Investigation of $A = 152$ radioactivities with mass-separated sources: Identification of ^{152}Lu

K. S. Toth
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

D. C. Sousa
Eastern Kentucky University, Richmond, Kentucky 40475

J. M. Nitschke and P. A. Wilmarth
Lawrence Berkeley Laboratory, Berkeley, California 94720
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Nuclides with $A = 152$ were produced in ^{58}Ni bombardments of ^{96}Ru and their decay properties were investigated following on-line mass separation. The isotope ^{152}Lu ($T_{1/2} = 0.7 \pm 0.1$ s) was identified by γ rays in its β-decay daughter, ^{152}Yb. Based on its decay characteristics, the parent state has a probable spin and parity assignment of $(4,5,6^-)$. Several new transitions were observed to follow the β decays of ^{152}Yb and the ^{152}Tm low-spin isomer; they established previously unknown levels in both ^{152}Tm and ^{152}Er. The additional γ rays in ^{152}Yb decay reduce from 100% to 88% the direct feeding to the one excited state in ^{152}Tm that had been known earlier. Nevertheless, the corresponding logft value is calculated to be 3.5, indicating that this is an allowed β transition which connects the 0^+ parent with a 1^+ excited state in ^{152}Tm. By comparing the β-decay rates of ^{148}Dy and ^{152}Ho, and the α- and β-decay rates of ^{152}Er, an α branch of 90 ± 4 % was deduced for ^{152}Er.

I. INTRODUCTION

Since its commissioning, the isotope separator OASIS,[1] on-line at the Lawrence Berkeley Laboratory SuperHILAC, has been used primarily in the investigation of short-lived nuclides on the neutron-deficient side of $N = 82$. Much of the research has involved a systematic study[2–4] of β-delayed-proton spectra. More recently, γ-ray spectral data have been utilized[5] to sort out low-lying levels in ^{149}Er and ^{149}Ho. Herein we report on the decay properties of $A = 152$ nuclei. In the study we identified a new isotope, ^{152}Lu, and obtained additional, previously unavailable, information on the β decays of ^{152}Yb and ^{152}Tm.

A 1.5-mg/cm^2 thick layer of ruthenium, enriched in ^{96}Ru to 96.5% and deposited onto a 2.0-mg/cm^2 thick HAVAR foil, was bombarded with 354-MeV ^{58}Ni ions. The beam energy at the center of the ruthenium layer, after the ^{58}Ni ions had traversed a window foil and the HAVAR substrate, was calculated to be 244 MeV. Following mass separation, the $A = 152$ products were collected with a programmable tape system and then transported to a counting station for radioactive assay. Figure 1 shows the detector arrangement. Facing the collected active layer were a Si particle ΔE-E telescope and a hyperpure Ge detector. On the other side of the collector tape there were a 1-mm thick plastic scintillator and an n-type Ge detector with a relative efficiency of 24%. In addition, a 52% n-type Ge detector was set to one side $\sim$4.5 cm from the radioactive source. Coincidences between particles, γ rays, x rays, and positrons were recorded in an event-by-event mode. Events in all detectors were tagged with a time signal for half-life information. In the present investigation a tape cycle time of 4 s was used. Data taken with the 24% γ-ray Ge detector were also recorded in a multispectrum mode wherein the 4-s cycle time was divided into eight 0.5-s intervals.

