^{26}Mg(t, ^{3}He) reaction and a spherical-shell-model description of ^{26}Na†

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(Received 19 September 1973)

The ^{26}Mg(t, ^{3}He) reaction at an incident energy of 23.5 MeV has been used to measure the ground-state mass and the energies of the excited states of ^{26}Na. The measured mass excess (-6.903 ± 0.020 MeV) is in agreement with that measured using the ^{26}Mg(^{7}Li, ^{7}Be) reaction and with the *most recent* β-decay end-point measurement. The spectrum of low-lying levels together with a recent assignment of 3^+ for the ground-state spin are not consistent with a rotational interpretation for ^{26}Na. These data, however, can be explained in terms of the spherical shell model.

[NUCLEAR REACTIONS ^{26}Mg(t, ^{3}He) E=23.5 MeV measured Q value, ^{26}Al levels.]

I. INTRODUCTION

Neutron-rich s-d-shell nuclei are the subject of several recent experimental studies.[1] Measurements of masses and experimental level schemes for these nuclei permit a test of the systematics of mass relationships and theoretical level schemes in the region away from stability. Nuclear reactions are particularly well suited for the study of such nuclei, as they are capable of mass measurements of the order of tens of keV, and data on excited states are obtained simultaneously. The (t, ^{3}He) charge-exchange reaction on neutron-rich targets represents an excellent method for the study of such nuclei.[2]

The low-lying levels of the F to Al nuclei with A=19–27 have been described[3–8] with considerable success in terms of the rotational model. Recent calculations[9] have demonstrated that the rotational aspects of these nuclei are calculable in terms of the spherical shell model with a full s-d-shell basis. Detailed studies of the T=0 (Ref. 4), T=1 (Refs. 4 and 5), and T=2 (Ref. 10) states of the mass-24 nuclei indicate that the spectrum of excited states in these nuclei requires a decrease in the deformation for an increase of T. Similarly measured static quadrupole moments of the first excited states of the even-even Ne and Mg isotopes indicate a ~30% decrease when two neutrons are added to the self-conjugate nuclei.[8, 11]

The present paper reports a measurement of the ground-state mass and the excitation energies of the levels of ^{26}Na using the ^{26}Mg(t, ^{3}He) reaction. Earlier measurements of the mass excess of the ^{26}Na ground state have differed considerably. A value of -6.853 ± 0.030 MeV was obtained from a study of the ^{26}Mg(^{7}Li, ^{7}Be) reaction[12]; whereas, values of -7.70 ± 0.30 and -7.20 ± 0.50 MeV had been obtained from β-decay end-point measurements.[13, 14] The low-lying level scheme for ^{26}Na is discussed and is compared with the levels of ^{24}Na (a known rotational nucleus[4, 5]) populated by the ^{24}Mg(t, ^{3}He) reaction.

II. EXPERIMENTAL PROCEDURE

The ^{26}Mg(t, ^{3}He)^{26}Na reaction was studied using the 23.5-MeV triton beam of the Los Alamos Van de Graaff facility. The reaction products were measured between 15 and 30° (lab angle) in 5° steps using an E-ΔE silicon surface-barrier-detector telescope with a 50-μm-thick ΔE detector. A third detector was placed behind the E detector, and its signal in anticoincidence was used to reduce background in the spectra due to chance coincidences. The masses of the reaction products were identified on line using standard techniques.[15] An experimental resolution of 45 keV full width at half maximum was obtained. Helium-3 energy spectra measured at 25 and 30° in the laboratory are shown in Fig. 1. Data obtained at the most forward angle was of only limited usefulness because of a large broad group resulting from the p(t, ^{3}He)n reaction. The ground-state Q value for the ^{26}Mg(t, ^{3}He) reaction was measured relative to that of the ^{16}O(t, ^{3}He) transition to the ground and 297-keV states[16] of ^{16}N (see Fig. 1).

