Evidence for Direct γ Production at Large x in $\psi(3100)$ Decay

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The inclusive γ and π^0 momentum spectra from $\psi(3100)$ decay have been measured in e^+e^- annihilation at SPEAR. When the γ spectrum is compared with that expected from π^0 decay, an excess of high-momentum γ's is observed. This excess is compared with that predicted by quantum chromodynamics for the decay of the ψ into a γ and two gluons.

We have discovered an excess of high-energy γ production over that expected from π^0 decays at the $\psi(3100)$. One possible explanation for this excess is hadronic production via the quantum chromodynamic (QCD) process by which a pair of charmed and anticharmed quarks annihilate into a γ and two gluons rather than the more copious annihilation into three gluons. This direct γ production is expected to occur at a significant rate: 12% of the three-gluon rate[1,2] (for a strong-coupling-constant value $\alpha_s = 0.2$) or 8.3% of the rate for all hadronic decays of the ψ.[3] We compare the observed γ excess with this model and with that expected from exclusive radiative decays of the ψ.

The experiment was run at SPEAR with the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory magnetic detector,[4] augmented by the lead-glass wall[5] (LGW) for e and γ detection. The LGW consists of two finely segmented layers of lead-glass counters, one layer 3.3 and the other 10.5 radiation lengths thick, with a fiducial region which covers $0.049\times 4\pi$ sr. Identification of γ's in the LGW is described by Scharre *et al.*[6] Spark-chamber information is combined with the lead-glass energy distribution to obtain an angular resolution of $\Delta\theta \cong 0.5°$. The γ energy resolution was measured using the reaction $e^+e^- \to \gamma\gamma$ to be $\Delta E/E = 0.08/E^{1/2}$ at $E = 1.89$ GeV.

The data sample used in this analysis consists of about 80 000 $e^+e^- \to \psi(3100) \to$ hadrons events with at least two detected charged particles. If only two oppositely charged particles are detected, they are required to be acoplanar with the beams by at least 20°. Two classes of events in this sample are considered in the analysis: those with at least one γ which has converted in the material (0.05 radiation length) surrounding the beam intersection region, and those with at least one photon detected in the LGW.

To determine the γ inclusive spectrum, one needs a trigger efficiency and charged-particle acceptance correction which compensates for the loss of neutral events and events with less than two detected charged particles. The γ conversion events are used to measure this trigger efficiency and acceptance since the e^+e^- conversion pair provides the trigger. This gives us a sample of events with a γ and anything else, including all neutrals. The trigger efficiency times acceptance shown in Fig. 1 is just the fraction of this sample which would have triggered without the conversion pair. It is independent of $x_\gamma = p_\gamma/E_{beam}$ within our statistics, and has an average value of 37%.

Figure 2 shows the γ inclusive spectrum for γ's in the LGW corrected for a constant 37% trigger efficiency and acceptance as determined above, and for a shower detection efficiency and LGW acceptance correction based on the Monte Carlo shower development program EGS.[7] The

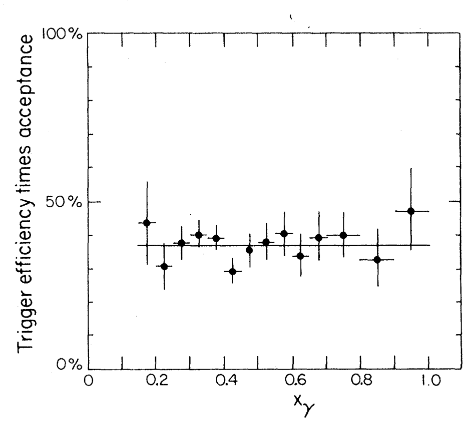

FIG. 1. Trigger efficiency times acceptance for two or more charged particles in the magnetic detector with a γ in the LGW vs x_γ $(=p_\gamma/E_{beam})$.

