Electromagnetic transitions in ^{22}Na

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Electromagnetic properties of excited states of ^{22}Na below 4.6-MeV excitation energy have been studied using the ^{23}Na(^{3}He, $\alpha\gamma$)^{22}Na and ^{19}F(α, $n\gamma$)^{22}Na reactions. Investigation of the decay scheme of the 4069-keV level using the ^{23}Na(^{3}He, $\alpha\gamma$)^{22}Na reaction shows a $(10 \pm 3)\%$ branch to the 1528-keV level, compared to a value of 21% reported previously. The existence of weak γ-ray transitions from the 1983-, 2211-, and 2572-keV levels has been confirmed from γ-ray spectra obtained above and below threshold for population of these levels via the ^{19}F(α, n)^{22}Na reaction. A long standing controversy regarding the spin of the 1983-keV level has been resolved by γ-ray angular distribution measurements close to threshold for the population of the 1983-keV level via the ^{19}F(α, n)^{22}Na reaction; the results show that $J^\pi(1983) = 3^+$. Neutron-γ correlation studies of the ^{19}F(α, $n\gamma$)^{22}Na reaction, taken in conjunction with previous data, impose limitations on spins and parities of several levels and on mixing ratios of associated γ-ray transitions. The spin-parity values are as follows, relatively unlikely assignments being bracketed: $J^\pi(3708) = 6^+(4^\pm)$; $J^\pi(4069) = 4^+$; $J^\pi(4466) = 1^-, 2^\pm, 3^-$, or 4^-; $J^\pi(4522) = 7^+, 5^\pm(4^-, 6^+)$.

[NUCLEAR REACTIONS ^{23}Na(^{3}He, $\alpha\gamma$), $E=8.46$ MeV; measured $\sigma(E_\alpha, E_\gamma)$. ^{22}Na level deduced γ branching. ^{19}F($\alpha, n\gamma$), $E=4.7$–6.1 MeV; measured $\sigma(E, E_\gamma)$. ^{22}Na levels deduced γ branching. ^{19}F($\alpha, n\gamma$), $E=5.0$–5.2 MeV; measured $\sigma(E_\gamma, \theta)$. ^{22}Na level deduced J, π, δ. ^{19}F($\alpha, n\gamma$), $E=11.2$ MeV; measured $\sigma(E_n, E_\gamma, \theta_{n\gamma})$. ^{22}Na deduced levels; ^{22}Na levels deduced J, π, δ, τ.]

I. INTRODUCTION

The ^{22}Na nucleus lies within a mass region where pronounced prolate deformations are known to occur. Its low-lying energy levels may be classified into a series of bands which are generally characteristic of those expected from the rotations of intrinsically deformed shapes. The large amount of experimental work devoted to this nucleus has been predominantly motivated by a desire to elucidate this classification and to extend it to higher energies.

The Brookhaven group have performed an extensive series of γ-ray spectroscopic studies,[1–6] and have interpreted their results in terms of the Nilsson model and the SU$_3$ classification scheme. Studies of various particle transfer reactions populating states in ^{22}Na have been made by Garrett and his collaborators[7–10]; they have considered their results in the light of the Nilsson model, and also of the extensive shell-model calculations performed by Halbert *et al.*[11] The results of other experimental investigations are summarized by Endt and Van der Leun,[12] and other relevant theoretical studies include the Hartree-Fock calculations by Lee and Cusson[13] and Gunye,[14] the weak-coupling calculations of Wong and Zuker,[15] and the Coriolis model calculations of Wasielewski and Malik.[16]

A rotational-band classification for excitation energies E_x up to 5 MeV is shown in Fig. 1; it is distilled from the works of various authors.[6,8,10,12,17] Spin assignments which had not been established by model-independent methods when the present work was begun are shown in parentheses. Evidence for the allocation of states to rotational bands is deduced from, for example, observation that their excitation energies follow an approximate $J(J+1)$ dependence, the presence of enhanced intraband $E2$ transitions, and the values of spectroscopic factors deduced from particle transfer reactions. Many of the assignments are quite speculative; this is particularly true for the $K^\pi=1^-$ and 1^+ bands, and for the higher members of the other bands, whose spins have generally been deduced from model-dependent arguments. From a study of the ^{10}B(^{16}O, α)^{22}Na reaction Del Campo *et al.*[17] have recently proposed extension of the $K^\pi=3^+$, $T=0$; $K^\pi=0^+$, $T=0$; and $K^\pi=1^-$, $T=0$ bands to spins as large as 10^+, 9^+, and 8^-, respectively, at excitation energies ranging up to 13.6 MeV. It is clearly desirable that spins, parities, and γ-decay characteristics should be firmly established for all levels involved in these speculations.

In the light of these general considerations, the work described in this paper was undertaken with the following specific objectives:

A. Investigation of some weak γ-ray transitions (Sec. II)

From studies of the reaction ^{20}Ne(^{3}He, $p\gamma$)^{22}Na, Olness *et al.*[2,6] found that the 4069-keV state decays 100% to the 1983-keV state, with an upper limit of 25% on any other branches. Anttila, Bister, and Arminen[18] studied the reaction ^{21}Ne(p,γ)^{22}Na and reported a 21% branch from the 4069-keV state to the 1528-keV 5^+ state. The only combination of spin assignments consistent with the branching-ratio and mean-lifetime ($\tau \leq 4$ fs) results of Anttila *et al.*, and with the restriction[12] that $J^\pi(1983) = 2^+$ or 3^+, is $J(4069) = 4$, $J^\pi(1983) = 3^+$. There appears to be no other secure experimental basis for a $J = 4$ assignment for the 4069-keV state. It has been generally conjectured[2,6] that the 4069-keV state is the 4^+ member of the $K^\pi = 0^+$, $T = 1$ band (see Fig. 1) and the analog of the 3356-keV 4^+, $T = 1$ state of ^{22}Ne. Although the $J = 4$ assignment deduced from the results of Anttila *et al.*

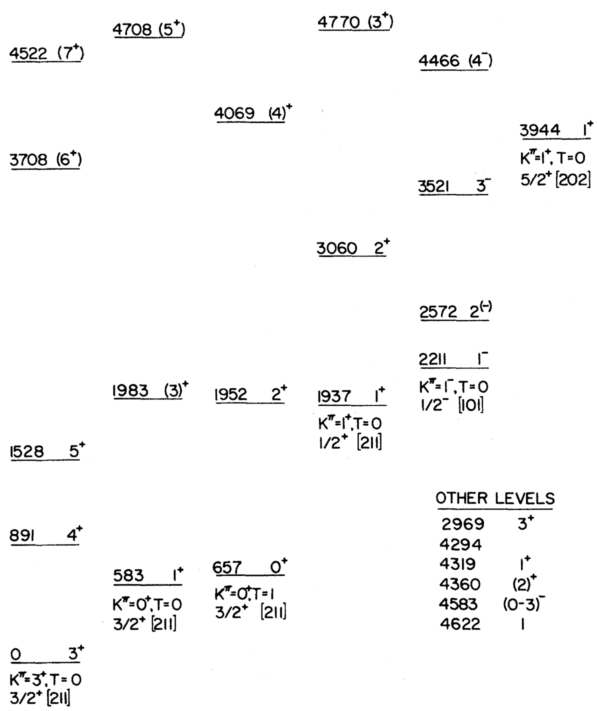

FIG. 1. Rotational-band classification of ^{22}Na states for $E_x < 5$ MeV. Excitation energies (in keV) are taken from reference 12 for $E_x < 3.4$ MeV, and from Ref. 6 for $E_x > 3.4$ MeV. Possible Nilsson configurations are indicated, assuming for each band that an unpaired nucleon in the $\frac{3}{2}^+$[211] orbit is coupled to an unpaired nucleon in the orbit shown.

supports this conjecture, the 21% branch to the 1528-keV 5^+ state raises some problems. Assuming that the $E2$ component has $|M|^2 \leq 10$ W.u. (Weisskopf units) (a conservative limit for a $\Delta K = 3$ transition as required by the classification shown in Fig. 1), the data of Anttila *et al.* imply an $M1$ strength of greater than 0.1 W.u. for a $\Delta K = 3$ transition. The $M1$ strength should be doubly inhibited by the K-selection rule for interband transitions, so this result constitutes a gross violation of the K-selection rule. Because the crucial branch to the 1528-keV level was observed in complex Ge(Li) singles spectra, it was decided to check the existence of this transition by selecting the appropriate particle group in the reaction ^{23}Na(^{3}He, α)^{22}Na and examining the spectrum of coincident γ rays.

