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DIRECT NEUTRON CAPTURE AND RELATED MECHANISMS

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ABSTRACT

We consider the evidence for the role of direct and related mechanisms in neutron capture at low and medium energies. Firstly, we compare the experimental data on the thermal neutron cross sections for E1 transitions in light nuclei with careful estimates of direct capture. Over the full range of light nuclei with small cross sections direct capture is found to be the predominant mechanism, in some cases being remarkably accurate, but in a few showing evidence for collective effects. When resonance effects become substantial there is evidence for an important contribution from the closely related valence mechanism, but full agreement with the data in such cases appears to require the introduction of a more generalised valence model. The possibility of direct and valence mechanisms playing a role in M1 capture is studied, and it is concluded that in light nuclei at relatively low gamma ray energies, it does indeed play some role. In heavier nuclei it appears that the evidence, especially from the correlations between E1 and M1 transitions to the same final states, favours the hypothesis that the main transition strength is governed by the M1 giant resonance.

I. INTRODUCTION

After more than half a century of study we still do not have a fully quantitative, or even universally applicable, theory of nucleon radiative capture. What we have is a number of models that are applicable in different mass number or energy regions, and a certain amount of basic theory that explains in principle why some of these models work in certain situations. Fortunately, high quality experimental work and data continue to be produced in this area and this is leading to continued quantitative development and application of capture models. The present authors, together with a number of colleagues, have been attempting to build up a systematic study of the relative importance of the simple direct process¹ in thermal neutron capture. We have found that for all the nuclides so far studied up to mass number 50, direct neutron capture appears indeed to be the dominant capture mechanism for electric dipole transitions, and in many cases gives a remarkably accurate account of the cross sections^{2,3,4,5}; the present status of this topic is reviewed in Section II.

In the cases so far studied the cross sections have been low (total thermal capture cross section < 1 b). Such low cross sections

are typical of truly off-resonant energy regions, in which direct (or potential) capture theory is applicable. Higher thermal capture cross sections are indicative of substantial resonance contributions, in which the question of relative importance of a simple valence model, closely related to potential capture, with respect to more complex compound nucleus processes must be addressed. One example of interplay, at similar levels of amplitude, of these three effects is found in thermal neutron capture of ^{41}Ca , and this is briefly described in Section III.A and B. The simple valence model of resonance capture⁵ has been found to be successful for a number of nuclides (see, for example, refs.^{6,7}) and some further remarks are made on this topic in Section III.C.

The success of the direct capture model in explaining E1 thermal neutron capture by light nuclei invites the speculation that it could also be a significant model for magnetic dipole transitions. We survey the evidence for this in Section IV. Valence M1 transitions from resonance states are also possible and some evidence for this process is discussed in Section V. Finally, the possibilities and evidence for some more complex but definitive mechanisms are recounted in Section VI.

II. DIRECT E1 THERMAL NEUTRON CAPTURE

Although low energy neutron capture can be regarded as the classical compound nucleus process (the original experimental evidence for large neutron capture cross sections motivated Bohr in the creation of the compound nucleus concept) it has also been known for a long time that far from resonances a direct form of radiative capture, not involving the compound nucleus, can exist. In this, the neutron in its initial scattering orbital can simply fall into a bound single-particle state of the zero-order potential well representation of the neutron-target interaction. What makes this form of direct capture particularly amenable to calculation is that the major component of the radial factor of the electric dipole matrix element arises outside the potential radius where the relevant wave-functions are well-known, being dependent only on the neutron scattering length (for the initial state), the binding energy of the final state and its single-particle spectroscopic factor θ_i^2 . Indeed, these factors are so dominant that many thermal neutron partial E1 cross sections can be quite accurately reproduced by a formalism that treats the potential with a sharp cut-off at the well radius and ignores all internal contributions to the matrix element. This version of the theory is known as channel capture, in distinction to the fuller version, called potential capture, that attempts to represent the wave functions more realistically (using a Woods-Saxon form of optical model for the initial state and a similar Eckart potential for the final state) and includes the internal contribution (from the wave functions projected on the internal continuation of the channels) to the matrix element.

The lightest nuclei for which E1 primary transitions are prominent in slow neutron capture are those from mass number $A=6-15$, i.e. those in which final states of the $1p_{1/2}$ and $1p_{1/2}$ shell are

available. Because in these nuclei (other than Li) a significant component of the $2s_{1/2}$ single particle state is just bound, the slow neutron scattering length is large compared with the potential radius, and hence there are large cancellations in the E1 radial matrix element giving rise to small cross sections despite the large spectroscopic factors for the single-particle p-wave content of the final states. Because of the large cancellations the cross sections are difficult to calculate accurately. Nevertheless, there is good agreement between experiment and theory, and the residual discrepancies indicate a very small admixture of more complex compound nucleus effects in the capture process¹.

In the next group of nuclei, A=19-22, the single-particle admixture of the final states is governed by the $2p_{1/2}$ shell, which is largely unbound in these nuclei with some spreading into weakly bound states. The E1 direct cross sections are therefore expected to be quite small because of small spectroscopic factors and the low energies of the transitions, but nevertheless we find that the experimental data^{6,7} are in quite good agreement with the direct capture theory. The comparison is shown in Table I.

