HARNESSING THE POWER OF CHIRAL PERTURBATION THEORY

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I have enjoyed noticing the puzzled looks around the conference this week as some participants carefully labelled themselves High Energy Physicists, taking some offense if they are called Nuclear Physicists, and *vice versa*. This is partly a trivial issue associated with US funding sources, but it also reflects some very deeply-held feelings about Quantum Chromodynamics (QCD): a High Energy Physicist finds the strong interactions a nuisance and is studying QCD to be able to eliminate them, while a Nuclear Physicist believes that the nature and origin of the strong interactions is one of the most important unsolved problems in the Standard Model and studies QCD to be able to explain them.

These "two cultures" are both present at this meeting. The prototypical High Energy Physicist might, for example, be trying to calculate the matrix elements for ϵ'/ϵ with the laudable goal of testing whether the Standard Model can indeed explain CP violation. On the other hand a Nuclear Physicist might be trying to calculate the superficially similar ratio of the rates for $K \rightarrow 2\pi$ via the $\Delta I = 1/2$ and $3/2$ channels for the light it might shed on the mesonic-analogs of the nucleon-nucleon weak forces.

I am highly prejudiced about the "proper" use of chiral perturbation theory (χPT) today. Of course we had to spend several decades understanding its techniques, and we are well-justified in continuing to probe its range of validity, but as a Nuclear Theorist I am ready for χPT to stop being so introspective and to instead begin to answer some questions for me about how the strong interactions *work*. In making this complaint I am inevitably reminded of a weekend when I was assigned to chauffeur the Feynman family on a camping trip in the beautiful desert park called Joshua Tree National Monument east of the Sierra Nevada Mountains, about a half-day's drive from Caltech. As a kid from the Texas countryside I had been driving since I was 14 years old, while as a New Yorker Feynman's driving experience was less complete. As a result, he had spent some time during the drive asking me questions about how cars worked (certainly more profitable than his initial attempt to discuss with a sophomore physics student how renormalization theory really worked). So it was natural when we pulled in for gas that he asked me how the automatic gasoline dispenser worked. I didn't know. However, when he

ventured a hypothesis, I could see that it was flawed and I explained why. Feynman instantly agreed which gave me the courage to propose a variant of his theory. He shot that idea down in a few seconds, just as the 1965 California surfer-type passed him the bill for the gas. Feynman held on tight to the \$10 he was handing back while he posed the question to our gas jockey. As he did so, a look of utter dismay filled our surfer's sunburned face: surely this was the stupidest man on earth he thought as he replied: "...well, you pull the trigger, see, and when the tank fills up it shuts off". It all depends on what you mean by understanding something.

In our case the question is not whether QCD is right. It's also not very interesting to study the radii of convergence of the χPT expansions. χPT has to be correct inside its radius of convergence, it's value is in summarizing a lot of physics in a few low energy constants. The question for us today has become why does the automatic dispenser shut off: what's going on at a deeper level and can we understand it in simple terms.

Let me give an example of a question that seems enormously interesting to me. I'm used to looking at hadrons from the perspective of a quark modeler and an applier of heavy quark symmetry. I.e., I look at hadrons as Zweig did originally: "atomic systems made literally of quark constituents, and group quarks in $SU(N_h)$ heavy quark flavor multiplets with $m \gg \Lambda_{QCD}$. In χPT one naturally starts with the approximation $m \ll \Lambda_{QCD}$ and groups quarks in light quark flavor $SU(N_l)$ multiplets like (u, d, s) . What is *very peculiar* is that the spectra of these systems don't seem to care, at least qualitatively, to which type of family they belong.

Consider first Figure 1, which shows some of what we know about the spectra of mesons with the *valence structure* $\bar{Q}q$ for $q = u, d$ (a light quark), and $\bar{Q} = \bar{b}, \bar{c}, \bar{s}$, and $\bar{q}$. Shown are states where the light degrees of freedom are carrying spin-parity $s_l^{\pi_l} = \frac{1}{2}^+$ or $\frac{3}{2}^-$, corresponding to the ground state multiplet with $J^P = (0^-, 1^-)$ and an excited state multiplet with $J^P = (1^+, 2^+)$. One notes immediately the remarkable qualitative adherence of these spectra to the rigorously required systematics of the heavy quark limit, even for $\bar{Q} = \bar{s}$ and $\bar{Q} = \bar{q}$ where they are not required to do so. In that limit

1. The splittings between the $s_l^{\pi_l} = \frac{3}{2}^-$ and the $s_l^{\pi_l} = \frac{1}{2}^+$ multiplets are approximately independent of m_Q .
2. The splittings within the ground state multiplet are rigorously controlled by the hyperfine interaction of the heavy quark and therefore vary like $1/m_Q$. Standard constituent quark masses ($m_d = m_u \equiv m_q = 0.33$ GeV, $m_s = 0.55$ GeV, $m_c = 1.82$ GeV, and $m_b = 5.20$ GeV) give a good description of this observed m_Q -dependence.

