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LETTER TO THE EDITOR

Correlations between (n, γ) and (d, p) reactions on $N = 82$ nuclei

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Abstract. The measured strengths of excitation in the (n, γ) and (d, p) reactions on the $N = 82$ nuclei ^{138}Ba, ^{140}Ce and ^{142}Nd are compared and it is found that they are strongly correlated for ^{138}Ba and ^{140}Ce but not for ^{142}Nd. The results for ^{138}Ba and ^{140}Ce may be explained in terms of the common unique parent assumption of Lane and Wilkinson. This suggests the predominance of direct capture in the thermal neutron cross section for these nuclei, whereas the ^{142}Nd cross section is thought to be largely due to compound nucleus formation as is the general rule.

For most nuclei the cross section for slow neutron capture followed by the emission of dipole radiation is dominated by compound nucleus formation. Lane and Lynn (1960a,b) have studied the mechanism of the slow neutron capture reaction theoretically and they concluded that there are other contributions to the cross section. There is a non-resonant part, which may be described as the direct scattering of the incoming s-wave neutrons by the nuclear surface into a low-lying orbit. This process is called direct capture or hard sphere potential scattering. In addition to compound nucleus formation the resonant part of the cross section also has a contribution from channel resonance capture, in which the incoming s- or p-wave neutron is scattered by the resonant state into a low-lying orbit with the emission of dipole radiation.

In the case of compound nucleus formation the decay of the resonant state is independent of its method of formation. As a consequence the partial radiative widths for transitions to low-lying states are statistically distributed, cannot be predicted, and we expect them to follow the Porter–Thomas distribution. In contrast Lane and Lynn (1960a,b) showed that for direct capture and channel capture one might expect various non-statistical effects. Under favourable circumstances one might expect to observe these non-statistical effects, and a great deal of experimental effort has been expended during the last seven or eight years in searching for evidence of these simple modes in the (n, γ) reaction mechanism. This effort has met with some degree of success.

Significant departures from the extreme statistical model have now been observed in a number of cases. Lone *et al* (1968) observed a positive correlation between reduced neutron widths and partial radiative widths for ^{169}Tm(n, γ)^{170}Tm which was explained in terms of the channel capture process. Later Lane (1970) showed that simple channel capture was not enough to explain these results and he discussed them in terms of the number of contributing doorway states. Further experimental results (Thomas 1972), including the study of more resonances and new resonance spin assignments, have since cast some doubt on this correlation. Rimawi *et al* (1969) observed enhanced M1 transitions to low-lying positive parity states in ^{94}Nb which they interpreted in terms of 2p–1h doorway states. Earlier Bartholomew *et al* (1970) had put forward a similar explanation for the enhanced gamma radiation at $E_\gamma \simeq 5$ MeV which is observed in both the (n, γ) and (d, pγ) reactions on nuclei near the $N = 82$ and $N = 126$ closed shells. Mughabghab *et al* (1970) and Mughabghab (1971) have also reported non-statistical effects in the $^{163}Dy(n, \gamma)^{164}Dy$ and $^{58}Ni(n, \gamma)^{59}Ni$ reactions.

Although the cross section for direct capture is expected to be much smaller than for resonance capture its existence has been verified directly by Wasson *et al* (1966) and Chrien *et al* (1967). These authors observed the interference between direct and resonance capture in the $^{59}Co(n, \gamma)^{60}Co$ and $^{238}U(n, \gamma)^{239}U$ reactions respectively. Earlier independent evidence for the existence of direct capture was provided by the observation (Groshev *et al* 1958) of a correlation between the strengths of excitation of levels in some light nuclei ($A < 60$) in the (n, γ) and (d, p) reactions. An even stronger correlation between (n, γ) and (d, p) strengths was later reported for the $^{138}Ba(n, \gamma)^{139}Ba$ reaction by Moragues *et al* (1969). The target nucleus ^{138}Ba has 82 neutrons and one expects it to have very similar properties to the other even Z, $N = 82$ nuclei. Mariscotti *et al* (1969) discussed the evidence available for the (n, γ) and (d, p) reactions on ^{140}Ce and ^{142}Nd. Unfortunately, the only results available for levels in ^{141}Ce and ^{143}Nd were for the first two excited states. Intriguingly there did appear to be a correspondence between the (n, γ) and (d, p) strengths for these levels suggesting that the correlation observed in the case of ^{139}Ba might also exist in these two nuclei. The results of further (d, p) and (n, γ) measurements on ^{140}Ce and ^{142}Nd have now become available and it is the purpose of the present work to discuss them.

