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α pickup from ^{24}Mg

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Angular distributions have been measured at a bombarding energy of 28 MeV for the reaction ^{24}Mg(d,^{6}Li) ^{20}Ne, populating most of the known levels below 9.1 MeV excitation. Results were compared with distorted wave Born-approximation calculations, and α spectroscopic factors extracted. Those for the g.s. band are in reasonable agreement with theoretical predictions. Members of the 7.20-MeV band are found to possess very large spectroscopic factors, in agreement with the core-excited nature of this band.

[NUCLEAR REACTIONS ^{24}Mg(d, ^{6}Li), E = 28.0 MeV; measured $\sigma(\Theta)$. ^{20}Ne deduced levels, S_α. DWBA analysis.]

I. INTRODUCTION

We report here on a study of the reaction ^{24}Mg(d, ^{6}Li)^{20}Ne. There are four $K^\pi = 0^+$ rotational bands in ^{20}Ne, with band heads at 0.0, 6.72, 7.20, and 8.3 MeV. These are depicted in Fig. 1. The configuration of the 8.3-MeV band consists dominantly of two or four nucleons in the fp shell and hence its members are not expected to be populated in α pickup from ^{24}Mg. The other three bands should be reached in pickup. The ground state (g.s.) and 6.72-MeV bands are predominantly $(sd)^4$ in character, and the 7.20-MeV band has a core-excited configuration,[1] $(sd)^6(1p)^{-2}$ and/or $(sd)^8(1p)^{-4}$. The measurement of α spectroscopic factors should aid in further elucidating the structure of this last band.

Two low-lying negative-parity rotational bands (depicted in Fig. 2) are known. One has $K^\pi = 2^-$ and is dominantly $(sd)^5(1p)^{-1}$ with $(\lambda\mu) = (82)$. The other has $K^\pi = 0^-$ and a large portion of the configuration $(sd)^3 fp$. If it were purely this configuration, its members would have zero strength in α pickup. It could, of course, obtain α-pickup strength by mixing with the $(sd)^5(1p)^{-1}$ band. However, such mixing is known to be small ($\lesssim 10\%$) from the small α spectroscopic factors measured[2] in α stripping on ^{16}O. On the other hand, if the 0^- band is largely $(\lambda\mu) = (90)$, it must have a significant amount of $(sd)^5(1p)^{-1}$ in order to be nonspurious, as discussed in Sec. III. In any event, measurable α-pickup strength to members of the 0^- band would indicate $(sd)^5(1p)^{-1}$ admixtures.

The reasonably strong population of the unnatural-parity members of the 2^- band indicates[3] a non-negligible component of nondirect processes, particularly α pickup to the natural-parity members of this band accompanied by inelastic scattering. However, coupled-channel calculations[4] indicate that such processes have a small effect on the allowed states, as evidenced by the fact that cross sections for them calculated with and without inelastic coupling are very similar. Thus, in what follows, we consider only zero-range distorted-wave Born-approximation (DWBA) calculations, assuming single-step α transfer. The effects of coupled channels and finite range will be communicated separately.[4]

Previous investigations[5,6] of the ^{24}Mg(d, ^{6}Li) reaction have been carried out at bombarding energies of 80 MeV (Ref. 5) and 35 MeV (Ref. 6). The

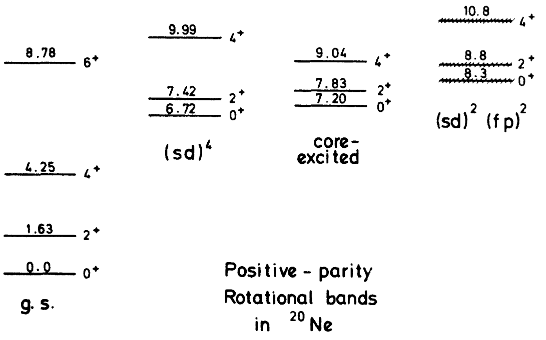

FIG. 1. Low-lying positive-parity rotational bands in ^{20}Ne.

