PHYSICAL REVIEW C VOLUME 12, NUMBER 6 DECEMBER 1975

Neutron resonances in ^{24}Na via the (d, p) reaction*

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(Received 18 June 1975)

Neutron resonances in ^{24}Na from $E_r = 0$ to 1 MeV are studied with the ^{23}Na$(d, p)^{24}$Na reaction at $E_d = 11.0$ MeV using a biased quadrupole spectrometer. Fractionated single-particle states are identified via their forward angle cross sections, using distorted wave Born-approximation predictions with resonance state form factors for the residual ^{24}Na system. Spectroscopic results are compared with those from (n, n) and/or (n, γ) studies over the same region of excitation.

NUCLEAR REACTIONS ^{23}Na(d, p), $E_d = 11$ MeV, measured $\sigma(\theta)$. ^{24}Na deduced levels, l, j, π, spectroscopic factors. DWBA analysis, resolution 12 keV; comparison to neutron total σ, ^{23}Na.

The total neutron cross section for Na is of considerable practical interest, since liquid sodium is the most likely coolant for fast-breeder-reactor applications. A total of 43 resolved resonances has been observed for the ^{24}Na system, over resonance energies ranging roughly from $E_r = 0$ to 1 MeV, using conventional (n, n) and (n, γ) techniques.[1]

We report in this letter a study of neutron resonances of ^{24}Na in this same region of excitation using the ^{23}Na$(d, p)^{24}$Na reaction at an incident deuteron bombarding energy of 11.0 MeV. A biased quadrupole spectrometer was used to achieve excellent particle identification with a single lithium-drifted silicon detector. Details of the operation of the spectrometer and the experimental techniques used in studying neutron resonances populated via the (d, p) reaction are given elsewhere.[2-4] The over-all experimental resolution was 15 keV full width at half maximum.

Angular distributions from $\theta_{\text{c.m.}} = 10°-90°$ as obtained in this experiment are shown in Fig. 1. The states at $E_x = 6.57$, 6.83, and 6.90 MeV are particle-bound, while the remaining 11 angular distributions are for unbound residual nuclear states (or multiplets where indicated in Fig. 1).

Recent work has shown that fairly conventional direct reaction spectroscopy may be used to make a spectroscopic analysis of fractionated single-particle states populated via (d, p) where the residual states are neutron unbound.[3-5] In one widely applied approach,[3,4,6,7] complex-energy eigenstates (Gamow functions) of single nucleons in a real Woods-Saxon potential are computed, somewhat in analogy with the usual "separation-energy" procedure used for bound final states for distorted wave Born-approximation (DWBA) calculations. The single-particle resonance width is obtained directly from such a calculation, i.e., knowledge of the resonance pole position yields at once the resonance energy and the single-particle width. DWBA calculations are then done using the Gamow state functions and comparison with the (d, p) data yields the spectroscopic quantity $(2J_F + 1)S$, where J_F is the final nuclear spin and S the spectroscopic factor. When J_F is known, one obtains the neutron widths directly, since $\sigma_{\text{exp}} \propto (2J_F + 1)(\Gamma_n/\Gamma_{\text{s.p.}})\sigma_l$ (DWBA). In principle, these partial widths may be compared with those extracted from (n, n) and/or (n, γ) work.

The solid lines shown in Fig. 1, for the unbound states, are the results of such spectroscopic analysis using Gamow state form factors within the framework of the DWBA. The solid curves for the three bound states employ the usual separation-energy bound-state form factor. The optical model potentials were taken from the literature.[8] Table I presents the results of our spectroscopic analysis and a comparison with (n, n) and/or (n, γ) work.

Earlier work[3,4,9] on Si and S has demonstrated that resonances populated in $(n, n)/(n, \gamma)$ are not necessarily strongly populated via (d, p) and vice versa. In the (n, n) and (n, γ) studies the resonance is populated as an intermediate or compound state, whereas in (d, p) the resonance is populated as a residual nuclear state. The angular momentum selectivity of the two types of reactions is very different.[4] Thus the extent to which neutron widths Γ_n extracted via the two techniques may be compared has essentially remained an open question.