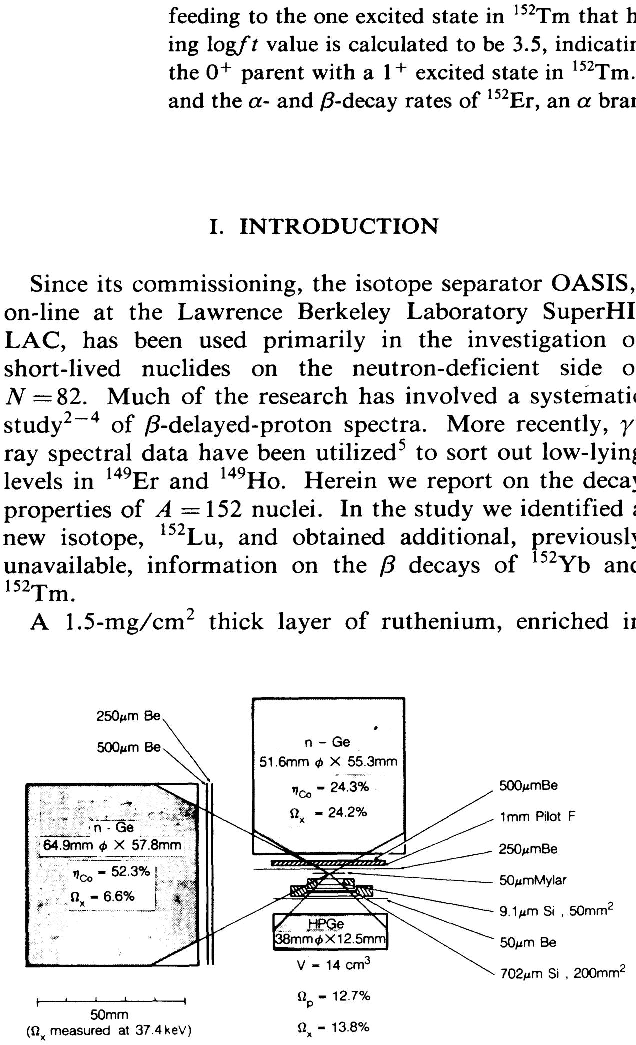

FIG. 1. Detector arrangement used in this investigation.

II. RESULTS

A. ^{152}Lu

Prior to now, the decay of ^{152}Lu had not been observed. Levels in its β-decay daughter, ^{152}Yb, however, had been studied[6] via in-beam γ-ray spectroscopy. In our investigation the energy of the ^{58}Ni ions was selected to optimize the production of ^{152}Lu. Nevertheless, its yield was anticipated to be extremely low since the maximum cross sec-

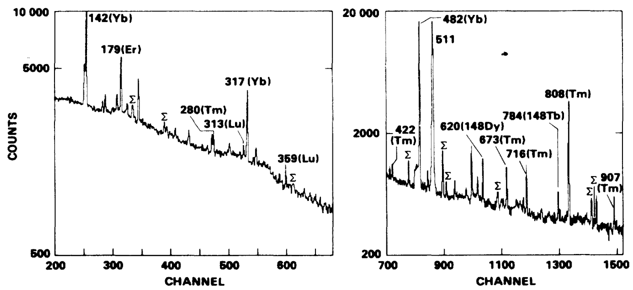

FIG. 2. Portion of the singles γ-ray spectrum measured with the 24% Ge detector (see Fig. 1); data represent the first 1.5 s of counting. Gamma rays of $A=152$ isotopes are labeled by energy and element; two transitions belonging to $A=148$ isotopes (the result of ^{152}Er α decay) are given nuclidic labels; and, sum peaks are indicated by Σ.

tion for the evaporation of one proton and one neutron from the ^{154}Hf compound nucleus was calculated to be 0.4 mb.

Three weak γ rays, 312.6, 358.7, and 1531.4 keV, known[6] to deexcite ^{152}Yb levels, were seen in our spectra to decay with a (0.7 ± 0.1)-s half-life, one that had previously not been observed in the $A=152$ isobaric chain. We therefore attribute them to the β decay of the new isotope ^{152}Lu. The 312.6- and 358.7-keV transitions are identified in Fig. 2, where we show a portion (0.1—1.0 MeV) of the singles γ-ray spectrum measured during the first 1.5 s of counting. In Fig. 2, γ rays assigned to $A=152$ isotopes are labeled by energy and element; two $A=148$ transitions (the result of ^{152}Er α decay) are identified by nuclide. Most of the unassigned strong transitions appear to be background γ rays since they were also observed during a previous $A=151$ investigation. Despite the fact that the time period covered in Fig. 2 emphasizes ^{152}Lu decay, one notes that the intensities of the 312.6- and 358.7-keV γ rays are much less than those of transitions assigned to other $A=152$ nuclides.

TABLE I. Energies and relative γ-ray intensities for transitions observed in the decay of ^{152}Lu, ^{152}Yb, and the ^{152}Tm low-spin isomer.

