Radiative and pionic decays of the D^* mesons and the magnetic moment of the charmed quark

Gerald A. Miller

Institute for Nuclear Theory, Department of Physics, FM-15, University of Washington, Seattle, Washington 98195

Paul Singer

Department of Physics, Technion—Israel Institute of Technology, Haifa, Israel
and Theory Division, CERN, Geneva, Switzerland*

(Received 2 September 1987)

The radiative and pionic decays of the D^* mesons are studied using a quark-bag model which includes effects of pion-exchange currents. We find that uncertainties in current experiments are large enough to allow a significant value of a possible charmed-quark anomalous magnetic moment. Therefore, improved experiments would be useful. Other consequences of an anomalous magnetic moment are the following. The ratio of hadrons to $\mu^+\mu^-$ pairs produced in e^+e^- annihilations should rise significantly as the center-of-mass energy increases from 40 GeV; the decay rate for $\psi J \rightarrow \eta_c + \gamma$ is reduced; and computed magnetic moments of charmed baryons are modified.

INTRODUCTION

It has been pointed out recently^{1,2} that the experimental data on the strong and electromagnetic decays of D^* mesons exhibit several puzzling features. These concern the ratio of the rates for $D^{*+} \rightarrow D^+ + \gamma$, $D^{*0} \rightarrow D^0 + \gamma$, the ratio of the rates for $D^{*+} \rightarrow D^0 + \pi^+$, $D^{*+} \rightarrow D^+ + \pi^0$, and the relative rates of the strong and electromagnetic decays. The published measurements on some of these decay modes, especially the $D^{*+} \rightarrow D^+ + \gamma$, have large uncertainties. Nevertheless, one cannot explain the problematic ratios with the existing theoretical treatments¹⁻⁶ for these decays.

We present a new analysis of the pionic and photonic decays of D^* , in which the cloudy bag model^{7,8} (hereafter CBM) is adapted to the description of heavy-quark-plus-light-quark systems. The present study establishes the boundaries within which these strong and electromagnetic decays can be understood on the basis of our approach, which includes also the possibility that the charmed quark has an anomalous magnetic moment. Such a moment may arise if the charmed quark is a composite object, an intriguing idea which has been occasionally entertained by various authors.

The use of the CBM allows us to incorporate the influence of the pionic decay channel on the hadronic wave function in a natural way. This effect, as well as the possibility of an anomalous magnetic moment for the c quark, has not been considered previously in the calculation¹⁻⁶ of D^* decays. The importance of the pionic contribution to the radiative decays of K^* mesons has been demonstrated recently.^{9,10}

On the basis of published results, the branching ratios for the D^{*+} decays are¹¹ $D^0\pi^+$, $(49 \pm 8)\%$; $D^+\pi^0$, $(34 \pm 7)\%$; and $D^+\gamma$, $(17 \pm 11)\%$. The ones for the D^{*0} are¹¹ $D^0\pi^0$, $(51.5 \pm 7.6)\%$ and $D^0\gamma$, $(48 \pm 7.6)\%$. Only upper limits for the total widths are known. These data

can be used to obtain¹ the ratio between charged and neutral radiative decays, taking D^{*+} and D^{*0} as an isospin doublet. Then

$$R_\gamma^{(\text{expt})} = \frac{\Gamma(D^{*+} \rightarrow D^+ \gamma)}{\Gamma(D^{*0} \rightarrow D^0 \gamma)} = 0.44 \pm 0.33. \quad (1)$$

The error displayed in Eq. (1) is so large that any theoretical value computed between zero and unity could be considered to be in agreement. In this paper we argue that the ratio R_γ is a very useful number which should be measured to higher accuracy. The point is that some very interesting speculations result from assuming that the central value of 0.44 is correct. These notions regarding the possible composite nature of the charmed quark could easily be ruled out (or possibly confirmed) with data of higher accuracy. In what follows we take the central value to be correct. Then Eq. (1) presents the most serious problem in the D^* decays. To illuminate this point, consider the simple quark model (SQM). The transition operator for the decay of the vector meson to a pseudoscalar meson and a photon of polarization ϵ and momentum $\mathbf{k}$ is given in terms of the quark's properties by

$$^{(\text{SQM})}\mu = \sum_i \frac{e_i}{2m_i} (\epsilon \times \mathbf{k}) \cdot \boldsymbol{\sigma}_i. \quad (2)$$

