Resonant Neutron Capture in $^{139}$La


AAEC Research Establishment, Private Mail Bag, Sutherland, N.S.W. 2232.

Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, U.S.A.

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 $\langle \Gamma_s \rangle = 55 \pm 6$ meV and $\langle \Gamma_p \rangle = 40 \pm 7$ meV. The p-wave neutron strength function obtained was $S_1 = (0.30 \pm 0.10) \times 10^{-4}$. 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 $\gamma$-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.

![Graph](image)

**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 ($\Delta E/E \lesssim 0.2\%$, FWHM) attainable at the 40 m station of the Oak Ridge Electron Linear Accelerator (ORELA). The $\gamma$-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,$\alpha$) 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 $\gamma$-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.
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 \( E_γ \gtrsim 4\cdot1 \text{ MeV} \). This includes the radiation to the low lying levels below \( \sim 1\cdot1 \text{ MeV} \).

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 \( A_\gamma = 2\pi^2\lambda^2g\Gamma_n\Gamma_\gamma/\Gamma \) below 15 keV (\( g \) is the spin weighting factor and \( \Gamma_n, \Gamma_\gamma \) and \( \Gamma \) 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 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 \( S_2 = 0.5 \times 10^{-4} \), was included in the calculated result. The p-wave strength function \( S_1 = (0.3 \pm 0.1) \times 10^{-4} \), obtained from the neutron widths of the resonances assuming \( R = 1.35 A^{1/3} \) fm, fits the measured cross section better than the value obtained by Hacken et al. (1976), namely \( S_1 = 0.7 \times 10^{-4} \).

**Table 2. Average resonance parameters for \(^{139}\text{La}\)**

<table>
<thead>
<tr>
<th>s-wave parameter</th>
<th>Value</th>
<th>p-wave parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level spacing ( \langle D \rangle_s ) (eV)</td>
<td>208 ± 10^4</td>
<td>Strength ( 10^4 S_0 )</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td>Strength ( \langle \Gamma \rangle_n ) (meV)</td>
<td>0.76 ± 0.13^4</td>
<td>Width ( \langle \Gamma \rangle_\gamma ) (meV)</td>
<td>40 ± 7</td>
</tr>
<tr>
<td>S.D. ( \sigma ) (meV)</td>
<td>23</td>
<td>High ( E_\gamma ) part ( \langle P \rangle_\gamma \pm 1 \sigma ) (%)</td>
<td>13.5 ± 6.5</td>
</tr>
<tr>
<td>Correlation ( \rho(g\Gamma_\gamma, g\Gamma_\gamma) )</td>
<td>-0.16 ± 0.20</td>
<td>High ( E_\gamma ) part ( \langle P \rangle_\gamma \pm 1 \sigma ) (%)</td>
<td>6.5 ± 4.0</td>
</tr>
</tbody>
</table>

\(^4\) From Hacken et al. (1976).

**Table 3. Average capture cross sections for \(^{139}\text{La}\)**

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

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

**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
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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 ($\rho(\Gamma_n^{\text{g.s.}}, \Gamma_{\gamma}^{\text{g.s.}}) > 0.4$) 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 $P, \Gamma_{\gamma}$, 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 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 $\gamma$-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.

**Acknowledgment**

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**Note added in proof**

The cross sections reported in Table 3 and shown in Fig. 2 do not include the $1/\nu$ component from the thermal capture cross section of 9.0 b.
References


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