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Direct thermal neutron capture

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ABSTRACT: We discuss the direct-capture theory pertaining to primary electric dipole (E1) transitions following slow-neutron capture. For light nuclides that we have studied (including ^{9}Be, ^{12}C, ^{13}C, ^{24}Mg, ^{25}Mg, ^{26}Mg, ^{32}S, ^{33}S, ^{34}S, ^{40}Ca, and ^{44}Ca), estimates of direct-capture cross sections using optical-model potentials with physically realistic parameters, are in reasonable agreement with the data. Minor disagreements that exist are consistent with extrapolations to light nuclides of generally accepted formulations of compound-nucleus capture. We also discuss the channel-capture approximation which is, in general, a good representation of these cross sections in heavier nuclei particularly if the scattering lengths are not different from the corresponding potential radii. We also draw attention to cases where the use of this formula leads to inaccurate predictions.

1. INTRODUCTION

In a series of papers on slow-neutron-capture by light nuclides, we have analyzed, in a quantitative manner, the importance of the direct-capture mechanism in an optical-model framework. In simple terms, this mechanism involves the transition of a single neutron orbiting in an s-state in the overall potential field of the target nucleus to a bound p-wave orbit. The basic theory of this mechanism was developed by Lane and Lynn [1] and by Cugnon and Mahaux [2]. This theory was employed in the analysis of experimental data in a fully quantitative way in a series of papers beginning with Raman et al. [3] on the S isotopes (this paper also contains a full resume of the theory) and following with Lynn et al. [4] on ^{9}Be and C isotopes and Kahane et al. [5] on the even Ca isotopes. In these papers, it was demonstrated that direct capture is indeed the predominant mechanism in these nuclides and that the remaining (usually small) discrepancies between these quantitative estimates and the experimental data can be attributed plausibly to contributions from the much more complicated and statistically oriented "compound-nucleus" contributions from local compound-nucleus levels. In the current paper, we discuss briefly the direct-capture theory and summarize the results obtained thus far on these compound-nucleus contributions.

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In the original Lane and Lynn [1] work, a very simple formula was established for "pure" direct capture, namely "hard-sphere" capture, in which the scattering wave function of the neutron was assumed to have a node at the radius of the nucleus; the nucleus, in turn, was assumed to be a hard sphere with negligible internal penetration of the neutron wave function permitted. This simple concept could be easily generalized to account for actual cases of neutron scattering, for which the thermal-neutron scattering length is generally different from the potential radius; this generalization is known as "channel" capture. This channel-capture formula was shown in the Lane and Lynn paper to be successful in explaining semi-quantitatively a considerable volume of capture data extant at that time. Since then this formula has been shown by Mughabghab [6] and by many others [see ref. 5 for a detailed list of references] to be approximately valid for many new and more precise data that have been published in the ensuing two decades. This success has even led to the use of this formula as a tool for determining nuclear quantities of interest (nuclear potential radii, for example). We have discussed elsewhere, both in general terms [7] and in specific terms [8], the somewhat uncritical use of the channel-capture formula. To buttress our criticisms, we present in the current paper an illustration that shows explicitly the consequences of those approximations.

2. ESTIMATES OF DIRECT CAPTURE

We calculate the cross sections of the main primary E1 transitions from the data on final-state excitation energies, (d,p) spectroscopic strengths, and scattering lengths. We employ two different approaches; (a) a combination of global optical model plus a valence contribution from local levels, which we call the [G+V] approach, and (b) a specialized optical model [S] approach in which the optical model parameters are chosen to reproduce the scattering length of the particular nuclide in question. In both approaches, we vary the real well-depth of the optical potential in order to reproduce the binding energy of the final state. The cross sections calculated by these two approaches differ at most by 6% thus reinforcing our confidence in the methods of calculation.