During their investigations of the reaction ^{19}F($\alpha, n\gamma$)^{22}Na, Baxter, Gillespie and Kuehner[19] found evidence for the existence of a (1.3 ± 0.4)% branch from the 2572- to the 657-keV level. Prior to this it had been believed that the 2572-keV level decayed 81% to the ground state and 19% to the 583-keV state.[1,2] A spin assignment of 2 for the 2572-keV level is well established, but there is still some doubt about the negative parity assignment, although the weight of the evidence suggests that it is probably correct.[12] Assuming negative parity, the weak branch to the 657-keV 0^+ state would be an $M2$ transition of strength 0.50 ± 0.16 W.u.,[19] which would be consistent with the $\Delta T = 1$ character required by the classification of Fig. 1. It was decided to study the ^{19}F($\alpha, n\gamma$)^{22}Na reaction below and above threshold for population of the 2572-keV level in order to confirm that the γ ray reported by Baxter *et al.* is in fact associated with the decay of the 2572-keV level. While this work was in progress Haas *et al.*[20] also reported the observation of this transition in singles spectra from the reaction ^{19}F($\alpha, n\gamma$)^{22}Na, finding a (1.8 ± 0.5)% branch. However, there is no indication that this identification was confirmed by investigation of threshold behavior. Haas *et al.* also reported previously unobserved weak branches from the 2572- and 1983-keV levels. It was decided to investigate whether these γ rays displayed the appropriate threshold behavior.

B. Measurement of the angular distribution of γ rays from the 1983→583 keV transition (Sec. III)

The $J = 3$ assignment for the 1983-keV level has not been firmly established. Angular correlation measurements[1] give $J^\pi = 2^+$ or 3^+, and transfer reactions[7] indicate $J^\pi = 3^+$, 4^+, or 5^+; taken together these results give $J^\pi = 3^+$. In addition, the work of Anttila *et al.* (discussed in Sec. I A) strongly supports $J^\pi = 3^+$. However, linear polarization measurements[19] suggest $J^\pi = 2^+$. Although the accumulated evidence favors the 3^+ assignment, further investigation is desirable. For this reason, the angular distribution of γ rays from the $1983 \to 583$ keV transition has been studied using the $^{19}F(\alpha, n\gamma)^{22}Na$ reaction at energies just above threshold for population of the 1983-keV state.

C. Angular-correlation studies of $^{19}F(\alpha, n\gamma)^{22}Na$ in collinear geometry (Sec. IV)

In an attempt to obtain model-independent spin assignments for some of the ^{22}Na states of interest, and multipole mixing ratios for associated γ-ray transitions, angular-correlation measurements of the reaction $^{19}F(\alpha, n\gamma)^{22}Na$ were performed in a collinear geometry (method II of Litherland and Ferguson[21]). Neutrons were detected at 0°, and the angular correlations of coincident γ rays were measured for transitions from the 3708-, 4069-, 4466-, and 4522-keV states. During the course of this work, Freeman *et al.*[22] published the results of similar measurements for the 3708-, 4466-, 4522-, and 4708-keV states; however, the geometry used by these authors did not ensure good definition of nuclear alignments, and hence neither rigorous spin assignments nor accurate values of mixing ratios could be obtained.

II. INVESTIGATION OF SOME WEAK γ-RAY TRANSITIONS

A. $^{23}Na(^3He, \alpha)^{22}Na$ reaction

The decay scheme of the 4069-keV level was investigated using the $^{23}Na(^3He, \alpha)^{22}Na$ reaction ($Q = 8161$ keV). A target of approximately 300 $\mu g/cm^2$ NaBr evaporated onto a thin carbon foil was bombarded with a beam of 8.46-MeV $^3He^{++}$ ions from the Australian National University EN tandem accelerator. α particles emitted at 20° to the beam direction were detected with a 600-μm $\times$50-mm$\times$8-mm position-sensitive detector placed in the focal plane of a 61-cm double-focusing magnetic spectrometer.[23] The detector bias was adjusted to separate α and proton groups of equal magnetic rigidity. γ rays in coincidence with α particles were detected at 90° in a 12.7-cm-diam $\times$10.2-cm-long NaI(Tl) crystal mounted with its axis vertical and its front face 4.1 cm above the target spot. Conventional fast-slow coincidence electronics were used to accumulate a two-parameter, 16-channel (position signal)$\times$256-channel (γ signal), α-γ coincidence spectrum in an IBM 1800 on-line computer. Further discrimination between α-γ and p-γ coincidence events was afforded by the different transit times through the magnetic spectrometer for α particles and protons of equal energies and rigidities. The spectrometer entrance slits were set to subtend ±2.25° vertically and ±1.5° horizontally at the target; these settings were chosen to provide an optimum compromise between yield and resolution. The beam current was limited to 80 nA to ensure that pileup in the γ detector remained within acceptable limits, and also to minimize evaporation of the target material. Even so it was necessary to move to a fresh target spot every few hours.

Figure 2 shows the spectrum of γ rays in coincidence with α particles populating the 4069-keV level, obtained after running for 40 h. The inset shows the position spectrum in coincidence with all γ rays, and the particle windows used to obtain the γ-ray spectrum presented. A correction for contamination by γ rays from the 3944-keV level was made by fitting two Gaussian peaks to the position spectrum and then subtracting an appropriate fraction of the 3944-keV level spectrum from the 4069-keV level spectrum. The correction amounted to 2.4% of the total coincidence counts. The real-to-random coincidence ratio was determined from a simultaneously accumulated time spectrum, and a correction for random coincidences (5%) was made by subtracting an appropriately normalized singles spectrum from the coincidence spectrum.

The data clearly show the 2086-keV γ ray corresponding to the main branch from the 4069-keV level, and also a weaker 2541-keV branch to the 1528-keV level. The full curve shown in Fig. 2

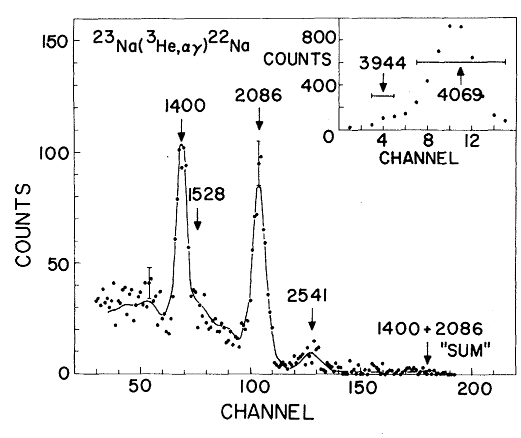

FIG. 2. The spectrum of γ rays in coincidence with α particles populating the 4069-keV level of ^{22}Na. The inset shows windows set on the α-particle position spectrum. The full curve is a line shape fit obtained as described in the text. All energies are in keV. The 2086- and 1400-keV γ rays arise from the cascade $4069 \to 1983 \to 583$ keV, and the 2541- and 1528-keV γ rays from the cascade $4069 \to 1528 \to 0$ keV.

represents a least squares fit to the data with line shapes measured for the experimental arrangement described. Allowance was made for summing of cascade γ rays, assuming isotropic angular distributions. The analysis yielded a branching ratio of $(10\pm 3)\%$ for the decay to the 1528-keV level; the quoted error includes allowances for statistical uncertainties, uncertainties in the detector relative efficiencies, and possible γ-ray angular distribution effects.[24]

The present result confirms the existence of a significant branch to the 1528-keV 5^+ level, as reported by Anttila *et al.*,[18] but the branching ratio obtained is smaller than the value of 21% reported by these authors. Assuming $\tau(4069)\leq 4$ fs,[18] a 21% branch would require $|M(E2)|^2 \geq 110$ W.u. if $J^\pi(4069)=3^+$. A branch of $(10\pm 3)\%$ would reduce this limit to $|M(E2)|^2\geq 36$ W.u. which, although large, cannot be rejected.[25] Furthermore, if $J^\pi=3^+$ is permitted for the 4069-keV level, then a 2^+ assignment for the 1983-keV level would also be permissible. Thus, the restrictions imposed by the branching ratio reported by Anttila *et al.*, i.e., $J(4069)=4$ and $J^\pi(1983)=3^+$, are relaxed by the present result to $J^\pi(4069)=3^+$, $4^\pm$ and $J^\pi(1983)=2^+$, 3^+.

