$f_{5/2}$ and $p_{1/2}$ neutron-hole states. It appears that low-lying quadrupole collective excitations may be occurring in these core nuclei and that these negative-parity states may arise from weak coupling.

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Levels of ^{124}Te from the Decay of 4.2-Day ^{124}I

R. C. RAGAINI* AND W. B. WALTERS

A. A. Noyes Nuclear Chemistry Center, Massachusetts Institute of Technology,† Cambridge, Massachusetts 02139

AND

R. A. MEYER

Lawrence Radiation Laboratory, University of California,‡ Livermore, California 94550

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The population of levels of ^{124}Te from the decay of 4.2-day ^{124}I has been investigated by studying the ^{124}I γ rays with a Ge(Li) Compton suppression spectrometer and with NaI(Tl)-Ge(Li) coincidence systems. Seventy-two γ rays were identified as originating from ^{124}I, and 62 of them were assigned to 24 levels of ^{124}Te. The levels populated from ^{124}I decay are compared to the levels of ^{124}Te populated from the decay of the ^{124}Sb isomers. The nature of the levels is discussed in the framework of the quasiparticle and spherical vibrational models.

I. INTRODUCTION

WE have recently reported the population of ^{124}Te levels from the β and γ radiations of the ^{124}Sb isomers.[1] As a continuation of our study of ^{124}Te, we have reinvestigated the decay of 4.2-day ^{124}I utilizing a Ge(Li) Compton suppression spectrometer and a Ge(Li)-NaI(Tl) γ-γ coincidence spectrometer. The high-resolution measurements on the decay of ^{124}I and on the decay of the ^{124}Sb isomers enable more detailed spin and parity assignments to be made than previously possible. Since our initial report of this work,[2] there have been several preliminary reports on the ^{124}I decay scheme,[3] as well as another study of the ^{124}Sb decay scheme,[4] all using unsuppressed Ge(Li) detectors. It is hoped that our results will resolve the differences among the other Ge(Li) studies, as the Compton suppression system reduces the errors in γ-ray intensities and energies by lowering the Compton background underneath full-energy peaks. Moreover, this background reduction also permits observation of low-energy peaks which are ordinarily obscured by Compton events.

Recently, Ruan and Inoue[5] measured the β rays and conversion electrons from ^{124}I decay with a double-focusing β-ray spectrometer and an orange spectrometer. In addition to the decays of ^{124}I and ^{124}Sb, the level structure of ^{124}Te has also been studied by nuclear-reaction spectroscopy. Collective excitations have been observed by inelastic scattering experiments,[6,7] and single-particle configurations have been investigated by the (d, t) reaction.[8] Furthermore, the spectrum of γ

* Present address: Brookhaven National Laboratory, Upton, N.Y. 11973.

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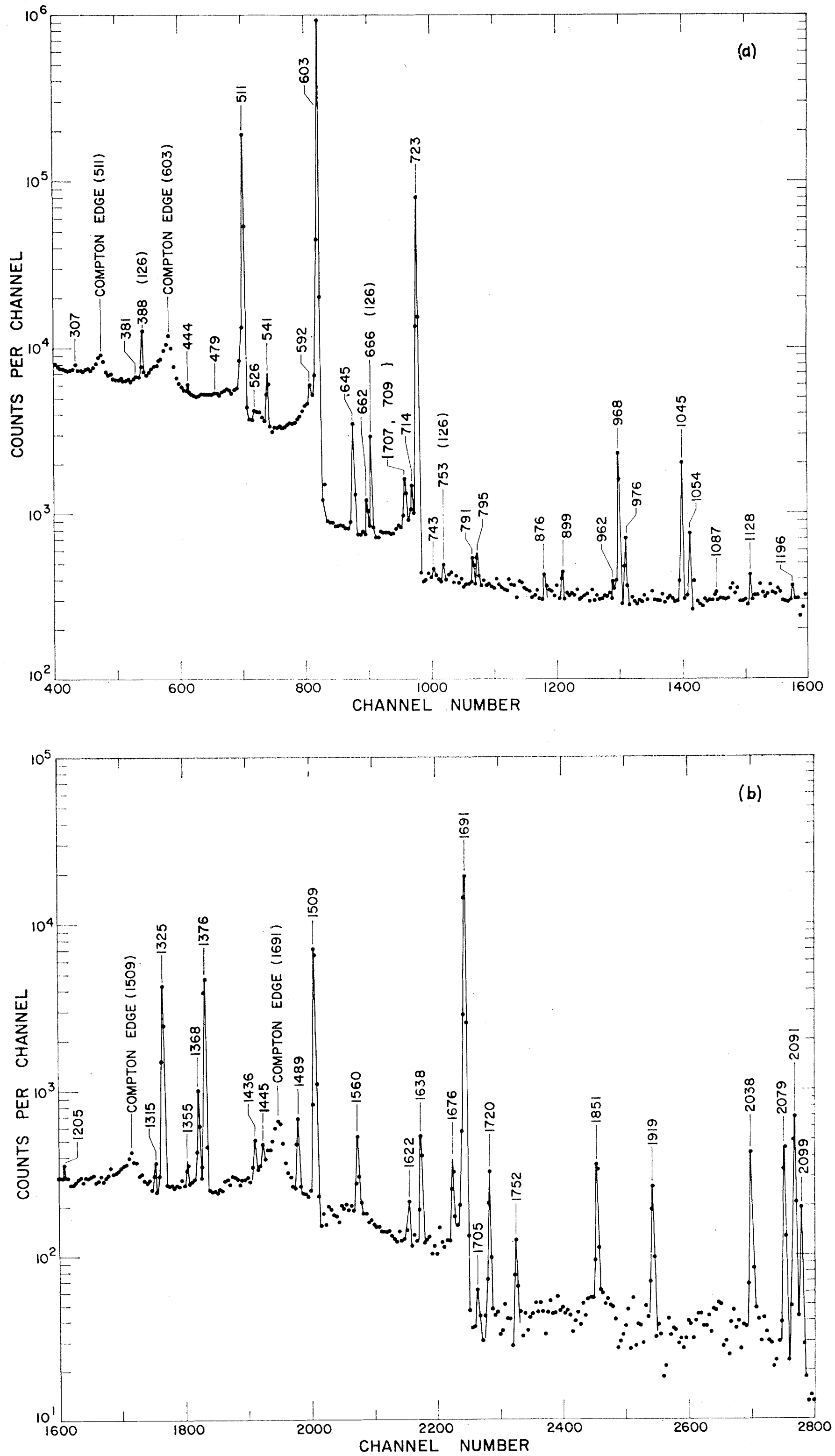

FIG. 1. γ-ray spectrum of ^{124}I taken with Ge(Li) Compton suppression system (a) 300–1200 keV, (b) 1200–2100 keV, (c) 2100–3000 keV. Interfering peaks from ^{126}I decay are marked as (126).

