Level Structure of ^{22}Ne by the ^{21}Ne$(d, p)^{22}$Ne Reaction*

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The ^{21}Ne$(d,p)^{22}$Ne reaction has been studied at 12-MeV incident energy. Angular distributions of protons have been extracted for 31 transitions leading to levels in ^{22}Ne up to 9.10-MeV excitation energy. Angular momentum transfers have been identified and spectroscopic factors extracted for 27 levels by comparison with distorted-wave Born-approximation predictions. Experimental spectroscopic factors for the low-lying states have been compared with the predictions of the unified rotational model. The results of the present study indicate that the ground-state rotational band of ^{22}Ne is formed by placing an additional neutron in Nilsson orbit No. 7 ($\frac{3}{2}^+[211]$). Several states have been identified which belong to $K^\pi = 1^+$ and 4^+ bands formed by stripping a neutron to Nilsson orbit No. 5 ($\frac{5}{2}^+[202]$) and to $K^\pi = 1^+$ and 2^+ bands formed by stripping to orbit No. 9 ($\frac{1}{2}^+[211]$).

I. INTRODUCTION

In this paper we present the results of a study of the nucleus ^{22}Ne using the ^{21}Ne$(d,p)^{22}$Ne reaction. This work was undertaken in order to complement the information from the ^{18}O(^{7}Li, t)^{22}Ne α-transfer reaction on the nuclear structure of ^{22}Ne.[1,2]

Rather limited spectroscopic information exists on the states of ^{22}Ne. Excitation energies are known with ±15-keV precision from a study of the ^{20}Ne$(t,p)^{22}$Ne reaction using a magnetic spectrograph.[3] Spins are known for selected levels below 6.70 MeV from a study of the angular correlations of deexcitation γ rays in the ^{19}F$(\alpha,p\gamma)^{22}$Ne reaction.[4-6] Three high-spin levels in ^{22}Ne above the neutron decay threshold which include the $J^\pi = 8^+$ member of the ground-state rotational band have also been studied utilizing γ-ray angular correlations following the ^{19}F$(\alpha,p\gamma)^{22}$Ne reaction.[7] Recently, the ^{21}Ne$(d,p)^{22}$Ne reaction has been investigated and parity assignments have been made to levels up to 6.70 MeV.[8] Additional information regarding spin and parity combinations is available for levels below 6.70 MeV from a study of the inelastic α scattering on ^{22}Ne[9] and for levels below 5.15 MeV from a study of the ^{23}Na$(d,{}^3$He$)^{22}$Ne pickup reaction.[10] Lastly, information regarding spins and parities of states in ^{22}Ne that are strongly excited by the ^{18}O(^{7}Li, t)^{22}Ne α-transfer reaction is also available.[1,2]

Since the early work of the Chalk River group[11,12] a large body of evidence has been accumulated which indicates nuclei in the lower half of the $2s$-$1d$ shell to be strongly deformed. In particular, the marked prolate deformation of the isotopes of Ne has been established recently through measurements of static quadrupole moments of the first excited states of ^{20}Ne and ^{22}Ne.[13,14] In view of the large deformations, these nuclei are expected to show pronounced collective behavior. The success of the collective model for ^{20}Ne has already been well demonstrated.[15,16] The nuclear structure of ^{22}Na, the isobar to ^{22}Ne, has also been investigated in the framework of the collective model.[17,18]

The present study of the ^{21}Ne$(d,p)^{22}$Ne reaction was undertaken using a gas target enriched in ^{21}Ne. The angular distributions of the outgoing deuterons have been compared with distorted-wave Born-approximation (DWBA) predictions and values for the angular momentum transfers l_n and the spectroscopic factors S_{lj} have been extracted from the experimental data. The resulting information on the nuclear structure of ^{22}Ne has been discussed in the framework of the Nilsson model.[19]

II. EXPERIMENTAL PROCEDURE AND RESULTS

The ^{21}Ne$(d,p)^{22}$Ne reaction was studied with a 12-MeV d^+ beam from the University of Pennsylvania tandem Van de Graaff accelerator. The reaction products were momentum-analyzed with the University of Pennsylvania multiangle magnetic spectrograph. Proton spectra were simultaneously recorded at 11 angles, varying from $7\frac{1}{2}$ to $82\frac{1}{2}°$ in $7\frac{1}{2}°$ steps, on Ilford K5 plates of 50-μ emulsion thickness. 15-mil-thick Mylar absorbers were used in front of the plates to stop elastically scattered deuterons. The enriched target gas, comprising 86.5% ^{21}Ne, 11.8% ^{20}Ne, and 1.7% ^{22}Ne, was contained in a rotating gas cell.[20] The pressure of the gas within the cell was initially read with a mechanical pressure gauge, and was continuously monitored during the exposure with the help of the deuteron elastic scattering spectrum recorded with a solid-state surface-barrier de-

tector at 15° scattering angle. The experiment was carried out at a mean gas pressure of 26.0 Torr.

