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Energy loss and mean ranges of ^{93}Nb in nickel and tantalum

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Abstract. A versatile nuclear track technique has been employed to measure energy loss and mean ranges of 18.04 MeV/u ^{93}Nb ions in nickel and tantalum. A polyallyldiglycol carbonate (CR-39) track detector has been calibrated and used in the present work to determine the energy of the transmitted heavy ions through metal targets. The passage of ^{93}Nb in nickel and tantalum was studied in terms of energy-loss rate and mean ranges. The experimental values are also used to check the validity of theoretical data obtained from a few commonly used theories and data tables. The experimental technique is also briefly discussed.

1. Introduction

In recent years several metals have been utilised as absorbers, filters, windows, backings and detectors in nuclear physics experiments. Hence it is necessary to know the range and energy-loss rate of heavy ions in metals. With the installation of several heavy ion accelerators, the demand for knowledge of the range and energy-loss rate has been considerably increased. Despite ever increasing demand, the available range and energy-loss data are very limited above 1 MeV/u ($u \equiv 1.66053 \times 10^{-27}$ kg) [1–10] and therefore it is customary to use theoretical values from different sources [11–15]. In the light of the above fact, it is important to determine the mean ranges and energy-loss rate of 18.04 MeV/u ^{93}Nb ions in nickel and tantalum and to compare these data with the corresponding theoretical values.

A versatile nuclear track technique [1, 2, 10] has been used to measure the mean ranges and energy-loss rate of ^{93}Nb in Ni and Ta. This technique is fairly accurate and does not require costly equipment, such as time-of-flight (TOF) [6], double time-of-flight (DTOF) [7], magnetic or recoil proton spectrometers [8, 9]. This technique can be used to measure the energy-loss rate and mean ranges of any heavy ion in any elemental and complex medium [1–5, 10].

2. Methodology

A sensitive track detector is calibrated for a desired heavy ion of different energies in terms of maximum etchable track lengths. The targets of desired material with precisely known thicknesses are placed before the same type of detectors and exposed to the same heavy ion of a given energy. The calibration curve and the measured track length in detectors give the energy of transmitted ion. An energy-loss curve may be plotted between transmitted energies as a function of target thickness. For a given target thickness x, the energy loss may be obtained as

$$\Delta E = E_i - E_x \tag{1}$$

where E_i and E_x are initial and transmitted energies respectively, after passing through a target of effective thickness Δx. It can be shown that

$$\Delta x = x_2 - x_1 \tag{2}$$

where x_1 and x_2 are the thickness of any two consecutive targets. Hence, the energy-loss rate may be determined from the equation

$$\left(\frac{dE}{dx}\right)_{\bar{E},\bar{x}} = \frac{E_i - E_x}{x_2 - x_1} \tag{3}$$

where the mean values of energy ($\bar{E}$) and target thickness ($\bar{x}$) are obtained from $\bar{E} = (E_i + E_x)/2$ and $\bar{x} = (x_1 + x_2)/2$.

By extrapolation of the energy-loss curve to $E_x = 0$ one can easily obtain the mean ranges (R) of heavy ions of energy (E) in any target. From this value, the mean ranges $R(E)$ at any energy E may be obtained from

$$R(E) = R - x(E) \tag{4}$$

where $x(E)$ is the target thickness which reduces the ion energy from E_i to E and is obtained from the energy-loss curve.

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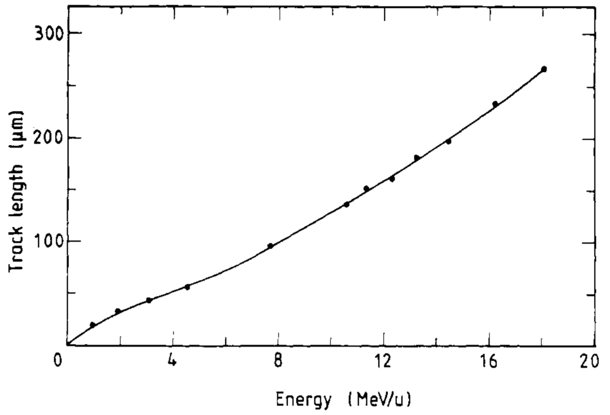

Figure 1. A plot showing the calibration curve between the energy of ^{93}Nb and the measured track length in CR-39. ●, present work.