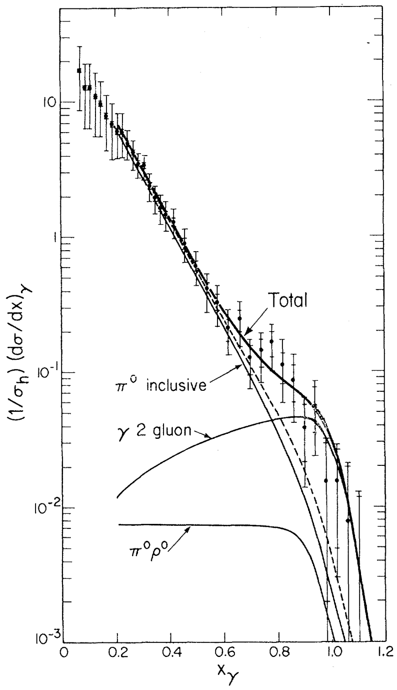

FIG. 2. Inclusive γ spectrum from ψ decay, normalized to the hadronic decays of the ψ. The dashed curve is the sum of the "π^0 inclusive" contribution scaled up by a factor of 1.12 and the "$\pi^0\rho^0$" contribution to the γ spectrum. The sum of the dashed curve and the "γ-two-gluon" spectrum, labeled "Total", is fitted to the data.

latter efficiency and acceptance is roughly a constant 4.4% above $x_\gamma = 0.2$ and decreases rapidly at lower x_γ. The inner error bars shown in Fig. 2 are statistical while the outer error bars include systematic errors added in quadrature. These systematic errors are obtained mainly from the statistical errors in the trigger efficiency of Fig. 1; also at low x_γ the systematic error in the efficiency of the LGW is significant.

Our analysis of π^0's is similar to that described in Ref. 6. For $\psi(3100)$ decays we find a clear π^0 signal in the $\gamma\gamma$ mass spectrum for $x_{\pi^0} < 0.25$, where $x_{\pi^0} = p_{\pi^0}/E_{\rm beam}$. The background under this signal, obtained by pairing uncorrelated γ's from separate events, ranges from ~45% of the total near $x_{\pi^0} = 0.3$ to ~20% near $x_{\pi^0} = 0.8$. The x_{π^0} distribution of the events remaining after background subtraction is shown in Fig. 3. Corrections are included for a trigger efficiency and charged-particle acceptance based on a statistical model Monte Carlo calculation for $\psi(3100)$ decays and for an LGW solid angle and π^0 detection efficiency similar to that of Ref. 6. Study of shower distributions of high-energy photons indicates that the loss of π^0's due to the two γ's coalescing is negligible. The outer error bars include a 17% systematic error added in quadrature.

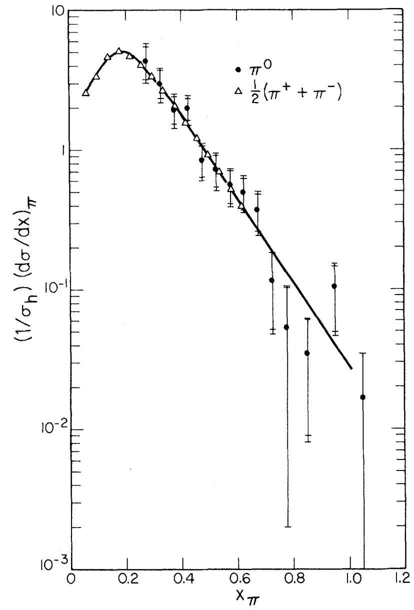

FIG. 3. Inclusive π spectra from ψ decay. The curve is fitted to the charged-π spectrum for $x < 0.65$ which is extrapolated to $x_\pi = 1$.

