ments, and particularly Dr. J. S. Levin and Dr. M. P. Kellogg for devising and setting up the computer system for recording and processing our counting data. We express also our appreciation to Dr. J. E. Sattizahn for his interest and support.

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

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PHYSICAL REVIEW C VOLUME 6, NUMBER 3 SEPTEMBER 1972

Resonance Fluorescence of ^{23}Na Above 3 MeV*

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(Received 14 May 1971; revised manuscript received 10 April 1972)

Five levels in ^{23}Na were studied using nuclear resonance fluorescence. A previously reported level at 3.91 MeV was identified as a doublet with levels at 3914.0 ± 1.8 and 3916.3 ± 1.8 keV. Levels of 5375.8 ± 2.7, 5742.7 ± 2.9, and 5768.3 ± 2.9 keV have widths ($g\Gamma$) of $2.45^{+0.48}_{-0.41}$, $1.29^{+0.10}_{-0.09}$, and $0.62^{+0.05}_{-0.04}$ eV, respectively, as measured by self-absorption experiments. The γ-ray branching ratios for these levels were measured with a 40-cm^3 Ge(Li) spectrometer.

I. INTRODUCTION

In recent years, considerable work has been done to determine and understand the level structure of odd-A nuclei in the $2s$-$1d$ nuclear shell. Indeed, for energies below 3 MeV, the spectroscopy of ^{23}Na is well known,[1,2] and has been described in terms of the Nilsson model[3,4] for deformed nuclei by several authors. Calculations by Bhatt[5] within the framework of the extreme single-particle Nilsson model are in agreement with the known ground-state properties of ^{23}Na and suggest a prolate spheroidal deformation ($\eta \sim 4.0$) for the nucleus. Glocke,[6] who considered the interactions between the ground state and the lowest-lying excited rotational bands (Nilsson orbits 7, 9, 5, and 6), successfully described the level scheme below 3 MeV, and predicted the spins of all but the 2.98-MeV level. As more experimental information became available, comparison of model predictions with the dynamic properties of ^{23}Na (γ-ray transition probabilities) were made by Howard, Allen, and Bromley,[7] and later by Poletti and Start.[1] A review of the recent work on the structure of ^{23}Na is given by Poletti *et al.*[8]

More recently, the study of ^{23}Na has been extended to higher energies. Crawley and Garvey[9] studied the level structure up to 6.0 MeV by the ^{23}Na(p,p') reaction, reporting levels at 5.38, 5.76, and 5.92 MeV. Dubois[10] and Hay and Kean[11] studied the ^{25}Mg(d,α) reaction and observed 23 levels between 4.43 and 7.13 MeV, including a level at 5.74 MeV. Poletti, Becker, and McDonald[2] studied decay modes and angular distributions from the ^{24}Mg(t, α) reaction and made spin assignments for many levels in this energy range. However, of the 23 levels observed by these experimenters, the widths of only the 3.91-,[12] 4.43-,[13] 6.01-,[14] and 7.10-MeV[15] levels are known, while the widths of all the levels below 3.9 MeV have been measured.[2, 16]

In the experiments described here, the resonance fluorescence technique was used to measure the energies, widths, and branching ratios of five levels in ^{23}Na at 3.914, 3.916, 5.376, 5.743, and 5.768 MeV. Rasmussen[12] also performed resonance fluorescence experiments on levels below 4 MeV, including that at 3.91 MeV. His measurements indicated the possibility that the 3.91-MeV level is a doublet, and stimulated the present investigation. In this work the presence and separation of the doublet are established. Preliminary results have been reported earlier.[17]

II. EXPERIMENTAL METHOD

A. Apparatus and Energy Measurements

The apparatus used for these experiments is shown in Fig. 1. An electron beam accelerated by the modified[18] FN Van de Graaff accelerator was momentum-analyzed to 0.05% and directed onto a 2.9-mg/cm^2 self-supporting Au foil. Electrons passing through the foil were then deflected 90° downward and collected in a graphite Faraday cup. The bremsstrahlung produced in the foil was incident on a sodium scatterer 15 cm square and 10 cm thick located 50 cm from the foil. During self-absorption measurements a sodium absorber 13 cm square by 10 cm thick was placed between foil and scatterer.

The scattered radiation was detected by four 4-in.×4-in. NaI(Tl) detectors located at an angle (noncoplanar) of 130° relative to the incident electron beam. In addition, a 40-cm^3 Ge(Li) detector was placed at an angle of 105°. The detectors were surrounded by a minimum of 20 cm lead, and the critical area between foil and detectors was occupied by Mallory "2000" metal. A 2-in.-thick lead and $\frac{1}{4}$-in.-thick graphite absorber were placed between each detector and the scatterer.