Table I. Primary E1 transitions from $^{19}\text{F}(n,\gamma)$, $^{20,22}\text{Ne}(n,\gamma)$ reactions

E_i (keV)	J^*	θ_i^2	E_γ (keV)	σ_{dir} (mb)	σ_{exp} (mb)	σ_{CK} (mb)
(A). $^{19}\text{F}(n,\gamma)$; $a = 5.38$ fm						
984	1 ⁻	0.0047	5618	0.096	0.14±0.01	0.004
1309	2 ⁻	0.0034	5292	0.080	0.23±0.02	0.052
1844	2 ⁻	0.0040	4757	0.103	0.19±0.02	0.013
4371		0.0006	2230	0.020	0.04±0.01	
4592		0.0040	2009	0.110	0.05±0.01	
4892		<0.0048	1709	<0.130	0.03±0.01	
5047	(2 ⁻)	0.0052	1554	0.130	<0.01	(0.130)
5224		0.018	1337	0.41	<0.01	
5319		0.011	1283	0.15	0.09±0.02	
5463		<0.023	1138	<0.3	<0.01	
5555	1 ⁻	0.01	1046	0.12	0.18±0.02	0.004
5810		0.10	791	0.1	<0.01	
5936	2 ⁻	0.086	665	1.22	1.44±0.09	0.009
6018	2 ⁻	0.136	584	1.75	3.48±0.20	0.29
(B). $^{20}\text{Ne}(n,\gamma)$; $a = 4.43$ fm						
4725	3/2 ⁻	0.475	2036	38.0	27±3	0.9
5694		0.1	1067	5.1	6.7	0.1
(C). $^{22}\text{Ne}(n,\gamma)$; $a = 3.70$ fm						
3221	3/2 ⁻	0.243	1980	23.5	25±4	0.02
3836		0.045	1365	3.2	3.6	0.01

The quantities σ_{CN} in the last column of Table I are inferred compound nucleus cross sections for the transition, deduced from the deviation between the direct capture theory estimate and experiment. While the largest cross section in the fluorine reaction is for the softest primary ray transition of 584 keV energy and is in strong qualitative agreement with the theory, the value of $\sigma_{\text{CN}}/E_\gamma^3$ is some two orders of magnitude greater than would be expected from Cameron's semi-empirical rule for partial radiation width magnitudes⁴. This cross section is now being remeasured so that the necessity of taking account of other mechanisms (e.g. collective coupling⁴) can be assessed.

In the next heavier group of nuclides ($A = 24-38$), the $2p_{1/2}$ single particle state becomes more deeply bound. In these conditions, we have found that agreement between the measured cross sections and theory is still generally good for both the isotopes of magnesium⁴ and of sulphur². The residual differences between theory and experiment, interpreted as "compound-nucleus" cross sections^{3,4}, are within the region expected from Cameron's semi-empirical relation⁴.

In the calcium isotopes the $2p_{1/2}$ state is admixed among final nucleus states of low excitation, and the $2p_{1/2}$ single particle state is to be found at excitations of 3 to 4 MeV. Unlike the Be, C group the $s_{1/2}$ state is not bound to any significant fraction, and the potential scattering length is expected to be lower than the potential well radius, although individual measured scattering lengths are somewhat larger than the expected value owing to local level fluctuations. In this group of nuclei some of the most precise examples of agreement of measured E1 cross sections with the direct capture theory are to be found³. The cross sections for $^{40,42}\text{Ca}$ have recently been remeasured⁹, and also new assessments of the spectroscopic factors have been made. The new comparison between theory and experiment is shown in Table II. It is apparent that the discrepancy between theory and experiment is very small, even for the weaker transitions to states at higher excitation energy, and the residual "compound nucleus" cross section (calculated neglecting experimental errors) is approximately two orders of magnitude lower than the measured cross sections. Agreement between theory and experiment for the target ^{44}Ca is not so good, the cross sections being systematically lower than those calculated from the model. This nucleus shows evidence of vibrational character, however, and it is plausible that collective coupling effects play a role in reducing systematically the direct cross sections⁴. Some other nuclei, especially in the Mg group, also show some evidence of systematic deviation from the rigid spherical direct model. Such target nuclei also have characteristic collective effects in their low-lying spectra.

