NUCLEAR REACTIONS, FUSION AND FISSION

Binding Energies:

${}^{11}_{5}B$	76.21MeV
${}^{4}_{2}He$	28.3MeV
${}^{12}_{6}C$	92.16MeV
${}^{14}_{6}C$	105.29MeV
${}^{14}_{7}N$	104.66MeV
${}^{2}_{1}H$	2.22MeV
${}^{3}_{2}He$	7.72MeV

1. Calculate the threshold energy needed to make the following reaction occur

$${}^{14}_{6}C + p \rightarrow {}^{14}_{7}N + n .$$

How much kinetic energy is required in the laboratory frame if the stationary target nuclei are:

(a) ${}^{14}_{6}C$ nuclei? [0.68MeV]

(b) Protons? (Take nuclear masses to be proportional to mass number). [9.45MeV]

2. (a) Calculate the energy released in the nuclear reaction

$$p + {}^{11}_{5}B \rightarrow 3\,{}^{4}_{2}He .$$

[8.69MeV]

(b) If the reaction is at a resonance when the incident protons have a kinetic energy of 3.65MeV in the laboratory frame, calculate the excitation energy of the compound nuclear state above the ground state of ${}^{12}_{6}C$ (take nuclear masses to be proportional to mass number). [19.3MeV]

(c) Draw an energy level diagram to represent the reaction.

3. *Neutrinos, they are very small.*
They have no charge and have no mass
And do not interact at all,
The Earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
[John Updike]

A 500-MeV muon neutrino (ν_μ) passing through matter interacts mainly with the neutrons in the nuclei. Assuming that half of the mass of a typical piece of matter is due to neutrons, that the neutrino has a total cross-section of 4×10^{-15} barns for interaction with a neutron and that all of the neutrons in a nucleus act independently work out the probability that the neutrino will interact as it passes through the Earth along a diameter.

Mean density of Earth = 5.5×10^{3} kg m^{-3}.
Mean diameter of Earth = 12,750 km. [8x10^{-6}]

4. The main nuclear reactions which convert hydrogen to helium in the Sun are:

$$p + p \rightarrow {}^{2}_{1}H + e^{+} + \nu_e \qquad (1)$$

$$p + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + \gamma \qquad (2)$$

$${}^{3}_{2}He + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + 2p \qquad (3)$$

(a) Estimate the mean thermal energy of nuclei at the centre of the Sun (T ~ 10^{7} K). By comparing this to the Coulomb energy of two protons separated by 1 fm, explain why these fusion reactions must proceed by quantum mechanical tunnelling.

(b) Why is reaction (1) special? Why does it set the overall time scale of hydrogen burning?

(c) How much energy is released in reactions (2) and (3)?
[5.5MeV;12.86MeV]

(d) The total power output of the sun is 3.9x10^{26}W. If it assumed that reactions (2) and (3) are the primary energy sources of the Sun, estimate the number of neutrinos that are released each second. [2x10^{38}]

(e) Considering reactions (2) and (3), what proportion of the mass of the reactants is converted into energy? (Take nuclear masses to be proportional to the mass number)

(e) Estimate the number of solar neutrinos that pass through you every day. Should you worry about this? (The distance from the Earth to the Sun is about 1.5×10^{11} m).
[~3x10^{19}]