Perturbation of the 360.3-57.6 keV gamma-gamma directional correlation in ^{127}I

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(Received 23 December 1976)

The γ-$\gamma(\theta)$ measurements of the $5/2^+$ (360.3 keV) $7/2^+$ (57.6 keV) $5/2^+$ cascade in ^{127}I have been performed with a NaI-Ge(Li) detector system using a ^{127}Te^{m+g} source in a highly diluted HCl solution. The expansion coefficients obtained are $A_2 = 0.38 \pm 0.02$ and $A_4 = 0.03 \pm 0.04$. Using another ^{127}Te^{m+g} source in a concentrated HCl solution, a time differential correlation measurement on the same cascade revealed the presence of a time dependent electric quadrupole perturbation. From the plot of $A_2(\bar{t})$ vs $\bar{t}$, the relaxation parameter $\lambda_2^{el} = (0.22 \pm 0.06) \times 10^9$ sec^{-1} and the unperturbed $A_2(0) = 0.41 \pm 0.05$ is obtained. The observed λ_2^{el} is consistent with that deduced from the theory of Abragam and Pound. Also using our $A_2(0)$, a $\delta(E2/M1)$ of 0.33 ± 0.09 is obtained for the 360.3 keV transition.

$$\left[\text{RADIOACTIVITY } {}^{127}\text{Te}^{m+g} \text{ [from } {}^{126}\text{Te}(n,\gamma)] : \text{ measured } \gamma\text{-}\gamma(\theta), \ \gamma\text{-}\gamma(\theta,t); \text{ deduced } \lambda_2^{el}, \ A_2(0), \ \bar{G}_2(\infty), \ \delta(360.3\gamma). \right]$$

I. INTRODUCTION

Earlier integral correlation measurements[1-6] on the 360.3-57.6 keV γ-γ cascade in ^{127}I, following the β^- decay of ^{127}Te^{m+g}, have been carried out using NaI-NaI detector systems. Auble and Kelly[3] have studied the variation of the cascade anisotropy by changing the density of the chloride source. The anisotropy was found to increase with decreasing density and showed a variation from 0.33 to 0.58. The maximum value was presumed to be the unperturbed value. Svensson et al.[5] have also studied the anisotropy of the above cascade using dilute nitric and hydrochloric acid sources in identical geometries. The two sources gave nearly the same result. Since the chemical surroundings of the Te^{4+} ions in the two sources are quite different, they tentatively assumed that the extranuclear perturbations are absent. Their anisotropy value ($A \approx 0.56$) was also in agreement with $A = 0.58$ of Auble and Kelly.[3] However, the anisotropy value obtained by Neeson, Roalsvig, and Arns[4] is ~ 0.64 using a dilute nitric acid source.

In measurements with NaI detectors, it is usually difficult to precisely estimate the contributions arising due to the interfering cascades and the Compton scattering of the high energy γ rays. We have, therefore, employed a NaI-Ge(Li) coincidence spectrometer to perform the integral correlation measurements. Using a highly diluted HCl source, we obtained a still higher value ($A \sim 0.70$) of the anisotropy. The question now arises as to which of the values is unperturbed. We, therefore, considered it worthwhile to look for the presence of any possible perturbation of the correlation by the time-differential perturbed angular correlation (PAC) method. No such measure-

ment exists in the literature. Our results clearly indicate a time dependent electric quadrupole perturbation and are found to be consistent with the theory of Abragam and Pound.[7]

II. MEASUREMENTS AND ANALYSIS

A. Source preparation

The ^{127}Te^{m+g} source for the integral correlation measurement was obtained from Oak Ridge National Laboratory. It was in the form of a highly diluted HCl solution. The counting source was prepared by taking a few drops of this chloride solution in a perspex vial of dimensions 3 mm diam $\times$ 4 mm.

For the time-differential experiment, a concentrated HCl source of high specific activity was obtained from New England Nuclear. The radiometric purity of the source was $> 99\%$. The counting source was prepared in the same manner as for the integral correlation measurements.

