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918 (1975); L. B. Okun and M. B. Voloshin, Institute of Theoretical and Experimental Physics Report No. ITEP-95, 1976 (unpublished).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[7]R. L. Ford and W. R. Nelson, SLAC Report No. SLAC-210, 1978 (unpublished).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

TABLE I. Predicted versus experimental radiative decay widths. The errors in the two η' widths (marked with *) are large due to the large uncertainty in the total width of the η' (Ref. 5). Rather than fit these two rates, we have used $\Gamma(\eta'\to\rho\gamma)$ and $\Gamma(\eta'\to\rho\gamma)/\Gamma(\eta'\to\omega\gamma)$ which is more precisely measured, in making the fit shown.

Decay	Amplitude	Γ_{th} (keV)	Γ_{exp} (keV)[a]
$\omega\to\pi\gamma$	$(\lambda_u-\lambda_d)\cos\alpha$	861	889 ± 50
$\rho\to\pi\gamma$	$(\lambda_u+\lambda_d)$	67	63 ± 8[b]
$\varphi\to\pi\gamma$	$(\lambda_u-\lambda_d)\sin\alpha$	5.9	5.7 ± 2.0
$\omega\to\eta\gamma$	$(\lambda_u+\lambda_d)\sin\beta\cos\alpha+2\lambda_s\cos\beta\sin\alpha$	4.4	$3^{+2.5}_{-1.8}$[c]
$\rho\to\eta\gamma$	$(\lambda_u-\lambda_d)\sin\beta$	57	50 ± 13[c]
$\varphi\to\eta\gamma$	$-2\lambda_s\cos\beta\cos\alpha+(\lambda_u+\lambda_d)\sin\beta\sin\alpha$	57	55 ± 12[c]
$\eta'\to\omega\gamma$	$(\lambda_u+\lambda_d)\cos\beta\cos\alpha-2\lambda_s\sin\beta\sin\alpha$	8.7	9 ± 3*
$\eta'\to\rho\gamma$	$(\lambda_u-\lambda_d)\cos\beta$	108	89 ± 29*
$\varphi\to\eta'\gamma$	$2\lambda_s\sin\beta\cos\alpha+(\lambda_u+\lambda_d)\cos\beta\sin\alpha$	0.23	...
$K_*^{\,0}\to K^0\gamma$	$\lambda_s+\lambda_d$	139	75 ± 35
$K_*^{\,+}\to K^+\gamma$	$\lambda_s+\lambda_u$	96	<80

[a]Reference 1. [b]Reference 2. [c]Reference 6.

yields $R\approx9$ which is far from the experimental value (two or more standard deviations).

Numerous attempts[3,4] have been made to fit these and the other radiative decays in Table I by including various symmetry-breaking effects. They have not met with complete success because (1) in some of them[3] the photon coupling is restricted in one way or another,[7] and (2) others[4] were hampered by their inability to fit a particularly low experimental value of $\Gamma(\rho\to\pi\gamma)$ which has recently been revised upward.[2] In this paper we show that, in light of the latest data, an acceptable fit is possible if we allow the quark magnetic moments to be arbitrary ($\mu_s\neq\mu_d\neq-\frac{1}{2}\mu_u$); and we point out that such an effect is a natural consequence of quantum chromodynamic (QCD) corrections to the decay amplitudes. Since our conjecture should also apply to the baryon magnetic moments, we also show that a good fit to the baryon octet moments also requires $\mu_u/\mu_d\neq-2$. Finally, we end with some speculations about interesting possibilities for heavy-quark systems.

