Nuclear Resonance Fluorescence from the 279-kev Level of Tl^{203} with an Ultracentrifuge*

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Resonance fluorescence from the 279-kev level of Tl^{203} was studied with the centrifuge method. Assuming a total conversion coefficient $\alpha_T=0.225$, a mean life $\tau_\gamma=(5.00\pm0.24)\times10^{-10}$ sec for gamma-ray emission was calculated from the resonance scattering measured at different source velocities. Combining this lifetime with the $B(E2)$ from Coulomb excitation, the absolute value of the mixing amplitude $\delta=(E2/M1)^{\frac{1}{2}}$ is $|\delta|=1.31_{-0.18}^{+0.24}$. The angular distribution of the resonance radiation was found to be of the form $W(\theta)=1+(0.87\pm0.08)P_2(\cos\theta)$. This angular distribution, together with the range of absolute values of δ given above, fixes the sign of δ as positive. The range of δ values permitted by the angular distribution measurements is $\delta=+1.20_{-0.12}^{+0.20}$.

I. INTRODUCTION

THE main features of the two radioactive decays which excite levels in Tl^{203} are summarized in Fig. 1. The special interest in these levels had its origin in the expectation that, since Tl^{203} has a single proton hole in the 82-proton shell, the properties of the Tl^{203} levels should be well described by the single-particle shell model. According to this model, the 401-kev transition between the second and first excited states was expected to be a fast $M1$ transition because it connects two d states. The $M1$ part of the 279-kev transition probability, on the other hand, was expected to be greatly reduced because this transition occurs between a d state and an s state and is therefore l forbidden. Measurements of the internal conversion[1] and the lifetime[2] showed that the $M1$ transition probability of the 279-kev transition is reduced by a factor of one thousand, while Coulomb excitation studies[3] indicated that the $M1$ transition probability for the l-allowed 401-kev transition is close to the independent-particle model estimate.

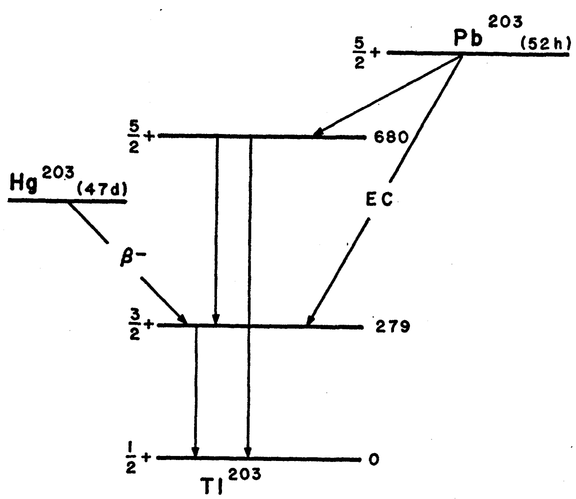

FIG. 1. The excited states of Tl^{203}. Energies are given in kev.

Following the prediction by Sliv and Listengarten[4] that the K and L_I shell conversion coefficients for $M1$ transitions in a nucleus with $Z=83$ should be lowered by a factor $\frac{2}{3}$, more detailed investigations of the conversion coefficients of the 279-kev transition in Tl^{203} were carried out. They led to the experimental confirmation of the existence of nuclear size effects in $M1$ conversion coefficients[5] and stimulated studies of the $E2/M1$ mixing ratio since knowledge of this ratio is essential for the evaluation of the finite-size effects. $\gamma-\gamma$ angular correlation measurements with the 401–279-kev cascade were not of much help in determining the mixing ratio of the 279-kev transition because both transitions in the cascade are mixed and the interpretation is, therefore, ambiguous. A mixing ratio independent of conversion data was obtained[3] from a study of the polarization of the Coulomb excited 279-kev radiation, which yielded a value $\delta=+1.50\pm0.08$ for the mixing amplitude of the 279-kev transition or a mixing ratio $\delta^2=2.25\pm0.25$. This mixing ratio is considerably higher than the values obtained from an analysis of the conversion data,[6] although it should be added that there exists considerable latitude in the interpretation of the conversion data. In view of the importance of the mixing amplitude of the 279-kev transition for the interpretation of other experiments involving Tl^{203}, as for instance, for the evaluation of nuclear structure effects[7] in conversion-electron–gamma angular correlations,[8,9] it was decided to obtain independent information on δ_{279} or $\delta^2_{279}=E2/M1$ using the resonance fluorescence technique. Under favorable circumstances, a measurement of the angular distribution of the resonant gamma rays with respect to the incident gamma-ray beam will, when combined with

