Aust. J. Phys., 1979, **32**, 551–60

keV Neutron Capture in ^{141}Pr†

R. B. Taylor,[A] *B. J. Allen,*[B] *A. R. de L. Musgrove*[B] *and R. L. Macklin*[C]

[A] Department of Physics, James Cook University of North Queensland, Townsville, Qld 4811.
[B] AAEC Research Establishment, Private Mail Bag, Sutherland, N.S.W. 2232.
[C] Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, U.S.A.

Abstract

The neutron capture cross section of ^{141}Pr has been measured with 0·2% energy resolution from 2·5 to 200 keV. Resonance parameters are given from 2·6 to 13·3 keV. The average s-wave radiative width is 88 meV, with a standard deviation of 27 meV. The s-wave reduced neutron widths and the corresponding radiative widths are not correlated, but the standard deviation of the s-wave radiative widths greatly exceeds that predicted by the statistical model.

Introduction

There have been several recent investigations of the neutron capture reaction below 100 keV for nuclides with 82 neutrons (Musgrove *et al.* 1977*a*, 1977*b*, 1979). As well as measuring the resonance parameters for individual resonances, the correlations between the s-wave reduced widths and the corresponding total radiative widths were calculated. The valence neutron model predicts such correlations, but only in nuclides where there are low lying $l_n = 1$ states in the residual nucleus. Doorway states involving the formation of $2p$–$1h$ states may also lead to a correlation, provided that the doorway states are common to both the neutron and γ-ray channels. The s-wave data for ^{138}Ba and ^{140}Ce (Musgrove *et al.* 1979) were of insufficient accuracy to show a significant correlation. A correlation was not observed in ^{139}La (Musgrove *et al.* 1977*a*), but in this nuclide all the low lying levels are $l_n = 3$. The only nuclide with 82 neutrons to show a significant correlation to date is ^{142}Nd (Musgrove *et al.* 1977*b*) which has several low lying $l_n = 1$ states.

It was decided to extend the neutron capture work on nuclides with 82 neutrons by carrying out measurements on ^{141}Pr. The presence of correlations can be attributed to $2p$–$1h$ states because any contribution from the neutron valence model is excluded, all the low lying states of ^{141}Pr being $l_n = 3$ (Kern *et al.* 1968). The thermal neutron capture γ-ray spectrum of ^{141}Pr (Kern *et al.* 1968) shows strong transitions to the low lying $l_n = 3$ levels, which could possibly indicate that the reaction proceeds through doorway states.

Experimental Details

The neutron capture cross section of ^{141}Pr was measured using the Oak Ridge Electron Accelerator (ORELA) with high resolution ($\Delta E/E = 0{\cdot}002$) at the 40 m

† Research supported in part by the U.S. Department of Energy under contract to Union Carbide Corporation.

Table 1. Resonance parameters for ^{141}Pr

Energies E are accurate to $\pm 0{\cdot}05\%$ and $g\Gamma_n\Gamma_\gamma/\Gamma$ values are accurate to $\pm 6\%$ or ± 1 meV. See text for the assignment of Γ_n, $2g\Gamma_\gamma$ and l values. References to data sources, where applicable, are: W, Wynchank *et al.* (1968); M, Morgenstern *et al.* (1969)

