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Thermal Neutron Capture in ^{151}Eu

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THERMAL NEUTRON CAPTURE IN ^{151}Eu

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Abstract: The γ-ray spectrum from the radiative capture of thermal neutrons in 96.83 % enriched ^{151}Eu has been investigated in the energy range 150 keV to 880 keV using a Ge(Li) detector in Compton suppression technique. The structure of the spectrum was found to be extremely complex. 273 full-energy peaks have been resolved in the energy interval studied. The data are believed to provide a useful contribution to the still unsettled problem of constructing a reliable transition diagram for the odd nucleus ^{152}Eu.

E NUCLEAR REACTIONS ^{151}Eu(n,γ), E = th; measured E_γ, I_γ. ^{152}Eu deduced transitions. Enriched target, Ge(Li) detector.

1. Introduction

The nucleus $^{152}_{63}$Eu is of particular interest in nuclear structure studies, since it belongs to the transition region between deformed and spherical nuclei. In $^{152}_{64}$Gd the first 2^+ state occurs at 344 keV and the energy ratio $E(4_1^+)/E(2_1^+)$ is 2.2 which is close to the properties of a spherical vibrational nucleus. On the other hand, the isobaric nucleus $^{152}_{62}$Sm is characterized by $E(2_1^+) = 122$ keV and a clear rotational structure with $E(4_1^+)/E(2_1^+) = 3.0$. Thus it may be expected that $^{152}_{63}$Eu exhibits both deformed and spherical states.

Theoretical predictions on such nuclei are very difficult and the theory is still in an early stage. The experimental knowledge of excited states in ^{152}Eu is also very poor. The main reason for this lack of information is the extremely complex level structure. In addition, the doubly odd nucleus ^{152}Eu cannot be studied by radioactive decay. It is attractive to investigate the structure of ^{152}Eu by radiative neutron capture, since ^{151}Eu has a large cross section for thermal neutrons.

The neutron capture process has already been studied by various techniques, and results and references have been summarized [1]). The most precise published data on the low-energy γ-ray spectrum have come from measurements with a crystal diffraction instrument in the energy range up to 225 keV [refs. [2,3])]. The high-energy spectrum has been examined using a Ge(Li) pulse-height spectrometer [4]). Earlier measurements of the internal conversion-electron spectrum by means of a magnetic spectrometer are reported in refs. [5,6]). Recently the low-energy part of this spectrum has been reinvestigated with very high resolution [7]). All these studies have shown that the capture spectrum of Eu has an extremely complex structure.

