# Properties of the 4.431-MeV Excited State of $Na^{23}$†

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Using the Doppler-broadened 4.43-MeV gamma line from the reaction $N^{15}(p,\alpha)C^{12*}$ as the exciting radiation, resonance fluorescence from the 4.431-MeV level in $Na^{23}$ has been observed. The 4.431-MeV ground-state transition, accounting for $(95\pm3)\%$ of the de-excitations, exhibits an isotropic angular distribution. This fact and the absence of branching to the 0.44-MeV $\frac{5}{2}+$ level make $\frac{1}{2}$ the most probable spin assignment. With this spin value, a self-absorption study leads to a partial width $\Gamma_0=(2.14\pm0.10)$eV for the ground-state transition. When this width is combined with the observed branching, a total width $\Gamma=(2.25\pm0.20)$eV is obtained for the 4.431-MeV level in $Na^{23}$, which is found to populate also the 2.39 MeV excited state in $(5\pm3)\%$ of its decays. A comparison of scattering and self-absorption data for different values of the ratio of natural width to Doppler width confirms the spin assignment of $\frac{1}{2}$ to the 4.431-MeV level, which might be the first member of the $K=\frac{1}{2}-$ band based on the Nilsson orbit 14. For a value $\eta=+4$ of the deformation parameter, the $E1$ transition probability calculated with Nilsson wave functions agrees with the experimental value.

## I. INTRODUCTION

A LEVEL at 4.431-MeV excitation energy is known[1] to exist in $Na^{23}$. A study[2] of the reaction $Ne^{22}(p,\gamma)Na^{23}$ indicated that this level decays directly to the ground state of $Na^{23}$ and has one of the spin-parity values $\frac{1}{2}\pm$, $\frac{3}{2}+$, $\frac{5}{2}+$. The strong ground-state transition and its possible dipole character suggested the feasibility of a resonance fluorescence experiment. The only discouraging information was the negative outcome of a resonance scattering experiment[3] in which a NaCl target had been placed in the high-intensity bremsstrahl beam from the Livermore linear accelerator. It was felt, however, that the background conditions for a line source would be at least one order of magnitude more favorable than those with the bremsstrahl continuum and that such a line source was available. The close agreement of the excitation energy of the $Na^{23}$ level with that of the first excited 4.433-MeV state in $C^{12}$ guaranteed that the reaction $N^{15}(p,\alpha)C^{12*}$ would be a powerful source of gamma rays resonant with the 4.431-MeV state in $Na^{23}$. In previous experiments at this laboratory,[4] gas-target assemblies using $N^{15}H_3$ had been designed which combined a high yield of Doppler broadened 4.43-MeV radiation with a low neutron background. A preliminary experiment[5] using such a target demonstrated a large resonance scattering effect and encouraged the more detailed study described in the following sections.

## II. EXPERIMENTAL PROCEDURES

A typical scattering geometry is shown in Fig. 1. With the exception of the angular distribution measurements, for which cylindrical scatterers of 14 in. i.d., 15.5 in. o.d., and 3 in. height were used, all the final experiments were carried out with scatterers of 10 in. i.d., 15 in. o.d., and 0.75 in. height (see Fig. 1). The sodium scatterers were made by pressing weighed chunks of the metal into appropriate forms. To preserve the sodium, it was found sufficient to dip it in hot ceresin wax and then wrap it in 0.0005-in. plastic foil. Magnesium oxide in magnesium containers served as comparison scatterer. Aluminum had to be avoided since it, too, gives rise to resonance scattering[6] of the Doppler-broadened 4.43-MeV line.

The proton beam entered the platinum-lined gas cell[4] through a 0.00025-in. tantalum window which was able to withstand proton currents of up to 4$\mu$A while containing $N^{15}H_3$ at atmospheric pressure. The path length within the cell was 1 in. The $E_p=3.00$-MeV resonance[7,8] of the reaction $N^{15}(p,\alpha)C^{12*}$ was used for most of the measurements since, of the higher energy resonances, it provided the most favorable ratio of gamma-ray yield and neutron yield. The source strength was monitored with a 2-in.$\times 1\frac{3}{4}$-in. NaI detector placed at a distance

