^{24}Na at $E_x = 4.7\text{–}5.9$ MeV from ^{22}Ne(^{3}He, p)

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Abstract. Analysis of data from the ^{22}Ne(^{3}He, p) ^{24}Na reaction has been extended to include 18 angular distributions for states between 4.7 and 5.9 MeV. A distorted-wave Born-approximation analysis allows the determination of ℓ value(s) for most of them. Results for J^π are compared with previous information. In general, agreement is good. Some apparent disagreements between current and past results are indicative of population of a different state in this reaction than the nearby one listed in the compilation.

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I. INTRODUCTION

In odd-odd nuclei, the level density can be quite high, even at reasonably low excitation. One such example is ^{24}Na, which has more than 60 levels below 6 MeV of excitation [1]. Considering the high level density, it is quite likely that some of these are unresolved doublets. We investigated this nucleus with the reaction ^{22}Ne(^{3}He, p) by using a gas target that was enriched in ^{22}Ne to 99.8% [2,3]. The experimental resolution was about 23 keV. Initially, we published results for eight states below 4.7 MeV with $\ell = 0$ angular distributions [2]. The first five of these were in good agreement with *sd*-shell shell-model calculations of 0^+ and 1^+ states. The others suggested excitations out of the *sd*-shell space. This is not surprising, because negative-parity states begin at 3.37 MeV in ^{24}Na. Later, we analyzed data for other states up to 4.7 MeV [3]. I recently continued the analysis to the region 4.7–5.9 MeV, and those results are presented here.

Several different reactions have been used to investigate ^{24}Na. They are summarized by Endt [1] and in Nuclear Data Sheets (NDS) [4]. Of particular interest here is the work of Tomandl *et al.* [5] on ^{23}Na(d,p) and ^{23}Na(n,γ); and the work of Vernotte *et al.* [6] on ^{25}Mg(d, ^{3}He). The latter collected good-resolution spectra at two angles—10° and 18°—up to 7 MeV excitation. A more recent ^{23}Na(n,γ) study by Firestone *et al.* [7] (hereinafter referred to as FRB) has provided more information.

II. ANALYSIS AND RESULTS

At the time of our initial study, many states did not have definitive J^π information. In the (^{3}He, p) reaction, because the *np* pair can be transferred with either $S = 0$ or 1, this reaction is less useful than, say, the (t,p) reaction—in which only $S = 0$ is allowed. For example, in (^{3}He, p), the presence of $\ell = 0$ requires $J^\pi = 0^+$ or 1^+. A clear contribution of an $\ell = 2$ component would eliminate the 0^+ possibility. In general, the presence of a given ℓ demonstrates $J = \ell$ or $\ell \pm 1$ and parity $\pi = (-)^\ell$. If the presence of two adjacent even- or odd-ℓ values can be established, then J is the value between them—i.e., $\ell = 2 + 4$ requires $J^\pi = 3^+$, but $\ell = 2$ alone allows $J^\pi = 1^+, 2^+$, or 3^+. Because the kinematics of the reaction favor low ℓ, the presence of $\ell = 2$ and the absence of $\ell = 0$ is sometimes taken to suggest $J^\pi \neq 1^+$.

In Ref. [3], nine states had reasonably certain J^π assignments, and thirteen did not have previous unique J^π assignments. A distorted-wave Born-approximation (DWBA) analysis allowed the identification of the ℓ value(s) for most of these, resulting in J^π assignments for a number of levels and J^π restrictions for most of the others. In some cases, we were unable to resolve two known closely spaced levels, but the extracted excitation energy revealed that most of the observed yield was contributed by only one of the two. For example, the two known states at 3656.1(6) and 3681.7(6) keV corresponded to an excitation energy of 3683(7) keV in our work, so that the $\ell = 0$ could be attributed to the upper one. Similar remarks hold for known states at 3933.9(9) and 3943.1(15), to be compared to our peak at 3931(4) keV, but here it is mostly the lower one we are populating.