Then, assuming $m_d \simeq m_u = m$ for the light quarks, one has¹

$$^{(\text{SQM})}R_\gamma = \left[\frac{2m - m_c}{2(m + m_c)} \right]^2. \quad (3)$$

The value most often quoted in the literature for the expected ratio is $\frac{1}{16}$, but it does not seem to be generally realized that the two-branch feature of Eq. (3) causes this outcome for both the SU(4)-symmetry model¹² ($m = m_c$) as well as for the commonly accepted values $m = 340$ MeV, $m_c \simeq 1700$ MeV. Thus two extremely different

ideas about quark masses give similar, very small results for the ratio. The existing calculations^{1-4,6} give $R_\gamma \simeq \frac{1}{16} - \frac{1}{25}$. (An exception is Ref. 5, which neglects the contribution of the charmed quark for no stated reason.) Indeed a wide range of values $\frac{1}{13} \lesssim R_\gamma \lesssim \frac{1}{27}$, derived from allowing m_c to vary between 1.3 GeV and 2 GeV, would be theoretically acceptable. Introducing¹ SU(4)-symmetry breaking in various other ways, usually leads to R_γ smaller than $\frac{1}{16}$. It is true that R_γ can reach the value $\frac{1}{4}$ in the SQM. However, using $m=0$ in the SQM causes an infinite proton magnetic moment. Similarly, the charmed hadrons would have an infinite mass if $m_c = \infty$. Thus the unambiguous prediction of the SQM is that R_γ should be close to $\frac{1}{16}$.

The second puzzle in D^* decays is the ratio

$$R_{\pi}^{(\text{expt})} = \frac{\Gamma(D^{*+} \rightarrow D^0 \pi^+)}{\Gamma(D^{*+} \rightarrow D^+ \pi^0)} = 1.44 \pm 0.38, \quad (4)$$

which differs from the result obtained by using isospin symmetry and the experimental mass differences:¹¹

$$R_{\pi} = 2.17 \pm 0.26. \quad (5)$$

The third challenge of these decays is to explain the relative size of the radiative and strong decays, which experimentally is given by

$$R_{\pi\gamma}^{0(\text{expt})} = \frac{\Gamma(D^{*0} \rightarrow D^0 \gamma)}{\Gamma(D^{*0} \rightarrow D^0 \pi^0)} = 0.94 \pm 0.20. \quad (6)$$

Before proceeding to the presentation of our model, we would like to reemphasize that the datum for $D^{*+} \rightarrow D^+ \gamma$ is plagued with a large uncertainty. While for $(D^{*0} \rightarrow D_\gamma)/(D^{*0} \rightarrow D^0 \pi^0)$ there are three measurements which agree well with one another, the $D^{*+} \rightarrow D^+ + \gamma$ rate is deduced from only one experiment.¹³ In this Mark II experiment at the SLAC e^+e^- storage ring SPEAR, the $D^{*+} \rightarrow D^+ + \gamma$ is determined from the recoil mass-squared spectrum produced opposite a detected charged D^+ . There are, in fact, six different production processes which lead to D^{*+} s in the final state; and from the Monte Carlo fit to the distribution one determines the different contributions to it, including $D^{*+} \rightarrow D^+ + \gamma$ and $D^{*+} \rightarrow D^+ + \pi^0$. Originally, Coles *et al.*¹³ gave a branching ratio $B(D^{*+} \rightarrow D^+ + \gamma) = 0.22 \pm 0.12$, which would make Eq. (1) even "worse." However, when these data are combined¹¹ with the $B(D^{*+} \rightarrow D^+ + \pi^0)$ of Mark II, the fit we quote is obtained.