E (keV)	$g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)	Γ_n (eV)	$2g\Gamma_\gamma$ (meV)	l	E (keV)	$g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)	Γ_n (eV)	$2g\Gamma_\gamma$ (meV)	l
2·600	14	0·02 M			5·008	30	0·7 M	68±2	0
2·607	26	0·28 M	63±4	0	5·039	31	0·18 M	96±3	0
2·670	5	0·01 M			5·049	23	0·07 M	64±2	
2·695	7	0·01 M			5·117	7		15±1	
2·710	6	0·01 M			5·139	25	1·4 M	52±1	1 M
2·792	5				5·227	9		19±1	
2·836	35	0·27 M	124±2	0	5·247	83	3·4±2·0	174±2	0 M
2·929	41	0·6 M	97±1	0	5·351	31	0·6 M	70±5	1 M
2·946	15	0·04 M			5·392	23	0·16 M	49±5	
2·975	44	0·27 M	129±3	0	5·418	16	0·16 M		
2·999	54	12·0±1·0	109±2	0 M	5·448	11			
3·034	6				5·598	35	11·1±1	70±3	0 M
3·079	8				5·646	42	0·8 M	94±5	0
3·159	28	0·90 M	64±1	0 M	5·730	42	3·4±2·0	86±3	0 M
3·225	11	0·02 M			5·782	3	0·02 W		
3·397	42	0·17 M		1 M	5·807	18	0·02 W		
3·475	63	0·9 M	146±2	0 M	5·835	3			
3·583	36	0·44 M	87±1	0	5·910	31	0·46 W	72±7	0
3·603	37	7·7±2·0	75±3	0 M	5·918	24			
3·635	4				5·937	20			
3·695	2				5·949	45	0·38 W	111±1	0
3·702	4				5·995	19	0·02 W		
3·725	13	0·08 M			6·015	3			
3·762	8	4·0±0·5	16±2	0	6·035	9			
3·783	42	6·0±0·5	86±3	0 M	6·050	5			
3·869	1		2±1		6·070	23	0·03 W		
3·903	10	0·04 M	21±1		6·252	46	0·39 W	119±2	0
3·971	11	0·02 M			6·267	17			
4·002	26	0·7 M	56±1	0 M	6·285	41	0·32 W	109±2	0
4·022	15	0·04 M	31±1		6·325	32	0·040 W	75±4	0
4·042	10		20±1		6·380	27			
4·368	8	0·02 M	17±1		6·465	14	0·04 W		
4·397	34	0·23 M	93±1	0	6·477	19			
4·474	37	0·18 M	111±6	0	6·580	40	0·149 W	95±4	0
4·496	3				6·703	40	4·9 W	95±7	0
4·511	4				6·720	40	3·3 W	82±3	0
4·523	35	1·01 M	75±5	0 M	6·755	8			
4·542	56	3·0±1·0	117±5	0 M	6·773	7	0·06 W	18±1	
4·556	21		43±2		6·795	21			
4·583	43	6·1±2	88±6	0 M	6·862	28			
4·620	9	4·1±2	19±2	0	6·882	11			
4·669	34	1·6 M	71±1	0 M	6·886	12			
4·679	19		40±1		6·915	6			
4·712	17		35±1		6·924	36	0·41 W	87±3	0
4·849	16	0·04 M			6·970	4			
4·870	8				7·005	3			
4·960	37		80±1	0	7·017	7			
4·974	36	1·3 M	76±1	0 M	7·045	1			

Table 1 (*Continued*)

E (keV)	$g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)	Γ_n (eV)	$2g\Gamma_\gamma$ (meV)	l	E (keV)	$2g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)	l	E (keV)	$2g\Gamma_n\Gamma_\gamma/\Gamma$ (meV)	l
7·074	34	0·33 W	86±2	0	9·772	22		12·750	63	0
7·163	47	4·2 W	117±5	0	9·785	28		12·805	14	
7·180	21				9·988	49		12·840	19	
7·217	31	2·6 W	81±3	0	10·022	37	0	12·922	52	0
7·236	10				10·050	54	0	12·975	15	
7·330	14		29±3		10·073	20		13·103	25	
7·345	51	6·8±3	103±5	0	10·092	26		13·149	47	0
7·387	39	0·03 W		0	10·232	34	0	13·210	41	0
7·400	31			0	10·275	58	0	13·242	45	0
7·424	9				10·412	30		13·315	30	
7·477	31	0·30 W	72±5	0	10·448	33	0			
7·500	17				10·557	31	0			
7·659	38			0	10·690	45	0			
7·682	32			0	10·742	13				
7·767	48	3·9 W	98±5	0	10·828	15				
7·822	34	0·08 W		0	10·852	2				
7·855	11				10·874	19				
7·862	12				10·938	36	0			
7·897	32	0·40 W	77±6	0	10·955	45	0			
7·955	20	0·32 W	46±5	0	10·995	34	0			
7·982	9				11·047	27				
8·040	38			0	11·114	55	0			
8·057	33	5·4±3	66±4	0	11·137	51	0			
8·115	18	0·7 W	39±3	0	11·175	25				
8·157	10				11·240	8				
8·213	56	3·2 W	146±3	0	11·261	32	0			
8·290	17	0·04 W		0	11·392	27				
8·382	18	0·16 W	45±3	0	11·462	22				
8·440	8				11·513	56	0			
8·475	5				11·542	42				
8·492	35	0·28 W	95±6	0	11·572	19				
8·547	41	1·3 W	88±5	0	11·591	28				
8·705	37			0	11·612	21				
8·795	28	8·4±3·4	56±5	0	11·703	34	0			
8·845	21				11·800	28	0			
8·907	45	2·7±1	93±5	0	11·898	39	0			
8·935	60	2·7±1	127±5	0	11·882	33	0			
9·062	34			0	11·914	36	0			
9·100	34			0	11·970	41	0			
9·112	20	3·5 W	40±2	0	12·037	55	0			
9·132	49			0	12·180	19				
9·200	11				12·205	20				
9·245	38			0	12·260	44	0			
9·255	34	9·6±4·0	79±4	0	12·295	33	0			
9·290	34			0	12·330	26				
9·431	41	10·0±4·0	84±4	0	12·365	46	0			
9·443	33			0	12·409	13				
9·502	24				12·444	44	0			
9·520	9				12·525	15				
9·543	46	5·9±3·0	90	0	12·562	55	0			
9·598	42	8·7±4·0	87±7	0	12·670	23				
9·635	27	8·0±4·0	53±5	0	12·720	64	0			