Data for a triplet of states at 4186(3), 4196.6(14), and 4206.8(9) keV were not analyzed in Ref. [3], but I include them here, where the energy is 4190(5) keV. The first and third members are 2^+, but the middle one has $J^\pi = (1,2)^-$ in the compilation, but 1^+, 2, 3^+ in NDS. If the 2^+ assignments are correct and an $\ell = 4$ component is indeed present in this angular distribution, then the middle state is 3^+. The new (n, γ) results [7] assign 2^- for the 4207 keV state, but the present angular distribution is inconsistent with that assignment. Of course, that state may not be populated in our experiment—as might be concluded from the extracted excitation energy of 4190(5), in between the energies of the two lower members at 4186(3) and 4196.6(14) keV.

Results for other states in the present energy range are listed in Table I, where they are compared with information from the compilation [1] and from Nuclear Data Sheets [4]. Angular distributions are displayed in Figs. 1 and 2, along with various DWBA curves, with the ℓ values labeled. Parameters of the DWBA calculations were the same as in Ref. [3]. Of the 18 other angular distributions, the present ℓ values agree with established J^π assignments for four of them, while five others appear to disagree. The four agreements are 2^- states at

TABLE I. Present results for levels of ^{24}Na compared with information from the literature. (Energies are in keV.)

Endt [1]		NDS [4]		Present work			FRB [7] [b]
E_x	J^π	E_x	J^π	E_x	ℓ	J^π [a]	
4186.8	2^+	4186.8	2^+				NL
4196.3	$(1,2)^-$	4196.4	$1^+, 2, 3^+$	4190(5)	$2+4$	$2^+, (3^+)$	(2^+)
4207.19	2^+	4207.10	2^+				2^-
4750.94	2^-	4750.99	2^-	4746(6)	$1+3$	2^-	
4772(7)		4772(7)	No J^π				NL
4891.35	$(3^+, 4^-, 5^+)$	4891.27 5	No J^π				NL
		4908.3	No J^π				$(2^+, 3)$
4939.4	$(1,3)^+$	4939.5	$(1,3)^-$	4927(6)	$(2+4); (2+3)$	(3^+)	1^-
4980(7)		4980(7)	No J^π	4974(5)	$2+4\ (1+3)$	3^+	NL
5030(2)		5031.0	$2^+, 3, 4^+$				NL
5044.9	$(1-3)^-$	5045.03	$(1-3)^-$	5044(3)	$1+3$	2^-	(1^-)
5059.72	2^-	5059.63	3^-	5064(4)	3	$3^-, 4^-, (2^-)$	
5117.41	1^-	5117.28	1^-	5119(3)	$1+3$	C	(2^-)
5160(8)		5160(8)	No J^π				NL
		5180.55	No J^π	5182(13)	4	$4^+, 5^+, (3)^+$	NL
5192.44	3^-	5192.35	3^-				
5250(2)	3^-	5252.26	3^-	5242(14)	$3\ (+1)$	C	NL
		5308.1	No J^π				$2^{(+)}$
5339.06	2^-	5339.02	2^-	5337(7)	$1+3$	2^-	
5397.19	$(1,3)^-$	5397.01	$(1,3)^-$				NL
		5408.29	No J^π	5405(10)	(4) or ns		NL
5432(8)	N	5432(8)	No J^π				NL
		5454.61	No J^π				$(1,2)^-$
5478.96	1^-	5479.05	1^-	5477(4)	2	$2^+, 3^+, (1^+)$	
		5571.57	No J^π	5572(5)	3	$3^-, 4^-, (2^-)$	(2^+)
5585(8)	*U*	5585(8)	No J^π				NL
5628.4	2^-	5628.4	2^-	5630(6)	4 (3)	$(4,5,3)^+$	NL
5660(20)		5660(20)	No J^π	5668(6)	(4) or ns		NL
5720(20)		5720(20)	No J^π	5740(9)	$2\ (+4)$	$3^+, (2,1)^+$	NL
5774(3)		5774(5)	No J^π	5779(10)	2 or $(1+3)$	C	(3^+)[c]
		5789.4	No J^π				NL
5809.66		5809.48	$1^+, 2$				2^-
		5850.65	No J^π				(2^+)
5862.9		5862.97	No J^π	5857(7)	2 or $(1+3)$	C	(2^+)
		5896.69	No J^π	5898(7)	4	$4^+, 5^+, (3^+)$	NL
5918.46		5918.22	$1^-, 2, 3^+$				(2^-)
5953.16		5953.31	No J^π				(1^-)

[a] Recommended from the ℓ value. A "C" in this column denotes consistency with previous information.
[b] NL denotes not listed in Ref. [7]. The absence of an entry in this column means the J^π in Ref. [7] is the same as in Ref. [4].
[c] FRB [7] list (3^+) in their Table II, but (2^+) in their text.

