Gamma-ray cascade population of the $\frac{19}{2}^-$ isomer in the decay of $^{133}Te^m$ to levels of ^{133}I

W. B. Walters
Department of Chemistry, University of Maryland, College Park, Maryland 20742

E. A. Henry and R. A. Meyer
Nuclear Chemistry Division, Lawrence Livermore National Laboratory, Livermore, California 94550
(Received 21 October 1983)

We have studied the decay of 55.4-min $^{133}Te^m$ to the levels of ^{133}I. The population of 47 excited states in ^{133}I following the decay of $^{133}Te^m$ is proposed and evidence for ten additional states is discussed. The observed decay patterns are found to be strongly influenced by the levels populated in the β decay of the $\frac{11}{2}^-$ parent cascade through an intermediate energy three-particle $\frac{19}{2}^-$ isomer rather than simply decaying by $E1$ γ rays to the lower-lying positive parity levels. We discuss the role of these structurally controlled γ ray cascades on processes occurring in nuclides near closed shells.

I. INTRODUCTION

The deexcitation of nuclei with energies between 2 MeV and the particle binding energy is generally treated in a statistical manner.[1] The initial approaches to such treatments were set forth by Huizenga and Vandenbosch[2] and by Sperber.[3] These treatments generally assume that when $E1$, $M1$, and to some extent, $E2$ transitions to lower levels are possible, such transitions will dominate the deexcitation process because the E^3 or E^5 energy dependence will outweigh the smaller differences in matrix elements that might exist for nearby levels. On the average, the spin population will move toward the centroid of the spins of available states. In general, very low spin initial populations will populate states with higher average spin and very high spin initial populations will populate states with lower average spin. Many studies of the decay of the $\frac{1}{2}^+$ states formed by the capture of thermal neutrons by even-even nuclei support the former process and many studies of the decay of the high spin populations formed in heavy ion reactions support the latter.

The direct influence of nuclear structure in the aforementioned processes has just begun to be explored.[1,4] Wide variation in isomer ratios found in neutron capture studies[5] and some of the isomer ratios measured in fission[6] can be attributed to nuclear structure effects not included in the statistical approaches.

One opportunity to explore these nuclear structure effects lies in studying the population of relatively high spin isomers by γ-ray cascades following β-decay population of levels possessing much lower spin values. Among a number of such isomers that have been identified is 9-s $\frac{19}{2}^-$ $^{133}I^m$ which can be indirectly populated following the decay of 55.4-min $\frac{11}{2}^-$ $^{133}Te^m$.

In this paper, we report the results of experimental studies of the decay of $^{133}Te^m$. We then note how the branching to the high spin isomers can occur because of the dominant influence of nuclear structure in a few γ-ray cascades, a process we call structurally controlled γ-ray cascades (SCGC).

II. EXPERIMENTAL PROCEDURES

The fission product $^{133}Te^m$ was isolated from gross fission products by radiochemical techniques. Experiments were conducted at both the Livermore Pool Type Reactor (LPTR) and the National Bureau of Standards Reactor. The samples were generally processed ~ 1 h following irradiation. For the singles and coincidence studies of $^{133}Te^m$ decay the tellurium was absorbed on an ion exchange resin that had a K_D of $\geq 10^6$ for tellurium and less than one for the daughter iodine. The experimental setup is shown in Fig. 1. During the coincidence measurement periods the daughter iodine was eluted away, while the adsorbed Te remained at the counting position.

Owing to the low Q_β value of ^{134}Te (1.3 MeV) and the long half-life of ^{132}Te (78 h) the only serious source of additional γ rays was 25 min $^{131}Te^g$ whose decay properties have been carefully studied in earlier investigations.[8]

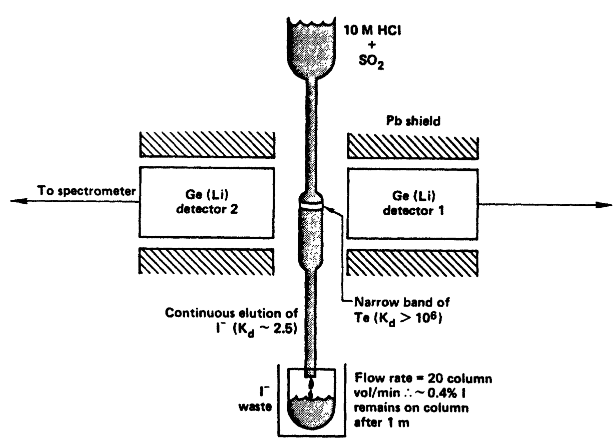

FIG. 1. Counting arrangement for samples of $^{133}Te^m$.

The γ-γ coincidence data were recorded on magnetic tape using a 60-ns coincidence window. Two Ge(Li) detectors of 10% relative efficiency and 2.4-keV full-width at half maximum for ^{60}Co 1332-keV γ rays were used.

In a separate experiment,[9] a solvent extraction separation was performed in order to establish the presence of the 9-s isomer in the $^{133}Te^m$ decay sequence. For this experiment, enriched ^{235}U was irradiated in the LPTR and tellurium separated radiochemically such that it was in solution after the final chemical isolation step. The Te solution was then subjected to iodine extraction in two separate SISAK experiments. The SISAK system[9] is used for continuous, rapid solvent extraction and has as its central component an $H=10$ centrifuge that provides rapid phase separation of two highly mixed immiscible liquids. In the experiments performed by Skarnemark *et al.*[9] the two separate SISAK-II configurations were used and are shown in Fig. 2. In both experiments the 9-s $^{133}I^m$ was detected downstream from the final iodine separation. Variable positions of the Ge(Li) detector(s) along the flow path were used to confirm the 9-s decay of the 647- and 912-keV γ rays that resulted from the isomer's deexcitation.

III. EXPERIMENTAL RESULTS

We present, in Table I, the γ rays that we assign to the decay of 55.4 min $^{133}Te^m$. The criteria for incorporation into this table include possession of a 55±5-min half-life or, for less intense γ rays, a constant intensity ratio in

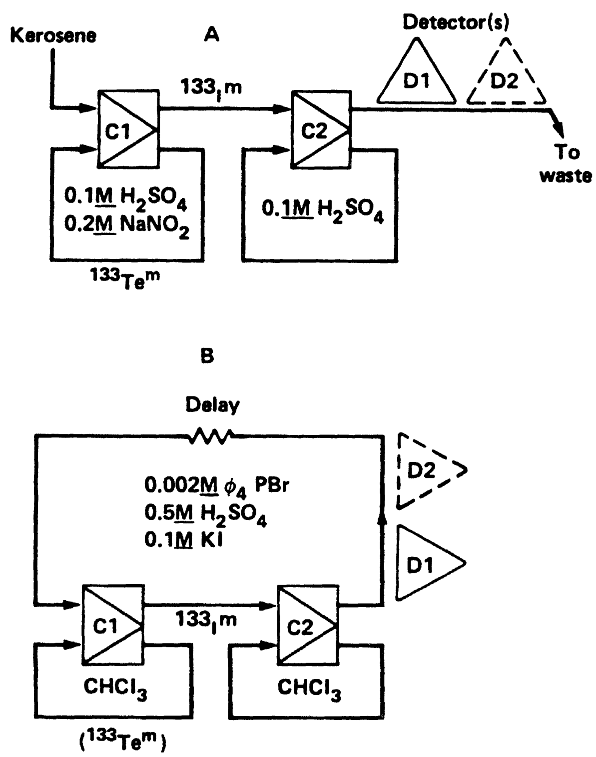

FIG. 2. SISAK configurations used to isolate 9-s $^{133}I^m$ from ^{133}Te.

spectra taken at different times with the more intense γ rays known to belong to $^{133}Te^m$ decay. A separate study of the decay of 12.4 min $^{133}Te^g$ was made,[16] hence it was possible to be more certain of which γ rays belong to $^{133}Te^g$ decay that comes to equilibrium with $^{133}Te^m$ decay. The γ rays with an energy of 897.7, 934.4, and 2027.7 keV were assigned to $^{133}Te^m$ decay by McIsaac;[10] however, we find they belong to the $^{133}Te^g$ decay. The energy values are in good agreement with those listed by McIsaac and those listed by Parsa *et al.*,[7] which have been included in a tabulation by Blachot and Fiche.[11] The energy values for four intense low energy peaks were measured by Börner *et al.*[12] using a bent crystal spectrometer. Their values had an uncertainty of between 14 and 35 eV. For three of the four peaks, the differences between their values and our values are less than the sum of the squares of the uncertainties and for the 261.6 keV γ ray, 261.626±0.007 vs 261.560±0.030 are within 2σ.

