Deformation effects in ^{36}Mg$(n,\gamma)^{37}$Mg radiative capture reaction

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Introduction

Most of the formation of heavy elements in the universe is generally accepted to be via the r-process at high temperatures and neutron densities. Such conducive environments can be found in post collapse phase of a type-II or type-Ib supernova. However uncertainties remain in determining the actual path of the r-process, more so because it passes through the neutron rich region of the nuclear chart where a large proportion of the nuclei are unknown. Other known sources of uncertainty are the seed nuclei for the r-process and their abundances. That would critically depend on the path followed through lighter elements while creating these seed nuclei Ref. [1]. In fact, the r-process path involving neutron-rich nuclei can, in principle, go upto the drip-line isotope once equilibrium between (n,γ) and (γ,n) nuclei is established. If, however, the (α,n) reaction becomes faster than the (n,γ) reaction on some "pre-drip-line" neutron-rich isotope, then r-process flow of radiative neutron capture followed by the $A(e^-\nu)$ reaction is broken and the reaction path will skip the isotope on the drip-line.

It is conjectured in Ref. [1] that at the relevant low temperatures (around $T_9 = 0.62$), the rate of ^{36}Mg$(\alpha,n)^{39}$Si reaction overwhelms those of ^{36}Mg$(n,\gamma)^{37}$Mg reaction. Consequently the Magnesium drip-line is bypassed and the alpha-capture turns the reaction flow to higher mass regions. However, this assertion is critically dependent on proper inclusion of structure effects of the nuclei involved. Recent Coulomb dissociation studies around the neutron number $(N) = 20$ have indicated that ^{37}Mg could be deformed and that it's ground state spin-parity may not follow the usual shell model scheme. This would obviously have consequences on the ^{36}Mg$(n,\gamma)^{37}$Mg reaction rate and the subsequent path followed to build up the abundances of seed nuclei for the r-process nucleosynthesis.

In this contribution we use the Coulomb dissociation (CD) method to calculate the rate of the ^{36}Mg$(n,\gamma)^{37}$Mg radiative capture reaction. The CD cross sections of the ^{37}Mg nucleus on a Pb target at the beam energy of 244 MeV/nucleon, for which new experimental data have recently become available [2], have been calculated within the framework of a finite range distorted wave Born approximation theory (FRDWBA) that is extended to include the projectile deformation effects [3]. This is then used to calculate the radiative capture cross section, as mentioned in the next section.

Formalism

Invoking the principle of detailed balance, the radiative capture cross section, σ_{bc}, for the process $b + c \to a + \gamma$ can be calculated from the photodisintegration cross section $\sigma_{a\gamma}$ of the time reversed reaction, $a + \gamma \to b + c$ as,

$$\sigma_{bc} = \frac{2(2j_a+1)}{(2j_b+1)(2j_c+1)}\frac{k_\gamma^2}{k_{bc}^2}\sigma_{a\gamma}, \qquad (1)$$

where j_a, j_b and j_c are the spins of particles a, b and c, respectively. k_γ and k_{bc} are the wave

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numbers of the photon and that of relative motion between b and c, respectively.

In turn, the two-body photodisintegration cross section can be related [4] to the relative energy spectra of the three-body elastic Coulomb breakup reaction ($a + t \rightarrow b + c + t$, t being a heavy target) as

$$\frac{d\sigma}{dE_{bc}} = \frac{1}{E_\gamma}\Sigma_\lambda n_{\pi\lambda}\sigma_{a\gamma}, \quad (2)$$

where $n_{\pi\lambda}$ is the virtual photon number of type π (electric or magnetic) and multipolarity λ. The photon energy is given by $E_\gamma = E_{bc} + S_n$, with S_n as the nucleon separation energy of the projectile a, which in principle can also be deformed.

The relative energy spectra can be obtained by considering the elastic breakup of a two-body composite 'deformed' projectile a into fragments b and c in the Coulomb field of a target t. For more details of the theory of Coulomb dissociation with deformed projectile we refer to [3].

Results and discussions

The data on the one-neutron separation reaction of ^{37}Mg on a ^{208}Pb target [2] have been analyzed within the extended FRDWBA theory. From comparison of calculations with the experimental data it was concluded that the most likely configuration for the ^{37}Mg ground state is ^{36}Mg(0^+)$\otimes$ $2p_{3/2}n$ with a quadrupole deformation parameter β_2 of 0.35.

As mentioned earlier, from the relative energy spectra in the Coulomb breakup of ^{37}Mg on a Pb target, we have estimated the photodissociation cross section of ^{37}Mg$(\gamma, n)^{36}$Mg reaction. The later was then converted to (n, γ) capture cross section on ^{36}Mg using the principle of detailed balance. This is the first calculation of the radiative capture rates with proper inclusion of deformation effects.

In Fig.1, we present our estimate for the ^{36}Mg$(n, \gamma)^{37}$Mg reaction rate as a function of stellar temperature for different quadrupole deformation parameter β_2. Comparing these rates with those obtained from a Hauser-Feshbach calculation of the ^{36}Mg$(\alpha, n)^{39}$Si reaction, we find that for stellar temperatures T_9 below 2 (in the units of 10^9 K), the rates of the reaction ^{36}Mg$(n, \gamma)^{37}$Mg dominate over those of the (α, n) reaction. Therefore, at the equilibrium temperature of the r-process (T_9 = 0.62) the $(n, \gamma)A(e^-\nu)$ process will continue to produce isotopes beyond ^{36}Mg and could reach to the Mg drip-line.

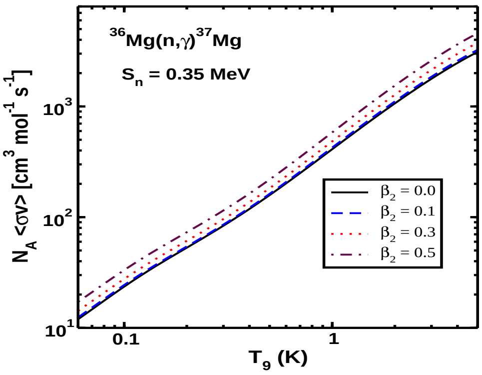

FIG. 1: ^{36}Mg$(n, \gamma)^{37}$Mg reaction rate as a function of stellar temperature for different quadrupole deformation parameter $\beta_2 = 0$ (solid), 0.1 (dashed) 0.3 (dotted) and 0.5 (dot-dashed). In each case the neutron separation energy was held fixed to 0.35 MeV

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