THE $^{24}Mg(\vec{p},d)$ REACTION TO THE $1/2^+$ STATE AT 2.36 MEV FOR PROTON ENERGIES FROM 27 to 150 MEV

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The availability of high-quality (p,d) data using polarized proton beams at medium energies permits rather stringent tests to be made of the underlying reaction mechanism. Any particular reaction model should provide a reasonable description of the cross-section and analyzing-power angular distributions, and the extracted spectroscopic information should be independent of the projectile energy.

The ℓ=0 transition to the $1/2^+$ state at 2.36 MeV in the $^{24}Mg(\vec{p},d)^{23}Mg$ reaction constitutes a particularly interesting and useful case for such a study since good data at several bombarding energies are already reported in the literature. Cross section data are available at 27.3, 33.6, 65.0, 80.0 and 94.8 MeV,[1-4] while analyzing-power data exist only at the highest three energies. Recently, Hatanaka et al.[3] have been able to obtain reasonable descriptions for the 94.8-MeV data as well as for their new data at 65 and 80 MeV using the adiabatic approximation including the usual finite-range and non-locality correction factors. However, the spectroscopic factors that they extracted with a standard binding well geometry (r_o = 1.25 fm, a_o = 0.65 fm) increase with energy from 0.10 at 33.6 MeV to 0.24 at 94.8 MeV. They showed, however, that they could improve further on the decription of the data by using an increased radius parameter of 1.65 fm for the binding-well geometry.

The goal of the present study was to examine the viability of conventional DWBA and adiabatic approximation calculations for this particular ℓ=0 transition to the 2.36-MeV state in ^{23}Mg over a still wider range of projectile energies (27.3 to 150.3 MeV), and to study the sensitivity of the derived spectroscopic strength to the various parameters involved in the calculations.

Cross sections and analyzing powers were measured at IUCF for this reaction at bombarding energies of 49.2 and 150.3 MeV. Because the QDDM spectrograph is limited to analyzing deuterons with energies below 125 MeV, it was necessary to use a counter telescope including intrinsic Ge and Si surface barrier detectors mounted in the 64" scattering chamber.[5] The cross section and analyzing-power data for the transition to the 2.36-MeV state are shown in Figs. 1 and 2. Uncertainties shown with the data points are statistical only. The overall normalization of the data was estimated to have an uncertainty of about 15% at 49.2 MeV and 25% at 150.3 MeV. Figs. 1 and 2 also show the data for the same transition at 27.3, 33.6, 65, 80 and 94.8 MeV from the previous studies.[1-4]

Exact finite range calculations were performed at all energies with the code DWUCK5,[6] which has recently been extended to include non-locality corrections in the usual fashion. Non-locality parameters of 0.85 fm for protons and neutrons and 0.54 fm for deuterons were employed. The use of exact finite range calculations has the advantage that the zero-range normalization factors are not needed and that any contributions from the D-state of the deuteron are correctly included.

A number of optical-model potentials were investigated for the purpose of generating the

