^- K^0) = 2 \cdot B(\eta_c \rightarrow \pi^0 K^+ K^-) = 2 \cdot B(\eta_c \rightarrow \pi^0 K^0 K^0)$ one obtains $B(\eta_c \rightarrow \pi K K) = 27\%$. This is a very large branching ratio. None of the other decay modes we investigated show much evidence for the η_c . The second largest signal is in the 4-C $\bar{p}p$ spectrum where there are 3 events near $2.97 \text{ GeV}/c^2$.

³¹E. Bloom, to be published in the proceedings of the Photon-Lepton Symposium at Fermilab (1979).

Chapter VII

SUMMARY

The experimental status of the charmonium system has advanced considerably in the last 2 years. Its current status is summarized in Figure 26. Our mass and branching ratio measurements are summarized in tables 5 and 6. The 3P states: $\chi(3415)$, $\chi(3510)$, and $\chi(3555)$ remain firmly established. The $\chi(3455)$ is effectively dead. Two experiments³² in addition to our own have set limits on its production in the decay $\psi' \rightarrow \gamma \chi$, $\chi \rightarrow \gamma \psi$ which is the way it was originally observed. For a short period of time there was a new candidate for the η_c' at a mass of 3.591 GeV/c².³³ It was also observed in $\psi' \rightarrow \gamma \eta_c'$. The Crystal Ball experiment³⁴ has set a limit well below the original measured branching ratio, effectively killing this state. The $\chi(2830)$ which was observed in the decay $\psi \rightarrow 3\gamma$ has also been eliminated by the Crystal Ball experiment. In its place as a candidate for the η_c there is a state at 2.970 ± 0.01 GeV/c² observed in the inclusive photon spectrum by the Crystal Ball group and exclusively in its decay to $\pi^2 K^0 K_s$ by this experiment.

³²M. Bartel et al., Phys. Lett. **79B**, 492 (1978); E. Bloom, to be published in the proceedings of the Photon-Lepton Symposium, Fermilab (1979).

³³M. Bartel et al., Phys. Lett. **79B**, 492 (1978).

³⁴E. Bloom, to be published in the proceedings of the Photon-Lepton Symposium, Fermilab (1979).

Figure 26: Charmonium level diagram: after. Solid lines indicate things confirmed by experiment. Dashed lines indicate things with a small amount of experimental evidence. Dotted lines indicate things predicted by the Charmonium model for which there is no experimental evidence.

TABLE 5

Masses of the known charmonium states.

The ψ and ψ' masses are not measurements from this experiment; they are the values used in the kinematic fits to obtain the other masses. The errors do not include an overall mass-scale uncertainty of $\pm 4 \text{ MeV}/c^2$.

State	mass (MeV/c ²)
$\eta_c(2970)$	2970. ± 10
$\psi(3095)$	3095.00
$\chi(3415)$	3412.9 ± 0.6
$\chi(3510)$	3508.1 ± 0.6
$\chi(3555)$	3555.3 ± 1.1
$\psi'(3684)$	3684.00

TABLE 6

Branching ratios for $\psi' \rightarrow \chi\psi$.

The $\pi\pi\psi$ branching ratios are taken from the Particle Data Group's Review of Particle Properties (1978). Since the number of detected $\pi^+\pi^-\psi$ events was used for normalization, all other branching ratios in this table are proportional to $B(\psi' \rightarrow \pi^+\pi^-\psi)$. The errors given include this uncertainty.

Decay mode	Total branching ratio (%)	from section
$\pi^+\pi^-\psi$	33. ± 3 .	
$\pi^0\pi^0\psi$	17. ± 2 .	
$\eta\psi$	2.8 ± 0.4	4.3, 5.2
$\gamma\chi(3415), \chi(3415) \rightarrow \gamma\psi$	<0.56	5.3
$\gamma\chi(3510), \chi(3510) \rightarrow \gamma\psi$	2.4 ± 0.6	5.3
$\gamma\chi(3555), \chi(3555) \rightarrow \gamma\psi$	1.1 ± 0.3	5.3
$\pi^0\psi$	0.15 ± 0.06	5.4

At this time there is no candidate state for the η_c' . We have no evidence for it, but it could easily hide under the peak from direct ψ'

decays or under the $\chi(3555)$ peak. Theorists can easily adjust the parameters of the charmonium potential to make the η_c' very difficult to observe. The 1P_1 state is also unobserved. This is not surprising because it cannot be produced directly in e^+e^- annihilation or in radiative ψ' decays.

With the deaths of the $\chi(2830)$ and $\chi(3455)$ states, the charmonium model now agrees fairly well with the experimental data. Work is now in progress to extend the model to the upilon system.

Studies of ψ' decays are interesting not only to gain information about the charmonium system, but also as a clean laboratory to study other decays. Particular examples of this are the study of the $\pi^+\pi^-$ dynamics in the decay $\psi' \rightarrow \pi^+\pi^-\psi$ and the observation of the decay $\psi' \rightarrow \pi^0\psi$ which violates isospin conservation.

Appendix A

TRIGGER

A.1 REQUIREMENTS

The beams at SPEAR consist of one small bunch each of e^+ and e^- ($.02 \times .2 \times 4$ cm) circulating in opposite directions around the storage ring. They cross in each interaction region at a rate of 1.28 MHz or every 780 ns. The trigger must determine which beam crossings produced interesting interactions, so the detector can be read out. To see how this should be done, we must define an "interesting interaction" and consider the possible backgrounds.