In Fig. 1(a) we show a typical lowest-order diagram contributing to $V\to P\gamma$ and in Fig. 1(b) we show the skeleton of a typical QCD correction diagram. For simplicity, an odd number ($\geqslant3$) of gluon lines connecting the inner loop with the external quark lines have been omitted from Fig. 1(b). It is clear that the sum of all such graphs contributes to the decay amplitude a nonzero amount[8] which may depend on the external hadron states. In the absence of a reliable way to calculate these QCD contributions[9] we treat them phenomenologically by assigning *effective* magnetic moments to the quarks. The important point to recognize about Fig. 1(b) is that since QCD is flavor independent, the photon coupling is the *same* for either external u or d quarks and probably not much changed for an external s quark. (The possibility of larger differences for the heavier c, b, and t quarks will be discussed later.) In this way, the relation $\mu_u/\mu_d=-2$ is broken.

To see how well this idea works in the most straightforward way we merley modify the simple SU(6) quark model by allowing the quarks to have arbitrary effective magnetic moments. An

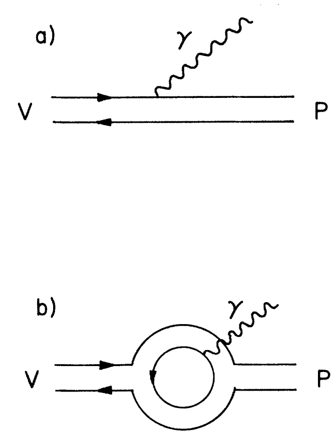

FIG. 1. (a) Typical lowest-order graph for $V\to P\gamma$; (b) skeleton of a typical QCD correction with gluon lines omitted for the sake of clarity.

easy way to calculate the resulting coupling is to write the interaction as

$$\mathrm{tr}P\{V,A\},$$

where P and V are the standard 3×3 SU(3) matrix representations for the pseudoscalar and the vector nonets, respectively. The photon matrix, A, is just a diagonal matrix with entries[10] $(\lambda_u,\lambda_d,\lambda_s)$. In addition we allow $\omega-\varphi$ mixing and $\eta-\eta'$ mixing (through angles which can be estimated using quadratic mass formulas). The results of fitting the decay widths (all except the K^* decays) by varying the quark moments and the mixing angles are shown in Table I. The angles α and β are related to the conventional mixing angles by $\beta=\delta-\theta$ and $\alpha=\varphi-\delta$, where φ is the conventional $\omega-\varphi$ mixing angle, θ is the conventional $\eta-\eta'$ angle, and $\delta=35.3°=\arcsin(1/\sqrt{3})$. For the fit shown $\theta=-10.3°$ and $\varphi=38.4°$, whereas quadratic mass formulas imply $\theta=-11\pm 1°$ and $\varphi=40\pm 1°$. Also, $\lambda_u=0.495$ GeV^{-1}, $\lambda_d=-0.275$ GeV^{-1}, and $\lambda_s=-0.145$ GeV^{-1}. Except for the K^* decays[2] the results are quite satisfactory. The poor fit to the strange-particle decay widths should perhaps not be surprising since we have included SU(6) breaking in the most minimal way (letting $\lambda_d\neq\lambda_s$); and we have not taken into account wave-function overlap and other effects. As an estimate of the magnitude of the QCD correction to the quark effective moments we note that the important ratio λ_u/λ_d is now equal to -1.80, which is reasonably close to -2.

As mentioned earlier, the anomalous magnetic-moment effect we have proposed for $V\to P\gamma$ should also contribute to the baryon magnetic moments. Since the size of the effect depends on the hadronic states in question, it is not clear how the effective moments for the radiative decays are related to the baryon moments. However, to the extent to which it is a good approximation to think of the quarks as having effective single-particle magnetic moments, we would expect the magnetic moments of the nucleon octet to reveal the presence of a flavor-independent anomalous moment with $\mu_u/\mu_d\sim-1.8$.