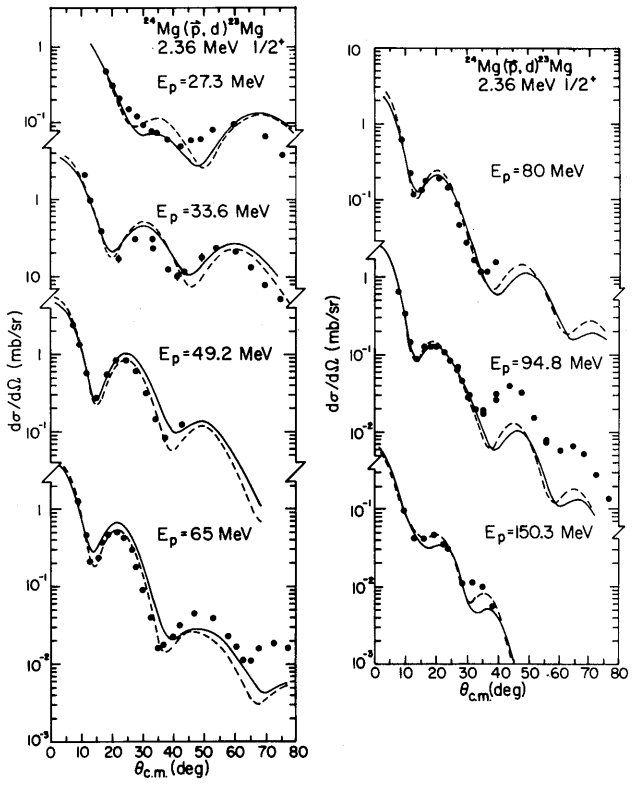

Figure 1. Comparison of the cross section angular distributions for the $1/2^+$ state at 2.36 MeV measured in the ^{24}Mg (p,d) reaction at various energies with the results of exact finite range calculations as described in the text. The solid lines are the results of calculations with the bound-state parameters of set A while the dashed lines are obtained with set B of Table 2.

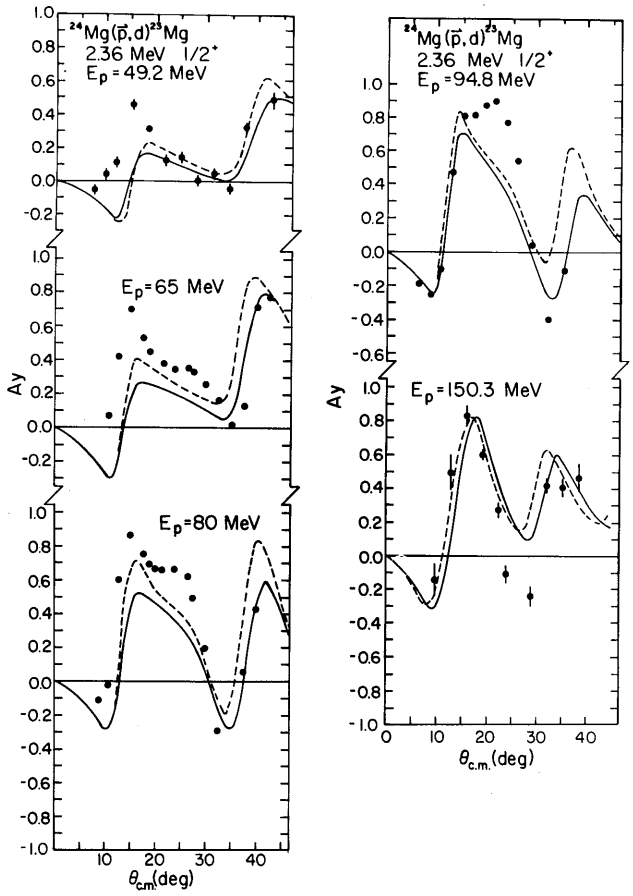

Figure 2. Analyzing-power comparisons with same description as in Fig. 1.

Schrödinger distorted waves for the incoming protons and outgoing deuterons. It was felt important to use proton optical-model parameters based directly on elastic-scattering cross section and analyzing-power data for ^{24}Mg. The energy-dependent parameters of De Leo et al.[7] met this criterion and were used for the energies up to 50 MeV. For the higher energies, parameters were used from the study of Hosono et al.,[8] based on elastic scattering data at 65 MeV; these were extended to other energies by assuming the same energy dependence found by De Leo et al. At 94.8 and 150.3 MeV, calculations were also carried out with parameters derived from the work of Schwandt et al.[9] These latter parameters did not provide satisfactory descriptions of the (p,d) data, The adiabatic calculation followed the prescription of Harvey and Johnson,[10] using the proton parameters discussed above evaluated at half the deuteron energy.

