High-Spin States in ^{22}Na

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Based on their selective population in the $^{12}C + ^{14}N \rightarrow \alpha + ^{22}Na$ reactions, states at $E_x = 4.466$, 4.522, and 4.708 MeV are suggested, respectively, as the 4^- member of the $K^\pi = 1^-$ band, the 7^+ member of the ground-state band, and the 5^+ member of the $K^\pi = 0^+$, $T = 0$ band. A very strongly populated state at 8.60 MeV may be the 8^+ member of the ground-state band.

The low-lying levels of ^{22}Na have been described with considerable success in terms of the collective model.[1-5] Several rotational bands have been identified from γ-ray decay studies,[6] lifetime measurements,[7] and single-[4,5] and two-nucleon[3] transfer reactions. Spin and parity assignments now appear definite for all but two of the levels below 4.2 MeV, and J^π values have been suggested[2,3] for those two states. Limits[5] have been placed on the spins and parities of all known final states up to 5.7 MeV, except for those at 4.294, 4.466, 4.522, 5.099, and 5.117 MeV (see Table I). Since states of low spins ($J \leq 5$) would be preferentially populated by the reactions that have been performed earlier, it is not surprising that only one state having $J > 5$ (the suggested[2] 6^+ level at 3.708) has been identified.

Positive-parity states having $J^\pi \leq 4^+$ can be populated in a direct-stripping reaction on ^{21}Ne ($J^\pi = \frac{3}{2}^+$) or in a direct-pickup reaction on ^{23}Na ($J^\pi = \frac{3}{2}^+$) by $l = 0$ or 2, or both. An observed low yield for a particular positive-parity state in both reactions is thus strong evidence that the state has $J > 4$ or that the state is of an unusual configuration. Two-particle transfer on ^{20}Ne can populate positive-parity states with $J \leq 5$ by depositing both nucleons into the *sd* shell and states with $J \leq 7$ by depositing both nucleons into the $f_{7/2}$ orbit. However, these $(f_{7/2})^2$ states are expected to lie quite high in ^{22}Na. Thus, a positive-parity state not observed to be directly populated in any of the three reactions either has a very unusual configuration or has $J > 5$. Similar arguments suggest $J > 3$ for negative-parity states not observed in pickup and stripping.

Recent studies of (^{12}C, α) reactions[8,9] have shown that the states selectively populated in this reaction either have high spin[8,10] or possess α cluster-like configurations.[9] We have, thus, used this reaction to search for the missing high-spin states that are expected to exist in ^{22}Na. In the present work, the states of ^{22}Na were investigated with the reaction $^{14}N + ^{12}C \rightarrow \alpha + ^{22}Na$ at center-of-mass energies of 21.0, 18.5, 16.2, and 13.9 MeV. For the highest energy experiment, a ^{14}N target was bombarded with a ^{12}C beam at a laboratory energy of 39 MeV. For the other three runs, a ^{12}C target was bombarded with a ^{14}N beam of energies 40, 35, and 30 MeV. In both reactions, data were obtained at forward angles. The combined studies then yield both forward- and backward-angle data, albeit at somewhat different center-of-mass energies.

The ^{14}N(^{12}C, α) reaction was studied at a laboratory energy of 39 MeV using the University of Pennsylvania's tandem accelerator and multiangle spectrograph. The target was 8.5 Torr (12.6 μg/cm^2) of natural nitrogen contained in a gas cell with no entrance window.[11] An α-particle spectrum obtained at 7.5° is shown in Fig. 1. The energy loss[12] of approximately 42 keV for 39-MeV ^{12}C ions in the target accounts for most of the observed width of the α groups. The 30-MeV ^{12}C(^{14}N, α) study was also performed at the University of Pennsylvania, using a 13-μg/cm^2 self-supporting natural C foil target. Angular distributions were measured in that study.[13] Data from the ^{12}C(^{14}N, α) reactions at 35 and 40 MeV were obtained using the Brookhaven National Laboratory's MP tandem accelerator and the Massachusetts Institute of Technology's multiple-gap spectrograph recently moved to Brookhaven National Laboratory (BNL). The target was a natural carbon foil of thickness 9 μg/cm^2, corresponding to energy losses[12] of approximately 54 and 51 keV for 35- and 40-MeV incident ^{14}N ions. A 35-MeV spectrum of this reaction obtained at a lab angle of