Isotope	E_γ (keV)	I_γ (relative)
^{152}Lu	312.6(3)	87(21)
^{152}Lu	347.9[a]	<15
^{152}Lu	358.7(3)	89(12)
^{152}Lu	1531.4(5)	100[b]
^{152}Yb	141.7(2)	13(1)
^{152}Yb	316.9(2)	7(1)
^{152}Yb	482.4(2)	100[b]
^{152}Yb	949.2(3)	0.7(2)
^{152}Tm	672.7(2)	9.5(10)
^{152}Tm	715.9(2)	13(1)
^{152}Tm	808.3(2)	100[b]
^{152}Tm	906.8(2)	6(1)
^{152}Tm	1063.0(3)[c]	2.5(5)
^{152}Tm	1106.4(3)[c]	2.5(5)
^{152}Tm	1716.0(3)	2.0(6)

[a]Transition not seen in ^{152}Lu decay but observed in-beam by Nolte *et al.* (Ref. 6).
[b]Normalization point for γ-ray intensities.
[c]Transition not placed in ^{152}Tm decay scheme.

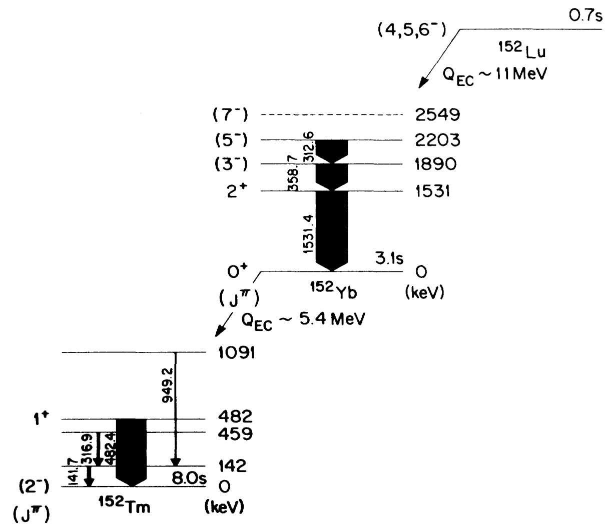

FIG. 3. Decay schemes of ^{152}Lu and ^{152}Yb.

Within error limits the three ^{152}Lu γ rays have equal intensities (Table I). We place them (Fig. 3) in a $5^-\to3^-\to2^+\to0^+$ yrast sequence as proposed in Ref. 6. The $7^-\to5^-$ 347.9-keV transition reported by Nolte *et al.*[6] was not seen in our spectra; a limit of <15% can be set for its intensity relative to that of the 1531.4-keV γ ray. Based on Q_{EC} values in Ref. 7 for neighboring Tm and Lu nuclei, the β-decay energy of ^{152}Lu is estimated to be ~11 MeV. With this Q_{EC}, the logft value for the transition that feed the 2203-keV ^{152}Yb level is calculated to be ~4.5, indicating that the β transition is allowed. Thus, if the spin assignment of the 2203-keV level is indeed 5^-, then the ^{152}Lu parent state must have negative parity and a spin of either 4, 5, or 6.

Delayed protons were also observed in the $A=152$ mass chain. They are assigned to the β decay of ^{152}Lu on the basis of half-life $(0.6\pm0.1$ s) and coincidences with Yb K x rays. Details of this particle decay mode will be discussed in a forthcoming publication[8] together with data obtained for two other doubly-odd $N=81$ delayed-proton emitters, i.e., ^{150}Tm and ^{148}Ho.

B. ^{152}Yb

The isotope ^{152}Yb was first characterized by Nolte *et al.*[6] They reported that it β decayed with a 3.2-s half-life to a single 1^+ level which then deexcited to the (2^-) low-spin isomer in ^{152}Tm by the emission of a 482-keV γ ray. This decay pattern is the same as those of other even-even nuclei above gadolinium with neutron numbers of 82, 84, and 86 (see, e.g., Ref. 9).

