An Experimental Study of ^{93}Nb Ion Ranges in Makrofol-E Detector

Dipangkar Kalita[1,a)], Raju Kalita[1], Yubaraj Sharma[2] and Atul Saxena[1]

[1]*Department of Physics, North-Eastern Hill University, Meghalaya, Shillong-793022, India*
[2]*Department of Physics, Don Bosco College, Tura, Meghalaya, Tura-794002, India*

[a)]Corresponding author: dipangkarnehu@gmail.com

Abstract: Ranges are measured for the passage of ^{93}Nb of various energies between 7.7-18.04 MeV/u in Makrofol-E detector using simple track etch techniques. Due to the high sensitivity of Makrofol-E and taking into account the accuracy of the measurements and the ion energies under consideration, the maximum etchable true track lengths are taken as the experimental ranges. The experimentally determined ranges are then compared with various semiempirical codes like SRIM-2013, DEDXT, LISE++: 0-[Hub 90], LISE++:1-[Zie], LISE++: 2-ATIMA1.2 (LS Theory), LISE++: 3-ATIMA1.2 (Without LS Theory) in order to assess their validity.

INTRODUCTION

Solid State Nuclear Track Detectors (SSNTDs) basically detect the passage of heavy ions through them and have many applications in science and technology [1,2], among which includes measurement of range and energy loss of ions in matter [3,4]. The study of range and energy loss of heavy ion has gained momentum over the years due to significant applications like design of absorbers, filters, windows and backing [5,6] and in medical therapies [7]. Due to the complexity and variety of the interaction between a projectile ion and the atoms of the bulk matter, a complete theoretical description still eludes our grasp and as a consequence, various purely-empirical and semi-empirical approaches have been invented over the years to calculate range and energy loss of heavy ions in matter viz. Northcliff and Schilling Data table [8], Hubert et al [9], SRIM [10], DEDXT [11,12], LISE++ [13] etc.

The objectives of the present work include generation of experimental range data for ^{93}Nb ion in Makrofol-E detector for a set of energies between 7.7 MeV/u to 18.04 MeV/u, which is not available anywhere in accessible literature [14] and also to compare and validate the predictions of various empirical formulations for the generated dataset. Makrofol-E is among the most sensitive SSNTDs with a high registration efficiency [1,15] and its various properties have been well documented [16,17]. Makrofol-E has been used in the study of composition of very heavy cosmic rays, heavy ion nuclear reactions, exploration of super heavy element etc. [18]. It has also been used in the production of microfilters, single–pore membranes and technical devices [19-21].

EXPERIMENTAL DETAILS

Detector

The Makrofol-E detector used in the current work is manufactured by Bayer AG, Germany by a casting process into the form of thin sheets which have the same chemical composition ($C_{16}H_{14}O_3$) as Lexan [22]. However, these polycarbonates have different type of behaviour than Lexan polycarbonate [23].

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Irradiation

Samples of Makrofol-E were exposed to a well-collimated beam of 18.04 MeV/u ^{93}Nb at the XO port of UNILAC, GSI, Darmstadt (Germany). Energy of ^{93}Nb ion was degraded by inserting Al foils of different known thickness (and accurately known energy-loss rate) in the path of the ion. All irradiations were done at an incident angle of 45° with respect to the detector surface, using an optimum flux of ~10^4 ions per cm^2.

Chemical Etching and Measurement of Track Parameters

After irradiation, the detectors are processed in the laboratory using chemical etching technique. The etchant used is 6N NaOH solution at 55±0.5°C and the etching is carried out for a period of spanning 2-3hours until rounded track tips are observed. After complete etching, the samples are washed under running water and dried by pressing between the sheets of absorbent paper and then left in a vacuum desiccator (with silica gel) for complete drying. Projected track lengths and track diameters are measured by a camera fitted transmitted optical microscope (magnifications 150X and 600X respectively) by scanning all over the detector surface. The maximum etchable true track length (Range) is calculated using the formula given by Dwivedi and Mukherji [24].

$$L = \frac{l}{\cos\phi} + \frac{V_G t}{\sin\phi} - V_G(t - t_c) \tag{1}$$

Where, V_G is the bulk etch rate, Ø is the angle of irradiation, t is the total etching time and t_c is the time of complete etching of track.

It should be noted that the difference between the range of an ion, and its etchable true track length for a given energy in a particular detector depends primarily on the energy loss of the ion near the end of its trajectory and the critical stopping power of the detector [22, 24-26], which are assumed to be negligible in comparison to the experiment error in the present case.

Empirical/Semi-empirical Formulation

SRIM is an acronym for Stopping and Range of ions in Matter, a program developed by J.P Bisersack based on range algorithms [27] and the stopping theory edited by Ziegler et. al. [5, 10]; the latest available version viz. SRIM-2013 is used in the present paper [28].

DEDXT is also a computer program based on the stopping power equation of Mukherji and Nayak [11] and it was programmed by K.K Dwivedi to calculate stopping power and range [12, 29].

LISE++ is a new generation of LISE code which measure the range and energy loss of ions in any detector material [5,30]. For calculation of range using (i) LISE++:0-[Hub90] are based on Hubert et al. [9] for ion energies between 2.5 MeV/u to 2 GeV/u in solids, (ii) LISE++:1-[Zie85] are based on Ziegler.et al. [31] (iii) LISE++:2-ATIMA1.2 (LS theory) and LISE++:3-ATIMA1.2 (without LS Theory) based on the ATIMA program [32].