flight path position. The experimental arrangement has been documented elsewhere (Macklin and Allen 1971; Macklin *et al.* 1971). The neutron flux was monitored by a thin ^{6}Li glass detector and the data were normalized with respect to the ^{6}Li(n, α)^{3}H cross section with an estimated uncertainty of about 5%. The cross sections below 12 keV were extracted from the data by fitting the resonances with a single-level Breit–Wigner theory and correcting for self-shielding, multiple scattering and the effects of prompt neutrons scattered into the detector. A Monte Carlo code was used for the analysis (Allen *et al.* 1979). These corrections for ^{141}Pr were small and their combined effects contributed only a few per cent to the error. Statistical errors are of the order of 1%. The target was 0·1 cm thick ($2{\cdot}89\times10^{-3}$ at. b^{-1}).

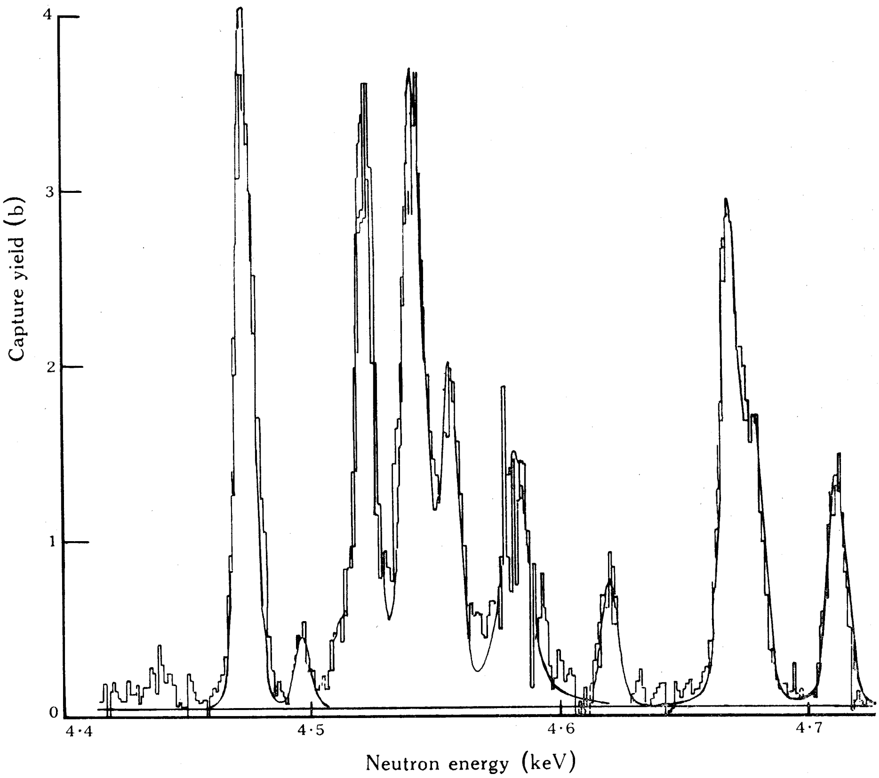

Fig. 1. Capture yield spectra for ^{141}Pr between 4·4 and ~4·7 keV showing Breit–Wigner single-level fits (curves) to experimental (n, γ) resonances (histogram).

Results

A typical portion of the low energy data, together with the Breit–Wigner fits to the resonances, is shown in Fig. 1. Details of the analysed resonances between 2·5 and 13·4 keV are given in Table 1. For resonances with a total level width $\Gamma > 5\times10^{-4}E_{\mathrm{R}}$, where E_{R} is the resonance energy, it is possible to extract a value of the neutron width Γ_{n} from the fitting of the resonance lineshape. For resonances with $\Gamma < 5\times10^{-4}E_{\mathrm{R}}$ the lineshapes are dominated by the energy resolution lineshape, and the fitting was done with Γ_{n} values obtained from Morgenstern *et al.* (1969)

for resonances below 5·75 keV and from Wynchank *et al.* (1968) for resonances above 5·75 keV; in these cases, the values of Γ_n used in the fitting are indicated by M and W respectively in Table 1. Where Morgenstern *et al.* quoted only a value of $g\Gamma_n$, with g the usual spin weight factor, we used the value $g = \frac{1}{2}$ to extract Γ_n. We assume that there is a misprint in the paper by Wynchank *et al.*, in that values quoted for $g\Gamma_n$ are actually for $2g\Gamma_n$; their results for resonances which are directly comparable with the results of Morgenstern *et al.* and the present work (Table 2 below) indicate that they are consistently high by a factor of two.

