Angular-Correlation Study of Na^{23} Using the $Mg^{24}(t,\alpha\gamma)Na^{23}$ Reaction*

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The $Mg^{24}(t,\alpha\gamma)Na^{23}$ reaction has been used to investigate the spins and decay modes of many of the levels in Na^{23} below an excitation energy of 6 MeV, as well as the multipole mixing ratios of the radiative transitions between these levels. γ radiation was detected in NaI(Tl) detectors located at angles between 0 and 90°, while outgoing α particles were detected in an annular detector placed at 180° with respect to the beam direction. Two-parameter techniques were used to measure the α-γ coincidence spectra. Analysis of the resultant γ-ray angular correlations, when combined with already existing data, enabled the following unambiguous spin assignments to be made: 2.98-MeV level $J=\frac{3}{2}$, 3.68-MeV level $J=\frac{3}{2}$, 3.91-MeV level $J=\frac{5}{2}$. Limitations on the possible spins of the 4.78-, 5.38-, and 5.74-MeV levels were obtained. The results are discussed in terms of the Nilsson model for Na^{23}.

I. INTRODUCTION

Nuclear reactions initiated by tritons generally have rather high positive Q values. It is therefore easy to populate a large number of levels in the residual nucleus by the use of quite modest tritium bombarding energies. There are, of course, other advantages resulting from the ability to accelerate tritium in a small electrostatic accelerator. These are well known.[1] In many cases it is possible to form nuclei which are difficult or impossible to reach by the acceleration of the more conventional projectiles (p, d, He^3, α). In other cases it is possible to investigate the properties of nuclei commonly formed by other reactions and to easily populate many of the higher excited states. We describe below the details of an investigation of the nucleus Na^{23} using the $Mg^{24}(t,\alpha\gamma)Na^{23}$ reaction ($Q=+8.120$ MeV). Angular distributions of the reaction γ rays were measured in a collinear geometry employing two-parameter analysis. In spite of the rather low bombarding energies available from the LMSC 3-MV Van de Graaff accelerator, this reaction enabled us to investigate, with ease, the properties of most of the excited states in Na^{23} below an excitation energy of 6 MeV. Our main interest lay in an attempt to determine decay modes of and spin assignments for the levels above 2.75 MeV. In addition to this, we were able to check previously assigned spins and decay modes of lower levels and the multipole mixing ratios of the radiative transitions between them. Recent work on the structure of the nucleus Na^{23} has been reviewed by Poletti *et al.*[2] who have also reported on the measurement of the mean lives of some of the levels below an excitation energy of 4 MeV. Portions of the present work have been described in previous reports.[3,4]

In Fig. 1 we give a summary of the decay properties and spin assignments for the levels in Na^{23} which we obtain from a synthesis of the present and previous work.[2] The decay modes of the 3.85- and 4.43-MeV levels which we did not excite strongly are taken from the compilation of Endt and van der Leun.[5] The decay properties of the 5.53-MeV level are from the recent investigation of Lindgren *et al.*[6]

II. EXPERIMENTAL METHOD

A tritium beam[1] of 2.80 MeV obtained from the LMSC 3-MV Van de Graaff accelerator was used to bombard a thin metallic Mg^{24} target supported on a 10-$\mu g/cm^2$-thick carbon foil. The Mg^{24} layer was approximately 100 $\mu g/cm^2$ thick. The α particles from the resulting $Mg^{24}(t,\alpha)Na^{23}$ reaction ($Q=+8.120$ MeV) were detected in annular surface-barrier detector which subtended an angle of $\theta_\alpha=(170\pm5)°$ at the target. Slits just behind the annular detector limited the beam spot to a 1 mm×1 mm square. Either one or three 10.2×10.2-cm NaI(Tl) γ-ray detectors were used to detect the γ rays resulting from the reaction. The results of the initial experiment which involved only the single γ-ray detector were checked using the three detector system. We will now describe this latter experimental setup. Two of the detectors were movable in the horizontal plane ($\varphi=0°$) and were placed with their front faces 15 cm from the target while the third (monitor) detector was fixed at about 10 cm from the target at an angle of $\theta_{\gamma1}=135°(\varphi=45°)$ with respect to the beam direction. The other two detectors could be set at angles $-78°\le\theta_{\gamma2}\le0°$ and $0°\le\theta_{\gamma3}\le+90°$, respectively. Coincidences were taken in random order at the following angles: $\theta_{\gamma2}=-78,-60,-45,-30,-0°$; $\theta_{\gamma3}=0,30,45,60,$ and $90°$. Detection at each angle was repeated once. Coincident pulses arising from the

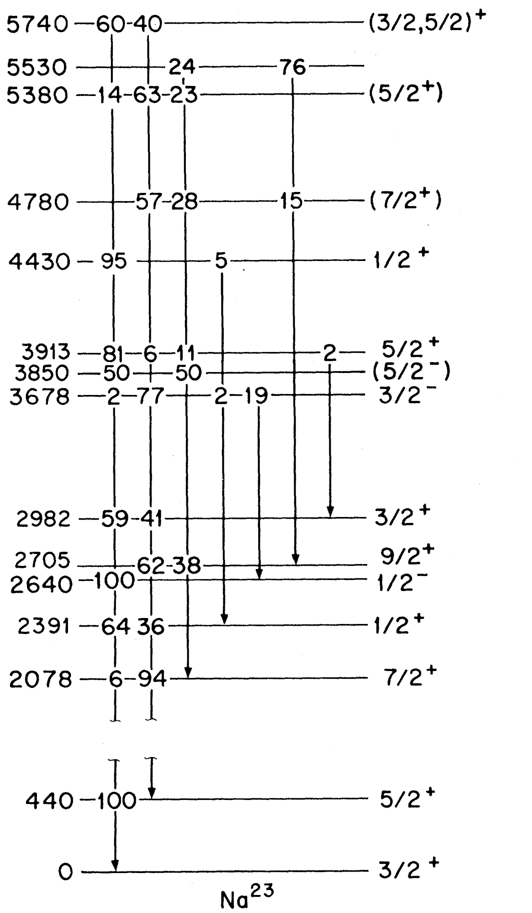

FIG. 1. Summary of the energies, spin-parity assignments and decay modes of the low-lying levels of Na^{23}, obatined from a synthesis of the present and previous work.

detection of an α particle in the annular detector and a γ ray in one of the three NaI(Tl) detectors were processed by the use of a small general purpose on-line computer. A full discussion of the multiparameter analysis system which we used has been given recently by Chalmers.[7] Our system differed in two main details (apart from the use of just three detectors) from that described in Ref. 7 and we shall mention these in turn. The output from the time-to-amplitude converter used as the coincidence device was fed to two single-channel analyzers set such that their separate outputs represented "true-plus-chance" events and "chance" events. These signals were then stored along with the ADC information, labeling the event as either a "true-plus-chance" event or a "chance" event. This scheme replaces the third or "Z" ADC described in Ref. 7. Outputs of the NaI(Tl) detectors were stabilized using constant amplitude pulses obtained from pulsed light diode sources. Analog stabilization was provided for the first and third detectors, while the second was stabilized digitally.