Spectra of the ^{24}Mg(t, ^{3}He) reaction populating states of ^{24}Na also were measured at the same

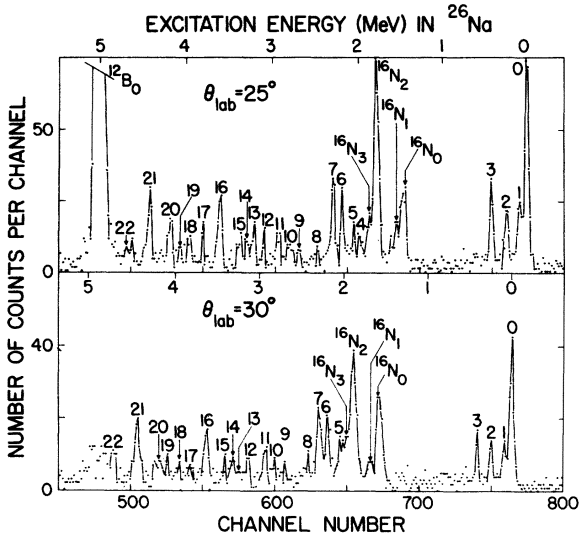

FIG. 1. Helium-3 energy spectra corresponding to the reaction ^{26}Mg(t, ^{3}He)^{26}Na measured at an incident triton energy of 23.5 MeV and at laboratory angles of 25° (top) and 30° (bottom). Excitation energies corresponding to the numbered groups are given in Table II. Groups corresponding to transitions on C and O impurities are labeled by the levels of the corresponding final nucleus.

incident energy and using similar experimental techniques. The population of the excited states of ^{24}Na using this reaction are compared with the ^{26}Mg(t, ^{3}He) results in Sec. IV. A complete analysis of the ^{24}Mg(t, ^{3}He)^{24}Na study will be published separately.[17]

III. GROUND-STATE MASS OF ^{26}Na

A Q value of -9.292 ± 0.020 MeV was measured for the ^{26}Mg(t, ^{3}He) transition to the ground state[18] of ^{26}Na. This value corresponds to a mass excess of -6.903 ± 0.020 MeV for the ^{26}Na ground state, and it is compared to earlier ground-state mass-excess measurements for ^{26}Na in Table I. The results of a more recent β-decay measurement[19] of the ^{26}Na mass also are shown. The present value is within the error of two of the β-decay end-point measurements,[14,19] however, it differs considerably from another value obtained from a third β-decay end-point measurement.[13] It also differs by 50 keV from the mass excess determined from the ^{26}Mg(^{7}Li, ^{7}Be)^{26}Na reaction.[12] This discrepancy is probably the result of an excited state of ^{26}Na observed at an excitation of 88 keV (see Table II). This state would not have been resolved from the ground state in the (^{7}Li, ^{7}Be) study. Its presence would shift the centroid of the unresolved states toward a more negative Q value, thus accounting for the more positive mass excess measured in the (^{7}Li, ^{7}Be) study (see Table I).

Mass excesses predicted using the mass relations of Garvey *et al.*[20,21] and recent compiled masses[22] are given for comparison in the bottom portion of Table I. Predictions using the mass formula of Zeldes, Grill, and Simievic[23] also are tabulated. The mass excesses calculated using the different mass relations of Garvey and Kelson differ considerably, and only one value is in reasonable agreement with the measured mass excess. Possible reasons for such discrepancies are discussed in Sec. V.

IV. EXCITED-STATE SPECTRUM OF ^{26}Na

Transitions also were observed populating several excited states of ^{26}Na (see Fig. 1). The excitation energies and the relative (t, ^{3}He) cross sections at 25 and 30° (laboratory angles) are

TABLE I. Mass excess of the ^{26}Na ground state.

Mass excess (MeV)	Method	Reference
Present work		
-6.903 ± 0.020	(t, ^{3}He) reaction	Present work
Other measurements		
-6.853 ± 0.030	(^{7}Li, ^{7}Be) reaction	12
-7.70 ± 0.30	β-decay end point	13
-7.20 ± 0.50	β-decay end point	14
-7.00 ± 0.20	β-decay end point	19
Predicted values		
	Garvey-Kelson mass relations	20, 21
-5.763	T relation	
-6.795	L relation [a]	
-7.586	L relation [b]	
-6.799	Zeldes, Grill, and Simievic mass formula	23

[a] Calculated using the masses of ^{25}Na, ^{26,28}Mg, and ^{28,29}Al.
[b] Calculated using the masses of ^{23,24}Ne, ^{24}Na, and ^{26,27}Mg.