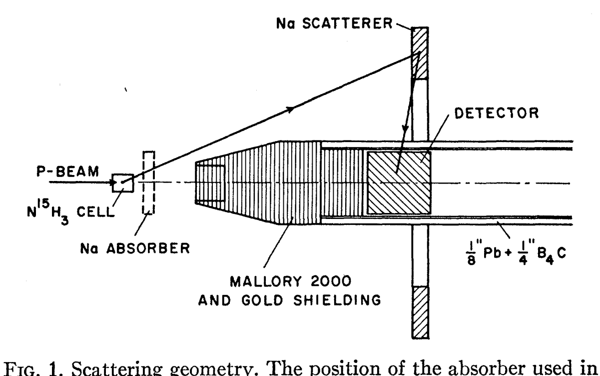


FIG. 1. Scattering geometry. The position of the absorber used in the self-absorption study is indicated by dashed lines.

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[1] W. W. Buechner and A. Sperduto, Phys. Rev. **106**, 1008 (1957).
[2] D. W. Braben, L. L. Green, and J. C. Willmott, Nucl. Phys. **32**, 584 (1962).
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[4] V. K. Rasmussen, F. R. Metzger, and C. P. Swann, Phys. Rev. **110**, 154 (1958).
[5] F. R. Metzger, Bull. Am. Phys. Soc. **7**, 453 (1962).
[6] F. R. Metzger, Contribution to the International Conference on Nuclear Physics, Paris, 1964 (unpublished).
[7] L. Lidofsky, K. Jones, R. Bent, J. Weil, T. Kruse, M. Bardon, and W. W. Havens, Bull. Am. Phys. Soc. **1**, 212 (1956).
[8] S. Bashkin and R. R. Carlson, Phys. Rev. **106**, 261 (1957).

of 7 ft from the $N^{15}H_3$ target. The scattered radiation was detected with a NaI crystal 3 in. in diameter and 3 in. long, the output of which was displayed with a RIDL 400-channel analyzer. After each run, this detector was placed at a distance of approximately 8 ft from the target and was exposed to the direct 4.43-MeV gamma radiation while the monitor accumulated a predetermined number of counts. This measurement then related the monitor counts to the source strength and was used for the determination of the absolute scattering cross sections. The variation of the counter efficiency with angle of incidence and with the distance from the source was also checked using the 4.43-MeV gamma rays emitted by an $Am^{241}$-Be source.

### III. DECAY MODES OF THE $Na^{23}$ 4.431-MeV LEVEL

Between the ground state of $Na^{23}$ and the 4.431-MeV level, nine excited states have been observed.[1] The decays of these states are sufficiently well known[2] to allow the statement that branching from the 4.431-MeV level to any one of them would result in the emission of gamma rays with $E_\gamma \geq 2$ MeV and with an intensity of at least 40% of the branch. By studying the gamma radiation with $E_\gamma \geq 2$ MeV level, one should, therefore, be able to detect branching to any one of the lower lying $Na^{23}$ levels. This is a very fortunate situation since the nonresonant background becomes quite large below 2 MeV. As may be seen from the upper part of Fig. 2, which shows typical pulse-height distributions of the radiation scattered from Na and from Mg+MgO, the background from natural radioactivity (ThC″) in the soil and in the concrete makes itself felt even at 2.62 MeV and reduces the accuracy with which the resonance effect can be measured. In the bottom part of Fig. 2, the difference curve, i.e., the pulse-height distribution of the resonance radiation, is compared with the pulse-height distribution of the direct 4.43-MeV beam (dashed line). For this comparison, the direct-beam distribution was adjusted to give the same total number of counts as the resonance radiation in the region from channel 55 to channel 90. The small differences in shape above channel 55 are attributed to the fact that the resonance radiation exhibits very little energy spread while the direct 4.43-MeV radiation from the $N^{15}$ target is Doppler shifted as well as Doppler broadened.

The only evidence for gamma rays originating from weak branches to excited states is found below channel 46, i.e., at energies below 2.6 MeV. In view of the decay properties of the $Na^{23}$ levels,[2] this means that the 0.44-, 2.64-, 2.98-, 3.68-, 3.85-, and 3.92-MeV levels are not directly populated from the 4.431-MeV level to an extent exceeding 2% of the ground-state transition. Of the remaining three levels, the 2.71-MeV level can be eliminated because of the absence of a peak at $2.71-0.44=2.27$ MeV. This leaves only the 2.08- and 2.39-MeV levels.

