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# INVESTIGATION OF THE $^{58}$Ni(n,$\gamma$)$^{59}$Ni THERMAL NEUTRON REACTION

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Abstract: In the present experiment we have measured the gamma-ray spectrum of thermal neutron capture on $^{58}$Ni in the energy range of 3.7 to 9.3 MeV. The experiment was carried out at the tangential irradiation facility of the IEA-R1 research reactor at São Paulo. The gamma-rays were detected by a Ge(Li)-NaI(Tl) pair spectrometer. The partial cross sections for nineteen primary gamma-ray transitions have been calculated and, by summing all of them, we have determined the total thermal neutron capture cross section for the $^{58}$Ni(n,$\gamma$)$^{59}$Ni reaction. The resultant value is 4.52 ± 0.10b. We have also calculated the theoretical value of the partial cross sections for eleven primary $E_1$ transitions based on the direct capture model and compared with the experimental results.

## Introduction

The low energy neutron radiative capture reaction has been a very important source of data on nuclear spectroscopy investigations. However, the mechanism of the reaction still presents some incertainties.

In 1936, N.Bohr /1/ formulated the statistical theory of the compound nucleus according to which the slow neutron capture is dominated by compound nucleus formation and the decay mode of the compound state is independent of its method of formation.

However, it has been shown that, for a large number of light nuclei and nuclei near closed shell, there are other contributions to the total cross sections, which manifest themselves in non--statistical effects. Various simple neutron direct capture reaction mechanism have been proposed to explain these non-statistical effects: direct or hard sphere capture model /2,3/, channel capture /2,3/ or valence neutron model /4,5/ and semi-direct process /6/ or capture through a doorway state formation /7/.

The study of $^{58}$Ni(n,$\gamma$)$^{59}$Ni reaction is of special interest because one expect correlation between (d,p) single-particle spectroscopic strengths and reduced radiative intensities for transitions to $\ell_n = 1$ final states following thermal neutron capture. Previous thermal neutron capture data on this reaction had been related (references 8 and 9 are the most recents) and are available in recent competations of the Nuclear Data Sheels /10/.

In the present experiment we have measured the gamma-ray spectrum of thermal neutron capture on $^{58}$Ni in the energy range of 3.7 to 9.3 MeV. We have calculated the partial cross section for the nineteen primary gamma-rays, and by summing all of them, we have determined the total thermal neutron capture cross section for the $^{58}$Ni(n,$\gamma$)$^{59}$Ni reaction. We have also calculated the theoretical value of the partial cross sections for eleven primary $E_1$ transitions based on the direct capture model and compared with the experimental results.

## Experimental Procedure

The experimental was carried out at the tangential irradiation facility of the IEA-R1 reactor of the IPEN. The basic features of the internal target facility are described in more details elsewhere /11/.

The target was a well mixed sample of natural nickel and melamine ($C_3H_6N_6$) contained within a reactor grade graphite capsule positioned close to the reactor core. At the target position the neutron flux is typically about $5.2\times10^{11}$ncm$^{-2}$s$^{-1}$ the gamma-rays emitted following thermal neutron capture in the sample were detected by a Ge(Li) NaI(Tl) pair spectrometer consisting of a 42.5cc true coaxial Ge(Li) detector which fits into a cylindrical opening in the common housing of two optically separeted 5" x 6" NaI(Tl) crystals facing the central Ge-crystal from opposite sides. The triple coincidences events were registred by a 8192-channel analyser system. The ADC is stabilized against zero and gain drifts using precision pulse generaters and a spectrum stabilizer.

The determination of the efficiency curve as a function of the gamma-ray energies was made experimentally, by measuring a set of gamma-rays with very well known energy and intensity values. For this purpose we used gamma-rays from $^{14}$N(n,$\gamma$)$^{15}$N and $^{35}$Cl(n,$\gamma$)$^{36}$Cl reactions in the region of 1.8 to 11 MeV. In order to make this calibration we have measured a mixed sample of melamine ($C_3H_6N_6$) and sodium chloride (NaCl). A detailed description of the experimental procedure to determine the efficiency of the detecting system can be encountend in reference 12.

The energies and intensities values for differents gamma-rays were taken from reference 13 for $^{15}$N and reference 14 for $^{36}$Cl.

## Cross Sections Calculation

When $^{14}$N and $^{58}$Ni from the sample were irradiated with thermal neutrons simultaneously, the capture gamma-ray spectra for both nuclei were recorded. Using the thermal neutron cross section value of 77.2 mb for $^{14}$N from reference 15 as the cross section standard, the partial cross section of a primary gamma-ray with energy E$\gamma$ produced by neutron capture in nickel target can be simply calculated by:

$$\sigma_1 I_{i1} = \frac{N_2 \varepsilon_2(E_{\gamma j})\, A_1}{N_1 \varepsilon_1(E_{\gamma i})\, A_2} \qquad (1)$$

where N is the total number of nuclei of the element, $\varepsilon(E_{\gamma i})$ is the relative efficiency of the detecting system for the $E_{\gamma i}$ energy and A is the area under the double escape energy peak of the measured gamma-rays obtained by a gaussian fitting in the computer code /16/, $\sigma$ and $I_i$ are the thermal neutron capture cross section and the transiton intensity, respectively. The subscripts 1 and 2 refer to nickel and nitrogen, respectively.

