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COMPARATIVE STUDIES IN DIRECT SLOW-NEUTRON CAPTURE CALCULATIONS

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ABSTRACT

Primary E1 transitions due to thermal neutron capture by the nuclides ^{9}Be, $^{32,34}S$, $^{40,42,44,46,48}Ca$, and ^{58}Ni are quantitatively interpreted by the Lane-Lynn formula and are compared with recent optical model calculations. The two approaches are equivalent provided the internal region of the nucleus is excluded in the optical model approach. Theoretical justifications for such a procedure are briefly presented.

1. INTRODUCTION

In a recent review Raman and Lynn[1] raised several questions with regard to the $^{9}Be(n,\gamma)^{10}Be$ study which was carried out in ref 2. As will be shown below, these points which were considered previously but not reported[2] due to space limitations, do not apply to ^{9}Be. At the outset, it is important to point out some of the distinct features of the Lane-Lynn[3] and the Raman et al[4] approaches. In the optical model approach as followed in Ref. 4 several parameters (the real and imaginary parts of the optical model potential, the diffusiveness of the nuclear surface and the radius) are adjusted to fit the potential scattering and neutron strength function data. The effect of the fine structure resonances was included by retaining the Lane-Lynn formula[3] which was adjusted by a factor C_{opt}. The latter quantity is estimated from the ratio of the potential cross section as predicted by the optical model to the corresponding value computed from the Lane-Lynn formula.[3] At this stage it is crucially important to point out that in this procedure[4] the internal region of the nucleus was included in evaluating the dipole overlap integral. By contrast, in the R-matrix approach (square well potential) only a single parameter, the interaction or channel radius, which separates the internal from the external region, is introduced i.e. a cut-off radius is present in the lower limit of the dipole integral. The basic overriding question is which approach gives a better description of the experimental data. On phenomenological grounds, I maintain that the Lane-Lynn approach succeeds remarkably well in accounting for the direct capture component of the reaction mechanism. The fundamental reason for the validity of the Lane-Lynn[3] approach as compared to that of Raman et al[4] rests on excluding the internal contribution of the nucleus. This procedure is supported by other reactions and its theoretical justification will be presented. Now I proceed to discuss each point raised in ref. 1 separately.

2. VALIDITY OF THE LANE-LYNN[3] FORMULA:

It is pointed out in ref. 4 that the Lane-Lynn expression gives at best accuracies to within 40%. Such an estimate is based not on a comparison between predictions and measurements but on an assessment of two theoretical approaches via C_{opt}. Detailed comparisons described in ref. 5-8 and compiled in ref. 9 demonstrated that, in spite of the approximations which were carried out in ref. 3, remarkable agreements (better than 20% in several cases) between the Lane Lynn predictions and the measurements were achieved. Similar comparisons carried out in ref. 10 for ^{36}S show: "the agreement is excellent if b_s [the coherent scattering length] is assumed to be 3.0 fm and

Table I

Comparison Between the Predictions of the Lane-Lynn and Raman et al. Approaches with the Experimental Data

Final Nucleus	Level Energy (keV)	J^{π}	E_{γ} (keV)	σ_{γ} [a] theory (mb)	σ_{γ} [c] theory (mb)	σ_{γ} exp. (mb)
^{35}S	2348	$3/2^-$	4638	205	142	163±15
	3802	$3/2^-$	3184	25.2	17.2	18.2±1.7
	4189	$1/2^-$	2797	14.7	11.8	15.9±1.5
	4903	$1/2^-$	2083	61.8	49.5	46±5
	4963	$3/2^-$	2023	37.5	27.1	33.6±3.0
	SUM			344.2	247.6	270±40
^{37}S	546	$3/2^-$	3657	232 [b]	172	161±18
	1992	$(3/2)^-$	2312	11.6 [b]	8.7	9.4±1.2
	2638	$1/2^-$	1666	52.0 [b]	45	52±7
	3622	$3/2^-$	1042	13.9 [b]	10.4	8.1±1.0
	3493	$(1/2)^-$	811	5.9 [b]	4.3	2.4±0.3
	SUM			315.4	240.4	230±20

a) R = 4.32 and 4.6 for ^{34}S and ^{36}S, respectively (ref. 4).
b) For ^{36}S, a_s = 3.2 is derived, which corresponds to R^{∞} = 0.30. The values are interpolated.
c) Present work.

still reasonable (i.e. within 20%) if b_s is 2.5 or 3.5 fm." This conclusion is in full agreement with previous studies[5-9] but is at variance with the view expressed in ref. 1.