The intensity values that we list are also in good, but not in total agreement with those of Parsa *et al.*[7] and of McIsaac.[10] In particular, the intensities for a number of low energy γ rays reported by Parsa *et al.* are higher than those reported by McIsaac and our own values.

We present our proposed decay scheme for $\frac{11}{2}^-$ $^{133}Te^m$ in Fig. 3. A total of 211 γ rays have been listed in Table I and 189 of these are shown in a level scheme involving 47 excited levels. Of these 47 levels, only the 5 at 312.07, 912.67, 1560.18, 1634.21, and 1776.63 keV have been established in prior studies. Of the 42 new levels, 5 are established on the basis of coincidences with the 312.07-keV γ ray, 19 with the 912.67-keV γ ray, 3 with the 647.51-keV γ ray which deexcites the 1776.63-keV level, and 2 with the intense 2005.33-keV γ ray. There are additional coincidences as well as ground state transitions for a number of these levels.

Of the remaining levels, the levels at 2005.5, 2826.3, 2968.1, and 3051.3 keV are suggested by the presence of high energy transitions that could only feed the ground or first excited states and corroborating energy sums that support ground state feeding. The placement of a level at 3028.2 keV is suggested by three γ rays whose energy sums with the levels they populate agree and by the placement of the 1573.5-keV γ ray which, because of its high energy, can only feed levels below 1600 keV. The level at 2807.9 keV is suggested by the presence of the 251.38-keV γ ray in the 863.96-keV γ ray gate in only part of its intensity, and corroborated by energy sums for three other γ rays. The level at 2426.5 keV is placed on the basis of the presence of the 178.0-keV γ ray in the gate with the 471.87-keV γ ray that deexcites the 2248.50-keV level. The level at 1990 keV is placed on the basis of a number of coincidences involving the 261.63-keV γ ray.

The two levels at 1798 and 1816 keV are placed on basis of indirect coincidence evidence. The 18.1-keV γ ray is not observed as is the case with the 39.9-keV γ ray, both of which are too low in energy to be observed in the coincidence spectra. The gate on the 334-keV γ ray shows large peaks at 164, 444, 863, 912, and 1348 keV. The 532 and 1348-keV γ rays originate from the 2261-keV level and are well established from other spectra. No 485-keV γ ray is observed in singles or in this gate to account for

TABLE I. Energy and intensity values for gamma rays in the decay of $^{133}Te^m$.

E_γ	(ΔE_γ)[a]	I_γ	(ΔI_γ)[a,b]	Coincidences	Placement From	Placement To
18.0		(7.0)[c]			1816	1798
20.86	(1)	7.3	(4)		1797	1776
39.9	(1)	3.3	(4)		1816	1776
		2.0	(4)		2559	2516
47.47	(1)	4.0	(3)		1776	1729
50.0	(2)	1.5	(1.1)		1942	1893
52.5	(3)	0.3	(2)			
74.05	(1)	6.8	(5)		1634	1560
81.61	(1)	5.8	(3)		1974	1893
86.85	(2)	0.8	(1)		1646	1560
88.064	(3)	24	(1)		1885	1797
92.33	(3)	3.6	(8)		2142	2049
94.989	(2)	52	(1)	47,213,261,(398),574	1729	1634
97.8	(1)	2.4	(4)		1990	1893
110.23	(7)	1.5	(4)		2371	2261
112.26	(15)	1.9	(8)		2005	1893
116.44	(9)	5[d]	(2)		1893	1776
119.58	(15)	2	(1)		2005	1885
136.64	(5)	2.8	(8)	2005,406[e]	2142	2005
150.80	(2)[f]	12	(1)	169,262,415,453[f],734,847	2142	1990
		6	(2)	912,949[f],997	1797	1646
157.6	(1)	2.0	(5)		2420	2261
164.40	(1)	17.5	(9)		1798	1634
169.025	(5)	95	(2)	150,201,210,213,(244),262, 278,355,406[e],(532), 565,630,642,647,670, 827,847,912,977	1729	1560
176.9	(5)	4	(2)		1885	1708
177.2	(2)	4	(1)		1974	1797
178.0	(2)	6	(2)		2426	2248
184.77	(10)	3	(1)		2556	2371
193.39	(2)	10.7	(5)		1990	1797
198.18	(8)	3	(2)		1974	1776
200.65	(8)	8	(2)		2142	1942
201.00	(1)	3	(1)		(1761	1560)
213.48	(1)	39	(1)		1942	1729
214.00	(1)	4	(1)		(1775	1560)
221.1	(1)	4.3	(9)		2211	1990
224.21	(7)	3	(1)		2595	2371
230.1	(2)	5	(2)			
235.0	(1)	3	(1)		(1795	1560)
240.9	(2)	6	(2)		2686	2445
244.41	(6)	6	(1)		2505	2261
248.9	(5)	0.6	(2)		2142	1893
251.38	(13)	5	(1)		2807	2556
257.82	(4)	8	(1)		2248	1990
261.616	(7)	142	(2)	95,151,165,169,179,181, 221,258,285,344,414, 461,605,648,565,768, 840,912,914,928,1005	1990	1729
278.00	(11)	10	(2)		(1838	1560)
281.2	(5)	2[c]	(1)		1797	1516
284.5	(3)	4[c]	(2)	4,(702),(1683)	2880	2595
294.82	(13)	4	(1)		2556	2261
307.9	(1)	5	(1)		2807	2500
312.072	(3)	40	(3)[e]	343,407[e],602,647,845[e], 995,996,1001[e],1021[e], 1061[e],1142,1204,1252[e], (1334),1392	312	g.s.

TABLE I. (*Continued*).

E_γ	$(\Delta E_\gamma)^a$	I_γ	$(\Delta I_\gamma)^{a,b}$	Coincidences	Placement From	To
314.24	(16)	7	(1)		2686	2371
318.8	(5)	4[d]	(2)		2261	1942
322.4	(2)	2	(1)		2371	2049
326.0	(4)	5[d]	(2)		2826	2500
334.245	(5)	60	(2)	149,165,193,319,369,444, 464,532,864,884,149,1348	2595	2261
		131	(20)		IT	
342.8	(3)	9	(1)		1797	1454
344.39	(5)	13	(2)	164,221,312,(322),414, 435,(507),540	2556	2211
345.6	(4)	4[d]	(3)	863,912,1143,1229,1454	2049	1704
347.31	(4)	12	(1)	261,363,472,863,912,914, 978,1136,1805,2005	2595	2248
355.4	(1)	11.7	(7)		2248	1893
360.8	(6)	0.8	(6)			
363.06	(7)	9	(1)	88,179,914	2248	1885
367.9	(2)	4	(1)		2373	2005
368.5	(2)	2	(1)		2261	1893
369.3	(2)	2	(1)		1885	1516
376.8	(1)	4	(1)		1892	1516
384.0	(7)	3	(2)		2595	2211
392.0	(2)	2	(1)		1307	914
396.97	(4)	13	(1)		2371	1974
406.00	(1)	7	(1)		(1966	1560)
413.2	(2)	12	(1)		2211	1797
415		~2	(1)		2420	2005
429.03	(5)	40	(2)	169,184,(315),912,1029	2371	1942
435.28	(5)	22	(3)		2211	1776
444.94	(2)	37	(2)	157,169,294,334,864,912	2261	1816
458.0	(7)	2	(1)		1974	1516
462.23	(3)	28	(4)		2467	2005
464.0	(5)	5[d]	(3)		2261	1791
471.87	(4)	15	(2)	178,347,632,863,912,(914)	2248	1776
474.7	(4)	2	(1)		2686	2211
478.62	(6)	17	(3)	314,356,978,980,1893	2371	1893
487.40	(6)	10	(2)		2373	1886
492.96	(15)	14	(2)	81,151,198,279,864,914, 1063,1974	2467	1974
495.0	(1)	3.5	(4)		2500	2005
507.2	(3)	8	(2)			
519.7	(1)	5	(2)	396,581,621,1142,1454	1974	1454
525.63	(14)	5	(2)		2516	1990
532.40	(5)	16	(1)		2261	1729
534.88	(4)	19	(2)		3051	2516
540.3	(2)	5	(2)	82,(134),342,(519),596, 756,847,844,1372	1454	914
555.0	(2)	2	(1)		2371	1816
565.3	(5)	1.2	(5)		2556	1990
574.11	(3)	13[d]	(2)	279,510,848,882,884,978, 980,912,	2467	1893
		22	(1)	914,1136,1893	2371	1797
581.38	(15)	9	(2)		2556	1974
586.4	(3)	5	(2)			
601.5	(2)	2.3[d]	(3)		1516	914
602.1	(2)	0.3	(1)		914	312
605.11	(4)	23	(1)		2595	1990
607.3	(8)	3	(2)		2500	1893
621.3	(5)	9[d]	(4)		2596	1974
623.3	(2)	5[d]	(2)		2516	1893

TABLE I. (*Continued*).

