Decay properties of ^{150}Tm and ^{150}Er

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The decay properties of ^{150}Tm and ^{150}Er (produced in ^{58}Ni bombardments of ^{96}Ru) were investigated following on-line mass separation. The half-life of ^{150}Tm was measured to be 2.2 ± 0.2 s rather than the value of 3.5 s available in the literature. Based on its decay characteristics, we suggest that this high-spin ^{150}Tm isomer has a spin assignment of 6^-. Among the ^{150}Er states fed by this 6^- isomer is the yrast 4^+ level (2294.8 keV) which up to now has been observed in neither β-decay nor in-beam γ-ray studies. New transitions observed in ^{150}Er decay establish several previously unknown levels in ^{150}Ho. While the additional γ rays reduce from 100% to 96% the feeding to the 476-keV state in ^{150}Ho known earlier, the corresponding logft value is calculated to be 3.6, indicating that this is an allowed, $0^+\rightarrow1^+$, beta transition. Photon intensities obtained for γ rays following the decay of the ^{150}Ho low-spin isomer resolve inconsistent values measured in two previous investigations.

I. INTRODUCTION

The isotope separator OASIS,[1] on-line at the Lawrence Berkeley Laboratory SuperHILAC, has been used primarily in the investigation[2] of β-delayed proton emitters on the extreme neutron-deficient side of $N=82$. Recently these studies have focused on the $N=81$ odd-odd precursors, ^{152}Lu, ^{150}Tm, and ^{148}Ho, in an effort to understand more fully the nature of the sharp proton peaks observed in the decays of the $N=81$ even-Z precursors (see, e.g., Ref. 3). The proton data for these odd-odd nuclei will be discussed in a forthcoming publication.[4] In this paper we present information, obtained in the $A=150$ study, concerning the level structures of ^{150}Er and ^{150}Ho as observed in the β decays of ^{150}Tm and ^{150}Er, respectively.

A 1.6-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 372-MeV ^{58}Ni ions. After the ^{58}Ni ions had traversed a window foil and the HAVAR substrate, the beam energy at the center of the target was calculated to be 267 MeV. The $A=150$ products were collected with a programmable tape system for 8 s and then transported to a counting station with a detector arrangement shown in Fig. 1. A Si particle ΔE-E telescope and a hyperpure Ge detector faced the radioactive layer while a 1-mm thick plastic scintillator and an n-type Ge detector with a relative efficiency of 24% were located on the other side of the collector tape. A 52% n-type Ge detector was set to one side ~4.5 cm from the radioactive source. Coincidences between particles, γ rays, x rays, and positrons were recorded in an event-by-event mode; all events were tagged with a time signal for half-life information. Singles data were also taken with the 24% γ-ray detector in a multispectrum mode in which the 8-s cycle time was divided into eight 1.0-s intervals.

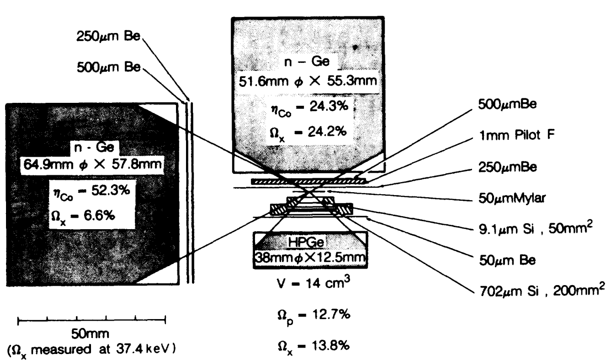

FIG. 1. Detector arrangement used in this study.

II. RESULTS

A. General

The bombarding energy was chosen to optimize the production of ^{150}Tm in the ^{96}Ru(^{58}Ni,n3p) reaction. At 267 MeV the calculated[5] cross section for this reaction is 22 mb while cross sections for the production of ^{150}Yb and ^{150}Er are predicted[5] to be 0.7 mb and 75 mb, respectively ($A=150$ nuclides with $Z>70$ have negligibly small yields). Mass-150 isobars with $Z<68$ could be produced only in interactions involving ruthenium isotopes with $A\geq98$ which comprised less than 3.5% of the target material. Thus ^{150}Ho (and ^{150}Dy), observed in our experiment, had to originate primarily from the decay of ^{150}Er.