given in Table II. Excited states at 0.21 ± 0.04, 2.21 ± 0.04, and 4.91 ± 0.04 MeV and a possible state at 0.84 ± 0.04 MeV were reported from the ^{26}Na(^{7}Li, ^{7}Be) study.[12] The superior resolution and better statistics of the present study and only one particle group per excited state[24] allow more detail in the identification of excited states. The state populated in the (^{7}Li, ^{7}Be) reaction at 0.21 MeV probably corresponds to the level observed at 241 keV (state No. 2) in the present study. Similarly the 2.21 ± 0.04-MeV level [from (^{7}Li, ^{7}Be)] would correspond to the summed strength of levels observed at 2186 and 2290 keV (levels Nos. 6 and 7) in the present study. These states, 241, 2186, and 2290 keV, together with the ground state and a state at 420 keV, contain the largest observed ^{26}Mg(t, ^{3}He) cross sections. The 420-keV state in the (^{7}Li, ^{7}Be) spectrum would not be distinguished from the transition leaving ^{26}Na in its ground state and ^{7}Be in its 431-keV first excited state.[24] It, therefore, appears as if the (t, ^{3}He) and (^{7}Li, ^{7}Be) charge-exchange reactions on ^{26}Mg probably select the same final states in ^{26}Na.

The observed spectrum of excited states for ^{26}Na is an interesting contrast to other mid s-d-shell odd-odd nuclei.[4-7, 25] Four states are identified below an excitation of 420 keV and no states are observed[26] between 420 and 1996 keV. In fact, the level structure is reminiscent of ^{16}N (see Ref. 16 and Fig. 1). Of course, states of ^{26}Na could exist in the 420- to 1996-keV excitation region that have remained undetected because they are weakly populated in the charge-exchange reactions. Additional levels below 420 keV also could remain undetected because of their weak population in these reactions or if they were not resolved from the more strongly populated levels.

TABLE II. ^{26}Mg(t, ^{3}He) relative cross sections for the states of ^{26}Na.

Level [a] No.	E_x [b] (keV)	$d\sigma/d\omega$ [c] 25°	30°	Level [a] No.	E_x [b] (keV)	$d\sigma/d\omega$ [c] 25°	30°
0	0	100	66	12	3123	9	12
1	88	34	22	(13)	3232	16	7
2	241	31	20	14	3310	11	17
3	420	36	21	15	3400	13	9
(4)	1996*	20	d	16	3618	32	29
5	2048	16	14	17	3814	11	10
6	2186	24	31	18	3966	11	9
7	2290	45	40	19	4083	5	10
8	2456	6	14	20 [e]	4190	21	13
9	2697	7	7	21	4440	31	35
10	2815	11	12	22 [e]	4702	7	16
11	2933	14	17				

[a] Level number in parentheses indicates that there may be some uncertainty in the existence of this level.
[b] The estimated uncertainty in the excitation energy is ±15 keV except for those states marked by an asterisk where the expected energy error is ±30 keV.
[c] The center-of-mass cross sections are expressed in relative units.
[d] Level covered by an impurity group.
[e] Probable doublet.

To further study the spectrum of states of odd-odd nuclei in this mass region as populated by the charge-exchange reaction, the levels of ^{24}Na have been excited using the ^{24}Mg(t, ^{3}He) reaction. Spectra of ^{24}Na and ^{26}Na at 25° lab angle populated using the (t, ^{3}He) reaction at the same incident (23.5-MeV) energy are compared in Fig. 2. The spins, parities, and assumed rotational-model configurations of the low-lying levels of ^{24}Na are summarized[4, 5] in Table III.

The low-lying levels of ^{22}Na (Refs. 6 and 7) and ^{24}Na (Refs. 4 and 5) have been described, with considerable success, in terms of the rotational model. This model describes the low-lying configurations of ^{26}Na as an unpaired proton in the $\frac{3}{2}^{+}[211]$ Nilsson level (see Fig. 3) coupled to an unpaired neutron in either the $\frac{1}{2}^{+}[211]$ Nilsson level for small deformations or the $\frac{5}{2}^{+}[202]$ level for large deformations. (These configurations are shown diagramatically in the upper portion of Fig. 4.) The $\pi \frac{3}{2}^{+}[211] \otimes \nu \frac{1}{2}^{+}[211]$ configuration would predict low-lying $K^{\Pi} = 1^{+}$ and 2^{+} rotational bands, and the $\pi \frac{3}{2}^{+}[211] \otimes \nu \frac{5}{2}^{+}[202]$ configuration would predict low-lying $K^{\Pi} = 1^{+}$ and 4^{+} bands. Bands thought to be based on both these two configurations[4, 5] are observed to be populated in ^{24}Na by the ^{24}Mg(t, ^{3}He) reaction (see Fig. 2 and Table III). Either configuration (assuming spacing and population similar to ^{24}Na) would give a very different low-lying spectrum than that observed for ^{26}Na. Additional evidence against a rotational interpretation for ^{26}Na is the recent assignment[19, 27] of $J^{\Pi} = 3^{+}$ to its ground state based on the observed β^{-} branches to the 2^{+} and 4^{+} levels of ^{26}Mg. In terms of the rotational model the ground state should be the lowest level in one of the rotational bands; however, none of the predicted bands have a 3^{+} band head.

