A Study of Single Proton States for the 21, 23Na Nuclei through (d,n) Reactions at 25 MeV

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I. 1. A Study of Single Proton States for the ^{21,23}Na Nuclei through (d,n) Reactions at 25 MeV

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An one-nucleon stripping reaction could be considered to transfer a nucleon to one of empty orbits in a target nucleus, if it proceeds through a direct reaction. It would be thus a useful tool for the study of single particle excitations. The (d,p) and (d,n) reactions are especially important, since these reactions are simpler than other one-nucleon transfer reactions and DWBA treatment for them is well established. In the (d,n) reaction, a time-of-flight facility with a long path is necessary for the high resolution experiment. Therefore, spectroscopic data for single proton states in nuclei had been insufficient at past. We have systematically carried out the high resolution experiments of the (d,n) reaction on sd-shell nuclei at $E_d = 25$ MeV. Since the direct reaction component would be dominant at this incident energy, more reliable data are expected to be obtained.

For the sd-shell nuclei the shell model wave functions by Brown and Wildenthal1) have been extensively used at present. The comparisons of observed spectroscopic results from a one-nucleon transfer reaction with predictions by the shell model with Brown and Wildenthal's wave functions would be important as one of good tests for their theory. Most of lighter sd-shell nuclei show a prolate deformation. Especially the ^{20}Ne and ^{22}Ne nuclei are strongly deformed, so it is possible for these nuclei to compare the experimental results with predictions by both the shell and Nilsson models.

The experiments were performed using deuteron beam from the AVF cyclotron and the time-of-flight facility with a 44 m flight path at the Cyclotron Radioisotope Center, Tohoku University. Two types of a gas cell were used as a target; a disk type cell with windows of about 10 mg/cm^2 platinum foils was used for measurements in ^{22}Ne and at forward angles in ^{20}Ne and a cylindrical cell having a length of 25 cm and windows of Havar foils for the measurements at backward angles in ^{20}Ne. Emitted neutrons from Havar foils were prevented from reaching the detectors by thick concrete shields and two collimators. The target thicknesses were about 1 mg/cm^2 in the case of the disk type cell and 3-6 mg/cm^2 in the cylindrical one, respectively. The isotopical enrichments of the targets were better than 99.8 % for the both gases. Errors in the absolute magnitude of the cross sections are estimated to be less than 15 %.

Typical neutron energy spectra in the ^{20,22}Ne(d,n)^{21,23}Na reactions at a laboratory angle of 10° are shown in Fig. 1. Overall energy resolution was about 200 keV for lower-lying states. Angular distributions for neutrons leading to the states in ^{21}Na and ^{23}Na are presented in Fig. 2, together with theoretical predictions labelled as DCVL and AD. Zero-range calculations were performed using the code DWUCK 4[2)] in which a wave function for an unbound proton can be calculated by the method of Vincent and Fortune.[3)] Optical potential parameters for deuteron obtained from a systematics of Daehnick et al.[4)] were used for the curves (DCVL). In Johnson and Soper's adiabatic approximation[5)] for deuteron potential (AD), optical potential parameters for protons and neutrons were taken from Becchetti and Greenlees[6)] and Carlson et al.[7)], respectively. The parameters from Carlson et al. were also used for neutrons in the exit channel. The finite-range and the non-locality corrections were made in the zero-range calculations.

In tables 1 and 2 the experimental spectroscopic factors for ^{21}Na and ^{23}Na are listed, respectively, comparing with those obtained from the shell and the Nilsson models. Large spectroscopic factors for 0.33 MeV and 2.42 MeV states of the ^{21}Na nucleus were obtained in the ^{20}Ne(d,n)^{21}Na reaction. These two states could be nearly pure single-particle states. Our results for the spectroscopic factors of above two states are not in good agreement with those by Burbank et al.[8)] and Haas et al.[9)] No l=3 transition has been reported in the previous experiments for ^{21}Na.[10)] The strong l=3 transition was observed at 5.02 MeV in the present experiment and it seems to be reasonable from our results of the (d,n) reactions at E_d = 25 MeV for other sd-shell nuclei. The results of the shell model calculation with Brown and Wildenthal's wave functions are in good agreement with the spectroscopic factors obtained in the present work. The results of Nilsson model calculation[12)] with Coliolis coupling also generally account for our experimental ones, as shown in Fig. 3 together with the comparison in ^{23}Na.