E_γ	$(\Delta E_\gamma)^a$	I_γ	$(\Delta I_\gamma)^{a,b}$	Coincidences	Placement From	To
629.0	(1)	6[d]	(2)		2445	1816
632.0	(4)	5[d]	(2)		2880	2248
636.5	(4)	4[d]	(2)		2686	2049
642.33	(9)	16[d]	(2)		2371	1729
647.51	(2)	351	(6)	74,86,134,201,216, 262,278,325,413,430, (681),827,884,912,945	1560	912
653.3	(6)	11	(4)		2595	1942
663.2	(2)	2.0[d]	(8)		2556	1893
681.0	(1)	2	(1)		(2241	1560)
698.1	(1)	17	(3)		2005	1307
702.91	(4)	44	(3)	208,210,863,912,914,978, 980	2595	1843
710.4	(1)	13	(3)		2595	1885
718.9	(2)	15	(4)		2516	1797
723.5	(2)	5[d]	(2)	307,314,326,647	2500	1776
724	(1)	2[d]	(1)	863	2371	1646
731.88	(1)	11	(2)		1646	914
734.00	(4)	32	(2)	151,(187),(295),912,(916),	1646	912
734.1	(1)	1.3[d]	(7)		2783	2049
739.79	(15)	11	(3)		2516	1776
742.9	(2)	7	(2)	92,182,995	2049	1307
753.3	(2)	6	(2)			
756.8	(4)	6	(2)			
779.67	(4)	32	(3)	863,912	2556	1776
782.11	(13)	6	(1)			
789.7	(3)	8	(2)		1704	914
791.7	(9)	2	(2)		1704	912
792.6	(9)	2	(2)		1707	914
792.9	(9)	2	(2)		2500	1707
794.7	(9)	19	(5)		1707	912
795.9	(9)	2	(2)		2500	1704
800.54	(54)	20	(5)	88,369,883,912,972,1885	2686	1885
805.1	(3)	3	(1)		2795	1990
816.34	(8)	14	(1)		2807	1990
819.3	(3)	3	(2)		2595	1776
827.05	(9)	10	(2)		2556	1729
851.7	(5)	2[d]	(1)		2826	1974
859	(1)	2[d]	(1)		2420	1560
863.955	(9)	283	(6)	86,88,116,150,177,194, 198,244,252,334,345, 348,435,444,463,472, 535,574,703,723,739, 780,801,819,847,914, 1007,(1104),(1136),1198	1776	912
882.70	(5)	40	(3)	914	1797	914
884.80	(6)	18	(3)		1797	912
		18	(3)	647	2445	1560
888.53	(15)	15	(3)		2595	1707
889.9	(3)	5[d]	(1)		2880	1990
891.4	(1)	19	(3)		2595	1704
912.671	(4)	1000	(3)	74,82,88,169,177,193, 244,262,286,334,(345), 435,445,472,540,574, 624,630,647,703,723, 734,780,791,792,796, 857,863,884,949,972, 980,1029,1042,1061, 1078?,1137,1196?,(1229),	912	g.s.

TABLE I. (*Continued*).

E_γ	(ΔE_γ)[a]	I_γ	(ΔI_γ)[a,b]	Coincidences	Placement From	Placement To
				1348,1458,(1507),(1532), 1587,1643,1683,1773, 1870,1967,2060		
914.774	(12)	198	(4)	112,194,356,478,574, 705,816,883,912,949, 1135,(1175),1227,1456	914	g.s.
945.2	(2)	11	(2)		2505	1560
949.2	(3)	12[d]	(3)	151,313,731,734,912	2595	1646
970.5	(2)	6	(3)		1885	914
972.64	(11)	10	(3)	81,97,111,112	1885	912
978.30	(4)	88	(3)	356,368,479,493	1893	914
980.26	(5)	27	(3)	493,574,608,623,663, 703,766,805,912,914	1893	912
995.2	(2)	9	(3)		1307	312
996.1	(3)	7	(5)		2556	1560
1007.5	(2)	12[d]	(3)	912,863	2783	1776
1015.1	(3)	2	(1)			
1029.88	(6)	22	(3)		1942	912
1035.5	(1)	2	(1)		2552	1516
1053.7	(3)	3	(1)		3028	1974
1059.8	(5)	1[d]	(1)		1974	914
1061.89	(6)	30	(3)	396,492,621,912	1974	912
1078.13	(15)	3	(2)		1990	912
1079.63	(14)	10	(2)		2595	1516
1090.5	(2)	2[d]	(1)		2005	914
1098.4	(2)	16	(4)		2552	1454
1103.9	(3)	2	(1)		2807	1704
1134.88	(15)	6	(2)		2049	914
1137.3	(5)	5[d]	(3)		2049	912
1142.74	(9)	24	(4)	(82),312,343,520	1454	312
1174.0	(5)	7	(2)		2482	1307
1198	(1)	4	(2)		2973	1776
1204.2	(2)	4	(1)		1516	312
1227.5	(8)	3[d]	(2)		2142	914
1229.6	(3)	4	(2)		2142	912
1252.0	(2)	6	(2)		3028	1776
1299.2	(2)	3[d]	(2)		2211	912
1307.2	(2)	7	(1)		1307	g.s.
1334	(1)	5	(4)		1333	g.s.
1348.87	(5)	27	(1)	110,334,912	2261	912
1372.3	(5)	5	(2)		2826	1454
1392.3	(5)	2	(1)		1704	312
1405.0	(9)	2	(1)		3051	1646
1455.0	(1)	13	(3)	312,343,566,860,	1454	g.s.
1456.0		2	(2)	914	2371	914
1458.9	(2)	3	(1)		2371	912
1506.2	(8)	5	(2)		2420	914
1516.26	(8)	23	(3)	281,369,376,397,459,497, 914?,1079	1516	g.s.
1537.0	(8)	1.6	(5)			
1552	(1)	3	(2)		2467	914
1570.0	(3)	2	(1)		2482	912
1573.5	(2)	5	(2)		3028	1454
1581.0	(8)	3	(2)			
1587.66	(6)	26	(3)	326,912	2500	912
1643.6	(5)	6	(2)		2556	912
1646.2	(3)	5	(2)		1646	g.s.
1683.23	(2)	7	(2)	(247),912	2595	912

TABLE I. (*Continued*).

E_γ	$(\Delta E_\gamma)^a$	I_γ	$(\Delta I_\gamma)^{a,b}$	Coincidences	Placement From	To
1693.3	(3)	0.2	(1)		2005	312
1704.4	(1)	13	(1)	93,345,795,891,912	1704	g.s.
1773.2	(1)	12	(1)		2686	912
1797.5	(2)	3.2	(8)		1797	g.s.
1870.8	(1)	10	(2)	912	2783	912
1881.2	(2)	4	(1)			
1885.62	(7)	18	(2)		1885	g.s.
1892.98	(8)	2.8	(7)	702	1893	g.s.
1914	(1)	1.0	(8)		2826	912
1967.8	(2)	3	(1)		2880	912
1974.6	(2)	0.7	(2)		1974	g.s.
2005.33	(9)	61	(4)	136,357,415,462,495	2005	g.s.
2016	(1)	0.8	(4)			
2049.66	(6)	22	(2)	92,286,322,636,734	2049	g.s.
2062	(1)	1.8	(5)		2974	912
2144.4	(5)	1.2	(3)			
2482.5	(4)	1.2	(4)		2482	g.s.
2826.3	(4)	2.5	(6)		2826	g.s.
2968.1	(4)	2.0	(3)		2968	g.s.
3051.3	(4)	5.8	(4)		3051	g.s.