The simplest explanation for the observation of a correlation between (n, γ) and (d, p) strengths is that given first by Lane and Wilkinson (1955), and discussed by Bockelman (1959), in terms of the 'common unique parent' (CUP) assumption. In their description the wavefunction of the system of A nucleons was expanded in terms of a complete set of orthogonal parent states ϕ_p of $A-1$ nucleons coupled to a single nucleon, each term being weighted by the appropriate coefficient of fractional parentage. The initial state (target plus neutron) in the (d, p) reaction is then the term whose parent state ϕ_{p0} is the ground state of the target nucleus. As a result γ_{dp}, the matrix element connecting the initial state and a given final state, will be proportional to the coefficient of fractional parentage which corresponds to ϕ_{p0} in the final state. In contrast the initial (capture) state in the (n, γ) reaction will normally be a complicated compound nucleus state and will be described by many terms in the expansion. If, however, the term whose parent state is ϕ_{p0} predominates in the expansion (CUP assumption) then $\gamma_{n\gamma}$, the matrix element for neutron capture to the same final state, will be proportional to the same coefficient of fractional parentage as γ_{dp}. $\gamma_{n\gamma}$ and γ_{dp} should then be correlated (Bockelman 1959).

The strength of excitation (G_{dp}) in the (d, p) reaction is given by $G_{dp} = (2J_f+1)S$ and the spectroscopic factor S is proportional to γ_{dp}^2 (Macfarlane and French 1960).

For s-wave neutron capture followed by El transitions the relative strength of excitation in the (n, γ) reaction ($G_{n\gamma}$) is proportional to the reduced transition probability $B(E1) = \gamma_{n\gamma}^2$. Here $G_{n\gamma} = I_\gamma/E_\gamma^3$ where I_γ and E_γ are the relative intensity and energy of the primary gamma ray.

For even–even target nuclei with spin zero and final states with $l_n = 1$ in the (d, p) reaction the CUP assumption leads (Bockelman 1959) to

$$\frac{\gamma_{n\gamma}^2}{\gamma_{dp}^2} \propto (2J_f+1). \qquad (1)$$

Hence $G_{n\gamma}/G_{dp}$ is expected to be constant if the CUP assumption holds.

For the $^{138}Ba(n, \gamma)^{139}Ba$ reaction Moragues *et al* (1969) reported values of $G_{n\gamma}$ and G_{dp} for six states with $l_n = 1$. They found a product-moment coefficient of correlation

$\rho = 0{\cdot}95$ for the observed values of $G_{n\gamma}$ and G_{dp}. This indicates a very strong correlation with only a small probability ($<0{\cdot}3\,\%$) that the observed values are consistent with zero correlation. This result supported the CUP assumption and suggested the predominance of direct capture in the ^{138}Ba(n, γ)^{139}Ba reaction.