In the case of the ^{22}Ne(d,n)^{23}Na reaction, five strong l=3 transitions were observed, which have not been reported in ref. 10. Our results for the spectroscopic factors agree with those by Powers et al.[13)] for lower-lying states. Observed spectroscopic factors for ^{23}Na are also reasonably reproduced by the calculations of the shell model and the Nilsson one with Coliolis coupling.[14)]

If we would ignore core excitations, the ground states of ^{20,22}Ne have two protons in the sd-shell. Thus, the limit of the sum of the spectroscopic factors is 10. The experimental sums of the spectroscopic factors for ^{20}Ne and ^{22}Ne in the case of adiabatic calculations are 9.73 and 10.23, respectively. In both cases most of the available strengths for the sd-shell has been exhausted within the experimental errors in the present measurements. The sum of the spectroscopic factors over the all observed states with the same spin and parity would denote a averaged number of holes in the orbit. In Fig. 4 the experimental and the theoretical proton holes in the ground states of ^{20}Ne and ^{22}Ne are illustrated, respectively. The shell model calculations were performed using Brown and Wildenthal's wave functions. The experimental results are in good agreement with the shell model predictions in both cases.

In conclusion, the spectroscopic factors for many proton states have been observed by the (d,n) reactions on the ^{20,22}Ne isotopes at $E_d = 25$ MeV. These results are in good agreement with the predictions of the shell model with Brown and Wildenthal's wave functions and the Nilsson model with Coliolis coupling. The sum rule limits for the sd-shell proton holes in the ground states of ^{20}Ne and ^{22}Ne have been satisfied in the present experiments.

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Table 1. Comparisons of spectroscopic factors obtained for ^{21}Na in the present experiment with those from other experiments and theories.

				$(2J+1)C^2S$					
Ex(MeV)	J^{π} a)	*l*	n*l*j	Present exp. DCVL	AD	(d,n) b) E_d=5.2 MeV	(d,n) c) E_d=5.9 MeV	Shell model d)	Nilsson model e)
0	3/2+	-						0.11	0.034
0.33	5/2+	2	1d5/2	3.55	3.76	2.43	2.1	3.78	4.07
2.42	1/2+	0	2s1/2	2.01	1.93	0.44	0.9	1.31	0.99
2.80	1/2-	1	1p1/2	0.26	0.26				
3.54	5/2+	2	1d5/2	0.16	0.16			0.10	0.14
4.17	3/2-	1	2p3/2	0.85	0.85				
4.29	5/2+	2	1d5/2	1.24	1.29			0.74	0.23
4.47	3/2+	2	1d3/2	1.40	1.44			1.18	1.77
5.02		3	1f7/2	3.01	3.23				
6.51	3/2+	2	1d3/2	0.68	0.71			0.68	1.31
6.91	(3/2+)	2	1d3/2	0.42	0.44			0.85	

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Table 2. Comparissons of spectroscopic factors obtained for ^{23}Na in the present experiment with those from other experiments and theories.