Table 1. Maximum etchable track length of ^{93}Nb ion in CR-39 detectors at different energies.

E (MeV/u)	L (µm)
0.98	20
1.84	33
3.10	41
4.60	54
7.70	95
10.50	136
11.34	155
12.32	160
13.30	180
14.44	196
16.20	233
18.04	266

3. Specimen preparation

Small detector plates (thickness ≈1.5 mm) were cut from a commercially available sheet of CR-39, produced from allyldiglycol carbonate of composition $C_{12}H_{18}O_7$ and density 1.32 g ml^{-1}. Nickel and tantalum foils of varying thickness (4–42 µm Ni and 5–40 µm Ta) were prepared by precision rolling of pure metals (4–9 s). In order to prepare the targets of desired thickness, these foils were suitably combined to give an effective thickness of Ni (6.0–116.8 µm) and Ta (7.0–105.1 µm). These targets were then mounted on special holders for irradiation.

4. Irradiation with heavy ions

A collimated beam of ^{93}Nb ions with 18.04 meV/u was used for irradiation. All the target–detector assemblies were exposed at UNILAC, GSI, Darmstadt with a dose of about 10^4 cm^{-2}. All irradiations were performed at angles of 30° and 45° with respect to the detector surface.

5. Chemical etching of detectors

The CR-39 detectors were etched in 6N NaOH at 55 °C for 2–4 h, till rounded track tips were observed. After complete etching and thorough washing, all the detectors were dried under vacuum.

6. Measurement of track parameters

Sharp conical tracks were observed under an optical microscope. Track lengths and track diameters were measured at magnifications of 675× and 1500× respectively. The true track lengths were obtained from the equation given by Dwivedi and Mukherji [16].

7. Detector calibration

CR-39 detectors were calibrated for energy measurements of ^{93}Nb in terms of maximum etchable track

Table 2. Values of nickel thickness, maximum etchable track length of ^{93}Nb in CR-39 detector, energy of the transmitted ^{93}Nb ion, total energy lost by the ions and the ranges obtained in nickel, along with the corresponding theoretical values of (*a*) Mukherji and co-workers [11–13]; (*b*) Northcliffe and Schilling [14]; (*c*) Hubert *et al* [15].

Target thickness (µm)	Track length (µm)	Ion energy (MeV/u)	Total energy lost (MeV/u)	^{93}Nb ranges in nickel (µm)			
				Experimental (present work)	Theoretical		
					(*a*)	(*b*)	(*c*)
Without target	266 ± 2	18.04 ± 0.1	0.0 ± 0.1	65.0 ± 2.0	63.0	—	66.0
6.0 ± 0.8	231 ± 2	16.30 ± 0.1	1.74 ± 0.1	58.0 ± 2.2	56.0	—	58.5
13.7 ± 0.9	218 ± 3	14.25 ± 0.2	3.79 ± 0.2	49.3 ± 2.2	48.0	—	50.0
27.4 ± 1.5	142 ± 4	11.05 ± 0.3	6.99 ± 0.3	37.2 ± 2.5	36.5	43.0	38.0
33.9 ± 0.8	121 ± 3	9.60 ± 0.2	8.44 ± 0.2	31.7 ± 2.2	32.0	37.0	33.0
41.9 ± 0.8	94 ± 3	7.65 ± 0.3	10.39 ± 0.3	25.0 ± 2.2	25.5	29.0	27.0
48.0 ± 1.0	53 ± 3	4.15 ± 0.3	13.89 ± 0.3	16.0 ± 2.3	16.0	16.0	16.0
69.2 ± 1.0	No tracks†	—	—	—	—	—	—

† ^{93}Nb ions were found to be completely absorbed in five other thicker foils of nickel ranging from 81.2 to 116.8 µm.

Table 3. Values of tantalum thickness, maximum etchable track length of ^{93}Nb ions in CR-39 detector, energy of the transmitted ^{93}Nb ion, total energy lost by the ions and the ranges obtained in tantalum, along with the corresponding theoretical values of (*a*) Mukherji and co-workers [11–13]; (*b*) Northcliffe and Schilling [14]; (*c*) Hubert *et al* [15].

