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PRODUCTION OF χ MESONS IN $225 \text{ GeV/c } \pi^- \text{Be}$ INTERACTIONS

A DISSERTATION

submitted by

SAHADAT HOSSAIN

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ABSTRACT

Gamma rays associated with ψ mesons have been studied in 225 GeV/c π^-B_e interactions. The ψ - γ mass spectrum shows an excess of 47 ± 11 events above background centered at 3.531 GeV/c² with an rms width of 22.4 MeV. Attributing this excess of events to the decay $\chi \rightarrow \psi\gamma$ implies that 38 ± 9 % of all ψ mesons are produced by this mechanism.

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CHAPTER I

INTRODUCTION

Ever since the discovery of the ψ meson¹ and its subsequent explanation as a bound state of a charm quark and anti-charm quark ($c\bar{c}$), different mechanisms have been suggested for its hadronic production. One suggested mechanism is that ψ is produced from radiative decays of intermediate χ states:

where A and B are any two interacting hadrons. The above mechanism predicts the presence of an extra gamma-ray associated with the ψ events and the possibility that a significant fraction of ψ may come from χ decays.

We report in this thesis the production of χ mesons in the reaction:

and the contribution of the χ meson to the ψ meson production.

The theoretical framework needed to describe the above reaction is discussed in this chapter. The experimental apparatus is described in chapter II and the calibration of the gamma-ray detector is described in chapter III. The method used to process the data is outlined in chapter IV and in chapter V we present the analyses of the data.

A. Charmonium Spectrum

All hadrons discovered prior to 1974 can be explained in terms of three valence quarks named up, down and strange (u , d , s) and their anti-quarks ($\bar{u}$, $\bar{d}$, $\bar{s}$). Baryons are considered as collections of three valence quarks whereas mesons are composed of a quark and an anti-quark. Apart from these valence quarks each hadron contains a sea of quarks and anti-quarks of all flavors. It is the valence quark content which is associated with the characteristic properties of each hadron. The discovery[1] of the J/ψ in 1974 led to the belief in the existence of a fourth quark named charm (c). The discovery[2] of the ψ and ψ' indicates the existence of a fifth quark named beauty or bottom (b). The existence of the charmed quark was predicted on theoretical grounds by Hara[3] and by Bjorken and Glashow[4] to construct a symmetrical picture of four quarks (u , d , s , c) and four leptons (ν_e , e , ν_μ , μ). The presence of the charmed quark was also necessary to resolve a vital problem of weak interactions in kaon decay[5]. The observed absence of a strangeness-changing neutral current was shown to follow naturally in a model

with four quarks. From the experimental side, the narrow width of the ψ and the rise above 4 GeV of the ratio[6]
 $R = \sigma(e^-e^+ \rightarrow \text{hadrons}) / \sigma(e^-e^+ \rightarrow \mu^-\mu^+)$ in electron-positron annihilation were clear indications of the existence of the charmed quark.

The discovery of the J/ψ opened a new channel of experimental investigation which led to the discovery of excited states of the ψ . Immediately it was realized[7] that the particle J/ψ is only one level of a system of states called charmonium. The different charmonium states known so far and some predicted are shown in Figure I-1. According to the theoretical hypothesis, a charmonium state is a bound state of a charmed quark and its anti-quark ($c\bar{c}$). The first discovered member of the charmonium family, J/ψ , has the quantum numbers of a photon with $J^{PC} = 1^{--}$ except for its large mass ($M_{\psi} = 3.098 \pm 0.003 \text{ GeV}/c^2$). The most striking feature of the ψ is its narrow width, $\Gamma_{\text{tot}}^{\psi} = 67 \pm 12 \text{ KeV}$. Its decay rate into hadrons is only an order of magnitude higher than its decay rate into pairs of leptons, e^-e^+ or $\mu^-\mu^+$. The decays into leptons are due to the electromagnetic interactions as shown in Figure I-2. There is no selection rule that forbids the decays $J/\psi \rightarrow$ hadrons via strong interactions, yet the hadronic width of J/ψ is at least three orders of magnitude smaller than the normal hadronic width for a heavy meson. The narrow hadronic width of ψ is believed to be due to the fact that most of its hadronic decays are forbidden by the

Figure I-1. The charmonium ($c\bar{c}$) spectrum.

Figure I-2. Electromagnetic decays of psi meson.

phenomenological OZI rule[8].

The discovery of the ψ' and its electromagnetic decays with the emission of a gamma-ray revealed the existence of a group of charmonium states (χ states) between the ψ and ψ' masses. Theoretically three chi (χ) states with $J^{PC} = 0^{++}, 1^{++}, 2^{++}$ (mass = 3.41, 3.51, 3.55 GeV/c²) are predicted. All of the χ states are even under charge conjugation hence radiative transitions like $\psi' \rightarrow \chi_J + \gamma$ and $\chi_J \rightarrow \psi + \gamma$, where $J = 0, 1, 2$ are possible. All these χ particles have been definitely observed in electron-positron interactions. The study of the production of χ mesons in hadronic collisions remains an active area of experimental investigation.

The existence of the pseudoscalar, $J^{PC} = 0^{-+}$, charmonium states (η_c and η_c') are also predicted. Although there are some indications[9] of the η_c in e^-e^+ collisions, there is no evidence for η_c or η_c' production in hadronic collisions at the present time.

B. Theoretical Models of Hadronic Production of Charmonium States.

Various models have been put forward as to the hadronic production mechanism for the charmonium states. The predictions of the various models are strikingly different so precise experimental results can be used as a test of the validity of these models. A list of the suggested mechanisms is:

1. Direct Fusion Model : a) $q\bar{q} \rightarrow J/\psi$
b) $c\bar{c} \rightarrow J/\psi$.
2. Cascade Fusion Model: a) $gg \rightarrow \chi_J \rightarrow J/\psi + \gamma$
b) $q\bar{q} \rightarrow \chi_J \rightarrow J/\psi + \gamma$.
3. Evaporation Model : a) $q\bar{q} \rightarrow g \rightarrow c\bar{c}$
b) $gg \rightarrow g \rightarrow c\bar{c}$.

Here 'q' stands for light quarks (u, d, s); 'c' for charmed quarks and 'g' for gluons.

1. Direct Fusion Model.

In the direct fusion model it is hypothesized, within the framework of Drell-Yan[10] mechanism, that the ψ or ψ' is produced by direct annihilation of either a) a light quark and an anti-quark or b) a charm quark and an anti-charm quark.

a) In the process[11] $q\bar{q} \rightarrow J/\psi$, as shown in Figure I-3a, the coupling of the $q\bar{q}$ system to the J/ψ is

Figure I-3. QCD processes for charmonium production.

very small, of the order of $g_{q\bar{q}\gamma}^2/4\pi \approx 10^{-5}$, hence this mechanism is of little significance and yields a negligible contribution to the total cross-section. In this mechanism, neglecting the mass of light quarks, QCD predicts[12] unambiguously the μ or e pair angular distributions from J/ψ decay to be of the form $d\sigma/d(\cos\theta) = 1 + \cos^2\theta$, where θ is the emission angle of μ (or e) relative to the incident beam direction in the J/ψ rest system. Experimentally it was found[13] that $d\sigma/d(\cos\theta) \approx 1 + \alpha \cos^2\theta$, with $\alpha = -0.28 \pm 0.22$ for incident protons or pions. These results contradict the model of J/ψ hadroproduction by direct $q\bar{q}$ annihilation.

b) In the mechanism $c\bar{c} \rightarrow J/\psi$, as shown in Figure I-3b, where c and $\bar{c}$ come from the sea of the interacting hadrons, the coupling constant $g_{c\bar{c}\gamma}^2/4\pi \approx 0.2 - 0.5$ is not small, but a very small charmed sea[14] enters the cross-section quadratically which makes the contribution negligible. If this process is dominant, a charmed quark distribution[11,15], $xdN/dx \sim (1-x)^5$, is needed to fit the data whereas the experiment[16] favors a distribution of $xdN/dx \sim (1-x)^{3 \pm 1}$. This model is also less favored because of the observed strong suppression of ψDD events[17] (experimentally $\sigma_{\psi DD}/\sigma_{\psi} < 3\%$). Furthermore the model predicts[12] that,

$$\frac{\sigma(AB \rightarrow \psi' X)}{\sigma(AB \rightarrow \psi X)} = \frac{\Gamma_{e^+e^-}(\psi') / m_{\psi'}^3}{\Gamma_{e^+e^-}(\psi) / m_{\psi}^3} = 0.27 \pm 0.04$$

where A and B are any two interacting hadrons, but the experiment[13,18] shows a much smaller value of

$$\frac{\sigma(AB \rightarrow \psi' X)}{\sigma(AB \rightarrow \psi X)} = 0.05 - 0.12$$

for different projectiles and at different energies.