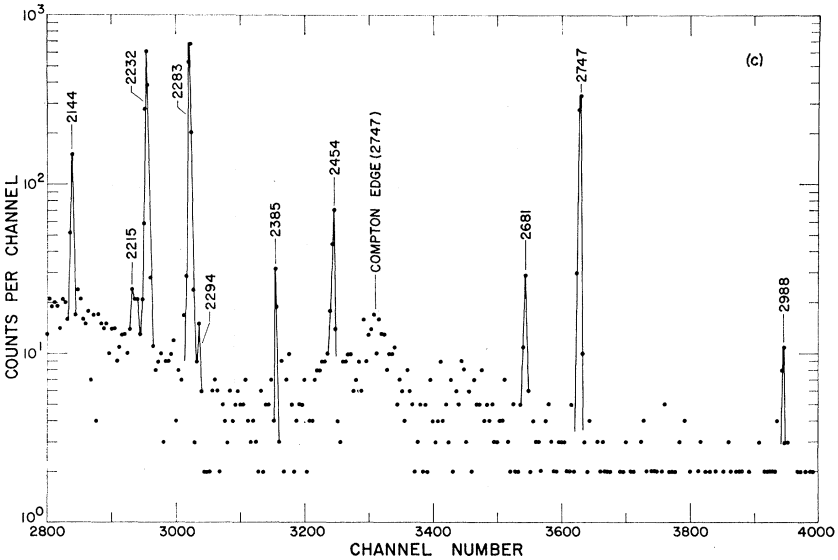

FIG. 1. (*Continued*).

TABLE I. Energies, positions, and intensities of γ rays emitted in the decay of 4.2-day ^{124}I.

Energy (keV)	Relative intensity	Transition (keV) From	To	Energy (keV)	Relative intensity	Transition (keV) From	To
307.2±0.5	0.030±0.015	3001.0	2693.73	1355.1±0.1	0.070±0.011	1957.7	602.72
336±1	0.029±0.015	2293.74	1957.7	1368.20±0.06	0.47±0.03	2693.73	1325.50
381.7±0.5	0.028±0.002			1376.0±0.1	2.75±0.03	2701.8	1325.50
444.1±0.1	0.055±0.015	2483.4	2039.3	1436.5±0.1	0.11±0.03	2039.3	602.72
478.7±0.5	0.043±0.004			1444.9±0.1	0.054±0.018	2693.73	1248.54
526.0±0.5	0.059±0.030	2483.4	1957.7	1479±1			
541.2±0.1	0.31±0.01	2834.98	2293.74	1488.9±0.1	0.30±0.01	2091.6	602.72
592.4±0.2	0.067±0.014	2885.97	2293.74	1509.49±0.04	4.94±0.04	2834.98	1325.50
602.72±0.04	100	602.72	GRD	1559.8±0.2	0.27±0.04	2885.97	1325.50
645.82±0.04	1.56±0.05	1248.54	602.72	1621.7±0.1	0.093±0.023	2224.6	602.72
662.4±0.5	0.090±0.006	2701.8	2039.3	1637.7±0.5	0.32±0.02	2885.97	1248.54
707.5±0.5[a]	0.11±0.05[a]	3001.0	2293.74	1675.8±0.4	0.18±0.04	3001.0	1325.50
709.2±0.5[a]	0.07±0.03[a]	1957.7	1248.54	1685±1			
713.8±0.2	0.18±0.02	2039.3	1325.50	1691.02±0.04	17.2±0.2	2293.74	602.72
722.78±0.04	16.5±0.3	1325.50	602.72	1705.5±0.3	0.023±0.004		
743.2±0.3	0.027±0.007	2701.8	1957.7	1720.37±0.14	0.28±0.02	2323.1	602.72
775.1±0.2	0.022±0.006			1752.2±0.1	0.082±0.010	3001.0	1248.54
790.7±0.2	0.046±0.013	2039.3	1248.54	1851.4±0.4	0.34±0.04	2454.0	602.72
795.3±0.2	0.072±0.005	2834.98	2039.3	1918.58±0.4	0.26±0.03	2521.3	602.72
846.6±0.4	0.004±0.002	2885.97	2039.3	2021±2	≤0.01		
876.5±0.2	0.043±0.010			2038.3±0.3	0.56±0.03	2641.0	602.72
899.0±0.1	0.049±0.027	2224.6	1325.50	2078.86±0.07	0.57±0.02	2681.6	602.72
928.0±0.4	0.0035±0.0015	2885.97	1957.7	2091.0±0.1[a]	0.94±0.01[a]	2693.73	602.72
961.76±0.09	0.037±0.004	3001.0	2039.3	2091.6[a]	≤0.05[a]	2091.6	GRD
968.22±0.08	0.68±0.01	2293.3	1325.50	2099.09±0.09	0.23±0.01	2701.8	602.72
976.32±0.14	0.17±0.02	2224.6	1248.54	2144.32±0.01	0.18±0.01	2746.9	602.72
984.4±0.5	0.023±0.005	2641.0	1656.7	2214.65±0.45	0.017±0.008		
1045.0±0.1	0.70±0.05	2293.74	1248.54	2232.25±0.07	0.94±0.02	2834.98	602.72
1054.0±0.2	0.20±0.01	1656.7	602.72	2275.8±0.5	0.010±0.005		
1086.6±0.1	0.03±0.01	2412.1	1325.50	2283.25±0.08	1.09±0.05	2885.97	602.72
1128.1±0.2	0.072±0.001	2454.0	1325.50	2294.4±0.5	0.017±0.003	2293.74	GRD
1195.7±0.5	0.031±0.011	2521.3	1325.50	2385.4±0.4	0.032±0.004	2987.8	602.72
1204.9±0.5	0.031±0.001	2454.0	1248.54	2453.9±0.3	0.11±0.03	2454.0	GRD
1236±1	0.009±0.005[b]	2483.4	1248.54[b]	2681.5±0.2	0.05±0.02	2681.3	GRD
1315.2±0.2	0.057±0.007	2641.0	1325.50	2746.9±0.1	0.76±0.03	2746.9	GRD
1325.50±0.04	2.37±0.08	1325.50	GRD	2987.6±0.3	0.013±0.006	2987.8	GRD

[a] Doublet resolved by utilizing results from ^{124}Sb ground-state decay (Ref. 1).

[b] Intensity and assignment from ^{124}Sb study (Ref. 1).

