Resonant Absorption of Gamma Radiation from the $Al^{27}(p,\gamma)Si^{28}$ Reaction*

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(Received December 2, 1957)

Gamma rays emitted by excited Si^{28} formed in the reaction $Al^{27}(p,\gamma)Si^{28}$ at $E_p=771$ kev have been selectively absorbed in silicon. Selective, or resonant, absorption occurs when the absorber is placed at such an angle that the loss of energy upon emission and reabsorption of the photons is restored by the Doppler shift resulting from the forward motion of the excited Si^{28} nucleus. A narrow slit in a lead collimator is filled with silicon powder, and the transmitted gamma radiation is detected by a scintillation counter. The absorption dip observed as the collimator is rotated through the resonant angle has a width (determined primarily by the width of the collimator slit) of 0.75 degree, the maximum absorption amounting to 21%. From the integral of the absorption as a function of angle, and from an absolute measurement of the (p,γ) integral cross section, the radiation width for transition to the ground state ($E_\gamma=12.33$ Mev) is determined to be 5.2 ± 0.5 ev, while 2.0 ± 0.5 ev is found for the proton width, and 9.0 ± 0.8 ev for the total width. The half-life calculated from the latter is $(4.5\pm0.4)\times10^{-17}$ sec. These values, together with the angular distribution of the ground-state radiation, measured by Gove *et al.* are consistent with a 1^+ assignment to the resonance level.

1. INTRODUCTION

THE conditions under which nuclear resonant fluorescence can be observed are rather limited. In general terms, we may classify into four groups the various means by which the loss of energy upon emission and reabsorption may be overcome to a sufficient degree to permit resonant absorption to take place. These are (1) Doppler broadening by increase of temperature, (2) Doppler broadening by previous emission and/or absorption, (3) Doppler shift by mechanical motion, and (4) Doppler shift by previous emission and/or absorption. In addition there is at least one more class of experiments, typified by the work of Hayward and Fuller,[1] in which the source of selectively scattered radiation is the bremsstrahlung emitted by a betatron. In methods making use of Doppler broadening the direction of motion of the emitting nucleus is not determined experimentally. In experiments making use of Doppler shift, such a determination is necessary. Methods (1), (2), and (3) have been successfully applied previously.[2] We report here upon an application of method (4). The relative merits of this method are discussed at the end of Sec. 3.

2. PRINCIPLES OF THE MEASUREMENT

Consider an excited nucleus in the target shortly after it has been formed by the absorption of a proton. It will be in motion (in the direction of the proton beam) with a velocity

$$V=(2E_pm_p)^{\frac{1}{2}}/M, \tag{1}$$

where M is the mass of the nucleus (after absorption of the proton) and m_p and E_p are the mass and kinetic energy of the proton, respectively. The high-energy radiation emitted in the reaction studied is emitted long before any slowing down by collision can possibly occur. Upon emission at an angle α with respect to the direction of motion of the nucleus, a gamma ray from a transition of energy E_0 will receive an increment of energy:

$$\Delta E_1=\frac{V}{c}E_0\cos\alpha=E_0\frac{m_p}{M}\left(\frac{2E_p}{m_pc^2}\right)^{\frac{1}{2}}\cos\alpha. \tag{2}$$

The energy which must be supplied externally in order that a photon may excite an identical nucleus to the same level as that from which it has been emitted is given by

$$\Delta E_2=E_0^2/Mc^2. \tag{3}$$

This energy difference is the sum of two equal parts, one representing the loss of energy to the recoil of the emitting nucleus and the other to the recoil of the absorbing nucleus. Roughly speaking, resonant fluorescence can occur when ΔE_1 and ΔE_2 do not differ by more than the width of the line. Equating Eqs. (2) and (3), we obtain for the resonant angle, α_r,

$$\cos\alpha_r=E_0/(2E_pm_pc^2)^{\frac{1}{2}}. \tag{4}$$

The apparatus used to detect this absorption effect is shown schematically in Fig. 1. The collimator consists of two lead blocks which can be rotated about a vertical axis through the target. The radiation from the target can reach the detector only through the narrow slit between the lead blocks. The appropriate element is placed in the collimator opening and the intensity of the full-energy gamma rays is recorded as a function of angle. The measurements described in

* A short account of the method and some preliminary results have appeared as a short contribution by one of the authors (P.B.S.) in the *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), p. 587.

