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Experimental Investigations of Alpha Particle Irradiation of Natural Nickel

Varun V Savadi[a], D P Singh[a*], S K Joshi[a], A Yadav[b], P P Singh[c], M K Sharma[d], Unnati[e], M M Mustafa[f], B P Singh[g] & R. Prasad[g]

[a]Department of Physics, University of Petroleum & Energy Studies, Dehradun-248 007, India

[b]Department of Physics, Jamia Milia Islamia, New Delhi -110 025, India

[c]Department of Physics, IIT, Ropar, Rup Nagar, Punjab-140 001, India

[d]Department of Physics, S V College, Aligarh-202 001, India

[e]Department of Physics, University of Delhi, New Delhi -110 067, India

[f]Department of Physics, University of Calicut, Thenjipalam, Kerala-673 635, India

[g]Department of Physics, Aligarh Muslim University, Aligarh (UP)-202 002, India

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Attempts have been made to measure the activity in irradiated natural Ni material induced by α-particles in the energy range 10-40 MeV followed by stack foil activation technique. Activity induced has been determined through the cross-sections obtained from various reactions for ^{58}Ni(*α, p*)^{61}Cu, ^{58}Ni(*α, pn*)^{60}Cu, ^{60}Ni(*α, p2n*)^{61}Cu, ^{60}Ni(*α, n*)^{63}Zn, ^{60}Ni(*α, 2n*)^{62}Zn,^{61}Ni (*α, 3n*)^{62}Zn and ^{61}Ni(*α, 2n*)^{63}Zn in α+^{nat}Ni interaction at different beam energies has been found to vary from 10-26 microns.

Keywords: nickel & nickel alloys; gamma spectroscopy; stack foil activation; yield; cross-section measurements; beam of alpha particles.

1 Introduction

Over a couple of decades there has been a growing concern to investigate the potential damage induced due to erosion in machinery and other related equipment in processing industries[1-3]. Surface degradation phenomenon such as wear, erosion, corrosion *etc*. are inevitable processes influencing industrial performance and efficiency. The functionality of materials, used in power generation plants and other processing industries with increased efficiency, is a field of current interest to meet the global energy demands[1-5]. Machinery, equipment and components utilised in various industries like; oil & gas, power plants and others are often subjected to slurry erosion leading to wear of materials pose a critical issue on performance, dependability and service life of components. Wear induced due to material erosion is often coupled with capital expenses and accountable for overall performance and service life of the industry[2-6]. The process of wear influencing corrosion & vice versa is highly interdependent and could lead to catastrophic & economic losses in modern types of machineries used in marine applications, chemical plants *etc*. often subjected to tribo-chemical interactions[7]. Selection of appropriate materials and various techniques leading to increased efficiency and service life of the industry components is a matter of concern in near future. A noble method of coating technique popularized as the "Electro-less Coating" was developed with its widespread applications across every domain of industry[8]. Over a last couple of decades, interestingly nickel based alloys and coatings have evolved mature subject of research and development from tribological applications point of view due to excellent anti wear & corrosion resistant properties[9-14]. Further, various non-destructive techniques available till date are used for measuring the surface defects and phenomenon like corrosion & erosion but are having their own limitations of testing[15-16]. Charged particle activation analysis is a nuclear non-destructive tool in which, a beam of appropriate energy is made to impinge on a very thin layer of material surface by light & heavy ions. Further total cross-sections obtained for various reaction products after employing stack foil activation at varying depths is used for estimation of surface wear in materials. In charged particle activation, very thin layer of surface is activated for measurements and is mostly preferred over conventional techniques due to its high precision and accuracy with recent advancement in accelerator technology[17-20]. Studies performed with help of stack foil activation have been of great use in determining surface wear induced in many components which can be measured simultaneously while being in