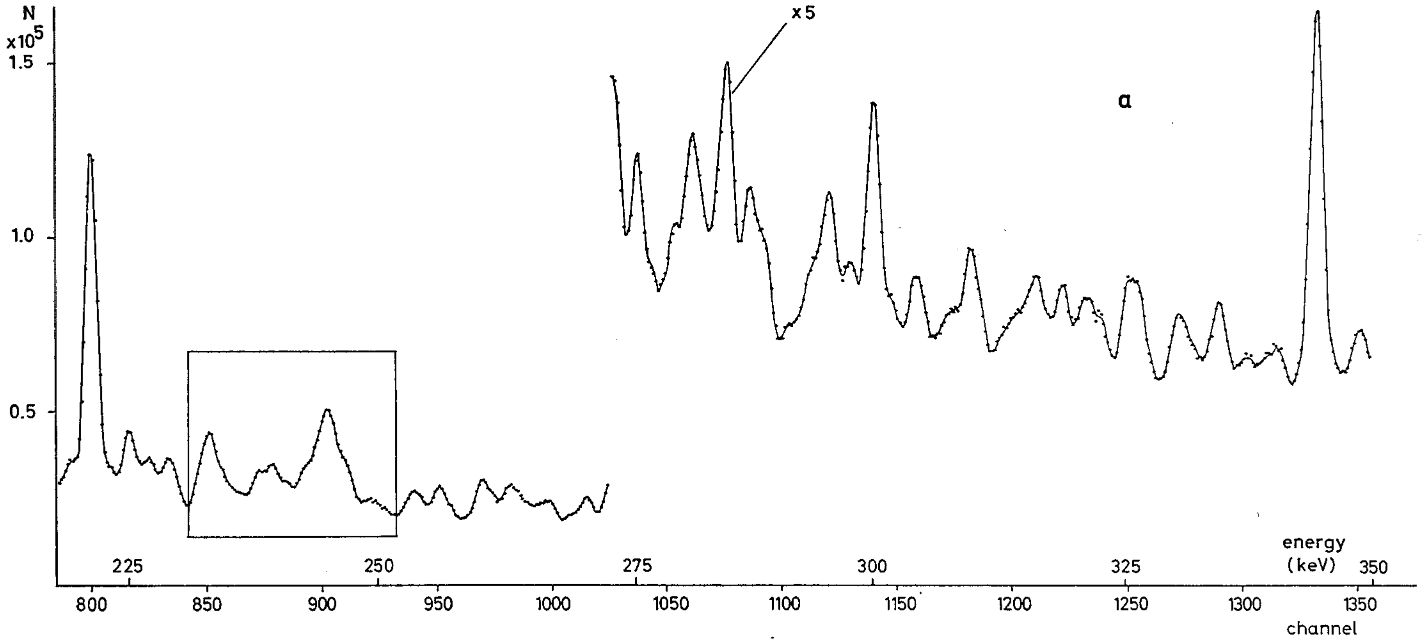

Fig. 1. (a) Sectional display of the neutron capture γ-ray spectrum as observed with the anti-Compton spectrometer. Analysis has been performed with the minimum number of peaks necessary to represent the experimental data within the statistical fluctuations and to reveal a χ^2 value of $\approx$ 1.