				(2J+1)C^2S						
Ex(MeV) a)	$J^{\pi};T$ a)	*l*	n*l*j	Present exp. DCVL	AD	(^{3}He,d) b) E=10,12MeV	(^{3}He,d) c) E=15MeV	(d,n) d) E=5.34MeV	Shell model e)	Nilsson model b)
0	$3/2^+$	(2)	1d3/2	(0.27)	(0.33)		0.32	(1.09)	0.20	0.16
0.44	$5/2^+$	2	1d5/2	2.44	2.91		2.10	(1.28)	2.51	2.68
2.39	$1/2^+$	0	2s1/2	0.60	0.50	0.73	0.50	0.28	0.45	0.57
2.98	$3/2^+$	2	1d3/2	1.48	1.68	0.87	1.28	0.69	0.90	0.99
3.68	$3/2^-$	1	1p3/2	0.15	0.15	0.07	$\leqq$0.076	0.		
3.91	$5/2^+$	2	1d5/2	0.35	0.39	0.30	0.27		0.18	0.95
5.74	$(3/2,5/2)^+$	2	1d5/2	0.45	0.47	$\leqq$0.37	0.21	0.20	$5/2^+$:0.23	$5/2^+$:0.96
6.31	$1/2^+$	0	2s1/2	0.30	0.27	0.50	0.27	0.18	0.23	0.56
6.92	$3/2^-$	1	2p3/2	0.49	0.53	0.80	2p1/2:0.30	0.19		
7.08	$3/2^-$	1	2p3/2	0.29	0.31	0.40	2p1/2:0.17	0.08		
7.45	$5/2^+$	3	1f7/2	1.55	1.62	1d3/2:0.73	1d3/2:0.58	2p3/2:0.11		
7.89	$5/2^+;3/2$	2	1d5/2	0.85	0.87	0.20	0.46	0.40		
8.42	$(3/2,5/2)^+$	2	1d3/2	0.50	0.52		1d5/2:0.18		$3/2^+$:0.19	
8.66	$1/2^+;3/2$	0	2s1/2	1.13	1.16	0.21	0.54	0.50	0.44	
9.67*)		1 or 2	2p3/2	0.31	0.32					
10.03*)		2	1d5/2	0.18	0.19					
10.94*)		2	1d3/2	0.40	0.42					
11.29*)		2	1d3/2	0.68	0.71					
11.54*)		3	1f7/2	0.46	0.49					
11.76*)		3	1f7/2	0.38	0.40					
11.88*)		3	1f7/2	0.24	0.24					
14.37*)		3								

a) Endt P. M. and Van der Leun C., Nucl. Phys. **A310** (1978) 1.
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*) Excitation energies were obtained in the present experiment.

