D_{3h} models for Si^{28}. Since this procedure does not alter the symmetry, the rotational formulas already obobtained[1] still apply. Two less vibrational parameters are required, however.

The trouble with these structures is that their vibrational-rotational bands *all* begin[1] with 0^+, 0^-, 1^+, or 1^-. So unobserved 0^+ or 1^+ levels have to be introduced below 4.23 MeV. Indeed, to fit the known low levels, we had to introduce at least *three* extra states below 7.00 MeV.

Other configurations which we have eliminated include the D_{5h} pentagon with particle at the center, the D_{6h} hexagon, and the O_h octahedron. The first two form oblate tops with w_1 very small. For each, a rotational series $K>0$ begins below 7.35 MeV. This is missing from the observed levels. On the other hand, the O_h structure does not allow for the 2^+ rotational level at 1.36 MeV, and for one of the 3^+ levels.

DISCUSSION

The agreement obtained in Table I suggests that the nucleons cluster in Ne^{20} to form a D_{2d} structure. Deviations from the assumed and calculated data can be explained qualitatively.

The results on Mg^{24} are less conclusive because fewer spin and parity assignments have been made. Nevertheless, they do favor the D_{4h} structure over the D_{3d} and D_{3h} ones, the other leading contenders.

PHYSICAL REVIEW VOLUME 152, NUMBER 3 16 DECEMBER 1966

Some Properties of the 2.98-MeV Level of Na^{23}†‡

V. K. RASMUSSEN AND N. A. KHAN*
Bartol Research Foundation of the Franklin Institute, Swarthmore, Pennsylvania
(Received 25 July 1966)

Nuclear-resonance-fluorescence techniques have been used to measure the mean life of the 2.98-MeV level of Na^{23}. The source of γ rays was the decay of the 2.98-MeV level of Al^{27}, as excited by inelastic scattering of 4.90-MeV protons. Using the branching ratio $\Gamma_0/\Gamma=0.56\pm0.06$, we find for the ground-state transition $\Gamma_0=(g_1/g_2)(77\pm12)\times10^{-3}$ eV and for the total width $\Gamma=(g_1/g_2)(140\pm20)\times10^{-3}$ eV, where g_1 and g_2 are the statistical weights for the ground and excited states. The mean life is then $\tau=(g_2/g_1)(4.7\pm0.8)\times10^{-15}$ sec. We find the angular distribution for the resonance scattering to be $1+(0.87\pm0.13)P_2(\cos\theta)$. For the spin sequence $\frac{3}{2}$-$\frac{3}{2}$-$\frac{3}{2}$ this limits the $E2/M1$ amplitude ratio to $0.37<\delta<1.43$. For the sequence $\frac{3}{2}$-$\frac{5}{2}$-$\frac{3}{2}$, the limits are $-1.50<\delta<-1.14$, $-0.47<\delta<-0.31$, and $1.01<\delta<1.82$. This is not in agreement with other recent results on this level, and we have been unable to find a plausible explanation for the difference. Our smallest value of δ^2 corresponds to a $B(E2)$ of approximately twice the single-particle value, $B(E2)_{SP}$.

1. INTRODUCTION

SEVERAL measurements of lifetimes of the lower levels of Na^{23} have been reported previously. Considerable confidence can be felt in the results for the first excited state, as recently summarized by Swann.[1] For the remaining levels, the results are less complete and less certain. Booth and Wright[2] have performed resonance fluorescence measurements using bremsstrahlung as the source of exciting radiation, and Barber *et al.*[3] have looked at inelastic electron scattering, with errors on the resultant transition probabilities of 35 and 50%, respectively. No better lifetime measurements for Na^{23} levels around 2–3 MeV have been reported, and the potentially informative angular distribution measurements for resonance scattering have not been made. We have therefore looked into the problem of how much could be done with resonance-fluorescence techniques,[4–7] using the Na^{23} (p,p') reaction as the γ-ray source. We found that at a proton energy of 5 MeV, which is just below the $Na^{23}(p,n)$ threshold, levels up to 3 MeV were excited with suitable intensities. Some measurements were made, but the extraneous neutrons were higher than desirable. We then established, as discussed later, that the 2.98-MeV γ ray from Al^{27} could be used to excite the Na^{23} level of the same nominal energy. With this source, the neutron background was much less, and, in addition, only the one level in Na^{23} was excited so that the scattered

† A preliminary report has been given at the Conference on Bases for Nuclear Spin-Parity Assignments, Gatlinburg, Tennessee, November 1965.

‡ Assisted by the U. S. Office of Naval Research Contract Nonr-3777(00).

* On leave of absence from the Pakistan Atomic Energy Commission, Karachi, Pakistan. Now at the Atomic Energy Centre, Lahore, Pakistan.

[1] C. P. Swann, Nucl. Phys. **42**, 602 (1963).

[2] E. C. Booth and Kenneth A. Wright, Nucl. Phys. **35**, 472 (1962).

