High-Energy γ Spectra Resulting from Neutron Capture in Hafnium Isotopes*

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(Received 26 January 1966)

The γ spectra resulting from thermal-neutron capture in targets of natural hafnium, enriched Hf^{177}, and enriched Hf^{179} were measured with lithium-drifted germanium detectors. The energies and intensities of 42 gamma lines in the range from about 5.5 to 7.6 MeV were determined and the transitions were identified with the reactions $Hf^{177}(n,\gamma)Hf^{178}$, $Hf^{178}(n,\gamma)Hf^{179}$, $Hf^{179}(n,\gamma)Hf^{180}$, or $Hf^{180}(n,\gamma)Hf^{181}$, The neutron separation energies were determined to be 7623 keV for Hf^{178}, 6098 keV for Hf^{179}, 7383 keV for Hf^{180}, and 5693 keV for Hf^{181}, the uncertainty in energy being ± 3 keV in each case. The gamma spectrum of each final nucleus was used to identify 28 new levels, and to verify 14 previously known levels. Some of these levels are discussed.

I. INTRODUCTION

THE recent development of lithium-drifted germanium detectors[1] has greatly improved the technique of measuring the high-energy gamma spectra resulting from thermal-neutron capture. In the past, such measurements were difficult because of the low efficiency for detecting high-energy gamma rays with high-precision instruments.[2] Large samples consisting of a natural-abundance mixture of isotopes were necessary to obtain sufficient intensity. As a result, unambiguous isotopic identification of capture lines was usually impossible. The germanium detectors with their higher detection efficiency and comparable or better resolution now make it feasible to use small samples of separated isotopes in experiments to measure high-energy gamma spectra. Such samples can be installed in and removed from a reactor quickly and easily so that several different isotopes can be studied in rapid succession.

The present work reports the results of gamma-ray measurements made with lithium-drifted germanium detectors on three different hafnium targets—an enriched Hf^{177} target, an enriched Hf^{179} target, and a target of natural hafnium. The ability to make isotopic assignments on the basis of measurements on the separated isotopes, together with the high precision of measuring gamma energies, enabled us to establish new levels and verify previously established levels.[3,4] We were also able to measure the neutron separation energies with a precision not obtainable in the past. The information contained in the spectra for the three targets was used to identify lines in Hf^{178}, Hf^{179}, Hf^{180}, and Hf^{181} and to determine the neutron separation energies of these four nuclei.

II. APPARATUS

The enriched Hf^{177} and Hf^{179} targets were obtained from Oak Ridge in the form of HfO powder. Their compositions, after correcting for earlier irradiations, are shown in Table IV (Sec. IV.1). The enriched samples were prepared by putting about 300 mg of the powder into a sample holder made of an alloy of ~85% Mg, 15% Al. The holder was fastened to a small aluminum tube which could be inserted into the core of the large reactor CP-5 at Argonne. The natural hafnium target was a metal foil weighing about 800 mg. The samples were irradiated in a neutron flux of about 3×10^{13} neutrons cm^{-2} sec^{-1}.

Gamma rays coming from the targets were detected by a lithium-drifted germanium detector with a detection volume of ~1.0 cc. The detectors were installed in the usual fashion in a vacuum chamber and cooled to the temperature of liquid nitrogen. In order to achieve a high detection efficiency for double-escape peaks, the germanium detectors were mounted as shown in Fig. 1, with the longest dimension of the depletion region parallel to the gamma beam. Pulses in the germanium were detected by a low-noise charge-sensitive preamplifier, amplified, and fed into a multichannel analyzer. The resolution width of the system was about 6 keV at 7.7 MeV and about 3 keV at 1 MeV. The thickness of the depletion region was about 3.5 mm.

To reduce background, the gamma beam was highly collimated by means of small apertures in 8-in. lead plugs. The collimators, which were adjusted to eliminate unwanted background lines from the aluminum tube

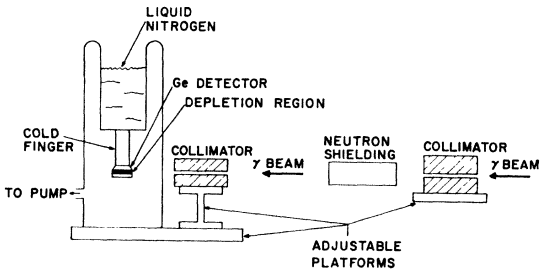

FIG. 1. Experimental arrangement for measuring neutron-capture γ rays by means of a lithium-drifted germanium detector.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] G. T. Ewan and A. J. Tavendale, Can. J. Phys. 42, 2286 (1964); A. J. Tavendale and G. T. Ewan, Nucl. Instr. Methods 26, 183 (1964).

[2] L. V. Groshev, A. M. Demididov, V. N. Lutzenko, and A. F. Malov, Izv. Akad. Nauk SSSR, Ser. Fiz. 24, 791 (1960).

[3] R. K. Smither, Phys. Rev. 129, 1691 (1963).

[4] L. V. Groshev, A. M. Demidov, V. A. Ivanov, V. N. Lutzenko, and V. I. Pelekhov, Izv. Akad. Nauk SSSR, Ser. Fiz. 28, 1244 (1964).

surrounding the target while permitting the gamma rays from the hafnium target to enter the detector, reduced the ratio of the intensity of aluminum background to hafnium capture lines to 0.1–0.2 of the value without them. The remaining background was measured by simply removing our samples and repeating our measurements.

III. EXPERIMENTAL PROCEDURE

In measuring high-energy gamma rays in the region around 6 MeV, stable electronics is an important factor. For a resolution width of 6 keV—which is 0.1% at 6 MeV—even a small drift in electronics during a run may easily double the line width. To guard against such drifts, data were collected as a series of runs of relatively short duration. Typically, data would be collected for a period of about 3 h on a multichannel analyzer and printed out, after which the analyzer would automatically reset and continue. Widening of our lines was noticed only rarely in these short runs. For those few cases in which drifts were excessive, the run was simply repeated and the bad data were not used.