Table II. Primary E1 transitions from $^{40,42}\text{Ca}(n,\gamma)$ reactions

E_f (keV)	J^*	θ_f^2	E_γ (keV)	σ_{dir} (mb)	σ_{exp} (mb)	σ_{CN} (mb)
(A). $^{40}\text{Ca}(n,\gamma)$; $a = 4.64$ fm						
1943	3/2 $^-$	0.535	6420	158	164 $\pm$ 11	0.06
2462	3/2 $^-$	0.152	5900	47	25 $\pm$ 2	3.4
3614	1/2 $^-$	0.065	4749	6.7	12.7 $\pm$ 1.0	0.95
3731	3/2 $^-$	0.015	4632	3.7	0.4 $\pm$ 0.1	1.7
3944	1/2 $^-$	0.435	4419	42.5	70 $\pm$ 7	3.4
4603	3/2 $^-$	0.03	3760	6.1	9.9 $\pm$ 0.9	0.46
4753	1/2 $^-$	0.135	3610	11.8	30 $\pm$ 2	4.2
5072	1/2 $^-$	0.01	3291	0.8	1.5 $\pm$ 0.2	0.1
5077	1/2 $^-$	0.01	3286	0.8	0.5 $\pm$ 0.1	0.03
5120	3/2 $^-$	0.005	3242	0.9	1.1 $\pm$ 0.2	0.01
5370	3/2 $^-$	0.005	2993	0.9	0.9 $\pm$ 0.2	0.0
5450	1/2 $^-$	0.02	2913	1.4	1.5 $\pm$ 0.2	0.0
5468	3/2 $^-$	0.022	2895	3.9	1.9 $\pm$ 0.2	0.4
5670	3/2 $^-$	0.008	2693	2.9	1.5 $\pm$ 0.2	0.2
5703	1/2 $^-$	0.045	2660	6.8	3.0 $\pm$ 0.5	0.8
5889	1/2 $^-$	0.015	2474	2.1	1.9 $\pm$ 0.2	0.01
(B). $^{42}\text{Ca}(n,\gamma)$; $a = 3.31$ fm						
593	3/2 $^-$	0.075	7339	55	42 $\pm$ 3	0.9
2046	3/2 $^-$	0.68	5886	413	375 $\pm$ 25	0.9
2103	3/2 $^-$	0.012	5830	7.5	6.7 $\pm$ 0.7	0.02
2611	1/2 $^-$	0.135	5322	29	32 $\pm$ 3	0.07
2878	1/2 $^-$	0.095	5055	20	20 $\pm$ 2	0.0
2943	3/2 $^-$	0.05	4989	26	29 $\pm$ 2	0.2
3286	3/2 $^-$	0.032	4647	16	21 $\pm$ 2	0.3
3316	1/2, 3/2 $^-$	0.04*	4617	4	4.6 $\pm$ 0.5	0.02
3572	3/2 $^-$	0.04	4360	18	25 $\pm$ 3	0.6
3869	1/2, 3/2 $^-$	0.05*	4063	4	2.7 $\pm$ 0.4	0.1
4207	1/2 $^-$	0.21	3726	67	67 $\pm$ 5	0.0
4249	1/2, 3/2 $^-$	0.055*	3684	8.5	7.9 $\pm$ 1.1	0.01
4901	1/2, 3/2 $^-$	0.09*	3032	11.5	11.5 $\pm$ 0.8	0.0
5037	1/2, 3/2 $^-$	0.095*	2896	11.7	13.8 $\pm$ 1.0	0.1

* Assumption $J = 1/2$

III. E1 VALENCE CAPTURE

A. Valence capture in the thermal neutron region

The thermal neutron total capture cross sections in the above cases are all small (<1 b) indicating that the influence of resonance wings is rather small. In some other cases of target nuclei with mass number less than 50, nearby resonances quite clearly have a major influence on the cross section, and their more

complex capture mechanisms have to be considered. Of these, the most elementary is the simple valence mechanism.

The formulation of thermal neutron direct capture theory within an optical model framework¹ gives rise to an imaginary term that is interpreted as the average resonance-resonance interference cross section of a simple valence transition from the single-particle component of the resonance to an equivalent component of the final state. From this term an estimate of the average valence radiation width $\langle \Gamma_{\gamma, \text{val}} \rangle$ may be obtained. Alternatively, the valence width may be calculated directly within the framework of R-matrix theory^{10,11}. The valence contribution appears in the thermal neutron cross section amplitude as a resonance type term proportional to $\Gamma_{\lambda(n)}^{1/2} \Gamma_{\lambda\gamma, \text{val}}^{1/2} / (E_\lambda - E)$. The individual valence radiation width for resonance λ has the important property of being proportional to the neutron width $\Gamma_{\lambda(n)}$. The valence term in the capture amplitude is constructive or destructive with respect to the potential capture amplitude, the resonance level E_λ being above or below thermal neutron energy E , respectively.

An interesting and important case of thermal neutron capture, in which the resonance influence is clearly dominant but not overwhelming, is that of ⁴³Ca. The total capture cross section is 6.2 b, which is at least an order of magnitude greater than the cases considered in Section 2. The coherent scattering cross section is well known¹, but the total scattering cross section is not, nor are the resonance parameters (especially of the nearest resonance at 1.48 keV) known accurately, so the resonance contribution to the spin-dependent scattering lengths at thermal cannot be accurately assessed. However, using the currently available values of the 1.48 keV resonance parameters¹², the assumption that the total angular momentum $J = 3$ and the computed value of the potential scattering length from Moldauer's optical model parameters¹³, we expect that $a_{J=3}$ is -3.7 fm with an uncertainty of $\pm 50\%$. The value of $a_{J=4}$ is constrained, on choosing $a_{J=3}$, by the measured value of the coherent scattering length. Comparison of the primary El cross sections with direct capture calculations shows most consistency with a value of $a_{J=3} \approx -5.7$ fm, which is within the range of uncertainty of the value expected from the resonance parameters. The corresponding value of $a_{J=4}$ is 1.8 fm, and the ensuing discussion is confined to this choice of the scattering properties.

The calculated values of the direct capture cross section to the final states of ⁴³Ca are shown in Table III, in comparison with experiment.

In many cases the final state spin is assigned on the basis of the closest match to the experimental datum. Even with this selection it is apparent that for a relatively small number of transitions there is no correlation between experiment and theory. (Part of this can be explained by the fact that the l_n assignments are not known for many states, especially at higher excitation, and some of these may have large $1f_{7/2}$ admixture). The overall magnitude of the theoretical cross sections matches the measured strength, however, the total direct capture cross section for the transitions listed in Table 3 being 3.1 b. These are the transitions to states

up to excitation 6.15 MeV and exhaust most of the $2p_{3/2}$ strength. There is also expected to be a contribution to the direct capture cross section from the $2p_{1/2}$ state. This is presumably to be found at higher excitation energies, to which the primary E1 transition strengths are unknown. We can make an estimate of the cross section to a single $p_{1/2}$ state 3.3 MeV below the neutron separation energy; it is 0.6b, giving a total direct cross section of 3.7b. These figures represent a very substantial fraction of the measured total capture cross section of 6.2b, indicating that even in this quasi-compound nucleus situation direct capture plays a significant role.