[3] W. C. Barber, J. Goldemberg, G. A. Peterson, and Y. Torizuka, Nucl. Phys. **41**, 461 (1963).

[4] F. R. Metzger, in *Progress in Nuclear Physics*, edited by O. R. Frisch (Pergamon Press, Inc., New York, 1959), Vol. 7, Chap. 2.

[5] F. R. Metzger, C. P. Swann, and V. K. Rasmussen, Nucl. Phys. **16**, 568 (1960).

[6] V. K. Rasmussen, F. R. Metzger, and C. P. Swann, Phys. Rev. **123**, 1386 (1961).

[7] N. A. Khan and V. K. Rasmussen, Phys. Rev. **138**, B1385 (1965).

spectrum was simpler. We are therefore concerned in the present paper with the excitation and decay of this 2.98-MeV level only.

In a recent article, Poletti and Start[8] review the evidence that leads to an assignment of $\frac{3}{2}^+$ ($\frac{5}{2}^+$) to this level, the parenthesis indicating an assignment which they cannot completely rule out. They review the discrepancy between their results and ours, as it was brought out at the Gatlinburg Conference. This will be discussed later in the present paper, but in brief summary, our angular distribution is too anisotropic to be consistent with their mixing ratios.

They find a branching for the level that agrees with several previous determinations of 55% to the ground state and 45% to the final excited state.

For Γ_0, the width for the ground-state transition, Booth and Wright find $(g_1/g_2)85\times10^{-3}$ eV, and Barber *et al.*[7] find $(g_1/g_2)50\times10^{-3}$ eV, where g_1 and g_2 are statistical weights for the ground and excited states. We have corrected Booth's value to correspond to the branching ratio given above.

2. THE γ-RAY SOURCE, AND OTHER EXPERIMENTAL DETAILS

The general considerations involved in nuclear-resonance-fluorescence measurements have been discussed by Metzger[4] and others.[5–7] Only special points will be mentioned here.

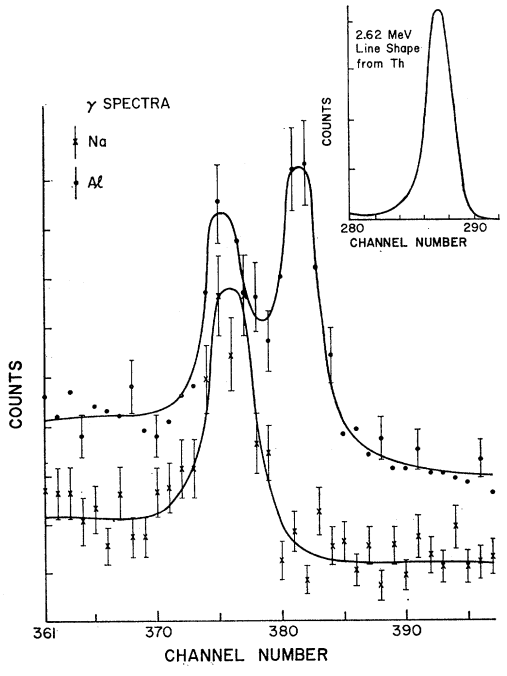

FIG. 1. Full-energy peaks in Ge(Li) detector for the 2.98-MeV γ ray from Na^{23} and the 2.98- and 3.00-MeV γ rays from Al^{27}, as taken for purposes of energy comparison. See text for details.

As noted in the Introduction, the 2.98-MeV γ ray from $Al^{27}(p,p')$ might be a suitable source for studying the Na^{23} level. The location of the Na^{23} level is given by Buechner and Sperduto[9] as 2.983 ± 0.007 MeV. Several values are given for the Al^{27} level,[10] ranging from 2.971 to 2.980 MeV, with errors of 4–6 keV. The decay of this level is known to be fast enough to give the full Doppler effect, so at $E_P=4.90$ MeV the γ ray should be broadened (because of motion in the c.m. system) by 13.2 keV and shifted (by the transformation from the c.m. system to the lab system) by 10.9 $\cos\theta$ keV, where θ is the angle with the proton beam at which the γ rays are observed. It is almost certain that one could find, by looking for resonance scattering, a value of θ at which the Al^{27} γ radiation would be in resonance with the Na^{23} level, especially since the magnitude of the effect is already known to be appreciable from the earlier measurements with $Na^{23}(p,p')$ as the γ-ray source. However, a direct energy comparison using Ge(Li) detectors is faster, and of significant accuracy. The detector used was 1.1 cm^2 in area and 0.4 cm thick with a resolution, set by the preamplifier, of 6 keV for Cs^{137}. Some of the spectra obtained are shown in Fig. 1. It is more or less apparent that the aluminum and sodium γ rays are Doppler broadened—for determining line shapes the data could be improved considerably, but at a cost of increased uncertainty in the energy comparison. Here a good part of the uncertainty is as to how much drift there could be in the electronics over the period of measurement which required, among other things, a change of target. In the absence of extensive experience with this technique, we would only say, from these particular data, that the two levels do not differ in energy by more than 4 keV.