As a further check on the stability of our electronics, calibration pulses were inserted into the detector input before and after each series of runs and at least every 24 h. The magnitude of these pulses was measured by means of a potentiometer to an accuracy of a few parts in 10^4. Five or six equally spaced pulse heights were used in each energy region so that the pulses completely covered the region. The voltage and channel positions of the pulses were recorded for each calibration. A large number of pulses was used to provide a check on the linearity of the electronic system.

The calibration pulses were also used to measure the energies of our double-escape peaks since the charge collected in the detector is directly proportional to the energy lost by a gamma ray in the depletion region of the germanium. Our pulser was calibrated every day against the double-escape peak of the 7722-keV aluminum line of our background. Slight changes in our calibration—due, perhaps, to changes in the stray capacitance across the germanium detector—were noticed from time to time. All our energies were determined in terms of voltages which were then converted to energy value by use of the calibration of the aluminum line. The energy of the aluminum line, in turn, was determined by the same method from the accurately measured value[5] of the 10 834.2-keV line in nitrogen. For this purpose, a BeN_3 sample was used.

To measure the energy dependence of the over-all efficiency for detecting gamma rays, we studied the capture spectrum from a BeN_3 target and compared the gamma intensities observed with those reported by

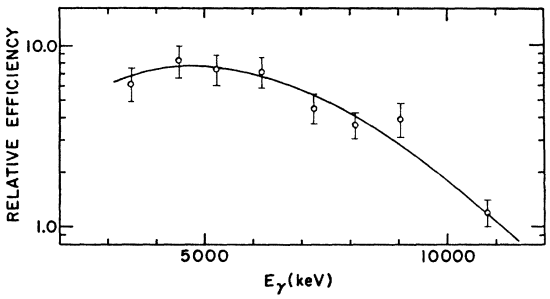

FIG. 2. Over-all efficiency of the germanium-diode detection system, plotted as a function of the γ-ray energy. The curve includes the effect of absorption in the neutron shielding interposed in the γ beam.

Bartholomew and Campion[6] for gamma lines in nitrogen. The relative variation in detection efficiency with gamma energy is shown by the curve in Fig. 2. This efficiency curve reflects the effect of absorption of gamma rays by neutron shielding and other material in our beam as well as the detection efficiency of the germanium detector itself.

IV. METHOD OF ANALYSIS AND ISOTOPIC IDENTIFICATION

All of the data printed out by our multichannel analyzer were analyzed to obtain the best fit for the positions, intensities, and widths of the lines, and also the statistical errors for these quantities. The energies of lines were computed from the positions by use of the calibration pulses mentioned in Sec. III. A nonlinear interpolation procedure was used to find the voltage corresponding to gamma lines from the calibration pulses. Usually the polynomial of the highest possible order was fitted to the series of calibration pulses. Only terms up to the second order were found to be of importance for the precision which we wished. Voltages were then converted to energies by means of our energy-versus-voltage calibration already mentioned.

1. Intensity Measurements

For each sample, the intensities of gamma rays found by the computer were corrected (by means of the curve in Fig. 2) for the variation in detection efficiency with energy. This correction gives the proper relative intensities of the gamma lines. In order to express the intensity of a gamma ray as the percent per neutron capture in the sample, the intensity of each line was compared with the intensity of the 5720-keV line, which appeared as a bright line in all the samples used. We will see later that this line is a Hf^{179} transition following the $Hf^{178}(n,\gamma)Hf^{179}$ reaction. Knowing the isotopic composition of all of our targets—in particular the percent Hf^{178} in the targets—and also the intensity of

[5] F. Everling, L. A. König, V. H. E. Mattauch, and A. H. Wapstra, Nucl. Phys. 18, 529 (1960).

[6] G. A. Bartholomew and P. J. Campion, Can. J. Phys. 35, 1347 (1957).

the 5720-keV line in natural hafnium (from the data of Groshev *et al.*[4]), we can find the computed intensity of the 5720-keV line in percent per neutron capture in the sample for each of our targets. Then, from the ratios of intensities of the other gamma lines to that of the 5720-keV line in a particular sample, we can find the intensities of these other gamma lines in percent per capture in the sample. Isotopic identification of γ lines was based on the variation in their intensities from sample to sample, and the intensity (percent per neutron capture in the capturing isotope) was computed for each line. Our intensity and energy measurements are shown in Tables I, II, and III.

TABLE I. Lines due to the $Hf^{177}(n,\gamma)Hf^{178}$ reaction. The neutron separation energy of Hf^{178} is $E_s=7623\pm3$ keV.

Gamma energy[a] E_γ (keV)	(E_s-E_γ) (keV)	Known levels Energy (keV)	Spin[b]	Source	Intensity[a] (% per capture in Hf^{177})
7530	93	93	2^+		0.065
7317	306	306	4^+		0.047
6445	1178	1174	(2^+)	(Groshev)	0.096
6354	1269	1269	2^+	(Smither)	0.454
6301	1322	1323	2^+	(Smither)	0.096
6239	1384	1384	(4)	(Smither)	0.100
6214	1409				0.064
6191	1432	1431	0^+	(Smither)	0.036
6172	1451	1453	4^+	(Groshev)	0.051
6110	1513	1513	4^+	(Smither)	0.820
6091	1532				0.109
6063	1560				0.121
5985	1637				0.141
5863	1760				0.052
5802	1821				0.390
5759	1864				0.195
5751	1872				0.096
5707	1916				0.154
5679	1954				0.046
5666	1957				0.166
5635	1988				0.122
5623	2000				0.101
5610	2013				0.153
5602	2021				0.076
5574	2049				0.275

[a] There is an error of 3 keV in the energies and 20% in the intensities.
[b] Parentheses indicate uncertainty in the spin assignments taken from previous work.

There were several sources of error in determining intensities. In addition to the statistical errors in the measurement, systematic errors were introduced by (1) an error in the intensity of the 5720-keV line in natural hafnium as measured by Groshev *et al.*,[4] (2) errors in our efficiency curve, (3) errors in the measured composition of our targets, and (4) errors in the cross sections of the isotopes.