* Supported by a grant from the National Science Foundation.
[1] D. Saxon, Phys. Rev. **83**, 849 (1948).
[2] F. R. Metzger, *Proceedings of the 1954 Glasgow Conference on Nuclear and Meson Physics* (Pergamon Press, New York, 1955), p. 201.
[3] F. K. McGowan and P. H. Stelson, Phys. Rev. **109**, 901 (1958).
[4] L. A. Sliv and M. A. Listengarten, J. Exptl. Theoret. Phys. (U.S.S.R.) **22**, 29 (1952).
[5] A. H. Wapstra and G. J. Nijgh, Nuclear Phys. **1**, 245 (1956).
[6] G. J. Nijgh and A. H. Wapstra, Nuclear Phys. **9**, 545 (1958–1959).
[7] E. L. Church and J. Weneser, Phys. Rev. **104**, 1382 (1956).
[8] B. I. Deutch and N. Goldberg, Phys. Rev. **117**, 818 (1960).
[9] T. R. Gerholm, B. G. Pettersson, B. van Nooijen, and Z. Grabowski (to be published).

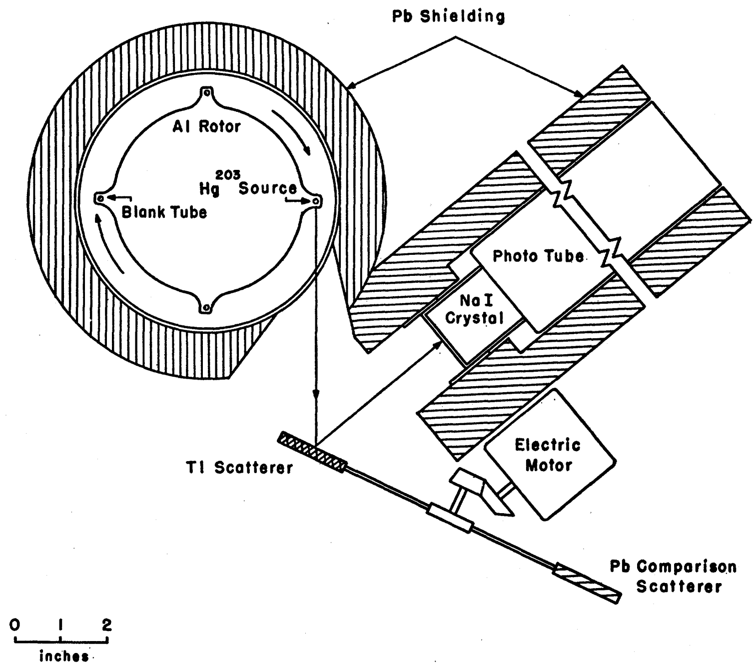

FIG. 2. A cut-out view of the experimental apparatus used with source 1.

some additional information concerning the range of possible $E2/M1$ ratios, allow one to determine δ. The absolute resonance scattering cross section, which may also be extracted from such a study, measures the total $E2+M1$ transition probability. A comparison with the Coulomb excitation yield, i.e., with the $E2$ transition probability, gives directly δ^2.

A measurement of the total $E2+M1$ transition probability with the resonance fluorescence technique is in itself of interest since in the past[10] some doubt had been expressed in lifetimes measured with that technique, and since the 279-kev transition in Tl^{203} is well suited for a comparison of different techniques for the determination of short lifetimes. In the last few months, a considerable number of new and more accurate results[11–15] has been added to the already existing list.[11] As will be shown later, the discrepancies between the lifetimes measured with a given method are, in general, as large or larger than the differences between the average lifetimes obtained with different techniques.

As far as the various resonance fluorescence techniques[16] are concerned, it was felt that with the thermal method an improvement over a previous measurement[17] would be, to say the least, very time consuming. The centrifuge method, which gives the best ratio of resonant to nonresonant scattering, was judged to be capable of a higher accuracy. The optimum speed for the 279-kev transition, $\approx$470 meters per second, did not present any problem, since even with aluminum rotors source speeds in excess of 1000 meters per second had been attained in our apparatus.

II. EXPERIMENTAL PROCEDURE

High specific activity Hg^{203}, obtained from the Oak Ridge National Laboratory, was converted from $Hg(NO_3)_2$ to HgS. About 25 mg of the HgS was added to a small centrifuge tube in a rubber matrix. Two such sources were prepared with activities of about 10 and 30 millicuries, respectively. The strength of each source was limited by the specific activity available at the time of preparation and the capacity of the centrifuge tube.

