Physics 218. Advanced Quantum Field Theory. Professor Michael Dine

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Winter, 2009. Syllabus

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Office hours: Tuesday, 10:00-12:00 (subject to change) or by appointment.

Course website: go to department website and click on Dine; follow link to Physics 218. Homework and solutions and handouts will be posted here.

Course Description:
Last quarter you learned the basics of quantum field theory: canonical quantization, path integral methods, Feynman diagrams in scalar field theory, and the rudiments of spin-1/2 particles. But there wasn't too much contact with real physics – things one can measure and study in experiments, or that we see around us in nature. We'll start with QED, and some very simple things, like the magnetic moment of the electron and the spin orbit coupling, moving on to basic process like Compton scattering at low and high energies. Then we'll move on to the Standard Model. This will require we develop an understanding of non-Abelian gauge theories.
Note on the text: We will continue to use the book by Srednicki, which we used last quarter. For me, it is fun to use a new book, after years of using the text by Peskin and Schroeder. There are some very nice features to this book, but others which I find less satisfactory. I will follow the book closely, but not in order. Some topics will be left for 222. It may be helpful if I list some of the positive features of the book, and some of the things I will do differently. Positives:

1. The treatment of each topic is very concise.
2. The path integral is developed early. This is a very efficient device for deriving Feynman rules, and almost essential in the case of non-Abelian gauge theories. More often than not, it is the most effective framework in which to study non-perturbative phenomena.
3. The LSZ formalism is introduced early on; again, this is a very efficient way to describe scattering amplitudes.
4. There is a heavy emphasis on two component spinors, and a number of very modern techniques for dealing with them (helicity formalism) are introduced. In many current experiments, fermions can be treated as approximately massless, and these techniques are both efficient and emphasize the essential physics.

Negatives:

1. There is not enough treatment of the canonical, operator setup. This sometimes obscures the physics (as Ed Witten says in a recent set of lectures – *for mathematicians!* – "The path integral approach is very powerful but involves an extra layer of abstraction") and in particular some of the essential quantum mechanics. While scattering amplitudes are readily formulated, via LSZ, in a path integral language, and certain other problems are most effectively treated

in this way, there are other problems which are not. We'll review a little bit the operator (and Hamiltonian) formalism early on and use it to understand certain physical questions.

2. One can overdo the use of two component fermions. Four component fermions are more useful in understanding non-relativistic systems. This includes electrons in atoms, for example, but also heavy quark systems (bound states of charm and bottom quarks, and the physics of the top quark at currently available energies). We'll look at some of these questions early on in the course.

3. There are a number of differences of convention from what I am used to. In some cases, I will try to adopt Srednicki's, but in others I will not. For the former, this will lead to sign errors occasionally, but I will do my best (and will count on you to correct me). In others, I will obstinately stick to my own. Some examples:

   (a) The metric: I like the metric Srednicki uses for discussions of gravity, but I find it awkward for discussing scattering processes. I prefer $p^2 = m^2$ to $p^2 = -m^2$, and I like to write the scalar field lagrangian as $\frac{1}{2}(\partial_\mu \phi)^2$, i.e. without a minus sign. But I'll do my best to adapt.

   (b) I prefer to normalize bosonic creation and annihilation operators as harmonic oscillator creation and annihilation operators. In finite volume (I will discuss finite volume, another topic which Srednicki omits), this means

   $$[a(\vec{p}), a^\dagger(\vec{p}^{\,\prime})] = \delta(\vec{p}, \vec{p}^{\,\prime}). \tag{1}$$

   In the infinite volume continuum, this becomes:

   $$[a(\vec{p}), a^\dagger(\vec{p}^{\,\prime})] = (2\pi)^3 \delta(\vec{p} - \vec{p}^{\,\prime}). \tag{2}$$

   Srednicki prefers his convention because the creation operators create states with a relativistic norm, but the above convention has other compensations. Note that it means that a free field is written:

   $$\phi(\vec{x}, t) = \int \frac{d^3k}{(2\pi)^3 \sqrt{2\omega(k)}} \left[a(\vec{k}) e^{ik\cdot x} + a(\vec{k})^\dagger e^{-k\cdot x} \right]. \tag{3}$$

   The *field* creates properly normalized states; the LSZ formula looks essentially the same.