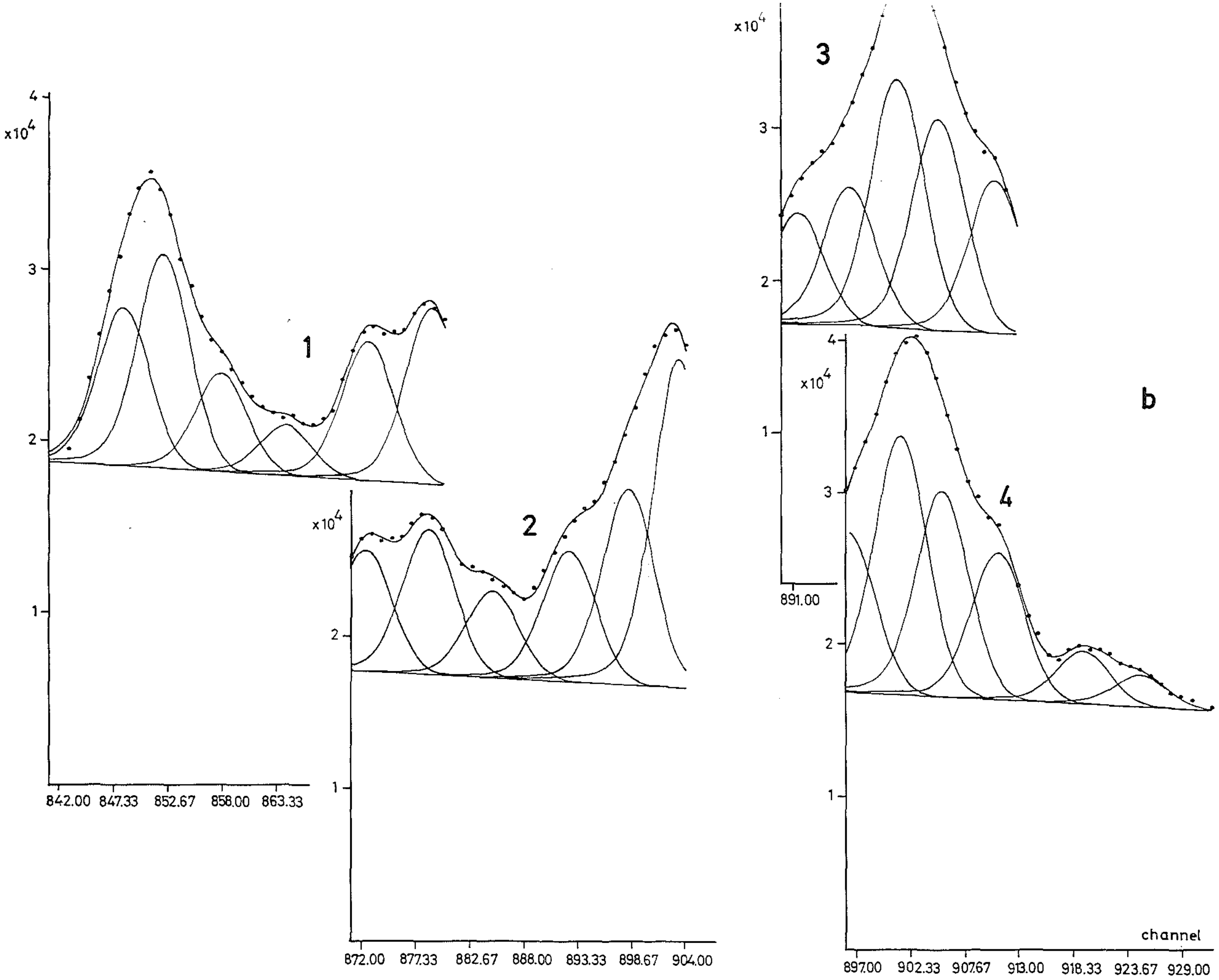

Fig. 1. (b) Computer analysis for a group of γ-rays (see window in (a)) using modified Gaussian functions.

Research on the isomeric states and the conversion-electron data have led to first efforts in constructing a level scheme for ^{152}Eu [refs. $^{8-12}$)]. At present attempts are being made in several laboratories to reinvestigate the capture reaction with improved techniques ^{7,13}). Though the new data have not yet been published, it is already obvious that the earlier decay schemes have to be revised in several respects. Reliable information on the level scheme is available at present only up to 150 keV excitation energy ^{7}).

It is the purpose of this article to report on precision measurements of the capture γ-ray spectrum in the energy range 150 keV to 880 keV by means of a Ge(Li) anti-Compton spectrometer. No attempt has been made to construct an extended transition diagram, since reliable conclusions will only be possible when additional information from other techniques is available.

2. Experimental procedure

A thermal neutron beam produced by a graphite scatterer in the tangential through-hole of the reactor FR 2 was used to irradiate a sample of enriched ^{151}Eu in external target geometry. The abundances of the isotopes and the relative cross-section contributions are summarized in table 1. Due to the enrichment and the high capture cross section of ^{151}Eu interference from capture in ^{153}Eu was negligible. Moreover the γ-ray spectrum from capture in ^{153}Eu was well known from a separate study of the reaction ^{153}Eu(n, γ)^{154}Eu which will be published elsewhere ^{14}). The data were also examined for the possibility of contributions from likely chemical contaminants. Results of a spectrographic analysis of the sample material ensured that in general interference from other elements was well below the detection threshold. The relative cross-section contributions of the large cross-section elements Cd, Sm, Gd and Dy were definitely less than 0.02, 0.04, 0.15 and 0.01 %, respectively. Nevertheless, from these elements the well-known capture lines at 181.94 keV, 199.28 keV (Gd), 333.94 keV, 439.39 keV (Sm) and 558.29 keV (Cd) which possess outstanding intensities in photons per capture may have contributed to the pertinent structures in the γ-ray spectrum.

TABLE 1

Isotopic composition of the target and relative cross-section contributions

Isotope	Atomic %	Capture cross section [a]) for thermal neutrons (b)	Relative cross-section contribution (%)
^{151}Eu	96.83	8800±100	99.86±0.04
^{153}Eu	3.17	390± 80	0.14±0.04

[a]) Ref. ^{1}).