[a]The values in parentheses denote the uncertainty in the last digits of the adjacent number.
[b]The intensity values are given relative to 1000 for the 912.6-keV γ ray.
[c]Intensity determined from decay scheme intensity balance requirements.
[d]Intensity derived from coincidence spectra.
[e]$^{133}Te^g$ ground state γ ray (in equilibrium with $^{133}Te^m$).
[f]γ ray from 25.0 min $^{131}Te^g$ decay.

the coincidence with the 863-keV γ ray coming from the 1776-keV level. The gate on the 863-keV γ ray shows strong peaks at 334 and 344 keV, indicating that the feeding from the 2261-keV level to the 1776-keV level is through the 444-keV γ ray. The gate on the 444-keV γ ray shows large peaks at 164, 334, 863, and 912 keV, whereas, the gate on the 913-keV peak *does not* show any intensity at 164 keV. Taken together, these coincidences indicate that the 334-keV γ ray must feed into the 2261-keV level, that the 444-keV γ ray must lie between the 2261- and 1776-keV levels, and that the 164-keV γ ray must lie below the 444-keV γ ray and feed directly or indirectly into the 9-s isomer at 1634 keV. In addition, the gate on the 334-keV doublet whose 344.4-keV member is well established as feeding into the 2211-keV level also shows (among other things) the 164-keV γ ray and a γ ray at 413 keV that is not observed in the 912-keV gate. These latter coincidences indicate a direct 413-164 cascade into the 1634-keV isomer and, as the 164-keV γ ray must be at least 444 keV below the 2261-keV level, indicate that the 164-keV γ ray is the lower member of the cascade. Therefore, a level must exist at 1798 keV that is directly populated by the 413-keV γ ray. Moreover, a level that is fed by the 444-keV γ ray must exist at 1816 keV that branches to both the 1798- and 1776-keV levels. We also observe weak peaks at 555 and 629 keV in the spectrum gated on the 863-keV γ ray that can be fed into the 1816-keV level from levels at 2371 and 2445 keV.

The branching of the 1816-keV level can be deduced from the 5.5±0.5 ratio of the intensity of the 864-keV γ ray to the intensity of the 164-keV γ ray in the gate on the 444-keV γ ray. This branching would place 7±1 intensity units via the 18.1-keV transition. This value is consistent with the intensity of the 164-keV transition. A minimum total intensity of 39 units must then be assigned to the 40-keV transition between the levels at 1816 and 1776 keV. As a pure 40-keV $M1$ transition has an $\alpha_T=11$, the I_γ would be 3.3. This value is less than the singles intensity of 5.3±0.4 and leaves a maximum 2.0±0.4 γ intensity units and 26 total intensity units to be assigned to the 39.9-keV transition between the 2556.30- and 2516.40-keV levels.

Energy sums suggest the possibility of additional levels at 2373, 2552, and 2795 keV. We have indicated these possibilities in parentheses in Table I but have not shown these levels in the decay scheme. Several energy sum possibilities also exist for the γ rays for which we show no assignment. None of the unassigned γ rays fit between any of the levels shown in the decay scheme.

The coincidence gate set on the 261.6-keV γ ray is also of interest. The 95.0-, 169.0-, 647.4-, and 912.7-keV γ rays show up with very low intensity, while the 150.8-, 221.1-, 257.8-, and 605.1-keV γ rays show up as very intense peaks. We attribute these data to a lifetime for the $\frac{15}{2}^-$ level at 1729.2 keV that is larger than the 60 ns gate that we used for our coincidence measurements. Using the ratio of expected counts to predicted counts in both the 150-keV gate which is in prompt coincidence with the

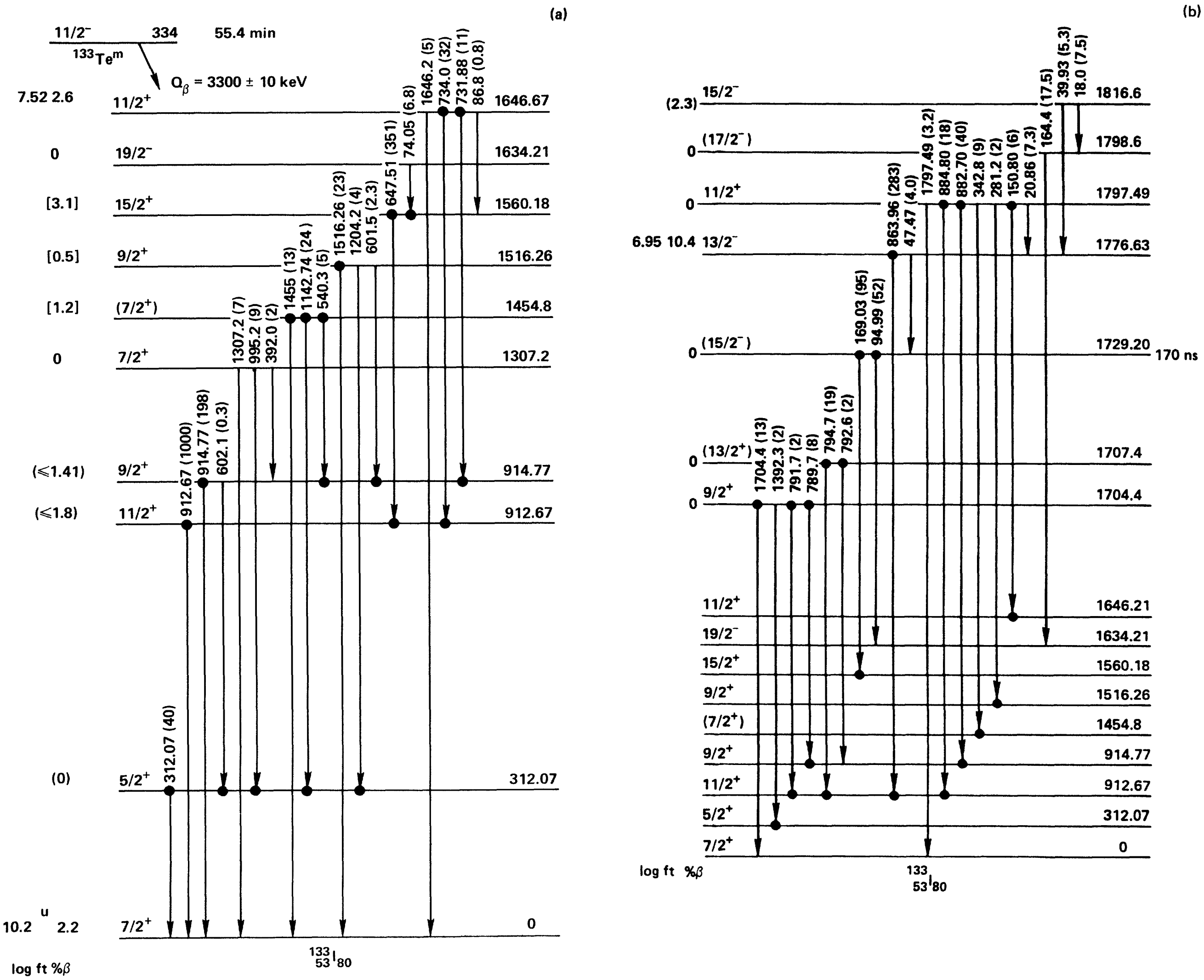

FIG. 3. Decay scheme for ^{133}Te^{m}. (a) Levels up to 1650 keV; (b) levels from 1660 to 1820 keV; (c) levels from 1830 to 1975 keV; (d) levels from 1980 to 2150 keV; (e) levels from 2160 to 2270 keV; (f) levels from 2280 to 2490 keV; (g) levels from 2500 to 2560 keV; (h) levels from 2570 to 2790 keV; (i) levels from 2800 to 3060 keV.

261.6-keV γ ray and the 169-keV gate which feeds out of the 1729-keV level, we can estimate the half-life of this level as approximately 170 ns. The partial half-life of the 95-keV $E2$ γ ray is thus approximately 800 ns, a value about 2 times faster than the 1.8 μs Weiskopf estimate for a 95-keV $E2$ transition.

