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Abstract. A systematic investigation of the average neutron capture cross sections at 25 keV is undertaken to study the structure of giant resonances in the p wave neutron strength functions. As a part of this program and to fill in the gaps in the existing cross section data, radiative capture cross sections for the following isotopes have been measured: ^{74}Se, ^{78}Se, ^{84}Sr, ^{109}Ag, ^{122}Te, ^{159}Tb, ^{169}Tm, ^{174}Yb, ^{176}Yb, ^{178}Hf, ^{179}Hf and ^{192}Os. The activation method and absolute gamma counting technique have been employed. The new results are reported with a discussion of the p wave neutron capture in these nuclei.

1. Introduction

Measurements of neutron capture cross sections at energies of a few kiloelectronvolts are of interest in many fields. The explosive development of nuclear astrophysics nearly three decades ago led to an early awareness that neutrons must play a fundamental role in stellar processes. According to the present day theory of element synthesis (Burbidge *et al* 1957) the heavy elements are expected to have been formed by the successive capture of neutrons that has occurred either on a rapid time scale (r process, in supernovae) or on a slow time scale (s process, in red giant stars). Since the temperature at which these processes occur in stars corresponds to a few tens of keV, accurate data on capture cross sections at 25 keV serve to throw light on the theories of nucleosynthesis. Secondly, the neutron capture cross section data at 25 keV are useful in the design and construction of fast reactors. Thirdly, at the incident neutron energy of 25 keV only s and p wave neutrons contribute to the capture process, predominantly. Using s wave resonance parameters relevant to the keV region s and p wave contributions can be separated out and the data can be further analysed to obtain the 'strength function'—a significant parameter in the nuclear optical model.

While a number of experimental and theoretical papers have appeared in the literature on the s wave neutron capture and size resonances, relatively few investigations seem to have been carried out on the p wave capture, particularly in heavy elements. The optical model (Feshbach *et al* 1954) predicted the 4p giant resonance of the neutron strength function around $A \simeq 216$ which falls in the region of unstable nuclides. The refined optical model theory of Buck and Perey (1962) predicts a bump in the p wave neutron strength function for deformed nuclei ($150 < A < 190$) while the theory of Fiedeldey and Frahn (1962) predicts almost a constant value ($\simeq 0{\cdot}2 \times 10^{-4}$) in this region. There are no sufficient experimental studies to shed light on these points. It is, therefore, felt that a systematic investigation of the p wave neutron capture in heavy nuclei would be interesting. As a part of this program and to fill in the gaps in the existing cross section data at 25 keV, the average capture cross sections have been measured for twelve isotopes for the first time, using the activation method and absolute gamma counting technique. These preliminary results are discussed in this paper with particular reference to p wave capture.

2. Experimental details

A 20 Ci Sb–γ–Be neutron source, supplied by Bhabha Atomic Research Centre, Trombay, India, was used to give neutrons of energies 25 ± 5 keV. The targets used were either metal powders or oxides with purities greater than 99·9%. The samples were kept in thin cylindrical perspex tubes of diameter 13 mm and irradiated at a height of 10 ft from the ground in an open space in order to minimize scattering effects. The source was normally kept inside a properly designed shield and brought into the open air for the duration of irradiation by means of a remote control arrangement. The activity produced in the samples was measured by the absolute gamma counting technique using a heavily shielded scintillation spectrometer employing a calibrated 7F8 well-type NaI(Tl) crystal. A 100 channel analyser was used for recording the gamma ray spectra. Simultaneously with the recording of the gamma ray spectrum, the halflife of the activity was also followed (wherever possible) by accepting the characteristic gamma ray in a wide window single channel analyser–scaler–timer unit for unique identification of the radioactive product formed in the nuclear reaction.

The capture cross section σ is evaluated using the well known expression

$$\sigma = \frac{A(1+\alpha)\lambda}{N\phi P\theta\{1-\exp(-\lambda t_{\mathrm{i}})\}\{\exp(-\lambda t_{\mathrm{a}})-\exp(-\lambda t_{\mathrm{b}})\}} \tag{1}$$

where A is the area of the characteristic photopeak, α the internal conversion coefficient, λ the decay constant of the product nucleus, N the number of nuclei of the target isotope present in the sample, and ϕ the incident neutron flux. P is the effective photopeak efficiency for the selected gamma ray, corrected for selfabsorption and cascade summing effects, θ the percentage abundance of the selected gamma ray, t_{i} the duration of irradiation, t_{a} is the time between the stoppage of irradiation and starting of counting and t_{b} the time between the stoppage of irradiation and stopping of counting.

The quantities θ, α and λ are taken from the literature (Lederer *et al* 1968). The effective photopeak efficiencies are taken from Sriramachandra Murty *et al* (1972). The incident neutron flux ϕ is determined using the reaction $^{127}\mathrm{I}(\mathrm{n},\gamma)^{128}\mathrm{I}$ as a secondary flux standard whose cross section is assumed (Robertson 1965) to be 832 ± 26 mb.