4.751 and 5.34 MeV, with $\ell = 1+3$; and 3^- levels at 5.06 and 5.25 MeV, with $\ell = 3$.

Given the high density of states, some of the apparent disagreements undoubtedly represent population of different states than the ones in the compilations. Of the disagreements, the 5.12-MeV state has a clear $\ell = 1+3$ angular distribution, while the J^π in both Endt and NDS is 1^-. However, the new (n, γ) results suggest (2^-), consistent with the present conclusion.

The next apparent disagreement may instead signal the population of a different state. A level at 5192.4 keV has a 3^- assignment in both compilations [1,4], whereas the present angular distribution for a state at 5182(13) keV is clearly $\ell = 4$. A state at 5180.55 keV in NDS has no J^π information and is not listed in the new (n, γ) work. I can thus assign $J^\pi = 4^+, 5^+, (3)^+$ for this state.

A state at 5397 keV has a $(1,3)^-$ assignment in both compilations, but the current angular distribution for a state at 5405(10) keV corresponds to $\ell = 4$ or is of non-stripping character (the state is very weak). Again, this may indicate the presence of two states. In fact, NDS lists a state at 5408.29 keV, with no J^π information, but this level is absent in Endt and (n, γ).

A state at 5477(4) keV is strong and had a clear $\ell = 2$ angular distribution in Ref. [3], while a level at 5479 keV is listed as 1^- in both compilations. A state at 5454.6 keV is listed in NDS with no J^π information and in (n, γ) as $(1,2)^-$, but

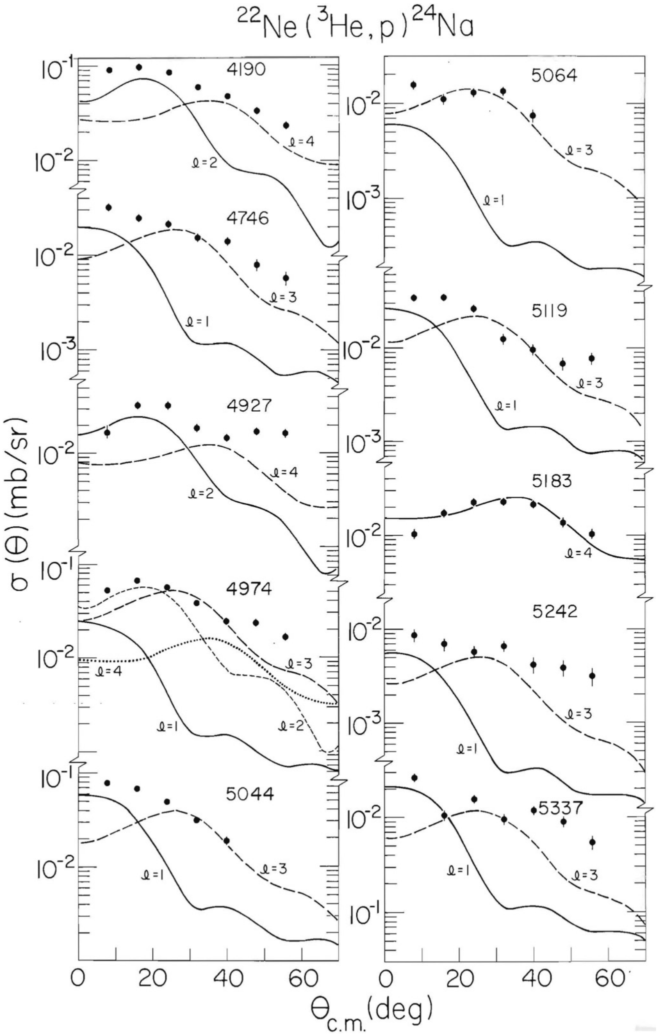

FIG. 1. Angular distributions and DWBA curves for the reaction ^{22}Ne(^{3}He, p)^{24}Na for states at 4.19 MeV and states between 4.7 and 5.4 MeV.