Since our analysis refers to data having large uncertainties, it should be mentioned at this point that a new set of data, presented as preliminary, has become available from the Mark III detector at SLAC (Ref. 14) as follows: the branching ratios for D^{*+} decays are found to be $D^0 \pi^+$, $(55 \pm 2 \pm 6)\%$; $D^+ \pi^0$, $(26 \pm 1 \pm 2)\%$; $D^+ \gamma$, $(19 \pm 3 \pm 8)\%$; and for D^{*0} decays one finds $D^0 \pi^0$, $(67 \pm 6 \pm 14)\%$ and $D^0 \gamma$, $(33 \pm 6 \pm 14)\%$. From these Mark III data one deduces $R_{\pi}^{(\text{expt})} = 0.99 \pm 0.72$, $R_{\pi}^{(\text{expt})} = 2.12 \pm 0.31$, and $R_{\pi\gamma}^{0(\text{expt})} = 0.49 \pm 0.25$. Since these new data are still unpublished we shall not use them in the analysis, but we remark with regard to the puzzles mentioned above that $R_{\pi}^{(\text{expt})}$ from Mark III fits the value ex-

pected from isospin symmetry of Eq. (5). On the other hand, the major problem of the R_γ ratio is confirmed by these new data. We shall return later to the significance of $R_{\pi\gamma}^{0(\text{expt})}$ from Mark III.

In the following we accept the central values of Eqs. (1) and (6). We then find that assuming that the c quark is a composite object with a nonzero anomalous magnetic moment (used in a variety of models) improves the agreement with data for R_γ and $M1$ decays of $c\bar{c}$ systems. Furthermore, other tests of our composite- c -quark hypothesis are suggested. The net result is the statement that it is important to improve the data.

THE MODEL

We now describe our CBM approach. In Refs. 9 and 10 (SM) we found that this model gives a very good account of the $M1$ radiative decays in the (u, d, s) sector. For the problem at hand, we modify the CBM by considering the heavy quark to be essentially at rest in the center of the spherical bag. The light quark moves relativistically in the color field^{4,5,15} of the heavy quark and is confined by the linear boundary condition of the MIT bag. The position of the heavy quark defines the center of mass.

The basic Lagrangian we use [Eq. (17) of SM] is that of the CBM with a pseudovector interaction between the light quarks and the pions throughout the hadronic volume,⁸ to which we add the isosinglet heavy quark which does not interact with the pion field and is practically at rest. The strength of the pion-quark coupling is the same as in SM.

The gluonic exchange between the heavy and the light quark is treated in the manner of Wilcox, Maxwell, and Milton,⁵ who employ a Coulomb-type potential $V(r) = -4\alpha_s/3r$, where α_s is the effective strong coupling constant. The light-quark wave function is obtained by solving the Dirac equation with the parameters $m=0$, $m_s=279$ MeV, and $\alpha_s=0.407$ determined by reproducing⁵ the spectrum of charmed mesons. The electromagnetic interaction is added to the Lagrangian via the usual minimal substitution, and the resulting current has a quark contribution and a pionic contribution [Eqs. (27)–(30) of Ref. 10 (SM)].

The matrix element M_{PV} for a radiative transition $V \rightarrow P\gamma$ is defined¹⁰ by

$$M_{PV} = -\frac{i}{\sqrt{3}}(\epsilon \times \mathbf{k})_{m_\gamma} \mu_{PV}, \quad (7)$$

where m_γ is a spherical vector component of the decaying particle. This leads to a decay width of

$$\Gamma_{V \rightarrow P\gamma} = \frac{e^2 \mu_{PV}^2 k^3}{9\pi}. \quad (8)$$

The effective transition moments μ_{PV} for the $D^* \rightarrow D_\gamma$ decays are given by

$$\mu_{D^+ D^0}^+ = -\frac{1}{\sqrt{3}}(\mu^D - 2\mu_c) - \mu^{\pi, D}, \quad (9)$$

$$\mu_{D^0 D^+}^0 = \frac{2}{\sqrt{3}}(\mu^D + \mu_c) + \mu^{\pi, D}. \quad (10)$$

TABLE I. Calculated radiative particle decay widths (keV) and the ratios R_γ , $R_{\pi\gamma}^0$ for various values of λ (Eq. 11).