At SPEAR the rate for e^+e^- to interact producing a particle in the detector is small (≈ 0.2 Hz), so it is reasonable to read in all such events. This allows a simple trigger criterion: read in all events with at least one track going through the detector. No additional requirement, e.g. high p_t , is needed to further reduce the rate. Another important requirement for this trigger is that its acceptance be easy to understand. For example, all events with any charged particle of $p_t > 100$ MeV and $|\cos\theta| < 0.65$ will cause a trigger with 100% efficiency. Such a simple trigger criterion allows the acceptance to be accurately determined by a Monte Carlo calculation, thus contributing small systematic errors to measurements of cross sections.

This trigger must reject backgrounds in addition to accepting all the events we want. Background rejection should be good enough to keep the total trigger rate below about 3 Hz. Higher trigger rates result in too much deadtime from event read-in and make data analysis unwieldy. The primary sources of background are cosmic rays, random firings of drift chamber wires and pipe counters (perhaps caused by synchrotron radiation); and beam gas events (interaction of the beam with residual gas in the beam line). The methods used to reject these backgrounds will be described later.

In addition to the above requirements necessary for normal data taking, special trigger modes are needed for calibrations and diagnostics. A cosmic ray trigger is needed. Triggers are needed for calibrations. For example the T0F system has a light flasher and optical fibers to provide light pulses to the counters. These pulses are recorded by the T0F electronics and a trigger must be generated so the data can be read out.

Selection of the trigger modes should be under computer control. Then no cables or switches need be moved, enhancing reliability. This reflects a basic philosophy in the construction of the electronics: the computer is more reliable than the people on shift.

A.2 THE TWO TIER TRIGGER SCHEME

To satisfy the above requirements we use a two tier trigger scheme. Each time the beams cross all the data from the detector is saved. Some of this data is used by the primary trigger to decide if the event is of

further interest. If the decision is negative, the electronics are reset and readied for the next beam crossing; thus this decision must be made in about 500 ns. For a positive decision the data are held and the secondary trigger logic is started. Since the primary trigger decision must be made so quickly it is very simple. Because it doesn't run very often, the secondary trigger logic can take more time and thus be more complex. Basically, it looks in the drift chambers for tracks coming from the beam line. The number of tracks determines whether the event will trigger. If it triggers, the event is recorded. If there is no trigger, the electronics is reset and enabled to record the next beam crossing. The secondary trigger logic takes about 35 μ s to find tracks and make its decision. During this time the detector is insensitive to new events; thus causing dead time. The sole purpose of the primary trigger is to make the secondary trigger logic run infrequently enough so the deadtime is negligible (<10%). In practice, this deadtime is a few percent.

A.3 THE PRIMARY TRIGGER

The Primary trigger logic is very simple both in theory and in implementation. For the normal charged particle trigger it requires a coincidence of beam crossing, pipe, and drift chamber majority (DCM). Beam crossing is a timing signal derived from a beam pickup electrode. The time between this signal and when the beams actually cross at the interaction region is constant to better than 0.1 ns. Pipe is the OR of signals from the two halves of the pipe counter. Each half is the time compensated coincidence of signals from the two layers which make up

each hemicylinder. That is, the pipe signal indicates that a charged particle went through the pipe counter. Pipe and beam crossing are put in a tight (12 ns) timing coincidence to reduce the cosmic ray rate by a factor of 12/780. DCM is true if at least 4 of 9 drift chamber layers have a hit in them. The 9 layers used include the inside 5 layers and 4 other layers chosen for convenience. The requirement of 4 of 9 layers results in a very high trigger efficiency for a track which goes through all the layers. This simple trigger results in a rate between 30 Hz at low energy and 2000 Hz at high energy. This is low enough to keep the secondary trigger deadtime below 10%.

Other primary triggers are used for other data-taking modes. The cosmic ray trigger requires a coincidence of a top TOF counter, a bottom TOF counter, pipe, DCM, and the condition that the beam bunches be >12 m from the interaction region. Triggers for calibrations are even simpler. In general, the calibrator (e.g. light flasher system) generates timing signals to control the primary trigger. These signals are routed by the computer controlled logic.

A.4 SECONDARY TRIGGER LOGIC

A.4.1 Requirements

The specifications for the secondary trigger logic are quite stringent. First of all, it must make the trigger decision in about 30 μ s. This speed is needed to limit deadtime to an acceptable value--defined as 10%. Experiments with Mark I indicate that the primary trigger rate should be at most 3 kHz, thus determining the 30 μ s that the secondary

trigger logic is allowed. In this time it must detect, with high efficiency, tracks going through the drift chamber. This means that extra hits in the chamber or tracks at nearly the same azimuthal angle shouldn't make it miss tracks. While efficiently finding real tracks, it must reject random hits in the drift chamber. These random hits are caused by synchrotron radiation or electronic problems. When the system was designed, the estimate of the number of random hits was very uncertain, but the best guess was about one per layer. Therefore, random hits at a density of several per layer should not cause false tracks to be found.

In general, the backgrounds for this new detector were very uncertain so it was quite important that the conditions for the secondary trigger be flexible. Wherever possible, the function of the hardware should be programmable via the on-line computer. Since the secondary trigger logic is quite complex and is essential to the experiment, it should have diagnostic features built in so it can be tested by the computer. For these same reasons, the system should be modular so it is easy to repair.