[1] E. Hayward and E. G. Fuller, Phys. Rev. **106**, 991 (1957).

[2] For a review of work up to 1955, see K. G. Malmfors, in *Beta- and Gamma-Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Chap. 23 (II). For more recent work, see F. R. Metzger, J. Franklin Inst. **260**, 239 (1955), and **261**, 219 (1956); F. R. Metzger, Phys. Rev. **101**, 286 (1956), and **103**, 983 (1956); H. Schopper, Z. Physik **144**, 476 (1956); V. Knapp, Proc. Phys. Soc. (London) **A70**, 142 (1957).

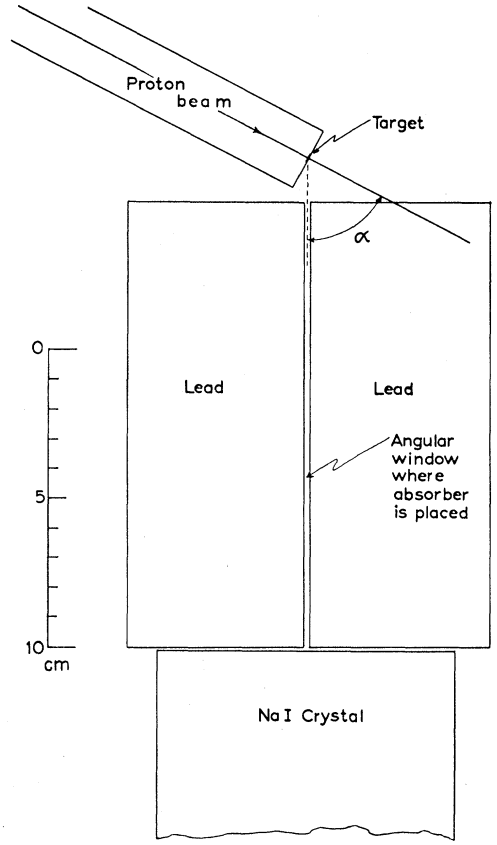

FIG. 1. A schematic horizontal cross section of the apparatus used to detect resonant absorption. The rectangles marked "Lead" constitute a collimator which permits the radiation from only a very narrow angular region to reach the detector. The collimator and the scintillation crystal are rotated as a unit about a vertical axis through the target spot.

Sec. 4 show that there is indeed strong absorption at the angle defined by Eq. (4) as compared to angles differing slightly from this angle.

3. THE ABSORPTION INTEGRAL

In this section it will be discussed how information on nuclear level parameters can be obtained from a measurement of the absorption as a function of angle.

Neither the width of the absorption dip nor the maximum absorption alone can yield information on the actual width of the level or on the absorption cross section since the natural width is small compared to the instrumental width. The latter is determined primarily by the width of the collimator slit. Quite direct information, however, can be obtained from the absorption integral

$$A_\alpha=\int_0^\pi A(\alpha)d\alpha=\int_0^\pi\{1-T(\alpha)\}d\alpha,$$

where $A(\alpha)$ and $T(\alpha)$ are the absorption and the transmission, respectively, at the angle α.

