Investigation of *K*-Shell Electron Capture in ^{158}Tb

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We have investigated the *K*-shell electron-capture decay of ^{158}Tb, and, contrary to an earlier claim, we find no evidence for *K* capture to a state at 1187 keV. Our results are consistent with recent measurements of related reaction *Q* values and invalidate the claim that ^{158}Tb decay is useful for determining the mass of the neutrino.

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In a recent Letter, Raghavan[1] has reported the observation of *K*-shell electron capture to the 1187-keV level in ^{158}Gd with a *Q* value of 156 ± 17 eV and he pointed out that this low-energy decay would be sensitive to the mass of the neutrino. In order for *K* capture to occur, the ground-state mass difference must be at least 1237.5 keV. The most recent compilations of Wapstra and Audi[2] quote a value of 1221.9 ± 1.6 keV, and Burke[3] has remeasured some of the reaction *Q* values used in the compilations and has found no significant errors. Burke *et al.*[4] have also examined the possibility that the reported *K*-capture decays were due to a long-lived isomer of ^{158}Tb at about 20-keV excitation. They found a previously unobserved rotational bandhead at 55 keV, but no other levels. Altzitzoglou *et al.*[5] have further examined the possibility of an isomeric level by using a ^{158}Tb (150 yr) target to measure the reaction *Q* values for $^{158}\mathrm{Tb}(p,d)^{157}\mathrm{Tb}$ and $^{158}\mathrm{Gd}(p,d)^{157}\mathrm{Gd}$. They found that the ^{158}Tb-^{158}Gd mass difference is 1215.4 ± 4 keV. These results would suggest that *K* capture to the 1187-keV level in ^{158}Gd is energetically forbidden. This conclusion is, however, not supported by the kinematics of the beta decay of ^{158}Tb to ^{158}Dy (see Fig. 1). The end point has been measured to be 850 ± 6 keV.[6,7] Combining this result with the ^{158}Gd-^{158}Dy mass difference, 283 ± 6 keV,[2] yields a ^{158}Tb-^{158}Gd mass difference of 1232 ± 8 keV,[2,8] in disagreement with the mass tables. And such a large mass difference might allow the reported *K* capture to occur. The purpose of this Letter is to present the results of a reinvestigation of the electron-capture decay of ^{158}Tb.

The ^{158}Tb decay scheme is shown in Fig. 1. The signature of a *K*-shell electron capture to the 1187-keV level would be the observation of a *K* x ray in coincidence with the 1187-keV gamma ray from the deexcitation of ^{158}Gd. A major experimental complication is that *L* and *M* captures result in an abundance of the 1187-keV gamma rays (1.9% of all decays) and *K* captures to lower levels in ^{158}Gd result in an abundance of *K* x rays. The γ-x accidental rate is, therefore, very high.

The ^{158}Tb source was chemically purified by means of ion-exchange chromatography and mass dispersed by the Princeton isotope separator.[9] It was placed between two detectors in close geometry. The gamma rays were analyzed with a 100-cm^3 coaxial germanium detector and the x rays with a planar detector. The detectors were surrounded with 10 cm of lead and the γ-ray detector was separated from the source by a graded filter (Al-Cu-Cd-Ta-Cd-Cu-Al) to prevent the 79.5-keV γ rays from distorting and summing with the higher-energy lines. The detectors were isolated from the shielding by an x-ray filter to prevent lead x rays from causing accidental coincidences in the detectors. Typical γ-ray and x-ray spectra are shown in Fig. 2.

We used standard fast-slow electronics to detect the γ-x coincidence. The fast coincidence circuit included amplitude and rise-time compensation. The slow coincidence circuit included pile-up rejection. The pulse heights were digitized and recorded on tape as individual events. Singles spectra and coincidence spectra were recorded at different times. The data tapes were read off line and the coincidence data were saved as a large, three-dimensional array (E_γ vs E_x vs time). This method of analysis allowed us to experiment with the location of windows for on- and off-time subtraction and to change the shape of the curve used to fit the peaks and background.