A.4.2 Basic Tracking Method

The method used in the secondary trigger logic is rather simple, if you ignore the complications. So first the basic idea will be explained and then the complications will be added one at a time. Suppose we have a system of planar drift chambers and want to find tracks going perpendicular to the plane of the chambers. We'll do this in one projection

only and won't use the drift time information. To do this, have each sense wire that is hit turn on a bit in a shift register, with a separate shift register for each plane (Figure 27). Put the outputs of the shift registers into an AND gate and its output into a counter. Clock the shift registers and the counter counts how many tracks there are. That's the basic idea. Note that by serially processing the data, only one AND gate is needed, rather than one for each possible position of the track. This savings of hardware comes at the expense of extra time to find the tracks, but we have 30 μ s, which is enough time.

The first complication is that tolerance must be added to the system. When tracks pass between two drift chamber cells either one or both may fire and a track should be found in either case. This is solved by putting a "widener" between each shift register and the AND gate (Figure 28). A widener extends any bit coming in by N bits, where N is programmable. It is deadtimeless; that is, if 3 consecutive bits come in, N+3 bits go out.

The next problem is that we don't want to require all the detectors to fire. They may be inefficient or we may want to use tracks that only go through the first half of the chambers. To do this, we just replace the AND gate with a memory. The outputs of all the wideners constitute the address of the memory. A memory of length 2^n , where n is the number of shift registers, allows you to program exactly which combinations of hits will be called a track. Now by making the memory word 2 bits wide, there are four possible outputs for each input. This allows the definition of a null track and three exclusive track classes, which we label

Figure 27: Simple straight track finding hardware.

Figure 28: Simple curved track finding hardware.

A, B, and C. For example, A tracks could be those that have hits in 3 of the 4 planes and B tracks could be those that only went through the first planes. This "Track Logic Memory" (TLM) makes the requirements for a track completely programmable.

So far we can only detect straight tracks. Curved tracks can be found by putting shift registers of different lengths between each widener and the TLM input. As shown in Figure 28, this straightens out curved tracks, so they can satisfy the TLM requirements. This still only detects tracks of a single curvature. We can make it span a small range of curvatures by using the wideners. Then to cover a large range of curvatures, we duplicate the circuit shown in the box of Figure 28, 24 times. Each one has a different set of shift register lengths to detect a different range of curvatures. Each circuit is in a separate module, called a Curvature Module. All the Curvature Modules are identical since the length of the shift register delay is programmable. These are called Variable Length Shift Registers, VLSR's. The set of delays and widths in a Curvature Module which allows it to detect tracks in a particular range of curvatures is called a road.

This describes the major principles of the track finding method. Several complications still remain. The actual drift chamber system is cylindrical so that different layers are at different radii and also have different numbers of wires. For the Curvature Modules to work properly, the shift registers must be clocked so that data about the same azimuthal angle comes simultaneously from all layers. This is done by using a "burped clock." That is the layer with the most cells is

clocked every cycle (clock tick) while, for example, a layer with $2/3$ that number of cells is clocked 2 of every 3 cycles. This keeps all layers moving at the same average angular speed so the data coming out of the shift registers is out of phase by at most half a clock tick. This remaining inaccuracy is compensated with the tolerance provided by the wideners in the Curvature Modules.

All of the tolerance we have added to the system now presents a problem, "chatter." A Curvature Module may detect a track for several clock ticks or several Curvature Modules may detect the same track. These should be counted as only 1 track. This is done by merging together all tracks found within a short time interval, the "antichatter interval." This effectively stops the double counting of tracks, but introduces the possibility of counting two tracks as one. Two tracks at nearly the same ϕ may be merged into one even if they have greatly different curvatures. Aside from inefficiencies in the drift chambers, this provides the only mechanism for missing a track. For a one particle trigger this causes no trigger inefficiency since one track will always be seen, but in multi-track triggers it introduces a small inefficiency.

We now have all the basic elements necessary for the secondary trigger logic. Figure 29 summarizes the system with each rectangle representing a separate CAMAC module. Data available to the trigger logic comes from 15 layers of drift chambers, with 144 to 252 cells per layer; 48 TOF counters; and ϕ strips of the endcap shower counters. The data are parallel loaded into shift registers with separate shift registers for each detector layer and one shift register bit for each detector

element. Any 12 of these shift registers are input to the trigger logic using the Test-and-Pickoff module. This module connects the beginning and end of each shift register and feeds the data to the Curvature Modules via a special CAMAC upper back plane bus. Working in parallel, 24 Curvature Modules use the data from the Test-and-Pickoff to look for tracks in their roads. Each Curvature Module is programmed to see tracks in a particular small range of momentum. Together they detect any track with a transverse momentum greater than 105 MeV. The outputs of the Curvature Modules go to three Track Counters which count the tracks and output the number found to the Master Interrupt Controller (MICKEY). After the track finding is complete, MICKEY uses the number of tracks found to decide if the event should be read into the computer. Accordingly, it either interrupts the computer or enables the detector to record the next event. Orchestrating this whole procedure is the Master Clock module. It provides the clocks and control signals to run the system. Finally, there is a Display Module which takes the same shift register data used by the Curvature Modules and displays it graphically on an x-y-z scope. This allows one to see the tracks and provides a very useful diagnostic of the shift register operation.

A.4.3 Details of the Trigger Logic Modules

Curvature Module

The Curvature Modules form the heart of the trigger logic system. They are used to define the roads which find tracks. All the other modules exist to feed data to or take data from the Curvature Modules.