An alternate description of the low-lying spectrum of states of ^{26}Na is the spherical shell model. Such a description is perhaps reasonable, since it is necessary to assume a considerably smaller deformation to describe the low-lying levels of ^{24}Na (Refs. 4 and 5) than for either ^{22}Na (Refs. 6 and 7) or ^{24}Mg (Ref. 4). Nearly spherical configurations also have been suggested for the low-lying levels of ^{24}Ne (Ref. 10) and for ^{25}Na (Ref. 28). In terms of the shell model the low-lying levels of ^{26}Na would be described as an unpaired $d_{5/2}$ proton coupled to an unpaired $s_{1/2}$ neutron (see

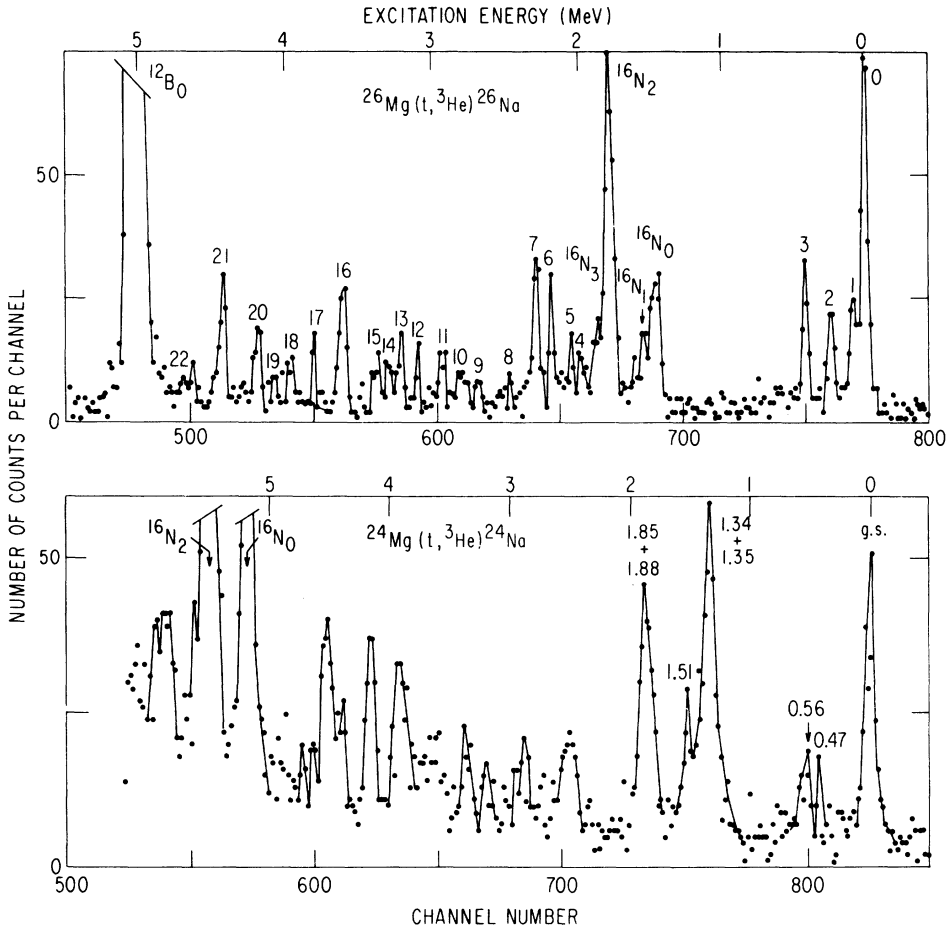

FIG. 2. Comparison of spectra for the reactions ^{26}Mg(t,^{3}He)^{26}Na (top) and ^{24}Mg(t,^{3}He)^{24}Na (bottom) measured at identical incident energies (23.5 MeV) and laboratory angles (25°). Excitation energies corresponding to the numbered groups in the ^{26}Na spectrum are contained in Table II. The suggested rotational-model configurations corresponding to the low-lying labeled states in the ^{24}Na spectra are contained in Table III.

