The Handbook of Mathematics, Physics and Astronomy Data is provided

KEELE UNIVERSITY

EXAMINATIONS, 2009/10

Level II

Wednesday, 26th May, 09:30–11:30

PHYSICS/ASTROPHYSICS

PHY-20002

STELLAR ASTROPHYSICS

Candidates should attempt to answer FOUR questions.

NOT TO BE REMOVED FROM THE EXAMINATION HALL

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1. The semi-empirical mass formula for the binding energy of a nucleus is

$$B(Z, N) = a_1 A - a_2 A^{2/3} - a_3 Z^2/A^{1/3} - a_4(Z-N)^2/A + \delta(Z, A)$$

where Z, N and A are the number of protons, neutrons and nucleons respectively.

(a) Taking each of the five terms in turn, outline the physical origin of the term and justify the form of its dependence on A, Z and/or N. [50]

(b) Explain why this formula produces a maximum value of binding energy per nucleon. [15]

(c) By referring to the formula, give an explanation for why, on a plot of Z versus N, the 'valley' of stable nuclei is curved. [15]

(d) Refering to the 'liquid drop' model of the nucleus, give an explanation of the process of fission of a heavy nucleus. [20]

2. a) Explain why nuclear reactions in Sun-like stars occur only in the central core. [10]

b) Explain (descriptively) why a reaction such as ${}^4\text{He} + {}^3\text{He} \rightarrow {}^7_4\text{Be}$ could not take place classically in Sun's core, and explain why it is necessary to invoke quantum mechanics. [20]

c) Explain why the ${}^7_4\text{Be}$ nucleus would not be the end-product of the nuclear burning currently occurring in the Sun's core, and state and explain what the dominant end-product would be. [20]

d) Construct a series of valid reactions that would transform the ${}^7_4\text{Be}$ nucleus into that end product. [30]

e) Draw a Feynmann diagram for any weak interactions you have invoked. [20]

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3. a) An 11-$M_\odot$ star undergoes supernova collapse to a neutron star. Draw a schematic diagram showing the internal composition of a star about to undergo supernova, and explain why collapse is initiated. [20]

b) An Earth-based detector has a total cross-section for the detection of an electron neutrino (ν_e) of 6×10^{-15} m^2. It detects 13 neutrinos from the supernova, which is 8 kpc (2.5×10^{20} m) away. How many electron neutrinos did the supernova produce? [15]

c) Outline the process called 'neutrino cooling' and explain why it is important in enabling a supernova collapse to occur. Hence adapt your above electron-neutrino rate to estimate the total number of neutrinos produced in the collapse. [20]

d) If the mean energy of the detected neutrinos was 3×10^{-12} J, what was the total energy radiated as neutrinos? [5]

e) Assume that, upon collapse, the $\approx$ 10-$M_\odot$ envelope was at a mean distance of 10^7 m from the center of the core, and that each nucleon has a cross-section to scattering neutrinos of 4.0×10^{-45} m^2. What fraction of the neutrino flux is absorbed by the envelope? [20]

f) Make a quantitative estimate of the initial ejection velocity of the envelope. [10]

g) What ultimately halts the collapse of the core? [10]

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4. a) The rate of a nuclear reaction in a star is given by

$$\text{Rate} \propto S(E)\, e^{-3(E_G/4kT)^{1/3}}$$

where the symbols have their usual meanings. Explain the physical origins of $S(E)$ and E_G. [20]

b) In considering the temperature dependence of the rate we can neglect $S(E)$ and consider only the exponential dependence. Hence, show that

$$\text{Rate} \propto T^{\beta} \quad \text{where} \quad \beta = (E_G/4kT)^{1/3}$$ [40]

c) Given that for two nuclei A and B we have $E_G = (\pi \alpha Z_A Z_B)^2 2 m_r c^2$ where $m_r = m_A m_B/(m_A + m_B)$ and $\alpha = 1/137$, find the temperature dependence of the rate of the reactions

$$p + p \rightarrow d + e^+ + \nu_e$$

and

$$p + {}^{12}\text{C} \rightarrow {}^{13}\text{N} + \gamma$$

when the temperature is 2×10^7 K. [25]

d) Explain the significance of your results for nuclear burning in main-sequence stars. [15]

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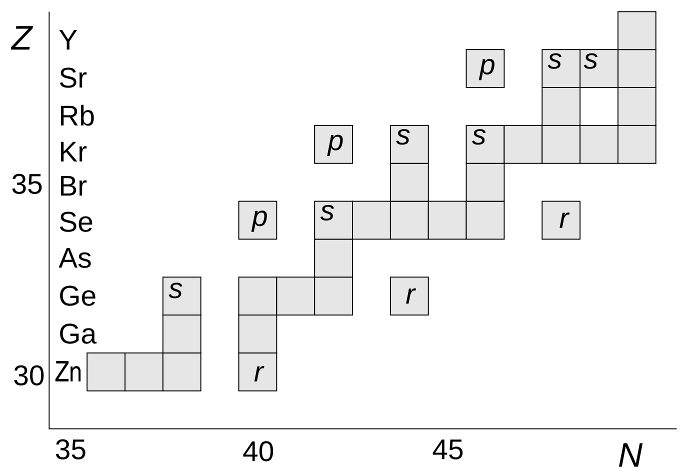
5. a) Explain what is meant by electron degeneracy pressure. [10]

b) Explain why nuclear burning cannot proceed steadily, but must be explosive, in material supported by electron degeneracy pressure. [20]

c) Considering post-main-sequence evolution, state *two* different evolutionary situations in which helium burning is ignited in degenerate material. [10]

d) For each of those two situations in part (c) describe what occurs when helium is ignited, and explain the effect that the helium ignition has on the structure of the star, and on its location on the H–R diagram. [2×30]

6. The diagram shows part of the 'stability valley' for heavy elements beyond iron.



a) Give an account of the origin of the nuclei labelled 's' in the plot. [40]

b) Give an account of the origin of the nuclei labelled 'r' in the plot. [40]

c) Give an account of the origin of the nuclei labelled 'p' in the plot. [20]