A cut-out view of the experimental apparatus used in the measurement of τ_γ with the first source is shown in Fig. 2. A thallium scatterer and its lead comparison scatterer automatically replaced one another every 20 minutes. The scatterers, $1\frac{1}{2}$ in. diameter and $\frac{1}{4}$ in. thick, were located about 13 cm from the mean position of the source and 9 cm from the detector. The detector, a 35 mm diameter and 40 mm long NaI(Tl) crystal mounted on an RCA 6342 photomultiplier tube, was shielded with lead from the direct radiation. A $\frac{1}{16}$-in. lead absorber interposed between the scatterer and detector attenuated the Compton-scattered gamma rays. Pulses from the phototube were fed through a nonoverloading amplifier into a pulse-height analyzer in the usual scintillation spectrometer arrangement. The scattered

[10] V. Knapp, Proc. Phys. Soc. (London) **A71**, 194 (1958).
[11] E. Bashandy, T. R. Gerholm and J. Lindskog, Arkiv Fysik **17**, 421 (1960).
[12] S. Gorodetzsky, R. Manquenouille, R. Richert, and A. Knipper, Compt. rend. **251**, 65 (1960).
[13] B. Johansson and T. Alvager, Arkiv Fysik **17**, 163 (1960).
[14] A. Schwarzschild and J. Kane, following paper [Phys. Rev. **122**, 854 (1961)].
[15] E. C. B. Pederson and R. E. Bell, Nuclear Phys. **21**, 393 (1960).
[16] F. R. Metzger in *Progress in Nuclear Physics*, edited by O. R. Frisch (Pergamon Press, New York, 1959), Vol. 7.
[17] F. R. Metzger, J. Franklin Inst. **261**, 219 (1956).

radiation was counted only when the direction of emission of the gamma rays striking the scatterer subtended an angle of less than ± 30 degrees with the tangent to the path of the source. This was accomplished with a gating pulse initiated by a light beam which was reflected from a mirror mounted on the driving shaft of the centrifuge. For the 279-kev transition in Tl^{203}, the spin sequence for resonant scattering is $\frac{1}{2}$–$\frac{3}{2}$–$\frac{1}{2}$. The angular distribution of the resonance radiation for this sequence is of the form $1+A_2P_2(\cos\theta)$ independent of the value of the mixing amplitude δ. Since $P_2(\cos\theta)$ vanishes near 126°, a scattering angle (130°) close to this zero was chosen in order to make the determination of the total cross section independent of the accurate knowledge of the coefficient A_2.

With the scattering angle of 130°, measurements were carried out with the source moving towards the scatterer with varying velocities, with the source at rest, and finally with the source moving away from the scatterer ("reverse" velocity). When the source is moving towards the scatterer, the emission line can be Doppler shifted so that it overlaps the absorption line completely, thus giving rise to the maximum resonance scattering effect. For complete overlap, the relative velocity of the absorbing and emitting nuclei should be 443 m/sec. Because of the finite size of the scatterer and the finite extent of the path, the effective relative velocity is smaller than the actual source velocity. Consequently, the optimum scattering effect occurs for our geometry at a source velocity of 467 m/sec. With the source moving away from the scatterer, the effect of the Doppler shift is to separate the two lines and to reduce the resonance effect practically to zero. With the source at rest, the intermediate situation of partial overlap exists.

The second source was used for the angular distribution measurements at a fixed source velocity of 467 m/sec, the velocity yielding the maximum scattering effect. The scatterers were rectangular solids $2\frac{1}{4}$ in. $\times 1\frac{1}{2}$ in. $\times\frac{1}{4}$ in. The geometry of Fig. 2 was slightly modified. Some of the lead shielding between the source and the detector was replaced by gold to increase the absorption of the direct beam. Scattering was measured at 105°, 130°, and 150°; this necessitated locating the scatterers in a range of 10–15 cm from the mean position of the source and in about the same range from the mean position of the detector.

III. EXPERIMENTAL RESULTS

The average differences between the counting rates with the thallium scatterer and the lead comparison scatterer for different velocities of source 1 are given in Table I. The errors quoted are purely statistical.

Since the residual resonance effect for the reverse velocity (-189 m/sec) is expected to be less than $\frac{1}{2}$% of the maximum resonance effect, the counting rate in the reverse position represents essentially the mismatch of the scatterers for all nonresonance effects.

TABLE I. The average difference $N(v)$ between the counting rate N_{Tl} with the thallium scatterer and the counting rate N_{Pb} with the lead scatterer as a function of the velocity (v) of source 1.

Velocity (v) in meters/sec	Counting rate difference $N(v)=N_{Tl}-N_{Pb}$ in counts/min
467	10.92±0.94
377	7.96±0.87
302	8.61±0.97
248	3.0 ±1.1
127	0.52±0.87
0	1.0 ±1.3
−189 (reverse)	0.5 ±0.7

In Table II, the average differences between the counting rates for source 2 with the thallium scatterer and the lead comparison scatterer for different scattering angles, taken at the velocity of the maximum resonance effect, are shown. The counting rates given in Table II are not indicative of the angular distribution, since the over-all solid angles for the three scattering positions differed considerably. Again, the errors given are purely statistical.

