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Resonant Neutron Capture in ^{139}La

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Abstract

The neutron capture cross section of ^{139}La has been measured with high energy resolution between 2·5 and 90 keV using the capture cross section facility at the 40 m station on the Oak Ridge Electron Linear Accelerator. Individual resonances were analysed to 15 keV and the average s- and p-wave radiative widths deduced were $\langle\Gamma_\gamma\rangle_s = 55\pm6$ meV and $\langle\Gamma_\gamma\rangle_p = 40\pm7$ meV. The p-wave neutron strength function obtained was $S_1 = (0\cdot30\pm0\cdot10)\times10^{-4}$. The s-wave resonances decay strongly to final f-wave states via a postulated doorway state mechanism. The transition strengths for these decays are not correlated with the neutron widths of the initial states.

Introduction

Our investigations of radiative neutron capture in even-A nuclei in the region of the $N = 82$ shell closure have indicated the presence of significant positive correlations between s-wave reduced neutron widths and corresponding total radiative widths (Musgrove *et al.* 1975, 1977). Such correlations are predicted by the valence neutron model when the incoming neutron can undergo a radiative transition to a single-particle final state without disturbing the core (Lynn 1968). In contrast, for neutron capture in ^{139}La, valence effects will be much diminished owing to the smaller neutron widths. The capture mechanism would be expected then to be principally described by the statistical model.

However, ^{139}La exhibits an anomalous decay spectrum. Allen *et al.* (1976) have reported an extraordinary enhancement of those decays leading to final f-wave levels below 600 keV in ^{140}La, following capture of 210 keV neutrons. More recently, Kenny and Allen (1977) have produced further documentation of this effect for bombarding energies in the range 10–70 keV, while Hughes *et al.* (1966) had earlier reported similar behaviour in the thermal capture spectrum. Since valence transitions cannot reach f-wave final states following s-wave capture, Allen *et al.* inferred that neutron capture proceeded via an intermediate $2p$–$1h$ doorway state. Such doorway states have been invoked in the past to explain the existence of the anomalous capture bump in the high energy γ-ray spectra for nuclei above tantalum (Bergqvist and Starfelt 1962; Bartholomew 1969). Evidently, not all the E1 strength is coupled into the giant dipole resonance in these nuclei. Calculations (Lane 1971) indicate that a few per cent of the giant dipole strength can remain in the threshold region forming a pygmy dipole resonance which serves as a common doorway state for both neutron and photon channels. In this situation, strong correlations are expected between neutron and radiative widths, even though valence effects might be insignificant, In the present nucleus, it is of interest to search for correlations between neutron and radiative widths since evidence for intermediate structure has recently been reported by Hacken *et al.* (1976) in the neutron widths below 5 keV.

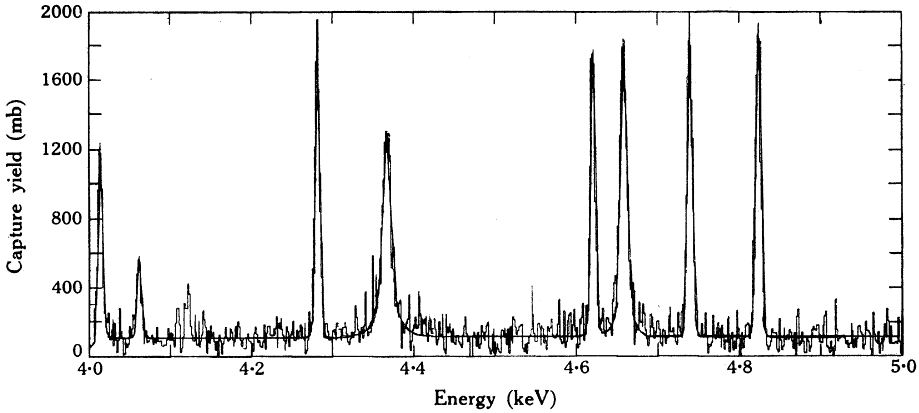

Fig. 1. Fit to the neutron capture data for ^{139}La between 4 and 5 keV.