Table III. Experimental data and calculated direct capture cross sections in the $^{43}\text{Ca}(n_{th}, \gamma)$ reaction

E_f (MeV)	J_f^*	θ_f^2	E_γ (MeV)	$J_f=2$	$J_f=3$	$\sigma_{\gamma,dir}^a$ $J_f=4$	$J_f=5$	$\sigma_{\gamma,expt}$ (mb)
1.157	2 ⁺	0.08	9.974	179				6.8
2.283	4 ⁺	0.007	8.848			12.3		22.9
2.656	2 ⁺	<0.02	8.474	28.5				4.3
3.044	4 ⁺	*	8.086			~0		41.5
3.301	2 ⁺	*	7.829	~0				37.2
3.357	2-4 ⁺	~0	7.773	~0	~0	~0	~0	188.5
3.776	2	~0	7.354	~0				30.4
3.923	3 ⁺ , 4, 5	0.32 ^b	7.208		71.2	46.2	14.9	96.1
4.196	2 ⁺	0.03	6.935	42.5				54.6
4.480	2 ⁺	0.06	6.651	80.0				26.0
4.584	2 ⁺ , 3, 4	~0	6.547	~0	~0	~0		146.3
4.651	2 ⁺	0.45	6.480	539				142.6
4.690	1-4	~0	6.441	~0	~0	~0		24.2
4.914	?	0.19 ^b	6.217	217	172	112	37.8	~0
4.992	?	0.08 ^b	6.139	88.9	70.5	46.1	15.5	~0
5.006	4 ⁺	0.40	6.125			229		230.6
5.130	2 ⁺ , 3 ⁺	0.96 ^b	6.001	206	164			210.2
5.231	2-5 ⁺	4.32 ^b	5.901	901	716	469	160	432.1
5.289	2-5 ⁺	2.16 ^b	5.842	445	353	231	79.2	72.5
5.342	2 ⁺	0.45	5.789	454	361	237	81.3	21.7
5.375	2-5 ⁺	0.56 ^b	5.756	113	89.6	58.8	20.2	52.7
5.459	2-4 ⁺	2.64 ^b	5.673	519	413	271		20.5
5.549	2-4 ⁺	3.20 ^b	5.582	615	489	321		61.4
5.733	2-5 ⁺	6.00 ^b	5.398	1095	872	574	210	232.5
5.867	2 ⁺ -5	1.28 ^b	5.264	225	179	118	42	73.8
6.040	2-5 ⁺	0.64 ^b	5.092	107	85	56	20	24.8
6.146	2-5 ⁺	3.68 ^b	4.984	594	473	313	112	69.4

^a Single entries are under the known spin of the final state.
Multiple entries for unknown or range of spin assignments.
Bold entries indicate favoured spin on basis of theory-expt.

^b Quantity shown is $(2J_f+1)\theta_f^2$

This is in some contrast to the resonance itself. The radiation width has not been directly measured, but if it is inferred from the thermal capture cross section and the 1.48 keV resonance parameters, it is found to be approximately 1.9 eV, but could be less than 1 eV if the interference between potential and valence capture is taken into account. The radiation width for the valence mechanism, evaluated as in ref.¹¹, is 0.13 eV for the final states listed in Table III and there will be an extra contribution of 0.028 eV from states centred from a $2p_{1/2}$ state centred about 7.8 MeV excitation. The smallness of the valence contribution compared with the apparent total radiation width of 1.9 eV is in contrast with the much larger ratio of direct to total at thermal and emphasises the importance of the constructive interference between resonance valence and potential capture at off-resonance energies.

The difference between the estimated direct and the measured capture cross sections of Table III can be used to estimate the magnitude of an assumed "compound nucleus" contribution to the capture. This turns out to be on average $\sigma_{\gamma, \text{cn}}/E_\gamma^3 = 3.10^{-8} \text{ b.MeV}^{-3}$, and leads to an estimate for the average radiation width for a single transition $\langle \Gamma_{\gamma, \text{cn}}/E_\gamma^3 \rangle = 3.10^{-8} E_\lambda \text{ eV.MeV}^{-3} = 4.5.10^{-3} \text{ eV.MeV}^{-3}$. This is almost four times larger than the Cameron semi-empirical estimate¹⁴ of compound nucleus radiation widths, but is about equal to the estimate obtained from the Brink-Axel giant resonance model^{15,16}. The latter model does not, however, explain the general spectrum shape; the calculated radiation width for gamma rays of energy below 5 MeV is only 0.13 eV, accounting for only 0.4b of the measured cross section of 3.9b for these transitions.

B. Generalised valence capture

The simple valence mechanism discussed above is special in its relationship to the entrance channel, which correlates the radiative width through this process to the neutron width of the resonance and gives systematic interference with the potential capture cross section in off-resonance situations. It is possible, however, to describe other aspects of the capture mechanism through single particle transitions of this type, but with the initial single particle motion not being that from the entrance channel. In this generalised valence model¹⁰ the single particle motion is in the field of an "inert" core, which can be one of many excited states of the target, or of the residual nucleus that results from removing a proton from the compound nucleus.

In a resonance state λ there will be an intensity admixture $c_{\lambda, x}^2$ of a single particle state x in the field of a non-changing core state x . If x represents the ground state of the target the radiative width to a final state $x@b$ can be calculated by the R-matrix treatment of ref.¹¹. For excited states x' of the core, the single particle state and associated radiative width in resonances at low neutron energy can be computed as a discrete bound state with binding energy approximately equal to the excitation of x' . The single particle radiative width is obtained directly and multiplied by $c_{\lambda, x'}^2$. While the configuration $x'@b$ is spread over the actual

final states it may be assumed that this spreading is sufficiently confined that the summed radiation width to these states is quite accurately represented by the single particle radiation width.