We compare the π^0 spectrum with the charged-particle spectrum measured in the same data sample. The charged-particle measurement is based on the spark-chamber system of the magnetic detector which has a resolution of $\Delta p/p \approx 0.013p$ (in GeV/c) over a solid angle of $0.60 \times 4\pi$ sr. A time-of-flight system with resolution of 0.35 nsec is used to obtain a statistical π-K separation up to 1.0 GeV/c ($x_\pi = 0.65$). We correct for trigger efficiency and acceptance with the same statistical model of $\psi(3100)$ decay used in the π^0 analysis. The measured $x_{\pi^\pm}$ distribution for π^+ or π^- production with $x_{\pi^\pm} < 0.65$ is shown in Fig. 3. Systematic errors of about 20% are not shown. We find that the π^0 and charged-π spectra agree in shape and that the ratio of π^0 to charged-π production is $N_{\pi^0}/(N_{\pi^+} + N_{\pi^-}) = 0.52 \pm 0.05$ (statistical) ± 0.07 (systematic) for $0.25 < x_\pi < 0.65$.

We now compare the observed γ spectrum of Fig. 2 with that expected from π^0 decay. This is done in two ways. For the first method we analytically calculate the γ spectrum using our measured π^0 spectrum. We find that π^0 decay accounts for about 90% of the observed γ's. The excess measured at low x_γ is within our systematic errors, while the excess for $x_\gamma > 0.6$ is above systematic errors and has a magnitude of $(3.4 \pm 0.8^{+1.4}_{-0.8})\%$ of all hadronic ψ decays, where the excess has been corrected for a $1+\cos^2\theta_\gamma$ angular distribution (this correction is 25% larger than for a flat angular distribution). The systematic error is mainly a 14% error in the measurement of the trigger efficiency of Fig. 1 for $x_\gamma > 0.6$ and a 30% uncertainty in the π^0 decay contribution.

The second method of calculating the π^0 decay contribution uses a fit to the charged-π spectrum to estimate the π^0 spectrum. The solid curve in Fig. 3 represents a hand fit to the measured $\pi^\pm$ data for $x_{\pi^\pm} < 0.40$, and an exponential fit to the six measured $\pi^\pm$ data points in the $0.40 < x_{\pi^\pm} < 0.65$ region, which is then extrapolated to $x_\pi = 1$. We extend the exponential fit to $x_\pi = 1$ since the charged-π spectrum has been measured[8] to be exponential with the superposition of a peak at $x_{\pi^\pm} \cong 0.94$ due to $\pi^\pm\rho^\mp$ decay. We find that the $\langle x_{\pi^0}\rangle = 0.95$ point in our π^0 data is higher than the exponential extrapolation and is consistent with the expected $\pi^0\rho^0$ effect. We use the shape determined from the charged-π data, solid curve in Fig. 3, with the absolute normalization determined by our π^0 measurement in a Monte Carlo calculation of the π^0 continuum contribution. The resulting γ spectrum is shown in Fig. 2 with the label "π^0 inclusive." The "$\pi^0\rho^0$" contribution to the γ spectrum is shown separately with its normalization determined by the measured[9] $\psi \to \pi\rho$ branching fraction $(1.1 \pm 0.2)\%$. Following this procedure, we find an excess of magnitude $(2.7 \pm 0.6^{+1.4}_{-0.8})\%$ for $x_\gamma > 0.6$ in agreement with the first method. We calculate that π^0 production a factor of about 4 above our measured π^0 distribution near $x_\pi = 1$ would be required to explain the measured excess at $x_\gamma \simeq 0.8$. This factor is nearly an order of magnitude larger than the error on our π^0 measurement in this region.

