Study of 5.69- and 5.78-MeV states in ^{21}Ne through the ^{20}Ne$(d,p)^{21}$Ne reaction

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We have investigated the states in ^{21}Ne at 5.69 and 5.78 MeV through the ^{20}Ne(d,p) reaction at 3.6 MeV. Distorted-wave Born-approximation (DWBA) fits have been performed for the angular distributions of these states; they indicate $l=1$ and 0 for the 5.69- and 5.78-MeV levels, respectively. Spectroscopic factors have been extracted. The correspondence between the states and their analog states in ^{21}Na is discussed.

[NUCLEAR REACTIONS ^{20}Ne(d,p), $E=3.6$ MeV measured $\sigma(\theta)$; ^{21}Ne levels deduced l, J, π, S.]

The many studies which have been performed recently on the ^{21}Ne nucleus[1] suggest that this nucleus is among the most rigidly deformed in nature. Thus, its static and dynamical properties can be well explained by the Bohr-Mottelson and Nilsson models.[2] However this general agreement has been proved for the lower excited states only and it is now interesting to see if this agreement can be extended to states of higher energy. In recent studies[3-7] of the ^{20}Ne$(d,p)^{21}$Ne reaction, angular distributions were reported for the states at $E_x \leq 6.61$ MeV of ^{21}Ne. But the proton energy resolution obtained in these studies did not allow a complete resolution of all the proton groups. In the present work, we study two states of relatively high energy: 5.69 and 5.78 MeV, but of simple structure, appearing to be the second J^π $\frac{1}{2}^+$ and $\frac{1}{2}^-$ states in the ^{21}Ne energy spectrum, for which we report additional information from the ^{20}Ne$(d,p)^{21}$Ne reaction.

The experimental data were obtained at an incident deuteron energy of 3.6 MeV, with the Lyon Haefely accelerator. A nonfocusing magnet was employed to separate proton groups from scattered deuterons at forward angles. The experimental arrangement is described in detail in Ref. 8. In the present experiment a gaseous target of natural neon (90.5% ^{20}Ne) was used in a differentially-pumped gas-scattering chamber. The pressure was approximately 5 Torr. The magnet allowed a variation of 0 to 60° (lab) in the effective scattering angle. The reaction products were detected by a surface-barrier detector with a large surface ($\simeq$450 mm^2) placed just at the exit of the magnet, and by other surface-barrier detectors mounted on a movable crown. The energy resolution was about 45 keV.

The absolute differential cross sections were

TABLE I. Optical-model parameters used in the DWBA calculations. The optical potential has the form:

$$V(r)=V_C(r)-V\frac{1}{1+e^x}-iW\frac{1}{1+e^{x'}}+iW_s\frac{d}{dx'}\frac{1}{1+e^{x'}}+\left(\frac{\hbar}{m_\pi c}\right)^2 V_{so}(\vec{\sigma}\cdot\vec{l})\frac{1}{r}\frac{d}{dx}\frac{1}{1+e^x},$$

where $x=(r-r_0A^{1/3})/a$, $x'=(r-r'_0A^{1/3})/a'$, and $V_C(r)$ is the usual Coulomb potential.

Particle	Potential	V (MeV)	W (MeV)	W_s (MeV)	V_{so} (MeV)	r_0 (fm)	r'_0 (fm)	a (fm)	a' (fm)	Ref.
deuteron	D_1	101.9	29.56	0	8.0	1.289	1.353	0.706	0.594	11
	D_2	117.5	21.6	0	0	1.30	1.30	0.708	0.662	4
proton	P_1	48.0	0	30.0	5.50	1.250	1.250	0.650	0.700	12
	P_2	61.14	0	20.61	0	1.25	1.25	0.65	0.47	13
neutron					6	1.25		0.65		

determined by comparison with the Kr(p,p) reaction at 2 MeV, which follows the Rutherford scattering law. Experimental errors came from uncertainties in gas pressure, in beam current, and from the normalization to the Kr(p,p) results. Finally, cross sections at forward angles were obtained with an accuracy better than ±10%.