IV. EVALUATION

For a centrifuge experiment with a single gamma-ray transition to the ground state, the effective resonance scattering cross section may be written in the form:

$$\sigma_R=\frac{2J_1+1}{2J_0+1}\frac{\lambda^2}{4\pi^{\frac{1}{2}}}\frac{\Gamma_0}{(1+\alpha_T)}\frac{1}{E_\gamma}\times\left[\frac{Mc^2}{2k(T_S+T_{SC})}\right]^{\frac{1}{2}}\exp\left[-\frac{M(E_\gamma/Mc-u)^2}{2k(T_S+T_{SC})}\right], \quad (1)$$

where J_1 and J_0 are the total angular momenta of the excited state and ground-state, respectively, E_γ is the energy of the gamma ray and λ the corresponding wavelength; Γ_0 is the partial width for the direct gamma-ray transition to the ground state, α_T designates the total conversion coefficient of the transition, M is the mass of the nucleus, k is Boltzmann's constant. T_S and T_{SC} are the effective temperatures[17] of the source and scatterer, respectively, u is the relative velocity of source and scatterer, and c is the velocity of light. For the 279-kev transition in Tl^{203}, a total conversion coeffi-

TABLE II. The average difference $N(467)$ at a velocity of 467 m/sec of source 2 between the counting rate N_{Tl} with the thallium scatterer and the counting rate N_{Pb} with the lead scatterer as a function of the scattering angle θ.

Run	$N(467)$ at scattering angle θ in counts/min 105°	130°	150°
1	59.1±3.1	86.2±2.2	47.2±2.0
2	51.6±2.7	77.7±3.4	49.4±2.0
3	55.9±3.1	86.0±3.5	43.7±2.2

cient $\alpha_T=0.225\pm0.005$ was used.[18] A Debye temperature of 96° was assumed[19] in the calculation of the effective temperatures $T_S=T_{SC}=296°$.

Using Eq. (1), the counting rates expected for different source velocities v and different values of Γ_0 were calculated for the various geometries. For this purpose, the contributions of different sections of the scatterer for the subdivisions of the source path had to be summed. The summations were carried out with Univac II. Since it was found that the Bureau of Standards[20] value of 147 barns/atom for the total electronic cross section at 279 kev ($Z=81$) differed from the Davisson and Evans[21] total cross-section value of 137 barns/atom by more than 5%, we determined this total cross section experimentally. Our measured value is 151 ± 3 barns/atom. Since a large fraction of the Rayleigh-scattered quanta is still capable of resonance scattering, and since a considerable portion of the outgoing quanta which are Rayleigh- or Compton-scattered will be detected because of the limited energy resolution of the scintillation detector, the effective cross sections for the incoming and outgoing radiation are somewhat smaller than this total cross section. The values used for the evaluation of the experimental data were $\sigma_{\text{incoming}}=143$ barns/atom and $\sigma_{\text{outgoing}}=141$ barns/atom. Using these cross sections, the counting rates expected for different source velocities and different values of the width Γ_0 were computed and were then compared with the observed counting rates given in Table I. The width Γ_0 found in this way corresponded to a gamma mean life $\tau_\gamma=\hbar/\Gamma_0=(5.10\pm0.28)\times10^{-10}$ sec. Three more values for τ_γ were obtained from the analysis of the three independent angular distribution measurements which had been carried out with source 2 (see Table II). All these values for the mean gamma lifetime τ_γ of the 279-kev transition in Tl^{203} are listed in Table III with their statistical uncertainties.

The counting rate versus velocity curve expected for a mean life $\tau_\gamma=5.00\times10^{-10}$ sec is compared in Fig. 3 with the experimental results obtained with source 1. The final value of the mean gamma lifetime,

$$\tau_\gamma=(5.00\pm0.24)\times10^{-10}\text{ sec},$$

includes corrections for air absorption as well as other small corrections and uncertainties in the angular definition of the gate, the elongation of the rotor, and the total electronic cross section.

As mentioned in the Introduction, one obtains the mixing ratio δ^2 of a transition by combining the data from nuclear resonance fluorescence and Coulomb excitation since

TABLE III. Experimental values for τ_γ, the mean gamma lifetime of the 279-kev level in Tl^{203}.

Source	τ_γ (sec)
1	$(5.10\pm0.28)\times10^{-10}$
2	$(4.78\pm0.47)\times10^{-10}$
2	$(4.97\pm0.38)\times10^{-10}$
2	$(5.00\pm0.58)\times10^{-10}$
Average 2	$(4.92\pm0.26)\times10^{-10}$
Average 1+2	$(5.00\pm0.19)\times10^{-10}$

$$\delta^2=\frac{\langle E2\rangle}{\langle M1\rangle}=\frac{\langle E2\rangle}{\langle M1+E2\rangle-\langle E2\rangle}, \tag{2}$$

where $\langle M1+E2\rangle$ is the transition probability measured by nuclear resonance fluorescence (or by delayed coincidences), $\langle M1\rangle$ is the magnetic dipole transition probability, and $\langle E2\rangle$ is the electric quadrupole transition probability—a quantity proportional to the Coulomb excitation parameter $B(E2)$.

