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PHYSICAL REVIEW C VOLUME 3, NUMBER 4 APRIL 1971

$E2/M1$ Multipole Mixing Ratios in the "Spherical" Nuclei Te^{124}, Te^{126}, and Xe^{126}†*

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(Received 23 November 1970)

$E2/M1$ mixing ratios of the 709-, 714-, and 723-keV transitions in Te^{124}, the 754-keV transition in Te^{126}, and the 491-keV transition in Xe^{126} were measured using the γ-γ directional-correlation technique. In addition, the measurements on the 646-603-keV, 1691-603-keV, and 2091-603-keV γ-γ cascades in Te^{124} are in agreement with pure $E2$ character of the 1691- and 2091-keV transitions in Te^{124}. Coaxial Ge(Li) and Na(Tl) scintillation detectors were used in different combinations depending on the energy resolution required for a particular measurement. The results for the mixing ratios are $\delta(709)=+0.04^{+0.03}_{-0.05}$, $\delta(714)=+0.98\pm0.19$, and $\delta(723)=-3.4\pm0.1$ for the transitions in Te^{124}; $\delta(754)=-5.5^{+0.4}_{-0.3}$ for the $2^{+\prime}\to2^+$ transition in Te^{126}; and $\delta(491)=+27^{+30}_{-9}$ for the $2^{+\prime}\to2^+$ transition in Xe^{126}. There is an indication that the mixing ratios for the $2^{+\prime}\to2^+$ transitions in even-even tellerium isotopes are negative and the mixing ratios of similar transitions in even-even Xe isotopes have positive values.

I. INTRODUCTION

The structure and the nature of the higher excited states of the even-even "spherical" nuclei in the mass region $100 \leq A \leq 150$ are not well understood. The first few excited states of these nuclei are interpreted as vibrational levels. However, the existence of crossover transitions from the two-phonon $2^{+\prime}$ state to the ground state and the observation of finite quadrupole moments of the 2^+ one-phonon states in many of these nuclei indicate that a description of these states in terms of harmonic oscillations of a spherical nuclear surface is not adequate. Furthermore, the existence of appreciable $M1$ components in the $2^{+\prime}\to2^+$ transitions cannot be understood on the basis of a purely vibrational model. Clearly, a more detailed microscopic description of the excited states of spherical nuclei is required before the relative strength of the $M1$ radiation components in γ transitions of spherical nuclei can be understood. The interplay between the vibrational modes and the two-quasiparticle states is probably of major importance and should be considered in detail. Theoretical work in the region of intermediate nuclei is in progress.[1] In the meantime, the present experimental work was undertaken in order to provide accurate experimental data on $E2/M1$ mixing ratios to test such calculations if and when they become available. In an earlier paper the $E2/M1$ multipole mixing ratios of the γ transitions in the "spherical" Cd^{110} nucleus have been discussed.[2] The present work describes an investigation of the $E2/M1$ multipole mixing ratios in the "spherical" nuclei Te^{124}, Te^{126}, and Xe^{126}.

II. LEVEL STRUCTURE OF THE Te^{124}, Te^{126}, AND Xe^{126} NUCLEI

The levels of Te^{124} have recently been reinvestigated by Auer, Reidy, and Wiedenbeck[3] and Meyer, Walters, and Ragaini[4] from the decay of Sb^{124} and by Ragaini *et al.*[5] from the decay of I^{124}. The lower excited states of Te^{124} (Fig. 1) exhibit a "vibrational" pattern which is expected for this "spherical" nucleus (proton number 52 and neutron number differing by only 10 from a closed neutron shell). The measurements of Warner and Draper[6] show, however, that the 4^+ level at 1249 keV could also be considered as a member of the ground-state quasirotational band. The $E2/M1$ mixing ratio of the 723-keV transition which proceeds between the two-phonon $2^{+\prime}$ and the one-phonon 2^+ level (in the vibrational picture), has been measured with conflicting results.[7-12] The three lowest excited states of Te^{126} show clearly a vibrational character. Little is known about the higher excited states which have been investigated through nuclear reactions.

