Theoretical investigations in the breakup of exotic nuclei

Gagandeep Singh*
Department of Physics, Indian Institute of Technology, Roorkee, UK - 247667, INDIA

The origin of the elements is a fundamental question and though various processes are theorized to explain the formation of nuclei, not all of them have been fully comprehended yet. The most famous example is the rapid neutron capture or the r-process, whose exact astrophysical sites are still ambiguous. It is responsible for production of nuclei heavier than iron near the neutron drip line, where movement away from the valley of stability effectuating extremely low binding energies leads to changes in the nuclear structure and forms what are called exotic nuclei. However, it has been asserted that even light and medium mass exotic nuclei have a significant impact on the terminal elemental abundances in the r-process stellar nucleosynthesis [1].

A class of these nucleon rich nuclei are termed as halos, where the Pauli principle forces the progressively added valence nucleon(s) to move in the classically forbidden region outside an already saturated core and form a misty envelope, thereby enhancing the matter radius of the nucleus and providing an extended density distribution. Due to the small separation energy of these halo nuclei and the presence of usually a broad featureless continuum above the ground state (usually the only bound state), conventional techniques for their study, like excitation spectroscopy, are not applicable. Further, direct capture reaction measurements at the energies corroborating the stellar environments are extremely difficult to perform. Therefore, indirect approaches are required to study these nuclei, both from the perspective of nuclear as well as astrophysics. Coulomb breakup reactions have emerged as an elegant tool to probe their structure. Coulomb dissociation (CD) works by exploiting the virtual photon field of a heavy target to study the breakup process of the projectile of interest, and then by use of the principle of detailed balance, allows one to analyze the time inverted capture reaction [2]. If the incident beam energy is high enough such that the projectile breaks up at large impact parameters, the nuclear contribution may effectively be ignored. Moreover, for the applicability of the study of the time reversed capture reaction from the photodisintegration reaction, it is mandatory that the reaction be single multipole dominated.

Low dissociation energies has lead CD to be applied quite successfully to study drip line nuclei like ^{11}Be, ^{19}C, ^{31}Ne, and ^{37}Mg among many others [3–5]. In this thesis, we have investigated ^{34}Na, whose role could also be vital in the path for r-process seed nuclei production, especially at the hydrostatic equilibrium temperature of $T_9 = 0.62$ ($T_9 = 1 = 10^9 K$) [1]. However, its ground state spin-parity and one neutron separation energy are not very well known [6, 7]. In fact, although it lies in the $N = 20 - 30$ mass region of the 'island of inversion', it is still not established whether it undergoes configuration reversal due to the $\nu(sd)^{-2}(fp)^2$ intruder configurations, which could guide it to be deformed.

Therefore, we try and put restrictions on the uncertain structural parameters of ^{34}Na by assuming its elastic Coulomb breakup as it is directed at a ^{208}Pb target at 100 Mev/u to eject ^{33}Na and a neutron [8]. For our analysis of CD of ^{34}Na, we have used the fully quantum mechanical theory of finite range distorted wave Born approximation (FRDWBA) evolved to include the effects of deformation in the projectile [4]. In its post form, FRDWBA includes the target-projectile interaction to all orders and the complete non-resonant continuum of the breakup fragments and is thus, free from ambiguities occurring in various first order theories. By use of the local momentum approximation (LMA), our formalism allows us to separate the breakup amplitude into two parts: a structure part involving the potential and hence, the effect of the defor-

*Electronic address: gagandph@iitr.ac.in,gags02@gmail.com

mation, and a dynamics controlling part of the reaction that can be evaluated analytically.

We start by calculating the triple differential cross-section for the elastic breakup reaction ^{34}Na + ^{208}Pb $\longrightarrow$ ^{33}Na + n + ^{208}Pb, and invoke the relevant Jacobians to obtain various reaction observables [8]. The total cross-section so obtained, apart from confirming the dominance of a single multipole ($E1$) for the reaction, in conjunction with the trend in the medium mass region in the island of inversion, suggests that ^{34}Na should have a dominant $^{33}\mathrm{Na}(3/2^+) \otimes 2p_{3/2}\nu$ ground state (g.s.) configuration. The relative energy spectra results with variation in one neutron separation energy (S_n) and quadrupole deformation (β_2) confirm the p-wave for the valence neutron. Our results for the relative energy spectra peak positions (with S_n = 0.17 MeV) encourage the application of scaling laws to weakly bound deformed nuclei, opening a new avenue for further research in this regard. Scaling, if applied in a consistent manner, can be used to indirectly get heuristic estimates about the binding energies and transitions in weakly bound exotic nuclei.

Halo nuclei, owing to their extension in the spatial coordinates, show restricted widths of their momentum distributions. The full width at half maximum (FWHM) values for the parallel momentum distribution (PMD) for some of the established halos like ^{11}Be and ^{19}C are $\sim$ 44 MeV/c [3], while we obtain an FWHM of $\sim$ 33 MeV/u and 36 MeV/u for ^{34}Na with and without deformation, respectively, indicating that indeed ^{34}Na is a strong halo nucleus. Computations for the angular distributions prove the forward domination of the reaction, justifying the negation of nuclear effects at the beam energy considered. The energy-angular distribution and average momenta results further overrule any post acceleration effects of the charged core ^{33}Na.

We then extend our study to explore the astrophysical significance of ^{34}Na and calculate the capture cross-section and rate for the ^{33}Na(n,γ)^{34}Na reaction [9]. The photodisintegration cross-section, which is used to obtain the capture cross-section by the principle of detailed balance, is calculated from the relative energy spectrum of ^{34}Na breaking elastically on ^{208}Pb at 100 MeV/u. The capture cross-section increases with increase in β_2 while with an increase in the S_n value, it first decreases and then increases. This flip is intriguing and vital as it occurs in the region contributing maximally to reaction rates. The cause of this reversal is explained analytically.

Finally, we compare the rate of ^{33}Na(n,γ)^{34}Na with that of the ^{33}Na(α,n)^{36}Al obtained from Hauser-Feshbach estimates using the NON-SMOKER code [10]. Our results confirm the strong domination of the ^{33}Na(n,γ)^{34}Na capture reaction over ^{33}Na(α,n)^{36}Al reaction at ^{33}Na waiting point for the equilibrium temperature of T_9 = 0.62. This should effectively push the r-process seed nuclei production ensuing from the competition between neutron capture and α-capture, towards the sodium drip line amplifying the abundances of ^{34}Na and ^{35}Na.

We encourage experiments to put our predictions on a firmer footing.

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