λ	$\Gamma(D^{*+} \rightarrow D^+\gamma)$	$\Gamma(D^{*0} \rightarrow D^0\gamma)$	$\Gamma(D_s^{*+} \rightarrow D_s^+\gamma)$	$R_\gamma = \frac{\Gamma(D^{*+} \rightarrow D^+\gamma)}{\Gamma(D^{*0} \rightarrow D^0\gamma)}$	$R_{\pi\gamma}^0 = \frac{\Gamma(D^{*0} \rightarrow D^0\gamma)}{\Gamma(D^{*0} \rightarrow D^0\pi^0)}$	$R_{D_\gamma^+} = \frac{\Gamma(D^{*0} \rightarrow D^+\gamma)}{\Gamma(D^{*+} \rightarrow D_\pi)}$
-0.3	5.8	9.9	2.0	0.59	0.26	7.4×10^{-2}
-0.2	5.3	10.6	1.6	0.50	0.28	6.8×10^{-2}
0	4.3	12.2	1.1	0.35	0.32	5.5×10^{-2}
0.2	3.5	13.8	0.71	0.25	0.36	4.5×10^{-2}
0.3	3.1	14.6	0.55	0.21	0.38	4.0×10^{-2}
0.5	2.3	16.4	0.28	0.14	0.43	2.9×10^{-2}
0.7	1.7	18.2	0.10	0.093	0.48	2.2×10^{-2}
0.8	1.4	19.2	0.048	0.073	0.50	1.8×10^{-2}
1.0	1.0	21.2	1.2×10^{-4}	0.047	0.55	1.3×10^{-2}
1.2	0.58	23.3	0.039	0.025	0.61	7.4×10^{-3}
1.5	0.19	26.6	0.26	7.1×10^{-3}	0.70	2.4×10^{-3}

μ^D is the light-quark contribution and is computed from the matrix element of the quark electromagnetic current operator [Eq. (44) of SM, but using the light-quark wave function described above]. For the heavy quark we assume the value of the static limit, which we multiply by a factor λ to take into account the possibility that the heavy quarks have an anomalous magnetic moment. We use $m_c = 1500$ MeV in the definition

$$\mu_c = \lambda \frac{e}{2m_c}. \quad (11)$$

This introduces an asymmetry between the charmed

quark and the light u, d, s quarks, for which only quite small anomalous moments are allowed, see below. However, it is possible¹⁶ that the anomalous moment is proportional to the square of the quark mass. In any case, the lack of knowledge about the origins of the quark spectrum suggests that such a possibility should be tested experimentally.

In the CBM, a u or d quark can emit a pion, which can radiate a photon and be reabsorbed. Including this term is mandated by the fact that the D^* also decays by pion emission. This pionic contribution to the decay ($\mu^{\pi,D}$) is given by Eq. (52) of SM, but with the quantity R replaced by $0.652R$. The reduction is caused by the attractive $V(r)$ which pulls the light-quark wave function towards the origin.

The application of the above inputs yields $\mu_D = 0.164$ fm, $\mu_c = 0.0658\lambda$ fm, and $\mu_D^{\pi} = 0.0487$ fm, using an average bag radius of 0.83 fm (Ref. 5). These results are used to compute the widths which are presented in Table I for several values of λ . The function R_γ is plotted in Fig. 1(a).

The same Lagrangian is then used to calculate the rates for the $D^* \rightarrow D\pi$ decays. The volume pseudovector π - q interaction leads to widths¹⁷ that are about 27% smaller than those of Refs. 4 and 5 which employ a pseudoscalar coupling at the bag surface. Our results are $\Gamma(D^{*+} \rightarrow D^+\pi^0) = 24.6 \pm 3.0$ keV, $\Gamma(D^{*+} \rightarrow D^0\pi^+) = 53.3 \pm 2.0$ keV, and $\Gamma(D^{*0} \rightarrow D^0\pi^0) = 38.2 \pm 10.5$ keV. The uncertainties arise from mass measurements, which critically influence the small available phase space. These widths give the value of R_π anticipated in Eq. (5). We can only hope that improved measurements will converge toward this value as already evident from the Mark III data.¹⁴ Figure 1(b) shows our results for $R_{\pi\gamma}^0$.