Coincidence events were stored associatively in 256-word buffers in the computer memory; when the buffer was filled, data were written onto magnetic tapes (ADC data). Approximately 4000 words of memory under program control were available for data storage and display. Digital pulse-height selection criteria imposed on the coincidence matrix caused the γ-ray spectra coincident with the various particle groups to be stored in the memory for subsequent examination and analysis (spectral data). Upon completion of the entire angular-correlation experiment, the pulse-height criteria could be changed and further analysis carried out by "playing back" the stored ADC data. To obtain the required γ-ray angular distributions the appropriate regions of the γ spectra in coincidence with the α-particle pulse height spanning a particular α group were summed using the computer and then suitably normalized. Some difficulty was experienced in obtaining a consistent normalization. In the end the different γ-ray angular distributions were normalized to that obtained from the 2.39-MeV level. This level has been shown[8] to give rise to isotropic γ-ray angular distributions and is almost certainly[2] of spin $\frac{1}{2}$. The distributions obtained in this manner were analyzed in terms of the Legendre polynomial expansion $W(\theta)=A_0[1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)]$ by the use of a Univac-1108 computer. Further analysis to obtain limitations on the possible spins of the excited states and to determine γ-ray multipole mixing ratios x was carried out in the standard manner.[9] The phase convention which we adopt is that of Rose and Brink,[10] which is opposite to that used by Poletti and Start[8] for $E2/M1$ mixing.

III. RESULTS

An example of the α spectra obtained in coincidence with all γ rays with $E_\gamma > 0.40$ MeV is given in Fig. 2. The resolution which we obtained was consistently less than 45 keV full width at half maximum (FWHM) for the α-particle groups. This enabled us to clearly separate the levels belonging to the two doublets at 3.9 and 2.7 MeV. The "chance" spectrum is displayed below the "true-plus-chance" spectrum. The peak labeled $O^{16}(t,\alpha)N^{15}$ arises from random γ coincidences with the intense α group arising from the $O^{16}(t,\alpha)N^{15}$ reaction ($Q=+7.687$ MeV). There was definite evidence for the excitation of all the levels reported by Dubois[11] below 5.8 MeV. The level at 5.762 MeV reported by Hay and Kean[12] did not appear to be excited in the present work. The 5.530-, 4.430-, 3.850-,

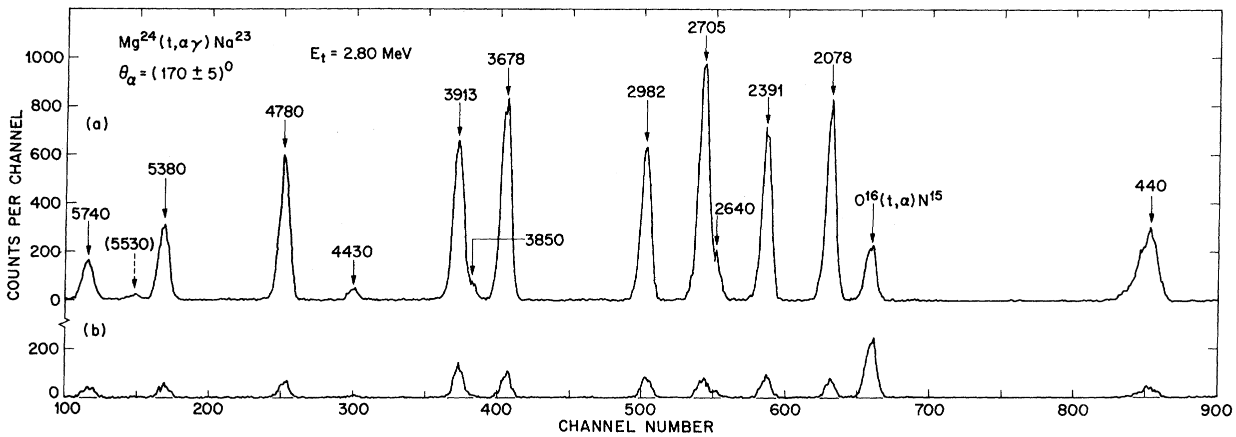

FIG. 2. An example of the α spectra obtained in coincidence with all γ rays with $E_\gamma \geq 400$ keV. Spectrum (a) is the "true-plus-chance" spectrum, while spectrum (b) is the spectrum arising from "chance" coincidence. The peak labeled $O^{16}(t,\alpha)N^{15}$ arises from random coincidences with the α group leading to the ground state of N^{15}. The α groups leading to levels in Na^{23} are labeled by their excitation energy in keV. The α particles leading to the Na^{23} 440-keV level were not completely stopped in the sensitive volume of the surface barrier detector. For this reason the corresponding line was broadened.

TABLE I. Summary of angular distribution results obtained from the $Mg^{24}(t,\alpha\gamma)Na^{23}$ reaction at a bombarding energy of 2.80 MeV. The angular distribution coefficients, a_2 and a_4 have been corrected for the finite size of the NaI(Tl) detector. The attenuation coefficients used in analyzing the data from the first run ranged from 0.85 to 0.87 for Q_2 and 0.56 to 0.61 for Q_4 for γ-ray energies ranging from 0.44 to 5.74 MeV. For the second run, the detectors were placed further from the target and Q_2 and Q_4 were taken to be 0.95 and 0.84, respectively, independent of the γ-ray energy. For the 2.98-MeV and higher-lying levels the quoted Legendre coefficients are averaged results. For the three lower levels, the results of the first run only are given.

Level	Transition	E_γ (MeV)	a_2	a_4
0.44	0.44→ 0	0.44	−0.22 ± 0.03	−0.06 ± 0.04
2.08	2.08→ 0.44	1.64	+0.01 ± 0.03	+0.07 ± 0.05
	0.44→ 0	0.44	−0.22 ± 0.01	−0.04 ± 0.03
2.71	2.71→ 0.44	2.27	+0.43 ± 0.03	−0.27 ± 0.06
	0.44→ 0	0.44	−0.19 ± 0.03	−0.02 ± 0.05
	2.71→ 2.08	0.63	−0.30 ± 0.06	+0.09 ± 0.09
2.98	2.98→ 0	2.98	+0.44 ± 0.03	−0.02 ± 0.04
	2.98→ 0.44	2.54	−0.03 ± 0.07	−0.06 ± 0.11
	0.44→ 0	0.44	−0.14 ± 0.03	−0.04 ± 0.05
3.68	3.68→ 0.44	3.24	−0.08 ± 0.03	−0.01 ± 0.03
	3.68→ 2.64	1.04	−0.65 ± 0.06	−0.02 ± 0.07
	0.44→ 0	0.44	−0.17 ± 0.02	−0.09 ± 0.06
3.91	3.91→ 0	3.91	+0.07 ± 0.02	+0.02 ± 0.02
	3.91→ 2.08	1.83	−0.32 ± 0.08	−0.04 ± 0.08
4.43	4.43→ 0	4.43	−0.04 ± 0.07	+0.02 ± 0.12
4.78	4.78→ 0.44	4.34	−0.05 ± 0.02	+0.00 ± 0.03
	4.78→ 2.08	2.70	+0.42 ± 0.05	−0.01 ± 0.07
	0.44→ 0	0.44	−0.19 ± 0.03	−0.06 ± 0.04
5.38	5.38→ 0.44	4.94	+0.24 ± 0.03	+0.00 ± 0.04
	0.44→ 0	0.44[a]	−0.13 ± 0.03	−0.11 ± 0.05
	5.38→ 2.08	3.30	+0.05 ± 0.07	−0.01 ± 0.08
5.74	5.74→ 0.44	5.30	+0.21 ± 0.04	+0.07 ± 0.06
	5.74→ 0	5.74	+0.20 ± 0.09	−0.01 ± 0.14
	0.44→ 0	0.44[a]	−0.10 ± 0.03	−0.16 ± 0.07