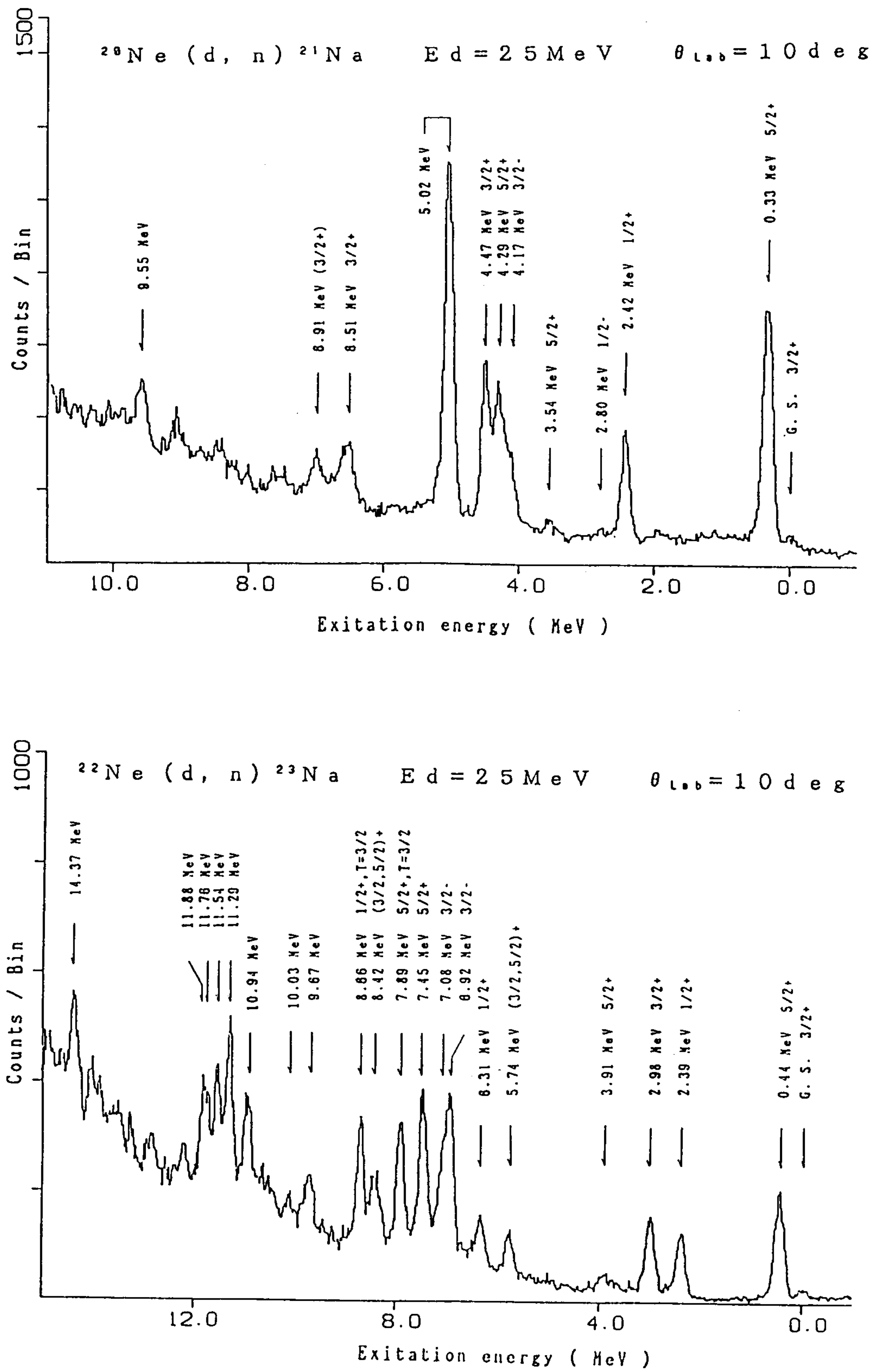


Fig. 1. Neutron energy spectra of $\theta_L = 10°$ in the ^{20,22}Ne(d,n)^{21,23}Na reactions at $E_d = 25$ MeV.