DISCUSSION

Now turn to the interpretation of our results, and first examine the meaning of λ . We simply chose $\lambda=1$ for $m_c = 1.5$ GeV, but for λ close to 1, say between 0.85–1.15, the variation from unity merely allows for the uncertainty in the value of m_c . If such a range of values of λ were derivable from the data, R_γ would be in the

FIG. 1. (a) The calculated ratio R_γ of Eq. (3) vs the anomalous magnetic moment of the charmed quark, λ , Eq. (11). Solid line, with pionic term $\mu^{\pi,D}$. Dashed line, without pionic term. (b) The calculated ratio $R_{\pi\gamma}^0$ of Eq. (8) vs λ .

range $\frac{1}{12} - \frac{1}{25}$ and there would be no puzzle. However, $R_\gamma^{(\text{expt})} \simeq 0.45 \pm 0.35$. If improved experiments keep it in the range $\frac{1}{2} - \frac{1}{6}$, we see no other way out but to assume that the charmed quark has an anomalous magnetic moment. With a moment of $\frac{1}{5}$ of the normal one, a ratio as large as $R_\gamma \simeq 0.3$ is predicted from our calculation, if $\mu^{\pi,D}$ is included. Of course, given the large errors displayed in Fig. 1(a), one cannot claim that $\lambda \neq 1$. One can say, however, that $\lambda \neq 1$ is not ruled out.

On the other hand, using $\lambda \simeq 0.2$ leads to a value of ~ 0.36 for $\Gamma(D^{*0} \rightarrow D^0 \gamma) / \Gamma(D^{*0} \rightarrow D^0 \pi^0)$, while the experimental value recorded in Eq. (6) is close to unity. It seems that there is no overlapping range in λ in our calculation which can accommodate both $R_\gamma^{(\text{expt})}$ and $R_{\pi\gamma}^{(\text{expt})}$ of Eqs. (1) and (6) within one standard deviation. Note, however, that the value of $R_{\pi\gamma}^0 = 0.49 \pm 0.25$ from the new experiment¹⁴ fits well our calculation with $\lambda = 0.7$ for its central value and, because of the large error, is consistent with all the values of λ given in the table within one standard deviation.

In any case it is worth noting that this ratio of electromagnetic to strong decays is particularly prone to uncertainty. Simple dimensional analysis shows that the electromagnetic rate is roughly proportional to the square of the bag radius (R), while the strong rate goes like R^{-3} . Thus $R_{\pi\gamma}^0 \propto R^5$ and a 15% increase in R , which would not affect the spectroscopy and the ratio R_γ much, would increase $R_{\pi\gamma}^0$ by about a factor of 2. Thus, we judge that any difficulty in explaining $R_{\pi\gamma}^{(\text{expt})}$ is not very great, and our result even agrees with the new data¹⁴ on the electromagnetic rates.

Let us consider further the notion that λ is significantly less than unity. For example, one may examine the $M1$ decays of the ψ mesons. Although there are many radiative decay channels, only the decay $\psi(3097)$ to $\eta_c(2980)$ is relevant for our purpose.¹⁸ This, as measured recently,¹⁹ occurs at a rate of $(1.27 \pm 0.36)\%$. The partial decay width is 0.80 ± 0.25 keV. We apply the SQM to obtain $\mu_{\psi, \eta_c} = 4\mu_c / \sqrt{3}$. This, along with Eqs. (7) and (8) gives a predicted transition rate of $2.85\lambda^2$ keV. A value of $\lambda = 0.53 \pm 0.08$ is then required. The use of a measurement setting the η_c mass²⁰ equal to 2968 MeV would increase the width and reduce the central value of λ to 0.45. Using both Ref. 11 and this most recent measurement gives $\lambda = 0.53^{+0.08}_{-0.13}$. Thus employing an anomalous charmed-quark magnetic moment may solve a long-standing difficulty²¹ in understanding the $M1$ decay of the $\psi(3097)$.

Experimental measurements of the ratio (R) of cross sections for the production of hadrons to $\mu^+ \mu^-$ pairs in $e^+ e^-$ annihilation do provide significant constraints on quark anomalous magnetic moments.^{22,23} Our proposal is that only heavy quarks have such a property, and for now we ignore the effect of the b quark. Thus, we examine the charmed quarks' contribution (R_c) to R , which for center-of-mass energies (W) greater than about 10 GeV is $\frac{4}{3}\lambda^2$. Then, e.g., setting λ to $\frac{1}{2}$ causes a reduction in the computed value of R by 1, if the magnetic (G_m) and electric (G_e) form factors are set to unity. This does not seem to be consistent with the high-energy