The 2.08-MeV level cannot be responsible for any appreciable portion of the peak at $\approx 2$ MeV since the ratio of the 2.35-MeV ($4.431 \rightarrow 2.08$) transition and the 2.08-MeV ground-state transition would be expected to be of the order of fifty.[9] This leaves only the 2.39-MeV state. If the rather uncertain peak near channel 42 is assumed to correspond to the ground-state transition from this level, then a composite peak due to the 2.04-MeV ($4.431 \rightarrow 2.39$) transition and the 1.95-MeV ($2.39 \rightarrow 0.44$) transition, and having approximately the observed intensity, would be expected in the region of channels 35 and 36. From a comparison of the relative peak heights, and taking into account the energy dependence of the crystal efficiency, the peak to total ratio, and the attenuation in the lead and boron carbide shield, it was estimated that the branch from the 4.431-MeV level to the 2.39-MeV level accounted for $(5\pm3)\%$ of the de-excitations of the 4.431-MeV level, leaving $(95\pm3)\%$ for the direct transition to the ground state.

### IV. TRANSITION PROBABILITIES

#### A. General Remarks

For an incident spectrum with a smooth energy distribution $N(E)$, the resonance scattering is proportional to $N(E_r)g\Gamma_0^2/\Gamma$, where $N(E_r)$ is the number of gamma rays per unit energy interval at the resonance energy $E_r$; $g=(2J_2+1)/(2J_1+1)$ is the ratio of the statistical weights of the excited state (spin $J_2$) and the ground state (spin $J_1$), $\Gamma_0$ is the partial width for the ground-

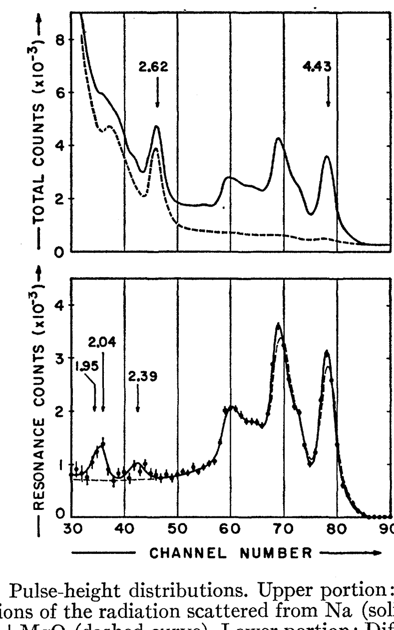


FIG. 2. Pulse-height distributions. Upper portion: Pulse-height distributions of the radiation scattered from Na (solid curve) and from Mg+MgO (dashed curve). Lower portion: Difference of the two upper curves, representing the pulse-height distribution of the resonance radiation. The dashed curve is the normalized pulse-height distribution of the incident radiation.

[9] A. J. Howard, J. P. Allen, D. A. Bromley, and J. W. Olness, Bull. Am. Phys. Soc. 9, 68 (1964).

state transition, and $\Gamma$ the total width of the excited level. When a nuclear reaction serves as the source of the exciting gamma radiation, $N(E_r)$ depends on the angular distributions and correlations of the reaction products, on the bombarding energy and thus on the target thickness and the excitation function; $N(E_r)$ is also affected by the slowing down and the scattering of the recoiling excited target nuclei prior to the emission of the gamma radiation. It is therefore not uncommon that the lack of knowledge of one or several of these factors affecting $N(E_r)$ becomes the source of considerable uncertainty in the determination of the width and hence the transition probability.

The dependence on $N(E_r)$ is avoided in a self-absorption experiment.[10,11] In such an experiment one measures the fractional reduction

$$R=[N_{\mathrm{sc}}(0)-N_{\mathrm{sc}}(l_a)]/N_{\mathrm{sc}}(0) \tag{1}$$

of the resonance scattering effect brought about by the insertion of an absorber of thickness $l_a$ into the incident beam (see Fig. 1). The absorber is, of course, made from the same material as the resonant scatterer. Before $R$ is calculated according to Eq. (1), the counting rate $N_{\mathrm{sc}}(l_a)$, observed with the scatterer in place, has to be corrected for the nonresonant electronic attenuation. In actual practice, the effect of the electronic attenuation is eliminated by measuring $N_{\mathrm{sc}}(0)$ with an absorber made of a different element but giving rise to the same electronic attenuation.

