PHYSICAL REVIEW VOLUME 174, NUMBER 4 20 OCTOBER 1968

Gamma-Ray Widths of the 3.00-MeV Level of Al^{27} and the 3.13-MeV Level of P^{31}†

S. W. Robinson, C. P. Swann, and V. K. Rasmussen
Bartol Research Foundation of The Franklin Institute, Swarthmore, Pennsylvania 19081

(Received 20 June 1968)

Nuclear resonant scattering of bremsstrahlung by the 3.00-MeV level of Al^{27} has been observed. From comparison with resonant scattering by the 2.98-MeV level of Al^{27}, and with the branching taken from the literature as $\Gamma_0/\Gamma=0.87$, widths $\Gamma_0=5.3\pm1.0$ meV and $\Gamma=6.1\pm1.2$ meV are obtained. These values are in some disagreement with inelastic electron scattering results. Comparison with Doppler-shift values tends to verify spin $=\frac{9}{2}$ for the 3.00-MeV level and to rule out spin $=\frac{3}{2}$. Self-absorption measurements of the resonant scattering by the 2.21- and 2.98-MeV levels of Al^{27} give $\Gamma=17.6_{-3.3}^{+2.9}$ meV and $\Gamma=125_{-13}^{+14}$ meV, in agreement with previous results. Self-absorption measurements for the 3.13-MeV level of P^{31} give $\Gamma=$ **66.3±7 meV.**

I. INTRODUCTION

The partial width for decay of the 3.00-MeV level of Al^{27} to the ground state has been calculated from inelastic electron scattering measurements[1] as $\Gamma_0=10.5\pm1.2$ meV. The total width has been measured by the Doppler-shift method as $\Gamma=3.0\pm0.5$ meV and $\Gamma=7.9\pm0.7$ meV.[2] A measurement involving the resonant scattering of bremsstrahlung gave $\Gamma=10_{-10}^{+3}$ meV.[3] By using a Ge(Li) detector, which will resolve the 2.98- and 3.00-MeV contributions, we have been able to get an improved result from the resonant scattering of bremsstrahlung.

A previous measurement of the width of the 3.13-MeV level of P^{31}, again by resonant scattering of bremsstrahlung,[4] gave 66 meV, with a 35% error. By performing a self-absorption measurement, we have reduced this error considerably.

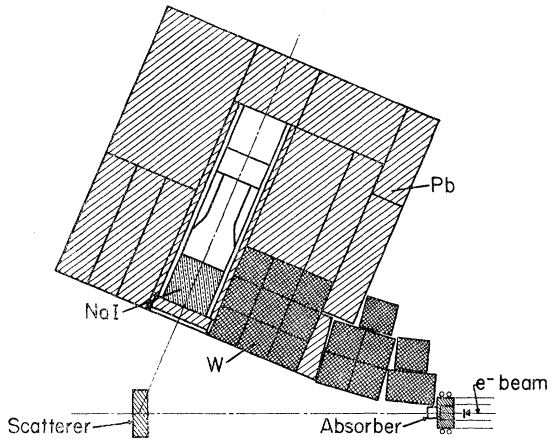


Fig. 1. Experimental arrangement. The electron beam enters from the right, passes through a thin gold radiator and is stopped in a water-cooled graphite block. Scatterers are placed on the beam axis, 20.0 in. from the gold radiator. Absorbers, if used, are placed against the beam dump. A 3×3-in. NaI detector is shown.

Several reasonably precise measurements of the widths of the 2.21- and 2.98-MeV Al^{27} levels have been made.[2] We have remeasured these widths, primarily as check on our methods. A more precise value for the width of the 3.00-MeV level enables us to make a correction to the data for the 2.98-MeV level.

II. EXPERIMENTAL METHOD

Nuclear resonant scattering of bremsstrahlung has been previously observed in several laboratories. The historical background has been discussed by Metzger[5] and the lifetime compilation of Skorka *et al.*[6] lists recent measurements. This is a preliminary report on our use of the method. We expect to publish, in the near future, a more complete discussion of several pertinent points.

