**RESULTS FROM THE CRYSTAL BALL DETECTOR AT SPEAR**

Crystal Ball Collaboration

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**Introduction**

The Crystal Ball detector is a device particularly suited to the measurement of photons with energies lower than 1 GeV. As shown in Fig. 1, the detector has as its principal component a 16 radiation length thick highly segmented shell of NaI(Tl) surrounding cylindrical proportional and magnetostrictive spark chambers. The main Ball and various elements of the central chambers cover 94% of 4π sr. Segmented endcap NaI(Tl) detectors of 20 radiation lengths behind magnetostrictive spark chambers supplement the main Ball. The Ball and endcaps close the solid angle for charged particle and photon detection to 98% of 4π sr. In addition (not shown in Fig. 1), detectors of inter-spersed iron and proportional tubes provide for μ-π separation over 15% of 4π sr. about θ_{CM} = 90°. A more complete description of the detector, its electronics, calibration and triggers can be found in Ref. 2.

The Crystal Ball collaboration has concentrated on two projects since SPEAR data taking began in December 1978:

1. A detailed study of the charmonium system. Data taking has been completed. Approximately 900K events at the J/ψ, 800K events at the ψ' and 50K events at ψ'' have been obtained.

2. A study of R_{hadron}, neutral energy, multiplicities, and other inclusive characteristics of the continuum above 3.9 GeV. This has been started and a fine energy scan has been made from E_{CM} ~ 3.9 GeV to E_{CM} ~ 4.5 GeV. In addition extensive data were obtained at E_{CM} = 5.2 GeV and 6.5 GeV.

In this report preliminary results will be presented from the data obtained as described in (1) and (2) above. In particular, QED at E_{CM} = 6.5 GeV, R_{hadron} and related inclusive distributions, n branching fractions at J/ψ and ψ'' and a detailed study of the psionium system will be discussed.

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QED and Tests of the Apparatus

One of the simplest physics processes to observe in the Ball is the QED reaction,

$$e^+ e^- \rightarrow \gamma\gamma$$  \hspace{1cm} (1)

The cuts used to select events for this process are shown in Table I.

Table I
Selection Criterion for Events Contributing to $e^+e^- \rightarrow \gamma\gamma$

(1) More than one major contiguous region of energy deposition (connected energy region) in the Ball.
(2) Two to four neutral particles identified by pattern recognition. (2 to 4 energy bumps with no associated chamber hits.)
(3) Two neutral particles with $E \geq 0.7 E_{\text{beam}}$.
(4) $|\cos \theta_\gamma| \leq 0.85$, where $\theta_\gamma$ is the photon angle to the $e^+$ beam.

A typical event, obtained at $E_{CM} = 7.4$ GeV, is shown in Fig. 2. As seen in the figure, the photons have a lateral energy spread in the Ball, with a number of modules having appreciable energy deposition. Typically for identified photons, the 12 modules around the module with the largest energy deposition, and this module are summed for analysis. Approximately, 95% of the energy of the photon is contained in this sum of 13 modules. Correction for average energy loss is easily made. The lateral shower spread is used to determine the direction of photons more accurately than a single module size would allow. For example with $E_{\gamma} \sim 1.5$ GeV we presently obtain $\sigma_{\text{projected}} \sim 1^0$. A single Ball module is $\sim 12^0$ on a side and geometrically yields $\sigma_{\text{projected}} = 3.5^0$. The angular resolution worsens as $E_{\gamma}$ lowers, with $\sigma_{\text{projected}} \sim 2.5^0$ presently obtained at $E_{\gamma} \sim 100$ MeV.

The resulting events are corrected for radiative effects (0.975), and $\gamma$ conversion in the beam pipe and tracking chambers (.94). After dividing by the luminosity, known to ±3% from an independent luminosity monitor (see Fig. 1), an absolute cross section is obtained. Figure 3 shows the absolute differential cross section measured at $E_{CM} = 6.5$ GeV, divided by QED theory. Good agreement to $\pm 10\%$ is found over the entire angular range displayed. A point-to-point
On integrating over $\cos \theta_y$, excellent agreement is obtained with QED as shown in Fig. 5. The error bars for Crystal Ball results are mainly systematic error estimates. The results of previous experiments are also shown.3-8

Measurement of $R_{\text{hadron}}$, Multiplicities and Neutral Energy

(a) The Selection of Hadronic Events and $R_{\text{hadron}}$

Figure 6(a) shows the measured total energy distribution for all events allowed by the Crystal Ball triggers at $E_{\text{CM}} = 4.0$ GeV; also shown as the dotted line is the extracted multi-hadron signal. Clearly there is a large background. Even though in this energy region the total calorimetry of the Ball is good ($\sigma(E) \approx 25\%$), calorimetry alone is not sufficient to separate the hadronic signal from cosmic ray, beam gas, QED, and other backgrounds.