The absorption $A(\alpha)$ can be written more explicitly as

$$A(\alpha)=\int_0^\infty[1-\exp\{-n\sigma(E)\}]f(E-E')dE, \quad (5)$$

where E is the energy of a gamma quantum incident on the collimator slit, and n is the number of absorber nuclei per unit area. The average energy E' of gamma quanta incident on the slit follows from Sec. 2 as

$$E'=E_0-\frac{E_0^2}{2Mc^2}+\frac{V}{c}E_0\cos\alpha. \quad (6)$$

The function $f(E-E')$, normalized so that

$$\int_0^\infty f(E-E')dE=1,$$

is the energy distribution of the gamma quanta which would be transmitted through the collimator in the absence of absorber. The width of this function (the instrumental width) is determined by the width of the collimating slit and by the angular divergence of the protons incident on the target. The absorption cross section $\sigma(E)$ is given by the Breit-Wigner expression:

$$\sigma(E)=g\left(\frac{\lambda^2}{8\pi}\right)\frac{\Gamma_{\gamma0}\Gamma_t}{(E-E_0')^2+(\frac{1}{2}\Gamma_t)^2}, \quad (7)$$

where $g=(2J_r+1)/(2J_g+1)$, with J_r and J_g the spins of the excited state and the ground state, respectively, while Γ_t and $\Gamma_{\gamma0}$ represent the total width of the excited state and the width for the ground-state transition. The resonance energy E_0' differs from the excitation energy E_0 of the level by an amount equal to the recoil loss: $E_0'=E_0+E_0^2/2Mc^2$. It might be remarked that Eq. (7) differs from that generally employed in the description of resonant fluorescence experiments in that the numerator contains $\Gamma_{\gamma0}\Gamma_t$ instead of $\Gamma_{\gamma0}^2$, since one is not interested in the process de-exciting the absorbing nucleus, but only in the cross section for removal of photons from the beam.

The absorption integral can now be evaluated from Eqs. (5) and (7):

$$A_\alpha=\int_0^\pi A(\alpha)d\alpha=\int_0^\infty dE\{1-e^{-n\sigma(E)}\}\times\int_0^\infty f(E-E')\frac{d\alpha}{dE'}dE'. \quad (8)$$

The factor $d\alpha/dE'$ is obtained by differentiation of Eq. (6). As the integrand of the second integral differs from zero over a very narrow energy region, this factor may be considered as constant and may be replaced by

the value $(d\alpha/dE')_r$ at resonance, yielding

$$A_\alpha=\left(\frac{d\alpha}{dE'}\right)_r\int_0^\infty dE\{1-\exp[-n\sigma(E)]\}. \quad (9)$$

It is seen that the function $f(E-E')$ has no influence on the absorption integral. By inserting the expression (7) for $\sigma(E)$, and by putting $x=2(E-E_0')/\Gamma_t$ and $\sigma_0=h(\lambda^2/2\pi)(\Gamma_{\gamma 0}/\Gamma_t)$ (where λ can be considered constant over the effective range of integration), one obtains

$$A_\alpha=\left(\frac{d\alpha}{dE'}\right)_r\frac{\Gamma_t}{2}\int_{-\infty}^{+\infty}\left\{1-\exp\left(\frac{-n\sigma_0}{1+x^2}\right)\right\}dx. \quad (10)$$

This integral appears in the analysis of neutron absorption curves and has been shown by von Dardel and Persson[3] to be expressible in terms of Bessel functions of the first kind with pure imaginary arguments. It is customary to denote these functions by $I_\nu(z)=\exp(-\frac{1}{2}i\pi\nu)J_\nu(iz)$,[4] where $J_\nu(z)$ is the Bessel function of the first kind. Applying the results of von Dardel and Persson to Eq. (10), one finally obtains

$$A_\alpha=\left(\frac{d\alpha}{dE'}\right)_r\frac{\Gamma_t}{2}\pi F(n\sigma_0), \quad (11)$$

where

$$F(n\sigma_0)=n\sigma_0\exp(-\tfrac{1}{2}n\sigma_0)[I_0(\tfrac{1}{2}n\sigma_0)+I_1(\tfrac{1}{2}n\sigma_0)].$$

The function $F(n\sigma_0)$ is plotted in Fig. 2.

