Examination NPAC 2021–2022	From nuclei to stars: nuclear astrophysics
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Don't forget to check first the useful information at the end.

General considerations

1) Which transformation occurs in hydrogen burning? What is the amount of energy released?
2) What are the two possible ways to burn hydrogen in stellar interiors?
3) Give a consequence of the competition between the pp chain and CNO cycle on stellar structure.
4) Describe briefly the classical novae phenomena where hydrogen is burnt explosively.

The ^{3}He(^{3}He,2p)^{4}He reaction

The ^{3}He(^{3}He,2p)^{4}He reaction is the 3rd reaction of the pp1 chain occuring in quiescent hydrogen burning. Its cross-section was measured at low energies at the LUNA laboratory using a ^{3}He$^+$ beam with an intensity of 300 eμA. The beam impinged a ^{3}He target having a thickness of 3.9x10^{17} at/cm^2 and the two protons in the exit channel of the reaction were detected in time coincidence with 8 silicon detectors. The detection coincident efficiency determined from Monte-Carlo simulation was ε = 5.3 %.

1) A total charge Q = 298 C was accumulated during 11.5 days at the center of mass energy of $E_{c.m.}$ = 24.36 keV, and 278 coincident events were recorded.
   a) Determine the number of incident ions.
   b) Determine the reaction cross-section at this energy.
   c) Determine the astrophysical S-factor at this energy.
2) Calculate the Gamow window properties (E_0 and ΔE) for the central temperature of the Sun, T = 15.6 MK.
3) The ^{3}He(^{3}He,2p)^{4}He reaction is a non resonant reaction and its astrophysical S-factor, which varies smoothly with the energy, can be considered as constant in a good approximation.
   a) What is the cross-section at the Gamow energy E_0?
   b) What would have been the number of detected events at the Gamow energy E_0 with the same experimental conditions?
4) Calculate the thermonuclear rate of the ^{3}He(^{3}He,2p)^{4}He reaction for the central temperature of the Sun.

The ^{25}Al(p,γ)^{26}Si reaction

Classical novae are powered by explosive hydrogen burning during which several γ-ray emitters such as ^{26}Al are produced. The quantity of ^{26}Al produced in such events depends crucially on the ^{25}Al(p,γ)^{26}Si reaction.

1) What are the two possible reaction mechanisms operating in the ^{25}Al(p,γ)^{26}Si radiative capture?
2) Calculate the Q-value of this reaction?
3) The ^{25}Al(p,γ)^{26}Si reaction operates at typical temperatures T_6 = 350, corresponding to the following Gamow window properties (E_0 = 331 keV and ΔE = 230 keV).
   a) What is the relevant excitation energy range in ^{26}Si for the ^{25}Al(p,γ)^{26}Si radiative capture?
   b) Let's consider now the resonant capture mechanism. Based on your previous answer, what are the ^{26}Si states that could potentially play a role in the ^{25}Al(p,γ)^{26}Si reaction rate? Calculate the associated resonance energies in the center of mass.

c) Determine the relative orbital angular momentum forming the ^{26}Si states identified previously. What is the most likely contributing state to the $^{25}Al(p,\gamma)^{26}Si$ reaction rate? Justify.

Useful information

1) **^{3}He:** $J^{\pi} = 1/2^{+}$, m = 3.016029 u, Z = 2; **proton:** $J^{\pi} = 1/2^{+}$, m = 1.007825 u, Z = 1; **^{26}Si:** $J^{\pi} = 0^{+}$, m = 25.992333 u, Z = 14; **^{25}Al:** $J^{\pi} = 5/2^{+}$, m = 24.990428 u, Z = 13; u = 931.494 MeV/c^2
2) **elementary charge:** $q_{e-} = 1.6\times10^{-19}$ C; **cross section unit:** 1 b = 10^{-24} cm^2
3) Table of ^{26}Si excited states properties (energy and spin/parity) between 5.2 MeV and 6.4 MeV.

E (level) [keV]	J^{π}
5289	4+
5518	(4+)
5676	1+
5890	0+
5929	3+
5946	0+
6101	
6295	2+
6383	(2+)