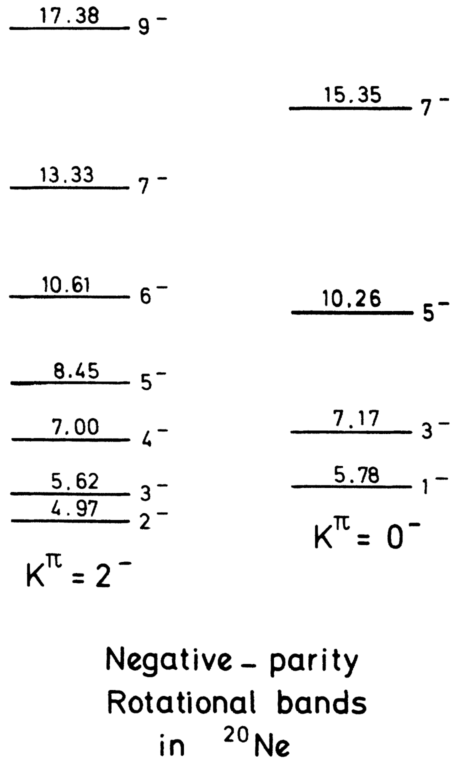

FIG. 2. Low-lying negative-parity rotational bands in ^{20}Ne.

former reported angular distributions for four states, but no spectroscopic factors. The latter reported results for five states, though for three of the five, the angular distributions contain only four points.

II. EXPERIMENTAL PROCEDURE AND RESULTS

Data were obtained with a 28-MeV deuteron beam from the Princeton cyclotron. The target was a gold-backed foil of about 100 $\mu g/cm^2$ of enriched (99.96%) ^{24}Mg. The absolute cross-section scale was determined by measuring yields to the lowest three states with a thick self-supporting foil (960 $\mu g/cm^2$) whose thickness was obtained by weighing. Outgoing ^{6}Li ions were detected in a Si-surface-barrier detector telescope. Data were collected at 11 angles between 8° and 42°. At a few angles, contaminant peaks from ^{12}C and ^{16}O overlapped peaks belonging to states in ^{20}Ne. Also, certain of the weaker states could not be analyzed at forward angles. A typical spectrum is given in Ref. 3. Energy resolution was about 160 keV, full width at half maximum.

Angular distributions are displayed in Figs. 3–5. Those for the unnatural-parity 2^- and 4^- states are shown in Fig. 3. These states are forbidden in direct α pickup and will not be discussed further herein. The remaining angular distributions were analyzed with DWBA, as outlined in Sec. IV.

III. CALCULATION OF THEORETICAL α-PICKUP AMPLITUDES

Spectroscopic amplitudes for the transfer of clusters of nucleons, correlated in such a way as to have zero quanta of internal excitation, are now quite easy to calculate in the framework of the SU(4)/SU(3) models. The calculations between states of $0\,\hbar\omega$ excitation (i.e., no core excitation) in the *sd* shell require the "*A* factor" of Draayer[7] [basically a sum over SU(3)$\supset$R(3) Clebsch-Gordan coefficients and unitary $9j$ recoupling coefficients for R(3)] and the SU(6)$\supset$SU(3) and SU(4)$\supset$[SU(2) $\times$ SU(2)] coefficients of fractional parentage (cfp), tabulated by Hecht and Braunschweig[8] for the leading spatial and SU(3) symmetries for one, two, three, and four nucleon transfer in the *sd* shell.

In the present paper, we are interested in α-particle pickup amplitudes leading from the ground state of ^{24}Mg to the ground-state and core-excited bands of ^{20}Ne. The ground-state to ground-state calculation is quite straightforward; the intensity is given by the following expression, assuming leading representations, i.e., $(\lambda\mu) = (84)$ for ^{24}Mg