The best way perhaps to illustrate these approaches is to present the initial state and final state wave functions, the radial integrand, and the radial integral for an actual case that we studied recently. The square of the radial integral is roughly proportional to the capture cross section. We show in fig. 1(a) the above quantities calculated for the 6.421-MeV primary E1 transition to the 1.943-MeV, $3/2^-$ final state in ^{40}Ca. The solid lines in fig. 1(a) are for the global optical potential given in ref. 5. From the initial state wave function it can be seen clearly that the global optical potential fails to (nor is it expected to) reproduce the measured scattering length of 4.9 fm. The difference is due to nearby compound-nucleus levels. These levels, in turn, will have some valence radiation width which arises from the projection of the single-particle s-wave state out of the compound-nucleus wave function. This width can be calculated with the same global potential. The direct-capture cross section can then be obtained by combining the amplitude representing the potential-capture cross section with the amplitude representing the valence contributions and by squaring the resulting quantity [see eq. (2) of ref. 5]. This then is the [G+V] approach. In the case shown in fig. 1(a), [G] alone gives 647 mb and [G+V] gives 160 mb, compared to 167 ± 25 mb from experiment.

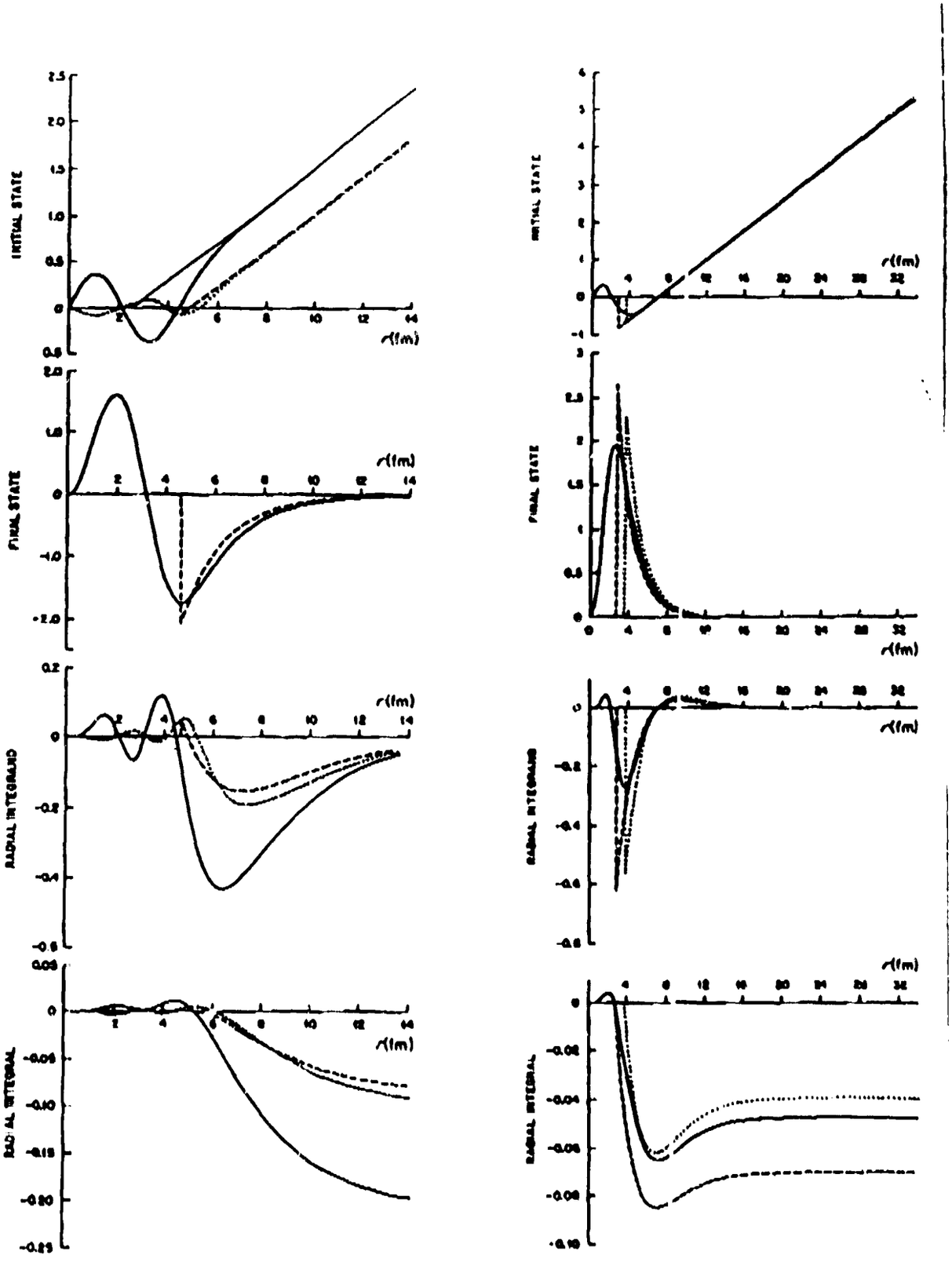

Fig. 1. Initial-state and final-state wavefunctions, radial integrand, and radial integral calculated for (a) the 6.421-MeV transition in ^{41}Ca and (b) the 6.810-MeV transition in ^{10}Be. The solid, dotted, and dashed lines are explained in the text. Additional details are given in refs. [4] and [5].

The dotted lines in fig. 1(a) are for a specialized [S] optical model that reproduces the scattering length. The final-state wave function in this case is the same as that for the [G+V] approach. In the [S] approach, no further adjustments are needed and the square of the radial integral is directly proportional to the direct-capture cross section. In fig. 1(a), the [S] result is 158 mb, again compared to 167 ± 25 from experiment.

In these optical-model calculations, we consistently seek and employ a set of optical-model parameters and final-state real potential parameters which are physically reasonable in the sense of being close to those expected from global models reproducing large bodies of data covering extensive ranges of scattering and energy-level properties. Optical-model parameters selected without due circumspection yield cross section predictions that can vary by as much as ± 30%. When care is exercised, however, the predictions are stable to ± 5% except when the radial integrand has large positive and negative terms that nearly cancel. Such cases warrant a careful and detailed study at least when it comes to the application of the Lane-Lynn direct-capture theory to such cases.