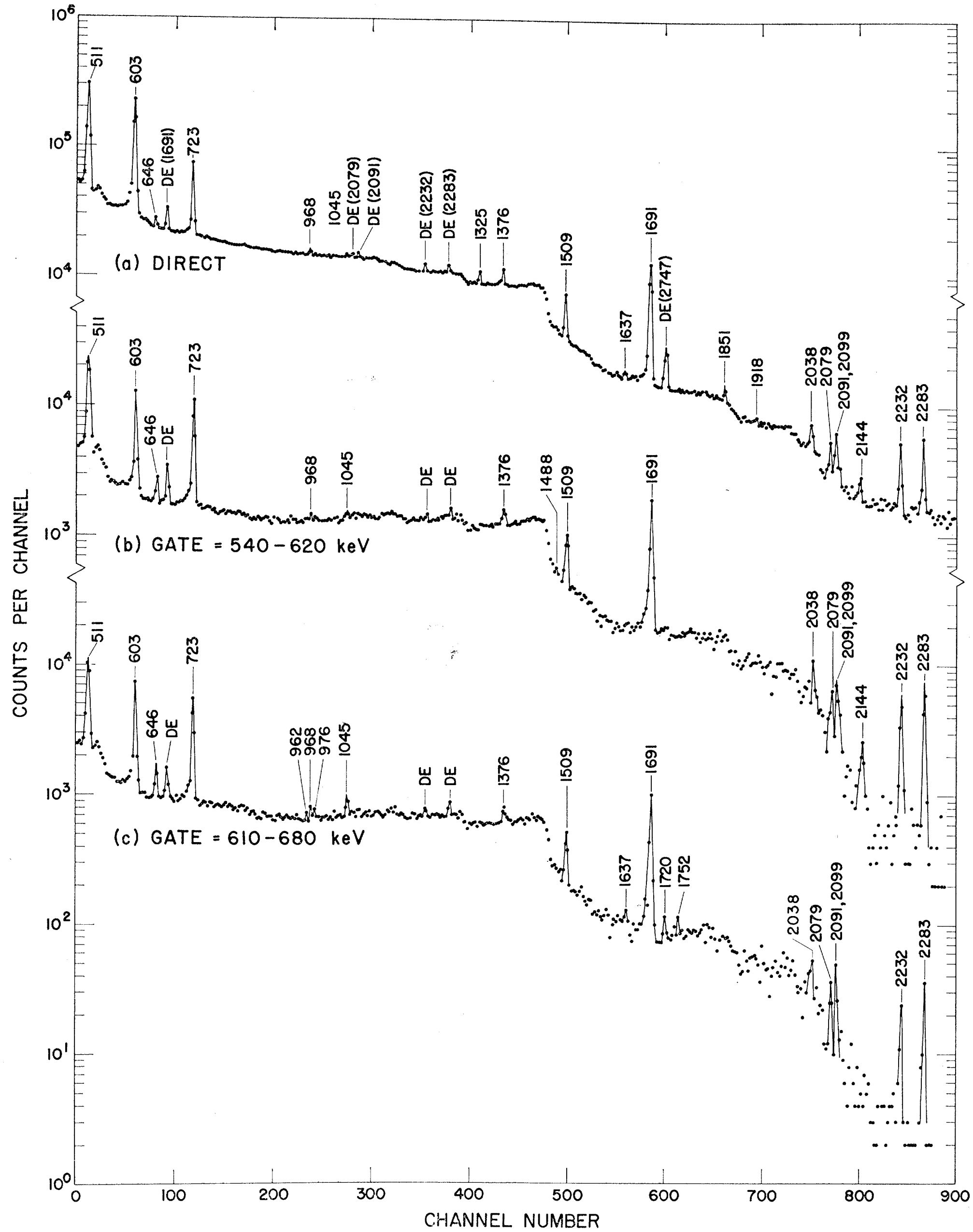

FIG. 2. Comparison of direct γ-ray spectrum of ^{124}I taken with (a) bare Ge(Li) detector; (b) Ge(Li) spectrum in coincidence with 540–620 keV, (c) with 610–680 keV.

rays from the capture of thermal neutrons by ^{123}Te has been studied.[9]

The behavior of the low-energy structure of spherical even-even nuclei is currently best described in terms of pure collective vibrations and interactions between single-particle and vibrational modes. The phenomenological approach to the description of collective modes has been the hydrodynamic vibrational model.[10] The quasiparticle calculations of Kisslinger and Sorenson[11] based on the pairing-plus-quadrupole model have exemplified the microscopic approach. Recently the quasiparticle second Tamm-Dancoff theory has been

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utilized to reasonably describe the low-lying states of even Sn isotopes in terms of zero-, two-, and four-quasiparticle excitations.[12]

It is hoped that the extensive detail of the decay properties of ^{124}Te, as revealed by the Compton suppression system, will allow a more complete analysis of the anharmonicities in the ^{124}Te spectrum and their correlation with two- and four-quasiparticle excitations.

II. EXPERIMENTAL PROCEDURES

A. Source Preparation

Separate and independent experiments were carried out at the Lawrence Radiation Laboratory at Livermore (LRL) and at the Massachusetts Institute of Technology (MIT). At MIT sources of ^{124}I were prepared by bombarding Sb enriched to 98.4% in ^{121}Sb at the MIT Cyclotron with 30-MeV ^{4}He ions. Isolation of 13.3-h ^{123}I and ^{124}I was accomplished by chemically separating the iodine fraction. The ^{123}I was allowed to decay away before measurements were performed on ^{124}I. The Al target wrapping was dissolved in HCl, and I^- carrier was added. Cold HNO_3 was added to dissolve the Sb and oxidize the I^- to IO_3^- and IO_4^-. Then $NH_2OH \cdot HCl$ was added dropwise until I_2 was formed, which was extracted with CCl_4 and washed. The CCl_4 was mixed with an aqueous $NaHSO_3$ solution to extract the I^-. This cycle was repeated several times to ensure source purity. The last aqueous solution containing I^- was made weakly acidic in HNO_3, and $AgNO_3$ was added to precipitate the I^-. This precipitate was then washed with water and alcohol and then mounted.

The ^{124}I sources used at LRL were produced by α bombardments on isotopically separated ^{121}Sb. The ^{124}I was isolated as PdI_2 by standard radiochemical procedures.[13]

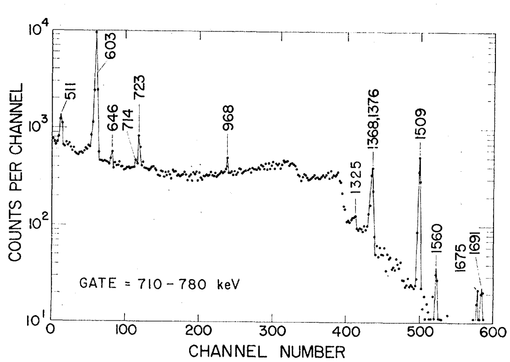

FIG. 3. Ge(Li) γ-ray spectrum of ^{124}I in coincidence with 710–780-keV gated region.

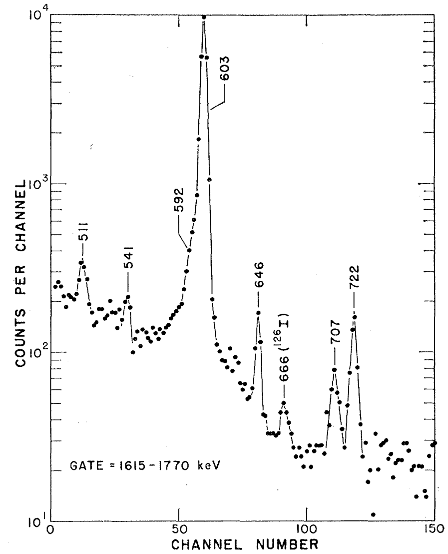

FIG. 4. Ge(Li) γ-ray spectrum of ^{124}I in coincidence with 1615–1770-keV gated region.

B. Data Acquisition

γ-ray spectra were taken at MIT with a 1.2-cm^3 planar Ge(Li) detector and auxiliary electronics previously described.[14] The operational full width at half-maximum was 2.6 keV for 662-keV γ rays. γ-γ coincidence experiments were conducted with the Ge(Li) detector and a 7.6×7.6-cm NaI(Tl) crystal using the MIT buffer memory and magnetic tape system.[14] This system recorded coincident events in a 1024×1024-channel configuration through the buffer unit onto magnetic tape, while a 4096-channel direct Ge(Li) spectrum was simultaneously stored in the core memory of the pulse-height analyzer. Resolving times (2τ) of $\approx$40 nsec were used in the coincidence system. The addresses of all coincident events which were stored on tape were analyzed at a later time, either by the pulse-height analyzer system or by the MIT 7044 computer in order to sort out coincidence spectra.