Since detailed calculations of the direct capture cross sections of $^{34,36}S$ carried out within the framework of the optical model are presently available,[4] it is highly informative to exhibit explicitly a comparison between those results and the present ones derived solely on the basis of the Lane-Lynn prediction on one hand and the measurement on the other. The $^{32,33}S$ results will not be discussed here since the conclusion[4] regarding compound nucleus contribution in ^{32}S is at variance with the measured[11-12] radiative width of the 102 keV resonance of ^{32}S and the spin-dependent coherent scattering lengths of ^{33}S are not measured yet.

The coherent scattering length of ^{34}S is very well determined while that of ^{36}S is not yet measured.[9] Nevertheless, the latter can be estimated with a reasonable degree of certainty with the aid of the potential scattering length[9,13] of ^{34}S and the variation of R' with mass number as predicted by the optical model and supported by systematics.[9] On this basis, a coherent scattering length of 3.2 + 0.2 fm is derived for ^{36}S. The results of the calculations are summarized in Table 1 and are compared with the measurements.[10] It is stressed that the same input parameters used in ref. 4 are adopted here. As is evident, the Lane-Lynn formula appears to give a better description of the measurements (within one standard deviation) than the optical model approach[4] which systematically yields overpredicted values by about 30%. The reason for this is attributed here to an overestimation[14] of C_{opt} due to the inclusion[4] of the contribution of the internal region.

Additional phenomenological evidence in support of the present conclusions (i.e. the accurate quantitative validity of the Lane-Lynn formula and the exclusion of the nuclear interior region contributions) is derived from the (n,γ) data of the even-even Ca isotopes. Previous studies[5,7-9] revealed that the direct neutron-capture component dominates over that of the compound nucleus and that the Lane-Lynn formula accounts quantitatively with reasonable accuracy for the observations. More recently[15], a reanalysis of the same data was carried out in terms of the optical-model-R-matrix formulation. Since an explicit comparison between the results of these two approaches was not reported[15], it is imperative to do so explicitly. It is important to note that the same input parameters used in ref. 15 are used here. In Table 2, a comparison between the results of the two approaches on one hand and the experimental data on the other is shown for the case of ^{44}Ca whose coherent scattering length is known. As verified in the last three columns of Table 2, two results readily emerge: (1) the Lane-Lynn formula is in better agreement with the experimental data, and (2) the results of ref. 15 are larger by 34% than the experimental data and the Lane-Lynn predictions. As emphasized in the previous discussion, the source of the discrepancy in this mass region is largely due to the inclusion of the internal nuclear region contribution. A similar analysis conducted here and summarized in Table 3 for the other Ca isotopes reveals the same trend.

Table 2. Comparison between two theoretical approaches for the reaction $^{44}Ca(n,\gamma)^{45}Ca$.

E_f (MeV)	$(2J_f+1)S_{dp}$	σ_γ[S][a] (mb)	σ_γ[LL][b] (mb)	σ_γ(exp) (mb)
1.435	0.43	127	99	95+10
1.900	2.35	631	475	460+46
2.249	0.35	74	66	85+10
2.842	0.40	85	64	35+5
3.241	0.13	25	17	21+4
3.418	0.68	105	92	95+10
3.783	0.11	17	13	8+3
3.838	0.24	33	28	14+3
4.616	0.40	40	35	31+5
5.000	0.47	39	34	16+4
SUM		1176[c]	923	860±50
				(880±50)[d]

a. Kahane, et al. Ref. 15.
b. Mughabghab present results.
c. Value larger by 34% than the experimental value.
d. Ref. 9.

Table 3. Comparison between the predictions of Ref. 15 and the present results for the direct E1 capture component of the total capture cross-sections of the even-even Ca isotopes.