The first column of Table I lists the resonance

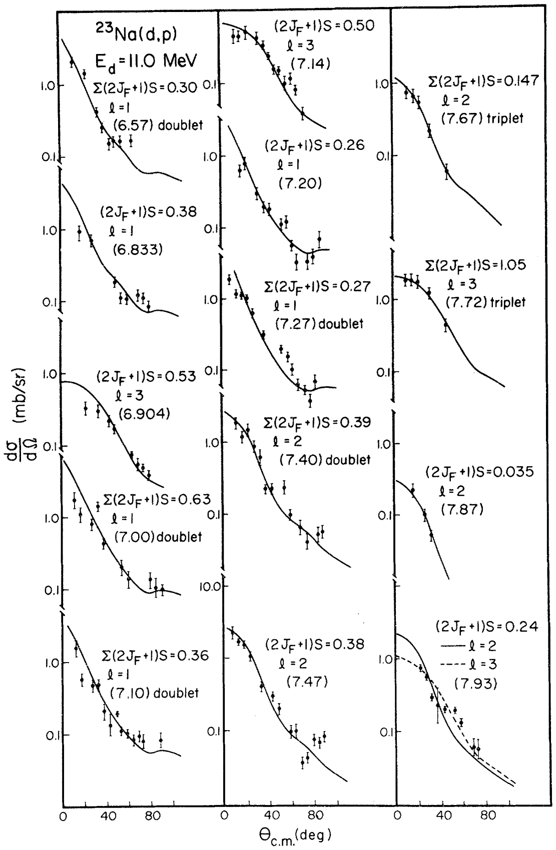

FIG. 1. Experimental angular distributions and DWBA calculations for states of ^{24}Na ranging from 6.57 to 7.93 MeV in excitation. The solid curves are DWBA predictions obtained as explained in the text. Extracted spectroscopic information is summarized in Table I.

energies reported from (n,n) and/or (n,γ) studies on ^{23}Na. Columns 3–5 list the spectroscopic information available from the neutron work. Many of the resonances seen in the neutron work could not be resolved in the present experiment. Column 2 of Table I lists states (or groups of unresolved states) in ^{24}Na seen in this experiment. States corresponding to $E_r = 117.8$, 219.5, 394.5, and 406.0 keV, reported in the neutron work,[1] are not seen in the present experiment. In column 6 of Table I are listed peak cross sections for resonance states observed via (d,p), but for which angular distributions could not be extracted. These cross sections are generally ≤ 0.1 mb/sr at 20° center of mass scattering angle and could not be separated from the proton-continuum background in a reasonable running time.

In contrast to our earlier work, no resonances are seen via (d,p) which are not seen via $(n,n)/(n,\gamma)$. Of the 11 angular distributions to unbound states which we were able to extract from the data, a total of 8 were to possible doublets or triplets based on the resonance energy information in column 1 of Table I. Columns 7–10 of Table I list the pertinent spectroscopic information extracted in the present (d,p) experiment as discussed below.

In order to extract the neutron width Γ_n from the (d,p) data, the spin J_F of the final nuclear state and the orbital angular momentum transfer l involved in the (d,p) reaction must be known, since one has $\sigma \propto (2J_F+1)S/(2J_I+1)\sigma_{\text{DWBA}}(l_j)$. The shape of the (d,p) angular distribution to unbound states in s-d shell nuclei at tandem energies has been found to be a fairly sensitive indicator of the orbital angular momentum transfer l.[3,4] However, the shape is not sensitive to J_F, so unless J_F is already known, all one can hope to extract from (d,p) data are $(2J_F+1)S$ and $(2J_F+1)\Gamma_n$. If J_F is known from the neutron resonance work, Γ_n can be calculated using the (d,p) data, and the neutron widths extracted via $(n,n)/(n,\gamma)$ and (d,p) techniques may be directly compared.

As Table I illustrates, the agreement of our results with those of neutron work is from fair to poor. The doublet seen at 7.00 MeV, if assumed to be $J_F=2$, $l=1$, for both members, yields from the (d,p) analysis $(2J_F+1)\Gamma_n = 8.7$ keV vs a value of 5.4 keV for the $J_F=2$, $l=1$, 7.012 MeV state reported in the neutron work. The state at 7.408 is the only state for which an unambiguous comparison between the two techniques can be made from the present data. The (d,p) analysis gives $(2J_F+1)\Gamma_n = 10.9$ keV, while the neutron work gives 28.5 keV. For the triplet at 7.67 MeV, assuming dominance by $J=4$, $l=2$ (since the shape of the angular distribution is best fitted by $l=2$), one has from the (d,p) analysis $(2J_F+1)\Gamma_n = 12.4$, while a state at 7.669 MeV from the neutron work has $J_F=4$, $l=2$, and $(2J_F+1)\Gamma_n = 540$. A similar gross disagreement occurs for the $J_F=3$, $l=2$ state at 7.782 MeV where (d,p) gives 5.32 keV while neutron work gives 281 keV. We suspect that the tabulated neutron widths for these last two states as extracted from neutron cross section measurements are in error since the total widths and the neutron widths for these states are tabulated as essentially equal. At these excitation energies inelastic neutron channels are open and one expects $\Gamma_n < \Gamma_T$. Also, the strong possibility exists that since selectivity between $(n,n)/(n,\gamma)$ and (d,p) is so very different, the states seen via (d,p) at 7.67 and 7.87 MeV are not the same states reported from the neutron studies. Their widths as seen in (d,p) are very small compared to the widths of the reported states seen in (n,n); hence, they were probably not seen in the neutron cross section measurements.

