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Study of ^{14}N(p,γ)^{15}O resonance reaction at E_p^{lab} = 278 keV

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Abstract. An implanted target (^{14}N on Ta) is prepared and characterized via surface and bulk characterization processes. The depth profile of the implanted ions is obtained experimentally by populating a narrow resonance state of ^{15}O through ^{14}N(p,γ) reaction induced with a laboratory proton energy of 278 keV. The experimental profile is then compared with devoted simulations to understand the locations of the implantated ions in the lattice structure. Later, the lifetimes of a few excited states of ^{15}O, relevant for applications in astrophysical scenario, have been determined using Doppler Shift Attenuation Method (DSAM).

1 Introduction

The reactions of interest in nuclear astrophysics mostly have very small cross - sections over the relevant energy range i.e. in the Gamow window region [1]. The ^{14}N(p,γ)^{15}O reaction, being the slowest one in the CNO cycle appears as a bottleneck. Low energy narrow resonances and sub-threshold resonances contribute in the reaction rate significantly depending on the level width (Γ) of the states. There is a sub-threshold resonance state at $E_{c.m.}$= -504 keV, corresponding to the E_x = 6.792 MeV state in the ^{15}O. The width of this state is not known with certainty according to the previous literatures [2]. As the sub-threshold resonance state decays nearly with 100% probability via gamma emission, it is possible to obtain the total radiative width Γ ($\simeq \Gamma_\gamma$) by measuring the lifetime of the state τ using the relation $\Gamma = \hbar/\tau$. The radiative width value can be then used to calculate the total reaction rate. In the present work, an implanted target has been used to measure a few of these level lifetimes.

2 Experimental Details

Implantation technique [1, 3] is one of the most effective methods to produce targets which are isotopically pure and can withstand high beam load over a long time. However, a few specific steps have to be followed before and after the preparation of these targets to make them useful for an experiment.

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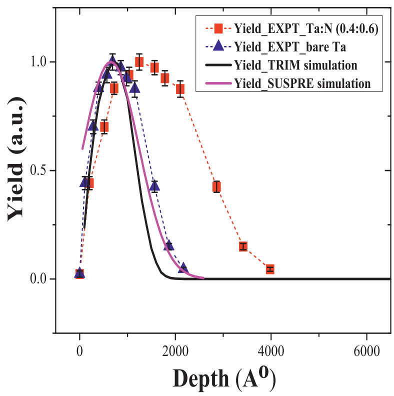

Figure 1. Comparison of experimental depth profile of implanted ions with simulation using SRIM and SUSPRE software. The experimental data points are shown with error bars including only statistical errors.

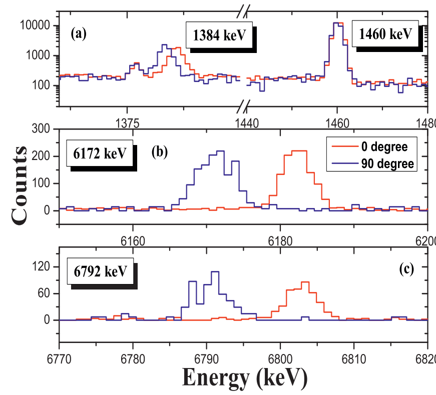

Figure 2. Relevant gamma-rays (a) 1384 keV, (b) 6172 keV and (c) 6792 keV emitted from ^{15}O. In each case the spectra are taken at two angles i.e. 0^o and 90^o. The room background gamma ray at 1460 keV shown in (a) indicates similar gains of the two spectra taken at these two angles.

2.1 The Implanted target

To specify the implantation energy of the ions, suitable backing and saturation dose, simulations were done with TRIM software [4]. The variation of the spatial distribution of the implanted ions in the backing as functions of their energies were determined to achieve appropriate linear thickness of the target as needed for the experiment. The choice of backing was fixed according to the results of our simulations of the sputtering yield of ^{14}N on various backing materials.

$^{14}N^{3+}$ ions from an ECR ion source [5] at Tata Institute of Fundamental Research (TIFR), Mumbai with energy 75 keV are implanted into 0.30 (5) mm thick Ta backing. Determination of the level lifetime using Doppler Shift Attenuation Method (DSAM) was one of the main motivations to prepare the implanted target. Therefore - the target thickness and thus implantation dose had to be kept within a prescribed limit [2]. The implantation dose was 7.8 $\times 10^{17}$ atoms/cm^2.

