# Study of bare atom beta decay and a low energy resonance state relevant to nuclear astrophysics

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It is well known that the abundance evaluation in stellar processes is determined by two nuclear physics inputs: β-decay rates and the Maxwellian averaged reaction rate ($N_A \langle\sigma v\rangle$).

In the theoretical programme, we have studied $\beta^-$ decay rates of fully ionized atoms both in terrestrial and stellar s-process conditions. In our experimental endeavour on the problems of nuclear astrophysics, we have measured the lifetime of a low energy resonance state in $^{25}$Al through the $^{24}$Mg(p, γ)$^{25}$Al reaction.

## $\beta^-$ decay of bare atoms in terrestrial and stellar s-process environments

The $\beta^-$ decay is a weak interaction process that allows the conversion of a neutron into a proton with the creation of an electron and an antineutrino in the continuum state. If there is vacancy in atomic bound orbits, then $\beta^-$ decay to atomic bound state becomes another possible decay channel. In 1947, Daudel *et al.* [1] first theoretically predicted this new branch of $\beta^-$ decay as the phenomenon of the creation of an electron in the empty bound atomic orbit. This is just the time-reversed process of atomic orbital electron capture. In the 1980s Takahashi *et al.* [2, 3] made elaborate studies of the bound state $\beta^-$ decay in the context of nuclear astrophysics. Takahashi and Yokoi [3] calculated $\beta^-$ decay rates including bound state $\beta^-$ decay of a number of nuclei relevant to the s-processes. However, in that work, they did not provide the bound and the continuum state $\beta^-$ decay rates separately. Thus, the importance of bound state decay in stellar processes was not clearly revealed. We could not trace in literature any further theoretical study on bound state $\beta^-$ decay in the context of nuclear astrophysics after the works of Takahashi and Yokoi [2]. With the availability of modern-day experimental $\beta^-$ decay half-lives (terrestrial) for neutral atoms, experimental Q values, and atomic physics inputs, it was inevitable to revisit some of the earlier works.

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Thus in our first attempt [4], we have studied the $\beta^-$ decay of some fully ionized (bare) atoms over the range of nuclei A = 60 – 240, which might be of interest for future measurements on bound state decay using a storage ring. In particular, calculations of $\beta^-$ decay rates to the continuum as well as bound states of these bare atoms, where information for neutral atom experimental half-life and $\beta^-$ decay branchings are terrestrially available, have been performed. The total decay rates obtained for the set of nuclei considered can be viewed as the maximum limiting values for the rates. We have also compared our calculated result with the rate measured in the storage ring experiment. In addition, some interesting phenomena of changes in $\beta^-$ decay branching for a number of bare atoms have been discussed, for the first time.

In our next attempt [5, 6], we have calculated $\beta^-$ decay rates to the continuum and bound states of some bare atoms in the stellar s-process environment having free electron density and temperature in the range $n_e = 10^{26}$cm$^{-3}$–$10^{27}$ cm$^{-3}$ and T = $10^8$ K–5 ×$10^8$ K, respectively. The presence of bare atoms in these particular situations has been confirmed by solving Saha ionization equation taking into account the ionization potential depression (IPD). At these temperatures, low lying excited energy levels of parent nuclei may have thermal equilibrium population and those excited levels may also decay via $\beta^-$ emission. The Nuclear Matrix Element (NME) of all the transitions of the set of 15 nuclei is calculated using nuclear shell-model. These NME are then used to calculate the comparative half-life ($ft_{1/2}$) of the transitions. Calculated terrestrial half-lives of the $\beta^-$ decays are in good agreement with the experimental results in most of the cases. Decay to bound and continuum states of bare atoms from ground/isomeric levels and excited nuclear levels have been calculated separately. The importance of the bound state $\beta^-$ decay in stellar situations has been shown explicitly. We have calculated total $\beta^-$ decay rates (bound state plus continuum state) taking into account IPD corrected neutral atom Q-value as a function of density and temperature. We have also presented results for the stellar $\beta^-$ half-lives and compared the ratio of neutral atom to bare atom half-lives for different density and temperature combinations.

## Lifetime measurement of the $E_x$=2485.3 keV level of $^{25}$Al populated through $^{24}$Mg(p,γ)$^{25}$Al resonance reaction

The $^{24}$Mg(p, γ)$^{25}$Al (Q = 2271.37 keV) is an important reaction for nuclear astrophysics relevant to various stages of stellar evolution. The reaction rates of this particular reaction at astrophysical energies have contributions from a low energy resonance at $E_p^{lab}$ = 223 keV. However, it has been pointed out [7] that at temperatures important for globular cluster red giant stars, the Gamow window is located far below the energy of this particular resonance. Thus, the contribution from the low - energy wing of this resonance has to be considered. B. Limata *et al.* [8] measured the strength of this resonance with higher precision. They pointed out that as the narrow resonance approximation is not valid [8] to evaluate the reaction rate at the low energy tail of this resonance, the γ-width of this resonance needs to be known to a higher precision.

Several attempts were made [7, 9] to measure the lifetime of the $E_x$ = 2485.3 keV resonance state of $^{25}$Al. P. B. Dworkin-Charlesworth [9] used the Doppler Shift Attenuation technique to measure the mean lifetime ($\tau = 8.4 \pm 3.0$ fs) of this state using an evaporated Mg target. Trautvetter and Rolfs [10] presumably adopted this lifetime to report a width of 75 meV for the 223 keV resonance state. Later D. C. Powell *et al.* [7] also studied this reaction ($E_p$ = 200 − 1700 keV) with an implanted $^{24}$Mg target with thick Ta backing. They obtained a mean lifetime $\tau = 5.3^{+2.9}_{-2.4}$ fs of the $E_x$ = 2485.3 keV level which corresponds to a total width of $\Gamma$ = 155 ± 48 meV with ∼ 50% uncertainty. Powell et al. [7] claimed that the result of Ref. [9] carries large systematic uncertainties due to the use of thick evaporated Mg and small Doppler shifts observed due to low bombarding energy close to $E_p \simeq 223$ keV. The significant difference between the two results and ∼50% uncertainty in each of them indicates a need for further measurements with higher precisions. Thus, we were motivated to remeasure the lifetime to check the value and understand the reason behind these differences, if possible. With an evaporated natural Mg target (Ta backing) we have performed an experiment at TIFR, Mumbai to measure the lifetime of the resonance state using the DSA technique.

Moreover, because of the large uncertainties in the experimental results, it is worth to see what the theory predicts. We have performed detailed shell-model (SM) calculations to predict the lifetime and other structural features of $^{25}$Al till the first non-yrast $1/2^+$ state, using three standard interactions successfully used earlier in this mass region.

We have obtained $\tau = 6.04^{+3.03}_{-2.65}$ fs. This lifetime value corresponds to the width of the resonance level = $108.98^{+85.18}_{-36.41}$ meV. The lifetimes of the resonance level obtained from SM calculations with w and cw interactions are in close agreement with the present experimental result. Although we have not been able to provide more precise results than earlier work, we could demonstrate that the large mismatch between the two earlier results does not arise from the use of the evaporated target. Our results for τ, using evaporated target, are in better agreement with that of Powell *et al.* [7]. Moreover, the theoretical results also match quite well with the present experimental value.

The author acknowledges the financial assistance received from DST-INSPIRE.

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