Table 1 lists values of $2g\Gamma_\gamma$ where $\Gamma_n > 2\Gamma_\gamma$. The fitting procedure does not fit Γ_γ if $\Gamma_\gamma > \Gamma_n$, while if $\Gamma_n \approx \Gamma_\gamma$ the accuracy in the value of Γ_γ depends on the accuracy in that of Γ_n. The l values given in Table 1 are as assigned by Wynchank *et al.* (1968) and Morgenstern *et al.* (1969). Where the level has not been previously assigned an l value we have assumed that $l = 0$ for $g\Gamma_n\Gamma_\gamma/\Gamma > 30$ meV or $\Gamma_n > 0{\cdot}2$ meV, otherwise we have assumed that $l \geqslant 1$.

Table 2. Comparison of Γ_n values

Energies E are expressed in keV and neutron widths Γ_n are expressed in eV

Present work[A]		Morgenstern[B]		Wynchank[C]	
E	Γ_n	E	Γ_n	E	Γ_n
2·999	12·0±1·0	2·998	11·1	2·998	14·0
3·603	7·7±2·0	3·601	9·1	3·603	9·4
3·783	6·0±0·5	3·780	7·4	3·780	9·1
4·542	3·0±1·0	4·536	4·7	4·544	5·3
4·583	6·1±2·0	4·578	7·6	4·587	5·5
5·247	3·4±2·0	5·240	3·4	5·250	2·9
5·598	11·1±1·0	5·593	13·3	5·600	11·2
5·730	3·4±2·0	5·724	3·1	5·734	3·0
7·345	6·8±3·0			7·347	8·5
8·057	5·4±3·0			8·062	5·4
8·795	8·4±3·4			8·804	8·4
8·907	2·7[D]±1·0			8·925	5·4
8·935	2·7[D]±1·0			—	—
9·255	9·6±4·0			9·258	9·6
9·431	10·0±4·0			9·443	10·9
9·543	5·9±3·0			9·553	5·9
9·598	8·7±4·0			9·621	15·6
9·635	8·0±4·0			—	—

[A] These Γ_n values were obtained by fitting to the resonance lineshapes.
[B] These Γ_n values were obtained by Morgenstern *et al.* (1969).
[C] These Γ_n values were obtained from Wynchank *et al.* (1968) using their values of $2g\Gamma_n^0$. For levels where J was not known, we assumed $g = \frac{1}{2}$.
[D] The values of Γ_n for the 8·907 and 8·935 keV resonances were chosen to give a sum of 5·4 eV and a weighted mean value for the resonance energy of 8·919 keV.

A comparison of our Γ_n values with those obtained by Wynchank *et al.* (1968) and Morgenstern *et al.* (1969) is given in Table 2. The present results are generally in good agreement with the earlier work. There are, however, two major discrepancies. Wynchank *et al.* found a resonance at 8·925 keV with a neutron width of 5·4 eV, while our data show two resonances at 8·907 and 8·935 keV which can both be fitted with $\Gamma_n = 2{\cdot}7$ eV. Wynchank *et al.* also found a resonance at $9{\cdot}621$ keV with $\Gamma_n = 15{\cdot}6$ eV, whereas we found two resonances at $9{\cdot}598$ and $9{\cdot}635$ keV with widths $\Gamma_n = 8{\cdot}0 \pm 4$ eV. In both cases it would appear that Wynchank *et al.* have been unable to resolve two close s-wave resonances.