Target thickness (µm)	Track length (µm)	Ion energy (MeV/u)	Total energy lost (MeV/u)	^{93}Nb ranges in tantalum (µm)			
				Experimental (Present work)	Theoretical		
					(*a*)	(*b*)	(*c*)
Without target	266 ± 3	18.04 ± 0.1	0.0 ± 0.1	59.0 ± 2.0	55.0	—	60.5
7.0 ± 0.7	234 ± 3	17.00 ± 0.1	1.04 ± 0.1	52.3 ± 2.1	51.5	—	56.5
13.2 ± 1.4	217 ± 4	15.58 ± 0.2	2.46 ± 0.2	46.6 ± 2.4	47.0	—	52.0
20.2 ± 1.4	159 ± 4	12.20 ± 0.3	5.84 ± 0.3	36.9 ± 2.4	36.5	—	41.0
26.5 ± 2.0	119 ± 3	9.50 ± 0.3	8.54 ± 0.3	29.8 ± 2.8	29.0	33.0	32.0
32.0 ± 2.0	106 ± 3	8.52 ± 0.3	9.52 ± 0.3	27.4 ± 2.8	26.5	30.0	29.0
38.1 ± 2.0	72 ± 3	5.90 ± 0.3	12.14 ± 0.3	21.2 ± 2.8	20.0	21.5	21.0
48.8 ± 2.3	29 ± 4	1.77 ± 0.3	16.27 ± 0.3	9.8 ± 3.0	9.0	9.5	—
52.5 ± 1.4	15 ± 3	0.74 ± 0.2	17.30 ± 0.2	5.8 ± 2.4	5.0	6.0	—
59.5 ± 1.4	No tracks†	—	—	—	—	—	—

† ^{93}Nb ions were found to be completely absorbed in four other thicker foils of tantalum ranging from 67.0 to 105.1 µm.

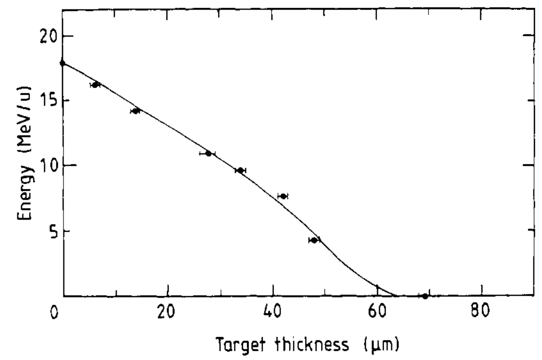

Figure 2. The energy-loss curve for ^{93}Nb in nickel. E_i = 18.04 MeV/u.

lengths. Several detectors were exposed to ^{93}Nb ions of varying energies between 0.98 and 18.04 MeV/u (obtained using Al-degrader foils) under similar conditions as described in section 4. The tracks were fully etched and maximum etchable track lengths were accurately measured. The experimental track lengths and energies of ^{93}Nb ions are listed in table 1. Figure 1

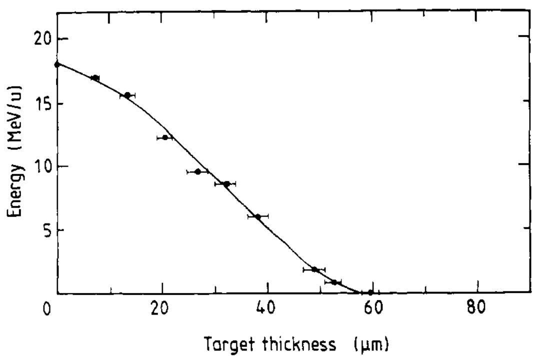

Figure 3. The energy-loss curve for ^{93}Nb in tantalum. E_i = 18.04 MeV/u.

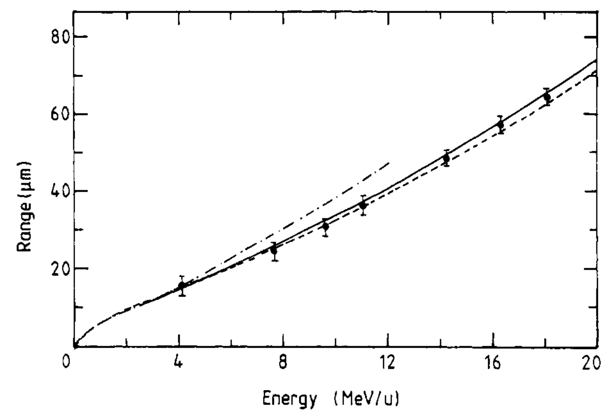

Figure 4. Mean ranges as a function of ion energy for ^{93}Nb in Ni, along with theoretical values calculated from (*a*) – – –, DEDXT [17]; (*b*) – · – · –, Northcliffe and Schilling [14] and (*c*) ———, Hubert *et al* [15].