TABLE III. Summary of configurations of states of ^{24}Na.

Excitation energy [a] (MeV)	J^{Π} Assigned [b]	Suggested [b]	K^{Π} [b]	Configuration [b]
0.0	4^+	4^+	4^+	$\pi 5/2^+[211]\otimes\nu 5/2^+[202]$
0.472	1^+	1^+	1^+	$\pi 5/2^+[211]\otimes\nu 5/2^+[202]$
0.563	(2^+)	2^+	1^+	$\pi 5/2^+[211]\otimes\nu 5/2^+[202]$
1.341		3^+	1^+	$\pi 5/2^+[211]\otimes\nu 5/2^+[202]$
1.347	1^+	1^+	1^+	$\pi 5/2^+[211]\otimes\nu 1/2^+[211]$
1.511	$(0,\ldots,5)^+$	5^+	4^+	$\pi 5/2^+[211]\otimes\nu 5/2^+[202]$
1.846	$(1,2)^+$	2^+	1^+	$\pi 5/2^+[211]\otimes\nu 1/2^+[211]$
1.885	$(0,\ldots,5)^+$	4^+	1^+	$\pi 5/2^+[211]\otimes\nu 5/2^+[202]$

[a] Reference 25.

[b] Reference 5; see also Ref. 4 for a discussion of the analog of these states in ^{24}Mg.

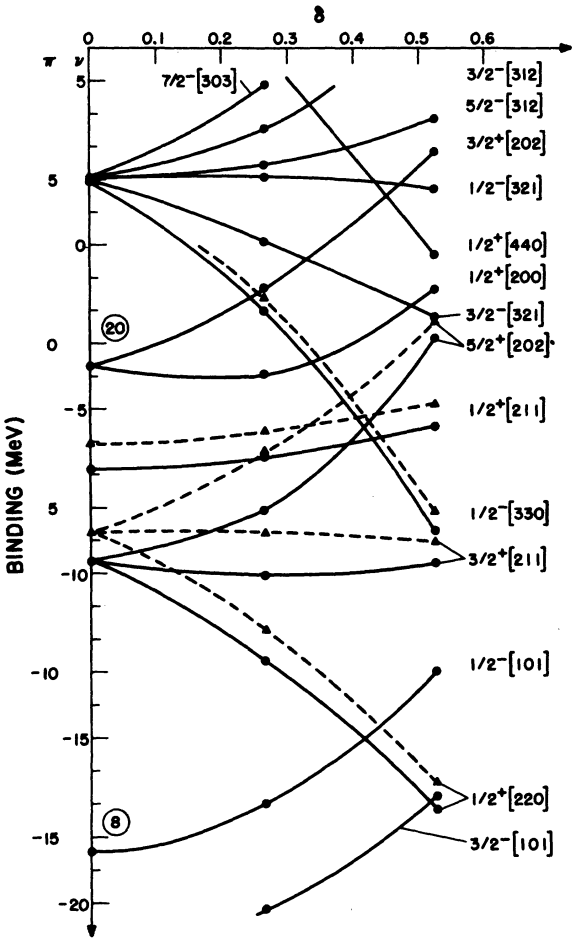

FIG. 3. Binding energies of deformed neutron (solid curves) and proton (dashed curves) states as calculated in a Woods-Saxon potential. Particulars of the calculation are contained in Ref. 6. The abscissa is the ellipsoidal deformation δ.