The level structure of Te^{126} shows similar interesting features. Whereas the lowest three excited states seem to conform to the vibrational picture, the higher excited states seem to be members of a rotational band up to 8^+ as found in $(\alpha, 2n)$ reactions.[13]

In the β decay of I^{126} only the "vibrational"-type levels of Te^{126} and Xe^{126} are populated. The decay scheme of I^{126} is shown in Fig. 2. The energy and intensity values are given as determined in the present investigation. They are in excellent agreement with the values of Singh and Taylor.[14] A weak γ transition of (2046 ± 2) keV was observed in this laboratory which seems to correspond to the 2044.4-keV transition as reported in Ref. 14. The existence of a 1377.7-keV transition[14] could not be confirmed because of the interfering 1376-keV transition due to the I^{124} impurity.

III. EXPERIMENTAL PROCEDURE

The directional-correlation measurements were performed using both NaI(Tl)-Ge(Li) and Ge(Li)-Ge(Li) detector combinations. The former employed a 3×3 in. NaI(Tl) scintillator in conjunction with a coaxial Ge(Li) detector (ORTEC, 25 cc). A conventional (fast-slow) coincidence apparatus was employed having a resolving time of approximately 35 nsec. The Ge(Li)-Ge(Li) apparatus consisted of two coaxial detectors (ORTEC, 30 cc); the coincidence analysis was performed using a time-to-amplitude-converter system having an effective resolving time of approximately 50 nsec.

Radioactive Sb^{124} was obtained from the New England Nuclear Corporation in HCl solution. The solution was concentrated as needed and the liquid was placed inside a cylindrical glass ampoule 1.5 mm in diameter. The length of the liquid column varied from 5–8 mm.

The I^{126} activity was produced as a result of (α, n) reactions on naturally occurring antimony (57% Sb^{121}, 43% Sb^{123}). Spectroscopically pure Sb metal powder was bombarded with 25-MeV α particles at the Argonne National Laboratory 60-in. cyclotron. The irradiated powder was packed into an ampoule 3 mm in diameter and 10 mm in length. A considerable amount of I^{124} activity resulted from this method of preparation, but the high resolution of the Ge(Li) detectors made it possible to correct easily for any effects on the measurement of the γ rays from I^{124}.

γ-ray spectra observed with Ge(Li) detectors from the Sb^{124} and I^{126} sources are shown in Figs. 3 and 4, respectively. The use of the solid-state detectors made possible a separation of the 723-keV transition from the 709- and 714-keV transitions in the Sb^{124}. A detail of this portion of the γ spectrum is shown in Fig. 5. The separation of these lines is significant in attempts to measure the 723–603-keV directional correlation, since both the 709- and 714-keV transitions are in coincidence with the 603-keV transition. In addition, as shown in Fig. 4 the 491-keV transition in I^{126} was resolved from the 511-keV positron-annihilation peak.

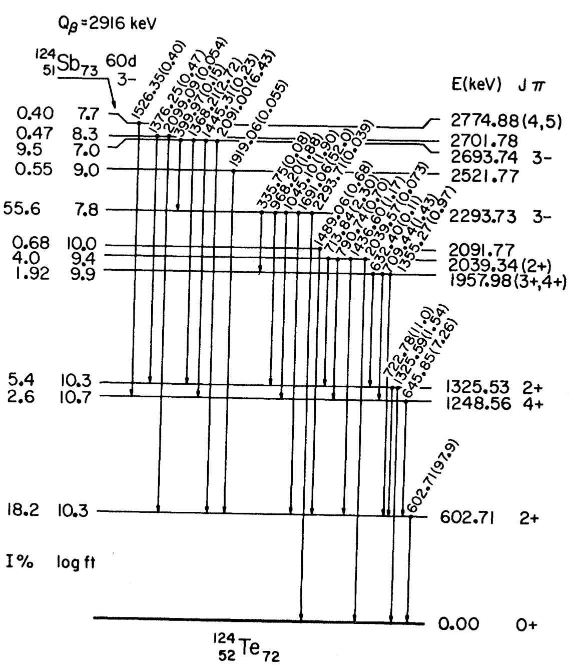

FIG. 1. The decay of Sb^{124}(60 day) to levels of Te^{124} (Ref. 3).