($W \sim 30\text{--}40$ GeV) data¹¹ for which $R \sim 4$. However, one may use the systematic normalization errors of the cross section [between $\sim 5\%$ and 20% (Ref. 11)] to estimate an "allowable" change (δR) in R . The higher-energy data has smaller systematic errors, so we set δR less than or equal to ~ 0.6 at $W = 5$ GeV and less than or equal to 0.3 at $W = 40$ GeV. With these limits we find a lower limit on λ of about 0.87. However, composite objects with anomalous magnetic moments have a finite size. Thus we follow Söding and Wolf²² and use

$$G_m(s) = (1 - s/M^2)^{-2}. \quad (12)$$

so that $R_c = \frac{4}{3}\lambda^2 G_m^2$. In the spacelike region of momentum transfer relevant here, $G_m(s)$ is greater than unity and rises as s approaches M^2 from below. The singularity at $s = M^2$ is assumed to be associated with the production of a real particle [with a nonzero width ignored in Eq. (12)]. The use of Eq. (12), with its significant dependence on s , distinguishes a composite-particle effect from one of QCD. For example, Geffen and Wilson,²⁴ invoke the photon's coupling to a quark loop intersected by three or more gluons. However, the form factors of QCD do not have the singular behavior of Eq. (12). The net result is that a value of λ less than unity is partially compensated by the factor G_m . With this, λ can be as small as 0.8, if $M = 180$ GeV. Using these values, one may compute δR for $40 \text{ GeV} < W < 100 \text{ GeV}$. We find that R rises by about two units in this interval. This is a prediction²⁵ which could be testable at $e^+ e^-$ machines such as the KEK collider TRISTAN and the SLAC Linear Collider, which will operate at higher energies. (However the influence of the Z seems to be much larger than that of compositeness, unless the $\sqrt{s}$ is significantly greater than the Z mass.) The angular distribution for $c\bar{c}$ production in $e^+ e^-$ annihilation depends on the value of λ , but a large range is allowed by present data.²⁶ A value of λ as large as 0.8 can act as one of 0.7 in Eq. (11), if one uses 1.7 GeV instead of 1.5 GeV for m_c .

Let us consider further tests. The decay rate for the process $D_s^{*+} \rightarrow D_s^+ \gamma$ provides an opportunity. The effective transition moment for $D_s^{*+} \rightarrow D_s^+ \gamma$ is [see Eqs. (7)–(10)] $(1/\sqrt{3})(2\mu_c - \mu_s^D)$. We find $\mu_s^D = 0.133$ fm which is very close to the value of $2\mu_c$ with $\lambda = 1$. Thus the transition strength is very sensitive to the value of λ . A few typical values are given in Table I.

Still another application is to predict the magnetic moments of charmed baryons. There are two noteworthy cases obtained by considering charmed baryons in the ground-state multiplet. In the SQM (Ref. 27) (with $m = 340$ MeV, $m_c = 1700$ MeV) the magnetic moment of the $\Lambda_c^- (udc)$ is carried by the charmed quark, so using $\lambda = 0.7$ decreases the magnetic moment from 0.37 to 0.26 nm. The other case is the possible $\Xi^{++} (ucc)$ for which the moments of the charmed and up quarks would tend to cancel. The SQM value of the magnetic moment is only -0.122 nm, so using $\lambda = \frac{1}{2}$ weakens the cancellation and gives -0.270 nm. Of course the necessary experiments are difficult and one would have to verify the validity of the SQM for charmed baryons.

SUMMARY

The radiative and pionic decays of the D^* mesons have been analyzed. The existence of pionic decay modes demands the inclusion of pionic components in the wave function. The cloudy bag model, which is well constrained by many other data, has been used to supply the necessary pionic terms. These terms provide substantial effects, as shown in Fig. 1. Nevertheless our results are similar to those of many others: one cannot account for the data (using one standard deviation) without assuming an anomalous magnetic moment $\lambda < 1$ [Eq. (11)] for the c quark. Allowing two standard deviations in Fig. 1(a) would remove the problem. Our detailed calculations give the predictions of Table I, for many possible values of λ .

The use of an anomalous magnetic moment for the c quark allows us to "explain" R_γ [as presently known, Eq. (1)] and the rate for $\psi(3097) \rightarrow \eta_c \gamma$. It is remarkable that the anomalous-magnetic-moment hypothesis survives these two different tests.