The spectroscopic factors derived from the present calculations are summarized in Table 1. At some energies more than one set of potentials was tried in order to assess the influence on the spectroscopic information. Table 1 shows that this influence is not strong, although some sets were clearly preferable with

Table 1 Spectroscopic Factors

E_p (MeV)	Pots[a]	$C^2S_{0\ 1/2}$ [b] (2.36 MeV)		$C^2S_{2\ 5/2}$ [b] (0.45 MeV)	
		1.25 fm / 0.65 fm	1.385 fm / 0.743 fm	1.25 fm / 0.65 fm	1.385 fm / 0.743 fm
27.3	g,g	0.13 [c]	0.10 [c]	2.4	1.40 [c]
33.6	g,g	0.15 [c]	0.10 [c]	2.1	1.20 [c]
49.2	g,g	0.16 [c]	0.10	2.1 [c]	1.15 [c]
	h,g	0.17 [c]	0.10	2.1 [c]	1.15 [c]
65.0	h,g	0.15 [c]	0.10	2.5 [c]	1.45 [c]
80.0	h,g	0.11	0.09	-	-
94.8	h,g	0.17	0.14	2.3	1.50 [c]
	h,h	0.20 [c]	0.18 [c]	2.9 [c]	1.90 [c]
	i,g	0.13 [c]	0.12 [c]	1.8	1.20 [c]
	i,h	0.14	0.14	2.3 [c]	1.60 [c]
150.3	h,h	0.40 [c]	0.38	2.5	2.20
	h,i	0.40 [c]	0.34	2.5	2.20
	i,h	- [d]	- [d]	1.1 [c]	- [d]
	i,i	- [d]	- [d]	1.1 [c]	- [d]
Theory		0.28 [e]		2.55 [e]	
		0.10 [f]		2.28 [f]	

a) Combination of proton and deuteron potential parameters used.
b) C^2 is the square of the isospin Clebsch-Gordan coefficient.
c) Poor fit in the sense of the text criterion.
d) Ambiguous, due to bad fit.
e) Shell model value from ref. 13.
f) Collective model value from ref. 12.
g) Ref. 6.
h) Ref. 8.
i) Ref. 7.

respect to the quality of the fit. Figs. 1 and 2 show the results of the calculations with the preferred potentials. The solid lines are the results of calculations with bound-state parameters of 1.25 and 0.65 fm (set A in Table 2) while the dashed lines are obtained with bound-state parameters of 1.385 and 0.743 fm (set B in Table 2). The latter values are consistent with values derived by Alons et al.[11] from coupled-channels calculations for the $^{26}Mg(p,d)^{25}Mg$ reaction.

Both the results obtained with bound-state parameter sets A and B describe the angular distributions of the cross sections quite well except at 27.3 MeV. If, as a criterion, a good fit implies that the slope at forward angles and the first diffraction peak are both fit well at the same time, the results obtained with set B are appreciably better except for the lowest two energies, where none of the

Table 2 Bound State Parameters

Set [a]	j^π	E_{exc} (MeV)	r_o (fm)	a_o (fm)	V_o (MeV)	λ [b]	B.E. [c] (MeV)
A	$5/2^+$	0.45	1.25	0.65	64.18	20	-16.98
	$1/2^+$	2.36	1.25	0.65	73.19	20	-18.89
B	$5/2^+$	0.45	1.385	0.743	57.68	20	-16.98
	$1/2^+$	2.36	1.385	0.743	65.14	20	-18.89

[a]) Refers to the geometrical parameters of the binding well.
[b]) The Thomas spin-orbit parameter: $V_{SO} = (\lambda/180.8)\ V_o$.
[c]) Binding energy.

calculations can meet this criterion. As Fig. 2 shows, the analyzing-power fits are also reasonable, describing the main features of the angular distributions at all energies. Again, at all energies the results obtained with set B are somewhat better than those obtained with set A.

