PHYSICAL REVIEW C VOLUME 12, NUMBER 6 DECEMBER 1975

Study of the ^{21}Ne(t, p)^{23}Ne reaction

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(Received 25 February 1975)

Investigation of the ^{21}Ne(t, p)^{23}Ne reaction with 3 and 3.25 MeV projectiles reveals eight new (energy) levels between $E_x = 5.3$ and 6.5 MeV. Absolute differential cross sections for 18 proton groups are reported. Distorted-wave Born approximation analysis and Hauser-Feshbach calculations indicate that $L = 0$ is involved in the formation of one of the members of the doublets at $E_x = 3.432$-3.458 and 4.995-5.036 MeV as well as in the formation of a new level at 5.74 ± 0.04 MeV. A mixture of $L = 0$ and $L = 2$ transfer is associated with the formation of the 1.822 MeV level. For these four levels $J^\pi = \frac{3}{2}^+$ is deduced.

[NUCLEAR REACTIONS ^{21}Ne(t,p), E=3.25 MeV, measured $\sigma(\theta)$; ^{23}Ne levels deduced E_x, L, π, J. Enriched target.]

I. INTRODUCTION

Although the $2s$-$1d$ shell has been extensively studied, little experimental evidence has been reported for the ^{23}Ne nucleus. The main source of spectroscopic information has been the ^{22}Ne(d,p) stripping reaction[1-6] and the ^{22}Ne($d,p\gamma$) reaction.[3,7-9] Details of the γ-ray decay scheme have also been deduced from the ^{22}Ne(n,γ) neutron capture[10-12] and the ^{23}Na($n,p\gamma$) reaction.[3] Further references on the properties of the ^{23}Ne nucleus may be found in the compilation of Ref. 13. Recently, a preliminary study[14] of the ^{21}Ne(t,p) two-nucleon transfer reaction performed at E_t = 3 MeV with a target enriched with ^{21}Ne to a concentration of 50% assigned $J^\pi = \frac{3}{2}^+$ to one of the levels at 5.0 MeV. The main purpose of the present investigation is to confirm and complete this work using a gas target consisting almost completely of ^{21}Ne.

II. EXPERIMENTAL PROCEDURE AND RESULTS

Experimental procedure

The triton beam was provided by the 3-MeV Van de Graaff accelerator at the Centre de Recherches Nucléaires de Strasbourg-Cronenbourg. After traversing the chamber, the beam entered a collector. The pressure in this collector was ~10^{-6} Torr. The beam current was typically 60–110 nA and the integrated beam charge was 3–6 mC for each measurement.

The target chamber, described in detail elsewhere,[15] consisted of a cylindrical body with a lid supporting four detection cones. To eliminate leaks, the interior microchamber was replaced by a faceted cylinder with Formvar windows of surface density 100 μg/cm^2. The energy loss of the emerging particles in these windows was negligible. The entrance and exit windows of the chamber were 0.7-μm nickel foils.

The enriched target consisted of 91% ^{21}Ne, ^{20}Ne (3.3%), and ^{22}Ne (5.7%). The pressure was ~20 Torr.

The reaction products were detected simultaneously at an azimuthal angle of 20° by four solid state telescopes (700-μm E-50-μm ΔE) capable of rotation in the horizontal plane from 20° to 160° (in the laboratory system). For each detected particle, four signals (E, ΔE, $E+\Delta E$, and a signal corresponding to a particular telescope) were routed by a multiplexer into a Hewlett-Packard (H-P) 2116 C computer and recorded on magnetic tape. On-line monitoring[16] of the spectra was performed during the course of the experiment by the same H-P computer. A monitoring detector was fixed at $\theta_{\text{lab}} = 160°$.

Results

Subtraction of the deuteron and α particle background permitted reconstruction of the proton spectra. The energy resolution was 40–50 keV and measurements were made of transitions to states with excitation energies up to 6.5 MeV. A typical proton spectrum at E_t = 3 MeV is shown in Fig. 1.