In principle it is possible to determine Γ_t and $\Gamma_{\gamma 0}$ from the variation of the absorption integral with absorber thickness (i.e., with n), since only one combination of Γ_t and $\Gamma_{\gamma 0}$ can fit the curve of Fig. 2 at two or more points. In practice the nonlinearity of $F(n\sigma_0)$ (upon which such a unique fit depends) is too small to make this method useful. Another independent observation is therefore necessary in order to determine Γ_t and $\Gamma_{\gamma 0}$. A yield measurement was used in this experiment to find the value of $(2J_r+1)\Gamma_\gamma\Gamma_p/\Gamma_t$, where Γ_γ is the total radiation width and Γ_p the proton width. The relationship between $\Gamma_{\gamma 0}$ and Γ_γ must also be known in order to interpret the results. The procedure followed in obtaining Γ_t, $\Gamma_{\gamma 0}$, and Γ_p is explained in the following paragraph.

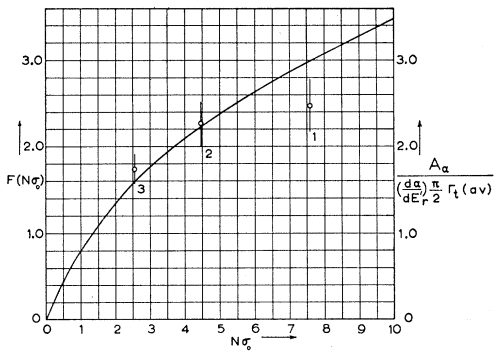

FIG. 2. The function

$$F(n\sigma_0)=n\sigma_0\exp(-\tfrac{1}{2}n\sigma_0)[I_0(\tfrac{1}{2}n\sigma_0)+I_1(\tfrac{1}{2}n\sigma_0)].$$

In Sec. 3 of the text it is shown that this function describes the variation of the absorption integral with absorber thickness. The experimental points, with corresponding errors, are plotted against the right-hand scale (see Sec. 5 of text).

Assuming that the quantity $\Gamma_\gamma\Gamma_p/\Gamma_t$ is measured to be equal to b electron volts, and that an analysis of the energy spectrum of the radiation emitted by the level in question gives the value of a, where $\Gamma_\gamma=a\Gamma_{\gamma 0}$, we can eliminate all variables except Γ_t from Eq. (11) in terms of a and b, obtaining

$$A_\alpha=\left(\frac{d\alpha}{dE'}\right)_r\frac{\pi}{2}\Gamma_t F\left\{\frac{H}{2a}\left[1\pm\left(1-\frac{4b}{\Gamma_t}\right)^{\frac{1}{2}}\right]\right\}, \quad (12)$$

where $H=ng(\lambda^2/2\pi)$. The plus sign is appropriate to the physical situation here, although the minus sign might be called for under different circumstances. From the graph of Fig. 2 and an auxiliary graph of the relation $[1+(1-4b/\Gamma_t)^{\frac{1}{2}}]$ as a function of Γ_t, one can quickly find the value of Γ_t which corresponds to a given pair of values of n and the measured absorption integral, A_α. This is done by first choosing an arbitrary value of Γ_t, corresponding to which the argument of F can be found from the known value of H and the auxiliary graph. The graph of Fig. 2 gives the corresponding value of F, which, multiplied by the appropriate factors [see Eq. (12)] gives the related value of A_α. This trial value is compared to the measured value of A_α and another trial value of Γ_t chosen. Three or four trials are sufficient to find the value of Γ_t corresponding to the measured value of A_α.