A recent measurement of the Ξ^0 magnetic moment[11]

$$\mu_{\Xi^0}=(-1.20\pm 0.06)\mu_N$$

gives us four well-determined baryon moments: μ_p, μ_n, μ_Λ, and μ_{Ξ^0}. Four other moments, μ_{Σ^+}, μ_{Σ^-}, $\mu_{\Sigma\Lambda}$, and μ_{Ξ^-}, are also known, but with large errors. The moment of the Σ^0 has not been measured but in almost any model $2\mu_{\Sigma^0}=\mu_{\Sigma^+}+\mu_{\Sigma^-}$. As is well known, the currently observed values of these moments cannot be fitted satisfactorily by a simple SU(6) quark model. When the effects of configuration mixing are included the fit is, if anything, worse as long as the ratio μ_u/μ_d is held fixed at -2. On the other hand, if we vary the u, d, and s moments freely, we find a very acceptable fit with

$$\mu_u/\mu_d\simeq-1.6,$$

a value close to the value $\lambda_u/\lambda_d=-1.80$ found for $V\to P\gamma$. In our best fit, the amount of non-$\underline{56}$ in the SU(6) wave functions is about 0.16 (16%). This value seems rather large[12]; however, the reader should once again bear in mind that we have included SU(3) breaking in a minimal way.

The value for the Σ^+ magnetic moment we used for the above fit was taken from the average computed by Bricman *et al.*[1] A new measurement for μ_{Σ^+} has just been reported,[13]

$$\mu_{\Sigma^+}=(2.30\pm 0.14)\mu_N,$$

which supercedes the earlier value obtained by this group. This will bring the average value for μ_{Σ^+} down very close to the new value. It is impossible to fit this new nunber with this simple scheme. To accomodate this new number we have modified our model by permitting different amounts of configuration mixing for each I-spin multiplet within the baryon octet. Again we found that it is impossible to find a satisfactory fit to the data *as long as we restrict* $\mu_u/\mu_d=-2$, despite the increased number of free parameters. Once we allow the moments to vary freely, we find an excellent fit provided, again, $\mu_u/\mu_d\simeq-1.6$. While a more complete treatment of the baryon system is required, we believe that the success of our simple approach constitutes supporting evidence for the existence of the anomalous moment effect we are proposing.

In conclusion we speculate about how this effect might appear in heavy-quark systems. We are intrigued by the fact that in QED the light-by-light scattering contribution to a fermion's anomalous magnetic moment increased rapidly when the fermion mass becomes much larger than the electron mass.[14] In our opinion it is probable that a similar result occurs for the anomalous moment considered in this paper so that we expect that it will become increasingly more important as the quark mass in the hadron increases. If the external quarks in Fig. 1 are massive while the quark in the loop of Fig. 1(b) is light then, intuitively, one would expect the anomalous (loop) term to become relatively more important since the light quark has a much larger magnetic moment. The effect, unfortunately, depends only on the $\ln(m/m_u)$ and the treatment of the bound states and coherent gluons is crucial, so that we cannot prove our conjecture.[15] Nevertheless, if we are correct, the consequences are interesting. Since the anomalous term is negative, if it is much more important for charmonium, it could appreciably cancel the "normal"-moment contribution. Thus, for example, the transition $\psi \to \eta_c \gamma$ would occur at a much smaller rate than that expected from simple bound-state models for ψ and η_c. A recent estimate of relativistic corrections to $M1$ transitions in charmonium by Kang and Sucher[16] finds a substantial reduction in this decay rate *provided* the confining potential transforms like a Lorentz *scalar*. The anomalous moment makes an *additional* correction that must be included. The situation can be clarified, however, by looking for the corresponding $M1$ transition in heavier-quark systems where relativistic corrections would be less important. For the heavier b quarks, the presumed constituents of the Υ, not only is the anomalous moment further enhanced, but the normal moment is reduced since the charge of the b quark is only half that of the charmed quark. Consequently, the anomalous term, which now *increases* the moment, would make transitions like $\Upsilon \to \eta_b \gamma$ much *larger* than predicted from the simple quark model.