Direct γ-ray spectra were taken at LRL using several Ge(Li) detectors, all with cooled FET preamplifiers. Spectra were taken using a 7-cm^3 detector as a normal detector and in a Compton suppression system.[15] For studying low-energy γ rays, a small slice Ge(Li) detector was used in the Compton suppression system. γ-γ coincidences were taken with a variable-angle spectrometer with an automatic subtraction mode for random events.[16]

III. RESULTS

Figure 1 shows the γ-ray spectrum of 4.2-day ^{124}I taken with the Ge(Li) Compton suppression spectrom-

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TABLE II. Summary of γ-γ coincidence results in ^{124}I decay.

Gated γ ray (keV)	γ rays observed in coincidence
602.72	646, 723, 961, 1355, 1368, 1376, 1488, 1509, 1622(?), 1691, 1851(?), 1918, 2038, 2079, 2091.0, 2099, 2144, 2232, 2283
645.82	961, 976, 1045, 1637, 1752
722.78	714, 968, 1368, 1375, 1509, 1560, 1675
1691.02	541, 592, 707

eter at LRL. The lines marked as (126) were identified as originating in the decay of 13.2-day ^{126}I. The energy calibration procedure of the intense γ rays was carried out using the technique of Gunnink *et al.*[17] which consisted of simultaneously observing the ^{124}I source with known standard γ rays. These energy values were then used as internal standards to obtain the values of the weaker lines using the Gunnink-Niday code[18] on the Livermore CDC computers. The reported γ-ray intensities were determined from spectra on several Ge(Li) detectors. An efficiency calibration technique[17] and the photopeak analysis routine of the Gunnink-Niday code[18] were utilized to calculate the γ-ray intensities. Hand calculations and spectral shape fits were used to analyze the weakest peaks, close-lying doublets, and areas of large background uncertainties. Table I lists the energies and intensities of all the observed γ rays which were assigned to the decay of ^{124}I. The listed data are consistent with the results at MIT and LRL. The energies also agree with those reported by us from the decay of the ^{124}Sb isomers.[1] There are several γ rays included in the list whose weak intensity prevented any definitive conclusions on their assignments, and hence these γ rays could not be unambiguously placed in the decay scheme.

Figure 2 contains a direct γ-ray spectrum taken with the MIT Ge(Li) detector shown in curve a and γ-γ coincidences with the NaI(Tl) detector gated on the energy regions 540–620 and 610–680 keV shown in curves b and c, respectively. The intensities of the 2232- and 2283-keV full-energy peaks shown in curve c are a quantitative measure of the amount of the 603-keV peak contained in the gate, and can be used to determine γ-rays coincidence with either the 603- or 646-keV γ rays or with both of them. Narrower energy gates, which are not shown, were also used in establishing the cascade relationships. Figure 3 shows the Ge(Li) spectrum coincident with the energy region 710–780 keV. In this spectrum, the intensity of the 1325-keV peak gives an indication of the number of gated Compton events associated with γ rays which feed the 1325-keV level. The spectrum coincident with the energy region 1615–1770 keV is shown in Fig. 4. The 646-keV peak is generated from the presence of the 1638- and 1752-keV full-energy peaks in the gate. Table II summarizes the results of the γ-γ coincidence measurements.

IV. DECAY SCHEME

The decay scheme of ^{124}I shown in Fig. 5 is based on our γ-ray measurements, the ^{124}I β-decay data and conversion electron results of Ruan and Inoue,[5] and on our study of the decay of the ^{124}Sb isomers.[1] We also utilize the conversion electron study of the ^{124}Sb ground-state decay by Grigor'ev *et al.*[19] The only levels which are populated by ^{124}I and not by ^{124}Sb occur at 2641, 2747, 2835, 2988, and 3001 keV; the last two levels being above the Q value for the ^{124}Sb ground-state decay. Conversely, the ^{124}Sb isomers decay to levels at 1747, 2183, 2349, 2711, and 2775 keV, which are not populated in ^{124}I decay. The 2641-keV level is deexcited by three independent cascades, one of which is seen in coincidence. The level at 2747 is established by the observation of a ground-state transition and the coincidence of the 603- and 2144-keV γ rays. Four independent cascades deexcite the level at 2835 keV. The level at 2988 keV is depopulated by a ground-state transition and the 2385-keV γ ray, which feeds the level at 603 keV. Five cascades deexcite the level at 3001 keV.

The recent β-ray spectrometer results of Ruan and Inoue[5] have been used in the calculations of the ft values for the populations of the ^{124}Te levels. They reported a gross β endpoint of 2146±15 keV, which yields a Q_{EC} of 3168±15 keV. In addition, they measured the

TABLE III. β decay of 4.2-day ^{124}I to levels of ^{124}Te.

Energy level (keV)	%β^+	%EC	logft
GRD	12.5	22.5	8.1
602.72	12.7	24.2	7.6
1248.54		≤0.063	≥9.8
1325.50	0.4	5.4	7.8
1656.7		0.11	9.4
1957.7		0.031	9.7
2039.3		0.031	9.6
2091.6		0.22	8.9
2224.6		0.16	8.8
2293.74		11.0	6.9
2323.1		0.18	8.6
2412.1		0.019	9.5
2454.0		0.35	8.2
2483.4		0.077	8.8
2521.3		0.18	8.3
2641.0		0.40	7.9
2681.6		0.39	7.8
2693.73		0.90	7.4
2701.8		1.94	7.1
2746.9		0.59	7.5
2834.98		3.93	6.4
2885.97		1.48	6.7
2987.8		0.028	8.1
3001.0		0.27	7.1

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[18] R. Gunnink, H. B. Levy, and J. B. Niday, Lawrence Radiation Laboratory, Livermore, Report No. UCRL-15140 (unpublished).

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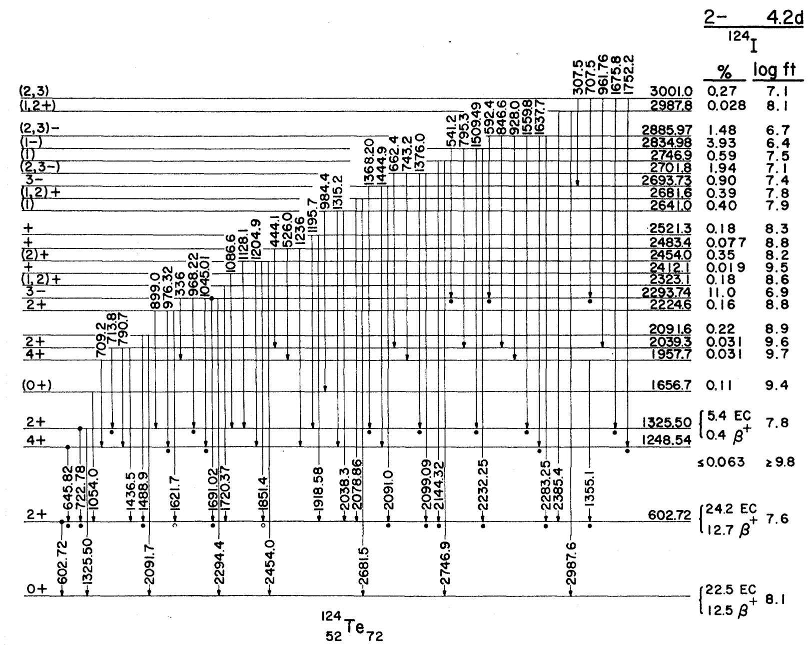

FIG. 5. Level scheme of ^{124}Te populated by decay of ^{124}I. Dots on the beginning and end of transitions indicate observation of γ-γ coincidences; open circles indicate questionable observations. Level separations not necessarily drawn to scale. The Q_{EC} is taken to be 3168 ± 15 keV as reported by Ruan and Inoue, Ref. 5.

relative intensities of the β groups populating the levels at 0, 603, and 1325 keV as 45.1, 49.4, and 5.1%, respectively. The capture branchings were calculated from the theoretical values of the capture-to-positron ratios of 1.9 for the unique first forbidden decay to the ground state, 1.8 for the first forbidden decay to the 603-keV 2+state, and 15 for the first forbidden decay to the 1325-keV 2+state, all taken from Wapstra *et al.*[20] The total populations of the excited states of ^{124}Te were calculated from the observed γ-ray intensities.