[a]No background subtracted for the photopeak distributions.

and 2.640-MeV levels were only weakly excited at the bombarding energy which we used. We will now briefly discuss the results obtained for the states below 2.75 MeV before considering the higher states in more detail.

A. States Below 2.75 MeV

Poletti and Start[8] have studied the levels of Na^{23} using the $Mg^{26}(p,\alpha)Na^{23}$ reaction in a collinear geometry. It is expected that their results should be similar to those obtained in the present work, since in both cases only the $m=\pm\frac{1}{2}$ magnetic substates in the residual nucleus need be considered. A direct comparison of the results indicate this is indeed so. We summarize in Table I the coefficients of the Legendre polynomial expansion describing the angular distributions obtained for the various γ rays deexciting these levels and in Table II we list the measured multipole mixing ratios which we obtained. Table II also lists the results of earlier work.[8,13,14] For the $0.44\rightarrow 0$ and $2.08\rightarrow 0.44$ transitions we are in excellent agreement with both the results of Refs. 6 and 11, while for the $2.71\rightarrow 2.08$ transition there is a small discrepancy between our measurement and that of Poletti and Start.[8] The mixing ratio of the $0.44\rightarrow 0$ transition as measured using both the (p,α) and (t,α) reactions to populate the level is somewhat larger than that obtained from the work of Mizobuchi, Katoh, and Ruan[14] and the published partial and total lifetimes of the level.[8]

B. 2.98-MeV Level

The Legendre coefficients characterizing the angular distributions of the γ rays deexciting this level are listed in Table I. For the angular distributions of the γ rays corresponding to the $2.98\rightarrow 0$ and $2.98\rightarrow 0.44$ transitions we are in agreement with the results quoted by Poletti and Start.[8] An example of the angular distributions which we obtained for the 2.98-MeV γ ray is given in the top half of Fig. 3, while the lower part of the figure

TABLE II. Multipole mixing ratios in Na^{23}.

Transition	$(J_i\rightarrow J_f)$	Mixing ratio: Present	Other[a]	
$0.44\rightarrow 0$	$(5/2\rightarrow 3/2)$	$-(0.08\pm 0.03)$	$-(0.08\pm 0.02)$[b]	$-(0.06\pm 0.04)$[c]
			$\lvert 0.05\pm 0.006\rvert$[d]	$-(0.045\pm 0.015)$[e]
$2.08\rightarrow 0.44$	$(7/2\rightarrow 5/2)$	$-(0.18\pm 0.04)$	$-(0.20\pm 0.03)$[b]	$-(0.24\pm 0.07)$[c]
$2.71\rightarrow 0.44$	$(9/2\rightarrow 5/2)$	$+(0.01\pm 0.03)$	$+(0.05\pm 0.07)$[b]	
$2.71\rightarrow 2.08$	$(9/2\rightarrow 7/2)$	$-(0.04\pm 0.03)$	$-(0.12\pm 0.04)$[b]	$-(0.02\pm 0.09)$[c]
$2.98\rightarrow 0$	$(3/2\rightarrow 3/2)$	$-(0.03\pm 0.06)$	$-(0.11\pm 0.05)$[b]	
$2.98\rightarrow 0.44$	$(3/2\rightarrow 5/2)$	$+(0.07\pm 0.21)$	$+(0.3\pm 0.3)$[b]	
$3.68\rightarrow 0.44$	$(3/2\rightarrow 5/2)$	$+(0.01\pm 0.05)$	$+(4.3^{+2.2}_{-1.0})$	
$3.68\rightarrow 2.64$	$(3/2\rightarrow 1/2)$	$+(0.11\pm 0.06)$	$+(1.4\pm 0.2)$	
$3.91\rightarrow 0$	$(5/2\rightarrow 3/2)$	$-(0.22\pm 0.03)$		
$3.91\rightarrow 2.08$	$(5/2\rightarrow 7/2)$	$-(0.12\pm 0.12)$	$\lvert x\rvert >14$	
$4.78\rightarrow 0.44$	$(3/2\rightarrow 5/2)$	$+(0.03\pm 0.08)$	$+(4.4\pm 1.6)$	
	$(5/2\rightarrow 5/2)$	$+(0.42\pm 0.08)$		
	$(7/2\rightarrow 5/2)$	$-(0.15\pm 0.04)$		
$4.78\rightarrow 2.08$	$(3/2\rightarrow 7/2)$	$+(0.52^{+0.38}_{-0.29})$		
	$(5/2\rightarrow 7/2)$	$0.36<x<0.83$		
	$(7/2\rightarrow 7/2)$	$+(0.06\pm 0.12)$		
$5.38\rightarrow 0.44$	$(3/2\rightarrow 5/2)$	$+(0.34\pm 0.15)$	$+(1.8\pm 0.5)$	
	$(5/2\rightarrow 5/2)$	$+(0.16\pm 0.07)$		
	$(7/2\rightarrow 5/2)$	$-(0.30\pm 0.05)$		
$5.38\rightarrow 2.08$	$(3/2\rightarrow 7/2)$	$-(0.01\pm 0.17)$	$+(1.6\pm 0.6)$	
	$(5/2\rightarrow 7/2)$	$+(0.19\pm 0.12)$	$+(3.9\pm 1.8)$	
	$(7/2\rightarrow 7/2)$	$+(0.33\pm 0.11)$		
$5.74\rightarrow 0$	$(3/2\rightarrow 3/2)$	$+(0.13\pm 0.17)$	$x<-3.3$	
	$(5/2\rightarrow 3/2)$	$-(0.30\pm 0.14)$		
$5.74\rightarrow 0.44$	$(3/2\rightarrow 5/2)$	$0.14<x<2.8$		
	$(5/2\rightarrow 5/2)$	$+(0.19\pm 0.12)$		

[a] For the 3.68-MeV and higher-lying levels, there have been no other measurements of mixing ratios. In these cases an entry in the third column indicates an alternative allowed region as measured in the present work.

[b] See Ref. 8.

[c] See Ref. 13.

[d] From measured partial $E2$ and total lifetimes. See Ref. 8.

[e] See Ref. 14.

