Preface

The purpose and motivation of these lectures can be summarized in the following two questions:

- What is the ground state (and its properties) of dense matter?
- What is the matter composition of a compact star?

The two questions are, of course, strongly coupled to each other. Depending on your point of view, you can either consider the first as the main question and the second as a consequence or application of the first, or vice versa.

If you are interested in fundamental questions in particle physics you may take the former point of view: you ask the question what happens to matter if you squeeze it more and more. This leads to fundamental questions because at some level of sufficient squeezing you expect to reach the point where the fundamental degrees of freedom and their interactions become important. That is, at some point you will reach a form of matter where not molecules or atoms, but the constituents of an atom, namely neutrons, protons, and electrons, are the relevant degrees of freedom. This form of matter, and its variants, constitute one important topic of these lectures and is termed nuclear matter. If you squeeze further, you might reach a level where the constituents of neutrons and protons, namely quarks and gluons, become relevant degrees of freedom. This form of matter, termed quark matter or strange quark matter, is the second important subject we shall discuss. By studying dense matter, we shall thus learn a lot about the fundamental theories and interactions of elementary particles. When trying to understand this kind of dense matter, we would like to perform experiments and check whether our fundamental theories work or whether there are new phenomena, or maybe even new theories, that we have not included into our description. Unfortunately, there are currently no experiments on earth which can produce matter at such ultra-high densities we are talking about. However, this does not mean that this kind of matter does not exist in nature. On the contrary, we are pretty sure that we have observed objects that contain matter at ultra-high density, namely compact stars. We may thus consider compact stars as our "laboratory". Thinking about the first question has therefore led us to the second.

If you are primarily interested in phenomenology, or if you are an astrophysicist, you may start from the second question: you observe a compact star in nature and would like to understand its properties. In this case you start from observations like the rotation frequency, the temperature of the star etc. and ask, why does the star rotate so slow/so fast, why does it cool down so slow/so fast? And these questions will inevitably lead you to the attempt to figure out the microscopic structure of the star, although you have started from macroscopic observables. You need to know whether the star contains nuclear matter or quark matter or both, in which phase the respective matter is present, and which properties these phases have. It is thus very natural, also from the astrophysicist's point of view, to study the first question.

In any case, we see that both questions are closely related and we don't have to decide which of the two points of view we take. If I have to characterize what awaits you in these lectures I would nevertheless say that we shall lean a bit more towards the fundamental aspects. In other words, we shall neglect many complications that arise from considering a realistic compact star. A star is a finite system, it is inhomogeneous, it underlies the laws of general relativity etc. Although our discussions are always motivated by the astrophysical application, we mostly discuss infinite, homogeneous systems and do not elaborate on general relativistic effects. Only in discussing the consequences of our microscopic calculations we shall, on a qualitative level, discuss the more realistic setting.

So what kind of physics will we discuss and which theoretical tools do we need? Since our focus is on nuclear and quark matter, the dominant interaction that governs the states of matter we are interested in is the strong interaction. The underlying theory for this interaction is Quantum Chromodynamics (QCD). Although this theory is uniquely determined by very simple symmetry principles, it is extremely hard to solve for most applications. Unfortunately (or fortunately, because this makes it interesting and challenging) matter at compact star densities eludes rigorous first-principle calculations. Therefore, we often have to retreat to simple phenomenological models or have to perform rigorous QCD calculations at asymptotically large densities and then extrapolate the results down to the density regime we are interested in.

In the physics of compact stars also the weak interaction plays an important role. We shall see that it is responsible for the chemical equilibration of the system, i.e., it fixes the various chemical potentials. It is also important for the understanding of cooling mechanisms of the star or for transport properties of nuclear and quark matter. Furthermore, our (mostly field-theoretical) treatment always includes nonzero chemical potentials and sometimes nonzero temperature (for many applications the zero-temperature approximation is sufficient). In this sense it goes beyond the standard vacuum field theory formalism. Basic elements of thermal quantum field theory at finite chemical potential are therefore explained in the appendix.

All this may sound exciting on the one hand, because it shows that the physics of compact stars is extremely rich (due to the diversity of involved physics I found it helpful to include a glossary of important terms at the end of these lecture notes). But on the other hand it may also sound like a big challenge for you if you are not familiar with advanced field theory. Nevertheless, these lecture notes are not primarily intended as a review for researchers (although they might find it useful too) but as a pedagogical introduction for graduate students and advanced undergraduate students. For some of our discussions all you need as a prerequisite is some knowledge in thermodynamics and statistical physics, for instance in Chap. 2, which deals almost exclusively with noninteracting systems. Some other sections, for instance the calculation of the neutrino emissivity in Chap. 5 indeed makes use of advanced field-theoretical methods at finite temperature. It is not the intention of these lectures to develop the theoretical tools in all details before we use them. More importantly, all calculations are physically motivated, thus by understanding the physics behind the results and calculations, these lectures aim at making you familiar with the theories and technicalities via "learning by doing". So at the end of these lectures you will have heard about the basic phenomena and possible microscopic explanations of the physics of compact stars, but also will be prepared to start theoretical research in this exciting field yourself, to possibly contribute to the answers to the two questions we have started with.

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