In order to separate the multi-hadronic component of the triggers, a number of cuts are needed, these are shown in Table II. The resulting measured total energy distribution for multi-hadronic events (including some $\tau\tau$ events) is shown in Fig. 6(b).

Figure 7 shows the measured $Z$ distribution of events satisfying cuts 1-6 of Table II. The additional $Z$ cut requirement of $|Z| < 12$ cm ($\sigma(E) \approx 2-3$ cm) has only a small effect on the resulting cross section.

After dividing by the integrated luminosity obtained from our independent small angle luminosity monitor, correcting for the multihadron efficiency resulting from the cuts of Table II, radiatively correcting, and subtracting the remnant $\tau\tau$ contribution ($\sim 0.4$ unit of $R$), we obtain preliminary values of $R_{\text{hadron}}$ as shown in Fig. 8. In the figure only the statistical errors are shown; additional systematic errors of $\pm 12\%$ are estimated. The largest contribution to the systematic error is the uncertainty in the multihadron efficiency ($91\% \pm 7\%$).
Fig. 6. (a) $E_{\text{measured}}$ (charge + neutral) vs. counts/100 MeV for all events allowed by the Crystal Ball triggers at $E_{\text{CM}} = 4.0$ GeV. The dotted line is the extracted multihadron signal also shown on a different vertical scale in Fig. 6(b). (b) $E_{\text{measured}}$ (charged + neutral) vs. counts/100 MeV for events satisfying the cuts of Table II. These events are essentially multihadrons plus some $\tau\tau$ events.

Table II
Selection Criterion for Multihadron Events (off resonance)

1. $E_{\text{TOT}} \geq 0.46 \times E_{\text{beam}}$
2. $E(|\cos \theta| < 0.85)/E_{\text{TOT}} > 0.5$, $\theta$ is the particle angle to the $e^+$ beam.
3. $> 3$ connected energy regions with $E_{\text{region}} > 50$ MeV.
4. $> 3$ (neutral + charged) tracks with $E_{\text{track}} > 20$ MeV.
5. At least one reconstructed charged particle track, which defines a vertex.
6. $|\Sigma P_1/|\Sigma P_1| < 0.65$, where the sums are over all particles in the event, and $P_1$ is the measured momentum assuming each charged particle is a pion, and each neutral particle is a photon (Nal(Tl) measures deposited energy).
7. $|z_{\text{vertex}}| < 12$ cm (see Fig. 7).
8. Beam gas and cosmic ray remnants are subtracted statistically run by run, using separated beam measurements.

Note: We estimate the total efficiency for multihadrons to be $91\% \pm 7\%$ based upon simple Monte Carlo studies.

Fig. 7. $Z(\text{cm})$ vs. counts/cm for events obtained by cuts 1-6 of Table II. The background to beam, beam interaction associated events is small.

Fig. 8. $R_{\text{hadron}}$ vs. $E_{\text{CM}}$ from the Crystal Ball. The measurement is preliminary. Only statistical errors are shown in the figure, and additional systematic error of $\pm 12\%$ is estimated. Note that the values of $R$ shown have $\tau\tau$ subtracted.

The major features of $R_{\text{hadron}}$ seen in Fig. 8 are similar to those seen in previous measurements of $R^{9-10}$.

We have also measured $R$ at 5.2 GeV with good statistical precision (not shown in Fig. 8). After treating this data as we did the 4 GeV region data, we obtain the preliminary result,

$$R_{\text{hadron}} = 3.8 \pm 0.1 \pm 0.5, \ E_{\text{CM}} = 5.2 \text{ GeV}. \quad (2)$$

The statistical error is shown first, our estimate of systematic error is shown separately last. This result is in good agreement with a DELCO Measurement$^{10}$ (also $\tau\tau$ subtracted) at $E_{\text{CM}} = 5.1$ GeV.