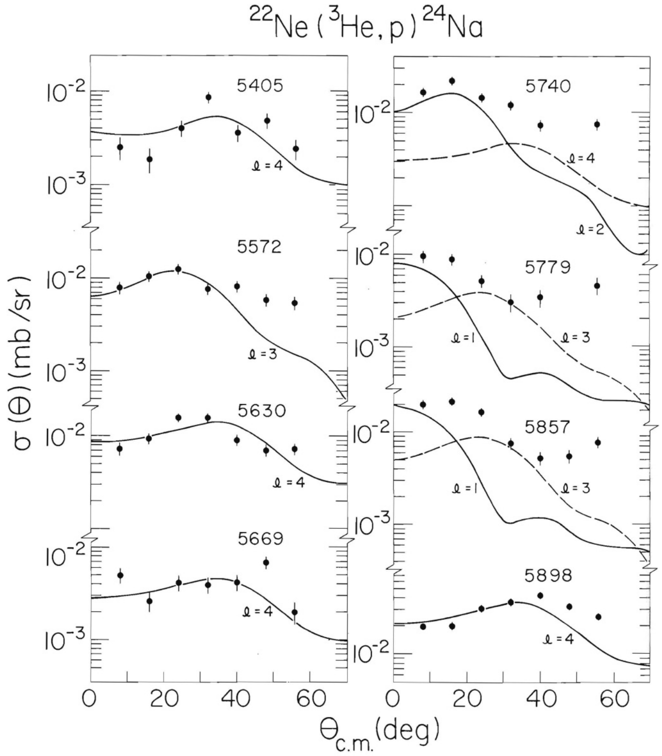

FIG. 2. Same as Fig. 1, but for states between 5.4 and 5.9 MeV.

that state is too far away to be the state observed in the present experiment.

A state at 5628.4 keV has a 2^- assignment in both compilations. The present angular distribution for a level at 5630(6) keV favors $\ell = 4$, (3). The data are displayed in Fig. 2 with $\ell = 4$, and again in Fig. 3 with an $\ell = 3$ curve, which does not provide an acceptable fit. If $\ell = 3$ and the 2^- assignments are correct, the absence of any $\ell = 1$ is surprising. I cannot rule out the presence of $\ell = 3$, with $\ell = 4$ dominating. This state is not listed in the new (n, γ) work [7].

I now discuss each of the other states in turn.

A state at 4891.3 keV has a J^π assignment of ($3^-, 4^-, 5^+$) in Endt, but no J^π information in NDS. The present experiment does not appear to populate this level.

A state at 4908.3 in NDS has no J^π listed, but is suggested to be (2^+, 3) in (n, γ). It is not populated in (^{3}He, p).

A state at 4939.4 keV is listed as $(1,3)^+$ by Endt and as $(1,3)^-$ in NDS. FRB made a firm assignment of 1^-. In the present experiment, a state at 4927(6) keV has an angular distribution characteristic of $\ell = (2 + 4)$ or $(2 + 3)$.

A level at 4980(7) keV in both Endt and NDS has no J^π in either, and it is not listed in FRB. It probably corresponds to the present state at 4974(5) keV, with $\ell = 2,4(1,3)$.

A state at 5030(2) keV has no J^π in Endt, and one at 5031.0 keV is listed as 2^+, 3, 4^+ in NDS. It is not listed in FRB, and it does not appear to be populated here.

A state at 5045 keV has an assignment of $(1 - 3)^-$ in both Endt and NDS. This is likely the present state at 5044(3) keV, with $\ell = 1 + 3$—indicating $J^\pi = 2^-$. However, FRB suggest (1^-).