Table III summarizes the results on the positron and electron-capture decay of ^{124}I. The β-group energies were obtained by subtraction of the level energies, as determined from the Ge(Li) measurements, from the Q value taken from Ruan and Inoue.[5] The $\log_{10} ft$ values were calculated from the above data with the use of the Moskowski nomograms as contained in Lederer *et al.*[21]

The $\log_{10} ft$ value for the population of the ground state is 8.1. However, it is more significant to quote the $\log_{10} f_1 t$ of 8.3 for this first forbidden transition, which is a typical value for an odd-odd nuclide.[22]

The 0+level at 1656 keV is directly populated in ^{124}I decay, but is fed a factor of 10^3 less in the ^{124}Sb ground-state decay. The spin-parity assignment is based on these data and on its probable population in the inelastic scattering experiments,[6,7] which are summarized in Table IV. This conclusion agrees with the results of the (n, γ) experiment.[9]

The level at 1747.0 keV, which is populated only in ^{124}Sb decay, was assigned a 5,6+value.[1] As shown in Table IV, the (n, γ) results indicate three possible levels in this energy region at 1736.5, 1747.4, and 1759 keV.[9] In addition, there is inconclusive evidence of decay from the neutron-capture state to levels at 1724, 1730, 1747, 1758, 1763, and 1770 keV.[9] Since decays from the capture state to well-known $J=3$ and $J=4$ levels were not observed and since a 1747-keV ground-state transition was observed,[9] the level populated at 1747.4 keV in the (n, γ) reaction cannot be the same level we observe at 1747.0 keV. As an additional substantiation of our results, Bergström *et al.*[23] propose a 6+level at 1748 keV in ^{124}Te by the ^{122}Sn$(\alpha, 2n\gamma)$ ^{124}Te reaction.

The intensity of the ground-state transition from the level at 2091.6 keV was difficult to obtain, because it forms an unresolvable doublet with the 2091.0 keV transition between the levels at 2693.73 and 602.72 keV. By comparing the intensity ratio of the 1691- and 2091-keV γ rays in a direct Ge(Li) spectrum to the ratio in a Ge(Li) coincidence spectrum gated on the 603-keV γ ray, we were able to indirectly estimate the intensities of the 2091.0- and 2091.6-keV γ rays from the decay of ^{124}Sb.[1] We have utilized those results in this paper, and have assigned an upper limit for the intensity of the 2091.6-keV γ ray. Two of the deexcitation γ rays of the 2091.6-keV level, the γ rays of 765 and 1489 keV, have been observed in the conversion electron spectrum of ^{124}Sb.[19] Using the electron data on Ref. 19

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TABLE IV. Population of ^{124}Te levels.

Level (MeV)[a,b]	^{124}I logft values[a]	^{124}Sb logft values[b]	Our J^π values[a,b]	Other measurements (MeV) (α,α')[c] (d,d')	(p,p')[d]	(d,t)[e]	(n,γ)[f]
0	7.7	···	0+	0	0	0 (0+)	0 (0+)
0.60272	7.6	10.6	2+	0.605 (2+)	0.606 (2+)	0.61 (2+)	0.60242 (2+)
1.24854	≥9.8	11.4	4+	1.24 (4+)	1.247 (4+)		1.24799 (4+)
1.32550	7.8	10.0	2+	1.31	1.323 (2+)	1.32 (2, 4+)	1.32482 (2+)
1.6566	9.4	≥13.8	(0+)	1.65	1.657		(1.6559 (0+))
							(1.7365)
1.7470	···	≥12.2	5, 6+		1.746		(1.7474)
							1.759
1.95785	9.7	9.8	4+	2.01			1.9562 (3, 4+)
2.03933	9.6	9.2	2+				2.03768 (2+)
2.09175	8.9	9.6		2.11			2.09065 (0, 1, 2+)
							2.1522 (0, 2+)
							2.171
2.18262	···	10.3	(1, 2+)	2.19			2.1812 (1, 2)
2.2246	8.8	10.5	2+				
2.29374	6.9	7.6	3−	2.30 (3−)			2.2931 (3−)
2.3231	8.6	10.4	(1, 2+)			2.31	2.3226 (0, 1, 2+)
2.3496	···	≥5.1[g]	4, 5, 6+				
2.4121	9.5	10.3	2, 3, 4+				
2.4540	8.2	10.5	(2+)			2.44	2.453
2.4834	8.8	9.1	2, 3, 4+				2.487
				2.49 (−)			(2.492)
2.5213	8.3	10.0	1, 2, 3, 4+				2.5195
							2.522
						2.53	2.530
						2.59	2.6004 (2+)
							2.617
2.6410	7.9	···	(1±)	2.65			2.6395
2.6816	7.8	9.8	(1, 2+)				2.681
2.69373	7.4	7.0	3−	2.69			2.6932 (3−)
2.7018	7.1	8.1	(2, 3−)				
2.7107	···	9.8	1, 2, 3, 4+				
2.7469	7.5	···	(1±)				2.7471 (1−)
2.77487	···	7.7	3, 4−				
							2.808
							2.818
2.83498	6.4	···	(1−)	2.84			
							2.858
2.88597	6.7	6.9	2, 3−				2.889
							2.932
							2.947
							2.976
2.9878	8.1	···	(1, 2+)				2.9887 (1, 2−)
3.0010	7.1	···	2, 3±				

[a] Results from this work.
[b] Results from ^{124}Sb ground-state decay; see Ref. 1.
[c] Reference 7.
[d] Reference 6.
[e] Reference 8.
[f] Reference 9; only levels below 3 MeV are listed.
[g] logft value from decay of 1.5-min ^{124}Sb 5+isomer; see Ref. 1.

and our γ-ray intensity (see Table V) we obtain a conversion coefficient of 0.82 ± 0.18, which is consistent with an $M1$ assignment. This and observation of the level in the (n,γ) experiment suggest an assignment of 1^+ for this level.

Combining the electron data from Grigor'ev *et al.*[19] and our γ-ray data,[1] the K-shell conversion coefficients for the 765- and 1489-keV lines are $(9.0\pm3.0)\times10^{-3}$ and $(0.98\pm0.16)\times10^{-3}$, respectively. The theoretical α_K values ($E1$, $E2$, $E3$, $M1$, $M2$, $M3$) are $(0.90, 2.3, 5.2, 2.9, 7.8, 18.1)\times10^{-3}$ for the 765-keV transition, and the theoretical α_K values ($E1$, $E2$, $E3$, $M1$, $M2$, $M3$) for the 1489-keV transition are $(0.26, 0.55, 1.0, 0.66, 1.45, 2.5)\times10^{-3}$. The conversion coefficient for the 1489-keV transition is very close to the theoretical $E3$ value. The 765-keV transition coefficient has a larger error associated with it, but it lies closest to the theoretical $M2$ value. These data indicate that the level is 4− or 5−, which conflicts with the γ-ray and β-decay data. The $\log_{10}ft$ data are difficult to reconcile with the conversion coefficient results, as a 4− or 5− assignment would require an ft enhancement of $\sim$100 for the second forbidden transitions relative to the normal range of values. This predicament makes the measurement of the possible 2091.6-keV transition to ground very crucial, since the existence of a ground-state transition would rule out a 4− or 5− assignment. The γ-ray and β-decay data are consistent and indicate an even-parity level of low spin. Because of the apparently conflicting results, we do not assign a spin-parity value to this level. A level at

TABLE V. ^{124}Te K-shell conversion coefficients.