7.5° is shown in Fig. 2. Absolute differential cross sections measured at 7.5° in the 39- and 35-MeV runs are presented in Table I. Also tabulated are absolute differential cross sections at 3.75° and total cross sections σ_T (obtained by integrating from 0 to 90°) measured in the 30-MeV run. Expected uncertainties of 20, 35, and 50% are assigned to the absolute cross-section scales of the 39-, 30-, and 35-MeV runs, respectively.

The spectra shown in Figs. 1 and 2 are typical of those observed in α-particle-producing, heavy-ion reactions, where ^{12}C is the target or incident particle.[9] Moderately strong transitions are observed to selected low-lying levels; at higher excitation energies, very intense groups are superimposed on a background caused by breakup and by formation or unresolved levels.

Since the ground states of ^{12}C, ^{14}N, and the α particle all have zero isospin, the $^{12}C + ^{14}N \rightarrow \alpha + ^{22}Na$ reaction can populate $T = 1$ final states only through isospin mixing. Indeed, those known or suspected $T = 1$ states that could be resolved from nearby states are very weakly populated. These include states at excitation energies of 0.657, 4.069, 5.165, 6.715, and 6.834 MeV (level Nos. 6, 15, 28, 50, and 52, respectively).

In both spectra (Figs. 1 and 2), the low-lying members of the ground-state rotational band (ground state, 3^+; 0.891 MeV, 4^+; and 1.528 MeV, 5^+) are among the strongest transitions observed below 4 MeV. The 3.708-MeV state (level 13), which has been suggested[2] to be the 6^+ member of the ground-state band, is as strongly populated in the 35-MeV ^{12}C(^{14}N, α) spectrum (Fig. 2) as the lower-spin members of this rotational band. The trend is apparent by inspection of the integrated

TABLE I. Cross sections for the $^{12}C + ^{14}N \rightarrow \alpha + ^{22}Na$ Reaction.

Level No.	E_x [a] (MeV)	J^π [a]	K^π [a]	$d\sigma/d\Omega$ (mb/sr) ^{14}N(^{12}C, α) [b] 39 MeV, 7.5°	^{12}C(^{14}N, α) 35 MeV, 7.5°	^{12}C(^{14}N, α) 30 MeV, 3.75°	$\sigma_{0-90°}$ [c] (mb) ^{12}C(^{14}N, α) 30 MeV
0	0.0	3^+	3^+	0.111	0.439	0.507	0.806
1	0.583	1^+	0^+	0.029	0.181	0.091	0.134
2	0.657	0^+, $T=1$	0^+	0.002	0.013	0.057	0.084
3	0.891	4^+	3^+	0.170	0.424	0.205	0.949
4	1.528	5^+	3^+	0.198	0.388	1.14	2.079
5	1.937	1^+	1^+	{0.044			
6	1.952	2^+, $T=1$	0^+		{0.328	{1.03	{1.51
7	1.984	3^+	0^+	0.099			
8	2.211	1^-	1^-	0.014	0.348	0.156	0.323
9	2.572	2^-	1^-	0.078	0.250	0.250	0.919
10	2.969	3^+	d	0.182	0.059	0.495	0.913
11	3.059	2^+	(1^+)	0.057	0.252	0.152	0.628
12	3.521	3^-	1^-	0.109	0.430	0.100	0.800
13	3.708	(6^+)	(3^+)	0.068	0.353	0.211	0.835
14	3.944	1^+	(1^+) [d]	0.027	0.033	0.228	0.269
15	4.069	$(4)^+$, $(T=1)$	(0^+)	0.014	0.002 [f]	0.023	0.125
16	4.294			0.011	{0.022	{0.402	{0.913
17	4.319	1^+		0.068			
18	4.360	$2^+(1^+)$	$2^+(1^+)$	0.015	0.027	0.010 [f]	0.063 [f]
19	4.466	(4^-) [e]	(1^-) [e]	0.136	{2.38	{0.575	{3.240
20	4.522	(7^+) [e]	(3^+) [e]	0.431			
21	4.583	$2^-(0^-, 1^-, 3^-)$	2^-	{0.035	0.009 [f]	{0.010 [f]	{0.063 [f]
22	4.622	1			0.016 [f]		
23	4.708	(5^+) [e]	(0^+) [e]	0.307	0.165	0.552	2.01
24	4.770	0^+-4^+	d	0.128	{0.013 [f]	0.008 [f]	0.050 [f]
25	5.061	1^+, 2^+		0.067		0.008 [f]	0.050 [f]
26	5.099			{0.148	{0.413	{0.992	{2.14
27	5.117						
28	5.165	$(2)^+$, $(T=1)$	2^+	0.035	0.005 [f]	0.008 [f]	0.050 [f]