We too observed the intense 482.4-keV γ ray (Fig. 2) to decay with a half-life of 3.1 ± 0.2 s. In agreement with the results of Ref. 6, the transition was seen in coincidence only with K x rays and annihilation radiation as shown in Fig. 4. However, x- and γ-ray coincidence data demonstrate that at least three other transitions follow ^{152}Yb decay. They are seen, together with the 482.4-keV transition, in Fig. 5(a), which shows γ rays in coincidence with Tm K α_1 x rays. Two of the new γ rays, 141.7 and 316.9 keV, are in coincidence with one another (Fig. 6), but not with the 482.4-keV transition. Also, another new γ ray, 949.2 keV, and the 141.7-keV transition are in coincidence [Fig. 6(b)]. Based on these data and on the measured photon intensities (Table I) we propose the ^{152}Yb decay scheme shown in Fig. 3.

The additional γ rays in ^{152}Yb decay reduce the direct feeding to the 482.4-keV level from 100% (Ref. 6) to 88%. Nevertheless, with a Q_{EC} of 5.4 MeV,[7] we calculate an allowed logft value of 3.5 for this β transition. Thus the level at 482.4 keV, as pointed out in Ref. 6, must be a 1^+ state. We also measured the intensity ratio (K x rays/482.4-keV γ ray) to be 0.30 ± 0.03. Based on the decay scheme shown in Fig. 3, this same ratio is calculated to be 0.307 if the 482.4-keV transition is $E1$ (0.312 if it is $M1$). The similarity between the experimental and calculated ratios indicates that while there may be more, so far unobserved, ^{152}Yb γ rays, their overall intensity is small compared to the total β-decay strength.

As mentioned above, the decays of even-even ^{148,150,152}Dy, ^{150,152,154}Er, and ^{152,156}Yb are very much alike,[9] i.e., most of the feeding proceeds to a single 1^+ level in the odd-odd daughter by an allowed β transition. This 1^+ state then emits a γ ray ($E1$ multipolarity in all cases where measurements have been made) to the low-spin isomer. In Fig. 7 we plot the excitation energies of the 1^+ levels relative to those of the 2^- isomers as a function of neutron number. One notes that there is a regular compression in energy spacing both as N and Z increase. It would appear that the levels involved have similar configurations despite the fact that the lighter nuclei have 83 neutrons and should be spherical while the transitional nuclei with 87 neutrons are close to the region of strong prolate deformation. Possible Nilsson shell-model configurations for these levels have been proposed in detail in Ref. 9, and the interested reader is referred to that work for a complete discussion.

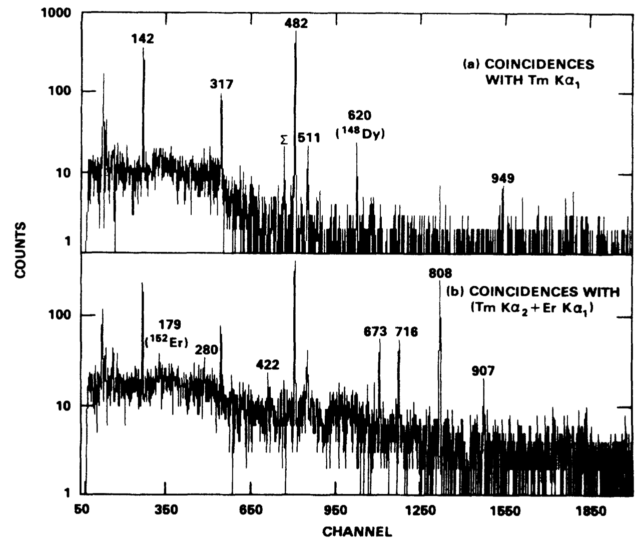

FIG. 5. Gamma rays observed in coincidence with Tm K α_1 [part (a)] and with Tm K α_2+Er K α_1 [part (b)] x rays.