To extract a coincidence yield from the data it was necessary to select events that were coincident with the K_α and K_β x rays or their sum peaks. The accidental events were subtracted by the placement of windows on either side of the timing peak associated with any one gamma-ray channel and calculation of the net yield to that channel. The resulting gamma-ray spectrum was fitted to a twelve-parameter function[8] that describes the shape of germanium spectra quite precisely. (The χ^2 of the fits was always less than 1 for peaks with less than 500 000 counts. For larger peaks,

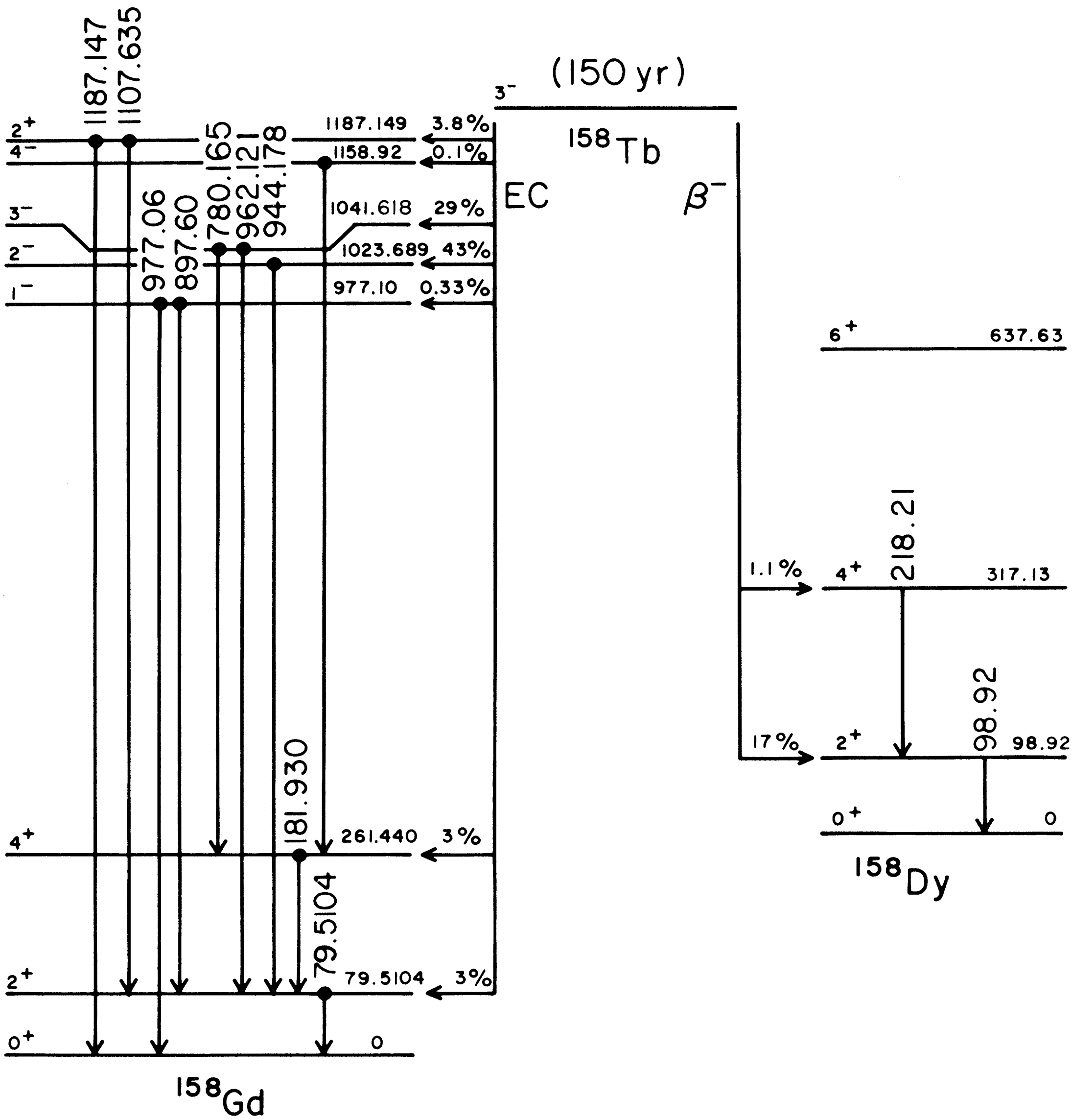

FIG. 1. Energy-level diagram for ^{158}Tb radioactive decay.

the χ^2 was 2 per million counts which is an indication that at about 1 million counts the systematic errors dominate over the statistical errors.) This procedure was adopted because, for the low-probability events being considered, accidental coincidence rates are energy dependent and single-channel-analyzer windows do not properly represent the backgrounds. The net coincidence yields in the gamma-ray spectra are listed in Table I.