Isotope	^{40}Ca	^{42}Ca	^{44}Ca	^{46}Ca	^{48}Ca
σ_γ(G+V)[a]	290	638	1124	675	891
σ_γ(LL)[b]	196	501	923	527	736
σ_γ(G+V)[a]/σ_γ(LL)[b]	1.48	1.27	1.21	1.28	1.21

a. Ref. 15.
b. Present results.
c. For a_s = 1.95 fm.

Other evidences drawn from other reactions will be cited in support of excluding the internal region.

To answer the assertion that the Lane-Lynn formula breaks down when the direct capture cross section is quite different from the estimate of hard sphere capture, I call upon the $^{58}Ni(n,\gamma)$ ^{59}Ni reaction. The bound coherent scattering length of ^{58}Ni is b_s = 14.4 + 0.1 fm which is quite different from an interaction radius of 5.226 fm ($R=1.35\ A^{1/3}$). Because b_s is much larger than R, strong destructive interference between hard sphere and resonance channel components occurs. The hard sphere and the potential capture cross sections are 0.380 b, and 0.110 b respectively. This is to be contrasted with a direct capture cross section of 5.014 b. Previously, this reaction was described[16] successfully in terms of valence capture. An alternative interpretation can be made in terms of direct capture of thermal neutrons via the Lane-Lynn formula. The results are displayed in Table 4 and are compared with recent measurements.[17] As shown, the quantitative agreement between the predicted and measured partial capture cross sections is surprisingly remarkable here (in spite of the proximity of compound resonances near thermal energy) except for the transition to E_x = 1302.9 keV. The latter transition in this particular case may be influenced by contribution of other processes.

Table 4. Comparison of predicted and measured capture cross-sections of primary E1 transitions populating low-lying states of ^{59}Ni.

Level Energy (keV)	J^π	E_γ (keV)	σ_γ Theory (b)	σ_γ[a] Exp (b)
0	$3/2^-$	8999.9	2.88	2.42±0.24
465.5	$1/2^-$	8534.1	1.18	1.18±0.10
877.9	$3/2^-$	8121.8	0.27	0.21±0.02
1302.9	$1/2^-$	7698.4	0.39[b]	0.060±0.008

a. Absolute intensities of Ref. 17 and capture cross-sections of Ref. 9 are adopted.

b. The total resonance contribution[9] is 0.48 b. For this transition, processes other than direct capture have a destructive contribution.

3. UNCERTAINTY OF THE (d,p) SPECTROSCOPIC FACTORS:

Although the uncertainty of the measured (d,p) spectroscopic factors is generally 15-20%, the excellent agreement between the experimental data[18-20] for the ground and first excited states and the theoretical values of Cohen and Kurath[22] gives confidence in the reliability of these parameters. Nonetheless, as stressed in ref. 2, the variation of the partial capture cross sections with the interaction radius for the ground and first excited states is such that the uncertainty of the spectroscopic factors plays an insignificant role in determining the spin dependence of the interaction radius. Due to uncertainties in the measured cross sections and the theoretical procedure of extracting the (d,p) spectroscopic factors, these quantities are dominated by systematic errors. In fact, if there is for example a 50% systematic error in the (d,p) spectrotopic factors, the derived value of $R_+ - R_-$ is virtually unchanged!

4. COMPOUND NUCLEUS CONTRIBUTION:

The question of the interfering component of compound nucleus contribution is generally a problem. This arises because of the presence of compound s-wave resonances close to the thermal energy. However, the s-wave resonances of ^{9}Be are valence in character and therefore arguments pertaining to this question are not applicable here. Raman[9] and Lynn[1] inappropriately applied Cameron's formula[21] to a light nucleus, ^{9}Be, to estimate the compound nucleus contribution. In addition, they unjustifiably assumed that one of the bound s-states located at an energy of -850 keV is the source of the compound nuclear process. First, the main assumption of the statistical model, that the single particle state is fragmented into numerous compound states, is violated here. Second, the -850 keV state has a single particle character. In the excitation energy region from the ground state to 21 MeV, only three s-states are known[9,22] in ^{10}Be. The average level spacing is of the order of a few MeV. The s-states at excitation energies of 5960 keV (1^-) and 6264 keV (2^-) are neutron bound by 851 keV and 547 keV respectively. The third state which is weak is located at 4.2 MeV above the neutron separation energy. From the polarization data[23], estimates of 0.76 and 0.46 are made for the (d,p) spectroscopic factors for the bound states at -547 and -851 keV respectively. The former is in good agreement with a value of $S_{dp} = 0.67$ derived on the basis of consideration[24] of isobaric analogue states of ^{10}B. It is evident that the sum of the (d,p) strengths of these two states exhausts the single particle strength in ^{10}Be. This situation is very similar to other neighboring nuclides.[22] It then follows that these states are not compound states and do not follow the statistical law of decay. Additional support for the single particle (nonstatistical) nature of these states comes from their predicted selective decay to the low lying states. Furthermore, the Weisskopf prescription of computing the compound nucleus contribution is based on the picture that the single particle radiative strength is dissolved uniformly into the various compound states reduced by the fraction D_s/D_o where D_s and D_o are the average spacings of the s-wave compound and single particle states respectively. It is clear that when $D_s = D_o$, as is the case for $^{9}Be + n$, the calculated "compound" nucleus radiative strength becomes identical to the single particle strength.