In writing Eqs. (5) through (11) the thermal motion of the emitting and absorbing nuclei has not been taken into account. The thermal motion of the emitting nuclei merely contributes (negligibly in this case) to the instrumental width. The thermal motion of the absorbing nuclei broadens the absorption line, however, and thus reduces the peak cross section. This has the effect of diminishing the self-absorption and thus of increasing the absorption integral.[3] It is probably not possible to reduce the absorption integral to known functions when the correct Doppler broadened cross section is substituted for that given in Eq. (7). The integral has been calculated, however, by von Dardel and Persson[3] and by Melkonian *et al.*[5] The latter authors have also developed an excellent approximation procedure for the analysis of neutron absorption integrals which has been adapted here to find the values of the level parameters. The increase in the absorption

[3] G. von Dardel and R. Persson, Nature **170**, 1117 (1952).
[4] G. N. Watson, *A Treatise on the Theory of Bessel Functions* (Cambridge University Press, New York, 1952).
[5] Melkonian, Havens, and Rainwater, Phys. Rev. **92**, 702 (1953).

integral due to thermal motion of the absorbing nuclei is described in terms of a parameter $\beta=2\Delta/\Gamma_t$, where $\Delta=(2kT/Mc^2)^{\frac{1}{2}}E_0$ is a measure of the Doppler width. The temperature T is not room temperature but somewhat above, and is determined according to Lamb[6] from the ratio of room temperature to the Debye temperature of the absorbing nuclei. In the present case the absorbing substance is silicon, the temperature $T\cong 400°$K, and $\Delta\cong 20$ ev.

In order to correct the values of the level parameters for the effect of thermal motion of the absorbing nuclei an approximate value of Γ_t is obtained by the method described above, on the assumption of no temperature motion. From this an approximate value of β is calculated. From curves given by Melkonian *et al.*,[5] covering a large range of values of β and $n\sigma_0$, a correction is found which must be applied to the value of the absorption integral. A new value of Γ_t is then calculated and the procedure repeated until Γ_t reaches a stationary value.

From the above analysis it can be seen that no assumptions need be made about the resolution of the apparatus, or the angular distribution of resonant scattering, in order to arrive at unique results for the level parameters. The statistical factor, g, must be known, as is always the case in resonant fluorescence experiments. This implies a prior knowledge of the spins of the excited and ground states. In addition, the decay scheme, at least in general outline, must also be known in order to find the relationship between $\Gamma_{\gamma 0}$ and Γ_γ. The measurement of absorption instead of scattering frees the interpretation of the assumptions regarding nonresonant scattering cross sections necessary when resonant scattering is measured.

4. EXPERIMENTAL

The Utrecht 800-kev cascade generator was used as a source of up to 30 μa of protons. The generator has recently been equipped with a 90° deflection magnet and converted from 50-cycle to 500-cycle operation. These changes have resulted in a much better beam definition and lower ripple than previously obtainable. The collimator, mounted on an angular distribution table in front of the counter, consists essentially of two precisely machined lead blocks, 4 cm×7 cm×14 cm. Adjustment was provided for the accurate alignment of the collimator slit on the target. The zero-degree mark of the angular distribution table was brought into line with the direction of the proton beam by optical means. A screw, operated by a synchro system from the generator control desk, was installed to vary the angle of the collimator and counter through a range of 4.2°. This mechanism was set so that the expected absorption dip would fall at the center of the available range. The collimator opening in this experiment was 1.90±0.02 mm. Top and bottom pieces of lead were provided to shield the counter from direct radiation. The counter, a 4 in.×4 in. NaI(Tl) scintillation crystal mounted on a Dumont type 6364 photomultiplier tube, is encased in a hollow lead cylinder with 8-cm thick walls. A 2-in. scintillation crystal is used as a monitor counter.