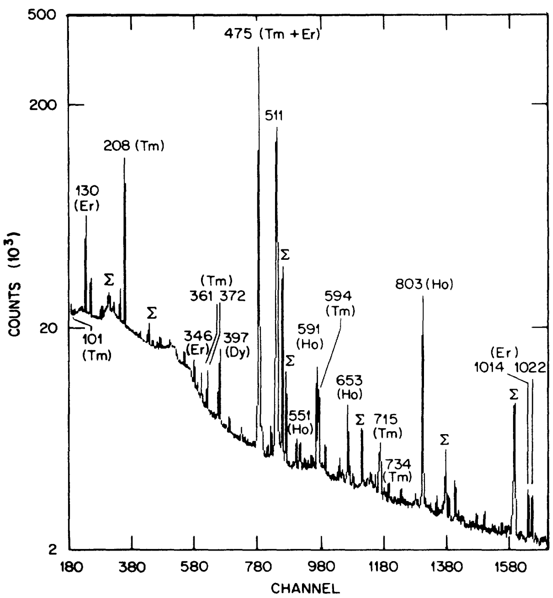

FIG. 2. Portion of the singles γ-ray spectrum measured with the 24% Ge detector (see Fig. 1) during 8-s counting intervals. Gamma rays that could be identified are labeled by energy and the element symbol of the parent nucleus. Sum peaks are indicated by Σ.

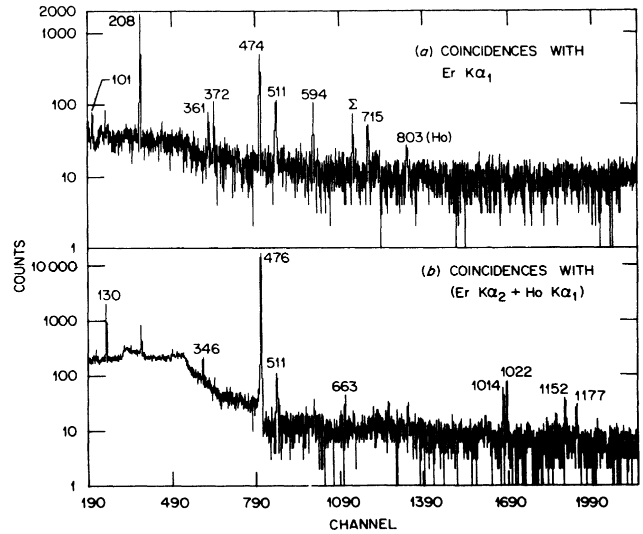

FIG. 3. Gamma rays observed in coincidence with Er $K\alpha_1$ [part (a)] and with Er $K\alpha_2$+Ho $K\alpha_1$ [part (b)] x rays.

A portion of the single γ-ray spectrum measured in this investigation is shown in Fig. 2. Gamma rays that could be assigned are labeled by energy and element. In accord with the calculated cross sections, Tm and Er γ rays are dominant. And, analysis of the γ- and x-ray spectral data revealed no evidence for the pressure of ^{150}Yb. As expected, ^{150}Ho γ rays were due mainly to the low-spin rather than to the high-spin isomer since only the former is populated in ^{150}Er decay. Most of the unassigned strong transitions appear to be background γ rays since they were also observed in experiments dealing with other mass numbers.

B. Decay of $^{150}_{69}Tm_{81}$ to levels in $^{150}_{68}Er_{82}$

The isotope ^{150}Tm was first identified by Nolte *et al.*[6] They reported the half-life to be 3.5±0.6 s and assigned four γ rays to ^{150}Tm decay which were known[7] to depopulate the first 5^-, 3^-, and 2^+ excited states in ^{150}Er.