While the self-absorption $R$ does not depend on $N(E_r)$, it is sensitive to the width of the absorption line. As long as the natural width is small, this width is the thermal Doppler width $\Delta=E_\gamma(2kt/Mc^2)^{1/2}$, and for small absorptions the self-absorption $R$ measures the ratio $g\Gamma_0/\Delta$. Since $\Delta$ is known, the self-absorption experiment is a measurement of the product of the statistical weight ratio $g$ and the partial width $\Gamma_0$ for the ground-state transition. A comparison of scattering and self-absorption data then provides information concerning $N(E_r)\Gamma_0/\Gamma$.

In the case of the 4.431-MeV level in $Na^{23}$, the situation is complicated by the fact that the natural width $\Gamma$ is of the same order of magnitude as the thermal Doppler width $\Delta$ and that the scatterers and absorbers were not really thin. Under these circumstances, the self-absorption depends also on $\Gamma$ because the depletion of the incident spectrum depends on the width of the absorption line which is now not $\Delta$, but a function of $\Gamma/\Delta$. On the other hand, as a consequence of this dependence on $\Gamma/\Delta$, information about $\Gamma$ itself may be obtained, i.e., the statistical factor may be determined under favorable circumstances.

Since the condition $\Gamma\ll\Delta$ is not fulfilled, the cross section has to be used in its general form[11]

$$\sigma_{\mathrm{abs}}=\sigma_{\mathrm{abs}}{}^0\psi(x,t)\,, \tag{2}$$

where

$$\psi(x,t)=\frac{1}{2(\pi t)^{1/2}}\int_{-\infty}^{\infty}\frac{\exp[-(x-y)^2/4t]}{1+y^2}dy \tag{3}$$

was first introduced[12] for neutron resonances and is tabulated,[13] and where the peak absorption cross section is

$$\sigma_{\mathrm{abs}}{}^0=2\pi\lambda\!\!\!^{-2}g(\Gamma_0/\Gamma)\,. \tag{4}$$

In Eqs. (2) and (3) $x=2(E-E_r)/\Gamma$ and $t=(\Delta/\Gamma)^2$; in Eq. (4) $\lambda\!\!\!^-$ is the photon wavelength divided by $2\pi$.

## B. Scattering Experiments

For the evaluation of the scattering geometry (Fig. 1) the scatterer was subdivided into sections bounded by cones of different cone angles with the center of the target cell as the common apex. For any given section, the contribution $\Delta N_{\mathrm{sc}}$ to the scattering may be written as

$$\Delta N_{\mathrm{sc}}=C(\Gamma_0/\Gamma)\int_0^\infty N(E)(1-e^{-n\sigma_{\mathrm{abs}}(E)l_s})dE\,, \tag{5}$$

where $C$ contains the solid angles, the detection efficiency, and the electronic attenuation. In Eq. (5), $n$ is the number of $Na^{23}$ nuclei per cm$^3$, $\sigma_{\mathrm{abs}}(E)$ is the cross section defined in Eq. (2), and $l_s$ is the length of the gamma beam path in the particular section of the scatterer.

If one expands the exponential in Eq. (5) and uses the fact that $N(E)$ is a very slowly varying function of the energy and that $\int_{-\infty}^{\infty}\psi(x)dx=\pi$, Eq. (5) goes over into

$$\Delta N_{\mathrm{sc}}=\tfrac{1}{4}CN(E_r)(\Gamma_0{}^2/\Gamma)nl_sg\lambda\!\!\!^{-2}\times\sum_{m=0}^{\infty}\left\{\frac{(-1)^m(n\sigma_{\mathrm{abs}}l_s)^m}{(m+1)!\pi}\int_{-\infty}^{\infty}\psi^{m+1}(x)dx\right\}\,, \tag{6}$$

where the expression outside the sum exhibits the $\Gamma_0{}^2/\Gamma$ dependence and represents the scattering one would expect for negligible depletion (self-absorption). The sum represents the effect of the self-absorption in the scatterer of finite thickness $l_s$. For the actual evaluation, Eq. (6) was rewritten in the following way:

$$\Delta N_{\mathrm{sc}}=CN(E_r)(\Gamma_0/\Gamma)\Delta\pi^{1/2}nK_0l_sS(K_0,t,l_s)\,, \tag{7}$$

where

$$S(K_0,t,l_s)=\sum_{m=0}^{\infty}\frac{(-1)^m(nK_0l_s)^m}{(m+1)!\pi}\times\left\{(2t^{1/2}\pi^{-1/2})^m\int_{-\infty}^{\infty}\psi^{m+1}(x)dx\right\}\,. \tag{8}$$

