The Handbook of Mathematics, Physics and Astronomy Data is provided

KEELE UNIVERSITY

EXAMINATIONS, 2010/11

Level II

Tuesday 24th May 2011, 9.30–11.30

PHYSICS/ASTROPHYSICS

PHY-20002

STELLAR ASTROPHYSICS

Candidates should attempt to answer FOUR questions.

NOT TO BE REMOVED FROM THE EXAMINATION HALL

1. The main branch of the p–p chain consists of the reactions

$$
\begin{array}{ll}
(i) & p + p \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu_e \\
(ii) & p + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma \\
(iii) & {}^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + 2p.
\end{array}
$$

Place the above reactions in order of their likelihood in the Sun's core, explaining and justifying your answer. [30]

Explain why the CNO cycle will be less probable at the temperature of the Sun's core. [10]

The p–p chain can be summarised as $4p \rightarrow {}^{4}\mathrm{He} + 2\nu_e + 27.8$ MeV. Calculate the expected flux of neutrinos at the Earth. [20]

Assume that a neutrino detector consists of 2000 kg of ^{37}Cl atoms, each of which has a cross-section to detection of neutrinos of 10^{-47} m^2. Find the number of neutrinos detected each day. [20]

Discuss reasons why the above experiment might detect fewer neutrinos than your calculated number. [20]

[$L_{\odot} = 4\times10^{26}$ W; Radius of Earth's orbit $= 1.5\times10^{11}$ m.]

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2. The semi-empirical mass formula for the binding energy of
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 ($a_2 = 17.23$ MeV and $a_3 = 0.697$ MeV).

Write down the equation for the triple-alpha reaction and use the above formula to estimate the energy it releases. [25]

Explain why that answer will not be accurate. Will it be less than or more than the true value? [10]

Despite the inaccuracy, use your answer to estimate the time that a 1-$M_\odot$ star spends on the horizontal branch. Assume that while on the horizontal branch it burns He amounting to 10% of its mass and that it has a luminosity attributable to the triple-alpha reaction of $L = 40\ L_\odot$. [25]

Why would the star's total luminosity be greater than the luminosity given in the last part? [10]

Describe the changes that take place, explaining the reasons for the changes, as the horizontal-branch star ascends the asymptotic giant branch. [30]

[$M_\odot = 2\times10^{30}$ kg; $L_\odot = 4\times10^{26}$ W.]

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3. The s-process path ends in the following loop.

$$
\begin{array}{lrcl}
\text{(i)} & {}^{209}_{83}\mathrm{Bi} + n & \rightarrow & {}^{210}_{83}\mathrm{Bi} + \gamma \\
\text{(ii)} & {}^{210}_{83}\mathrm{Bi} & \rightarrow & {}^{210}_{84}\mathrm{Po} + e^{-} + \bar{\nu}_e \\
 & {}^{210}_{84}\mathrm{Po} & \rightarrow & {}^{206}_{82}\mathrm{Pb} + {}^{4}\mathrm{He} \\
 & {}^{206}\mathrm{Pb} + n & \rightarrow & {}^{207}\mathrm{Pb} + \gamma \\
 & {}^{207}\mathrm{Pb} + n & \rightarrow & {}^{208}\mathrm{Pb} + \gamma \\
 & {}^{208}\mathrm{Pb} + n & \rightarrow & {}^{209}\mathrm{Pb} + \gamma \\
 & {}^{209}\mathrm{Pb} & \rightarrow & {}^{209}\mathrm{Bi} + e^{-} + \bar{\nu}_e
\end{array}
$$

Explain why the s process proceeds by n captures but not by p captures. [15]

By stating a condition for the s process, state which of the reactions (i) and (ii) has the shorter timescale. [15]

Identify one weak interaction in the above sequence. Draw a Feynman diagram (at the nucleon level) for that reaction. [20]

Identify the alpha decay in the above sequence. Explain why heavy nuclei are prone to alpha decay. Give a descriptive account of how alpha decay occurs in such a nucleus. [25]

Noting that the s-process path ends as above, give an account of how nuclei heavier than ${}^{210}_{84}\mathrm{Po}$ are created. [25]

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4. The heavy particle D^+ consists of the quarks $(c\bar{d})$. It dec
D^0 $(c\bar{u})$ and a π^+ $(u\bar{d})$. Draw a quark-level Feynman diagra
this decay. [20]

The D^0 then decays to a K^- $(\bar{u}s)$ and another pion. Write down the equation for this decay and draw the Feynman diagram, stating which force mediates the decay. [20]

The pions that are created in the above reactions can decay to leptons of the muon family. Construct a valid equation for such a decay and draw the Feynman diagram. [20]

Now give a valid decay by which the charged muon from the last reaction can decay to a positron, and again draw the Feynman diagram. [20]

Give a possible decay of the K^- into lighter particles, again drawing the Feynman diagram. [20]

[The u quark has a charge of +2/3; the d has a charge of –1/3].

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5. The mass fractions of hydrogen, helium and heavier elem denoted by X_1, X_4 and X_A respectively, where the three tog add up to 1. Consider the number of particles present when eac 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]

Discuss the effect of nuclear burning on $\bar{m}$ and hence discuss the consequences of hydrogen burning on the core of the star. Hence outline the differences between a zero-age main-sequence star and a star that is about to leave the main sequence. [25]

After leaving the main sequence on a Hertzsprung–Russell diagram, a star evolves rapidly across the Hertzsprung Gap. Discuss what is happening to the star (in both the core and the envelope) and the reasons for the changes. [25]

What halts the rapid evolution of a star on the far side of the Hertzsprung Gap? Describe, with the aid of a schematic diagram, the different zones within a star at the start of the red giant branch. [20]

6. Discuss each of the following topics:

(i) Why the density of nuclei can be considered to be always the same. [25]

(ii) The 'fusion window'. [25]

(iii) The nature and behaviour of a virtual (as opposed to real) particle. [25]

(iv) The change in the Hertzsprung–Russell diagram of a cluster with age. [25]