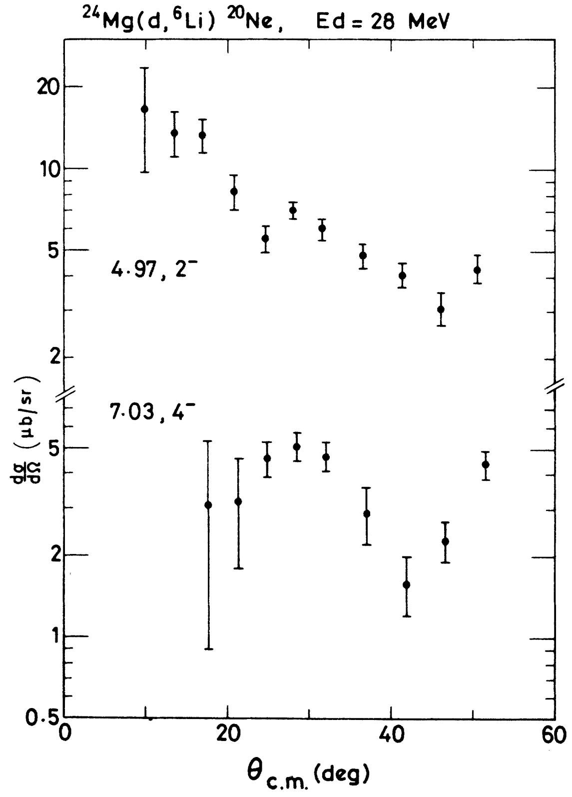

FIG. 3. Angular distributions for unnatural parity 2^- and 4^- states.

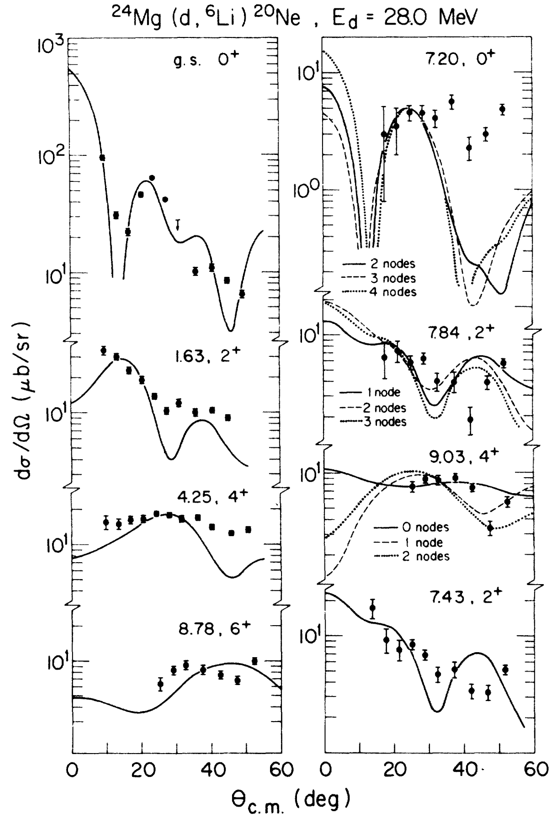

FIG. 4. Angular distributions for the ^{24}Mg(d, ^{6}Li) reaction at 28.0 MeV, populating known positive-parity states of ^{20}Ne. Curves are results of DWBA calculations, assuming α cluster transfer. Relative spectroscopic factors are listed in Table I.

and (80) for ^{20}Ne:

$$S_\alpha(^{20}\mathrm{Ne},J)=G^2(sd^4)(\tfrac{24}{20})^8C^2\langle(80)L\,(80)L\,\|\,(84)\rangle^2,$$

where

$$G^2(sd^4)=\tfrac{315}{8192}\ ,$$

$$C^2=\langle[4](80),[4](80)|\}[44](84)\rangle^2=2.33465$$

(Hecht and Braunschweig[8]) and the last bracket is an SU(3) ⊃ R(3) Clebsch-Gordan coefficient. The resulting values of the pickup spectroscopic factors leading to the various members of the ^{20}Ne g.s. band are given in Table I.