It is important to point out here that these bound s-states determine the center of gravity of the single particle state at E_x = 6.075 MeV, i.e. close to the neutron separation energy. This indicates that the peak of the 2S neutron strength function is located close to atomic mass number 9 for zero neutron energy. This conclusion, which is in agreement with the optical model prediction, is crucially important in settling the question of the contribution of the internal region to the radiative process as will be shown next.

5. THE QUESTION OF THE CONTRIBUTION OF THE INTERNAL REGION:

As shown in refs. 25-26 when the single particle state is located close to the neutron threshold, such as in Be, 99% of the contribution to the dipole integral arises from the external region. On the other hand, for nuclei located 20 atomic mass units away from the peaks of the s-wave strength functions (such as for the S and Ca isotopes) the contribution[26] of the internal region can be as high as 30%. On the basis of this observation, it is expected that the predictions of two approaches would diverge for nuclei located in the minima of the s-wave strength functions and converge for nuclei close to the peaks of the s-wave neutron strength functions. This expectation is verified by a calculation of the potential capture cross section for A=56 carried out within the Lane-Lynn approach. The calculated value is 0.052 b which is in very good agreement with a reported value[4] of 0.050 b on the basis of the optical model prediction. In addition, this is in agreement with previous comparisons for the S and Ca isotopes (Table 1-Table 3).

6. THE ROLE OF THE INTERACTION RADIUS:

Previous comparisons between the predictions of the two theoretical approaches and the measurements strongly suggested that the internal region must be excluded in the evaluation of the dipole radial integral. This procedure would then bring about closer agreements between the two theoretical approaches on one hand and the measurements on the other. Similar conclusions regarding the use of a cut off radius can be found in the literature connected with studies of other direct mechanisms such as the (d,p) and (p,γ) reactions. In the former reaction applied to ^{6}Li it was imperative[27] to introduce a cut off radius of 3.8 fm in order to best fit the position of the peak of the differential cross sections. For the latter reaction, the $^{12}C(p,\gamma)^{13}N$ can be cited where it was concluded[28] that the extranuclear direct capture formalism fully accounted for the data, i.e. no internal background is required. The physical justification for the use of a cut off radius can be made on the grounds of the finite range and nonlocal effects of the nuclear force.[27-30] An additional argument in support of the exclusion of the contribution of the internal region to the electric dipole matrix element can be made on the grounds of the large reduction of the effective charge of the neutron in the internal region because of the strong coupling with the giant dipole resonance.[33-34]

To summarize, it is shown that the Lane-Lynn formula applied to the nuclides ^{9}Be, ^{32,34}S, $^{42-48}$Ca, ^{58}Ni seems to give a better description of the data than the optical model- R matrix approach. Compound nucleus contribution is negligible in ^{9}Be (n,γ) ^{10}B, because the bound states possess predominantly pure single particle character (valence). In addition it is shown

for $^{34,36}S$ and the even-even Ca isotopes that the contribution of the internal region, though small in ^{9}Be, nevertheless should be excluded in general.

7. REFERENCES

1. S. Raman and J.E. Lynn, 4th International Symposium on Neutron Induced Reactions, Smolenice, C.S.S.R. (June 17-21, 1985).