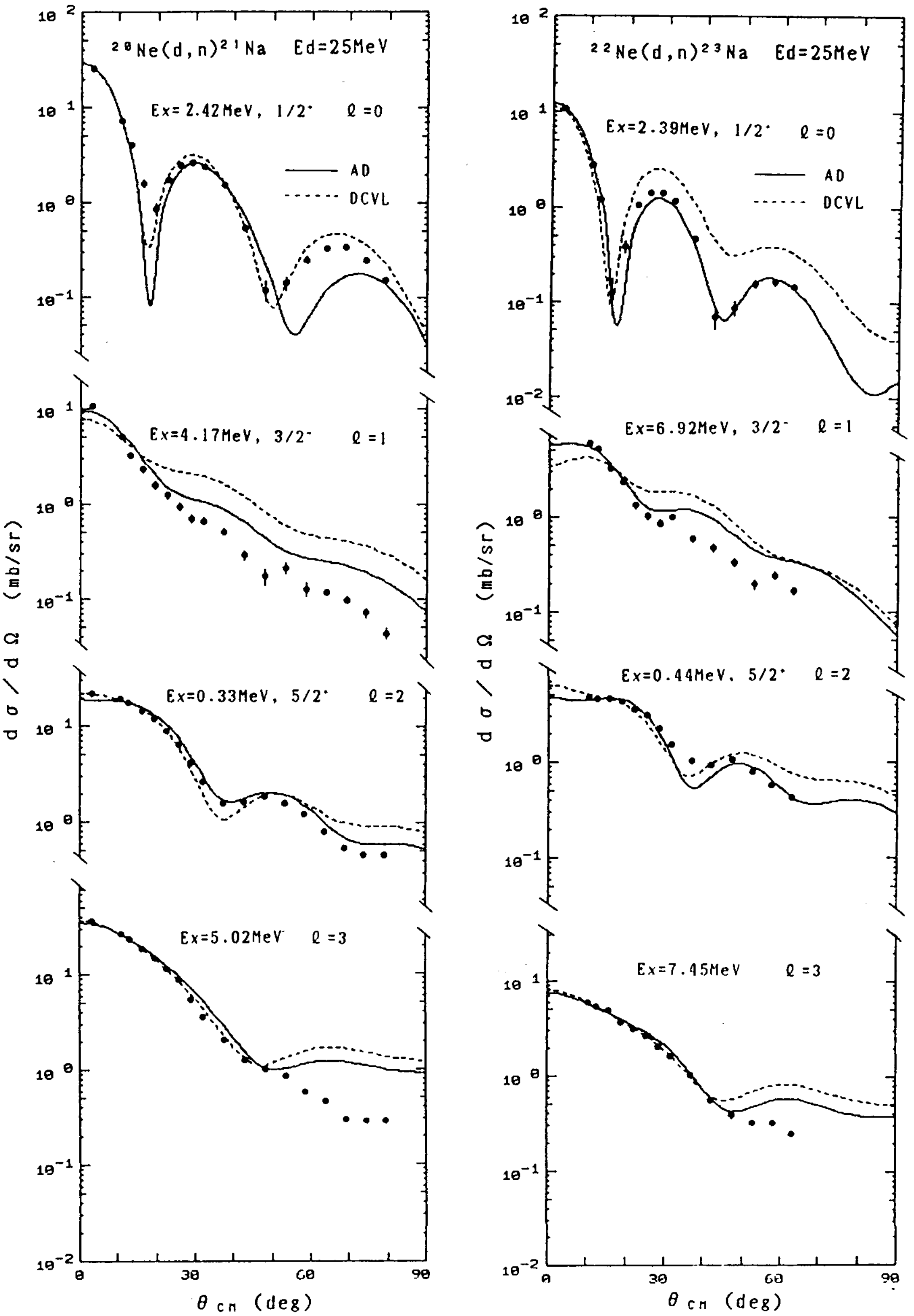
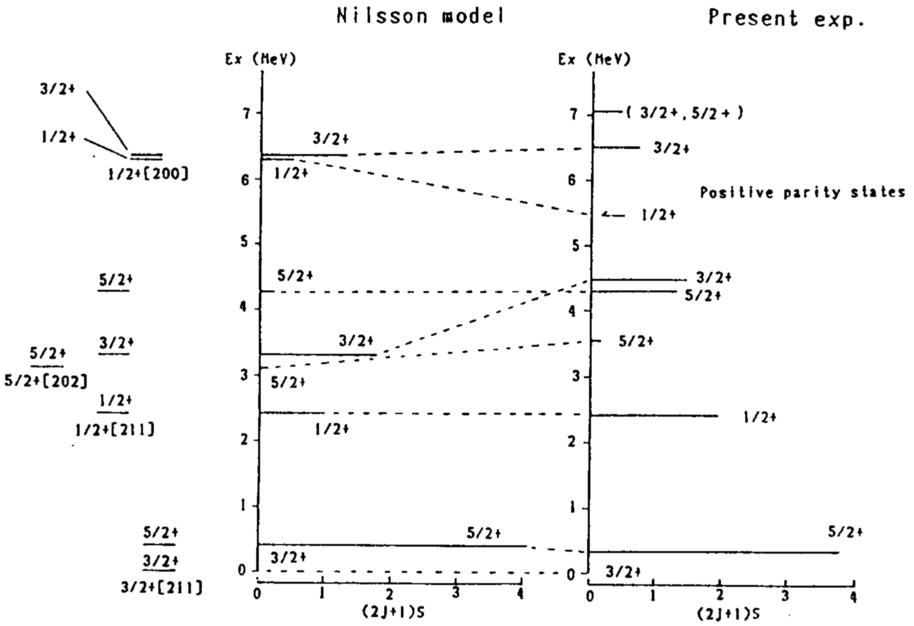


Fig. 2. Typical angular distributions of emitted neutrons with l=0, 1, 2 and 3 in the ^{20,22}Ne(d,n)^{21,23}Na reactions. The curves labelled as AD (solid lines) and DCVL (dashed lines) are theoretical predictions obtained by using potential parameters for deuteron from adiabatic approximation and a systematics of Daehnick et al., respectively.