For pickup to core-excited states, SU(3) and angular momentum recoupling techniques are required. These have been described, together with the formulas required for the evaluation of spectroscopic amplitudes, by Anyas-Weiss *et al.*[9] and Hecht[10] and will not be reproduced here. We have calculated pickup amplitudes to 5p-1h, 6p-2h, and 8p-4h states in ^{20}Ne assuming pure strong coupling SU(3) wave functions and to the 8p-4h states assuming weak coupling configurations of the form $[^{12}\mathrm{C}_J\otimes{}^{24}\mathrm{Mg}_{0^+}]^J$. Two low-lying negative parity bands are known in ^{20}Ne, which are believed to have the SU(3) quantum numbers (82) and (90), respectively. The nonspurious (90) state must be written as a linear combination[8] of $p^{-1}sd^5$ and sd^3pf states, i.e.,

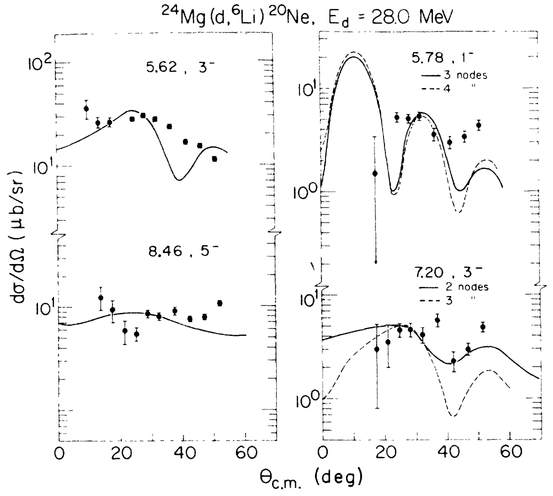

FIG. 5. Same as Fig. 4, but for negative-parity states. The absence of detectable yield at $\theta_{\mathrm{c.m.}}\sim 14°$ for the 5.78-MeV state and the 7.17–7.20 MeV doublet suggests that the former does not have an $L=1$ shape and the latter consists mostly of the 0^+ member.

$$|(90)\,\mathrm{non}\text{-}sp\rangle=(\tfrac{3}{5})^{1/2}p^{-1}sd^5+(\tfrac{2}{5})^{1/2}sd^3pf\,;$$

thus only that fraction of the (90) state which arises from the $p^{-1}sd^5$ configuration (60%) can contribute to the pickup strength. The strongly coupled 6p-2h and 8p-4h states are assumed to carry SU(3) labels (84) and (88), respectively, and these are free from spurious c.m. motion.

The calculations of these spectroscopic amplitudes require, in addition to cfp's for the p and sd shells (tabulated by Jahn and van Wieringen[11] and Hecht and Braunschweig,[8] respectively), SU(3) Racah coefficients for stretched configurations. An analytical formula for these has been given by Hecht.[10] The results for the cases of interest are given in Table I.

We compare in Table II the expected spectroscopic factors for the 7.20-MeV band, assuming 6p-2h and 8p-4h configurations, the latter in both strong coupling and weak coupling.

The remaining states of interest are those in the 6.72-MeV band, which is a mixture of $(\lambda\mu)=(42)$ and (04). The calculated spectroscopic factors for these configurations, and for the g.s. band, have been given by Draayer.[7]

TABLE I. Results of the ^{24}Mg(d, ^{6}Li)^{20}Ne reaction.

E_x (MeV)	J^{π}	K_i^{π}	L	$2(N-1)+L$	S_{α}[a] (exp)	S_{α} (SU$_3$)	($\lambda\mu$)
0.0	0^+	0_1^+	0	8	0.081	0.081	(80)
1.63	2^+	0_1^+	2	8	0.025	0.0102	(80)
4.25	4^+	0_1^+	4	8	0.069	0.0648	(80)
5.62	3^-	2^-	3	7	0.25	0.215	(82)
5.78	1^-	0^-	1	$\underline{7}$;9	($\underline{0.034}$;0.015)	0.030	(90)
7.17	3^-	0^-	3	$\underline{7}$;9	($\underline{<0.06}$;≤0.03)	0.071	(90)
7.20	0^+	0_3^+	0	$\underline{4}$;6;8	$\underline{0.054}$;0.012;0.010	0.0606[b]	(88)
7.42	2^+	0_2^+	0	8	0.054	0.0[c]	(42)
7.84	2^+	0_3^+	2	$\underline{4}$;6;8	$\underline{0.48}$;0.091;0.046	0.0557[b]	(88)
8.46	5^-	2^-	5	7	0.16	0.041	(82)
8.78	6^+	0_1^+	6	8	0.57	0.148	(80)
9.04	4^+	0_3^+	4	$\underline{4}$;6;8	$\underline{1.12}$;0.65;0.18	0.0225[b]	(88)

[a] Present work. Normalized to 0.0806 for the g.s.