2. Cascade Fusion Model.

In this model[19-21] the assertions are that the J/ψ is not produced by direct fusion of $q\bar{q}$ or $c\bar{c}$, but produced through intermediate states which subsequently decay radiatively into J/ψ . These intermediate states are $3PJ$ states ($3P0$, $3P1$, $3P2 = \chi_0, \chi_1, \chi_2$) with $JPC = 0^{++}, 1^{++}, 2^{++}$. Thus this model predicts the presence of an extra gamma-ray associated with the ψ event.

a) The deep inelastic[22] electron-nucleon scattering data show that 50% of the nucleon momentum is carried by light quarks, the remaining 50% of the momentum being carried by neutral partons. These neutral partons may be identified with the gluons, thus gluon-gluon fusion is a natural candidate for the fusion model. In parallel with Carlson and Suaya's[20] calculations, the total cross-section for the process $gg \rightarrow \chi_J \rightarrow J/\psi + X$ (Figure I-3c) can be written in the form,

$$\sigma_{gg}(AB \rightarrow \psi + X) = 8\pi^2/M_\psi^3 \Gamma_{e\psi}(\chi_J) F_{AB}(\tau)$$

where $\tau = M_{\chi}^2 / s$ and $F_{AB}(\tau)$ is the so called "excitation function". If $f_g^A(x)$ and $f_g^B(x)$ are the gluon distribution functions of the beam A and the target B particles then,

$$F_{AB}(\tau) = \tau \int_{\tau}^1 \frac{dx}{x} f_g^A(x) f_g^B(\tau/x)$$

Γ_{eff} is the effective width for the elementary process $gg \rightarrow \chi_J$ and is given by

$$\Gamma_{eff}(gg\chi) = \sum_{J=0}^2 (2J+1) \frac{\Gamma(gg \rightarrow \chi_J)}{\Gamma_{tot}(\chi_J)} \Gamma(\chi_J \rightarrow \gamma\gamma)$$

The X_F spectrum of the χ_J states in the center of mass is given by,

$$\frac{d\sigma_{gg}}{dX_F}(AB \rightarrow \chi_J + X) = \frac{8\pi^2}{M_{\chi_J}^3} (2J+1) \Gamma(gg \rightarrow \chi_J) \frac{x_+ f_g^A(x_+) x_- f_g^B(x_-)}{x_+ + x_-}$$

where,

$$x_{\pm} = \frac{1}{2} \left[(X_F^2 + 4c)^{1/2} \pm X_F \right]$$

The J/ψ spectrum includes smearing due to the decay $\chi_J \rightarrow J/\psi + \gamma$ and is given by,

$$\frac{d\sigma}{dX_F}(AB \rightarrow \gamma + \gamma) = \frac{8\pi^2}{M_{\chi}^3} \Gamma_{eff} \frac{M_{\chi}^2}{M_{\chi}^2 - M_{J/\psi}^2} \int_{x_L}^{x_U} \frac{dx}{x^2 + \tau} f_g^A(x) f_g^B(\tau/x)$$

where,

$$x_L = \frac{M_{J/\psi}^2}{M_{\chi}^2} x_U = \frac{1}{2} \left[\left(X_F^2 + \frac{4M_{J/\psi}^2}{s} \right)^{1/2} + X_F \right]$$

Based on counting rule[23] arguments the gluon distribution function for the proton is taken as $dN/dx \sim (1-x)^5/x$ and that of pion as $dN/dx \sim (1-x)^3/x$. Once a specific functional form of the gluon distribution is assumed for the beam and the target particles the excitation function $F_{AB}(\tau)$ can be evaluated numerically.

Assuming that the χ_J is a $c\bar{c}$ state in which the quarks are moving non-relativistically in a potential of the form, $V(r) = -4/3 \alpha_g / r + \lambda r$ ($\lambda = 0.2029 \text{ GeV}^2$, $\alpha_g = 0.19$), where the first term is the strong interaction Coulomb potential and the last term provides the quark confinement, then the relations among the two-gluon annihilation widths are found to be,

$$\begin{aligned} \Gamma(gg \rightarrow \chi_0) &= 15/4 \Gamma(gg \rightarrow \chi_2) . \\ \Gamma(gg \rightarrow \chi_1) &= 1/15 \Gamma(gg \rightarrow \chi_0) . \end{aligned} \quad \text{I-1}$$

The $\Gamma(gg \rightarrow \chi_1)$ term arises from $gg \rightarrow gq\bar{q} \rightarrow \chi_J$, but otherwise $\Gamma(gg \rightarrow \chi_1) = 0$ by Yang's theorem.

The relative abundance of the three χ states in the cascade gluon-gluon fusion model then becomes (by relation I-1)

$$\chi_0 : \chi_1 : \chi_2 = 15 : 1 : 4$$

This relation must be modified by a factor of $(2J+1)$, where J is the spin of the particular χ state, to account for equal population of all spin states. Furthermore taking into account the branching ratio for different χ states in

the $\gamma\gamma$ decay mode ($\text{BR}(\chi_0 \rightarrow \gamma\gamma) = 2.7\%$, $\text{BR}(\chi_1 \rightarrow \gamma\gamma) = 31.5\%$, $\text{BR}(\chi_2 \rightarrow \gamma\gamma) = 15.4\%$)[24] the ratios for $\chi \rightarrow \gamma\gamma$ become ,

$$\chi_0 : \chi_1 : \chi_2 = 1.0 : 2.3 : 7.6$$

The angular distributions for the decay muons, photons and the joint distribution of the muon and photon in the χ rest frame for gg fusion are calculated by Ioffe[12] and Kühn[25]. The results can be expressed in the form,

$$W_\mu(\nu) = 1 + \alpha \cos^2 \nu$$

$$W_\gamma(\theta) = 1 + \delta \cos^2 \theta$$

$$W_{\mu\gamma}(\nu, \theta, \beta) = 1 + a \cos^2 \nu + b \cos^2 \theta + c \cos^2 \beta \\ + d \cos \nu \cos \theta \cos \beta + e \cos^2 \nu \cos^2 \theta$$

where ν and θ are the μ and γ emission angles relative to the beam direction, β is the angle between μ and γ in the χ rest frame, and $\alpha, \delta, a, b, c, d$ and e are numerical constants. The expressions for the angular distributions of the decay particles for various χ states are shown in Table I-1.

b) For the process $q\bar{q} \rightarrow \chi_0 \rightarrow J/\psi + \gamma$ the X_F distributions and the total cross-section can be expressed as

$$\frac{d\sigma_{q\bar{q}}}{dX_F} = \frac{8\pi^2}{9M_\chi^3} \frac{\Gamma_{\text{eff}}(q\bar{q}\chi)}{X_+ + X_-} \sum_{q,\bar{q}} X_+ f_q^A(X_+) X_- f_{\bar{q}}^B(X_-) \quad \text{and}$$

$$\sigma_{\text{tot}} = \frac{8\pi^2}{9M_\chi^3} \Gamma_{\text{eff}}(q\bar{q}\chi) \sum_{q,\bar{q}} \int_{\tau}^1 \frac{dx}{x} f_q^A(x) f_{\bar{q}}^B(\tau/x)$$

The relative abundance of the three χ states in the $q\bar{q}$ fusion process is calculated by Kühn[25] and the result is

$$\chi_0 : \chi_1 : \chi_2 = 0 : 4 : 1$$

The angular distributions of the decay particles of different χ states in the $\gamma\gamma$ decay mode for cascade $q\bar{q}$ fusion is predicted by Ioffe and the results are shown in Table I-1.

C. Evaporation Model.

Another model[26] frequently cited for charmonium hadroproduction is the so called "Evaporation Model". According to this model the reactions $q\bar{q} \rightarrow g \rightarrow c\bar{c}$ and $gg \rightarrow g \rightarrow c\bar{c}$ (Figures I-3e, I-3f) take place as if the quarks were free. The bound-state production cross-section is then calculated by integrating the free-quark cross section over a small energy range around the mass of the bound state[27]. The created $c\bar{c}$ system will not be in color singlet state and thus it is assumed that the color evaporates by soft-gluon emission.

In this model the relative abundance of the three χ states is calculated by Kühn[25] and the result is

$$\chi_0 : \chi_1 : \chi_2 = 1 : 3 : 5$$

The angular distributions of the χ decay particles in the $\gamma\gamma$ decay mode for the evaporation model calculated by Kühn is shown in Table I-1.

Table I-1. Angular distributions of a) muons b) photons and
c) muon/photon simultaneously in χ rest frame.

