300 keV. Figure 3 illustrates this similarity by showing six such anomalies on an expanded scale with their (p,n) threshold energies aligned. The shapes observed here are definitely not attributable to the simple Breit-Wigner interference shape, and differ markedly from the single-minimum shapes observed previously in (d,p) reactions[1,2] and calculated by Tamura and Watson.[3]

From a spectroscopic viewpoint, the nonanalogous anomaly is the equivalent of protons bombarding an excited target and allows the study of states in the residual nucleus which have the configuration of a hole coupled to an excited state of the target core. As in quasi-inelastic scattering, such an effect is most likely to be observed when the excited state of the target is collective, since this effect occurs through the deformed isospin potential. ^{98}Mo is therefore a good nucleus for the study of isospin coupling. In addition, the strength of the interference term is expected to be stronger when there are available in the last shell more neutrons through which charge-exchange coupling can occur.

In summary, we have observed the effect of isospin coupling in the incident (^{98}Mo$+p$) channel in the form of anomalies in the excitation functions for several different outgoing channels, at (p,n) threshold energies to the ground-state and excited-state analogs of ^{98}Mo. The latter effect implies the need for a Y_l distortion of the isospin potential of at least $l=2$. The simultaneous observation of these anomalies in several channels and the similarity of their shapes should provide a significant challenge for coupled-channel calculations.

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[1]C. F. Moore, C. E. Watson, S. A. A. Zaidi, J. J. Kent, and J. G. Kulleck, Phys. Rev. Letters 17, 926 (1966).

[2]R. Heffner, C. Ling, N. Cue, and P. Richard, Phys. Letters 26B, 150 (1968).

[3]T. Tamura and C. E. Watson, Phys. Letters 25B, 186 (1967).

[4]L. S. Michelman and C. F. Moore, Phys. Letters 26B, 446 (1968); J. G. Kulleck, T. I. Bonner, and L. S. Michelman, Bull. Am. Phys. Soc. 13, 1428 (1968).

[5]S. A. Hjorth and B. L. Cohen, Phys. Rev. 135, B920 (1964).

[6]J. P. Bondorf, C. Ellegaard, J. Kantele, H. Lutken, and P. Vedelsby, Nucl. Phys. A101, 338 (1967).

[7]G. R. Satchler, R. M. Drisko, and R. H. Bassel, Phys. Rev. 136, B637 (1964).

CORRELATIONS BETWEEN (n,γ) AND (d,p) REACTIONS ON $N=82$ NUCLEI*

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Correlations between the measured strengths of excitation in the (n,γ) and (d,p) reactions on the $N=82$ nuclei Ba^{138}, Ce^{140}, and Nd^{142} are discussed. The results are shown to be consistent with the common unique parent assumption of Lane and Wilkinson.

The neutron capture reaction is generally regarded as the classic case of the compound-nucleus or resonance reaction, but it may also proceed as a direct reaction. The mechanism of direct neutron capture has been discussed by Bockelman[1] and Lane and Lynn.[2] These authors conclude that the radiative cross section for this process may be expected to be much smaller than that observed in the more typical resonance neutron capture reaction. The existence of direct capture has recently been confirmed by Wasson et al.[3] and by Chrien et al.,[4] who deduced direct-capture cross sections of the order of a few millibarns for the reactions Co$^{59}(n,\gamma)$ and U$^{238}(n,\gamma)$ from the observation of interference between direct and resonance capture.

Independent evidence for the occurrence of direct capture is provided by the observation[5] of a correspondence between the (n,γ) and (d,p) reactions in some light nuclei ($A \leq 60$). In the present work we present the first evidence of this type for heavier nuclei ($A \sim 140$). A strong correlation is observed between the (n,γ) and (d,p) reactions for three nuclei with $N=82$. The purpose of this Letter is to show that these results are wholly consistent with the "common unique parent" (CUP) assumption suggested by Lane and Wilkinson[6] some years ago and that this assumption may describe the situation better than was hitherto thought.[1]

Lane and Wilkinson considered the wave function of the system of A nucleons 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 usual coefficients of fractional parentage. In this representation the initial state in the (d,p) reaction (target plus neutron) is naturally described by one term of the expansion, namely, that term whose parent state is the ground state of the target nucleus φ_{p_0}. Consequently the matrix element[7] γ_{dp} connecting the initial state to a given final state will be proportional to the coefficient of fractional parentage which corresponds to the same parent state φ_{p_0} in the expansion of that final state. On the other hand, the initial (capture) state of a typical (n,γ) reaction, in which the formation of a compound nucleus takes place, will be described by many terms in the expansion. However, if, in a particular case, the term whose parent state is φ_{p_0} predominates in this expansion (CUP assumption), then the matrix element[8] $\gamma_{n\gamma}$ will be approximately proportional to the same coefficient of fractional parentage as that to which γ_{dp} is proportional. A correlation between the two matrix elements $\gamma_{n\gamma}$ and γ_{dp} should then be observed. A similar situation occurs if the CUP assumption applies to the final state instead of the initial state. Indeed, as pointed out by Bockelman,[1] it may occur that both the initial and final states are of this type. Such a situation would correspond to a direct capture process. Experimentally one would expect to approach this situation, in which the ground state of the target nucleus represents the predominant parent state in either or both of the initial and final states, when the target is a closed-neutron-shell nucleus.

