

Levels in ^{166}Ho deduced from the (n,γ) reaction

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A high precision study of the $^{165}\text{Ho}(n,\gamma)^{166}\text{Ho}$ reaction, analyzed with advanced signal processing methods, has revealed the presence of 270 transitions with photon energy greater than 4050 keV. Application of a statistical model suggests that these transitions are most likely primary in nature and hence directly reflect the levels in ^{166}Ho up to an excitation above 2 MeV. The present data substantiate much of the level energy data below 1 MeV previously reported but, in most instances, with marked improvement in precision. In addition, new information on the previously unexplored region above this energy is presented. The level energies deduced from the high energy measurements have been refined, when possible, through use of crystal spectrometer data. The neutron separation energy is found to be 6243.68(2) keV. When the density of levels in ^{166}Ho is treated using a statistical model in which this quantity is represented by a constant temperature, the value for this parameter is found to be 520 keV.

INTRODUCTION

As part of a study to explore the form of the $E2$ strength function¹ using the thermal neutron capture reaction, high precision data were obtained for several nuclides including ^{166}Ho . Examination of the most recent compilation of the level structure of ^{166}Ho (Ref. 2) reveals that, while considerable information exists below an excitation energy of about 1 MeV, above this energy little is known. Because of the high statistical precision attained in this study and the advanced signal processing methods available, we undertook to partially rectify this paucity by conducting further and more extensive analysis of the data.

The level scheme of ^{166}Ho as proposed² is based upon the thermal neutron capture work of Motz *et al.*³ and Rasmussen *et al.*⁴ as well as the resonance neutron capture work of Bollinger and Thomas.⁵ The study of Motz *et al.*³ included low-energy crystal spectrometer data, useful for obtaining precise energies once the presence of a level has been established, as well as (d,p) measurements. The particle work, though possessing lower resolution and precision, does not suffer from the possible ambiguity of transition placement associated with the neutron reaction. The work of Rasmussen *et al.*⁴ covers a wider range of the photon spectrum with a quality comparable to that of Motz *et al.*

The work of Bollinger and Thomas⁵ provides a much improved indication of the levels that exist within the first MeV of excitation. Because of resonance averaging, their measurements display a marked dampening in the Porter-Thomas⁶ fluctuations. Consequently, transitions that occur are not likely to be missed. The effectiveness of this method for sensing the presence of levels can be most easily summarized by noting that these authors report 73 states below 1 MeV while the thermal capture studies, Refs. 3 and 4, yield 30 and 20, respectively. The (d,p) investigations (Ref. 3) reveal 42 levels in the same interval.

Examination of the high energy (n,γ) results³⁻⁵ shows

energy spreads of 1–2 keV for transitions observed by all investigators. Such lack of precision, and most likely accuracy, has limited utilization of the crystal spectrometer data since, without small errors, the possibility of chance matches is extremely high. Of some 350 low-energy transitions, Motz *et al.*³ were able to place only 66 while Bollinger and Thomas,⁵ with a more complete set of detected levels and improved precision, made use of an additional 29. If a marked improvement could be realized in the accuracy and precision of primary γ -ray measurements, then it should be possible to refine the deduced level energies through use of the crystal spectrometer results. If successful, information regarding decay modes and hence insight into spin range and parity for the levels considered would also be obtained. An effort to attain this goal was another reason for undertaking the present study.

EXPERIMENTAL PROCEDURE

The present study was conducted at the tangential irradiation facility⁷ at the McMaster University Nuclear Reactor. Samples, which were contained within reactor grade graphite capsules, were subjected to a neutron flux of about 5×10^{12} n cm⁻² sec⁻¹ when the reactor was operated at its nominal power level of 2 MW. The collimation system produced a 1 cm² beam at the detector site, some 2 m from the sample. About 50 cm of Lucite was embedded within the collimator in order to prevent fast neutrons, scattered from the sample, from reaching the detector.

The detector, a 10% efficient intrinsic germanium device (Princeton Gamma-Tech), was centered within a quadrisectioned NaI(Tl) annulus. A resolution of from 3.1 to 4.5 keV, FWHM, was obtained for the photon range 4–6.2 MeV. All spectral measurements were stabilized against changes in both gain and zero through use of an NS 635. The zero was established by means of a ^{22}Na source and the gain by use of high energy transition in ^{166}Ho . Encodement of the selected signal was accom-

plished with a 13-bit NS 409 analog-to-digital converter (ADC) with the gain being established at a nominal 0.74 keV/channel. For acceptance, an event was required to be in time coincidence with annihilation photons, observed in opposite quadrants of the annulus, and in anticoincidence with the remaining quadrants. This latter condition was included in order to suppress events which emit bremsstrahlung⁸ thereby reducing the background continuum. Acceptable events were collected in a data acquisition system designed about a NOVA 2 computer.⁹