[10] F. R. Metzger, Phys. Rev. **103**, 983 (1956).
[11] See, e.g., F. R. Metzger, Prog. Nucl. Phys., **7**, 53 (1959).
[12] H. A. Bethe and G. Placzek, Phys. Rev. **51**, 450 (1937).
[13] M. E. Rose, W. Miranker, P. Leak, L. Rosenthal, and J. K. Henrickson, Westinghouse Atomic Power Division Report SR-506, Vols. I and II, 1954 (unpublished).

The main reason for this modification was that the value of the sum $S$ had previously been calculated as a function of $nK_0l_s$ for different values of $t$. In Eqs. (7) and (8) $K_0$ is the peak cross section for the pure Doppler form,[11] i.e., $K_0=g\lambda^2\Gamma_0/(4\pi^{1/2}\Delta)$.

The total scattering counting rate was calculated by summing over the different sections of the scatterer, using $N(E_r)=9.23\times10^{-6}N_{\text{total}}$ and $\Delta=6.94$ eV. The results of this calculation are compared in Fig. 3 with the observed scattering. It may be seen from this figure that the spin dependence of the scattering is small, and that the scattering is compatible with a range of $g\Gamma_0$ values extending from 1.0 to 1.16 eV.

The value $N(E_r)=9.23\times10^{-6}N_{\text{total}}$, used in evaluating the scattering data, was obtained by assuming a rectangular shape for the 4.43-MeV line from the reaction $N^{15}(p,\alpha)C^{12*}$ at the $E_p=3.0$-MeV resonance. From $\alpha$-$\gamma$ coincidence measurements[4] it has been concluded that $N(E_r)$ at the resonant energy for the first excited state in $C^{12}$ was $(0.86_{-0.06}^{+0.2})$ times the average value. Comparisons of scattering and self-absorption data[4] for $C^{12}$ and $B^{11}$ indicated that the actual value was close to unity when both the 3.0- and 3.3-MeV resonances were used. In a separate experiment with a sodium scatterer it was determined that for the 4.431-MeV level, the fraction of resonant gamma rays at the 3.3-MeV resonance exceeded the fraction at the 3.0-MeV resonance by only $(1\pm4)\%$. This means that $N(E_r)/N_{\text{total}}$ for $E_r=4.431$ MeV is also close to the average value of $9.23\times10^{-6}$ if one utilizes only the 3.0-MeV resonance.

### C. Self-Absorption Experiment

With an absorber of path length $l_a$ in the incident beam, the scattering from a given section of the scatterer is changed from the value given by Eq. (5) to

$$\begin{aligned}\Delta N_{\text{sc}}(l_a)&=C(\Gamma_0/\Gamma)\int_0^\infty N(E)e^{-n\sigma_{\text{abs}}(E)l_a}(1-e^{-n\sigma_{\text{abs}}(E)l_s})dE\\&=C(\Gamma_0/\Gamma)\left\{\int_0^\infty N(E)(1-e^{-n\sigma_{\text{abs}}(E)[l_a+l_s]})dE-\int_0^\infty N(E)(1-e^{-n\sigma_{\text{abs}}(E)l_a})dE\right\},\end{aligned}\quad(9)$$

i.e., $\Delta N_{\text{sc}}(l_a)$ is the difference of two terms of the type shown in Eq. (5) and modified in Eqs. (6) and (7). In terms of the sum $S$ defined in Eq. (8), the fractional reduction $R$ defined in Eq. (1) takes on the form

$$R=1-\frac{(l_a+l_s)S(K_0,t,l_a+l_s)-l_aS(K_0,t,l_a)}{l_sS(K_0,t,l_s)}.\quad(10)$$

Using this expression, $R$ was calculated for values $l_a=1.38$, 2.76, and 4.14 cm, corresponding to sodium absorbers of 1.27-, 2.54-, and 3.81-cm thickness, for $K_0$ values corresponding to values of $g\Gamma_0$ ranging from 0 to 1.3 eV, and for $t$ values ranging from ten to infinity. The results of the calculations for the 3.81-cm absorber are compared in Fig. 4 with the experimental value of the self-absorption, $R=0.565\pm0.019$. A considerable spin dependence is observed and will be discussed in Sec. V. In Table I are summarized the averages of the widths obtained with the three different absorbers for spins of $\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$.