B. ^{19}F$(\alpha, n)^{22}$Na reaction

The reaction ^{19}F$(\alpha, n)^{22}$Na ($Q=-1950$ keV) was used to study weak branches from the 1983-, 2211-, and 2572-keV states. In each case singles γ-ray spectra were obtained at bombarding energies below and above the kinematic threshold for population of the level. Targets consisted of 2 mg/cm^2 SrF_2 evaporated onto 0.25-mm-thick tungsten. Both planar and coaxial Ge(Li) detectors were used. γ rays were identified from their energies observed at 90° to the beam direction and branching ratios were deduced from spectra taken at 0, 55, 90, and 125°. The results obtained are listed in Table I, together with relevant results of previous workers. Figure 3 shows spectra taken below and above threshold for the weak γ rays of energies 1983, 2211, 1915, and 361 keV. The threshold behavior of these γ rays confirms their assignment to ^{22}Na levels as proposed by previous workers. Quantitatively the branching ratios obtained are in satisfactory agreement with those reported previously. Contributions to peaks from summing of cascade γ rays were found to be negligible. The spectra showed no evidence of previously unreported γ-ray transitions from ^{22}Na levels.

Assuming that the 1983-keV state has $J^\pi=3^+$ and a mean lifetime of (2.40 ± 0.25) ps,[20] the present branching ratio for the ground-state transition corresponds to $|M(E2)|^2\leq 0.06$ W.u. where the limit allows for the possibility of pure $E2$ radiation. This is a weak $E2$ transition, as would be expected if $\Delta K=3$ in accord with the rotational-band classification of Fig. 1. The shell-model calculations of Preedom and Wildenthal[26] also predict that this $E2$ transition should be weak [$|M(E2)|^2=0.016$ W.u.].

If the 2572-keV level has $J^\pi=2^-$ and a mean lifetime of (8.8 ± 0.9) ps,[20] then the present result for the branching ratio to the 657-keV 0^+ state corresponds to $|M(M2)|^2=(0.6\pm 0.3)$ W.u. This is quite a strong $M2$ transition for this mass region,[25] which supports the $\Delta T=1$ nature of the transition required by the classification of Fig. 1.

III. ANGULAR DISTRIBUTION OF γ RAYS FROM THE 1983→583 keV TRANSITION

The angular distribution of 1400-keV γ rays emitted in the transition between the 1983-keV state and the 583-keV 1^+ state was measured using the reaction ^{19}F$(\alpha, n\gamma)^{22}$Na at bombarding energies E_α of 5.0, 5.1, and 5.2 MeV, close to the kinematic threshold for population of the 1983-keV state ($E_\alpha=4.76$ MeV). A target of approximately 120 μg/cm^2 BaF_2 evaporated onto a 0.25-mm-thick tantalum backing was mounted at 45° to the beam direction and bombarded with beams of $^4He^{++}$ ions. The energy loss of the beam in the target was thus

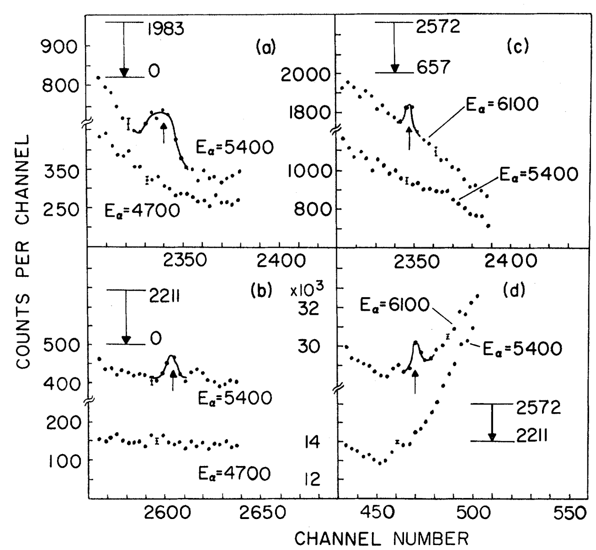

FIG. 3. Ge(Li) spectra showing threshold behavior of the following weak γ rays from the reaction ^{19}F$(\alpha, n\gamma)$-^{22}Na: (a) $E_\gamma=1983$ keV, $E_{th}=4761$ keV; (b) $E_\gamma=2211$, $E_{th}=5037$; (c) $E_\gamma=1915$, $E_{th}=5474$; (d) $E_\gamma=361$, $E_{th}=5474$. All energies shown in the diagram are in keV. The arrows indicate the positions expected for appropriate γ rays. The data have been smoothed by a three-point averaging procedure.

TABLE I. Branching ratios for some weak γ-ray transitions in ^{22}Na.

Initial state (keV)	Kinematic threshold in ^{19}F$(\alpha, n)^{22}$Na (keV)	Final state (keV)	E_γ (keV)	Branching ratio (%) Warburton *et al.* (Ref. 1)	Baxter *et al.* (Ref. 19)	Haas *et al.* (Ref. 20)	Present work
1983	4761	0	1983	<2		1.7 ± 0.3	1.9 ± 0.3
		583	1400	100		98.3 ± 0.3	98.1 ± 0.3
2211	5037	0	2211	1 ± 1			1.7 ± 0.5
		657	1554	99 ± 1			98.3 ± 0.5
2572	5474	0	2572	82 ± 5	80 ± 3	75 ± 2	73.0 ± 4.0
		583	1989	18 ± 5	19 ± 3	21 ± 2	23.5 ± 3.0
		657	1915	<5	1.3 ± 0.4	1.8 ± 0.5	2.5 ± 1.0
		2211	361	<7		2.4 ± 1.0	1.0 ± 0.3

about 70 keV. The general arrangement was similar to that described in detail by Bell *et al.*[27] γ rays were detected in a 40-cm^3 Ge(Li) detector rotatable in an arc of 12-cm radius centered on the target, and in a similar detector fixed at 90° relative to the incident beam direction. Singles γ-ray spectra were simultaneously accumulated from both detectors. Data were taken with the moving detector at angles of 0, 15, 30, 45, 60, 75, and 90° in random order, and several angles were repeated at each energy to check reproducibility. Integrated charges of 500, 400, and 300 μC at each angle were used for $E_\alpha = 5.0$, 5.1, and 5.2 MeV, respectively.

Angular distributions were extracted by normalizing the yield of the 1400-keV γ ray in the moving counter to that of the 583-keV γ ray in the fixed counter. Appropriate corrections, totalling less than 5%, were made for analog-to-digital converter dead time, attenuation of γ rays in the target backing and anisotropy of the target-detector geometry. The latter was determined by assuming that the angular distributions of γ rays from the long-lived 583-keV state ($\tau = 352$ ns[12]) was isotropic. As a check the angular distributions were also extracted by normalizing the 1400-keV yield to the 583-keV yield in the same (moving) counter, which cancels out dead-time and anisotropy effects, requiring only a relative attenuation correction of less than 1.5%.

The average of the angular distributions obtained at the three bombarding energies, 5.0, 5.1, and 5.2 MeV, was compared with the predictions of the computer program MANDY of Sheldon and Van Patter,[28] which assumes a statistical compound nucleus reaction mechanism. This program has been applied successfully to a number of (α, n) reactions in the 2*s*-1*d* shell (see, for example, Ref. 29), and is expected to be applicable to the present case because of the low outgoing neutron energy and the high level density in the compound nucleus. A statistical analysis for the relevant excitation region in the ^{23}Na compound nucleus has been carried out previously by Seaman, Leachman, and Dearnaley,[30] and further support for the assumption of a statistical compound nucleus reaction in the present case is provided by the similarity of the angular distributions at 5.0-, 5.1-, and 5.2-MeV bombarding energy (see Table II), and that at 5.48 MeV, measured using a thick target by Warburton, Olness, and Poletti.[1]

For the calculation, using MANDY, of magnetic substate populations of ^{22}Na levels, transmission coefficients were calculated from the optical model parameters of Hodgson[31] and Bock *et al.*[32] While the majority of previous authors have allowed at most an arbitrary 10% variation of population parameters from the MANDY predictions (see, for example, Ref. 29), in the present work more generous allowance was made for the effects of statistical fluctuations. Because the bombarding energy in the ^{19}F$(\alpha, n)^{22}$Na reaction was, for the levels of interest, not far above the kinematic threshold, only $l = 0$, $l = 1$ and, to a lesser extent, $l = 2$ neutrons should contribute significantly to the reaction cross section. The relative contributions of these partial waves in the MANDY calculations were varied between the extremes of, on the one

TABLE II. Legendre polynomial fits to the angular-distribution data for the 1400-keV γ ray.