TABLE 2

Gamma rays in the energy range 150 keV to 880 keV as observed with the Ge(Li) anti-Compton spectrometer

Energy [a])		Intensity [b])		Remarks [c])
E (keV)	$\pm\Delta E$ (eV)	I	$\pm\Delta I$	
150.67	90	0.20	0.04	
153.64	250	0.22	0.04	
154.35	250	0.22	0.04	
156.13	150	0.04	0.02	
157.46	70	0.19	0.04	
158.55	100	0.12	0.03	
160.19	40	0.16	0.03	doublet ?
163.17	180	0.09	0.02	
163.86	120	0.15	0.03	
165.85	300	0.04	0.02	
166.92	50	0.26	0.05	
168.78	60	0.58	0.13	
169.45	100	0.38	0.11	
170.62	250	0.17	0.04	doublet ?
171.78	220	0.43	0.09	
172.47	350	0.13	0.02	
175.22	250	0.03	0.01	
176.35	180	0.07	0.02	
178.43	100	0.07	0.02	
179.78	40	0.25	0.04	
181.04	100	0.09	0.02	
182.22	40	0.28	0.04	181.94 Gd(n,γ) possibly contributes
183.63	100	0.085	0.020	
186.73	80	0.26	0.05	
187.77	80	0.25	0.05	
190.43	100	0.16	0.04	
191.38	100	0.18	0.04	
192.90	70	0.36	0.11	
194.13	90	0.21	0.05	
195.54	300	0.055	0.020	
196.59	300	0.11	0.02	
197.75	150	0.20	0.05	
199.15	60	0.33	0.07	199.28 Gd(n,γ) possibly contributes
203.16	150	0.19	0.04	doublet ?
204.07	500	0.075	0.025	
205.09	400	0.12	0.03	
206.37	70	0.73	0.13	
207.49	100	0.25	0.05	doublet ?
208.68	150	0.21	0.04	
209.93	200	0.12	0.02	
212.53	200	0.11	0.02	
214.47	100	0.25	0.04	
215.2	500	≈ 0.015		
216.75	150	0.08	0.02	
219.13	300	0.05	0.02	
221.16	60	1.25	0.20	
223.00	300	0.08	0.02	
224.89	100	0.24	0.03	

Table 2 (continued)

Energy [a]		Intensity [b]		Remarks [c]
E (keV)	$\pm\Delta E$ (eV)	I	$\pm\Delta I$	
226.00	350	0.08	0.02	
227.06	250	0.12	0.03	
228.51	300	0.10	0.03	
229.28	300	0.12	0.03	
232.29	150	0.16	0.03	
233.22	150	0.23	0.05	
234.54	250	0.11	0.03	
236.06	400	0.06	0.02	
237.90	150	0.15	0.03	
239.35	120	0.18	0.03	
240.81	200	0.11	0.03	
242.44	150	0.15	0.03	
243.64	200	0.20	0.03	
244.70	200	0.34	0.09	
245.63	250	0.25	0.07	
246.89	200	0.19	0.03	
248.79	250	0.065	0.020	
250.06	300	0.045	0.015	
253.21	150	0.09	0.03	
254.13	200	0.07	0.02	
255.97	150	0.14	0.03	
256.96	250	0.05	0.02	
260.31	80	0.18	0.03	
261.49	180	0.10	0.02	
263.10	100	0.16	0.03	
264.24	200	0.10	0.02	
265.65	400	0.065	0.020	
267.08	150	0.10	0.02	
269.46	450	0.02	0.01	
270.91	80	0.12	0.02	≈ 25 % 271.0 from β^- decay $^{152\mathrm{m}_1}$Eu
273.14	300	0.10	0.03	
273.75	250	0.19	0.07	
275.99	70	0.16	0.02	
277.35	400	0.015	0.010	
279.76	150	0.08	0.02	
281.36	150	0.18	0.05	
282.40	250	0.11	0.03	
283.96	250	0.10	0.03	
285.11	80	0.32	0.07	
287.26	200	0.18	0.03	
288.74	200	0.13	0.02	
291.61	400	0.02	0.01	
293.31	350	0.08	0.02	
294.37	450	0.08	0.03	
295.40	150	0.19	0.04	
296.7	600	0.075	0.035	
298.0	600	0.090	0.045	
299.77	90	0.36	0.06	
301.49	200	0.065	0.020	
303.69	400	0.065	0.025	

TABLE 2 (continued)

