Microscopic optical model and bridging the waiting points in *rp* process

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The relative abundance of elements is an important area of study in nuclear astrophysics. Proton and neutron capture and their inverse processes as well as β-decay play an important role in creating the heavy elements. Particularly rapid proton capture (rp process) in explosive nucleosynthesis of nuclei is an important ingredient in driving the abundance along the $N = Z$ line. For example, X-ray bursts provide a large flux of protons at peak temperatures around 1.5-2 GK and are expected to play a significant role in the creation of nuclei up to mass 110.

The nuclei which have the highest abundance in an equilibrium in a chain is called the waiting point for the chain. Once equilibrium is established, the process has to wait for the beta decay of the waiting point nucleus to proceed to heavier nuclei. Certain $N = Z$ waiting point nuclei, *viz.* ^{56}Ni, ^{64}Zn, ^{68}Se and ^{72}Kr have long lifetimes, their total lifetime being large compared to the time scale of typical X-ray bursts (10-100 sec). Thus they provide a bottleneck in the rp-process which would slow down the rate of hydrogen burning and lead to extended burst tails unless proton capture can reduce these lifetimes. X-ray burst model calculations are therefore particularly sensitive to the rates of proton capture for these nuclei.

Experimental measurements of proton capture rates in these nuclei are not available as they are unstable and theoretical calculations remain our only guide. A microscopic optical model calculation based on theoretical mean field densities are expected to provide us with reliable rates. With this in mind, we have calculated theoretical density profiles in a Relativistic Mean Field (RMF) approach. The calculations have been carried out in co-ordinate space assuming spherical symmetry. Pairing has been introduced under the BCS approximation using a zero range pairing force of strength 300 MeV-fm for both proton and neutrons. The RMF+BCS equations are solved under the usual assumptions of classical meson fields, time reversal symmetry, no-sea contribution, etc. The microscopic optical model potentials for the reactions are obtained using effective interactions derived from the nuclear matter calculation in the local density approximation, *i.e.* by substituting the nuclear matter density with the density distribution of the finite nucleus. In the present work, the microscopic nuclear potentials have been obtained by folding the density dependent DDM3Y effective interaction[1] with the microscopic densities. rates were calculated in the Hauser-Feshbach formalism using the computer package TALYS1.2[2]. This method has already been applied in mass 60 region in [3].

A small network has been designed which includes the following processes. The waiting point nucleus with $Z = N$. which acts as a seed, may capture a proton. The resulting nucleus, with $Z = N + 1$, may either capture another proton or undergo photodisintegration emitting a proton to go back to the seed nucleus. The nucleus with $Z = N + 2$ may also undergo photodisintegration. In addition, all the three nuclei mentioned above may undergo β decay. The photodisintegration rates at different temperatures have been calculated from the proton capture rates using the principle of detailed balance. The flux has been taken as 10^6 particles per second and the proton fraction has been taken as 0.7.

The results for seed nuclei ^{56}Ni and ^{64}Ge are

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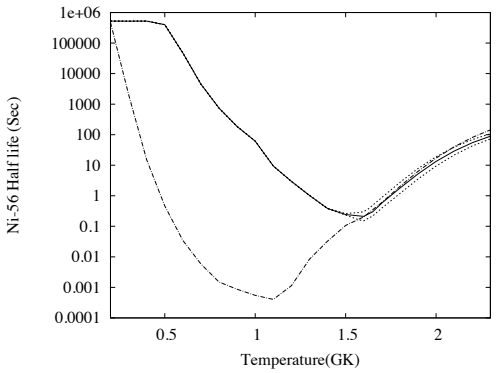

FIG. 1: Half life values in ^{56}Ni as a function of temperature. The solid line represents the results of our calculation while the dashed lines mark the two extremes for the errors in the Q-values of the reactions involved. The dash dotted line shows the results obtained using the rates from [4].

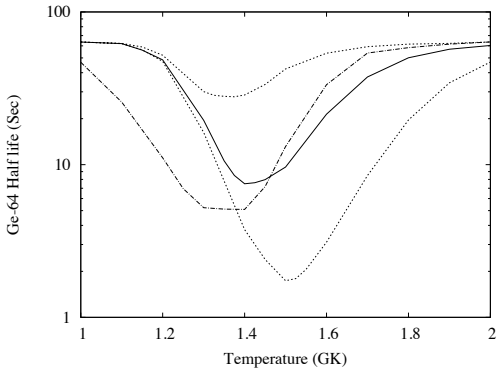

FIG. 2: Half life values of ^{64}Ge as a function of temperature. See caption of Fig. 1 for details.

shown in Figs.1 and 2. One can see that the lifetime indeed gets reduced, reaching the minimum around 1.5 GK temperature, thus bridging the gap at waiting point for nucleosynthesis to proceed along the $Z = N$ line. For ^{56}Ni, the lifetime becomes less than 1 second. However, for ^{64}Ge, one can see that the change is significantly dependent of the Q-value of the reactions. One of the major drawbacks in these calculations is the lack of knowledge about the Q-values in reactions other than the ones involving ^{56}Ni as seed. Since experimental values are not available, we have used the Q-values and their errors adopted in [5]. It is clear that the life time values may vary over a large range corresponding to the uncertainty over the Q-values. Predictions of Q-value for the reaction ^{64}Ge(p,γ), for various mass formulae, vary from -0.1 MeV to -0.4 MeV. It is clear that the life time value will differ significantly for the various values. Thus accurate measurement of the Q-values are required before one can be confident about the mechanism. Results for (p,γ) processes for ^{68}Se and ^{72}Kr seed nuclei follow a pattern similar to ^{64}Ge.

We also note that the rates from [4] produce significantly different results in case of ^{56}Ni seed with the lifetime decreasing to millisecond level. For ^{64}Ge also, the results are somewhat different. The lowest lifetime value and the temperature around which it is obtained is comparable. However in both the cases, the lifetime values start to decrease much earlier and the ranges over which significant change in lifetime takes place are much broader. This is a consequence of a larger value of the rates form [4].

Acknowledgments

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