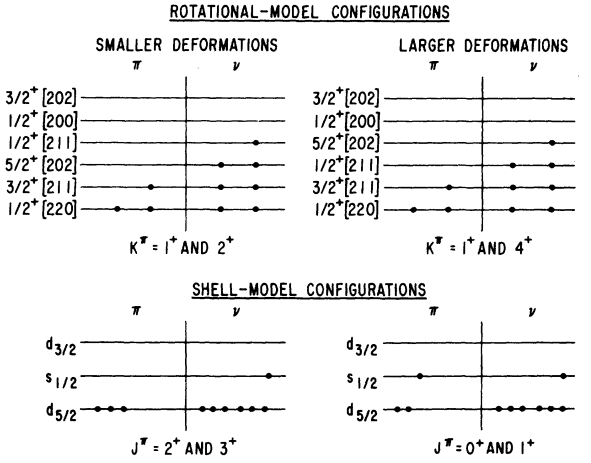

FIG. 4. Rotational-model (top) and spherical-shell-model (bottom) configurations for the low-lying levels of ^{26}Na. See text for a discussion of ^{26}Na in terms of these configurations.

lower-left diagram of Fig. 4). Such a configuration, $\pi d_{5/2} \otimes \nu s_{1/2}$, would produce a 2^+ and a 3^+ state. Other low-lying spherical-shell-model states in ^{26}Na would be obtained by promoting an unpaired proton from the $d_{5/2}$ to the $s_{1/2}$ orbit (see lower-right portion of Fig. 4). States of $J^\pi = 0^+$ and 1^+ then are obtained by the couplings of an unpaired proton and neutron in the $s_{1/2}$ orbit. States in ^{26}Na of a pure $\pi s_{1/2} \otimes \nu s_{1/2}$ configuration would not be populated in the ^{26}Mg(t, ^{3}He) reaction if the proton configuration of ^{26}Mg is pure $(d_{5/2})^4$. It is known, however, from a study of the ^{26}Mg-(d, ^{3}He)^{25}Na proton-pickup reaction[29] that there is sizable $s_{1/2}$ proton strength (~15% of the $d_{5/2}$ proton strength) in the ^{26}Mg ground state. States of the $\pi s_{1/2} \otimes \nu s_{1/2}$ configuration in ^{26}Na could be populated through the $\pi s_{1/2}$ components in the ^{26}Mg ground state or by mixing with other configurations in ^{26}Na, e.g. $\pi d_{5/2} \otimes d_{3/2}$ which would give states having $J^\pi = 1^+$, 2^+, 3^+, and 4^+.

V. CONCLUSIONS

The mass excess of ^{26}Na has been measured and the low-lying states of ^{26}Na have been studied using the ^{26}Mg(t, ^{3}He) reaction. The measured Q value is consistent with the ^{26}Na mass excess obtained from the ^{26}Mg(^{7}Li, ^{7}Be) reaction[12] and with some of the β-decay end-point measurements[14,19] (see Table I).

The 3^+ ground-state spin and parity[19,27] and the spectra of low-lying levels (at least four levels below an excitation of 420 keV and a large gap between 420 and 1996 keV with no observed states[26]) of ^{26}Na cannot be understood in terms of the rotational model which has been successful explaining the level structure of the lighter even-mass Na isotopes.[4-7] The spherical shell model is consistent with the spin of 3^+ for the ground state of ^{26}Na (Refs. 19 and 27), and it also is possible to explain the observed level structure of ^{26}Na in terms of this model. To explain the population of four low-lying states of ^{26}Na in the (t, ^{3}He) reaction, however, requires either sizable $s_{1/2}$ strength in the ^{26}Mg ground state, considerable mixing among the final shell-model configuration in ^{26}Na, or processes other than simple one-step direct transfer in the mechanism of the (t, ^{3}He) reaction.

Such a rapid change of the coupling scheme from deformed to spherical could account for the gross discrepancy between the observed mass and that predicted using certain mass relations (see Table

I). For example, the T relation of Garvey *et al.*[20] uses masses of predominately deformed nuclei to predict the ground-state mass of ^{26}Na. The L relations, however, use masses of nuclei with larger neutron excesses to predict the mass of ^{26}Na, and increased binding is predicted. Similar large discrepancies between observed and predicted masses are observed for other neutron-rich nuclei in this mass region.[19]

The mechanism of the (t, ^{3}He) reaction at present is not sufficiently understood to interpret angular distributions corresponding to the various transitions. More definitive experimental data on ^{26}Na, therefore, awaits a better understanding of the charge-exchange reaction or studies of ^{26}Na utilizing other reactions to populate ^{26}Na.

ACKNOWLEDGMENTS

We wish to thank the authors of Ref. 19 for communicating their results prior to publication. The assistance of S. Orbesen and P. M. Kurjan in obtaining and analyzing the data is gratefully acknowledged.

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†Work performed under the auspices of the U. S. Atomic Energy Commission.

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