The first error will introduce the same percent error in all of our intensities; the second similarly affects all lines in a given energy region; the third, all lines computed on the basis of a given target; and the fourth, all the lines of a given isotope (but not the relative intensities of lines emitted by the same isotope). The combination of these systematic errors is believed to be more important than our statistical errors in determining intensities. Accordingly, the errors quoted in Tables I, II, and III are in percent of the quoted values. These errors vary between 20 and 30%. Errors in the relative intensities of two lines in the same isotope and close in energy are smaller than the quoted errors.

TABLE II. Lines due to the $Hf^{179}(n,\gamma)Hf^{180}$ reaction. The neutron separation energy in Hf^{180} is $E_s=7383\pm3$ keV. Levels marked with an asterisk passed the test described in Sec. V.2.

Gamma energy[a] E_γ	(E_s-E_γ) (keV)	Known levels Energy (keV)	Spins	Proposed levels[a] (keV)	Intensity[a] (% per capture in Hf^{179})
7074	309	309	4^+		0.046
6742	641	641	6^+		0.055
6231	1152			1152*	0.020
6203	1180			1180*	0.033
6196	1187			1187	0.016
6190	1193			1193*	0.036
6123	1260			1260*	0.036
6095	1288			1288*	0.084
6012	1371			1371*	0.124
5953	1430			1430	0.056
5915	1468			1468*	0.026
5842	1541			1541*[b]	0.186
5773	1610			1613*	0.298

[a] The error in energy is ±3 keV, that in intensity is $\pm20\%$.
[b] Data from the bent-crystal spectrometer indicate that this level is a doublet.

For the sample of natural hafnium, we were able to check our intensities with those given previously by Groshev *et al.*[4] Within experimental error, our germanium-diode measurements agree very well with the Compton-spectrometer results of Groshev *et al.*[4] In some cases we found that the lines reported previously were actually doublets or triplets. In each of these cases, the sum of our intensities agreed—again within experimental error—with the intensity of the single line reported in the previous measurement.

Since all of our intensities were computed on the assumption that the strong 5720-keV line in hafnium is in Hf^{179}, it is necessary to justify this assumption. To do this, we first established the identification of the 7317- and the 7530-keV lines. The energy of these lines places them well above the neutron separation energies

TABLE III. Lines due to the $Hf^{178}(n,\gamma)Hf^{179}$ and $Hf^{180}(n,\gamma)Hf^{181}$ reactions. The neutron separation energy E_s is 6098 ± 3 keV for Hf^{179}, and 5693 ± 3 keV for Hf^{181}.

Energy[a] E_γ (keV)	(E_s-E_γ) (keV)	Known levels Energy (keV)	Spin and parity	Intensity[b] (% per capture in Hf^{178})
		A. From $Hf^{178}(n,\gamma)Hf^{179}$		
5720	378	378	$\frac{1}{2}^-$	8.75 (Groshev)
5676	422	421	$\frac{9}{2}^-$	1.49
		B. From $Hf^{180}(n,\gamma)Hf^{181}$		
5693	0	0	...	17.0
5646	47	...	...	5.0

[a] The error in each energy is ±3 keV.
[b] The error in intensity is $\pm20\%$ for the $Hf^{178}(n,\gamma)Hf^{179}$ lines and $\pm30\%$ for the $Hf^{180}(n,\gamma)Hf^{181}$ lines.

TABLE IV. Information for isotopic identification of gamma lines. For a 100% line following neutron capture in a given isotope, the expected intensities in the three targets are equal to the contributions to the total cross section (last three columns). These values, computed from the capture cross section σ and the abundances in the three targets, are given for each stable isotope of hafnium.

Capturing isotope	Thermal neutron cross section (b)	Composition of target (%)			Contribution to total cross section (%)		
		Natural	Enriched Hf^{177}	Enriched Hf^{179}	Natural	Enriched Hf^{177}	Enriched Hf^{179}
Hf^{174}	1500±1000	0.18	~0.1	<0.1	2.5	0.45	<2.
Hf^{176}	15±15	5.15	~0.4	<0.1	0.7	0.02	<0.02
Hf^{177}	380±30	18.39	80.0	1.2	65.2	95.4	7.2
Hf^{178}	75±10	27.08	17.2	4.6	18.9	3.98	5.4
Hf^{179}	65±15	13.78	1.1	83.6	8.4	0.22	85.1
Hf^{180}	14±5	35.44	1.1	10.0	4.3	0.05	2.2

of all the hafnium isotopes except Hf^{178} and Hf^{180} (and the 7530-keV line is well above the neutron separation energy of Hf^{180}). Since these lines appear in the spectra of the natural hafnium and in the enriched Hf^{177} targets, but not in the enriched Hf^{179} target, their assignment of $Hf^{179}(n,\gamma)Hf^{180}$ may be ruled out. Therefore these lines can be identified only with Hf^{178}. Further verifications of this identification are (1) the fact that the ratio of the intensities of these two lines (7317- and 7530-keV) is the same in natural hafnium as it is in the enriched Hf^{177} target, showing that the lines are from the same isotope; (2) their separation (213 keV) is exactly the separation between the 93- and 306-keV first and second excited levels of Hf^{178}; and (3) these two levels (spins 2^+ and 4^+, respectively) can be reached by transitions from the capturing levels (spins 3^- and 4^-) in Hf^{178}.

We can now identify the 5720-keV line as arising from $Hf^{178}(n,\gamma)Hf^{179}$ since the intensity of the 5720-keV line, relative to that of either of the two lines in Hf^{178}, varies from the natural hafnium to the enriched Hf^{177} target in exactly the manner expected for a Hf^{179} line. From the Q value of Vergnes and Sheline,[7] the energy of the intense 5720-keV line is in excellent agreement with that of an $E1$ transition from the capturing state to the 378-keV $\frac{1}{2}^-$ isomeric level in Hf^{179}.