From ^{124}I decay				From ^{124}Sb decay				
E_γ [a] (keV)	I_γ [a]	I_{e_k} [b]	$10^3\alpha_K$ [c]	E_γ [d] (keV)	I_γ [d]	I_K [e]	$10^3\alpha_k$ [c]	$10^3\alpha_k$(theor) [f]
602.72	100	100	4.2	602.72	100	100	4.2	4.23 ($E2$)
645.82	1.56	1.8	4.8	645.82	7.35	6.6	3.7	3.5 ($E2$)
709.2	0.07			709.31	1.45	1.2	3.5	3.45 ($M1$)
713.8	0.18			713.82	2.44	1.6	2.8	2.6 ($E2$)
722.78	16.5	10.3	2.6	722.78	11.5	7.5	2.7	2.6 ($E2$)
				765.3	0.028	0.06	9.0	5.2/7.9 ($E3/M2$)
790.7	0.046			790.78	0.76	0.44	2.4	2.0/2.5 ($E2/M1$)
968.22	0.68			968.25	1.87	0.33	0.74	0.57 ($E1$)
1045.0	0.70			1045.24	1.88	0.25	0.45	0.49 ($E1$)
1325.50	2.37	0.46	0.81	1325.49	1.44	0.30	0.87	0.70/0.84 ($E2/M1$)
1355.1	0.070			1355.17	0.95	0.20	0.89	0.80 ($M1$)
1368.20	0.47			1368.23	2.40	0.22	0.38	0.30 ($E1$)
1376.0	2.75	0.19	0.29					0.29 ($E1$)
1436.5	0.11			1436.66	1.04	0.17	0.68	0.60/0.72 ($E2/M1$)
1488.9	0.30			1489.03	0.67[g]	0.13	0.82	0.66 ($M1$)
1509.49	4.94	0.26	0.22					0.26 ($E1$)
				1526.35	0.40	≤0.04	≤0.42	0.25 ($E1$)
1691.02	17.2	1.05	0.26	1691.02	49.8	2.5	0.21	0.21 ($E1$)
2091.0	0.94	0.08	0.36	2091.0	5.71	0.20	0.15	0.15 ($E1$)

[a] Results from this work.
[b] K-shell conversion data taken from Ruan and Inoue, Ref. 5.
[c] Conversion coefficients normalized to 4.2×10^{-3} for the 602.72-keV transition, assuming a pure $E2$ multipolarity.
[d] Results from Meyer *et al.*, Ref. 1.
[e] K-shell conversion data taken from Grigor'ev *et al.*, Ref. 19.
[f] Theoretical values taken from L. A. Sliv and I. M. Band, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1963).
[g] The original intensity quoted in Ref. 1 was incorrect. The correct value is 6700.

2090.6 keV was populated in the (n,γ) reaction,[9] and it was assigned a value of (0+, 1+, 2+), which is consistent with our decay data.

Only one γ ray is shown as deexciting the level at 2323 keV; however, our results for ^{124}Sb decay show additional transitions to the 1325-keV and ground states.[1] Similarly, for the 2412-keV level the ^{124}Sb data show a transition to the 1248-keV level which is not seen in the ^{124}I decay.

The levels at 2641 and 2747 keV are assigned spin-parity values of (1±) since the $\log_{10}ft$ values indicate either allowed or first forbidden transitions, and the absence of these levels in the ^{124}Sb decay scheme tends to rule out possible allowed decays in that instance. The transitions from these levels to 0+ levels are considered evidence against 3+ assignments.

The combination of $\log_{10}ft$ values from ^{124}I and ^{124}Sb decay for the level at 2681 keV allows spin-parity values of 1, 2, 3+. The ground-state transition rules out a possible 3+ assignment, since it is not likely that a 2682-keV $M3$ transition would compete to such an extent with a 2079-keV $M1/E2$ transition.

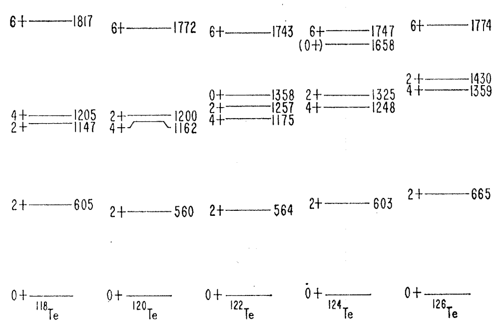

FIG. 6. Low-energy level structures of even-A Te isotopes, 118–126. From Refs. 4, 23, 32, and 33.

The data from our experiments permit a (2, 3±) assignment for the level at 2701 keV. Table V shows conversion coefficients for the major transitions in ^{124}I and ^{124}Sb decay using our Ge(Li) data and the conversion electron data from Ruan and Inoue[5] and from Grigor'ev *et al.*[24] The conversion coefficient for the 1376-keV transition to the $2+_2$ level is 0.29×10^{-3}. This value is to be compared with theoretical values of $(0.30, 0.65, 0.73, \text{and } 1.8)\times10^{-3}$ for $E1$, $E2$, $M1$, and $M2$ transitions, respectively. On the basis of an assumed $E1$ multipolarity for the 1376-keV transition, the possible spin-parity values are limited to (2, 3−).

The level at 2775 keV is fed only in ^{124}Sb decay. The conversion coefficient of the 1526-keV γ ray, which decays to the 1248-keV 4+level, is of $E1$ character. Combining these data with the observed $\log_{10}ft$ of 7.7 for the β population of this level indicates that the assignment for this level is 3, 4−. Its absence in the ^{124}I decay scheme is an indication that the probable value is 4− rather than 3−.

The $\log ft$ of 6.4 for the population of the level at 2835 keV is indicative of an allowed transition, while the absence of this level in the ^{124}Sb decay scheme is evidence against an allowed decay in that case. The only

[24] The conversion coefficients were calculated on the basis of normalizing the coefficient for the 602-keV transition to the value for a pure $E2$ transition of 4.23×10^{-3} calculated by Sliv and Band, as stated in Table V, footnote f.

TABLE VI. Relative reduced transition probabilities for even-parity ^{124}Te levels.[a]

From (keV)	To (keV)				
	GRD	$(2+_1)$ 603	$(2+_2)$ 1325	$(4+_2)$ 1248	$(2+_3)$ 2039
1325 $(2+_2)$	1.0	152[b]			
1957 $(4+_3)$		1.0	7.8	39.2	
2039 $(2+_3)$	0.104	1.0	78	14.6	
2182 (2+)[c]	0.394	1.0	24.6		
2224 (2+)	$\leq 10^{-3}$	1.0	11.0	45.4	$\leq 10^4$
2454 (2+)	0.083	1.0	2.61	0.82	

[a] Calculated for pure $E2$ γ transitions.
[b] Calculated on the basis that $\delta^2(E2/M1)=11.6$, as reported in Ref. 25.
[c] Populated in ^{124}Sb ground-state decay only.

assignment consistent with these data is $J^\pi=(1-)$, which is in agreement with the observed conversion coefficient for the 1509-keV transition to the $2+_2$ level.