χ_J	gluon fusion	quark fusion	evaporation
(a)			
χ_0	Isotropic	Isotropic	-----
χ_1	-----	$1 - 1/3 \cos^2 \nu$	$1 + 1/5 \cos^2 \nu$
χ_2	$1 + \cos^2 \nu$	$1 - 1/3 \cos^2 \nu$	$1 + 21/73 \cos^2 \nu$
(b)			
χ_0	Isotropic	Isotropic	-----
χ_1	-----	$1 - 1/3 \cos^2 \theta$	$1 + 1/5 \cos^2 \theta$
χ_2	$1 + \cos^2 \theta$	$1 - 1/3 \cos^2 \theta$	$1 + 21/73 \cos^2 \theta$
(c)			
χ_0	$1 + \cos^2 \beta$	$1 + \cos^2 \beta$	-----
χ_1	-----	$1 - \cos \nu \cos \theta \cos \beta$	$\left\{ \begin{array}{l} 1 - 1/2 \cos^2 \beta \\ + 1/2 \cos \nu \cos \theta \cos \beta \end{array} \right\}$
χ_2	$\left\{ (1 + \cos^2 \nu)(1 + \cos^2 \theta) \right\}$	$\left\{ \begin{array}{l} 1 + \cos \nu \cos \theta \cos \beta \\ - 2 \cos^2 \nu \cos^2 \theta \end{array} \right\}$	$\left\{ \begin{array}{l} 1 + 3/11 \cos^2 \nu \\ + 3/11 \cos^2 \theta + 1/22 \cos^2 \beta \\ + 3/22 \cos \nu \cos \theta \cos \beta \end{array} \right\}$

CHAPTER II

APPARATUS

A. General Description.

The main purpose of this experiment was to detect κ mesons, produced in π^-N interactions and decaying into $\psi\gamma$, where the ψ is detected via its decay into μ^+ and μ^- .

A schematic drawing of the apparatus is shown in Figure II-1.

The 225 GeV/c π^- beam impinged on a beryllium target. The trajectories of charged particles produced in the target were determined from hits in five doublets of multiwire proportional chambers. The curved trajectories in the magnetic field region were measured by five triplets of multiwire chambers. The downstream trajectories of these charged particles were determined from hits in four drift chamber planes. Finally the muons were identified by a scintillation hodoscope placed behind the hadron absorber. The gamma rays were detected by an 148 element lead-glass shower detector placed some 17 m downstream of the target.

Most of the equipment used was newly built and came

Figure II-1. Experimental setup.

from four institutions : Fermilab, University of Illinois-Urbana, Oxford University and Tufts University. The apparatus can be divided into the following essentially independent sections:

1. Beam System.
2. Target.
3. Spectrometer Magnet.
4. Multiwire Proportional and Drift Chambers.
5. Cerenkov Counter.
6. Muon Hodoscope.

The apparatus will be described briefly in the above order. We use a right-handed co-ordinate system whose Z axis is along the beam direction, the Y axis vertically upwards and the X axis is directed to the left of the beam looking downstream.

1. Beam System.

The 225 GeV/c π^- beam was taken out of the NO (slow) beam line of the Fermi National Accelerator. The beam line is shown in Figure II-2.

There were six proportional wire beam chambers (BC1-6) along the beam line which were used to determine the X and Y co-ordinates of the beam particles. Four of the beam chambers were X measuring and two were Y measuring in the order XXXYXY. The active area of the chambers was 20 cm by 20 cm with 2 mm wire spacings. The six beam chambers

Figure II-2. Beam system.

were associated with six eight-element 2.5 cm by 2.5 cm beam hodoscopes placed adjacent to the chambers.

Halo beam particles were vetoed by three scintillation counters through which holes had been drilled where the beam particles were expected to pass. In addition to these veto counters the entire upstream end of the muon laboratory was covered with a veto-wall of scintillation counters.

Three Cerenkov detectors in the beam line filled with helium at low pressure were used to identify the species of the beam particle.

2. Target.

The target was six pieces of beryllium, each piece measuring 5.5" x 3" x 1/2" stacked together to form a target of 5.5" x 3" x 3" with 3" thickness in the beam direction. The target could easily be placed in the beam line through a lever, pulley and mirror system without the shut down of the beam. This was particularly useful during trigger studies when the target has to be placed or removed from the beam line very often.

3. Spectrometer Magnet.

The spectrometer magnet, called the Chicago Cyclotron Magnet (CCM) and originally used in Fermi's 450 MeV cyclotron at the University of Chicago, was used as a particle spectrometer by observing the deflection of the

charged particle trajectory in the magnetic field region. The CCM, which weighs some 2000 tons, is supported on a concrete pillar sunk 24.4 m into the Earth. The CCM pole faces have a diameter of 4.94 m, with a gap of 1.3 m. Operated at a power of 2 MW (4100 Amps) a field of 14.5 KG is produced which gives a momentum kick of 2.23 GeV/c. In such a magnetic field a charged particle of 215 GeV/c would display a deflection of about 10 milliradian whereas a particle of momentum 5 GeV/c or less will never reach the set of chambers on the downstream side of the magnet.

4. Multiwire Proportional and Drift Chambers.

Downstream of the target (upstream of the CCM) were five 80 cm by 80 cm multiwire proportional chambers (MWPC), each having double planes. Each of the first four MWPC's measured X and Y and the last one tilted at $\pm 45^\circ$ measured U and V. Each chamber had 512 wires with 1.5 mm wire spacings. The 80 cm chamber planes were used in reconstructing the upstream straight tracks of the charged particles.

Following these there were five 1.1 m by 1.2 m U. of I. chambers (MWPC) each having three planes (VYU, 11° tilt) placed in the CCM magnetic field region. Two of these chambers had to be moved to the downstream side of the magnetic field when one of the downstream drift chambers failed to work and the downstream track finding was in uncertainty. These chambers measured the trajectories of

charged particles bending in the magnetic field region.

All of the chambers upstream of the CCM were MWPC's since the high particle density required good spatial and time resolution and short dead time, but allowed small area. In contrast all the chambers downstream of the CCM were drift chambers. There were four 1.2 m by 2.4 m drift chamber planes. Each plane had 60 cells with 4 cm cell size and measured X and Y of the downstream tracks. Unfortunately the fourth drift chamber never worked during the entire course of the experiment.

5. Cerenkov Counter.

In order to identify the types of hadrons coming from an interaction, an 18-cell Cerenkov counter was placed downstream of the CCM. The cells were 1.8 m long and were arranged two high by nine wide. Each cell had a mirror to focus the light on a 12.7 cm diameter photomultiplier tube. The working medium was nitrogen at atmospheric pressure.

6. Muon Hodoscope.

Muons were identified by a scintillation counter hodoscope M. The M hodoscope was placed downstream of a 4.5 m thick steel wall. The M hodoscope had 44 active elements and was configured in the so called 'Bow Tie' pattern as shown in Figure II-3. This arrangement was particularly useful in reducing background in the dimuon sample by eliminating muons of low P_T due to inflight decays

Figure II-3. Muon hodoscope.

of pions and ρ, ϕ . The 'Bow Tie' preferentially accepts muons coming from the decay of a high mass object. This M hodoscope was used in the dimuon trigger requiring that muons be found in the opposite quadrants of the hodoscope. Figure II-3 shows how the 'Bow Tie' configuration works. The center of the circles corresponds to the position of a particle produced with a momentum of 25 GeV/c and the three circles represent the smearing due to a P_T of either 0.2 or 0.6 or 1.5 GeV/c. We see that only those particles with the higher value of P_T will hit the hodoscope.

B. Gamma Ray Detector.

The gamma-rays were detected by a lead-glass proportional-tube shower detector. Figure II-4 is a schematic drawing of a section of the active elements in the gamma ray detector. Two 24-element vertical columns of lead-glass blocks (converter) belonging to Tufts University were mounted transverse to the beam line. These blocks are of type SF-2, whose properties are listed in Table II-1. Each block measures $58.4 \times 6.35 \times 6.35 \text{ cm}^3$. In between the two columns was a gap of 1.5 cm for inserting LED's and optical fibres for gain monitoring purposes. Each block was wrapped with aluminized mylar and then wrapped with black optical tape to make it light tight. Upstream of these 48 blocks were one layer of 6.4 mm of steel sheet, mainly for supporting the blocks, and one layer of 3.2 mm of lead sheet. The entire converter assembly was then wrapped with black polyethylene to check further light leakage.

Figure II-4. Gamma ray detector.

Table II-1. Properties of converter lead-glass blocks.

Type	SF2	
Composition	51%	PbO
(by weight)	41%	SiO ₂
	7%	K ₂ O
	1%	Na ₂ O
Radiation length	2.75	cm
Density	3.86	g/cm ³
Refractive index	1.65	
Critical energy	16.5	MeV

This converter assembly constituted 3.3 radiation lengths in total. The assembly was mounted on a movable frame to enable easy access to the remainder of the detector.