Typical pulse-height distributions for incident electron beam energies slightly above (open circles) and slightly below (closed circles) the 5.74-MeV level are shown in Fig. 2. The difference between the two spectra in the photopeak area is taken as the resonant scattering yield. Since the cross sections for competing elastic scattering processes do not vary appreciably over the 10-keV energy range, contributions from these processes

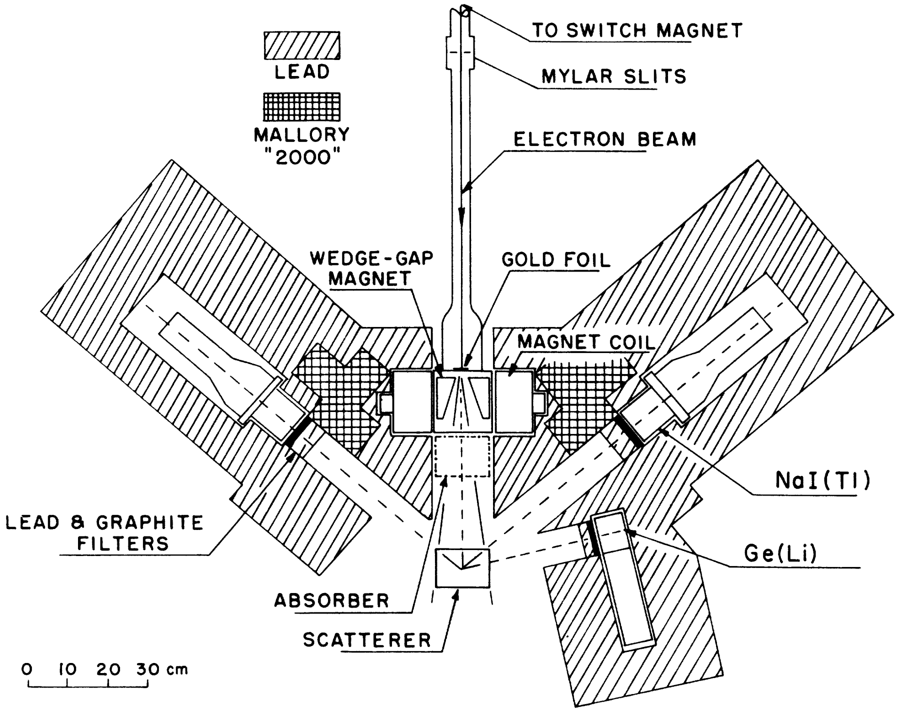

FIG. 1. Top view of the experimental apparatus. Two NaI(Tl) detectors were located on each side of the apparatus, one above another. The 0.001-in. Mylar slits were used as an aid to initial steering of the electron beam, and were not struck by the beam during data runs.

are accounted for when the difference is taken. A comparison scatterer is not necessary.

Since the bremsstrahlung cross section at the high-frequency limit is finite, the resonant scattering yield will increase abruptly as the kinetic energy of the electron beam is increased from below to above the energy of the resonant level. The yield curve, traditionally called an isochromat, shows this increase over an energy range of about 2 keV. This 2-keV width is primarily due to the finite resolution of the electron momentum analysis system. Isochromats taken with the dispersion of the momentum analysis system deliberately increased, indicate that the effect of energy loss of electrons penetrating the foil was not observable. Since the isochromat method is also used for the calibration of the analysis system,[18] it is possible to measure excitation energies to an accuracy of 0.05% if the statistics of the data are adequate.

B. Width Measurements

When bremsstrahlung is used as the source of exciting radiation, the yield Y_{SC} of scattered photons from a level of resonance energy E_r and width Γ is

$$Y_{\mathrm{SC}} = I(E_r)W(\theta)K\int\sigma_{\mathrm{SC}}(E)dE \qquad (1)$$

in the thin-scatterer approximation. Here $I(E_r)$ is the number of photons of resonant energy, $W(\theta)$ is the angular-correlation function, and K accounts for such additional effects as detector efficiency and target density. The Doppler-broadened resonant scattering cross section $\sigma_{\mathrm{SC}}(E)$ is given by

$$\sigma_{\mathrm{SC}}(E) = 2\pi\bar{\lambda}^2 g(\Gamma_0/\Gamma)^2\psi(x,t),$$

where Γ_0 is the ground-state partial width and g is the statistical weight. The function $\psi(x,t)$ is the convolution of the nuclear resonance shape and the Doppler broadening of the level due to thermal motion of the target nuclei. A discussion of Eq. (2) is given by Metzger.[19]

A self-absorption experiment is similar to a scattering experiment except that an absorber of the same material as the scatterer is placed in the incident bremsstrahlung beam path. The incident radiation is attenuated in the resonance region, and the yield Y_{SA} is correspondingly reduced. If the two experiments are combined, the transmission $T = Y_{\mathrm{SA}}/Y_{\mathrm{SC}}$, when corrected for electronic attenuation in the absorber, is a measure of the self-absorption cross section. The advantage of the technique is that $I(E_r)$, $W(\theta)$, and K in Y_{SA} and Y_{SC} cancel out in the expression for T for a thin scatterer.