Production and decay of η's can contribute to the observed excess, but the process $\psi \to \eta +$ anything has not yet been measured. We find that an η/π^0 ratio of about 8 at $x \simeq 1$ would be required for the η to explain the measured excess at $x_\gamma \simeq 0.8$. This ratio is larger than the η/π^0 ratio of 0.1–1 observed in large-$p_\perp$ hadronic production of η's.[10] Monte Carlo studies show that if the η inclusive spectrum is similar to the π^0 spectrum, then the resulting γ spectrum would be similar to the "π^0 inclusive" spectrum of Fig. 2 for $x_\gamma > 0.2$. To allow for an η contribution in the second method of analysis we renormalize the "π^0 inclusive" curve upward. For example, the dashed curve in Fig. 2 represents a renormalization upward by a factor of 1.12 (as determined in a fit described below) with the "$\pi^0\rho^0$" contribution added to it. If we normalize by this factor, we find that an excess of magnitude $(2.4 \pm 0.5^{+1.5}_{-0.9})\%$ for $x_\gamma \geq 0.6$ remains.

To compare the excess with the QCD prediction we perform a maximum-likelihood fit to the data with the sum of the "π^0 inclusive" and "$\pi^0\rho^0$" spectra and a "γ–two-gluon" spectrum of the form given in Ref. 2 folded with an $8\%/\sqrt{E}$ resolution, shown in Fig. 2. The normalizations of the "π^0 inclusive" and "γ–two-gluon" spectra are the two free parameters of the fit while the "$\pi^0\rho^0$" spectrum normalization is fixed. The sum of these three spectra, labeled "Total" in Fig. 2, fits the data well. We show in Fig. 4 the γ spectrum at high x with the renormalized π^0 contribution (dashed curve of Fig. 2) subtracted. The errors shown are statistical only. The solid curve is the "γ–two-gluon" spectrum. If we correct for the low-x_γ part of the spectrum by using the "γ–two-gluon" spectrum from Ref. 2, we obtain $\Gamma(\psi \to \gamma + \text{two gluons})/\Gamma(\psi \to \text{hadrons}) = (3.5 \pm 0.7^{+2.3}_{-1.2})\%$. This is smaller than the 8.3% predicted by QCD for $\alpha_s = 0.2$ and could correspond to a higher strong coupling constant for $\psi(3100)$ decay.

The dashed curve in Fig. 4 is the expected γ distribution from the measured[11] exclusive processes $\psi \to \gamma\pi^0, \gamma\eta, \gamma\eta', \gamma f$. The contribution from

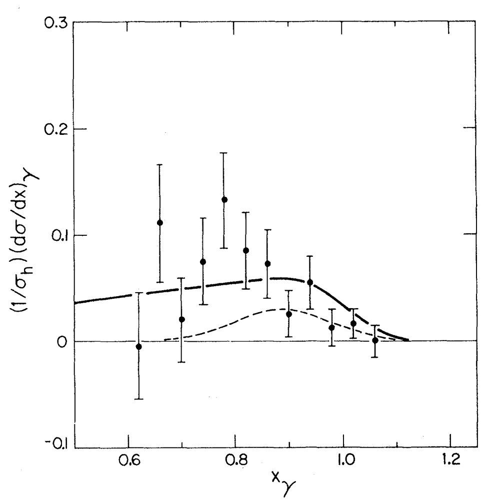

FIG. 4. Subtracted γ inclusive spectrum. Systematic errors, which vary in magnitude from 0.08 at $x_\gamma = 0.6$ to 0.02 at $x_\gamma = 1.0$, are not shown. Solid curve is the "γ–two-gluon" spectrum and the dashed is the sum of previously measured exclusive decays of the ψ into γ's (Ref. 11).

these decays accounts for about 25% of the observed excess. However, these final states (except for the $\gamma\pi^0$ which is small in any case[11]) could be produced via a γ plus two-gluon intermediate state.

In conclusion, we have measured inclusive γ and π^0 production in ψ decay. We find agreement between the π^0 spectrum and $\frac{1}{2}(\pi^+ + \pi^-)$ production. When the γ spectrum is compared with that expected from π^0 decay as determined from the measured π^0 spectrum, we observe an excess of high momentum ($x_\gamma > 0.6$) photons of magnitude $(3.4 \pm 0.8^{+1.4}_{-0.8})\%$ of all hadronic ψ decays. We have considered the η as a possible source of these excess γ's and have found that an excess remains after one renormalizes the π^0 contribution upward to allow for an η contribution which has the same shape as the π^0 decay contribution. The measured excess could be explained by the QCD decay of the $\psi(3100)$ into a γ and two gluons, or, in part, by previously measured exclusive decays.