The analysis was carried out by fitting the measured differential cross section with an incoherent sum of a direct reaction and a compound nucleus reaction cross section in the following form:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = S\left(\frac{d\sigma}{d\Omega}\right)_{\text{Di}} + R\left(\frac{d\sigma}{d\Omega}\right)_{\text{CN}} .$$

The direct reaction cross section $(d\sigma/d\Omega)_{\text{Di}}$ was computed with the DWBA code DWUCK.[9] The compound nucleus contribution is obtained from a Hauser-Feshbach calculation. The reduction factor R was treated as an empirical normalization factor for the compound nucleus contribution. The value of R used ($R = 0.35$) was the one obtained by matching the calculated Hauser-Feshbach cross section to the experimental cross sections for the ^{20}Ne(d,α) reactions which do not contain any discernible direct component.[10] The optical-potential parameters used in the analysis (see Table I) were the same as those recently used[4-6] in the DWBA calculations of the ^{20}Ne(d,p) reaction. The deuteron potential set of parameters D_1 was that obtained by Lutz *et al.*[11] by fitting the data of elastic scattering of deuterons by ^{22}Ne; the parameter set D_2 was deduced by Chambon *et al.*[4] from the analysis of the same experimental data. The proton-optical parameters P_1 were taken from Rosen, Beery, and Goldhaber[12]; the proton parameters P_2 were calculated from the formulas of Perey.[13] These different potentials are listed in Table I.

The bound-state form factor for the transferred neutron was calculated with a Woods-Saxon-type potential well with $r_0 = 1.25$ fm and $a = 0.65$ fm. We performed the calculations for the combinations of potentials (D_1, P_1) and (D_2, P_2) used successively in the ^{20}Ne(d,p) reaction by Howard *et al.*[5,6] and Chambon *et al.*[4] The results of DWBA calculations are shown in Figs. 1 and 2. It is found that the different sets of potentials produce fits which are not too dissimilar. The DWBA calculations indicate that the angular momentum transfer for the 5.69-MeV state is $l_n = 1$ (Fig. 1), in agreement with the results of Howard.[5] The angular distribution displayed in Fig. 2 for the 5.78-MeV state indicates

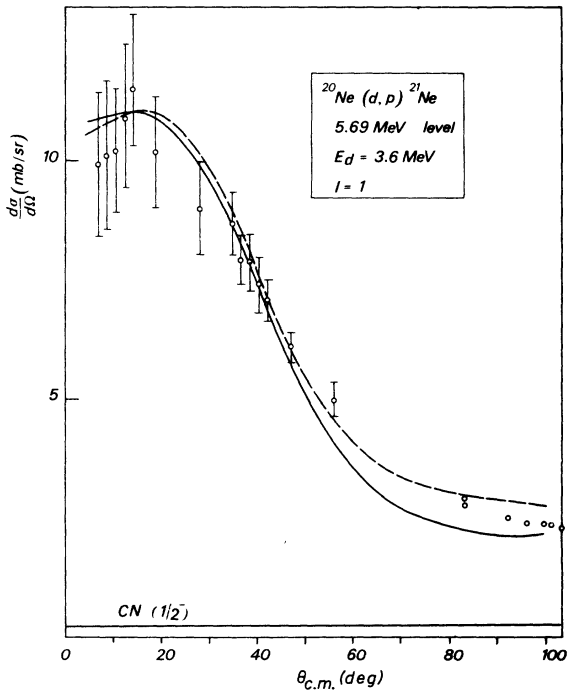

FIG. 1. ^{20}Ne$(d,p)^{21}$Ne angular distribution for the 5.69-MeV level at $E_d = 3.6$ MeV. The solid and dashed curves represent $l = 1$ DWBA fits (including the Hauser-Feshbach contribution) for (D_1,P_1) and (D_2,P_2) potential parameter sets, respectively.

