Physics 8805: Nuclear Few- and Many-Body Physics
Discussion questions and exercises for QCD 1

[Last revised on August 27, 2014 at 09:00:32.]

Overview of exercises and discussion questions. The problems here range from basic (and generally quick) to quite sophisticated (quick and not so quick) and are organized according to the lecture schedule. Comments on the pedagogy:

- The underlying philosophy is that students learn most effectively when they actively fill in details of arguments or explicitly address conceptual questions. Some of the problems here are designed to lead the student to go back over particular lecture material to make sure it is understood while others extend the lectures and still others introduce new topics.

- Given that students have limited time to spend on these exercises, we do not attempt to develop the type of problem-solving skills that require students to struggle over problems. Rather, we point the way rather explicitly and let the student fill in details. That way they can actually can work through multiple problems in the time before the next lectures. To further aid this process we will often have a sequence of hints that can be revealed to those who are stuck on an exercise.

- It is essential to try the exercises and to ask questions incessantly. Not everyone will be prepared to do all of the exercises completely, but with help from your classmates, other participants, and the instructor everyone can take away the essential points. If you are unsure of what a word or phrase means in some context or what a symbol stands for, please ask during the lectures (or at least afterwards)!

- Because most of the problems are still new, they have mostly not been tested for how long they will take to complete. We will make adjustments as we proceed through the course to make sure it is possible to finish the most relevant exercises in a timely manner. (So you won't have to complete them all.) Suggestions for new or improved problems are always welcome.

- The exercises are divided into categories (sometimes implicitly) according to the type of problem. We have followed the lead of the "Six Ideas that Shaped Physics" texts by Thomas Moore, which has: conceptual discussion questions (which should be discussed with others, including instructors), two-minute questions (if the material was understood, an answer is possible in a couple of minutes), basic skills problems, synthetic problems (putting skills together), rich context (real-life problems), and advanced problems (for those who already have additional background or problems that might take a long time).

- We will attempt to accumulate answers collectively. More on this as we proceed!

QCD 1

1. Two-minute exercises and discussion questions on QCD 1.

   (a) Why in quantum mechanics does it seem that we can just specify a Hamiltonian (e.g., the Coulomb potential) and start calculating observables, while for QCD (and other field theories) we not only have to specify the Lagrangian, we have to specify a regularization and renormalization scale and scheme before we can get answers?

   (b) Spot the Error: There are two types of electric charge: $+$ and $-$, and three types of color charge: red, green, and blue.

   (c) With respect to what scale(s) are the c, b, t quarks called heavy?

   (d) Have you heard about the s quark before? If yes, in what context?

   (e) A possible way to "see" quarks and gluons is in jets. What happens in these events?

   (f) Does the QED coupling $\alpha_{\text{QED}} = e^2/4\pi$ run with Q like α_s does? If so, why do atomic and condensed matter physicists always use $1/137.035$?

   (g) If you and your friend each do a QCD calculation with the same diagrams but use α_s at different scales, will you get the same answer? If not, how could that happen?

   (h) Does the running coupling in QCD mean that the QCD Hamiltonian is not unique? Would you say that if you used α_s at two different scales that you were using two different Hamiltonians?

   (i) Using the Particle Data Group website `http://pdg.lbl.gov/`, discuss which properties of the neutron and proton are similar and identify differences. What about for the three pions?

   (j) Explore some other hadrons using the Particle Data Group website. Which fit into the picture of hadrons from the QCD 1 and which don't?

   (k) Which is more important in making a neutron more massive than a proton: the light quark mass difference or the electromagnetic contribution? Or do you think such considerations are too simplistic?

   (l) What is the evidence for *spontaneous* chiral symmetry breaking in
       i. the mass spectrum of pseudoscalar ($J^{\pi} = 0^-$) mesons;
       ii. the mass spectrum of vector and axial vector ($J^{\pi} = 1^{\mp}$) mesons?

   (m) What is the evidence for *explicit* chiral symmetry breaking in the spectrum of pseudoscalar ($J^{\pi} = 0^-$) mesons?

   (n) When must the pion be considered a light particle and when can it be treated as a heavy particle?

   (o) If the neutron lifetime is so short, why are there *any* stable nuclei?

(p) One observes a marked resonance when a π^+ pion is scattering off a proton. Which baryon does this correspond to and at which energy of the π^+ does this occur (the proton is at rest)?

(q) At sufficient energy in proton-proton collisions it is possible to create a pion, $p + p \rightarrow p + n + \pi^+$. At which energy in the center-of-mass frame does pion production start?

2. Two-minute exercises on units plus one rich-context problem using dimensional analysis.

(a) We typically use units in which $\hbar = c = 1$ and express quantities as powers of MeV or fm or both, using $\hbar c \approx 197.33$ MeV–fm to convert between them. If we take for the nucleon mass $M_N = 939$ MeV/c^2, what is $\hbar^2/M_N$ numerically in terms of MeV and fm? [Hint: This should be almost immediate if you insert the right factors of c.]

(b) For the scattering of equal mass (nonrelativistic) particles, if the laboratory energy E_{lab} is related to the magnitude of the relative momentum k_{rel} (i.e., the momentum each particle has in the center-of-mass frame) by $E_{\text{lab}} = C k_{\text{rel}}^2$, what is C? If the mass is $M_N = 939$ MeV, what is the value of C in MeV–fm^2?

(c) [From N. Goldenfeld.] Use dimensional analysis to estimate the phase speed v of waves on shallow water of height h neglecting surface tension and viscous effect. Consider waves with long wavelength $\lambda \gg h$.