Following the converter were three planes of proportional tubes (P-tubes) for the purpose of shower position determination. Each plane had 194 tubes each of 13 mm diameter. The tubes were staggered to obtain a tube spacing of 8 mm. The first plane of tubes measured the X coordinate and the last two planes of tubes tilted at $\pm 60^\circ$ measured the U and V coordinates of the shower.

Finally a 10 by 10 array of 100 large lead-glass blocks (absorber) each measuring $15 \times 15 \times 45 \text{ cm}^3$ and belonging to University of Illinois and Fermilab were mounted in fly's eye configuration in a light tight movable box. These absorber blocks constituted 18 radiation lengths in the beam direction and contained the bulk of the remaining shower.

The entire gamma ray detector constituted 21.5 radiation lengths, more than enough to contain the entire shower. The detector had an active area of $152 \times 152 \text{ cm}^2$ with a beam hole of $15 \times 15 \text{ cm}^2$ to save the blocks from radiation damage.

C. Trigger and Data Logging.

The trigger requirement was that there be simultaneous hits in the opposite quadrants of the M hodoscope. Upon receiving an event trigger interrupt, the computer would interrogate the CAMAC system to retrieve the data. The data were then written to a buffer on the disk. At the end of the beam spill the acquired data was written on to a 9-track 6250 bpi tape.

The data logging was done using a PDP 11/45 computer of 124K words of memory and an LSI computer of 28K memory. The major functions of these two computers are shown in Figure II-5. At the beginning of each run and between spills the calibration records for the lead-glass and Cerenkov counters were written out. The on-line data acquisition system RTMULTI allowed considerable online monitoring of equipment performance through histograms, XY plots and event displays.

The assembling of this large amount of equipment and getting it to work at an acceptable level of performance was a great challenge and an enjoyable achievement for the members of the experimental group. We spent about ten weeks in setting up the equipment, six more weeks for tune up and

testing and finally two weeks for electron calibration of the gamma ray detector. During the last six weeks of data taking we recorded a total of 4.1×10^6 dimuon triggers on tape. The analyses of this data will be described in the following chapters.

Fig.II-5. Computer hardware configuration.

CHAPTER III

CALIBRATION OF GAMMA RAY DETECTOR

An electromagnetic shower detector should be limited primarily by the statistical nature of shower development. The total Cerenkov light created in the lead-glass is proportional to the energy of the incident particle. An ideal photomultiplier (PM) tube produces an output signal which is directly proportional to the total Cerenkov light. Thus the PM signal of a lead-glass block is directly proportional to the energy deposited in that block.

To keep track of the gain changes of the lead-glass blocks the response of each lead-glass block was monitored at the beginning of each run and between spills by the LED and Argon lamp-optical fibre calibration system. Light from an argon flash lamp was carried by optical fibre light guides to the face of each lead-glass block opposite the PM tube. The stability of the flash lamp was also checked using a reference PM tube. Two separate flash lamps and fibre optics system were used, one for the converter blocks and the other for the absorber blocks. Both lamps were synchronously driven by the same flash driver. The signals

from the LED's, mounted on the face of the blocks opposite to the PM tube were recorded separately. The argon flash lamp and the LED signals constituted two independent gain monitoring systems.

Calibration for all the lead-glass blocks of the gamma ray detector was done in two phases using a 15 GeV electron beam. In the first phase all the absorber blocks of the fly's eye array with no converter blocks in front were exposed to the 15 GeV electron beam. In the second phase the absorber blocks were exposed with the converter blocks in place. The reason for selecting the 15 GeV electron energy was that the accepted chi decay gamma ray energy lies between 10 and 20 GeV (Monte Carlo prediction). The electron beam was directed to the center of each absorber block using the 1E42 rotating dipole magnet. The response (pedestal subtracted) of a typical absorber block, with no converter block in front, to a 15 GeV electron beam is shown in Figure III-1. The electron peak is centered at channel 148. The peak at the low-side is due to minimum-ionizing particles. The tail of the low-side peak is due to hadronic showers.

The proportionality constant between the PM signal of a lead-glass block and the energy deposited in that block, called the calibration constant (energy coefficient), was obtained by off-line study of a large sample of electron showers in the lead-glass array. Each block was assumed to produce a signal which is proportional to the energy

Figure III-1. Response (pulse height minus pedestal) of a typical absorber lead-glass block, with no converter block in front, at 15 GeV electron beam. The electron peak is at channel 148.

deposited, $E_{ij} = \lambda_j S_{ij}$, where λ_j is the calibration constant for the j th block, E_{ij} is the energy deposited in the j th block by the i th electron and S_{ij} is the signal in the j th block due to the i th electron. The sum of all deposited energy must then equal the incident electron energy,

$$E_i = \sum_j E_{ij} = \sum_j \lambda_j S_{ij} \dots\dots\dots \text{III-1}$$

From equation (III-1) a χ^2 can be formed,

$$\chi^2 = \sum_i (E_i - \sum_j \lambda_j S_{ij})^2.$$

Minimization of this χ^2 reduces to a simple symmetric matrix inversion. The conditions,

$$\partial \chi^2 / \partial \lambda_K = 0, \text{ give}$$

$$\sum_i E_i S_{ik} = \sum_j (\sum_i \lambda_j S_{ij}) S_{ik}.$$

$$\text{or} \quad a_K = \sum_j A_{jK} \lambda_j, \quad \lambda_j = \sum_K (A^{-1})_{jK} a_K \dots\dots \text{III-2}$$

$$\text{where} \quad a_K = \sum_i E_i S_{iK} \quad \text{and} \quad A_{jK} = \sum_i S_{ij} S_{iK}.$$

Equation (III-2) is the basic mathematical relationship that has been used to find the calibration constants. The calibration constants (energy coefficients) that we obtained are shown in Figure III-2. These constants were then used to calculate the total energy of each shower.

In calibrating the lead-glass blocks the following event selection criteria were used,

- a) Only events within the electron peak were used

Figure III-2. Calibration constants of the lead-glass blocks.

(hadrons rejected). The electron peak was usually between 130 to 160 ADC channels (Figure III-1).

b) Electrons with known position and energy were used. The position of the electron was determined by projecting tracks found in the 80 cm by 80 cm chambers to the face of the lead-glass array. The energy of the electron was measured from tracks found upstream and downstream of momentum tagging magnet 1E41.

c) A geometrical boundary cut (5 cm inside the periphery) was applied so that no energy could have been lost either in the beam hole or outside the array.

d) Groups of adjacent blocks were calibrated at a time and electrons which shared more than 3-5% of energy (assuming equal calibration for all the blocks) with the surrounding blocks were discarded.

e) The signal from the beam line block was always looked at and a cut at about 10 channels has been used to discard those electrons which have undergone bremsstrahlung.

f) A second and third pass was done discarding those events whose measured energy disagreed with the beam energy by more than ± 2.0 GeV.

The energy resolution of the gamma ray detector expressed as the FWHM is shown in Figure III-3. The statistical nature of the shower energy determination implies that $\Delta E \propto \sqrt{E}$. The result we obtained is $\Delta E(\text{FWHM})/E = 0.5 + 15/\sqrt{E} \%$, where E is the electron energy in GeV. The energy resolution of the detector, at different

Figure III-3. Energy resolution curve (% FWHM vs $1/E^{-1/2}$) of the gamma ray detector.

Figure III-4. Measured energy minus known electron energy (ΔE) for a) 7.5 GeV, b) 15 GeV, c) 25 GeV and d) 50 GeV electron beams.

energies, has also been studied. The differences between measured energy and the known beam energy are shown in Figures III-4 for different incident electron beam energies.

The fractions of energy deposited in the converter and the absorber blocks are shown in Figure III-5 as a function of mean electron beam energy. Figures III-6 through III-9 show the energy distributions in the converter blocks, absorber blocks, total measured energy and the beam energy at various electron energies.

Figure III-10a displays the average of measured energy as a function of mean electron beam energy. The detector was found to be linear to better than 1% for electron showers in the energy range 15 to 25 GeV. The linearity was better than 3% over the range 7.5 to 15 GeV and 25 to 50 GeV. The correlation between the energy deposited in the converter and the absorber blocks is shown in Figure III-10b for 15 GeV electron showers.

The three planes of proportional tubes (P-tubes), which constituted about 0.2 radiation length, are expected to absorb some of the shower energy. The P-tube array was calibrated as a lead-glass block assuming that the deposited energy is proportional to the total pulse height from all three planes. We measured an average of 0.6 GeV energy loss in the P-tube array, which is 40% of the energy loss in the converter blocks, for 15 GeV electron showers. The result is shown in Figure III-11a. The correlation between the

energy deposited in the converter blocks and the energy loss in the P-tube array is displayed in the Figure III-11b. It has been observed that calibration (or no calibration) of P-tube array affects the absorber blocks by less than 1% but affects the converter blocks by 30-35 %. Since the energy loss in the P-tube array is intimately related with the energy loss in the converter blocks and since the inclusion of the P-tube array did not noticeably improve the energy resolution of the gamma-ray detector we decided not to use the P-tube information in our final determination of the gamma ray energies.