Figure 29: Secondary Trigger Logic block diagram

Figure 30 shows a block diagram of a Curvature Module. There are 12 channels of widener and Variable Length Shift Register (VLSR). Each widener is CAMAC programmable to extend an incoming bit by 0 to 15 bits. Each VLSR is CAMAC programmable to delay an incoming bit by 1 to 64 clock ticks. The setting of these delays and widths determines the shape of track the Curvature Module will find. Since the wideners and VLSR's are fundamental to the system, being duplicated 12 times in each of 24 curvature modules, a detailed schematic is shown in Figure 31. The VLSR isn't a shift register at all; perhaps variable length delay would be a better name for it. It consists of a 6 bit parallel loadable counter which addresses a fast RAM. During each clock cycle the counter is incremented (if it overflows it is reset to the value in the CAMAC programmed register); data from the RAM is latched; and incoming data from the widener is stored in the RAM. Thus the RAM acts as a circular buffer. The length of this buffer is determined by the contents of the register.

The outputs of the 12 VLSR's go to an address register which addresses a 2^{12} word by 2 bit RAM, the Track Logic Memory (TLM). This address is also available on an internal connector where it is used to diagnose problems with the module. The TLM is used to decide if the pattern of layers with bits on is a track. Since each pattern of bits addresses a different location in the TLM, the criteria for a track are completely general. This is much more flexible than a majority logic circuit. For example, the current criteria for an A track are that channel 12 must be on and at least 4 of the 6 bits in channels 6-11 must be on. The appropriate data to form this requirement are loaded into

Figure 30: Curvature Module block diagram

counters. Next it generates 341 clock pulses at 10 MHz which go to the other modules via Lemo cable daisy chain. Simultaneously it generates 12 separate burped clocks. These go to fan-out panels which make several copies (converted to the appropriate logic level) of it to send to the modules that record detector data in the shift registers (e.g. the drift chamber TAC's). The Figure shows the burped clock for a layer which has 2/3 of 252 channels, so it is clocked 2/3 of the time. The burping pattern is stored in a 252 word by 12 bit PROM in the Master Clock.

GATE is the final signal generated by the Master Clock. The Track Counters only record tracks when GATE is true. This occurs during the last 252 clock ticks. 252 is the number of clock ticks needed because the outside drift chamber layer has 252 cells and the burped clock is setup so all layers need 252 clock ticks to rotate 2 π radians. 64 of the 89 clock ticks before GATE turns true are necessary to flush data from the previous event out of the VLSR's. The other 25 are necessary for more obscure reasons.

The remaining features of the Master Clock are for diagnostic purposes. Its PROM is computer readable. It has a single clock mode which allows the computer to directly access data in the shift registers, and it can clock the shift registers at 10 MHz for 252 clock ticks. For manual debugging the outputs of the burping PROM are displayed on LED's and there is a pushbutton to generate a clock cycle.

Figure 32: Master Clock block diagram

Figure 33: Master Clock timing diagram

The Test-and-Pickoff Module

The Test-and-Pickoff is the simplest module in the system. About all it contains are multiplexers and TTL to ECL and ECL to TTL converters. It has two main functions: feeding data from the end of the shift registers onto the upper CAMAC backplane, for use by the Curvature Modules; and sending this data back into the beginning of the shift registers, thus making them circular. The converters are necessary because the shift registers are ECL while the trigger logic is TTL. The multiplexers are used for diagnostics. By putting the Master Clock in single clock mode, the computer can load the shift registers with data, read them back out, and send data directly to the Curvature Modules. Data can be put in manually using front panel switches, and it can be read out using LED's.

The Track Counter Module

There are 3 Track Counters in the system: 1 each for A, B, and C tracks. They count and record the tracks found by the Curvature Modules. Figure 34 shows how this is done. Data comes from up to 32 Curvature Modules into latches. When a Curvature Module finds a track, the time count (which indicates the azimuthal angle of the track) is saved in a register, and the antichatter counter starts counting. When this counter counts to the value in the preset antichatter register, the track counter is incremented and the track information is saved in the 54 word by 44 bit track data memory. In this way, all tracks found within the antichatter interval are merged together. The data saved are the contents of the 32 input latches; the 8 bit time counter, which

counts the clock ticks since GATE turned true; and the 4 bit chatter counter, which counts those clock ticks during the antichatter interval that had a true track input. After this data is saved, the latches are reset and the next track awaited. At the end of the scan cycle, when GATE turns false, special action is taken to correctly handle tracks at this boundary. A recently found track whose antichatter interval isn't complete is recorded and counted anyway to prevent its being lost. However, if this is done and a track was found at the beginning of the scan, then they should have been merged together--so one is subtracted from the track count (this is called "condition A"). The track count addresses a 64 word by 2 bit RAM which is preset with CAMAC. The 2 bit output of this goes to MICKEY to be used in the final trigger decision. This RAM has always been programmed to indicate the number of tracks found (in the form 0 tracks→0, 1 track→1, 2 tracks→2 and 3 or more tracks→3).

Diagnostic features of the Track Counter include the ability to read the antichatter register, track data memory, and trigger logic memory. Read out of the track data memory is used not only for diagnostics, but the tracks recorded there are logged on tape for use by the tracking program in locating tracks. LED's on the front panel indicate the number of tracks found and the output of the trigger logic memory.

MICKEY

The Master Interrupt Controller (MICKEY) links the primary trigger, secondary trigger, and computer. It provides the sole method for the detector electronics to interrupt the computer. When its primary trig-

Figure 34: Track Counter block diagram

ger input goes true, MICKEY immediately generates a wait output which prevents the detector electronics from being cleared. Next it sends START to the secondary trigger logic which answers with BUSY. When the track finding is done, BUSY goes false, and MICKEY uses the Track Counter outputs to decide if there is a trigger. This decision is based on 2 bits of output from each of 3 Track Counters, and two spare bits, making 8 total. These address a 2⁸ bit ram in MICKEY which was previously programmed with a one in those addresses which should cause a trigger. Like the Curvature Modules' track logic memories, this allows completely general trigger requirements. If there is no trigger, MICKEY turns off Wait which resets the detector electronics and enables it to record the next beam crossing. If there is a trigger, MICKEY interrupts the computer to initiate event readout. The last CAMAC instruction in an event readout causes a reset sequence, enabling the detector.