Figure 3 is a yield curve of the $Al^{27}(p,\gamma)Si^{28}$ reaction in the region of the resonance ($E_p=771$ kev) studied. The value given for the resonance energy is that found by Broström *et al.*[7] In order to obtain the curve shown the target had to be freshly prepared. Since the ground-state radiation only appears in the one resonance studied, a thicker target could be used in the measurement of resonant absorption. In the determinations of yield and spectra, however, extreme care had to be taken. It was found that after about ten minutes of bombardment the carbon deposit on the target began to endanger the purity of the line by broadening it as well as shifting its apparent energy (upwards). One precaution was necessary in the resonant absorption experiment in view of the fact that about 10% of the total radiation width was due to de-excitation to the first excited state of Si^{28} (at 1.78 Mev). The 4-in. crystal-multiplier combination could not resolve the radiation emitted in transitions to this level from the ground-state transitions, and so pulses were only accepted from near the top of the pulse distribution due to the 12.33-Mev radiation, upwards.

In determining the resonant absorption the experimental procedure was to load the collimator with a known amount of silicon powder and then to record the number of full energy gamma rays stopped in the crystal as the angle of the collimator was varied about α_r in 0.28° steps. A 2-in. crystal was used as a monitor. In order to reduce the effect of discriminator drifts the angle of the collimator was varied over the available range in about an hour. This procedure was repeated from 20 to 30 times until the desired number of counts was obtained. A separate run was also made with

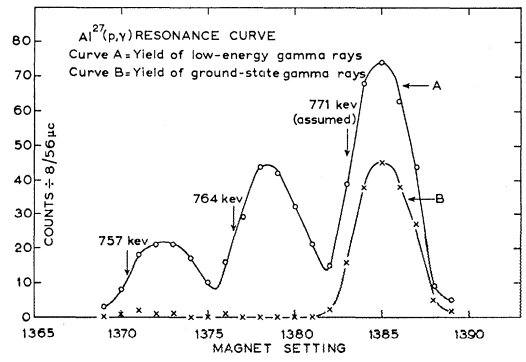

FIG. 3. A graph of the gamma-ray yield in the region of the resonance studied (771 kev). The values of the resonance energies at 757 kev and 764 kev are based on the assumption of an energy of 771 kev for the highest resonance.

[6] W. E. Lamb, Phys. Rev. **55**, 190 (1939).

[7] Broström, Huus, and Tangen, Phys. Rev. **71**, 661 (1947).

empty collimator to be sure that no unsuspected variation with angle existed. Approximately 400 microampere hours were deposited on the target during a run. The background of the counter and the "leak-through" radiation from the penetration of the collimator by radiation not falling on the slit were quite constant, each amounting to approximately 2% of the total counting rate. The "leak-through" was determined by a separate measurement with the collimator closed.

5. RESULTS

Three separate measurements (runs) of the absorption integral were made with varying amounts of silicon in the collimator. The results of one of these measurements is shown in Fig. 4. The centroid of the absorption dip falls at 14.7 turns of the adjusting screw. The expected position was 14.0 turns [from the alignment procedure used, and from a calculation of the resonant angle given in Eq. (4)]. The agreement ($\sim$0.1°) is

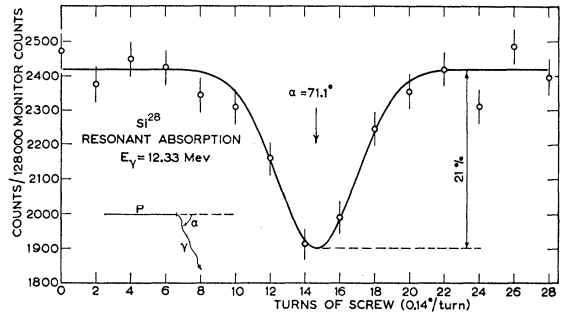

FIG. 4. A measurement of the absorption as a function of angle with silicon powder completely filling the collimator slit. The arrow marked $\alpha=71.1°$ indicates the centroid of the absorption dip. This angle is calculated from Eq. (4). The solid curve is a Gaussian of 0.75° full width at half-maximum and 21% maximum absorption.