The Bartol Van de Graaff accelerator has been modified so that either an electron or a proton beam can be obtained. A small analyzing magnet and appropriate electrostatic steering and focusing elements direct the electron beam to a thin gold radiator. Most of the experimental arrangement is shown in Fig. 1. Not shown are the monitor counter, a 4-cc Ge(Li) detector on the beam axis 10 ft from the target, and shielded by a minimum of 4½ in. of Pb, and a secondary wall of low-background concrete blocks which shields the 3×3-in. NaI or 30-cc Ge(Li) detector from natural radioactivity in the building walls.

The scatterers are 3.0-in.-diam cylinders of lengths up to 2¼ in. When the NaI crystal is used to detect the scattered radiation, comparison scatterers, matched to give the same nonresonant scattering, are also necessary. With the much better resolution of the Ge detector, comparison scatterers are not required. Typical pulse-height spectra for NaI are shown in Fig. 2.

The energy calibration of the electron beam analyzing magnet was based on the thresholds for resonant scat-

---

† Work supported by the U. S. Office of Naval Research.

[1] R. M. Lombard and G. R. Bishop, Nucl. Phys. **A101**, 601 (1967).

[2] P. M. Endt and C. Van der Leun, Nucl. Phys. **A105**, 1 (1967).

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

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

[5] F. R. Metzger, in *Progress in Nuclear Physics*, edited by O. R. Frisch (Pergamon Press, Inc., New York, 1959), Vol. 9.

[6] S. J. Skorka, J. Hertel, and T. W. Retz-Schmidt, Nucl. Data **A2**, 347 (1966).

tering by the 2.208- and 2.980-MeV levels of Al^{27}. Results of one such measurement are shown in Fig. 3, where we have plotted the number of counts in the channels corresponding to the 2.98-MeV full-energy peak versus the field in the analyzing magnet. The finite slope at the endpoint is attributable primarily to the thickness (8 mg/cm^2) of the gold radiator used. The upper energy limit of the bremsstrahlung spectrum can be determined to 3 or 4 keV from these measurements, which is an accuracy quite adequate for our present purposes.

Consideration of such factors as counting rates and peak to background ratios has led us to the conclusion that the optimum electron beam energy for a resonance scattering measurement is, generally, 100–200 keV above the threshold for the level of interest.

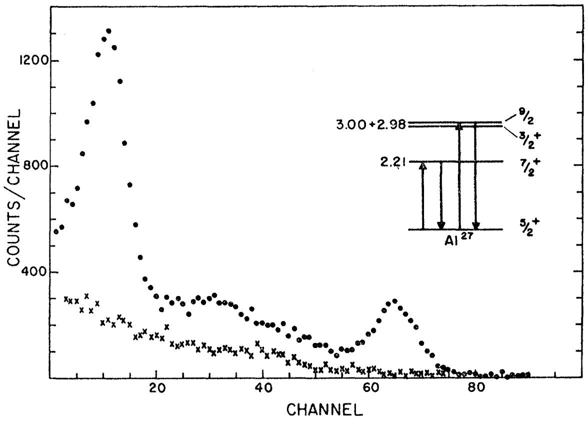
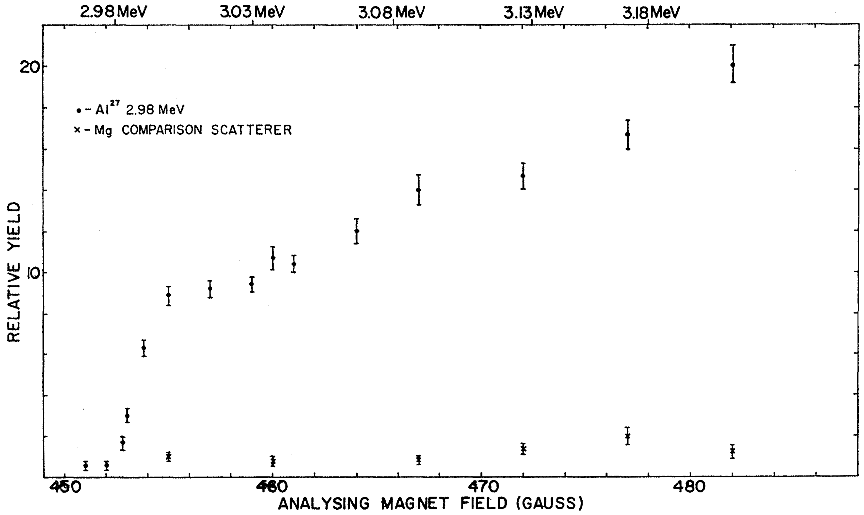


FIG. 2. NaI spectra of the bremsstrahlung as scattered by Al and Mg.