At this point, we would like to add a few comments on our approach which led us to assume an anomalous magnetic moment for the c quark, resulting from a composite structure. As we already mentioned all previous "conventional" calculations³⁻⁶ of D^* decays predict an R_γ ratio which is smaller by an order of magnitude than the central value of Eq. (1). The cloudy-bag-model calculation presented here, which we believe to be more adequate and complete than previous attempts (and works very well in the s, d, u , sector¹⁰), does not improve on the above discrepancy if the c quark has no anomalous moment.

What else can be done? One might hope that QCD corrections to the vertex will give rise to an effective anomalous moment of the required size. However, these corrections are expected to be of magnitude α_s/π from lowest-order diagrams and this is not sufficient for the required effect. In fact, such corrections to the bag model have been calculated explicitly by Ushio²⁸ for the anomalous magnetic moments of the octet of baryons and shown to contribute generally only a few percent, and for some specific states up to about 10%. This is in agree-

ment with the QCD vertex corrections to the semileptonic decay of the c quark, which is also approximately 10% (Ref. 29).

At this point, we turn to the possibility of a composite structure for the c quark, which could be the source of an anomalous magnetic moment. Although the characteristic scale of compositeness was taken here, as limited by experiment,²² to be a few hundred GeV, it is possible that this will cause substantial anomalous magnetic moments of the heavy quarks, as emphasized, e.g., in Ref. 26 (see also Ref. 30 for further discussion of this point). Accordingly we assume Eqs. (11) and (12) as a working hypothesis, which has the consequences presented in the paper and, as we have shown, may be tested experimentally. Needless to say, the question of a detailed model for composite quarks and its various additional implications is beyond the scope of this article.

It should be mentioned that the possibility of an anomalous magnetic moment of the charmed quark has been considered also in connection with the angular distribution of heavy-fermion pair production in e^+e^- annihilation,²⁶ as well as for the $E1$ radiative transitions in charmonium.³¹ No conclusive evidence is obtainable at present, the data for these processes being compatible with nonvanishing anomalous moments, but not requiring it.

We conclude by joining others^{1,2} in making a call for further experimental investigation. Precise experimental values of the D^* widths, $M1$ decay rates of the ψ , and R could determine whether or not the charmed quark is a composite object.

ACKNOWLEDGMENTS

P.S. acknowledges the hospitality of the Institute for Nuclear Theory at the University of Washington during his stay and the hospitality of the Theory Division at CERN. We acknowledge stimulating discussions with D.B. Lichtenberg, R.D. Carlitz, G. Eilam, E.M. Henley, H. Harari, L.S. Kisslinger, T. Rizzo, and A.W. Thomas. This work was supported in part by the M. Lutin Fund, the Fund for Promotion of Research at the Technion, and the U.S. Department of Energy.

*Permanent address.

¹R. L. Thews and A. N. Kamal, Phys. Rev. D **32**, 810 (1985).

²J. Rosner, Comments Nucl. Part. Phys. **16**, 109 (1986).

³S. Ono, Phys. Rev. Lett. **37**, 655 (1976); R. H. Hackman *et al.*, Phys. Rev. D **18**, 2537 (1978); E. Eichten *et al.*, *ibid.* **21**, 203 (1980); N. Barik and S. N. Jena, Phys. Lett. **101B**, 282 (1981).

⁴D. Izatt, C. DeTar, and M. Stephenson, Nucl. Phys. **B199**, 269 (1982).

⁵W. Wilcox, O. V. Maxwell, and K. A. Milton, Phys. Rev. D **31**, 1081 (1985).

⁶S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985). This work contains a detailed treatment of configuration mixing and relativistic effects.

⁷S. Thberge, A. W. Thomas, and G. A. Miller, Phys. Rev. D **22**, 2838 (1980); **23**, 2106(E) (1981); A. W. Thomas, S. Thberge, and G. A. Miller, *ibid.* **24**, 216 (1981); S. Thberge

and A. W. Thomas, Nucl. Phys. **A393**, 252 (1983).

⁸A. W. Thomas, J. Phys. G **7**, L283 (1981); M. A. Morgan, G. A. Miller, and A. W. Thomas, Phys. Rev. D **33**, 817 (1986).

⁹G. A. Miller and P. Singer, Phys. Lett. **154B**, 75 (1985).

¹⁰P. Singer and G. A. Miller, Phys. Rev. D **33**, 141 (1986).