The dashed lines in Fig. 1(a) and the dashed and dotted lines in Fig. 1(b) correspond to the channel-capture approximation which will be discussed later in this paper.

3. COMPOUND-NUCLEUS RADIATIVE CAPTURE

For the nuclides that we have studied (^{9}Be, ^{12}C, ^{13}C, ^{32}S, ^{33}S, ^{34}S, ^{40}Ca, and ^{44}Ca) the calculated cross sections for most of the primary transitions are in good agreement with the data. We attribute any differences to a compound-nucleus component in the capture amplitude from the tails of nearby resonance states. The term "compound-nucleus radiative amplitude" is used in our work as a generic term for mechanisms involving more general features of the wave functions than the simple projections of neutron motion in the field of the unexcited core of the target.

We can attempt to assess the plausibility of this compound-nucleus hypothesis in the following way. From the theoretical value of direct-capture cross section calculated by either the [G+V] or [S] method and from the experimental value, we deduce the compound-nucleus capture cross section using

$$\sigma_{\gamma}(\mathrm{exp}) = (\sigma_{\gamma,\mathrm{dir}}{}^{1/2} \pm \sigma_{\gamma,\mathrm{CN}}{}^{1/2})^{2} , \qquad (1)$$

and remove from this quantity the factor $E_{\gamma}{}^{3}$. From the average value of $\sigma_{\gamma,\mathrm{CN}}/E_{\gamma}{}^{3}$ for each case, we deduce a quantity proportional to the compound-nucleus radiation width from the relation [see eq. (12) of ref. 5]

$$\frac{\langle \Gamma_{\gamma,\mathrm{CN}}/E_{\gamma}{}^{3} \rangle}{E_{\lambda}} = \frac{k \langle \sigma_{\gamma,\mathrm{CN}}/E_{\gamma}{}^{3} \rangle}{2\pi R \, R'_{\mathrm{loc}}} . \qquad (2)$$

This quantity can then be compared with the Cameron semi-empirical relationship [9] deduced from a wide range of neutron resonance radiation widths,

$$\frac{\Gamma_{\gamma,CN}/E_\gamma^3}{D} = 0.33 \times 10^{-9} A^{2/3}\ \mathrm{MeV}^{-3} \ . \qquad (3)$$

The resonance energy E_λ (which can be positive or negative) can be expected to be of the order of or rather smaller than the level spacing D. Therefore, we expect the quantity on the left-hand side of eq. (2) to be about equal to or somewhat larger than the quantity on the right-hand side of eq. (3).