The data can be reduced to a form that is subject to direct theoretical interpretation by our taking the ratio of coincidences to singles (c/s) for the 1187-keV line and normalizing it to the c/s ratio for the 977-keV line. Thus,

$$R=[c(1187)/s(1187)][c(977)/s(977)]^{-1}$$

is independent of the nuclear matrix elements and all of the geometric and electronic efficiency factors,[1,8] but will depend on the atomic wave-function overlaps at the origin. We have used the values recommended by Bambynek *et al.*[10] in our analysis.

Table I lists the limits on $R(1187/977)$ for each of the four runs. The first run used a 2.2-μCi source, which was too strong, and this led to subtle distortions in the spectra and a false signal plus a high accidental rate. The source strength was reduced for runs 2–4. The third run used a different germanium detector on the γ side, and the fourth run used a different detector on the x-ray side. The average 1187-keV K-capture rate is $R=-0.09\pm0.48$, consistent with zero, and excludes the previous result at the 95% confidence level.

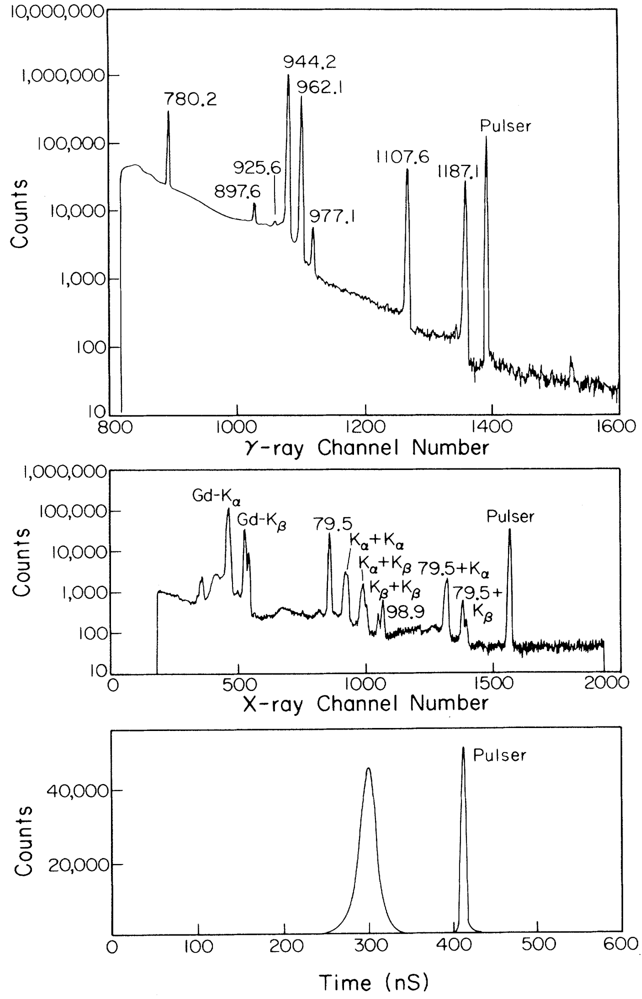

FIG. 2. Typial γ-ray, x-ray, and time spectra.

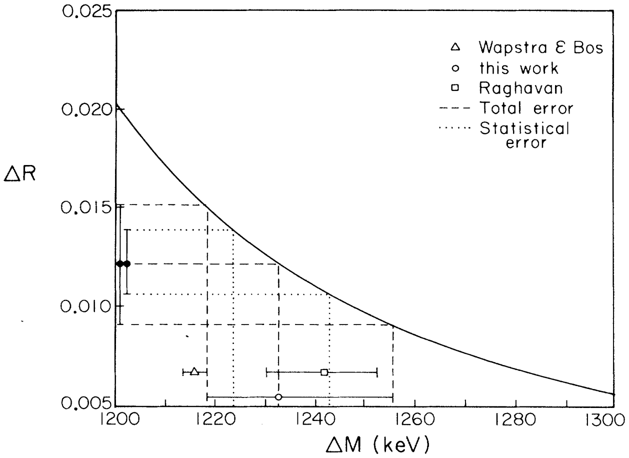

FIG. 3. $R(977/977) - R(962/977)$ as a function of the ^{158}Tb-^{158}Gd ground-state mass splitting.