Initially a 0.4 g sample of holmium oxide (>99.9%, Aldrich Chemical Co.) was placed within a graphite capsule, inserted into the irradiation position and counted for a total of 240 h. This choice of sample size and counting period resulted in a 1% transition yielding a spectral peak which contained approximately 1.6×10^5 events. Throughout the acquisition period a daily check was made to ensure that stabilization of both gain and zero had been maintained. This was followed by irradiation of a well mixed sample consisting of melamine ($\text{C}_3\text{H}_6\text{N}_6$) and holmium oxide in order to obtain both energy and intensity calibrations through use of the $^{14}\text{N}(n,\gamma)^{15}\text{N}$ reaction. This sample, for which the stabilization points were identical to those used for the holmium target, was counted for a total period of 50 h. Finally, an empty graphite capsule was inserted into the irradiation position and the emitted radiation collected for a period of 90 h. The resultant spectrum was used to assess the significance of any background contribution. The capsule material revealed only traces of titanium but, of course, all spectra contained the radiative contribution from both neutron capture and inelastic scattering by carbon. Fortunately, the simplicity of this spectrum poses few problems in the way of interference.

The quality of the measurement can be seen in Fig. 1. Here is shown, through use of square root scale for the ordinate, the high energy portion of the $^{165}\text{Ho}(n,\gamma)^{166}\text{Ho}$ spectrum.

SPECTRAL ANALYSIS

Once it had been established that interference from the capsule, contaminants in the sample and the irradiation facility, were small and well defined, analysis of both the holmium and the calibration spectra were undertaken. Initially the "toe" associated with each peak, which is visible most clearly in the high energy region (see Fig. 1), was removed by application of an appropriate filter.¹⁰ Elimination of this relatively high frequency component made subsequent estimation of the background continuum sufficiently simple that the entire process could be automated.¹¹ When this first stage of the data reduction was completed, a detailed comparison between the holmium and the calibration spectrum was made. This revealed that, within the limit of detectability, the gain and zero of the two pulse height scales and the resolution for both measurements were identical. The ratio of the intensity of the holmium component in the calibration run to that of the holmium sample alone was then determined by fitting regions, throughout the entire spectrum, devoid of nitrogen peaks. This factor was then used to obtain the spec-

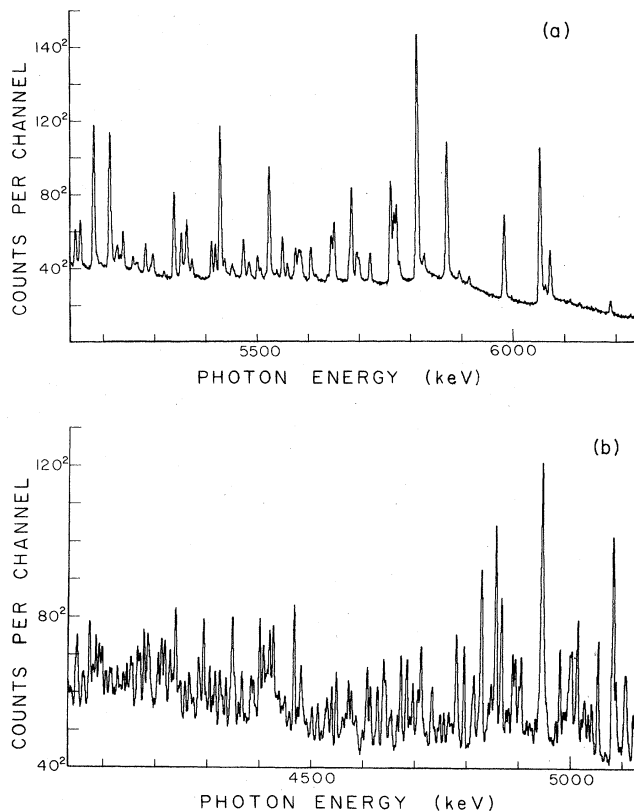


FIG. 1. The upper portion of the $^{165}\text{Ho}(n,\gamma)^{166}\text{Ho}$ spectrum is shown using a square root ordinate. The energy resolution in this region averaged 3.8 keV and a 1% transition possess in excess of 1.6×10^5 counts. The toe, clearly visible in the region around 6 MeV, makes removal of the underlying continuum difficult.

trum for nitrogen capture alone through weighted subtraction of the holmium contribution. Knowledge of this ratio permits the intensity calibration to be accomplished using separate spectra. Identity of the two scales allows the energy calibration to be achieved conveniently again with simplified spectra. The remaining background was then removed from both the nitrogen and the holmium spectrum in preparation for deconvolution.

When complex spectra are to be analyzed in complete detail, a procedure such as deconvolution is vital. The time and effort required when other methods, such as nonlinear regression, are used make such global application impractical. Actually deconvolution, even for simple spectra, makes subsequent estimation of peak centroid and area so straightforward that intervention by an analyst is unnecessary. Until recently no practical technique for deconvolution was available. However, with the development of a Bayesian based algorithm,¹²⁻¹⁴ it is now possible to obtain very significant resolution enhancement without encountering the common problem of uncontrolled noise growth. Application requires quantitative knowledge of the response function and its dependence upon energy. This iterative procedure, which is most effective when any underlying background is removed, yields a result in which spectral components occupy, be-

cause of centroid retention, an average of two channels.