In contrast to the scattering results, the widths given here are not affected by any error in the value assumed for the ratio $N(E_r)/N_{\text{total}}$.

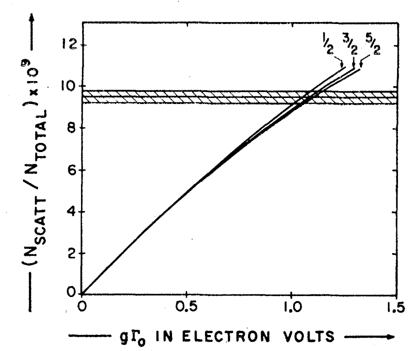


FIG. 3. Comparison of the experimental resonance scattering (shaded area) with the scattering, expected as a function of $g\Gamma_0$, for different values of the spin of the 4.431-MeV level.

TABLE I. Average values for the products $g\Gamma_0$ and for the widths $\Gamma_0$ established for different spin values by the self-absorption studies with absorbers of three different thicknesses.

| | $g\Gamma_0$ (eV) | $\Gamma_0$ (eV) |
|---|---|---|
| Spin $\frac{1}{2}$ | $1.07\pm0.05$ | $2.14\pm0.10$ |
| Spin $\frac{3}{2}$ | $0.92\pm0.04$ | $0.92\pm0.04$ |
| Spin $\frac{5}{2}$ | $0.86\pm0.05$ | $0.57\pm0.03$ |

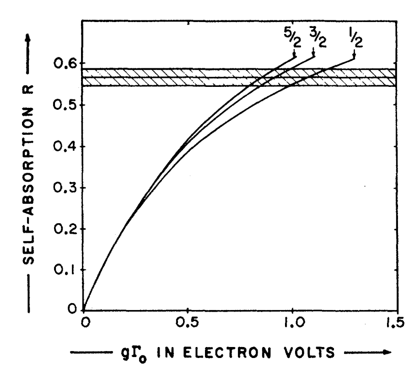


FIG. 4. Comparison of the experimental value (shaded area) of the self-absorption $R$ for a Na absorber of 3.81-cm thickness with the self-absorption expected, as a function of $g\Gamma_0$, for different values of the spin of the 4.431-MeV level.

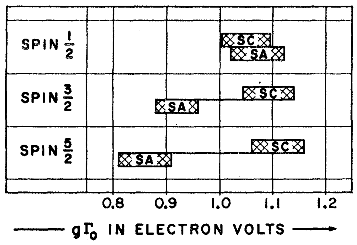


FIG. 5. Comparison of the results of the evaluation of the scattering and the self-absorption experiments assuming different values for the spin of the 4.431-MeV level. The rectangles labeled SC refer to the scattering data, the rectangles labeled SA depict the ranges of allowed $g\Gamma_0$ values established in the self-absorption experiments.

### V. SPIN OF THE 4.431-MeV LEVEL

The results of the $Ne^{22}(p,\gamma)Na^{23}$ studies[2] are compatible with spin values of $\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ for the 4.431-MeV level. The resonance fluorescence experiment provided additional clues concerning the possible spin in the form of the branching information of Sec. III, of angular-distribution data for the 4.431-MeV resonance radiation, and of a comparison of self-absorption and scattering data.

#### A. Spin and Branching

The absence of branching to the 0.44-MeV $\frac{5}{2}+$ first excited state favors the assignment of spin $\frac{1}{2}$. The validity of this argument is increased by the fact that the first excited state is considered[14–16] to be a member of the ground-state band.