The average parameters for resonances below 10 keV are given in Table 3. These are the average s- and p-wave level spacings $\langle D_s \rangle$ and $\langle D_p \rangle$, the number N_s of s-wave resonances in the energy range, the s-wave neutron strength function S_0, the average s-wave radiative width $\langle \Gamma_\gamma \rangle_s$ and its standard deviation SD, and the correlation coefficient $\rho(g\Gamma_n^0, g\Gamma_\gamma)$ between the s-wave neutron widths and the accompanying radiative widths. The data for resonances above 10 keV were excluded because of uncertainties in Γ_n, Γ_γ and l. The data for resonances below $2{\cdot}6$ keV were taken from Mughabghab and Garber (1973). In determining the average resonance parameters, all previously measured s-wave resonances and all resonances with a measured $\Gamma_n > 0{\cdot}5$ eV were taken as s wave. Since the spread of Γ_n values has a Porter–Thomas

Table 3. Average resonance parameters for ^{141}Pr below 10 keV

Energy range (keV)	$\langle D_s \rangle$ (eV)	N_s	$10^4 S_0$	$\langle \Gamma_\gamma \rangle_s$ (meV)	SD (meV)	$\rho(g\Gamma_n^0, g\Gamma_\gamma)$	$\langle D_p \rangle$ (eV)
0–10·0	116±10	88	1·8	88±9	27	−0·08±0·12	104±10[A]
2·6–10·0	109	68	1·4	91±9	28	−0·01±0·12	85[A]

[A] These values are not corrected for missed p-wave resonances.

Table 4. Average capture cross sections for ^{141}Pr

Energy interval (keV)	σ (mb)	Energy interval (keV)	σ (mb)	Energy interval (keV)	σ (mb)
3–4	385±30	10–15	195±15	50–60	75±10
4–5	390±30	15–20	160±15	60–80	61±8
5–6	425±35	20–30	130±15	80–100	55±7
6–8	335±30	30–40	97±10	100–150	47±7
8–10	241±25	40–50	85±10	150–200	32±6

distribution, the probability of finding p-wave resonances with such a large width is considerably less than 1%. All other resonances (except where stated otherwise) have been taken as p wave. Where Γ_n or $2g\Gamma_n$ had been previously measured, that value was used to determine Γ_γ. The above analysis accounts for most s-wave resonances. For $g\Gamma_n \Gamma_\gamma / \Gamma < 15$ meV, it was assumed that $\Gamma_n < \Gamma_\gamma = 80$ meV, and Γ_n was found from the resonance fits. The remaining resonances all had $g\Gamma_n \Gamma_\gamma / \Gamma \approx 40$ meV, and could be fitted by either assuming $\Gamma_n > \Gamma_\gamma \approx 80$ meV or $\Gamma_\gamma > \Gamma_n \approx 80$ meV; however, the latter gives unrealistically high values of Γ_n (>150 meV) to too many levels. It was decided to assign $\Gamma_n = 500$ meV arbitrarily, and obtain Γ_γ from the fits. These levels were all assumed to have $l = 0$. The effect of these resonances on the average resonance parameters is minimal.

Above 10 keV, the capture cross section was obtained by subtracting the time-independent background (which is proportional to $1/\sqrt{E}$ in this energy region) from the average capture cross section. This background contributes 22% of the total γ-ray yield at 35 keV. At 35 keV, a 3% multiple-scattering correction and a 10% prompt background correction is also required. The self-shielding factor is 0·99. The cross section is plotted in Fig. 2, and compared with a statistical model calculation using the average resonance parameters listed in Table 3. Average cross sections are given in Table 4. The Maxwellian averaged capture cross section at $kT = 30$ keV is 111 ± 15 mb.

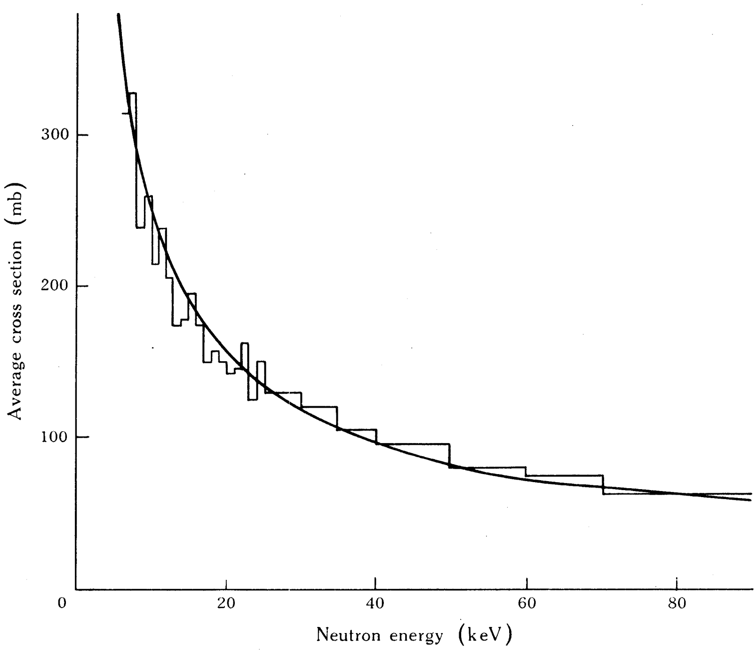

Fig. 2. Average (n, γ) cross section for ^{141}Pr as a function of the neutron energy between 4 and 90 keV, showing experimental cross sections averaged over the indicated energy intervals (histogram) and the theoretical curve calculated from the adopted average resonance parameters given in Table 3.