RESULTS AND DISCUSSION

The obtained experimental ranges (maximum etchable true track lengths) of ^{93}Nb at various energies in Makrofol-E detector are presented in Table 1; the error-terms/uncertainty indicated for the experimental values in the table are the standard deviations of about 30 numbers of tracks length measurements. Table 1 also contains the computed values of ranges using various codes, details of which were mentioned in the previous sub-section [9-13, 28-30]. Figure 1 shows the experimental as well as the empirical range values as a function of ion-energy; it is clear from the figure that the experimental data has a higher degree of non-linear character than the almost-linear character of the curves of the computed values. At lower energies (around the 9.1 MeV/u region) of the observation range, almost all the empirical formulations under-estimate the experimental values while at the higher energies (beyond 13.3 MeV/u) they over-estimate.

In Figure 2, we have plotted percentage deviations of the computed ion ranges from the corrected experimental range data to obtain a clearer picture of their differences. It is clear from the figure that at relatively higher energies (greater than 11.3 MeV/u), there is a good agreement (normally within 5%) between LISE++0-[Hub 90] formulation and experiment range values. But at relatively lower energies (7.7- 9.1 MeV/u) there is a good agreement (normally with 10%) between experimental range and the values obtained from DEDXT, SRIM-2013 and LISE++:1-[Zie] formulation.

TABLE 1. Experimental and theoretical ranges at various energies of ^{93}Nb ion in Makrofol-E detector

Energy (MeV/u)	Experimental Range (μm)	SRIM-2013 (μm)	DEDXT (μm)	LISE++: 0-[Hub 90] (μm)	LISE++: 1-[Zie] (μm)	LISE++:2-ATIMA 1.2 (LS Theory) (μm)	LISE++:3-ATIMA 1.2 (Without LS Theory (μm)
18.04	270.06±2.6	298.31(10)*	307.32(14)*	284.18 (5)*	305.1 (13)*	305.38(13)*	299.67(11)*
14.4	203.97±3.04	223.61(10)	230.15 (13)	210.99 (3)	229.84 (13)	226.99(11)	225.20(10)
13.3	190.74±2.56	202.58(6)	208.5 (9)	190.93 (0)	208.11 (9)	204.69(7)	203.67(7)
11.3	160.14±3.6	166.98(4)	171.93 (7)	156.37 (-2)	171.34 (7)	167.4(5)	167.22(4)
9.1	145.74±3.5	130.91(-10)	135.36 (-7)	121.82 (-16)	133.37 (-8)	130.06(-11)	130.06(-11)
8.1	123.18±1.8	115.37(-6)	119.83 (-3)	107.2 (-13)	116.68 (-5)	114.08(-7)	114.08(-7)
7.7	109.01±2.76	109.49(0)	105.20 (-3)	101.6 (-7)	110.22 (1)	107.9(-1)	107.9(-1)

*In parenthesis, the percentage deviation is simply the deviation (or difference) between the experimental and calculated values i.e. $[(R_{Theo} - R_{exp})/R_{exp}] \times 100$.

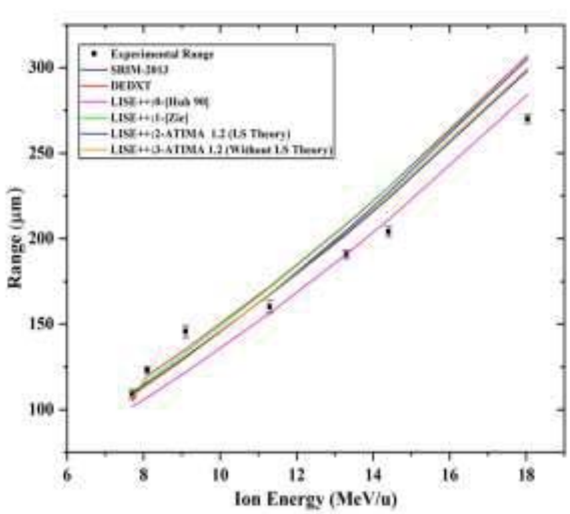

FIGURE 1. Experimental ranges of ^{93}Nb ion in Makrofol-E detector and comparison with SRIM-2013, DEDXT, LISE++:0-[Hub90], LISE++: 1- [Zie], LISE++:2-ATIMA1.2 (LS Theory) and LISE++:2-ATIMA1.2 (Without LS Theory)].

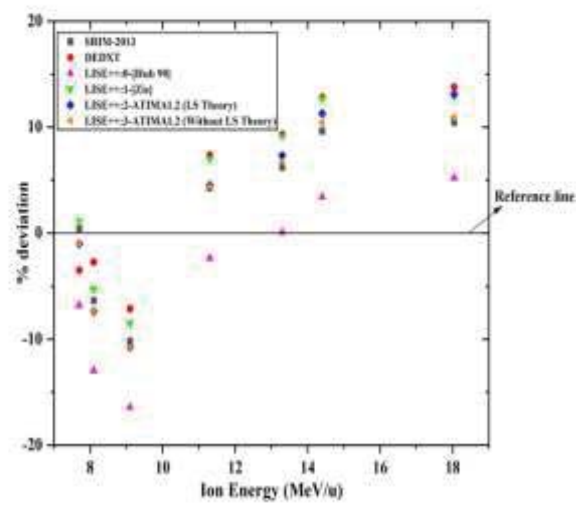

FIGURE 2. Percentage deviation of the theoretically predicted values of ranges from experimental data.

CONCLUSION

Experimental range values for the passage of ^{93}Nb in Makrofol-E detector for various energies 7.7 MeV/u to 18.04 MeV/u is reported, which were not available in earlier literature. Based on the comparison exercise with theoretical/empirical formulations, it can be concluded that, at higher energies the experimental values are closer to the LISE++:0-[Hub90] code. - and at lower energies, DEDXT, SRIM-2013 and LISE++:1-[Zie] formulation provide good agreement with the experimental values.

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