[b] See Table II for theoretical spectroscopic factors for other configurations.

[c] For ($\lambda\mu$) = (04), this number is 0.011. The physical state contains comparable admixtures of the two representations.

IV. ANALYSIS AND DISCUSSION

The DWBA calculations were performed with the code DWUCK,[12] using the optical-model and bound-state parameters listed in Table III. No attempt was made to improve the fits by varying these parameters. The DWBA curves are compared with the experimental angular distributions in Figs. 4 and 5. Curves were normalized to the data, and α-particle spectroscopic factors, S, were extracted with the expression

$$\sigma_{\exp}(\theta) = NS\,\frac{\sigma_{\mathrm{DW}}(\theta)}{2J+1}\,,$$

where J is the transferred angular momentum and (here) is equal to the final-state J and to the transferred orbital angular momentum L. For states of reasonably certain configuration the number of quanta was assumed to be given by

$$2(N-1)+L=\sum_{i=1}^{4}[2(n_i-1)+l_i]\,,$$

where $n_i - 1$ and l_i are the quantum numbers of the individual nucleons making up the α particle, and $N-1$ and L are the number of radial nodes and the transferred L value for the α-particle form factor. For other states, a variety of configurations was assumed, and the α quantum numbers were calculated from the above expression.

Angular distributions for the known[13] positive-parity states are displayed in Fig. 4. Resulting spectroscopic factors are listed in Table I. Since the overall normalization factor N is not known, we have normalized the g.s. spectroscopic factor to the theoretical value 0.0806 of Draayer.[7] All other spectroscopic factors are given with this same normalization. (This corresponds to $N = 1.25$.)

TABLE II. Spectroscopic factors for the 7.20-MeV band for various configurations.

		Strong coupling		Weak coupling		
E_x (MeV)	J^{π}	(6p–2h)[a]	(8p–4h)[b]	$^{12}\mathrm{C}_J \otimes {}^{24}\mathrm{Mg}_0$	$^{12}\mathrm{C}_0 \otimes {}^{24}\mathrm{Mg}_J$	Exp[c]
7.20	0^+	0.0255	0.0606	0.194	0.194	0.054
7.83	2^+	0.0054	0.0557	0.972	0	0.476
9.04	4^+	0.0148	0.0225	1.750	0	1.121

[a] ($\lambda\mu$) = (84)

[b] ($\lambda\mu$) = (88)

[c] Assuming pickup of four excitation quanta.

TABLE III. Optical-model parameters. Potentials in MeV, lengths in fm.

Channel	V_0	r_0	a	$W' = 4W_D$	r'_0	a'	r_{0c}
^{6}Li	190	1.05	0.89	47.32	1.95	0.55	2.50
d	105	1.02	0.86	80	1.42	0.65	1.30
bound state	varied	1.90	0.60	...	...	...	1.90

Spectroscopic factors for the 0^+, 2^+, and 4^+ members of the g.s. band are in reasonable agreement with theoretical predictions that assume a pure $(\lambda\mu) = (80)$ configuration in ^{20}Ne and $(\lambda\mu) = (84)$ in ^{24}Mg. They differ considerably from those obtained[5] in a recent study of the ^{24}Mg(d, ^{6}Li) reaction at $E_d = 35$ MeV.