The response function for the spectrometer used in this work was found to be indistinguishable from a Gaussian distribution. Determination of the energy dependence of the width parameter was hampered because of the paucity of single line components in the holmium spectrum. However, through use of the transitions from carbon and those of holmium which appeared to be strong and isolated,² it was found that the variance of the response could be represented by a quadratic function of channel number. The deconvolution algorithm, as presently implemented, uses a stationary response function while operating on a spectral section of any selected length. In view of the variation in response width with energy, as revealed in the fitting, a segment of 50 to 100 channels was found to be small enough to permit the imposition of such constancy without significant loss in resolution enhancement.

The sequence of steps used to analyze the present measurements can be seen, for the uppermost part of the holmium spectrum, through examination of Figs. 1 and 2. The high energy half of Fig. 1 is shown in the upper segment of Fig. 2 where the result obtained after the toe has been removed is illustrated. Comparison of the two spectra reveals that the residual underlying continuum in the latter displays a much higher degree of constancy. The lower panel of Fig. 2 presents the spectrum obtained after deconvolution. Here, while both ordinates are square root scales, the amplitude of the deconvolved spectrum has been reduced by a factor of 4.

The steps, as illustrated, were conducted throughout both the holmium and the nitrogen spectrum. This was followed by use of a computer search program to obtain all statistically significant spectral components. The search is a straightforward task, as can be seen from Fig. 2, because each component is delimited by zero content channels. The peak area and centroid are readily computed with both quantities (as has been shown in Ref. 14), re-

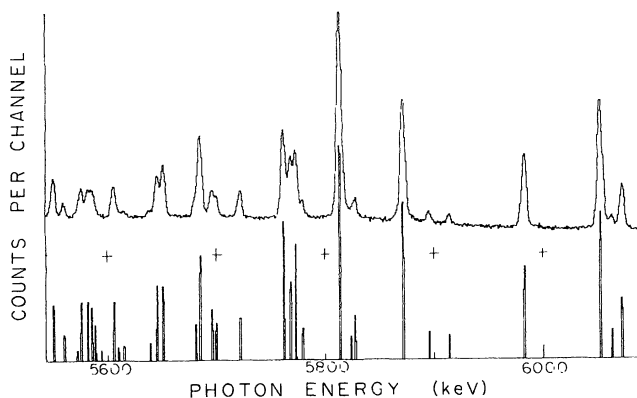


FIG. 2. The upper portion shows the high energy section of Fig. 1 after removal of the toe. Following estimation and subtraction of the background, deconvolution was used to produce the lower spectrum. Again a square root ordinate has been used; however, the scale for the deconvolved spectrum has been compressed by a factor of 4. The ease with which spectral components can be obtained is apparent in this latter spectrum.

taining the values displayed in the original data provided that the background is correctly estimated and the deconvolution is complete. To assess the fidelity of the background generated, the compiled estimates for area and centroid were used as inputs to a nonlinear fitting program. The program, based upon the simplex method,¹⁵ was used to fit short spectral sections to the components found in the deconvolution process as well as to a linear background. This was done for the energy region from 5.2 to 6.2 MeV using the spectrum with the toe removed. The differences observed in area and centroid were usually well within error; however, in all cases where changes occurred, the results reported are from the latter treatment.

Regression analysis was not applied throughout the entire spectrum and hence a procedure for error evaluation was required. The approach used consisted of first establishing the errors associated with the area and centroid of all the components found in the deconvolved spectrum by treating each as an isolated peak residing upon a known background. A closed form expression for the increase in parameter error due to the presence of neighbors has been derived¹⁶ using the variance-covariance matrix. The factor obtained from this expression, which is generally only dependent upon neighbor spacing in units of resolution width, is then used multiplicatively to adjust the original singlet values.

ENERGY AND INTENSITY CALIBRATION

Deconvolution of the $^{14}\text{N}(n,\gamma)^{15}\text{N}$ spectrum and tabulation of the detected components was followed by determination of a channel number to energy transformation function. The recently reported¹⁷ energy values for the transitions of nitrogen, which have average uncertainties of 20 eV and are based upon a neutron separation energy of 10833.302(12) keV,¹⁸ were used to determine the parameters for a model which related energy to channel number through a quadratic relationship. Evaluation of the error in the pulse height to energy transformation revealed an uncertainty of about 17 eV in the region of present concern, i.e., from 4 to 6 MeV and an error of less than 10 eV for the corresponding excitation energies. When this is combined with the 12 eV uncertainty in the ^{15}N neutron separation energy, a minimum error of 18 eV in photon energy is obtained.