Experimental Details

The neutron capture cross section for ^{139}La was measured in the neutron energy range 2·5–90 keV with the high resolution ($\Delta E/E \lesssim 0\cdot2\%$ FWHM) attainable at the 40 m station of the Oak Ridge Electron Linear Accelerator (ORELA). The γ-ray detector system has been documented by Macklin and Allen (1971) and Macklin *et al.* (1971). The data were corrected for dead time effects and normalized with respect to the ^{6}Li(n, α) cross section with an estimated uncertainty for the present run of about 5%. With resonance neutron widths from Hacken *et al.* (1976), a Monte Carlo code was used to correct the data, resonance by resonance, for self-shielding and multiple-scattering effects using Breit–Wigner single-level theory to generate the cross sections. At the same time, the correction for prompt neutrons scattered into the γ-ray detector was determined from the calculated scattering cross section and a stored neutron detection efficiency file (Allen and Musgrove 1977). However, these combined corrections were rather small for ^{139}La and added less than 1% to the error. Statistical errors were also of order 1% for the present measurement.

A natural lanthanum target 0·10 cm thick (0·0028 atom b^{-1} in ^{139}La) was used in the measurements.

Results

A fit to a portion of the data is shown in Fig. 1 and details of the analysed resonances between 2·5 and 15 keV are given in Table 1. In most cases, the neutron widths of Hacken *et al.* (1976) gave fits which are consistent with our data. However, a few exceptions have been noted. Several resonances not seen in the transmission data were observed, most of which we ascribe to p-wave capture on the basis of the Bayes theorem test (see e.g. Bollinger and Thomas 1968). Hacken *et al.* also used this test to separate s- and p-wave resonances in transmission and their assignments have been used in the present data set.

Table 1. Resonance parameters for ^{139}La

E^{A} (eV)	$g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)	Γ_n^{B} (meV)	$2g\Gamma_\gamma$ (meV)	l	P^{C} (%)	E^{A} (eV)	$g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)	Γ_n^{B} (meV)	$2g\Gamma_\gamma$ (meV)	l	P^{C} (%)
2668	10±1	(72)	~28	0	8	8690	20±2	(745)	42±4	0	7
2861	21±1	(396)	48±4	0	14	8708	19±2	(242)	44±5	(1)	9
2972	6±1			(1)	11	8848	20±2	(180)	51±7	(1)	0
3000	20±1	(11500)	41±3	0	21	8928	27±3	(7360)	55±6	0	20
3126	1·0±0·2			1	0	9235	22±2	(96)		(1)	8
3293	20±1	(2060)	41±3	0	17	9328	16±2	(193)	37±5	(1)	0
3430	7±1			(1)	4	9628	9±1	(98)	22±8	(1)	0
3461	5±1			(1)	7	9698	30±3	(334)	72±8	0	29
3488	11±1	(14400)	22±2	0	11	9785	16±2	(119)	42±6	(1)	23
3552	8±1			(1)	8	9900	48±5	(2460)	99±10	0	15
3734	34±2	(180)	108±20	0	9	10008	32±3	(4060)	64±7	0	11
3755	23±1	(5140)	47±3	0	13	10092	16±2	(84)	~52	(1)	0
4013	7±1			1	12	10235	30±3	(4853)	61±7	0	16
4060	3·0±0·5			1	5	10322	12±2	(122)	31±8	(1)	3
4281	13±1				11	10396	20±3	(591)	43±6	0	1
4367	23±1	7000±1000	46±2	0	14	10608	34±4	(576)	78±9	0	8
4620	14±1				5	10758	23±3	(622)	49±6	0	17
4658	24±1	(3550)	48±3	0	16	11078	14±2	(100)	~38	1	7
4740	16±1	(102)	48±8	0	6	11140	4±1			1	0
4824	17±1	(152)	45±5	0	11	11190	23±3	(1800)	47±5	0	10
5172	5±1			1	4	11438	14±2	(107)	39±9	1	0
5194	19±1	(130)	53±7	(0)	8	11545	51±5	(2800)	106±15	0	23
5297	5±1			(1)	6	11700	12±2	(100)	~32	1	0
5360	29±2	3000±500	60±4	0	20	11812	15±2	(100)	~43	1	0
5538	16±1	(250)	37±4	0	4	11938	12±2	(524)	25±5	0	10
5841	25±1	(1200)	52±4	0	22	12015	22±3	(723)	46±6	0	11
5855	29±2	(150)	93±12	0	17	12085	10±2			1	21
5872	14±1	(138)	37±6	0	8	12170	43±5	(1830)	90±10	0	5
5891	12±1				8	12440	24±3	(1160)	49±6	0	14
5987	20±1	(580)	42±3	0	7	12705	55±5	(1900)	117±12	0	6
6148	9±1			1	5	13070	11±2	(100)	~30	1	19
6347	17±2	(191)	42±4	(0)	3	13130	16±2	(5040)	32±4	0	12
6470	25±2	(4200)	51±3	0	22	13160	10±2	(100)	~26	1	12
6570	25±3	(1500)	52±3	0	10	13215	17±2	(100)	~51	1	19
6873	25±3	7000±1000	50±3	0	10	13320	24±3	(1710)	50±6	0	10
7004	41±3	(1200)	88±7	0	7	13435	29±4	(2180)	60±8	0	22
7075	13±2	(135)	33±6	(1)	22	13520	30±4	(1490)	62±8	0	11
7109	21±2	(270)	51±4	(0)	14	13730	3±1			1	18
7150	28±2	(2600)	57±4	0	19	13850	16±2	(160)	41±8	1	2
7460	28±2	(260)	71±6	(0)	23	14040	16±2	(190)	37±7	1	10
7478	29±3	(2000)	61±6	0	20	14165	25±3	(1800)	52±6	0	16
7565	15±2	(260)	34±5	(0)	0	14245	37±4	(4250)	75±9	0	23
7638	6±1			1	0	14385	17±3	(1700)	35±6	0	15
7918	29±3	(360)	70±8	0	26	14615	40±4	(4000)	81±8	0	18
8044	54±5	5000±1000	111±10	0	14	14740	3±1			1	14
8190	20±2	(271)	47±6	(1)	11	14840	24±3			1	6
8378	22±2	(457)	48±6	0	2	14925	51±6	(5050)	105±12	0	24
8535	33±3	(5000)	67±7	0	22						