The Display Generator

The Display Generator records the shift register data in its RAM and then displays it on an x-y-z scope. The detector layers are represented by 12 circles, whose radii can be set with potentiometers. Points corresponding to cells with 1's in them are intensified. Thus tracks are visible on the display. The display generator has a remote control panel which controls how often a new event is displayed and whether primary or secondary triggers are displayed.

While this display is not essential to the operation of the detector, it is extremely useful. When we first turned on the detector, the on-line software wasn't ready yet. So this hardware display provided the

first evidence that the drift chambers worked, allowing unscrambling of cables and crude measurements of efficiencies. It is also useful for diagnosing problems with the shift registers, since it displays their contents.

A.5 DETERMINING THE ROADS

With the description given above, one can see that this hardware provides a very flexible and programmable track finding system. Now we'll describe how it is programmed: all 203,164 bits of it.

The Track Logic Memory (TLM) in the Curvature Modules contains most of these bits. Fortunately it is easy to program. Currently the requirements for an A track are that 4 or more of the 6 axial drift chamber layers must be on and the TOF counter must fire. With the axial layers fed into channels 6 to 11 and the TOF into channel 12 of the trigger logic, the character string "6-11>3;12=1;" (meaning channels 6 through 11 must have more than 3 hits and channel 12 must have 1 hit) totally describes the setup of the TLM. A subroutine decodes this string and fills a 4096 byte array which is then used to program the TLM. The requirements for B and C tracks are encoded in similar fashion. An important point to note is that the requirements for A, B, and C tracks must be exclusive. Because only two bits are used to encode 3 track types, a particular pattern of layers being on can not be both an A and a B track. Also note that all curvature Modules which find A tracks have their TLM's programmed identically. This is not necessary, but it is convenient.

Even though there are many fewer bits of information, the delays (lengths of variable length shift registers) and widths used to define the Curvature Module roads are harder to determine than the TLM data. For A tracks we need a set of roads which will find, with 100% efficiency, all circular tracks starting at the beam line and having a radius of curvature larger than some minimum radius. The following geometric algorithm, illustrated in Figure 35, is used to generate the roads.

1. Draw a circle of diameter 1.7 meters which goes through the beam line.
2. Draw diameter AB perpendicular to the diameter which goes through the beam line.
3. Divide this diameter into equal segments, the number of segments being the number of roads wanted. Currently there are 22 roads for A tracks.
4. Draw circular arcs through these points, the beam line and the point diametrically opposite the beam line.
5. Each banana shaped object is a road for a Curvature Module. Together the roads span all curvature space down to 0.85 m. To get the delays and widths for a road, the following is done.
6. Calculate ϕ (the azimuthal angle) of the right side of the road at the radius of each detector layer to be used. Also

calculate $\Delta\phi$, the angular distance between the two sides of the road.

7. Convert these angles from radians to clock ticks by multiplying by $252/2\pi$ and rounding off to the nearest integer. Note that this conversion factor is independent of the number of cells in the layer, because the burped clock makes all layers shift at the same angular speed.
8. Adding one to $\Delta\phi$ then gives the width. The addition of one is an empirically determined margin providing enough tolerance to give 100% track finding efficiency. A typical width is 4.
9. To get the delays, add the same number to all the ϕ 's for this road, choosing the number to make layer 12 have a delay of 30. This is done to reduce chatter; that is two roads finding the same track will find it at about the same time because their delays are about the same.

That completes the generation of roads for A tracks. Currently only 2 roads are used to find B tracks: one for positive and one for negative particles. These roads are generated by hand in a method similar to that used for A tracks, which are calculated by the computer. The roads for B tracks are designed to find tracks with a curvature greater than 1.7 m and any dip angle for which the track goes through the inside 5 drift chamber layers. The minimum curvature track that these roads are designed to find is determined by the requirements that all delays and widths must be in the ranges 0-63 and 0-15 which are the limits of the hardware.

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Figure 35: The roads

Having generated these roads, it is necessary to see if they work. This is done using the trigger logic simulator, a program which uses the IBM computer to simulate the trigger logic. This program, originally used to aid in the design of the trigger logic, accurately simulates its hardware and is capable of calculating the exact characteristics of the tracks recorded by the Track Counters. To test a set of roads, we just set up the simulator with those delays and widths, generate tracks with random phi, dip, and curvature (within the ranges the roads are supposed to cover), and see if it finds them. When doing this, the TLM is setup to require that all channels be on. The current set of roads found 999 of 1000 tracks. The last one was found when the criteria in the TLM were relaxed to allow one channel to be off.

The simulator is also used to determine the noise immunity of the system. Random cells in the shift registers are turned on and tracks are sought. Figure 36 shows the probability of finding a track as a function of the number of random points. This was generated with 24 Curvature Modules and a TLM requirement of 5 or more of the 6 axial drift chamber layers. For fewer than 20 random points the probability of finding a track is very small. The Mark II drift chambers are very quiet; they average about one random point per event. In fact I've never seen an event with a secondary trigger that didn't clearly have a track in it (except for "beam burp" events where most of the drift chamber cells are on). Thus the system is sufficiently immune to random cells firing.