The single particle neutron states that are likely to be significant in the low energy s-wave neutron resonances of ^{43}Ca are the $3s_{1/2}$, $2d_{3/2}$ and $1g_{9/2}$. From the optical model parameters¹¹ it is found that the R-matrix representation of the first two will lie a little above the neutron separation energy and the third will be a weakly bound discrete state. The states that are likely to be dominant in the final state configuration are $2p_{1/2}$, $1f_{7/2}$ and, to much smaller extent, $2p_{3/2}$ and $1f_{5/2}$. The $1f_{7/2}$ sub-shell will already be nearly half-filled in the core states of ^{43}Ca , so we ought, as an approximate procedure, to reduce the computed radiation widths to configurations involving the $1f_{7/2}$ state by a factor of about one half. The median energy of the $2p_{1/2}$ state appears experimentally at 5.8 MeV below the neutron separation energy. With the well depth that reproduces this value the $1f_{7/2}$ state would be bound by about 10 MeV. We find from the spectroscopic factors of the (d,p) data that there are very strong $\ell_n=3$ states near 8 MeV binding.

With single particle states of this character, with an assumed Lorentzian spreading of half-width 2 MeV, and discrete core states of ^{43}Ca that comprise the ground state, the 0.37 MeV state, the 0.59 MeV state and a simple level density representation of core states above that, we can compute roughly the neutron contribution to the valence width and its spectral form. We find a total radiation width for high energy gamma rays of the right magnitude, about 0.4 eV, and a component for low energy gamma rays (<5 MeV) of about 0.2 eV. This is last is a factor of about 3 too low, but we note that we have not allowed for the greater strength of $1f_{7/2}$ state associated with more highly excited cores, nor included the valence proton contributions which are expected to be centred at lower gamma ray energies. We conclude that the generalised valence model is capable of a better representation of the electric dipole capture process, at least for light nuclei, than either of the other two commonly used models in resonance level studies.

C. El valence mechanism in resonances

A great deal of experimental work has been done to establish evidence for the existence of the simple valence mechanism in neutron resonance levels. Most of this work has centred on C, Fe, Ni and Mo isotopes. It is summarised here.

The lightest nucleus for which El valence capture has been investigated in detail is the ^{13}C target. This has a substantial p-wave resonance at 153 keV. Using the R-matrix description of the $2p_{1/2}$ component of the resonance¹¹ it is found that the valence model reproduces the partial radiation widths of the three primary El transitions to states in ^{14}C with substantial $2s_{1/2}$ and $1d_{3/2}$ character to within experimental error. This is quite remarkable inasmuch as the initial state does not stem from a size resonance in the low energy p-wave strength function, and the conditions might therefore be said not to be too favourable for valence capture.

In the much higher mass number region, $A=50-60$, the conditions for valence capture are expected to be optimal. Here there is a peak in s-wave neutron strength function due to the location of the $3s_{1/2}$ single particle state close to binding, and the low lying final states are often dominated by the $2p_{3/2,1/2}$ single particle states. There are several strong E1 transitions from the strong s-wave resonance at 7.68 keV in the cross section of ^{56}Fe ($\Gamma_n=1043$ eV) to a host of final states with very significant p-wave spectroscopic factors. Raman *et al*¹⁷ measured the relative intensities of these and found that they were in good agreement with the ratios of valence calculations (using the optical model method), but that the absolute total of the calculated valence widths exceeded the measured total radiation width by about 30%. We have recalculated the valence widths using the R-matrix method and find agreement with the total width and the renormalised partial widths. This resonance appears to provide an almost perfect example of valence capture.

However, in the radiative cross section of the neighbouring even nucleus, ^{56}Fe , anomalies appear. From the strong 27.7 keV resonance ($\Gamma_n = 1420$ eV) the transitions to the ground and first excited states are of about equal strength¹⁸, yet the valence theory indicates that the ground transition should be about an order of magnitude weaker than the experimental value. The valence theory reproduces accurately the width to the first excited state. A similar phenomenon is observed for thermal neutron capture, which is dominated not so much by potential capture as by the strong bound level lying between a few and about 10 keV below the neutron separation energy. The valence plus potential capture model gives a cross section of 0.037 b for the ground transition, which is to be compared with the experimental value, 0.65 b. We speculate that the ground state could contain a major component of $|2^+ \otimes 1f_{7/2}$, where $|2^+$ is the first vibrational state of the ^{56}Fe core, and the strong transitions to this state are from the $|2^+ \otimes 2d_{3/2,5/2}$ components of the s-wave resonance¹⁹.