Corresponding author: (E-mail:dpsingh19@gmail.com)

situ-operations with precision ranging from micro-meters to nanometres[17-20]. Recent boost in accelerator technology has now made it possible to measure surface degradation on desired surface of component by using appropriate charged particles either by using stack foil activation followed by offline γ-spectroscopy or by indirect measurement method[21-23]. Several such studies have been carried out on many materials & alloys such as nickel titanium, platinum, rhodium niobium & copper *etc* applicable in large number of industries[24-36]. In the present work, stack foil activation is employed in natural nickel material to estimate the activity induced. Analysis of the amount of activity induced has been determined through the cross-sections obtained from various reaction channels with energy ranging from 10-40 MeV. It has been observed that the activity induced in Ni is found to vary from 10-26 microns[37-38]. Different reaction residues obtained from various α-channels in current experiment have very good half-lives and total cross-section values which can further be explored for research and industrial applications.

2 Experiment Details

To measure the cross-sections of various reaction products in α+^{nat}Ni interactions at ≈10–40 MeV[39] and subsequently used to study the amount of residual activity induced in natural Ni materials, experiments were performed at the Variable Energy Cyclotron Centre (VECC), Kolkata, India. For irradiation, natural nickel targets were prepared by rolling technique. A stack consisting of 8 target foils made up of ^{nat}Ni material each backed by aluminium catcher of appropriate thickness obtained by energy loss calculation from SRIM/TRIM was impinged by a 40 MeV α-beam. The approximate thickness of ^{nat}Ni foils were 1.13, 1.8, 1.15, 0.9, 1.33, 1.19, 1.05 & 1.63 mg/cm^{2}respectively each backed by aluminium catcher of approximate thickness of 1.3, 2.8, 1.47, 1.18, 1.41, 1.22, 1.24 & 2.23 mg/cm^2. The total irradiation time was ≈ 12 h with a beam current ≈ 100 nA. The average beam energy on a given target foil and degrader was calculated by using the code SRIM based on stopping power and range calculations. A pre-calibrated HPGe detectors coupled with multi-channel analyzer system has been used for post irradiation analysis. The overall error has been estimated from the errors of cross-section in generating the calibration curves and the activity measurement of the irradiated samples and has been found ≤ 15%. Statistical errors has been deduced and fitted with a fourth-order polynomial function, where the uncertainty from the fitting is found to be ≈ 3% for the energy range of interest. Errors introduced due to solid angle defect is found to be less than ≤ 2% as demonstrated by Gardener *et al.*[40]. The human errors introduced due to non-uniformity and inaccurate determination of foil thickness at various positions has been found to be ≈ 1%. The errors from the fluctuations in the beam current were found to be ≈ 3%. Errors introduced due to attenuation in beam current while traversing through thickness of foil has been found to be ≤ 2%[41].

3. Measurement & Analysis

To measure the range/depth of activity induced in Ni material, the cross-sections for ^{58}Ni(*α, p*)^{61}Cu, ^{58}Ni(*α,pn*)^{60}Cu, ^{60}Ni(*α, p2n*)^{61}Cu, ^{60}Ni(*α, n*)^{63}Zn, ^{60}Ni(*α, 2n*)^{62}Zn,^{61}Ni(*α, 3n*)^{62}Zn and ^{61}Ni(*α, 2n*)^{63}Zn reactions have been measured by using the activation technique followed by off-line *γ* spectroscopy[39].

3.1. Measurement of Yield Curves:

The yield curves for various isotopes; ^{61,60}Cu &^{63,62}Zn populated through different reaction for$^{58,\ 60,\ 61\ nat}$Ni material with α beam have been obtained at different energies and different depths. The stopping power of different materials has been used to obtain the incident energies on different samples. Area under the yield curves across different energies ranging from 10-40 MeV was integrated to obtain the residual curves. The yield per micron thickness against the depth as well as incident energy for residual isotopes viz; ^{61,60}Cu, ^{63}Zn &^{62}Zn is shown in Figs. 1-3(a). For proper polynomial fit of the experimental data, theoretical cross-section values (obtained from PACE 4) have been included below 25 MeV for reactions [(^{58}Ni(*α, pn*); ^{60}Ni(*α, p2n*); ^{60}Ni(*α, n*); ^{60}Ni(*α, 2n*); ^{61}Ni(*α, 3n*); ^{61}Ni(*α, 2n*)]. Total cross section values mentioned in Table 1 have been used for obtaining yield curves.

