1. Overview

a. Comments on the course: philosophy and logistics and goals

- Our topic for this course is nonrelativistic few-body and many-body (mostly many-fermion) theory applied to low-energy nuclear systems (with connections to QCD and cold atom systems). We will address modern theoretical approaches to nuclear forces and their impact on nuclear structure, reactions and astrophysics. An important part of the modern approach is effective field theory (both chiral and pionless) and renormalization group methods.
- The structure of the course will be based on the observation that "active learning" is more effective than straight lectures during which you are passively listening. As we all know from experience, you really learn the physics when you do problems and discuss the underlying concepts (or, even more so, when you have to teach it!). So the most important part will be discussions and actual problem solving among the participants and the instructor. To make this possible, we will incorporate some methods found by education researchers to be effective in more elementary settings, such as in-class peer discussions and "flipping" of lectures (so they are viewed outside of class as videos). Throughout, students are highly encouraged to discuss and work on assignments with each other. We will experiment with facilitating this with an online student-driven question-and-answer system in the spirit of StackExchange.
- There is a References page on the course website[1] and a Links page with pointers to recent talks where nuclear forces are relevant. An operational goal for the course is that by the end most or all of the listed lecture notes, review articles, essays and talks will be understandable (at least in part) to the participants.
- One of the indirect goals of the program is to iterate on curricular materials, including lecture notes and exercises. No one makes the most effective presentation the first time, and although we have taught this material before, it was not in the context of this course, where extensive and immediate feedback is available about what works and what doesn't, what is emphasized correctly or overemphasized, and what are the remaining questions or conceptual difficulties. Many of the exercises/questions are being tried for the first time (at least by us), so this is the first battle test, with the expectation that many modifications will be made.

b. Comment on the exercises

- As noted above, the underlying philosophy is based on the observation (e.g., by Physics Education researchers) that students learn most effectively when they actively fill in details of arguments or explicitly address conceptual questions. Some of the exercises are designed to lead the student to go back over particular lecture material to make sure it is understood while others extend the lecture and still others introduce topics not yet touched upon.
- We do not attempt to develop the type of problem-solving skills that require students to struggle over individual problems for many hours. (In your research, there will naturally be

[1] `http://www.physics.ohio-state.edu/~ntg/8805/nuclear.php`

many opportunities to struggle!) Rather, the idea is to guide the students rather explicitly but let them fill in details. That way they can work through many problems in the time between lectures. This is facilitated by having hints available so that the discovery process is quicker.

- The plan for developing these problems has included stepping through the important review articles and key papers (and some of the corresponding key talks) and identifying at each step exercises or questions that test important points to understand and/or fill in details that are assumed by the author(s). This should be an on-going process.
- We have several categories of problems: conceptual questions, which should be discussed with others, including the instructor(s); two-minute questions (i.e., 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 (primarily for those who have additional background).
- As we proceed, we will indicate for each problem whether it is essential for the current lectures or less generally relevant or mostly of cultural interest. (Maybe essential for the next lecture, by the next week, or later.)
- To the students: it is essential to try the exercises and ask questions incessantly. Not everyone will be prepared to do all of the exercises completely, but with help from our many instructors everyone can take away the essential points. If you are unsure of what a word or phrase means in some context ("correlations", "effective interaction", "renormalize", "scale separation", ...), or what a symbol stands for, please ask during the lectures or at least soon afterwards!
- We will illustrate general principles with concrete (but generally simplified) examples. At the same time, we will discuss subtleties (and subject you to our prejudices) and how to generalize.
- Students: When you get a chance, look at some recent talks and identify places (it may be many!) where you don't understand. A good exercise is to imagine you have to present the talk given just the slides; where do you get stuck or confused?

c. Some things to think about as we proceed (a partial list!)

- Points of emphasis
  - We are interested in the nuclear many-body problem, which means structure, reactions, and the consequences (e.g., for astrophysics). But we don't have the Hamiltonian fully determined! There are still open questions but what is different from earlier decades is that the framework to make systematic progress is in place.
  - The Hamiltonian for low-energy nuclear physics (by which we mean the physics of nuclear structure and reactions such as studied at existing and planned rare isotope beam facilities) is not unique. It is *scale* or *resolution* dependent, analogous to the running coupling in QCD, and it is *scheme* dependent (i.e., there are different ways to implement it at a given scale). We can fit effective (field) theory with different cutoffs or

  use renormalization group transformations (or other unitary transformations) to change the resolution scale. Physical observables should be independent of such changes, but problems can become easier or hard to solve and the physics *interpretation* can change (e.g., how important is some piece of the three-body force?).
  - We want to connect to the *full* Standard Model. For the strong interaction, this means qualitatively and quantitatively connected to QCD. But connecting to QCD is not the same as using quarks and gluons as our variables. Further, it means that pion scattering and πN scattering should be described in a unified framework, which in turns is connected to lattice QCD.

- What are some of the most active controversies or open questions involving forces?
  - Phenomenological vs. chiral EFT potentials: what are the advantages and disadvantages?
  - How high in energy is a good reproduction of phase shifts needed for nuclear physics?
  - Controversy over NN chiral EFT renormalization/power counting or philosophy.
  - Do we need three-body forces? (cf. recent N2LO Pounders and JISP16)
  - Nature of the three-body force? (E.g., long-range part attractive or repulsive?)
  - What is the role of three-body forces (for specified NN potentials) in determining the drip lines or other features?
  - What is the neutron matter equation of state up to neutron star densities?
  - How do you use 3-body interactions as density dependent two-body interactions?
  - Is chiral symmetry important for nuclear structure? If so, how? If not, why not?
  - How do we determine theoretical error bars?
  - How can we connect with LQCD calculations?
  - Should properties of larger nuclei be used to constrain LECs rather than just few body?
  - What are the advantages and disadvantages of the growing list of many-body methods?
  - Is it better to do free-space chiral EFT as input to many-body calculations or should EFT be merged with the many-body method?
  - and so on ...

- There are many open questions. We have to avoid dogma and leave open the possibility of different resolutions of these issues.