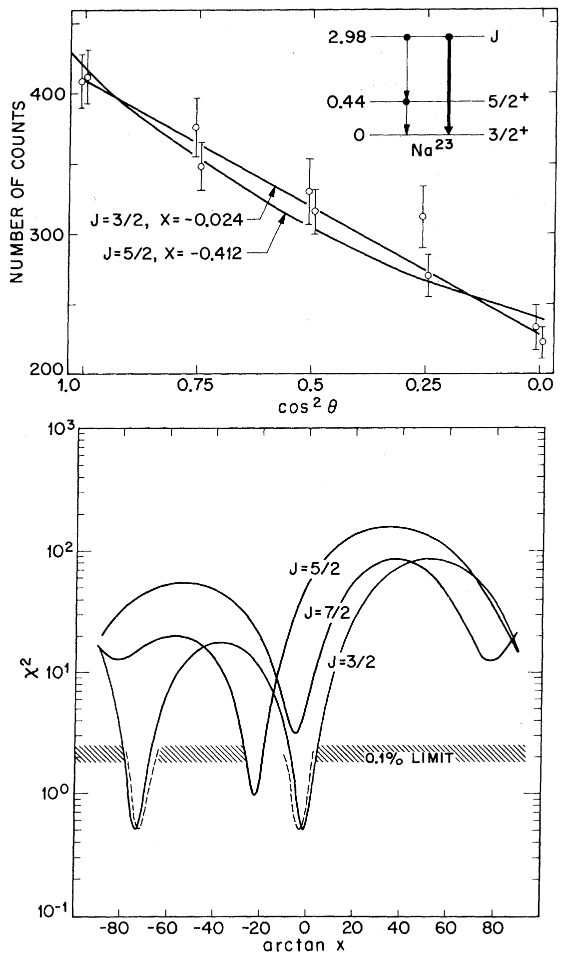

FIG. 3. Summary of the angular distribution obtained for the 2.98-MeV γ ray corresponding to the ground-state decay of the 2.98-MeV level in Na^{23}. The upper part of the figure shows the angular distribution as observed with the use of the third NaI(Tl) detector (see text) while the lower part displays the results of a least-squares analysis of the angular distribution as a function of the spin of the 2.98-MeV level and the multipole mixing ratio (x) of the deexcitation γ ray. The anisotropy of the observed distribution rules out $J=\frac{1}{2}$ while $J\geq\frac{9}{2}$ is ruled out be the known lifetime of the level. The spin $J=\frac{7}{2}$ is rejected at the 1% confidence level. See text for a discussion of the alternative $J=\frac{3}{2}$ or $\frac{5}{2}$ assignments.

shows the results of analysis of this angular distribution in terms of the level spins and multipole mixing ratios involved. For all three of the angular distributions which we measured, minima were obtained for $J_i=\frac{3}{2}, x=-0.03\pm0.06$ or $-(3.6\pm1.2)$, and $J_i=\frac{5}{2}, x=-0.42\pm0.07$ (J_i is the spin of the initial state). However, in each case and also in the work of Poletti and Start,[8] the minimum χ^2 value obtained for $J=\frac{5}{2}$ was not as low as that for $J=\frac{3}{2}$.

In order to make a statistically significant choice between the alternate spin possibilities, the three sets of data taken at Lockheed were analyzed simultaneously in the least-squares-fitting program. For $J=\frac{5}{2}$, the resulting minimum value of $\chi^2=1.38$ at $x=0.42$ in a least-squares fit with 26 degrees of freedom falls just below the 10% confidence level.[15] This is to be compared with the minimum $\chi^2=0.71$, $x=0.0$ for the assumption $J=\frac{3}{2}$. On the basis of the angular distribution observed in the $Ne^{22}(He^3, d)Na^{23}$ reaction, Dubois[16] has assigned even parity to the 2.98-MeV level. Thus, the 2.98-MeV level has a most probable spin-parity assignment $J^\pi=\frac{3}{2}^+$. Lindgren *et al.*[17] have also concluded that the 2.98-MeV level has $J=\frac{3}{2}$. This assignment is based on a careful analysis of the angular correlation of the 2.98-MeV γ ray, measured in the $Mg^{26}(p,\alpha\gamma)$-Na^{23} reaction.

C. 2.64- and 3.68-MeV Levels

Figure 4 displays the γ spectrum in coincidence with α particles leading to the 3.68-MeV level. This spectrum originated from the addition of all the spectra obtained at the different angles. Major decays to the 0.44- and 2.64-MeV levels were observed while we have assigned weak branches to both the ground state and the 2.39-MeV level. We do not observe the 10% decay branch to the 2.08-MeV level reported by Braben, Green, and Willmott,[18] nor do these workers report a branch to the 2.39-MeV level. For future reference we adopt from Table III the branchings measured in the present work. As the Legendre coefficients (see Table I) for the $3.68\to0.44$ transition were small, it was necessary to attempt to analyze the distribution of the much more anisotropic 1.04-MeV γ ray corresponding to the $3.68\to2.64$ transition in order to obtain a spin assignment for the 3.68-MeV level. But to do this successfully, it is necessary to know the spin of the 2.64-MeV level. We will, therefore, first discuss the experimental evidence which implies $J^\pi=\frac{1}{2}^-$ for the 2.64-MeV level. Recently, Dubois[16] using the $Ne^{22}(He^3, d)Na^{23}$ reaction has shown that the 2.64-MeV level has $J^\pi=\frac{1}{2}^-$ or $\frac{3}{2}^-$ while its lifetime is 0.15 ± 0.03 psec.[2] The $J^\pi=\frac{3}{2}^-$ alternative together with the isotropic γ-ray angular distribution measurement[8] requires $x_{2.64}(M2/E1)=+(0.26\pm0.05)$ resulting in $|M(M2)|^2=2.0\pm0.7$ single-particle units[19] for the $2.64\to0$ transition. While $M2$ transitions of almost this enhancement have been established, they are exceedingly rare in this region of the Periodic Table.[20] The spin and parity of the 2.64-MeV level is then almost certainly $J^\pi=\frac{1}{2}^-$. We can now interpret the angular distribution obtained for the 1.04-MeV γ ray corresponding to the $3.68\to2.64$ transition. Figure 5 gives an example of the angular distributions which we obtained for this γ ray