Figure III-5. Fraction of energy vs energy, deposited in a) converter blocks and in b) absorber blocks. E_1 and E_2 are the energies deposited in the converter and absorber blocks and E is the electron energy.

Figure III-6. Energy deposited in a) converter blocks, b) absorber blocks, c) total measured energy and d) beam energy distributions for 7.5 GeV electrons.

Figure III-7. Energy deposited in a) converter blocks, b) absorber blocks, c) total measured energy and the d) beam energy distributions for 15 GeV electrons.

Figure III-8. Energy deposited in a) converter blocks, b) absorber blocks, c) total measured energy and the d) beam energy distributions for 25 GeV electrons.

Figure III-9. Energy deposited in a) converter blocks, b) absorber blocks, c) total measured energy and the d) beam energy distributions for 50 GeV electrons.

Figure III-10. a) Mean electron energy vs average measured energy
b) correlation between energies deposited in absorber and in converter blocks for 15 GeV electron showers.

Figure III-11. a) Energy deposited in P-tube array, b) correlation between energies deposited in the converter and in the P-tube array for 15 GeV electron showers.

CHAPTER IV

EVENT RECONSTRUCTION

The off-line analysis of the data was performed using the Fermilab CYBER 175 computer system. In the first pass of the analysis the pedestals and the begin-run calibrations (the response of the phototubes to the Argon flasher and LED signals) for the lead-glass blocks were stored labeled by the run number in a random access mass storage file. Diagnostic analysis of the equipment performance was also done. In the second pass the charged particle tracks were reconstructed, muons were identified and the events with dimuon mass greater than $2.5 \text{ GeV}/c^2$ were written in the original format to a different tape (DIMU TAPE). The accumulated events in the DIMU TAPE were once again reconstructed for charged particle tracks and a data summary tape was written (PSI DST). The events in the PSI DST were then analysed to reconstruct the gamma rays and a new data summary tape was written (CHI DST). The final analysis was done on this CHI DST.

The event reconstruction consists of: A) Reconstruction of Charged-Particle Tracks, B) Muon Identification and the

γ Reconstruction, C) Gamma-Ray Reconstruction and D) Reconstruction of the χ Mesons.

A. Reconstruction of Charged-Particle Tracks.

The charged-particle track reconstruction programs, developed by R. Raja at Fermilab, consist of several independent tasks. The major reconstruction routines are described in the sections to follow.

1. The Beam Particle Track.

The six beam hodoscopes and their associated chambers were used to find the momentum and the trajectory of the incident beam particle. The beam hodoscope elements upstream and downstream of the momentum defining magnet 1E41 were first searched for hits. If a hit was found in an element then the associated chamber region behind the fired hodoscope element was searched for a possible hit. If a matching hit was found its position was used otherwise the center of the hit hodoscope element was taken as the position. The pairs of X-measuring planes upstream and downstream of the 1E41 magnet were used to calculate the bend-plane projection of the beam track. If more than one track was found upstream or downstream then an impact parameter analysis was done. The combination of upstream and downstream tracks which gave a minimum magnitude for the difference of impact parameters at the center of the 1E41 magnet was declared to be the beam track. The momentum of the beam particle was then calculated using the X-view

slopes of the track upstream and downstream of 1E41 and the Y-view slope downstream of 1E41.

The intersection of the beam particle track with the target was used later to help determine the vertex position of the events.

2. Reconstruction of Straight Tracks Upstream of the Magnet.

The upstream straight tracks were found using the "Angle Method". In this method tracks in the X and Y views were reconstructed independently. All hits in all upstream planes were first transformed into corresponding angles using the trial vertex determined by the beam track. The program started with the most negative angle (irrespective of plane) and searched for angles in other planes within a three milliradian angular road. If two additional angles within this road were not found, the initial angle was abandoned and the next most negative angle was considered (this did not necessarily involve a change of planes). When three or more angles within the road were found then a least-square fit was applied to calculate the track parameters. The fitted track parameters were then used to see if any bad points ($\delta x > 2$ mm) were included in the fit. If a bad point was included the program dropped that point and refitted to find the track parameters. If less than two hits survived in the fit or if the fitted track did not pass within 2.5 cm of the trial vertex as given by the beam track

then the program dropped this most negative angle and proceeded to the next most negative one. Thus a track candidate was declared found once a) there were at least 3 hits within the angular road, b) there were at least 2 hits that survived the tolerance cut in the track refitting procedure and c) the track passed near the trial vertex. All the tracks found in the X and Y views were then used to find a weighted average vertex for the event. The information from the tilted planes were then used to match each Y track with an X track.

3. Reconstruction of Tracks in the Magnetic Field Region.

In the plane perpendicular to the constant magnetic field (the X-Z plane) the path of a charged particle is a segment of a circle to which the incident and exiting tracks are tangents. In the plane containing the magnetic field (the Y-Z plane) the trajectory of the charged particle is essentially a straight line. The program considered all matched X and Y upstream tracks and fitted circles to X-view hits in the magnetic field region. The fit circle was constrained to be tangent to the upstream track. The program calculated the momentum of the charged particle using a hard edge model of the magnetic field and predicted the parameters of the downstream track. The predicted downstream track was then matched with tracks found in the downstream drift chambers. Once a matching track was found the downstream track parameters were

recalculated using the drift chamber information. A charged particle track reconstructed event is shown in Figure IV-1.

B. Muon identification and the γ Reconstruction.

Muons were identified using the information from the M hodoscope downstream of the steel absorber. Each downstream track was projected onto the face of the M hodoscope and if a hit in the predicted element was found then the track was tagged as a muon. The sign of the charge of the muon (in general any charged particle) is given by the sign of the radius of curvature of the track found in the magnetic field region.

The masses of all pairs of positive and negative muons were calculated. The dimuon invariant mass spectrum we obtained is shown in Figure IV-2. A clear γ signal of FWHM ~ 150 MeV at ~ 3.1 GeV/c² is observed.

Figure IV-1. A charged particle track reconstructed event.

Figure IV-2. The dimuon mass spectrum.

C. Gamma Ray Reconstruction.

An electromagnetic-shower initiating particle (gamma-ray, electron, positron) upon entering the lead-glass converter blocks produces an electromagnetic cascade through mainly pair-production and bremsstrahlung processes. The density of shower particles has a sharp maximum in the central region of the shower. The charged shower particles produce signals in the proportional tubes located immediately downstream of the converter blocks. Thus the P-tubes provide a measure of the transverse shower development. A histogram of the P-tube signals from a single shower shows a characteristically peaked profile with nearly exponential decrease in intensity on the two sides of the peak. Figure IV-3 was generated by superimposing the profiles of many 15 GeV electron showers. Each profile was normalized to equal shower area (the integrated P-tube signal). The central region of the plot is well described by an exponential decrease in intensity with increasing distance from the shower center. A double exponential was required to fit the profile over a broad range.

An estimate for the position of the centroid of a shower was calculated from a weighted average of P-tube positions:

$$X = \sum_{j=1}^N X_c(j) S_j^2 / \sum_{j=1}^N S_j^2 \quad \text{.....IV-1}$$

where $X_c(j)$ is the center of the j th tube, S_j is the signal from the j th tube and N is the number of tubes used to form

Figure IV-3. A 15 GeV electron shower profile (transverse) observed in the X-plane of the P-tube array.

the average. The exponent, 2, used in this estimator was empirically determined. In a test run we histogrammed the difference between the predicted position of the electron showers (measured by a multiwire proportional chamber placed just before the converter blocks), and the position as determined from the P-tube signals according to the equation IV-1. We found best resolution for exponents of 2 to 3. Figure IV-4a shows such a resolution curve for an exponent of 2. The spatial resolution in each P-tube plane was found to be 0.8 cm (FWHM) which is roughly equal to the spacings between the centers of two adjacent tubes.

1. Shower Location.

A shower is defined as a P-tube signal with a dip of signal intensity on both sides of this tube. Each P-tube was examined with its adjacent tubes for a local maximum in signal intensity. A threshold of $\sim 2-3$ times the signal intensity from a minimum ionizing particle was imposed. This threshold was scaled to compensate for the observed decrease in shower intensity from the X-plane to V-plane. Using electron showers from the calibration run, it has been measured that the shower intensity falls according to the ratio 1.0 : 0.91 : 0.83 from first plane through third plane.