B. Integral correlation

The coincidence spectrometer employed a movable 2.54 cm diam $\times$ 3.81 cm NaI(Tl) detector and a fixed 21 cm^3 Ge(Li) detector. The NaI detector was set to accept the 57.6 keV photopeak. A copper absorber of appropriate thickness was used in front of this detector to cut off the 28.6 keV iodine K x rays. The detectors were shielded with graded lead cones to guard against Compton scattering of the 417.9 keV and the higher energy γ rays. The coincident Ge(Li) spectra were recorded at angles 90°, 120°, 150°, 180°, 180°, 210°, 240°, and 270°. The data from the corresponding angles in the two quadrants were stored in a

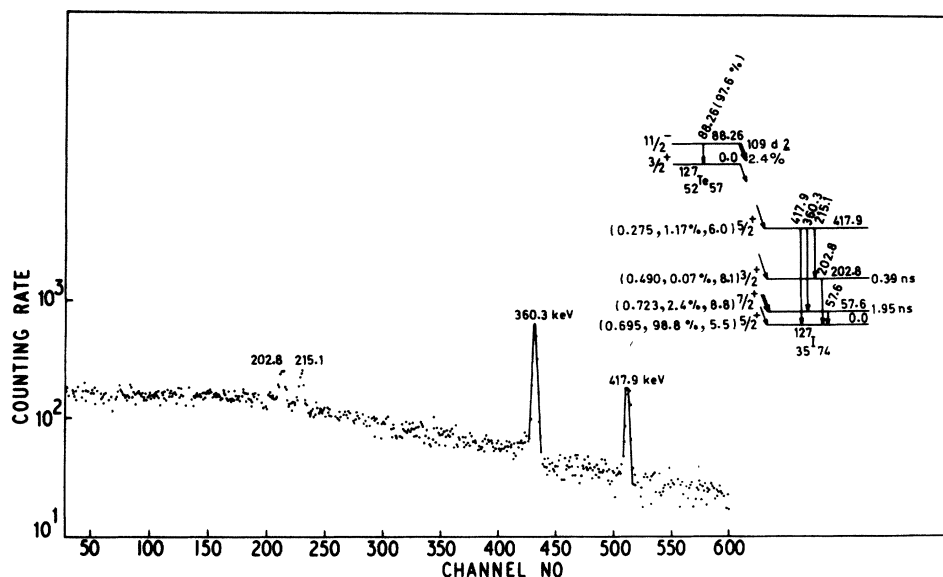FIG. 1. A part of the Ge(Li) γ-ray spectrum in coincidence with the 57.6 keV photopeak.

4×1024 mode of a 4096-channel analyzer. Simultaneously, the singles counts from both detectors were also recorded for normalization purposes. A typical coincidence spectrum recorded at $\theta = 90°$ in a short run is shown in Fig. 1. The relevant part of the decay scheme of $^{127}\text{Te}^{m+g}$ is shown as an insert in this figure. Chance coincidences under the 360.3 keV peak were estimated by normalizing the 417.9 keV peak in the singles to the 417.9 keV chance peak seen in the coincidence spectrum. The solid angle correction factor for the Ge(Li) detector was taken from Camp and Van Lehn.[8] The data were analyzed by the method of weighted least squares fit to obtain the expansion coefficients.

C. Time-differential correlation

The timing coincidence spectrometer consisted of 2.54 cm diam $\times$ 1.27 cm and 2.54 cm diam $\times$ 2.54 cm NE 111 plastic scintillators coupled to XP-1021 photomultipliers and constant fraction pulse height triggers. The scintillator of 1.27 cm height was used on the 57.6 keV side and a copper absorber of 0.63 mm thickness was used in front of it to cut out the intensity of the iodine K x rays to ~0.1%. Aluminum absorber of ~2 mm thickness was used in front of the other scintillator to cut off the 723 keV β particles feeding the 57.6 keV level in ^{127}I. The energy gates for the 57.6 and 360.3 keV transitions were 70% and 77% of their respective Compton distributions. The time calibration of the time-to-amplitude–analog-to-digital system was carried out by observing the shift of the prompt resolution curve using a ^{60}Co source with the introduction of

accurately calibrated delays and was found to be (270 ± 3) ps per channel.

The full width at half maximum of the prompt curve at the above energy settings using a ^{60}Co source was 1.0 ns with a slope $(\frac{1}{2})$ of 250 ps.

The delayed time coincidence spectra were recorded at 90°, 135°, 180°, 180°, 225°, and 270°, and the data from the corresponding angles in the two quadrants were stored in 128 channel subgroups of the 4096-channel analyzer. Simultaneously, the singles counts from both detectors were also recorded for normalization purposes.

Figure 2 shows the delayed time coincidence spectra recorded at 90°(I), 135°(II), and 180°(III). After subtracting chance coincidences and normalizing with the gate counts, the data at each corresponding channel in the delayed region were analyzed by the weighted least squares method for obtaining $A_2(t)$ coefficients. The delayed region so chosen was well outside the prompt part and the short-lived $(T_{1/2} \approx 0.4$ ns) delayed component due to the 215.1-202.8 keV γ-γ cascade. The 0.4 ns component appears on both sides of the centroid due to wide energy gates.