Using the Coulomb excitation value[22] of $B(E2)=(0.61\pm0.07)\times10^{49}$ measured by McGowan and Stelson, and our value of the mean gamma lifetime of the 279-kev level, the mixing amplitude was calculated to be $|\delta|=1.31_{-0.18}^{+0.24}$. The main error in this value stems

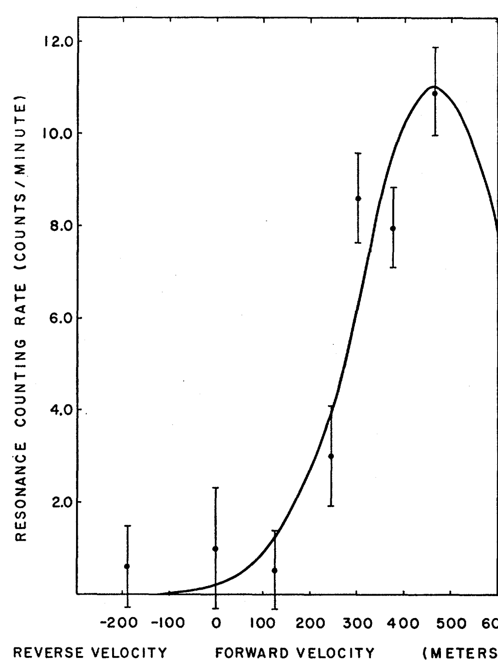

FIG. 3. The resonance scattering effect as a function of the velocity of the source. The heavy line represents the theoretical counting rate for $\tau_\gamma=5.00\times10^{-10}$ sec. The experimental points from the first (weak) source are shown for comparison purposes.

[18] G. J. Nijgh, A. H. Wapstra, L. Th. M. Ornstein, N. Salomons-Grobben, and J. R. Huizenga, Nuclear Phys. **9**, 528 (1958–1959).

[19] F. Seitz, *The Modern Theory of Solids* (McGraw-Hill Book Company, Inc., New York, 1940).

[20] G. W. Grodstein, *X-Ray Attenuation Coefficients from 10 kev-100 Mev*, National Bureau of Standards Circular No. 583 (U. S. Government Printing Office, Washington, D. C., 1957).

[21] C. M. Davisson and R. D. Evans, Revs. Modern Phys. **24**, 79 (1952).

[22] The value of $B(E2)$ listed in reference (3) was calculated for $\alpha'=0.246$. We have corrected this value for $\alpha_T=0.225$ by multiplying with the factor $(1+\alpha_T)/(1+\alpha_T')$.

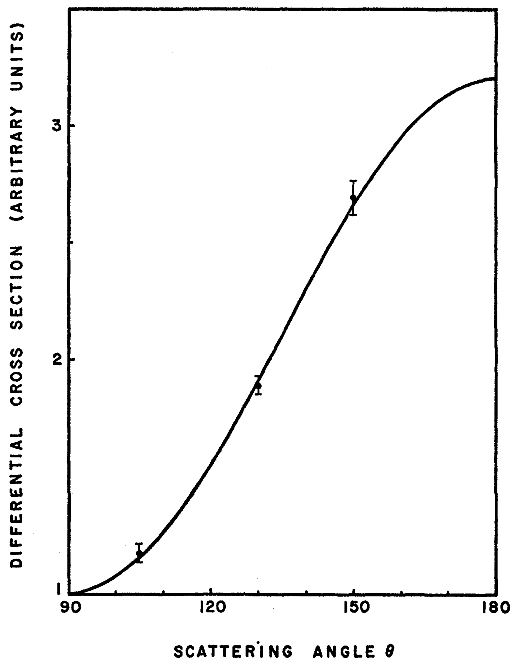

FIG. 4. The differential cross section in arbitrary units versus the scattering angle. The heavy curve is the mean square fit to the angular distribution data uncorrected for the finite size of the detector.

from the uncertainty in the Coulomb excitation value for $B(E2)$.

As has been mentioned previously, the angular distribution of the resonance radiation for a $\frac{1}{2}$-$\frac{3}{2}$-$\frac{1}{2}$ spin sequence has the form $1+A_2P_2(\cos\theta)$. The coefficient A_2 for the 279-kev transition in Tl^{203} was determined by a least-squares fit to the angular distribution data obtained with source 2 (Table II). The values obtained for the three separate runs are given in Table IV. The error of the average value was calculated from the deviations of the individual runs from the mean.

The average differential cross sections from the three runs with source 2 are compared in Fig. 4 with the angular distribution $1+0.86P_2(\cos\theta)$. When the correction for the finite extension of the detector is applied, the coefficient A_2 is changed from 0.86 to 0.87±0.08, the value listed in Table IV.

For a mixed $M1+E2$ transition, we have

$$A_2=[1/(1+\delta^2)]^2[F_2(LLj'j)+2\delta F_2(LL'j'j)+\delta^2F_2(L'L'j'j)]^2, \quad (3)$$

TABLE IV. Experimental values of the coefficient A_2 in the angular distribution $W(\theta)=1+A_2P_2(\cos\theta)$ of the resonance radiation from the 279-kev level.