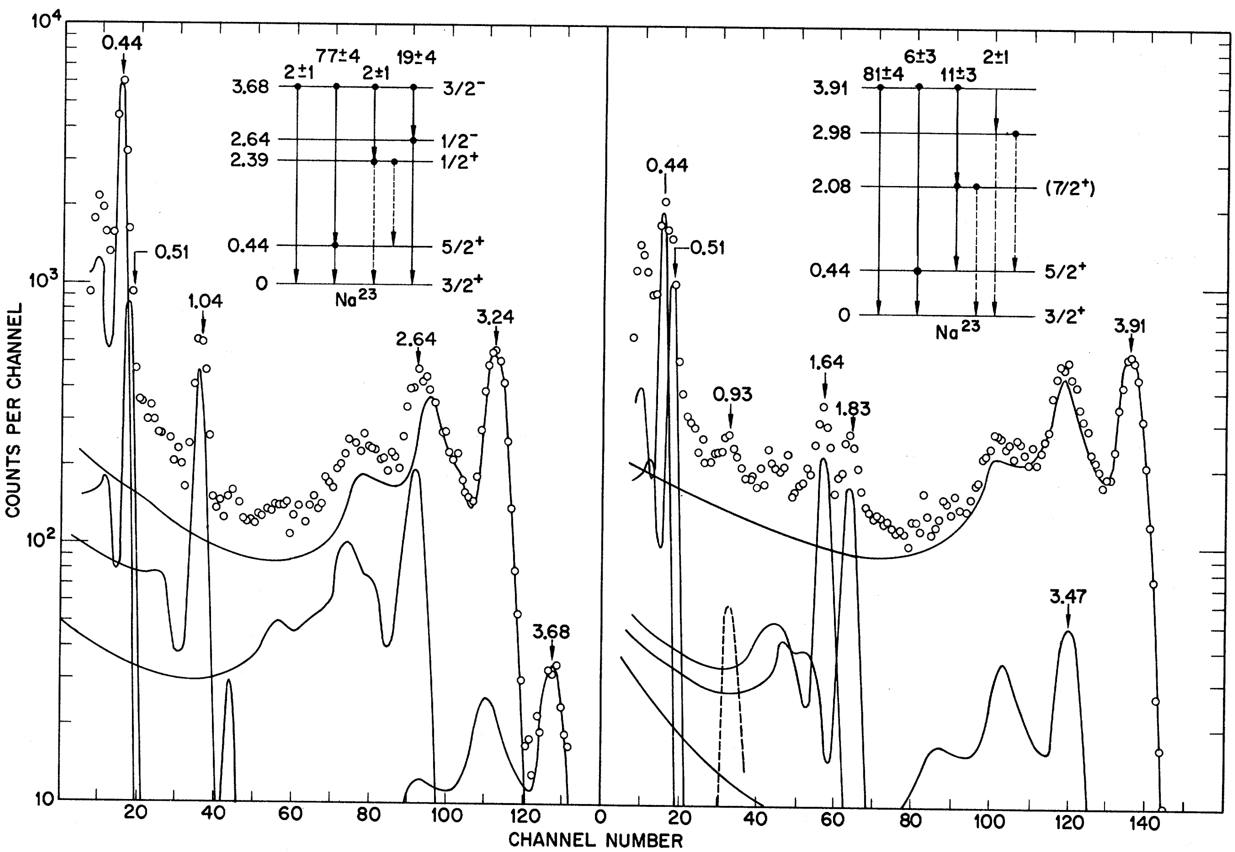

FIG. 4. γ-ray spectra obtained in coincidence with α particles populating the 3.68- and 3.91-MeV levels of Na^{23}. The continuous curves represent the decomposition of each spectrum into its constituent γ rays.

and the resulting χ^2 versus $\arctan x$ analysis. From this it can be seen that both $J=\frac{1}{2}$ and $\frac{5}{2}$ are completely ruled out while $J=\frac{3}{2}$ is allowed. Dubois[16] found $J^\pi=(\frac{1}{2},\frac{3}{2})^-$ for the 3.68-MeV level; our combined results, then, result in a $J^\pi=\frac{3}{2}^-$ assignment. Averaging the results obtained from our three different angular distributions we obtain $x=+(0.11\pm0.06)$ or $+(1.36\pm0.20)$. The larger of these two values can be eliminated since the known lifetime limit and decay modes of this level imply that for $x>1.16$, $|M(E2)|^2>110$ in single-particle units.[19] For the $3.68\rightarrow0.44$ transition which is the major decay mode from the 3.68-MeV level we obtain $x=+(0.01\pm0.05)$ or $(4.3^{+2.2}_{-1.0})$. The larger of these two values can be eliminated since $x>3.3$ requires $|M(M2)|^2>63$ single-particle units. In summary, then (with the almost certain assignment of $J^\pi=\frac{1}{2}^-$ to the 2.64-MeV level), the spin parity of

TABLE III. Decay modes of some excited states of Na^{23} measured in the present work.

State (MeV)	Decay to 0.0	0.44	2.08	2.39	2.64	2.71	2.98	3.68	3.91
2.08	6 ± 2	94 ± 2							
2.39	64 ± 4	36 ± 4	<2						
2.64	~100								
2.70	<2	62 ± 4	38 ± 4	<6					
2.98	59 ± 4	41 ± 4	<4	<1	<6				
3.68	2 ± 1	77 ± 4	<3	2 ± 1	19 ± 4				
3.91	81 ± 4	6 ± 3	11 ± 3	<4	<4	<4	2 ± 1	<2	
4.43	~100								
4.78	<2	57 ± 4	28 ± 5	<2	<6	15 ± 4	<5	<3	<3
5.38	14 ± 4	63 ± 7	23 ± 5	<2	<2	<3	<5	<10	<2
5.74	60 ± 10	40 ± 10				all less than 10%			

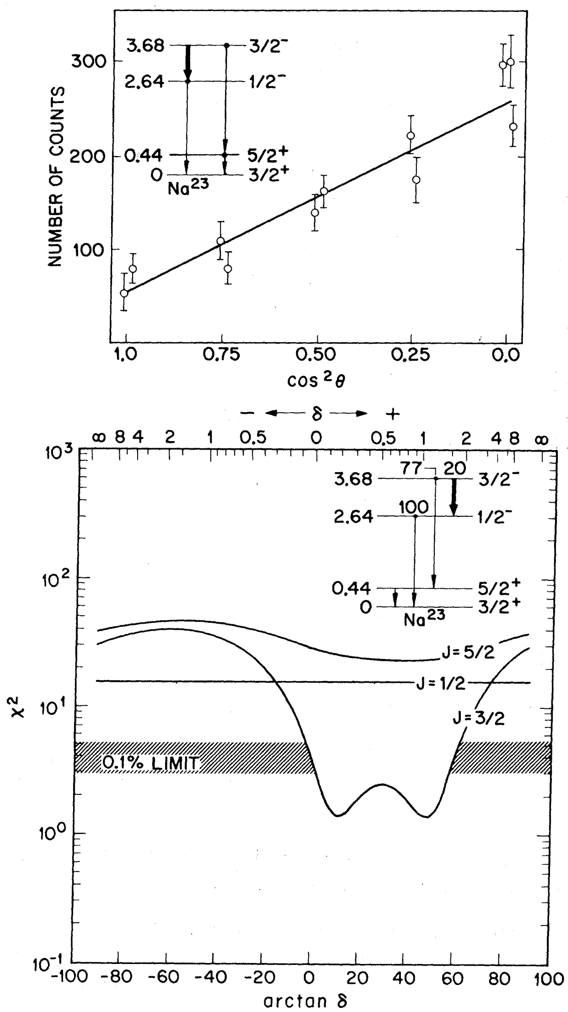

FIG. 5. Summary of the angular distribution obtained for the 1.04-MeV γ ray corresponding to the 3.68 → 2.64 transition. $J=\frac{7}{2}$ is ruled out by the known upper limit on the mean life of the level. The upper part of the figure shows the angular distribution as observed with the use of the third NaI(Tl) detector (see text) while the lower part displays the results of the least-squares analysis: $J=\frac{3}{2}$ is the only spin value allowed by this analysis.

the 3.68-MeV level is $\frac{3}{2}^-$ and both major decays are dipole or nearly so.