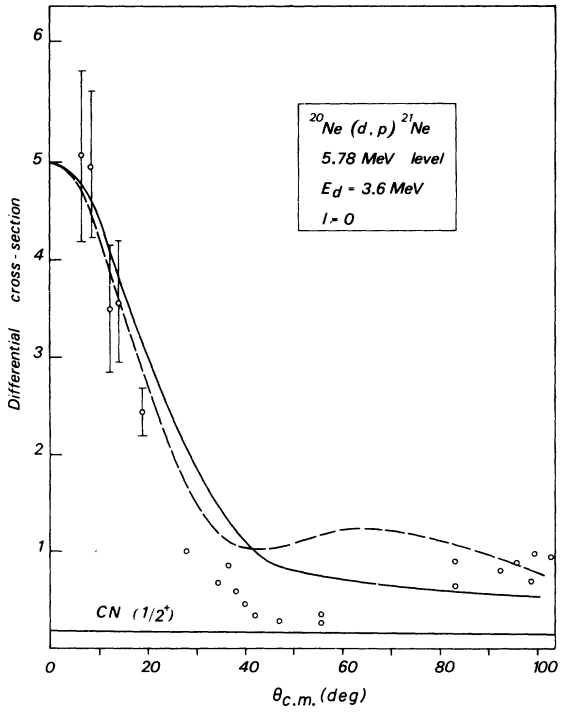

FIG. 2. ^{20}Ne$(d,p)^{21}$Ne angular distribution for the 5.78-MeV level at $E_d = 3.6$ MeV. The solid and dashed curves represent $l = 0$ DWBA fits (including the Hauser-Feshbach contribution) for (D_1,P_1) and (D_2,P_2) potential parameter sets, respectively.

TABLE II. Spectroscopic factors for the reaction $^{20}Ne(d,p)^{21}Ne$.

Level [a] (MeV)	J^{π} [b]	l Ref. 6	l Present work	S_{exp} Ref. 6	S_{exp} Present work (D_1,P_1)	S_{exp} Present work (D_2,P_2)	S_{th} Ref. 2
5.69	$(\frac{1}{2},\frac{3}{2})^-$	1	1	0.22	0.26	0.31	0.06
5.78	$\frac{1}{2}^+$		0		0.066	0.084	0.41

[a] Reference 6.
[b] The J^{π} values have been obtained from Ref. 6 and from the findings of the present work.

a peak at 0° and is well fitted by the angular momentum transfer $l_n = 0$. Thus, a $J^{\pi} = \frac{1}{2}^+$ assignment for the 5.78-MeV state in ^{21}Ne is well established. Spectroscopic factors S were extracted for these two states and are listed in Table II. The spectroscopic factor for the 5.69-MeV state is in reasonable agreement with the value obtained by Howard, Pronko, and Whitten.[6]

It is interesting to compare these experimental results with the prediction of the Nilsson model and to investigate the correspondence between these ^{21}Ne states at 5.69 and 5.78 MeV and their isobaric analog states in ^{21}Na.

The theoretical energy spectra of ^{21}Ne and ^{21}Na are alike in the Nilsson model and have already been computed.[2,14] It appears that the second $\frac{1}{2}^+$ state in ^{21}Ne just identified in this work with a 5.78-MeV excitation energy has a principal component on the head member of the rotational band based on an odd-particle in Nilsson orbit No. 11 ($k^{\pi} = \frac{1}{2}^+$). Similarly, the second $\frac{1}{2}^-$ state just identified with a 5.69-MeV energy, seems to be the theoretical state obtained after Coriolis band mixing and coming chiefly from the third member of the rotational band based on the Nilsson orbit No. 14 ($k^{\pi} = \frac{1}{2}^-$). The theoretical values of the spectroscopic factors (d,p) for these two states[2] are compared with the experimental ones in Table II. The agreement is rather poor.