A level at 5060 keV is listed as 2^- by Endt, but 3^- in NDS. The current angular distribution for a state at 5064(4) keV is

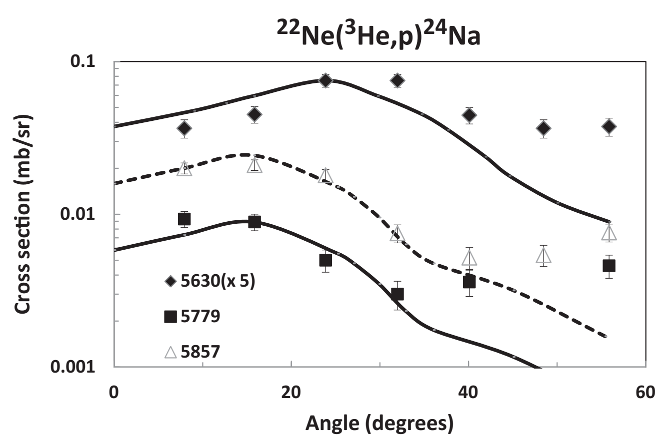

FIG. 3. Angular distributions for states at 5630 keV (solid diamonds), 5779 keV (solid squares), and 5857 keV (open triangles). The first is compared with an $\ell = 3$ curve; the other two with $\ell = 2$.

dominated by $\ell = 3$, with perhaps a hint of $\ell = 1$. The presence of $\ell = 1$ is not compelling, so the preferred assignment is 3^-, 4^-, (2^-).

A state at 5308.1 keV has no J^π listed in NDS, but $2^{(+)}$ in FRB. The present experiment does not see this state.

NDS lists a state at 5571.57 keV, with no J^π information. The present state at 5572(5) has $\ell = 3$, implying $3^-, 4^-, (2^-)$, but it is listed as (2^+) in FRB. The absence of $\ell = 1$ argues against a 2^- assignment.

A level at 5585(8) keV has unnatural parity in Endt and no J^π information in NDS. This state is not seen here, and it is not listed by FRB.

The present 5668(6) keV angular distribution is $\ell = (4)$ or non-stripping. This state is quite weak. A state at 5660(20) keV in both Endt and NDS has no J^π information in either. FRB do not list it.

My 5740(9) keV angular distribution is dominated by $\ell = 2$, with perhaps some $\ell = 4$, implying $J^\pi = 2^+, 3^+, (1^+)$. A state at 5720(20) keV in both Endt and NDS has no J^π information in either. FRB do not list it.

My 5779(10) keV angular distribution is dominated at forward angles by $\ell = 1$ or 2, with perhaps some contribution from $\ell = 3$ or 4 at larger angles. A state at 5774 keV in both Endt and NDS has no J^π information in either, but is suggested as (2^+) by FRB. In Fig. 3, an $\ell = 2$ curve provides an acceptable fit at forward angles, consistent with (2^+) of FRB.

A state at 5809 is listed as 1^+, 2 by NDS and 2^- by FRB. It is not seen here.

My state at 5857(7) keV probably corresponds to the state at 5863 in both compilations, with no J^π information. The angular distribution requires $\ell = 2$ (Fig. 3) or a combination of 1 and 3 (Fig. 2). FRB suggest (2^+). The $\ell = 2$ curve displayed with the data in Fig. 3 provides a reasonable fit. However, a state at 5863 keV was populated via p-wave pickup in the ^{25}Mg$(d,^3$He) reaction—requiring negative parity.

The 5898(7) keV angular distribution appears to favor $\ell = 4$. A state at 5897 keV has no J^π information in NDS, and the state is not listed in FRB.

III. SUMMARY

Analysis of data from the ^{22}Ne$(^3$He$,p)$ ^{24}Na reaction has been extended to include 18 angular distributions for states between 4.7 and 5.9 MeV. A DWBA analysis allows the determination of ℓ value(s) for most of them. In some cases, it is clear that the state being populated in the $(^3$He$,p)$ reaction is different from a nearby state in the compilation. This is not surprising, considering the level density in this nucleus. NDS lists 34 states in this energy range. Reference [5] states that they did not observe levels at 4772(7), 5160(8), and 5432(8) keV. They state "There is no explanation why we could not see these levels. Thus, we consider these levels at least as questionable." None of these states are populated in the present work. Thus, it is likely that these states do not exist.

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