The spectroscopic factors obtained with set A fluctuate somewhat with energy up to 94.8 MeV, and are consistent with the values found by Hatanaka et al.[3] and with the value of 0.18 found in ref. 12 from a study of the ^{24}Mg(d,t) reaction at 21 MeV. Furthermore, they are intermediate between the present shell model value and the collective model value of Nelson and Roberson,[12] though closer to the latter. At 150.3 MeV the apparent spectroscopic factor calculated with set A jumps to a value that is about three times as large as the values found at lower energies. When set B is used, the calculated spectroscopic factor is constant up to 80 MeV (being exactly equal to the collective model value of ref. 12) and then starts to increase with energy, reaching a value about four times as large at 150.3 MeV.

In summary, the adiabatic approach to the (p,d) reaction description appears to describe the experimental cross-section and analyzing-power data fairly well for this transition over a wide range of energies, especially when the geometry of set B is used for the bound-state calculation. The spectroscopic factors obtained are in reasonable agreement with the theoretical values at energies up to 95 MeV, the values obtained with set B in particular being independent of energy up to 80 MeV. Beyond that energy, however, this approach clearly fails for the ℓ=0 transition since it would imply an effective energy dependence of the spectroscopic factor. This is illustrated in Fig. 3 where the experimental and theoretical cross sections at the first diffraction maximum are plotted against the proton energy. The theoretical values are those obtained with set B assuming a spectroscopic factor of 0.10 at all energies and the preferred optical model parameters as indicated above. The experimental and theoretical curves are quite consistent up to about 90 MeV, but then a major departure between the two curves is noted when going up to 150 MeV.

In order to examine the normalization of the data at 150.3 MeV, calculations were also performed for the ℓ=2 transition to the strongly excited $5/2^+$ state at 0.45 MeV, using the same parameter sets used for the $1/2^+$-state calculations. The spectroscopic factors obtained are included in Table 1 together with their

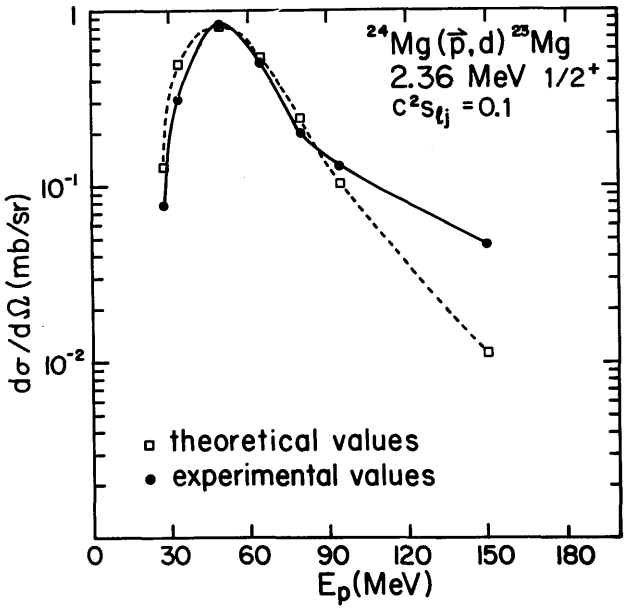

Figure 3. Comparison of the experimental results and theoretical adiabatic calculations as described in the text for the cross section of the ℓ=0 transition to the $1/2^+$ state at 2.36 MeV at the first diffraction maximum as a function of the incident proton energy.

theoretical values. As can be seen, the spectroscopic factor appears to be again quite sensitive to the bound-state geometry chosen, the difference between the values obtained with set A and set B being almost a factor of two at the lower energies but becoming smaller at high energies. For this state it was found that the fits obtained with set A were generally better than those obtained with set B. Furthermore, the geometrical parameters of set A lead to a value for the spectroscopic factor independent of energy over the whole range investigated and quite consistent with the theoretical values given in Table 1. The preference for another bound-state geometry is by no means contradictory. It may indeed be dependent on the particular orbit from which pickup of the valence nucleon occurs, as is shown for instance in ref. 11.

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