3. The splitting inside the excited state multiplet with $s_l^{\pi\ell} = \frac{3}{2}^+$ should also vary like $1/m_Q$.
4. There is a second 1^+ state expected in the mass region of the $s_l^{\pi\ell} = \frac{3}{2}^+$ multiplet. It is part of an $s_l^{\pi\ell} = \frac{1}{2}^-$ multiplet with $J^P = (0^+, 1^+)$ predicted by dynamical models. (In an $L - S$ basis, the two 1^+ states correspond to atomic 3P_1 and 1P_1 states.) In the kaonic sector, all four of these state are known, and analysis of their decay modes shows that the two eigenstates $K_1(1280)$ and $K_1(1420)$ are almost pure $s_l^{\pi\ell} = \frac{3}{2}^+$ and $s_l^{\pi\ell} = \frac{1}{2}^+$ states, respectively. *I.e.*, in this case the presumed light $\bar{s}$ quark is behaving just as a heavy quark is supposed to behave.
5. The coupling constants for the decays of corresponding states of $\bar{Q}q$ and $\bar{Q}'q$ spectra should be equal. *E.g.*, the coupling constants for $D_2^* \rightarrow D\pi$ and $D_2^* \rightarrow D^*\pi$ should be equal to those for $K_2^* \rightarrow K\pi$ and $K_2^* \rightarrow K^*\pi$, respectively, if both $\bar{c}$ and $\bar{s}$ were heavy quarks; these coupling constants are in fact equal to within about 20% even though the $\bar{s}$ is light.

What is the physics behind this remarkable heavy-quark-like behaviour of even the chiral quarks? Consider the extreme case of $m_Q \rightarrow \infty$ where the $\bar{Q}q$ problem simplifies to the problem of a valence light quark (more precisely, of "brown muck" with q quantum numbers) in the static fields generated by the fixed source $\bar{Q}$. Perhaps this system is characterized by the formation of a flux tube confining q to the origin and by spontaneous chiral symmetry breaking ($s\chi SB$) which gives the essentially massless quark an effective mass m_c^{const} . *I.e.*, these systems operate in the true (nonperturbative) QCD vacuum and not one that is near to the perturbative vacuum. In such circumstances, one can rather easily imagine how the remarkable systematics of Figure 1 arise. For a heavy quark like the charm quark, $s\chi SB$ is nearly irrelevant to its effective mass m_c^{const} in the true vacuum; in contrast, the fact that it is confined by a flux tube to q is critical to the behaviour of $\bar{c}q$ systems. As one passes from $\bar{Q}$ to $\bar{b}$ to $\bar{c}$ to $\bar{s}$ to $\bar{q}$, the relevance of confinement to the spectrum appears as a slowly evolving function of the $\bar{Q}q$ reduced mass, but $s\chi SB$ becomes more and more critical for light quarks, leaving $\bar{q}$ with a substantial effective mass. Thus, vacuum structure has made the difference between the behaviour of $\bar{Q}q$, $\bar{b}q$, $\bar{c}q$, $\bar{s}q$, and (nonsinglet) $\bar{q}q$ systems depend on the value of a parameter, $1/m_i^{const}$, which does not vary over a large range compared to $1/\Lambda_{QCD}$.

Of course it would not be impossible for QCD to exhibit qualitatively different behaviour for the various values of m_i^{const} relevant to Fig. 1, but the option of "no phase transition" is certainly *a priori* a plausible one. (Needless

Figure 1. Heavy-light mesons with $s_l^{\pi\ell} = \frac{1}{2}^+$ and $\frac{3}{2}^-$ as a function of the mass m_Q of the heavy quark. The relative splittings of the $\bar{Q}d$ states are shown to scale with the center-of-gravity of the ground state multiplets aligned for valence $\bar{b}d$, $\bar{c}d$, $\bar{s}d$, and $\bar{u}d$ systems. $\bar{B}^*$ and $\bar{B}$ are the $J^P = 1^-$ and 0^- "ground state" multiplet with light-degrees-of-freedom spin-parity $s_l^{\pi\ell} = \frac{1}{2}^+$, while $\bar{B}_2^*$ and $\bar{B}_1^*$ with $J^P = 2^+$ and 1^+ are an excited heavy quark spin multiplet with $s_l^{\pi\ell} = \frac{3}{2}^-$.

to say, in view of the data, the "no phase transition" option becomes much more than a logical possibility!) In contrast, if $m = 0$ were an option (*e.g.*, in a world without $s\chi SB$), qualitatively different behaviours in the limits $m \rightarrow \infty$ and $m \rightarrow 0$ would be completely plausible, and perhaps even to be expected.

Figure 2 shows some of what we know about the evolution of quarkonium spectroscopy as a function of the quark mass for $b\bar{b}$, $c\bar{c}$, $s\bar{s}$, $s\bar{q}$, and $q\bar{q}$. The diagram displays the 0^{--} , 1^{--} , 2^{++} , and 3^{--} states of each sector. Once again the simplest explanation for the persistence of quark-model-like quarkonium behaviour to light quark systems is that $s\chi SB$ has in fact made light quarks into sufficiently massive quarks that all of these systems behave similarly at

Figure 2. The $Q\bar{Q}$ states from the heaviest to the lightest: $b\bar{b}$, $c\bar{c}$, $s\bar{s}$, $d\bar{d}$, and $u\bar{u}$. Shown are the states in each sector with $J^{PC} = 0^-, 1^-, 2^+$ and 3^- ; relative splittings are shown to scale with the center-of-gravity of the "ground states" 0^- and 1^- of each sector aligned.

low energy.

Of course the key puzzle this qualitative picture leaves unanswered is why $m_\pi = 0$. However, the venerable Nambu- Jona-Lasinio model gives us insight into how this peculiar circumstance arises: the massless quark develops a constituent mass m^{const} (its effective mass for propagating through the vacuum), but at the same time it develops residual interactions which force $m_\pi = 0$ but leaves $m_\rho \simeq 2m^{const}$.

The relation of constituent and current quarks is an old and ambitious one, but there are many much more modest questions χPT can answer for us. I hope the next conference in this Series will focus on these questions, especially those relevant to the pion content of the nucleon as measured in various (scalar, vector, ...) channels, and the contribution of the "pion cloud" to various elementary observables of the nucleon.