This will be a challenging course – for you and for me. It is important to devote a lot of time to it. You will need to keep up with the reading. The reading has to be done in a very active way, with pen and lots of scrap paper ready. Similarly for review of class notes. The problem (probably about five) will be challenging.

Books on Reserve:

1. M. Peskin and Schroeder, *Quantum Field Theory* – this has been the "work horse" of quantum field theory textbooks for a number of years. It's treatment remains up to date. It is sometimes, perhaps, too thorough. E.g. it has more on renormalization theory than one can hope to cover in two quarters.

2. S. Weinberg, *Quantum Field Theory.* Something of an encyclopedia. Unlike Srednicki or Peskin and Schroder, not ideal for a first exposure to the subject, but contains many deep insights.

3. T. Banks, Quantum Field Theory – provides many insights into the topics we will discuss here. A short book, but one needs to do some work to get its full value.

4. J. Bjorken and S. Drell – a classic early text. The first volume's discussion of Feynman diagrams is still valuable. Much of the other material is somewhat dated, and has been superseded by the texts above.

5. Itzykson and Zuber: Another encyclopedic text. Has a number of useful, worked out Feynman diagram computations, and good discussions of a number of particular topics. Again, a bit hard to use as a first time text.

6. L. Brown, Quantum Field Theory: idiosyncratic, discusses a variety of topics not found in other books.

I will put other books on reserve from time to time as seems appropriate.

Homework, exams,etc: There will be a problem set about once per two weeks. There will probably be a project in lieu of a final. By mid quarter, we'll want to discuss possible projects.

Very **tentative Schedule; will be updated as quarter progresses and I have a better sense how thoroughly certain topics were covered in 217 last fall. It is important to do the indicated reading.**

1. Week 1 (Jan. 7). Some review: Canonical Quantization. Applications to the electromagnetic field. Coupling of spinors to electromagnetism. Simple-minded derivation of the basic formula for the scattering matrix. The Kallen-Lehman representation and its connection to the LSZ formula. Chapters 54-58 and handouts.

2. Week 2 (Jan. 12,14). Review of the Dirac equation and new features. Non-relativistic limit: spin orbit force, electron magnetic moment. Simplified derivations of spinor properties. More on both two component, four component spinors. Feynman rules for spinors coupled to scalars; applications to Higgs decay to bottom quarks, others. Chapters 41-48, 51,53 and handouts.

3. Week 3 (Jan. 19,21). Basic processes in Quantum Electrodynamics: Total cross section for e^+e^- annihilation; Compton scattering, pair annihilation to photons, etc. in high, low energy limits. Chapters 59, 60 and handouts.

4. Week 4 (Jan. 26, 28). Loop corrections in quantum electrodynamics: renormalization, muon $g-2$. Chapters 62-64, 66-68 and handouts. Infrared Divergences (chapter 26).

5. Week 5 (Feb. 2,4). Non-Abelian gauge theories. Basic features. Quantization. Chapters 69-72.

6. Week 6 (Feb 9, 11). Quantization of non-abelian gauge theories (continued). The Standard Model.

7. Week 7 (Feb. 16, 18). Symmetries and their breaking. Goldstone and Higgs phenomena. Quantizing spontaneously broken gauge theories. Chapters 24,30-32. Chapters 84, 87-89

8. Week 8 (Feb. 23, 25). Asymptotic freedom of QCD. High Energy processes in QCD. Chapters 73, 78, 81.

9. Week 9 (Mar. 2,4) High energy processes in QCD. Precision tests of the Standard Model. Chapter 90 and handouts.

10. Week 10 (Mar. 9,11) Effective field theory and renormalization group. Applications: unification of couplings (Grand unified theories); condensed matter systems. Chapters 28, 29 and handouts.

11. Week 11 (Mar. 16) Beyond the Standard Model: the gauge hierarchy problem and related issues. Supersymmetry as an opportunity to apply methods of effective field theory. Chapter 90 and handouts.