Thermal Neutron Induced Charged Particle Reactions on $^{58,59,61}$Ni

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The thermal neutron induced charged particle spectroscopy on $^{58,59,61}$Ni (target nuclei) was done at the 87 m thermal neutron curved guide of the Grenoble high flux reactor. In the $^{59}$Ni($n,\alpha$)$^{56}$Fe reaction two lines showed up corresponding to $\alpha$-particle transitions to the ground and first excited states in $^{56}$Fe with $\sigma_{\alpha g}=13.1\pm1.1$ b and $\sigma_{\alpha 1}=0.188\pm0.01$ b. A value of $\sigma_{\alpha 2}\leq13$ mb was obtained for the two-step $^{59}$Ni($\gamma\alpha$)$^{56}$Fe reaction. The technique to unfold the $\gamma\alpha$-spectrum and to get information on the primary low energy $\gamma$-rays is given and the present and our previous data on the $^{143}$Nd($\gamma\alpha$)$^{140}$Ce reaction are analysed. For the $^{59}$Ni($n,p$)$^{59}$Co reaction $\sigma_{p0}=1.34\pm0.18$ b, $\sigma_{p1}<0.30$ b were determined. The cross-sections for the $^{58}$Ni($n,\alpha$)$^{55}$Fe and $^{61}$Ni($n,\alpha$)$^{58}$Fe reactions were $\sigma_{\alpha 0}\leq30$ mb and $\sigma_{\alpha 0}\leq30$ mb respectively; these and $\sigma_{p1}$ upper limit values are about 20–1500 times lower than the existing data. The other results are compared with the existing data and the differences are explained. The experimental data are compared with the values obtained from the statistical model.

Nuclear Reactions $^{58,59,61}$Ni($n,\alpha$), $^{59}$Ni($n,\gamma\alpha$), $^{59}$Ni($n,p$), $E$ = thermal; measured $\sigma(E_{\gamma})$, $\sigma(E_{\alpha})$, $\sigma(E_{p})$. $^{60}$Ni levels, deduced $\alpha$- and $p$-branching ratios and the nature of low energy primary $\gamma$-rays. Enriched targets.

1. Introduction

The slow neutron induced ($n,\alpha$)- and ($n, p$)-reactions are usually difficult to study, because of low probability ($\approx 10^{-5}$–$10^{-6}$) of $\alpha$ or $p$-decay of the compound state formed by the capture of a neutron by the target nucleus, compared to its decay by $\gamma$-ray emission [1–3]. For good spectroscopy work, the neutron beam should have low background from fast neutrons and $\gamma$-rays which tend to increase the background and degrade the energy resolution of the charged particle detector. This results in a low limit of the cross-section that one can measure and, hence, the number of transitions that one can detect.

Due to simple but stringent $J^P$ selection rules, the ($n, \alpha$)-reaction gives information such as their spin and parity ($J^P$) on highly excited compound nucleus states. This work is important for the theory of $\alpha$-particle decay by yielding knowledge of $\alpha$-particle clusters in these compound nucleus levels and their $\alpha$-decay to the various states of the final nucleus [4]. Moreover, the two-step ($n, \gamma\alpha$)-reaction gives information on the primary low energy ($E_\gamma$ up to $\approx 1$–2 MeV) $\gamma$-rays which is very difficult to get with the other possible methods [13, 14].

Nickel isotopes (particularly $^{59}$Ni) were chosen to study for the following reasons:

1. As nickel ($^{58}$Ni and $^{61}$Ni isotopes) is a constituent of reactor construction materials such as stainless steel, the important cross-sections of ($n, \alpha$)- and ($n, p$)-reactions on $^{59}$Ni ($T_{1/2}\approx8\times10^3$ yr) following the $^{58}$Ni($n,\gamma$)$^{59}$Ni reaction, lead to swelling and embrittlement of these materials. However, the existing values of these cross-sections (Table 2) vary by over a factor of about 3. Using the intense and low background thermal neutron beam available at the Gren-
oble high flux reactor, this work aimed at measuring these cross-sections with good precision.