A sharper comparison of these two energies may be made by observing the resonant scattering of the aluminum γ ray by a sodium scatterer. One notes that the Doppler broadening of the γ ray is less than the total shift that may be realized by changing the angle of observation with respect to the beam. Thus, if there is any region (i.e., range of value of this angle) where the Al γ ray is shifted into resonance with the Na level, this region will have a boundary and the location of the boundary will depend on the difference in level energies. Finding the precise location of this boundary is made fairly simple by the fact that the Doppler broadening has a sharp cutoff—for isotropy, for example, the distribution in energy of the photons is rectangular, with a slight rounding of the edges due to the range of energy of protons that excite the γ ray (target-thickness effect) and to the angular divergence of the proton beam. The finite size of the scatterer also spoils the sharpness of the edge somewhat. For levels quite close in energy, as the Al^{27} and Na^{23} levels seem to be, one

[8] A. R. Poletti and D. F. H. Start, Phys. Rev. **147**, 800 (1966).

[9] W. W. Buechner and A. Sperduto, Phys. Rev. **106**, 1008 (1957).

[10] P. M. Endt and C. Van der Leun, Nucl. Phys. **34**, 1 (1962).

can use scatterers of both materials and find the shift of the edge, rather than try to locate the edge absolutely.

For our measurements we used ring scatterers $13\frac{3}{4}$-in. i.d., 16-in. o.d., and 1-in. long, of Na and Al. For comparison purposes we used a Mg scatterer, for which we noted that the counting rate was the same as with no scatterer. The γ rays were produced by bombarding a thick, 99.999% pure aluminum target with 4.90-MeV protons.

For both Al and Na scatterers, there was no resonant scattering for γ rays emitted at angles less than 51° to the proton beam. This was the expected cutoff angle for aluminum—that the sodium cutoff should be apparently identical is somewhat surprising. The level energies then differ, nominally, only by the 30-eV difference in recoil energy when a 3-MeV photon is absorbed by mass 23 or mass 27. The probable error in the measurement is estimated at around 250 eV—there are uncertainties in the experiment that one should check before quoting a more restrictive value, but one can hardly justify further concern for this particular number.

A small residual-scattering effect was observed with the aluminum scatterer at angles less than 51°. This was attributed to the 3.00-MeV level of Al^{27}, which has, according to Schaller and Miller,[11] a decay rate 10 times or more slower than the 2.98-MeV level. The excited nucleus then has time before decaying to lose some of its energy and original direction (see, for example Metzger, Ref. 5) so that resonant photons may be observed outside the "allowed" region.

Further measurements on the properties of the Na^{23} level were made with a 14.25-in. i.d.×17.25-in. o.d.×4 in. long sodium-metal scatterer, a modification of one described previously.[7] Because of the limited range over which the Al^{27} γ ray is resonant with the Na^{23} level, measurements were made at 90° to the proton beam. Other aspects of the ring geometry used also resembled closely the arrangement shown in Fig. 3 of Ref. 7 with the obvious change of aluminum to sodium in scatterers and absorbers. We continued to use magnesium for comparison scatterers and absorbers.

The magnesium absorber was made of thin plates spaced apart by an amount sufficient to give an average density equal to that of sodium (as in the aluminum absorber of Fig. 3 of Ref. 7). The magnesium scatterer was of the same weight as the sodium scatterer, and had, therefore, very nearly the same total number of electrons. Matching for average density did not seem to be necessary for the scatterers. In fact, it was noted that the counting rate with no scatterer (and with the proton beam on target) was approximately the same as that with the magnesium scatterer, an effect which means that what small scattering there is from magnesium is compensated for by the amount by which it shields the detector from general room background.

Other details of the self-absorption measurements and of measurements of the angular distribution of the resonant scattering were so similar to those of Ref. 7 that it seems unnecessary to repeat them here.

Two measurements, not described in the previous paper,[7] were made. These were intended to ascertain whether or not linear polarization of the resonant-energy radiation, as it comes from the source, (the nuclear reaction) could significantly distort the measured angular correlation. We point out first that this radiation *may* be polarized, as follows from the same sort of argument that indicates that it *may* have an anisotropic angular distribution. From symmetry, the polarization vector must lie in (or be perpendicular to) the plane determined by the incoming proton beam and the direction of observation of the γ ray. Furthermore, the amount and sign of the polarization may be a function of the angle of observation with respect to the proton beam.

Now the polarization-direction correlation for resonantly scattered γ rays may be written as[12]

$$A_0+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)+\cdots(\pm)\cos2\gamma \times[B_2P_2^{(2)}(\cos\theta)+B_4P_4^{(2)}(\cos\theta)+\cdots], \quad (1)$$

where γ is the angle between the plane of polarization and the plane of scattering. There seems to be no practical ring geometry for angular-correlation measurements for which one can be certain that effects of the polarization term in Eq. (1) will cancel out. A measurement of a type made previously by Rasmussen, Metzger, and Swann,[6] that enables one to estimate the importance of the term, is illustrated in Fig. 2. One compares the resonant scattering with the detector first in, and then perpendicular to, the plane of the beam and scatterer. Any difference implies both that the source is giving partially polarized resonance radiation and that at least one of the coefficients B in Eq. (1) is nonzero.