(In Ref. 1, the 1187-keV K-capture yield was measured relative to the $944+79.5=1023.5$ keV sum line yield. The change in normalization increases R by 3% and is unimportant for our purposes.)

An additional check on the ground-state mass splitting is to measure the K/total capture ratios to other levels in ^{158}Gd. The strong transitions at 944 and 962 keV are good candidates, but, as observed in Ref. 1, these transitions cascade through the 79.5-keV level which can internally convert and cause a false γ-x coincidence. Fortunately, the difference $R(944/977) - R(962/977)$ will cancel this effect. Our third run was designed explicitly for this measurement. We found that ΔR is 0.0122 ± 0.0017 if only statistical errors are considered. We estimate that the areas deter-

TABLE I. The observed K_x-γ coincidence rates. The raw number of coincidences is listed in column 7 and is to be compared to the total rate of each γ ray in singles as described in the text. The reduced coincidence yield, R, can be compared directly to theory and is a strong function of the ground-state mass splitting between ^{158}Td-^{158}Gd.

Source strength (μCi)	Coincidence counting time (days)	Resolving time (ns)	Run No.	E_γ (keV)	Singles	Coincidences	10^4R	ΔR
2.2	30	60	1	1187	62 000(280)	100(65)	2.0(13)	
				977	7680(140)	62 300(325)		
0.43	30	50	2	1187	122 700(400)	−20(25)	−0.5(7)	
				977	15 600(200)	46 250(282)		
0.43	10	60	3	1187	92 300(345)	10(30)	0.3(9)	
				977	11 790(185)	41 800(265)		
0.43		60	3	944	2 887 200(20000)	13 199 700(4000)		0.0122(17)
				962	1 342 400(1350)	6 079 200(2700)		
0.43	15	60	4	1187	114 300(400)	10(45)	0.25(10)	
				977	13 600(400)	47 100(250)		

mined by our peak-fitting procedures were accurate to ±0.1% and, therefore, the total error on ΔR is 0.0030. In Fig. 3 the experimental value of ΔR is compared to the theoretical value of ΔR as a function of the ground-state mass splitting. The range of values is so large that we cannot distinguish between the values of ΔM found in Ref. 1 and the mass tables of Ref. 2. It thus seems that the systematic errors were underestimated in the original work.

We have recently learned that Von Dincklage *et al.*[11] have remeasured the β^- spectrum from ^{158}Tb decay. By use of the correct shape of this first forbidden nonunique transition they report that the beta-decay end point is 842 ±6 keV. Altzitzoglou and Naumann[9] have also reexamined this β^- decay and they measure the end-point energy to be 843 ±4 keV. The ^{158}Tb-^{158}Gd ground-state mass splitting derived from these measurements would be 1225 ±7 keV.

In summary, we have found no evidence for K capture to the 1187-keV level of ^{158}Gd. Our results call into question whether the transition occurs at all, and, in view of the recently available reaction Q-value measurements by Burke[3] and Altzitzoglou *et al.*,[5] and the β^--decay measurements by Von Dincklage *et al.*[11] and Altzitzoglou and Naumann,[9] it seems that the transition is kinematically forbidden.

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[1] R. Raghavan, Phys. Rev. Lett. **51**, 975 (1983).

[2] A. H. Wapstra and G. Audi, to be published.

[3] D. G. Burke, Phys. Rev. C **29**, 2339 (1984).

[4] D. G. Burke *et al.*, Phys. Lett. **146B**, 392 (1984).

[5] T. Altzitzoglou *et al.*, Phys. Rev. C **31**, 360 (1985).

[6] R. A. Naumann *et al.*, Bull. Am. Phys. Soc. **7**, 34 (1962).

[7] F. Schima *et al.*, Nucl. Phys. **63**, 305 (1965).

[8] J. Thomas and J. LoSecco, Phys. Rev. C **31**, 577 (1985).

[9] T. Altzitzoglou and R. Naumann, to be published.

[10] W. Bambynek *et al.*, Rev. Mod. Phys. **49**, 77 (1977).

[11] R. Von Dincklage *et al.*, to be published.