Figure 1 shows a proton energy spectrum measured at 15° (lab). The numbers adjacent to the peaks refer to the level numbering of Table I. Contaminant groups resulting from ^{20}Ne, ^{22}Ne, and ^{16}O impurities in the target are labeled using the corresponding level energy in the residual nuclei ^{21}Ne, ^{23}Ne, and ^{17}O. 31 states, up to 9.10-MeV excitation energy in ^{22}Ne, are seen in this experiment. The doublets at 5.34 and 7.65 MeV are clearly resolved. In addition, the present experiment located a pair of levels at 8.55- and 8.59-MeV excitation energy. Previously, only a single level had been reported at 8.57 MeV.[3] The full width at half maximum of the proton groups is 25 keV. The excitation energies corresponding to the labeled groups of Fig. 1 are listed in the second column of Table I. The errors associated with these numbers are estimated to be less than ±10 keV. The first column lists excitation energies previously obtained by a study of the ^{20}Ne$(t,p)^{22}$Ne reaction with a magnetic spectrograph.[3] No attempt was made to extract excitation energies corresponding to the extremely weakly excited groups labeled 9, 14, and 35, nor the group labeled 11 which is obscured by a contaminant. No transition leading to the 6.90-MeV excited state corresponding to level number 17 was observed. This state has been seen only in the ^{18}O(^{7}Li, t)^{22}Ne reaction.[2]

Angular distributions of protons leading to 31 states in ^{22}Ne are shown in Figs. 2 to 5. The error bars are statistical only. Errors in measured cross sections are estimated to be less than ±20% and are attributable to uncertainties in beam-current integration and target gas pressure measurements. Transitions leading to the ground state and the states at 5.92, 6.24, 6.70 and 8.97 MeV were too weak for the extraction of angular distributions. The distribution of protons leading to the state at 8.39 MeV could not be extracted for more than the three smallest angles owing to the

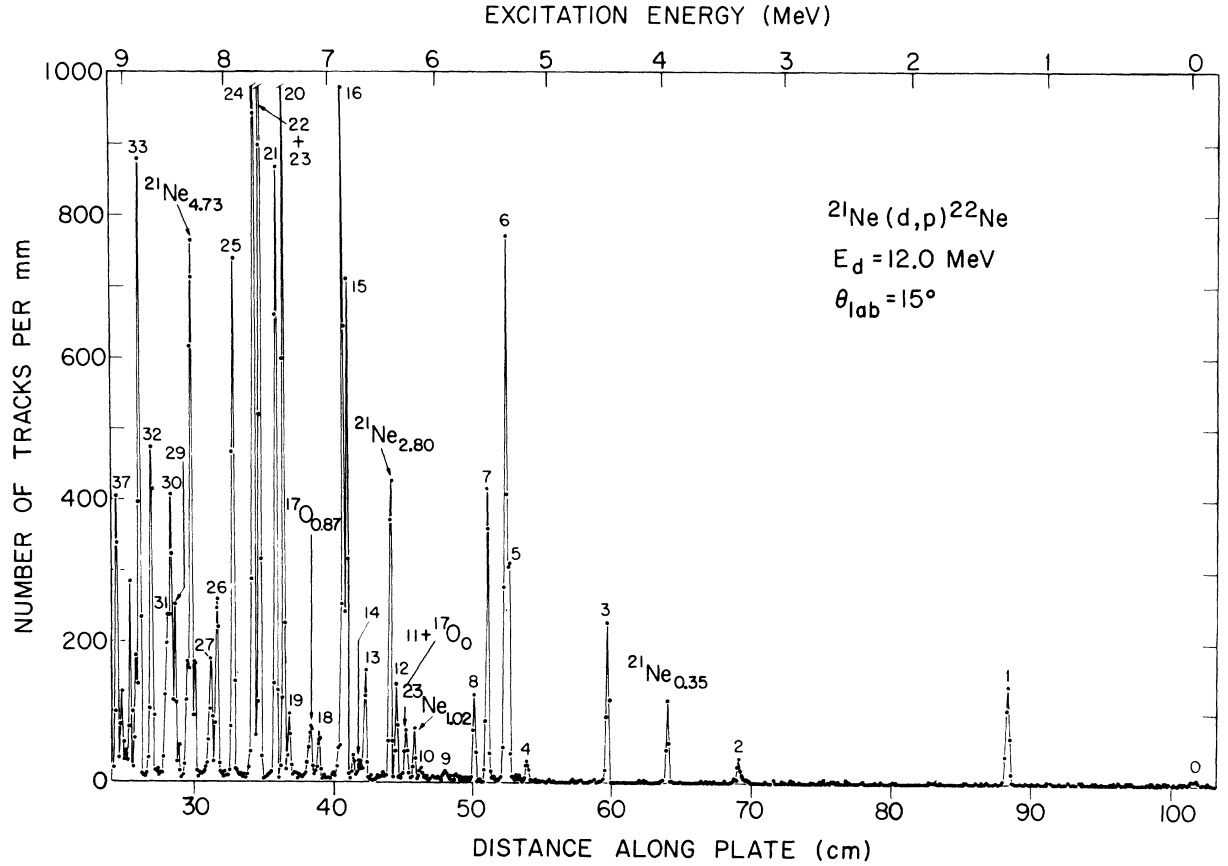

FIG. 1. Proton energy spectrum for the reaction ^{21}Ne$(d,p)^{22}$Ne at a bombarding energy of 12.0 MeV and a laboratory angle of 15°. The numbers adjacent to the peaks refer to the level numbering of Table I. Contaminant groups are identified by the level energy of the corresponding residual nucleus.

presence of impurity groups arising from ^{20}Ne in the target, and hence is not shown. The solid curves shown are DWBA predictions calculated with the code DWUCK.[21] No acceptable fits could be found for the angular distributions of protons leading to the states at 5.15, 6.12, 6.35 and 9.04 MeV (Fig. 5). The transitions are in general weak and appear to proceed via a nondirect mechanism.