D. 3.91-MeV Level

The summed γ-ray spectrum in coincidence with α particles leading to the 3.91-MeV level is displayed on the right of Fig. 4. The major decay is to the ground state while weaker decays were observed to both the 2.08- and 0.44-MeV levels. A possible decay of $(2\pm1)\%$ was seen to the 2.98-MeV level. Our results are in major agreement with those of Wernbom-Selin and Arnell[21] although these latter workers quote somewhat more intense branchings to both the 0.44- and 2.08-MeV levels and do not report a branch to the 2.98-MeV level.

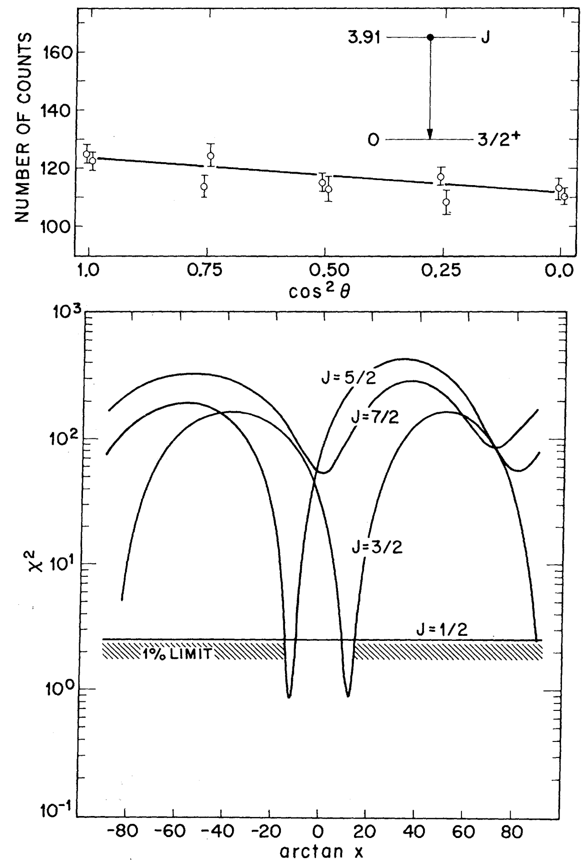

FIG. 6. Summary of the results obtained for the angular distribution of the 3.91-MeV γ ray from the 3.91-MeV level. Although the distribution is nearly isotropic $J=\frac{1}{2}$ is ruled out at the 1% limit in the least-squares fitting. Solutions are obtained for $J=\frac{3}{2}$ and $\frac{5}{2}$ while $J=\frac{7}{2}$ is ruled out by a very large margin. Analysis of the angular distribution of the 3.91 → 2.08 transition eliminates $J=\frac{3}{2}$ (see text).

A χ^2 versus $\arctan x$ fitting is summarized in Fig. 6 for the ground-state decay. Spin assignments of $\frac{1}{2}$ and $\frac{7}{2}$ are ruled out leaving as possible candidates $J=\frac{3}{2}, x=+0.21\pm0.03$ and $|x|>12$ and $J=\frac{5}{2}$, $x=-0.22\pm0.03$. For the $(11\pm3)\%$ branch to the 2.08-MeV level the three distributions when averaged and corrected for the finite solid angle subtended by the γ-ray detector yielded $a_2=-0.32\pm0.08$ and $a_4=-0.04\pm0.08$. A least-squares fit to these coefficients yielded $x=-0.48\pm0.20$ and $|x|>2.9$ for $J_i=\frac{3}{2}$, and $x=-(0.12\pm0.12)$ and $|x|>14$ for $J_i=\frac{5}{2}$. If we now combine the known lifetime limit[8] for the 3.91-MeV level with the branching and mixing ratios measured in this work for $J_i=\frac{3}{2}$, we obtain $|M(E3)|^2>3000$ for the possible octupole component of the 3.91 → 2.08 transition. This is quite unreasonable, hence the spin of the 3.19-MeV level is

$J=\frac{5}{2}$. (The $\frac{5}{2}$ assignment is the only spin assignment consistent with the lifetime limit and empirical γ-ray widths.) Dubois[6] has assigned even parity to this level.

E. 4.78-MeV Level

In Fig. 7 we display the summed γ-ray spectrum in coincidence with α particles leading to the 4.78-MeV level. Like Wernbom-Selin and Arnell,[21] we see major branches to the 0.44- and 2.08-MeV levels. We do not, however, see γ rays corresponding to decays to the ground state, the 2.98- and 3.68-MeV levels as reported in Ref. 21. We do see a 0.63-MeV γ ray which we consider to arise from a 15% branch to the 2.71-MeV level. For clarity we have not drawn the full-energy peaks of the 2.27- and 2.07-MeV γ rays associated with the 15% decay to the 2.71-MeV level. These two photopeaks would fall at channels 78.5 and 71.5 and have peak heights 35 and 60% as high as the 2.70-MeV peak. They are represented by the excess of counts in the region of channels 65–82.

From the least-squares fitting of the angular distribution of the 4.34-MeV γ ray corresponding to the $4.78\rightarrow 0.44$ transition we were able to eliminate spins of $J\geq\frac{9}{2}$ for the 4.78-MeV level. The anisotropy of the angular correlation corresponding to the $4.78\rightarrow 2.08$ transition rules out $J=\frac{1}{2}$ but $J=\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ all gave acceptable solutions for values of the mixing ratios listed in Table II. We are not able to further limit the spin of this level. Dubois has made a tentative assignment of $\frac{7}{2}^+$.

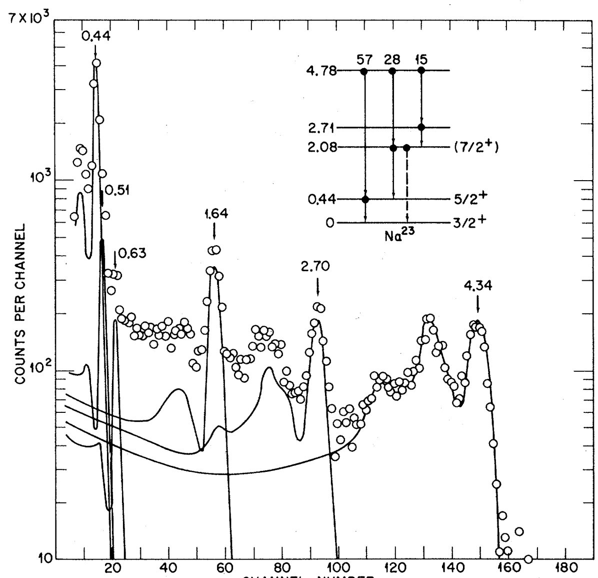

FIG. 7. γ-ray spectra obtained in coincidence with α particles populating the 4.78-MeV level of Na^{23}.