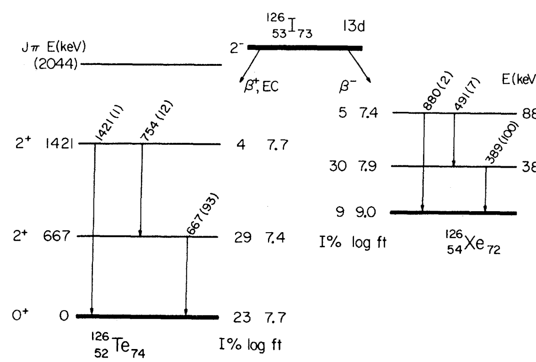

FIG. 2. The decay of I^{126}(13 day) to levels of Te^{126} and Xe^{126}.

The various directional correlations were measured by determining the coincidence counting rates at seven different angles between 90 and 270° in the case of the NaI(Tl)-Ge(Li) measurements, and at nine different angles in the case of the Ge(Li)-Ge(Li) measurements. The counting rates were corrected for chance coincidences and for effects of competing cascades, and the directional-correlation coefficients were extracted by fitting the measured counting rates to a function of the form

$$W(\theta)=A_0'+A_{22}'P_2(\cos\theta)+A_{44}'P_4(\cos\theta)\,,$$

where

$$A_{kk}'=A_{kk}Q_{kk}G_{kk}\,.$$

The correlation coefficients A_{kk} are defined in terms of the mixing ratios δ of Krane and Steffen.[2] The geometrical correction factors Q_{kk} were applied to correct for the finite solid angles of the detectors.[15] The perturbation factors G_{kk} were assumed to be equal to unity, the short lifetimes of