The presence of 5 γ rays between 792 and 796-keV is required by the coincidence data and the presence of 789.5-keV γ rays in the 794-keV gate. The two levels at 1704 and 1707 keV are firmly established by the presence of the 891-keV γ ray in the 1704-keV gate and the 888-keV γ ray in the 794-keV gate. The intensity distribution of the 28 intensity units in the 5 γ rays is governed by the need to have sufficient γ-ray intensity out of the 1707-keV gate to balance the intensity input.

Another feature of the coincidence spectra is the presence in the 647-keV gate of a number of γ rays not observed in the singles spectra. These γ rays are of some importance as the level scheme shows only 305 intensity units emitted the $\frac{15}{2}^+$ 1560-keV level, whereas the γ-ray intensity emitted is 351±6 intensity units. Thus, either substantial unique first-forbidden β-ray feeding exists or some γ-ray feeding has not been observed. The calculated β branch for a $\log f_1 t = 8.5$ is 0.3% or 4 intensity units. Because of the total conversion coefficient of 23.2 for the 74-keV $M2$ transition, the small uncertainty of the intensity for the 74-keV γ ray is magnified and could account for $\frac{1}{4}$ of the 45+16 γ-ray plus conversion-electron intensity unit difference. We can identify six transitions in the 647-keV γ-ray gate which are too low in intensity to be clearly observed in the singles spectra. These γ rays are the 201-keV ($I_\gamma=3$), 214-keV ($I_\gamma=4$), 235-keV ($I_\gamma=3$), 278-keV ($I_\gamma=10$), 406-keV ($I_\gamma=7$), and 681-keV ($I_\gamma=5$) γ rays. If none are in cascade with another of the group they could suggest a group of six additional levels with spins ($\frac{11}{2}^+$ and $\frac{13}{2}^+$) that feed into the $\frac{15}{2}^+$ level at

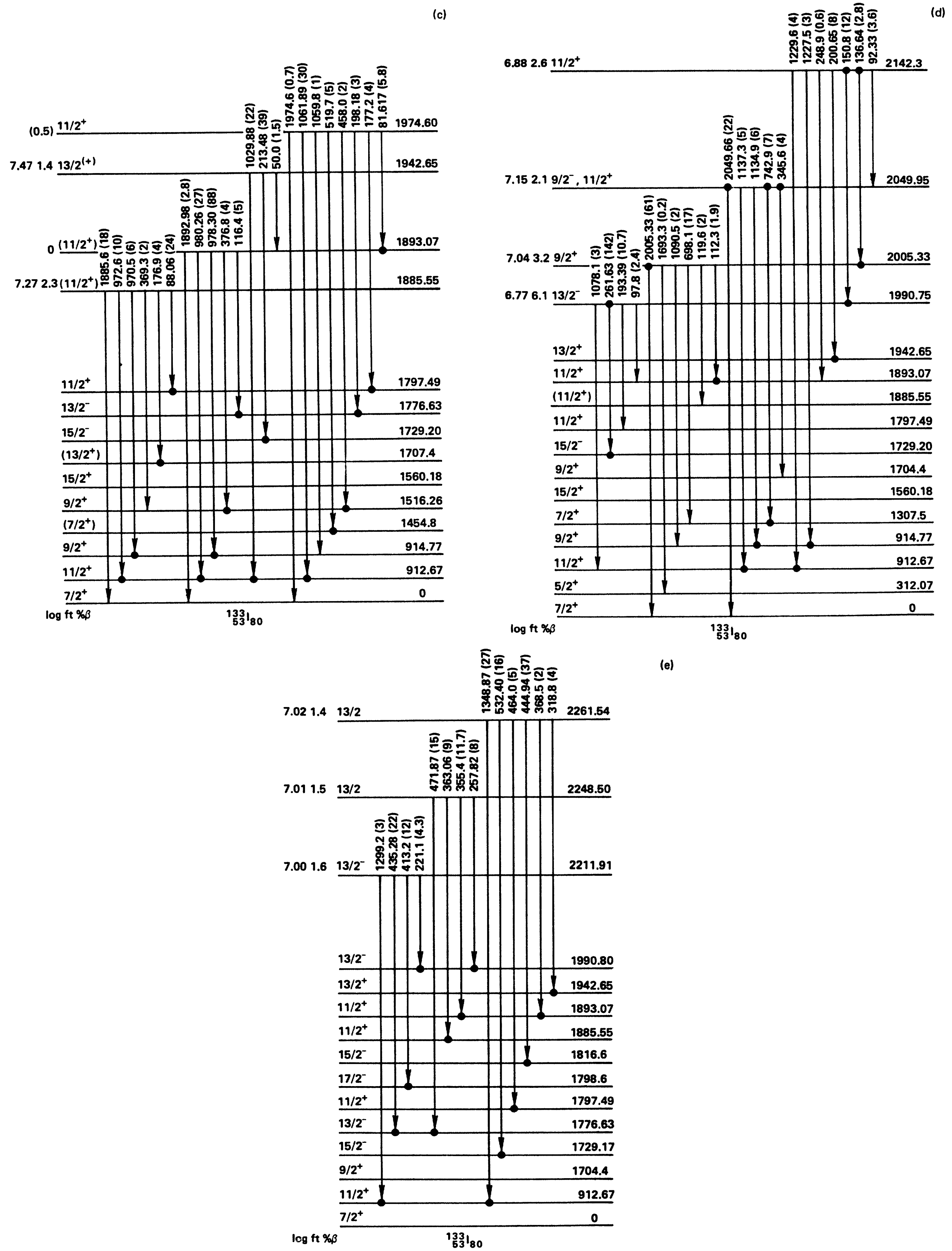

FIG. 3. (*Continued*).

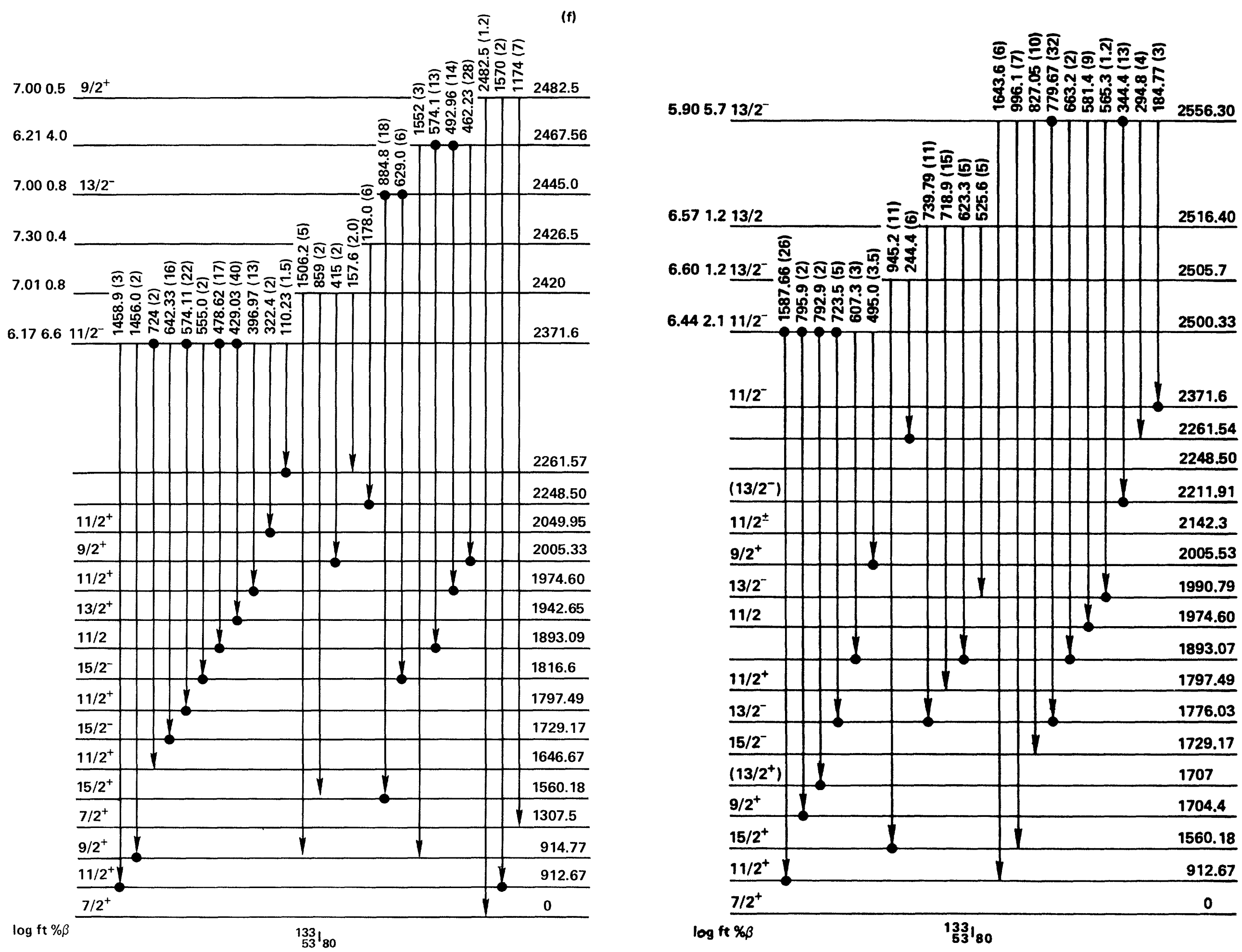

FIG. 3. (*Continued*).