If the scatterer is large, as in the present work, the attenuation of incident and scattered radiation in the volume of the scatterer must be considered. In addition, the detector efficiency, the angle θ, and $I(E_r)$ may vary over the scattering volume and may not rigorously be canceled in the ratio T. The function T vs Γ has been computed for the experiments described here, using several geometries and experimental parameters. The function $\psi(x,t)$ was generated using the Adler-Naliboff approximation.[20] Our results indicate that realistic variations of $W(\theta)$, $I(E_r)$, and K over the scatterer volume have a small effect on the resulting transmis-

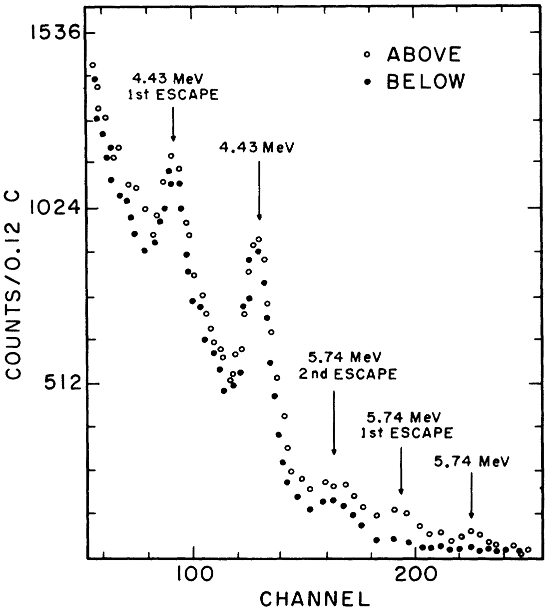

FIG. 2. NaI(Tl) pulse-height distributions taken above (open circles) and below (filled circles) the 5.74-MeV level in ^{23}Na. The difference in electron beam energy for the two runs is about 10 keV.

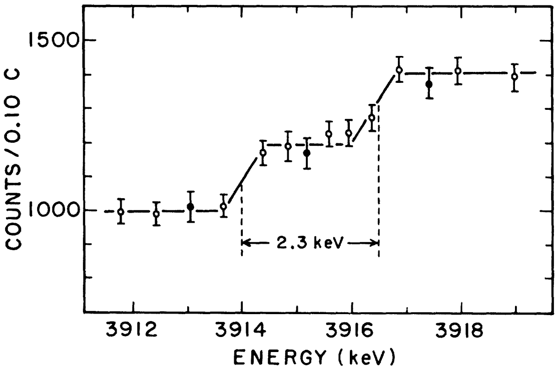

FIG. 3. Isochromat for the 3.914- and 3.916-MeV levels in ^{23}Na. The filled circles represent points used for self-absorption measurements.

sion compared to other experimental errors, notably statistics. The experimental value for Γ is obtained from the measured transmission using the computed T vs Γ curve. The statistical uncertainty in T is about 15% for the 3.91-MeV level and about 6% for the three levels above 5 MeV. The uncertainties in the level widths are larger because of nonresonant absorption in the absorber, which makes the T vs Γ curve less sensitive to changes in Γ.

For the 3.91-MeV levels, the approximation of Ofer and Schwarzschild[21] is valid and was used to obtain widths from the measured transmissions.

C. Branching Ratio Measurements

A Ge(Li) spectrum was taken above and below each of the three excitation energies above 5 MeV. Branching ratios were obtained from the photopeak intensities of the resonant γ rays and the related cascade γ rays. Corrections were made for the energy dependence of the detector efficiency and for the attenuation of the radiation in the lead and graphite absorbers.

The 3.91-MeV γ rays were observed but not resolved with the Ge(Li) detector. Low yields prevented observation of the other decay modes of the 3.91-MeV levels.

III. RESULTS

A. 3.91-MeV Doublet

The yield curve near 3.91 MeV (Fig. 3) shows a double step indicating levels of 3914.0 ± 1.8 and 3916.3 ± 1.8 keV. The level spacing of 2.3 ± 0.4 keV is more accurate than the absolute energies because calibration errors offset one another. Self-absorption measurements on the doublet levels were difficult due to the low yields and detector gain shifts. Our results indicate a width $g\Gamma = 28 \pm 27$ meV for the 3914-keV level and $g\Gamma = 49 \pm 27$ meV for the 3916-keV level. The branching ratio $\Gamma_0/\Gamma = 0.81$, quoted by Poletti[8] for the unresolved doublet, is assumed for each level.