Energy [a]		Intensity [b]		Remarks [c]
E (keV)	$\pm\Delta E$ (eV)	I	$\pm\Delta I$	
304.37	400	0.065	0.025	
306.7	600	≈ 0.02		
307.65	350	0.045	0.020	
309.36	100	0.13	0.02	
310.24	250	0.06	0.02	
313.20	300	0.04	0.01	
314.49	350	0.06	0.02	
315.89	180	0.11	0.02	
316.9	500	0.045	0.020	
318.9	600	0.12	0.02	
319.8	500	0.035	0.020	
321.09	350	0.11	0.02	
322.53	380	0.08	0.02	
325.28	180	0.14	0.02	
326.50	180	0.13	0.02	
330.34	150	0.11	0.02	
331.68	300	0.06	0.01	
333.72	450	0.05	0.02	333.94 Sm(n, γ) probably contributes
334.66	150	0.12	0.02	
337.16	280	0.05	0.01	
338.93	450	0.035	0.010	
340.24	250	0.065	0.020	
344.27	60	0.73	0.07	≈ 100 % 344.24 from β^- decay ^{152m_1}Eu
346.0	600	0.035	0.020	
348.58	350	0.12	0.02	
350.26	450	0.05	0.02	
352.6	500	0.045	0.020	
354.9	650	0.065	0.020	
355.1	500	0.08	0.02	
358.10	400	0.09	0.02	
359.4	700	0.05	0.02	
360.1	600	0.030	0.015	
364.77	150	0.12	0.02	
366.52	150	0.14	0.02	
369.21	250	0.08	0.02	
370.63	150	0.14	0.02	
372.5	700	0.03	0.01	
374.1	500	0.04	0.01	
376.75	180	0.12	0.02	
379.03	250	0.085	0.020	
381.55	300	0.08	0.02	
384.4	1000	≈ 0.01		
387.6	500	0.055	0.020	
388.5	1000	≈ 0.02		
389.9	600	0.06	0.02	
390.8	500	0.075	0.020	
392.2	600	0.060	0.025	
393.3	600	0.075	0.030	
395.78	400	0.055	0.020	
397.27	350	0.09	0.02	

Table 2 (continued)

Energy [a]		Intensity [b]		Remarks [c]
E (keV)	$\pm\Delta E$ (eV)	I	$\pm\Delta I$	
399.75	450	0.045	0.020	
401.33	400	0.05	0.02	
403.76	400	0.08	0.02	
404.91	400	0.09	0.02	
406.72	450	0.045	0.020	
408.76	300	0.06	0.02	
411.21	250	0.065	0.020	
413.09	350	0.08	0.02	
414.64	300	0.12	0.02	
417.6	500	0.03	0.01	
418.7	600	≈ 0.02		
422.40	350	0.07	0.02	
423.73	300	0.15	0.03	
426.54	250	0.09	0.02	
427.78	350	0.06	0.02	
432.75	200	0.13	0.02	
434.39	350	0.055	0.020	
436.6	500	0.04	0.02	
438.1	600	0.055	0.020	
439.5	600	0.07	0.02	439.39 Sm(n, γ) possibly contributes
441.27	400	0.09	0.02	
443.4	500	0.05	0.02	
445.01	300	0.085	0.020	
446.97	250	0.07	0.02	
449.44	400	0.080	0.025	
450.1	600	0.080	0.025	
452.0	700	0.035	0.010	
453.7	600	0.06	0.02	
455.47	400	0.10	0.02	
456.6	700	0.05	0.02	
458.09	450	0.065	0.020	
459.69	200	0.14	0.02	
461.55	300	0.065	0.020	
465.75	450	0.045	0.010	
468.1	600	≈ 0.025		
472.37	300	0.09	0.02	Energy and intensity determination possibly affected by background from ^{10}B(n, α)
474.12	450	0.055	0.020	
478.1	500	0.02	0.01	
479.6	500	0.035	0.010	
481.82	300	0.05	0.01	
483.9	600	≈ 0.015		
485.9	600	≈ 0.015		
488.73	350	0.035	0.010	
491.2	800	≈ 0.01		
492.9	800	≈ 0.03		
494.13	350	0.045	0.020	
496.8	600	0.03	0.02	
498.5	500	0.04	0.02	
500.08	400	0.05	0.02	
501.7	500	≈ 0.025		

TABLE 2 (continued)