III. ANALYSIS

The angular distributions of the outgoing protons were compared with DWBA predictions calculated with the code DWUCK.[21] l_n values and spectroscopic factors were extracted from the experimental cross sections using the expression

$$\sigma_{\exp}(\theta) = 1.53 \frac{2J_f+1}{2J_i+1} \sum_{nlj} S_{nlj} \frac{\sigma_{nlj}(\theta)}{2j+1} .$$

J_i and J_f are the total angular momenta of the ground state of the target nucleus and the residual state, respectively. The spectroscopic factor S_{nlj} measures the overlap between the residual nuclear state and the one formed by vector coupling the transferred neutron to the ground state of the target nucleus. $\sigma_{nlj}(\theta)$ is the differential cross section for the absorption of a neutron with quantum numbers n, l, and j calculated by the code DWUCK. The factor of 1.53 is associated with the use of a Hulthén wave function for the

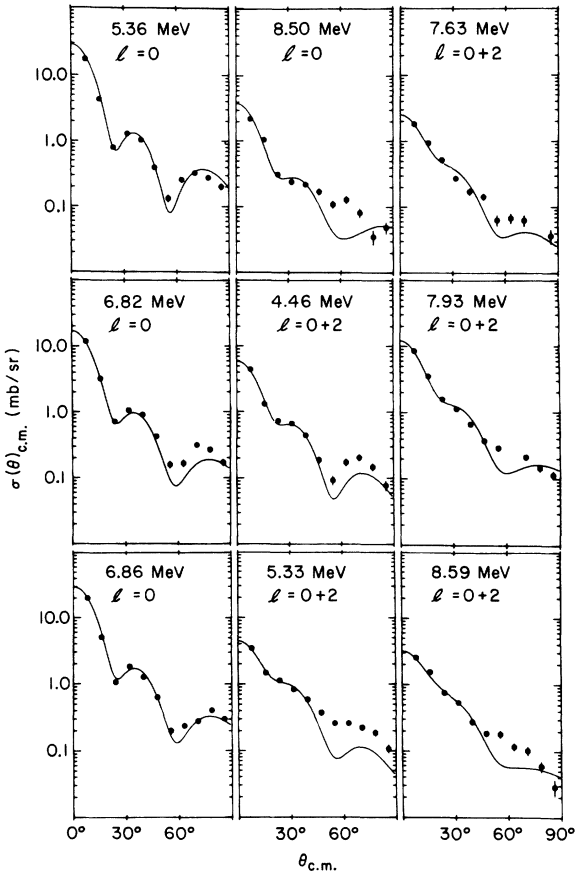

FIG. 2. Proton angular distributions from the ^{21}Ne-$(d,p)^{22}$Ne reaction exhibiting pure $l_n=0$ and $l_n=0+2$ admixed character, respectively. The solid curves are DWBA predictions for stripping of the neutron to the $2s_{1/2}$ and the $2s_{1/2}+1d_{5/2}$ orbits, respectively.

TABLE I. Results of the ^{21}Ne$(d,p)^{22}$Ne reaction. Spin and parity assignments for the states below 6 MeV and the 6.82-6.86-MeV doublet are discussed in the text. For assignments for the remaining states see Ref. 2.

Level No.	E_x (MeV) (Ref. 3) [a]	E_x (MeV) Present work [b]	l_n	$(2J+1)S$	J^π
g.s.	0.000	0.000	2	≤0.20	0^+
1	···	1.275	2	3.25	2^+
2	3.343	3.358	2	0.44	4^+
3	4.473	4.458	0+2	0.27+0.72	2^+
4	5.139	5.152 [c]			2^-
5	5.340	5.331	0+2	0.15+1.40	$(1)^+$
6		5.359	0	1.56	$(2)^+$
7	5.520	5.516	2	2.26	4^+
8	5.633	5.638	2	0.49	3^+
9	5.917	···			2^+
10	6.117	6.120 [c]			
11	6.242	···			0^+
12	6.349	6.350 [c]			6^+
13	6.647	6.644	2	0.72	+
14	6.696	···			
15	6.823	6.821	0	0.92	2^+
16	6.860	6.858	0	1.65	$(1)^+$
17	···	6.90 [d]			0^+
18	7.047	7.055	1	0.054	1^-
19	7.331	7.341	2	0.35	0^+
20	7.402	7.402	1	0.67	−
21	7.484	7.488	1	0.66	1^-
22	7.633	7.630	0+2	0.12+0.41	2^+
23	7.663	7.658	1	0.71	−
24	7.720	7.722	1	0.83	3^-
25	7.913	7.927	0+2	0.63+0.72	+
26	8.071	8.079	2	0.53	+
27	8.122	8.141	2	0.59	2^+
28	8.368	8.387 [e]			
29	8.488	8.504	0	0.24	+
30	8.575	8.548	2	0.84	+
31		8.585	0+2	0.16+0.51	2^+
32	8.724	8.736	1	0.43	−
33	8.844	8.859	2	1.44	+
34	8.890	8.903	1	0.095	−
35	8.970	···			
36	9.034	9.042 [c]			
37	9.069	9.097	1	0.31	−

[a] ^{20}Ne$(t,p)^{22}$Ne reaction, estimated error ±15 keV.
[b] ^{21}Ne$(d,p)^{22}$Ne reaction, estimated error ±10 keV.
[c] No stripping.
[d] Observed in ^{18}O(^{7}Li, t)^{22}Ne reaction only (Ref. 2).
[e] Obscured by impurity group.

deuteron.

The optical-model parameters used in the DWBA calculations are listed in Table II. The values for the entrance channel were taken similar to those derived from detailed analysis of deuteron elastic scattering from nuclei around mass number 40 (Yntema and Satchler[22] and Bassel[23]). Optical-model parameters for the exit channel were calculated using parametric expressions derived from proton elastic scattering measurements from $1p$-shell nuclei.[24] The bound-state wave function was computed for a neutron in a Woods-Saxon potential with a radius parameter of 1.26 fm and a diffuseness of 0.60 fm. A Thomas spin-orbit strength of $\lambda = 25$ was used. The well depth was adjusted to give the neutron a binding energy of $B = [2.224 + Q(d,p)]$ MeV.