3.2. Calibration curves:

Plot for amount of residual activity induced in $^{58,\ 60,\ 61\ nat}$Ni material has been deduced with the help of total cross-section measured values from yield curves. The residual activity induced through α beams with energy range 10-40 MeV in ^{58}Ni(α, P)^{61}Cu; ^{58}Ni(α, Pn)^{60}Cu; ^{60}Ni(α, n)^{63}Zn; ^{60}Ni(α, 2n)^{63}Zn; ^{61}Ni(α, 2n)^{63}Zn &^{61}Ni(α, 3n)^{62}Zn has been shown in Figs.1-3(b). The total yield of the isotope in the given material may be obtained from the integral area under the yield curves. The percentage of remaining activity is computed graphically using polynomial fit by decreasing the

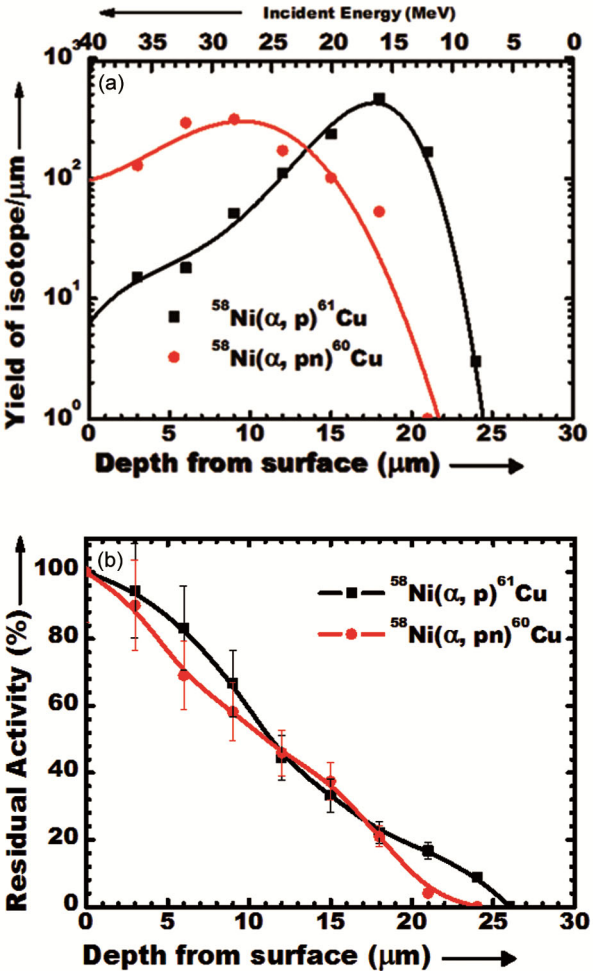

Fig. 1(a-b) — Relative Yield curves for ^{58nat}Ni Material; b–Calibration curves for ^{58nat}Ni at incident energies ranging from 10-40 MeV