[A] The uncertainty in the energy values is ±0·15%.
[B] Assumed values from Hacken *et al.* (1976) are given in parentheses; results from the present shape analysis which were different from their values are shown with errors.
[C] The values of P are roughly the percentage of the γ-decay spectrum with $E_\gamma \gtrsim 4\cdot1$ MeV (i.e. feeding the low lying levels below ~1·1 MeV).

Since we are interested in the proportion of high energy γ-rays following resonance capture, we extracted from the data that fraction of the γ-decay yield with $E_\gamma \gtrsim 4\cdot1$ MeV. This includes the radiation to the low lying $l_n = 3$ states and is shown as a percentage P in Table 1.

The average resonance parameters obtained from the present data are given in Table 2. Capture cross sections averaged over convenient energy ranges were obtained by summing the calculated capture areas $A_\gamma = 2\pi^2\lambda^2 g\Gamma_n\Gamma_\gamma/\Gamma$ below 15 keV (g is the spin weighting factor and Γ_n, Γ_γ and Γ are respectively the neutron, radiative and total resonance widths). Above 15 keV the background was subtracted and average self-shielding and multiple-scattering corrections were applied to the integrated capture yield to give the capture cross section. At high energies the uncertainty in the background subtraction is an increasing factor in the cross section error. The results for the cross section are given in Table 3 along with the 30 keV Maxwellian

Table 2. Average resonance parameters for ^{139}La

s-wave parameter	Value	p-wave parameter	Value
Level spacing $\langle D\rangle_s$ (eV)	208 ± 10^A		
Strength $10^4 S_0$	$0\cdot76\pm0\cdot13^A$	Strength $10^4 S_1$	$0\cdot3\pm0\cdot1$
Width $\langle\Gamma_\gamma\rangle_s$ (meV)	55 ± 6	Width $\langle\Gamma_\gamma\rangle_p$ (meV)	40 ± 7
S.D. σ (meV)	23		
High E_γ part $\langle P\rangle_s\pm1\sigma$ (%)	$13\cdot5\pm6\cdot5$	High E_γ part $\langle P\rangle_p\pm1\sigma$ (%)	$6\cdot5\pm4\cdot0$
Correlation $\rho(g\Gamma_n^0, g\Gamma_\gamma)$	$-0\cdot16\pm0\cdot20$		
Correlation $\rho(g\Gamma_n^0, P_s g\Gamma_\gamma)$	$-0\cdot03\pm0\cdot20$		

^{A} From Hacken *et al.* (1976).