E_α (MeV)	a_2 [a]	a_4 [a]
5.0	0.44 ± 0.03	−0.17 ± 0.04
5.1	0.35 ± 0.04	−0.20 ± 0.04
5.2	0.40 ± 0.04	−0.06 ± 0.04
Average	0.40 ± 0.02	−0.14 ± 0.03

[a] $a_i = A_i / A_0 Q_i$, where $Q_2 = 0.997$ and $Q_4 = 0.971$.

hand, zero contribution from $l=0$ outgoing neutrons and, on the other hand, zero contribution from $l=1$ outgoing neutrons; the $l=2$ contribution was allowed to vary from zero to twice the value calculated from the optical model parameters. In addition the effect of varying the relative transmission coefficients for neutrons with total angular momenta $j=l+\frac{1}{2}$ and $j=l-\frac{1}{2}$ was investigated and found not to affect significantly the MANDY predictions.

Figure 4 shows the averaged angular distribution for the 1983 → 583 keV transition and the best fits to the data for $J(1983)=2$ or 3 and $J(583)=1$ obtained using the predictions of MANDY for the magnetic substate populations of the 1983-keV level. Clearly the data are consistent only with $J(1983)=3$. Also shown in Fig. 4 are the measured angular distributions for the 1952 → 583 keV decay in ^{22}Na, and the MANDY prediction for this $2^+ \rightarrow 1^+$ transition with a mixing ratio of 0.04 ± 0.06 (Ref. 4). It can be seen that the two are in good agreement even though, because of the low yield at 5.0 and 5.1 MeV, experimental angular distributions could not be averaged over bombarding energy as was done for the 1983 → 583 keV transition. The success of the MANDY predictions in the case of the 1952 → 583 keV transition is taken as further support for the validity of applying this analysis to the neighboring 1983-keV level.

While strong arguments have been advanced above for the applicability of MANDY to the resolution of the $J=(2, 3)$ ambiguity for the 1983-keV level, it is not intended to imply that this method of analysis can be applied indiscriminately to angular distributions from the ^{19}F$(\alpha, n\gamma)^{22}$Na reaction, even when observed close to threshold; for example, the angular distributions for the 2211 keV $(1^-) \rightarrow 657$ keV (0^+) transition were found to be markedly different at 5.1- and 5.2-MeV bombarding energy ($A_2=-0.77 \pm 0.07$ and -0.36 ± 0.07, respectively), perhaps in part merely reflecting the fact that for a $J=1$ level all the substates are substantially populated, and so the nuclear alignment is more sensitive to the precise values of the population parameters.

In summary, it is concluded from the angular distribution results that the 1983-keV level has $J=3$, with the mixing ratio of the 1983 → 583 keV transition being given (see Fig. 4) by arctan$\delta = 0.6° \pm 1.1°$ or arctan$\delta = 79° \pm 1°$. The phase convention for mixing ratios is that of Rose and Brink[33] and the standard errors on arctanδ were estimated using the procedures described by Archer, Prestwich, and Keech.[34] The possibility arctan$\delta = 79° \pm 1°$ can be rejected since it implies a miraculously large $M3$ strength when taken in conjunction with branching ratio and lifetime data.[20] A 3^- assignment can also be rejected since it requires $|M(M2)|^2 \geq 400$ W.u. (assuming a reasonable $E3$ strength of ≤ 100 W.u.). Thus for the 1983-keV level $J^\pi = 3^+$, and arctan$\delta = 0.6° \pm 1.1°$ for the 1983 → 583 keV transition.

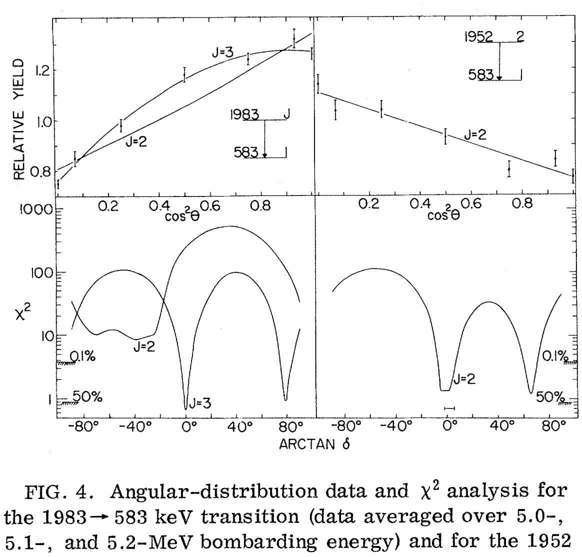

FIG. 4. Angular-distribution data and χ^2 analysis for the 1983 → 583 keV transition (data averaged over 5.0-, 5.1-, and 5.2-MeV bombarding energy) and for the 1952 → 583 keV transition (data obtained at 5.2 MeV only). Magnetic substate populations have been allowed to vary as described in the text. The horizontal error bar on the χ^2 plot for the 1952 → 583 keV transition indicates the mixing-ratio range determined by Warburton, Poletti, and Olness (Ref. 4).

IV. ANGULAR-CORRELATION STUDIES OF ^{19}F$(\alpha, n\gamma)^{22}$Na IN COLLINEAR GEOMETRY

The reaction ^{19}F$(\alpha, n\gamma)^{22}$Na has been used to study the angular correlations of γ-ray transitions from the 3708-, 4069-, 4466-, and 4522-keV levels of ^{22}Na. A beam of ^{4}He^{++} ions was used to bombard a 2-mg/cm^2 target of SrF_2 evaporated onto a 0.5-mm-thick tungsten backing. The target chamber arrangement was similar to that described in Sec. III. Neutrons were detected in a 7.5-cm-diam × 10-cm-long liquid (NE 213) scintillator placed at 0° to the beam direction and 10 cm from the target. γ rays were detected in two Ge(Li) counters of 50- and 30-cm^3 active volume placed 8.0 and 7.5 cm, respectively, from the target. The former counter could be rotated between 90 and 145° relative to the beam direction and was used to measure the angular correlations; the latter was fixed at 90° and served as a monitor of reaction yield.

For each Ge(Li) counter conventional fast/slow coincidence circuitry was used to select and route real and random neutron-γ coincidence spectra into 2 × 2048 channels. The neutron pulse-shape discrimination circuit gated both coincidence circuits; therefore the fixed-counter spectra accurately monitored any changes in reaction yield, target condition, neutron detection efficiency, and count-rate-dependent effects. Furthermore, the coincidence-time windows and pulse-shape windows were frequently checked during the measurements.

It is known[12] that the 4708-keV level of ^{22}Na has a 40% branch to the 4069-keV level, which could introduce some population of magnetic substates of the latter level other than those directly populated by the ^{19}F$(\alpha, n)^{22}$Na reaction (for neutron detection at 0°). A preliminary excitation function was measured to find an energy at which the relative populations of the 4069- and 4708-keV levels were favorable. The 4708 → 4069 keV transition (639 keV) is obscured by the 637-keV transition between the 1528- and 891-keV levels. The intensity of the other branch from the 4708-keV level, namely 60% (2725 keV) to the 1983-keV level, was therefore compared with the intensity of the 4069-1983 = 2086 keV γ ray. The most suitable beam energy was found to be 11.2 MeV, where the relative intensities of the 2086- and 2725-keV transitions were about 10 to 1, and this energy was used for the angular-correlation measurements. The beam current was maintained between 15 and 25 nA to limit count-rate-dependent effects on dead time and resolution. Twenty-five coincidence spectra were taken, in random order, with the movable Ge(Li) detector at angles of 90, 115, 125, 135, and 145°. The typical charge per run was 200 μC.