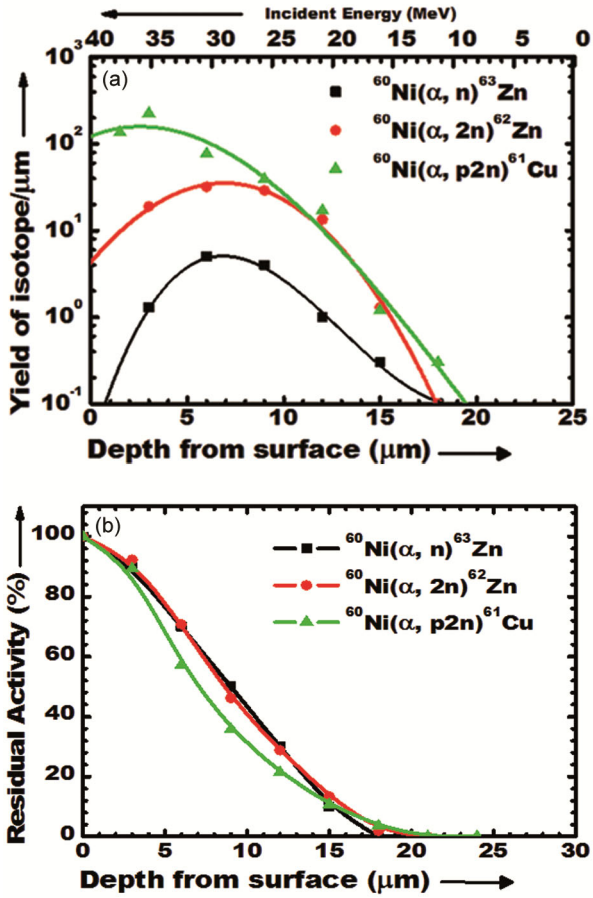

Fig. 2(a-b) — Relative Yield curves for ^{60nat}Ni Material; b-Calibration curves for ^{58nat}Ni at incident energies ranging from 10-40 MeV

thickness corresponding to each foil of stack one by one as shown in Figs. 1-3(b). It has been observed that the activity induced in Ni is ranging upto ≈ 26μm.

Measurement of cross-sections and residual activity induced are expressed in Eqs 1-4.Total thickness of ^{nat}Ni material is assumed to be x_t mg/cm^2 irradiated by α beam having 90^0 angle of incidence, then activity induced in total thickness of material where, x_i(i= 1, 2, ..., 8) (mg/cm^2) is given by Eq^n (1).

$$x_t = x_1 + x_2 + \ldots x_n = \sum_{i=1}^{n} x_i \qquad \ldots (1)$$

It is obvious that as the beam traverse across the thickness x_1 to x_n, it continuously keeps on loosing energy as a result of which total cross-section obtained will vary according to the beam energy and thickness which is stated in Eq^n (2.1).

$$A_n = NI\sigma_1 x_1 S + NI\sigma_2 x_2 S + \ldots NI\sigma_n x_n S \qquad \ldots (2.1)$$

Further Eq^n (2.1) is reduced to Eq^n (2.2) when the cross-sections obtained across the varying thickness remains almost constant.

$$= NIS \sum_{i=1}^{n} \sigma_i x_i \qquad \ldots (2.2)$$

Amount of activity induced is directly dependent on the total cross-section values obtained across different beam energy and varying thickness in a given stack of metallic foil. In case of remnant activity measurement has to be carried for a particular thickness x_1 as compared to total thickness x_n, it can be expressed with Eq^n (3) in which ratio A_{n-1}/A_n is independent of N, I and t_i for a particular isotope.

$$\frac{A_{n-1}}{A_n} = \frac{\sum_{i=2}^{n} \sigma_i x_i}{\sum_{i=1}^{n} \sigma_i x_i} \qquad \ldots (3)$$

Further if the cross-section values obtained remains constant through the entire thickness x_t of the material, then eq^n (3) can be further deduced and expressed by eq^n(4) in which activity produced is simply proportional to the depth.

Table I — Spectroscopic properties of isotopes ^{60,61}Cu &^{62,63}Zn used in Stack Foil Activation technique.

Reaction	Residue	Half-life	γ -ray energies (keV)	Natural abundance (%)	Total Cross-Section (mb)
^{58}Ni(α, p)	^{61}Cu	3.33 h	283.0, 656.0	68.007	1453
^{58}Ni(α, pn)	^{60}Cu	23.7 min	826.3, 1332.5	68.007	897.1
^{60}Ni(α, $p2n$)	^{61}Cu	3.33 h	283.0, 656.0	26.223	301
^{60}Ni(α, n)	^{63}Zn	38.47 min	669.86, 926.27	26.223	30.2
^{60}Ni(α,$2n$)	^{62}Zn	9.186 h	548.4, 596.7	26.223	92.4
^{61}Ni(α,$3n$)	^{62}Zn	9.186 h	548.4, 596.7	1.140	13.5
^{61}Ni(α,$2n$)	^{63}Zn	38.47 min	669.86, 926.27	1.140	406