For the other six angular distributions extracted from the data l_j and $(2J_F+1)\Gamma_n$ values are listed in

TABLE I. Resonance parameters for ^{24}Na.

Energy (n,n) (keV)	Energy (d,p) (MeV)	J	l	(n,n) $(2J+1)\Gamma_n$ (keV)	$d\sigma(\theta_{c.m.})$ (mb/sr)	l_j	(d,p) $\Gamma_{s.p.}$ (keV)	$(2J+1)S$	$(2J+1)\Gamma_n$ (keV)
	6.564					$p_{3/2}$		0.30	bound
	6.580								
	6.833					$p_{3/2}$		0.38	bound
	6.904					$f_{7/2}$		0.53	bound
2.84	6.961	1	0	1.2 [a]	0.9(25)				
7.53	6.967		1						
31.4	6.990		1			$p_{3/2}$	13.8	0.63	8.7
52.9	7.012	2	1	5.4 [a]					
74.2	7.033								
77.0									
80.2					0.16(25)				
84.0									
86.0									
87.8	7.047								
117.8	···		1						
129.7	7.089		1			$p_{3/2}$	89.8	0.36	32.3
139.5	7.099		1						
169.0	···								
180.0	7.139								
190.0	7.149					$f_{7/2}$	0.336	0.50	0.0168
202.5	7.162	1	0	13.5 [a]	0.02(20)				
219.5	···	0	1	15 [a]					
238.0	7.200	2	1	19.5 [a]		$p_{3/2}$	233	0.26	60.6
242.0		0	1	3.5 [a]					
266.0	7.225				0.2(10)				
281.0	7.240				0.02(10)				
299.5	7.259	2	0	9 [a]		$p_{3/2}$	343	0.27	92.6
322.0	7.281								
366.0	7.325				0.02(20)				
394.5	···	1	1	77.4					
406.0	···								
431.2	7.390	0	1	7.80					
448.6	7.408	2	2	28.5		$d_{5/2}$	27.9	0.39	10.9
508.8	7.468					$d_{5/2}$	39.4	0.38	15.0
544.3	7.503	1	0	106	0.08(20)				
564.1	7.523				0.35(20)				
597.6	7.557	1	1	77.4	0.09(20)				
599.8	7.559								
627.0	7.523				0.08(20)				
683.4	7.642								
709.7	7.669	4	2	540		$d_{5/2}$	82.9	0.15	12.4
726.6	7.686	3	1	315					
748.3	7.702								
766.4	7.725					$f_{7/2}$	4.13	1.05	4.33
780.4	7.739	4	2	392					
912.6	7.872	3	2	281		$d_{5/2}$	152	0.035	5.32
968.0	7.927					$d_{5/2}$	173	0.24	41.5
						$f_{7/2}$	9.04	0.44	3.98
986.5	7.946	1	2	81.6	0.06(30)				

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[a] F. Rahn *et al.*, Phys. Rev. C 8, 1827 (1973).

Table I, but comparison must await assignments from neutron cross section measurements.

The neutron resonances in ^{24}Na seen via (d,p) are dominated by $l=1$, 2, and 3, consistent with expectations based on the single-particle shell model and consistent with results of (n,n) and (n,γ) studies. In those few cases where extracted resonance parameters can be compared between $(n,n)/(n,\gamma)$ and (d,p), the agreement is reasonable. With much improved experimental resolution (≤ 5 keV) such as that available with large magnetic spectrographs, another study of (d,p) to unbound states in ^{24}Na would provide valuable information.

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*Work supported in part by the ERDA and the Robert A. Welch Foundation.

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