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Cross sections and isomer ratios for some neutron capture reactions

A LAKSHMANA RAO and J RAMA RAO

Laboratories for Nuclear Research, Andhra University, Waltair, India

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Abstract. Neutron capture cross sections leading to the isomeric states in seven nuclei have been measured, for the first time, using the activation technique and absolute gamma counting method, employing an antimony-beryllium neutron source and a calibrated well-type NaI(Tl) crystal. In two reactions, $^{116}Cd(n,\gamma)^{117m,g}Cd$ and $^{151}Eu(n,\gamma)^{152m_1,m_2}Eu$ where cross sections have been measured for a pair of states in each case, the isomeric cross section ratio' has been employed to extract the spin cutoff factor following Huizenga and Vandenbosch formalism. A comparison is made with theoretical predictions based on various models of level density to throw light on the nuclear moments of inertia.

1. Introduction

Capture cross sections of nuclei for neutrons, particularly of intermediate energy ($\simeq 30$ keV), have significant astrophysical importance (Burbidge *et al* 1957). They are useful for an understanding of the nucleosynthesis occurring in stars where the neutrons have precisely the same energy at the high temperatures existing in the stellar interior. The cross sections also serve a practical purpose in the design and construction of nuclear reactors. A survey of previous work done on the capture cross sections at 25 keV neutron energy reveals that most of the cross sections measured were partial cross sections leading only to the ground states of the product nuclei concerned. The cross sections for the formation of the isomeric states have not been measured extensively owing either probably to their short half lives or to their relatively recent discovery. However, these isomeric state cross sections are essential to know the total cross section as well as to obtain the 'isomer ratio' the analysis of which provides valuable information on the spin dependence of nuclear level density, the nature of the transitions between highly excited states and the moments of inertia of nuclei.

In view of this importance, the present work was undertaken to measure the isomeric state cross sections in eight reactions for the first time, using the absolute gamma counting technique under 4π geometry with a calibrated well-type NaI(Tl) crystal. In the interesting reaction $^{116}Cd(n,\gamma)^{117m,g}Cd$ where the isomeric and ground states of the product nucleus ^{117}Cd have the same halflife ($\simeq 3$ h) both the cross sections (previously unreported) have been measured by identifying the states through characteristic gamma lines in their decay. In the reaction $^{151}Eu(n,\gamma)^{152m_1,m_2}Eu$, cross sections have been measured for both the isomeric states of the product nucleus ^{152}Eu. The isomeric cross section ratios in the above two reactions have been analysed using the formalism of Huizenga and Vandenbosch (Huizenga and Vandenbosch 1960, Vandenbosch and Huizenga 1960) to extract experimental spin cut-off factors for the nuclei ^{117}Cd and

^{152}Eu. The values are compared with theoretical predictions based on the Fermi gas, superconductor and independent pairing models to throw light on the moments of inertia of these nuclei.

2. Experimental details

An antimony–beryllium source of strength 20 Ci, obtained from the Bhabha Atomic Research Centre, Bombay was used to give neutrons of 25 ± 5 keV energy. Targets used were natural samples of elements obtained in metallic powder or oxide form with a chemical purity greater than 99·9 %. The powdered samples were put in thin perspex cylindrical tubes of about 1·5 cm diameter and 3·5 cm height and were irradiated at a height of 10 ft from the ground by a remote control arrangement developed for the purpose. The duration of irradiation for each sample was adjusted to produce the activity of interest in preference to other long lived interfering activities that might be produced owing to the use of natural elements as targets. The irradiated samples were transferred manually and the activities produced were detected with a scintillation spectrometer consisting of a 7F8 Harshaw well-type NaI(Tl) crystal and a 100 channel analyser. Simultaneously with the recording of the gamma ray spectra on the 100 channel analyser, the halflife of the activity produced was also studied in a separate channel consisting of a wide-window single channel analyser, attached to a scaler–timer unit. The study of the halflife as well as the gamma spectrum enables unique identification of the reaction product.

From the gamma ray spectrum, a prominent peak, characteristic of the product nucleus of a particular reaction was selected for analysis and its area was determined. The area A thus computed is related to the cross section C for the particular reaction through the equation

$$C = \frac{A(1+\alpha)\lambda}{PN\theta\phi(1-e^{-\lambda t_i})(e^{-\lambda t_a}-e^{-\lambda t_b})} \tag{1}$$

where P is the effective photopeak efficiency of the selected gamma ray after correction for source absorption and cascade effects, θ is the percentage abundance of the gamma ray in the decay of the product nucleus, α its internal conversion coefficient, ϕ the flux of the incident neutrons, N the number of target nuclei in the sample, λ the decay constant of the product nucleus, t_i the duration of irradiation, t_a the time interval between the end of the irradiation and the starting of the counting and t_b the time interval between the end of the irradiation and end of the counting.

The neutron flux ϕ was determined by using the $^{127}I(n,\gamma)^{128}I$ reaction as the secondary flux standard whose cross section was taken as 832 ± 26 mb from the literature (Robertson 1965). The total and photopeak efficiencies for cylindrical sources for the 7F8 NaI(Tl) crystal were determined experimentally (Sriramachandra Murty *et al* 1972) for a gamma energy range of 0·032–1·69 MeV and were used in these studies. The relevant spectroscopic information on the characteristic gamma rays used in the calculation of cross sections is summarized in table 1.