2. S.F. Mughabghab, Phys. Rev. Lett. 54, 986 (1985).

3. A.M. Lane and J.E. Lynn, Nucl. Phys. 17, 58o (1960).

4. S. Raman, R.F. Carlton, J.C. Wells, E.T. Jurney, and J.E. Lynn, Phys. Rev C, 32, 18 (1985).

5. S.F. Mughabghab and R.E. Chrien, in Neutron Capture Gamma-Ray Spectroscopy, Edited by R.E. Chrien and W.R. Kane, p 265 (Plenum, New York), 1979.

6. S.F. Mughabghab, Phys. Lett., 81B, 93 (1979).

7. S.F. Mughabghab, in Proceedings of the Specialists' Meeting on Neutron Cross Sections of Fission Product Nuclei, Bologna, 1979, edited by C. Coceva and G.C. Panini, "E. Clementel" CNEN Centre Report NEANDC(E)201 "L", p. 179.

8. S.F. Mughabghab, in Proceedings of the Conference on Nuclear Data Evaluation Methods and Procedures, Upton, New York, 1981, edited by B.A. Magurno and S. Pearlstein, Brookhaven National Laboratory Report BNL-NCS-51363, Vol. I, p. 339.

9. S.F. Mughabghab, M. Divadeenam, and N.E. Holden, Neutron Cross Sections Vol. 1A (Academic Press, New York) 1981.

10. C.E. Thorn, J.W. Olness, E.K. Warburton, and S. Raman, Phys. Rev C, 30, 1442 (1984).

11. J. Halperin, C.H. Johnson, R.R. Winters, and R.L. Macklin, Phys. Rev. C, 21, 545 (1980).

12. B. Lundberg and I. Bergquist, Phys. Sci. 2, 265 (1970).

13. R.F. Carlton, W.M. Good, J.A. Harvey, R.L. Macklin, and B. Castel, Phys. Rev. 29C, 1980 (1984).

14. S.F. Mughabghab, Phys. Rev. Lett., 56, 399 (1986).

15. S. Kahane, J.E. Lynn and S. Raman, Phys. Rev. 36C, 533 (1987).

16. S.F. Mughabghab, Phys. Lett., 35B, 469 (1971).

17. A.F.M. Ishaq, A. Robertson, W.V. Prestwich, and T.J. Kennett, Z. Physik, A281, 365 (1977).

18. S.E. Darden, G. Murillo, and S. Sen, Nucl. Phys. A266, 29 (1976).

19. K.W. Kemper, G.E. Moore, R.J. Puigh, and R.L. White, Phys. Rev. 15C, 1726 (1977).

20. S. Cohen and D. Kurath, Nucl. Phys. A101, 1 (1967).

21. A.G.W. Cameron, Can. J. Phys. 37, 322 (1959).

22. F. Ajzenberg-Selove, Nucl. Phys. A413, 1 (1984).

23. F.W. K. Firk et al., in Nuclear Cross Sections and Technology, U.S. National Bureau of Standards Special Publication No. 425 (U.S. GPO Wahsington, D.C., 1975) p. 875.

24. M.L. Roush, F.C. Young, P.D. Forsyth, and W.F. Hornyak, Nucl. Phys. A-128, 401 (1969).

25. S.F. Mughabghab in Neutron Capture Gamma-Ray Spectroscopy edited by K. Abrahams, F. Stecher-Rasmussen and P. Van Asshe (Reactor Centrum Nederland Petten 1975) p53.

26. J. Cugnon and C. Mahaux, Annal of Phys. 94, 128 (1975).

27. C.R. Mclenahan and R.E. Segel, Phys. ReV C, 11, 360 (1975).

28. J.C. Brown, R.G. Seyler, T.L. Tsin, and S.L. Blatt, Phys. Rev. C, 1607 (1985).

29. P.E. Hodgson Nuclear Reactions and Nuclear Structure (Clarendon, Oxford, 1971) p. 456.

30. Yu. P. Antuf'ev et al., Yad. Fiz. 40, 53 (1984).

31. B. Castel and C. Mahouxc, Z. Phys. A, 318, 31 (1984) and references therein.

32. Y. K. Ho and C. Coceva, 6th International Symposium on Capture Gamma-Ray Spectroscopy, August 31 - September 4, 1987, Leuven.

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