Lines resulting from capture in Hf^{179} were difficult to see in the natural and enriched Hf^{177} targets because of their low intensity in these samples and because of the interference of strong lines from $Hf^{177}(n,\gamma)Hf^{178}$. However, the high enrichment of Hf^{179} in the enriched Hf^{179} target greatly enhanced the intensity of lines from $Hf^{179}(n,\gamma)Hf^{180}$ while reducing the intensity of the interfering lines. [The ratio of the intensity of any particular γ line from $Hf^{179}(n,\gamma)Hf^{180}$ to that of some line from $Hf^{177}(n,\gamma)Hf^{178}$ is 80 times as great for the enriched Hf^{179} target as it is for the natural target.]

Isotopic identifications for lines in Hf^{178}, Hf^{179}, or Hf^{181} were made by comparing the observed intensity variation from target to target with the variation expected from the isotopic compositions of the targets. Table IV lists the capturing isotopes, their capture cross sections, their abundances in each target, and the consequent isotopic contributions to the total cross section of each isotope. The energies and intensities of the observed lines are shown in Table V. To compare the observed intensity variations with the expected ones, the intensity of a line in each of the enriched targets was

TABLE V. Measured energies and intensities of the observed gamma lines from neutron capture in hafnium. The energies in parentheses (second column) are previously measured[a] energies.

Energy (keV)		Intensities (% per capture in sample) Natural	Enriched Hf^{177}	Enriched Hf^{179}	Capturing isotope
7530	(7526)	0.045	0.062	...	Hf^{177}
7317	(7310)	0.025	0.045	...	Hf^{177}
7074	...	...	...	0.039	Hf^{179}
6742	...	...	...	0.047	Hf^{179}
6445	(6442)	0.058	0.091	0.013	Hf^{177}
6354	(6352)	0.304	0.430	0.087	Hf^{177}
6301	(6295)	0.070	0.091	...	Hf^{177}
6239	(6234)	0.079	0.095	...	Hf^{177}
6231		...	...	0.017	Hf^{179}
6214	(6216)	0.048	0.061	...	Hf^{177}
6203	...	...	...	0.028	Hf^{179}
6196	(6195)	...	...	0.014	Hf^{179}
6191		0.039	0.034	...	Hf^{177}
6190		...	...	0.030	Hf^{179}
6172	(6166)	0.044	0.049	...	Hf^{177}
6123		...	...	0.030	Hf^{179}
6110	(6106)	0.655	0.780	0.050	Hf^{177}
6095		...	...	0.071	Hf^{179}
6091	(6088)	0.130	0.104	...	Hf^{177}
6063	(6056)	0.113	0.115	...	Hf^{177}
6012		...	...	0.106	Hf^{179}
5987	(5984)	0.128	0.134	...	Hf^{177}
5953			...	0.048	Hf^{179}
5915		...	...	0.022	Hf^{179}
5863		0.042	0.049	...	Hf^{177}
5842		...	...	0.158	Hf^{179}
5802	(5803)	0.249	0.370	0.015	Hf^{177}
5773		...	...	0.254	Hf^{179}
5759	(5755)	0.161	0.185	0.021	Hf^{177}
5751		0.072	0.091	0.007	Hf^{177}
5720	(5716)	1.65 (def)	0.348 (def)	0.474 (def)	Hf^{178}
5707		0.181	0.147	0.026	Hf^{177}
5693	(5690)	0.770	...	0.374	Hf^{180}
5679		0.031	0.044	...	Hf^{177}
5676	(5671)	0.301	0.060	0.090	Hf^{178}
5666		0.108	0.158	...	Hf^{177}
5647		0.187	...	0.085	Hf^{180}
5635	(5637)	0.109	0.116	0.008	Hf^{177}
5623		0.093	0.096	...	Hf^{177}
5610		0.132	0.146	...	Hf^{177}
5602		0.071	0.072	...	Hf^{177}
5574	(5570)	0.306	0.262	0.019	Hf^{177}

[7] M. N. Vergnes and R. K. Sheline, Phys. Rev. 132, 1736 (1963).

[a] See Ref. 4.

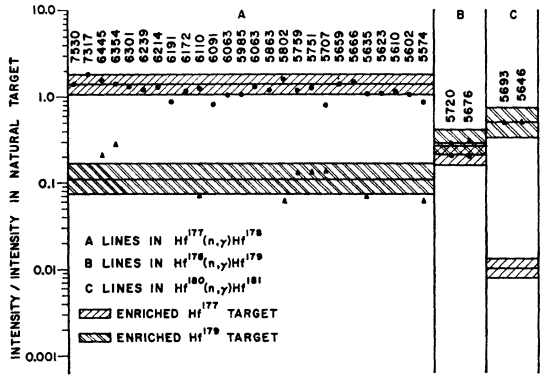

FIG. 3. Plot for isotopic identification of γ lines from neutron capture in hafnium isotopes. Lines in part A are from the $Hf^{177}(n,\gamma)Hf^{178}$ reaction, those in B from $Hf^{178}(n,\gamma)Hf^{179}$, and those in C from $Hf^{180}(n,\gamma)Hf^{181}$. For each line, the ratio of the intensity in the enriched target to the intensity in the natural target is represented by a circle for the enriched Hf^{177} target and by a triangle for the enriched Hf^{179} target. The energies of the lines are given in keV at top of figure.

divided by its intensity in the natural target (if it appears in the spectrum of the natural target). The values of this ratio for the Hf^{177} target (circles) and for the Hf^{179} target (triangles) for each observed line (labeled with its energy in keV) were then plotted on a semilog scale (Fig. 3). The expected values of the ratios were plotted as shaded bands whose widths represent the experimental errors or the expected standard deviations. For lines in Hf^{178} resulting from neutron capture in Hf^{177}, for example, one sees (last three columns in the third row of Table IV) that the expected ratio of the intensity in the enriched Hf^{177} target to the intensity in the natural hafnium target is $95.4/65.2 = 1.4$ and that the expected ratio for the enriched Hf^{179} target is $7.2/65.2 = 0.11$. The two bands for this isotope (part A of Fig. 3) are therefore centered at 1.4 and 0.11, respectively. The plotted points for all observed lines from the $Hf^{177}(n,\gamma)Hf^{178}$ reaction should fall in or near the band corresponding to the enriched target used. Parts B and C of Fig. 3 are similar plots for lines from the $Hf^{178}(n,\gamma)Hf^{179}$ and $Hf^{180}(n,\gamma)Hf^{181}$ reactions, respectively. It is clear from these plots that every line seen in the natural target can be unambiguously identified with capture in a particular isotope (Hf^{177}, Hf^{178}, or Hf^{180}); no point falls significantly outside the appropriate band.