2.1. Errors

The errors associated with the measured cross sections are the root mean square errors corresponding to the various terms appearing in expression (1). Errors in the quantities

Table 1. Relevant spectroscopic information used in the calculation of cross sections

Serial number	Reaction	Spin of the product state	Halflife of the product state	E_γ(MeV) detected	θ (%)	α	Measured cross section (mb)
1	$^{74}Ge(n,\gamma)^{75m}Ge$	7/2	48 s	0·139	100	1·77	25 ± 3
2	$^{85}Rb(n,\gamma)^{86m}Rb$	6	61·2 s	0·560	100	0·018	$35{\cdot}0 \pm 3{\cdot}6$
3	$^{110}Pd(n,\gamma)^{111m}Pd$	11/2	5·5 h	0·170	68	1·28	$7{\cdot}6 \pm 1{\cdot}0$
4	$^{116}Cd(n,\gamma)^{117m}Cd$	11/2	3 h	1·07	28	0·001	$18{\cdot}2 \pm 2{\cdot}9$
5	$^{116}Cd(n,\gamma)^{117g}Cd$	1/2	3 h	1·57	23·5	0·0005	$61{\cdot}2 \pm 9{\cdot}0$
6	$^{121}Sb(n,\gamma)^{122m}Sb$	8	4·2 m	0·061 0·075	100 100	0·8 4·96	$2{\cdot}0 \pm 0{\cdot}3$
7	$^{151}Eu(n,\gamma)^{152m_1}Eu$	0	9·3 h	0·122	13·6	0·98	3200 ± 500
8	$^{151}Eu(n,\gamma)^{152m_2}Eu$	8	96 m	0·09	100	0·35	60 ± 8
9	$^{196}Pt(n,\gamma)^{197m}Pt$	13/2	80 m	0·346	97	6·79	12 ± 2

N, t_i, t_a and t_b are less than 1% each. The errors in the measured efficiency values are estimated to be about 6% for gamma energies greater than 0·2 MeV and about 10% for lower energy gamma rays. The maximum statistical error in the photopeak areas is less than 3%. The error in the iodine cross section is about 3%. The errors on the parameters α, θ and λ are adopted by consulting the relevant original references. In general the errors in α ranged between 5 to 9%. Comparatively, the errors in the values of λ are much less, ranging from 0·1 % to 5%. The error in the gamma ray percentage abundance was about 10% for complex decay schemes and less for simpler decay schemes. Compounding all the errors described above according to the theory of propagation of errors the overall error on the measured cross section is evaluated and presented alongside the experimental value in table 1.

2.2. Isomer ratios

The isomer ratios, defined as the ratio of the cross section for the formation of high spin state to the sum of the cross sections for the formation of low and high spin states, are determined for the reactions $^{116}Cd(n,\gamma)^{117m,g}Cd$ and $^{151}Eu(n,\gamma)^{152m_1,m_2}Eu$ from the measured cross sections. These ratios are analysed using the Huizenga and Vandenbosch formalism (Huizenga and Vandenbosch 1960, Vandenbosch and Huizenga 1960) to extract the spin cut-off factor σ, for the nuclei ^{117}Cd and ^{152}Eu, following in detail a procedure described elsewhere (Lakshmana Rao *et al* 1970). For comparison, theoretical values of the spin cut-off factors are computed using the three commonly employed models of level density, the shifted Fermi gas model (SFM), the superconductor model (SCM) and the independent pairing model (IPM).

3. Results and discussion

The isomeric state cross sections for eight reactions, together with the ground state cross section for ^{117}Cd, measured for the first time by the present authors are shown in the last column of table 1. In table 2 are presented the 'isomer ratios' for the two reactions $^{116}Cd(n,\gamma)^{117m,g}Cd$ and $^{151}Eu(n,\gamma)^{152m_1,m_2}Eu$, together with the experimental and

Table 2. Comparison of experimental and theoretical results for two reactions

Reaction	Experimental isomer ratio	Experimental spin cut-off factor σ_{exp}	Theoretical spin cut-off factors		
			σ_{SFM}	σ_{SCM}	σ_{IPM}
$^{116}Cd(n,\gamma)^{117m,g}Cd$	$0{\cdot}23 \pm 0{\cdot}04$	$4{\cdot}9 \pm 1$	4·8	3·5	3·3
$^{151}Eu(n,\gamma)^{152m_1,m_2}Eu$	$0{\cdot}0184 \pm 0{\cdot}0037$	$2{\cdot}4 \pm 0{\cdot}5$	6·1	4·9	4·1

theoretical spin cut-off factors for the nuclei ^{117}Cd and ^{152}Eu. It can be seen from table 2 that in the first case the experimental spin cut-off factor is in excellent agreement with the theoretical value based on the SFM thereby indicating that the moment of inertia of ^{117}Cd corresponds to the rigid body moment of inertia predicted by the model. In the second case, the experimental spin cut-off factor however does not agree with any of the theoretical predictions. The experimental value is about one third of the theoretical value predicted by the SFM, thereby suggesting a drastic reduction in the moment of inertia of ^{152}Eu as compared to the rigid body value. In view of the fact that ^{152}Eu is a strongly deformed nucleus, this is in line with the general expectation.

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