The fits to the experimental data shown in Figs. 2 to 4 were computed in the zero-range, local interaction approximation (ZRL). No lower cutoff was used in the radial integration. Cross sections for selected states were also computed by doing a finite-range, nonlocal interaction (FRNL) calculation using the appropriate options of the code DWUCK. The finite range parameter chosen was 0.621, and nonlocal range parameters used were, respectively, 0.85, 0.85, and 0.54 for protons, neutrons, and deuterons. The predicted angular distribution shapes were found to be very similar for both the ZRL and the FRNL calculations. However, peak cross sections computed with FRNL corrections were found to be on the average about 15% higher than those computed in the ZRL approximation.

Evidence was found for $l_n = 0$ and 2 admixtures for the transitions leading to the states at 4.46, 5.33, 7.63, 7.93, and 8.59 MeV (Fig. 2). The percentage admixture was determined by a χ^2-minimization program that tested the goodness of fit to the experimental points with composite DWBA predictions. The angular distribution of protons leading to the 1.28-MeV state (Fig. 4) was tested for an $l_n = 0$ admixture. Such an admixture, if at all present, is found to be less than 10%. No significant $l_n = 2$ admixtures appear to be present in the $l_n = 0$ transitions to the states at 5.36, 6.82, 6.86, and 8.50 MeV (Fig. 2). Such admixtures would be difficult to detect and an upper limit of 20% of the corresponding $l_n = 0$ spectroscopic factor has been assumed for the $l_n = 2$ spectroscopic

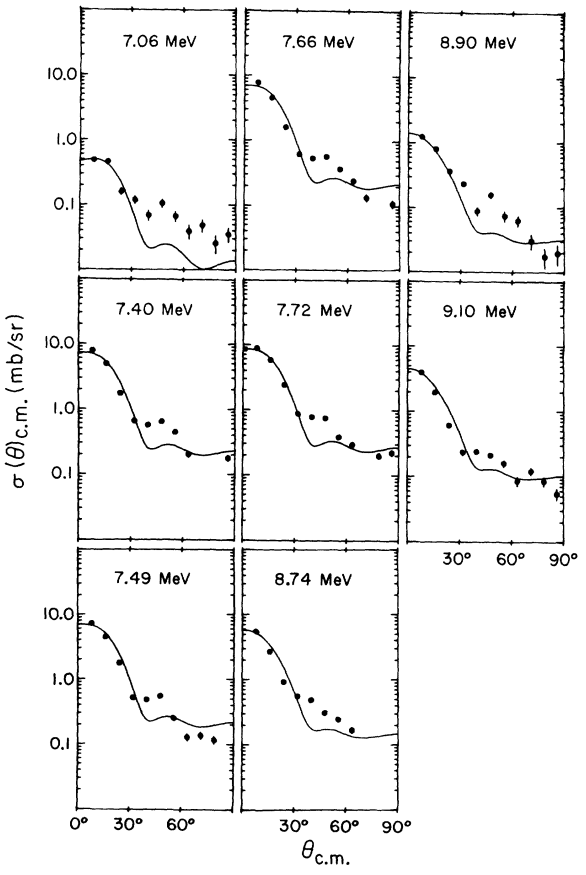

FIG. 3. Proton angular distributions from the ^{21}Ne-$(d,p)^{22}$Ne reaction exhibiting pure $l_n = 1$ character. The solid curves are DWBA predictions for stripping of the neutron to the $2p_{3/2}$ orbit.

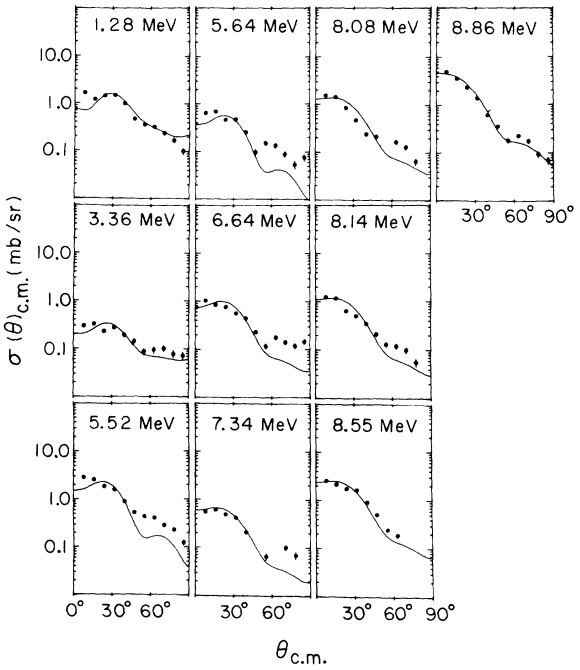

FIG. 4. Proton angular distributions from the ^{21}Ne-$(d,p)^{22}$Ne reaction exhibiting pure $l_n = 2$ character. The solid curves are DWBA predictions for stripping of the neutron to the $1d_{5/2}$ orbit.

factor in the discussion. No evidence was found for significant $l_n = 3$ admixtures in the angular distributions showing predominantly $l_n = 1$ shapes (Fig. 3).

