Studies in nuclear structure and big bang nucleosynthesis using proton beams

Monalisha Dhibar*
Deptartment of Physics, Indian Institute of Technology Roorkee, Roorkee - 247667, INDIA

The use of light-ions in nuclear research has multiple applications. Capture reactions of low energy protons on different targets are one of the major tools for studies in nuclear astrophysics. On the other hand, inelastic scattering of protons provides valuable information about structures of low-lying excited states in nuclei. Light-ion induced reactions are also most important means for studying the fundamental aspects of nucleon-nucleon interaction. It is a paradigm in nuclear physics research that the last four decades has witnessed predominance of heavy ion induced reactions. This has led to decline in low energy light ion facility. However, the phenomenal improvements in modern radiation detectors and associated techniques make it imperative to revisit light-ion induced reactions. The present thesis work aims to study two different proton-induced reactions namely, inelastic scattering of protons on ^{12}C nucleus and radiative capture of proton by deuteron which are of fundamental importance for nuclear structure and for nuclear astrophysics, respectively.

Studies of radiative capture of proton by deuteron d(p,γ)^{3}He is a reaction of great significance both in nuclear astrophysics and few-body nuclear physics. There are mainly three different scenarios in which the depletion or production of helium can take place via d(p,γ)^{3}He reaction, namely, the Big Bang Nucleosynthesis (BBN), production in low-mass protostars, and production in low to medium mass stars like our sun[1, 2]. From experimental standpoint, the beam energy for this reaction is varied over a wide range depending upon the exact nature of the problem one is interested in. In very low energy region, say, from 2.5 keV to 30 keV sufficient data are available covering the Gamow peak region[3]. But the situation is rather unclear for BBN energy region that ranges from 30 keV to 300 keV [4]. Therefore, the measurements of cross section and S-factor for d(p,γ)^{3}He reaction at BBN relevant energies are of great fundamental importance. The measurements were carried out at the ECR ion source facility in TIFR, Mumbai. The cross-section and astrophysical S(E) factor for d(p,γ)^{3}He reaction were carried out at three different beam energies, namely, 100 keV, 175 keV and 250 keV. The capture gamma rays produced from the reaction were measured using a large volume cylindrical 3.5″× 6″ $LaBr_3$:Ce detector [5]. Realistic GEANT4 simulations were carried out in order to estimate the energy dependent efficiency of the detector. The cross sections and astrophysical S(E) factors measured by us [6] are in excellent agreement with the latest theoretical calculations [4].

Another important aspect of proton induced reaction is inelastic scattering. The formal theory of inelastic scattering of protons off ^{12}C nucleus involves two steps. The two steps are, initial excitation of the nucleus followed by the de-excitation to a lower (or ground) state. These steps are not equally well understood. The de-excitation is release of energy via a gamma ray with a known energy and angular momentum. However, a variety of questions are to be answered in order to have a fuller understanding of the excitation mechanism. It is essential to understand the true nature of excited state, single-particle or collective. The excited state may also represent an interplay of single particle and collective modes of excitations. From the theoretical standpoint, one also needs to understand the importance of exchange process for identical particles, the alpha particle clustering of ^{12}C, etc. For the proton capture on ^{12}C reaction, it is also significant to assess the role of giant resonance effects in ^{13}N. The measurement of ^{12}C(p,p′γ)^{12}C

*Electronic address: physics.monalisha3@gmail.com

plays a very important role in answering these questions. On a different plane, this reaction also is of great significance in nuclear astrophysics [7, 8]. From the analysis point of view, the scattering of proton in the energy range of 10 to 30 MeV is not well understood. While the optical model formalism works well at higher energies, reproduction of data in the lower energy (10 to 30 MeV) appears to be more complicated. All these above mentioned reasons provide enough justification for studying the ^{12}C(p,p$'\gamma$)^{12}C reaction up to about 30 MeV. The measurements were carried out with proton beams of 8 to 22 MeV at the 14 MV BARC-TIFR pelletron accelerator facility. We have measured the gamma-rays corresponding to the decay from the states of the ^{12}C nucleus, namely, 4.43, 9.64, 12.7 and 15.1 MeV. For all the above mentioned states, the differential cross sections were determined by measuring the angular distribution of the gamma rays for six different angles, namely, 45°, 60°, 75°, 90°, 105° and 135°. Finally, the total cross section for all four states were obtained by integrating the respective angular distributions. The optical model analysis was performed to generate the inelastic scattering cross section for each state. The cross section obtained from experimental measurements and theoretical calculations were compared and found to be in good agreement with each other [9]. We have also calculated the gamma decay cross section using phenomenological optical model potential for the first time. The calculated differential gamma cross section for each state was compared with measured gamma cross section. We have reported, for the first time, the cross section and branching ratio of 9.64 MeV state of ^{12}C nucleus using ^{12}C(p,p$'\gamma$)^{12}C reaction.

The present thesis work also discusses our studies on different aspects of large volume $LaBr_3$:Ce detectors. We report the results of experimental measurements and GEANT4 simulations for efficiency calibration and coincidence summing correction of a large volume (1246 cm^3) cylindrical 3.5$''\times$ 6$''$ $LaBr_3$:Ce detector [10]. We have applied a method proposed by Vidmar *et al.*, [11] for the first time, for correcting the simulated and measured efficiencies extracted using ^{22}Na source that emits coincident gamma rays with different decay intensities. In addition, we also report in-depth studies of properties and response of large volume square bars (2$''\times$2$''\times$8$''$) of $LaBr_3$:Ce detectors, individually, and in a compact array of four square bars with gamma rays up to 22.5 MeV [12]. The properties studied include uniformity of the crystal, internal radioactivity, energy resolution, timing resolution, linearity of the response and detection efficiencies. The response of the array for 22.5 MeV gamma-rays produced from ^{11}B(p,γ)^{12}C capture reaction and for 15.1 MeV gamma-rays produced from inelastic scattering of ^{12}C(p,p$'\gamma$)^{12}C are studied in detail. The measured absolute efficiencies (both total detection and photo-peak) for ^{137}Cs are compared to those obtained using realistic GEANT4 simulations.

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