[a] Excitation energies, spin, parity, and band assignments (except those noted by a superscript) are from the literature as summarized in Ref. 5.

[b] Reference 13.

[c] Cross section integrated from 0–90° in the center-of-mass system.

[d] See Ref. 5.

[e] Suggested from the present study.

[f] Upper limit for the cross section.

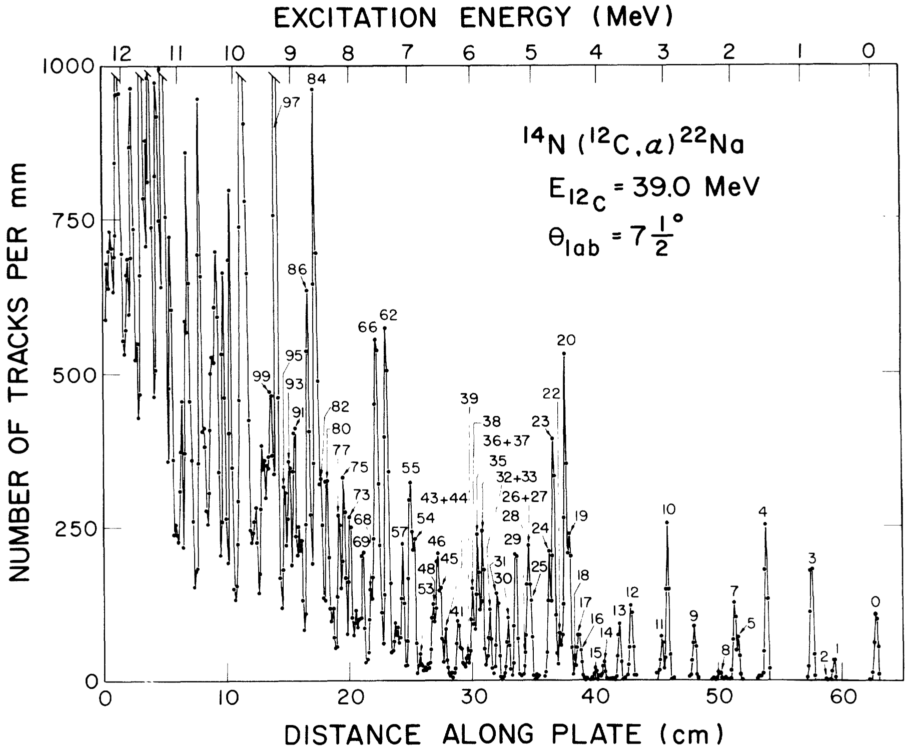

FIG. 1. α-particle spectrum from the ^{14}N(^{12}C, α)^{22}Na reaction at a bombarding energy of 39 MeV. Excitation energies and differential cross sections corresponding to specific levels are listed in Table I. The level numbering scheme is the same as used in Refs. 3–5.

cross sections displayed in the last column of Table I. Even though there are a few exceptions, the general trend is that higher-spin states possess larger integrated cross sections. The cross section integrated from 0 to 90° for the 3.708-MeV level in the 30-MeV ^{12}C(^{14}N, α) study is larger than that for the other levels in this excitation region (Table I), even though this level is not selectively populated at the extreme forward angles.