(b) Multiplicities and Neutral Energy Fraction

Using the events of our multihadron sample with the additional requirements that $E_{\text{track}} > 40$ MeV (this requirement implies, $P_\gamma > 100$ MeV), and $\cos \theta_{\text{charged}} < 0.925$, we obtain preliminary multiplicities as shown in Fig. 9. Note that these multiplicities are corrected for acceptance, but not corrected for $\gamma$ conversion,
In Crystal Ball measurements the main component of Eneutral which is directly observed are photons with Eγ > 40 MeV. In previous Mark I measurements\(^1\) ECM - Echarged was used to infer Eneutral. The preliminary Crystal Ball results shown in Fig. 9(d) thus indicate that the previously observed rise with ECM of (ECM - Echarged) / ECM, the "energy crisis", is not due to photons with Eγ > 40 MeV.

The result (5) is considerably smaller for the J/ψ than the 0.4 previously estimated.\(^{13}\) This unexpectedly low η inclusive branching fraction when combined with the large neutral energy fraction at J/ψ and the analysis of Ref. 13, implies a still undetermined source of photons in J/ψ decays. A candidate for such a source are the prompt γ's predicted by QCD\(^{14}\) in γγ decay of the J/ψ.

\[\text{Br}(J/\psi \rightarrow \eta + x) = 0.12 \pm 0.03 \pm 0.04\]

\[\text{Br}(\psi'' \rightarrow \eta + x) = 0.19 \pm 0.03 \pm 0.06\]

Inclusive η Branching Fraction at J/ψ and ψ''

Figure 10 shows a distribution of the mass of all photon pairs with Mγγ > 300 MeV. The data shown were obtained at ECM = 3.772 GeV (ψ''). A signal at the η mass is evident. No cuts other than hadronic cuts similar to those of Table II have been applied to the events. A similar distribution was produced for J/ψ data. Both distributions were fit to a Gaussian centered at a fixed mass of the η with fixed experimental mass resolution, plus a variable polynomial background. The η mass, M_η, and resolution, σ_M, were found from a fit to data at the J/ψ with good statistics to be,

\[M_\eta = 543 \pm 11 \text{ MeV}, \quad \sigma_M = 22 \text{ MeV}
\]

where the error on M_η is mainly systematic. After radiative corrections the preliminary results for the inclusive branching fraction are,

\[\text{Br}(J/\psi \rightarrow \eta + x) = 0.12 \pm 0.03 \pm 0.04\]

\[\text{Br}(\psi'' \rightarrow \eta + x) = 0.19 \pm 0.03 \pm 0.06\]

The first error is the statistical error estimate of the fit. The second error is our estimate of systematic effects - primarily acceptance. We expect that some of the second systematic error would cancel in a ratio between the two numbers.

The result (5) is considerably smaller for the J/ψ than the 0.4 previously estimated.\(^{13}\) This unexpectedly low η inclusive branching fraction when combined with the large neutral energy fraction at J/ψ and the analysis of Ref. 13, implies a still undetermined source of photons in J/ψ decays. A candidate for such a source are the prompt γ's predicted by QCD\(^{14}\) in γγ decay of the J/ψ.
The Psionium System

Figure 11 shows the states of psionium, interpreted by the charmonium model, at the time of the last lepton-photon conference. Since that time, and particularly as Crystal Ball measurements have become available over the past 6 months, the picture has radically changed. At the time of the Hamburg Conference the \( \eta_c \) candidate \( \chi(3455) \) had been seen by 3 experiments and published by one.\(^3\) The second photon in the \( \chi(3410) \) cascade also seemed well established at a rate consistent with QCD predictions.\(^1\)

Fig. 11. The state of knowledge of the psionium system, as interpreted by the charmonium model, at the last lepton photon conference (minus crosses). The crosses are some of the contributions of the Crystal Ball herein reported.

The \( \eta_c \) candidate \( X(2820) \) had been seen in one experiment,\(^16\) while another experiment\(^13\) using hadron beams provided weaker supporting evidence for a meson in that mass range (2.8-3.0 GeV). The existence of the intermediate states \( \chi(3550) \), \( \eta_c' \) and \( \chi(3410) \) was firmly established from measurements of inclusive photon spectra\(^20,21\) as well as cascade decays of the \( \psi' \).\(^1,16\) However, that these states were the intermediate \( P \)-states sought in non-relativistic charmonium models\(^22\) was based more on theoretical prejudice than experimental fact.\(^16,17\) Indeed, given the difficulty the theoretical models had with \( \chi(3455) \) and \( X(2820) \) being the \( 0^- \) states of charmonium, little hard experimental evidence existed which supported the details of the popular models.\(^23,24\) On examining the totality of experimental evidence then available, a natural conclusion was that the non-relativistic charmonium model of the \( J/\psi \) system was basically flawed. The existence of the \( X(2820) \) and \( \chi(3455) \) thus became pivotal elements in the theoretical understanding of the psionium system. The crosses in Fig. 11 anticipate the results from the Crystal Ball presented in Sections (a) and (b). It appears the theorists may breathe a sigh of relief.