Table 1: Direct capture cross sections for primary E1 transitions, calculated with specialized optical model parameters, are compared with experimental values. The compound-nucleus contributions are deduced using eq. (1).

Primary E_γ(MeV)	$\sigma_{\gamma,dir}$ [S] mb	σ_γ(exp) mb	$\sigma_{\gamma,CN}$ mb
	(A) ^{24}Mg(n,γ) reaction		
3.918	17	36	3.5
3.054	5	9	0.6
2.610	0.2	0.1	0.02
	(B) ^{25}Mg(n,γ) reaction		
4.217	14	12	0.08
3.832	16	35	3.7
3.744	12	12	0.0
3.551	3	9	1.6
	(C) ^{26}Mg(n,γ) reaction		
7.884	40	24	2.0
1.617	10	5	0.9
0.535	0.3	0.01	0.2

Before testing this conjecture, we present in table 1 the results of some recently completed optical-model calculations of the direct-capture cross sections for the Mg isotopes. When combined with our previously published results, we are now in a position to assess the overall situation concerning the compound-nucleus contributions for the nuclides that we have studied. The results are summarized in table 2. It is apparent that the qualitative kind of agreement anticipated in the preceding paragraph is indeed found for nearly all nuclides in that table. As an explanation for the abnormally low value in the case of ^{13}C, we note that only one transition is included in the average and its radiation width is subject to Porter-Thomas fluctuations.

Table 2: Summary of compound-nucleus contributions

Nucleus	Number of transitions	Our result $\frac{\langle \Gamma_{\gamma,CN}/E_\gamma^3 \rangle}{E_\lambda}$ (MeV^{-3})	Cameron $\frac{\langle \Gamma_{\gamma,CN}/E_\gamma^3 \rangle}{D}$ (MeV^{-3})
^{9}Be	3	-0.5×10^{-9}	1.4×10^{-9}
^{12}C	2	-1.3×10^{-9}	1.7×10^{-9}
^{13}C	1	-0.01×10^{-9}	1.8×10^{-9}
^{24}Mg	3	-13×10^{-9}	2.7×10^{-9}
^{25}Mg	4	19×10^{-9}	2.8×10^{-9}
^{26}Mg	3	540×10^{-9}	2.9×10^{-9}
^{32}S	7	40×10^{-9}	3.3×10^{-9}
^{33}S	12	-23×10^{-9}	3.4×10^{-9}
^{34}S	5	53×10^{-9}	3.5×10^{-9}
^{40}Ca	6	-6.4×10^{-9}	3.8×10^{-9}
^{44}Ca	10	$\approx 1.8 \times 10^{-9}$	4.1×10^{-9}

In only one case — that of ^{26}Mg — does it appear that the quantity listed in column 3 of table 2 is excessively greater than the Cameron estimate listed in column 4. Furthermore, the compound-nucleus effects deduced for all three transitions are separately much greater than the Cameron value suggesting that there is a mechanism other than compound-nucleus capture operating here and that this mechanism could well be anticorrelated with the direct-capture mechanism. We note that unlike the other nuclides listed in table 2 the Mg isotopes are deformed or deformable targets. This fact gives rise to the possibility of coupling in a correlated manner certain inelastic channels to the elastic scattering of the incident neutron. A radiative capture component will be associated with these coupled-channel wavefunctions and this component will affect the calculated capture cross section. If it reduces the overall direct-capture cross section, it might be unnecessary to hypothesize a large compound-nucleus contribution. We are currently carrying out detailed calculations to test this idea.