F. 5.38-MeV Level

The summed γ-ray spectrum in coincidence with α particles leading to the 5.38-MeV level is displayed in the upper half of Fig. 8. The γ decay of this level has not previously been reported. We determine the major decay to be to the 0.44-MeV level with lesser decays to the ground state and 2.08-MeV level. Analysis of both the 4.94 ($5.38\rightarrow 0.44$) transition and the 3.30 ($5.38\rightarrow 2.08$) transition did not yield an unambiguous spin assignment for the 5.38-MeV level. We were only able to limit the possible spins to $J=\frac{3}{2}$, $\frac{5}{2}$, or $\frac{7}{2}$. For each spin possibility the allowed region for the mixing ratio of both the 4.94- and 3.30-MeV transitions is given in Table II. The tentative assignment given by Dubois[11] $J^\pi=(\frac{3}{2},\frac{5}{2}^+)$ for the 5.38-MeV level is reasonable in view of the decay modes and mixing ratios measured in the present work. The observed 23% decay to the 2.08-MeV level indicates that $J=\frac{5}{2}$ is the most likely of these two tentative assignments.

G. 5.74-MeV Level

In the lower half of Fig. 8, we display the summed γ-ray spectrum in coincidence with α particles leading to the 5.74-MeV level. We determined the branching for this level to be 60 ± 10%

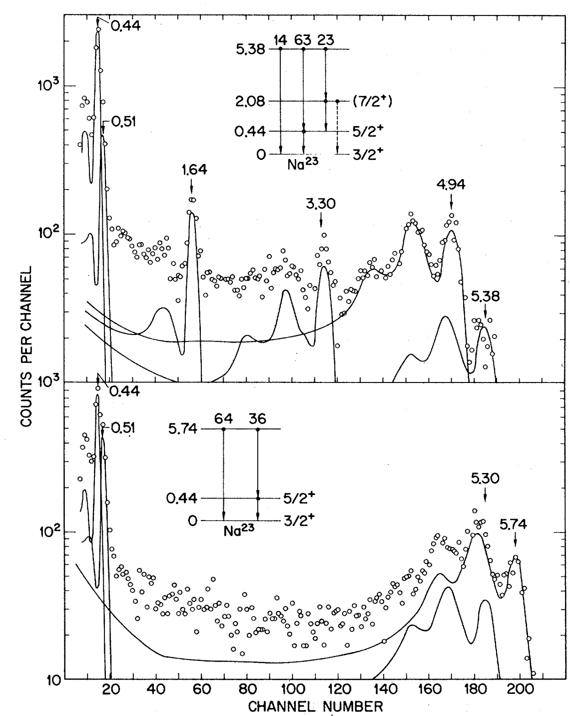

FIG. 8. γ-ray spectra obtained in coincidence with α particles populating the 5.38- and 5.74-MeV levels of Na^{23}.

and 40 ± 10% to the ground state and 0.44-MeV level, respectively. The γ-ray decay modes of this level were previously unknown. The observed anisotropy of the γ-ray angular distributions rule out a spin assignment of $J=\frac{1}{2}$ while $J=\frac{7}{2}$ is rejected at the 5% confidence limit. For $J=\frac{3}{2}$ and $\frac{5}{2}$ good fits to the experimental angular distributions could be obtained for the regions of the multipole mixing ratio listed in Table II. Dubois[11] has tentatively assigned $J^{\pi}=(\frac{3}{2},\frac{5}{2})^+$ to the level.

IV. DISCUSSION

A. Calculation of Transition Strengths in the Ground-State Band

Recent work[2,22,23] has yielded lifetimes or limits on lifetimes for a number of the low-lying excited states of Na^{23}. These results together with the now firm spin-parity assignment of $\frac{7}{2}^+$ and $\frac{9}{2}^+$ to the levels at 2.08 and 2.71 MeV and a tentative assignment of $\frac{11}{2}^+$ to the state at 5.53 MeV make it interesting to reexamine the Nilsson[24] model calculation of $M1$ and $E2$ transition probabilities within the ground-state band. Howard, Allen, and Bromley[25] for the purposes of calculating these matrix elements assumed that the ground state and levels at 0.44 and 2.08 MeV arose only from the $K^{\pi}=\frac{3}{2}^+$ orbit 7 of Nilsson.[24] Dubois[16] in a recent paper has shown that this is not necessarily so and indeed has carried out a band-mixing calculation which includes the band from which these levels arise as one of the mixed bands. However, for the ground state and the levels at 0.44, 2.08, and 2.71 MeV the amplitudes for the orbit 7 component of the wave functions were 0.986, 0.872, 0.914, and 0.749, respectively. Thus at least for the lowest three levels the assumption of Howard, Allen, and Bromley[25] is not unreasonable, while for the 2.71-MeV level the orbit 7 component is still the major one. In view of this and the relatively large uncertainties associated with the experimentally determined lifetimes we have not attempted to take into account all the components listed by Dubois[16] and instead follow Howard, Allen, and Bromley[25] and just consider the major component. As Table IV shows, for the $M1$ intraband transitions, this gives quite good agreement with experiment in the two cases where partial $M1$ widths can be inferred from measured lifetimes. (We have taken $\eta=+4$, and $g_R=0.30$.) For the 2.08-MeV level, the upper limit $\tau<0.23$ psec adopted by Poletti *et al.*[2] for the lifetime for this state together with the measured mixing and branching ratios gives a limit of $\Gamma_{M1}(2.08\rightarrow 0.44)>2.6$ meV. This is not in disagreement with the calculated width of $\Gamma_{M1}=40.0$ meV but is not a very stringent test either. Durell *et al.*[22] quote a lifetime of (0.22 ± 0.03) psec for this level at 2.08 MeV. This implies $\Gamma_{M1}(2.08\rightarrow 0.44) = 2.7\pm 0.5$ meV, i.e., a factor of 14.8 narrower than the calculated width for this transition. In addition their measurements would imply quite small enhancements of (1.45 ± 0.48) and (3.2 ± 0.8) single-particle units,[19] respectively, for the two $E2$ transitions $2.08\rightarrow 0$ and $2.08\rightarrow 0.44$ compared to the established $E2$ enhancement of 22.5 ± 2.5 single-particle units for the $0.44\rightarrow 0$ transition. For these reasons and the reasons given by Poletti *et al.*,[2] it would be interesting to see a further measurement of the lifetime of this level. The lifetime of the 5.53-MeV level is not known, consequently we do not have any experimental information on transitions from this level.

For the $E2$ transitions within this band the relevant expression given by Howard, Allen, and Bromley[25] contains the factor $(1+Y_{E2}{}^c)^2$, where

$$Y_{E2}{}^c \simeq ZA^{1/3}\epsilon(1+\tfrac{1}{2}\epsilon)/G_{E2}\,,$$

and $G_{E2}=+0.5a_{21}{}^2-a_{22}{}^2$ for orbit 7. The quantity ϵ is related to the deformation parameter η and the

TABLE IV. Calculated and experimental $M1$ and $E2$ widths for some low-lying levels in Na^{23}.