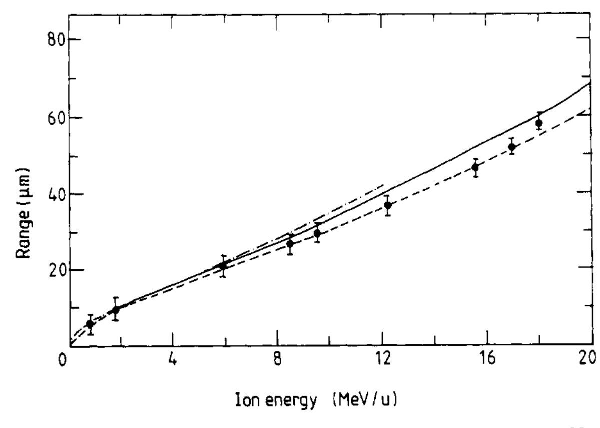

Figure 5. Mean ranges as a function of ion energy for ^{93}Nb in Ta, along with theoretical values obtained from (*a*) – – –, DEDXT [17]; (*b*) – · – · –, Northcliffe and Schilling [14] and (*c*) ———, Hubert *et al* [15].

shows a calibration curve for ^{93}Nb ions in CR-39 detectors up to an energy of 18 MeV/u.

8. Experimental errors

Ion energies were measured precisely with the help of a TOF system and found to be accurate within 0.1%. The targets of nickel and tantalum were found to be uniform within 1–5%. The accuracy in track length measurement has been estimated to be $\pm 0.5\,\mu$m. The error in measuring the energy of degraded ions varies between 0.1 and 0.3 MeV/u. The uncertainty in determining the energy loss of ^{93}Nb ions in Ni and Ta is normally less than 5% which reflects an error of the same magnitude in range measurements.

9. Results and discussion

The measured energy loss and mean ranges of ^{93}Nb ions in nickel and tantalum are listed in tables 2 and 3 respectively. The energy of the transmitted ions is obtained from the calibration curve for measured track length. Figures 2 and 3 show plots of the energy loss of ^{93}Nb ions with respect to penetration depth in nickel and tantalum respectively. These plots are generated by plotting transmitted ion energy as a function of target thickness. By extrapolating the fitted energy-loss curves, we have found that $65.0 \pm 2.0\,\mu$m of nickel and $59.0 \pm 2.0\,\mu$m of tantalum would be just sufficient to absorb 18.04 MeV/u ^{93}Nb ions. From figures 2 and 3, the mean ranges of ^{93}Nb in nickel and tantalum at several energies have also been obtained and are listed in tables 2 and 3 along with the calculated values from the stopping-power equations of Mukherji and co-workers [11–13] and from data tables of Northcliffe and Schilling [14] and Hubert *et al* [15]. These range data are plotted in figures 4 and 5 for nickel and tantalum respectively. In nickel the measured mean ranges are in good agreement with the calculated values from

Table 4. Values of experimental and theoretical ((*a*) Mukherji and co-workers, (*b*) Hubert *et al*) energy-loss rate of ^{93}Nb in Ni at various mean ion energies and target thicknesses.

	dE/dx (MeV mg^{-1} cm^2)			
		Theoretical		
$\bar{E}$ (MeV/u)	Experimental	(*a*)	(*b*)	$\bar{x}$ (mg cm^{-2})
1	24.66	22.02	—	53.05
2	30.51	32.76	—	49.85
3	34.48	36.30	36.21	47.18
4	35.94	36.78	36.06	44.33
5	36.56	36.06	35.36	42.11
6	36.56	34.91	34.44	39.52
7	35.52	33.63	33.43	37.03
8	33.43	32.35	32.41	34.01
9	31.34	31.12	31.41	31.78
10	29.25	29.96	30.44	28.40
11	28.21	28.88	—	25.10
12	27.16	27.65	—	21.63
13	26.12	26.70	—	17.98
14	25.70	25.80	—	14.51
15	25.49	24.95	26.27	10.95
16	25.07	24.16	—	7.39
17	24.03	23.41	—	3.74