We have made such measurements using Na, Al, and comparison Mg scatterers in which we looked at the 2.98-MeV γ ray scattered from both Al and Na, and the 2.21-MeV γ ray scattered from Al. Observations were made at 90° to a 5.00-MeV proton beam and 65° to a 4.50-MeV beam, using an aluminum target in both cases.

Another possible approach is to cancel the polarization term, i.e., to measure the angular correlation with $\cos2\gamma\approx0$. Four "point" scatterers, arranged as in Fig. 3, fulfill this condition reasonably well—the extreme values of $\cos2\gamma$ are ±0.5 and to first order any polarization effect should cancel. However, the polarization may be a rapidly varying function of the angle

[11] L. A. Schaller and W. C. Miller, Bull. Am. Phys. Soc. **9**, 666 (1964).

[12] L. W. Fagg and S. S. Hanna, Rev. Mod. Phys. **31**, 711 (1959); S. Devons and L. J. B. Goldfarb, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. 42, Sec. III, p. 434.

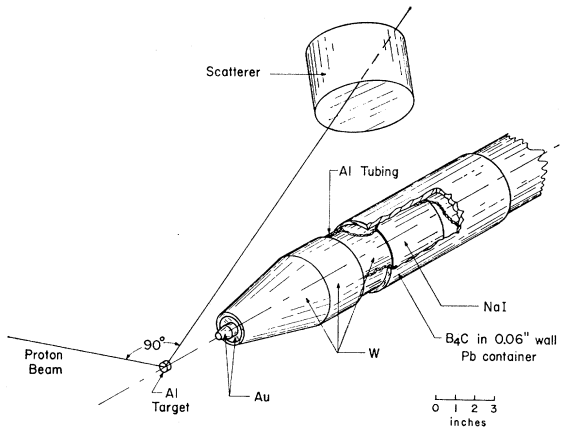

FIG. 2. "Point-scatterer" arrangement used to determine if the 2.98-MeV resonant radiation from the $Al^{27}(p,p')$ reaction was partially linearly polarized. The angle γ in Eq. (1) is the angle between the plane determined by the proton beam and the scatterer and the plane determined by the target, scatterer, and NaI detector. As shown, it is 90°. Measurements were also made for $\gamma=0°$, 180°, and 270°. They were reached by rotating the NaI detector around the target-scatterer axis.

between the beam and the direction of observation, so that there might be a net, but considerably reduced, effect. The amount of scattering material shown in Fig. 3 is, for the present case, rather the minimum allowed by intensity considerations. Measurements were made of the angular correlation using Na and Mg scatterers of dimensions shown in Fig. 3 and $Al^{27}(p,p')$ at $E_p=4.90$ MeV as the γ-ray source.[13]

3. RESULTS

Typical data from the self-absorption measurement are shown in Fig. 4. It is clear that radiation of 2.98-MeV energy is scattered, and shows self-absorption effects. The peak at 2.54 MeV results from the cascade decay of the state through the level at 0.44-MeV. The peak at 2.21 MeV is a result of using some aluminum in constructing the sodium scatterer. A correction is then required for the data involving the 2.98-MeV level. Using relative intensities from the work described in Ref. 7 it follows that the correction at 2.98-MeV is about 10% of the 2.98-MeV peak of Fig. 4.

The amount of resonant radiation scattered out of the incident beam by the absorber is (25±5)%. From the calculated values of this self-absorption as a function of $(g_2/g_1)\Gamma_0$, where g_2/g_1 is the ratio of statistical factors $(2I+1)$ for the excited and ground states and Γ_0 is the width for the ground-state transition, we find a width of $(g_1/g_2)(87\pm20)\times10^{-3}$ eV.

From the amount of scattering observed, and using $\Gamma_0/\Gamma=0.56\pm0.06$ we find $\Gamma_0=(g_1/g_2)(75\pm8)\times10^{-3}$ eV.

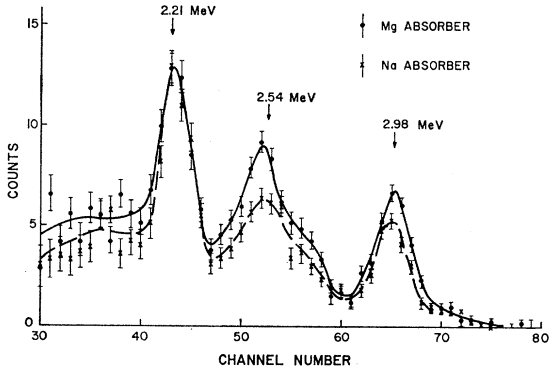

FIG. 4. Typical self-absorption data. The points represent Al-scatterer–Mg-scatterer differences. The peak at 2.21-MeV results from using Al in construction of the Na scatterer. Note that it shows no Na–Mg-absorber difference.