Recently Wilson and Booth (1974) have studied both the ^{140}Ce(d, p)^{141}Ce and ^{142}Nd(n, γ)^{143}Nd reactions and have measured $G_{dp} = (2J_f + 1)S$ for the observed levels. Christensen *et al* (1967) have also reported values of G_{dp} for levels in ^{142}Nd. Since the primary gamma-ray intensities in the ^{140}Ce(n, γ)^{141}Ce (Gelletly *et al* 1970) and ^{142}Nd(n, γ)^{143}Nd (Mariscotti *et al* 1974) reactions have also been measured it is now possible to examine whether the correlation observed for ^{139}Ba extends to the other $N = 83$ nuclei. The results of interest for ^{141}Ce and ^{143}Nd are summarized in table 1. Only the results for states assigned $l_n = 1$ in the (d, p) reaction are listed for ^{141}Ce. As for ^{139}Ba (Moragues *et al* 1969) no other states were observed to be populated in the (n, γ) reaction. For ^{143}Nd a number of other states, either not observed in the (d, p) reaction or with positive parity, were observed in the (n, γ) reaction and are listed in table 1. For both nuclei the values of $G_{n\gamma}$ have been normalized to the value of G_{dp} reported by Wilson and Booth (1974) for the first excited state. The final column of table 1 gives $G_{n\gamma}/G_{dp}$.

Figure 1 shows a comparison of $G_{n\gamma}$ and G_{dp} for all the levels in ^{139}Ba, ^{141}Ce and ^{143}Nd which have been assigned $l_n = 1$. The excitation energy and spin assignment are shown on the left and $G_{n\gamma}$ and G_{dp}, normalized to G_{dp} for the first excited state, are shown on the right. The similarity between the results for ^{139}Ba and ^{141}Ce is striking.

There is clearly a close correspondence between $G_{n\gamma}$ and G_{dp} in both cases. The correlation coefficient of $\rho = 0{\cdot}96$ obtained for ^{141}Ce is almost identical to that reported (Moragues *et al* 1969) for ^{139}Ba and again has almost zero probability ($<0{\cdot}1\,\%$) of being consistent with zero correlation. The strong similarity between ^{139}Ba and ^{141}Ce is completed by thermal cross sections (see figure 1), which are of the same order as the crude theoretical estimate of about 0·2 b for the direct capture cross section (Lane and Lynn 1960a,b).

This striking result can clearly be interpreted in terms of the CUP assumption and although such correlations do not constitute proof of direct capture they suggest strongly that direct capture dominates the thermal cross section in both ^{138}Ba(n, γ) and ^{140}Ce(n, γ).

For ^{143}Nd the correspondence between $G_{n\gamma}$ and G_{dp} for the first two excited states, which was noted by Mariscotti *et al* (1969), clearly does not extend to the higher excited states. Several points of difference emerge. First the cross section is very much larger than for ^{138}Ba or ^{140}Ce, which suggests the presence of a bound level close to the neutron binding energy. Secondly in contrast with ^{139}Ba and ^{141}Ce primary neutron capture gamma rays are observed to levels not seen in the (d, p) reaction, levels assigned $l_n = 3$ and a positive parity level (Christensen *et al* 1967) at 1608·6 keV. No meaningful value of ρ can be obtained for the $l_n = 1$ levels in this case since either $G_{n\gamma}$ or G_{dp} is effectively zero for several of them. Even for those where $G_{n\gamma}$ and G_{dp} are available there is no significant degree of correlation. Thus these results rule out the suggestion made by Mariscotti *et al* (1969) that ^{142}Nd(n, γ)^{143}Nd is a case where there is a correlation between $G_{n\gamma}$ and G_{dp} because of the predominance of the parent state ϕ_{p0} in the final state and not the initial state. Instead the thermal cross section for ^{142}Nd is probably dominated by compound nucleus formation as is the general rule.