(a) \( J/\psi \rightarrow 3\gamma \) and the Existence of \( X(2820) \)

Figure 12 shows the extent of our data taking at the \( J/\psi \) and \( \psi' \). The units of the figure are \( \mathcal{Z}(\text{nb}^{-1}) \). The total number of \( J/\psi \)'s obtained was approximately 900K, the total number of \( \psi' \)'s was approximately 800K. All of these data have now been analyzed for the processes

\[ J/\psi \rightarrow \psi' \rightarrow \pi^+ \pi^- \]  
\[ \psi' \rightarrow \gamma\gamma \]  

Processes (6) and (7) bare directly on the question of the existence of the DASP \( X(2820) \). We have discussed process (6) previously,\(^2,23\) thus I will only quickly review our result here. Figure 13 shows events of process (6) obtained from our entire \( J/\psi \) data sample. The Dalitz plot is shown, and the dotted line indicates the expected location of \( X(2820) \). We expect a clustering of \( \geq 50 \) events about this line if the DASP branching fraction is used. No such clustering is observed, and a fit to the Dalitz plot yields,

\[ \text{Br}(J/\psi \rightarrow \gamma X(2820)) < 0.3 \times 10^{-4} \text{ (90\% C.L.)} \]  

Fig. 13. The \( J/\psi \rightarrow 3\gamma \) Dalitz plot, the \( \eta \) and \( \eta' \) signals are clearly evident as is a general background arising from the QED 3\gamma process. The vertical dashed line indicates the expected position of the DASP \( X(2820) \); \( \geq 50 \) events are expected clustering about this line.

As an independent check to the upper limit (8), we have considered the process (7). In considering (7) the 3\gamma QED background present in (6) arising from
radiative corrections to process (1), will be totally absent. Thus a much cleaner Dalitz plot will result. A typical event of process (7) is shown in Fig. 14. The selection criteria for these events are given in Table III.

Table III
Selection Criteria for Events of Process (7)

1. All particles have $|\cos \theta_1| < 0.9$, $\theta_1$ is the particle angle to the $e^+\text{beam}$. 
2. Two charged particles plus 3 neutrals in the event. 
3. $E_Y > 20$ MeV. 
4. Angle between pairs of particles, $\cos \theta_{ij} < 0.9$. 
5. $8 \text{ GeV}^2 < M_{\text{neut}}^2 < 11 \text{ GeV}^2$. 
6. 3C fit satisfied with $\chi^2 < 30$. 

The resulting preliminary Dalitz plot is shown in Fig. 15. Essentially only $\eta$ and $\eta'$ decays are seen. The dotted lines indicate the range of $M_{\psi'}$ in which $X(2820)$ events should appear given our estimated resolution. No events are seen in this band which are outside the $\eta$ band. Using the ratio of our measured $\eta$ and $\eta'$ yield for this process to the yields from process (6), and independent Monte Carlo estimates of efficiency we find preliminary values,
\[
\text{Br}(J/\psi \to \gamma X(2820)) < 0.5 \times 10^{-4} \quad (90\% \text{ C.L.}) \quad (9)
\]
and, including one event which lies closer to the X band than any other band we obtain,
\[
\text{Br}(J/\psi \to \gamma X(2820)) < 0.8 \times 10^{-4} \quad (90\% \text{ C.L.)} \quad (10)
\]
We also find,
\[
\text{Br}(J/\psi \to \gamma \eta'/J/\psi \to \gamma \eta) = 7.9 \pm 3.6 \quad (11)
\]
These values compare well with our previously reported values, obtained from process (6).

A summary of DASP and Crystal Ball results is shown in Fig. 16. The upper limits shown are for a narrow \(\eta\), that is one narrower than the present Crystal Ball resolution (-8.5 MeV FWHM @ \(E_\gamma = 100\) MeV). The theory is from Ref. 22. The figure indicates that after examining the two processes (6) and (7) the Crystal Ball has no signal for the DASP X(2820).

