Examination NPAC 2020–2021	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) Give some general characteristics of Globular Clusters.
2) Describe the stellar evolution up to their fate of a 2 $M_\odot$ and 10 $M_\odot$ star.
3) Give the lifetime of a 2 $M_\odot$ and 10 $M_\odot$ star.
4) Justify why Globular Clusters mostly contain low mass stars (remember that Globular Clusters are formed from the collapase of very large molecular clouds, and that *stars were born at the same time*).

The ^{30}Si(p,γ)^{31}P reaction

Anomalies in elemental abundances have been observed in the red giant star population of Globular Clusters. In this context it has been shown that the ^{30}Si(p,γ)^{31}P radiative capture destroying ^{30}Si in quiescent burning play an important role.

1) What are the two possible reaction mechanisms operating in the ^{30}Si(p,γ)^{31}P radiative capture?
2) Calculate the *Q*-value of this reaction?
3) The ^{30}Si(p,γ)^{31}P reaction operates at typical temperatures T_6 = 100 in red giant stars. Calculate the Gamow window properties (E_0 and ΔE).
4) What is the relevant excitation energy range in ^{31}P for the ^{30}Si(p,γ)^{31}P radiative capture?
5) Let's consider now the resonant capture mechanism. Based on your previous answer, what are the ^{31}P states that could potentially play a role in the ^{30}Si(p,γ)^{31}P reaction rate? Calculate the associated resonance energies in the center of mass.
6) Determine the relative orbital angular momentum forming the ^{31}P states identified previously. What is the most likely contributing state to the ^{30}Si(p,γ)^{31}P reaction rate? Justify.

Experimental approach

The ^{30}Si(p,γ)^{31}P reaction rate can be computed as the sum of the contribution of individual resonances.

0) Give the complete formula of the resonance strength in case of the ^{30}Si(p,γ)^{31}P reaction.

1) Indirect method

a) Justify why for low resonance energies (say $E_{c.m.}$ < 400 keV) the proton width (Γ_p) is much smaller than the γ-ray partial width (Γ_γ). Write an approximate form of the resonance strength. What is the partial width that should be determined?
b) What kind of transfer reaction can you use to study the ^{30}Si(p,γ)^{31}P reaction? What is the important parameter(s) extracted in such experimental approach? How is it linked to the proton width?
c) During an angular distribution measurement, an ^{3}He^{1+} beam of 500 nA impinges an enriched ^{30}Si target containing 5×10^{17} atoms/cm^2. Deuterons from the reaction are detected with a magnetic spectrometer having an acceptance corresponding to a detection efficiency of 9.6×10^{-4}. At a detection angle of 10° the number of detected deuterons is 16200 during 3 hours. Calculate the number of incident ^{3}He^{1+} ions and the cross section of the ^{30}Si(^{3}He,d)^{31}P reaction in these conditions.

2) *Direct method*

a) The $^{30}Si(p,\gamma)^{31}P$ reaction is also important in explosive events (type Ia supernova) where higher temperatures ($T_9 \approx 1 - 2$) are involved. Explain qualitatively why the resonances of interest in this context will have higher energies than in the previous case of red giant stars.

b) For energies greater than say $E_{c.m.}$ = 400 keV direct measurements can be performed. Imagine an experimental setup for such measurement.

Useful information

1) **proton:** $J^\pi = 1/2^+$, m = 1.007825 u, Z = 1; **^{30}Si:** $J^\pi = 0^+$, m = 29.973770 u, Z = 14; **^{31}P:** m = 30.973762 u, Z = 15; u = 931.494 MeV/c^2
2) **elementary charge:** $q_{e-} = 1.6\times10^{-19}$ C; **cross section unit:** 1 mb = 10^{-24} cm^2
3) Table of ^{31}P excited states properties (energy and spin/parity) in the 7 MeV region.

E (level) [keV]	J^π
7158	
7214	$1/2^-$, $3/2^-$
7314	$1/2^+$, $3/2^+$
7346	
7356	
7440	$3/2^+$
7442	$11/2^+$
7466	$5/2^-$
7572	
7687	
7718	
7736	$5/2^-$, $7/2^-$