We determine a much shorter half-life for ^{150}Tm, 2.2±0.2 s, and observe more transitions in its disintegration. These new γ rays can be seen in Fig. 2, as well as in Fig. 3(a), where transitions in coincidence with Er $K\alpha_1$ x rays are shown. Additional data are presented in Figs. 4 and 5, which show γ rays in coincidence with the 207.7-keV ($3^- \rightarrow 2^+$), and the 1579.0-keV ($2^+ \rightarrow 0^+$) and 474.4-keV ($5^- \rightarrow 3^-$) transitions, respectively. Three of the new γ rays, i.e., 100.7, 360.5, and 372.4 keV, have been observed[7,8] in-beam and deexcite the yrast 6^+, 7^-, and 8^+ levels. Two others, i.e., 508.4 and 715.4 keV, establish the existence of what is probably the hitherto unidentified first 4^+ level in ^{150}Er. The 508.4-keV γ ray can be seen in Fig. 5(a) as a shoulder on the low-energy side of the annihilation radiation peak. It stands out more markedly in the inset of Fig. 6; this figure shows ^{150}Er transitions in coincidence with ^{151}Yb β-delayed protons (see Ref. 9). These γ rays follow protons emitted from ^{151}Tm states fed by the β decay of the ^{151}Yb $h_{11/2}$ isomer. For this reason ^{150}Er levels with spins up to at least 6 (the 360.5-keV γ ray deexcites[7,8] the yrast 6^+ state) are populated by the delayed protons. Because spin and parity changes impose less stringent selection rules in particle decay than in β decay, the 4^+ level is predicted[9] from statistical model calculations to be the level most heavily fed by β-

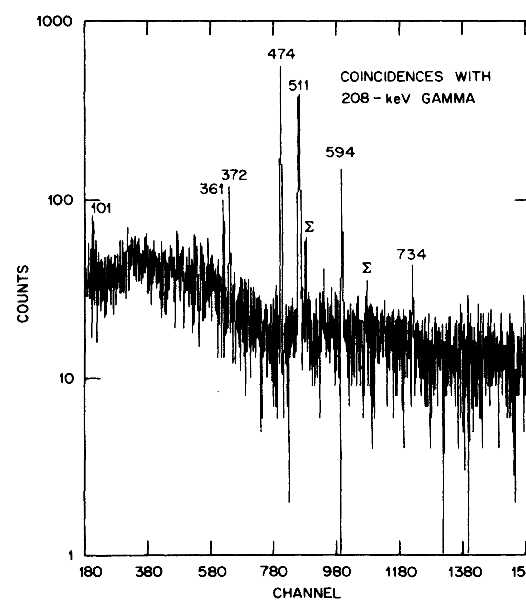

FIG. 4. Gamma-ray spectrum seen in coincidence with the 208-keV transition in ^{150}Tm decay.

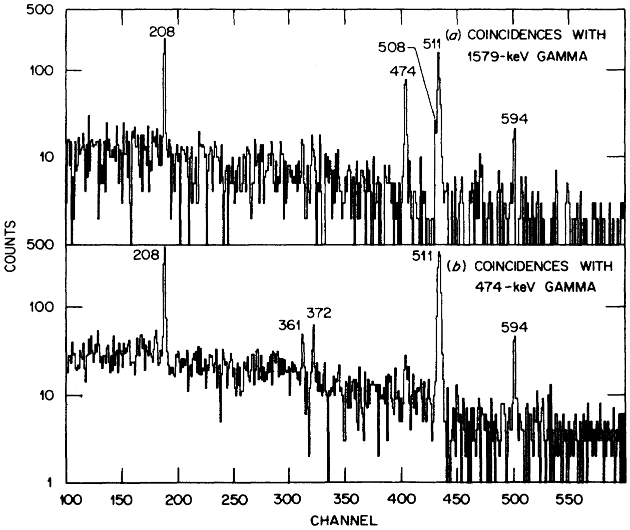

FIG. 5. Gamma-ray spectra observed in coincidence with the 1579-keV [part (a)] and 474-keV [part (b)] transitions in ^{150}Tm decay.

delayed-proton emission from the ^{151}Yb $h_{11/2}$ isomer. As a result, the 508.4- and 715.4-keV transitions are relatively more intense in Fig. 6 than in γ-ray spectra observed in ^{150}Tm β decay.

Transition energies and photon intensities of γ rays assigned to ^{150}Tm are summarized in Table I. Our proposed decay scheme is shown in Fig. 7 where, in addition to the levels discussed in the preceding paragraph, two others are indicated at 2996 and 3228 keV based on the coincidence relationships of the new 734.6- and 594.1-keV transitions (see Table I). From β-decay energies available[10] for neighboring Tm and Ho nuclei we estimate the ^{150}Tm Q_{EC} to be $\sim$11 MeV. We then calculate a logft value of $\sim$4.7 for the β decay to the 5^- level at 2261 keV if the total decay strength is assumed to be encompassed by the sum of the 1579.0- and 1786.6-keV γ-ray intensities (Table I). The allowed logft value indicates a spin and parity assignment of 4^-, 5^-, or 6^- for the ^{150}Tm parent state. Since the 6^+, 7^-, and 8^+ ^{150}Er levels are also observed, our data favor the 6^- assignment, in disagreement with Nolte *et al.*,[6] who suggested 4^- or 5^- assignments; they, as noted earlier, did not see γ rays from levels with spins greater than 5.