The efficiency of the detection system and the determination of the absolute intensity for the transitions of holmium were based upon the nitrogen spectrum. The intensity of the transitions of nitrogen¹⁹ were used in conjunction with the observed peak areas to deduce the efficiency. This was fit to an analytical form previously reported.¹⁶

Determination of the absolute transition intensity with the mixed source technique requires the relative value of the effective neutron capture cross sections for the reactions involved. The irradiation position in this study has a ratio of thermal to resonance flux of about 40 and it is therefore necessary to consider the contribution of resonance capture. Data reveal²⁰ that the ^{165}Ho thermal neutron cross section is 66.5(3.3) b and the resonance integral, 700(20) b. The sample used for intensity calibration had a near spherical form and, using the mean chord²¹ associat-

TABLE I. High energy photons observed in the $^{165}\text{Ho}(n,\gamma)^{166}\text{Ho}$ reaction.

No.	Photon energy (keV)		Intensity/100 000		No.	Photon energy (keV)		Intensity/100 000	
1	6189.33	19	6	1	51	5338.30	2	182	10
2	6072.46	4	63	3	52	5318.25	68	3	1
3	6063.21	16	14	1	53	5296.86	10	31	2
4	6052.66	3	374	20	54	5292.47	30	9	1
5	5982.84	3	141	8	55	5282.54	6	46	3
6	5913.96	29	6	1	56	5266.39	66	8	2
7	5895.57	24	8	1	57	5263.83	99	6	2
8	5871.54	3	372	20	58	5258.45	14	17	1
9	5827.28	15	25	2	59	5238.79	5	64	4
10	5823.50	54	6	1	60	5232.95	18	14	1
11	5813.55	2	936	51	61	5227.40	15	33	3
12	5779.02	13	29	2	62	5224.39	50	10	2
13	5772.78	4	144	8	63	5220.16	233	2	2
14	5767.92	4	124	7	64	5217.47	54	10	2
15	5761.71	3	223	12	65	5213.25	3	403	22
16	5721.62	7	38	2	66	5188.76	22	11	1
17	5699.89	15	33	2	67	5181.84	2	429	23
18	5695.47	10	43	3	68	5155.71	4	88	5
19	5685.01	4	191	10	69	5146.18	5	66	4
20	5680.50	21	40	2	70	5128.96	3	265	14
21	5651.04	4	101	6	71	5122.22	7	40	2
22	5645.39	5	73	4	72	5112.61	30	11	1
23	5638.73	63	5	1	73	5108.66	11	62	4
24	5614.82	52	5	1	74	5105.84	12	61	4
25	5609.30	109	8	1	75	5102.34	27	14	1
26	5605.27	8	50	3	76	5096.91	36	7	1
27	5588.18	33	15	2	77	5088.79	4	74	4
28	5585.28	17	35	3	78	5082.28	3	332	18
29	5581.52	10	39	2	79	5068.65	54	4	1
30	5575.50	6	46	3	80	5053.50	4	113	6
31	5559.73	16	15	1	81	5044.17	126	4	2
32	5550.21	4	65	4	82	5041.52	14	45	4
33	5538.70	55	5	1	83	5035.02	9	32	2
34	5524.21	2	257	14	84	5028.70	23	33	4
35	5517.62	80	4	1	85	5026.38	29	26	4
36	5507.09	21	11	1	86	5022.02	13	23	2
37	5501.55	8	31	2	87	5013.59	4	147	8
38	5484.71	11	22	1	88	5008.77	12	24	2
39	5473.82	4	62	3	89	5002.93	6	89	5
40	5454.29	148	3	2	90	4999.39	7	87	5
41	5451.62	42	13	2	91	4995.44	10	43	3
42	5436.90	12	20	1	92	4990.94	14	26	2
43	5428.47	2	420	23	93	4986.76	12	28	2
44	5418.99	5	49	3	94	4979.79	4	97	5
45	5411.40	5	56	3	95	4972.19	19	14	1
46	5373.43	9	25	2	96	4954.34	11	30	2
47	5367.23	30	9	1	97	4949.84	7	68	4
48	5362.96	4	106	6	98	4945.18	7	405	22
49	5358.18	17	16	1	99	4942.56	9	124	8
50	5352.50	4	78	4	100	4938.83	13	31	2

TABLE I. (Continued).