Finally, the simulator is used to determine the antichatter interval, the time for which tracks are merged together. It's important to get this right. If it's too small, one track may be counted as two. This allows a single track to cause a two particle trigger, unnecessarily increasing the trigger rate. If the antichatter interval is too large, tracks are merged together when they shouldn't be. This causes an inefficiency. The optimum size is found with the simulator by generating random tracks and increasing the antichatter interval until they don't chatter. The current antichatter intervals for A and B tracks are 5 and 15.

Figure 36: Sensitivity to random noise points in the detector

A.6 EVOLUTION

Now that the general techniques for programming the trigger logic have been described, we'll show how the trigger requirements have evolved with time. When Mark II was designed, the background conditions at SPEAR were not well understood and those at PEP were completely unknown. This made flexible trigger criteria important. To this add the fact that we're not smart enough to anticipate all possible problems and a flexible trigger becomes mandatory. The following description of how this flexibility was used to overcome problems as they occurred illustrates the advantages of a programmable system. Only the major trigger changes are described below; other techniques were tried for short periods of time.

We started out with a simple one particle trigger. All 24 Curvature Modules required 5 or more of the 6 axial layers for an A (barrel), track. B and C tracks were not used. A tracks are called barrel tracks because they must go all the way through the cylindrical, or barrel, part of the detector. B tracks are called endcap tracks, because they are allowed to go out the end of the cylinder into the endcap. The roads for barrel tracks found tracks down to a radius of curvature of 0.8 m (a transverse momentum of 98 MeV). This was an acceptable trigger at low energies, but at high energies (>6 GeV) the trigger rate increased to about 10 Hz. This was unacceptable. Many of the events which triggered had only one track, often coming from large z . To reduce the trigger rate we went to the 1.5 particle trigger.

The 1.5 particle trigger requires one barrel track plus another track which can be either a barrel or endcap track (called a half track because it need only go through part of the drift chamber). Monte Carlo studies show that requiring an extra half track causes little reduction in the acceptance for hadronic events. So the 1.5 particle trigger is a good means to reduce the background.

This trigger was implemented with a technique quite different than was originally planned. The original plan had all 24 Curvature Modules finding both A and B tracks. A tracks would require 5 or more of the 6 axial drift chamber layers. B tracks would require 4 or more of the inside 5 drift chamber layers (including 3 stereo layers) and a hit in an endcap shower counter. This wouldn't work for several reasons. The liquid argon endcap wasn't installed yet. When it was finally installed, its signal to noise ratio for minimum ionizing particle was too small to be useful in the trigger. The second problem is that the definitions of A and B tracks must be exclusive. Due to the hardware design, a Curvature Module can not simultaneously detect A and B tracks. To make the definitions exclusive we could, for example, require that A tracks do not have an endcap hit in their road. This, unfortunately, allows A tracks to be missed. Another solution would be to label as C tracks those patterns that satisfy both the A and B criteria. This would work except for the third problem: track chatter. A single track could be counted by more than one track counter. For example if there is a barrel track with an endcap hit nearby, it could get counted first as an A track (before the endcap hit enters the road) and then as a C track (when the endcap hit enters the road). In fact, track chatter

will be a problem nearly anytime a Curvature Module is used to find multiple track types.

Considering the problems caused by using all 24 Curvature Modules to find both A and B tracks, we decided to use 22 for A tracks and 2 for B tracks. This radical change required only software modifications. Not a single cable was moved. This demonstrates the flexibility of a programmable system. The 22 roads for A tracks span the same curvature space as before. The B roads find tracks down to a curvature of 1.7 m. They required 4 or more of the inside 5 drift chamber layers to have a hit. No endcap hit was required. Using only 2 roads for the B tracks was made possible by the small number of random drift chamber hits. The roads could be wide with a small probability of random hits causing a track to be found. With this requirement for B tracks, both barrel and endcap tracks are found as B tracks. This solves the track chatter problem. We know that all barrel tracks are counted as both A and B tracks. Thus the requirement for the 1.5 particle trigger was at least one A track and at least 2 B tracks.

The next change to the track finding criteria was made necessary by low drift chamber efficiency. Typically 4% of the drift chamber cells are dead due to electronics or high voltage problems. Sometimes a whole layer must be turned off due to a broken wire. To prevent these problems from causing significant track finding inefficiencies, we reduced the efficiency requirements for tracks. A tracks now require 4 or more of the 6 axial drift chamber layers; B tracks require 3 or more of the inside 5 layers. For a 95% cell efficiency, the combinatoric calcula-

tion gives track efficiencies of 0.997 and 0.998. Unfortunately the dead cells are not randomly distributed so the actual inefficiency is slightly higher than this.

The last change to the track finding criteria was made to reduce the trigger rate. 30% of our triggers were caused by single low momentum tracks which didn't reach the TOF counters or out-of-time cosmic rays which didn't latch the TOF counters. To eliminate these we required A tracks to have a TOF counter latch. To avoid delays of more than 63 in the TOF channel we also reduced the curvature acceptance from 0.8 to 0.85 meters.

This resulted in the final configuration, used during most of our data taking. 22 Curvature Modules sought A tracks. They spanned curvatures down to 0.85 m (105 MeV). They required a TOF counter and 4 or more of the 6 axial drift chamber layers to fire. 2 Curvature Modules sought B tracks. They spanned curvatures down to 1.7 m (209 MeV). They required 3 or more of the 5 inside drift chamber layers (2 axial and 3 stereo). Since all barrel tracks are seen as both A and B tracks (neglecting drift chamber inefficiencies), the requirement for the 1.5 particle trigger is at least 1 A track and at least 2 B tracks or at least 2 A tracks. To reduce the trigger rate at high energy, we sometimes used a 2 particle trigger, requiring at least 2 A tracks.