Discussion

Praseodymium-141 has a ground state spin and parity $5/2^-$, so that s-wave neutron capture populates 2^- and 3^- resonances. It is not possible to separate the resonances on the basis of their spins because of the closeness of the g factor ($g = 5/12$ and $7/12$). The values of $g\Gamma_n$ and the radiative widths for the s-wave resonances are consistent with zero correlation (see Table 3), a result similar to that obtained for ^{139}La. An estimate of the valence contribution to the average total radiative width is approximately 0·9 meV (Allen and Musgrove 1978), which is approximately 1% of the total radiative width (88 meV). The lack of correlation is consistent with the small contribution that valence capture makes to the radiative width, and also indicates that the capture mechanism is unlikely to be due to a single doorway state.

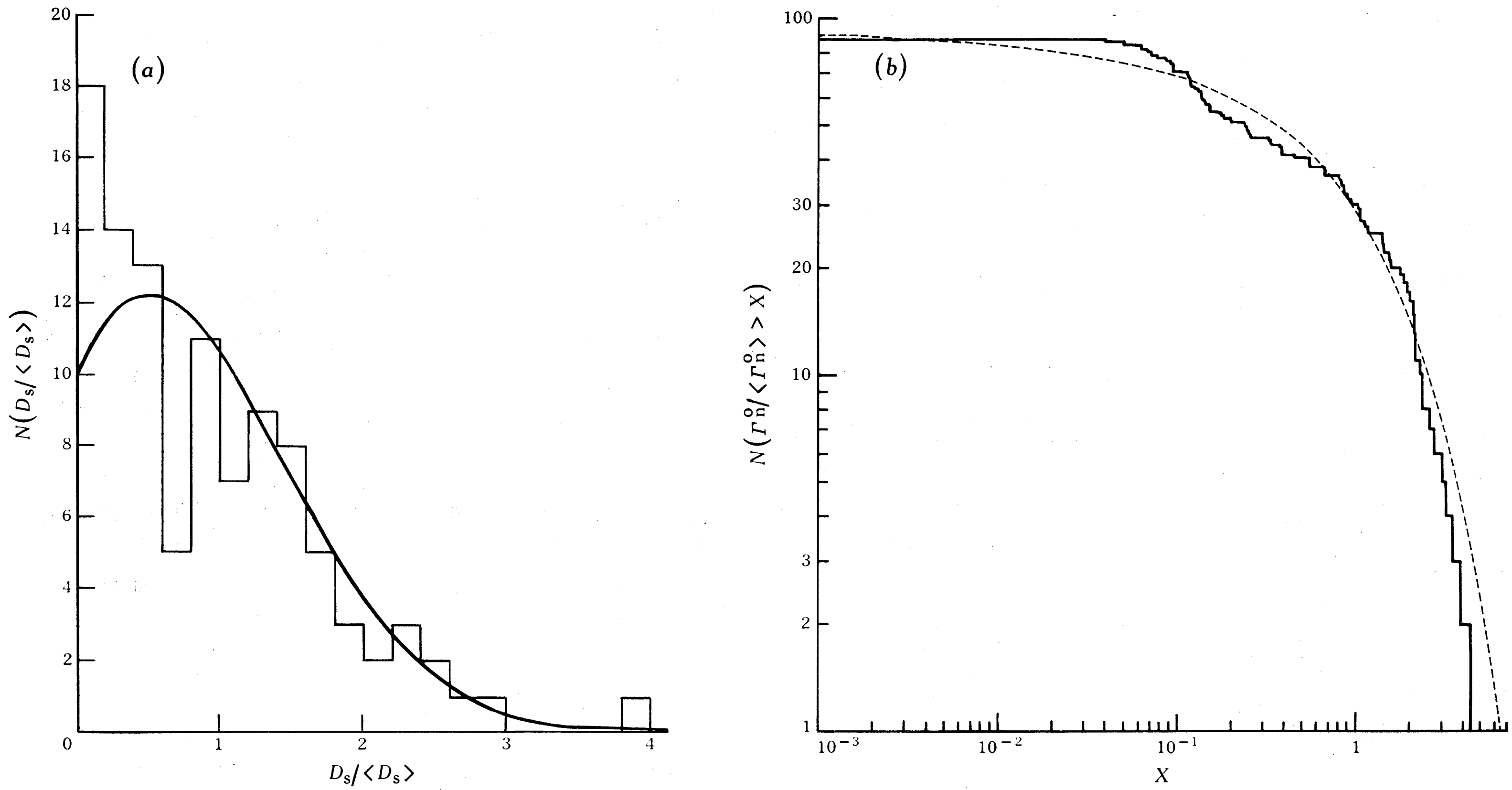

Fig. 3. Comparison between experimental (histogram) and theoretical (curve) distributions for s-wave resonances in ^{141}Pr, showing:

(*a*) The number N of resonances as a function of $D_s/\langle D_s\rangle$, where D_s is the s-wave resonance spacing. The curve is the Wigner distribution for $\langle D_s\rangle = 0{\cdot}1$ keV for two spin states.

(*b*) The cumulative number N of resonances with $\Gamma_n^0/\langle\Gamma_n^0\rangle$ greater than a given value X, as a function of X. The curve is the Porter–Thomas distribution for $\langle\Gamma_n^0\rangle = 0{\cdot}018$. The number of resonances calculated is 91, but only 88 are observed between 0 and 10 keV.

The s-wave resonance spacing and reduced neutron width distributions are given in Figs 3*a* and 3*b*. The latter shows good agreement with the Porter–Thomas distribution. While resonance width correlations are not observed, the observed standard deviation of the s-wave radiative widths (27 meV) is too large to be accounted for by statistical model calculations (Allen 1978; Allen and Musgrove 1979), as is shown below.

The statistical standard deviation is derived from the summation of the E1 and M1 γ-ray transitions to allowed final states μ from resonance λ. This summation has the form

$$\Gamma_{\lambda\gamma} = \sum_{\mu} \Gamma_{\lambda\mu} \propto D_J^\pi \sum_{\mu} \{E_{\gamma\mu}^n(\mathrm{E1}) + R\, E_{\gamma\mu}^n(\mathrm{M1})\},$$