No.	Photon energy			No.	Photon energy				
	(keV)		Intensity/100 000		(keV)		Intensity/100 000		
101	4933.10	15	19	1	151	4651.17	18	22	2
102	4925.59	32	11	1	152	4643.66	9	62	4
103	4921.59	25	14	1	153	4639.83	15	85	6
104	4916.09	21	15	1	154	4637.39	24	29	3
105	4911.53	59	5	1	155	4629.59	44	21	5
106	4904.89	6	86	5	156	4627.62	25	52	6
107	4900.58	8	47	3	157	4623.28	27	11	1
108	4893.71	5	92	5	158	4615.51	43	27	7
109	4888.62	5	92	5	159	4613.71	30	47	8
110	4880.91	11	29	2	160	4608.14	9	87	5
111	4876.33	16	24	2	161	4604.68	16	28	2
112	4872.21	101	3	1	162	4599.16	15	20	1
113	4866.83	6	180	10	163	4588.64	54	11	2
114	4863.49	19	23	2	164	4586.10	28	24	3
115	4855.89	5	311	17	165	4582.08	21	18	1
116	4851.71	11	36	2	166	4577.50	9	55	3
117	4846.87	7	62	4	167	4572.01	8	64	4
118	4841.87	11	35	2	168	4566.96	12	32	2
119	4837.78	34	10	1	169	4562.43	47	14	3
120	4827.84	4	273	15	170	4560.06	38	19	3
121	4822.16	13	23	2	171	4556.26	47	7	1
122	4813.84	7	76	4	172	4548.64	7	73	4
123	4810.00	12	35	2	173	4539.34	8	54	3
124	4794.72	5	98	5	174	4533.00	32	19	3
125	4784.76	46	11	2	175	4530.41	23	35	3
126	4781.95	41	23	5	176	4527.00	20	21	2
127	4779.73	14	122	8	177	4519.77	63	4	1
128	4776.34	51	8	1	178	4512.55	11	35	2
129	4771.86	38	16	2	179	4501.39	12	28	2
130	4769.19	56	11	2	180	4491.23	31	11	1
131	4765.15	13	30	2	181	4486.77	60	9	2
132	4756.49	13	24	2	182	4483.95	30	20	2
133	4749.05	18	23	2	183	4480.06	9	82	5
134	4745.46	37	10	1	184	4474.19	18	18	1
135	4738.11	26	11	1	185	4466.89	7	150	8
136	4733.04	7	66	4	186	4458.05	28	11	1
137	4722.36	40	7	1	187	4449.47	15	27	2
138	4716.78	17	18	1	188	4444.86	37	9	1
139	4711.52	6	123	7	189	4438.16	32	11	1
140	4706.02	11	52	3	190	4426.67	9	73	4
141	4702.68	51	9	2	191	4419.79	10	63	4
142	4699.17	98	5	2	192	4414.12	24	17	2
143	4696.15	12	59	4	193	4408.05	16	56	4
144	4690.69	13	25	2	194	4405.08	110	5	2
145	4684.74	17	88	7	195	4400.66	9	118	7
146	4682.63	36	24	5	196	4392.63	29	14	1
147	4677.09	47	7	1	197	4388.67	13	48	3
148	4672.89	7	102	6	198	4384.31	11	57	3
149	4666.75	12	25	2	199	4378.90	63	5	1
150	4654.85	13	31	2	200	4373.41	35	9	1

TABLE I. (Continued).

No.	Photon energy			Intensity/100 000	No.	Photon energy			
	(keV)					(keV)			
201	4366.79	9	64	4	236	4189.31	30	46	5
202	4360.66	18	19	2	237	4187.04	45	38	7
203	4352.80	11	47	3	238	4185.01	31	73	7
204	4348.37	11	151	8	239	4181.62	51	12	2
205	4344.69	15	34	2	240	4178.46	15	96	6
206	4335.98	11	47	3	241	4171.06	20	64	4
207	4329.72	37	21	3	242	4168.40	48	20	4
208	4327.40	55	15	3	243	4165.89	21	75	5
209	4324.33	15	61	4	244	4155.90	18	45	3
210	4315.48	10	62	4	245	4152.70	20	51	3
211	4310.56	16	24	2	246	4149.29	35	15	2
212	4304.77	10	58	3	247	4145.29	15	48	3
213	4297.68	16	26	2	248	4139.98	44	27	5
214	4292.78	12	138	8	249	4137.96	55	20	5
215	4289.35	71	7	2	250	4134.49	61	12	3
216	4286.13	21	38	3	251	4131.95	43	17	3
217	4282.98	14	69	4	252	4127.84	23	41	3
218	4273.88	27	20	2	253	4125.01	53	12	2
219	4270.78	79	9	3	254	4121.16	30	15	2
220	4268.17	40	20	3	255	4116.19	18	35	2
221	4265.33	18	50	3	256	4112.47	16	46	3
222	4257.68	12	38	2	257	4106.48	42	28	5
223	4248.29	16	37	2	258	4104.43	46	24	5
224	4244.72	20	26	2	259	4098.23	17	72	4
225	4238.77	10	179	10	260	4095.21	27	30	3
226	4232.89	13	47	3	261	4091.98	16	88	5
227	4228.59	21	65	5	262	4086.32	14	90	5
228	4226.08	36	20	3	263	4082.60	28	30	3
229	4220.65	31	24	3	264	4079.86	24	44	3
230	4218.03	19	85	5	265	4075.95	43	28	5
231	4213.94	28	40	4	266	4073.90	37	102	9
232	4211.61	23	77	6	267	4071.61	46	19	4
233	4206.22	17	64	4	268	4063.66	25	29	3
234	4203.29	27	24	2	269	4060.74	22	37	3
235	4192.43	39	14	2	270	4050.46	15	97	6

ed with this, the thick sample formula and the reported resonance parameters,²⁰ the contribution to capture from resonance neutrons was computed. A value equal to 3.7% that of thermal capture was found thereby leading to an effective cross section of 69.0 b. Nitrogen has a resonance integral which increases the thermal value of 77.2(21) mb (Ref. 22) by 1 mb. The error in absolute intensity arising from the combination of the uncertainty in the cross section ratio and that in the nitrogen transition intensities is about 6%.