With this final configuration, it is now interesting to examine the trigger rates and determine what causes the triggers. The vast majority of triggers come from the following processes.

1. First order QED: $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$.
2. Second order QED, mainly $e^+e^- \rightarrow e^+e^-e^+e^-$, $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$, and $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$.
3. Hadron production.
4. Cosmic rays.
5. Beam gas: collisions of beam particles with residual gas in the vacuum chamber within the detector.
6. Beam wall, caused by beam gas collisions upstream of the detector resulting in off energy electrons which are overfocused into the beam pipe in the detector.
7. Beam burps: events where a large fraction of the drift chamber cells fire.

The contributions of these event types to the trigger rate varies rapidly with energy and varies by factors of 2 for different running conditions at the same energy. Table 7 gives representative trigger rates for two beam energies. Beam gas and beam wall events are lumped together in the Table because they are hard to distinguish. They each contribute 1/3 to 2/3 of the rate. The rates for beam gas, beam wall, and cosemics have been roughly calculated using known pressures, cross sections, and fluxes. These rates agree with the measured rates within a factor of two.

TABLE 7
Contributions to the trigger rate

Quantity	Increases with	Run 1	Run 2
Beam Energy		1.85	2.90 GeV
Hadron Rate	Luminosity	0.07	0.11 Hz
QED rate	Luminosity	0.11	0.22 Hz
Cosmic rate		0.25	0.28 Hz
Beam burp rate		0.03	0.10 Hz
Beam gas + beam wall rate	Pressure, Current	0.37	1.54 Hz
Secondary trigger rate		0.82	2.25 Hz

The Table shows that only 15% of the events are useful beam-beam interactions (QED and hadrons). The rest are garbage which we'd rather not read in. What improvements can be made? Most of the background comes from beam gas and beam wall events. These are uniformly distributed in z . So a trigger which had z resolution and which required tracks to come from small z would eliminate most of these events. This z resolution is very desirable. The z resolution provided by wire hits without drift time information is too poor. Even with the drift times it is still a difficult problem, because there are many more roads in $r-\phi-z$ space than in $r-\phi$ space. A more advanced track finding scheme may be necessary to find tracks in this larger space in the small available time.

Another possible improvement would require the tracks to come from near the interaction region. This would eliminate many beam wall triggers. Again our resolution is too poor. Adding chambers near the beam

pipe improves this resolution allowing discrimination against beam wall events. These chambers will be added at PEP.

An easier improvement is to use 50% more track logic memory in the Curvature Modules so that the definitions of A, B, and C tracks don't have to be mutually exclusive. This makes it easier to use a Curvature Module to find more than one track type and eliminates the problem of track chatter.

These improvements will certainly make a better, more flexible trigger logic; but in fact, the current system works quite well. The trigger rate is only 1 to 3 Hz. It finds tracks very efficiently over a well defined kinematic range. This allows cross sections to be measured with small systematic errors. It is highly programmable and thus flexible. It is modular and has many built in diagnostic features; this makes repairs easy. Except for the data shift registers, it is highly reliable. The mean-time-between-failures is over 3 months. In short, it does what it is supposed to do, and it does it well.

Appendix B QUALITY CONTROL

It is very important to ensure that the data taken with Mark II are of high quality. We can't afford to let a serious malfunction go unnoticed since, if the detector isn't working properly, valuable running time is lost. Problems must be found with the on-line program, since the off-line analysis is about a month behind data taking.

The task of keeping Mark II running properly should not be underestimated. It is an extremely complex device. There are over 8000 detector elements and over 275 power supplies. There are 7 CAMAC branches. There are timing signals which must be stable to .2 ns. There are complex subsystems, like the secondary trigger logic, whose malfunction make the data completely useless. To check that all of this is working is not a small task. It requires careful planning to include enough diagnostic features in the electronics. Many man-months of software development are necessary to implement the tests. In the long run, this effort pays off: the detector is not down very much.

The rest of this appendix gives brief descriptions of the tests which are done. It does not give every detail of every test, rather it shows the scope of the tests. They range from measuring voltages to measuring drift chamber efficiencies by doing on-line tracking. Important things are checked in multiple ways. Enough checks are done so it is very difficult for a problem to go undetected.

B.1 CALIBRATIONS

The calibration of the barrel liquid argon counters provides a good example of how calibrations test the electronics. Special calibrator electronics dump a programmable amount of charge on each detector strip. This deposited charge is amplified and recorded by the electronics used for normal data taking. The system is pulsed 20 times in this way; means and standard deviations are calculated. This whole procedure is repeated 6 times with 6 different values of the charge. For each channel the 6 means are fit with a quadratic. This is later used to convert pulse height data to deposited energy. The pedestal, gain, and quadratic coefficients of the fit, the χ^2 of the fit, and the standard deviations of each point are required to be within specified ranges. If they are not, the channel is bad. It is flagged so data from it will not be used, and a list of bad channels is generated so they can be repaired. There are so many channels of electronics that it is impossible to keep them all working. Normally common mode failures, affecting many channels, are fixed immediately. Individual bad channels are repaired when the experiment is not running for some other reason.

Calibrating a system typically takes 3 minutes. Calibrations are done for the liquid argon barrels, liquid argon endcap, proportional chamber endcap, drift chamber, and time-of-flight systems. Normally they are done once each 8 hour shift. Often they are done when SPEAR has no beams, so no data is lost.