Some slight difficulty was encountered in identifying three doublets at about 6091, 6191, and 5676 keV in natural hafnium. In each case, the doublet was found to result from a fortuitous near-equality of the energies of lines in two different hafnium isotopes. Comparison between the relative intensities of these lines in the enriched Hf^{177} and enriched Hf^{179} targets led to identification of the two isotopes responsible for each doublet and to determination of the intensity of the line in each isotope. The total intensity of the doublet expected in the natural target was then computed. In all three cases, the fact that the computed intensity agreed well with the measured one confirmed that the lines had been correctly resolved.

2. Explanation of Spectra

The gamma-ray spectra obtained with the natural hafnium, enriched Hf^{177}, and enriched Hf^{179} targets are shown in Figs. 4, 5, and 6, respectively. Except for the labeled background lines (such as the two high-energy aluminum lines and the two high-energy iron lines) the energy labels in Fig. 4 designate lines due to natural hafnium. Except where otherwise noted all labeled lines in Fig. 5 are in Hf^{178}, and all labeled lines in Fig. 6 are in Hf^{180}.

Isotopic assignment was not attempted for hafnium lines below 5574 keV. Because of the large number of lines in this region, especially for the natural hafnium sample, more and more doublets and closely-spaced lines appeared at lower energies. Consequently, clear identifications become increasingly difficult and none of these lines are labeled with their energies or isotopic assignments.

3. Neutron Separation Energies

From the isotopic identifications and energy measurements we were able to determine that the neutron separation energy was 7623 keV for Hf^{178}, 6098 keV for Hf^{179}, 7383 keV for Hf^{180}, and 5693 keV for Hf^{181}. The uncertainty in energy in each case is 3 keV. Let us now consider these separation energies individually.

In Hf^{178}, the previous value[4] of the neutron separation energy was 7619 ± 5 keV. The capture state can be 3^- or 4^- and we would expect states with spins 2, 3, 4, and 5 to be populated most strongly from the capture state. From energy and spin considerations the 7530- and 7317-keV transitions in Hf^{178} were identified as transitions from the capture state to the 2^+ 93-keV and the 4^+ 306-keV levels, respectively. Both the 7530- and the 7317-keV transitions, when added to the energies of the respective levels to which they go, give the same value of the neutron separation energy, namely 7623 ± 3 keV.

For Hf^{180}, the previous neutron separation energy[8] was 7320 ± 60 keV. The spin of the capture state can be 4^+ or 5^+; and states of spins 3, 4, 5, and 6 would be populated most strongly from the capture state. Accordingly, the 7074- and 6742-keV transitions must be transitions from the capture state to the 4^+ 309-keV and 6^+ 641-keV levels, respectively. For each of these transitions, the transition energy and the energy of the level to which it goes add up to the same value of the neutron separation energy (7383 keV).

The neutron separation energy in Hf^{179} was found from the 5720-keV transition to the 378-keV isomeric

[8] W. H. Johnson, Jr., and V. B. Bhanot, Phys. Rev. **107**, 1669 (1957).

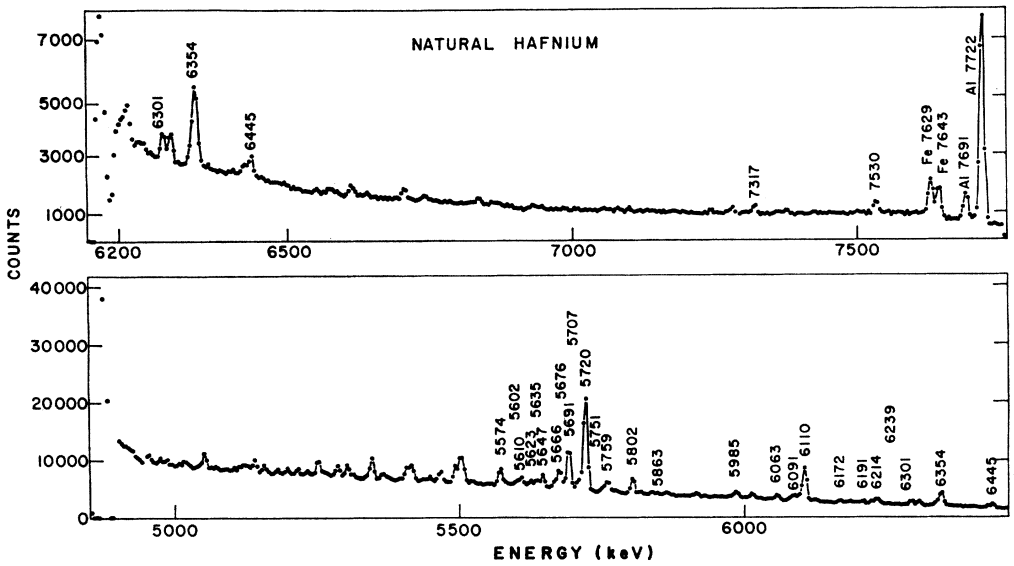

FIG. 4. Neutron-capture gamma-ray spectrum from a natural hafnium target. Except for the background lines (for which the elements responsible are also noted), all lines labeled with their energies (keV) are from capture in hafnium.