Once a shower maximum was found, the shower position was determined according to

$$U_i(K) = \frac{\sum_{j=1}^N U_c(j) S_{ij}^2}{\sum_{j=1}^N S_{ij}^2}$$

where k is the plane number, i is the shower number, j is the tube number, $S_{ij} = 0$ if tube j does not contribute to shower i , otherwise S_{ij} is the signal from the tube j , N is the number of tubes (usually 3) used in forming the average and $U_c(j)$ is the position of the center of the j th tube. Each shower maximum (tube number at the maximum intensity) was stored along with the shower position, the full width at half maximum, the signal in the peak channel (shower intensity) and the integrated signal (shower area).

The program stored a maximum of 15 showers for each plane. If the number of showers was greater than 15 then the threshold was increased stepwise until the search for maxima yielded 15 or fewer showers. Conversely if no shower was found the threshold was lowered (only once to avoid an infinite loop). Showers which lose very little energy in the converter blocks (unconverted and late-converted gamma rays) will produce small signals in the P-tubes and generally will remain undetected. However it should be noted that the probability that a gamma ray does not convert in a 3.3 radiation length material is only about $\exp(-3.3 \times 7/9) = 7.6\%$.

Showers which were within ~ 3 -5 tube diameters to each other were reduced to a single shower. The profile of each shower is expected to behave according to the relation $I = I_0 \exp(-0.82 |x|)$ (Figure IV-3). If the centers of any two showers in a P-tube plane were within a distance of $\ln(I_0/I_{th})/0.82$, where I_0 is the signal in the peak channel

and I_{th} is the threshold used in the P-tube signal, then they were merged into a single shower.

Combinations of showers from all three planes were then searched for a triplet. A triplet is a set of three maxima, one from each plane. Each gamma-ray was defined as a unique triplet. The redundancy afforded by the three P-tube planes was employed to eliminate triplets that are physically impossible. The condition used on the co-ordinates of the corresponding maxima in the three planes was $|DX| = |X_i - (X_i)_{uv}| < 1.5$ cm, where X_i is the X-coordinate measured by X-plane and $(X_i)_{uv}$ is the X-coordinate calculated from U and V. DX was calculated after projection to a common Z co-ordinate. In principle DX should be zero, but because of the finite position resolution of the P-tubes we set the upper limit to be 1.5 cm. We have histogrammed DX before this condition is applied and found 80-85% of the signals within this cut. The DX distribution for 15 GeV electron showers measured using the calibration data is shown in Figure IV-4b.

The triplets that survived the DX cut were further checked for matching of shower area. We required that the difference in shower areas between a pair of P-tube planes be less than a quantity which is proportional to the sum of the shower areas in a physically possible triplet. In particular defining

$$DA_1 = \frac{A_x - A_u}{A_x + A_u} \quad \text{and} \quad DA_2 = \frac{A_u - A_v}{A_u + A_v}$$

Figure IV-4. Distributions of a) X measured minus X predicted ($X - X_p$), b) X measured minus X calculated from U and V ($X - X_{UV}$) for 15 GeV single electron showers.

we required that $|DA_1| < 0.7$ and $|DA_2| < 0.7$ where A_x , A_u and A_v are the shower areas in the X, U and V planes respectively. The distributions of DA_1 and DA_2 for 15 GeV electron showers measured using the calibration data are shown in Figure IV-5. Once a triplet was found its Y co-ordinate was calculated from U and V.

The program kept a maximum of 15 triplets. If the number of triplets was greater than 15 then the spatial cut DX was lowered stepwise until the number fell within 15.

The position of each triplet was then projected to the absorber(converter) lead-glass blocks and if 500(25)MeV energy (pulse height times the calibration constant) was not found in the predicted block then that triplet was discarded. Triplets that were closer by less than one absorber block (15 cm) were merged into a single triplet keeping the position of the triplet which has the biggest integrated signal.

A reconstructed two-gamma-ray event is displayed in Figure IV-6. The lines perpendicular to the three P-tube planes correspond to the pulse height distributions, the inner lines correspond to the shower peaks and the letters 'E' correspond to the reconstructed positions of the showers as found by the program.

Figure IV-5. Distributions of a) DA_1 and b) DA_2 for single electron showers.

Figure IV-6. A space point reconstructed 2-shower event.

2. Shower Energy Fit.

The energy of a shower was measured by projecting its position to the upstream and downstream lead-glass arrays and summing the energies dumped in the predicted blocks. If two or more showers shared their energies in one or more blocks then a sharing algorithm was applied to calculate their energies.

Let $F_{ij} = f_i(x_j, y_j)$ be the fraction of shower j contained in the i th block where x_j, y_j are the coordinates of the shower center at the front face of the lead-glass blocks. The total signal in the block i is then given by $S_i = \sum_{j=1}^{N_s} F_{ij} E_j$, where E_j is the energy of the j th shower and N_s is the total number of showers in an event. If the measured signal in the i th block is denoted by Q_i then minimization of χ^2 gives,

$$\chi^2 = \sum_i (Q_i - S_i)^2 = \sum_i [Q_i - \sum_{j=1}^{N_s} F_{ij} E_j]^2.$$

$$\partial \chi^2 / \partial E_K = 0 \text{ gives}$$

$$\sum_i Q_i F_{ik} = \sum_{j=1}^{N_s} E_j [\sum_i (F_{ik} F_{ij})].$$

Defining

$$A_{Kj} \equiv \sum_i (F_{ik} F_{ij}), \quad (A_{Kj} = A_{jK})$$

$$a_k \equiv \sum_i Q_i F_{ik}$$

we obtain

$$a_K = \sum_{j=1}^{N_s} E_j A_{Kj}$$

or

$$E_j = \sum_{K=1}^{N_s} (A^{-1})_{jK} a_K \quad \dots \dots \dots \text{IV-2}$$

Equation IV-2 is the solution for the energy deposited by jth shower in the detector and the solution reduces to a symmetric matrix inversion. The above solution will be meaningful if the showers are well separated so that a block does not completely contain two or more showers.

In order to calculate F_{ij} , the transverse shower profile integrated over depth must be known. The P-tube planes provided a measure of this profile at the front face of the absorber blocks, but the longitudinal development was not sampled. We assumed a reasonable form for F_{ij} to be,

$$F_{ij} = f_i(x,y) = \int_{\text{block } i} A e^{-b|r(x,y)|} da \quad \dots\dots\text{IV-3}$$

where x,y are the co-ordinates of the shower center at the face of the block and r indicates the transverse profile is purely radial. The exponential form is consistent with our calibration data (Figure IV-3).

Equation IV-2 with fraction calculated according to equation IV-3 can in principle be used to calculate the energy of any type of shower - both sharing and isolated. But because of possible error in the fraction calculation we used equation IV-2 for showers which shared their energies with one or more blocks and calculated the energies of the isolated showers by direct summing of the energies from the struck blocks.

Each shower was projected onto the face of the absorber blocks (and converter blocks) and the blocks which

fell within 6 cm (2.5 cm for converter blocks) of the shower centroid were flagged (It is to be noted that more than 98% of the energy[28] of an electromagnetic shower lies within ~ 5 cm of its centroid). If a shower hits the corner of an absorber block there will be four such blocks whereas if it hits the block center there will be one such block. These flagged blocks were then examined to determine the total fraction of energy deposited in all of them by the rest of the showers in an event. If the total fraction was less than 2.5% (5% for converter blocks) the shower was declared isolated and its energy was calculated by summing the energies deposited in the flagged blocks. The total energy of a shower is then the sum of the energies deposited in the absorber blocks and the converter blocks.

The response of the lead-glass blocks was observed to decrease as the experiment progressed due to radiation damage (yellowing) of the blocks. The effect of yellowing on the central absorber block (beam line block, maximally yellowed) is shown in Figure IV-7. This figure shows the begin-run Argon lamp signal of the block (normalized to the begin-run Argon lamp signal observed at run number 400) as a function of run number. The response of this block decreased by a factor of about 2 over the runs 400 to 700 (~ 2 weeks of time). The LED and Argon lamp signals generated at the beginning of each run have been used to compensate for this yellowing. If λ_0 and L_0 (A_0) are the calibration constant and the LED (Argon lamp) signal found

Figure IV-7. Effect of radiation damage (yellowing) on beam-line absorber block.

at the time of electron calibration then the calibration constant (λ_i) for i th run is taken as $\lambda_i = \lambda_0 \times LO(A0) / Li(Ai)$, where $Li(Ai)$ is the LED (Argon lamp) signal for i th run.

To demonstrate the performance of the pattern-recognition program and the gamma ray detector resolution a search for π^0 has been performed. The γ - γ mass spectrum (for events with 2 gamma-rays only) for a sample of dimuon triggers obtained immediately after the electron calibration is shown in Figure IV-8. A clear π^0 signal with FWHM = 30 MeV is observed. The dotted curve is a background calculated using uncorrelated γ 's normalised to the number of background events in the mass range 0.25-0.40 GeV/c².

Figure IV-8. The gamma-gamma mass spectrum for events with 2 gamma-rays only.

