Investigations in radiative capture reactions

M. Dan[1*]
[1] *Department of Physics, Indian Institute of Technology Roorkee, Roorkee 247 667, India*

Introduction

What is the origin of chemical elements that we see in the universe? Is there a limit of nuclear existence? What happens if we add more neutrons to a stable nucleus? These fundamental questions have been addressed with the study of nuclei away from the valley of stability, especially at and near the drip lines (the limit of neutron or proton binding). Nuclei, very close to the drip lines can exhibit quite different behavior (having very short half-lives and very small one- or two-nucleon separation energies) compared to those of the stable isotopes. Properties of these nuclei are essential inputs to the theoretical calculations on stellar burning which otherwise are often forced to rely on the assumptions about nuclear masses, decays and level structures extracted from stable nuclei [1].

In this light mass region, small changes in reaction rate due to neutron or α-capture or β-decay can ultimately affect the eventual r-process path, thereby affecting the abundance pattern [2]. Considering the above background, we may claim that exotic nuclei in the low mass region need more studies in order to achieve deeper understanding about their structures and reactions involving them. This thesis is focused mainly on the application of Coulomb breakup as an indirect method to calculate radiative capture reactions of low neutron rich nuclei away from the line of stability.

Overview of the thesis work

In this context, we used the finite range distorted wave Born approximation (FRDWBA) to explain various structural properties and reaction observables for these nuclei. It is then used to calculate radiative capture cross sections of these nuclei and thereby also to estimate the associated reaction rates.

We, first, discuss the application of the methodology to a low mass nucleus, ^{11}Be. Here, we use a sophisticated many body wave function deduced from the antisymmetrized molecular dynamics (AMD) to calculate the static properties such as one neutron separation energy, charge and matter radii of ^{11}Be and also used as an input to the fully quantum mechanical Coulomb breakup theory of FRDWBA to calculate exclusive and inclusive reaction observables such as triple differential cross-section, neutron energy distribution, parallel momentum distribution, relative energy spectrum, and dipole response of ^{11}Be in the breakup of ^{11}Be on a heavy target [3]. The results are also compared with the available experimental data, and also with those obtained from a phenomenological wave function derived using a Woods-Saxon (WS) potential whose depth is adjusted to fit the one neutron separation energy of ^{11}Be. These results agreed well with the available theoretical estimates and the experimental data. We have also calculated the ^{10}Be$(n,\gamma)^{11}$Be radiative capture reaction rates and compared our results with the available data. In this work, we combine a microscopic nuclear structure model, AMD, with a reaction model to discuss both the static and dynamical properties of a neutron-halo nucleus ^{11}Be.

The ^{18}C$(n,\gamma)^{19}$C radiative capture reaction have been studied, next, by considering the halo character of ^{19}C. It was postulated that the (n,γ) reaction network will be broken at the ^{18}C isotope and follow the ^{18}C$(\alpha,n)^{21}$O reaction path. In this context, it is important to find the most abundant Carbon isotope closer to the neutron drip line.

We compute the relative energy spectrum for elastic Coulomb breakup of ^{19}C on a Pb

*Electronic address: `mdan@ph.iitr.ac.in`

target at a beam energy of 67 MeV/u using the FRDWBA theory. We report the $^{18}C(n,\gamma)^{19}C$ capture cross-section as a function of relative energy. Estimation of the energy range contributing to the reaction rates is done by calculating the integrand of the reaction rate expression. Later, we calculate the reaction rate of $^{18}C(n,\gamma)^{19}C$ and compare it with $^{18}C(\alpha,n)^{21}O$ at the relevant astrophysical temperatures. Radiative capture cross-section of ^{18}C calculated using FRDWBA theory agrees well with the experimental data, whereas the statistical model calculation lies orders of magnitude lower. We conclude that at equilibrium temperature of $T_9 = 0.62$, the $^{18}C(n,\gamma)^{19}C$ reaction rate is orders of magnitude higher than that of the $^{18}C(\alpha,n)^{21}O$ reaction, thereby pushing the Carbon isotope abundance towards the neutron drip line [4].

Finally, the $^{19}N(n,\gamma)^{20}N$ reaction rate has been calculated. In case of ^{20}N, it has been suggested that the contribution to the reaction rate from the excited states of the core is as vital as that of the ground state. However, it will be interesting to see the range of the temperatures for their contribution. Our results are in well agreement with the experimental values and boost the hypothesis that the contribution of the core excited states to the radiative neutron capture reaction rates is significant only at higher temperatures [5]. It is also observed that the reaction rates for different diffuseness are almost identical at low temperature and some differences is seen at higher temperatures.

Like the light nuclei close to the neutron drip line exhibiting exotic behavior such as halo phenomenon, medium mass nuclei show another exotic behavior. For instance, nuclei with a depression in the central part of their nuclear density are termed as"bubble" nuclei. It has been also observed that the bubble nuclei are usually sharper in their nuclear surface region, i.e., the nuclear diffuseness is very small and there exists a vacancy in lower angular momentum state.

According to the standard shell model the valance neutron of ^{20}N occupies in the $d_{5/2}$ or in the $d_{3/2}$. It means there exist a vacancy in the 1s-orbit, which agree with the basic properties of bubble nuclei. Interestingly, the reaction rate for smaller diffuseness agrees with the experimental one. Therefore, we may cautiously say that the ^{20}N is probably a bubble nucleus and has smaller nuclear surface diffuseness in its ground state. Experiments are encouraged in order to put our predictions on a more solid footing.

Acknowledgments

Gratefully acknowledge a doctoral fellowship from Ministry of Education, India.

References

[1] R. Chatterjee and M. Dan, J. Astrophys. Astr. **41**, 51, (2020).

[2] M. Terasawa, K. Sumiyoshi, T. Kajino, G. J. Mathews, and I. Tanihata, Astrophys. J. **562**, 470 (2001).

[3] M. Dan, R. Chatterjee and M. Kimura, Eur. Phys. J. A **57**, 203, (2021).

[4] M. Dan, G. Singh, R. Chatterjee and Shubhchintak, Phys. Rev. C. **99**, 035801 (2019).

[5] G. Singh, Shubhchintak, M. Dan and R. Chatterjee, J. Phys.: Conf. Ser. **1643**, 012065 (2020).