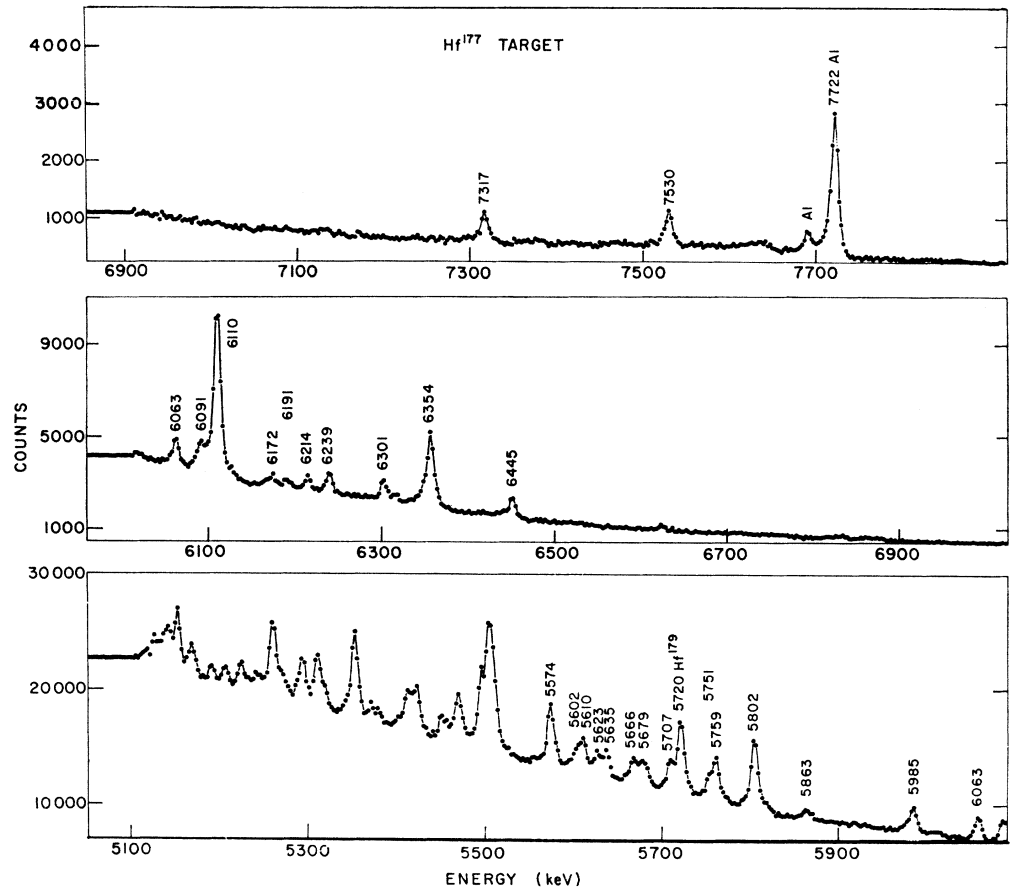

FIG. 5. Neutron-capture gamma-ray spectrum from the enriched Hf^{177} target. Except where otherwise noted, all lines labeled with their energies (keV) are from transitions in Hf^{178}.

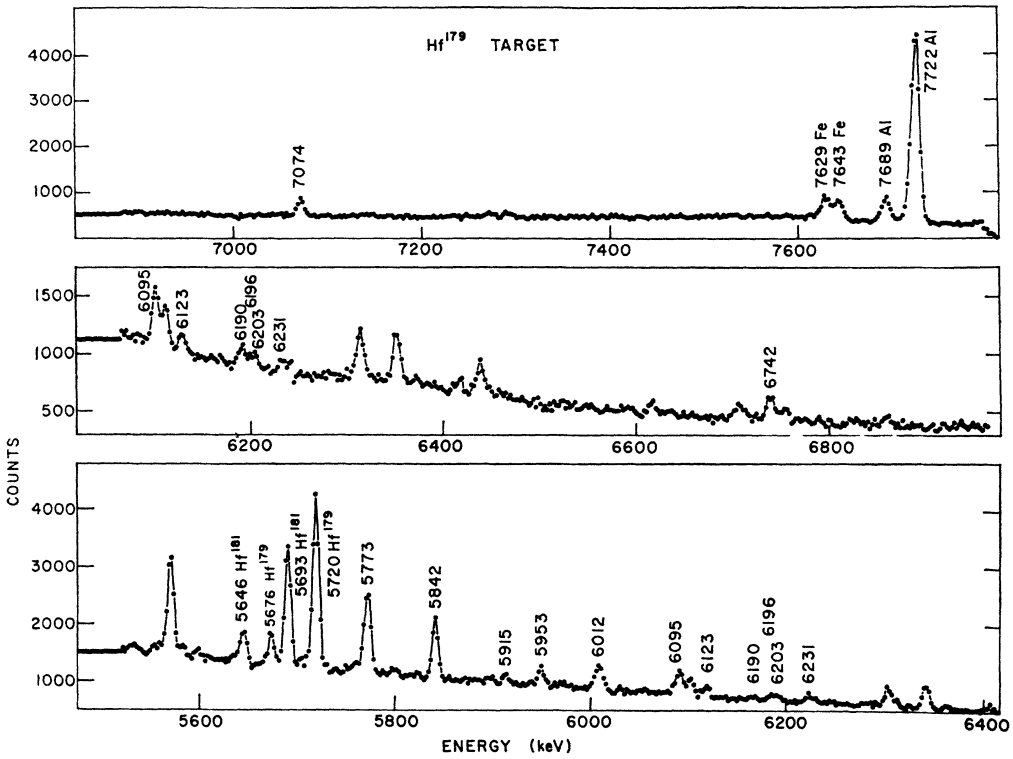

FIG. 6. Neutron-capture gamma-ray spectrum from the enriched Hf^{179} target. Except where otherwise noted, all lines labeled with their energies (keV) are from transitions in Hf^{180}.

level. The identification of this transition has already been discussed at the beginning of Sec. IV.1. The previous neutron separation energy, computed from the Q value found in the (d,p) work of Vergnes *et al.*,[7] was 6098±14 keV—in exact agreement with our value of 6098±3 keV.