Rasmussen[12] reports a self-absorption result for the unresolved doublet of $g\Gamma_0 = 7^{+16}_{-7}$ meV, and a scattering result of $g\Gamma_0 = 45 \pm 5$ meV. A self-absorption width can be obtained from the present data by ignoring the yield measurement taken "between" the two levels. The scattering width should be the sum of our measured widths. Our results for the unresolved doublet are then $g\Gamma_0 = 29 \pm 26$ meV for self-absorption and $g\Gamma_0 = 54 \pm 38$ meV for scattering. Both results agree reasonably well with those of Rasmussen.

Additional information concerning the two levels is available from the ratio of the two step heights in Fig. 3. For each level, this height should be proportional to $g\Gamma_0{}^2/\Gamma$. The ratio, obtained in conjunction with the self-absorption data, is $Y(3916)/Y(3914) = 0.83 \pm 0.11$, indicating a roughly equal scattering yield for each level.

Although the 3.48-MeV branch to the first excited state was observed, attempts to determine the branching ratios from the doublet levels were unsuccessful because of excessive background under the peak and frequent detector gain shifts. The branches to higher excited states were not observable, also because of background. Attempts to observe branching with a Ge(Li) detector have been unsuccessful thus far.

In view of the doublet structure of the 3.91-MeV level, the assignment of $\frac{5}{2}^+$ for this state by Poletti

TABLE I. Experimental results.

Energy level	Transition	Branching ratio	Branching ratio	Transmission		Possible spin	$g\Gamma$
(keV)	(keV)	(present work)	(other work)[a]	$\Gamma = 0$[b]	experimental		(meV)
3914.0 ± 1.8	3914		0.81	0.730	0.665 ± 0.058	$(\frac{5}{2}^+)$[a]	28 ± 27
3916.3 ± 1.8	3916		0.81	0.730	0.622 ± 0.054	$(\frac{5}{2}^+)$[a]	49 ± 27
5375.8 ± 2.7	5376	0.12 ± 0.08	0.14 ± 0.04	0.760	0.484 ± 0.029	$(\frac{5}{2}^+)$[a]	2450^{+480}_{-410}
	4935	0.69 ± 0.15	0.63 ± 0.07				
	3297	0.19 ± 0.07	0.23 ± 0.05				
5742.7 ± 2.9	5743	0.71 ± 0.13	0.60 ± 0.10	0.766	0.298 ± 0.012	$(\frac{3}{2}^+, \frac{5}{2}^+)$[a]	1400^{+120}_{-100}, 1290^{+100}_{-90}
	5302	0.29 ± 0.05	0.40 ± 0.10				
5768.3 ± 2.9	5768	0.73 ± 0.15		0.767	0.395 ± 0.029	$(\frac{5}{2}^+)$[c]	800^{+120}_{-100}
	5327	0.27 ± 0.13					

[a] Branching ratios and spins reported by Poletti *et al.* (Refs. 1, 2, 8).

[b] Expected transmission if only electronic absorption were present (no resonant absorption).

[c] Spin of $\frac{5}{2}^+$ arbitrarily chosen to allow comparison with other widths.

et al. must be reexamined. Rasmussen[12] suggests by comparison of the present results with those of others that the lower member is $\frac{5}{2}^+$ and the upper is spin $\frac{1}{2}$. It is indeed possible for both levels to have spin $\frac{5}{2}$. One level could be a member of the $K^\pi = \frac{1}{2}^+$ band based on the 2.39-MeV level (members at 2.98, 3.91, and 4.78 MeV), while the other may be the lowest member of a $K^\pi = \frac{5}{2}^+$ band (Nilsson orbit 5). Further statements are not possible until separate spins and branching ratios can be determined for the levels.

B. Higher Levels

Results for the levels studied in this work are given in Table I. Branching ratios for the levels above 3.91 MeV were obtained from Ge(Li) spectra. Branching ratios for the 5375.8- and 5742.7-keV levels are in agreement with those reported by Poletti *et al.*[8] The widths Γ for the levels are determined for the spins reported by Poletti *et al.* The experimental widths $g\Gamma$ vary slightly with the assumed spin.

A search conducted in this laboratory for the reported 5.782-MeV level indicates a width ($g\Gamma_0^2/\Gamma$) of less than 5 meV. Ground-state transitions of about 6.3 and 6.9 MeV were observed, but the levels have not been isolated.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to D. Justice for his assistance with the data taking.

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*Work supported by the National Science Foundation.

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