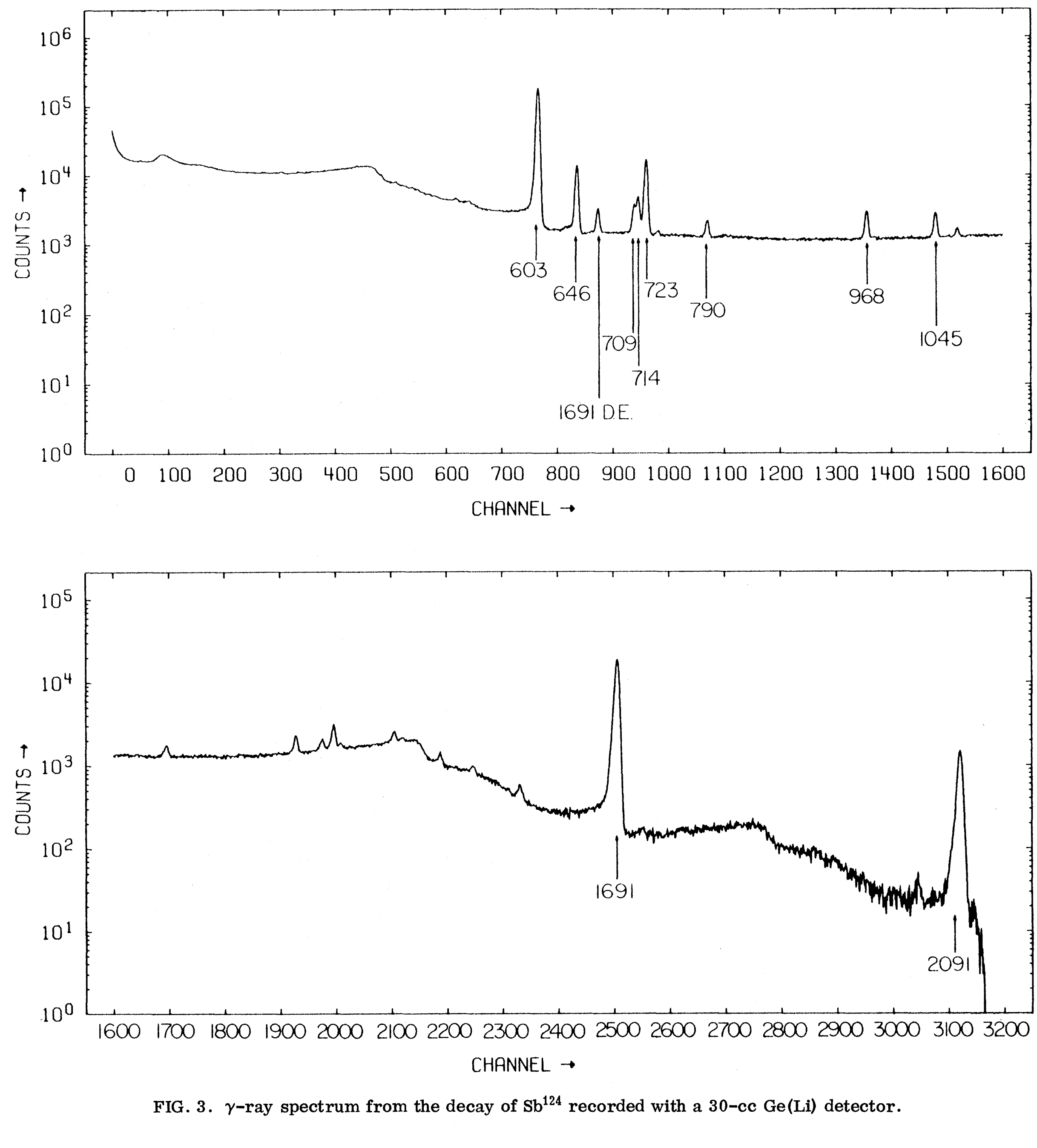

FIG. 3. γ-ray spectrum from the decay of Sb^{124} recorded with a 30-cc Ge(Li) detector.

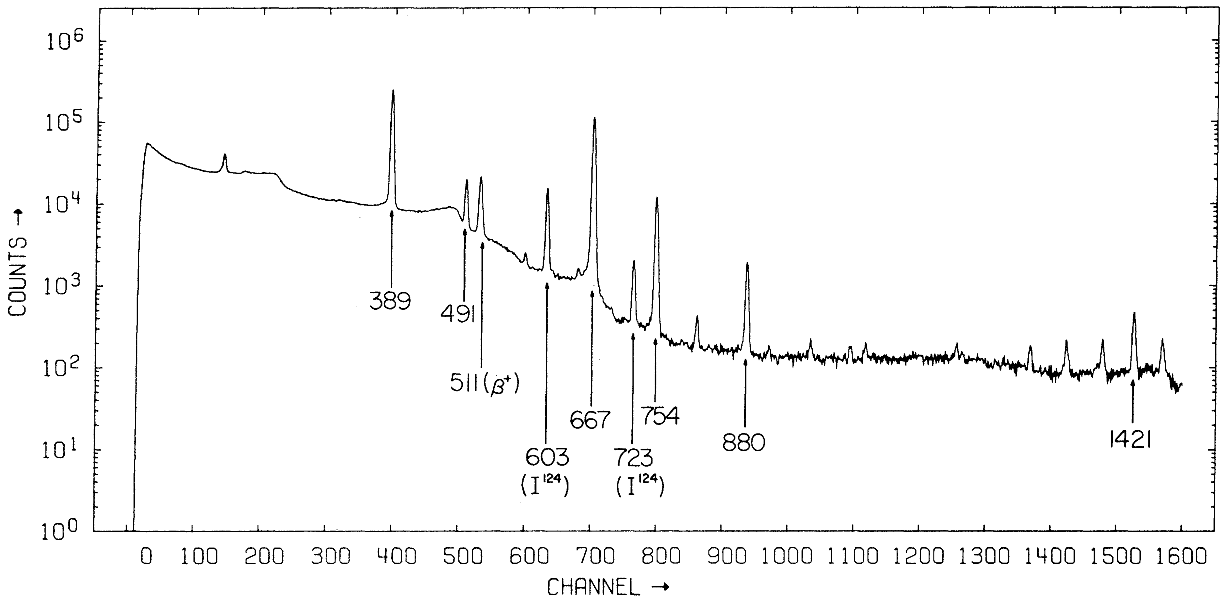

FIG. 4. γ-ray spectrum from the decay of I^{126} recorded with a 30-cc Ge(Li) detector.

the states involved in this measurement making external perturbations negligible.