RESULTS

The energy and intensity of the transitions observed in the $^{165}\text{Ho}(n,\gamma)^{166}\text{Ho}$ reaction for the energy range 4.05 to

6.19 MeV are presented in Table I along with the associated errors. Translation of these data into the energy of ^{166}Ho states requires the neutron separation energy and, more importantly, some assurance that the transitions are primaries. The most recent Q value²³ is reported to be 6243.69(11) keV. This value, deduced using ten well established levels,² exhibited an error of 0.03 keV but was subsequently increased to 0.11 keV to account for the uncertainty in the ^{15}N neutron separation energy. The error in this commonly used standard has been markedly reduced¹⁸ with the result that the uncertainty for ^{166}Ho now becomes 0.05 keV. The same procedure was repeated with the data in Table I. A total of 18 levels reported to have high precision² were used to obtain a Q value of

TABLE II. Summary of energy values for some low-lying ^{166}Ho states.

No.	Previous results ^a		Constructed from crystal data		Primary transitions		Mean level energy ^b	
1	54.239	2			54.22	19	54.239	2
2	171.074	5			171.093	33	171.074	5
3	180.467	6			180.34	16	180.467	6
4	190.901	6			190.88	11	190.898	5
5	260.661	7			260.707	20	260.666	7
6	278.2	10	278.69	10			278.69	10
7	295.7	15	295.996	42			295.996	42
8	329.775	9			329.59	29	329.775	9
9	348.257	10			347.98	24	348.257	10
10	371.984	10			372.013	13	371.995	8
11	377.806	10	377.86	20			377.806	10
12	416.084	8	416.076	29	416.28	15	416.084	8
13	421.0	20	420.041	21	420.06	54	420.041	21
14	430.030	13	430.10	20	430.012	11	430.020	8
15	452.0	10	452.623	13			452.623	13
16	464.480	30	464.503	16	464.54	13	464.498	14
17	470.839	12	470.93	13	470.779	29	470.831	11
18	475.5	10	475.668	19	475.642	33	475.662	16
19	481.845	13	481.787	60	481.844	19	481.843	11
20	514.0	20	514.423	29			514.423	29
21	522.000	30	522.036	28	521.941	64	522.012	19
22	542.9	10	543.626	17	543.68	14	543.626	17
23	547.956	17	548.010	84	548.090	96	547.962	16
24	558.562	17	558.571	13	558.549	29	558.566	10
25	562.910	15	562.95	12	563.06	21	562.911	15

6243.68(2), in agreement with the previous result. The genesis of the observed transitions remains to be ascribed if the results of Table I are to be used to deduce level energies.

Evidence for the presence of levels inferred from neutron capture gamma rays is best provided by high energy, high intensity transitions since these are almost always primary. For these, but particularly for transitions with diminished intensity, there is a possibility that a particular gamma ray does not originate from an exit channel of the compound nucleus but rather arises from the decay of an intermediate state. A procedure that provides a quantitative assessment of the chance of this occurring has been devised²⁴ and it is now possible to assign a confidence level to the existence of a state inferred in this way. The treatment is based upon a statistical model in which the level density is characterized by a constant nuclear temperature.²⁵ To carry out the associated computation, estimates for the temperature and the density of those states which can be populated by dipole radiation are needed. To assist in obtaining the former and also to check the validity of the model for the case of ^{166}Ho , analysis of the spectral data in the region of photon energy from 3.1 to 4.05 MeV was performed. This 940 keV span yielded 190 transitions which, when used in conjunction with the data of Table I, displayed an energy dependence^{26,27} for the

level density consistent with the exponential form assumed in the model. Employing the resonance spacing results,²⁰ a temperature of 570(15) keV was deduced—a value not too different from that of 520 keV reported some time ago by Gilbert and Cameron.²⁸ Performing the calculation, which gives the probability that a transition characterized by an energy and an intensity is a primary, reveals that all entries in Table I are of this class at the 0.999 confidence level.²⁴

At the present time the level scheme of ^{166}Ho is well established at low excitation with level energy uncertainties set by the crystal spectrometer results. At higher excitation the uncertainty increases markedly because the precision of the high energy measurements has been, to date, insufficient to allow level energy refinement through use of the crystal spectrometer data. The precision of the present data appeared to be adequate to permit imposition of the constraints that are necessary for the reliable application of the Ritz method. To assess the quality of the present level energy estimates, the agreement between our measurements and well established low-lying levels was examined with the result that observed differences were accounted for by assigned errors. Based upon this result it was decided to use the present results and the unassigned crystal data to obtain more precise estimates for levels up to 815 keV, an energy delimited by the intense

TABLE II. (Continued).