In the mass number 90-100 region, the p-wave strength function peaks, and valence transitions to $3s_{1/2}$ and $2d_{3/2,5/2}$ components of the final states become possible. Studies of p-wave resonances in the cross sections of several Mo isotopes reveal evidence of such transitions. They are most apparent in the cross section of ^{98}Mo , in which the lowest three $J^\pi = 1/2^-$ resonance levels have partial radiation widths to a sequence of ten even parity final states that are reproduced to within a factor of two or three by the valence model, using the measured data on neutron widths and spectroscopic factors, the agreement being better the larger the reduced neutron width of the resonance¹⁹. The $J^\pi = 3/2^-$ resonances show a roughly similar order of magnitude of model calculation and data for the final states with large spectroscopic factors, but there is little correlation for individual transitions. For ^{100}Mo , order of magnitude agreement is found for the single measured $J^\pi = 1/2^-$ resonance, but not for the $J^\pi = 3/2^-$ initial states²⁰. In the cross section of ^{92}Mo the correlation between theory and experiment is rather weak for the individual transitions from the $J^\pi = 1/2^-$ resonances, but the resonance averaged calculated partial radiation width agrees with

the average experimental width for final states with large spectroscopic factors²¹. There is not even this degree of agreement for the $J^\pi = 3/2^-$ resonances. It is still suggestive that the valence radiation widths often approach the order of magnitude of the measured partial widths, however, and again we might speculate on the role of a generalised valence model; in the molybdenum case a major individual component might be $|2^+\rangle \otimes 2f_{7/2} \rightarrow |2^+\rangle \otimes 2d_{5/2}$, $|2^+\rangle$ again indicating the first vibrational state of ^{92}Mo . The single particle radiation width of this transition is approximately twice that of the $|2^+\rangle \otimes 3p_{3/2} \rightarrow |2^+\rangle \otimes 2d_{5/2}$ component. The former transition could certainly feature significantly in the $J^\pi = 3/2^-$ resonances, but is not allowed from the $J^\pi = 1/2^-$ resonances and would thus explain the qualitative difference between the two initial spins.

IV. MAGNETIC DIPOLE DIRECT CAPTURE

Because of the success of the simple direct capture theory in explaining a great deal of the data on cross sections of primary E1 transitions following thermal neutron capture by a wide range of light nuclei, it is natural to ask if a similar theory may be valid for M1 capture. In this case, the chances of a successful theory are slimmer for two reasons. The first is that in the E1 case the matrix elements are concerned with the electrostatic dipole moment, whereas in the second case the M1 operator depends on currents that may be much more poorly described by the simple wave functions of such a model. The second reason is that the radial component of the E1 matrix element is more strongly weighted to the channel region, where the wave functions are well established by the energies of the initial and final states, than is the radial M1 element. In fact in the M1 case it is often stated that there can be no direct capture that is analogous to E1 direct capture because the radial wave functions are necessarily orthogonal in a simple potential well. However, because of the complexity of the nucleus, we usually find it necessary to describe the radial wave functions of the initial and final states with different potentials (just as we usually do for E1 capture).

The simple form for the magnetic dipole operator for a neutron (magnetic moment μ_n in nuclear magnetons) impinging on the potential field provided by a target nucleus with magnetic moment μ_I is

$$H'_{m,n} = \frac{e\hbar}{2mc} \left(\frac{3}{4\pi} \right)^{1/2} \left(\frac{\mu_I I_n}{I} + \frac{\mu_n \sigma_{n,n}}{\sigma} \right) \quad (1)$$

Here, e is the protonic charge, c the velocity of light, I is the target nucleus spin operator and σ the Pauli spin operator for the neutron. From this expression the reduced matrix element for the spin factor can be computed, while the radial matrix element is simply the integral of the product of the initial state X_i radial wave function and the final state, Φ_f , radial wave function.

It is well-known²² that the use of this simple impulse operator in the cross section expression for thermal neutron capture by the

proton accounts for the major part of the cross section ($0.3326b$), with only about 10% remaining to be explained by meson exchange effects. Application to the capture cross section of ${}^3\text{He}$ leads to controversial results²³, with some authors claiming that meson exchange currents account for the major part of the cross section. With the elementary approach we are testing here, using Eckart potential forms with parameters adjusted to give the thermal neutron scattering length ($a_{J=1} = 3.0 \pm 0.1$ fm) for the initial state and the binding energy (20.58 MeV) for the final state we find $\sigma_{\gamma, \text{dir}} \approx 80 \mu b$, with a spread of about 20% due to reasonable changes in the Eckart parameters and about 15% due to the experimental uncertainty in the scattering length. This is to be compared with the most recent experimental result²⁴, $54 \pm 6 \mu b$, and indicates that the simple direct capture M1 model is of some validity in the $1s_{1/2}$ shell nuclei.

Significant M1 transitions are not to be expected in slow neutron capture by the 1p shell nuclei, until the upper end of the group is approached. Here, starting with the ${}^{10}\text{Be}$ compound nucleus, a significant fraction of the $2s_{1/2}$ single particle level becomes just bound. The low gamma ray energies of the transitions to the states sharing in this component of the $2s_{1/2}$ orbital make these viable candidates for the direct capture mechanism. The thermal neutron cross section for the transition to the $J_f^\pi = 2^-$ state bound by 0.347 MeV is $13.5 \mu b$. The direct capture model gives $37\theta_c^2 \mu b$, and the spectroscopic factor θ_c^2 is expected³ to be in the range 0.2 - 0.3. Similarly, in the ${}^{12}\text{C}(n, \gamma)$ reaction the cross section to the -1.857 MeV state is $5.6 \pm 0.5 \mu b$, and the model cross section is about $25\theta_c^2 \mu b$. In the ${}^{13}\text{C}(n, \gamma)$ reaction the cross section to the $J_f^\pi = 0^-$ state at -1.274 MeV is $67 \mu b$, and the model cross section is $68\theta_c^2$, while the experimental and theoretical cross sections to the $J_f^\pi = 1^-$ level at -2.08 MeV are $34 \mu b$ and $24.5\theta_c^2 \mu b$, respectively. All these comparisons signify a qualitatively important role for the direct capture mechanism in this region of mass and energy.