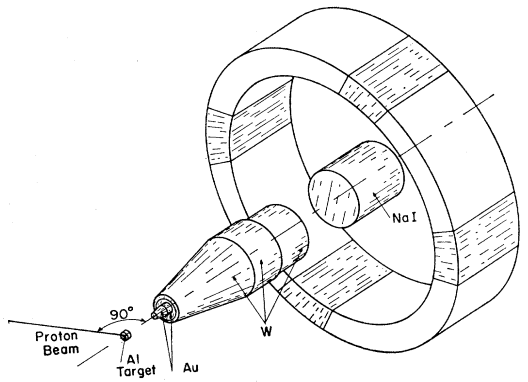

FIG. 3. "Polarization insensitive" arrangement of point scatterers. The angle γ of Eq. (1) is as defined in the caption of Fig. 2. The centers of the scatterer segments are set at values of γ satisfying $\cos2\gamma=0$.

[13] We might point out, finally, that only a very small fraction (within the "allowed cone," about 1/2500) of the photons from the source are of resonant energy, so that simple measurements with a conventional γ-ray polarimeter on all the γ rays would not be relevant.

We take a weighted mean of these values, and estimate the importance of other sources of error to get our final value, $\Gamma_0=(g_1/g_2)(77\pm12)\times10^{-3}$ eV. The total width is $\Gamma=(g_1/g_2)(140\pm20)\times10^{-3}$ eV and the corresponding mean life is $(g_2/g_1)(4.7\pm0.8)\times10^{-15}$ sec.

Data obtained in the angular-distribution measurements were very similar to those shown in Fig. 4. They could be fitted by the distribution for resonant scattering $1+(0.94\pm0.17)P_2(\cos\theta)$. No appreciable $P_4(\cos\theta)$ term was required by the data. This is not expected since the coefficient of this term is zero for the spin sequence $\frac{3}{2}$-$\frac{3}{2}$-$\frac{3}{2}$, and for $\frac{3}{2}$-$\frac{5}{2}$-$\frac{3}{2}$ is small for any reasonable quadrupole strength. The error given on the coefficient of P_2 is entirely statistical, this being by far the largest of any of the expected errors.

The results of measurements to detect effects of linear polarization of the resonant γ rays may be expressed in terms of an asymmetry $A=(C_0°-C_{90°})/(C_0°+C_{90°})$, where $C_0°$ is the counting rate with the detector in the plane of the beam and scatterer, and

$C_{90°}$ the rate with the detector at 90° to the plane, the counting rate with the Mg scatterer being subtracted out and the scattering angle in both cases being approximately 90°.

We first discuss the Al 2.21-MeV γ ray. Here we found, at $E_p=5.00$ MeV, $A=0.045\pm0.012$, and at 4.50 MeV, $A=0.040\pm0.015$, confirming a previous speculation[7] that the incident resonant photons were partially polarized at this proton energy. The bases for this speculation were that instead of the expected $1+0.23P_2$ correlation for the resonant scattering, we had found $1+0.37P_2$. We noted that with the data obtained and $\gamma=90°$, this is indistinguishable from $1+0.23P_2+0.05(\cos2\gamma)P_2^{(2)}$ and that for the established mixing ratio, $\delta=0.47$, the correlation for a completely polarized source would be $1+0.23P_2+0.12(\cos2\gamma)P_2^{(2)}$. The asymmetry found above is somewhat too small to explain these results quantitatively. This is not too disturbing since the point scatterer samples only a part of the resonant radiation that the ring scatterer sees. It is clear, however that the source is partially polarized, which introduces a note of caution into our discussion of results with the 2.98-MeV γ ray.

For this latter γ ray (and $E_p=5.00$ MeV) we find for aluminum $A=0.01\pm0.04$, and for sodium $A=0.05\pm0.07$, which would allow some polarization effect. An example here is informative. Consider the spin sequence $\frac{3}{2}$-$\frac{3}{2}$-$\frac{3}{2}$, and take the mixing ratio $\delta=0.22$. Then for a completely polarized source the correlation would be $1+0.5P_2+(\pm)0.1(\cos2\gamma)P_2^{(2)}$, where the sign choice depends on the direction of polarization. For the plus sign ($\gamma=90°$) and our three scattering angles, this would resemble closely $1+0.75P_2$, and the asymmetry ratio as defined above would be $A=0.4$, which is considerably larger than the observed ratio.

Measurements were also made with this "point" geometry for a scattering angle of 140°, and the angular distributions in the two planes found to be $1+(0.82\pm0.4)P_2$ and $1+(0.53\pm0.4)P_2$, consistent with our other values, and with some polarization effect.