The steps involved in extracting a cross section, and thus a level width or lifetime from resonant scattering data have been discussed in many places (see, for example, the review article by F. R. Metzger[5]), and we refer the reader to such sources for details. The most troublesome problem with the bremsstrahlung source is the determination of the incident flux. We are as yet not certain of the best way to do this. Schiff's[7] integration of the Bethe-Heitler formula is nominally valid only if the total energy E of the scattered electron is large compared to the electron rest mass μ, and if the photon emission angle lies in the range $(\mu/E_0)^2 < \theta < \mu/E_0$, where E_0 is the incident electron energy. The contribution from small angles is not negligible, and the experimentally optimum energy is too close to the endpoint. The Schiff formula is still at least a useful guide to the properties of the bremsstrahlung beam, and we are currently investigating its possible quantitative significance for our measurements. We have found that when integrated over the scatterer it fits, quite closely, the slope of the data of Fig. 2 (ignoring the initial rise). It also predicts, with reasonable success, the variation of bremsstrahlung intensity with angle over a range of 0° to 4°. Similar results for both the slope and angular distribution have been obtained for 2.21 MeV (Al^{27}) and 3.56 MeV (Li^6). Some part of this agreement is fortuitous, since the calculated values were for a thin gold radiator ignoring any contribution from the graphite beam stopper, whereas we find experimentally that the latter makes an appreciable contribution to the resonantly scattered intensity, one that is energy-dependent and several times larger than theoretically expected.

The 4-cc Ge(Li) monitor counter is useful in determining the incident flux. One can get quite clean and easily interpreted spectra for 100 keV or so down from the upper energy limit provided that there is enough lead between the source and the detector to keep the the total counting rate below a few thousand a second. Rather long runs are then required to get statistically significant data near the endpoint.

FIG. 3. Excitation of the 2.98 level of Al^{27} as a function of electron beam energy. The upper curve is for an Al scatterer. The total counts in the full-energy peak at 2.98 MeV, for runs of a constant total incident beam are plotted versus the field in the analyzing magnet. The lower curve refers to the same channels in the spectrum with a Mg scatterer. The detector was a 3×3-in. NaI crystal, so that the contribution of the 3.00-MeV level should be subtracted. See Fig. 5.



---

[7] L. I. Schiff, Phys. Rev. 83, 252 (1951).

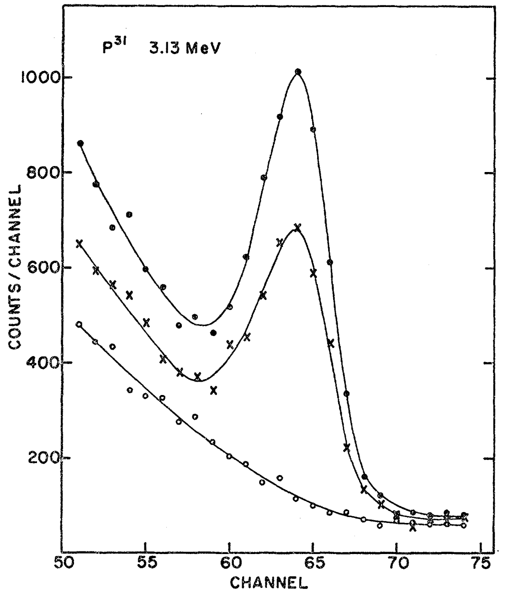


FIG. 4. Scattered spectra at a γ-ray energy around 3.13-MeV. The upper curve is for the P scatterer and Al absorber, the middle curve for the P scatterer and P absorber. With a S scatterer, the data with the P absorber and the Al absorber agreed to within the statistical errors, and the lower curve is the average of these two sets of data.

On the other hand, a knowledge of the incident flux is not necessary if one performs a self-absorption measurement.[5] When the counting rate in the resonantly scattered line is high enough to make this a feasible procedure, it should be done, as was the case for three of the four examples reported here. An aluminum absorber of 9.10 g/cm^2, a phosphorus absorber of 8.53 g/cm^2, and two comparison absorbers, matched to these for nonresonant attenuation, were used.