The contaminants were negligible except for ^{12}C which hinders summation of the p_3 group peaks at forward angles. In spite of its small percentage in the gas target, the ^{20}Ne isotope appears in the spectra, in agreement with the relatively important ^{20}Ne(t,p) cross sections[17,18] for several ^{22}Ne levels (at E_x = 6.24 MeV, for example). In addition, the ground state and the state at E_x = 4.76

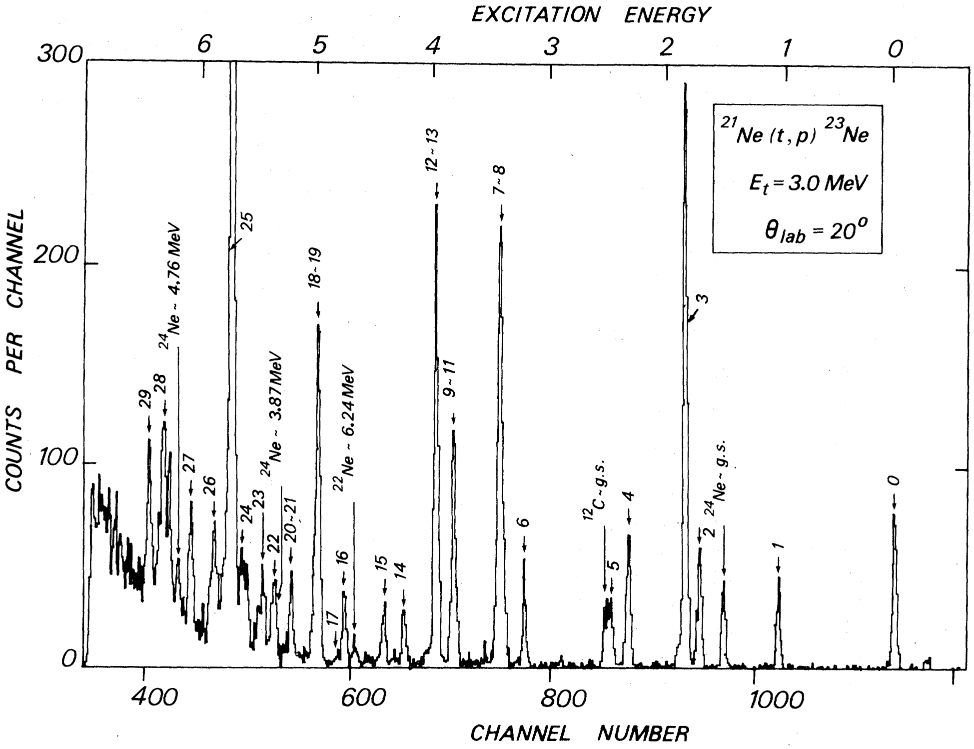

FIG. 1. Typical proton spectrum at $E_t = 3$ MeV and $\theta = 20°$ (in the laboratory system). The numbering of ^{23}Ne proton groups is consistent with Table I.

MeV in ^{24}Ne, which are strongly fed[19] via the ^{22}Ne(t,p) reaction at forward angles, also appear in the spectra. This is in agreement with the absolute differential cross section measured[20] for this reaction at $E_t = 3$ MeV (e.g., for $E_x = 4.76$ MeV, $d\sigma/d\Omega \sim 2$ mb/sr at $\theta_{\text{lab}} = 20°$).

The spectra exhibit eight prominent peaks, corresponding to ^{23}Ne levels located in the 5.3–6.8-MeV excitation energy range, which have not been investigated to date. In case of ambiguity, the identity of these levels in ^{23}Ne was supported by absolute differential cross-section measurements for the ^{20}Ne(t,p) and ^{22}Ne(t,p) reactions at the same energy, $E_t = 3$ MeV (Refs. 18 and 20, respectively). Our results for the excitation energies of these new levels are listed in Table I (column 3). We have not measured the energies of the lower levels because they are already known with much better accuracy than one could expect from this ^{21}Ne(t,p) study.

Absolute normalization of the differential cross sections was obtained by comparison of the (t,p) cross sections with the cross sections for elastic proton scattering on krypton at $E_p = 3$ MeV, assuming a pure Coulomb scattering process as described in Ref. 21.

The quasi-isotropic distributions are shown in Fig. 2, while the angular distributions exhibiting the classical direct interaction pattern are displayed in Fig. 3. The relative uncertainties in the differential cross sections are based upon the method of analysis and include statistical errors. They are estimated to be less than 15%, as shown by the error bars on the figures. Systematic errors in the absolute normalization of the cross sections are believed to be ~20%.