1560.2-keV. These levels would lie at 1761, 1775, 1795, 1838, 1966, and 2241 keV. These $32+8$ intensity units would nearly complete the feeding of the 1560-keV level. These unplaced γ rays can be observed in spite of their low intensity because the two most intense γ rays feeding into the 1560.2-keV level come from the 9-s and 170-ns isomers, and thus eliminate from the 647 gate the strongest γ rays feeding into those isomers. It must be also noted that the observed feeding into the 9-s isomer is 174 units, whereas the outfeeding into the 1560.2-keV level is 164 units, assuming a pure $M2$ 74.05-keV transition ($\alpha_T=23.2$). As the total conversion coefficient, α_T, for an $E3$ transition is 100, an $E3$ admixture of 10% would account for the feeding of the 1560.2-keV $\frac{15}{2}^-$ level.

The β-ray branching was computed by summing the γ-ray intensity feeding the ground state and adding a two percent direct branch to the ground state which was estimated from systematic data of related nuclei. The 2% value is an estimate based on the $\log f_1 t$ values of 9.9, 10.1, and 10.6 for decay of $\frac{11}{2}^-$ isomers in ^{127}Te, ^{129}Te, and ^{131}Te, respectively, to the $g_{7/2}$ states in the daughter nuclides. This results in a normalization factor of 0.069 for converting from relative γ-ray intensity to γ rays per 100 decays. The difference between γ-ray intensity in and out of a level is attributed to β feeding. For all of these levels below 1646 keV, the net feeding is a small number that is a difference between two large numbers and has a large uncertainty. As the percentage of β feeding and log*ft* to the levels below 1646 keV have no real signifance, we have shown for them only a bracketed value for the percentage of β feeding and no log*ft* values in the decay scheme figures.

The log*ft* values were compared by adding the log*f* values for a Q of 3300 keV from the tables of Gove and Martin[13] and the log*t* (partial) values calculated assuming a 17% isomeric transition (IT) decay for the 55.3-min ^{133}Te^m isomer. The resultant partial half-life of 4000 s was used with the listed β percentage to compute the log*t* (partial) values.

At the time of the discovery[14] of the 9-s isomer in ^{133}I, the level structure of ^{133}I was not well characterized. Only the 912- and 647-keV cascade was well established,[7] and spins and parities of $\frac{7}{2}^+$ and $\frac{5}{2}^+$ established for the ground and 312-keV levels. The $\frac{11}{2}^+$ and $\frac{15}{2}^+$ assignments for the 912.7- and 1560.2-keV levels arise from the half-life of 9 s for the isomer and the absence of any 721.6-keV crossover transition from the isomer to the 912.7-keV level. Bergstrom *et al.*[14] note that the half-life

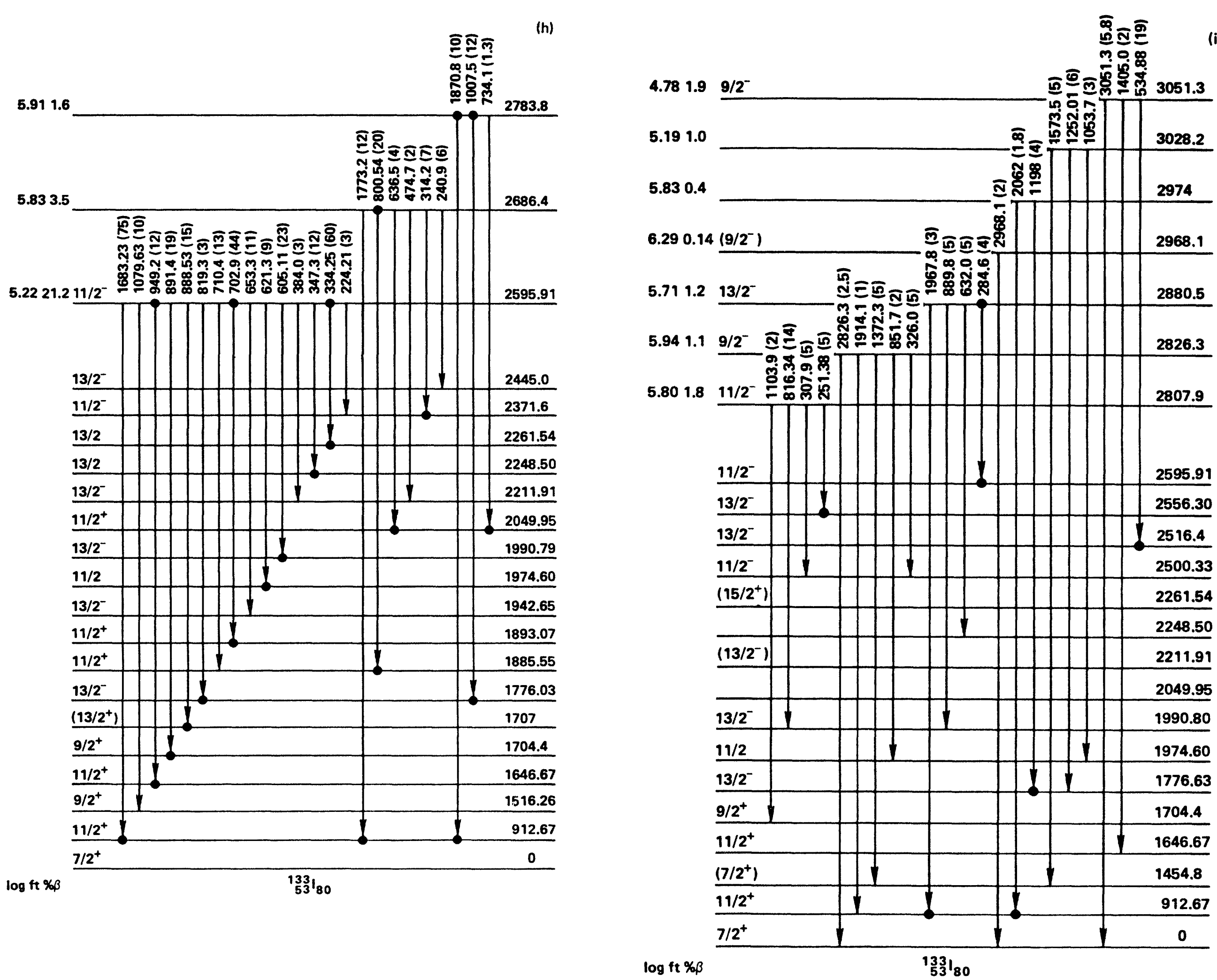

FIG. 3. (*Continued*).

and the K/L conversion electron ratio for the 74-keV transition indicate an $M2$ or $E3$ transition. If the isomer was a $\frac{17}{2}^-$ isomer, the half-life of a 721-keV $E3$ transition would be $\sim 10\ \mu s$. As we can set an upper limit of $\sim 1\%$ for such a γ branch, $E3$ hindrance of 10^7 would be required. As such a high hindrance is quite unlikely, the minimum spin for the isomer is $\frac{19}{2}^-$ and the 912.7-keV level must be $\frac{11}{2}^+$. The 1560.2-keV level could be $\frac{13}{2}^+$ and the 74-keV transition could be an $E3$ transition. However, the α_T value for a 74-keV $E3$ transition is ~ 100 vs 23 for an $M2$ transition.[15] The extra factor of 75 multiplied by the $I_\gamma = 6.8$ that we observe for the 74-keV γ ray would add 500 intensity units to the feeding of the 1560.2-keV level. Thus, the 74-keV transition must be largely $M2$, the 1560.2-leV level must be $\frac{15}{2}^+$, and the 9-s isomer must be $\frac{19}{2}^-$.