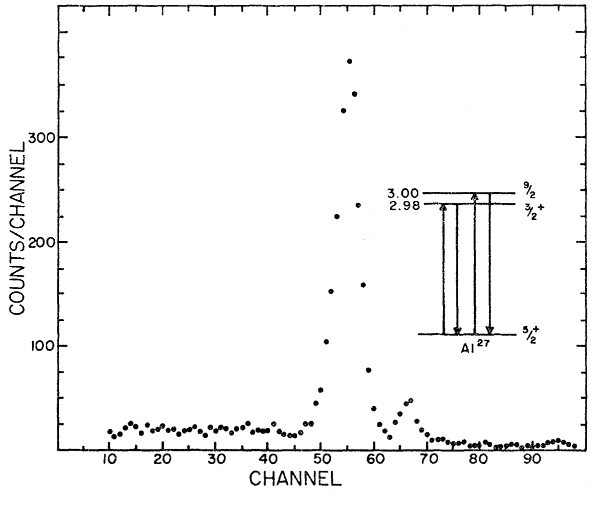


FIG. 5. A small portion of the spectrum in a Ge(Li) detector with an Al scatterer. The two peaks are full-energy peaks for 2.98- and 3.00-MeV γ rays.

The 3×3-in. NaI detector was used for the self-absorption measurements. With the electron beam energy set at 3.17 MeV, the P (or comparison) scatterer, and the P (or matching) absorber, the data shown in Fig. 4 were obtained. It was verified that the threshold for excitation of the phosphorus peak was at 3.13 MeV.

With an electron beam energy of 3.09 MeV, an Al (or comparison) scatterer and an Al (or comparison) absorber, similar self-absorption data were obtained for the 2.21- and 2.98-MeV levels of Al^{27}. With the 30-cc Ge(Li) detector and an Al scatterer, the spectrum shown in Fig. 5 was obtained after 15 h of running with an average beam of around 20 μA. The scattered intensity was taken as proportional to the number of counts in 7 channels centered on the peaks, after subtracting a background given by 7 channels above the 3.00-MeV peak. A small correction for the high-energy tail of the 2.98-MeV peak was also made.

III. RESULTS AND DISCUSSION

A. Levels in Al^{27}

The aluminum absorber gave a resonant attenuation of (28.9±3.6)% for the 2.21-MeV γ ray. Taking the level spin as $\frac{7}{2}$, the effective scatterer and absorber temperature as 326°K, and assuming no branching, the measured self-absorption corresponds to a width for the 2.21-MeV level of Al^{27} of $17.6_{-3.3}^{+2.9}$ meV or a mean life $\tau=37_{-5}^{+9}$ fsec, where the errors given are essentially statistical. Our value is in good agreement with previous results.[2]

It is clear from Fig. 5 and the known small branching that the 2.98-MeV transition is much faster than the 3.00-MeV transition and will dominate the self-absorption for the unresolved 2.98–3.00-MeV peak of Fig. 2. A sufficiently accurate correction for the 3.00-MeV contribution can thus be made directly from the data of Fig. 5, giving a self-absorption for the 2.98-MeV level of (37.7±2.8)%. Taking the level spin as $\frac{3}{2}$, the effective temperature at 326°K, and assuming 99% branching to the ground state, we get $\Gamma=125_{-13}^{+14}$ meV ($\tau=5.3_{-0.5}^{+0.6}$ fsec) for the 2.98-MeV level of Al^{27}. This is in agreement with previous work from this laboratory[8] after a correction has been made for effects of the 3.00-MeV level, and with the result of Schaller and Miller,[3] where the correction is not required.