4. CHANNEL-CAPTURE FORMULA

The channel-capture formula is given by

$$\sigma_{\gamma,ch} = \sigma_{\gamma,hs}\left[1 + \frac{R-a_s}{R}\, y\, \frac{y+2}{y+3}\right]^2 \qquad (4)$$

where the hard-sphere cross section is given by

$$\sigma_{\gamma,hs} = \frac{0.0614}{R/E_{lab}}\left[\frac{Z}{A}\right]^2\left[\frac{M_t+m_n}{M_t}\right]^3 \frac{2J_f+1}{6(2I+1)}\, S_{dp}\left[\frac{y+3}{y+1}\right]^2 y^2 \qquad (5)$$

and

$$y^2 = \frac{2mE_\gamma R^2}{\hbar^2} . \qquad (6)$$

The symbols have the following meaning:

- R - potential radius
- a_s - scattering length
- E_{lab} - laboratory energy of incident neutron
- M_t - target mass
- m_n - neutron mass
- J_f - spin of the final state
- I - spin of the target nucleus
- S_{dp} - spectroscopic factor
- and m - reduced mass of the neutron + nucleus system.

The channel-capture formula is an approximation to a more precise estimate of the cross section obtained from a model of direct capture based on single-particle motion in a nuclear optical-potential well. The principal approximations are that the initial radial wave function is precisely linear with a node at the s-wave scattering length and that the final p-state wave function is exactly a spherical Hankel function of order 1. These approximations are based on the assumption that the nucleus is extremely sharp edged. Deviations from these simple analytical forms arising from the diffuseness of the nuclear potential beyond the potential radius are totally ignored. Other approximations in the formula are the use of a very crude estimate of the p-state wave function at the potential radius R (the amplitude of the wave function is taken as $\sqrt{2/R}$) and the complete neglect of any contribution to the radial dipole integral from the internal region of the nuclear potential well.

The approximations inherent in the channel-capture formula are shown by dashed lines in fig. 1(a). The initial state is modified slightly compared to the specialized optical-model wave function (dotted line). The final-state wave function is however modified considerably compared to the optical-model wave function. Nevertheless the changes are such that the final calculated cross section, represented by the square of the radial integral, is quite similar (but ≈ 20% smaller) to that given by the specialized optical model. For $R = 4.57$ fm and $a_s = 4.90$ fm, the channel-capture approximation yields a cross section of 112 mb for the 6.421 MeV transition, compared to 158 mb from the specialized optical-model approach and 167 ± 25 mb from experiment.

In general, the channel-capture formula should be adequate for treating direct capture in heavy nuclei ($A > 30$ for example) so long as the scattering length and the corresponding potential radius do not differ by much and the required accuracy in the predicted cross sections is typically only about 20%.

The situation can be much more complicated in the case of lighter nuclei. Take ^{9}Be for example. The specialized optical-model treatment ($a_s = 7.0$ fm), shown by the solid line in fig. 1(b), leads to a direct-capture cross section of 6.9 mb for the 6.810-MeV transition to the

ground state of ^{10}Be compared to the measured value of 1.9 ± 0.5 mb. In fig. 1(b), we also show two different representations of the channel capture approximation. The dashed lines are for R = 2.81 fm and the dotted lines for R = 3.76 fm. It is immediately clear from this figure that the mock up of the final state wave function in the channel-capture approximation is especially poor. Moreover there is strong cancellation between the negative and positive portions of the radial integrand. The net result is that the direct capture cross section is very sensitive to the value assumed for the potential radius. A choice of R = 2.81 fm results in a channel-capture cross section of 14.8 mb; R = 3.76 fm results in 4.8 mb. This sensitivity arises more from the modifications made to the wave functions, and from the large cancellations particular to this case, than from any significant contributions from the internal region of the potential well. [The internal contribution is negligible also in the ^{40}Ca case shown in fig. 1(a).] Therefore in ^{9}Be a wide range of capture cross section values can be predicted depending merely on an arithmetical rather than physical choice of the potential radius.

On the basis of careful studies and detailed calculations, we conclude that in the case of light nuclei and in cases where the scattering length is much greater than the potential radius the blind use of the channel-capture formula is not to be recommended.

5. ACKNOWLEDGMENTS

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