2. The spectroscopical study to detect as many \( \gamma \) and proton transitions as possible.

3. Our and other previous work [5, 6] showed that the two-step \((n, \gamma \alpha)\)-reaction cross-section is in some cases \(\approx 3-4\%\) of the \((n, \alpha)\)-reaction cross-section. As \(\sigma_\alpha\) for \(^{59}\text{Ni}(n, \alpha)^{66}\text{Fe}\) is quite important (Table 2), we hoped to study the \((n, \gamma \alpha)\)-reaction and through it get information on the primary low energy \(\gamma\)-rays emitted by \(^{60}\text{Ni}\) (see Sect. 7.4).

2. Experimental Method

The details of the experimental set up used in this work have been given in [1]. Briefly, the 87 meter long curved neutron guide of the Grenoble high flux reactor was used for this work. It has a thermal neutron flux \(\phi_{\text{th}} \approx 10^9\) neutrons/cm\(^2\)-s, with \(\phi_{\text{epi}} / \phi_{\text{th}} \approx 10^6\), and the direct \(\gamma\)-ray flux is down by \(\approx 10^6\). The available beam size is \(3 \times 5\) cm\(^2\). A gold-silicon surface barrier detector of 450 mm\(^2\) area and 100 \(\mu\)m depletion depth detects the charged particles. It is placed outside the neutron beam at \(\approx 5\) cm from the centre of the target which is inclined at an angle of 30\(^\circ\) with respect to the incident neutron beam. The whole system is placed inside a vacuum chamber. The detector has an energy resolution of 50-60 keV for \(\alpha\)-particles and the background conditions allow to measure cross-sections down to \(\approx 1\) \(\mu\)b for \(E_\gamma \geq 4\) MeV.

3. Targets and Cross-Section Normalization

The \(^{58}\text{Ni}\) and \(^{61}\text{Ni}\) targets were prepared from nickel powder enriched to 99.9\% and 93\% in \(^{58}\text{Ni}\) and \(^{61}\text{Ni}\) respectively. The \(^{59}\text{Ni}\) was produced by irradiating \(^{58}\text{Ni}\) for 4 months in the R2 reactor at Studsvik with a total thermal neutron fluence of \(2.2 \times 10^{21}\) n/cm\(^2\). After this irradiation, Co and Fe formed during the irradiation were removed through a chemical treatment. Then the atomic percentage of \(^{59}\text{Ni}\) in the irradiated metal was determined from two independent measurements using different mass spectrometers. A value of \(0.85 \pm 0.01\%\) was obtained.

Thick circular targets of 14 mm dia. of \(^{58}\text{Ni}, ^{59}\text{Ni}\) and \(^{61}\text{Ni}\) were prepared by vacuum deposition of material on 12 \(\mu\)m of aluminium. The thicknesses of the nickel deposits were determined by micro-weighing and subsequently compared using X-ray fluorescence.

Table 2 gives the various details on the nuclei studied here such as the thermal neutron capture cross-section values, the \(J^\pi\) values of the capturing states of the nuclei studied, of the states of the final nuclei reached after charged particle decay, the calculated

<table>
<thead>
<tr>
<th>Isotope studied</th>
<th>Target</th>
<th>Method of target preparation</th>
<th>Thickness ((\mu)g/cm(^2))</th>
<th>Data recording Time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{58}\text{Ni})</td>
<td>Nickel powder enriched to 99.9% in (^{58}\text{Ni})</td>
<td>Vacuum deposition</td>
<td>(500 \pm 14,165 \pm 5)</td>
<td>45, 46</td>
</tr>
<tr>
<td>(^{59}\text{Ni})</td>
<td>(^{58}\text{Ni}) powder enriched to 0.85% in (^{58}\text{Ni})</td>
<td>Vacuum deposition</td>
<td>(165 \pm 5)</td>
<td>46</td>
</tr>
<tr>
<td>(^{61}\text{Ni})</td>
<td>Nickel powder enriched to 93% in (^{61}\text{Ni})</td>
<td>Vacuum deposition</td>
<td>(82 \pm 3)</td>
<td>89</td>
</tr>
</tbody>
</table>