IV. RESULTS

In cases where it was feasible, directional correlations were measured for a given cascade using both NaI(Tl)-Ge(Li) and Ge(Li)-Ge(Li) configurations, in order to obtain a consistent set of results.

A summary of the present investigation of the Te^{124} γ rays is given in Table I. Results of some of the more recent measurements by other authors are presented for comparison. Good agreement was obtained between the NaI(Tl)-Ge(Li) and Ge(Li)-Ge(Li) results of the present work in all cases. The low efficiency of the Ge(Li) detector

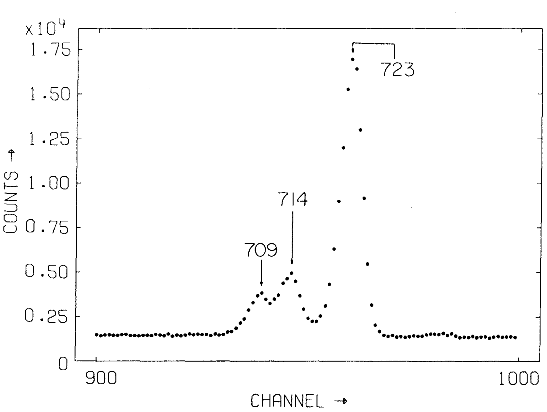

FIG. 5. Ge(Li) γ-ray spectrum of Sb^{124} in the 700-keV energy region.

for high-energy γ rays made measurement of the 2091–603-keV directional correlation impossible for the Ge(Li)-Ge(Li) configuration. The resolution necessary for cascades involving the 709- and 714-keV transitions necessitated the use of the Ge(Li)-Ge(Li) system only.

As a check on the results involving the 709- and 714-keV transitions, the 1-3 directional correlation was measured between the 603-keV transition and the 709–714-keV doublet. The results of this measurement were (with A_{00} normalized to unity)

$$A_{22} = 0.070 \pm 0.009 ,$$

$$A_{44} = 0.052 \pm 0.015 .$$

Assuming the composition of the doublet to be 38% of the 709-keV and 62% of the 714-keV transitions, the directional-correlation coefficients calculated on the basis of the results presented in Table I would be $A_{22} = 0.102$ and $A_{44} = -0.009$. The discrepancy between the calculated and measured values may be accounted for by considering the window accepting the doublet to include also a small amount (15%) of the 723-keV transition, as well as a portion (25%) due to the Compton-background events primarily from the 1691-keV transition. It should be noted that neither of these corrections is necessary for the analysis of the 714–723-keV and 709–646-keV correlations.

Results for the directional-correlation coefficients obtained from measurements on the I^{126} decay are shown in Table II. The large anisotropy characteristic of the 511-keV positron-annihilation

TABLE I. Results for the directional-correlation coefficients of the Te^{124} γ rays.

Cascade (E in keV)	Spin sequence	A_{22}	A_{44}	Reference
646-603	$4^+-2^+-0^+$	0.12 ± 0.04	0.00 ± 0.05	12
		0.099 ± 0.005	0.007 ± 0.008	Present, NaI(Tl)-Ge(Li)
		0.121 ± 0.025	0.010 ± 0.030	Present, Ge(Li)-Ge(Li)
714-723	$2^+-2^+-2^+$	0.220 ± 0.015	-0.026 ± 0.030	Present, Ge(Li)-Ge(Li)
709-646	$4^+-4^+-2^+$	0.187 ± 0.017	0.011 ± 0.033	Present, Ge(Li)-Ge(Li)
723-603	$2^+-2^+-0^+$	0.14 ± 0.03	0.26 ± 0.04	12
		0.152 ± 0.008	0.304 ± 0.012	Present, NaI(Tl)-Ge(Li)
		0.130 ± 0.015	0.295 ± 0.020	Present, Ge(Li)-Ge(Li)
1691-603	$3^--2^+-0^+$	-0.063 ± 0.004	-0.009 ± 0.006	11
		-0.072 ± 0.005	-0.007 ± 0.005	a
		-0.099 ± 0.026	0.03 ± 0.03	12
		-0.060 ± 0.006	0.000 ± 0.008	Present, NaI(Tl)-Ge(Li)
		-0.064 ± 0.020	-0.005 ± 0.025	Present, Ge(Li)-Ge(Li)
2091-603	$3^--2^+-0^+$	-0.058 ± 0.005	0.001 ± 0.005	b
		-0.052 ± 0.012	0.037 ± 0.018	11
		-0.069 ± 0.015	0.004 ± 0.020	Present, NaI(Tl)-Ge(Li)