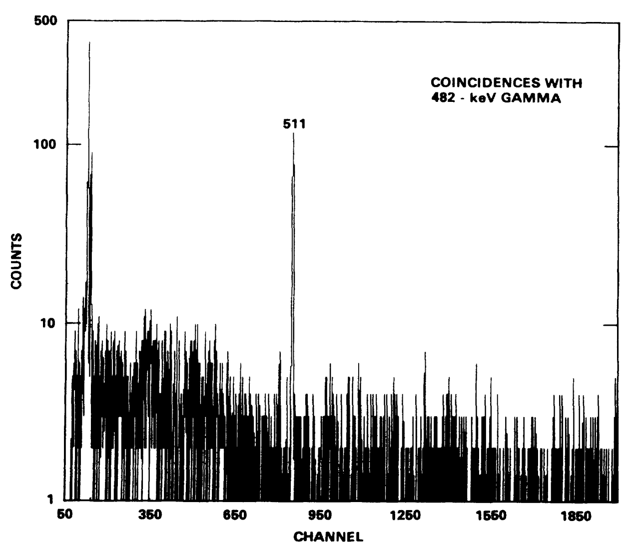

FIG. 4. Gamma-ray spectrum seen in coincidence with the 482-keV transition in ^{152}Yb decay.

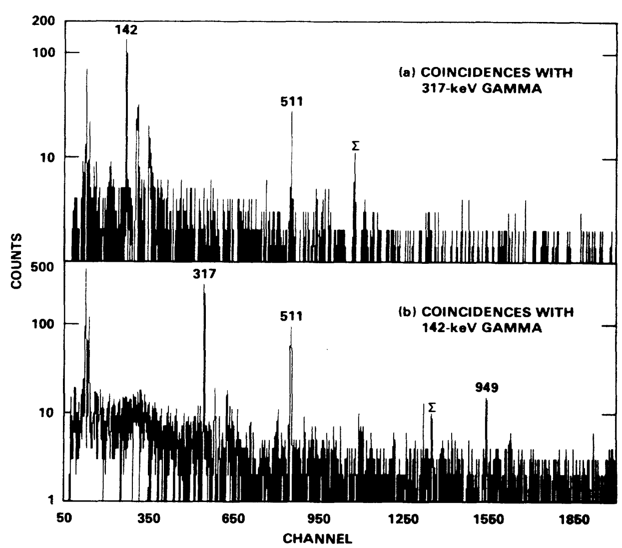

FIG. 6. Gamma-ray spectra observed in coincidence with the 317-keV [part (a)] and 142-keV [part (b)] transitions in ^{152}Yb decay.

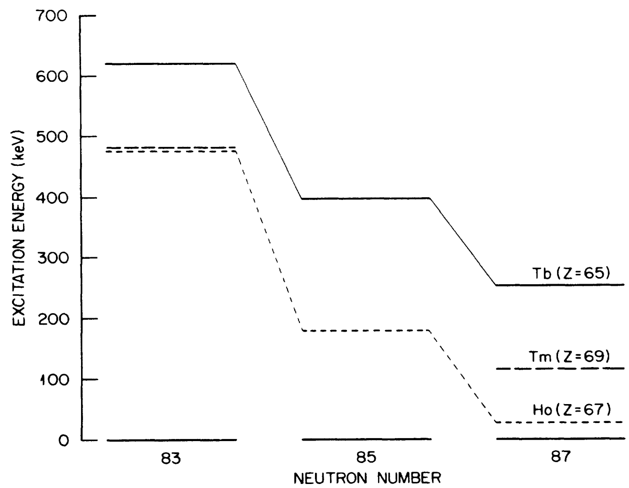

FIG. 7. Excitation energies of 1^+ levels relative to the low-spin isomers in odd-odd terbium, holmium, and thulium nuclei with $N=83$, 85, and 87.

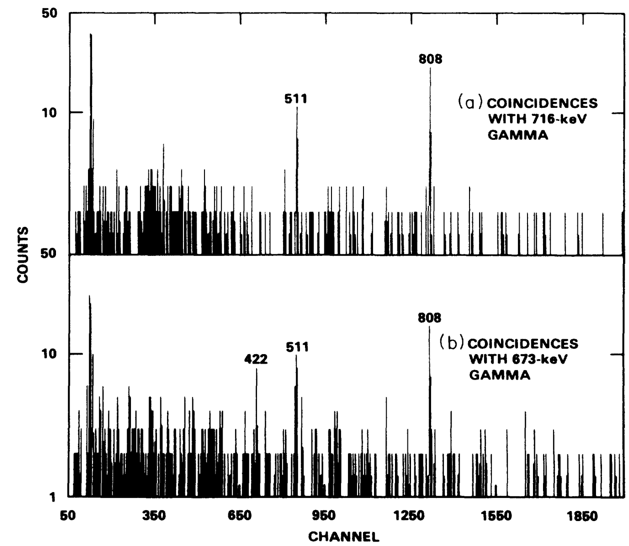

FIG. 8. Gamma-ray spectra seen in coincidence with the 716-keV [part (a)] and 673-keV [part (b)] transitions in the decay of the ^{152}Tm low-spin isomer.