D. Reconstruction of the χ Mesons.

The χ mesons were reconstructed by combining the γ meson with each gamma ray in an event. Any dimuon mass combination between $2.95 < M_{\mu^+\mu^-} < 3.20$ GeV/c² was taken as a γ event. The energy of the γ was constrained so that its mass is exactly 3.098 GeV/c². In particular, we calculated $\vec{P}_\gamma = \vec{P}_{\mu^+} + \vec{P}_{\mu^-}$ and insisted that $E_\gamma = \sqrt{|\vec{P}_\gamma|^2 + (3.098)^2}$ instead of $E_\gamma = E_{\mu^+} + E_{\mu^-}$, where $(\vec{P}_\gamma, E_\gamma)$, $(\vec{P}_{\mu^+}, E_{\mu^+})$ and $(\vec{P}_{\mu^-}, E_{\mu^-})$ are the four momenta of the γ , μ^+ and μ^- respectively.

Gamma rays of energy less than 1.0 GeV and greater than 30.0 GeV were discarded. The 1.0 GeV cut removes gamma rays in an energy range where our shower detection is uncertain, but does not remove any χ signal (χ -decay gamma rays were calculated to have $E_\gamma > 5.0$ GeV in our detector, Figure V-3b). The 30.0 GeV cut was calculated to remove less than 4.5% of the χ signal.

Any 2γ pair compatible with the π^0 mass ($0.1 < M_{\gamma\gamma} < 0.2$ GeV/c²) was discarded while forming γ - γ combinations.

The γ - γ mass spectrum thus obtained is shown in Figure IV-9. Figure IV-10 shows the γ - γ mass spectrum for $5.0 < E_\gamma < 30.0$ GeV. In both cases a clear χ signal of width ~ 60 MeV (FWHM) around 3.52-3.60 GeV/c² is observed.

Figure IV-9. The $\gamma\text{-}\gamma$ invariant mass spectrum for $1.0 < E_{\gamma} < 30.0$ GeV.

Figure IV-10. The ψ - γ invariant mass spectrum for $5.0 < E_\gamma < 30.0 \text{ GeV}$.

CHAPTER V

EVENT DISTRIBUTIONS

A. Acceptance Characteristics.

The acceptance of the apparatus has been calculated by Monte Carlo technique. We generated χ events of mass 3.53 GeV/c² according to the distribution :

$$\frac{d^2\sigma}{dX_F dP_T} \propto (1-X_F)^{2.0} P_T e^{-2.2P_T}$$

The generated χ was then allowed to decay isotropically into $\gamma\gamma$ and the γ in turn to decay isotropically into $\mu^+\mu^-$. The decay products were then propagated through our apparatus to see if the event was finally accepted.

The generated X_F distribution of the χ 's is shown in Figure V-1a and the accepted distribution is shown in Figure V-1b. The acceptance as a function of X_F is shown in Figure V-1c. Figures V-2a and V-2b show $1/P_T dN/dP_T$ as a function of P_T for the generated and accepted χ events and Figure V-2c is their ratio. Figures V-3a and V-3b show the generated and accepted χ -decay gamma-ray energy distributions.

Figure V-1. X_F distributions $\propto$ events a) generated, b) accepted and c) acceptance as a function of X_F .

Figure V-2. P_T distributions of χ a) generated, b) accepted and c) acceptance as a function of P_T .

Figure V-3. Chi decay gamma-ray energy distributions
a) generated and b) accepted.

The acceptance for the χ -decay ψ alone is found to be 10.8% for all X_F (21.6% for $X_F > 0$). Requiring that both the ψ and γ be detected drops the acceptance for χ detection to 4.62% (9.24% for $X_F > 0$). Hence the acceptance for the χ -decay gamma ray once the ψ has been detected is 43 ± 1 %.

B. The Dimuon Mass Spectrum.

The dimuon mass spectrum in the range 2.5-3.6 GeV/c^2 is shown in Figure V-4. A MINUIT fit to a gaussian-shaped resonance over a background of the form $\sim \exp(-am-bm^2)$ has been performed in the mass range 2.5-3.6 GeV/c^2 . The fit gives 490 ± 28 events (above background) in the mass range $2.95 < M_{\mu^+\mu^-} < 3.20$ GeV/c^2 with width $\sigma = 59 \pm 4$ MeV centered at 3.088 ± 0.004 GeV/c^2 . The fit has an 87% confidence level with a χ^2 of 15 for 22 degrees of freedom.

C. The ψ - γ Spectrum.

The ψ - γ mass spectrum for $1.0 < E_\gamma < 30.0$ GeV is shown in Figure V-5. A shape for the background was calculated by combining a ψ event with all the gamma rays of a different ψ event (uncorrelated γ rays). A MINUIT fit to a gaussian-shaped resonance over this combinatorial background has been performed in the mass range $3.24 < M_{\psi\gamma} < 3.80$ GeV/c^2 . The fitted background normalization (solid curve) was then used to extrapolate the background over the remaining ψ - γ mass spectrum (dotted curve). A 5.4% normalization error was estimated in the

Figure V-4. The fitted dimuon mass spectrum. The curves shown are the results of a MINUIT fit to a gaussian-shaped resonance over a background of the form $\sim \exp(am - bm^2)$.

Figure V-5. The fitted ψ - γ mass spectrum for $1.0 < E_{\gamma} < 30.0 \text{ GeV}$. The curve shown is obtained by fitting a gaussian shaped resonance over the background calculated by combining a τ event with all the γ -rays of a different τ event.

fitting procedure. The fit was done at a 91% confidence level with a χ^2 of 8.4 for 15 degrees of freedom. An excess of 47 ± 11 χ events in the range $3.480 < M_{\gamma\gamma} < 3.560$ GeV/c² with $\sigma = 22.4 \pm 6.3$ MeV/c² and centered at 3.531 ± 0.008 GeV/c² is found.

The τ - γ mass spectrum for $5.0 < E_\gamma < 30.0$ GeV with the background calculated in the same way is shown in Figure V-6. The gamma ray energy cut $E_\gamma > 5.0$ GeV is found to affect only the lower end of the τ - γ mass spectrum but does not affect the χ signal at all.

The gamma ray energy distribution associated with all dimuon events in the range $2.95 < M_{\mu^+\mu^-} < 3.20$ GeV/c² (γ -region) is shown in Figure V-7a. Figure V-7b shows the gamma ray energy distribution for all τ - γ masses in the range $3.48 < M_{\tau\gamma} < 3.56$ GeV/c² (χ -region).

An excess of 35 ± 17 events in the mass range $3.16 < M_{\tau\gamma} < 3.24$ GeV/c² (low-mass peak in Figure V-5) is also observed and remains to be explained. To check any large error in the background calculation shown in Figure V-5, we have calculated the background by two other independent methods. In the first method the shape of the background was calculated by forcing the non- τ events in the mass range $2.25 < M_{\mu^+\mu^-} < 2.50$ GeV/c² to be the τ events ($M_{\mu^+\mu^-} = 3.098$ GeV/c²) and then combining these events with the γ -rays of another non- τ event in the same mass range. In the second method the shape was calculated by combining

Figure V-6. The fitted $\psi\gamma$ mass spectrum for $5.0 < E_{\gamma} < 30.0 \text{ GeV}$. The curve shown is obtained by fitting a gaussian-shaped resonance over the background calculated by combining a ψ event with all the γ -rays of a different ψ event.

Figure V-7. Energy spectrum of gamma-rays associated with events in the a) ψ -region and b) χ -region.

the actual Υ events with the gamma rays of non- Υ events just below $(2.75 < M_{\mu^+\mu^-} < 2.95 \text{ GeV}/c^2)$ and above $(3.2 < M_{\mu^+\mu^-} < 4.0 \text{ GeV}/c^2)$ the Υ mass. These backgrounds were then normalized by fitting the shape of the background plus a gaussian-shaped resonance to our Υ - γ mass spectrum in the range $3.24 < M_{\Upsilon\gamma} < 3.8 \text{ GeV}/c^2$. The fitted normalization was then used to extrapolate the background over the remaining Υ - γ spectrum. In both cases the shape of the fitted background near the χ region was found to be similar to the background shape shown in Figure V-5, but to be about 10% lower near the low-mass peak region. Thus the low-mass signal in the range $3.16 < M_{\Upsilon\gamma} < 3.24 \text{ GeV}/c^2$ was calculated to be even 40% larger.

The excess of events at the low-mass region could be due to a χ state decaying into $\Upsilon\pi^+\pi^-\pi^0$ [29] with the π^0 decaying into 2γ . If one of the π^0 decay γ 's happens to hit the detector then a signal at a mass of $\sim m_\Upsilon + m_{\pi^0}/2 = 3.17 \text{ GeV}/c^2$ is expected. Detailed study to confirm this signal remains to be done.