III. ANALYSIS OF ANGULAR DISTRIBUTIONS

The differential cross sections (Figs. 2 and 3) suggest that both the direct interaction (DI) process and compound nucleus (CN) process must be included in the analysis. For simplicity, we represent the theoretical cross sections by an incoherent sum of both contributions:

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

The CN contribution was obtained from a Hauser-Feshbach calculation. The "reduction factor"[22] R was treated as an empirical factor and was determined by matching the calculated Hauser-Feshbach cross sections to the experimental cross-sections for the $\frac{5}{2}^+$ ground state, the $\frac{7}{2}$ state at 1702 keV, and the $\frac{5}{2}^+$ state at 2315 keV, all of

TABLE I. Previous and present results for the excitation energies and spin and parity assignments of the ^{23}Ne states. The numbering of the levels is consistent with that of the ^{22}Ne$(d,p\gamma)$ study of Ref. 9 (up to level No. 13).

Level number	E_x (keV)		J^π	
	Previous works	Present work	Previous works	Present work
0	Ground state		$\frac{5}{2}^{+}$ [b]	
1	1071.1 ± 0.2 [a]		$\frac{1}{2}^{+}$ [b]	
2	1702.0 ± 0.4 [a]		$\frac{7}{2}$ [b]	
3	1822.8 ± 0.3 [a]		$(\frac{3}{2})^{+}$ [b,c]	$\frac{3}{2}^{+}$
4	2315.5 ± 0.6 [a]		$\frac{5}{2}^{+}$ [d]	
5	2517.8 ± 0.8 [a]			
6	3221.1 ± 0.4 [a]		$\frac{3}{2}^{-}$ [b]	
7	3432.3 ± 0.6 [a]	e	$\frac{3}{2}^{+}$ [d]	$\frac{3}{2}^{+}$
8	3458.2 ± 0.6 [a]			
9	3830.5 ± 1.2 [a]	e	$\frac{1}{2}^{-}$ [d]	
10	3837.5 ± 0.9 [a]			
11	3843.3 ± 1.1 [a]			
12	3988.2 ± 0.7 [a]	e	$\frac{3}{2}^{+}(\frac{5}{2})^{+}$ [d]	
13	4010 ± 3 [a]			
14	4270 ± 15 [b]			
15	4430 ± 3 [b]			
16	4755 ± 5 [b]			
17	4867 ± 15 [b]	f		
18	4995 ± 15 [b]	e	$\frac{3}{2}^{+}$ [g]	$\frac{3}{2}^{+}$
19	5036 ± 15 [b]			
20	5186 ± 15 [b]	e		
21	5226 ± 15 [b]			
22		5366 ± 40		
23		5481 ± 40		
24		5649 ± 40		
25		5745 ± 40		$\frac{3}{2}^{+}$
26		5899 ± 40		
27		6093 ± 40		
28		6329 ± 40 [h]		
29		6445 ± 40		

[a] J. E. Christiansson **et. al.** (Ref. 9).

[b] See the compilation by P. M. Endt and C. van der Leun (Ref. 13).

[c] See comments in Sec. III.

[d] W. A. Wonk and P. A. Quin (Ref. 6).

[e] This multiplet is unresolved in the present experiment.

[f] This level is not observed in the present experiment.

[g] B. Chambon **et. al.** (Ref. 14).

[h] Energy of the upper member of a doublet.

which apparently do not contain a DI component (see Fig. 2). The value thus obtained ($R = 0.13$) was then used for all other transitions. One notes that this reduction factor is smaller than for other reaction studies in the same mass region (see for example Ref. 18) presumably because the spin and parity of many levels in the residual nuclei are still unknown and are not included in this treatment. The theoretical cross section is thus overestimated. However, since the calculation was performed to approximate the contribution of the CN process, the results are thought to be meaningful. In addition, the angular distributions for the 1017 keV ($J^\pi = \frac{1}{2}^+$) and 3221 keV ($J^\pi = \frac{3}{2}^-$) states were calculated assuming no DI component; in Fig. 2 the results are shown to be in satisfactory agreement with the quasi-isotropic experimental cross sections. This indicates that the above R value is probably reliable.