Figure 5 shows the sum of all coincidence spectra from the moving Ge(Li) detector. All but one of the major peaks have been identified with established γ transitions from levels in ^{22}Na up to $E_x = 5166$ keV. The unidentified γ ray has an energy of 3375 ± 3 keV. Considering levels of ^{22}Na at excitation energies below the limit imposed by kinematics and the neutron-detection threshold ($E_x \simeq 6$ MeV), the most likely origin is a transition from the level at $E_x = 5317 \pm 5$ keV[12] having an energy of either 3380 ± 5 or 3365 ± 5 keV, corresponding to final states at 1936.9 ± 0.2 or 1951.9 ± 0.2 keV, respectively; the former possibility gives a better match of energies. The γ-ray energies E_γ were separately obtained from internal calibration of the sum of all 90° spectra in each counter, relying mainly on the reported[12] energies of the intense ground-state transitions from the long-lived

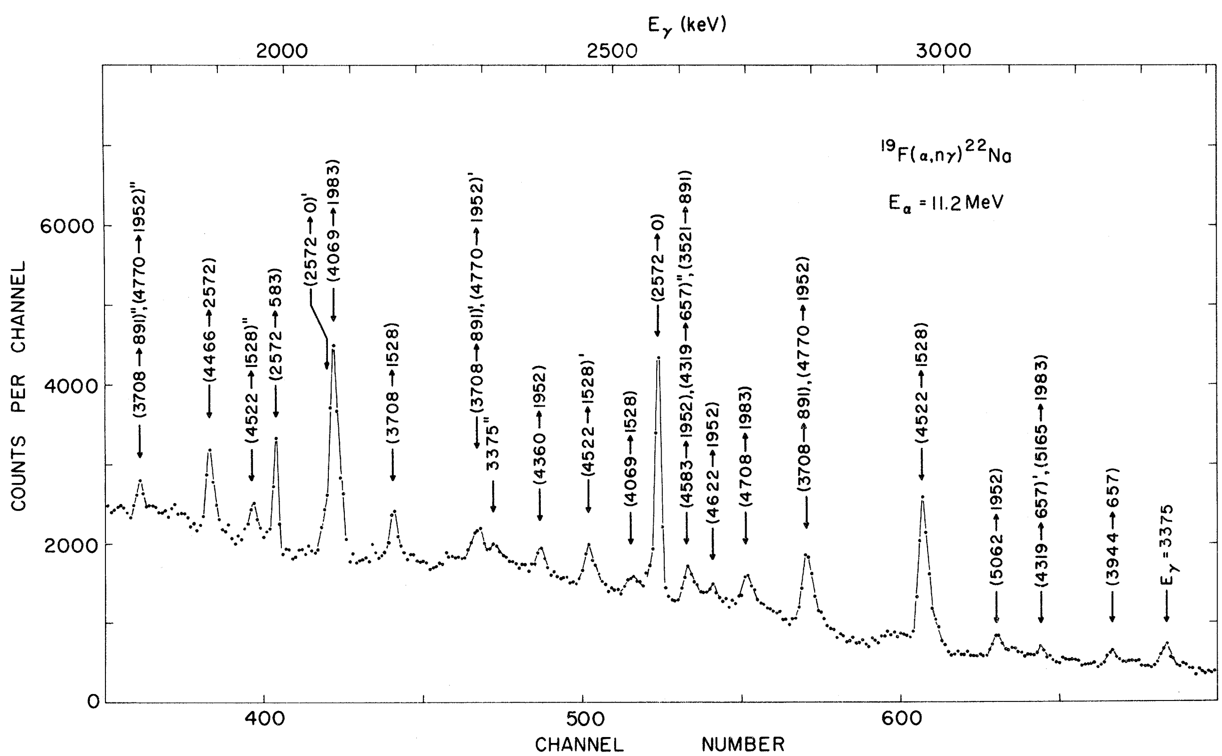

FIG. 5. Portion of Ge(Li) spectrum of γ rays in coincidence with neutron emitted at 0° from the reaction ^{19}F$(\alpha, n\gamma)$-^{22}Na at $E_\alpha = 11.2$ MeV. The data shown represent the sum of spectra taken at 90, 115, 125, 135, and 145° with the moving detector during the angular-correlation measurements. To simplify presentation the spectrum has been compressed by adding channel contents in pairs. Transitions between states in ^{22}Na are identified. All energies are in keV.

(2571.5 ± 0.3)- and (1527.9 ± 0.2)-keV levels. The values obtained from the two counters were in splendid agreement. The γ-ray energies were averaged and combined with the known[12] excitation energies E_x of the final states to give the excitation energies E_i of the initial states listed in Table III.

There is a peak in the spectrum of Fig. 5 which is attributed to the 2541-keV γ ray emitted in the 4069 → 1528 keV transition. It is possible that other γ rays could contribute to this peak, e.g. if the 5107-keV level[12] decayed to the 2572-keV level, it would produce a γ ray of energy 2535 keV. However there is no positive evidence for the existence of such competing γ rays. Assuming that the peak concerned arises entirely from the 4069 → 1528 keV transition, and allowing for a small contribution to the 4069 → 1983 keV peak from the first escape peak of the 2572-keV γ ray, the 4069 → 1528 keV branch is found to be (12 ± 3)% from the 125° data, and (12 ± 2)% from consideration of the data summed over all angles. This result provides excellent confirmation of the (10 ± 3)% value obtained in the present work from studies of the ^{23}Na(^{3}He, $\alpha\gamma$)^{22}Na reaction (sec. II A), particularly as it eliminates uncertainties arising from angular-distribution effects; it is in clear disagreement with the 21% result reported by Anttila *et al.*[18] Although the present experiment was not specifically designed for lifetime determinations, conventional Doppler shift attenuation analysis of the neutron-γ coincidence data for the 4069 → 1983 keV transition yielded an upper limit of 30 fs for the lifetime of the 4069-keV level; this result is consistent with the only previously reported value of ≤4 fs (Anttila *et al.*[18]).

Angular correlations were extracted for the 1895-, 2088-, 2177-, and 2996-keV γ rays (Table III). They are identified with the following transitions in ^{22}Na: 4466 → 2572,[22] 4069 → 1983,[6] 3708 → 1528,[2] and 4522 → 1528 keV,[22] respectively. Here again the level energies correspond to those given in Refs. 6 and 12. The angular correlations were normalized to the total counts observed between 620 and 1480 keV in the fixed-counter spectra. Corrections were made for random coincidences (about 5%). Extensive cross checks were made between total neutron yield, integrated charge, total coincidence yields and coincidence yields of the strong 891- and 1369-keV γ rays in both counters to ensure that all the data were self-consistent. The 2088-keV peak was imperfectly resolved from the first-escape peak of the 2572-keV γ ray. Uncertainties introduced into determination of the 2088-keV γ-ray yield by corrections (~10%) for this contamination were estimated to be ≤1%.

Corrections for anisotropy in the target-detector geometry were deduced from the following measurements: (a) the angular distribution of γ rays from the decay of the 2311-keV $J^\pi = 0^+$ level of ^{14}N produced via the reaction ^{11}B(α, n)^{14}N using a target of natural boron on tungsten and a beam energy

TABLE III. γ-ray energies and angular-correlation results.

E_i [a] (Initial level) (keV)	E_γ [b] (keV)	E_f [c] (Final level) (keV)	Legendre polynomial coefficients [d] a_2	a_4	$J_i \to J_f$	Arctan δ [e] (deg)
3704.4 ± 1.0	2176.5 ± 1.0	1527.9 ± 0.2	0.65 ± 0.15	0.92 ± 0.21	4 → 5	+68 ± 12
					6 → 5	−75 ± 7
4071.4 ± 0.6	2088.2 ± 0.5	1983.2 ± 0.3	−0.26 ± 0.10	0.14 ± 0.16	4 → 3	0 ± 4
					3 → 3	64 ± 24
4467.0 ± 0.7	1895.5 ± 0.6	2571.5 ± 0.3	0.56 ± 0.26	−0.11 ± 0.31	1 → 2	−55 ± 25; +35 ± 15
					2 → 2	−35 ± 40
					3 → 2	−50 ± 25
					4 → 2	-4^{+16}_{-24} [f]
4523.4 ± 0.7	2995.5 ± 0.6	1527.9 ± 0.2	0.40 ± 0.08	−0.17 ± 0.10	3 → 5	+27 ± 18
					4 → 5	+38 ± 15
					5 → 5	−41 ± 8
					6 → 5	−26 ± 5
					7 → 5	1 ± 4

[a] Deduced from $E_i = E_\gamma$ (this work) + E_f (Ref. 12).
[b] This work.
[c] Reference 12.
[d] $a_i = A_i/A_0Q_i$, where $Q_2 = 0.98$, $Q_4 = 0.96$.
[e] Standard errors calculated using the procedure of Ref. 34.
[f] A deeper minimum in the χ^2 plot at arctan $\delta = -60°$ can be rejected on the grounds of excessive octupole enhancement.