The two most energetic levels populated by ^{124}I occur at 2988 and 3001 keV, and they are above the Q value for ^{124}Sb ground-state decay. As the $\log_{10}ft$ value for the population of the 2988-keV level is in the range of first forbidden transitions and since the level decays to the ground state, the probable assignments are $J^\pi=(1, 2+)$. Because of the ambiguity of the $\log ft$ value for the population of the 3001-keV level, we were not able to postulate a narrow range of spin-parity assignments.

V. DISCUSSION

A. Models

The low-energy level structures of the even Te isotopes can be discussed in the framework of the harmonic vibrational model.[10] The first 2+ states in the isotopes 118–126 all display strongly enhanced $E2$ transitions, and the ratio of the energy centroid of the two-phonon triplet to the one-phonon state equals 1.90, 2.10, 2.15, 2.16, and 2.08 for masses 118, 120, 122, 124, and 126, respectively, as can be seen in Fig. 6. The microscopic description of vibrational behavior in terms of the pairing-plus-quadrupole model has been utilized with improved single-particle energies to reasonably describe the first 2+ and 3− states of spherical nuclei, including the Te isotopes[25]; the energies, reduced transition probabilities, and gyromagnetic factors have been calculated and agree reasonably well with experiments.

It is well known, however, that the harmonic vibrational approach must be modified to account for observed anharmonicities in even nuclei; the static quadrupole moments of the first 2+ states are large and not zero as predicted; also, the energy systematics and transition rates of the two-phonon states deviate from predictions. Angular correlation measurements[26] have shown that the $2+_2$ to $2+_1$ transition in ^{124}Te has an $M1$ component of 7.9%, contrary to the prediction of B $(M1, 2+_2 \to 2+_1)=0$. The harmonic approximation worsens as the excitation energy increases; this is primarily due to coupling with other modes, including single-particle excitations. Because of the many valence neutrons outside closed shells, the Te isotopes cannot be explained using exact shell-model calculations, while seniority calculations using truncated configuration spaces have had limited success.[27] From an experimental point of view, it is difficult to distinguish between the vibrational excitations, the phonon states modified by coupling with particle modes, and the so-called pure quasiparticle states. We shall utilize the vibrational rule that one-phonon transitions are enhanced while two- or higher-phonon transitions are hindered in order to identify multiple phonon states. The quasiparticle states as well as the coupled phonon-quasiparticle states must be approached on a qualitative basis because of the lack of calculations and the complexity of the level structure.

Before discussing the structure of ^{124}Te, it is useful to describe the wave functions of the odd-odd parent nuclei, ^{124}I and ^{124}Sb, which can be done in the shell-model framework. Since the $\pi(1g_{7/2})^n\nu(1h_{11/2})$ configuration is the only one in this region which can yield a 2− coupling, the ^{124}I ground state is assumed to be either $\pi(1g_{7/2})^3\ \nu(1h_{11/2})$ or $\pi[(2d_{5/2})_0{}^2(1g_{7/2})]\nu(1h_{11/2})$ or a mixture of both configurations. The behavior of the odd Sb isotopes indicates that $\pi(1g_{7/2})\nu(1h_{11/2})$ is the predominant configuration of the ^{124}Sb ground state. This conclusion is consistent with the comparison of the observed ^{124}Sb magnetic dipole moment[28] of $\pm$ 1.26 μ_N with empirical moments calculated from neighboring nuclei. The $\pi(1g_{7/2})\nu(1h_{11/2})$ and $\pi(2d_{5/2})\nu(1h_{11/2})$ configurations yield empirical moments of -1.63 and -3.44 μ_N, respectively.

B. Even-Parity Levels

The $\beta^\pm$ decays to the $2+_1$ level in ^{124}Te are quite interesting because the level is fed 10^3 times more strongly from ^{124}I decay than from ^{124}Sb decay. The very large $\log_{10}ft$ for ^{124}Sb decay (10.6) seems to be due to two effects, one of which also applies to ^{12}I decay. Since the basic transition must occur between the $1h_{11,2}$

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TABLE VII. Relative reduced transition probabilities for odd-parity ^{124}Te levels.[a]

From (keV)	To (keV)	$2+_1$ (603)	$2+_2$ (1325)	$4+_2$ (1248)	$2+_3$ (2039)	$4+_3$ (1957)	$(2+_4)$? (2224)
2293 (3−)		1.00	0.20	0.16		0.21	
2693 (3−)		1.00	0.27	0.11	0.01	0.54	
2701 (2, 3−)		1.00	43.0	b	12.4		74.9
2835 (1−)		1.00	17.0		1.70		
2886 (2, 3−)		1.00	7.71	b	0.073	b	

[a] Calculated for pure $E1$ γ transitions.

[b] Possibility of 2 − assignment prevents calculation.

neutron and $1g_{7/2}$ proton orbitals, the shell-model j-selection rule reduces the $\Delta J=1$ matrix elements, thereby allowing the B_{ij} matrix elements (the β-decay matrix elements of rank two) to become the dominant term in the transition, in the case of ^{124}Sb.[29] However, the B_{ij} matrix element $(1/R\int B_{ij}=1.4\times10^{-2})$ is still much smaller than predicted by the shell model $(1/R\int B_{ij}=1.5)$ or the collective model $(1/R\int B_{ij}=3.4)$. This reduction is interpreted as being due to a cancellation between the largest terms leading to the B_{ij} matrix element caused by particle-hole interactions associated with the collective vibration.[30] The B_{ij} matrix element contributes to a lesser extent in the first forbidden β^+ decay of ^{124}I(2−) and β^- decay of ^{122}Sb(2−) to Te $2+_1$ states. Two possible values of $1/R\int B_{ij}$ for ^{122}Sb of 0.312 and 0.304 have been reported.[31] In these cases, the $\Delta J=0$ matrix elements evidently are only slightly affected by the j-selection rule and consequently contribute to the decay more than the B_{ij} matrix element. Therefore, the bulk of the difference between the $\log_{10}ft$ values seems to be a shell-model angular momentum effect, while the collective effects would be essentially the same in each case, serving to raise the $\log_{10}ft$ values above the "normal" values. Some additional hindrance would result from configuration mixing of the $2d_{5/2}$ proton orbital into the ^{124}Sb ground state because the proton would not enter into the β decay. Although the $\log_{10}ft$ values for the population of the 2+ level at 1325 keV are somewhat closer together, the above interpretation should apply to the $\beta^\pm$ transitions to this level also.