Table 3. Average capture cross sections for ^{139}La

The Maxwellian averaged cross section $\langle\sigma.v\rangle/v_T$ at 30 keV is 50 ± 5 mb

Energy range (keV)	Cross section (mb)	Energy range (keV)	Cross section (mb)
3–4	155 ± 8	20–25	42 ± 6
4–5	107 ± 6	25–30	50 ± 6
5–6	128 ± 7	30–40	41 ± 5
6–7	64 ± 4	40–50	35 ± 5
7–8	120 ± 7	50–60	32 ± 5
8–9	105 ± 6	60–70	26 ± 5
9–10	60 ± 5	70–80	25 ± 5
10–15	56 ± 6	80–90	24 ± 5
15–20	60 ± 7		

averaged cross section, which is of astrophysical significance. In Fig. 2 the measured capture cross section is compared with a statistical model calculation using the average resonance parameters of Table 2. A nominal d-wave contribution, using a d-wave neutron strength function $S_2 = 0\cdot5\times10^{-4}$, was included in the calculated result. The p-wave strength function $S_1 = (0\cdot3\pm0\cdot1)\times10^{-4}$, obtained from the neutron widths of the resonances assuming $R = 1\cdot35A^{\frac{1}{3}}$ fm, fits the measured cross section better than the value obtained by Hacken *et al.* (1976), namely $S_1 = 0\cdot7\times10^{-4}$.

Discussion

Lanthanum-139 has a target spin and parity $7/2^+$ so s-wave neutrons form compound nucleus states of 4^+ and 3^+ ($g = 9/16$ and $7/16$ respectively). The two g values are too close together to allow separation in either the present experiment or the previous transmission analysis of Hacken *et al.* (1976). However, when taken over both spin states, the correlation between 57 s-wave radiative widths and the corresponding reduced neutron widths is consistent with zero. The calculated valence width for ^{139}La, using the optical model formulation of the valence theory (Lane and Mughabghab 1974; Barrett and Terasawa 1975) is $\lesssim 1$ meV so the lack of an initial state correlation is expected. However, the result contrasts sharply with the significant positive correlations ($\rho(g\Gamma_n^0, g\Gamma_\gamma) > 0\cdot4$) recorded for the odd-$A$ isotopes of neodymium (Musgrove *et al.* 1977) which also have negligibly small valence components. There is also zero correlation between the s-wave neutron widths and the fraction of the radiative width $P_s \Gamma_\gamma$ involved in the high energy decay to the $l_n = 3$ states. Therefore, if the transitions to the final f-wave levels arise from the postulated radiative

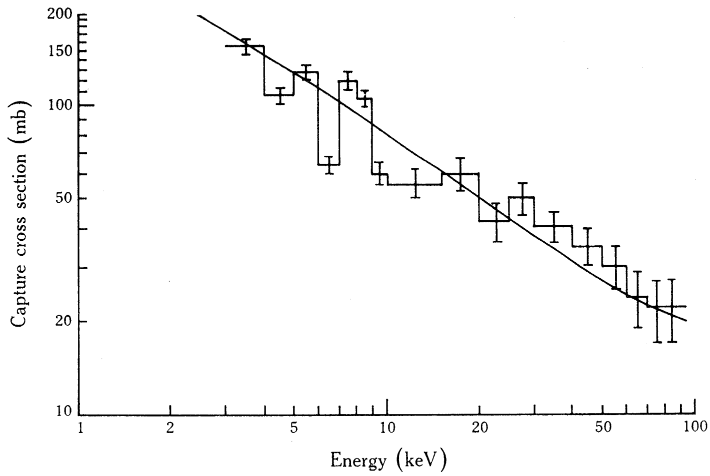

Fig. 2. Measured average neutron capture cross section for ^{139}La compared with a statistical model calculation using the average resonance parameters of Table 2.

doorway mechanism of Allen *et al.* (1976), it appears that this is not also a common doorway state for the neutron channel. Equally, the reported intermediate structure in the neutron channel between 3 and 4 keV is not reflected in the radiative widths to any discernible extent.

The s-wave resonances have a significantly larger fraction of their decay in high energy γ-rays than p-wave resonances. This confirms the findings of Wasson *et al.* (1969), who measured spectra from both s- and p-wave resonances at low energy, and agrees with calculations made by Kenny and Allen (1977). The disparity observed between the average s- and p-wave radiative widths reflects, in part, the greater proportion of high energy decays following s-wave neutron capture.

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Note added in proof

The cross sections reported in Table 3 and shown in Fig. 2 do not include the $1/v$ component from the thermal capture cross section of $9\cdot0$ b.

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