E_α of 11.2 MeV (i.e., beam conditions identical to those for the ^{22}Na observations); (b) as for (a), but with $E_\alpha = 8.0$ MeV, which gave cleaner spectra; (c) observation of the angular variation in the intensity of γ rays from a 1-mm-diam ^{60}Co source placed at the position of the beam spot observed on the target; and (d) direct measurement of the geometry. These four procedures gave mutually compatible results. At 90°, the correction relative to 145° was $(5.0 \pm 2.5)\%$; it was less at other angles. Corrections to the nominal angle were less than ±1°.

Figure 6 shows the measured correlations. The error bars include uncertainties arising from statistical effects, background interpolations under the γ-ray peaks, and the anisotropy corrections. Figure 7 shows the results of least-squares fits to the data calculated for various possible spin sequences; χ^2 is plotted against arctan δ, where δ is the multipole mixing ratio. These fits are shown by the full curves in Fig. 6. For neutron detection at 0°, the ^{19}F$(\alpha, n)^{22}$Na reaction can populate directly the $m = 0$, ±1 magnetic substates of the final nucleus. Since the effective angle subtended at the target by the liquid scintillator for neutrons corresponding to the levels of interest was about ±15°, the population of the next higher substate ($m = \pm 2$) may be estimated[21] as approximately 7%. The following substate restrictions were therefore adopted:

$$0 \leq P(m=0) \leq 1\,,$$
$$0 \leq P(m=\pm 1) \leq 1\,,$$
$$0 \leq P(m=\pm 2) \leq 0.1\,,$$
$$\sum_{m=0}^{J} P(m) = 1\,.$$

The $P(m)$ are defined so that, for example, $P(m=\pm 1)$ is the sum of the equal populations of the $m=+1$ and $m=-1$ magnetic substates. Table III presents the results of Legendre-polynomial fits to the distributions, and the mixing ratios permitted by the results of the least-squares fits of Fig. 7 for various spin sequences.

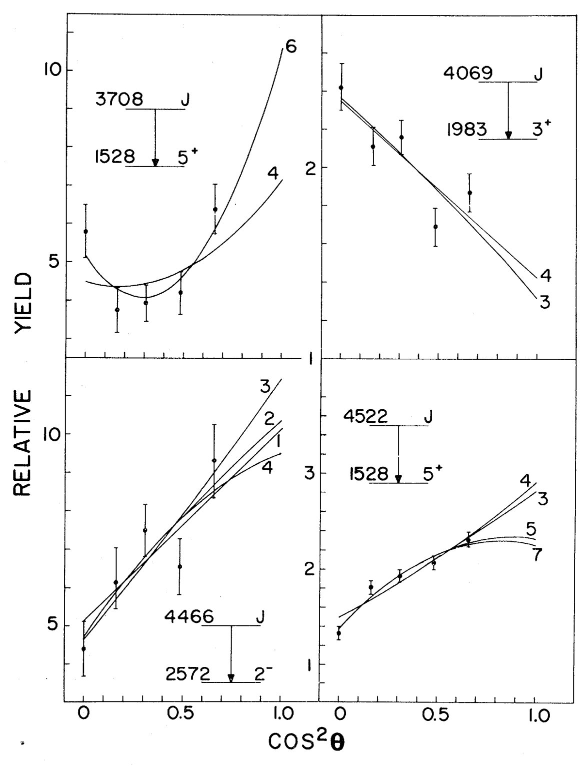

FIG. 6. Angular correlation data for the reaction ^{19}F$(\alpha, n\gamma)^{22}$Na. The full curves represent best fits to the γ-ray distributions for various spin sequences. For small values of $\cos^2\theta$, the following pairs of curves are very similar, and in each case have been represented by a single curve: (i) 4466→2572, $J=2$ and 4; (ii) 4522→1528, $J=3$ and 4; (iii) 4522→1528, $J=5$ and 7.

A. 3708-keV level

From their coincidence studies of the ^{20}Ne$(^3$He$, p\gamma)^{22}$Na reaction, Poletti *et al.*[2] report that this level decays 65% to the 891-keV 4^+ state and 35% to the 1528-keV 5^+ state. Warburton *et al.*[35] used Doppler-shift attenuation studies of the 2817-keV transition to the 891-keV level to determine

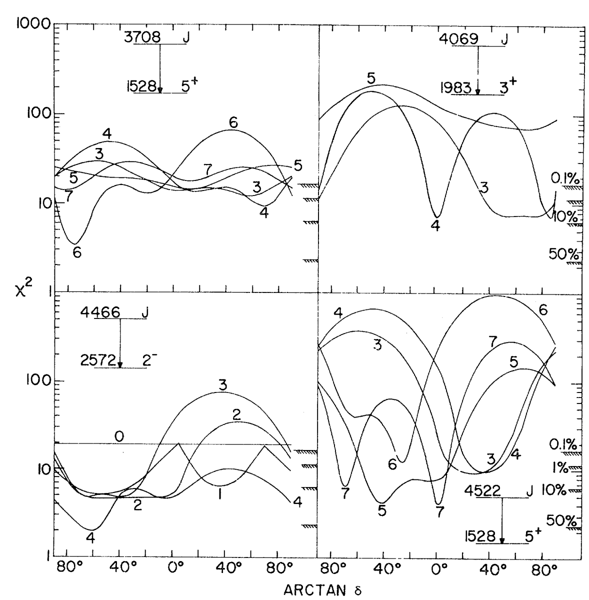

FIG. 7. Results of least squares fits to the angular distributions of Fig. 6 for various spin sequences. Confidence levels for the χ^2 statistic are indicated.

the mean lifetime of the 3708-keV level as 52 ± 17 fs. These two pieces of information together imply that the spin of the level is 3, 4, 5, or 6, and on this basis it has been generally assumed that the 3708-keV level is the 6^+ member of the $K^\pi = 3^+$, $T=0$ rotational band. The level is strongly populated[10] in the heavy-ion reaction $^{12}C(^{14}N, \alpha)$-^{22}Na, which is consistent with a high-spin assignment. Recently, Haas *et al.*[20] have made further Doppler-shift measurements of the 2817-keV γ ray, obtaining a value of 80 ± 40 fs for the lifetime; they have reanalysed the data of Warburton *et al.*[35] to obtain a value of 75 ± 25 fs, and recommend that a lifetime of 77 ± 20 fs be adopted. Freeman *et al.*[22] have studied the reaction $^{19}F(\alpha, n\gamma)^{22}Na$, and report branching ratios of $(75 \pm 7)\%$ and $(25 \pm 7)\%$ to the 891- and 1528-keV levels, respectively. Their angular-correlation measurements of the $3708 \rightarrow 891$ keV transition are consistent with a $J=6$ assignment for the 3708-keV level. However their neutron detector at 0° subtended a half-angle of 38°; hence there was little restriction on substate populations, and no rigorous spin assignments could be made.

The excitation energy obtained in the present work from the transition to the 1528-keV level is 3704.4 ± 1.0 keV (Table III). This is significantly different from the value 3708 ± 1 keV given by Warburton *et al.*[6,35] However, a γ ray of energy 2818.0 ± 0.7 keV was also observed; if this gamma ray is ascribed to a transition to the 891-keV level, then the excitation energy obtained is 3708.9 $\pm$ 0.8 keV, in good agreement with the result of Warburton *et al.* But the latter γ ray could be contaminated by 2818-keV radiation from the $4770 \rightarrow 1952$ keV transition (a 100% branch[6]). For this reason no attempt was made to analyze the angular correlation of the 2818-keV γ ray. It is not obvious that previous authors who have studied the $3708 \rightarrow 891$ keV transition have considered this possible contamination.

In order to investigate the possibility that the $4770 \rightarrow 1952$ keV transition could cause difficulties in studying the $3708 \rightarrow 891$ keV transition, singles spectra from the reaction $^{19}F(\alpha, n\gamma)^{22}Na$ were taken below and above threshold for population of the 4770-keV state. A 50-cm^3 Ge(Li) detector was located at 90° to the beam direction, and the target consisted of 3 mg/cm^2 SrF_2 on a thick tungsten backing. The kinematic thresholds for population of the 3708- and 4770-keV levels are $E_\alpha = 6849$ and 8136 keV, respectively. At $E_\alpha = 8000$ keV, the relevant γ-ray peak was found to have an energy of 2814.8 ± 0.7 keV; at $E_\alpha = 9000$ keV, i.e., above threshold for the 4770-keV level, the peak energy was found to be 2817.6 ± 0.5 keV. These results indicate that for beam energies above threshold for the 4770-keV level, the $4770 \rightarrow 1952$ keV transition cannot be ignored in studying the $3708 \rightarrow 891$ keV transition. The data obtained at $E_\alpha = 8000$ keV produce a level excitation energy of 3705.7 ± 0.7 keV; combining this result with the value deduced from the present (n, γ) coincidence data (3704.4 ± 1.0 keV) yields a best value of $E_x = 3705.2 \pm 0.5$ keV.