Previously published results[1,19,23,26] have established the 4+ level at 1248 keV and the 2+ level at 1325 keV as having the characteristics of the corresponding members of the two-phonon triplet. The level at 1657 keV is postulated as being the 0+ member of this triplet; however, since the experimental evidence accumulated for this level is not yet conclusive, the assignment must remain tentative. It is interesting to note that the ft value of the level at 1657 keV is a factor of $10^{1.7}$ less than the population of the ground state in the decay of ^{124}I. In the decay of ^{122}I(1+) to ^{122}Te, the ft value for the population of the two-phonon 0+ level at 1358 keV is also a factor of $10^{1.7}$ less than the ft value for the ground state.[32] As Table IV shows, this level was populated in the (p, p') reaction as was the two-phonon 0+ state in ^{122}Te, which occurs at 1358 keV.[4]

The low $\log_{10}ft$ value for the population of the 1747-keV level by the 1.5-min 5+ isomer of ^{124}Sb seems to indicate that this level is a two-quasiparticle level.[1] As pointed out above, the (n, γ) results[9] show that there are several low-spin levels which occur very close to the level we observe. Because of this high-level density, we cannot be sure that the 1746-keV level populated in the (p, p') experiment is the same level we report at 1747.0 keV. Inelastic scattering reactions such as (p, p') preferentially excite collective states; however, since Cookson and Darcey[6] did not report the transition strength for their observed level, their results cannot be used to demonstrate whether the level is collective, pure quasiparticle, or a mixture of several quasiparticle configurations. Although the β- and γ-decay data permit a 5, 6+ assignment for the 1747-keV level, Bergström *et al.*[23] have proposed a 6+ assignment from observing the angular distributions of the γ rays from the ^{122}Sn$(\alpha, 2n)^{124}$Te reaction. Therefore, it is reasonable to assume that this level is composed of several sets of two-quasiparticle configurations. In this region the $2d_{5/2}$ and $1g_{7/2}$ orbitals are the proton orbitals which lie closest to the Fermi energy and, hence, are the most likely candidates for the quasiproton components. Both the $\pi[(2d_{5/2})(1g_{7/2})]$ and $\pi(1g_{7/2})^2$ configurations can couple to 6+, and the 1747-keV level most likely contains a mixture of both configurations. In order to explore the possibility of neutron particle-hole excitations contributing to the 1747-keV level wave function, we can utilize the results of recent ^{124}Te$(d, p)^{125}$Te experiments. Jolly[8] has shown that the emptiness (U_j^2) of the neutron orbitals in ^{124}Te is

$$U^2(2d_{5/2})=0.06, \qquad U^2(3s_{1/2})=0.08, \qquad U^2(2d_{3/2})=0.31.$$

It is also possible to infer from Jolly's results[8] that the $1g_{7/2}$ neutron orbital is full $(U_j^2=0)$, and that the $1h_{11/2}$ neutron orbital is approximately half-full $(U_j^2\cong$

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[33] I.-M. Ladenbauer-Bellis and H. Bakru, Phys. Rev. **175**, 1507 (1968).

0.5). Therefore, neglecting excitations into the next major shell and assuming that the $2d_{5/2}$ and $1g_{7/2}$ neutron orbitals are full, only the $\nu(1h_{11/2})^2$ configuration can couple to 6+.

An additional complication is the interaction of the three-phonon 6+ state. The centroid of the three-phonon multiplet should lie at 1.8 MeV, and the three-phonon 6+ state should lie close to the centroid energy due to the statistical weighting factor of $2J+1$. As can be deduced from Fig. 6, $E(6+)/E(2+_1)$ equals 3.00, 3.16, 3.09, 2.90, and 2.67 for masses 118–126, whereas the vibrational model predicts a ratio of 3.0. Perhaps the lowering of the 6+ energy relative to the $2+_1$ energy as the neutrons increase can be explained by the increasing admixture of two-quasiparticle configurations into the 6+ level, thereby stabilizing the level relative to the phonon energy.

As we have pointed out previously,[1] the favored decay of the levels at 1957 and 2039 keV to the two-phonon states make them likely candidates for members of the three-phonon quintet. If this is so, it appears that the 4+ and 2+ members of the three-phonon band are populated and occur at 1957 and 2039 keV, respectively. The relative moments of the 2183-keV level, as shown in Table VI, indicate that this level has three-phonon decay characteristics. This situation raises a confusing issue, however, since the 2039- and 2183-keV levels both appear to belong to the three-phonon band. The decay data do not rule out a 1+ assignment for the 2183-keV level, however, and if this level is 1+, it is undoubtedly of two-quasiparticle character. On the other hand, the existence of two such three-phonon 2+ states would indicate band mixing or a splitting of the strength of the three-phonon 2+ states, most likely by interaction with 2+ two-quasiparticle states.

The level at 2224 keV possesses a very large reduced transition moment to the 2039-keV 2+ state relative to its other decays. This characteristic seems to label it as a four-phonon band member, whose unperturbed centroid should occur at 2.5 MeV. The decays of the levels at 2483, 2521, and 2775 keV to the three-phonon multiplet are favored relative to other decays, thereby indicating these levels as possible four-phonon band members. The levels at 2412, 2454, and 2711 keV prefer to decay to the two-phonon levels. The significance of these characteristics is not known; they might reflect band mixing, quasiparticle-phonon mixing, or other anharmonic effects.

C. Odd-Parity Levels

The evidence which establishes the 3− level at 2293 keV as the one-octupole-phonon state was extensively discussed in our report on the ^{124}Sb decay scheme.[1] Also discussed was the liklihood that the 2693-keV 3− level is a member of the coupled quadrupole-octupole phonon quintet. It is difficult to analyze the composition of the other odd-parity levels because of the ambiguity in spin values. Because of the parity ambiguity for the 2641-, 2747-, and 3001-keV levels we could not include them in Tables VI or VII. Table VII shows relative transition moments for the levels at 2701, 2835, and 2886 keV, which are considered to be of odd-parity. The decay of the levels at 2835 and 2886 keV both favor the $2+_2$ state relative to the $2+_1$ and $2+_3$ states, which would seem to be a characteristic of coupled quadrupole-octupole states. In addition, both states have very strong transitions to the one-octupole-phonon state at 2293 keV. The (d,t) and (α,α') experiments populate a state at 2.84 MeV; however, the poorer resolutions prevent any definite comparison with the state which we report at 2835 keV.

The level at 2701 keV behaves very differently from the other odd-parity states; it does not decay to the one-octupole state, and it very strongly favors decay to the 2224-keV level which we have tentatively assigned as the $2+_4$ state. The meaning of this decay is not yet understood.

D. Quasiparticle Levels

There have been several levels mentioned in this paper as possibilities for quasiparticle levels: the levels at 1747, 2349, 2641, and 2747 keV. Because of the high density of phonon levels, pure quasiparticle levels must have spin-parity values unlike those of nearby phonon levels in order to avoid mixing. Of the states populated in ^{124}Sb and ^{124}I decay, the levels at 1747 and 2349 keV are the lowest possible observed two-quasiparticle states, and both of these are strongly populated by the 5+ isomer of ^{124}Sb.[1] Since the most likely configuration for the 5+ isomer is $\pi(1g_{7/2})\nu(2d_{3/2})$, and since the β^- decay probably occurs between the $\nu(d_{3/2})$ and $\pi(d_{5/2})$ orbitals, the most probable particle configuration for the 1747- and 2348-keV levels is $\pi[(d_{5/2})(g_{7/2})]$. For ^{124}Te, the first two-quasiproton level can occur at $\sim$2.0 MeV, as calculated from odd-even mass differences. However, the first quasineutron level should not occur until 2.5 MeV, due to the increased pairing energy for neutrons.[11] Therefore, it is probable that excited neutron configurations do not contribute greatly to the 1747- and 2349-keV levels.

The 2641- and 2747-keV levels are possible quasiparticle levels, because they are likely $J=1$ states. Since there are several quasiproton and quasineutron configurations which can couple to $J=1$, it is not useful to discuss them in detail without further experimental evidence.

It would be extremely interesting if proton pickup and neutron stripping and pickup reactions were carried out for ^{124}Te. These direct reactions would help to determine the quasiparticle character of the excited states.