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radiation caused significant problems in the measurements of the 491–389-keV directional correlation using the NaI(Tl) detector. Even with the NaI detector accepting the 389-keV transition (since the 491-keV transition cannot be resolved from the 511-keV line), the wide window widths necessary for the NaI detector resulted in the acceptance of a substantial amount of Compton background from the 511-keV radiation, with its corresponding large anisotropy. Thus it was necessary to use the Ge(Li)-Ge(Li) combination to measure this particular correlation.

To investigate the effects of the Compton background due to the positron-annihilation radiation, the single-channel-analyzer windows of the Ge(Li) detectors accepting the 389- and 491-keV peaks were moved so as to accept only the Compton background in an energy region either above or below the peak. Investigations made with various combinations of window settings yielded a set of results which was reasonably consistent, particularly in view of the large statistical uncertainty due to the low counting rates. The directional correlation involving the Compton background showed the expected sharp peak at 180°. Such a correlation does not lend itself well to a Legendre-polynomial analysis, and hence the measured coincidence counting rates of the 491–389-keV correlation were corrected for these effects before the correlation coefficients were extracted.

No such problems arose in the measurement of the 754–667-keV correlation, since both γ rays lie above 511 keV, and hence this measurement could be performed using both detector combinations.

The mixing ratio for electric-quadrupole–magnetic-dipole admixture is defined in terms of the electromagnetic field multipole operators $\vec{A}_L^{(\pi)}$ as[2]

TABLE II. Results for the directional-correlation coefficients of γ rays from the decay of I^{126}.

Isotope	Cascade (E in keV)	Spin sequence	A_{22}	A_{44}	Reference
Te^{126}	754-667	$2^+-2^+-0^+$	0.01 ± 0.02	0.35 ± 0.04	21
			0.059 ± 0.009	0.268 ± 0.014	20
			0.062 ± 0.009	0.330 ± 0.015	Present, NaI(Tl)-Ge(Li)
			0.052 ± 0.028	0.291 ± 0.035	Present, Ge(Li)-Ge(Li)
Xe^{126}	491-389	$2^+-2^+-0^+$	-0.03	0.29	21
			-0.071 ± 0.025	0.294 ± 0.041	20
			-0.103 ± 0.012	0.341 ± 0.030	Present, Ge(Li)-Ge(Li)

$$\delta(\gamma_n)=\frac{\langle I_{n+1}\|\vec{\mathrm{j}}_N\vec{\mathrm{A}}_2^{(E)}\|I_n\rangle}{\langle I_{n+1}\|\vec{\mathrm{j}}_N\vec{\mathrm{A}}_1^{(M)}\|I_n\rangle}$$

or, in terms of the Bohr-Mottelson[16] multipole matrix elements, as

$$\delta(\gamma_n)=k_n\frac{\sqrt{3}}{10}\frac{\langle I_{n+1}\|\mathfrak{M}(E2)\|I_n\rangle}{\langle I_{n+1}\|\mathfrak{M}(M1)\|I_n\rangle}=k_n\frac{\sqrt{3}}{10}\Delta(\gamma_n)\,,$$

where the latter equation is evaluated in natural units ($\hbar=m_e=c=1$). In Table III are presented the mixing ratios $\delta(\gamma_n)$ and $\Delta(\gamma_n)$ derived from the directional-correlation coefficients given in Tables I and II.