within the expected alignment error and is an excellent check upon the correctness of the interpretation. No analogous check exists in those experiments in which the scattering of Doppler-broadened radiation is measured. The solid curve in Fig. 4 is a Gaussian of full width at half maximum of 0.75°, and a maximum absorption of 21%. This curve is seen to fit the points well. Elementary considerations of the various sources of instrumental broadening lead to the expectation of a width of about 0.88°. The fact that the observed width is less than this is almost certainly accounted for by the failure of the proton beam to fill the slits completely. The value of $(d\alpha/dE')_r$ calculated from Eq. (6) is 3.38 $\times10^{-3}$ degree/ev, yielding an instrumental width of 220 ev.

In the three separate runs the value of n was varied over a factor of about 3.4. In Table I are shown the resulting values of the absorption integral. It would have been extremely difficult either to increase n above the largest value used (the collimator was full) or

TABLE I. Measured values of the absorption integral. The errors given are standard errors determined by statistics only.

Run	n (10^{23} atoms/cm^2)	$A_\alpha=\int_0^\pi A(\alpha)d\alpha$ (degrees)
1	3.01	0.176±0.018
2	1.59	0.145±0.016
3	0.876	0.104±0.009

decrease it below the smallest (the absorption would have been so small that adequate precision would have been difficult to achieve). Thus it is not surprising that it was not practical to determine Γ_t and $\Gamma_{\gamma 0}$ from the variation of the absorption integral with n. The quantity $(2J_r+1)\Gamma_\gamma\Gamma_p/\Gamma_t$ was therefore determined by a yield measurement[8] made with a target of saturation thickness. The result found is $(2J_r+1)\Gamma_\gamma\Gamma_p/\Gamma_t=4.7$ ±1.5 ev. The ground-state branching ratio was determined from a scintillation spectrum taken with a Hutchinson-Scarrott pulse analyzer. The result of this measurement is $\Gamma_{\gamma 0}/\Gamma_\gamma=0.75\pm0.09$. About 10% of the decay proceeds to the 1.78-Mev level in Si^{28}. A good part of the remainder proceeds to a level at about 4.9 Mev.

From each of the measurements of the absorption integral, and from the determination of the (p,γ) yield and of the branching ratio, the level parameters Γ_t, $\Gamma_{\gamma 0}$, and Γ_p were determined by the procedure described in Sec. 3. In Table II the results are given for Γ_t both for the preliminary determinations neglecting thermal motion of the absorbing nuclei, and for the corrected values when this is taken into account. The weighted average value of Γ_t is 9.0±0.8 ev. The error assigned to Γ_t was the largest of the internal and external errors, which in the present case were almost equal. The corresponding average values of $\Gamma_{\gamma 0}$ and Γ_p are 5.2±0.5 and 2.0±0.5 ev, respectively. From the uncertainty principle and the value of Γ_t one finds a half-life of (4.5±0.4) $\times10^{-17}$ sec. In Fig. 2 the numbered experimental points correspond to the three runs. As can be seen by comparing with Eq. (11), the right-hand ordinate scale of Fig. 2 should equal $F(n\sigma_0)$. The Doppler-corrected absorption integral for each point was plotted against the value of $n\sigma_0$ corresponding to the individual meas-

TABLE II. The values of $n\sigma_0$ and Γ_t calculated for each of the determinations of the absorption integral.

Run	Neglecting thermal motion $n\sigma_0$	Neglecting thermal motion Γ_t (in ev)	Corrected for thermal motion $n\sigma_0$	Corrected for thermal motion Γ_t (in ev)
1	8.8	10.2	7.6	7.5±0.9
2	4.8	11.6	4.5	9.1±1.2
3	2.7	12.0	2.6	9.9±1.0
		Weighted average:		9.0±0.8

[8] See, e.g., Van der Leun, Endt, Kluyver, and Vrenken, Physica **22**, 1223 (1956).

urement, after dividing by the weighted average of Γ_t and the constant factor $\frac{1}{2}\pi(d\alpha/dE')_r$.