The distorted wave Born approximation (DWBA) double stripping cross sections were computed from the code DWUCK.[23] The two-nucleon bound

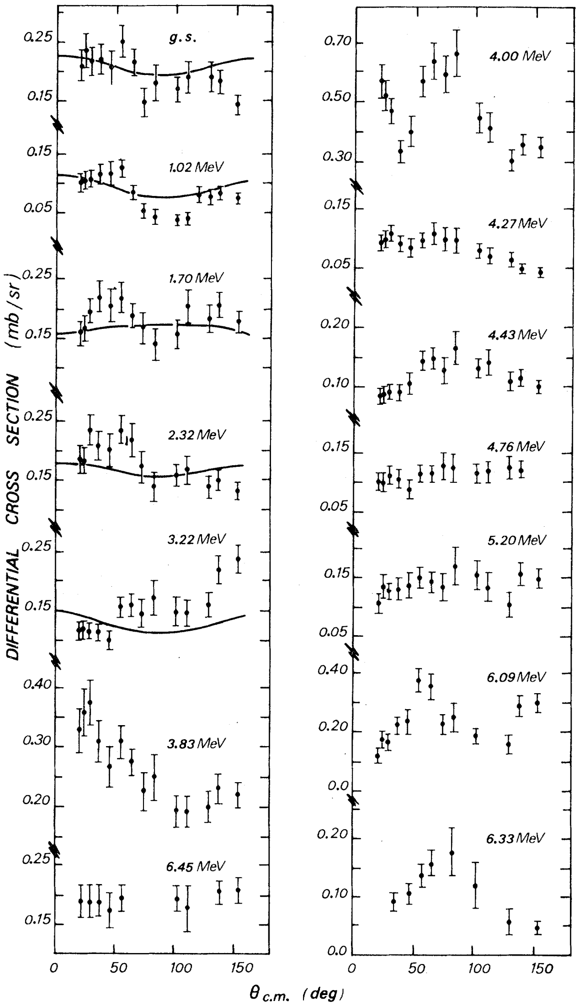

FIG. 2. Differential cross sections observed in the ^{21}Ne(t,p) reaction at E_t=3.25 MeV. The solid lines represent the Hauser-Feshbach cross sections multiplied by the reduction factor. The curves are labeled by the corresponding ^{23}Ne excitation energies (see the text for more details and references).

state form factor was calculated from a code written by C. Morand using an approximate form[19] of the Glendenning theory.[24]

The optical potentials used to calculate the distorted waves and the transmission coefficients have the form:

$$V(r)=V_C(r)-V(1+e^{x})^{-1}-iW(1+e^{x'})^{-1}$$
$$+iW'\frac{d}{dx}(1+e^{x'})^{-1}\,.$$

In this expression, $V_C(r)$ is the Coulomb potential (where the nuclear radius is $1.4A^{1/3}$ fm, A being the mass number), V is the real potential depth, W and W' are the imaginary depths, and x and x' are related to the relative radial coordinate by:

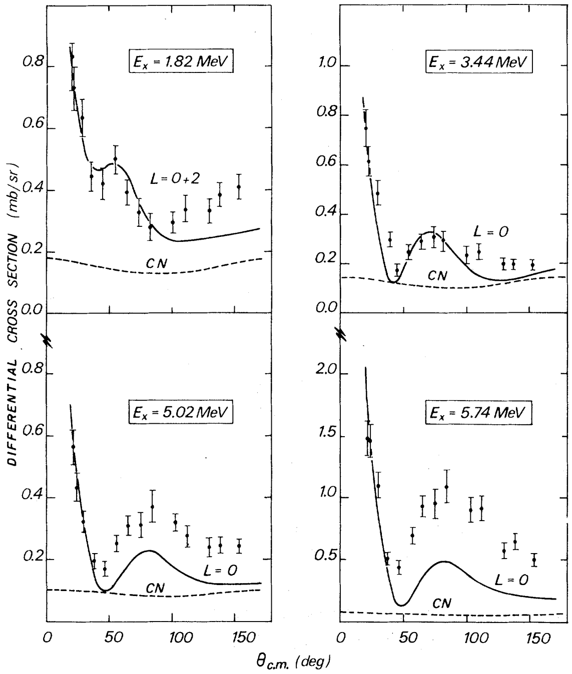

FIG. 3. Differential cross sections observed in the formation of ^{23}Ne states via $L=0,2$ transfer in the ^{21}Ne$(t,p)^{23}$Ne reaction at $E_t=3.25$ MeV. The solid curves represent DWBA fits including Hauser-Feshbach calculation. The latter (multiplied by the reduction factor) is represented by the dashed curve labeled CN.

$$x=(r-r_0A^{1/3})/a \quad\text{and}\quad x'=(r-r_0'A^{1/3})/a'\,.$$

The parameters of the potentials (V, W, W', r_0, r_0', a, and a') were taken from Refs. 4 and 25–28 and are listed in Table II. They are in agreement with those previously employed in analysis of the ^{20}Ne$(t,p)^{22}$Ne reaction.[18]

The results are shown in Fig. 3 for the four following levels (which exhibit apparent direct interaction characteristics).