where $R = 0\cdot14$ is the average ratio of M1 and E1 transition strengths (Bollinger 1973) and the exponent n determines the γ-ray strength function ($n = 3$ for a single-particle model). Discrete low lying levels have mostly known spins and parities J_μ^π below $1\cdot2$ MeV. At higher energies the Gilbert–Cameron (1956) prescription for the level density formula is used; the Fermi gas formula at high energies joins smoothly to a constant temperature formula at low energies. The junction energy is obtained by fitting the discrete levels found at low energies and the spacing of neutron resonances at the separation energy D_J^π. The statistical model assumption is that the average transition strength to a final state μ is independent of the final state configuration.

The variance σ_γ^2 of the s-wave radiative widths is deduced after removal of the variance σ_g^2, resulting from the spin factor g, from the observed variance σ_{obs}^2 of the measured product $g\Gamma_\gamma$; it is thus given by

$$\sigma_\gamma^2 = \langle\Gamma_\gamma\rangle^2\left(\frac{\sigma_{\mathrm{obs}}^2}{\langle g\Gamma_\gamma\rangle^2} - \frac{\sigma_g^2}{\langle g\rangle^2}\right),$$

where $\langle g\rangle$, $\langle\Gamma_\gamma\rangle$ and $\langle g\Gamma\rangle$ are the average values. This variance is the sum of the variances resulting from the different neutron capture mechanisms and from the experimental error σ_{exp}, that is,

$$\sigma_\gamma^2 = \sigma_{\mathrm{exp}}^2 + \sigma_{\mathrm{S}}^2 + \sigma_{\mathrm{V}}^2 + \sigma_{\mathrm{D}}^2,$$

where the subscripts S, V and D denote the statistical, valence and doorway components. The statistical variance can be calculated as follows. The statistical partial radiative width $\langle\Gamma_{\lambda\mu}\rangle$ is the expectation value for the distribution of $\Gamma_{\lambda\mu}$ over many resonances λ. The quantity is therefore assumed to follow a χ^2 distribution with one degree of freedom ($\nu = 1$) and with unit mean and variance, so that

$$\sigma_\mu^2 = 2\langle\Gamma_{\lambda\mu}\rangle^2.$$

The total width and variance of the statistical component for m partial widths are given by

$$\Gamma_{\lambda\gamma} = \sum_1^m \langle\Gamma_{\lambda\mu}\rangle \qquad \text{and} \qquad \sigma_{\mathrm{S}}^2 = \sum_1^m \sigma_{\lambda\mu}^2 = 2\sum\langle\Gamma_{\gamma\mu}\rangle^2$$

The relative variance of the weight of m χ^2 distributions (with $\nu = 1$) is

$$\sigma_{\mathrm{s}}^2/\langle\Gamma_{\lambda\mu}\rangle^2 = 2/\nu_{\mathrm{eff}},$$

where ν_{eff} is the effective number of degrees of freedom. Note that $\nu_{\mathrm{eff}} \ll m$ because of the E_j^3 weighting of the partial radiative widths to the low lying states.