#### B. Spin and Angular Distribution

The angular distribution of the resonance radiation to the ground state was investigated in a geometry similar to the one depicted in Fig. 1, but using the scatterers mentioned in Sec. II. Scattering angles ranging from 90 to 140° were realized by moving the detector along the symmetry axis while keeping the scatterer in the same position relative to the source of the exciting radiation. In this way effects on the angular-distribution results, stemming from the possible variation of $N(E_r)/N_{\text{total}}$ with the angle of emission, were minimized. Because of the weakness of the branch to the 2.39-MeV level, the angular distributions of the 2.04-MeV radiation and/or of the 2.39- and 1.95-MeV gamma rays could not be measured.

The best fit to the experimental data was obtained with the value $A_2=-0.02\pm0.07$ for the coefficient in the angular-distribution function $W(\theta)=1+A_2P_2(\cos\theta)$. This value is certainly consistent with the isotropy expected for spin $\frac{1}{2}$, but it also permits other spin assignments provided the quadrupole to dipole mixing ratio $\delta^2$ is properly chosen. For spin $\frac{3}{2}$, $\delta^2$ has to be either larger than seven or has to fall into the interval $0.01<\delta^2<0.2$. For spin $\frac{5}{2}$, the mixing ratio is restricted to $0.006<\delta^2<0.1$. While the large $\delta^2$ values for spin $\frac{3}{2}$ can be excluded based on the width reported in Sec. IV, the two intervals imposed on the $\delta^2$ values are not unusual for $E2/M1$ mixtures. Spins $\frac{3}{2}$ and $\frac{5}{2}$ can, therefore, not be ruled out on the basis of the angular-distribution experiment.

#### C. Spin and Scattering Data

The information obtained in Sec. IV concerning the widths is summarized in Fig. 5. For each spin value, the range of $g\Gamma_0$ values allowed by the scattering data is indicated by a rectangle labeled SC, while the range of $g\Gamma_0$ values allowed by the self-absorption data is indicated by a rectangle labeled SA. From the comparison in Fig. 5 one concludes that the spin of the 4.431-MeV state in $Na^{23}$ is most probably $\frac{1}{2}$. As was discussed in the preceding subsections, this spin assignment is in accord with all the other experimental information. It might be mentioned that, even if one adds to the statistical errors shown in Fig. 5, the spread due to the uncertainty in $N(E_r)$, the upper limit established for $N(E_r)/N_{\text{total}}$ by the $\alpha$-$\gamma$ coincidence data does not reduce the scattering width for spin $\frac{3}{2}$ sufficiently to achieve overlap with the self-absorption values.

The type of spin determination described here should be feasible whenever the natural width is several eV and when there exists sufficient information concerning $N(E_r)/N_{\text{total}}$. As far as this latter ratio is concerned, the recently developed high-resolution gamma-ray detectors[17] should be of considerable value since they will enable one to measure directly the line shape of the Doppler-broadened exciting radiation.

### VI. PARITY OF THE 4.431-MeV LEVEL

Resonance fluorescence studies usually provide only indirect information concerning the parity of the excited state because the main scattering process is parity independent. However, the progress made in the study of 180° electron scattering[18] has opened up the possibility of obtaining parity information from a combination of the two methods. To be observed with ease, the levels in question should have widths of at least a few tenths of an electron volt. The 180° electron scattering favors $M1$ transitions over $E1$ transitions while, as mentioned above, resonance scattering is impartial. If a certain fast transition is observed with both techniques, it is most probably magnetic dipole. If a transition is only observed in the resonance fluorescence experiment, but not in 180° electron scattering, then it is an electric-dipole transition.

[14] E. B. Paul and J. H. Montague, Nucl. Phys. **8**, 61 (1958).
[15] A. B. Clegg and K. J. Foley, Phil. Mag. **7**, 247 (1962).
[16] W. Gloeckle, Z. Physik **178**, 53 (1964).
[17] See, e.g., G. T. Ewan and A. J. Tavendale, Nucl. Instr. Methods **26**, 183 (1964).
[18] W. C. Barber, J. Goldemberg, G. A. Peterson, and Y. Torizuka, Nucl. Phys. **41**, 461 (1963).