3. Method of analysis

At the incident neutron energy of 25 ± 5 keV only s and p wave neutrons contribute, predominantly, to the capture process. The s wave contribution is computed using s wave resonance parameters relevant to the keV region (recently reported by Musgrove 1970) and with the help of the following expression derived, by Bilpuch *et al* (1960), on the basis of the Breit–Wigner theory of resonance:

$$\sigma_{\mathrm{c}}^{l} = \frac{(1{\cdot}3 \times 10^{6})(2l+1)\pi\bar{\Gamma}_{\gamma l}}{E_{\mathrm{n}}\bar{D}_{l}}\left\{1-\mathrm{e}^{b_l}(b_l\pi)^{1/2}\left(1-\frac{2}{\sqrt{\pi}}\int_{0}^{\sqrt{b_l}}\mathrm{e}^{-t^{2}}\,\mathrm{d}t\right)\right\} \tag{2}$$

where

$$b_l = \frac{\bar{\Gamma}_{\gamma l}}{2V_l S_l \bar{D}_l \sqrt{E_n}}.$$

σ_c^l is the cross section for an incident neutron of angular momentum l and energy E_n (expressed in eV), V_l is the penetration factor for a neutron of angular momentum l ($V_l = 1$ for $l = 0$), $\bar{D}_l$, S_l and $\bar{\Gamma}_{\gamma l}$ are, respectively, the experimentally measured average level spacing, the lth wave neutron strength function and the radiation width.

The p wave capture cross sections have been obtained by subtracting the s wave neutron contributions from the experimentally measured average cross sections. The contributions due to d and higher angular momentum partial waves are assumed to be negligible at this energy.

4. Associated errors

The errors associated with the measured cross sections are the root mean square errors corresponding to the various terms appearing in expression (1). The statistical error in the photopeak areas varies from 1 to 3% depending upon the statistics. The error in the flux determination using a standard iodine cross section is about 7%. Errors in each of the quantities N, t_i, t_a and t_b are less than 1%. The errors in α, λ and θ are taken as reported in the literature. All these errors are compounded according to the well known rules of propagation of errors for each case and the resultant error is quoted for the measured cross section.

Similarly for the s wave cross sections, computed using expression (2), the errors are affixed on the basis of errors involved in each of the quantities $\bar{\Gamma}_{\gamma 0}$, S_0, D_0 etc and in each case errors are taken as reported in the literature. The errors affixed to the p wave cross sections are the root mean squares of the errors associated in the measured cross sections and the computed s wave cross sections.

5. Results and discussion

The average capture cross sections, for twelve isotopes, measured in the present investigation (for the first time) are reported in column 2 of table 1. The experimental results for ^{159}Tb and ^{169}Tm are in good agreement with the recent theoretical estimates (column 3) of Musgrove (1970) at 25 keV. For the remaining cases, excluding isomeric state cross sections, for which the theoretical estimates are not available at 25 keV, comparison is made with the theoretical estimates of Musgrove at 30 keV (values with daggers in column 3). Our experimental results, which are larger than these theoretical estimates at 30 keV, show qualitative agreement with them.

For all the cases for which ground state cross sections are measured the s wave contribution is computed using the method outlined previously and are reported in column 4. The p wave contributions to the capture, obtained by deducting the s wave contribution from the experimentally measured capture cross section, are given in column 5. It is clear from these results that p wave capture is generally quite predominant in heavy nuclei. More extensive and systematic investigations are in progress to extract the p wave neutron strength functions in this region to compare them with theoretical predictions.

Table 1. Average neutron capture cross sections and s and p wave neutron capture at 25 ± 5 keV

Reaction	σ_{expt}(mb)	σ_{theor}(mb)	σ_s(mb)	$\sigma_p = \sigma_{\mathrm{expt}} - \sigma_s$(mb)
^{74}Se(n, γ)^{75}Se	198 ± 30	142†	96 ± 18	102 ± 35
^{78}Se(n, γ)^{79m}Se	98 ± 14	—	—	—
^{84}Sr(n, γ)^{85m}Sr	470 ± 56	—	—	—
^{109}Ag(n, γ)^{110m}Ag	75 ± 10	—	—	—
^{122}Te(n, γ)^{123m}Te	177 ± 23	—	—	—
^{159}Tb(n, γ)^{160}Tb	2949 ± 340	2550	2339 ± 500	610 ± 604
^{169}Tm(n, γ)^{170}Tm	1564 ± 220	1820	1078 ± 210	486 ± 300
^{174}Yb(n, γ)^{175}Yb	245 ± 34	103†	61 ± 20	184 ± 40
^{176}Yb(n, γ)^{177}Yb	210 ± 31	90†	46 ± 14	164 ± 34
^{178}Hf(n, γ)^{179m}Hf	217 ± 27	—	—	—
^{179}Hf(n, γ)^{180m}Hf	215 ± 25	—	—	—
^{192}Os(n,γ)^{193}Os	296 ± 37	168†	66 ± 16	230 ± 40

† Theoretical values at 30 keV.

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