1.822-MeV level. This state was assigned $J^\pi=\frac{3}{2}^+$ from the reaction ^{22}Ne$(d,p)^{23}$Ne by Lutz *et al.*,[2] who fitted the angular distribution with $l_n=2$ and distinguished $j=\frac{3}{2}$ from $j=\frac{5}{2}$ transitions by the method given by Lee and Schiffer.[29] From the ^{22}Ne$(d,p\gamma)$ reaction,[8] the $p-\gamma$ angular correlation measurements led to $J=\frac{3}{2}$. However, according to Endt and van der Leun,[13] determination of the spin value is not definitive [these authors quote $J^\pi=(\frac{3}{2})^+$]. The present angular distribution is well fitted by a mixture of $L=0$ and $L=2$. For this single state, it requires $J^\pi=\frac{3}{2}^+$.

3.433-MeV level. A doublet is presently known[9] to exist at (3432.3 ± 0.6) MeV and (3458.2 ± 0.6) MeV. A state at 3.43 MeV was populated via $l_n=2$ in the ^{22}Ne$(d,p)^{23}$Ne reaction,[2] requiring $J^\pi=(\frac{3}{2},\frac{5}{2})^+$.

TABLE II. Optical model parameters used in the DWBA and Hauser-Feshbach calculations.

Channel	Potential	V (MeV)	r_0 (fm)	a (fm)	W (MeV)	r_0' (fm)	a' (fm)	W' (MeV)	Ref.
$t+{}^{21}$Ne	T	160	1.20	0.72	25	1.40	0.84	0	22
$p+{}^{23}$Ne	P	50	1.25	0.65	0	1.25	0.47	46	23
$n+{}^{23}$Na	N	47	1.32	0.66	0	1.26	0.48	38	24
$d+{}^{22}$Ne	D	117	1.30	0.71	22	1.30	0.66	0	4
$\alpha+{}^{20}$F	A	200	1.42	0.56	16.5	1.42	0.56	0	25

The present angular distribution for this unresolved doublet is approximately fitted assuming a $L=0$ transfer. It is probable that one of the members of the doublet has $J^\pi=\frac{3}{2}^+$, in agreement with the recent result obtained from the ^{22}Ne(d,p) reaction.[6]

4.995-5.036-MeV doublet. The angular distribution is well fitted with $L=0$, leading to $J^\pi=\frac{3}{2}^+$ for one of the members of the doublet. This result confirms the previous determination[14] using the ^{21}Ne(t,p) reaction at $E_t=3$ MeV.

5.74-MeV level. No information has been reported about this state which is strongly fed in the present ^{21}Ne(t,p) reaction. The angular distribution is given approximately by $L=0$. Thus, if only a single state exists at 5.74 MeV, it must have $J^\pi=\frac{3}{2}^+$.

J^π assignments for previous work and this study are listed in Table I (column 4 and 5, respectively).

IV. SUMMARY

The ^{21}Ne(t,p)^{23}Ne reaction at $E_t=3$ and 3.25 MeV with a target consisting of 91% ^{21}Ne populated all previously known ^{23}Ne energy levels (or multiplets) except one at $E_x=4567$ keV. In addition, excitation energies were measured for eight previously unreported levels with E_x between 5.3 and 6.5 MeV. Absolute differential cross sections were measured for 18 proton groups (see Figs. 2 and 3) and an analysis employing DWBA and Hauser-Feshbach calculations is consistent with $L=0$ transfer (or a mixture of $L=0$ and $L=2$) for the ^{23}Ne levels at $E_x=1.82$ and 5.74 MeV and for one of the members of the doublets at $E_x=3.43$ and 5.0 MeV.

ACKNOWLEDGMENTS

The authors would like to thank Professor D. Magnac-Valette and her staff for their hospitality at the Centre de Recherches Nucléaires at Strasbourg-Cronenbourg. They are grateful to Professor M. Lambert for his interest in this work and for a critical reading of the manuscript. They are indebted to Dr. Y. Chanut for his help during the data acquisition, and to Professor H. Beaumevieille for useful comments. The technical assistance of N. Madjar and A. Gardon is appreciated. One of us (A.D.) acknowledges the generous allocation of computer time by the Ministry of Agriculture at Algiers.

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[*] Work partially supported by the Commissariat â l'Energie Atomique.

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