Table 5. Values of experimental and theoretical ((*a*) Mukherji and co-workers, (*b*) Hubert *et al*) energy-loss rate of ^{93}Nb in Ta at various mean ion energies and target thicknesses.

	dE/dx (MeV mg^{-1} cm^2)			
		Theoretical		
$\bar{E}$ (MeV/u)	Experimental	(*a*)	(*b*)	$\bar{x}$ (mg cm^{-2})
1	13.10	12.16	—	86.49
2	17.37	18.09	—	80.68
3	19.72	20.22	19.27	75.70
4	20.50	20.95	19.76	71.05
5	20.95	21.15	19.78	66.73
6	21.29	20.99	19.57	62.08
7	21.51	20.69	19.24	58.10
8	21.29	20.25	18.85	53.78
9	21.06	19.74	18.43	49.63
10	20.84	19.21	18.00	45.32
11	19.94	18.68	—	40.84
12	19.61	18.16	—	36.19
13	19.04	17.66	—	31.71
14	18.38	17.18	—	26.89
15	17.92	16.73	15.96	21.75
16	16.25	16.30	—	16.10
17	14.01	15.89	—	9.63

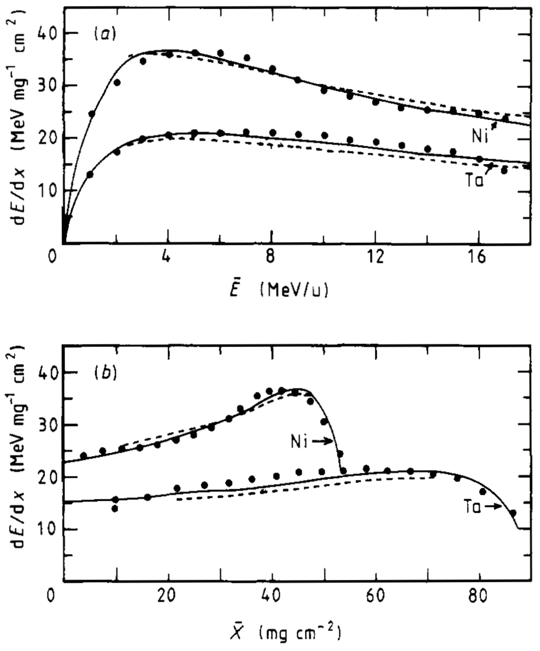

Figure 6. Plots of experimental energy-loss rate of ^{93}Nb in Ni and Ta along with theoretical values [15, 17] as a function of (*a*) mean ion energy $\bar{E}$ and (*b*) mean target thickness $\bar{x}$. For both plots ●, experimental; ----, [15]; —— [17].

the stopping-power equations of Mukherji and co-workers [11–13] and the values of Hubert *et al* [15], whereas the ranges predicted by Northcliffe and Schilling [14] are 5–15% higher above 6 MeV/u. On the other hand, the mean ranges in tantalum agree fairly well with the calculated values of Mukherji and co-workers [11–13], except the highest energy data point, while those of Northcliffe and Schilling [14] and Hubert *et al* [15] are overestimated by 8–10% above 10–12 MeV/u. The energy-loss rate of ^{93}Nb ions in nickel and tantalum was obtained by differentiating the energy-loss curves as a function of mean ion energy ($\bar{E}$) and mean target thickness ($\bar{x}$). Tables 4 and 5 list the values of experimental energy-loss rate ($\mathrm{d}E/\mathrm{d}x$) for ion energy of 1 MeV/u and the corresponding mean target thickness, along with the calculated energy-loss rate of ^{93}Nb ions in nickel and tantalum using computer program DEDXT [17] based on the stopping-power equations of Mukherji and co-workers [11–13]. The plots of $\mathrm{d}E/\mathrm{d}x$ versus $\bar{E}$ and $\bar{x}$ are shown in figures 6(*a*) and (*b*) respectively. In the case of nickel, the discrepancies are 2–10%, while in tantalum our results show good agreement.

10. Conclusion

The present investigation provides a simple experimental technique for measuring mean ranges and energy-loss rate of any heavy ion in any elemental or complex medium. One drawback is that in this technique, the track detector needs to be calibrated for each ion, but once it is done, the detector can be used for such measurements on that ion in any medium. Though other sophisticated instruments such as TOF, DTOF, magnetic spectrometers or recoil proton spectrometers may give more precise measurements than the proposed technique, the simplicity and low cost of this technique make it quite useful.

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