The question now arises whether or not the 4.431-MeV transition in $Na^{23}$ was observed in 180° electron scattering. Barber *et al.*[18] studied 180° electron scattering from $Na^{23}$. They did not report the observation of a peak at 4.4 MeV, but they did observe a small bump at 4.6 MeV. The energy is sufficiently uncertain[19] to leave the possibility that the small bump at 4.6 MeV might be attributed to the 4.431-MeV level. If this is done, $g\Gamma_0$ as obtained from the electron-scattering data is $\approx 0.4$ eV with a quoted error of $\pm 40\%$. This is to be compared with the resonance fluorescence value of $1.07\pm 0.05$ eV. While the difference between these two values strongly favors the assumption that the 4.431-MeV transition was not observed in the electron-scattering experiment and is therefore an electric dipole, it must be admitted that the experimental points of the electron-scattering data in the region of interest are rather widely spaced and that the main peak could have been missed.[19] An improvement in the electron-scattering data by a factor of two would certainly be sufficient to enable a definite conclusion as to the parity of the 4.431-MeV state.

Another, though rather weak, argument in favor of the negative-parity assignment is the large width of the ground-state transition which slightly exceeds the Weisskopf estimate[20] for an $M1$ transition.

## VII. CONCLUSIONS AND DISCUSSION

The results of the preceding sections may be summarized as follows:

(1) The 4.431-MeV level in $Na^{23}$ is most probably a $J^{\pi}=\frac{1}{2}-$ state which decays by $E1$ radiation to the $Na^{23}$ ground state and to the 2.39-MeV level with branches of $(95\pm 3)\%$ and $(5\pm 3)\%$, respectively.

(2) The partial width for the ground-state transition is $\Gamma_0=(2.14\pm 0.10)$ eV. The total width of the 4.431-MeV level is $\Gamma=(2.25\pm 0.20)$ eV, corresponding to a mean lifetime of $\tau=(2.9\pm 0.3)\times 10^{-16}$ sec.

When the levels of $Na^{23}$ are described in the unified model,[21] the ground state is considered to be the lowest member of the $K=\frac{3}{2}$ band based on Nilsson orbit 7. If the higher intrinsic states are generated by promoting a single particle from this orbit to successively higher orbits, the first negative-parity levels expected to appear are those belonging to the $K=\frac{1}{2}-$ band based on Nilsson orbit 14 which is responsible[22] for the negative-parity states in $Mg^{25}$ and $Al^{25}$ at excitation energies of 3–4.5 MeV. Assuming the 4.431-MeV state in $Na^{23}$ to be the $J=\frac{1}{2}$ member of the $K=\frac{1}{2}-$ band, and using a value $(\eta=4)$ of the deformation parameter consistent with the measured quadrupole moment, the calculated $E1$ ground-state transition probability agrees very well with the observed width which, incidentally, is approximately 1/30 of the Weisskopf estimate.

Good agreement with the experimental transition probability is also obtained for the $E1$ transition to the 2.39-MeV level if the latter is assumed to be the $J=\frac{1}{2}$ member of the $K=\frac{1}{2}$ band based on Nilsson orbit 9. However, this assumption[14] has to be viewed with some reservation since the spin assignment to the 2.39-MeV level is far from being well established. The observed branching from the 2.39-MeV level to the $\frac{5}{2}+$ first excited state is much larger than expected for a level with spin $\frac{1}{2}$ and actually favors a $\frac{3}{2}$ assignment. An experimental verification is badly needed.[23]

The apparent absence of branching from the 4.431-MeV level to the excited state at 2.64-MeV is somewhat surprising if this state is given[2] the role, assigned by others to the 2.39-MeV level, of the $J=\frac{1}{2}$ member of the $K=\frac{1}{2}$ band based on Nilsson orbit 9. However, if the 2.64-MeV level represents a core excitation, branching is not expected. Such a core excitation, namely the promotion of a proton from the filled Nilsson orbit 6 to the partially filled orbit 7, was suggested[15] on the basis of the strong excitation of 2.65-MeV gamma radiation in the bombardment of magnesium with 150-MeV protons.

[19] W. C. Barber (private communication, 1964).

[20] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), Chap. 12.

[21] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **29**, No. 16 (1955).

[22] A. E. Litherland, H. McManus, E. B. Paul, D. A. Bromley, and H. E. Gove, Can. J. Phys. **36**, 378 (1958).

[23] *Note added in proof*. Recent studies of the reaction $Ne^{22}(d,n)$-$Na^{23}$ lend strong support to the assignment of spin $\frac{1}{2}$ to the 2.39-MeV level. [E. B. Paul and J. H. Montague, Nucl. Phys. **54**, 497 (1964).]