Spectroscopic factors extracted with DWBA calculations in the ZRL approximation are listed in Table I. Cross sections for the $l_n = 2$ transitions were calculated for the $1d_{5/2}$ neutron configuration, because low-lying states reached by $l_n = 2$ transitions are expected to be based predominantly on Nilsson states originating from the $1d_{5/2}$ orbit. Spectroscopic factors extracted assuming the $1d_{3/2}$ configuration would be 20–30% higher. Cross sections for the $l_n = 1$ transitions were calculated for the $2p_{3/2}$ neutron configuration. Spectroscopic factors extracted for the $1p_{1/2}$ configuration would be as much as 2.5 times higher. Spectroscopic factors for the $l_n = 0$ transitions were extracted assuming the transfer of a $2s_{1/2}$ neutron. Errors in the measured spectroscopic factors are estimated to be less than ±50%. They are attributed to errors in the measured absolute cross sections as well as uncertainties associated with the choice of the optical-model parameters and of the proper configuration of the transferred neutron in a deformed well.

The possible spin and parity combinations of levels excited by $l_n = 0$, 1, and 2 transitions in the ^{21}Ne$(d,p)^{22}$Ne reaction are listed in Table III. Of the spin assignments indicated in Table I, those corresponding to states below 6 MeV and to the 6.82-6.86-MeV doublet are discussed in Sec. IV. The remaining assignments have been made from the combined results of the ^{18}O$(^7$Li$, t)^{22}$Ne reaction study and the present experiment, and have been discussed elsewhere.[2]

Information regarding the filling of the ^{22}Ne configurations via the ^{21}Ne$(d,p)^{22}$Ne reaction can be obtained from the (d,p) sum rule,[25]

$$\sum[(2J_f+1)/(2J_i+1)]S_{nlj} = N_{nlj},$$

where N_{nlj} is the number of neutron holes in the nlj shell orbital of the target nucleus and the sum extends over all states with the same nlj. Experimentally, up to 9.10-MeV excitation energy the spectroscopic strength $\sum(2J_f+1)S_{nlj}$ is found to be 14.87 for $l_n = 2$ transitions and 5.70 for $l_n = 0$ transitions. In the independent-particle spherical shell model, one assumes that the ^{21}Ne ground-state configuration has three neutron holes in the $1d_{5/2}$ orbit, whereas the $2s_{1/2}$ and higher levels are completely empty. Thus the predicted $l_n = 2$ and $l_n = 0$ strengths leading to the $1d_{5/2}$ and $2s_{1/2}$ orbits are 12 and 8, respectively. Although concepts regarding the filling of shell-model orbitals are not strictly applicable for deformed nuclei and some of the $l_n = 2$ strength is presumably due to transitions leading to the $1d_{3/2}$ configuration, one is probably justified in assuming that essentially most of the $1d_{5/2}$ and $2s_{1/2}$ strength has been located in the present experiment.

The spectroscopic strength measured for $l_n = 1$ transitions leading to states up to 9.10-MeV excitation energy is 3.76 assuming a $2p_{3/2}$ configuration for the transferred neutron. This value would be approximately 2.5 times higher if a $1p_{1/2}$ configuration is assumed. Thus most if not all of the observed $l_n = 1$ strength is due to transitions leading to the $2p_{3/2}$ configuration. The sum-rule prediction for this configuration is 16 which is far from being exhausted by the states studied in the present experiment.

Hecht and Satchler[26,27] have given a prescription for calculating spectroscopic factors for single-nucleon-pickup and stripping reactions on deformed nuclei in a model in which a single nucleon is coupled to an inert core of well stabilized deformed equilibrium shape. Assuming no band mixing, the expression for the spectroscopic factor corresponding to stripping of a single nucleon on an odd-A target is

$$S_{nlj} = g^2[(2J_i+1)/(2J_f+1)]\langle J_i\, j \pm K_i (K_f \mp K_i) | J_f K_f\rangle^2 \times c_{j\Omega}{}^2 \delta(|\Omega|, |K_f \mp K_i|)\langle f | i\rangle^2,$$

where $g = \sqrt{2}$ if K_i or $K_f = 0$, and $g = 1$ otherwise $\langle f | i\rangle$ is the overlap between initial and final vibra-

TABLE II. Optical-model parameters used in the DWBA analysis of the ^{21}Ne$(d,p)^{22}$Ne reaction. The potential used was $U(r) = V_c(r, r_{0c}) - Vf(r, r_0, a) + i4a' W_D[df(r, r'_0, a')/dr] + \vec{\sigma}\cdot\vec{l}\,(\hbar/m_\pi c)^2 (V_{so}/r)[df(r, r_0, a)/dr]$, where $f(r, r_0, a) = \{1 + \exp[(r - r_0 A^{1/3})/a]\}^{-1}$ is the usual Woods-Saxon form factor. For references, see text.

Channel	V (MeV)	W_D (MeV)	V_{so} (MeV)	r_0 (fm)	a (fm)	r'_0 (fm)	a' (fm)	r_{0c} (fm)
$d + ^{21}$Ne	105	17.0	6.0	1.02	0.86	1.42	0.65	1.30
$p + ^{22}$Ne	a	b	5.5	c	0.57	c	0.50	c

[a] $V = 60.0 + 0.4\,(Z/A^{1/3}) + 27.0\,\{(N-Z)/A\} - 0.3E_{c.m.}$.
[b] $W_D = 0.64\,E_{c.m.} + 10.0\,(N-Z)/A$ for $E_{c.m.} < 13.8$ MeV
$= 9.60 - 0.06\,E_{c.m.} + 10.0\,(N-Z)/A$ for $E_{c.m.} \geq 13.8$ MeV.
[c] $r_0 = r'_0 = r_{0c} = 1.15 - 0.001\,E_{c.m.}$.

tional states, and is usually assumed as unity for relatively small excitation energies. The $c_{j\Omega}$ are coefficients of expansion of the single-particle Nilsson wave function in a spherical basis.[19] Since the experiment does not distinguish between different j values, the predicted spectroscopic factors have to be summed over j before a comparison with the experiment can be made. The coefficients $c_{j\Omega}$ were calculated by diagonalizing the Nilsson Hamiltonian in the $|j\Omega\rangle$ representation.[28] A spin-orbit strength $C=-0.26\ \hbar\omega_0$ and a well-flattening parameter $D=-0.035\ \hbar\omega_0$ were used in the calculation. These appear to be better values for light nuclei than those used by Nilsson.[29,30] A comparison of the experimentally determined spectroscopic factors for the low-lying levels and those predicted by the Nilsson model is presented in the next section.