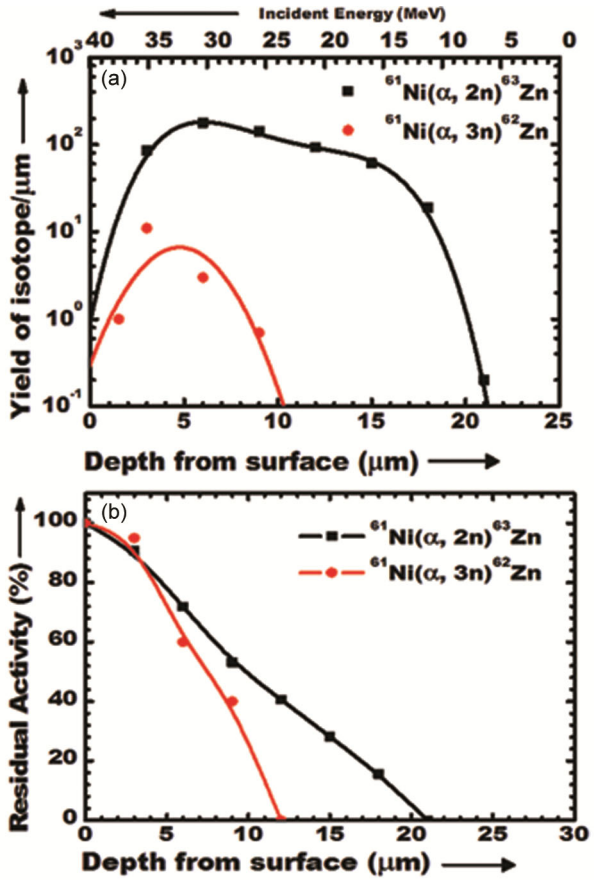

Fig. 3a-b — Relative Yield curves for ^{60nat}Ni Material; b-Calibration curves for ^{58nat}Ni at incident energies ranging from 10-40 MeV

$$\frac{A_{n-1}}{A_n} = \frac{\sum_{i=2}^{n} x_i}{\sum_{i=1}^{n} x_i} = \frac{\sum_{i=2}^{n} x_i}{x_t} \quad \ldots (4)$$

However with the change in cross-section values across the thickness of stack foil activated metallic sample calibration curves are obtained in accordance with Eq^{n}(3).

4 Conclusion

As Nickel has significant importance in terms of applications across various critical industries in the form of coatings & alloys, in the present work stack foil activation technique had been explored employing α beam with energy ranging from 10-40 MeV in ^{nat}Ni targets. As shown in Figs. 1-3(b) the maximum residual activity induced is found to be 26μm from the depth of the surface. As ^{61,60}Cu are populated through (α,p) & (α, pn) reactions while irradiating the same ^{nat58}Ni target, the activity induced in ^{60}Cu via (α, pn) reaction is observed to be less by 3μm i.e nearly 23μm as compared to that of ^{61}Cu obtained through (α,p) reaction. The least amount of activity induced is found to be 21μm in case of ^{63}Zn populated through α, 2n reaction on ^{nat61}Ni target. ^{62}Zn populated through two different reactions with ^{nat}Ni targets *i.e.* α, 2n & α, 3n *via* ^{60}Ni &^{61}Ni target materials is having activity contribution ranging ≈ 12-20 μm. In the present study activity induced through all possible reactions in ^{nat}Ni material has been reported. As ^{62}Zn has comparatively longer half-live of nearly 10hrs, the experimental data obtained can be used further as a future scope employing TLA for investigating surface wear and erosion phenomena at earlier stages in critically important industries like nuclear plants, power plants & other process industries applications where small failure would lead to catastrophic effects.

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