D. Pattern Recognition Efficiency.

The efficiency of the γ -finding program was calculated using Monte Carlo generated showers. The χ mesons were generated in the range $0.0 < X_F < 1.0$ according to the form $d^2\sigma / dX_F dP_T^2 \propto \exp(-6X_F) \times \exp(-6P_T^2)$. The events were then augmented with π^0 mesons generated according to measured inclusive production cross-sections. The number

of π^0 's in each event was generated according to measured π^0 multiplicities.

The development of the electromagnetic showers for gamma rays which strike the detector was calculated by a Monte Carlo program. The program calculated the detailed development of the shower in the lead and steel material of the passive radiator, in the lead-glass material of the active preradiator and in the aluminium material of the P-tube array. No further shower development was calculated in the absorber array. The absorber blocks were assumed to absorb all the energy of the shower particles which enter them.

The pulse heights in the active preradiator blocks and in the P-tube element were taken to be proportional to the path length of the charged particles which travel through them. Since no shower was generated in the absorber blocks the pulse heights (energy) in these blocks were smeared by a gaussian distribution with the measured resolution of $\frac{\sigma_E}{E} = 6/\sqrt{E} \%$.

The γ -finding program was then run on this sample of generated events. The differences of the positions and energies of the showers found by the program from their known positions and energies were calculated. Defining a γ -decay γ to be found if the position error was less than 1.0 cm and the energy error was less than 1.0 GeV, the efficiency of the program was calculated to be $75 \pm 2 \%$.

This method did not take into account any hardware problems in the P-tube array. Larger fluctuations in the shower intensity profile were observed in the P-tube data than were predicted by the Monte Carlo model. The larger fluctuations were due to the gain variations from tube to tube as well as to the presence of chance signals from out-of-time background events. Using electron showers of ~ 10 -20 GeV an estimate for the efficiency of the P-tube array was made. Using the calibration data electrons of known position and energy were projected to the P-tube array. Requiring a minimum of 100 MeV energy deposit in the converter lead-glass blocks a search for matching showers in all three planes, beyond the given threshold, was performed. This method found a 80 ± 4 % efficiency for the P-tube array. This result gives an upper limit only and should not be taken seriously. The efficiency was observed to decrease if the energy cut in the converter block is lowered. Attributing the P-tube inefficiency to the pattern recognition the upper limit for the γ -finding efficiency dropped to $(0.75 \pm 0.02) \times (0.80 \pm 0.04) = 60 \pm 3$ %.

Another method used to estimate the efficiency of the γ -finding software was to merge 10-20 GeV electron showers from the calibration data with dimuon events (multi γ -ray events) and then run the program on this data. This method gave a 58 ± 2 % efficiency for the pattern recognition program. The 2 % error shown is statistical error only.

E. Results.

Using our data we have performed an estimate for the fraction ($F_{\gamma\chi}$) of γ coming from χ decays. Attributing 47 ± 11 χ events to the process $\chi \rightarrow \gamma\gamma$ (out of 490 γ 's) we measure (with an acceptance of 0.43 ± 0.01 and software efficiency of 0.58 ± 0.02),

$$F_{\psi\chi} = \frac{B_{\chi \rightarrow \psi\gamma}}{\sigma_{\chi}} / \sigma_{\psi} = (47 \pm 11) / (490)(0.43 \pm 0.01)(0.58 \pm 0.02) \\ = 0.38 \pm 0.09$$

i.e. some 29-47 % of the γ production is due to production of χ which decay into $\gamma\gamma$.

We compare our result with the other available results obtained in π^- Be interactions. This comparison is shown in Table V-1 and plotted in Figure V-8 as a function of $\sqrt{s}$. Our result is consistent with the results of other experiments performed at nearly the same energy but is inconsistent with the results of the lower-energy experiments. Assuming all experimental results are correct, Figure V-8 shows a rising value[30] for the fraction $F_{\gamma\chi}$ as a function of $\sqrt{s}$. The rise of $F_{\psi\chi}$ with $\sqrt{s}$ indicates that gluon-gluon fusion dominates quark-antiquark fusion at higher beam energies.

Table V-1. Summary of χ Production in π^- Be Interactions.

Experiment	P_{lab} (GeV/c)	$\sqrt{s}$ (GeV)	Number of χ 's seen	F_{χ} Fraction of χ 's from χ 's	X_F peaks at
T. Kirk (ref.31)	217	20.2	17.2 ± 6.6	0.70 ± 0.28	0.5
Y. Lemoigne (ref. 32)	150	16.8	60 ± 32	0.08 ± 0.04	---
Y. Lemoigne (ref.32,33)	150 175	17.3 (avg)	15 ± 5	0.11 ± 0.04	---
Wall Collaboration (ref. 34)	175	18.1	95 ± 15	0.36 ± 0.05	---
Y. Lemoigne (ref. 35)	185	18.6	184 ± 33	0.31 ± 0.11	---
This Experiment	225	20.6	47 ± 11	0.38 ± 0.09	0.4

Figure V-8. Fraction of ψ' coming from χ ($F_{\psi\chi}$) as a function of $\sqrt{s}$, measured by different experiments in π^- Be interactions. Each point corresponds to a different experiment (see Table IV-1).

CHAPTER VI

CONCLUSIONS

We have studied the reaction :

in a large-aperture multi-particle spectrometer.

A sample of 490 ψ mesons, produced in π^-N interactions at an average center of mass energy of $\sqrt{s} = 20.6$ GeV, has been observed in the decay mode $\psi \rightarrow \mu^+\mu^-$.

A study of the gamma-rays associated with the ψ -events has been performed using a lead-glass proportional-tube shower detector.

A χ signal of 47 ± 11 events (above background) has been found via its decay into $\psi\gamma$, at a mass of 3.531 ± 0.008 GeV/c² with a width of $\sigma = 22.4 \pm 6.3$ MeV/c². The $\sigma = 22.4$ MeV/c² width of the χ state is due to the

experimental resolution and was not good enough to resolve the $\chi(3.51)$ and $\chi(3.55)$ states. We interpret this χ signal as a mixture of $\chi(3.51)$ and $\chi(3.55)$ states which we were unable to resolve.

We measure that $38 \pm 9\%$ of the ψ mesons come from the radiative decay of the χ mesons. Our result agrees well with the results of other experiments (Table V-1) at nearly the same energy but disagrees with the results obtained at lower beam energies.

The gluon fusion model²⁰ predicts production cross sections for $\chi \rightarrow \psi \gamma$ in the ratio 1:7.6 for $\chi_0(3.41): \chi_2(3.55)$. Although production of $\chi_1(3.51)$ by fusion of two gluons is forbidden by Yang's theorem it can be produced by gluon-gluon fusion with the emission of a soft gluon. Given the small number of events near $3.42 \text{ GeV}/c^2$ our result is consistent with the gluon-gluon fusion model.

For the gluon fusion case the relative abundance of $\chi_1: \chi_2$ is 1:4.²⁰ Taking into account the $(2J+1)$ factor the average branching ratio for χ_1 and χ_2 states is:

$$\overline{\text{BR}}_{gg} = \frac{3 \times 0.315 + 20 \times 0.154}{3+20} = 0.175.$$

For the quark fusion case the average branching ratio for χ_1 and χ_2 states is:

$$\overline{\text{BR}}_{q\bar{q}} = \frac{12 \times 0.315 + 5 \times 0.154}{12+5} = 0.267.$$

Therefore, we calculate

$$\frac{\sigma_{\chi_1 + \chi_2}^{gg}}{\sigma_{\psi}^{direct}} = \frac{0.38 \pm 0.09}{(0.62 \pm 0.23) \times 0.175} = 3.502 \pm 0.43$$

$$\frac{\sigma_{\chi_1 + \chi_2}^{q\bar{q}}}{\sigma_{\psi}^{direct}} = \frac{0.38 \pm 0.09}{(0.62 \pm 0.23) \times 0.267} = 2.29 \pm 0.43$$

LIST OF SYMBOLS

ψ	psi meson.
ψ'	psi prime meson.
χ	chi meson.
ρ	rho meson.
ϕ	phi meson.
μ	muon.
γ	gamma-ray.
σ	cross section.
Γ	decay or annihilation width.
λ_j	calibration constant for jth lead-glass block.
σ_E	energy resolution.
E	energy.
FWHM	full width at half maximum.
LED	light emitting diode.
m_ψ, M_ψ	mass of the ψ meson.
$m_{\psi'}$	mass of the ψ' meson.
M_χ	mass of the χ meson.
P_T	transverse momentum.
s	center of mass energy squared.
X_F	Fynman X. ($X_F = P_L^{cm} / P_{max}^{cm} \approx 2P_L^{cm} / \sqrt{s}$).
U. of I.	University of Illinois.

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