IV. DISCUSSION

In the unified collective model[19] the ground state of ^{21}Ne is obtained by placing the odd neutron in Nilsson orbital No. 7 with $K^\pi=\frac{3}{2}^+$ and

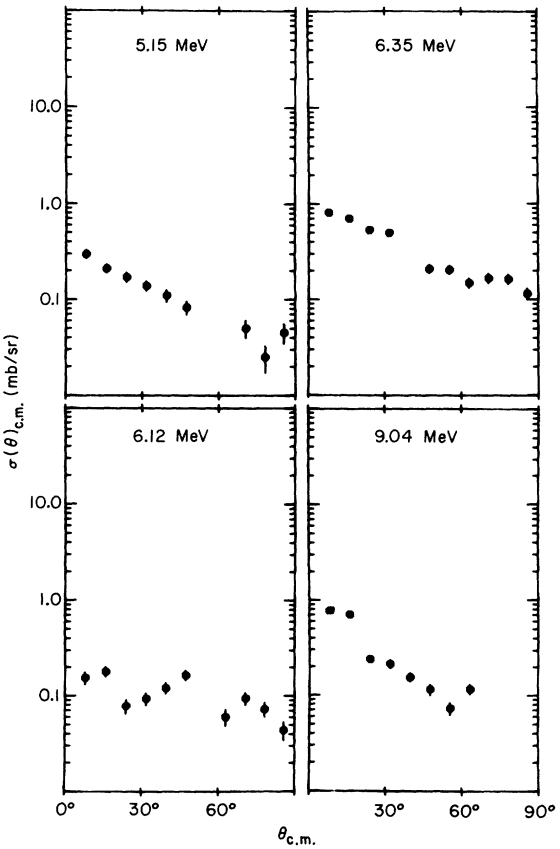

FIG. 5. Proton angular distributions from the ^{21}Ne-$(d,p)^{22}$Ne reaction not exhibiting characteristics of direct reactions.

TABLE III. Possible spin-parity combinations for states excited by the ^{21}Ne$(d,p)^{22}$Ne reaction.

l_n	J^π
0	1^+, 2^+
0+2	1^+, 2^+
2	0^+, 1^+, 2^+, 3^+, 4^+
1	0^-, 1^-, 2^-, 3^-

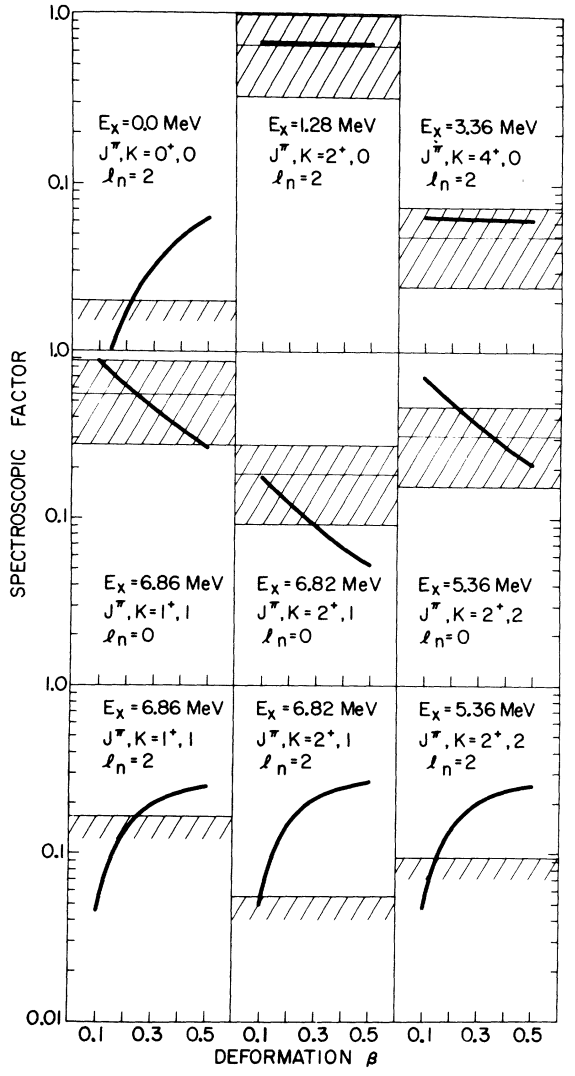

FIG. 6. Comparison of predicted and measured spectroscopic factors for low-lying states in ^{22}Ne excited by the ^{21}Ne$(d,p)^{22}$Ne reaction. The horizontal lines across the individual figures represent experimental values and the shaded areas indicate estimated errors. The curves are the predictions of the rotational model plotted as a function of the nuclear deformation. The top row depicts levels originating from the neutron transfer to Nilsson orbit No. 7 ($\frac{3}{2}^+$[211]) and the calculations in the middle and bottom rows are for levels resulting from neutron transfer to orbit No. 9 ($\frac{1}{2}^+$[211]).