When, also, our preliminary report[14] on the Na^{23} 2.98-MeV level was found to be in disagreement with other recent work,[8] we decided to repeat our angular-correlation measurement using the polarization-insensitive scatterer of Fig. 3. Some of the data taken were rejected because the neutron background was too high. The major part of the data used in plotted is Fig. 5. A least-squares fit gives the distribution $1+(0.80\pm0.18)P_2(\cos\theta)$. Addition of a P_4 term was not considered necessary, for the reasons indicated above.

Again we find agreement with our previous values. We assume that there is no polarization distortion of the scattering and take as our final result the mean of the most accurate distributions, $1+(0.87\pm0.13)P_2(\cos\theta)$.

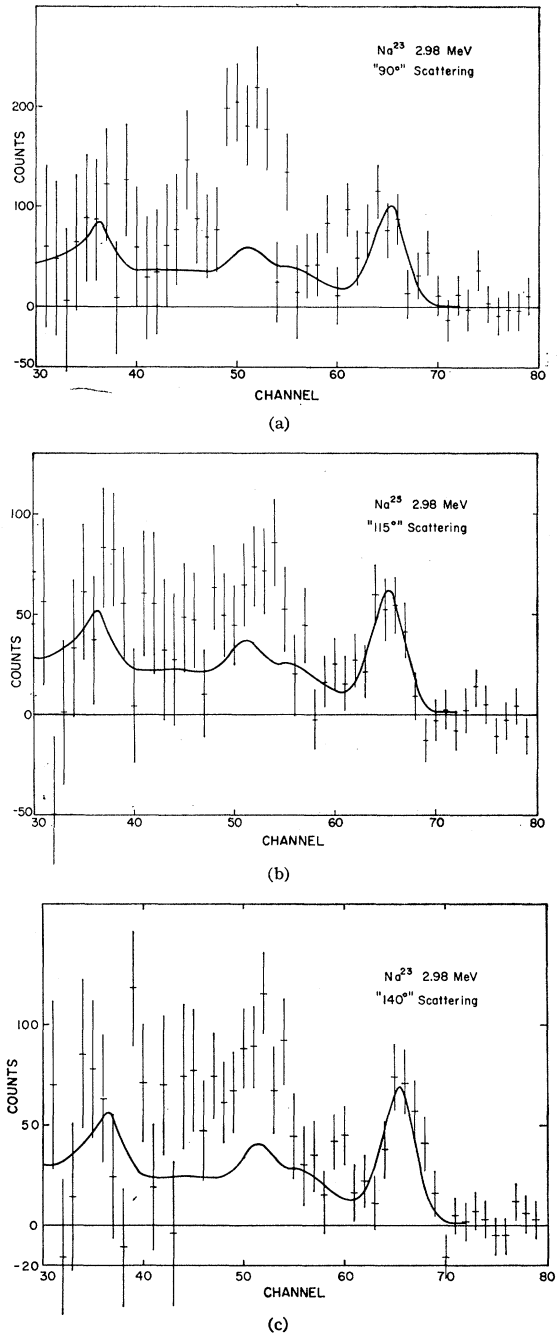

FIG. 5. Some of the data taken with the polarization-insensitive scatterer. The points plotted are Na-scatterer–Mg-scatterer differences for the nominal scattering angles noted. The solid curve is the (approximate) line shape for a single γ ray of 2.98 MeV. The additional peak in the data at channel 534 is from the cascade $2.98\rightarrow0.44$.

Because of the importance of this correlation for the discussion of the following section, we should consider the possible errors a little further. Our tests for possible source polarization were not too sensitive, and this uncertainty (which we find difficult to make quantitative)

[14] N. A. Khan and V. K. Rasmussen, Bull. Am. Phys. Soc. **11**, 595 (1966).

is not included in the above error. Otherwise, it is a reasonable representation of the accuracy of our measurement if taken as a standard deviation. Possible effects of the neutron background are also difficult to estimate. It was noted that for runs rejected because of high neutron background the correlation tended to be more isotropic. On the other hand, one can imagine two or three ways in which neutron background could increase the apparent anisotropy. The shielding of the detector from a neutron source by the Na scatterer could differ from the shielding by the Mg scatterer, and the difference could change when the detector is moved to change the scattering angle. Alternatively, fast neutrons could be scattered anisotropically, and not by the same amount by Na as by Mg. Or, fast neutrons from target could be scattered inelastically by the scatterers, and the resultant γ rays be anisotropic. For none of these examples, however, can we imagine that only the 2.98-MeV level[15] of Na^{23} (or a level with an identical decay scheme) would be excited. It is then significant that the scattered spectrum (Na-Mg difference, corrected for Al in the Na scatterer where required) shows no indication of γ rays other than the two expected from this level.