The differential nonlinearity curve for the system was also recorded. The nonlinearity was estimated to be <1% and hence no correction was applied.

The solid angle correction factors for the correlation geometry (source-to-detector distance = 3 cm) and at the energy settings mentioned above were determined experimentally by the method given in Ref. 9. The instrumental angular resolution curve was obtained by recording 511-511 keV coincidences using a ^{22}Na source. The correction factors were obtained by direct numerical integra-
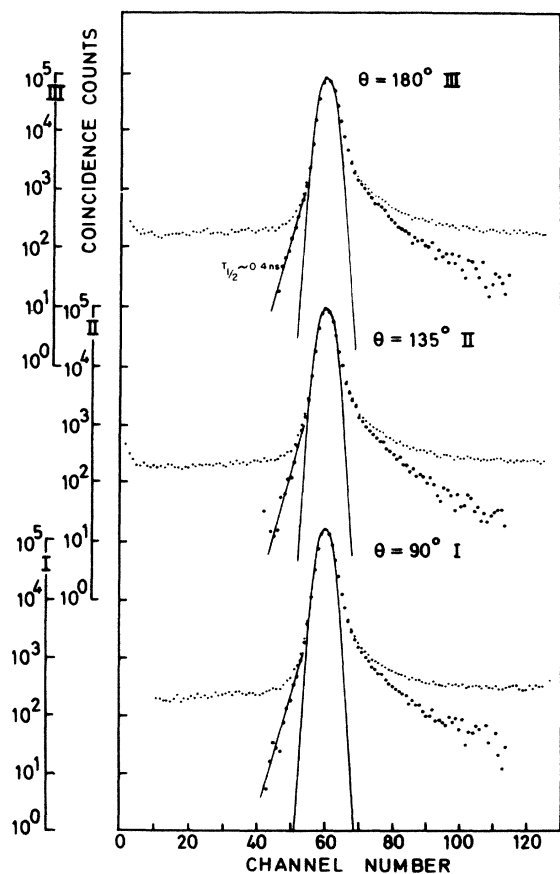
FIG. 2. The delayed time coincidence spectra record-
ed at $\theta = 90°$(I), 135°(II), and 180°(III) for the 360.3-57.6
keV γ-γ cascade in ^{127}I. $T_{1/2} \sim 0.4$ ns seen on the left side
corresponds to the 202.8 keV level.

tion over the experimental resolution curve. These
are: $Q_2 = 0.798 \pm 0.005$; $Q_4 = 0.468 \pm 0.006$.

III. RESULTS AND DISCUSSION

The solid angle corrected expansion coefficients
as obtained from our integral measurements are
$A_2 = +0.38 \pm 0.02$ and $A_4 = +0.03 \pm 0.04$. Since our
A_2 value was higher than all the previously report-
ed values,[1-6] one option was to accept it as the un-
perturbed value. Alternatively, it was still open
to confirm or deny the presence of extranuclear
perturbation directly by the time-differential PAC
method.

The results of our differential correlation mea-
surements are as follows: After applying finite
time resolution correction[10] to the $A_2(t)$ coeffi-
cients, a plot of $A_2(\bar{t})$ vs $\bar{t}$ is shown in Fig. 3,
which exhibits the exponential behavior of the per-
turbation. The $A_2(\bar{t})$ values were weighted least
squares fitted to the equation

$$A_2(\bar{t}) = A_2(0)e^{-\lambda_2^{el}\bar{t}}, \qquad (1)$$

yielding a λ_2^{el} (the relaxation parameter) value of
$(0.22 \pm 0.06) \times 10^9$ sec^{-1}, and the solid angle cor-
rected unperturbed expansion coefficient $A_2(0)$
$= 0.41 \pm 0.05$. From our recent measurement,[11]
$T_{1/2}$(57.6 keV level) $= 1.95 \pm 0.01$ ns. This gives
$\lambda_0 = (0.355 \pm 0.002) \times 10^9$ sec^{-1}. Knowing λ_2^{el} and
λ_0 and using the relation