Two other even Z, $N = 82$ nuclei, ^{136}Xe and ^{144}Sm, are stable but unfortunately too few results are available at present for discussion. The strong correlations observed

Table 1. Results from the (n, γ) and (d, p) reactions on the $N = 82$ nuclei, ^{140}Ce and ^{142}Nd. For ^{140}Ce only those states assigned $l_n = 1$ have been listed. In the case of ^{142}Nd some states not assigned $l_n = 1$ or not observed in the (d, p) reaction are listed because they are populated by primary capture gamma rays. The first two columns give the excitation energies (in keV) E_l and the spins and parities (J_f^π) of the states of interest. The third, fourth and fifth columns give the energy E_γ, intensity I_γ (relative to the strong 662 keV and 742 keV ground state transitions in ^{141}Ce and ^{143}Nd respectively), and strength $G_{n\gamma}(= I_\gamma/E_\gamma^3)$ of the primary gamma rays observed in the (n, γ) reaction. In both cases the values of $G_{n\gamma}$ have been normalized to the value of G_{dp} for the first excited state as given by Wilson and Booth (1974). The strengths $G_{dp} = (2J_f + 1)S$ given in column 6 are those measured by Booth and Wilson (1974). Column 7 gives the values of G_{dp} for ^{143}Nd reported by Christensen *et al* (1967). The last column lists the ratio $G_{n\gamma}/G_{dp}$ where G_{dp} is taken from column 6.

Nucleus	E_l	J_f^π	E_γ	I_γ	$G_{n\gamma}$	G_{dp}†	G_{dp}‡	$G_{n\gamma}/G_{dp}$†
^{141}Ce	662·0	$\frac{3}{2}^-$	4766·6	$48·0 \pm 4·8$	1·84	1·84		1·00
	1137·0	$\frac{1}{2}^-$	4291·4	$22·1 \pm 2·4$	1·16	0·78		1·50
	1808·7	$\frac{3}{2}^-$	3619·7	$4·0 \pm 0·9$	0·35	0·38		0·92
	1994·0	$\frac{1}{2},\frac{3}{2}^-$	3435·0	$2·0 \pm 0·4$	0·24	0·09		2·66
	2189·6	$\frac{1}{2},\frac{3}{2}^-$	3239·0	$2·7 \pm 0·6$	0·33	0·29		1·14
	2336·3	$\frac{1}{2},\frac{3}{2}^-$	3092·5	$2·8 \pm 0·6$	0·40	0·27		1·48
	2410·8	$\frac{1}{2},\frac{3}{2}^-$	3017·1	$4·7 \pm 0·6$	0·71	0·49		1·46
	2425·6	$\frac{1}{2},\frac{3}{2}^-$	3003·3	$3·9 \pm 0·6$	0·59	0·85		0·71
	2522·9	$\frac{1}{2},\frac{3}{2}^-$	2905·9	$3·0 \pm 0·7$	—	—§		—
^{143}Nd	742·0	$\frac{3}{2}^-$	5380	$30·8 \pm 3$	2·26	2·26	1·60	1·0
	1305·5	$\frac{1}{2}^-$	4820	$8·7 \pm 0·6$	0·89	1·03	0·74	0·87
	1608·6	$\frac{1}{2},\frac{3}{2}^+$	4512	$2·6 \pm 0·4$	0·32	—	—	—
	1774.4	$\frac{1}{2},\frac{3}{2}^-$	4347	$11·6 \pm 0·8$	1·61	—	—	—
	1799·4	$\frac{1}{2},\frac{3}{2}^-$	4323	$4·9 \pm 0·5$	0·69	—	—	—
	1852.8	$\frac{1}{2},\frac{3}{2}^-$	4265	$3·8 \pm 1·0$	0·56	0·28	1·04	2·0
	1901·0‖	$(\frac{5}{2}^-)$	4217	$0·72 \pm 0·2$	0·11	—	—	—
	2004·2‖	$(\frac{5}{2}^-)$	4113	$1·2 \pm 0·3$	0·20	—	—	—
	2125·7	$\frac{1}{2},\frac{3}{2}^-$	3991	$1·4 \pm 0·3$	0·25	0·19	0·16	1·32
	2252	$\frac{1}{2},\frac{3}{2}^-$	—	$\leqslant 0·04$	—	0·23	0·24	—
	2318·1	$\frac{1}{2},\frac{3}{2}^-$	3805	$0·4 \pm 0·1$	0·08	0·18	0·12	0·44
	2363	$(\frac{1}{2},\frac{7}{2}^-)$	—	$\leqslant 0·5$	—	1·03	0·20	—
	2419	$\frac{1}{2},\frac{3}{2}^-$	—	$\leqslant 0·04$	— }	0·22	—	—
	2428	$\frac{1}{2},\frac{3}{2}^-$	—	$\leqslant 0·04$	— }		—	—
	2462	$\frac{1}{2},\frac{3}{2}^-$	—	$\leqslant 0·05$	—	0·08	—	—
	2534·5	$\frac{1}{2},\frac{3}{2}^-$	3592	$5·0 \pm 0·6$	1·23	0·35	—	3·54