Run No.	A_2
1	0.83±0.08
2	1.02±0.08
3	0.76±0.07
Average	0.87±0.08

where j' and j are the angular momenta of the ground state and excited state, respectively, and δ^2, the mixing ratio, denotes the intensity ratio of the radiation with angular momentum L' to the L radiation. The F_2 coefficients are tabulated by Ferentz and Rosenzweig.[23]

Using Eq. (3), one computes for the $\frac{1}{2}$-$\frac{3}{2}$-$\frac{1}{2}$ spin sequence a coefficient,

$$A_2=[1/(1+\delta^2)]^2[0.5000-1.732\delta-0.5000\delta^2]^2. \quad (4)$$

This coefficient A_2 is plotted versus the mixing amplitude δ in Fig. 5 for positive and negative values of δ. The only intersection of our lifetime and angular distribution data is on the curve of positive δ. This result is consistent with the polarization Coulomb excitation experiment[3] which also yielded a positive mixing amplitude. The range of values determined from the angular distribution is $\delta=+1.20_{-0.12}^{+0.20}$ which is in excellent agreement with $|\delta|=1.31_{-0.18}^{+0.24}$ obtained from the comparison of the Coulomb excitation and resonance fluorescence lifetimes.

Any attenuation of either the angular correlation of the resonance radiation or the polarization of the Coulomb excitation in the thallium metal would lower the value of δ derived from these measurements. The agreement with the measured δ from the distributions and lifetimes indicates that there are no appreciable extranuclear effects[24] which attenuate the distribution or polarization of the radiation from that level.

V. DISCUSSION

Table V lists the most recent values of the mean gamma lifetime of the 279-kev level in Tl^{203} obtained with four different techniques.

In 1958, Knapp[10] suggested that the lifetimes measured by Coulomb excitation are longer than those arrived at by resonance fluorescence studies. Recent more accurate evidence has demonstrated agreement between the Coulomb excitation and resonance fluorescence techniques, for example in Ni^{60}, Ge^{72}, and Ge^{74}.[25]

As one can see in Table V, there is also agreement for the mean gamma lifetime of the 279-kev level in Tl^{203} when one compares the present resonance fluorescence value with the Coulomb excitation result of McGowan and Stelson.[3] The resonance fluorescence results in Tl^{203} also agree with the average of the recent delayed-coincidence measurements, the values being $(5.00\pm0.24)\times10^{-10}$ sec and $(4.83\pm0.08)\times10^{-10}$ sec, respectively. There is greater disagreement among the values obtained by the delayed coincidence method[11,12,14,15] than between the average results obtained by the techniques of delayed coincidences, Coulomb excitation, and resonance fluorescence. The lifetime obtained with the new

[23] M. Ferentz and N. Rosenzweig, Atomic Energy Commission Report, Argonne National Laboratory, ANL-5324, 1955 (unpublished).
[24] R. M. Steffen, *Advances in Physics*, edited by N. F. Mott (Taylor and Francis, Ltd., London, 1955), Vol. 4, p. 293.
[25] P. H. Stelson and F. K. McGowan, Bull. Am. Phys. Soc. 4, 232 (1959).

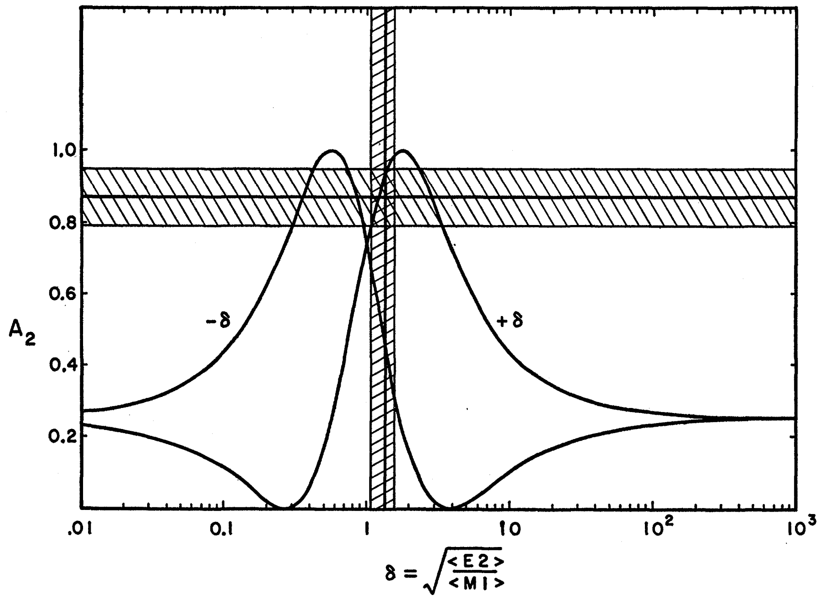

FIG. 5. The angular distribution coefficient A_2 as a function of the positive and negative values of δ, the mixing amplitude. The cross-hatched lines indicate the experimental A_2 and its error as well as $|\delta|$ and its error obtained from a comparison of the Coulomb excitation and resonance fluorescence lifetimes.

technique of high-frequency deflection[13] seems low; the value lies more than two standard deviations below the lifetimes obtained by the other methods of measurement.