The width for the Al^{27} 3.00-MeV level was calculated from the scattering relative to the 2.98-MeV level, as shown in Fig. 5. The decay of the 3.00-MeV level was assumed to be 87%[2] directly to the ground state, and the angular distribution for the resonance scattering was taken as that for a pure quadrupole $\frac{5}{2}$-$\frac{9}{2}$-$\frac{5}{2}$ transition. That for the 2.98-MeV scattering was taken as for a pure dipole $\frac{5}{2}$-$\frac{3}{2}$-$\frac{5}{2}$ transition in agreement with the measured distribution of Khan and Ramsussen.[8] The

---

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

change in bremsstrahlung intensity in going from 2.98 to 3.00 MeV was taken from Fig. 2, which does not give exactly what we want, but cannot be a bad approximation. The variation in detector efficiency was assumed to be determined by the Compton cross section for these two energies, and appropriate account was taken of resonant absorption in the scatterer. If our value for the width of the 2.98 level is taken, then the ground-state width for the 3.00-MeV level of Al^{27} is $\Gamma_0 = 5.3 \pm 1.0$ meV and the total width is $\Gamma = 6.1 \pm 1.2$ meV or $\tau = 0.11$ psec, where the errors given include an estimate of contributions other than statistical.

Our result is in disagreement with the inelastic electron scattering result[1] $\Gamma_0 = 10.5 \pm 1.2$ MeV. One notes that in the analysis of the electron scattering measurements, the possibility of a contribution from the 2.98-MeV level is ignored. It would be simplest to assume that the difference between our result and the electron scattering result represents the $E2$ component of the 2.98–ground-state transition. However, because of the effect of the statistical factor $(2J_{\text{ex}}+1)/(2J_{\text{gnd}}+1)$, this would be larger $[\Gamma(E2) \simeq 12 \text{ meV}]$ than allowed by the $E2/M1$ mixing ratio $\delta = 0.01 \pm 0.01$ given by Sheppard and Van der Leun. Examination of the validity of another assumption, that the $M1$ component of the 2.98-MeV transition contributes to the electron scattering, would require reanalysis of the data (cf. Lombard and Bishop's treatment[1] of electron scattering to the 2.21-MeV level of Al^{27}). While we have not ventured to do this, we regard it as a reasonably plausible explanation of the discrepancy.

Our result falls between the values 3.0 meV and 7.9 meV obtained from Doppler-attenuation measurements.[2] Since the calculation of a lifetime from a Doppler-shift measurement does not involve the level spin, while the resonance fluorescence calculation does (through the statistical factor given above), this may be regarded as confirming, to some extent, a spin assignment of $\frac{9}{2}$. It would also seem to rule out $\frac{3}{2}$, a value previously considered allowable for this level,[2] since our result would then be $\Gamma \simeq 15$ meV.

B. 3.13-MeV Level in P^{31}

The self-absorption for the 3.13-MeV level of P^{31} was $(31.3 \pm 2.3)\%$. Taking the spin sequence in the transition as $\frac{1}{2}$-$\frac{1}{2}$-$\frac{1}{2}$, and the effective temperature of the absorber and scatterer as 300°K, and assuming 100% branching to the ground state, the level width is found to be 66.3 ± 7 meV ($\tau = 9.9 \pm 1.1$ fsec), in agreement with the earlier result using the bremsstrahlung source.

Glaudemans, Wiechers, and Brussaard[9] have calculated wave functions for the $2s_{1/2}\ 1d_{3/2}$ shell (Si^{29}-Ca^{40}) and Wiechers and Brussaard[10] have used these wave functions to calculate ground-state magnetic moments. They find agreement with experimental values only if they define effective g factors for protons or neutrons in the $2s_{1/2}$ or $1d_{3/2}$ shells. They then calculate $M1$ widths for various transitions in these nuclei. For the $3.13 \rightarrow$ ground-state transition in P^{31} they predict 458 meV with the single-particle g factor and 86 meV with the effective g factor, the latter being in reasonable agreement with experiment. We note in passing that they have compared their similar predictions of 0.300 or 0.046 meV for the 1.27-MeV level of P^{31} with an erroneous experimental value of 2.8 meV. Their agreement with the correct value, 0.85 meV,[11] is somewhat better.

ACKNOWLEDGMENTS

We thank Dr. F. R. Metzger, Dr. S. Fallieros, and Dr. M. Soga for continuing advice and assistance.

---

[9] P. W. M. Glaudemans, G. Wiechers, and P. J. Brussaard, Nucl. Phys. **56**, 548 (1964).

[10] G. Wiechers and P. J. Brussaard, Nucl. Phys. **73**, 604 (1965).

[11] R. J. A. Levesque, C. P. Swann, and V. K. Rasmussen, Phys. Rev. **132**, 1205 (1963).