By far the strongest transition observed below 7 MeV in both Figs. 1 and 2 is that to the 4.522-MeV level (level 20) of ^{22}Na. This state was only weakly populated by the single-[4,5] and two-nucleon[3] transfer reactions (with no hint of a direct-like process) and was suggested[5] as a possible high-spin state. It is an excellent candidate for the 7^+ member of the ground-state rotational band.

For nuclei with $A = 18-22$, recent shell-model calculations[14] in a full $1d_{5/2}$-$2s_{1/2}$-$1d_{3/2}$ basis give good agreement with most of the observed experimental properties of low-lying levels. In particular, predicted excitation energies of high-spin states appear[14] to be quite reliable. Figure 3 contains the predicted excitation energies from these shell-model calculations for the lowest positive-parity state of each spin 3–9. Also plotted are the experimental excitation energies. The agreement between theory and experiment is seen to be excellent for the 3^+–6^+ members of the ground-state band. If the 4.522-MeV state is indeed the 7^+ member of this band, the agreement for that state is also quite good.

The next strongest state below 7 MeV in Fig. 1 and in the integrated cross sections is the state at $E_x = 4.708$ MeV (level 23). This level has been suggested from γ-decay studies[2] to be the 5^+ member of the $K^\pi = 0^+$, $T = 0$ rotational band. This state was only weakly excited in the single-nucleon transfer reactions[4,5] and was populated by a probable $L = 4$ transfer in the ^{20}Ne(^{3}He, p) reaction.[3] All the evidence is consistent with the 4.708-MeV level's being the 5^+ member of the $K^\pi = 0^+$, $T = 0$ rotational band.

The 4.466-MeV state (level 19) also was weakly excited in one- and two-nucleon transfer and was suggested[5] as a possible high-spin state. It is not resolved from the stronger 4.522-MeV level in the ^{12}C(^{14}N, α) runs, but it is populated with moderate strength in the ^{14}N(^{12}C, α) reaction. The 4^- member of the 1^- rotational band is expected[2] in this region of excitation. We tentatively identify this 4^- state as the experimental level at 4.466 MeV.