Several techniques like X - ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM) and secondary ion mass spectrometry (SIMS) have been adopted to identify the surface contamination of the implanted target before and after implantation [6]. From XPS measurement, impurities like C, O, F and Na were found on the target surface. In SIMS measurement the target surface is sputtered with 40 nA and 5 keV Cs ions to study the depth profile of the impurities. The concentration of C, F and Na were found to decrease sharply with the depth in the backing. However, O impurities persisted till larger depth.

To know the stoichiometry of the target, Rutherford backscattering spectrometry (RBS) has been performed at IUAC, New Delhi. $^4He^{+2}$ beam with 12.2 nA current with energy 3.65 - 3.70 MeV from 1.7 MV Pelletron accelerator was used. The RBS spectrum was taken for the ^{14}N implanted on Ta and also for bare Ta. The experimental spectrum at 3.682 MeV was analysed with the SIMNRA package [7]. The best fit of the spectrum was obtained with the Ta/N ratio of 0.667(33) [6].

2.2 Utilization of the Target

The experiment on the $^{14}N(p,\gamma)^{15}O$ resonance reaction has been performed at TIFR, Mumbai using ECRIA [5]. The proton beam energy was varied from 278 keV to 312 keV to get the depth profile of the implanted ions. Typical proton beam current was 3-4 μA. The lifetime data were acquired at a fixed beam energy of 293 keV. Two semiconductor gamma-ray detectors were used in the experiment. A BEGe (broad energy germanium detector) with 18% relative efficiency and an HPGe detector with 30% relative efficiency were used. The electrically cooled hand-held BEGe detector was placed at 4 different angles like 0^o, 25^o, 50^o, 70^o and the LN_2 cooled HPGe detector at 90^o, 120^o and 137^o angles, to cover the whole range of angles. The experimental data of BEGe detector were acquired using its in-built data acquisition system based on GENIE 2000 [8] software. A CAEN digitizer (16k channel, 100 MS/s, 14 bit) was used to acquire the data of other detector.

3 Experimental Results

3.1 Analysis of yield curve

The yield of the most intense primary gamma ray of ^{15}O (i.e. 1384 keV) populated in the resonance reaction has been measured. The photopeak area under 1384 keV is divided by the total charge accumulated and plotted as a function of proton beam energy in lab frame. From the yield plot, the energy thickness (ΔE) of the target comes out to be 21 keV. We get a nearly flat plateau from 288 keV to 300 keV. To compare the experimental depth profile with TRIM simulation, the proton energy is expressed in terms of linear thickness using SRIM stopping power [4]. As the yield profile obtained for RBS measured Ta/N ratio - 0.667 (Ta:N = 0.4:0.6) is much wider than the TRIM simulation results, the ratio is varied to match the simulated profile. Even by using stopping power of $\simeq$ 270-300 keV proton in bare Ta, the experimental depth profile differs from the simulated profile, especially at the falling edge. As an alternative, a quick ion implantation calculator, SUSPRE [9], developed by University of Surrey, Guildford, UK has been used. In contrast to the Monte Carlo Simulation approach of SRIM, SUSPRE uses a numerical solution to the Boltzmann Transport Equation. It generates an approximate solution and is based on the Projected Range ALgorithm (PRAL). The experimental plot with bare Ta matches well with the simulated profile generated by SUSPRE calculation (Figure 1). Thus it is clear that the target density is similar to Ta, which indicates that the nitrogen atoms are located only at the interstitial positions of Ta lattice, not at the substitutional positions.

3.2 Lifetime analysis

Although the recoil velocity of the ^{15}O ion is $< 0.2\%$ of speed of light (c), as most of the secondary gamma rays emitted from the ^{15}O resonance state at 7.556 MeV have energies greater than 5 MeV, and the level lifetimes are $\simeq$ 2-10 fs, the gamma rays are fully Doppler shifted (see Figure 2). The shift is largest at 0^o, compared to the unshifted centroid at 90^o. The DSAM has been used to determine the lifetimes of the 6.792 MeV and 5.181 MeV states. From preliminary analysis, the lifetime of the sub-threshold resonance state (6.792 MeV) has been determined to be $\simeq$ 2 fs, which agrees reasonably well with the literature value [2].

4 Summary

An ^{14}N implanted target on Ta backing has been prepared and characterized. The depth profile of the implanted target is measured experimentally and compared with simulation results. Simulations based on numerical approach explained the data better than the Monte Carlo simulation. A preliminary estimate of the lifetime of the sub-threshold state has been determined. Detailed analysis is in progress.

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