C. ^{152}Tm low-spin isomer

Since ^{152}Tm cannot be made in ^{58}Ni bombardments of ^{96}Ru, its independent production in our study could only occur in reactions involving heavier ruthenium isotopes ($A\geq 98$) that make up less than 3.5% of the target material. Most of the ^{152}Tm activity seen in our measurements therefore originated from ^{152}Yb decay and for that reason it was due mainly to the low-spin rather than the high-spin isomer. The decay of the high-spin state is characterized[10] by a cascade of four γ rays which deexcite the yrast 8^+, 6^+, 4^+, and 2^+ levels in ^{152}Er. Contrastingly, the low-spin isomer does not populate[6] the 8^+ and 6^+ levels, and, in its decay the intensity of the $4^+\rightarrow 2^+$ 672.7-keV transition is $\sim 13\%$ (Ref. 6) that of the $2^+\rightarrow 0^+$ 808.3-keV γ ray, while in the high-spin decay this ratio is $\sim 76\%$ (Ref. 10).

That the high-spin ^{152}Tm isomer was present in our sources can be seen in Fig. 2, where we have identified the 279.7-keV ($8^+\rightarrow 6^+$) and 422.5-keV ($6^+\rightarrow 4^+$) γ rays. A clear indication that this species was produced independently comes from the fact that these two transitions decayed with the 5.2-s half-life measured by Liang *et al.*[10] On the other hand, the 672.7- and 808.3-keV γ rays did not decay with the 8.0-s half-life[6] of the ^{152}Tm low-spin isomer; instead their decay curves were essentially flat during the 4-s counting period as a result of continued production from the ^{152}Yb parent.

^{152}Tm γ rays are identified in the singles spectrum (Fig. 2), and in Fig. 5(b), where they are shown in coincidence with Er K α_1 x rays. In these spectra one notes a new intense 715.9-keV transition. It is in coincidence [Fig. 8(a)] with the 808.3-keV but not with the 672.7-keV γ ray [whose coincidence spectrum is shown in Fig. 8(b)]. We suggest that the 715.9-keV γ ray deexcites the previously unobserved first 3^- level in ^{152}Er; it should be noted that the 3^- level in neighboring even-even nuclei lies below the 4^+ state. However, this proposal is consistent with two trends in level energy systematics: (1) as N becomes progressively larger than 82, configuration mixing begins to lower the 4^+ level, and (2) as Z becomes greater than 64, the 3^- level in $N=82$ isotones increases in energy. The 906.8-keV γ ray [Figs. 2 and 5(b)] was observed in coincidence with the 808.3-keV transition. We tentatively propose that it and a 1716.0-keV transition deexcite the second 2^+ state in ^{152}Er. The decay scheme for the ^{152}Tm low-spin isomer is shown in Fig. 9.

Gamma-ray energies and intensities are summarized in Table I. The strengths of the γ rays feeding the 808.3-keV level account for only about 30% of the $2^+\rightarrow 0^+$ transition intensity. Since this 2^+ level cannot be fed strongly by the ^{152}Tm (2^-) isomer, most of the β decay must proceed to higher-lying states. These then deexcite either directly to the ground state or through the 808.3-keV level in a very fragmented pattern since no intense γ rays other than the ones listed in Table I could be identi-

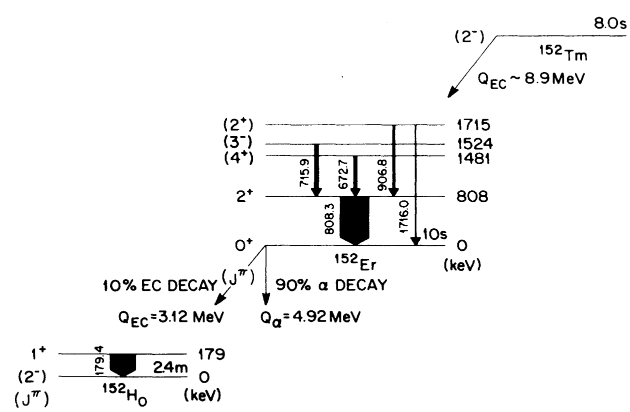

FIG. 9. Decay schemes of ^{152}Tm (low-spin isomer) and ^{152}Er.

fied. The situation would then be similar to that observed[11] for the decay of the 2^- ^{148}Tb isomer to levels in ^{148}Gd.