Energy [a])		Intensity [b])		Remarks [c])
E (keV)	$\pm \Delta E$ (eV)	I	$\pm \Delta I$	
505.84	400	0.055	0.020	
507.8	500	0.065	0.020	
509.4	1000	0.06	0.02	
510.86	300	0.16	0.07	$e^+(e^-, \gamma)$ contributes
512.19	450	0.10	0.03	
517.6	500	0.03	0.01	
520.11	200	0.08	0.02	
522.5	800	0.02	0.01	
523.9	600	0.03	0.01	
526.35	200	0.07	0.02	
531.7	800	≈ 0.01		
539.44	350	0.045	0.020	
541.86	450	0.035	0.015	
545.9	600	≈ 0.015		
549.94	400	0.035	0.015	
554.5	500	0.05	0.02	
555.8	500	0.06	0.02	
558.00	400	0.05	0.02	558.29 Cd(n, γ) possibly contributes
561.07	450	0.06	0.02	
562.85	350	0.09	0.02	≈ 100 % 563.2 from EC decay ^{152m_1}Eu
566.73	450	0.05	0.02	
568.5	600	0.035	0.015	
570.3	800	≈ 0.02		
571.8	600	0.035	0.015	
574.70	450	0.035	0.015	
576.9	500	≈ 0.035		
579.82	450	0.04	0.02	
582.2	700	0.02	0.01	
588.2	500	0.03	0.01	
592.0	1000	≈ 0.01		
595.43	400	0.05	0.02	
599.4	600	≈ 0.02		
603.9	500	0.03	0.01	
609.00	400	0.05	0.02	
616.16	350	0.05	0.02	
620.83	450	0.035	0.010	
624.1	700	0.02	0.01	
628.84	350	0.045	0.020	
631.2	600	0.02	0.01	
633.4	600	0.025	0.010	
639.9	800	0.025	0.010	
660.9	700	0.025	0.010	
663.4	1000	≈ 0.01		
668.1	500	0.025	0.010	
670.7	500	0.025	0.010	
676.80	400	0.03	0.01	
688.56	400	0.04	0.01	
691.7	500	0.03	0.01	
697.5	600	0.03	0.01	
699.83	450	0.045	0.020	≈ 40 % 700.0 from β^- decay ^{152m_1}Eu

TABLE 2 (continued)

Energy [a])		Intensity [b])		Remarks [c])
E (keV)	$\pm\Delta E$ (eV)	I	$\pm\Delta I$	
703.1	500	0.055	0.020	
705.0	600	0.035	0.015	
709.6	600	0.030	0.015	
713.4	600	0.045	0.015	
721.0	900	0.025	0.015	
723.2	1000	≈ 0.015		
726.2	700	≈ 0.02		
730.5	600	0.040	0.015	
732.3	600	0.045	0.020	
740.6	500	0.045	0.020	
743.4	500	0.04	0.02	
750.8	800	0.030	0.015	
776.0	800	≈ 0.02		
779.2	500	0.040	0.015	
799.7	600	0.035	0.015	
802.2	700	≈ 0.025		
815.2	500	0.04	0.02	
825.1	500	≈ 0.025		
841.57	50	4.58		EC decay ^{152m_1}Eu
850.0	700	≈ 0.025		
852.3	600	0.030	0.015	
860.1	1000	< 0.015		
863.8	700	0.030	0.015	
869.9	500	0.04	0.02	
877.3	500	0.045	0.020	

a) In the case of unresolved complex structures the energy given refers to the centroid. Before making use of the data it is important to notice the comments in the text.

b) The intensities listed are relative intensities. They were normalized to a value of 4.58 for the 841.57 keV γ-ray from the ^{152m_1}Eu EC decay. On the basis of the hitherto known cross section and decay data, the intensities given in column 3 are expected to deviate not more than 30 % from the absolute intensities in photons per 100 captures. In the case of unresolved complex structures the intensity quoted refers to the total intensity of the components.

c) The γ-ray energies for the ^{152}Eu EC and β^- decay have been adopted from the compilation ref. [16]).

High-resolution measurements have been performed using the Karlsruhe Ge(Li) anti-Compton spectrometer †) which during these measurements consisted of a 5 cm^3 Ge(Li) diode, a 50 cm ø × 40 cm plastic scintillator of type NE 102A and a 10.16 cm ø × 15.24 cm NaI(Tl) detector. The energy resolution including long-term instabilities was 1.96 keV FWHM for the 841.57 keV γ-ray from the ^{152m_1}Eu (9.3 h) EC decay. The response function of the spectrometer was determined with a set of absolutely calibrated γ-ray sources. Details on the experimental arrangement and the procedures applied in spectrum stabilization, spectrum analysis, energy and intensity calibration and nonlinearity correction may be found in ref. [15]) and the literature given there.