For single-particle models, the effective degrees of freedom for the distribution of $\Gamma_\gamma(2^+)$ and $\Gamma_\gamma(3^+)$ are 280 and 330 respectively, corresponding to a standard deviation of ~ 7 meV. The valence contribution will be negligible whereas the experimental error (10%) contributes ~ 9 meV. A standard deviation of 15 meV results from the variation of the g factor since the resonance spins are unknown.

The observed standard deviation implies the existence of a further capture mechanism which contributes ~ 20 meV to the standard deviation of the s-wave radiative widths. If the giant resonance model is used ($n = 5$), the E_γ^5 energy dependence increases the statistical standard deviation to 16 meV, and the excess standard deviation is reduced to 13 meV.

A similar result was observed in ^{139}La (Musgrove *et al.* 1977*a*), where a standard deviation of 23 meV was observed for $\langle \Gamma_\gamma \rangle = 55$ meV. Capture γ-ray spectra (Allen *et al.* 1976) for ^{139}La exhibit anomalous high energy strength to the low lying $l_n = 3$ states, and a $2p$–$1h$ interaction was put forward to explain this observation. If a similar effect occurs in ^{141}Pr then the excess standard deviation could be accounted for by enhanced transitions to the $l_n = 3$ low lying states. It would be of considerable interest therefore to observe capture γ-ray spectra in ^{141}Pr over a wide neutron energy range.

Acknowledgment

The financial assistance of the Australian Institute of Nuclear Science and Engineering is acknowledged.

References

Allen, B. J., Kenny, M. J., Barrett, R. F., and Bray, K. H. (1976). *Phys. Lett.* B **61**, 161.

Allen, B. J., and Musgrove, A. R. de L. (1979). Proc. 3rd Int. Symp. on Neutron Capture γ-ray Spectroscopy and Related Topics. (Eds R. E. Chrien and W. R. Kane) p. 538 (Plenum: New York).

Allen, B. J. (1978). Ph.D. Thesis, University of Wollongong.

Allen, B. J., and Musgrove, A. R. de L. (1978). *Adv. Nucl. Phys.* **10**, 129.

Allen, B. J., Musgrove, A. R. de L., Macklin, R. L., and Winters, R. R. (1979). *In* 'Neutron Data of Structural Materials for Fast Reactors' (Ed. K. H. Böckhoff), p. 506 (Permagon: Oxford).

Bollinger, L. M. (1973). Proc. Asilomar Conf. on Photonuclear Reactions and Applications (Ed. B. L. Berman) Conf-730301, p. 783 (Lawrence Livermore Lab.).

Gilbert, A., and Cameron, A. G. W. (1956). *Can. J. Phys.* **43**, 1446.

Kern, J., *et al.* (1968). *Phys. Rev.* **173**, 1133.

Macklin, R. L., and Allen, B. J. (1971). *Nucl. Instrum. Methods* **92**, 565.

Macklin, R. L., Hill, N. W., and Allen, B. J. (1971). *Nucl. Instrum. Methods* **96**, 509.

Morgenstern, J., Alves, R. N., Ruben, J., and Samoud, C. (1969). *Nucl. Phys.* A **123**, 561.

Mughabghab, S. F., and Garber, D. I. (1973). 'Neutron Cross Sections', Vol. 1 (3rd edn), National Neutron Cross Section Center, Brookhaven Lab., BNL-325.

Musgrove, A. R. de L., Allen, B. J., Boldeman, J. W., and Macklin, R. L. (1977*b*). AAEC Rep. No. E401.

Musgrove, A. R. de L., Allen, B. J., and Macklin, R. L. (1977*a*). *Aust. J. Phys.* **30**, 599.

Musgrove, A. R. de L., Allen, B. J., and Macklin, R. L. (1979). *Aust. J. Phys.* **32**, 213.

Wynchank, S., Garg, J. B., Havens, W. W., Jr, and Rainwater, J. (1968). *Phys. Rev.* **166**, 1234.

Manuscript received 14 February 1979