It follows from these investigations that all previous studies of the $3708 \rightarrow 891$ keV transition using the $^{19}F(\alpha, n\gamma)^{22}Na$ reaction at bombarding energies above the 4770-keV level threshold should be examined to ensure that account was taken of possible competition from the $4770 \rightarrow 1952$ keV transition. This applies, for example, to the excitation energy and lifetime determinations by Warburton *et al.*,[35] and to the branching-ratio and angular-correlation studies of Freeman *et al.*[22] It will be assumed in the following discussion that the level decays $(65 \pm 10)\%$ to the 891-keV state and $(35 \pm 10)\%$ to the 1528-keV state,[2] and that the mean lifetime of the level is (80 ± 40) fs.[20]

The present angular-correlation data for the 2176-keV γ ray to the 1528-keV 5^+ state strongly favor $J(3708) = 6$. The next most likely assignment is $J=4$, and this can be rejected at the 3% confidence limit. For $J=6$, $\arctan\delta = -75° \pm 7°$, i.e., $\delta = -3.7^{+1.4}_{-4.4}$. The $J^\pi = 6^-$ possibility can be rejected because this would imply $|M(M2)|^2 \geq 240$ W.u. For $J^\pi = 6^+$, $|M(E2)|^2 = (19^{+19}_{-7})$ W.u., and $|M(M1)|^2 = (9^{+17}_{-7}) \times 10^{-4}$ W.u.

B. 4069-keV level

The excitation energy obtained from the present results is 4071.4 ± 0.6 keV (Table III), which is in good agreement with the value of 4069 ± 2 keV listed by Warburton *et al.*[6] Evidence for a $J^\pi = 4^+$ assignment for this level, and for its identification as the 4^+ member of the $K^\pi = 0^+$, $T=1$ band, has been discussed in detail in Secs. I and II of this paper. The present angular-correlation data for the 2088-keV transition to the 1983-keV level (shown in Sec. III to have $J^\pi = 3^+$) are consistent with $J(4069) = 3$ or 4; all other possibilities are excluded by previous lifetime and branching-ratio data. If the lifetime of the 4069-keV level is taken to be ≤ 4 fs (Anttila *et al.*[18]), then the mixing ratio obtained in the present work for $J(4069) = 3$ corresponds to a minimum quadrupole strength of 500 W.u. if $E2$, or 2.5×10^4 W.u. if $M2$. Thus the present results, together with the lifetime value of Anttila *et al.*, show that the spin of the 4069-keV state is 4, and that for the 2088-keV transition $\arctan\delta = 0° \pm 4°$. Assuming the branching ratio obtained in the present work (Sec. IIA), the $M1$ strength of the 2088-keV transition is found to be

≥ 0.75 W.u. This is quite strong, and implies a T-allowed transition, as required by the classification of Fig. 1. Because the value obtained for δ is consistent with zero, and only an upper limit is available for the lifetime of the state, no limitations can be placed on the $E2$ strength of the $4069 \rightarrow 1983$ keV transition.

C. 4466-keV level

On the basis of its selective population in the $^{12}C(^{14}N, \alpha)^{22}Na$ reaction, Hallock *et al.*[10] tentatively identified the 4466-keV level as the 4^- member of the $K^\pi = 1^-$, $T = 0$ band based on the 2211-keV 1^- state. The angular-correlation data of Freeman *et al.*[22] for the 1894-keV transition to the 2572-keV level are consistent with a pure $E2$ transition from a 4^- to a 2^- state; however, as indicated previously, their experimental geometry did not ensure good definition of nuclear alignments, and hence rigorous spin assignments were not possible. The decay scheme of the 4466-keV level has not yet been investigated in detail; the 1894-keV transition to the 2572-keV state is the only γ-decay branch yet reported.[22] γ-ray singles spectra from the reaction $^{19}F(\alpha, n\gamma)^{22}Na$ taken during the present work confirm that the 1894-keV γ-ray displays the correct threshold behavior for its identification with a transition from the 4466-keV level; the kinematic threshold for population of the 4466-keV state is $E_\alpha = 7768$ keV, and the 1894-keV γ ray was clearly present at $E_\alpha = 8000$ keV and higher energies, but absent at $E_\alpha = 7500$ keV. Freeman *et al.* measured a mean lifetime for the level of 145^{+65}_{-40} fs. If it is assumed that the 1894-keV γ ray represents a major branch, i.e., $\geq 10\%$, then the spin and parity may be restricted, on the basis of this lifetime value, to 0^-, $1^\pm$, $2^\pm$, $3^\pm$, or 4^-. The present angular correlation for the transition to the 2572-keV level is clearly anisotropic (Fig. 6), which eliminates the 0^- possibility. The mixing ratios obtained for $J = 1$ and 3 (Table III) require implausibly strong $M2$ components for positive parity $|M(M2)|^2 \geq 12$ and 36 W.u., respectively, assuming again that $J^\pi(2572) = 2^-$ and that the observed 1894-keV transition represents a branch of greater than 10%. Hence, the combination of lifetime and angular-correlation data restricts $J^\pi(4466)$ to 1^-, $2^\pm$, 3^- or 4^-. If $J^\pi = 4^-$, and if the branching ratio for the 1894-keV transition is assumed to be 50%, then the $E2$ strength of the transition is 31^{+12}_{-10} W.u.

The excitation energy obtained from the present work, 4467.0 ± 0.7 keV, is in good agreement with previous values.[6,22]

D. 4522-keV level

Olness *et al.*[6] suggested that the $J^\pi = 7^+$ member of the $K^\pi = 3^+$, $T = 0$ band based on the ground state of ^{22}Na should lie in the region of excitation energy from 4.4 to 5.3 MeV. Garrett *et al.*[9] found that the 4522-keV state is weakly populated in one- and two-nucleon transfer reactions, and that it may therefore be a high-spin state. On the basis of its selective population in the $^{12}C(^{14}N, \alpha)^{22}Na$ reaction, Hallock *et al.*[10] suggested that the 4522-keV state is the 7^+ member of the $K^\pi = 3^+$, $T = 0$ band. Del Campo *et al.*[17] found that the 4522-keV state is populated in the $^{10}B(^{16}O, \alpha)^{22}Na$ reaction with a strength and angular distribution consistent with the predictions of Hauser-Feshbach calculations for $J^\pi = 7^+$. Freeman *et al.*[22] found a 2994-keV transition between the 4522-keV level and the

TABLE IV. Summary of available information on $E2$ and $M1$ transition strengths within the $K^\pi = 3^+$ rotational band based on the ground state of ^{22}Na. It is assumed that the spin-parity assignments of Fig. 1 are correct. The data for the $3708 \rightarrow 1528$ keV transition are from the present work (see Section IV.1); other data are taken from the compilations of references 12 and 22. The intrinsic quadrupole moments Q_0 and the quantity $(g_K - g_R)$ have been calculated from the data using rotational-model expressions. The shell-model predictions for $|M(E2)|^2$ and $|M(M1)|^2$ are from the calculations of Ref. 26.