No.	Previous results ^a		Constructed from crystal data		Primary transitions		Mean level energy ^b	
	Energy	Error	Energy	Error	Energy	Error	Energy	Error
26	577.130	14	577.11	21			577.130	14
27	588.103	15	588.16	21			588.103	15
28	592.500	15	592.530	62	592.517	34	592.504	13
29	598.460	30	598.122	40	598.168	43	598.143	29
30	605.030	20	605.029	23	604.83	63	605.029	15
31	628.0	10	628.575	20	628.74	52	628.575	20
32	634.310	18	634.318	13	634.3	11	634.315	11
33	638.320	30	638.289	13	638.285	75	638.294	12
34	654.90	50	655.265	19	655.39	33	655.265	19
35	658.1	15	658.276	14	658.29	17	658.276	14
36	662.30	50	662.044	22	662.047	98	662.044	21
37	667.7	10	668.048	49	668.070	57	668.057	37
38	671.30	80	671.797	10			671.797	10
39	683.40	30	683.816	11	683.84	16	683.816	11
40	693.650	30	693.374	16	693.358	44	693.372	15
41	704.30	30	704.62	21	704.87	56	704.65	20
42	719.00	20	719.384	52	719.354	23	719.359	21
43	725.8	15	725.586	12	725.94	80	725.586	12
44	736.00	20	736.473	18	736.48	22	736.473	18
45	741.30	40	742.031	22	742.023	83	742.031	21
46	759.0	10	758.675	24	758.86	11	758.684	23
47	768.80	30	769.822	44	769.754	46	769.790	32
48	792.3	10	791.669	21	791.96	42	791.670	21
49	807.30	3	806.683	31	806.68	12	806.683	30
50	814.30	20	815.122	45	815.101	24	815.106	21

^aThe entries in the first column are the most precise energies found in the studies or deductions of Refs. 3 or 5.

^bThe mean level energy and error were found from weighted combinations of the entries in each row except for entry No. 29 and those above No. 33. In these cases, the mean was obtained using only the last two columns.

5428 keV transition and above the cutoff of the crystal data.

A computer program was developed which explored the ways in which low-energy transitions could be placed within the context of levels. The data base used encompassed the 260 unassigned transitions² from the crystal spectrometer measurements together with 58 levels. The energies of the levels used were the most precise values available. These were generally those of Motz *et al.*³ below 500 keV and those obtained from the present data above this energy. Exceptions to this were the 278 and 296 keV levels taken from the resonance work⁵ and the 514 keV level taken from the (d,p) results.³ Transitions were identified if their energy matched a level difference within combined error and, when adequate spin and parity information was available, if the multipolarity was $E1$, $E2$, $E3$, or $M1$. For each decay mode found for a particular level, the energy and error was determined. After the entire search had been completed, all decay channels established for a given level were combined to obtain a final level energy and associated error. This procedure was successful in placing a total of 136 transitions from the

set of 260. The level energies deduced with these are presented in Table II.

Table II gives a summary of level energies obtained here and previously.² The first column contains the previous values with associated error while the second gives the estimates obtained using the crystal data as indicated above. The third column gives the level energies deduced from the present high-energy measurements and the final column, a weighted average of all entries. Values excluded from the averaging, usually because of an apparent inaccuracy, are indicated in the table footnote. Examination of those previous results below the 598 keV level for which a small error has been assigned with those obtained from the high energy transitions reveals excellent agreement within assigned error. (The reduced χ^2 for the two data sets in this interval is 0.9.) Also it can be seen that the present results have precisions approaching those found with the crystal data in cases where the primary transition is intense.

Upon moving to higher levels of excitation, the previous results are usually found to have errors in excess of the new data. However, the level energy refinement

TABLE III. Additional levels observed in ^{160}Ho .