The values of Γ_t and $\Gamma_{\gamma 0}$ which can be obtained from the variation of the absorption integral alone are in agreement with the much more precise values given above.

The calculations above depend on the value of J_r assumed, as was mentioned earlier. The existence of a strong ground-state transition limits the choice to either one or two (since the ground state of Si^{28} has spin and parity assignment 0^+). If the spin were two with positive parity the state would certainly be formed by s capture and the angular distribution of the radiation would be isotropic. Since this definitely is not the case (see below) this possibility can be ruled out. Spin two with negative parity can be left out of consideration since the ground-state radiation would be $M2$ while the radiation to the 1.78-Mev level (known to have a spin and parity assignment 2^+) would be $E1$. In this case the transition to the 1.78-Mev level would certainly be more intense than that to the ground state, even in the case of T forbiddenness.

The above arguments show that the spin of the 771-kev level is one, permitting the determination of the total and partial widths, as described above.

The question of the parity of the 771-kev level can also be decided virtually without ambiguity. In order to show this we employ two independent arguments. The first involves the angular distribution of the ground-state radiation. If the level had a spin and parity assignment 1^- it would almost certainly be formed by p capture, with channel spin 2. The calculated angular distribution of the $E1$ ground-state radiation would then be $1-0.14\cos^2\theta$. If, on the other hand, the level assignment were 1^+ the level would be de-excited by (pure) $M1$ radiation and would be formed by d capture with channel spins 2 and 3 possible. In the first case the angular distribution would be $1+\cos^2\theta$, and in the second, $1-0.20\cos^2\theta$. The angular distribution as measured by Gove *et al.*[9] is $1-(0.20\pm0.03)\cos^2\theta$, if one neglects their P_1, P_3, and P_4 terms which are either zero or very small. The experimental result is therefore in disagreement with a 1^- level assignment, although this is not quite excluded. The result is in agreement with a 1^+ level assignment if it is assumed that only channel spin 3 participates in the capture process.

[9] H. E. Gove (private communication).

A 1^+ level assignment is strengthened by the value of Γ_p determined in this experiment. The expected value of Γ_p is given by

$$\Gamma_p=(2k/\pi K)v_1 D, \tag{13}$$

in which k is the proton wave number outside the nucleus, K is the proton wave number inside the nucleus (taken as 10^{13} cm^{-1}), v_1 is the penetration factor of the Coulomb barrier (computed with $r_0=1.5\times10^{-13}$ cm), and D is a proportionality constant with the dimensions of energy.

For a 1^- assignment (p capture) our measured value of Γ_p would require a value of 50 kev for D. A 1^+ assignment (d capture), on the other hand, would lead to $D=700$ kev. The latter value of D is in much better agreement with the average value ($D=2$ Mev) found for this region of the periodic table.[10]

No information on the parity of the resonance level can be obtained from the radiation width. Both an $M1$ transition or a T-forbidden $E1$ transition would have widths of the observed order of magnitude.

CONCLUSIONS

A new measuring technique involving resonant absorption of gamma rays has been used to determine the parameters of a level in Si^{28} produced in the reaction $Al^{27}(p,\gamma)Si^{28}$. The freedom of this method from assumptions regarding nonresonant scattering, and the spectral composition of the incident radiation, have permitted the attainment of low relative errors not easily reached in other types of resonant fluorescence experiments.

ACKNOWLEDGMENTS

This investigation is part of the research program of the "Stichting voor Fundamenteel Onderzoek der Materie," and was made possible by financial support from the "Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek."

The authors wish to express their appreciation of the help received from their colleagues, especially A. M. Hoogenboom and E. Gelsema, in the setting up of the experiment, the taking of data (a total of over 100 hours), and in the calculations. A fruitful discussion with Professor L. van Hove is also gratefully acknowledged.

[10] C. van der Leun (private communication).