For the 279-kev level in Tl^{203}, from our measured lifetime and δ, we find the experimental value for the reduced magnetic dipole matrix element $M_{\mathrm{exp}}^2=0.032\pm0.004$. Using the configuration mixing of Arima *et al.*[26] and Kisslinger,[27] $M_{\mathrm{theor}}^2=0.267$, a factor of 8 higher than the experimental result. It is disturbing that although Tl^{203} has one less than a closed proton shell, one of the poorest fits of magnetic dipole transition probabilities of Arima *et al.* is found in this nucleus.[27a] Kisslinger mentions a recent calculation that indicates that a 20% admixture of collective excitations to the wave functions could alter the gamma lifetime without changing the theoretical conversion coefficient or the agreement with the ground-state magnetic moment. It seems as though the measurement of another experimental parameter, for example, the magnetic moment of the 279-kev excited state, would be needed to check the admixture coefficients.

The angular distribution value of δ does confirm that the mixing amplitude in the 279-kev transition has a positive sign. The knowledge of the sign of δ is necessary for the analysis of the recent conversion electron-gamma angular correlations[8,9] since it provides another restriction on the possible parameters which can enter the correlations. These correlations examine finite-nuclear-size effects upon the conversion electron parameters which enter angular correlation theory. Gerholm *et al.*[9] concluded from their measurements that if the $E2$ conversion coefficients were increased by 10%, their results would be consistent with the nuclear structure theory of Church and Weneser.[7]

Since the well-measured K-conversion coefficient α_K may be written as $\alpha_K=(\beta_1+\alpha_2\delta^2)/(1+\delta^2)$, where β_1 is the $M1$ K-conversion coefficient and α_2 is the $E2$ K-conversion coefficient, one can arrive at possible values for α_2 from the measured values of δ and α_K and assuming plausible $M1$ conversion coefficients. Using the average $\delta=+1.43\pm0.07$ computed from the three independent determinations of the mixing amplitude (see Table V, footnote a), $\alpha_K=0.162\pm0.003$,[6] and the as-

TABLE V. Recent experimental values of the mean gamma-ray lifetime of the 279-kev transition in Tl^{203}.

τ_γ (10^{-10} sec)	Method	Author(s)
4.7 ±0.8	Resonance fluorescence	Metzger[c]
5.1 ±0.5	Delayed coincidences	Berlovich and Dubinkin[d]
5.2 ±0.6	Coulomb excitation[a]	McGowan and Stelson[e]
3.9 ±0.5	High-frequency deflection[b]	Johansson and Alvager[f]
5.1 ±0.4	Delayed coincidences[b]	Bashandy *et al.*[g]
5.10±0.30	Delayed coincidences[b]	Gorodetzsky *et al.*[h]
4.26±0.18	Delayed coincidences[b]	Pederson and Bell[i]
4.95±0.10	Delayed coincidences[b]	Schwarzschild and Kane[j]
4.83±0.08	Average delayed coincidences	
5.00±0.24	Resonance fluorescence	Present work (1960)

[a] Corrected for the average $\delta'=+1.43\pm0.07$ computed from the three independent determinations of the mixing amplitude: the polarization of the Coulomb excitation (1.50 ± 0.08), Coulomb excitation and resonance fluorescence lifetimes ($1.31\pm_{0.18}^{0.24}$), and the angular distribution of the resonance fluorescence radiation ($1.20\pm_{0.12}^{0.20}$).
[b] For the cases in which $T_{\frac{1}{2}}$, the half-life of the 279-kev level, was listed, the value was corrected by a factor $(1+\alpha_T)/0.693$, where $\alpha_T=0.225$ is the total conversion coefficient.
[c] See reference 17.
[d] E. E. Berlovich and G. V. Dubinkin, J. Exptl. Theoret. Phys. (U.S.S.R.) 32, 223 (1957) [translation: Soviet. Phys. JETP 5, 164 (1957)].
[e] See reference 3.
[f] See reference 13.
[g] See reference 11.
[h] See reference 12.
[i] See reference 15.
[j] See reference 14.