$$\bar{G}_2(\infty) = \frac{\lambda_0}{\lambda_0 + \lambda_2^{el}} \qquad (2)$$

for a time dependent perturbation, the integral
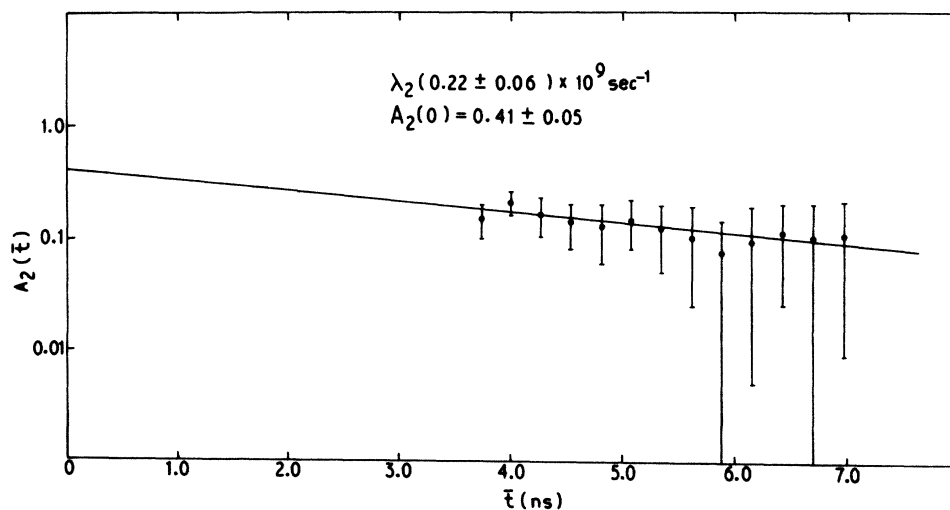attenuation coefficient $\bar{G}_2(\infty) = 0.62 \pm 0.06$.

FIG. 3. Plot of $A_2(\bar{t})$ (solid angle corrected) vs $\bar{t}$ from the time-differential measurement in ^{127}I for a concentrated
HCl source.

TABLE I. A_2 coefficients ($A_4 \approx 0$ within experimental error) for the 360.3–57.6 keV γ-γ cascade in ^{127}I.

Reference	Source form	Integral Detectors used	A_2
Jha and Leonard (Ref. 1)	Liquid nitrate	NaI-NaI	0.29 ± 0.04
Tandon et al. (Ref. 2)	Conc. liquid chloride	NaI-NaI	0.29 ± 0.01
Auble and Kelly (Ref. 3)	Liquid chloride	NaI-NaI	0.32 ± 0.02
Neeson et al. (Ref. 4)	Liquid nitrate	NaI-NaI	0.35 ± 0.02
Svensson et al. (Ref. 5)	Conc. liquid chloride	NaI-NaI	0.313 ± 0.008
Begzhanov et al. (Ref. 6)	Liquid chloride	NaI-NaI	0.325 ± 0.021
Present work	Dilute liquid chloride	NaI-Ge(Li)	0.38 ± 0.02
		Differential Detectors used	$A_2(0)$
Present work	Conc. liquid chloride	Plastic (NE111)- plastic (NE111)	0.41 ± 0.05

The A_2 values obtained from our integral and differential measurements are compared with those of earlier investigations in Table I.

In the HCl solution Te exists as $\mathrm{TeCl_3^+}$, $\mathrm{TeCl_4}$, and $\mathrm{TeCl_6^{--}}$.[12] Raman data[12] on both the solid and the liquid $\mathrm{TeCl_4}$ show that it also exists in the ionic state $\mathrm{TeCl_3^+Cl^-}$. Since all the radicals have ionic structure, they will produce rapidly fluctuating electric field gradients due to Brownian motion. Interactions of the inhomogeneous electric fields with the nuclear electric quadrupole moment of the 57.6 keV state ($Q = -0.71$ b)[13] will produce time dependent perturbation of the correlation.

For time dependent electric quadrupole interactions in liquid sources, the theory of Abragam and Pound[7] gives for the relaxation parameter

$$\lambda_2^{el} = \frac{3}{80} \left(\frac{eQ}{\hbar} \right)^2 \left\langle \left(\frac{\partial^2 v}{\partial z^2} \right)^2 \right\rangle \times \tau_c$$

$$\times \frac{k(k+1)[4I(I+1) - k(k+1) - 1]}{I^2(2I-1)^2}, \quad (3)$$

where the coupling factor $eQ\langle \partial^2 v / \partial z^2 \rangle / \hbar$ is 2π times the frequency $\Delta\nu_Q$ frequently used to describe the electric quadrupole interactions. τ_c represents the correlation time for the ions in the liquid. From nuclear paramagnetism and Debye's studies of polar liquids, it is well known that the correlation time τ_c in a liquid is roughly proportional to its viscosity[14] and is $\sim 10^{-11}$ sec for dilute aqueous solutions at room temperature. For a concentrated HCl source used by us, we have estimated $\tau_c \approx 2$

$\times 10^{-11}$ sec.