In two other odd-odd $N=81$ isotones, ^{146}Tb and ^{148}Ho, low-spin, (1^+), isomers have been observed.[6] Our γ-ray

TABLE I. Energies and γ-ray intensities for transitions observed in the decay of ^{150}Tm and ^{150}Er.

Isotope	E_γ (keV)	I_γ (relative)
^{150}Tm	100.7(2)	1.2(3)
^{150}Tm	207.7(1)	90(5)
^{150}Tm	360.5(2)	5(1)
^{150}Tm	372.4(2)	10(2)
^{150}Tm	474.4(4)	95(8)
^{150}Tm	508.4(5)[a]	$\sim$10
^{150}Tm	594.1(2)	15(2)
^{150}Tm	715.4(3)	7(2)
^{150}Tm	734.6(3)	1.7(3)
^{150}Tm	1400.4(4)[b]	4.5(5)
^{150}Tm	1579.0(3)	100[c]
^{150}Tm	1786.6(3)	10(3)
^{150}Er	130.0(1)	2.6(3)
^{150}Er	346.1(2)	0.5(1)
^{150}Er	476.0(2)	100[c]
^{150}Er	663.3(3)[b]	0.2(1)
^{150}Er	1014.0(3)	0.9(2)
^{150}Er	1022.1(3)	0.9(2)
^{150}Er	1151.9(3)	0.5(1)
^{150}Er	1177.1(3)[b]	0.3(1)
^{150}Er	1320.5(4)	0.2(1)
^{150}Er	1450.9(3)	0.3(1)
^{150}Er	1490.4(3)	0.4(1)

[a]Transition seen only in coincidence data.
[b]Transition not placed in proposed decay scheme.
[c]Normalization point for γ-ray intensities.

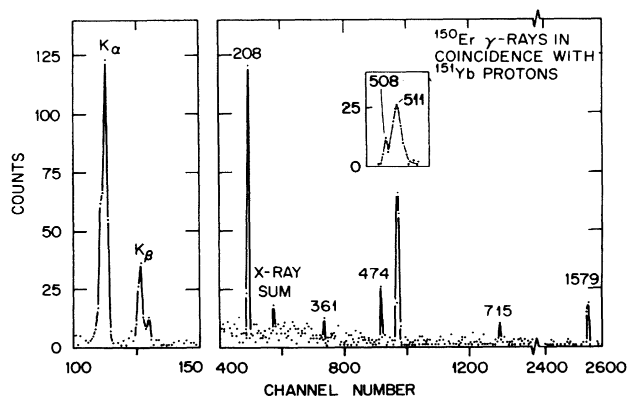

FIG. 6. Gamma rays in ^{150}Er, and K x rays measured in coincidence with ^{151}Yb β-delayed protons.

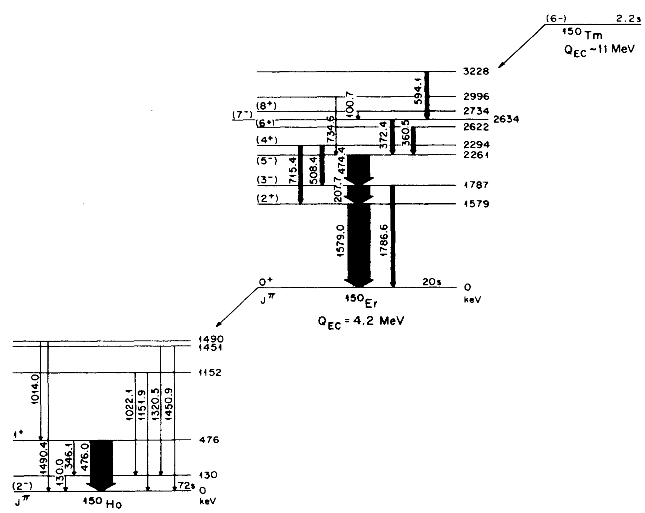

FIG. 7. Decay schemes of ^{150}Tm and ^{150}Er.