To test this assumption we have chosen to study the (n,γ) reaction on the $N=82$ targets Ba^{138}, Ce^{140}, and Nd^{142}. The (d,p) reactions on these nuclei have already been studied.[9,10] These results enable us to compare the strengths with which a given final state is excited in the two reactions.

The details of the measurements on the reactions $Ba^{138}(n,\gamma)$ and $Ce^{140}(n,\gamma)$ will be presented elsewhere.[11] We shall only be concerned here with those results of the (n,γ) reactions which are relevant to the comparison with the (d,p) reaction data.

Our analysis is limited to those states which have been assigned $l_n=1$ in the (d,p) reaction studies, as no primary transitions in the (n,γ) reactions were observed to populate final states with $l_n\neq 1$. Since we are dealing with s-wave capture this implies $E1$ multipolarity for the observed primary transitions. Hence the relative strength $G_{n\gamma}$ of excitation in the (n,γ) reaction is proportional to the reduced transition probability $B(E1)$ $(\equiv \gamma_{n\gamma}{}^2)$. In our analysis we use $G_{n\gamma}=I_\gamma/E_\gamma{}^3$ where I_γ and E_γ are the energy and intensity of the primary γ ray.

The corresponding strength of excitation in the (d,p) reaction, which is deduced from the intensities of the groups of outgoing protons, is given by $G_{dp}=(2J_f+1)S$ where J_f is the spin of the final state and the spectroscopic factor S is proportional to $\gamma_{dp}{}^2$.[12]

In the present case, in which we deal with even-even (spin-0) targets and $l_n=1$ states, the CUP assumption of Lane and Wilkinson leads to[1]

$$\gamma_{n\gamma}{}^2/\gamma_{dp}{}^2 \propto 2J_f+1. \tag{1}$$

In terms of the excitation strengths $G_{n\gamma}$ and G_{dp}, which are defined above, Eq. (1) becomes[13]

$$G_{n\gamma}/G_{dp}=\text{const.} \tag{2}$$

A plot of $G_{n\gamma}$ vs G_{dp} is shown in Fig. 1 for the levels assigned $l_n=1$ in Ba^{139}. As can be seen, there is a strong correlation between these two quantities which is clearly in agreement with Eq. (2). The correlation coefficient corresponding to this set of values is $\rho=0.95$ and the probability that this value is consistent with a mean value $\bar{\rho}=0$ (no correlation) is less than 0.3%. The results obtained for Ba^{139} appear, then, to provide support for the CUP assumption and at

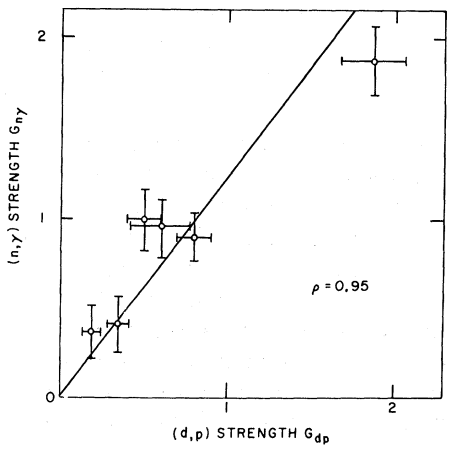

FIG. 1. The strength of excitation $(G_{n\gamma}=I_\gamma/E_\gamma{}^3)$ in the reaction $Ba^{138}(n,\gamma)$ plotted against the strength of excitation $[G_{dp}=(2J_f+1)S]$ in the reaction $Ba^{138}(d,p)$ for levels in Ba^{139}. The slope of the straight line corresponds to an average value of all the measured ratios $G_{n\gamma}/G_{dp}$ (see Table I).

the same time suggest the predominance of direct capture in the reaction $Ba^{138}(n,\gamma)$. Two additional facts in support of this interpretation should be noted. (1) A crude theoretical estimate[2] of the expected cross section for direct capture yields $\sigma_{thermal}(\text{direct capture}) \sim 0.2$ b, which is consistent with the total experimental cross section $\sigma_{thermal}(\text{exp}) = 0.35 \pm 0.15$ b.[14] (2) The first unbound resonance in the reaction $Ba^{138}(n,\gamma)$ is found[14] at 31.7 keV and its contribution to the thermal cross section is less than 4 mb.