B.2 TRIGGER LOGIC TEST

The secondary trigger logic is also tested once per shift. It is impossible to check that all possible inputs (there are $\sim 10^{100}$) give the correct output, so tests are done to check the function of each part. The program TRGTEST both programs and tests the trigger logic. It reads and checks the burped clock PROM in the Master Clock. It shifts data through the shift registers at 10 MHz, reads them out, and checks the output. It sets the delays and widths and measures them at full speed by using the shift registers and track counters. It sets and checks the Curvature Modules' Track Logic Memories and the Track Counters' memories. Finally, into the shift registers it feeds data designed to make each Curvature Module find a track, checking that the Track Counters correctly record the tracks. All of this requires less than 30 seconds. If any test fails, more tests are done to determine the cause of the problem. TRGTEST then types instructions for fixing the problem (e.g. it tells which module to change).

B.3 BEGIN RUN TESTS

A data taking run typically lasts 1-2 hours. New runs are begun when tapes are changed or when there is a long interruption of data taking (e.g. when SPEAR injects). As part of the begin run sequence, the computer does a series of tests. If a test fails, an error message is typed on the terminal. The operator can then abort the run and fix the problem. The tests include the Crate Verifier test, the MICKY test, the BADC test, the parallel load test, and the muon system test.

The Crate Verifier test checks that CAMAC communications are working properly. A Crate Verifier module resides in the leftmost slot of each CAMAC crate. This module exists only for diagnostic purposes. It latches the command and write lines, allowing the computer to read them back out. By doing a series of operations to each crate, the computer checks that all CAMAC lines work properly. The Crate Verifier also has an ADC which is used to check the power supply voltages in the crate.

The MICKEY test is very simple. Its 256 bit memory, which determines how many tracks are needed for a trigger, is filled, read out, and checked.

The BADC (Brilliant Analog to Digital Converter) test is more complex. The BADC's digitize the signal voltages from the modules which record data from the drift chambers and shower counters. Using constants determined in the calibrations, they do a quadratic correction to the voltage, converting it to time (in units of 0.1 ns) or energy (in units of 0.1 MeV). Channels with voltage below a threshold are not recorded. Since the actual pulseheights are not logged on tape, it is important to check that the BADC's properly perform the corrections. First the constants are loaded into the BADC's memory, read out, and checked. Then it is put into a special diagnostic mode, where instead of digitizing an analog signal, it uses for input the contents of a special register. It performs the quadratic correction on this number, using the calibration constants. This is done for each channel the BADC would normally digitize. The results are read in and compared to a similar calculation done by the on-line computer. This test checks that the arithmetic is done correctly, but doesn't test the ADC.

The ADC's are checked by the parallel load test. For this test the whole system is set up as it would be for data taking. Each system (drift chamber, shower counter, and TOF) is pulsed with the pulser used for its calibration. The BADC's digitize and convert the data. The results are read in and checked. This finds channels which have changed since the last calibration. After the BADC's are read in, the trigger logic is used to check the shift register contents. This checks that both zeros and ones can be parallel loaded into the shift registers. Only the parallel load test checks this. All other shift register tests only check their continuity.

The muon system test is similar to the parallel load test. The muon system is pulsed, read out, and checked.

B.4 TESTS DONE EVERY 4 MINUTES

Several tests are done every 4 minutes during a run. All the NIM bin voltages (both DC and AC components), preamp power supply voltages, and high voltages are read out, checked, and logged on tape. This is done using 32 channel scanning ADC modules. The beam parameters (energy, currents, vacuum pressure, orbits...) are received from the SPEAR computer, checked, and logged on tape. Finally, the trigger logic shift registers are checked by shifting bits through them and reading them out. This is done every 4 minutes because a single bad shift register can spoil the trigger efficiency, and the shift registers were unreliable.

0.5 OTHER TESTS

Many other tests are performed on the data that is read for an event. Parts of the read-in require the CAMAC hardware to scan through modules until the proper number of bytes have been read. We check that the scan ended at the correct module. Part of the event block contains the times of a dozen important signals in the primary trigger (e.g. TDC start and Gate for the Sample and Hold modules). These are checked. The on-line event analysis checks for many errors. Examples are too many drift chamber cells fired or the muon system's fiducial marker isn't correct. These errors are indicated in large characters on the event display.

The event display itself is an important diagnostic. The raw data is graphically displayed along with the tracks found by the on-line analysis. A new event is displayed every few seconds. Watching this, the operator can easily see groups of drift chamber cells which are always on or high energy electrons with small liquid argon pulseheight.

While the event display is nice, a more important use of the on-line analysis is for a final check of the data quality. No matter how many hardware tests are done, some subtle problems can be missed. The ultimate test is to use the data for its intended purpose. The on-line analysis is a slightly simplified version of the off-line analysis. It finds drift chamber tracks, associates TDC counters with them, finds liquid argon pulseheights, and associates muon chamber hits with the drift chamber tracks. Based on the track topology, events are then classified as cosmics, hadrons, elastic scattering, etc. Cross sections, efficiencies, time distributions, pulse height distributions, and

singles rates are accumulated. These are printed out at the end of each run and carefully examined by the operator.

A lot of time and money has gone into these diagnostics. Has it paid off? Very rarely has a problem gone undetected. When it does happen, a new diagnostic is put in to catch it should it happen again. Considering its complexity, the Mark II is down very little. Not only do the diagnostics tell you there is a problem, they normally point directly to the cause of the problem. Fixing it just involves putting in a spare module. So considering the value of the data, the diagnostics have paid off handsomely.