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[1]Except where otherwise noted, all the experimental numbers cited in this paper come from C. Bricman *et al.*, Phys. Lett. 75B, 1 (1978). Note, however, that the value they report for the $\eta' \to \omega\gamma$ branching ratio is incorrect. The correct number is $\Gamma(\eta' \to \omega\gamma)/\Gamma(\eta' \to \text{all}) = (3.0 \pm 0.6)\%$. C. J. Zanfino *et al.*, Phys. Rev. Lett. 38, 930 (1977).

[2]The number quoted here for $\Gamma(\rho \to \pi\gamma)$ is the preliminary result of a high-energy Primakoff effect experiment performed by T. Jensen *et al.*, in Proceedings of the Conference on Lepton and Photon Interactions at High Energies, Fermilab, 1979 (to be published). In a recent paper [A. N. Kamal and G. L. Kane, Phys. Rev. Lett. 43, 551 (1979)], Kamal and Kane point out that if the original data of B. Gobbi *et al.* [Phys. Rev. Lett. 33, 1450 (1974), and 37, 1439 (1976)], which found $\Gamma(\rho \to \pi\gamma) = 35 \pm 10$ keV, is reanalyzed to include A_2 exchange, a value of $\Gamma(\rho \to \pi\gamma) = 66 \pm 8$ keV is likely. They also point out that A_2 exchange effects may considerably alter the analysis of the K^* radiative widths as well.

[3]B. J. Edwards and A. N. Kamal, Phys. Rev. Lett. 36, 241 (1976), and 39, 66 (1977); D. H. Boal, R. H. Graham, and J. W. Moffat, Phys. Rev. Lett. 36, 714 (1976).

[4]A. Grunberg and F. M. Renard, "SU(3), quark model, and VDM solutions for the radiative transitions problem," Universite des Sciences et Techniques du Languedoc Report, 1976 (to be published); A. Bohm and R. B. Teese, Phys. Rev. D 18, 330 (1978), and references therein; A. N. Kamal, Phys. Rev. D 18, 3512 (1978). These authors have previously investigated the effects of anomalous magnetic moment contributions.

[5]D. M. Binnie *et al.*, Phys. Lett. 83B, 141 (1979); G. S. Abrams *et al.*, Phys. Rev. Lett. 43, 477 (1979).

[6]D. E. Andrews *et al.*, Phys. Rev. Lett. 38, 198 (1977).

[7]Typical restrictions on the photon coupling include the requirement that $\mu_u = -2\mu_d$ or that the photon couple like an element of an SU(3) octet. Neither of these has any firm theoretical basis when applied to the *magnetic* coupling of the photon.

[8]Conventional wisdom would have us believe that the QCD corrections of Fig. 1(b) are dominated by graphs with low-mass quarks (u, d, s) in the loops. In the limit of SU(3), where $m_u = m_d = m_s$ these graphs would exactly cancel since the sum of the quark charges is vanishing. However, symmetry breaking prevents this cancellation and the sum of the graphs is not zero.

[9]The sixth-order perturbation-theory result for a free quark has the opposite sign from that required by our model [see J. Settles *et al.*, Phys. Rev. D 20, 2154 (1979)]. Coherent gluon effects are crucial, however. For example, a gluon string model for mesons yields a preliminary estimate which has the right sign and magnitude; H. Suura, private communication. See also, H. Suura, Phys. Rev. D 20, 1412 (1979).

[10]In fitting the radiative decays we use the parameters λ_u, λ_d, λ_s rather than μ_u, μ_d, μ_s, since, in general, bound-state effects will make them different.

[11]K. Heller, private communication.

[12]See, for example, N. Isgur, G. Karl, and R. Koniuk, Phys. Rev. Lett. 41, 1269 (1978).

[13]Settles *et al.*, Ref. 9.

[14]J. Aldins, S. J. Brodsky, A. J. Dufner, and T. Kinoshita, Phys. Rev. D 1, 2378 (1970).