The resultant spectrum was analysed by the gauss V computer code /16/ which gives the area under the peaks. We used the 5297, 5592, 7298 and 8310 keV gamma-ray transitions from $^{14}N(n,\gamma)$ reaction as standards in order to evaluate the partial cross sections of the primary gamma-rays of the $^{58}Ni(n,\gamma)$ reaction. The total cross section was then calculated by summing all the partial cross sections.

$$\sigma = \sum_i \sigma I_i \qquad (2)$$

Following Ishag /8/, we have assumed that the 5459 and 5621 keV transitions are primary gamma-rays. The total thermal neutron capture cross section determined here is 4.52 $\pm$ 0.10 barns which is in very good agreement with the 4.6$\pm$0.30 barns value of the reference 17 and with a value of 4.5 barns reported by Ishag /8/.

## Discussion

Experimentally the non-statistical effects can be seen by studying the behavior of the correlation coefficient $\rho$ between $\ell = 1$ (d,p)-spectroscopic strengths and E1 primary $(n,\gamma)$ intensities reduced by a factor $E^n$, where E is the primary gamma-ray energy.

For the largest value of the correlation coefficient $\rho$ we have: for $n \sim 1$ indicating direct capture, for $n \sim 2$-3 indicating valence capture and for $n > 3$ indicating the formation of doorway states.

The figure 1 shows the correlation coefficient $\rho$ as a function of the power of the $^{59}Ni$ gamma-ray energy. As can be seen, a value of $\rho = 0.987$ is obtained at maximum for $n = 0$ and this value remains quite constant in the range $0 < n < 3$, and for $n > 3$, the value of decreases quickly. Thus et is not clear which of the process (direct capture or valence capture) is causing the observed non.statistical effect, however from the behavior of the curve we can descard the process of the formation of doorway states.

Mughabghab /18/ has used the valence neutron model to predict the intensities of some transitions leading to the low-lying $p_{1/2}$ and $p_{3/2}$ states in $^{59}Ni$, following s-wave thermal neutron capture in $^{58}Ni$.

Here, we compare the measured partial cross sections of the primary transitions with the theoretical predictions calculated by the direct capture model using the full expression given by Mughabghab /19/ for the potential capture of an s-wave neutron.

The calculated values for the partial direct capture cross sections are given in the Table 1. Although the experimental results are not so well reproduced as in the other cases /19/, the magnitude order of the results is correct.

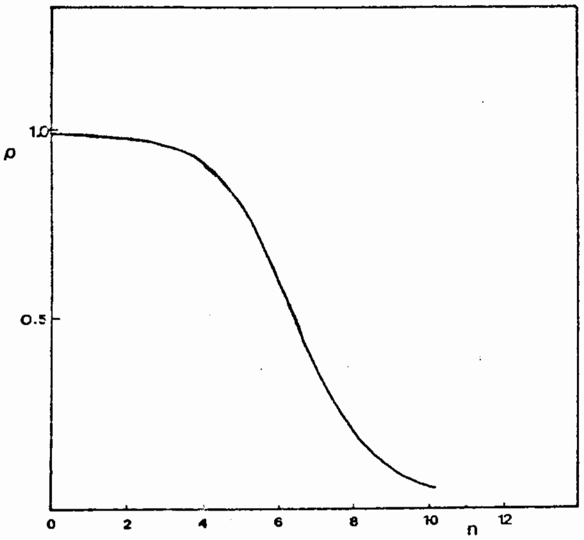

Figure 1 - The Correlation Coefficient $\rho$ as a Function of n Between $(2J+1)S_{dp}$ and $I_\gamma/E_\gamma^n$ for $^{59}Ni$

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Table 1. Theoretical and Experimental Partial Cross-Sections for Some E1 primary Transitions in $^{59}Ni$

| Transition Energy $E_\gamma$ (keV) | Intensity $I_\gamma$ per 100n | Level Energy Ex (keV) | $J_f^-$ | $(2J_f+1)Sdp$[a] | Partial cross sections Theory | Experiment |
|---|---|---|---|---|---|---|
| 8999.18 | 52.71 | 0 | $3/2^-$ | 2.740 | 2.714 | 2.381 ± 0.045 |
| 8534.21 | 25.14 | 465.06 | $1/2^-$ | 1.260 | 1.112 | 1.136 ± 0.022 |
| 8121.09 | 4.56 | 873.09 | $3/2^-$ | 0.324 | 0.257 | 0.206 ± 0.004 |
| 7697.43 | 1.33 | 1301.52 | $1/2^-$ | 0.519 | 0.366 | 0.060 ± 0.001 |
| 7263.56 | 0.33 | 1734.78 | $3/2^-$ | 0.031[b] | 0.019 | 0.015 ± 0.001 |
| 6583.65 | 2.63 | 2414.91 | $3/2^-$ | 0.104 | 0.052 | 0.119 ± 0.002 |
| 6105.13 | 2.35 | 2893.8 | $3/2^-$ | 0.025 | 0.011 | 0.106 ± 0.002 |
| 5972.84 | 0.92 | 3025.7 | ? | 0.070 | 0.028 | 0.041 ± 0.001 |
| 5817.08 | 3.54 | 3181.81 | ? | 0.065 | 0.025 | 0.160 ± 0.003 |
| 4977.18 | 0.30 | 4035 | $1/2^-$, $3/2^-$ | 0.053 | 0.014 | 0.014 ± 0.001 |
| 4031.35 | 0.53 | 4968 | $1/2^-$ | 0.032 | 0.005 | 0.024 ± 0.001 |

a) Reference /20/
b) Reference /21/