Some additional incidental remarks may be in order. We take account of the finite size of the counter and scatterer not by using attenuation coefficient but by subdividing the scatterer (in a manner described in many previous publications) calculating absorptions in and out, solid-angle factors, Legendre polynomials, etc., for each subdivision and then using appropriate weighted means. In other cases, subdivision of the detector also has given us no appreciable change in the result. Neglecting it can only give a P_2 coefficient slightly smaller than the true coefficient. Also, for resonance scattering (transition up≡transition down), all coefficients are non-negative. Since for the range 90° to 140°, P_2 is increasing and P_4 decreasing, adding a physically sensible P_4 term can only increase the P_2 coefficient. Finally, we note that the counting rate for the Mg scatterer was roughly independent of scattering angle, so that it is the rate with the Na scatterer that changes rather drastically to give the angular distribution.

Figure 6 shows the calculated coefficients for the direction-direction correlation as a function of δ, the $E2/M1$ amplitude ratio for the spin sequences $\frac{3}{2}$-$\frac{3}{2}$-$\frac{3}{2}$ and $\frac{3}{2}$-$\frac{5}{2}$-$\frac{3}{2}$. The range of δ allowed by our measurements is for intermediate spin $\frac{3}{2}$, $0.37<\delta<1.43$, and for intermediate spin $\frac{5}{2}$, $-1.50<\delta<-1.14$, $-0.47<\delta<-0.31$, and $1.01<\delta<1.82$.

As is apparent from Figs. 4 and 5, we also get information on the cascade transition $2.98\rightarrow 0.44$, although

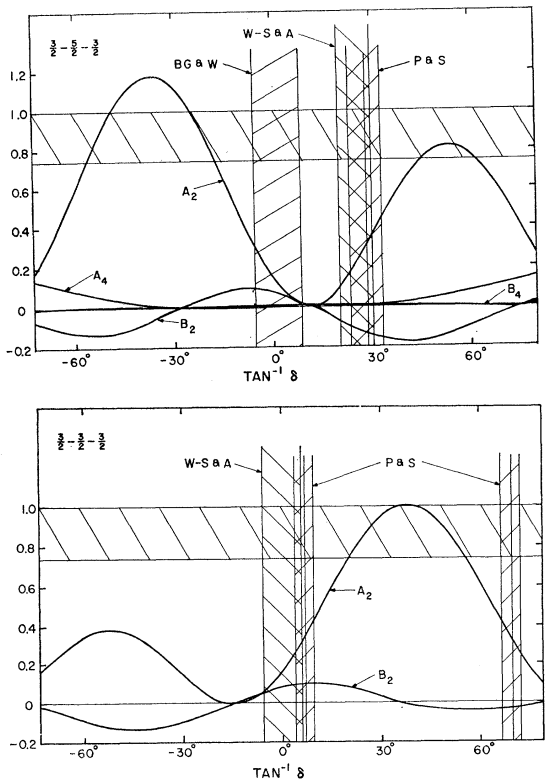

FIG. 6. Values of the coefficients in Eq. (1) as a function of the mixing ratio δ for the spin sequences $\frac{3}{2}$-$\frac{3}{2}$-$\frac{3}{2}$ and $\frac{3}{2}$-$\frac{5}{2}$-$\frac{3}{2}$. Values of the coefficient A_2 allowed by our work are indicated by a horizontal band, values of δ allowed by other work by vertical bands. Here the initials "P & S" refer to Poletti and Start, Ref. 8. "B G & W" refer to D. W. Braben, L. L. Green, and J. C. Willmott [Nucl. Phys. **32**, 584 (1962)] and "W-S & A" to E. Wernbom-Selin and S. E. Arnell [Arkiv Fysik **31**, 113 (1966)]. In this last work errors are not given, so that the extent of the vertical band indicates our estimate of a reasonable error.

the uncertainties are increased in subtracting out the ground-state transition. We find $(40\pm10)\%$ of the decays by this cascade (assuming that the only other decay is to the ground state) in agreement with the work of others. For the angular correlation we find $1-(0.08\pm0.4)P_2(\cos\theta)$, based on only the first set of measurements in which the complete ring scatterer was used. The error given is statistical only, and other contributions may be significant.

4. DISCUSSION

The smallest value of the mixing ratio allowed by our measurements corresponds to $\delta^2\approx0.1$, and to a $B(E2)$ for the ground-state transition of approximately twice the single-particle value $B(E2)_{SP}$.[16] Some upper limit may also be set on the mixing ratio on the basis of the largest $B(E2)$ that seems reasonable. Perhaps $\delta^2=1$ corresponding to $10B(E2)_{SP}$ could be considered suitable for this rather light nucleus. The $M1$ part of

[15] Inelastic scattering also requires a source of fast neutrons. There are few (p,n) reactions with low enough thresholds to convert 5.00-MeV protons to neutrons of >3 MeV, and excitation of the 2.98-MeV level seems to increase only slowly with neutron energy. See J. M. Freeman and J. H. Montague, Nucl. Phys. **9**, 181 (1958).

[16] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Rev. Mod. Phys. **28**, 432 (1956).

the transition is 0.1 Weisskopf unit for $\delta^2=0.1$. Two calculations applying the Nilsson model to this level of Na^{23} (and others) have recently been published[17,18] and the transition rates are compared with experiment in Table I. It is seen that the theoretical $M1$ rates are three times too fast and the theoretical $E2$ rates are 2600 and 20 times too slow.