![Fig. 16. Summary of results for \(J/\psi \to 3\gamma\) using processes (6) and (7). The theory is that of Ref. 22. Note that the upper limit shown for process (7) assumes no X(2820) candidates seen. Including the one possible candidate closer to the X band than \(\eta\) or \(\eta'\) bands raises the limit to \(0.8 \times 10^{-4}\).](image)

(b) The \(\psi'\) Gamma Cascades and the Existence of \(\chi(3455)\)

All of our \(\psi'\) events have been analyzed for the \(\psi'\) gamma cascade process,
\[
\psi' \to \gamma \chi \to \gamma J/\psi \to e^+e^- \quad (12)
\]
A typical example of which is shown in Fig. 17. This analysis yields a total of 1705 candidates after the cuts described in Table IV are applied.
RUN # 1094  EVENT # 3782  ETOT = 3612  ECM = 3684

#  TRK T
1  1422 C e
2  1602 C e
3  445 N \gamma_2
4  125 N \gamma_1

1038 IN ***
1019 IN +++

Fig. 17. A typical event of process (12). The cross lined regions indicate the sum of module energies used to estimate particle energies, and photon angles.

Table V
Crystal Ball Cascade Preliminary Results,
\( BrC = Br(\psi' \rightarrow \gamma \chi) \cdot Br(\chi \rightarrow \gamma J/\psi) \)

\( \chi(3510 \pm 4) \): 1027 events
\[ BrC = 2.1\% \pm 0.07\% \text{ (statistical)} \]
\[ \pm 0.21\% \text{ (acceptance)} \]
\[ \pm 0.30\% \text{ (J/\psi \rightarrow \ell^+\ell^-)} \]

\( \chi(3555 \pm 4) \): 531 events
\[ BrC = 1.13\% \pm 0.05\% \text{ (statistical)} \]
\[ \pm 0.11\% \text{ (\psi')} \]
\[ \pm 0.16\% \text{ (J/\psi \rightarrow \ell^+\ell^-)} \]
\[ \pm 0.15\% \text{ (acceptance)} \]

\( \chi(3410 \pm 6) \): 29 events, 13.0 estimated \( \pi^0\pi^0 \) background,
\[ BrC < 0.05\% \text{ (90\% C.L.)} \]

\( \chi(3455) \): 23 events, 9 estimated \( \pi^0\pi^0 \) background,
\[ BrC < 0.045\% \text{ (90\% C.L.)} \]

\( \chi(3591) \): 21 events
\[ BrC < 0.06\% \text{ (90\% C.L.)} \]

No other states yet seen.
+ Mass obtained from \( \psi' \) inclusive photon spectrum.
Fig. 18. Low mass vs. high mass scatter plots at various stages of analysis. (a) Raw data resulting from steps 1-5 of Table IV. Observed photon energies are used to calculate the plotted masses. (b) The data of (a) after kinematic fitting, 3C for $\gamma\mu^+\mu^-$, and 5C for $\gamma\mu^+\mu^-$ and $\gamma\mu^+\mu^-$ final states. (c) The data of (b) after $\eta$'s are removed (see Fig. 19).

Fig. 19. $M_{\gamma\gamma}$ distribution for all fitted events of process (12) (see Fig. 18(b)). $\eta$'s are removed in this analysis by a $M_{\gamma\gamma}$ cut at 530 MeV (vertical arrow in figure).

Fig. 20. The high mass projection of the scatter plot of Fig. 18(c). No signal is evident except $\gamma(3555)$ and $\gamma(3510)$. The vertical arrows indicate the positions of the states expected at 3415 MeV, 3455 MeV and 3591 MeV.

Fig. 21. A summary of the results of previous measurements of process (12). The results are shown as a scatter plot of low mass vs. high mass as was Fig. 18(c).
Table VI

Previous Results for \( \text{Br}(J^P) \equiv \text{B}(\psi' \to \gamma X J^P) \cdot \text{B}(X J^P \to \gamma J/\psi) \)