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Note added.—We are aware of a recent measurement of γ production in $\psi(3100)$ decay (G. S. Abrams *et al.*, SLAC Report No. PUB-2415) which confirms the existence of an excess at high x_γ but disagrees with this experiment in the excess at intermediate x_γ (about 0.6).

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[1]T. Appelquist *et al.*, Phys. Rev. Lett. 34, 365 (1975); M. S. Chanowitz, Phys. Rev. D 12, 918 (1975); L. B. Okun and M. B. Voloshin, Institute of Theoretical and Experimental Physics Report No. ITEP-95, 1976 (unpublished).

[2]S. J. Brodsky *et al.*, Phys. Lett. 73B, 203 (1978).

[3]A. Barbaro-Galtieri, in Proceedings of the Fourteenth Rencontre de Moriond, March 1979 (to be published), obtains $\Gamma(\gamma\text{-two-gluons})/\Gamma(\text{hadrons}) = (0.0185 \pm 0.0013)/(\alpha_s + 0.0234)$.

[4]J.-E. Augustin *et al.*, Phys. Rev. Lett. 34, 233 (1975).

[5]A. Barbaro-Galtieri *et al.*, Phys. Rev. Lett. 39, 1058 (1977).

[6]D. L. Scharre *et al.*, Phys. Rev. Lett. 40, 74 (1978).

[7]R. L. Ford and W. R. Nelson, SLAC Report No. SLAC-210, 1978 (unpublished).

[8]W. Braunschweig *et al.*, Phys. Lett. 63B, 115 (1976).

[9]C. Bricman *et al.*, Phys. Lett. 75B i, 1 (1978).

[10]For example, G. J. Donaldson *et al.*, Phys. Rev. Lett. 40, 684 (1978).

[11]The ψ decay branching ratios for these final states are $B(\gamma\pi^0) = (7.3 \pm 4.7) \times 10^{-5}$, W. Braunschweig *et al.*, Phys. Lett. 67B, 243 (1977); $B(\gamma\eta) = (1.3 \pm 0.4) \times 10^{-3}$, W. Bartel *et al.*, Phys. Lett. 66B, 489 (1977); $B(\gamma\eta') = (2.4 \pm 0.7) \times 10^{-3}$, W. Bartel *et al.*, Phys. Lett. 64B, 483 (1976); $B(\gamma f) = (2.0 \pm 0.7) \times 10^{-3}$, G. Alexander *et al.*, Phys. Lett. 72B, 493 (1978).

Magnetic Properties of the Low-Lying Hadrons

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It is proposed that the effective magnetic moment of quarks in hadrons should have an anomalous moment contribution because of the magnetic coupling of the photon to three or more gluons. We estimate this nonperturbative effect phenomenologically and find strong evidence for it from the measured decay rates $V \to P + \gamma$ and the observed magnetic moments of baryons.

For several years analyses of the radiative decays of vector mesons have been plagued by their inability to explain in any simple way the anomalously large observed[1,2] value of the ratio

$$R = \frac{\Gamma(\omega \to \pi\gamma)}{\Gamma(\rho \to \pi\gamma)} = \frac{889 \pm 50\ \text{keV}}{63 \pm 8\ \text{keV}} = 14.1 \pm 2.0.$$

Except for small corrections due to phase-space differences and $\varphi - \omega$ mixing effects, simple quark-model ideas predict that this ratio is simply related to the magnetic moments of the u and d quarks (μ_u and μ_d) by the formula

$$R_{\text{th}} = (\mu_u - \mu_d)^2/(\mu_u + \mu_d)^2.$$

Applying the notion that the moments are proportional to the quark charges ($\mu_u/\mu_d = -2$) then