A statistical model with microscopically folded optical potential to study the astrophysical radiative neutron capture reactions near the Sn-Sb-Te region of *s*-process

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Introduction

It is now well-known that the nuclei heavier than iron are synthesized by slow neutron capture process (*s*-process), rapid neutron capture process (*r*-process), and the proton capture process (*p*-process). The abundances of elements produced by each of these processes can be determined by constructing and solving complex networks that consist of a set of coupled differential equations involving a large number of radiative neutron capture reaction rates as inputs. To determine the exact contribution of the processes to the isotopic abundances of nuclei, separate network calculations for *s*-, *r*-, and *p*-processes are required. However, r- and *p*-processes that occurs in explosive astrophysical environments proceeds along the extreme neutron and proton-rich side, respectively in the nuclear chart. Hence, they deal with radioactive exotic nuclei, experiments for which are impossible to perform in the terrestrial laboratory. Though the *s*-process proceeds along the stability valley, reaction cross sections for many isotopes are either not measured or the old experimental cross sections suffer from inherent systematic and statistical uncertainties. Even a small uncertainty in reaction cross sections can result in incorrect abundances. Hence, there is an urgent and dire need for reliable theoretical statistical model calculations of radiative neutron capture cross sections/ reaction rates. The (n,γ) cross sections are important in *p*-process as well that involves photo-disintegration reactions the rates of which can be obtained from forward (n,γ) reactions via the detailed balance calculation. The Sn-Sb-Te region near the $Z = 50$ shell closure is very interesting as the nucleosynthesis in this region takes place via a delicate interplay of all three processes. In this paper, we have presented the theoretical neutron capture data for several nuclei near magic $Z = 50$ shell over a range of energies of astrophysical interests calculated with our statistical model predictions using the reaction code TALYS [1].

Model framework

Our statistical model is based on compound nuclear Hauser-Feshbach formalism. We need a neutron optical model potential (OMP) to determine the transmission coefficients in the entrance channel. We have formulated a novel neutron OMP in microscopic folding model approach. The real density-dependent M3Y nucleon-nucleus interaction (V_{NN}) has been folded with target radial matter densities [$\rho(r)$]. $V_{NN} = 7999\frac{e^{-4r}}{4r} - 2134\frac{e^{-2.5r}}{2.5r} - 276(1-0.005E/A)$; $V_{fold} = \int V_{NN}|\mathbf{r}-\mathbf{r}'|\rho(\mathbf{r}')d\mathbf{r}'$; This folded potential (V_{fold}) is taken as both the real and the imaginary parts of our OMP. The densities are taken from our relativistic-mean-field (RMF) model. The Lagrangian density of our model are based on FSUGold parameterization [3]. The Hauser-Feshbach theory demands a large number of overlapping levels in the compound nucleus so that an average of the individual resonances can be obtained. Hence, nuclear level densities are the important imgredients in our model calculation. Since the exit channel has photons, dominant E1 γ-ray strength functions are also important. We have taken these ingredients from latest microscopic calculations [4, 5]. More details can be available in Refs. [6–8].

TABLE I: Binding energy (B.E.) and rms charge radius values (r_c)

Nucleus	B.E. (MeV)		r_c (fm)	
	Theo.	Expt.	Theo.	Expt.
^{112}Sn	952.49	953.53	4.576	4.595
^{114}Sn	970.67	971.57	4.589	4.610
^{121}Sb	1026.62	1026.33	4.658	4.680
^{123}Sb	1042.35	1042.10	4.672	4.688
^{120}Te	1016.92	1017.24	4.667	4.704

To check the feasibility of our RMF model, charge density distributions of several nuclei near the Sn shell closure are calculated by folding the RMF point proton density [$\rho_p(r)$] with a standard Gaussian form factor $F(r)$. $\rho_{ch}(\mathbf{r}) = e\int \rho_p(\mathbf{r}')F(\mathbf{r}-\mathbf{r}')d\mathbf{r}'$; $F(r) = (a\sqrt{\pi})^{-3}exp(-r^2/a^2)$. Here, $a = \sqrt{2/3}a_p$, with $a_p = 0.8$ fm, being the root-mean-square (rms) charge radius of proton. Next, rms charge radius values and binding energies are calculated and compared with available experimental data [9, 10]. Within stars, neutron velocities are quickly thermalized and hence, cross sections have to be folded with Maxwellian-Boltzmann distribution to obtain the so-called Maxwellian-averaged cross section (MACS) values. Maxwellian-averaged reaction rates taking into account the contribution of the ground as well as the excited states are also calculated in a similar way.

FIG. 1: Elastic scattering angular distributions for ^{116}Sn. Solid lines represents theoretical results.