The $\frac{7}{2}^+$ assignment for the 1307.2-keV level arises from the branching that we observe and the indirect feeding observed[16] in the decay of $\frac{3}{2}^+$ $^{133}Te^g$. Firm assignments of $\frac{15}{2}^-$ for the 170 ns 1729-keV level and $\frac{13}{2}^-$ for the 1776.6-keV level arise from the $M1$ character of the 47.5-keV transition, the strong β decay to the 1776.6-keV level, and the branch from the 1729.2-keV level to the 9-s $\frac{19}{2}^-$ isomer. Spin and parity of $\frac{11}{2}^-$ is indicated for the strongly β-fed levels at 2500.33, 2595.91, and 2807.9 keV as they all must be negative parity levels and none of them feed the well-established $\frac{15}{2}^-$ and $\frac{15}{2}^+$ levels at 1560.2 and 1729.17 keV, respectively, and all three feed the lower-lying $\frac{9}{2}^+$ levels. These levels may be contrasted with the strongly β-fed 2556.30-keV level that feeds both the $\frac{15}{2}^-$ and $\frac{15}{2}^+$ and no $\frac{9}{2}^+$ levels, and is thus assigned $\frac{13}{2}^-$ spin and parity. Less certain $\frac{13}{2}^-$ assignments are indicated for the levels at 2505.7, 2516.40, and 2880.5 keV that feed no $\frac{9}{2}^+$ states. The levels at 1516, 1704, and 2005-keV are limited to $\frac{9}{2}^+$ spin and parity by their branches to the $\frac{5}{2}^+$ state at 312 keV, and by transitions into these levels from the $\frac{11}{2}^-$, 2500- and 2595-keV levels. The $\frac{7}{2}^+$ assignment for the 1454-leV level is suggested by the absence of feeding from the numerous $\frac{11}{2}^-$ levels higher in the ^{133}I nucleus which do not feed one or more $\frac{9}{2}^+$ levels.

The levels at 1797, 1893, and 1974 keV are assigned

$\frac{11}{2}^+$ on the basis of branches to the $\frac{7}{2}^+$ ground state and branches to the $\frac{13}{2}^-$ level at 1776.6 keV.

The 1798.6-keV level is assigned $\frac{17}{2}^-$ on the basis of its strong feeding to the $\frac{19}{2}^-$ isomer. The 1816.6-keV level is assigned $\frac{15}{2}^-$ on the basis of its feeding to both the 1798.6-keV level and the $\frac{13}{2}^-$ level at 1776.6 keV.

The 1990.8-keV level is assigned $\frac{13}{2}^-$ spin and parity on the basis of strong γ-ray feeding to the $\frac{15}{2}^-$ level at 1729.2 keV, and weak γ-ray feeding only to three $\frac{11}{2}^+$ levels. Spin and parity of $\frac{13}{2}^-$ are fixed for the level at 2211.9 keV by its branches to the high spin level at 1798.6, to the $\frac{11}{2}^+$ level at 912.7 keV, and by the β branch limiting the spin to $\frac{13}{2}$. The levels at 3051.3, 2968.1, and 2826.3 keV are assigned $\frac{9}{2}^-$ spin and parity on the basis of allowed feeding and ground state γ-ray branches.

The levels at 2049.9 and 2142.3 keV are not likely separated by over one unit of angular momentum in view of the 92-keV transition between them. The 2049.9 can be either $\frac{11}{2}^+$ or $\frac{9}{2}^+$ on the basis of its decay. It is fed from levels at higher energy that feed $\frac{11}{2}$ and $\frac{13}{2}$ levels but no $\frac{9}{2}$ levels. The 2142.3-keV level feeds both $\frac{13}{2}^-$ and $\frac{13}{2}^+$ levels as well as $\frac{9}{2}^+$ levels ensuring an $\frac{11}{2}$ spin. The transition between these two levels indicates they probably have the same parity. Thus the 2049.45-keV level could be $\frac{9}{2}^-$ and the 2142.3-keV level could be $\frac{11}{2}^-$, or they could both be $\frac{11}{2}^+$ levels, the assignment favored by the feedings of the 2686.4- and 2783.8-keV levels.

The $\frac{9}{2}^+$ assignment for the 914.77-keV level is supported by strong systematic evidence, limited to $\frac{9}{2}^+$ by its branch to the $\frac{5}{2}^+$ level at 312.07 keV and numerous other feedings in the decay of $^{133}Te^g$.

The $\frac{11}{2}^+$ assignment for the 1646.67-keV level is established by its branches to $\frac{7}{2}^+$ and $\frac{15}{2}^+$ levels. The strong β feeding limits the 2248.50-, 2261.54-, and 2211.91-keV levels to $\frac{9}{2}$, $\frac{11}{2}$, or $\frac{13}{2}$ spin values. The logft values allow both positive or negative parity values. As two of these levels have major branches to levels that feed into the $\frac{19}{2}^-$ isomer, $\frac{13}{2}^-$ is the preferred assignment for all three levels.

Spin and parity of $\frac{11}{2}^-$ are required for the 2371.6-keV level by the allowed β branch and the γ-ray branches to $\frac{9}{2}^+$ and $\frac{15}{2}^+$ levels.

IV. DISCUSSION

The electromagnetic deexcitation of medium energy nuclear levels (1 MeV $< E_{\text{excit}} <$ 10 MeV) is generally expected to occur to the lowest-lying energy level available to $E1$, $M1$, or $E2$ transitions. Among the assumptions that lead to this expectation is the E^3 or E^5 energy dependence of the $M1$, $E1$, or $E2$ electromagnetic operator and the expected configurational mixing among the levels with low J at these energies. However, if these mechanisms are blocked, structurally controlled gamma-ray cascades (SCGC) could occur. For example, the energy dependence could be suppressed by the robbing of strength through higher lying giant collective structure and the configurational mixing could be suppressed by occurrence of unique structures, such as coexisting shape isomers that did not mix with other levels.[4] The occurrence of strong SCGC at medium energies could effect a number of features of nuclear deexcitation. For example, current experiments using beta delayed neutron and high-energy γ-ray data suggest that at or about the neutron binding energy small mini-resonances occur.[17] Part of the assumption that enters these calculations is that the Γ_γ to Γ_n ratio follows a smooth and predictable prescription. If, however, SCGC occurs, the assumed beta strength to levels below B_n could instead appear in the minimum area, as shown in Fig. 4 for the case of ^{87}Br decay to ^{87}Kr (Ref. 18), thereby yielding a smoothing of the mini-resonant structure. That is, β feeding attributed to levels just below B_n could actually be going to levels above B_n that decay by low-energy unobserved γ rays to the levels below B_n. Such a feature would simultaneously reduce the hump below B_n and transfer that strength to fill in the valley above B_n. Although the required increase in SCGC is perhaps too large, tests of its possible occurrence must be made before general application of these beta decay models can be used. Here we use $^{133}Te^m$ decay as a crude SCGC case at modest energy.