Excitation energy (keV)	Excitation energy (keV)	Excitation energy (keV)	Excitation energy (keV)	Excitation energy (keV)	Excitation energy (keV)	Excitation energy (keV)							
824.58	5	1137.75	14	1327.50	22	1498.13	37	1657.50	30	1838.52	110	1998.89	21
832.18	5	1141.25	27	1332.06	59	1505.49	27	1661.52	22	1842.95	11	2004.84	12
870.14	10	1146.67	36	1338.70	7	1510.55	8	1666.10	11	1850.97	30	2010.72	15
876.35	31	1154.79	6	1343.01	10	1521.23	41	1671.59	10	1854.94	15	2015.02	25
880.61	5	1161.30	4	1349.87	7	1526.81	18	1676.64	13	1859.30	13	2017.53	38
885.39	17	1174.93	54	1354.97	7	1532.07	8	1681.17	49	1864.71	63	2022.96	33
891.07	4	1190.09	5	1362.68	12	1537.57	13	1683.54	41	1870.20	36	2025.58	23
905.28	3	1199.42	126	1367.26	17	1540.92	52	1687.34	48	1876.82	11	2029.67	32
925.32	68	1202.07	16	1371.37	101	1544.43	99	1694.96	9	1882.95	19	2032.00	27
946.72	10	1208.57	9	1376.76	9	1547.45	14	1704.26	10	1890.80	13	2037.39	20
951.11	30	1214.89	25	1380.11	20	1552.91	14	1710.60	34	1895.23	14	2040.32	29
961.05	6	1217.21	31	1387.70	7	1558.86	22	1713.19	26	1898.92	17	2051.18	40
977.19	66	1221.56	14	1391.88	12	1560.96	39	1716.60	22	1907.62	12	2054.30	34
979.75	99	1230.00	6	1396.72	8	1566.51	48	1723.84	63	1913.89	40	2056.60	50
985.13	15	1234.82	13	1401.72	13	1570.71	9	1731.05	12	1916.21	57	2058.60	37
1004.80	5	1240.66	8	1405.81	34	1576.85	13	1742.21	14	1919.28	18	2061.98	53
1010.63	18	1244.20	10	1415.75	6	1588.75	15	1752.37	31	1928.13	12	2065.15	18
1016.18	16	1248.15	11	1421.43	14	1592.43	19	1756.84	60	1933.05	18	2072.55	23
1019.20	50	1252.65	15	1429.75	9	1599.94	11	1759.65	32	1938.84	12	2075.21	51
1023.42	233	1256.83	13	1433.60	13	1603.77	19	1763.54	12	1945.93	17	2077.72	25
1026.11	55	1263.80	6	1448.87	7	1606.21	27	1769.41	19	1950.83	15	2087.71	20
1030.34	4	1271.40	20	1458.83	47	1614.01	47	1776.71	9	1954.26	72	2090.91	23
1054.82	22	1289.25	12	1461.65	44	1615.98	30	1785.55	29	1957.48	24	2094.32	36
1061.74	4	1293.75	8	1463.87	20	1620.32	28	1794.13	16	1960.63	17	2098.32	17
1087.87	5	1298.41	11	1467.25	52	1628.09	47	1798.74	38	1969.73	28	2103.63	48
1097.40	6	1301.03	13	1471.73	40	1629.89	36	1805.44	33	1972.83	80	2105.64	59
1114.62	4	1304.76	14	1474.40	57	1635.46	12	1816.93	11	1975.44	43	2109.12	62
1121.36	8	1310.49	15	1478.45	14	1638.93	17	1823.82	12	1978.28	21	2111.66	45
1130.98	30	1318.00	32	1487.11	13	1644.44	16	1829.49	25	1985.93	14	2115.77	26
1134.93	13	1322.00	26	1494.54	19	1654.96	55	1835.55	19	1995.32	18	2118.60	55

achieved through use of unassigned crystal data is seen to have been quite effective in reducing the magnitude of the level energy error. Overall consistency among the column entries is seen to be good with only three clear exceptions; the levels at energies of 598, 693, and 807 keV. There is a trend above 600 keV for the values in the first and third columns to show divergence which we attribute to an inaccuracy in the energy scale used by Bollinger and Thomas.⁵ With the exception of the three cases identified, their level energy estimates have been used in this region, by Buyrn,² to produce a set of adopted values. The level energies at variance come from the work of Motz *et al.*³ who coincidentally used all three in a tentative assignment to the configuration $(523\uparrow - 523\downarrow)$. The fact that the 807 keV state in such a configuration has a spin of 6^+ would require the observed primary transition to be $E3$ or $M2$ since the possible spins of the compound state are 3^- and 4^- . Bollinger and Thomas⁵ infer from their resonance averaging technique that the spin of this state is either 2^+ or 5^+ with the latter being preferred. The other two transitions could be $E1$ since their assignments of 4^+ and 5^+ lie within the spin range $2-5$ which can be reached via dipole radiation. The energy differences for these transitions, as found by Motz *et al.* and ourselves, are seen to exceed error by factors far in excess of that for the other entries. Using our measured values for the initial estimate of the level energy, refined values were obtained which agree well with the high-energy results. It would appear

that the values found by Motz *et al.* using the Ritz principle, poorly defined level energies, and to some extent the collective model, are not correct. The energies observed here for the 589 and 693 keV levels imply that the previously assigned decay modes are no longer appropriate. Because of these inconsistencies, we conclude that the identification of these three levels as members of the rotational band associated with the $(523\uparrow - 523\downarrow)$ state is doubtful.

Motz *et al.*³ reported high energy transitions populating levels at 198 and 339 keV which are not observed in the present work. Based upon an estimated sensitivity of their experiment, we would have readily detected these transitions if present.

Finally, the data in Table I have been used to find level energies for the region above that presented in Table II. Since no precise level information is available, Table III contains only the present results. The rapidity with which level density increases with excitation energy is apparent. Even for a selective reaction such as that used here, details concerning levels above 2 MeV clearly will require improved resolution than that currently available.

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