

# A SUMMARY OF SELF-STUDY QUESTIONS

February 2010

## Elementary particle physics

1. What are leptons, hadrons, mesons and baryons?
2. Name the known and expected quarks and leptons and place them in families. What is the charge of the different particles? What spin do they have?
3. What is "flavor" and "color"?
4. Give a motivation to the introduction of the notation "color".
5. Which kinds of force mediating particles exists according to the standard model?
6. Describe the  $\beta^-$  decay at the quark level using Feynman diagrams.

## Nuclear physics

1. Write down the semi-empirical mass formula (you do not have to give numerical values of constants) and give a motivation for the different terms.
2. Derive an expression for the  $\beta$ -stability line.
3. Discuss different types of instability in atomic nuclei. In which part of the nuclear chart are the different decay modes most important?
4. Describe different types of excitations in atomic nuclei.
5. Describe how electron capture works. Drawing a figure may be helpful.
6. In a star most atoms are fully ionized. Even so, electron capture is possible. Explain why.
7. Why do we have electron capture instead of  $\beta^+$  decay in one of the pp-chains? Both processes would lead to the same final result.

## Nuclear reactions

1. What is cross section? Describe schematically how the cross section can be expressed in terms of the Compton wavelength.
2. Derive an expression for the average number of reactions occurring per time and volume unit between two different kinds of particles, assuming thermal equilibrium. The expression shall contain an integral over the relative velocity.
3. Rewrite the expression such that we integrate over the energy instead. Notice that the relative velocity has a Maxwell-Boltzmann distribution:

$$\Phi(v) d^3v = 4\pi v^2 \left( \frac{\mu}{2\pi kT} \right) e^{-\mu v^2/2kT} dv$$

4. Derive an expression for the number of nuclear reactions in stars when the energy is close to a resonance in the cross section.

5. Give an example of an important process in which a resonance plays a key role.
6. Write down and motivate an expression for the non-resonance cross section for thermal reactions between two atomic nuclei with  $Z_1$  ( $N_1$ ) and  $Z_2$  ( $N_2$ ) protons (neutrons) respectively.
7. Show how the maximum of the cross section is shifted away from that of the Maxwell-Boltzmann distribution
8. Show that the number of fusions (per time and volume unit) of heavier atomic nuclei (e.g.  $\alpha + {}^{16}\text{O}$ ) in a star has a much stronger temperature dependence than the number of fusions of e.g. two protons.

## Cosmology

1. The Fridman equation can be written

$$H^2 - \frac{8\pi G}{3} \cdot \rho = -k \cdot R^{-2}$$

- a) What is the meaning of  $H$ ,  $R$  and  $k$ ? Describe the variation of  $R$  with time for different values of  $k$ .
  - b) What is the critical density? How can it be expressed as a function of  $H$ ?
  - c) How do the matter density and the radiation density depend on  $R$ ? What are the consequences for the development of the early universe?
  - d) Describe and explain the origin of the cosmic background radiation.
2. The amount of  ${}^2\text{D}$ ,  ${}^4\text{He}$  and  ${}^7\text{Li}$  produced in the Big Bang depends primarily on the average density.
    - a) The average density can with good accuracy be put equal to the (at the time) critical density. Why?
    - b) Describe and explain briefly how the relative abundance of the three nuclei  ${}^2\text{D}$ ,  ${}^4\text{He}$  and  ${}^7\text{Li}$  depends on the average density of the universe.
    - c) The amount of  ${}^4\text{He}$  produced depends on additional factors. Mention two of these.
    - d) Mention some problems that are encountered when one tries to determine the original helium abundance through observations. What conclusions can be drawn from existing data?

## Hydrogen burning

1. Electron capture occurs in one of the pp-chains. Which one? Which nuclei are involved?
2. Hydrogen burning involves a series of nuclear reactions referred to as the pp-chains. Two of the pp-chains are responsible for most of the energy production. Describe these two pp-chains.
3. In which type of stars are the pp-chains the most important hydrogen burning process?

4. In which type of stars is the CNO-cycle the most important hydrogen burning process?
5. Describe the CNO-cycle and explain why the elements C, N and O Consumed. are not

### Helium burning

1. The first step in helium burning is the so called triple-alpha process. Describe this process.
2. Additional helium burning reactions occur after the triple-alpha process. Describe these reactions and explain why there is not a long chain of helium burning reactions which could successively lead to the creation of heavy elements during the normal helium burning phase.
3. A side branch of helium burning starts with the reaction  $^{14}\text{N}(\alpha, \gamma)^{18}\text{F}$  and leads via  $\beta^+$  decay and further  $\alpha$  reactions to the production of  $^{25}\text{Mg}$ . Explain why this chain of reactions is important for the production of heavy elements with a mass larger than about 60.

### Advanced burning

1. After the helium burning phase, a heavy star goes through additional burning phases. What are these burning phases called and what is the dominating end product of each phase?
2. A heavy star has a particular structure when it has used up nearly all its nuclear fuel and is about to collapse. Show this structure by drawing a figure. Indicate the elements that dominate in different regions of the star.
3. Reactions with alpha particles are important during the silicon burning phase. Give examples of a few such reactions. Which are the heaviest elements that can be formed during the silicon burning phase?

### The *s*-process

1. Explain, using a schematic figure, how the *s*-process works.
2. The abundance curve for the heavy elements have a number of well-defined peaks (see figure). Some of these peaks can be explained as a result of the *s*-process. Describe how, and mark out the peaks that are related to the *s*-process.
3. The lightest isotopes of many heavy elements are very rare compared to the heavier isotopes, How can this difference be explained?
4. Discuss the time scale for the *s*-process? What life-time must a nucleus have in order to have time to capture a neutron before it  $\beta$ -decays?

### The *r*-process

1. How many neutrons per nucleus (in the Fe peak) are required for the *r*-process to start?
2. Which are the two types of nuclear reactions that the *r*-process depends on?

3. Explain the notation "*waiting point nuclei*". What is the connection between these nuclei and certain peaks in the relative cosmic abundance. Mark these peaks in the attached figure.
4. Which are the heaviest nuclei that can be directly produced in the *r*-process? Which are the heaviest nuclei along the  $\beta$  stability line that are produced through  $\beta$  decay of *r*-process nuclei? Why can heavier nuclei not be produced?
5. In what environment is the *r*-process operating?

### Experimental data

1. Experimental information about cross sections for astrophysically important reactions is often limited even for well studied nuclear reactions. Explain why.
2. Experimental cross sections are often available for reactions related to explosive burning. What is the reason for this?
3. The possibilities to study *p*-, *s*- and *r*-process nuclei in the laboratory are very different. For which of the processes are most (least) experimental data available. What does the difference depend on?
4. What is the astrophysical *S*-factor? Why is it useful?

### Stellar evolution

1. Stars cannot be much lighter than  $0.1 M_{\odot}$ , nor much heavier than  $100 M_{\odot}$ . What is the reason for these mass limits?
2. How can the age of a star be determined?
3. When discussing the structure and development of stars, one often distinguish between light and heavy stars. At approximately which mass goes the limit? What is the difference in structure between the two kinds of stars during the main sequence phase?
4. Helium burning occurs under drastically different conditions in light and heavy stars. What is the major difference and what consequences does it have for the reaction speed?
5. During which phase of a star's life can there be a helium flash? What is required for a helium flash to occur?
6. Elements with a mass greater than 60 can be synthesized in stars through the *s*-process. During which phases of a star's life can this process operate?
7. Mention some situations which can result in a supernova explosion and discuss what kind of nuclear processes that are assumed to occur in connection to them.
8. Discuss the final fate of stars with different masses.