E_i (MeV)	E_f (MeV)	$\Gamma(M1)_{th}$ [a]	$\Gamma(M1)_{ex}$	$\Gamma(E2)_{th}$	$\Gamma(E2)_{ex}$	$\Gamma(tot)_{th}$	$\Gamma(tot)_{ex}$
0.44	0.00	0.58	0.40 ± 0.02	b	$(1.19\pm0.13)\times10^{-3}$	0.58	0.40
2.08	0.44	40.0	>2.6	0.56	>0.11		
	0.00	···	···	1.16	>0.17	41.7	>2.9
2.71	2.08	2.52	2.3 ± 0.4	0.003	$(1.5^{+1.8}_{-1.1})\times10^{-2}$		
	0.44			2.68	3.7 ± 0.7	5.20	6.0 ± 1.1
5.53	2.71	242.0	?	3.75	?		
	2.08	···	···	26.4	?	272	?

[a] All widths in millielectron volts (meV).

[b] For this transition, the experimental value was used to determine the quantity Y_{E2}. With Y_{E2} fixed, the other $E2$ transition could then be predicted. The value adopted for the relevant mixing ratios were $0.44\rightarrow 0$; $x=-(0.07\pm0.02)$, $2.07\rightarrow 0.44$; $x=-(0.20\pm0.03)$, and $2.71\rightarrow 2.08$; $x=-(0.08\pm0.04)$.

spin-orbit coupling parameter κ by

$$\kappa\eta = \epsilon[1 - \tfrac{1}{3}\epsilon^2 - \tfrac{2}{27}\epsilon^3]^{-1/3}.$$

The term $Y_{E2}{}^c$ was introduced by McManus and Sharp[26] to take account of the collective contribution to the $E2$ matrix element. This quantity is a rather sensitive function of η and κ and now that a number of the $E2$ widths are determined experimentally it is more useful to take $(1 + Y_{E2}{}^c)$ as an adjustable parameter determined by the partial $E2$ width of the 0.44-MeV level. If this is done, the $E2$ widths listed in Table IV are obtained. For both transitions originating from the 2.61-MeV level the agreement between theory and experiment is reasonable while again for the 2.08-MeV level the upper limits are not in disagreement with the theory but are not particularly helpful either.

V. CONCLUSION

The spectroscopy of the levels in Na^{23} is becoming quite well known below an excitation energy of 5.74 MeV as indicated in Fig. 1. More recent work has extended measurements to yet higher excitation energies.[27] In Sec. IV A, we have applied concepts of the simple rotational model to transition strengths within the ground-state band; a rather more elaborate calculation still within the framework of the rotational model but including Coriolis coupling has been described in Ref. 27.

There are some further measurements of interest in this region of excitation energy in Na^{23}. Some small discrepancies exist among the various partial and total lifetime measurements of the 0.44-MeV level: A direct measurement of the total lifetime using the Recoil-Distance Method[28] is probably feasible with some refinement of present techniques. Measurements of the lifetimes of the 2.08-, 2.39-, 2.64-, 2.70-, 3.68-, 3.85-, and 3.91-MeV levels by the Doppler-shift attenuation[29] using either heavy ion beams or detection of the outgoing proton to define the initial recoil velocity more accurately would all be very useful. The spin and decay modes of the 3.84-MeV level need further investigation. Verification (or otherwise) of the weaker decay modes of both the 3.68- and 3.91-MeV levels would be of interest, especially the 2% branch $3.91 \rightarrow 2.98$ which is probably an $M1$ intraband transition. The decay of the 4.43-MeV level needs to be remeasured as does the mixing ratio of the $2.71 \rightarrow 2.08$ transition. Definitive measurements of the lifetimes, spins, and parities of the levels at 5.38, 5.53, and 5.74 MeV are still needed.

We would like to take this opportunity to correct an error in Ref. 2. Stanley of Stanford University has pointed out that the computations of $\Gamma(E1)$ for the 2.64- and 3.68-MeV levels in Ref. 2 need correction. The multiplicative factor in Eq. (2) of Ref. 2 should be unity rather than $\sqrt{\frac{5}{3}}$, resulting in $G_{E1} = -0.0740$. The corresponding $E1$ transition strengths may readily be corrected, if they are multiplied by 0.60. The major conclusions of the discussion are unchanged.

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Inelastic Scattering of 31-MeV Alpha Particles from Zn^{64} and Zn^{66}

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The (α, α') reaction on Zn^{64} and Zn^{66} has been studied using the 31-MeV α-particle beam from the Massachusetts Institute of Technology cyclotron, with an over-all energy resolution of 80–120 keV. Angular distributions are presented, both for levels with known spin, and for levels whose spin and parity have not been previously determined. New 3^-, 4^+, and 5^- assignments are made both by comparison with levels of known spin and with the distorted-wave Born approximation. Good angular distributions are presented for the weak states at 1.81 MeV (2^+) and 2.32 MeV (4^+) in Zn^{64}. They are both out of phase with the 2^+ and 4^+ single-excitation states. The slope of the angular distribution for the 2.32-MeV (4^+) level is shallower than for the single-excitation 4^+ state, while the slopes are the same for the 2^+ states. Transition strengths in Zn^{64} and Zn^{66} are compared. Fractionation of 3^- strength in Zn^{64} has been observed, but it is smaller than that found in the calcium isotopes.

I. INTRODUCTION

The nuclear spectroscopy of the zinc isotopes has been studied by several authors.[1-9] Many levels have been found up to an excitation energy of 4.8 MeV[10]; however, spin assignments have been made only for some of the levels up to approximately 3 MeV in excitation. A comprehensive review of the available data, up to 1967, has been given by Verheul,[11] and Pancholi and Way.[12,13] We studied the inelastic α-particle scattering from Zn^{64}, Zn^{66}, Zn^{68}, and Zn^{70} with an energy resolution of 80–120 keV. This paper reports the results from Zn^{64} and Zn^{66}. The purpose of the experiment was to measure the variation in excitation strength as neutrons are added to the $1f_{5/2}$ shell and to see if the fractionation of 3^- strength observed in the region of $A = 40-48$ and $A = 90$[14,15] would also be present in the Zn isotopes. In addition, we decided to obtain more detailed angular distributions for the low-lying weaker levels, which are generally interpreted as double-excitation states.[1,2,4,5] The available data for Zn^{68} and Zn^{70} will be published at a later date. Good angular distributions are presented for some of the weaker states at high excitation energies, and new spin assignments are given for them. A comparison of transition strengths is made between levels in Zn^{64} and Zn^{66}, and with the results from other reaction experiments.

II. EXPERIMENT

We used the 31-MeV α-particle beam from the Massachusetts Institute of Technology cyclotron. The beam handling system and scattering chamber have already been described.[14,15] The scattered α particles were detected by single semiconductor counters and their signal was fed into the usual electronic counting system. The beam direction was fixed by a left-right split Faraday cup.[15] Variations in beam direction were monitored by two counters fixed on opposite sides of the beam. The beam direction was measured by left-right scattering of α particles from gold. Due to variations in the beam direction over long periods of time, we estimate the angular uncertainty to be 0.2°. The