(SPIN Assignment are Educated Guesses)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( M_X (1^+) )</th>
<th>( \text{Br}(1^+)% )</th>
<th>( M_X (2^+) )</th>
<th>( \text{Br}(2^+)% )</th>
<th>( M_X (0^+) )</th>
<th>( \text{Br}(0^+)% )</th>
<th>( M_X (0^-) )</th>
<th>( \text{Br}(0^-)% )</th>
</tr>
</thead>
<tbody>
<tr>
<td>DASP(^26)</td>
<td>3508 ± 4</td>
<td>1.7 ± 0.4</td>
<td>3552 ± 6</td>
<td>1.4 ± 0.4</td>
<td>3413 ± 5(^{\text{h}})</td>
<td>0.3 ± 0.2</td>
<td>--</td>
<td>&lt; 0.4</td>
</tr>
<tr>
<td>Mark I(^16)</td>
<td>3503 ± 4</td>
<td>2.4 ± 0.8</td>
<td>3551 ± 4</td>
<td>1.0 ± 0.6</td>
<td>3414 ± 3(^{\text{h}})</td>
<td>0.2 ± 0.2</td>
<td>3454 ± 7</td>
<td>0.8 ± 0.4</td>
</tr>
<tr>
<td>Pluto(^26)</td>
<td>seen</td>
<td>1.2 ± 1.0 ± 0.6</td>
<td>seen</td>
<td>0.9 ± 1.0 ± 0.5</td>
<td>seen</td>
<td>0.7 ± 0.8 ± 0.5</td>
<td>seen</td>
<td>1.2 ± 0.9 ± 0.6</td>
</tr>
<tr>
<td>DESY-Heid(^27)</td>
<td>3505 ± 3</td>
<td>2.5 ± 0.4</td>
<td>3551 ± 4</td>
<td>1.0 ± 0.2</td>
<td>3420 ± 10</td>
<td>0.14 ± 0.09</td>
<td>--</td>
<td>&lt; 0.25(^{\ast})</td>
</tr>
</tbody>
</table>

\( \text{h} \) Mass determined from hadronic decays.

\( \ast \) New state reported, \( \chi(3591 ± 7) \), \( \text{Br}(0^-) = (0.18 ± 0.06)\% \).

\( \dagger \) Mark II preliminary result:\(^28\) \( \text{Br}(3455) < 0.12\% \) (90% C.L.).

(c) The Cascade Angular Correlations and the Spin of the \( \chi \)'s

As described in Ref. 29, a determination of the spin of the \( \chi \)'s and the multipolarity of the photon transitions in the cascade can be made by analyzing the angular correlations among the particles of the cascade. In Fig. 22 is shown a definition of the kinematics of the cascade process. With \( T' \) the three vector of the first photon and \( T \) the three vector of final photon of the cascade, we define

\[
\cos \theta' = \hat{z} \cdot \frac{T'}{|T'|},
\]

\[
\tan \phi' = \frac{\hat{z} \cdot (\gamma' \times T')}{\hat{z} \cdot (\gamma' \times T')} 
\]

where \( \hat{z} \) is direction of \( e^+ \) beam (13).

In \( \chi \) Frame: \( \cos \theta_{YY} = \frac{T_1 \cdot \gamma}{|T_1||\gamma|} \)  (13)

In \( J/\psi \) Frame: \( \cos \theta = \frac{T_1 \cdot \gamma}{|T_1||\gamma|} \)

\[
\tan \phi = \frac{T_2 \cdot (\gamma' \times \gamma)}{T_2 \cdot (\gamma' \times \gamma) - \left(\frac{T_1}{T_1 \cdot (\gamma' \times \gamma)}\right)}
\]

where all 3-vectors are evaluated in the frame specified. The angular correlation function which results is a function of all five angles defined in (13).

An initial attempt has been made to use the correlations, plus other information to obtain the spins of the \( \chi \) states.\(^16\) Tentative assignment of \( 2^+ \) to \( \chi(3555) \) and \( 1^+ \) to \( \chi(3510) \) has been made\(^17\) based on a very limited amount of data. The Crystal Ball results presented here represent greater than a factor of ten more data than contained in the previous Mark I analysis. Thus, even though our spin analysis is still in its very preliminary stages, I will present some initial results on the \( \chi \) spin determinations from our data. Ideally, a full angular correlation analysis should be made on the events to extract the greatest possible amount of information. This analysis is still in progress, and so here I will present only one dimensional (single angle) distributions to compare with the previous spin assignments, assuming \( E_1 \) dominance for the multipolarity of the \( \gamma \) transitions.

Figure 23 shows the angular distributions from \( \chi(3555) \). The data is shown with statistical errors only. A Monte Carlo result assuming spin 2 for this \( \chi \) state and \( E_1 \) dominance for the multipolarity of the photon emissions is also shown. Reasonable agreement is seen between data and Monte Carlo. This is also true in Fig. 24 which presents \( \chi(3510) \) angular distributions and spin \( 1, E_1 \) dominated Monte Carlo. Thus at present we find no conflict with previous spin, multipolarity assignments to \( \chi(3555) \) and \( \chi(3510) \) cascades. However, our present analysis does not exclude other spin assignments and other multiplicities. We expect that the full correlation analysis will allow a more definite determination.