Unfortunately the information currently available on the reactions $Ce^{140}(d,p)$ and $Nd^{142}(d,p)$ is much more limited than in the case of the reaction $Ba^{138}(d,p)$. In both cases the (d,p) strength has only been measured[10] for the first two excited states which have been assigned $l_n = 1$. The experimental results for all three nuclei are summarized in both Table I and Fig. 2. Only the results for states assigned $l_n = 1$ and having known values of both $G_{n\gamma}$ and G_{dp} are included. In Fig. 2 the values of $G_{n\gamma}$ and G_{dp} are indicated graphically on the right of each level scheme. Ba^{139} provides the only case where more than two levels are available for a comparison of the two reactions. It is noteworthy, however, that $G_{n\gamma}$ and G_{dp} for the first two excited states in Ce^{141} and Nd^{143} appear to be correlated in the same way as for the corresponding levels in Ba^{139}.

Table I. Results from the (n,γ) and (d,p) reactions on $N = 82$ nuclei. Only states assigned $l_n = 1$ are listed. The first two columns give the energies (in keV) and the spins and parities of the states excited in both reactions. The third, fourth, and fifth columns show the energy E_γ (in keV), intensity I_γ, and strength $G_{n\gamma}$ $(=I_\gamma/E_\gamma^3)$ of the primary γ rays observed in the (n,γ) reaction (Ref. 11). The intensities I_γ are given as a percentage of the intensity of the γ ray depopulating the first excited state. The values $G_{n\gamma}$ are normalized to the G_{dp} strength for the first excited state. The strengths $G_{dp} = (2J_f + 1)S$ and the spectroscopic factors S obtained from the (d,p) reaction (Refs. 9 and 10) are shown in the sixth and seventh columns. The last column contains the ratios $G_{n\gamma}/G_{dp}$. The reported G_{dp} strength (Ref. 10) for the 1292-keV level in Ba^{139} is not included here because this level could not be resolved from the 1284-keV level in the (d,p) reaction studies see Ref. 11).

			(n,γ)			(d,p)		
	E_f	J_f^π	E_γ	I_γ	$G_{n\gamma}$	G_{dp}	S	$G_{n\gamma}/G_{dp}$
Ba^{139}								
	627.26	3/2-	4096.1±0.7	60 ±7	1.90±0.20	1.90±0.20	0.48	1.0±0.2
	1081.9	1/2-	3641.4±0.7	20 ±3	0.91±0.13	0.80±0.08	0.40	1.1±0.2
	2129.3	(1/2-)	2594.1±1.0	8 ±1	1.01±0.25	0.50±0.10	(0.25)	2.0±0.9
	2156.0	(1/2-)	2567. ±2	3.0±1.5	0.38±0.20	0.20±0.06	(0.10)	2.0±1.6
	2186.4	(1/2-)	2537.0±1.5	3 ±1	0.42±0.14	0.35±0.10	(0.18)	1.2±0.7
	2481.4	(3/2-)	2242 ±1	5 ±1	0.97±0.20	0.60±0.12	(0.15)	1.7±0.7
Ce^{141}								
	662.0	3/2-	4766.6±0.8	50 ±6	1.70±0.15	1.70±0.20	0.42	1.0±0.2
	1137.0	1/2-	4291.4±0.8	22 ±3	1.05±0.10	0.76±0.08	0.38	1.4±0.3
Nd^{143}								
	742	3/2-	5380	16.0±1.5	1.60±0.15	1.60±0.20	0.40	1.0±0.2
	1310	1/2-	4820	4.7±0.5	0.66±0.07	0.50±0.05	0.25	1.3±0.3

Despite this similarity in the behavior of the three isotopes studied the case of Nd^{143} is clearly different from the other two. For Ba^{139} and Ce^{141} the observed correlation between the (n,γ) and (d,p) excitation strengths and the magnitudes of the total thermal-neutron capture cross section are consistent with the CUP assumption and the direct or potential neutron capture mechanism as discussed by Lane and Lynn.[2] For Nd^{143}, however, the measured thermal-neutron capture cross section is ~17 b, which suggests the presence of a bound level close to the neutron binding energy in this nucleus. This would normally lead us to expect that the capture state has a complicated configuration. Thus Nd^{143} may be a case in which a correlation with the (d,p) reaction arises from the predominance of the parent state φ_{p_0} in the final state only. This hypothesis seems to be consistent with the measurement of relatively large spectroscopic factors for the

