The University Of Sheffield.

DEPARTMENT OF PHYSICS AND ASTRONOMY

Spring Semester 2006-2007

NUCLEAR ASTROPHYSICS

Answer question ONE (COMPULSORY) and TWO other questions.

A formula sheet and table of physical constants is attached to this paper.

All questions are marked out of ten. The breakdown on the right-hand side of the paper is meant as a guide to the marks that can be obtained from each part.

COMPULSORY

1 (a) Briefly explain each of the six items listed below, indicating their relevance to the synthesis of elements and the chemical composition of astrophysical bodies.

(i) Natural Broadening;

(ii) Curve of Growth;

(iii) Chandrasekhar Limit;

(iv) Seismic P-wave;

(v) Gravitational differentiation;

(vi) Iron Helium phase transition.

[6]

(b) Estimate the height of the Coulomb barrier for the reaction

$$^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Li} + \gamma$$

(assume that an element with atomic number A has a nuclear radius given by $1.25 \times A^{1/3}$ fm).

[2]

(c) The total energy release in a Type Ia supernova is about 10^{43} J. Assuming that a candidate process for the provision of this energy is

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg} + \gamma$$

calculate the mass of carbon that has to be consumed. (The atomic mass of ^{12}C is 12 u and that of ^{24}Mg is 23.985042 u.)

[2]

2 (a) The binding energy of a nucleus can be approximated using a three-term expression involving *A* and *Z* which originates when the liquid drop model of the nucleus is considered. Describe these 3 terms via their analogies with a charged liquid droplet and give the form of their relationship to *A* and *Z*. [3]

(b) A more accurate estimate of the binding energy of a nucleus is achieved when adding a further two terms to the expression, both of which come from the shell model of the nucleus. What two features of the chart of nuclides do these terms address? Give their relationship to *A* and *Z*. [2]

(c) The first reaction in the ppI chain of thermonuclear reactions is usually written as:

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu_e \quad (Q = 0.42\ \mathrm{MeV})$$

This is in fact two separate reactions each with its own associated *Q* value. Describe these two reactions and their *Q* values. [3]

(d) Why is this reaction the rate-defining step in the ppI chain and what is the consequence of this? [1]

(e) Some text books incorrectly write the *Q* value of this reaction as $Q = 1.44$ MeV – why is this so? [1]

3 (a) Describe the events leading up to the onset of primordial nucleosynthesis in the first few minutes after the Big Bang. Your answer should include a discussion of the processes taking place and the effect of the rapidly decreasing temperature. [3]

(b) In the early Universe the neutron to proton ratio was "frozen out" at a value of 0.2. At a time *t* seconds later, the Universe having further cooled, the formation of deuterons started. At the time when deuteron production started the neutron to proton ratio (n:p) had fallen to 0.135.

(i) Estimate the temperature at which n:p was frozen at 0.2. [1]

(ii) Why did deuteron production not start immediately at the time when n:p was frozen at 0.2? [1]

(iii) Given that the time between freeze-out and the start of deuteron production was 300 seconds, calculate the lifetime of the neutron. [3]

(iv) Use value of n:p above to estimate the primordial abundance of Helium-4. How does this value compare with current day observations? [2]

4 (a) Outline the two main nuclear processes thought to be responsible for the production of elements heavier than iron. In your discussion indicate the typical neutron densities and timescales relevant to the two processes. [3]

(b) One of these processes naturally terminates with the production of ^{209}Bi. Why is this so? [1]

(c) Describe the *local approximation*. Which of the two nuclear processes that you have described above is it relevant to? Your answer should include an indication of why the process is self-regulating. Why does the *local approximation* break down near to neutron magic numbers? [3]

(d) Two isotopes in an evolved star exist such that isotope B is being created by neutron absorption occurring on isotope A. Isotope B is being destroyed by both neutron absorption and β decay, the mean lifetime with respect to the latter process being 12 minutes. Given that isotope B is in equilibrium abundance and that the equilibrium density of isotope B is 5×10^{-4} that of isotope A, estimate the neutron density in the star. Assume that for any heavy nucleus the product of the neutron absorption cross-section and neutron velocity is approximately 3×10^{-23} m^{3}s^{-1}. [3]

5 (a) Describe the composition of *primary* cosmic rays, indicating how their composition differs from that of the universal relative abundance of elements. [2.5]

(b) Explain briefly the importance of cosmic rays in the context of understanding elemental abundances. [1.5]

(c) The *Fermi mechanism* of shock acceleration can account for a power law energy spectrum for primary cosmic rays. Derive this power law form of the energy spectrum, making clear your assumptions. [3]

(d) Given that the nuclear cross-section for a nucleus of mass number A is approximately $\pi R_0^2 A^{2/3}$, where $R_0 = 1.2 \times 10^{-15}$m, estimate the probability that the incident primary cosmic ray proton will fail to interact in the atmosphere, making clear your assumptions. [3]

END OF QUESTION PAPER