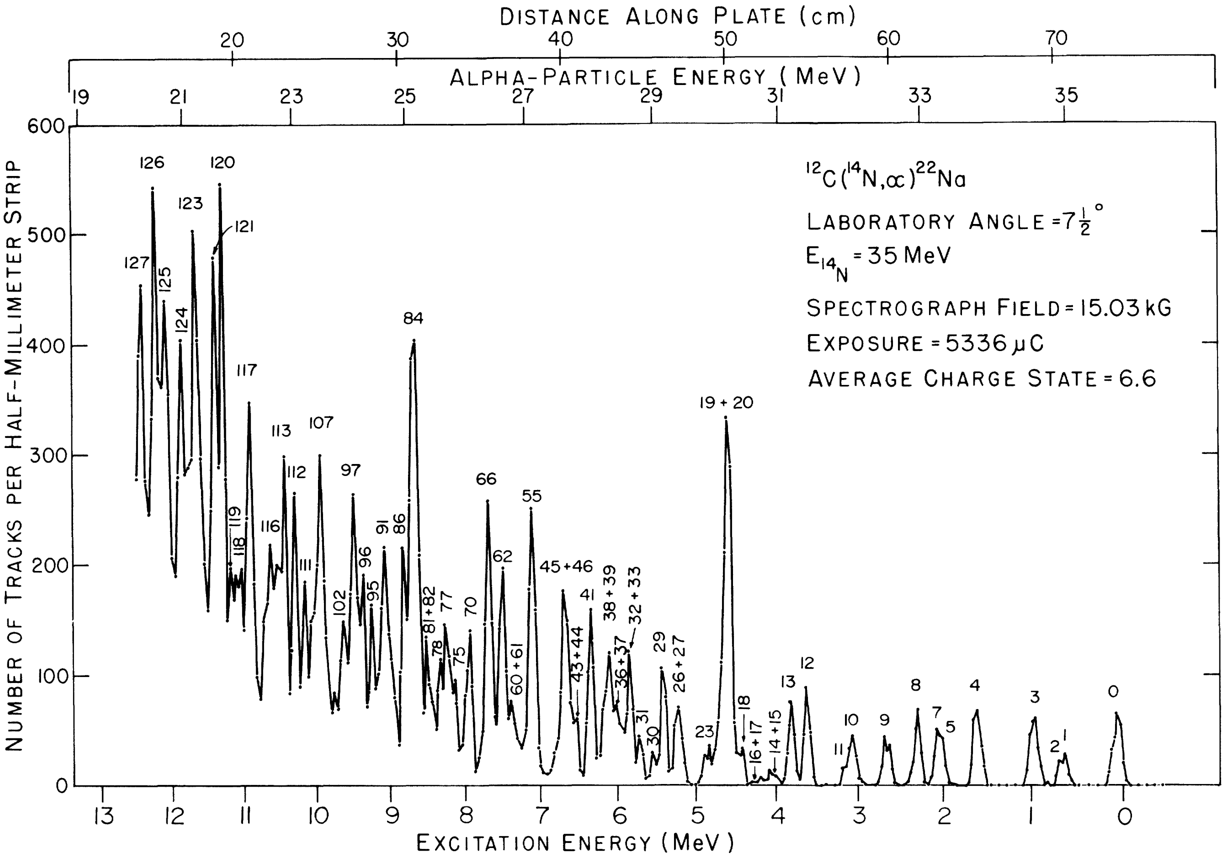

FIG. 2. α-particle spectrum from the ^{12}C(^{14}N, α)^{22}Na reaction at a bombarding energy of 35 MeV. Excitation energies and differential cross sections corresponding to specific levels are listed in Table I. The level numbering scheme is the same as used in Refs. 3–5.

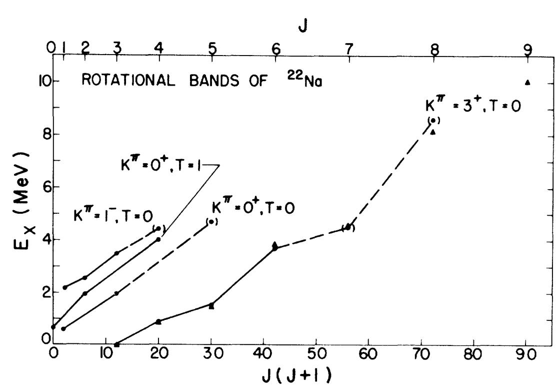

FIG. 3. Plot of excitation energies for states of spin J versus $J(J+1)$ for the low-lying rotational bands of ^{22}Na. The identifications suggested in the present work are included in parentheses. The triangles indicate the predicted excitation (Ref. 14) of the lowest level of spin J. Other known rotational bands in ^{22}Na are summarized in Refs. 4 and 5.

The lowest 8^+ state of ^{22}Na is predicted[14] at an excitation energy of 8.15 MeV, and a second 7^+ level is predicted at 8.5 MeV. In the 35- and 40-MeV ^{12}C(^{14}N, α) exposures, as well as in the 39-MeV ^{14}N(^{12}C, α) exposure, the 3^+, 4^+, 5^+, 6^+, and suggested 7^+ members of the ground-state rotational band are all strongly populated, and the transition to the 8.60-MeV level is the strongest observed below 9 MeV. (See Figs. 1 and 2.) Thus, it appears the 8.60-MeV state also has high spin and is a good candidate for the 8^+ member of the ground-state band.

These tentative assignments should, of course, be confirmed by further study. More specific spectroscopic information may be obtained by studying the decay modes of these states. The $^{12}C + {}^{14}N \rightarrow \alpha + {}^{22}Na$ reaction should serve as a convenient means of selectively populating them for such a study.

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