$[Nn_z\Lambda] = [211]$, where prolate deformation has been assumed. Considering only pure configurations, the intrinsic state corresponding to the ground-state rotational band of ^{22}Ne obtained by neutron transfer on ^{21}Ne is formed by placing an additional neutron into the $\frac{3}{2}^+[211]$ level. The lowest excited positive-parity intrinsic configurations in ^{22}Ne are reached by placing the additional neutron into Nilsson orbit No. 9 ($\frac{1}{2}^+[211]$), resulting in $K^\pi = 1^+$ and 2^+ bands, or Nilsson orbit No. 5 ($\frac{5}{2}^+[202]$), resulting in $K^\pi = 1^+$ and 4^+ bands. Although the assumption of pure configurations represents an oversimplification, spectroscopic factors were calculated as indicated in the previous section for the states belonging to the above mentioned rotational bands. The theoretical predictions have been plotted as functions of the deformation parameter and are compared with experimental results in Fig. 6. The measured spectroscopic factors are depicted as horizontal lines, the estimated experimental uncertainties are indicated by the shaded regions.

The top row of Fig. 6 compares theoretical predictions with experimental results for the 0^+, 2^+, and 4^+ members of the ground-state rotational band in ^{22}Ne at 0.0, 1.28, and 3.36 MeV. The transition to the ground state of ^{22}Ne was too weak for the extraction of a precise spectroscopic factor, and the line marked S_{exp} only indicates an upper limit to the experimental spectroscopic factor. The agreement between experimental results and theoretical predictions is well within experimental limits for a reasonable range of deformations, indicating that the configuration for the ground-state rotational band in ^{22}Ne is essentially that of a neutron pair in orbit No. 7. The second 2^+ level at 4.46 MeV has been interpreted as the band head of the lowest $K^\pi = 2^+$ rotational band.[1,4] This would seem to require placing the transferred neutron level into Nilsson orbit No. 9. However, although this configuration yields agreement between measured and predicted values of the $l_n = 2$ strength, the predicted $l_n = 0$ strength appears to be grossly exaggerated (see for comparison the calculation for the 5.36-MeV state on Fig. 6). Thus significant configuration and band mixing appears to be present among the ^{22}Ne excited states.

Because of the $2s_{1/2}$ parentage of Nilsson orbit No. 9, the 1^+ and the two 2^+ states based on this configuration will exhibit strong $l_n = 0$ spectroscopic factors. Conversely, orbit No. 5 has a pure $1d_{5/2}$ parentage independent of the deformation, and the 1^+ and the 2^+ state arising from it should be populated by pure $l_n = 2$ transfers. Experimentally, the three strongest $l_n = 0$ transfers lead to the states at 5.36, 6.82, and 6.86 MeV. Of these, the 6.82-MeV state has been assigned 2^+ from the results of ^{18}O(^{7}Li, t)^{22}Ne α-transfer reaction.[2] In the same experiment,[2] the 5.36-MeV state is populated with average strength allowing for natural parity and therefore 2^+, consistent with the observed triton angular distribution, whereas the 6.86-MeV state does not seem to be excited favoring unnatural parity and consequently a 1^+ assignment. It is, therefore, likely that the probable 1^+ and 2^+ states at 6.86 and 6.82 MeV and the probable 2^+ state at 5.36 MeV are to be associated with the $K^\pi = 1^+$ and 2^+ bands resulting from the coupling of Nilsson orbit No. 9 to orbit No. 7. Theoretical predictions calculated with this assumption are compared with the experimental data in the last two rows of Fig. 6. The agreement between calculated and experimental $l_n = 0$ strengths is quite satisfactory.

The $l_n = 2$ strengths for the transitions leading to the 5.36-, 6.82-, and 6.86-MeV states could not be extracted from the experimental data because of the predominance of the $l_n = 0$ strength. An upper limit of 30% (allowing for a 50% error) of the corresponding $l_n = 0$ strengths has been assumed for the experimental $l_n = 2$ strengths which is reasonably consistent with the theoretical expectations (Fig. 6).

If the above assignments are correct, the dominant configuration for the remaining as yet unassigned low-lying excited states is probably a neutron in Nilsson orbit No. 5 coupled to the neutron in orbit No. 7. Since orbit No. 5 has a pure $|j\Omega\rangle = |\frac{5}{2}\frac{5}{2}\rangle$ configuration the calculated spectroscopic factor has no $l_n = 0$ component, and does not depend on the deformation. The predicted values for the 1^+, 2^+, and 3^+ members of the resulting $K^\pi = 1^+$ rotational band are 0.67, 0.28, and 0.07, respectively. For the 4^+ members of the $K^\pi = 1^+$ and $K^\pi = 4^+$ bands, arising out of the configuration indicated above, one obtains 0.008 and 0.44, respectively.

The measured $l_n = 2$ strength for the 2^+ state at 4.46 MeV is 0.14 which is reasonably close to the value given above. The 5.33-MeV level is excited by a combination of $l_n = 0$ and 2 transitions indicating positive parity and spin 1 or 2. The fact that the 5.33-MeV state does not appear to be populated in the ^{18}O(^{7}Li, t)^{22}Ne reaction[2] favors unnatural parity and therefore 1^+. If spin 1 is assumed, the experimental $l_n = 2$ strength becomes 0.47, in rather close agreement with the value calculated above for the 1^+ band head based on orbit No. 5. The observation of small $l_n = 0$ admixtures in the transitions to the 4.46- and 5.33-MeV states indicates that configuration mixing is present to some extent.

The level at 5.64 MeV has been assigned spin 2 or 3 by Kutschera, Pelte, and Schrieder,[6] and

was found to have unnatural parity.[9] It is excited by an $l_n = 2$ transition in the present reaction, indicating an assignment of 3^+. This 3^+ state at 5.64 MeV is a likely candidate for being the 3^+ member of the $K^\pi = 1^+$ band arising from orbit No. 5; both the experimental and the predicted spectroscopic factors are 0.07. However, reasonable agreement is also possible by assigning this state as the 3^+ member of the $K^\pi = 2^+$ band based on orbit No. 9.