In $^{133}Te^m$ decay to ^{133}I levels, the percentage of the γ decay passing through the $\frac{19}{2}^-$ isomer is 11.5% while 18% passes through the $\frac{15}{2}^-$ isomer at 1729. The cascades from levels above 1780 keV can be studied in much more detail and the $E1$ suppression can be more easily observed for both the $\frac{15}{2}^-$ level at 1729 keV and the $\frac{13}{2}^-$

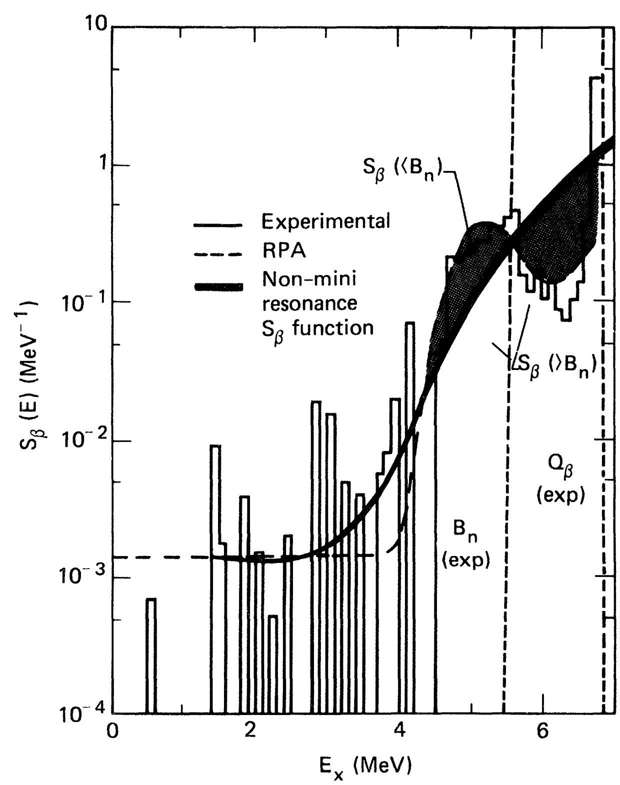

FIG. 4. Beta strength function with mini-resource (see Ref. 18). The shaded area shows consequences of weak SCGC (see text), the heavy line shows the consequences of unexpected strong SCGC.

level at 1776 keV. The relative $E1$ hindrance for the 863-keV γ ray is 90. For the 169-keV $E1$ transition from the $\frac{15}{2}^-$ level at 1729 keV, a hindrance of 10^5 can be deduced. This value is well within the usual range of 10^5—10^6 hindrances found for $E1$ transitions at low energies. Thus, a few hindered transitions in this 1.5—2.5 MeV range can redirect a significant fraction of the γ-ray strength into levels that would not be expected to carry much transition strength based on a statistical calculation.

The decay of the $\frac{13}{2}^-$ 1990-keV level exhibits yet another important structural effect. In the decay of this level, the $E1$ branching to higher lying, more configurationally mixed levels occurs in preference to decay to lower lying particle core coupled levels. Comparison of the intensity of the 92.8- and 1078.2-keV $E1$ transitions shows a relative hindrance factor of 1000.

Finally, in this line of discussion, the decay of the strongly β-fed 2595.9 keV $\frac{11}{2}^-$ level offers an opportunity to actually determine what fraction of its decay reaches the $\frac{15}{2}^-$ isomer and the $\frac{19}{2}^-$ isomer. The primary decay is to seven $\frac{13}{2}$ levels, six $\frac{11}{2}$ levels, and two $\frac{9}{2}$ levels (assuming our assignments are correct). The structural influences can be more clearly demonstrated by noting that nearly all the feeding of the $\frac{19}{2}^-$ isomer comes from the $\frac{15}{2}^-$ isomer and that a major portion (55%) of the feeding of the $\frac{15}{2}^-$ isomer comes through the 261.6-keV γ ray from the $\frac{13}{2}^-$ levels at 1990 keV and the remaining feeding from only six of the fifteen other high-spin ($\frac{11}{2}^-$ or $\frac{13}{2}^\pm$) levels above it. Moreover, only 10% of the feeding of the $\frac{15}{2}^-$ isomer at 1729 keV comes from levels over 2400 keV.

These analyses lead us to point out that nuclear structure effects stand out quite sharply in the population of isomers with relatively high spin lying at energies below 2 MeV. These isomers appear to derive much of their feeding from only a few levels where nuclear structure effects channel the γ decay to the isomer. It also appears that this feeding is localized to levels within 700 keV of the level in question.

The presence of such structures at higher energies could have a significant effect on the shape of the beta strength function. As illustrated in Fig. 4, current data from neutron measurements, high energy γ ray measurements, and the assumptions of classical values of Γ_n and Γ_γ allow the construction of a beta-strength function S_β for ^{87}Br decay to ^{87}Kr (Ref. 18). That is, the γ-ray measurements were made via singles and low statistics ($< 10^7$ events) in γ-ray coincidence studies. From this a decay scheme was constructed. The neutron spectra were measured using high resolution ^{3}He ionization chambers. The two measurements were combined along with the assumption that above B_n one could calculate any missing γ-ray strength by known values of Γ_n and Γ_γ. However, let us assume there are strong SCGC due to the occurrence of unsuspected structures in this energy region. Then the levels that decay by SCGC will be unaccounted for. Taking account of that will change S_β in two ways. First, it will increase S_β above B_n, and second, the SCGC will mostly populate levels slightly lower in energy than B_n, thereby decreasing area S_β ($<B_n$) and increasing that area S_β ($>B_n$). The effect will be most important in the region ~700 keV below the unobserved levels as we have noted earlier that most SCGC involves γ rays <700 keV. This hypothesis is illustrated by the heavy line in Fig. 4. Whether SCGC by itself would be of sufficient strength to totally alter S_β to a non-mini-resonance shape is questionable. However, recent evidence from time of flight neutron spectra of ^{85}As has shown additional high energy neutron intensity originally "missing" in spectra taken with ^{3}He detectors.[19] Thus, the extent of any SCGC should be examined in sufficient detail to exclude any SCGC contributions. Such an experiment would require high statistics three-parameter $\gamma\gamma t$ coincidence studies (N.B. the time parameter is necessary in order to account for possible lifetimes of SCGC band heads).

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

[1] S. F. Mughabghab and R. E. Chrien, in *Neutron Capture Gamma-Ray Spectroscopy*, edited by R. E. Chrien and W. R. Kane (Plenum, New York, 1979), p. 265.
[2] J. R. Huizenga and R. Vandenbosch, Phys. Rev. 120, 1305 (1960); 120, 1313 (1960).
[3] D. Sperber, Nucl. Phys. A90, 665 (1967).
[4] M. Guttormsen, J. Rekstad, A. Henriquez, F. Ingebretsen, and T. F. Thorsteinsen, Phys. Rev. Lett. 52, 102 (1984).
[5] S. F. Mughabghab and D. I. Garber, Brookhaven National Laboratory Report BNL-325, 3rd. ed., 1973 (unpublished).
[6] H. O. Denschlag, H. Braun, W. Faubel, G. Fischbach, H. Meixler, G. Paffrath, W. Porsch, M. Weis, H. Schrader, G. Siegert, J. Blachot, Z. B. Alfassi, H. N. Erten, T. Isak-Bran, T. Tamai, A. C. Wahl, and K. Wolfsberg, in *Physics and Chemistry of Fission* (IAEA, Vienna, 1980), Vol. 2, p. 153.
[7] B. Parsa, G. E. Gordon, and W. B. Walters, Nucl. Phys. A110, 674 (1968).
[8] S. V. Jackson, W. B. Walters, and R. A. Meyer, Phys. Rev. C 11, 1323 (1975).
[9] K. G. Skarnemark, H. C. Griffin, E. A. Henry, and R. A. Meyer, Lawrence Livermore National Laboratory Report UCRL-87634, 1982 (unpublished).
[10] L. D. McIsaac, Phys. Rev. 172, 1253 (1968).
[11] J. Blachot and C. Fiche, At. Data Nucl. Data Tables 20, 241 (1977).
[12] H. G. Börner, W. F. Davidson, J. Almeida, J. Blachot, J. A. Pintson, and P. H. M. Van Assche, Nucl. Instrum. Methods 164, 579 (1979).
[13] N. B. Gove and M. J. Martin, Nucl. Data Tables 10, 206 (1971).
[14] I. Bergstrom, S. Borg, G. B. Holm, and B. Rydberg, *Proceedings of the International Conference on Properties of Nuclides*

far from the Region of Beta-Stability (CERN, Geneva, 1970), p. 1012.

[15]F. Rosel, H. M. Fries, K. Adler, and H. C. Pauli, At. Data Nucl. Data Tables 21, 110 (1978).

[16]H. G. Hicks, J. H. Landrum, E. A. Henry, R. A. Meyer, S. Brandt, and V. Paar, Phys. Rev. C 27, 2203 (1983).

[17]B. F. Petrow, Yu. W. Naumow, and H. V. Klapdor, Z. Phys. A 292, 73 (1979).

[18]K.-L. Kratz, W. Rudolph, H. Ohm, H. Franz, M. Zendel, G. Herrmann, S. G Prussin, F. M. Nuh, A. A. Shihab-Eldin, D. R. Slaughter, and W. Halverson, Nucl. Phys. A317, 335 (1979).

[19]M. Shaana, Institut für Kernphysik, Kernforschungsanlage-Jülich Report Jül-Spez-99, 1981, p. 60.