^{21}Na



^{23}Na

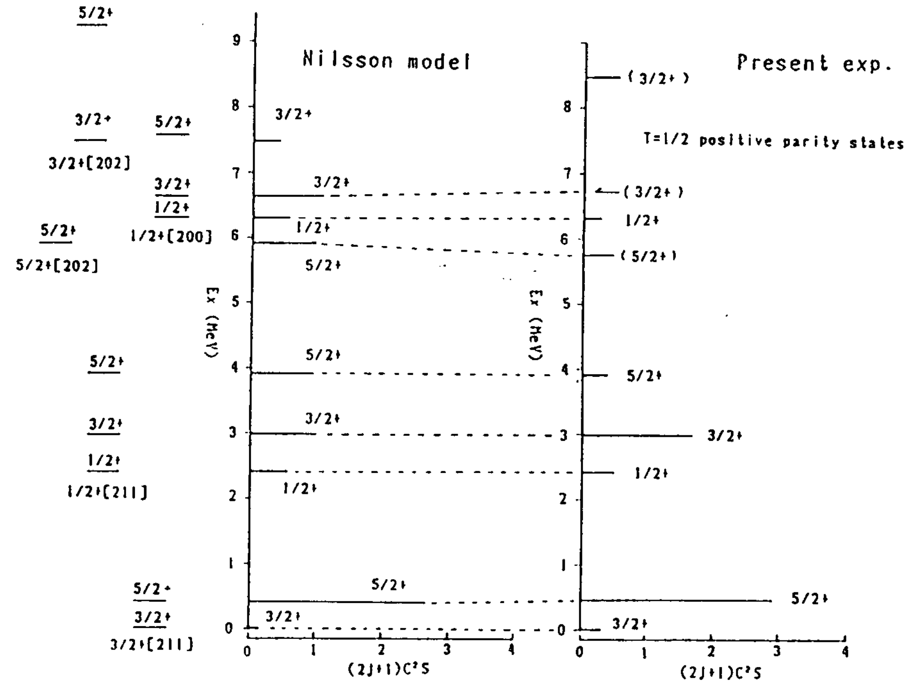


Fig. 3. Comparisons between the experimental results and predictions by the Nilsson model for spectroscopic factors and excitation energies of the positive parity states in ^{21,23}Na.

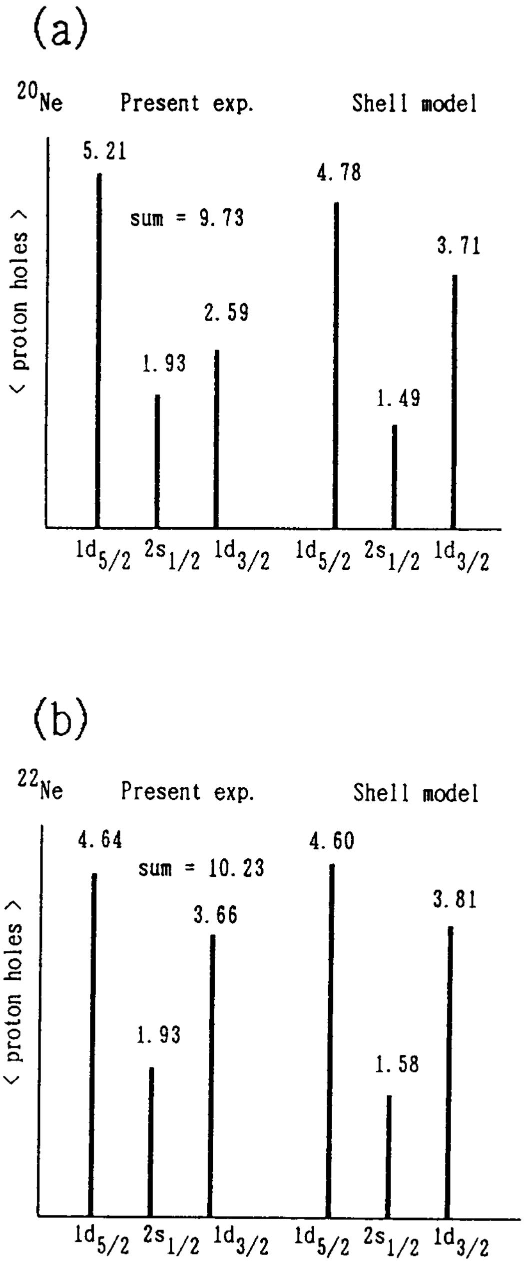


Fig. 4. Numbers of proton holes in s- and d-shells for the ground states of ^{20}Ne (a) and ^{22}Ne (b) obtained from the present experiments and shell model calculations.