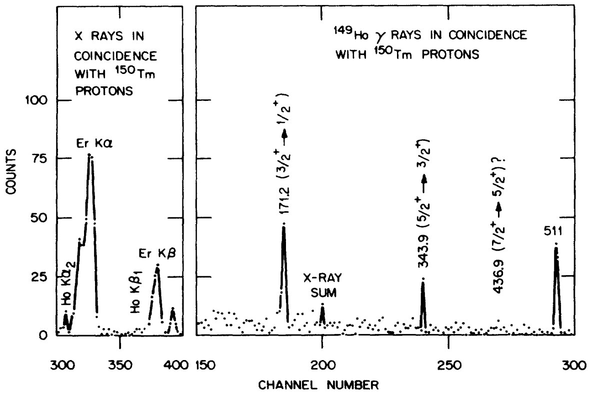

FIG. 8. Gamma rays in ^{149}Ho, and K x rays measured in coincidence with ^{150}Tm β-delayed protons.

data yield no indication for the presence of this low-spin species in ^{150}Tm. This is not surprising because in heavy-ion-induced reaction the production cross section overwhelmingly terminates in high-spin isomers. (In Ref. 6 the ^{146}Tb and ^{148}Ho low-spin isomers were populated in the decays of their respective 0^+ even-even parents.) Also, these (1^+) isomers decay[6] about 90% of the time to the 0^+ ground states of their daughters. We do, however, have evidence from the ^{150}Tm (β-delayed-proton)-(γ-ray) coincidence data that a low-spin isomer does indeed exist. This coincidence spectrum, which represents γ rays in ^{149}Ho, is shown in Fig. 8. Besides K x rays one sees the $d_{5/2} \rightarrow d_{3/2}$ and $d_{3/2} \rightarrow s_{1/2}$ transitions that have been observed[11] in the β decay of the $s_{1/2}$ ^{149}Er ground state. (A weak γ-ray peak may be present in Fig. 8, whose energy corresponds to the $g_{7/2} \rightarrow d_{5/2}$ transition.[11]) The intensity ratio of the two ^{149}Ho γ rays is measured to be essentially the same in both ^{150}Tm proton decay and in ^{149}Er β decay; this strongly suggests that ^{150}Er levels with spins of ≤ 2 are being fed in ^{150}Tm β decay and implies that a low-spin (1^+) isomer in ^{150}Tm does exist. Note that, based on expected isomer production ratios and on the decay patterns[6] of the 1^+ states in ^{146}Tb and ^{48}Ho, the contribution of this low-spin ^{150}Tm isomer to the total intensity of the 1579.0-keV γ ray (Table I) would only be about 1% or 2%.

C. Decay of $^{150}_{68}$Er$_{82}$ to levels in $^{150}_{67}$Ho$_{83}$

The isotope ^{150}Er was identified concurrently by Nolte *et al.*[6] and by Moltz *et al.*[12] Both investigations reported that the nuclide decayed by means of an allowed β transition to a single 1^+ state in ^{150}Ho. This level was then deexcited by the emission of a 476-keV γ ray to the ^{150}Ho low-spin isomer whose probable spin (Refs. 6 and 13) is 2^-.

Our data confirm these previous results. In particular, one notes in Fig. 9(a) that the spectrum in coincidence with the 476.0-keV transition is overwhelmingly dominated by x rays and annihilation radiation. However, we also observed ten other γ rays in ^{150}Er decay, one of which, a 1014.0-keV γ ray, is in coincidence with the 476.0-keV γ ray [Fig. 9(a)]. Most of these new transitions can be seen in Figs. 2 and 3(b), and in Fig. 9(b), which shows the spectrum in coincidence with a 130.0-keV γ ray whose photon intensity is about 2.6% that of the 476-keV transition.

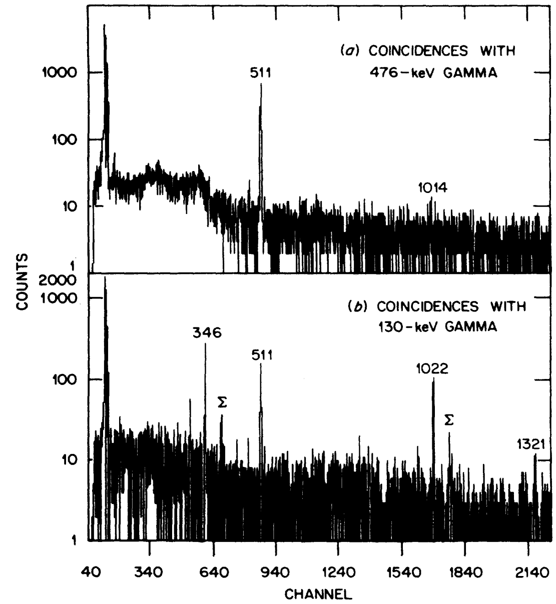

FIG. 9. Gamma-ray spectra observed in coincidence with the 476-keV [part (a)] and 130-keV [part (b)] transitions in ^{150}Er decay.