V. DISCUSSION

A. $Sb^{124}\rightarrow Te^{124}$

The results of the present investigation for the 646–603-keV cascade are consistent with the 4^+-2^+-0^+ spin assignments, with results overlapping the expected values $A_{22}=0.102$, $A_{44}=0.009$. It is interesting to note, however, that there is some disagreement regarding the spin assignment of the 1249-keV level. Although the 4^+ assignment would certainly be preferred on the basis of the systematics of two-phonon levels in "vibrational" even-even nuclei, the directional-correlation measurement alone cannot distinguish between an $I=4$ assignment, with the 646-keV transition being pure $E2$, and an $I=3$ assignment, with the 646-keV transition being mixed $E2/M1$ having $\delta\approx 0.25$. Values of spin of the 1249-keV level lower than 3 and higher than 4 are excluded on the basis of the decay characteristics. The evidence from measurements of the K-conversion coefficients is contradictory; results based on measurements of conversion coefficients from the decay of Sb^{124} indicate a pure $E2$ character for the 646-keV transition,[5,17] but the value obtained[5] from the decay of I^{124} to Te^{124} is in agreement with an $M1$ character for this radiation. In addition, the results of Dorikens-Vanpraet, Demuynck, and Dorikens (DDD)[11] based on γ-γ measurements indicate a spin assignment of $I=3$ for the 1249-keV level. At the present time, however, it must be assumed that the $I=4$ assignment is correct, on the basis of the systematics of even-even nuclei in this mass region. The absence of direct feeding to the 1249-keV level from the $I^{124}(I^\pi=2^-)$ decay supports this conclusion.

TABLE III. $E2/M1$ mixing ratios of γ transitions in Te^{124}, Te^{126}, and Xe^{126}.

Isotope	Transition E (keV)	Transition Spins	δ (γ)	Δ (γ) (natural units)
Te^{124}	723	$2^{+\prime}$-2^+	-3.4 ± 0.1	-13.9 ± 0.4
	714	$2^{+\prime\prime}$-$2^{+\prime}$	$+0.98\pm 0.19$	$+4.1\pm 1.3$
	709	$4^{+\prime}$-4^+	$+0.04^{+0.03}_{-0.05}$	$+0.17^{+0.13}_{-0.21}$
Te^{126}	754	$2^{+\prime}$-2^+	$-5.5^{+0.4}_{-0.3}$	$-21.6^{+1.6}_{-1.2}$
Xe^{126}	491	$2^{+\prime}$-2^+	$+27^{+30}_{-9}$	$+162^{+180}_{-54}$

The results of various recent measurements of the mixing ratio of the 723-keV transition are in reasonably good agreement with the present results. Measurement of β-γ directional correlations by Raghavan, Grabowski, and Steffen[7] indicated the range of values $-2.8\leq\delta(723)\leq -1.0$. Measurements of β-γ-γ directional correlations by Glaubman and Oberholtzer[10] have yielded $\delta(723)=-4.1\pm 0.6$, and the γ-γ measurements of DDD[11] and Stelson[12] have yielded $\delta(723)=-2.4$ and $\delta(723)=-3.4\pm 0.6$, respectively. While this latter result agrees precisely with the present value, the recent result $\delta(723)=-7.5\pm 2.0$ obtained in the experiment with oriented Sb^{124} nuclei by Sites and Steyert[18] is at variance with it.

The results of the present work for the 1691–603-keV and 2091–603-keV directional correlations are in agreement with the results for 3^--2^+-0^+ cascades, with both the 1691- and 2091-keV transitions being of essentially $E1$ character ($|\delta|<2\times 10^{-2}$). The K-conversion-coefficient measurements confirm almost pure $E1$ character of these transitions.[5,17]

