Integral Prompt Gamma Emission Cross-sections for ^{35}Cl: Experimental Measurement and Theoretical Analysis using the TALYS and the EMPIRE

Ashwini Udupi, Priyada Panikkath, P.K. Sarkar*
Manipal Centre for Natural Sciences, Manipal University, Manipal, Karnataka 576104, India
**email: pradip.sarkar@manipal.edu*

Introduction

In Prompt Gamma Neutron Activation Analysis (PGNAA), the cross section of chlorine is of importance while estimating the chlorine concentrations in samples. The present work emphasis on the measurement of integral prompt gamma (0.788 MeV, 1.16 MeV and 1.95 MeV) emission cross-sections of ^{35}Cl using saturated aqueous NaCl solution and an Am-Be neutron source placed inside a concrete bunker. Theoretical analysis of the measured cross sections are done using the TALYS 1.8 [1] and the EMPIRE 3.2 [2] nuclear reaction model codes.

Experimental Details

A saturated aqueous solution of NaCl is irradiated with a cylindrical Am-Be neutron source of 592 GBq placed inside a thick concrete bunker and an opening of 40 cm X 40 cm to one side of the bunker allows neutrons to reach the sample. The spectrum near sample will have a significant low energy components and less high energy components compared to the bare Am-Be spectrum due to multiple scattering and consequent energy degradation of neutrons inside the concrete bunker. The prompt gammas emitted from the sample are measured using a NaI (Tl) detector of 5 cm in diameter and 5 cm in length placed below the sample and is covered with an annular lead shield.

Background originated from the surrounding walls and the concrete bunker is measured and subtracted from the obtained prompt gamma spectrum for the sample. The chlorine peaks considered in the present analysis are 0.788 MeV, 1.164 MeV and 1.954 MeV along with the 2.2 MeV gamma from neutron interaction with hydrogen, ^{1}H (n, γ) ^{2}H.

Nuclear Model calculations

The nuclear model calculations for ^{35}Cl (n, γ) ^{36}Cl are performed with reaction model codes like the TALYS 1.8 [1] and the EMPIRE 3.2 [2]. The prompt gamma emission cross sections as well as the total capture cross sections are calculated for 1 eV to 12 MeV. Both these codes use Hauser-Feshbach statistical model to calculate the cross sections. The estimation depends on various parameters like nuclear level density, pre equilibrium emission, optical model potential etc. The nuclear parameters required for the calculations are taken from the latest Reference Input Parameter Library (RIPL) available within the code.

In the present EMPIRE estimation, the default level density model (EMPIRE-specific level densities) that is adjusted to RIPL-3 experimental widths and discrete levels are used. The optical model parameters obtained by a global potential suggested by Koning and Delaroche is used in the calculation. In the TALYS-1.8 estimation, the level density parameters were calculated using the constant temperature + Fermi gas model and the local nucleus specified optical model parameters were used.

Results and Discussions

The differential energy emission cross-sections obtained from the EMPIRE and the TALYS codes are folded with emergent neutron spectra from the concrete bunker which is plotted in Fig. 1 with experimentally obtained background subtracted gamma spectra for a matching of the peak positions.

The area under the prompt gamma peak for chlorine and hydrogen are given as,

$$A_x = N_x \emptyset_T C_x^I \qquad (1)$$

where $C_x^I = \int \sigma_x(E)\, P(E)\, dE$ and x is either Cl or H.

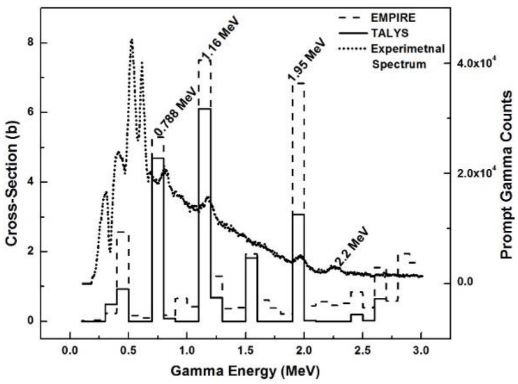

Fig 1: The EMPIRE 3.2 and the TALYS 1.8 estimated cross-sections is plotted along with the experimentally measured prompt gamma spectrum.

Here N_x is the number of Cl or H nuclei present in the sample, $\sigma_x(E)$ is the energy dependent neutron induced prompt gamma emission cross-section of Cl and H and $\emptyset_T$ is the energy integrated total neutron fluence with an energy dependent spectral shape $P(E)$ (a probability distribution). The total neutron fluence $\emptyset_T$ can be eliminated by taking the ratio A_{Cl}/A_H.

$$A_{Cl}/A_H = (N_{Cl}C_{Cl}^I)/(N_H C_H^I) \qquad (2)$$

For the estimation of C_{Cl}^I from the experimental data, C_H^I is calculated by folding the cross section values of hydrogen from ENDF/B-VII.1 database [3] with emergent neutron spectra from the concrete bunker. The estimated energy dependent emission cross sections for different prompt gamma emission energies of ^{35}Cl obtained from the TALYS and the EMPIRE calculations are shown in Fig. 2.

The integral cross sections of prompt gamma emission energies of ^{35}Cl are obtained by folding the incident neutron spectra with theoretical estimations (as given in Fig. 2). A comparison of such integral cross sections from theoretical estimations and experimental measurements are given in Table1. From Table1 it is observed that experimental cross sections are in better agreement with the TALYS estimations than the EMPIRE results.

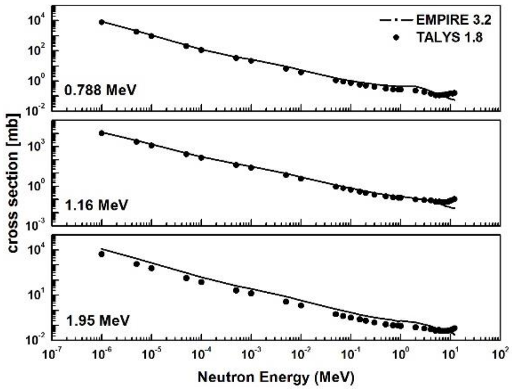

Fig 2: Theoretically estimated cross sections from the EMPIRE and the TALYS codes for different ^{35}Cl gamma emissions.

Table1: Emission cross sections for different chlorine peaks in units of barn.

	Emission cross section (b)		
Gamma Energy (MeV)	0.788	1.16	1.95
EMPIRE	5.25	7.48	6.84
TALYS	4.63	6.11	3.07
Experiment	4.64 ±0.04	5.68 ±0.05	3.28 ±0.03

Conclusions

The level density and gamma strength functions used in the TALYS and the EMPIRE needs to be optimized in order to match the experimental results.

Acknowledgement

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Reference:

[1] Koning, A. J. et al., "TALYS-1.8." (2011).
[2] Herman, M. et al., Nucl. Data Sheets 108.12, 2655-2715 (2007).
[3] Chadwick. M. B. et al., Nucl. Data Sheets 112, 2887 (2011).