[15]Estimates of the contribution of the quark *color* anomalous moment to the effective heavy-quark hyperfine interaction find that it is small for $q^2 \sim M^2$, M the quark mass. [See, for example, H. J. Schnitzer, Phys. Rev. D 19, 1566 (1979)]. Although the values estimated for the color anomalous moment increase

with decreasing q^2, they cannot be extended to the neighborhood of $q^2 = 0$, our region of interest.

[16]J. S. Kang and J. Sucher, Phys. Rev. D 18, 2698 (1978).

Sensitivity and the Role of Level Crossings in Measurements of Parity Nonconservation using Metastable Atoms

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The author points out that experiments to measure parity nonconservation in metastable atoms, such as hydrogen in the 2S state, are not, in general, made more sensitive by operating near level crossings in a magnetic field. New possibilities related to this observation are mentioned.

There are at present a considerable number of experiments under way to measure parity nonconservation (PNC) in atoms.[1-9] The prospect of measurements in hydrogenic atoms such as hydrogen, deuterium, and tritium, is particularly important because such experiments promise precise determinations of all the PNC, weak-neutral-current electron-nucleon coupling constants at low energy.[10] It has been widely held that in order to maximize the sensitivity of hydrogenic-atom experiments one should aim to work near a magnetic-field-induced $2s$-$2p$ level crossing where the s-p mixing due to the weak interaction is largest.[11] The purpose of this Letter is to point out that proximity to a level crossing is not at all a fundamental requirement. This observation opens up a number of essentially unexplored, new possibilities for experiments in metastable atoms.

All experiments presently under way to measure PNC effects in atoms involve resonant transitions from an initial atomic state to a final one.[1-9] The quantity measured in these experiments is always the result of interference between two transition amplitudes, one parity conserving and one not. In each case a PNC amplitude of the kind shown schematically in Fig. 1 is the one being studied. Here $H_{\rm PNC}$ is the PNC part of the weak-neutral-current Hamiltonian and ϵ is an oscillating electric field which resonantly drives the $E1$ transition. The PNC amplitude, $A_{\rm PNC}$, and some parity-conserving amplitude, $A_{\rm PC}$, both contribute to a resonance rate given by

$$N\eta|A_{\rm PC}+A_{\rm PNC}|^2 \simeq N\eta[|A_{\rm PC}|^2 \pm 2|A_{\rm PC}||A_{\rm PNC}|], \quad (1)$$

where N is the number of atoms per second available for resonance, η is the detection efficiency, and the $A_{\rm PNC}^2$ term has been neglected. The relative phase between $A_{\rm PC}$ and $A_{\rm PNC}$ has been chosen to maximize the interference term which the experiments measure.

First it is useful to discuss how one can characterize the sensitivity of experiments which measure an interference between $A_{\rm PNC}$ and $A_{\rm PC}$. The total detected rate is the resonance rate given in Eq. (1) plus a background rate. The signal to be detected is the change in this rate associated with a change in the relative sign between $A_{\rm PC}$ and $A_{\rm PNC}$. This signal, generally called the asymmetry, is given by

$$2N\eta|A_{\rm PC}||A_{\rm PNC}|. \quad (2)$$

The sensitivity of such an experiment is characterized by the size of the asymmetry relative both to the noise and to the systematic errors. We consider the noise first.

The noise at the detector in a 1-Hz bandwidth may be written as

$$(N\eta)^{1/2}|A_{\rm PC}| + \sigma(A_{\rm PC}) + \sigma', \quad (3)$$

where the first term is approximately the statistical noise in the resonance rate, the second term is all other noise related to $A_{\rm PC}$, and σ' is all

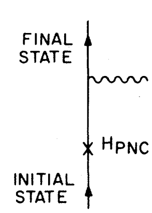

FIG. 1. The kind of transition amplitude presently being studied. $H_{\rm PNC}$ is the PNC weak-neutral-current interaction and ϵ is a resonant oscillating electric field.