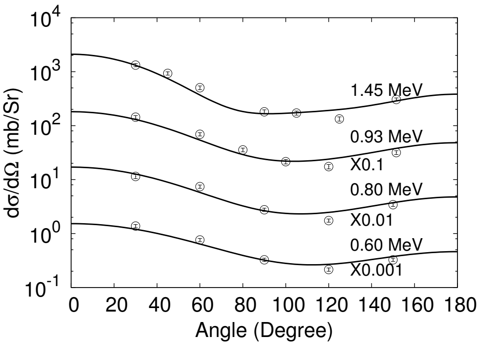
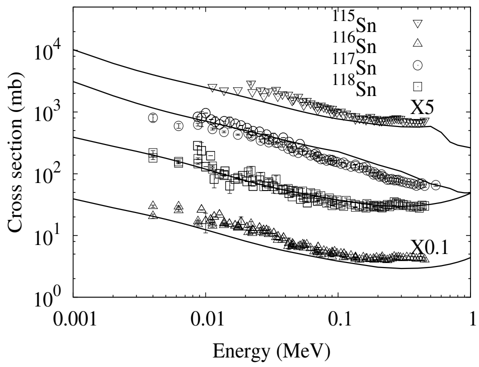


FIG. 2: Cross sections from the present calculation for $^{115-118}$Sn. Solid lines represents theoretical results.



Results

Table I shows the rms charge radius values and binding energies from our RMF model compared to available experimental data. The good agreements between theory and experiment suggest that our RMF model is feasible and reliable.

We have plotted the differential elastic scattering cross sections at various low energies for the target ^{116}Sn in Fig. 1. The reasonable agreement with the experiment suggests that our folding potential is good enough. Fig. 2 shows the radiative neutron capture cross sections on several Sn isotopes compared with experimental data available in National Nuclear Data Center [2]. The reasonable agreement with the available experimental data indicates that the model can be extended to the experimentally unknown regions for astrophysical applications. In s-process, β-decay rates are greater than average neutron capture rates. However, there are certain long-lived radioactive branch point isotopes that have comparable neutron capture and β-decay rates. In Table II, Maxwellian-averaged cross sections over a range of s-process energies are presented for some unstable branch-point isotopes near the Sn-Sb-Te region. Table III presents astrophysical reaction rates for rare p-isotopes of Sn, that are produced only in p-process over a range of temperatures relevant to astrophysical p-process. For the sake of comparison, the rates from BRUSLIB database are also listed. As can be seen that our rates are quite different from BRUSLIB rates and hence, it will be interesting to observe the impact of these differences on astrophysical calculations.

TABLE II: MACSs over a range of thermal energies for a few branch-point nuclei near the Sn shell closure.

kT (MeV)	MACS (mb)		
	^{121}Sn	^{122}Sb	^{127}Te
0.005	683	3601	2400
0.010	437	2346	1565
0.015	338	1855	1241
0.020	281	1572	1060
0.025	244	1377	939
0.030	217	1229	851
0.040	179	1012	727

TABLE III: Astrophysical reaction rates over a range of stellar temperatures for some rare p-nuclei.The rates are in the order of 10^7.

T_9(GK)	$N_A < \sigma v >$ (cm^3 mol^{-1} sec^{-1})					
	^{112}Sn		^{114}Sn		^{115}Sn	
	Pres.	Ref.[11]	Pres.	Ref.[11]	Pres.	Ref.[11]
1.0	3.171	3.335	1.752	1.303	4.389	2.934
2.0	4.043	4.189	2.228	1.662	5.631	3.551
3.0	5.389	5.597	3.018	2.203	6.652	3.640
4.0	6.954	6.647	3.878	2.367	5.304	1.849
5.0	4.971	4.296	3.647	1.359	2.287	0.707

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References

[1] A. J. Koning *et. al.*, in *Proceedings of the International Conf. on Nucl. Data for Sci. and Technol., April 22-27, 2007, Nice, France*, eds. O. Bersillon *et. al.*, (EDP Sciences, Cedex, France, 2008), p. 211; http://www.talys.eu
[2] http://www.nndc.bnl.gov
[3] B. G. Todd-Rutel *et. al.*, Phys. Rev. Lett. **95** 122501 (2005).
[4] S. Goriely *et. al.*, Phys. Rev. C **78**, 064307 (2008).
[5] R. Capote *et. al.*, Nuclear Data Sheets **110**, 3107 (2009).
[6] S. Dutta *et. al.*, arXiv:1610.02677 [nucl-th].
[7] S. Dutta *et. al.*, Phys. Rev. C **93**, 024602 (2016).
[8] S. Dutta *et. al.*, Phys. Rev. C **94**, 054611 (2016).
[9] I. Angeli *et. al.*, Atomic Data Nucl. Data Tables **99**, 69 (2013).
[10] M. Wang *et. al.*, Chin. Phys. C **36**, 1603 (2010).
[11] www.astro.ulb.ac.be/bruslib/