† Values of G_{dp} from Wilson and Booth (1974).

‡ Values of G_{dp} from Christensen *et al* (1967).

§ This level was observed by Wilson and Booth (1974) but a value of G_{dp} could not be obtained because of the presence of an impurity line.

‖ These are probably the levels reported by Wilson and Booth (1974) at 1902 and 2008 keV with $l_n = 3$.

for ^{139}Ba and ^{141}Ce, which appear to suggest that the direct capture is enhanced by the strong nuclear structure effect of the $N = 82$ closed shell and the availability of the 4s–3p single-particle transition in this region (Lane 1970), also suggest that similar correlations should be observed for ^{144}Sm and ^{136}Xe where the total thermal cross sections are also small and resonance capture should not interfere.

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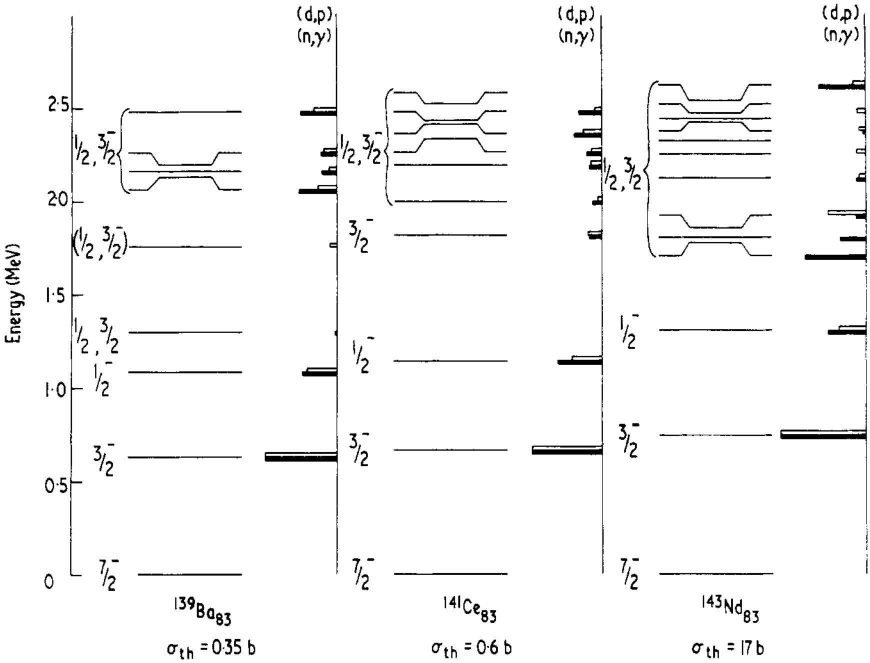

Figure 1. Levels in ^{139}Ba, ^{141}Ce and ^{143}Nd which have been assigned $l_n = 1$ in the (d, p) reaction on the corresponding $N = 82$ nuclei. An energy scale is shown on the left. The spin and parity is shown on the left of each level. The strengths of excitation obtained in the (n, γ) and (d, p) reactions, normalized to the strength of excitation of the first excited state in the (d, p) reaction (Wilson and Booth 1974) are shown graphically on the right of each level scheme. The thermal capture cross section (σ_{th}) for each of the three target nuclei is given below the appropriate level scheme.

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