The discrepancy between our mixing ratios and those of others has been discussed already by Poletti and Start, and we do not have too much to add. The various allowed values are diagrammed in Fig. 6. A change of sign of the mixing ratio would give agreement for three of the measurements for $|\delta|=0.5$ and spin $\frac{5}{2}$, but this is not allowed according to the discussion of phases by Poletti and Start[4] (we use, and have used, the Biedenharn convention). In addition, we have been able to compare the expressions used (for both spin $\frac{3}{2}$ and $\frac{5}{2}$) by Poletti and Start to describe the decay of the level with those we use to describe the excitation and decay, and find them to be identical. This would seem to rule out any error in sign.

For intermediate spin $\frac{3}{2}$, the only area where agreement is even approachable is around $\delta=0.22$. But this requires that several measurements, including that of Poletti and Start, differ by a couple of standard deviations from the "correct" value.

We find no convincing explanation of this experimental disagreement. One point that should be mentioned is that there are claims in the literature of a second level in Na^{23} close to 2.98 MeV. In the decay of Ne^{23} Penning and Schmidt,[19] and Lancman *et al.*[18] find a 2.87-MeV γ ray which they consider to be the ground-state decay of Na^{23} level. On the basis of average cross-section measurements of the $Mg^{25}(d,\alpha)$ Na^{23} reaction Gontchar *et al.*[20] suggest a doublet with spins (3/2, 5/2) and (11/2, 9/2). The large spin, which would preclude any appreciable decay direct to the ground state, is presumably not a firm assignment. Finally, we note that in our measurements with the Ge(Li) detector we saw a 2.90-MeV γ ray when a quite pure (nominally 99.99%) sodium target was bombarded by 4.90- and 5.00-MeV protons. The yield was of the order of half that of the 2.98-MeV γ ray. We cannot be certain, however, that it does not result from an impurity, and find reasons to doubt that it results from the $Na^{23}(p,p)$ reaction. Most significant is that the level was not seen by Buechner and Sperduto.[9] The region in their spectrum where the inelastic proton group would fall was free of any other groups, so that its relative intensity would have to decrease by a factor of 20 or so in going from 5 to 7–7.5-MeV incident proton energy.

If there is a second level—we emphasize that this is speculative—then we would not excite it with the $Al^{27}(p,p)$ source because of the 80-keV energy difference. The other measurements represented in Fig. 6, on the other hand, would presumably not resolve it. The disagreement would then be understandable, although it remains somewhat surprising that the branching ratio is the same.

Note added in proof. We have since looked at the γ-rays from Ne^{23} decay with a Ge (Li) detector and fail to find a 2.90-MeV γ ray of the intensity given by Lancman *et al.* We have also looked without success for the corresponding inelastic proton group from Na^{23} (p,p') at 90° (lab) and incident proton energies of 4.4 to 4.9 MeV.

Finally, we note that for the 2.98-MeV level we confirm the rejection of certain other values of spin and parity. The observation of anisotropy rules out spin $\frac{1}{2}$. Odd parity for spins $\frac{3}{2}$ or $\frac{5}{2}$ is made unlikely by the speed of the transition, which would require an $M2$ enhancement of at least two orders of magnitude. Spin $\frac{7}{2}$, with a pure quadrupole transition to the ground state, is ruled out by the observed angular distribution and any appreciable mixing in of higher multipoles would seem to be unlikely, since the transition is so fast.

TABLE I. Comparison of transition rates for the decay 2.98-MeV → 0 of Na^{23}.

	Theory (sec^{-1})		Experiment (sec^{-1})[a]	
Spin	$\frac{5}{2}$[b]	$\frac{3}{2}$[c]	$\frac{5}{2}$	$\frac{3}{2}$
$M1$ rate	2.2×10^{14}	2.9×10^{14}	7×10^{13}	1.0×10^{14}
$E2$ rate	2.4×10^{9}	7.1×10^{11}	7×10^{12}	1.4×10^{13}

[a] For the smallest values of the mixing ratio allowed by our measurements.
[b] Glöckle *et al.*, Ref. 17.
[c] Lancman *et al.*, Ref. 18.

ACKNOWLEDGMENTS

We wish to thank Dr. A. R. Poletti for informative discussions and a prepublication copy of his manuscript, and Dr. S. Fallieros for informative discussions.

[17] W. Glöckle, Z. Physik **178**, 53 (1964); (private communication).
[18] H. Lancman, A. Jasinski, F. Kownacki, and J. Ludziejewski, Nucl. Phys. **69**, 384 (1965).
[19] J. R. Penning and F. H. Schmidt, Phys. Rev. **105**, 647 (1957).
[20] V. Y. Gontchar, M. H. S. Bakr, and H. M. Omar, Nucl. Phys. **62**, 410 (1965).