Transition (energies in keV)	$\delta(E2/M1)$	$\|M(E2)\|^2$ (W.u.)	Q_0 (b)	$\|M(M1)\|^2$ (W.u.)	$g_K - g_R$	Shell-model predictions $\|M(E2)\|^2$ (W.u.)	Shell-model predictions $\|M(M1)\|^2$ (W.u.)
$891(4^+) \rightarrow 0(3^+)$	$-(3.1 \pm 0.3)$	24.9 ± 1.2	0.512 ± 0.012	$(2.8 \pm 0.3) \times 10^{-4}$	0.035 ± 0.002	24.6	4.2×10^{-4}
$1528(5^+) \rightarrow 0(3^+)$		5.3 ± 0.4	0.48 ± 0.02			5.7	
$1528(5^+) \rightarrow 891(4^+)$	$-(2.00 \pm 0.15)$	15 ± 5	0.42 ± 0.06	$(2.2 \pm 0.7) \times 10^{-4}$	0.025 ± 0.004	21.6	7.8×10^{-4}
$3708(6^+) \rightarrow 891(4^+)$		11 ± 3.5	0.52 ± 0.08			8.7	
$3708(6^+) \rightarrow 1528(5^+)$	$-(3.7^{+4.4}_{-1.4})$	19^{+19}_{-7}	$0.51^{+0.21}_{-0.11}$	$(9^{+17}_{-7}) \times 10^{-4}$	$0.047^{+0.032}_{-0.025}$	15.6	1.0×10^{-3}
$4522(7^+) \rightarrow 1528(5^+)$		8 ± 3	0.38 ± 0.07			10.4	
$4522(7^+) \rightarrow 3708(6^+)$		<240		$<2.3 \times 10^{-2}$		12.8	1.3×10^{-3}

1528-keV 5^+ state; no other information on the decay scheme of the level has been published. γ-ray singles spectra from the reaction ^{19}F(α, $n\gamma$)^{22}Na taken during the present work confirm that the 2994-keV γ-ray displays the correct behavior for its identification with a transition from the 4522-keV level; the kinematic threshold for population of the 4522-keV state is $E_\alpha = 7836$ keV, and the 2994-keV γ ray was clearly present at $E_\alpha = 8000$ keV and higher energies, but absent at $E_\alpha = 7500$ keV. The angular correlation obtained by Freeman *et al.*[22] for this transition was consistent with a pure $E2$ transition between 7^+ and 5^+ states, but a rigorous spin assignment could not be made. They also measured the mean lifetime of the 4522-keV level to be 115^{+50}_{-35} fs. On the basis of this lifetime, and assuming conservatively that the transition to the 1528-keV level represents a branch of greater than 2%, the spin and parity of the 4522-keV level may be restricted to $J^\pi = 3^+$, $4^\pm$, $5^\pm$, $6^\pm$, or 7^+. The mixing ratios required by the present angular-correlation data (Table III) for the transition to the 1528-keV state eliminate $J^\pi = 3^+$, 4^-, and 6^-, provided that the transition represents a branch of greater than 0.01, 14, and 20%, respectively (the requisite transition strengths would be $|M(M3)|^2 \geq 30$ W.u., $|M(M2)|^2 \geq 3$ W.u. and $|M(M2)|^2 \geq 3$ W.u., respectively). In addition $J = 3$, 4, and 6 assignments can be rejected at 3, 3, and 1% confidence levels, respectively. Thus, the combined lifetime and angular-correlation data require $J^\pi = 4^+$, $5^\pm$, 6^+, or 7^+, and strongly favor $J^\pi = 5^\pm$ or 7^+. If $J^\pi = 7^+$, then the $E2$ transition to the 1528-keV 5^+ state has a strength of 8 ± 3 W.u., assuming that the transition is a 100% branch; this is a reasonable assumption, since the only other possibly significant decay mode would be to the 3708-keV 6^+ state, which Freeman *et al.* find to be less than 3%.

The excitation energy obtained in the present work (4523.4± 0.7 keV) is in good agreement with previous values.[6,22]

V. CONCLUSIONS

The results reported in this paper may be summarized as follows:

(a) Particle-γ coincidence studies of the reaction ^{23}Na(^{3}He, $\alpha\gamma$)^{22}Na show that the 4069-keV level of ^{22}Na has a branch of (10± 3)% to the 1528-keV 5^+ state. Investigation of the spectrum of γ rays emitted in coincidence with neutrons from the reaction ^{19}F(α, $n\gamma$)^{22}Na confirms this result, yielding a value of (12± 2)%.

(b) Evidence for the existence of several weak γ transitions reported by other workers from studies of the reaction ^{19}F(α, $n\gamma$)^{22}Na has been placed on a secure footing by taking data below and above threshold for population of the initial state involved. The results are shown in Table I.

(c) The angular distribution of 1400-keV γ rays from the 1983-keV state populated in the reaction ^{19}F(α, $n\gamma$)^{22}Na was studied at energies close to the kinematic threshold; the results resolve the long-standing $J^\pi = 2^+$ or 3^+ ambiguity for the 1983-keV state, which is shown to have $J^\pi = 3^+$.

(d) Angular-correlation studies of the reaction ^{19}F(α, $n\gamma$)^{22}Na were made in collinear geometry. The results, taken in conjunction with other data, impose limitations on spins and parities of several levels, and on the mixing ratios of associated γ-ray transitions. The spin-parity values are as follows: $J^\pi(3708) = 6^+$, with $J = 4$ rejected at the 3% confidence level; $J^\pi(4069) = 4^\pm$; $J^\pi(4466) = 1^-$, $2^\pm$, 3^-, or 4^-; $J^\pi(4522) = 5^\pm$ or 7^+, with $J^\pi = 4^-$ and 6^+ rejected at the 3% and 1% confidence levels, respectively.

The data obtained on spins and parities provide a more substantial basis than previously existed for the assignments assumed in the rotational-band classification of Fig. 1. It has been shown previously[4,22] that intraband $E2$ and $M1$ transition strengths are in reasonable agreement with the predictions of the rotational model. Table IV lists available information on $E2$ and $M1$ transitions within the ground-state band. The data are taken from previous compilations,[12,22] except that the results obtained in the present work are given for the 3708(6^+) → 1528(5^+) transition. It is assumed for the sake of the present discussion that the spin-parity assignments of Fig. 1 are correct. The intrinsic quadrupole moments Q_0 have been deduced from the $E2$ strengths, and the quantity $(g_K - g_R)$ from the $M1$ strengths. It is seen that Q_0 is approximately constant within the band, implying that the relative $E2$ strengths are in approximate agreement with the predictions of the rotational model. The internal consistency of the $(g_K - g_R)$ values is only fair, but they are in reasonable agreement with the value of (0.056± 0.012) deduced[4] from the measured magnetic moments of the ground state and the 583-keV state. The rotational model predicts[4,22] that the $E2/M1$ mixing ratios for transitions within the ground-state band should be large and negative, in agreement with the values in Table IV. The picture presented thus far of general agreement between experiment and the predictions of the simple rotational model is marred by the observation of a substantial branch from the 4069-keV state (assumed $J^\pi = 4^+$, $T = 1$) to the 1528-keV state ($J^\pi = 5^+$, $T = 0$). Although the branching ratio obtained in the present work is smaller than that previously reported,[18] it still corresponds to an $M1$ transition of strength

$|M(M1)|^2 \geq 0.03$ W.u. [assuming $\tau(4069) \leq 4$ fs[18] and $|M(E2)|^2 \leq 10$ W.u.]. According to the rotational-model classification, the transition would have $\Delta T = 1$, $\Delta K = 3$, and would be doubly-inhibited by the K-selection rule. But a strength of $|M|^2 \geq 0.03$ W.u. falls within the upper half of the distribution of T-allowed $M1$ strengths for this mass region,[25] and thus the observed transition presents a significant difficulty for the simple rotational model. Probably this difficulty could be overcome by assuming substantial mixing of other K values in the 4069-keV level, but this would be at the expense of the simplicity, and hence the attractiveness, of the model.

Preedom and Wildenthal[26] found that the shell model was able to account for the observed "rotational" properties of positive-parity states in ^{22}Na as a consequence of coherent motion among the six extracore nucleons. Indeed, the shell-model results agreed with data which deviated from the predictions of the simple rotational model; for example, the shell model gave a better description of the J dependence of excitation energies of levels within a rotational band than did the rotational model. Freeman *et al.*[22] found that their measurements of $M1$ and $E2$ transition strengths in ^{22}Na were in remarkably close agreement with the predictions of Preedom and Wildenthal. From Table IV it is clear that for the $3708(6^+) \rightarrow 1528(5^+)$ transition, the shell-model predictions are in excellent agreement with the new results reported in this paper.

Although the simple rotational model has had striking success in accounting for the general features of the level scheme and electromagnetic transition rates in ^{22}Na, deficiencies become evident when detailed comparison is made with experiment. Such deficiencies cannot be overcome without increasing the complexity, and hence decreasing the aesthetic appeal, of the model. On the other hand, recent shell-model calculations display impressive agreement with experiment. Freeman *et al.*[22] point out that the predictions of the shell model and the rotational model diverge more strongly when higher-spin states are considered. It is therefore of great interest to investigate the lifetimes and decay modes of the high-spin members of rotational bands recently suggested by Del Campo *et al.*[17]

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