Beyond the 1p shell the $2s_{1/2}$ single particle state becomes moderately to strongly bound. Magnetic dipole transitions to moderately bound levels with substantial components of this single particle state are found in ${}^{19}\text{F}$ and ${}^{20,22}\text{Ne}$ thermal neutron capture. In the ${}^{19}\text{F}$ case the direct capture model is found to under-represent the cross sections to the two strongest $s_{1/2}$ states (at binding energies of 3.075 and 3.113 MeV) by a factor of about 4. But that to the more strongly bound state at 5.545 MeV is under-calculated by three orders of magnitude. It is also to be remarked that transitions to states with $1d_{3/2}$ content, which are inaccessible on the direct capture model, have cross sections at least as great as those to the $2s_{1/2}$ states. In the ${}^{20}\text{Ne}(n, \gamma)$ reaction, there is one state with substantial $s_{1/2}$ content, the 2.794 MeV state ($E_\gamma = 3.966$ MeV) with $\theta_c^2 = 0.85$, with a cross section of 0.14 mb. The calculated direct cross section is one order of magnitude greater. In the ${}^{22}\text{Ne}(n, \gamma)$ reaction, the state at 1.02 MeV ($E_\gamma = 4.18$ MeV, $\theta_c^2 \approx 0.5$) has a cross section of 0.9 mb, and the calculated cross section is 0.6 mb. These comparisons indicate that the simple direct process has a substantial but not predominant role to play in this regime of M1 capture.

In the higher mass group of nuclides around magnesium the direct capture theory fails to explain the observed M1 primary transitions by up to two orders of magnitude, and this ratio rapidly worsens in general for heavier nuclei.

V. MAGNETIC DIPOLE VALENCE CAPTURE

Magnetic dipole capture transitions from resonances are surprisingly strong compared with electric dipole gamma rays of similar energy, the former often being found, on average, to be less than one order of magnitude weaker than the latter. In addition, suggestive correlations have been found in some cases between transitions to the same final states from s-wave and p-wave resonances. Again, one can speculate that a valence mechanism, analogous to that of E1 capture, may play a role.

Following the study of thermal neutron capture it follows that the most likely candidates for valence capture will occur in very light nuclei. The lithium nuclei are the lightest nuclei with suitable resonances. The fast neutron capture cross section of ${}^7\text{Li}$ through the p-wave resonance at 255 keV ($J^\pi = 3^+$) has attracted special interest because of its astrophysical importance, and has recently been remeasured²⁵. ${}^7\text{Li}$ has its ground state ($I^\pi=2^+$) at 2.033 MeV below the neutron separation energy and one excited state ($I^\pi=1^+$) bound by 1.058 MeV. The thermal neutron capture cross section to these two states is reproduced to within the accuracy of the spectroscopic factors by the E1 direct capture model²⁶. The s-wave scattering length can be deduced from the total cross section and angular distribution data to well above 0.5 MeV and the E1 capture cross section estimated through this energy range, enabling the M1 radiation width in the resonance to be deduced. The best estimate of this quantity is $\Gamma_\gamma = 0.08 \pm 0.02$ eV. The valence radiation width can be calculated by the R-matrix method¹¹, substituting the operator of eq.1, to give $\Gamma_{\gamma, \text{val}} = 0.093$ eV. This good agreement between the model and observation is in accord with the evidence from thermal neutron capture that this simple mechanism is predominant for very light nuclei and relatively low energy transitions.

More data are required to test the M1 valence model at slightly higher mass numbers. As it is, little more information is available until we reach ${}^{35}\text{Cl}$. From the bound s-wave resonance dominating the thermal neutron cross section of this nucleus there are strong M1 transitions to the ground state and several even parity excited states of the compound nucleus²⁷. The valence model fails to explain the radiative widths for these transitions by some 3 to 4 orders of magnitude. Similarly, for the p-wave resonances at 9.48 keV and 11.2 keV in the cross section of ${}^{56}\text{Fe}$ and at 1.157 keV in that of ${}^{56}\text{Fe}$ there is three orders of magnitude discrepancy^{28,29}. This trend is borne out by studies of the M1 transitions from s-wave resonances of the Mo isotopes^{19,20,21}.

VI. CORRELATIONS BETWEEN M1 AND E1 TRANSITION STRENGTHS

In some of the above cases (especially the Cl and Fe isotopes)

strong correlations have been observed between M1 radiative widths and widths or cross sections to the same final states reached from another resonance or energy region by E1 gamma rays. Such correlation can also imply a correlation between the M1 radiative width and the neutron width, as well as the (d,p) spectroscopic factor. These suggest initially a simple valence explanation, although, as we have seen such an explanation is not borne out quantitatively.

Similar correlations between thermal neutron M1 radiative cross sections and (d,p) spectroscopic factors to s-wave single particle components of final states have been noted previously and explained by a semi-direct mechanism¹⁰. This can be extended readily to resonance transitions. Let us denote a residual nucleus (core) state by χ_x and a single particle orbiting in the average field of this core by ϕ_a . Then we can assume that a compound nucleus resonance state can be expanded as

$$X_\lambda = \sum_{x,a} c_{\lambda,x,a} \chi_x \phi_a \quad (2)$$

The final state X_μ has a similar expansion

$$X_\mu = \sum_{x',a'} c_{\mu,x',a'} \chi_{x'} \phi_{a'} \quad (3)$$

The core states for these two expansions do not need to be actual states of the possible residual nuclei but can be conceptual states provided that these form a complete set.