The spin assignments for the 1958- and 2039-keV levels have been made on the basis of decay systematics,[4] rather than on the basis of previous directional-correlation measurements. Considering the excitation energy only, one is tempted to classify these levels as three-phonon excitation (in the vibrational picture). The branching ratios of these states to the one- and two-phonon levels indicate some collective vibrational nature, with the transitions to the two-phonon levels enhanced somewhat over those to the one-phonon level. It is to be expected that quasiparticle effects may be present at these high energies; such effects would tend to reduce the collective nature of the levels. Since the quasiparticle admixtures in these levels would be expected to be considerably greater than that in the 1326-keV level, it would be expected that the nature of the 709- and 714-keV transitions would be considerably less collective than that of the 723-keV transition. Based on the spin assignments of 2^+ and 4^+ for the 2039- and 1958-keV levels, this interpretation would be consistent with the $E2/M1$ mixing ratios measured in the present work; i.e., with both transitions showing substantial $M1$ admixtures.

It should be noted that on the basis of the directional-correlation measurements involving the 709-

and 714-keV transitions, the spin assignment of 3^+ for either the 1958- or the 2039-keV levels may not be excluded. An assignment of 3^+ for the 1958-keV level would be consistent with the directional correlation for a 3^+-4^+-2^+ cascade with $\delta(709) \approx -0.45$, while a 3^+ assignment for the 2039-keV level would result in $\delta(714) \approx -0.3$ for the 3^+-2^+-2^+ directional correlation.

Using our value for $\delta(723)$ and Sliv's conversion coefficients[19] one can calculate the K-conversion coefficient for the 723-keV transition in Te^{124} as $\alpha_K(723) = 2.7\times 10^{-3}$. The agreement between this calculated value and the measurements reported in Refs. 5 and 17 is excellent. The experimentally measured K-conversion coefficient for the 714-keV γ transition[5,17] when used with our $\delta(714)$ measurement strongly supports the 2^+ assignment for the 2039-keV level. However, on the basis of the measured conversion coefficients and our mixing-ratio data it is not possible to decide between the 3^+ and 4^+ spin-parity assignment for the 1958-keV state in Te^{124}.

B. $I^{126} \rightarrow Te^{126}$ and Xe^{126}

The results of the present investigation for the $2^{+\prime}$-2^+-0^+ cascade in Te^{126} show agreement between the NaI(Tl)-Ge(Li) and Ge(Li)-Ge(Li) results; in addition the agreement with previous values as measured by Sakai *et al.*[20] is good. However, in previous investigations[20,21] of Xe^{126} using NaI(Tl) detectors unambiguous values for the $2^{+\prime}$-2^+ mixing ratio were not obtained, because of the problems associated with the positron-annihilation radiation. Such investigations have generally indicated large values of δ, results which are not inconsistent with those of the present work.

It is of interest to note the variations in values of δ in this mass region. The $2^{+\prime}$-2^+ mixing ratio in Te^{122} has been measured[21] to be $\delta = -3.7 \pm 0.3$. This latter result, together with those of the present investigation for Te^{124} and Te^{126} indicate that the values for the mixing ratios in all three of these even-even tellurium isotopes are negative. However, results for the $2^{+\prime}$-2^+ transitions in Xe^{128} ($\delta = +6.4 \pm 1.5$)[21] and for Xe^{132} ($\delta \approx +5$)[22] indicate a trend toward positive mixing ratios in even-even isotopes. At present, no explanation can be offered for this contrast. Tamura and Yoshida[23] have computed that the $(g\frac{7}{2})^2$ two-quasiproton state occurs at 1.36 MeV in Te and at 1.60 MeV in Xe; it thus would be expected to have a substantial influence on the properties of the $2^{+\prime}$ state in Te($E_{2^{+\prime}} \approx 1.3$ MeV), but not nearly as much influence in the case of the $2^{+\prime}$ state of even-even nuclides of Xe($E_{2^{+\prime}} < 1$ MeV in $Xe^{126,128}$, $E_{2^{+\prime}} \approx 1.3$ MeV in Xe^{132}).

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†Work supported by the U. S. Atomic Energy Commission under Contract No. At(11)1)-1746 (Chicago Operations Office).

*A preliminary report of this investigation has been presented at the International Conference on Angular Correlations in Delft, The Netherlands, 17–21 August 1970.

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