For Hf^{181}, the previous neutron separation energy[9] was 5.80±0.08 MeV. The spin of the capture state is $\frac{1}{2}^+$ and the spin of the ground state is $\frac{1}{2}^-$. From the spin values, the approximate neutron separation energy, and the fact that the 5693-keV transition is the highest energy transition we could observe in Hf^{181}, we could conclude that this must be an $E1$ transition from the capture state to the ground state. The neutron separation energy, then, is 5693±3 keV.

V. DISCUSSION OF RESULTS

1. Levels in Hf^{178}

The high-energy gamma lines we observed in Hf^{178} were found to agree very well with the low-energy data.[3] In addition to the known levels observed at 93 and 306 keV, we verified seven other levels discovered in previous experiments.[3,4] Figure 7 shows a level scheme for the decay from the capture state to previously known levels and to many new levels indicated by our data. The second column of Table I shows the energies of levels as determined from our high-energy data. One of the previously known levels (the 1174-keV level found by Groshev *et al.*[4]) disagrees with our energy determination by more than 3 keV. (It is 4 keV lower than ours.) With only one exception (the 1431.25-keV level,[3] which has previously been assigned a spin of 0^+), the spins of the levels to which we observe transitions agree with the values expected for levels populated from the capture state. The combination of our data with low-energy data indicates that a spin of 2^+ would be more likely for this level. The previous spin assignments for the previously known levels are indicated in the fourth column of Table III.

2. Levels in Hf^{180}

With the aid of the usual assumption that all of the high-energy gamma rays result from transitions originating from the capture state, our accurate values of the neutron separation energies of Hf^{180} and our high-energy gamma rays enable us to propose a new level at the terminus of each gamma transition. No direct check of these levels is available since we know of no low-energy decay scheme for Hf^{180} that includes levels at energies above the 9^- level at 1143 keV. However,

[9] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.), Appendix 4, NRC 6-6-A5.

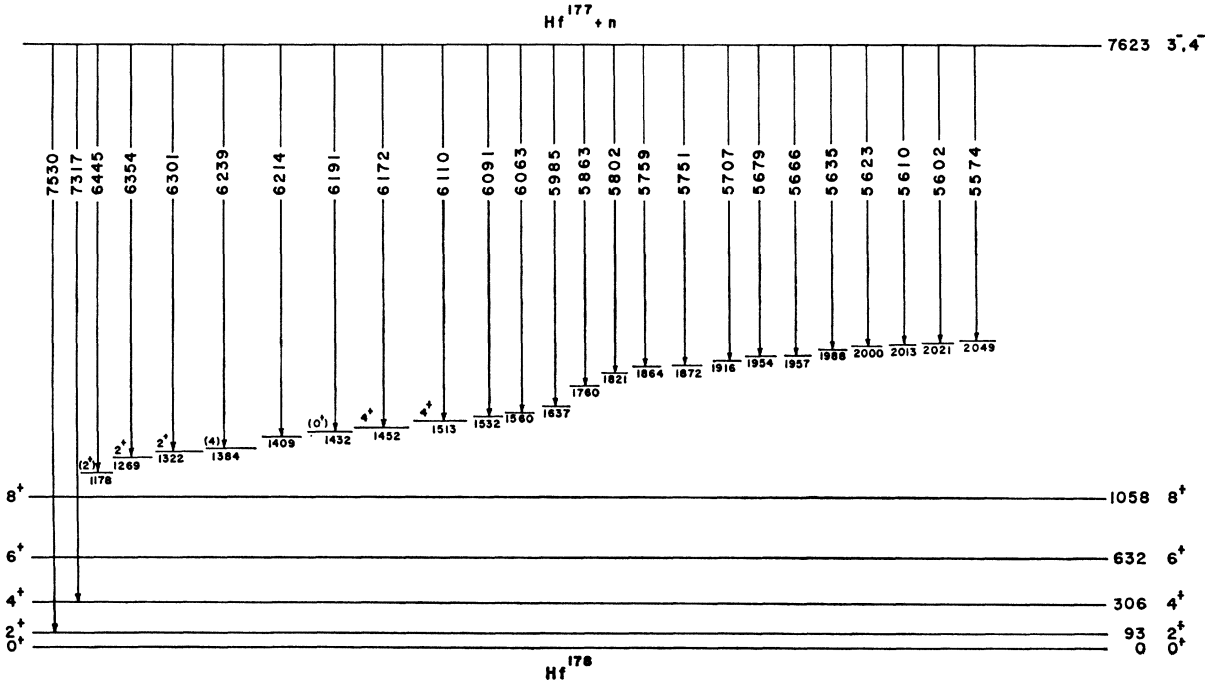

FIG. 7. Transitions to levels in Hf^{178}. Levels known from low-energy data (Refs. 3 and 4) are indicated by showing the spin assignments.

low-energy gamma lines from the $Hf^{179}(n,\gamma)Hf^{180}$ reaction had been measured very precisely[10] with the Argone bent-crystal spectrometer. As a check on our data for each proposed new level, we checked our data by searching the bent-crystal data for a gamma ray that might depopulate this level to the level in the ground-state rotational band—i.e., a gamma ray for which (within the experimental error of ± 3 keV) the energy matched the difference between our proposed new level and the known level in the ground-state rotational band. Whenever a match was found, the energy of the level was defined more precisely (within less than 1 keV) by use of the accurate measurements of low-energy gamma transitions and levels. With the aid of the bent-crystal data, we then attempted to construct a consistent decay scheme with γ transtions between those levels whose energies had been refined, subject to the requirement that each refined level be connected to another by at least two transitions. We succeeded in constructing a scheme containing nine of our eleven new levels. To see if an inaccurate or even completely false set of gamma rays would check just as well with the bent-crystal data, we simulated erroneous data by adding random energies from -100 keV to $+100$ keV to each of our original set of high-energy gamma rays. Many such sets of erroneous data were constructed, and for each set we again attempted to construct a decay scheme according to the same rules as before. In all of the random attempts, we found far fewer matches for possible transitions to the ground-state rotational band than we found for the actual lines. When we attempted to use these matching lines to construct a decay scheme in accordance with the same rules as before, no decay scheme containing any new levels could be found for any of these sets of random gamma rays. We, therefore consider this to be a significant check on the mutual consistency of the high- and low-energy data as well as the usefulness of combining the two different kinds of data.