The level at 5.52 MeV has been assigned a spin value between 3 and 6 from the results of the ^{19}F-$(\alpha, p\gamma)^{22}$Ne angular-correlation study.[6] It was excited by a pure $l_n = 2$ transition in the present experiment, restricting the spin and parity assignment to 3^+ or 4^+. Only the last assignment is acceptable in view of the fact that the level has been found to have natural parity in the α scattering experiment on ^{22}Ne.[9] The large $l_n = 2$ strength observed for the transition leading to the state at 5.52 MeV suggests that it is also based on Nilsson orbit No. 5, the experimental value of 0.25 favoring the identification of this state with the $K^\pi = 4^+$ band head.

Of the remaining states below 6 MeV the 5.15-MeV state has been assigned 2^- (Refs. 9, 10) and the 5.92-MeV state is found to be 2^+ from the combined results of Refs. 6 and 9.

By assigning a dominant $K^\pi = 1^+$ component based on orbit No. 5 to the 2^+, 1^+, and 3^+ states at 4.46, 5.33, and 5.64 MeV, the usual level ordering of a rotational band becomes reversed. However, $K = 1$ bands can be decoupled[31] with a consequent reduction and perhaps even inversion of the usual rotational level spacing and ordering. In addition, because of the proximity of other 2^+ states the 4.46-MeV level can be further depressed by Coriolis interaction. It has also been suggested,[8] to identify the 4.46-MeV state with the band head of the $K^\pi = 2^+$ band based on orbit No. 9, and the 5.33-5.36-MeV doublet with the 1^+ and 2^+ members of the $K^\pi = 1^+$ band based on the same orbit. However, the agreement between experimental and calculated strengths assuming this configuration is relatively poor. This becomes especially evident in view of the additional information available from the 5.33-5.36-MeV doublet which has been resolved in the present experiment. Extensive configuration mixing would be required in order to bring the calculated and the experimental strengths into agreement with each other. Spectroscopic strengths have also been calculated in the independent-particle shell model.[32] The agreement between experimental and calculated values is satisfactory for the members of the ^{22}Ne ground-state rotational bands. For the higher excited states, only strengths for selected transitions were available from the published data, and no attempt was made to assign theoretical counterparts to the levels discussed above.

V. CONCLUSIONS

The picture of ^{22}Ne that emerges from the results of the present reaction study is that of a strongly deformed nucleus with several low-lying rotational bands. By comparing measured spectroscopic factors with those predicted on the basis of a simple model assuming pure Nilsson configurations with no band mixing, it is possible to identify several states as members of these low-lying rotational bands. Thus, spectroscopic factors extracted for transitions leading to the three lowest levels in ^{22}Ne are in good agreement with those predicted for the 0^+, 2^+, and 4^+ members of the $K^\pi = 0^+$ ground-state rotational band. In addition, it has been suggested that the 2^+, 1^+, and perhaps the 3^+ state at 4.46, 5.33, and 5.64 MeV have predominantly the configuration of a neutron in Nilsson orbit No. 5 ($\frac{5}{2}^+[202]$) coupled to a neutron in orbit No. 7 ($\frac{3}{2}^+[211]$) forming a $K^\pi = 1^+$ band. The $K^\pi = 4^+$ band head resulting from these two configurations has been identified as the 5.52-MeV 4^+ state. The level ordering observed for the members of the $K^\pi = 1^+$ band indicates the presence of configuration mixing. The results of the present experiment also suggest that the 2^+ state at 5.36 MeV and the 1^+ and 2^+ pair at 6.86 and 6.82 MeV are, respectively, based primarily on the $K^\pi = 2^+$ and the $K^\pi = 1^+$ band resulting from the coupling of a neutron in Nilsson orbit No. 9 ($\frac{1}{2}^+[211]$) to one in orbit No. 7 ($\frac{3}{2}^+[211]$).

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Rotational Bands in ^{22}Ne Excited by the ^{18}O(^{7}Li, t)^{22}Ne Reaction*

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The ^{18}O(^{7}Li,t)^{22}Ne reaction has been studied at 12-MeV incident energy. Angular distributions have been extracted for 22 triton groups leading to states in ^{22}Ne up to 8.59 MeV in excitation energy. The experimental angular distributions have been compared with the predictions of the Coulomb-distorted plane-wave model. L values have been assigned and relative α-cluster widths have been extracted for the strong transitions. Significant α clustering has been observed for 10 states in ^{22}Ne between 6.24- and 8.59-MeV excitation energy. Spin and parity assignments have been made to these states from the combined results of the ^{18}O(^{7}Li,t)-^{22}Ne and ^{21}Ne(d,p)^{22}Ne reaction. The classification of the α-cluster states into rotational bands has been discussed within the framework of the SU(3) model.

I. INTRODUCTION

This paper describes an investigation of ^{22}Ne using the ^{18}O(^{7}Li, t)^{22}Ne reaction. In recent years the (^{7}Li, t) reaction has been used extensively to populate α-cluster states in light nuclei.[1-9] The available experimental evidence indicates that, especially for nuclei at the beginning of the 2s-1d shell, the dominant reaction process for the strong transitions at intermediate bombarding energies is the direct transfer of an α cluster with zero spin and isospin.[2-9] It has also been demonstrated that a plane-wave direct-reaction model which incorporates Coulomb distortions and the relative p-state nature of the α-plus-triton clusters in the ^{7}Li projectile, can give a good description of the shape of the angular distributions and the kinematic dependence of the cross sections.[6] The success of the direct-reaction plane-wave model allows the (^{7}Li, t) reaction to be used as a useful spectro-