[26] A. Arima, H. Horie, and M. Sano, Progr. Theoret. Phys. (Kyoto) **17**, 567 (1957).
[27] L. S. Kisslinger, Phys. Rev. **114**, 292 (1959).
[27a] *Note added in proof.* Recently, A. deShalit [Phys. Rev. (to be published)] has suggested that the first two excited states of Tl^{203} might be described in terms of excitations of the even-even core (Hg^{202}) coupled to the odd proton in its lowest state. This description appears to account adequately for the main properties of the electromagnetic transitions between the three lowest states of Tl^{203}.

sumption that β_1 is the theoretical value of Sliv[28] or Rose,[29] one finds that for all possible values of δ within the experimental error, $\alpha_{2\ \mathrm{exp}}$ is slightly smaller than the theoretical $E2$ conversion coefficient. With the same values of α_K and δ, but $\beta_{1\ \mathrm{theor}}$ lowered by 10% from the Sliv or Rose values, as indicated by the Kisslinger calculation, $\alpha_{2\ \mathrm{exp}}$ is equal to the theoretical $E2$ conversion coefficient within experimental error. Thus, our experimental results for the mixing amplitude δ do not suggest that experimental $E2$ K-conversion coefficients are larger than the theoretical predictions. Recent measurements[30] of $E2$ transitions in Pt^{194}, Pt^{196}, and Hg^{198} actually indicate that experimental $E2$ conversion coefficients in these nuclei are 10% lower than the theoretical values.

[28] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Reports, 1956 [translation: Reports 57ICC K1 and 58ICC L1, issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].

[29] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).

[30] C. DeVries, E. J. Bleeker, and N. Salomons-Grobben, Nuclear Phys. 18, 454 (1960).

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Lifetime of the 279-kev State of Tl^{203}†

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The lifetime of the first excited state of Tl^{203} at 279 kev has been measured using the delayed coincidence technique. From analysis of the exponential decay observed with an electronic time-to-pulse-height converter, the mean life was determined to be $(4.05\pm0.08)\times10^{-10}$ sec. The decay of this state was observed using sources of Hg^{203} and Pb^{203}, both sources yielding the same mean life within statistical errors. This value of the lifetime agrees very well with the recent determination by Deutsch and Metzger utilizing the resonance fluorescence method.

INTRODUCTION

THE lifetime of the first excited state of Tl^{203} has been measured many times both directly by delayed coincidence methods and indirectly by resonance fluorescence and Coulomb excitation.[1,2] Since the various coincidence measurements showed very poor consistency it was never possible to either compare the methods or to be sure of the lifetime of this state. Further, the transition from the first excited state is known to display anomalous internal conversion coefficients. Although consideration of nuclear systematics as well as the internal conversion data would not admit the existence of two states near 279 kev, such a situation might have explained both the anomalous conversion coefficients as well as the dispersion in lifetime measurements.

Although there is no reason to suspect that nuclear lifetimes and the state widths as determined from nuclear resonance fluorescence would not conform to the usual uncertainty relation such a discrepancy has been suggested.[3] The transition in Tl^{203} is particularly suited to checking this point, especially in view of the recent improvements in the delayed coincidence method which allows the direct observation of the exponential decay without recourse to centroid measurements. Both the fluorescence and the electronic measurements can now be performed with errors of less than 5%. The resonance measurement is reported by Deutsch and Metzger in the preceding paper.

In an attempt to clarify the situation we have remeasured this lifetime using the improved fast coincidence technique.[4,5] In order to obviate any experimental difficulties as well as to prove the singularity of the 279-kev state, we have observed the exponential decay of this state when it is populated by the β^- decay of Hg^{203} and, in a second measurement, when populated by the γ decay of the 680-kev level of Tl^{203} which is fed in the K capture of Pb^{203}.

$Hg^{203} \rightarrow Tl^{203}$ MEASUREMENT

Hg^{203} (47-day) was obtained from Oak Ridge National Laboratory. β^--γ delay measurements were obtained using the fast-coincidence system described previously[4,5] in connection with measurements of the first excited states of O^{17} and F^{17}. A diphenyl acetylene scintillator $\frac{3}{8}$ in diam$\times\frac{1}{8}$ in. thick was mounted on a 56AVP phototube for the detection of β^- particles. The γ detector was a $1\frac{1}{2}$ in.$\times1\frac{1}{8}$ in. plastic scintillator (Pilot B) mounted on an RCA 7264 phototube.

The time spectrum obtained as well as a comparison with the spectrum obtained with identical energy channels using a Au^{198} source is shown in Fig. 1. The data analysis was performed by analysis of the exponen-

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[1] For a review of earlier work see E. Bashandy, T. R. Gerholm, and J. Lidskog, Arkiv Fysik 17, 421 (1960).

[2] A summary of the more recent measurements is given by B. Deutsch and F. Metzger, preceding paper [Phys. Rev. 122, 848 (1961)].

[3] V. Knapp, Proc. Phys. Soc. (London) A71, 194 (1958).

[4] R. E. Bell and M. H. Jorgensen, Nuclear Phys. 12, 413 (1959).

[5] J. V. Kane, R. Pixley, R. Schwartz, and A. Schwarzschild, Phys. Rev. 120, 162 (1960).