(d) The Hadronic Width of \( \chi(3410) \) and QCD

The small upper limit to the \( \chi(3410) \) cascade branching fraction is a surprising result given current theoretical models of the \( 0^+ \) decay process. One such model, the lowest order QCD estimation of the hadronic width is the \( \chi \) states is represented in Fig. 25. Two gluons are exchanged in this model for \( 0^+ \) and \( 2^+ \) hadronic decays, while 3 gluons are exchanged for \( 1^+ \) decay. A detailed calculation of these processes has been made\(^30\) and results in predicted ratios for the hadronic widths of the \( \chi \) states. The theory predicts for \( 1^+ \) gluons,
The results of the last section indicate consistency of the data with the canonical \( J^P \), multipolarity assignments of the charmonium model, and so these are assumed in the following. Using our presently measured upper limit on the \( 0^+(3410) \) cascade, and the analysis of Ref. 17 as applied to Crystal Ball data, I find (see also the talk of C. Quigg at this conference),

\[
\Gamma(2^+ \to h) \leq 0.07 \quad \Gamma(0^+ \to h) \quad (15)
\]

The theory expects this ratio to be 0.27. Thus, qualitatively taking into account our experimental errors I find a factor of two to four disagreement with the theory. Qualitatively, the \( 0^+ \) seems too broad as compared to the \( 2^+ \). The resolution of this disagreement may lie in consideration of higher order QCD contributions to the hadronic widths. This point is discussed briefly by J. Ellis in his report to this Conference.

(e) Inclusive Photon Studies at the \( \psi' \)

We have presently analyzed essentially all \( \psi' \) data for the process,

\[ \psi' \to \gamma + \text{anything} \quad (16) \]

and these results will be presented here.

The \( J/\psi \) data has not yet been fully analyzed for the process,

\[ J/\psi \to \gamma + \text{anything} \quad (17) \]

and so I will not present any results on the \( J/\psi \) inclusive at this Conference.

The cuts used to select photons appearing in the inclusive spectrum of Fig. 26 are shown in Table VII.

<table>
<thead>
<tr>
<th>Table VII</th>
<th>Cuts Used to Generate Inclusive ( \gamma ) Spectra</th>
</tr>
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<tbody>
<tr>
<td>(1)</td>
<td>Hadronic events are selected in a manner similar</td>
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<tr>
<td></td>
<td>to that shown in Table II.</td>
</tr>
<tr>
<td>(2)</td>
<td>(</td>
</tr>
<tr>
<td></td>
<td>( \theta_{ei} ) is the particle angle to the</td>
</tr>
<tr>
<td></td>
<td>( e^+ ) beam.</td>
</tr>
<tr>
<td>(3)</td>
<td>Charge particle-photon angular cut, ( \cos \theta_{CG} &lt; 0.85 ).</td>
</tr>
<tr>
<td>(4)</td>
<td>Identified charged particles are removed.</td>
</tr>
<tr>
<td>(5)</td>
<td>( n^0 )'s are subtracted with a currently used</td>
</tr>
<tr>
<td></td>
<td>algorithm which removes about 0.5 ( n^0 ) per event.</td>
</tr>
<tr>
<td>(6)</td>
<td>For the remaining photons, 50 MeV &lt; ( E_\gamma ) &lt; 1000 MeV.</td>
</tr>
</tbody>
</table>

Note that the abscissa in Fig. 26 is in \( E_\gamma \). This is because our fractional energy resolution changes only by a factor of 2 over the range of \( E_\gamma \) shown. Steps (3) and (5) of Table VII introduce inefficiencies for the remaining photons which vary smoothly as a function of \( E_\gamma \). We need a Monte Carlo simulation of the hadronic production process in order to estimate these inefficiencies accurately. This Monte Carlo is not yet available and so only very approximate estimates of absolute branching fractions can be made.