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†) See ref. [15]) and the literature cited there.

3. Experimental results and discussion

The capture γ-ray spectrum has been investigated between 150 keV and 880 keV. The data were taken with a channel width of about 230 eV. A typical sectional display of the pulse-height distribution is shown in fig. 1a. The spectrum was found to be extremely complex. 273 γ-ray lines have been identified in the energy interval studied. In the lower part of the spectrum the average distance between resolved peaks is about 1.5 keV. In order to obtain optimum accuracy in the energy determination, a method using overlapping energy intervals has been applied in the computer analysis, i.e. each peak has been fitted at least once with the greatest possible accuracy. This is illustrated in fig. 1b for a small section of the spectrum shown in fig. 1a. The results of the measurement are summarized in table 2.

In view of the high line density it is reasonable to assume that many of the γ-rays listed in the table represent closely spaced doublets or complex structures. In such cases the energy given refers to the centroid and the intensity is the total intensity of the components. It should be stressed that no previous data were available to help resolve the spectrum. For determining the quoted uncertainties in the energy values consideration was given to: (i) the uncertainty in the height of the Compton background under the peaks, (ii) the statistical fluctuations in the pulse-height distribution, (iii) the goodness of fit obtained in the spectrum analysis, (iv) possible errors in the nonlinearity correction function and (v) the uncertainties associated with the energy standards.

The γ-ray intensities listed in table 2 are relative intensities. They were normalized to a value of 4.58 for the 841.57 keV γ-ray from the ^{152m_1}Eu EC decay. This value was calculated from the total radiative capture cross section [17]) (8800 ± 100 b), the cross section for production of the 9.3 h isomeric state (3100 ± 400 b) and the γ-ray intensity [16]) $I(841.57) = 13 \pm 1\,\%$ reported for the ^{152m_1}Eu EC decay. Taking into account a proper half-life correction and assuming[†] that the very pronounced 841.57 keV peak is essentially a transition in ^{152}Sm one may deduce from these data the absolute intensities of the capture lines in photons per 100 captures. On the basis of the above cross-section and decay data it is therefore expected that the intensities listed in column 3 of table 2 do not deviate more than about 30 % from the absolute values. In the energy range from 150 keV to 225 keV the results can be compared with the previous crystal diffraction data [3]). While there is excellent agreement in the γ-ray energies, the intensities from table 2 are systematically lower than those from ref. [3]) by about a factor of 3. This result is somewhat confusing and throws some doubt on the absolute intensities given in ref. [3]), since it is unlikely that the cross-section and decay data are subject to errors in this order of magnitude.

The errors quoted for the intensities in table 2 include uncertainties arising from the Compton background, the statistics, the fitting procedure and the spectrometer

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[†] The line shape and the result of a control measurement after irradiation of the target strongly support this assumption. It is in contrast to the compilation ref. [1]) where a γ-ray with 841.4 keV and $I_\gamma = 1.61$ is assigned to ^{152}Eu.

response function. In general, the main contribution comes from the possible errors in the determination of the background under the peaks.

Though the present research has brought about very detailed information on the capture γ-ray spectrum, it would be unreasonable to make any attempt in establishing a transition diagram on the basis of these data alone. The Ritz combination principle has proved to be very successful in many cases. However, one can easily show that the number of chance combinations is of the order of $n^3 \Delta E/E$, where n is the number of lines in the energy interval E and ΔE the mean energy error. In the present case one may obtain nearly 10^4 combinations by chance. The situation does not change substantially, when the primary transition data from ref. ^{4}) are taken into account. Additional information from other techniques, in particular from conversion electron and coincidence measurements, is therefore highly desirable. At present efforts are being made to further improve the performance of the anti-Compton spectrometer used in this study. The new version will allow both a considerable improvement of the quality and detail of the data in the energy interval studied and an extension of the research to higher γ-ray energies.

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