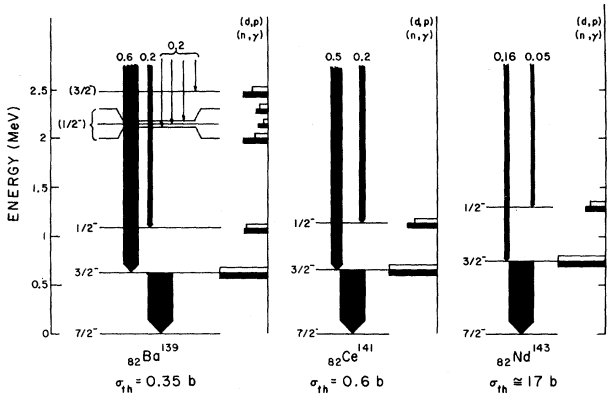

FIG. 2. Levels in Ba^{139}, Ce^{141}, and Nd^{143} which have been assigned $l_n = 1$ in the (d,p) reaction on the corresponding $N = 82$ target nuclei. An energy scale is shown on the left. The strengths of excitation obtained in the (n,γ) and (d,p) reactions, normalized for the first excited state, are shown graphically on the right of each partial level scheme. The widths of the arrows representing the gamma transitions in the (n,γ) reaction are proportional to their measured intensities. The intensities of the primary transitions relative to the intensity of the transition de-exciting the first excited state in the same nucleus are indicated above the arrows representing the transitions.

first excited $\frac{3}{2}^-$ and $\frac{1}{2}^-$ states. It is worth noting that the transitions to these states in Nd^{143} occur in $\leq 21\%$ of the total captures as compared with the corresponding values of 70 and 80% for Ce^{141} and Ba^{139}. This tendency of the capture state in Nd^{143} to decay via other paths is consistent with the interpretation that the initial state in this case is more complicated than in Ba^{139} and Ce^{141}. The reaction mechanism underlying this interpretation may be the channel resonance capture process postulated by Lane and Lynn.[2]

Further information on the reactions $Nd^{142}(d,p)$ and $Ce^{140}(d,p)$ would clearly be of great interest. If the spectroscopic factors for higher levels in Nd^{143} are small then a description in terms of the CUP assumption or the theory of Lane and Lynn would suggest that the correlation between the (n,γ) and (d,p) reactions which is observed for the first two excited states should disappear since the final states would no longer have pure configurations.

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[1]C. K. Bockelman, Nucl. Phys. 13, 205 (1959).

[2]A. M. Lane and J. E. Lynn, Nucl. Phys. 17, 563, 586 (1960).

[3]O. A. Wasson, M. R. Bhat, R. E. Chrien, M. A. Lone, and M. Beer, Phys. Rev. Letters 17, 1220 (1966).

[4]R. E. Chrien, D. L. Price, O. A. Wasson, M. R. Bhat, M. A. Lone, and M. Beer, Phys. Letters 25B, 195 (1967).

[5]L. V. Groshev, A. M. Demidov, V. N. Lutsenko, and V. I. Pelekhov, in Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958 (United Nations, Geneva, Switzerland, 1958), Vol. 15, p. 138. See also the review article of G. A. Bartholomew, Ann. Rev. Nucl. Sci. 11, 259 (1961).

[6]A. M. Lane and D. H. Wilkinson, Phys. Rev. 97, 1199 (1955).

[7]A. M. Lane, Proc. Phys. Soc. (London) A66, 977 (1953).

[8]A. M. Lane and L. A. Radicati, Proc. Phys. Soc. (London) A67, 167 (1954).

[9]J. Rapaport and W. W. Buechner, Phys. Letters 18, 299 (1965), and private communication.

[10]C. A. Wiedner, A. Heusler, J. Solf, and J. P. Wurm, Nucl. Phys. A103, 433 (1967), and private communication.

[11]J. A. Moragues, M. A. J. Mariscotti, W. Gelletly, and W. R. Kane, Phys. Rev. (to be published).

[12]M. H. Macfarlane and J. B. French, Rev. Mod. Phys. 32, 567 (1960).

[13]Equation (2) does not agree with Eq. (5) of Ref. 1. This disagreement arises from the association of $G_{n\gamma}$ with $(2J_f+1)\gamma_{n\gamma}{}^2$ in Ref. 1 instead of $\gamma_{n\gamma}{}^2$. See also J. R. Comfort, Phys. Rev. Letters 21, 1030 (1968).

[14]M. D. Goldberg, S. G. Mughabghab, S. N. Purohit, B. A. Magurno, and V. M. May, Brookhaven National Laboratory Report No. BNL-325, 1966 (unpublished).