TALYS calculation and a short review of the experimental status of proton capture studies on p-nuclei: A guide to future investigation

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Introduction

After Big Bang nucleosynthesis the charged particle reactions are the primary processes of nucleosynthesis till mass $A \approx 60$. For the heavier elements neutron capture through *s* (slow) and *r* (rapid) process [1-3] becomes the dominant process. There is a small fraction (~ 35 nuclei between Se [Z=34] to Hg [Z=80]) of proton-rich nuclei which are 10-1000 times less abundant than *s*- or *r*-nuclei and cannot be synthesized through the neutron capture processes as they are on the neutron deficient side of the β-stability line. These are synthesized by a different astrophysical process, traditionally called the *p*-process or γ-process, and these nuclei are referred to as the *p*-nuclei [1-6]. Few studies suggest that some of the *p* nuclei can also be produced in charged particle reactions [7]. In recent years, serious efforts have been given to both theoretical and experimental investigations to understand the *p*-process nucleosynthesis.

Present Work

Nuclear reaction rates are essential ingredients for investigation of energy generation and nucleosynthesis processes in stars. These reaction rates are functions of the densities of the interacting nuclei, their relative velocities and reaction cross-sections [6,8]. The present work is primarily an attempt to provide guidance for future experimental studies involving cross-section measurements. Theoretical calculations has been performed to estimate the cross-section values and the status of the corresponding experimental measurements has been reviewed.

The charged particle induced reactions play key roles in the *p*-process nucleosynthesis. These reactions take place within a narrow energy window called Gamow window (ΔE_0) around the effective burning energy known as Gamow peak E_0, which lies well below the Coulomb energy E_c. The Gamow peak arises from folding the Coulomb penetration probability with the Maxwell-Boltzmann velocity distribution and is given by

$$E_0 = \left(\frac{bkT}{2}\right)^{\frac{3}{2}}, \; b = 31.28\, Z_1\, Z_2\, A^{1/2} \text{ keV}^{1/2}$$

The corresponding expression for Gamow window is given by,

$$\Delta E_0 = \frac{4}{\sqrt{3}}(E_0 k_B T)^{1/2}$$

The cross-section for charge particle reactions for $E < Ec$ (E is the center of mass energy for the reacting system) is given by,

$$\sigma = S(E)\frac{1}{E}exp\big(-2\pi\eta(E)\big).$$

The theoretical estimates of proton induced reaction cross-sections have been calculated for all the *p*-nuclei using TALYS [9] code. In the present calculation default parameters [9] are used. These results, when compared with the existing experimental data, help us to identify the systems which require reinvestigation or the systems where no or very little experimental data exists.

The results of the present TALYS calculations are plotted against the proton energy, a few of which are shown in Fig. 1 for the region around Gamow energy. The corresponding experimental values obtained from the KaDONiS [10] database are included for comparison in the figure. Also included are the corresponding values given in the TENDL tabulation [11]. The experimental parameters used by various groups [10] are summarized in Table 1.

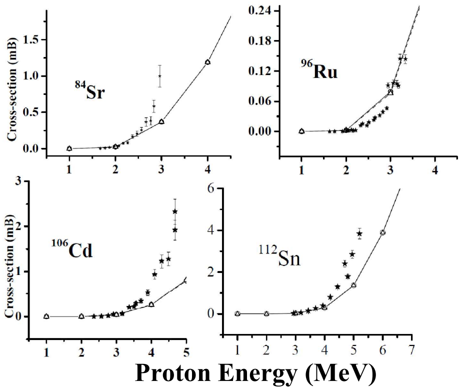

Fig.1: Present TALYS calculation results (open circle) plotted and compared with experimental results (solid star) and TENDL values (open triangle). The theoretical values connected to guide the eye.

TABLE 1: Some experimental parameters used from References given in KaDONiS [10] database.

p-nuclei	Proton energy (MeV)	Target& Backing	γ-Ray Detector	Beam Current
^{74}Se	1.3 -3.6	Nat. Se (thick Al) 200-700 $\mu g/cm^2$	Single HPGe	5-10 μA
^{78}Kr				
^{84}Sr	1.5 – 3	Nat. SrF2 (thick C)	Single HPGe	5-10 μA
^{92}Mo	1.5 – 3	Nat. Mo (1mm Al) 0.12 – 0.5 μm	Single HPGe	45 μA
	Gamow region	Enriched ^{92}Mo 400 $\mu g/cm^2$	13 HPGe(HOKUS)	200nA
^{94}Mo	1.5 - 3	Nat. Mo (1mm Al) 0.12 – 0.5 μm	Single HPGe	45 μA
^{96}Ru	1.5-3.5	Nat. Ru(1mm Al)	Single HPGe	20-50 μA
^{98}Ru	1.5-3.5	Nat. Ru(1mm Al)	Single HPGe	20-50 μA
^{102}Pd	2.68–6.85	Nat. Pd(Al 1mm Al) 420-520nm	Single HPGe	10 μA
^{106}Cd	2.4-4.8	Nat Cd and enriched (96.47%) (3μmAl) 100 600 $\mu g/cm^2$	Single HPGe	500nA
^{108}Cd	2.4-4.8	Nat Cd and enriched (2.05%) (3μmAl) 100-600 $\mu g/cm^2$	Single HPGe	500nA
^{112}Sn	3-8.5	Enriched (98.9%) 2.7 $mg/cm2$	Two BGO (one HPGe for energy calibration)	100-150 nA
^{114}Sn	1-3.7	Enriched (71.1%) 0.05 $mg/cm2$	Two coaxial HPGe	
^{120}Te	2.5-8	Enriched (99.4%) 128$\mu g/cm^2$(20$\mu g/cm^2$C) 456$\mu g/cm^2$(1.5mg/cm^2C)	Two Clover detectors	80-320nA

Future Plan

The cross sections of the charged particle capture reactions on p-nuclei are extremely small (Fig.1). To make the measurements possible in the Gamow region one needs low energy high current accelerators. FRENA [12] at the Saha Institute of Nuclear Physics, Kolkata, is going to provide us with the facility to perform such studies. Initially experiments will be carried out using the activation method which is free from beam induced backgrounds and the analysis of the low cross-section events becomes less erroneous. The experimental results will be compared with TALYS estimates as well as the previous results [10]. This exercise will help us to validate our experimental and analytical techniques. Once satisfied, we shall attempt to investigate the systems where very few or no data exists.

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