PHY140Y

35 Models of the Nucleus and Nucleosynthesis

35.1 Overview

- Nuclear Theory
- Nucleosynthesis

35.2 Nuclear Theory

The atomic nucleus has been the focus of much experimental study since the 1930's, when its structure as a "bag" of protons and neutrons began to emerge. However, the behaviour of the forces that dominate the behaviour of the nucleus, the strong and electromagnetic, have made the development of a fundamental theory of the nucleus a very significant challenge.

Today, nuclear theory still is an area where much remains to be understood. The fact that any interesting nucleus involves ≥ 3 nucleons means that even if one could write down the behaviour of the forces involved in analytical form (which we cannot), a closed-form solution for the behaviour of the nucleus still would not be within our ken. In order to make progress in this area, theorists have had to resort to approximations and simplifications of the nucleus that they hope on the one hand retain the essential features of the nucleus and on the other have accessible solutions. There are three broad classes of theories in vogue today, and I will briefly describe each one.

35.2.1 Shell Model

The Shell Model of the nucleus attempts to model the nucleus by supposing an effective potential energy function that each nucleon is interacting in. The model then predicts, in a manner similar to how we solved the hydrogen atom, that we would expect to find individual nucleons in "shells" with specific energies and behaviours.

This model works relatively well to describe some of the features of a nucleus. However, it suffers from the fact that one has to put in "by hand" what the effective nuclear potential should look like. This is something that you would like any theory to be able to describe.

35.2.2 Liquid Drop Model

The Liquid Drop Model starts by assuming that we can treat this bag of nucleons as something akin to a drop of a liquid, with both internal forces and a surface tension. The kinematics of the nuclear "liquid" are then taken by from the average properties and dynamics of the collection of nucleons.

It may seem surprising, but the liquid drop model works rather well, especially for the much larger and less stable nuclei. That this model works at all is perhaps frightening, but it illustrates what power we have in taking the continuum limit even when dealing with only handfuls of particles.

35.2.3 Collective Model

The last theory I will mention is known as the Collective Model. It approaches the kinematics of a nucleus by assuming that the dominant modes of behaviour arise from "collective" motion of the nucleons, so that one can describe the detailed behaviour as a superposition of these collective modes.

This model also has worked well in large nuclei, and seems to have many of the elements of what we think might be a true theory of nuclear structure. It allows one to put into the theory some of the basic symmetries of the nucleus and predict rather specific behaviour. Overall, it has been perceived as a fairly effective approach to understanding nuclear physics.

35.3 Nucleosynthesis

As a concrete example of what we know about nuclear physics and what we have to learn, let us consider how the universe developed the heavier elements that seem to be ubiquitous in our environment. I should first note that the universe is by far dominated by a single element, hydrogen. One can find some concentrations of helium, but between these two elements we have a large fraction of the total visible mass of the universe.

In the early universe, according to the Big Bang model, about the only elements produced as the universe cooled were hydrogen and helium, with the former being much more prolific than the latter. Stars formed from the hydrogen, and the process of fusion (a topic we don't have time to discuss in detail) began to burn some of the hydrogen and form heavier elements. However, the creation of the heavier elements could not be formed from stellar fusion itself. It required a process that only could take place in explosive conditions, those found in a supernova.

When a star goes supernova, the stellar material experiences extremes in temperature and pressure. Under these conditions, a "hot CNO" process takes place, which is illustrated in Fig. 1. The process starts with $^{12}_{6}$C. The nucleus absorbs a proton to form $^{13}_{7}$N, and then absorbs another proton to form $^{14}_{8}$O. This nucleus β decays to form $^{14}_{7}$N, which then absorbs a proton to form $^{15}_{8}$O. This nucleus then inverse-β decays to form $^{15}_{7}$N, which then emits an α particle and a proton to return to $^{12}_{6}$C. This CNO cycle continues until on occassion one of the radioactive elements follows a different path to "break out" of this cycle to produce a heavier element. These rather rare processes nonetheless provide the opportunity to create these heavier elements, an opportunity that doesn't come in other ways.

Thus, most of the stuff around us had extremely explosive origins!

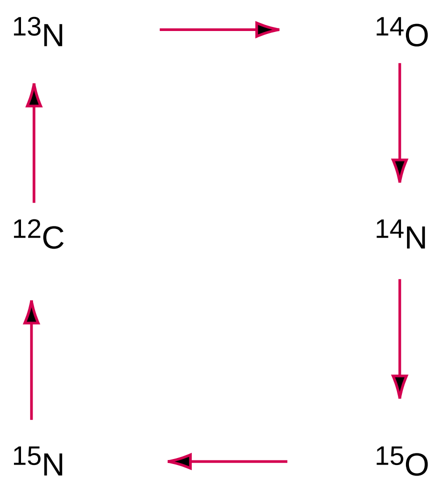

Figure 1: The CNO cycle, showing the isotopes that are formed during the process.