Suppose that we have in the former expansion a significant core state $\chi_{x=(M1)x'}$ that has the form $D_{M1} \chi_{x'}$, where D_{M1} is proportional to the (full) magnetic dipole operator, i.e. x is the magnetic dipole giant resonance state¹⁰ built on x' . Then the partial radiation width of compound state λ to state μ due to this component and a common single particle state p alone will be

$$\Gamma_{\lambda \rightarrow \mu, (M1)} = c_{\lambda, (M1)x', a}^2 c_{\mu, x', a}^2 \Gamma_{\chi_{(M1)x'}} \quad (4)$$

where the giant dipole radiation width is

$$\Gamma_{\chi_{(M1)x'}} = (16\pi k \gamma^3 / 9) | \langle \chi_{(M1)x'} \| H_{M1} \| \chi_{x'} \rangle |^2 / (2J_\mu + 1) \quad (5)$$

Clearly, eq.4 is maximised for some combination of c' , $(M1)c'$ and p for which the expansion coefficients $c_{\lambda, (M1)x', a}$ and $c_{\mu, x', a}$ are large. If the latter is large then the former can be large when the energy of the transition from λ to μ is about equal to the magnetic dipole giant resonance energy. The partial radiation width is further intensified if the M1 giant resonance is narrow, and this is most likely to be the case if x' is a residual nucleus ground state ($x'=0$ for the target nucleus).

The electric dipole transition from some opposite parity resonance λ' to the same final state μ can be large by the generalised valence mechanism if the expansion coefficient $c_{\lambda', x', a}$ for a suitable single particle state a' , connecting to a by the E1 operator, is large. The commonality of $c_{\mu, x', a}$ thus gives rise to

correlations of the M1 and E1 partial radiation widths from λ and λ' respectively, although the mechanisms for the two kinds of transition can be totally different. If $x'=0$, $c_{\mu,x,a}^2$ is the spectroscopic factor for the single particle state a , and the correlation with (d,p) is thereby established; if $x'(\neq 0)a'$ is the entrance channel for the neutron the connection with the simple valence model for resonance λ' is apparent.

In ^{35}Cl the available neutron and proton orbits for forming the collective 1^+ spin excitation¹¹ are the $1d_{3/2}$ to $1d_{5/2}$ states. The excitation energy can be estimated to be 11.5 MeV and the M1 giant resonance radiation width to be 137 eV. Using the latter figure, a giant resonance half-width of 1 MeV and an s-wave resonance spacing of about 40 keV we estimate an expansion coefficient $c_{\lambda,(M1),x,a}^2$ of about 0.01 and a partial M1 radiation width of about $0.6c_{\lambda,x,a}^2$ eV if the giant resonance is centred at 11.5 MeV and about ten times greater than this if it is centred at the gamma ray energy. There is some degree of correlation of the thermal neutron capture M1 transition strengths with the spectroscopic factors to the even parity final states, so if we use the latter to obtain the final estimates of the partial widths we find agreement with the assumption that the M1 giant resonance is centred close to the gamma ray energy, i.e. about 3 MeV lower than the collective spin excitation estimate.

The $^{56}\text{Fe}(n,\gamma)$ reaction provides another interesting example of E1-M1 correlations. In this case the final state spins are predominantly of odd parity, several of them having considerable values of spectroscopic factors to $p_{1/2}$ and $p_{3/2}$ single particle orbits. We have already considered the E1 transitions from thermal neutron capture in Section III, showing that for some there is substantial agreement with direct capture theory and for others surprisingly little. The M1 transitions to the same final states from the 1157 eV resonance, a p-wave resonance with $J^\pi=1/2^-$, show a considerable degree of correlation with the thermal neutron transitions¹⁹. In ^{56}Fe the M1 giant resonance is formed principally from the $1f_{7/2} \rightarrow 1f_{5/2}$ spin-orbit change, and its energy is expected to be about 14 MeV. With this value (and a half-width of about 1 MeV) the M1 partial radiation width will be about $50c_{\lambda,x,a}^2$ meV. This is considerably smaller than some of the observed widths from the 1157 eV resonance, suggesting again that the M1 giant resonance energy is considerably lower than the above estimate. There is some, but not perfect, correlation of the M1 radiation widths with the final state (d,p) strength, suggesting that the target core is an important, but not the only significant, configuration for the spin excitation.

VII. CONCLUSION

There is now a very substantial body of evidence to show that the simple direct or potential capture process is the predominant mechanism for electric dipole transitions at off-resonance energies in light nuclei ($A \leq 50$). Closely related to the potential capture process is the valence process, which explains many E1 capture transitions from cross section resonance states. At resonance

energies, however, many E1 transitions are clearly not of simple valence character, but the magnitude of the widths for such transitions are qualitatively consistent with the valence process even though the required correlation with the individual resonance neutron width is absent. This suggests that a generalised valence process may be operative, a nucleon changing its single particle orbital in the field of an excited state of the core.

It is not expected that M1 capture mechanisms can be dominated to such an extent by direct or valence processes. Nevertheless, for very light nuclei ($A \leq 15$) and comparatively low energy gamma ray energies such processes do seem to carry some validity. It is clear, however, that for heavier nuclei the simple single particle transition mechanism fails by some two to four orders of magnitude to explain both thermal and resonance capture data. For these, and especially to explain some of the remarkable correlation effects involving both M1 and E1 transitions from initial states of different parity, the extension to resonances of the semi-direct mechanism¹⁰, in which the core state undergoes a M1 giant resonance transition while the extra nucleon remains in a relatively low-lying single particle orbital, appears to be capable of explaining the data, but there is an implication that the M1 giant resonance lies at considerably lower excitation energies than estimates from theory of correlated nucleon motions suggest¹¹.

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