Further evidence comes from positron spectra measured with the intrinsic hyperpure Ge detector (this technique is described in Ref. 12) in coincidence with the 482.4- and 808.3-keV γ rays observed in the 24% n-type Ge detector. The endpoint energies of the two positron spectra were found to be approximately the same, i.e., $\sim$4.0 MeV. A Q value of $\sim$5.5 MeV is then calculated for ^{152}Yb, in agreement with the decay energies of 5.4 ± 0.6 MeV listed in the 1983 Atomic Mass Table[7] and of $5.05^{+0.18}_{-0.15}$ MeV deduced from a capture-to-positron ratio measurement.[13] Similarly, if one assumes that most of the β decay proceeds to the 808.3-keV level, then our positron endpoint would result in a Q_{EC} of about 5.8 MeV for ^{152}Tm. This value is much less than the Q_{EC} of 8.9 MeV listed in Ref. 7. It is also less than the $(6.96^{+0.12}_{-0.10})$-MeV value reported by Habenicht *et al.*[13] In their measurement, however, the determination was made for the high-spin ^{152}Tm isomer; no information is available concerning the separation energy between the two isomers. Nevertheless, our value of 5.8 MeV means that levels above the 808.3-keV state are strongly fed in the β decay.

D. ^{152}Er

The electron-capture decay branch of the well-known α emitter ^{152}Er was recently identified[9] with the use of a helium gas-jet transport system. It was found to feed predominantly a single 1^+ level which then deexcited by emitting a 179.4-keV γ ray to the 2^- ^{152}Ho isomer. Our singles and coincidence spectra confirm this decay scheme (Fig. 9). The 179.4-keV γ ray can be seen in Fig. 2 together with the 620.2- and 784.5-keV transitions that follow the decay of ^{148}Dy (the α-decay daughter of ^{152}Er) and ^{148}Tb, respectively. A weak 613.8-keV γ ray corresponding to the $2^+\rightarrow0^+$ transition in ^{152}Dy from ^{152}Ho decay was also seen in our singles spectra. By assuming that the 620.2-keV γ ray represents[14] 100% of all ^{148}Dy decays and that the 613.8-keV γ ray encompasses all of the ^{152}Ho low-spin isomer's 90% β-decay branch (Ref. 15), we deduce an α branch of 94 ± 4 % for ^{152}Er. An independent branching ratio was also determined by comparing the intensity of the 179.4-keV γ ray with the total number of 4.79-MeV α particles detected in the ΔE-E telescope; this value was found to be 86 ± 4 %. These ratios agree with two previous measurements, i.e., 86 ± 4 % (Ref. 16) and 93 ± 4 % (Ref. 17). Based on these determinations we adopt an α branch of 90 ± 4 % for ^{152}Er.

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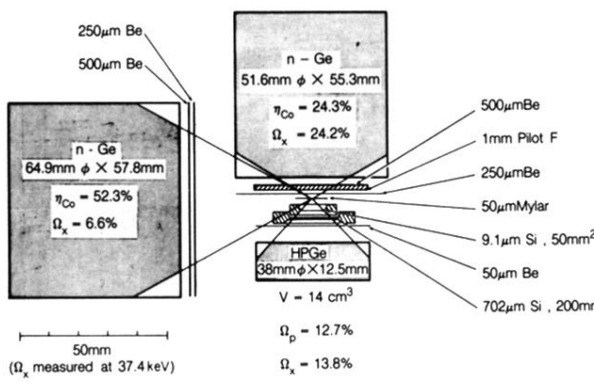

FIG. 1. Detector arrangement used in this investigation.