The proposed new levels are indicated in the fourth column of Table II. An asterisk marks each level that fits the test just described. Figure 8 is a level scheme showing the decay from the capture state to the previously known levels at 306 and 641 keV and to the proposed new levels.

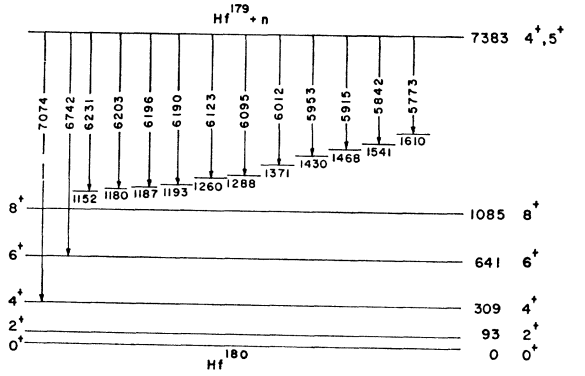

FIG. 8. Proposed level scheme of Hf^{180} based on high-energy (n,γ) data. All energies are in keV.

[10] R. K. Smither (unpublished data).

3. Levels in Hf^{179} and Hf^{181}

Only two gamma lines have been observed in each of these isotopes. Their energies and intensities are shown in Table III. When the Hf^{179} lines are compared with the Hf^{181} lines, both isotopes are seen to show intense $E1$ transitions from the capture state (a $\frac{1}{2}^+$ state in each case) to a low-lying $\frac{1}{2}^-$ state (the $\frac{1}{2}^-$ isomeric level at 378 keV in Hf^{179} and the $\frac{1}{2}^-$ ground state in Hf^{181}), and also a somewhat less intense (but still strong) transition from the capture state to a level just above the $\frac{1}{2}^-$ level. The spacing from the $\frac{1}{2}^-$ level to the level just above it is about the same in both isotopes —44 keV in Hf^{179} and 47 keV in Hf^{181}. The levels which we observed in Hf^{179} have also been observed in (d,p) work and have been identified with the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels in the $\frac{1}{2}^-(510)$ Nilsson band.[7] The present data suggest that the ground state and 47-keV state, to which we have observed transitions in Hf^{181}, are the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels in the $\frac{1}{2}^-(510)$ band.

It is interesting to see how our measurements on Hf^{179} and Hf^{181} compare with known data on W^{183}. The latter has the same number of neutrons as Hf^{181}, differing only in that it has an additional pair of protons. The ground state of W^{183}, like that of Hf^{181}, is a $\frac{1}{2}^-(510)$ state; and this isotope has intense $E1$ transitions from the capture state to the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels in the $\frac{1}{2}^-(510)$ band. The transition rates are 13% and 3%, respectively.[11] The ratio (4.3:1) of these two intensities in W^{183} agrees fairly well with the ratios (5.9:1 and 3.4:1) for the corresponding transitions in Hf^{179} and Hf^{181}, respectively. The energy separation between the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels in the (510) band of W^{183} is 46 keV, which is close to the (44±3)-keV separation in Hf^{179} and the (47±3)keV separation in Hf^{181}.

ACKNOWLEDGMENTS

We would like to acknowledge our indebtedness to H. Mann and his co-workers who provided us with the germanium detectors and gave us much assistance during this work.

[11] G. A. Bartholomew, J. W. Knowles, and P. J. Campion, Atomic Energy Commission, Ltd. Report No. AECL-954-43, 1960 (unpublished).

PHYSICAL REVIEW VOLUME 146, NUMBER 3 17 JUNE 1966

Further Study of Nuclear Resonant Scattering Using Neutron-Capture Gamma Rays

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(Received 11 October 1965)

The study of resonance scattering of neutron-capture gamma rays has been extended using 22 capture gamma sources and 57 scattering targets. About 50 resonance-scattering events have been observed in 23 elements and the effective cross sections evaluated. Some cases of complex spectra are described. The association of the scattering with nuclei in the region of closed shells is clearly shown. Problems of minimum observable cross sections are discussed and some further applications of the technique are suggested.

INTRODUCTION

MANY instances of nuclear resonant scattering of gamma rays have been observed[1–4] when various elements are irradiated with monoenergetic neutron-capture gamma rays. Resonant scattering occurs when the energy of the gamma ray (after correction for target recoil) happens to overlap, partially or entirely, an individual nuclear level in the target nucleus. In the works referred to above the scattered spectra, in the energy range 6–9 MeV, were measured using sodium-iodide detectors positioned at an angle of 135° to the incident radiation. Despite the poor energy resolution of these detectors—which permitted the determination of the peak energy with a precision of only 50 keV—it was usually possible to identify unambiguously the particular capture gamma-ray line responsible for the resonance, using the published tabulations[5] of capture gamma rays, and thence to determine the energy of the resonant level in the target nucleus to the same accuracy as that of the known gamma line, i.e., to within 10 keV in most cases. A comparison of the intensity of the scattered and incident beam, permitted an evaluation of the effective

[1] G. Ben-David and B. Huebschmann, Phys. Letters 3, 82, (1962).
[2] B. Arad, G. Ben-David, I. Pelah, and Y. Schlesinger, Phys. Rev. 133, B684 (1964).
[3] H. H. Fleischmann, Ann. Physik 12, 133 (1963).
[4] C. S. Young and D. I. Donahue, Phys. Rev. 133, 1724 (1963).

[5] *Nuclear Data Sheets*, complied by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.).