Based on coincidence information and on γ-ray intensities (Table I) we propose a scheme (Fig. 7) for ^{150}Er β decay which is more complete than the previously available one.[6,12] Despite the fact that four new ^{150}Ho levels are populated, the 476.0-keV state still receives $\sim$96% of the direct β-decay strength. The logft for this β transition, calculated with a 20-s half-life and a $Q_{\rm EC}$ of 4.2 MeV,[10] is 3.6, indicating that the β decay is allowed and that the 476.0-keV level does indeed have a 1^+ spin and parity assignment. The interested reader is referred to Ref. 14 for a discussion of possible spherical and Nilsson shell-model configurations of these 1^+ and 2^- states in odd-odd nuclei with $N=83$, 85, and 87 and with $Z \geq 65$.

D. ^{150}Ho low-spin isomer

The ^{150}Ho low-spin isomer was initially characterized by Liang *et al.*[13] They reported a half-life of 88 ± 15 s for this radioactivity and showed that it populated the first

TABLE II. Energies and γ-ray intensities for transitions observed in the decay of the ^{150}Ho low-spin isomer.

E_γ (keV)	I_γ (relative) (this work)	I_γ (relative) (Ref. 6)	I_γ (relative) (Ref. 13)
591.3(2)	25(3)	31(3)	44(15)
653.4(2)	17(2)	30(5)	
803.3(2)	100	100	100
983.0(5)[a]	$\sim$10		

[a]Transition observed only in coincidence data.

2^+ (804 keV) state in ^{150}Dy as well as the hitherto unobserved first 3^- (1395 keV) level. The 4^+ (1457 keV) level, fed[15] in the decay of the high-spin isomer, was apparently not populated. Subsequently, Nolte *et al.*[6] also investigated the ^{150}Ho low-spin decay. Within errors their half-life of 72 ± 4 s agreed with the one reported in Ref. 13. However, the $4^+\rightarrow2^+$ 653-keV transition was also observed; its intensity was the same was that of the $3^-\rightarrow2^+$ 591-keV γ ray.

In agreement with Nolte *et al.*,[6] we too observe the 653.4-keV γ ray in the decay of the ^{150}Ho low-spin isomer. The intensity of that γ ray (Fig. 2) could not be accounted for by the high-spin isomer decay, i.e., the $8^+\rightarrow6^+$, 551.0-keV, and $6^+\rightarrow4^+$, 393.9-keV γ-ray intensities were only about 15% that of the 653.4-keV transition. Thus, the first 4^+ state in ^{150}Dy is populated by the ^{150}Ho low-spin isomer. Our photon intensities for the three transitions, corrected for the presence of the high-spin isomer, are compared in Table II with those of Refs. 6 and 13. A 983.0-keV γ ray was observed in coincidence with the 803.3-keV transition. Based on decay patterns of neighboring odd-odd nuclei, we suggest that the 983.0-keV γ ray deexcites the second 2^+ level in ^{150}Dy.

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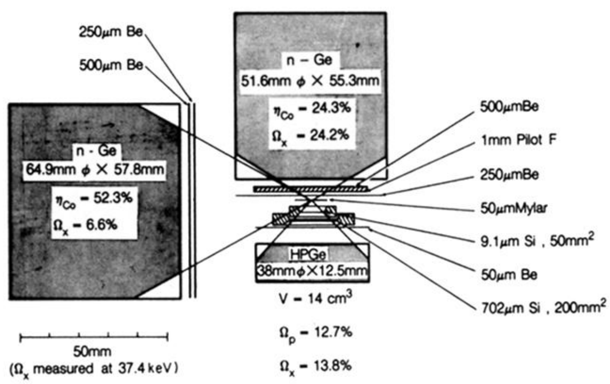

FIG. 1. Detector arrangement used in this study.