The purpose of my presentation is not to give absolute branching fractions on the known \( \chi \) states, but to present evidence for the existence of a new state \( \Upsilon(2.98) \) seen under the arrow in Fig. 26. The well-
established $\chi$ states, $\chi(3410)$, $\chi(3510)$, and $\chi(3555)$ are evident in the figure. Also clearly seen, but not relatively so large is a bump at $E_\gamma = 0.64 \pm 0.02$ GeV corresponding to a mass of, $M_U = 2.98 \pm 0.02$ GeV. This result is more clearly seen in Fig. 27 where a blowup of the region of the new state is shown. Figure 27(a) shows the data, fitted with a function. This function is the sum of a Gaussian of arbitrary amplitude and position and relative width, $\sigma_0 = 0.038$, fixed at about our resolution, plus a quadratic background. $\sigma_0$ was obtained by first allowing a variable $\sigma$ in the fit. The resulting $\sigma_0$ was then fixed for subsequent fits. The background was fit both separately, and also simultaneously with the variable Gaussian parameters. Both techniques yielded state parameters equal within errors. In both cases the statistical significance of the effect was over 5 standard deviations. A particular fit yielded,

$$E_\gamma^U = 634 \pm 20 \text{ MeV}.$$ 

Estimated Yield $U = 1624 \pm 252$ counts.

Figures 27(a) and (b) show the results of this fit. In Fig. 27(b) the fitted background has been subtracted yielding an obvious indication of a state.

We call this state $U$ since its nature is presently unknown.\textsuperscript{31} Using essentially educated guesses of our photon efficiency in the region of 600 MeV I estimate,

$$\text{Br}(\psi' \rightarrow \gamma U) = 0.2\% \text{ to } 0.5\%.$$ 

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Fig. 26. Preliminary inclusive photon spectrum generated from 800K $\psi'$ events. The cuts which are used to produce this spectrum are given in Table VII. The well-established states $\chi(3555)$, $\chi(3510)$ and $\chi(3410)$ are clearly evident starting on the left. The next bump to the right is the second cascade photons from $\chi(3555)$ and $\chi(3510)$. The last little bump (under the arrow) is a new state $U(2.98 \pm 0.02)$.

Fig. 27. A blowup of the $\psi'$ inclusive photon spectrum in the region of the $U(2.98 \pm 0.02)$. (a) shows the fit to the data described in the text. Full fit and background from the fit are shown. (b) shows the data with background (as estimated from the fit) subtracted. A greater than 5$\sigma$ effect is seen at $E_\gamma = (634 \pm 20)$ MeV.
Summary

A number of major conclusions can be drawn from the results presented in this report:

(1) The richness of continuum physics at SPEAR energies is yet to be fully revealed.
(2) The X(2820) and X(3455) 0+ candidates are not seen by the Crystal Ball.
(3) A new state has been discovered, U(2.98 ± 0.02 GeV), by examining our inclusive photon spectrum at the ργ; we are in the process of examining our J/ψ inclusive photon spectrum for indications of the U there.
(4) The "old fashioned" non-relativistic charmonium model may not be so bad after all.

References


10. J. Kirkby, presentation at this conference.


Questions and Answers

Q: (Osborne, MIT) What is the background in the inclusive γ spectrum?

A: We don't know. The problem is to determine what the character of the photon background is in detail. One thing we do is to subtract π0's; most of the background should go away but it doesn't. The reason is that the efficiency of subtracting π0 is only about 50% right now. We hope to improve this efficiency as time goes on. But, in order to comprehend the details we have to use a Monte Carlo simulation of hadronic production, take the number of π0's we see and use that to normalize the Monte Carlo to completely subtract the π0's, and see what's left. That sort of a technique we hope to use at the psi to see if there's any prompt photons at the psi.

Q: Well, if it's π0, it should peak at m_π0/2. Does it?

A: There is a peak at m_π0/2 if you plot it vs. a linear scale rather than a logarithmic scale but the distribution is very broad.

Q: (Wolf) I want to make a comment and I have a question. The comment is on the X(2.8). All I can say is we have reanalyzed the 3γ data. The conclusion is the same as in the paper. We could not get rid of the enhancement at 2.8 GeV so that's where it stands.

A: Have you fit the whole Dalitz plot at once and seen what the answer is? Our limit comes out as a fit to the entire Dalitz plot.

Q: No we have not done that. The question I have is have you looked for the forbidden decay of \( \psi' \rightarrow \pi^0 J/\psi \).

A: \( \pi^0 J/\psi \).

Q: Yes.

A: We have started such a study. We expect to be able to say something soon on this process.

Q: (Estia J. Eichten, Harvard) From the inclusive gamma distribution from the psi what kind of a limit is put on the branching ratio of the \( \psi + \gamma \) and its U state when its mass is 2.976?

A: You mean what can we do in principle or what have we done?

Q: What have you done?

A: We reported an upper limit on the order of 1% for a narrow ηc in the past. We are working on that right now.