The Handbook of Mathematics, Physics and Astronomy Data is provided

KEELE UNIVERSITY

EXAMINATIONS, 2012/13

Level II

Thursday, 16th May 2013, 13:00–15:00

PHYSICS/ASTROPHYSICS

PHY-20002

STELLAR ASTROPHYSICS

Candidates should attempt to answer FOUR questions.

NOT TO BE REMOVED FROM THE EXAMINATION HALL

1. Rapid nuclear burning, during a supernova, of a core consisting $^{12}_{6}$C and $^{16}_{8}$O tends to produce $^{28}_{14}$Si and then $^{56}_{28}$Ni.

(a) Explain qualitatively (but referring to terms of the semi-empirical mass formula) why $^{56}_{26}$Fe is more stable than $^{56}_{28}$Ni. [20]

(b) Why would short-timescale explosive nuclear burning of $^{28}_{14}$Si tend to produce $^{56}_{28}$Ni rather than $^{56}_{26}$Fe? [20]

(c) Write down reactions by which, in the aftermath of a supernova, $^{56}_{28}$Ni decays to $^{56}_{26}$Fe. [20]

(d) Estimate the energy released by each transformation of ^{56}Ni into ^{56}Fe. If a supernova creates 1 solar mass of ^{56}Ni, estimate the total energy generated. [30]

(e) If, in the aftermath of a supernova event, the optical lightcurve were dominated by ^{56}Ni decay, what would you expect the shape of the lightcurve to be? [10]

[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 $a_3 = 0.697$, $a_4 = 23.3$; the rest-mass energy of a proton is 938.3, that of a neutron is 939.6 and that of an electron is 0.5; all values in MeV.]

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2. The p–p chain reactions are:

$$p + p \rightarrow d + e^{+} + \nu_e$$
$$p + d \rightarrow {}^{3}\mathrm{He} + \gamma$$

$${}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2p \qquad {}^{3}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{7}\mathrm{Be} + \gamma$$

$$e^{-} + {}^{7}\mathrm{Be} \rightarrow {}^{7}\mathrm{Li} + \nu_e \qquad p + {}^{7}\mathrm{Be} \rightarrow {}^{8}\mathrm{B} + \gamma$$
$$p + {}^{7}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He} \qquad {}^{8}\mathrm{B} \rightarrow {}^{8}\mathrm{Be}^{*} + e^{+} + \nu_e$$
$${}^{8}\mathrm{Be}^{*} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

(a) From the above reactions, identify two that involve the weak force. Draw a Feynman diagram for each of these. [20]

(b) Give a qualitative account of how the production of ^{3}He occurs. Explain why it can occur at temperatures well below those expected from classical physics. [20]

(c) Explaining your answer, discuss whether you would expect the fusion of $p + d$ to be faster or slower than that of ${}^{3}\mathrm{He} + {}^{3}\mathrm{He}$. [20]

(d) Explain why the fusion of two ^{3}He nuclei does not result in a $Z = 4$ nucleus, but instead produces ^{4}He. [20]

(e) Name the alternative set of stellar reactions which can result in burning hydrogen into helium. Explain qualitatively why they would be less important in the core of a low-mass star. [20]

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3. (a) What is meant by a *virtual* particle? [

(b) Why must the mediator particles (such as photons) in a Feynman diagram be virtual? [10]

(c) The pion has a rest-mass energy of 135 MeV. Use this to calculate the range of the strong force. [20]

(d) Pions are quark–anti-quark pairs of u and d quarks (charge $+\frac{2}{3}$ and $-\frac{1}{3}$ respectively). Draw a quark-level Feynman diagram for a strong-force-binding interaction between two nucleons. [10]

(e) Suggest a valid decay path for the π^0 and draw a Feynman diagram for the decay. [20]

(f) Suggest a valid decay path for the π^+ and draw a Feynman diagram for the decay. [20]

(g) Why is the π^0 lifetime much shorter than that of the π^+? [10]

4. (a) Why is ^{4}He the dominant product of burning hydrogen? [10]

(b) Explain why burning H to ^{4}He must produce neutrinos. [10]

(c) If the rest mass of a proton is 1.668×10^{-27} kg and that of a ^{4}He nucleus is 6.626×10^{-27} kg estimate the energy released in forming each ^{4}He nucleus. [10]

(d) The solar energy received at the Earth's surface is 1370 W m^{-2}. Estimate the flux of solar neutrinos passing through Earth. [20]

(e) A neutrino detector consists of 2000 kg of ^{71}Ga atoms, each of which has a cross-section to detection of neutrinos of 10^{-47} m^2. What is the rate at which neutrinos are detected? [20]

(f) Write down a reaction for the detection of a solar electron neutrino by ^{71}Ga. [10]

(g) The detector is left running for 100 hours and detects 140 neutrinos. Discuss this result. [20]

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5. (a) The mass fractions of hydrogen, helium and heavier elements denoted by X_1, X_4 and X_A respectively, where the three together add up to 1. Consider the number of particles present when each element is ionized, and hence show that the mean mass of a particle in a stellar core is given by

$$\bar{m} = \frac{2m_{\mathrm{H}}}{1 + 3X_1 + \frac{1}{2}X_4}$$

where m_{H} is the hydrogen mass. [30]

(b) What are the minimum and maximum values of $\bar{m}$ in a star? [10]

(c) Referring to the perfect gas law explain why changes in $\bar{m}$ result in changes in a star's structure. [10]

(d) Making reference to the virial theorem, describe the changes in the core of a main-sequence star over its main-sequence lifetime, and state the effect these have on the luminosity of the star. [25]

(e) Describe the changes that give rise to the Hertzsprung Gap on an H–R diagram. [25]

6. Give an account of the evolution of a low-mass star starting from the Horizontal Branch and describing the ascent of the AGB. Draw schematics of the different zones within the star, showing the nuclear-burning regions. Your account should explain the changes in location on the H–R diagram, the avoidance of the Hayashi forbidden region, the occurrence of shell flashes, and the eventual expulsion of a planetary nebula. [100]