Finally, we investigated the correspondence between the ^{21}Ne states at 5.69 and 5.78 MeV and their analog states in ^{21}Na. The analog states of these ^{21}Ne states are expected at $E_x \gtrsim 5$ MeV in ^{21}Na and hence, can be observed in the elastic scattering $^{20}Ne(p,p)$. Using the recent results about ^{21}Na obtained by Lambert *et al.*[14] from the $^{20}Ne(p,p)$ elastic scattering, the suggested correspondence is as follows: the $\frac{1}{2}^-$, 4.98-MeV state of ^{21}Na is the analog of the 5.69-MeV state of ^{21}Ne and the $\frac{1}{2}^+$, 5.46-MeV state of ^{21}Na is the analog of the 5.78-MeV state of ^{21}Ne. This correspondence is shown in Fig. 3 by dashed lines. If this correspondence is correct, the reduced widths for the analog states of ^{21}Ne and ^{21}Na are related by $\gamma_n^2 \simeq \gamma_p^2$. Table III indicates the values

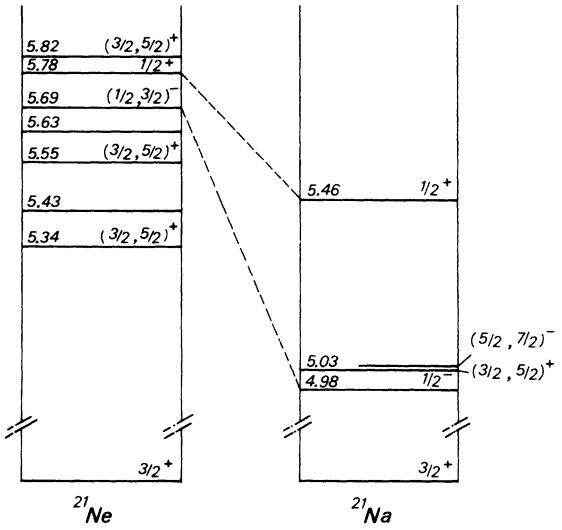

FIG. 3. Energy level diagrams for ^{21}Ne and ^{21}Na, showing the suggested correspondence for the 5.69- and 5.78-MeV states in ^{21}Ne and their analog states in ^{21}Na as explained in the text. The data for ^{21}Ne are taken from Ref. 6 and from the present work. The data for ^{21}Na are taken from Ref. 14.

TABLE III. Comparison of the reduced widths γ_n^2 and γ_p^2 for the isobaric analog states of ^{21}Ne and ^{21}Na.

E_x (^{21}Ne) [a] (MeV)	J^{π} (^{21}Ne) [b]	E_x (^{21}Na) [c] (MeV)	J^{π} (^{21}Na) [c]	Γ_p [c] (keV)	γ_n^2 [d,e] (keV)	γ_p^2 [d] (keV)
5.69	$(\frac{1}{2},\frac{3}{2})^-$	4.98	$\frac{1}{2}^-$	180	220–270	190
5.78	$\frac{1}{2}^+$	5.46	$\frac{1}{2}^+$	110	54–69	53

[a] Reference 6.
[b] Reference 6 and this work.
[c] Reference 14.
[d] Calculated with $R = 5.2$ fm.
[e] The two γ_n^2 values were calculated from $^{20}Ne(d,p)$ spectroscopic factors extracted with (D_1,P_1) and (D_2,P_2) combinations, respectively.

of γ_n^2 computed by the method described in Ref. 15 from the (d, p) spectroscopic factors and the values of γ_p^2 extracted from the ^{20}Ne(p, p) elastic scattering resonances. The reduced widths γ_n^2 are in reasonably good agreement with the reduced widths γ_p^2; the deviation of γ_n^2/γ_p^2 from unity is well within the experimental uncertainties ($\simeq$30%). The results confirm the suggested correspondence between the ^{21}Ne states at 5.69 and 5.78 MeV and the ^{21}Na states at 4.98 and 5.46 MeV, respectively.

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