From microwave spectroscopic data, it is well known that large quadrupole couplings occur in covalently-bonded I atoms. The interaction frequency $\Delta\nu_Q$ for ^{127}I in ICl is ~ 3000 Mc.[15] Substituting the value of τ_c, $\Delta\nu_Q$, and $I = \frac{7}{2}$ in Eq. (3), λ_2^{el}(theory) $= 0.20 \times 10^9$ sec^{-1}. This compares well with our λ_2^{el}(expt.) $= (0.22 \pm 0.06) \times 10^9$ sec^{-1}.

Hence our differential correlation measurements clearly indicate the presence of time dependent electric quadrupole interactions in the HCl source.

Using our $A_2(0) = 0.41 \pm 0.05$ and $\delta(57.6\gamma) = -0.086 \pm 0.005$,[13] a $\delta(E2/M1)$ of $+0.33 \pm 0.09$ is obtained (following the sign convention of Krane and Steffen) for the 360.3 keV transition, which corresponds to $\sim 10\%$ $E2$ admixture. This is about twice the δ value quoted earlier.[13] Using our value of $\delta(360.3\gamma)$, known half-life[16] of the 417.9 keV level, the branching ratio[13] and the theoretical[17] $\alpha(M1)$ $= 0.025$ and $\alpha(E2) = 0.0247$, the $E2$ transition rate for the 360.3 keV $\frac{5}{2}^+ \rightarrow \frac{7}{2}^+$ transition in ^{127}I has been calculated and compared with the corresponding single particle estimate.[18] This gives an enhancement factor of ~ 44 which indicates that the 417.9 keV level is not purely a single particle level but has some collective features. This view has been supported by Goldstein and De Pinho.[19] Using the intermediate coupling approach of the unified model, they have suggested that the 417.9 keV level in ^{127}I may be supposed to correspond to a partial excitation of the core due to the recoupling of the odd particle with a pair of protons moving in the same orbital as the unpaired proton.

[1]S. Jha and R. Leonard, Phys. Rev. 136, B1585 (1964).

[2]P. N. Tandon, S. H. Devare, and H. G. Devare, in *Proceedings of the International Congress on Nuclear Physics, Paris, 1964,* edited by P. Gugenberger (Centre National de la Recherche Scientifique, Paris, 1964), Vol. II, p. 56.

[3]R. L. Auble and W. H. Kelly, Nucl. Phys. 73, 15 (1965).

[4]J. F. Neeson, J. P. Roalsvig, and R. G. Arns, Can. J. Phys. 44, 1313 (1966).

[5]A. G. Svensson, R. W. Sommerfeldt, L. O. Norlin, and P. N. Tandon, Nucl. Phys. A95, 653 (1967).

[6]R. B. Begzhanov, K. T. Salikhbaev, and D. Gaffarov, in Proceedings of the 19th Annual Conference on Nuclear Spectroscopy and Structure of Atomic Nuclei, Erevan, 1969 (unpublished), p. 77.

[7]A. Abragam and R. V. Pound, Phys. Rev. 92, 943 (1953).

[8]D. C. Camp and A. L. Van Lehn, Nucl. Instrum. Methods 95, 611 (1971).

[9]E. L. Church and J. J. Kraushaar, Phys. Rev. 88, 419 (1952).

[10]E. Bodenstedt, H. J. Körner, C. Günther, and J. Rade-

loff, Nucl. Phys. 22, 145 (1961).

[11]S. Sanyal, A. Kumar, S. K. Soni, S. L. Gupta, and S. C. Pancholi, Phys. Rev. C 14, 1285 (1976).

[12]W. A. Dutton, in *Tellurium,* edited by W. C. Cooper (Van Nostrand Reinhold, Toronto, 1971), p. 139.

[13]R. L. Auble, Nucl. Data B8, 77 (1972), $A = 127$.

[14]G. E. Pake, *Solid State Physics* (Academic, New York, 1956), Suppl. 2, p. 68; P. Debye, *Polar Molecules* (Dover, New York, 1945); N. Bloembergen, E. M. Purcell, and R. V. Pound, Phys. Rev. 73, 679 (1948).

[15]W. Gordy, W. V. Smith, and R. F. Trambarulo, *Microwave Spectroscopy* (John Wiley, New York, 1953), p. 258.

[16]H. Langhoff, Nucl. Phys. 63, 425 (1965).

[17]R. S. Hager and E. C. Seltzer, Nucl. Data A4, Nos. 1, 2 (1968).

[18]S. A. Moszkowski, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy,* edited by K. Siegbahn (North-Holland, Amsterdam, 1965), Vol. 2, p. 863.

[19]I. V. Goldstein and A. G. dePinho, Z. Naturforsch. 26A, 1987 (1971).