¹¹Particle Data Group, M. Aguilar-Benitez *et al.*, Phys. Lett. **170B**, 1 (1986).

¹²A. Kazi, G. Kramer, and D. H. Schiller, Acta Phys. Austriaca **45**, 195 (1976).

¹³M. W. Coles *et al.*, Phys. Rev. D **26**, 2190 (1982).

¹⁴D. Hitlin, talk at 1987 International Symposium on Lepton and Photon Interactions at High Energies, Hamburg, 1987 (unpublished).

¹⁵E. V. Shuryak, Phys. Lett. **93B**, 134 (1980).

¹⁶S. J. Brodsky and S. D. Drell, Phys. Rev. D **22**, 2236 (1980).

¹⁷We computed pionic decay widths of the K^* mesons in G. A.

- Miller and P. Singer, Phys. Lett. **130B**, 98 (1983). There is an error in that paper, the term $\alpha_0^{K^*K}$ correctly equals $\sqrt{3}/2$ giving $\bar{f}^{K^*K}=4.4$.
- ¹⁸The only other *observed* decay of possible relevance is $\psi(3685) \rightarrow \eta_c \gamma$. However, this is a hindered $M1$ transition and computing the rate involves more assumptions.
- ¹⁹J. E. Gaiser *et al.*, Phys. Rev. D **34**, 711 (1986).
- ²⁰D. Bisello *et al.*, Phys. Lett. B **179**, 289 (1986).
- ²¹R. McClary and N. Byers, Phys. Rev. D **28**, 1692 (1983), have suggested using an anomalous moment for the transition $\psi(3097) \rightarrow \eta_c \gamma$. Note that in Ref. 6 the computed rate for this transition is too large (and $R_\gamma = \frac{1}{25}$), in contrast with their excellent results for (u, d, s) transitions. Multiplying the amplitude of Ref. 6 by $\lambda=0.50$ leads to excellent agreement for the ψ decay and improves the ratio R_γ . The anomalous moment also enters in the rate for $\psi \rightarrow e^+ e^-$. For relative s states one multiplies the expression by $(2\lambda^2 + 1)/3$. Including this in Ref. 6 leads to excellent agreement with experiment for such states. However, this rate seems difficult to evaluate, so the good agreement obtained here could be model dependent. See also K. Königsman, Phys. Rep. **139**, 243 (1986) and G. Hulth and H. Snellman, Phys. Rev. D **24**, 2978 (1981).
- ²²P. Söding and G. Wolf, Annu. Rev. Nuc. Part. Sci. **31**, 231 (1981).
- ²³D. J. Silverman and G. L. Shaw, Phys. Rev. D **27**, 1196 (1983), parametrize the annihilation cross section in terms of constants F_1 and F_2 and find that λ is close to unity. However, F_1, F_2 could have momentum dependence making their formulas equivalent to those of Ref. 22 and therefore allowing the effects we compute.
- ²⁴D. A. Geffen and W. Wilson, Phys. Rev. Lett. **44**, 370 (1980).
- ²⁵Note that Eq. (12) is somewhat arbitrary. One could replace the exponent -2 by $-n$, change M to $\sqrt{n}/2M$, and not influence δR for $W < 40$ GeV. The use of a larger mass decreases δR at higher energies: $\delta R(100 \text{ GeV}) = 1.7$, if $n = 5$.
- ²⁶G. Domokos *et al.*, Phys. Rev. D **32**, 247 (1985).
- ²⁷J. Franklin, D. B. Lichtenberg, W. Namgung, and D. Carydas, Phys. Rev. D **24**, 2910 (1981); S. N. Jena and D. P. Rath, *ibid.* **34**, 196 (1986).
- ²⁸K. Ushio, Phys. Lett. **158B**, 71 (1985).
- ²⁹See, e.g., R. Rueckl, CERN report, 1983 (unpublished).
- ³⁰V. Visnic-Triantafyllou, Phys. Lett. **95B**, 47 (1980); G. L. Shaw, D. Silverman, and R. Slansky, *ibid.* **94B**, 57 (1980); S. Kovesi-Domokos and G. Domokos, *ibid.* **103B**, 229 (1981).
- ³¹S. Godfrey, G. Karl, and P. J. O'Donnell, Z. Phys. C **31**, 77 (1986).