For the 6^+ member of the g.s. band, at 8.78 MeV, both experiment and theory produce a large spectroscopic factor, though the experimental value is much larger. Because in the standard DWBA treatment of a pickup reaction, higher-lying states are more tightly bound, resulting in smaller wave functions at the nuclear surface, high-lying states have quite large spectroscopic factors even for small measured cross sections. Hence competing nondirect processes cause a larger uncertainty in the spectroscopic factors for these states. Nevertheless, experiment and theory agree that the spectroscopic factor for the 6^+ state is large.

The 2^+ state at 7.43 MeV is a member of a rotational band built on the 0^+ state at 6.72 MeV. This band is thought to be dominantly of an excited $(sd)^4$ character. The 0^+ member was too weak in the present experiment to allow an angular distribution to be extracted. For the 2^+ state, assuming $2(N-1)+L=8$, the resulting spectroscopic factor is 0.054. The theoretical 2^+ state with $(\lambda\mu) = (42)$ is predicted to have zero α strength. For $(\lambda\mu) = (04)$, the model strength is 0.011. Since the physical state is dominantly of these two representations, the measured spectroscopic factor is more than 10 times the theoretical one. Thus our results indicate mixing with other configurations, especially (80).

The states at 7.20, 7.84, and 9.03 MeV are the 0^+, 2^+, and 4^+ members of a core-excited 0^+ band. The 0^+ state is not completely resolved from a nearly 3^- level at 7.17 MeV. But the absence of detectable yield for the doublet at angles near 12° (where an $L=0$ shape has a deep minimum) indicates that most of the cross section arises from the 0^+ member of the doublet.

We have performed DWBA calculations for members of this core-excited 0^+ band assuming $2(N-1)+L=4$, 6, and 8—corresponding, respectively, to $(1p)^4$, $(1p)^2(sd)^2$, and $(sd)^4$ pickup. Results for all three assumptions (listed in Table I) show that the spectroscopic factors for all three states are large. They also increase with increasing J, much as what one expects for $^{16}\text{O} \to {}^{12}\text{C} + \alpha$. The very large spectroscopic factors obtained for these states imply that they have a large component of an α hole in the ^{24}Mg (g.s.). The increase of S_α with J and the large absolute values of S_α appear to eliminate a 6p-2h configuration, with $(\lambda\mu) = (84)$, for these states. The measured spectroscopic factors are midway between those predicted for weakly and strongly coupled 8p-4h states. It appears that these states can be well represented as linear combinations of the form

$$^{20}\text{Ne}(J) = \sum_{J_1,J_2} A_{J_1J_2J}\,[^{24}\text{Mg}(J_1) \otimes {}^{12}\text{C}(J_2)]_J \,,$$

but that the linear combination needed to fit the data is not the same as that in the SU(3) representation with $(\lambda\mu) = (88)$.

The large S_α for the 7.84-MeV state, and its nearness to the 7.42-MeV 2^+ state, suggest that the latter probably gets its α-pickup strength by mixing with the former. The mixing needed is less than 10%.

Angular distributions for the negative parity states are displayed in Fig. 5. The 3^- and 5^- members of the 2^- band have quite large spectroscopic factors, consistent with their dominant $(sd)^5(1p)^{-1}$ configuration. As mentioned above, most of the 7.17–7.20-MeV cross section appears to arise from the 0^+ state. We compare the data with $L=3$ curves, showing that a 3^- state should have a measurable cross section near 12°. Nevertheless, even if *all* the cross section for the doublet belongs to the 3^- state, its spectroscopic factor is less than 25% of that for the 3^- state at 5.62 MeV, indicating that mixing between the two is small. The 1^- state at 5.78 MeV is weak and does not have an $L=1$ angular distribution. This, also, is consistent with the assumed configuration for members of the 0^- band.

In summary, we have obtained spectroscopic factors for a number of states in ^{20}Ne below 10 MeV excitation. Results for all states are in reasonable agreement with theory. The 7.42-MeV 2^+ state is stronger than expected in the absence of mixing. Members of the 7.20-MeV 0^+ band and of the 2^- band have very large spectroscopic factors. The 1^- and 3^- members of the 0^- band are very weak. Our results are consistent with previous information regarding the major configurations of all these states.

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